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MIL-HDBK-5J
31 January 2003

SUPERSEDING
MIL-HDBK-5H
1 December 1998

DEPARTMENT OF DEFENSE HANDBOOK

METALLIC MATERIALS AND ELEMENTS FOR AEROSPACE VEHICLE STRUCTURES

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AMSC N/A **FSC 1560**

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FOREWORD

1. This handbook is approved for use by all Departments and Agencies of the Department of Defense and the Federal Aviation Administration. This is the last planned edition of MIL-HDBK-5. MIL-HDBK-5J is equivalent to MMPDS-01, the first edition of the Metallic Material Properties Development and Standardization Handbook, which is maintained by the Federal Aviation Administration. The FAA plans to publish annual updates and revisions to the MMPDS. As a result, MIL-HDBK-5J is scheduled to be reclassifed as noncurrent in the Spring of 2004. It will be superseded at that time by the MMPDS Handbook.

2. This handbook is for guidance only. This handbook cannot be cited as a requirement. If it is, the contractor does not have to comply.

3. This document contains design information on the strength properties of metallic materials and elements for aerospace vehicle structures. All information and data contained in this handbook have been coordinated with the Air Force, Army, Navy, Federal Aviation Administration, and industry prior to publication, and are being maintained as a joint effort of the Federal Aviation Administration and the Department of Defense.

4. The electronic copy of the Handbook is technically consistent with the paper-copy Handbook; however, minor differences exist in format; e.g., table or figure position. Depending on monitor size and resolution setting, more data may be viewed without on-screen magnification. The figures were converted to electronic format using one of several methods. For example, digitization or recomputation methods were used on most of the engineering figures like typical stress-strain and effect of temperature, etc. Scanning was used to capture informational figures such as those found in Chapters 1 and 9. These electronic figures were also used to generate the paper-copy figures to maintain equivalency between the paper copy and electronic copy. In all cases, the electronic figures have been compared to the paper-copy figures to ensure the electronic figures are technically equivalent. Appendix E provides a detailed listing of all the figures in the Handbook, along with a description of each figure's format.

5. Beneficial comments (recommendations, additions, deletions) and any pertinent data which may be of use in improving this document should be addressed to: Chairman, MIL-HDBK-5 Coordination Activity (937-656-9133 voice, 937-255-4997 fax), AFRL/MLSC, 2179 Twelfth St., Room 122, Wright-Patterson AFB, OH 45433-7718, by using the Standardization Document Improvement Proposal (DD Form 1426) appearing at the end of this document or by letter. Alternatively, comments may be sent directly to: Chairman, MMPDS Coordination Activity (609-485-4784 voice, 609-485-4004 fax), AAR-431, Aging Aircraft Structural Integrity Research, FAA William J. Hughes Technical Center, Atlantic City International Airport, Atlantic City, NJ 08405.

EXPLANATION OF NUMERICAL CODE

For chapters containing materials properties, a deci-numeric system is used to identify sections of text, tables, and illustrations. This system is explained in the examples shown below. Variations of this deci-numerical system are also used in Chapters 1, 8, and 9.

Example A 2.4.2.1.1

General material category (in this case, steel) . . . .

A logical breakdown of the base material by family characteristics (in this case, intermediate alloy steels); or for element properties . . . .

Particular alloy to which all data are pertinent. If zero, section contains comments on the family characteristics . . . .

If zero, section contains comments specific to the alloy; if it is an integer, the number identifies a specific temper or condition (heat treatment) . . . .

Type of graphical data presented on a given figure (see following description) . . . .

Example B 3.2.3.1.X

Aluminum . . . .

2000 Series Wrought Alloy . . . .

2024 Alloy . . . .

T3, T351, T3510, T3511, T4, and T42 Tempers . . . .

Specific Property as Follows . . . .

Tensile properties (ultimate and yield strength)	1
Compressive yield and shear ultimate strengths	2
Bearing properties (ultimate and yield strength)	3
Modulus of elasticity, shear modulus	4
Elongation, total strain at failure, and reduction of area	5
Stress-strain curves, tangent-modulus curves	6
Creep	7
Fatigue	8
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CHAPTER 1

GENERAL

1.1 PURPOSE AND USE OF DOCUMENT

1.1.1 INTRODUCTION — Since many aerospace companies manufacture both commercial and military products, the standardization of metallic materials design data, which are acceptable to Government procuring or certification agencies is very beneficial to those manufacturers as well as governmental agencies. Although the design requirements for military and commercial products may differ greatly, the required design values for the strength of materials and elements and other needed material characteristics are often identical. Therefore, this publication provides standardized design values and related design information for metallic materials and structural elements used in aerospace structures. The data contained herein, or from approved items in the minutes of MIL-HDBK-5 coordination meetings, are acceptable to the Air Force, the Navy, the Army, and the Federal Aviation Administration. Approval by the procuring or certificating agency must be obtained for the use of design values for products not contained herein.

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1.1.2 SCOPE OF HANDBOOK — This Handbook is primarily intended to provide a source of design mechanical and physical properties, and joint allowables. Material property and joint data obtained from tests by material and fastener producers, government agencies, and members of the airframe industry are submitted to MIL-HDBK-5 for review and analysis. Results of these analyses are submitted to the membership during semi-annual coordination meetings for approval and, when approved, published in this Handbook.

This Handbook also contains some useful basic formulas for structural element analysis. However, structural design and analysis are beyond the scope of this Handbook.

References for data and various test methods are listed at the end of each chapter. The reference number corresponds to the applicable paragraph of the chapter cited. Such references are intended to provide sources of additional information, but should not necessarily be considered as containing data suitable for design purposes.

The content of this Handbook is arranged as follows:

Chapter(s)	**Subjects**
1	Nomenclature, Systems of Units, Formulas, Material Property Definitions, Failure Analysis, Column Analysis, Thin-Walled Sections
2-7	Material Properties
8	Joint Allowables
9	Data Requirements, Statistical Analysis Procedures

1.2 NOMENCLATURE

1.2.1 SYMBOLS AND DEFINITIONS — The various symbols used throughout the Handbook to describe properties of materials, grain directions, test conditions, dimensions, and statistical analysis terminology are included in Appendix A.

1.2.2 INTERNATIONAL SYSTEM OF UNITS (SI) — Design properties and joint allowables contained in this Handbook are given in customary units of U.S. measure to ensure compatibility with government and industry material specifications and current aerospace design practice. Appendix A.4 may be used to assist in the conversion of these units to Standard International (SI) units when desired.

1.3 COMMONLY USED FORMULAS

1.3.1 GENERAL — Formulas provided in the following sections are listed for reference purposes. Sign conventions generally accepted in their use are that quantities associated with tension action (loads, stresses, strains, etc.), are usually considered as positive and quantities associated with compressive action are considered as negative. When compressive action is of primary interest, it is sometimes convenient to identify associated properties with a positive sign. Formulas for all statistical computations relating to allowables development are presented in Chapter 9.

1.3.2 SIMPLE UNIT STRESSES —

f_t = P / A (tension) [1.3.2(a)]
f_c = P / A (compression) [1.3.2(b)]
f_b = My / I = M / Z (bending) [1.3.2(c)]
f_s = S / A (average direct shear stress) [1.3.2(d)]
f_x = SQ / Ib (longitudinal or transverse shear stress) [1.3.2(e)]
f_x = Ty / I_p (shear stress in round tubes due to torsion) [1.3.2(f)]
f_s = (T/2At) (shear stress due to torsion in thin-walled structures of closed section. Note that A is the area enclosed by the median line of the section.) [1.3.2(g)]
f_A = Bf_H ; $f_T = Bf_L$ (axial and tangential stresses, where B = biaxial ratio) [1.3.2(h)]

1.3.3 COMBINED STRESSES (SEE SECTION 1.5.3.4) —

$f_A = f_c + f_b$ (compression and bending) [1.3.3(a)]

$f_{s\max} = \left[f_s^2 + \left(f_n/2 \right)^2 \right]^{1/2}$ (compression, bending, and torsion) [1.3.3(b)]

$f_{n\max} = f_n/2 + f_{s\max}$ [1.3.3(c)]

1.3.4 DEFLECTIONS (AXIAL) —

e = δ / L (unit deformation or strain) [1.3.4(a)]
E = f/e (This equation applied when E is obtained from the same tests in which f and e are measured.) [1.3.4(b)]
δ = eL = (f / E)L [1.3.4(c)]
= PL / (AE) (This equation applies when the deflection is to be calculated using a known value of E.) [1.3.4(d)]

1.3.5 DEFLECTIONS (BENDING) —

di/dx = M / (EI) (Change of slope per unit length of a beam; radians per unit length) [1.3.5(a)]

$i_2 = i_1 + \int_{x_1}^{x_2} [M/(EI)]dx$ — Slope at Point 2. (This integral denotes the area under the curve of M/EI plotted against x, between the limits of x_1 and x_2.) 1.3.5(b)]

$y_2 = y_1 + i(x_2 - x_1) + \int_{x_1}^{x_2} (M/EI)(x_2 - x)dx$ — Deflection at Point 2. [1.3.5(c)]

(This integral denotes the area under the curve having an ordinate equal to M/EI multiplied by the corresponding distances to Point 2, plotted against x, between the limits of x_1 and x_2.)

$y_2 = y_1 + \int_{x_1}^{x_2} i dx$ — Deflection at Point 2. (This integral denotes the area under the curve of $x_1(i)$ plotted against x, between the limits of x_1 and x_2.) [1.3.5(d)]

1.3.6 DEFLECTIONS (TORSION) —

$d\varphi / dx = T/(GJ)$ (Change of angular deflection or twist per unit length of a member, radians per unit length.) [1.3.6(a)]

$\Phi = \int_{x_1}^{x_2} [T/(GJ)]dx$ — Total twist over a length from x_1 to x_2. (This integral denotes the area under the curve of T/GJ plotted against x, between the limits of x_1 and x_2.) [1.3.6(b)]

$\Phi = TL/(GJ)$ (Used when torque T/GJ is constant over length L.) [1.3.6(c)]

1.3.7 BIAXIAL ELASTIC DEFORMATION —

$\mu = e_T/e_L$ (Unit lateral deformation/unit axial deformation.) This identifies Poisson's ratio in uniaxial loading. [1.3.7(a)]

$Ee_x = f_x - \mu f_y$ [1.3.7(b)]

$Ee_y = f_y - \mu f_x$ [1.3.7(c)]

$E_{biaxial} = E(1 - \mu B)$ — B = biaxial elastic modulus. [1.3.7(d)]

1.3.8 BASIC COLUMN FORMULAS —

$F_c = \pi^2 E_t (L'/\rho)^2$ where $L' = L/\sqrt{c}$ — conservative using tangent modulus [1.3.8(a)]

$F_c = \pi^2 E (L'/\rho)^2$ — standard Euler formula [1.3.8(b)]

1.3.9 INELASTIC STRESS-STRAIN RESPONSE —

$e_{total} = f / E + e_p$ (elastic strain response plus inelastic or plastic strain response) [1.3.9(a)]

where

$e_p = 0.002 * (f/f_{0.2ys})^n$, [1.3.9(b)]

$f_{0.2ys}$ = the 0.2 percent yield stress and

n = Ramberg-Osgood parameter

Equation [1.3.9(b)] implies a log-linear relationship between inelastic strain and stress, which is observed with many metallic materials, at least for inelastic strains ranging from the material's proportional limit to its yield stress.

1.4 BASIC PRINCIPLES

1.4.1 GENERAL — It is assumed that users of this Handbook are familiar with the principles of strength of materials. A brief summary of that subject is presented in the following paragraphs to emphasize principles of importance regarding the use of allowables for various metallic materials.

Requirements for adequate test data have been established to ensure a high degree of reliability for allowables published in this Handbook. Statistical analysis methods, provided in Chapter 9, are standardized and approved by all government regulatory agencies as well as MIL-HDBK-5 members from industry.

1.4.1.1 *Basis* — Primary static design properties are provided for the following conditions:

Tension	F_{tu} and F_{ty}
Compression	F_{cy}
Shear	F_{su}
Bearing	F_{bru} and F_{bry}

These design properties are presented as A- and B- or S-basis room temperature values for each alloy. Design properties for other temperatures, when determined in accordance with Section 1.4.1.3, are regarded as having the same basis as the corresponding room temperature values.

Elongation and reduction of area design properties listed in room temperature property tables represent procurement specification minimum requirements, and are designated as S-values. Elongation and reduction of area at other temperatures, as well as moduli, physical properties, creep properties, fatigue properties and fracture toughness properties are all typical values unless another basis is specifically indicated.

Use of B-Values — The use of B-basis design properties is permitted in design by the Air Force, the Army, the Navy, and the Federal Aviation Administration, subject to certain limitations specified by each agency. Reference should be made to specific requirements of the applicable agency before using B-values in design.

1.4.1.2 *Statistically Calculated Values* — Statistically calculated values are S (since 1975), T_{99} and T_{90}. S, the minimum properties guaranteed in the material specification, are calculated using the same requirements and procedure as AMS and is explained in Chapter 9. T_{99} and T_{90} are the local tolerance bounds, and are defined and may be computed using the data requirements and statistical procedures explained in Chapter 9.

1.4.1.3 *Ratioed Values* — A ratioed design property is one that is determined through its relationship with an established design value. This may be a tensile stress in a different grain direction from the established design property grain direction, or it may be another stress property, e.g., compression, shear or bearing. It may also be the same stress property at a different temperature. Refer to Chapter 9 for specific data requirements and data analysis procedures.

Derived properties are presented in two manners. Room temperature derived properties are presented in tabular form with their baseline design properties. Other than room temperature derived properties are presented in graphical form as percentages of the room temperature value. Percentage values apply to all forms and thicknesses shown in the room temperature design property table for the heat treatment condition indicated therein unless restrictions are otherwise indicated. Percentage curves usually represent short time exposures to temperature (thirty minutes) followed by testing at the same strain rate as used for the room temperature tests. When data are adequate, percentage curves are shown for other exposure times and are appropriately labeled.

1.4.2 STRESS — The term "stress" as used in this Handbook implies a force per unit area and is a measure of the intensity of the force acting on a definite plane passing through a given point (see Equations 1.3.2(a) and 1.3.2(b)). The stress distribution may or may not be uniform, depending on the nature of the loading condition. For example, tensile stresses identified by Equation 1.3.2(a) are considered to be uniform. The bending stress determined from Equation 1.3.2(c) refers to the stress at a specified distance perpendicular to the normal axis. The shear stress acting over the cross section of a member subjected to bending is not uniform. (Equation 1.3.2(d) gives the average shear stress.)

1.4.3 STRAIN — Strain is the change in length per unit length in a member or portion of a member. As in the case of stress, the strain distribution may or may not be uniform in a complex structural element, depending on the nature of the loading condition. Strains usually are present also in directions other than the directions of applied loads.

1.4.3.1 Poisson's Ratio Effect — A normal strain is that which is associated with a normal stress; a normal strain occurs in the direction in which its associated normal stress acts. Normal strains that result from an increase in length are designated as positive (+) and those that result in a decrease in length are designated as negative (-).

Under the condition of uniaxial loading, strain varies directly with stress. The ratio of stress to strain has a constant value (E) within the elastic range of the material, but decreases when the proportional limit is exceeded (plastic range). Axial strain is always accompanied by lateral strains of opposite sign in the two directions mutually perpendicular to the axial strain. Under these conditions, the absolute value of a ratio of lateral strain to axial strain is defined as Poisson's ratio. For stresses within the elastic range, this ratio is approximately constant. For stresses exceeding the proportional limit, this ratio is a function of the axial strain and is then referred to as the lateral contraction ratio. Information on the variation of Poisson's ratio with strain and with testing direction is available in Reference 1.4.3.1.

Under multiaxial loading conditions, strains resulting from the application of each directional load are additive. Strains must be calculated for each of the principal directions taking into account each of the principal stresses and Poisson's ratio (see Equation 1.3.7 for biaxial loading).

1.4.3.2 Shear Strain — When an element of uniform thickness is subjected to pure shear, each side of the element will be displaced in opposite directions. Shear strain is computed by dividing this total displacement by the right angle distance separating the two sides.

1.4.3.3 Strain Rate — Strain rate is a function of loading rate. Test results are dependent upon strain rate, and the ASTM testing procedures specify appropriate strain rates. Design properties in this Handbook were developed from test data obtained from coupons tested at the stated strain rate or up to a value of 0.01 in./in./min, the standard maximum static rate for tensile testing materials per specification ASTM E 8.

1.4.3.4 Elongation and Reduction of Area — Elongation and reduction of area are measured in accordance with specification ASTM E 8.

1.4.4 TENSILE PROPERTIES — When a metallic specimen is tested in tension using standard procedures of ASTM E 8, it is customary to plot results as a "stress-strain diagram." Typical tensile stress-strain diagrams are characterized in Figure 1.4.4. Such diagrams, drawn to scale, are provided in appropriate chapters of this Handbook. The general format of such diagrams is to provide a strain scale nondimensionally (in./in.) and a stress scale in 1000 lb/in. (ksi). Properties required for design and structural analysis are discussed in Sections 1.4.4.1 to 1.4.4.6.

1.4.4.1 Modulus of Elasticity (E) — Referring to Figure 1.4.4, it is noted that the initial part of stress-strain curves are straight lines. This indicates a constant ratio between stress and strain. Numerical values of such ratios are defined as the modulus of elasticity, and denoted by the letter E. This value applies up to the proportional limit stress at which point the initial slope of the stress-strain curve then decreases. Modulus of elasticity has the same units as stress. See Equation 1.3.4 (b).

Other moduli of design importance are tangent modulus, E_t, and secant modulus, E_s. Both of these moduli are functions of strain. Tangent modulus is the instantaneous slope of the stress-strain curve at any selected value of strain. Secant modulus is defined as the ratio of total stress to total strain at any selected value of strain. Both of these moduli are used in structural element designs. Except for materials such as those described with discontinuous behaviors, such as the upper stress-strain curve in Figure 1.4.4, tangent modulus is the lowest value of modulus at any state of strain beyond the proportional limit. Similarly, secant modulus is the highest value of modulus beyond the proportional limit.

Clad aluminum alloys may have two separate modulus of elasticity values, as indicated in the typical stress-strain curve shown in Figure 1.4.4. The initial slope, or primary modulus, denotes a response of both the low-strength cladding and higher-strength core elastic behaviors. This value applies only up to the proportional limit of the cladding. For example, the primary modulus of 2024-T3 clad sheet applies only up to about 6 ksi. Similarly, the primary modulus of 7075-T6 clad sheet applies only up to approximately 12 ksi. A typical use of primary moduli is for low amplitude, high frequency fatigue. Primary moduli are not applicable at higher stress levels. Above the proportional limits of cladding materials, a short transition range occurs while the cladding is developing plastic behavior. The material then exhibits a secondary elastic modulus up to the proportional limit of the core material. This secondary modulus is the slope of the second straight line portion of the stress-strain curve. In some cases, the cladding is so little different from the core material that a single elastic modulus value is used.

1.4.4.2 Tensile Proportional Limit Stress **(F_{tp})** — The tensile proportional limit is the maximum stress for which strain remains proportional to stress. Since it is practically impossible to determine precisely this point on a stress-strain curve, it is customary to assign a small value of plastic strain to identify the corresponding stress as the proportional limit. In this Handbook, the tension and compression proportional limit stress corresponds to a plastic strain of 0.0001 in./in.

1.4.4.3 Tensile Yield Stress **(TYS or F_{ty})** — Stress-strain diagrams for some ferrous alloys exhibit a sharp break at a stress below the tensile ultimate strength. At this critical stress, the material elongates considerably with no apparent change in stress. See the upper stress-strain curve in Figure 1.4.4. The stress at which this occurs is referred to as the yield point. Most nonferrous metallic alloys and most high strength steels do not exhibit this sharp break, but yield in a monotonic manner. This condition is also illustrated in Figure 1.4.4. Permanent deformation may be detrimental, and the industry adopted 0.002 in./in. plastic strain as an arbitrary limit that is considered acceptable by all regulatory agencies. For tension and compression, the corresponding stress at this offset strain is defined as the yield stress (see Figure 1.4.4). This value of plastic axial strain is 0.002 in./in. and the corresponding stress is defined as the yield stress. For practical purposes, yield stress can be determined from a stress-strain diagram by extending a line parallel to the elastic modulus line and offset from the origin by an amount of 0.002 in./in.

strain. The yield stress is determined as the intersection of the offset line with the stress-strain curve.

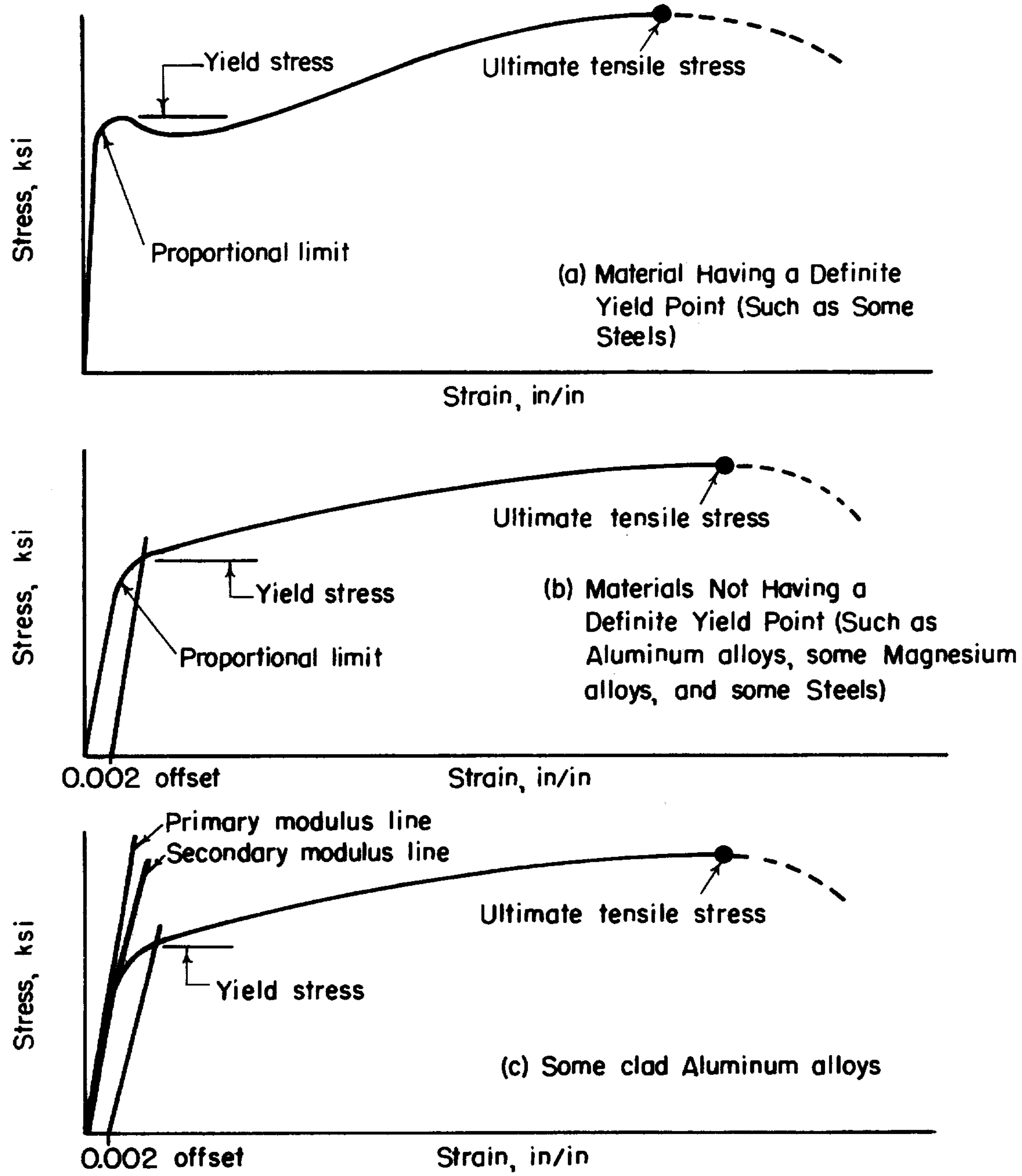

Figure 1.4.4. Typical tensile stress-strain diagrams.

1.4.4.4 ***Tensile Ultimate Stress* (TUS or F_{ty})** — Figure 1.4.4 shows how the tensile ultimate stress is determined from a stress-strain diagram. It is simply the maximum stress attained. It should be noted that all stresses are based on the original cross-sectional dimensions of a test specimen, without regard to the lateral contraction due to Poisson's ratio effects. That is, all strains used herein are termed engineering strains as opposed to true strains which take into account actual cross sectional dimensions. Ultimate tensile stress is commonly used as a criterion of the strength of the material for structural design, but it should be recognized that other strength properties may often be more important.

1.4.4.5 ***Elongation (e)*** — An additional property that is determined from tensile tests is elongation. This is a measure of ductility. Elongation, also stated as total elongation, is defined as the permanent increase in gage length, measured after fracture of a tensile specimen. It is commonly expressed as a percentage of the original gage length. Elongation is usually measured over a gage length of 2 inches for rectangular tensile test specimens and in 4D (inches) for round test specimens. Welded test specimens are exceptions. Refer to the applicable material specification for applicable specified gage lengths. Although elongation is widely used as an indicator of ductility, this property can be significantly affected by testing variables, such as thickness, strain rate, and gage length of test specimens. See Section 1.4.1.1 for data basis.

1.4.4.6 ***Reduction of Area (RA)*** — Another property determined from tensile tests is reduction of area, which is also a measure of ductility. Reduction of area is the difference, expressed as a percentage of the original cross sectional area, between the original cross section and the minimum cross sectional area adjacent to the fracture zone of a tested specimen. This property is less affected by testing variables than elongation, but is more difficult to compute on thin section test specimens. See Section 1.4.1.1 for data basis.

1.4.5 COMPRESSIVE PROPERTIES — Results of compression tests completed in accordance with ASTM E 9 are plotted as stress-strain curves similar to those shown for tension in Figure 1.4.4. Preceding remarks concerning tensile properties of materials, except for ultimate stress and elongation, also apply to compressive properties. Moduli are slightly greater in compression for most of the commonly used structural metallic alloys. Special considerations concerning the ultimate compressive stress are described in the following section. An evaluation of techniques for obtaining compressive strength properties of thin sheet materials is outlined in Reference 1.4.5.

1.4.5.1 ***Compressive Ultimate Stress* (F_{cu})** – Since the actual failure mode for the highest tension and compression stress is shear, the maximum compression stress is limited to F_{tu}. The driver for all the analysis of all structure loaded in compression is the slope of the compression stress strain curve, the tangent modulus.

1.4.5.2 ***Compressive Yield Stress (CYS or F_{cy})*** — Compressive yield stress is measured in a manner identical to that done for tensile yield strength. It is defined as the stress corresponding to 0.002 in./in. plastic strain.

1.4.6 SHEAR PROPERTIES — Results of torsion tests on round tubes or round solid sections are plotted as torsion stress-strain diagrams. The shear modulus of elasticity is considered a basic shear property. Other properties, such as the proportional limit stress and shear ultimate stress, cannot be treated as basic shear properties because of "form factor" effects. The theoretical ratio between shear and tensile stress for homogeneous, isotropic materials is 0.577. Reference 1.4.6 contains additional information on this subject.

1.4.6.1 ***Modulus of Rigidity (G)*** — This property is the initial slope of the shear stress-strain curve. It is also referred to as the modulus of elasticity in shear. The relation between this property and the modulus of elasticity in tension is expressed for homogeneous isotropic materials by the following equation:

$$G = \frac{E}{2(1+\mu)} \qquad [1.4.6.1]$$

1.4.6.2 ***Proportional Limit Stress in Shear*** **(F_{sp})** — This property is of particular interest in connection with formulas which are based on considerations of linear elasticity, as it represents the limiting value of shear stress for which such formulas are applicable. This property cannot be determined directly from torsion tests.

1.4.6.3 ***Yield and Ultimate Stresses in Shear*** **(SYS or F_{sy})** ***and*** **(SUS or F_{su})** — These properties, as usually obtained from ASTM test procedures tests, are not strictly basic properties, as they will depend on the shape of the test specimen. In such cases, they should be treated as moduli and should not be combined with the same properties obtained from other specimen configuration tests.

Design values reported for shear ultimate stress (F_{su}) in room temperature property tables for aluminum and magnesium thin sheet alloys are based on "punch" shear type tests except when noted. Heavy section test data are based on "pin" tests. Thin aluminum products may be tested to ASTM B 831, which is a slotted shear test. Thicker aluminums use ASTM B 769, otherwise known as the Amsler shear test. These two tests only provide ultimate strength. Shear data for other alloys are obtained from pin tests, except where product thicknesses are insufficient. These tests are used for other alloys; however, the standards don't specifically cover materials other than aluminum

1.4.7 BEARING PROPERTIES — Bearing stress limits are of value in the design of mechanically fastened joints and lugs. Only yield and ultimate stresses are obtained from bearing tests. Bearing stress is computed from test data by dividing the load applied to the pin, which bears against the edge of the hole, by the bearing area. Bearing area is the product of the pin diameter and the sheet or plate thickness.

A bearing test requires the use of special cleaning procedures as specified in ASTM E 238. Results are identified as "dry-pin" values. The same tests performed without application of ASTM E 238 cleaning procedures are referred to as "wet pin" tests. Results from such tests can show bearing stresses at least 10 percent lower than those obtained from "dry pin" tests. See Reference 1.4.7 for additional information. Additionally, ASTM E 238 requires the use of hardened pins that have diameters within 0.001 of the hole diameter. As the clearance increases to 0.001 and greater, the bearing yield and failure stress tends to decrease.

In the definition of bearing values, t is sheet or plate thickness, D is the pin diameter, and e is the edge distance measured from the center of the hole to the adjacent edge of the material being tested in the direction of applied load.

1.4.7.1 ***Bearing Yield and Ultimate Stresses (BYS or F_{bry}) and (BUS or F_{bru})*** — BUS is the maximum stress withstood by a bearing specimen. BYS is computed from a bearing stress-deformation curve by drawing a line parallel to the initial slope at an offset of 0.02 times the pin diameter.

Tabulated design properties for bearing yield stress (F_{bry}) and bearing ultimate stress (F_{bru}) are provided throughout the Handbook for edge margins of e/D = 1.5 and 2.0. Bearing values for e/D of 1.5 are not intended for designs of e/D < 1.5. Bearing values for e/D < 1.5 must be substantiated by adequate tests, subject to the approval of the procuring or certificating regulatory agency. For edge margins between 1.5 and 2.0, linear interpolation of properties may be used.

Bearing design properties are applicable to t/D ratios from 0.25 to 0.50. Bearing design values for conditions of t/D < 0.25 or t/D > 0.50 must be substantiated by tests. The percentage curves showing temperature effects on bearing stress may be used with both e/D properties of 1.5 and 2.0.

Due to differences in results obtained between dry-pin and wet-pin tests, designers are encouraged to consider the use of a reduction factor with published bearing stresses for use in design.

1.4.8 TEMPERATURE EFFECTS — Temperature effects require additional considerations for static, fatigue and fracture toughness properties. In addition, this subject introduces concerns for time-dependent creep properties.

1.4.8.1 Low Temperature — Temperatures below room temperature generally cause an increase in strength properties of metallic alloys. Ductility, fracture toughness, and elongation usually decrease. For specific information, see the applicable chapter and references noted therein.

1.4.8.2 Elevated Temperature — Temperatures above room temperature usually cause a decrease in the strength properties of metallic alloys. This decrease is dependent on many factors, such as temperature and the time of exposure which may degrade the heat treatment condition, or cause a metallurgical change. Ductility may increase or decrease with increasing temperature depending on the same variables. Because of this dependence of strength and ductility at elevated temperatures on many variables, it is emphasized that the elevated temperature properties obtained from this Handbook be applied for only those conditions of exposure stated herein.

The effect of temperature on static mechanical properties is shown by a series of graphs of property (as percentages of the room temperature allowable property) versus temperature. Data used to construct these graphs were obtained from tests conducted over a limited range of strain rates. Caution should be exercised in using these static property curves at very high temperatures, particularly if the strain rate intended in design is much less than that stated with the graphs. The reason for this concern is that at very low strain rates or under sustained loads, plastic deformation or creep deformation may occur to the detriment of the intended structural use.

1.4.8.2.1 Creep and Stress-Rupture Properties — Creep is defined as a time-dependent deformation of a material while under an applied load. It is usually regarded as an elevated temperature phenomenon, although some materials creep at room temperature. If permitted to continue indefinitely, creep terminates in rupture. Since creep in service is usually typified by complex conditions of loading and temperature, the number of possible stress-temperature-time profiles is infinite. For economic reasons, creep data for general design use are usually obtained under conditions of constant uniaxial loading and constant temperature in accordance with Reference 1.4.8.2.1(a). Creep data are sometimes obtained under conditions of cyclic uniaxial loading and constant temperature, or constant uniaxial loading and variable temperatures. Section 9.3.6 provides a limited amount of creep data analysis procedures. It is recognized that, when significant creep appears likely to occur, it may be necessary to test under simulated service conditions because of difficulties posed in attempting to extrapolate from simple to complex stress-temperature-time conditions.

Creep damage is cumulative similar to plastic strain resulting from multiple static loadings. This damage may involve significant effects on the temper of heat treated materials, including annealing, and the initiation and growth of cracks or subsurface voids within a material. Such effects are often recognized as reductions in short time strength properties or ductility, or both.

1.4.8.2.2 Creep-Rupture Curve — Results of tests conducted under constant loading and constant temperature are usually plotted as strain versus time up to rupture. A typical plot of this nature is shown in Figure 1.4.8.2.2. Strain includes both the instantaneous deformation due to load application and the plastic strain due to creep. Other definitions and terminology are provided in Section 9.3.6.2.

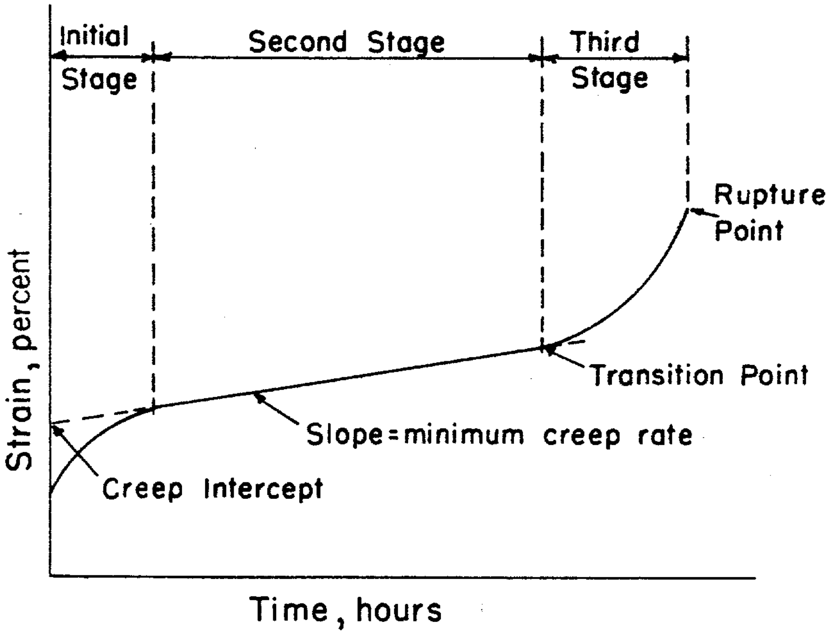

Figure 1.4.8.2.2. Typical creep-rupture curve.

1.4.8.2.3 Creep or Stress-Rupture Presentations — Results of creep or stress-rupture tests conducted over a range of stresses and temperatures are presented as curves of stress versus the logarithm of time to rupture. Each curve represents an average, best-fit description of measured behavior. Modification of such curves into design use are the responsibility of the design community since material applications and regulatory requirements may differ. Refer to Section 9.3.6 for data reduction and presentation methods and References 1.4.8.2.1(b) and (c).

1.4.9 FATIGUE PROPERTIES — Repeated loads are one of the major considerations for design of both commercial and military aircraft structures. Static loading, preceded by cyclic loads of lesser magnitudes, may result in mechanical behaviors (F_{tu} , F_{ty} , etc.) lower than those published in room temperature allowables tables. Such reductions are functions of the material and cyclic loading conditions. A fatigue allowables development philosophy is not presented in this Handbook. However, basic laboratory test data are useful for materials selection. Such data are therefore provided in the appropriate materials sections.

In the past, common methods of obtaining and reporting fatigue data included results obtained from axial loading tests, plate bending tests, rotating bending tests, and torsion tests. Rotating bending tests apply completely reversed (tension-compression) stresses to round cross section specimens. Tests of this type are now seldom conducted for aerospace use and have therefore been dropped from importance in this Handbook. For similar reasons, flexural fatigue data also have been dropped. No significant amount of torsional fatigue data have ever been made available. Axial loading tests, the only type retained in this Handbook, consist of completely reversed loading conditions (mean stress equals zero) and those in which the mean stress was varied to create different stress (or strain) ratios (R = minimum stress or strain divided by maximum stress or strain). Refer to Reference 1.4.9(a) for load control fatigue testing guidelines and Reference 1.4.9(b) for strain control fatigue testing guidelines.

1.4.9.1 *Terminology* — A number of symbols and definitions are commonly used to describe fatigue test conditions, test results and data analysis techniques. The most important of these are described in Section 9.3.4.2.

1.4.9.2 *Graphical Display of Fatigue Data* — Results of axial fatigue tests are reported on S-N and ε - N diagrams. Figure 1.4.9.2(a) shows a family of axial load S-N curves. Data for each curve represents a separate R-value.

S-N and ε - N diagrams are shown in this Handbook with the raw test data plotted for each stress or strain ratio or, in some cases, for a single value of mean stress. A best-fit curve is drawn through the data at each condition. Rationale used to develop best-fit curves and the characterization of all such curves in a single diagram is explained in Section 9.3.4. For load control test data, individual curves are usually based on an equivalent stress that consolidates data for all stress ratios into a single curve. Refer to Figure 1.4.9.2(b). For strain control test data, an equivalent strain consolidation method is used.

Elevated temperature fatigue test data are treated in the same manner as room temperature data, as long as creep is not a significant factor and room temperature analysis methods can be applied. In the limited number of cases where creep strain data have been recorded as a part of an elevated temperature fatigue test series, S-N (or ε - N) plots are constructed for specific creep strain levels. This is provided in addition to the customary plot of maximum stress (or strain) versus cycles to failure.

The above information may not apply directly to the design of structures for several reasons. First, Handbook information may not take into account specific stress concentrations unique to any given structural design. Design considerations usually include stress concentrations caused by re-entrant corners, notches, holes, joints, rough surfaces, structural damage, and other conditions. Localized high stresses induced during the fabrication of some parts have a much greater influence on fatigue properties than on static properties. These factors significantly reduce fatigue life below that which is predictable by estimating smooth specimen fatigue performance with estimated stresses due to fabrication. Fabricated parts have been found to fail at less than 50,000 cycles of loading when the nominal stress was far below that which could be repeated many millions of times using a smooth-machined test specimen.

Notched fatigue specimen test data are shown in various Handbook figures to provide an understanding of deleterious effects relative to results for smooth specimens. All of the mean fatigue curves published in this Handbook, including both the notched fatigue and smooth specimen fatigue curves, require modification into allowables for design use. Such factors may impose a penalty on cyclic life or upon stress. This is a responsibility for the design community. Specific reductions vary between users of such information, and depending on the criticality of application, sources of uncertainty in the analysis, and requirements of the certificating activity. References 1.4.9.2(a) and (b) contain more specific information on fatigue testing procedures, organization of test results, influences of various factors, and design considerations.

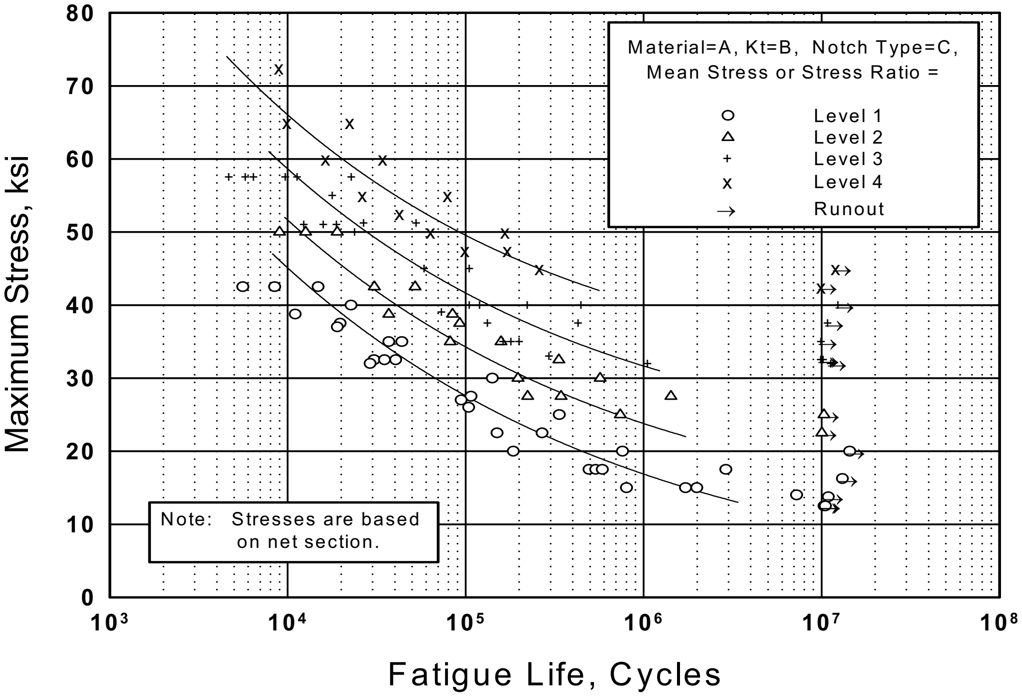

Figure 1.4.9.2(a). Best fit S/N curve diagram for a material at various stress ratios.

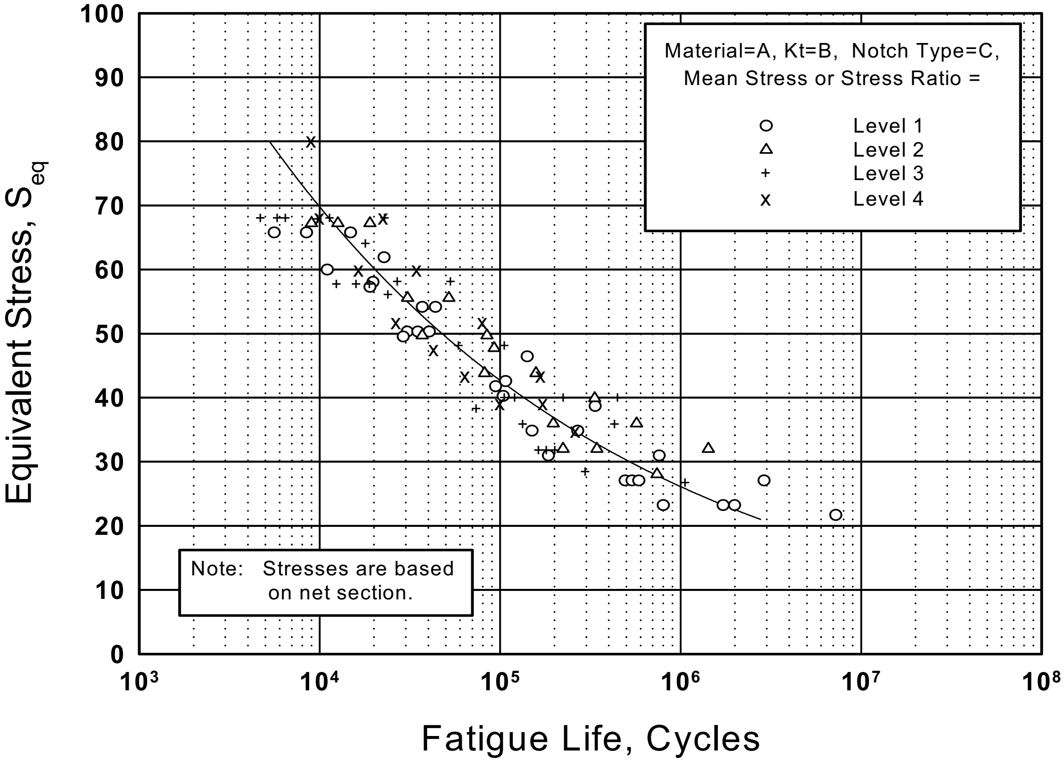

Figure 1.4.9.2(b). Consolidated fatigue data for a material using the equivalent stress parameter.

1.4.10 METALLURGICAL INSTABILITY — In addition to the retention of strength and ductility, a structural material must also retain surface and internal stability. Surface stability refers to the resistance of the material to oxidizing or corrosive environments. Lack of internal stability is generally manifested (in some ferrous and several other alloys) by carbide precipitation, spheroidization, sigma-phase formation, temper embrittlement, and internal or structural transformation, depending upon the specific conditions of exposure.

Environmental conditions, that influence metallurgical stability include heat, level of stress, oxidizing or corrosive media, and nuclear radiation. The effect of environment on the material can be observed as either improvement or deterioration of properties, depending upon the specific imposed conditions. For example, prolonged heating may progressively raise the strength of a metallic alloy as measured on smooth tensile or fatigue specimens. However, at the same time, ductility may be reduced to such an extent that notched tensile or fatigue behavior becomes erratic or unpredictable. The metallurgy of each alloy should be considered in making material selections.

Under normal temperatures, i.e., between -65°F and 160°F, the stability of most structural metallic alloys is relatively independent of exposure time. However, as temperature is increased, the metallurgical instability becomes increasingly time dependent. The factor of exposure time should be considered in design when applicable.

1.4.11 BIAXIAL PROPERTIES — Discussions up to this point pertained to uniaxial conditions of static, fatigue, and creep loading. Many structural applications involve both biaxial and triaxial loadings. Because of the difficulties of testing under triaxial loading conditions, few data exist. However, considerable biaxial testing has been conducted and the following paragraphs describe how these results are presented in this Handbook. This does not conflict with data analysis methods presented in Chapter 9. Therein, statistical analysis methodology is presented solely for use in analyzing test data to establish allowables.

If stress axes are defined as being mutually perpendicular along x-, y-, and z-directions in a rectangular coordinate system, a biaxial stress is then defined as a condition in which loads are applied in both the x- and y-directions. In some special cases, loading may be applied in the z-direction instead of the y-direction. Most of the following discussion will be limited to tensile loadings in the x- and y-directions. Stresses and strains in these directions are referred to as principal stresses and principal strains. See Reference 1.4.11.

When a specimen is tested under biaxial loading conditions, it is customary to plot the results as a biaxial stress-strain diagram. These diagrams are similar to uniaxial stress-strain diagrams shown in Figure 1.4.4. Usually, only the maximum (algebraically larger) principal stress and strain are shown for each test result. When tests of the same material are conducted at different biaxial stress ratios, the resulting curves may be plotted simultaneously, producing a family of biaxial stress-strain curves as shown in Figure 1.4.11 for an isotropic material. For anisotropic materials, biaxial stress-strain curves also require distinction by grain direction.

The reference direction for a biaxial stress ratio, i.e., the direction corresponding to B=0, should be clearly indicated with each result. The reference direction is always considered as the longitudinal (rolling) direction for flat products and the hoop (circumferential) direction for shells of revolution, e.g., tubes, cones, etc. The letter B denotes the ratio of applied stresses in the two loading directions. For example, biaxility ratios of 2 and 0.5 shown in Figure 1.4.11 indicate results representing both biaxial stress ratios of 2 or 0.5, since this is a hypothetical example for an isotropic material, e.g., cross-rolled sheet. In a similar manner, the curve labeled B=1 indicates a biaxial stress-strain result for equally applied stresses in both directions. The curve labeled $B = \infty$, 0 indicates the biaxial stress-strain behavior when loading is applied in only one direction, e.g., uniaxial behavior. Biaxial property data presented in the Handbook are to be considered as basic material properties obtained from carefully prepared specimens.

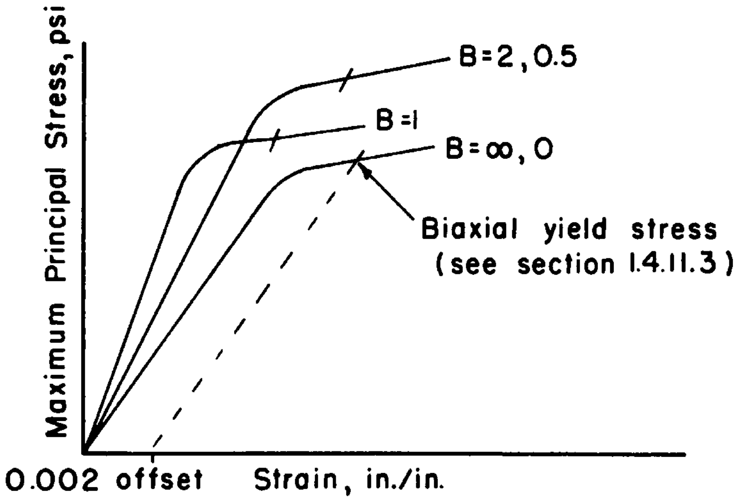

Figure 1.4.11. Typical biaxial stress-strain diagrams for isotropic materials.

1.4.11.1 ***Biaxial Modulus of Elasticity*** — Referring to Figure 1.4.11, it is noted that the original portion of each stress-strain curve is essentially a straight line. In uniaxial tension or compression, the slope of this line is defined as the modulus of elasticity. Under biaxial loading conditions, the initial slope of such curves is defined as the biaxial modulus. It is a function of biaxial stress ratio and Poisson's ratio. See Equation 1.3.7.4.

1.4.11.2 ***Biaxial Yield Stress*** — Biaxial yield stress is defined as the maximum principal stress corresponding to 0.002 in./in. plastic strain in the same direction, as determined from a test curve.

In the design of aerospace structures, biaxial stress ratios other than those normally used in biaxial testing are frequently encountered. Information can be combined into a single diagram to enable interpolations at intermediate biaxial stress ratios, as shown in Figure 1.4.11.2. An envelope is constructed through test results for each tested condition of biaxial stress ratios. In this case, a typical biaxial yield stress envelope is identified. In the preparation of such envelopes, data are first reduced to nondimensional form (percent of uniaxial tensile yield stress in the specified reference direction), then a best-fit curve is fitted through the nondimensionalized data. Biaxial yield strength allowables are then obtained by multiplying the uniaxial F_{ty} (or F_{cy}) allowable by the applicable coordinate of the biaxial stress ratio curve. To avoid possible confusion, the reference direction used for the uniaxial yield strength is indicated on each figure.

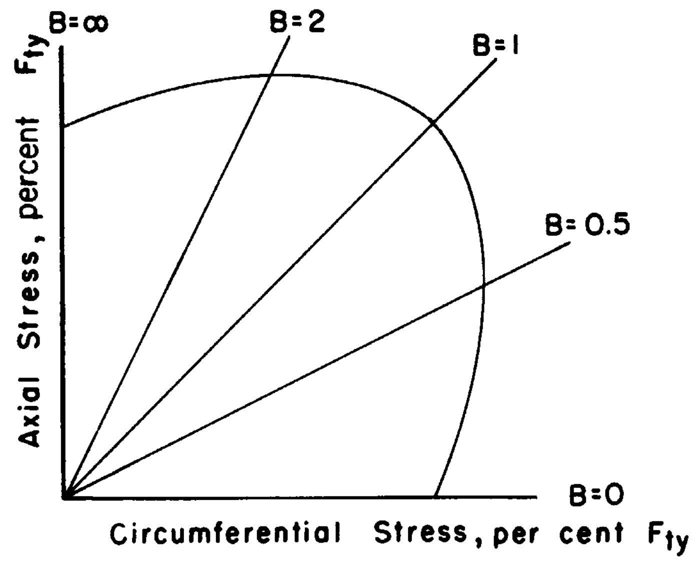

Figure 1.4.11.2. Typical biaxial yield stress envelope.

1.4.11.3 ***Biaxial Ultimate Stress*** — Biaxial ultimate stress is defined as the highest nominal principal stress attained in specimens of a given configuration, tested at a given biaxial stress ratio. This property is highly dependent upon geometric configuration of the test parts. Therefore, such data should be limited in use to the same design configurations.

The method of presenting biaxial ultimate strength data is similar to that described in the preceding section for biaxial yield strength. Both biaxial ultimate strength and corresponding uniform elongation data are reported, when available, as a function of biaxial stress ratio test conditions.

1.4.12 FRACTURE TOUGHNESS — The occurrence of flaws in a structural component is an unavoidable circumstance of material processing, fabrication, or service. Flaws may appear as cracks, voids, metallurgical inclusions, weld defects, design discontinuities, or some combination thereof. The fracture toughness of a part containing a flaw is dependent upon flaw size, component geometry, and a material property defined as fracture toughness. The fracture toughness of a material is literally a measure of its resistance to fracture. As with other mechanical properties, fracture toughness is dependent upon alloy type, processing variables, product form, geometry, temperature, loading rate, and other environmental factors.

This discussion is limited to brittle fracture, which is characteristic of high strength materials under conditions of loading resulting in plane-strain through the cross section. Very thin materials are described as being under the condition of plane-stress. The following descriptions of fracture toughness properties applies to the currently recognized practice of testing specimens under slowly increasing loads. Attendant and interacting conditions of cyclic loading, prolonged static loadings, environmental influences other than temperature, and high strain rate loading are not considered.

1.4.12.1 ***Brittle Fracture*** — For materials that have little capacity for plastic flow, or for flaw and structural configurations, which induce triaxial tension stress states adjacent to the flaw, component behavior is essentially elastic until the fracture stress is reached. Then, a crack propagates from the flaw suddenly and completely through the component. A convenient illustration of brittle fracture is a typical load-compliance record of a brittle structural component containing a flaw, as illustrated in Figure 1.4.12.1. Since little or no plastic effects are noted, this mode is termed brittle fracture.

This mode of fracture is characteristic of the very high-strength metallic materials under plane-strain conditions.

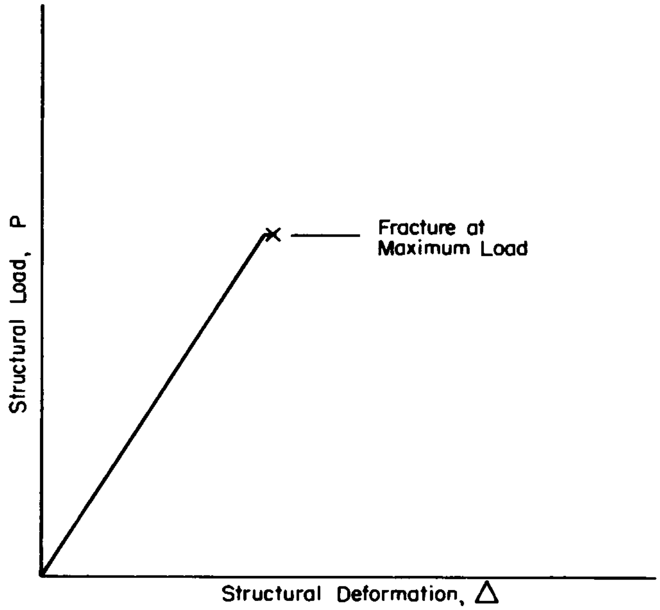

Figure 1.4.12.1. Typical load-deformation record of a structural component containing a flaw subject to brittle fracture.

1.4.12.2 ***Brittle Fracture Analysis*** — The application of linear elastic fracture mechanics has led to the stress intensity concept to relate flaw size, component geometry, and fracture toughness. In its very general form, the stress intensity factor, K, can be expressed as

$$K = f\sqrt{a}Y, \text{ ksi} \cdot \text{in.}^{1/2} \qquad [1.4.12.2]$$

where

f = stress applied to the gross section, ksi
a = measure of flaw size, inches
Y = factor relating component geometry and flaw size, nondimensional. See Reference 1.4.12.2(a) for values.

For every structural material, which exhibits brittle fracture (by nature of low ductility or plane-strain stress conditions), there is a lower limiting value of K termed the plane-strain fracture toughness, K_{Ic}.

The specific application of this relationship is dependent on flaw type, structural configuration and type of loading, and a variety of these parameters can interact in a real structure. Flaws may occur through the thickness, may be imbedded as voids or metallurgical inclusions, or may be partial-through (surface) cracks. Loadings of concern may be tension and/or flexure. Structural components may vary in section size and may be reinforced in some manner. The ASTM Committee E 8 on Fatigue and Fracture has developed testing and analytical techniques for many practical situations of flaw occurrence subject to brittle fracture. They are summarized in Reference 1.4.12.2(a).

1.4.12.3 ***Critical Plane-Strain Fracture Toughness*** — A tabulation of fracture toughness data is printed in the general discussion prefacing most alloy chapters in this Handbook. These critical plane-strain fracture toughness values have been determined in accordance with recommended ASTM testing practices. This information is provided for information purposes only due to limitations in available data quantities and product form coverages. The statistical reliability of these properties is not known. Listed properties generally represent the average value of a series of test results.

Fracture toughness of a material commonly varies with grain direction. When identifying either test results or a general critical plane strain fracture toughness average value, it is customary to specify specimen and crack orientations by an ordered pair of grain direction symbols per ASTM E399. [Reference 1.4.12.2(a).] The first digit denotes the grain direction normal to the crack plane. The second digit denotes the grain direction parallel to the fracture plane. For flat sections of various products, e.g., plate, extrusions, forgings, etc., in which the three grain directions are designated (L) longitudinal, (T) transverse, and (S) short transverse, the six principal fracture path directions are: L-T, L-S, T-L, T-S, S-L and S-T. Figure 1.4.12.3(a) identifies these orientations. For cylindrical sections where the direction of principle deformation is parallel to the longitudinal axis of the cylinder, the reference directions are identified as in Figure 1.4.12.3(b), which gives examples for a drawn bar. The same system would be useful for extrusions or forged parts having circular cross section.

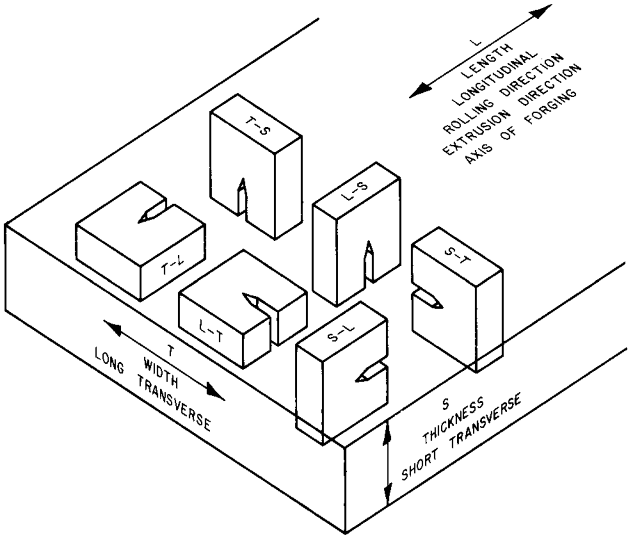

Figure 1.4.12.3(a). Typical principal fracture path directions.

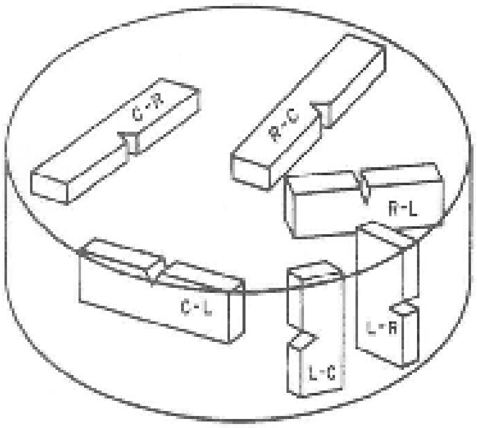

Figure 1.4.12.3(b). Typical principal fracture path directions for cylindrical shapes.

1.4.12.3.1 *Environmental Effects* — Cyclic loading, even well below the fracture threshold stress, may result in the propagation of flaws, leading to fracture. Strain rates in excess of standard static rates may cause variations in fracture toughness properties. There are significant influences of temperature on fracture toughness properties. Temperature effects data are limited. These information are included in each alloy section, when available.

Under the condition of sustained loading, it has been observed that certain materials exhibit increased flaw propagation tendencies when situated in either aqueous or corrosive environments. When such is known to be the case, appropriate precautionary notes have been included with the standard fracture toughness information.

1.4.12.4 ***Fracture in Plane-Stress and Transitional-Stress States*** — Plane-strain conditions do not describe the condition of certain structural configurations which are either relatively thin or exhibit appreciable ductility. In these cases, the actual stress state may approach the opposite extreme, plane-stress, or, more generally, some intermediate- or transitional-stress state. The behavior of flaws and cracks under these conditions is different from those of plane-strain. Specifically, under these conditions, significant plastic zones can develop ahead of the crack or flaw tip, and stable extension of the discontinuity occurs as a slow tearing process. This behavior is illustrated in a compliance record by a significant nonlinearity prior to fracture as shown in Figure 1.4.12.4. This nonlinearity results from the alleviation of stress at the crack tip by causing plastic deformation.

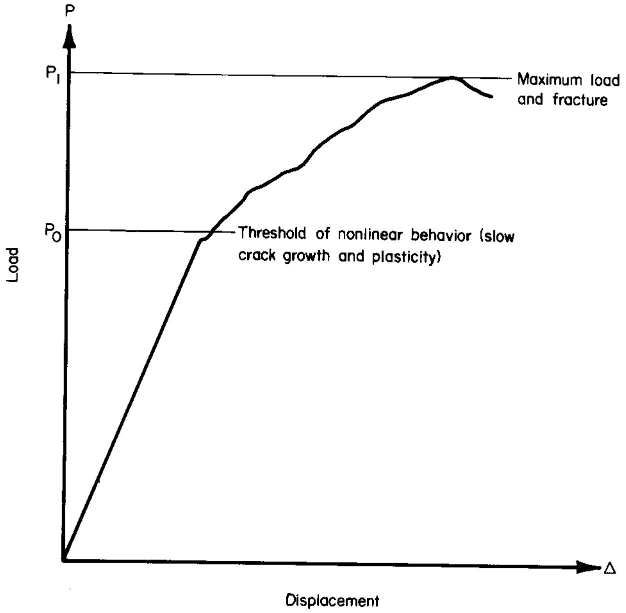

Figure 1.4.12.4. Typical load-deformation record for non-plane strain fracture.

1.4.12.4.1 *Analysis of Plane-Stress and Transitional-Stress State Fracture* — The basic concepts of linear elastic fracture mechanics as used in plane-strain fracture analysis also applies to these conditions. The stress intensity factor concept, as expressed in general form by Equation 1.4.12.2, is used to relate load or stress, flaw size, component geometry, and fracture toughness.

However, interpretation of the critical flaw dimension and corresponding stress has two possibilities. This is illustrated in Figure 1.4.12.4.1. One possibility is the onset of nonlinear displacement with increasing load. The other possibility identifies the fracture condition, usually very close to the

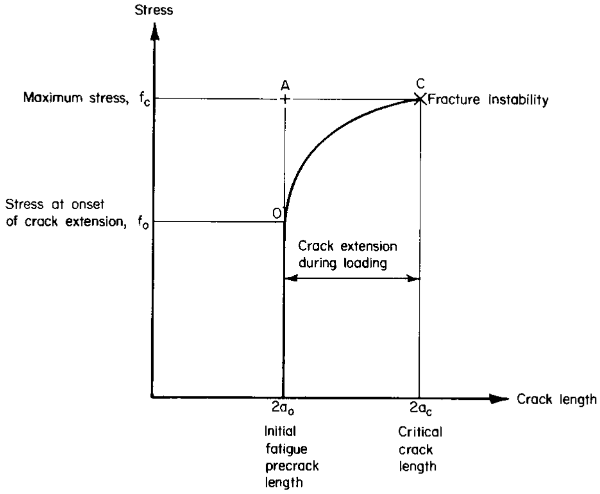

Figure 1.4.12.4.1. Crack growth curve.

maximum load. Generally, these two conditions are separated in applied stress and exhibit large differences in flaw dimensions due to stable tearing.

When a compliance record is transformed into a crack growth curve, the difference between the two possible K-factor designations becomes more apparent. In most practical cases, the definition of nonlinear crack length with increasing load is difficult to assess. As a result, an alternate characterization of this behavior is provided by defining an artificial or “apparent” stress intensity factor.

$$K_{app} = f\sqrt{a_o}Y \qquad [1.4.12.4.1]$$

The apparent fracture toughness is computed as a function of the maximum stress and initial flaw size. This datum coordinate corresponds to point A in Figure 1.4.12.4.1. This conservative stress intensity factor is a first approximation to the actual property associated with the point of fracture.

1.4.12.5 ***Apparent Fracture Toughness Values for Plane-Stress and Transitional-Stress States*** — When available, each alloy chapter contains graphical formats of stress versus flaw size. This is provided for each temper, product form, grain direction, thickness, and specimen configuration. Data points shown in these graphs represent the initial flaw size and maximum stress achieved. These data have been screened to assure that an elastic instability existed at fracture, consistent with specimen type. The average K_{app} curve, as defined in the following subsections, is shown for each set of data.

1.4.12.5.1 *Middle-Tension Panels* — The calculation of apparent fracture toughness for middle-tension panels is given by the following equation.

$$K_{app} = f_c\left(\pi a_o \cdot \sec \pi a_o / W\right)^{1/2} \qquad [1.4.12.5.1(a)]$$

Data used to compute K_{app} values have been screened to ensure that the net section stress at failure did not exceed 80 percent of the tensile yield strength; that is, they satisfied the criterion:

$$f_c \le 0.8(TYS)/(1-2a/W) \qquad [1.4.12.5.1(b)]$$

This criterion assures that the fracture was an elastic instability and that plastic effects are negligible.

The average K_{app} parametric curve is presented on each figure as a solid line with multiple extensions where width effects are displayed in the data. As added information, where data are available, the propensity for slow stable tearing prior to fracture is indicated by a crack extension ratio, $\Delta 2a/2a_o$. The coefficient (2) indicates the total crack length; the half-crack length is designated by the letter “a.” In some cases, where data exist covering a wide range of thicknesses, graphs of K_{app} versus thickness are presented.

1.4.13 FATIGUE CRACK GROWTH — Crack growth deals with material behavior between crack initiation and crack instability. In small size specimens, crack initiation and specimen failure may be nearly synonymous. However, in larger structural components, the existence of a crack does not necessarily imply imminent failure. Significant structural life exists during cyclic loading and crack growth.

1.4.13.1 Fatigue Crack Growth — Fatigue crack growth is manifested as the growth or extension of a crack under cyclic loading. This process is primarily controlled by the maximum load or stress ratio. Additional factors include environment, loading frequency, temperature, and grain direction. Certain factors, such as environment and loading frequency, have interactive effects. Environment is important from a potential corrosion viewpoint. Time at stress is another important factor. Standard testing procedures are documented in Reference 1.4.13.1.

Fatigue crack growth data presented herein are based on constant amplitude tests. Crack growth behaviors based on spectrum loading cycles are beyond the scope of this Handbook. Constant amplitude data consist of crack length measurements at corresponding loading cycles. Such data are presented as crack growth curves as shown in Figure 1.4.13.1(a).

Since the crack growth curve is dependent on initial crack length and the loading conditions, the above format is not the most efficient form to present information. The instantaneous slope, $\Delta a/\Delta N$, corresponding to a prescribed number of loading cycles, provides a more fundamental characterization of this behavior. In general, fatigue crack growth rate behavior is evaluated as a function of the applied stress intensity factor range, ΔK, as shown in Figure 1.4.13.1(b).

1.4.13.2 Fatigue Crack Growth Analysis — It is known that fatigue-crack-growth behavior under constant-amplitude cyclic conditions is influenced by maximum cyclic stress, S_{max}, and some measure of cyclic stress range, ΔS (such as stress ratio, R, or minimum cyclic stress, S_{min}), the instantaneous crack size, a, and other factors such as environment, frequency, and temperature. Thus, fatigue-crack-growth rate behavior can be characterized, in general form, by the relation

$$da/dN \approx \Delta a/\Delta N = g(S_{max}, \Delta S \text{ or } R \text{ or } S_{min}, a, ...). \qquad [1.4.13.3(a)]$$

By applying concepts of linear elastic fracture mechanics, the stress and crack size parameters can be combined into the stress-intensity factor parameter, K, such that Equation 1.4.13.3(a) may be simplified to

$$da/dN \approx \Delta a/\Delta N = g(K_{max}, \Delta K, ...) \qquad [1.4.13.3(b)]$$

where

K_{max} = the maximum cyclic stress-intensity factor
ΔK = $(1-R)K_{max}$, the range of the cyclic stress-intensity factor, for $R \geq 0$
ΔK = K_{max}, for $R \leq 0$.

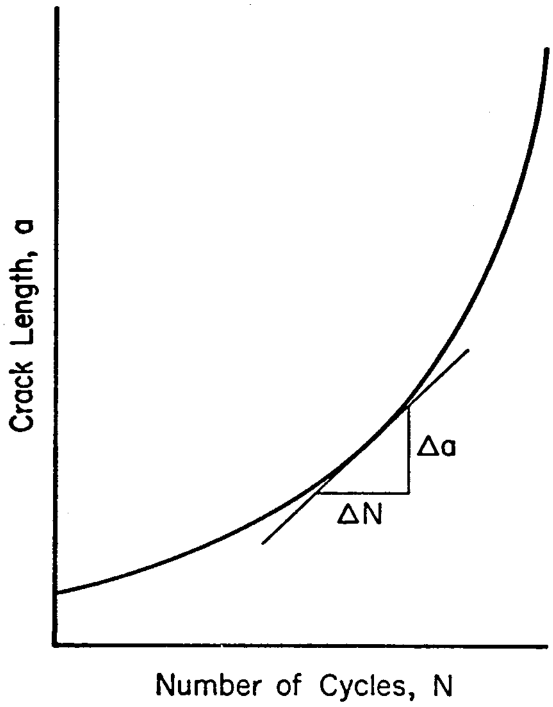

Figure 1.4.13.1(a). Fatigue crack-growth curve.

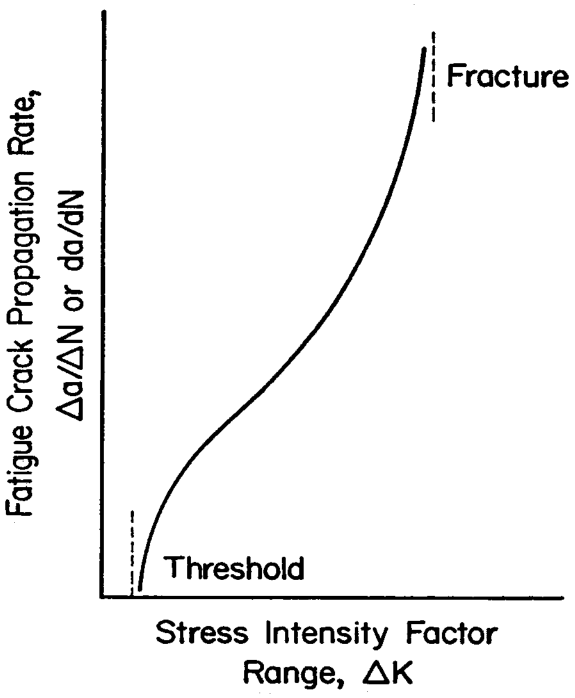

Figure 1.4.13.1(b). Fatigue crack-growth-rate curve.

At present, in the Handbook, the independent variable is considered to be simply ΔK and the data are considered to be parametric on the stress ratio, R, such that Equation 1.4.13.3(b) becomes

$$da/dN \approx \Delta a/\Delta N = g(\Delta K, R). \qquad [1.4.13.3(c)]$$

1.4.13.3 ***Fatigue Crack Growth Data Presentation*** — Fatigue crack growth rate data for constant amplitude cyclic loading conditions are presented as logarithmic plots of da/dN versus ΔK. Such information, such as that illustrated in Figure 1.4.13.3, are arranged by material alloy and heat treatment condition. Each curve represents a specific stress ratio, R, environment, and cyclic loading frequency. Specific details regarding test procedures and data interpolations are presented in Chapter 9.

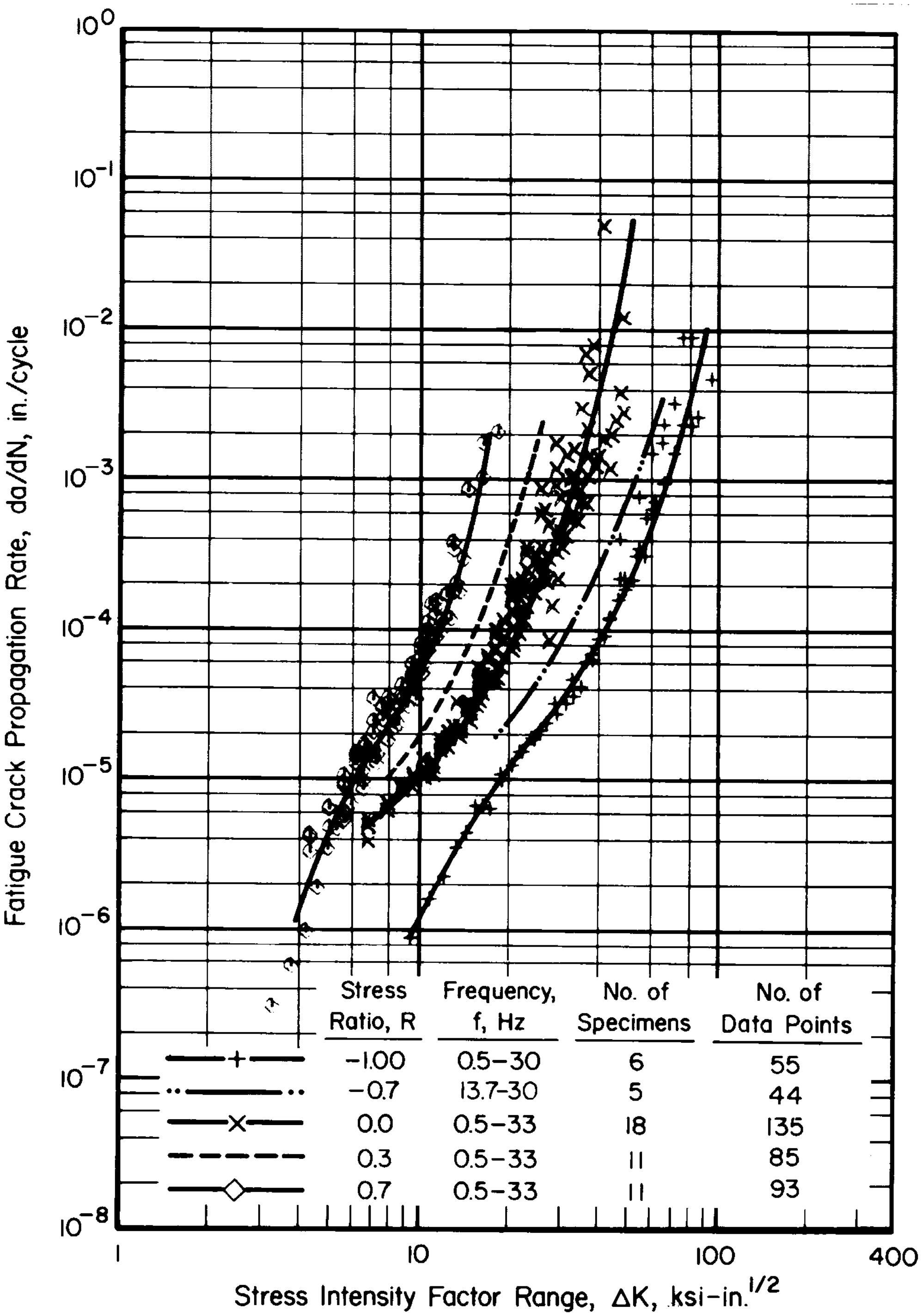

Figure 1.4.13.3. Sample display of fatigue crack growth rate data.

1.5 TYPES OF FAILURES

1.5.1 GENERAL — In the following discussion, failure will usually indicate fracture of a member or the condition of a member when it has attained maximum load.

1.5.2 MATERIAL FAILURES — Fracture can occur in either ductile or brittle fashions in the same material depending on the state of stress, rate of loading, and environment. The ductility of a material has a significant effect on the ability of a part to withstand loading and delay fracture. Although not a specific design property for ductile materials, some ductility data are provided in the Handbook to assist in material selections. The following paragraphs discuss the relationship between failure and the applied or induced stresses.

1.5.2.1 *Direct Tension or Compression* — This type of failure is associated with ultimate tensile or compressive stress of the material. For compression, it can only apply to members having large cross sectional dimensions relative to their lengths. See Section 1.4.5.1.

1.5.2.2 *Shear* — Pure shear failures are usually obtained when the shear load is transmitted over a very short length of a member. This condition is approached in the case of rivets and bolts. In cases where ultimate shear stress is relatively low, a pure shear failure can result. But, generally members subjected to shear loads fail under the action of the resulting normal stress, usually the compressive stress. See Equation 1.3.3.3. Failure of tubes in torsion are not caused by exceeding the shear ultimate stress, but by exceeding a normal compressive stress which causes the tube to buckle. It is customary to determine stresses for members subjected to shear in the form of shear stresses although they are actually indirect measures of the stresses actually causing failure.

1.5.2.3 *Bearing* — Failure of a material in bearing can consist of crushing, splitting, tearing, or progressive rapid yielding in the direction of load application. Failure of this type depends on the relative size and shape of the two connecting parts. The maximum bearing stress may not be applicable to cases in which one of the connecting members is relatively thin.

1.5.2.4 *Bending* — For sections not subject to geometric instability, a bending failure can be classed as either a tensile or compressive failure. Reference 1.5.2.4 provides methodology by which actual bending stresses above the material proportional limit can be used to establish maximum stress conditions. Actual bending stresses are related to the bending modulus of rupture. The bending modulus of rupture (f_b) is determined by Equation 1.3.2.3. When the computed bending modulus of rupture is found to be lower than the proportional limit strength, it represents an actual stress. Otherwise, it represents an apparent stress, and is not considered as an actual material strength. This is important when considering complex stress states, such as combined bending and compression or tension.

1.5.2.5 *Failure Due to Stress Concentrations* — Static stress properties represent pristine materials without notches, holes, or other stress concentrations. Such simplistic structural design is not always possible. Consideration should be given to the effect of stress concentrations. When available, references are cited for specific data in various chapters of the Handbook.

1.5.2.6 *Failure from Combined Stresses* — Under combined stress conditions, where failure is not due to buckling or instability, it is necessary to refer to some theory of failure. The "maximum shear" theory is widely accepted as a working basis in the case of isotropic ductile materials. It should be noted that this theory defines failure as the first yielding of a material. Any extension of this theory to cover conditions of final rupture must be based on evidence supported by the user. The failure of brittle materials under combined stresses is generally treated by the "maximum stress" theory. Section 1.4.11 contains a more complete discussion of biaxial behavior. References 1.5.2.6(a) through (c) offer additional information.

1.5.3 INSTABILITY FAILURES — Practically all structural members, such as beams and columns, particularly those made from thin material, are subject to failure due to instability. In general, instability can be classed as (1) primary or (2) local. For example, the failure of a tube loaded in compression can occur either through lateral deflection of the tube acting as a column (primary instability) or by collapse of the tube walls at stresses lower than those required to produce a general column failure. Similarly, an I-beam or other formed shape can fail by a general sidewise deflection of the compression flange, by local wrinkling of thin outstanding flanges, or by torsional instability. It is necessary to consider all types of potential failures unless it is apparent that the critical load for one type is definitely the controlling condition.

Instability failures can occur in either the elastic range below the proportional limit or in the plastic range. These two conditions are distinguished by referring to either "elastic instability" or "plastic instability" failures. Neither type of failure is associated with a material's ultimate strength, but largely depends upon geometry.

A method for determining the local stability of aluminum alloy column sections is provided in Reference 1.7.1(b). Documents cited therein are the same as those listed in References 3.20.2.2(a) through (e).

1.5.3.1 ***Instability Failures Under Compression*** — Failures of this type are discussed in Section 1.6 (Columns).

1.5.3.2 ***Instability Failures Under Bending*** — Round tubes when subjected to bending are subject to plastic instability failures. In such cases, the failure criterion is the modulus of rupture. Equation 1.3.2.3, which was derived from theory and confirmed empirically with test data, is applicable. Elastic instability failures of thin walled tubes having high D/t ratios are treated in later sections.

1.5.3.3 ***Instability Failures Under Torsion*** — The remarks given in the preceding section apply in a similar manner to round tubes under torsional loading. In such cases, the modulus of rupture in torsion is derived through the use of Equation 1.3.2.6. See Reference 1.5.3.3.

1.5.3.4 ***Failure Under Combined Loadings*** — For combined loading conditions in which failure is caused by buckling or instability, no theory exists for general application. Due to the various design philosophies and analytical techniques used throughout the aerospace industry, methods for computing margin of safety are not within the scope of this Handbook.

1.6 COLUMNS

1.6.1 GENERAL — A theoretical treatment of columns can be found in standard texts on the strength of materials. Some of the problems which are not well defined by theory are discussed in this section. Actual strengths of columns of various materials are provided in subsequent chapters.

1.6.2 PRIMARY INSTABILITY FAILURES — A column can fail through primary instability by bending laterally (stable sections) or by twisting about some axis parallel to its own axis. This latter type of primary failure is particularly common to columns having unsymmetrical open sections. The twisting failure of a closed section column is precluded by its inherently high torsional rigidity. Since the amount of available information is limited, it is advisable to conduct tests on all columns subject to this type of failure.

1.6.2.1 Columns with Stable Sections — The Euler formula for columns which fail by lateral bending is given by Equation 1.3.8.2. A conservative approach in using this equation is to replace the elastic modulus (E) by the tangent modulus (E_t) given by Equation 1.3.8.1. Values for the restraint coefficient (c) depend on degrees of ends and lateral fixities. End fixities tend to modify the effective column length as indicated in Equation 1.3.8.1. For a pin-ended column having no end restraint, $c = 1.0$ and $L' = L$. A fixity coefficient of $c = 2$ corresponds to an effective column length of $L' = 0.707$ times the total length.

The tangent modulus equation takes into account plasticity of a material and is valid when the following conditions are met:

(a) The column adjusts itself to forcible shortening only by bending and not by twisting.
(b) No buckling of any portion of the cross section occurs.
(c) Loading is applied concentrically along the longitudinal axis of the column.
(d) The cross section of the column is constant along its entire length.

MIL-HDBK-5 provides typical stress versus tangent modulus diagrams for many materials, forms, and grain directions. These information are not intended for design purposes. Methodology is contained in Chapter 9 for the development of allowable tangent modulus curves.

1.6.2.2 Column Stress (f_{co}) — The upper limit of column stress for primary failure is designated as f_{co}. By definition, this term should not exceed the compression ultimate strength, regardless of how the latter term is defined.

1.6.2.3 Other Considerations — Methods of analysis by which column failure stresses can be computed, accounting for fixities, torsional instability, load eccentricity, combined lateral loads, or varying column sections are contained in References 1.6.2.3(a) through (d).

1.6.3 LOCAL INSTABILITY FAILURES — Columns are subject to failure by local collapse of walls at stresses below the primary failure strength. The buckling analysis of a column subject to local instability requires consideration of the shape of the column cross section and can be quite complex. Local buckling, which can combine with primary buckling, leads to an instability failure commonly identified as crippling.

1.6.3.1 Crushing or Crippling Stress (f_{cc}) — The upper limit of column stress for local failure is defined by either its crushing or crippling stress. The strengths of round tubes have been thoroughly investigated and considerable amounts of test results are available throughout literature. Fewer data are available for other cross sectional configurations and testing is suggested to establish specific information, e.g., the curve of transition from local to primary failure.

1.6.4 CORRECTION OF COLUMN TEST RESULTS — In the case of columns having unconventional cross sections which are subject to local instability, it is necessary to establish curves of transition from local to primary failure. In determining these column curves, sufficient tests should be made to cover the following points.

1.6.4.1 Nature of "Short Column Curve" — Test specimens should cover a range of L'/ρ values. When columns are to be attached eccentrically in structural application, tests should be designed to cover such conditions. This is important particularly in the case of open sections, as maximum load carrying capabilities are affected by locations of load and reaction points.

1.6.4.2 Local Failure — When local failure occurs, the crushing or crippling stress can be determined by extending the short column curve to a point corresponding to a zero value for L'/ρ. When a family of columns of the same general cross section is used, it is often possible to determine a relationship between crushing or crippling stress and some geometric factor. Examples are wall thickness, width, diameter, or some combination of these dimensions. Extrapolation of such data to conditions beyond test geometry extremes should be avoided.

1.6.4.3 Reduction of Column Test Results on Aluminum and Magnesium Alloys to Standard Material — The use of correction factors provided in Figures 1.6.4.3(a) through (i) is acceptable to the Air Force, the Navy, the Army, and the Federal Aviation Administration for use in reducing aluminum and magnesium alloys column test data into allowables. (Note that an alternate method is provided in Section 1.6.4.4). In using Figures 1.6.4.3(a) through (i), the correction of column test results to standard material is made by multiplying the stress obtained from testing a column specimen by the factor K. This factor may be considered applicable regardless of the type of failure involved, i.e., column crushing, crippling or twisting. Note that not all the information provided in these figures pertains to allowable stresses, as explained below.

The following terms are used in reducing column test results into allowable column stress:

F_{cy}	is the design compression yield stress of the material in question, applicable to the gage, temper and grain direction along the longitudinal axis of a test column.
F_c'	is the maximum test column stress achieved in test. Note that a letter (F) is used rather the customary lower case (f). This value can be an individual test result.
F_{cy}'	is the compressive yield strength of the column material. Note that a letter (F) is used rather than the customary lower case (f). This value can be an individual test result using a standard compression test specimen.

Using the ratio of (F_c' / F_{cy}'), enter the appropriate diagram along the abscissa and extend a line upwards to the intersection of a curve with a value of (F_{cy}' / F_{cy}). Linear interpolation between curves is permissible. At this location, extend a horizontal line to the ordinate and read the corresponding K-factor. This factor is then used as a multiplier on the measured column strength to obtain the allowable. The basis for this allowable is the same as that noted for the compression yield stress allowable obtained from the room temperature allowables table.

If the above method is not feasible, due to an inability of conducting a standard compression test of the column material, the compression yield stress of the column material may be estimated as follows: Conduct a standard tensile test of the column material and obtain its tensile yield stress. Multiply this value by the ratio of compression-to-tensile yield allowables for the standard material. This provides the estimated compression yield stress of the column material. Continue with the analysis as described above using the compression stress of a test column in the same manner.

If neither of the above methods are feasible, it may be assumed that the compressive yield stress allowable for the column is 15 percent greater than minimum established allowable longitudinal tensile yield stress for the material in question.

1.6.4.4 *Reduction of Column Test Results to Standard Material-Alternate Method* — For materials that are not covered by Figures 1.6.4.4(a) through (i), the following method is acceptable for all materials to the Air Force, the Navy, the Army, and the Federal Aviation Administration.

(1) Obtain the column material compression properties: F_{cy}, E_c, n_c.

(2) Determine the test material column stress (f_c') from one or more column tests.

(3) Determine the test material compression yield stress (f_{cy}') from one or more tests.

(4) Assume E_c and n_c from (1) apply directly to the column material. They should be the same material.

(5) Assume that geometry of the test column is the same as that intended for design. This means that a critical slenderness ratio value of (L'/ρ) applies to both cases.

(6) Using the conservative form of the basic column formula provided in Equation 1.3.8.1, this enables an equality to be written between column test properties and allowables. If

$$\left(L'/\rho\right) \text{ for design} = \left(L'/\rho\right) \text{ of the column test} \qquad [1.6.4.4(a)]$$

Then

$$\left(F_c/E_t\right) \text{ for design} = \left(f_c'/E_t'\right) \text{ from test} \qquad [1.6.4.4(b)]$$

(7) Tangent modulus is defined as:

$$E_t = df/de \qquad [1.6.4.4(c)]$$

(8) Total strain (e) is defined as the sum of elastic and plastic strains, and throughout the Handbook is used as:

$$e = e_e + e_p \qquad [1.6.4.4(d)]$$

or,

$$e = \frac{f}{E} + 0.002\left(\frac{f}{f_y}\right)^n \qquad [1.6.4.4(e)]$$

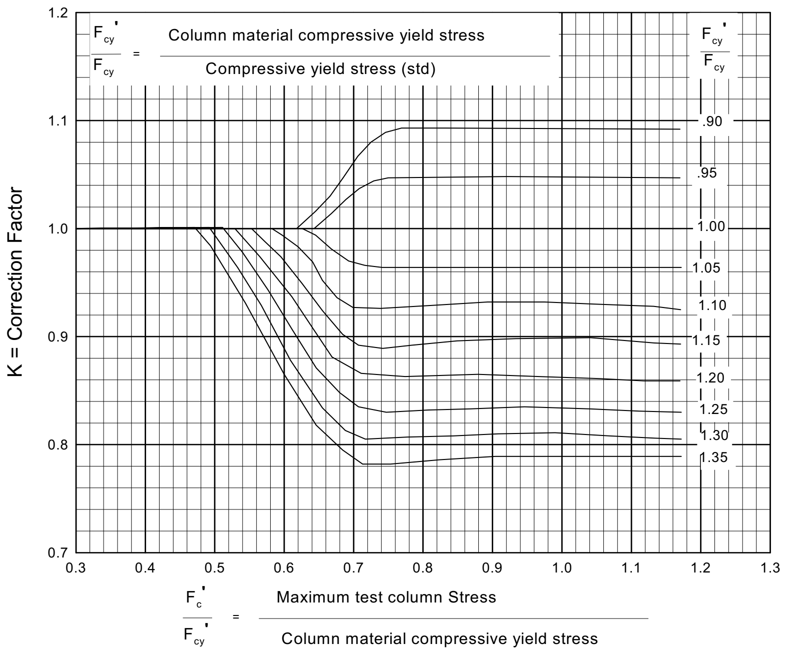

Figure 1.6.4.4(a). Nondimensional material correction chart for 2024-T3 sheet.

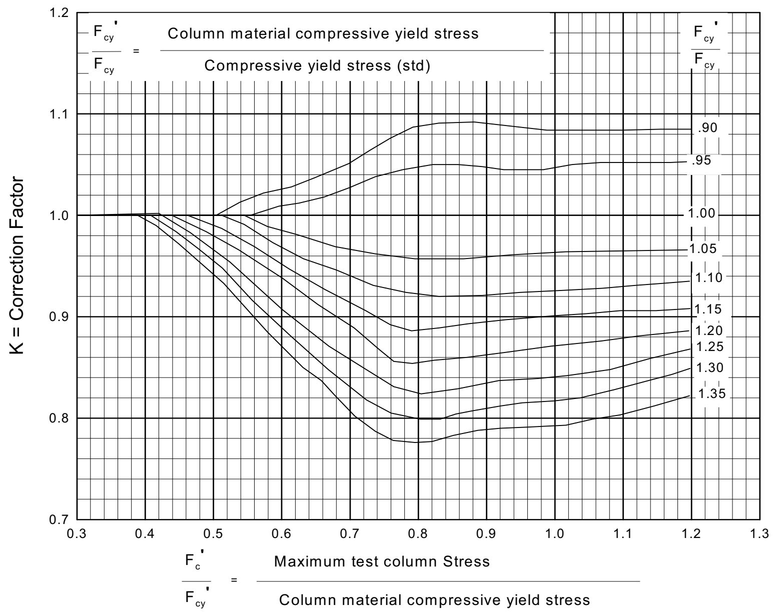

Figure 1.6.4.4(b). Nondimensional material correction chart for 2024-T3 clad sheet.

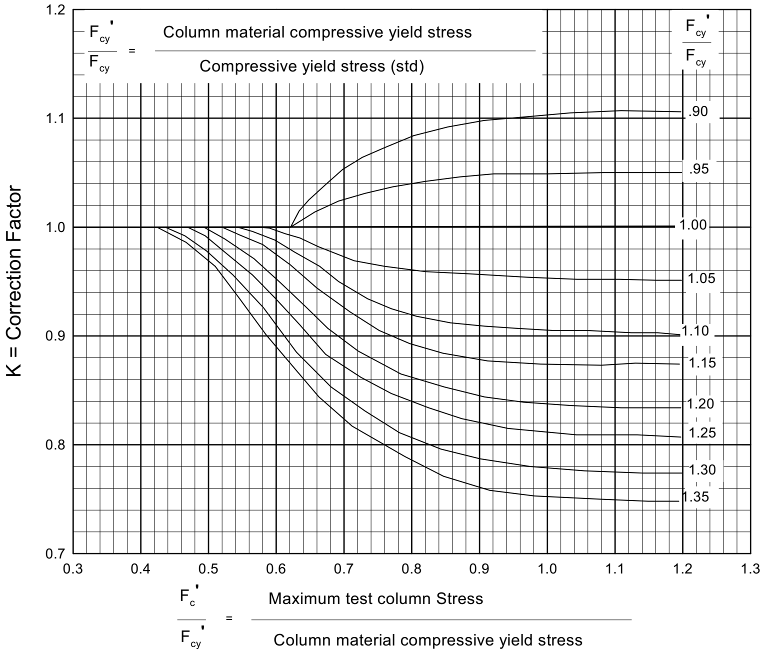

Figure 1.6.4.4(c). Nondimensional material correction chart for 2024-T4 extrusion less than 1/4 inch thick.

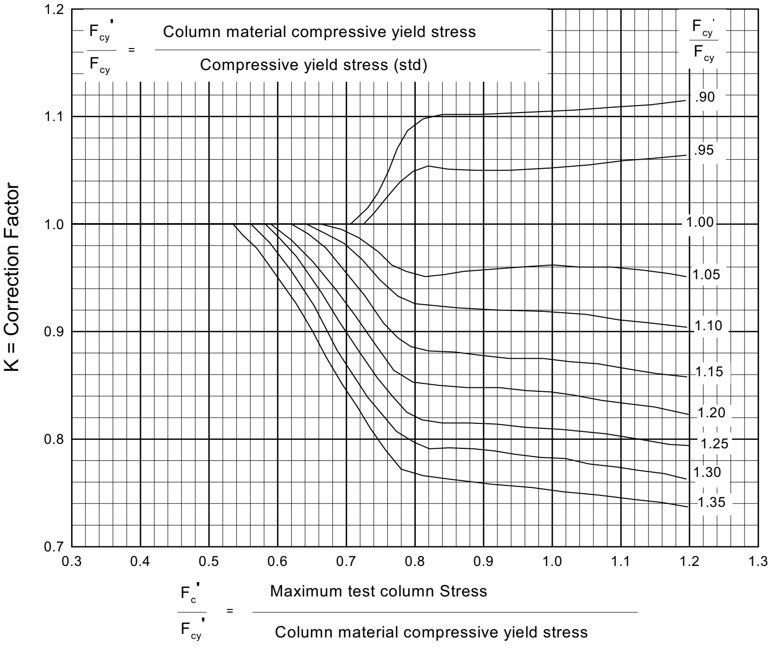

Figure 1.6.4.4(d). Nondimensional material correction chart for 2024-T4 extrusion 1/4 to 1-1/2 inches thick.

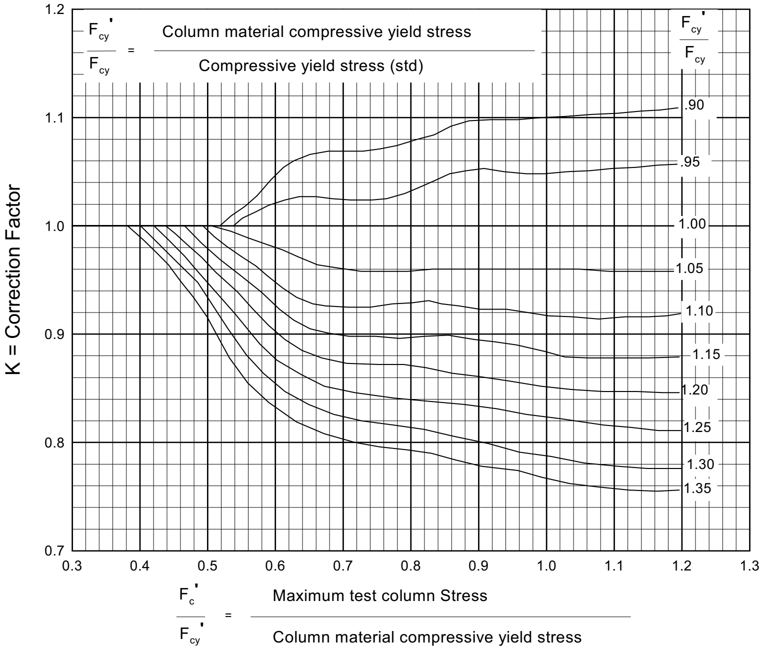

Figure 1.6.4.4(e). Nondimensional material correction chart for 2024-T3 tubing.

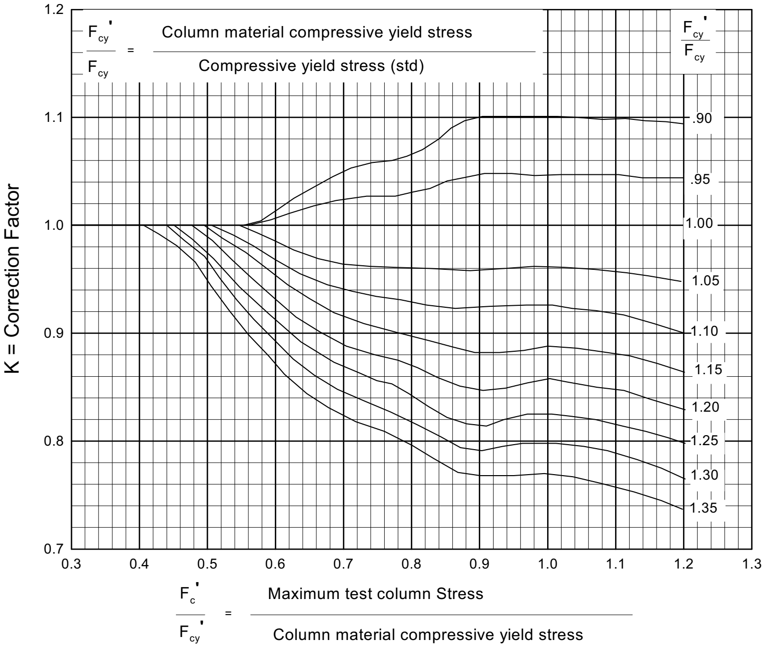

Figure 1.6.4.4(f). Nondimensional material correction chart for clad 2024-T3 sheet.

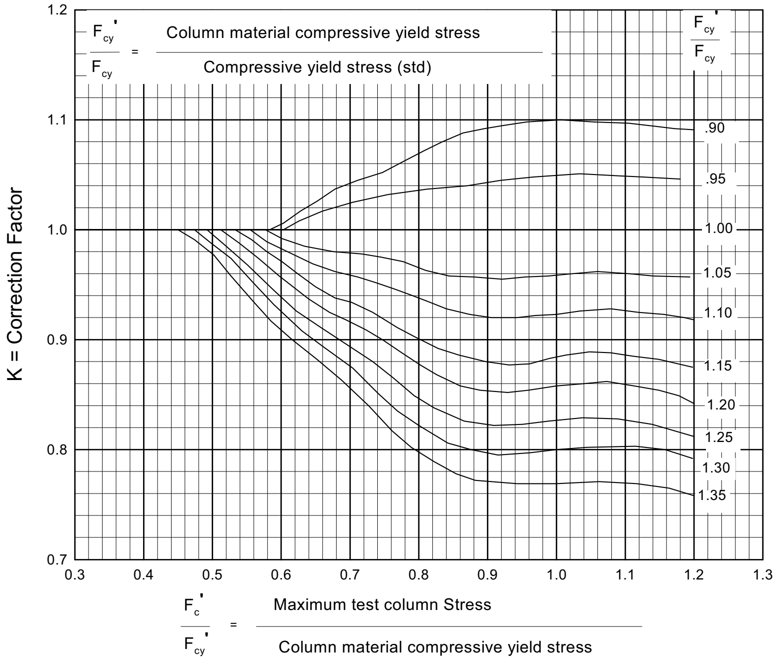

Figure 1.6.4.4(g). Nondimensional material correction chart for 7075-T6 sheet.

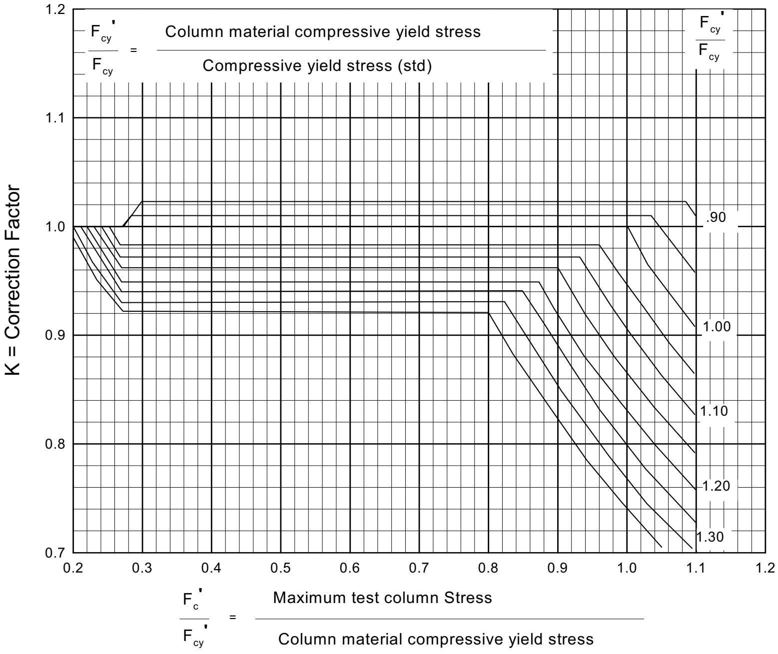

Figure 1.6.4.4(h). Nondimensional material correction chart for AZ31B-F and AZ61A-F extrusion.

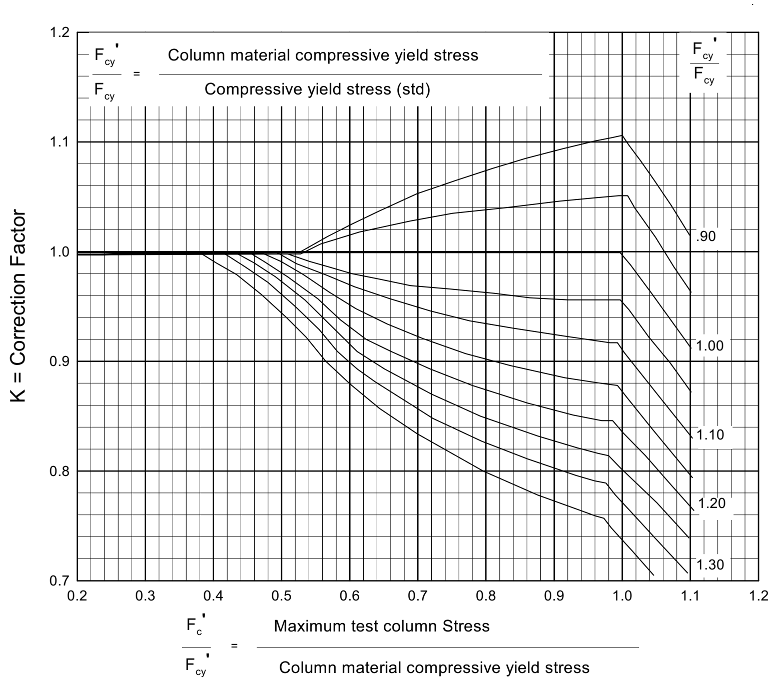

Figure 1.6.4.4(i). Nondimensional material correction chart for AZ31B-H24 sheet.

Equation 1.6.4.4(c) can be rewritten as follows:

$$E_t = \frac{f}{\frac{f}{E} + 0.002n\left(\frac{f}{f_y}\right)^n} \qquad [1.6.4.4(f)]$$

Tangent modulus, for the material in question, using its compression allowables is:

$$E_t = \frac{F_c}{\frac{F_c}{E_c} + 0.002n_c\left(\frac{F_c}{F_{cy}}\right)^{n_c}} \qquad [1.6.4.4(g)]$$

In like manner, tangent modulus for the same material with the desired column configuration is:

$$E_t' = \frac{f_c'}{\frac{f_c'}{E_c} + 0.002n_c\left(\frac{f_c'}{f_{cy}'}\right)^{n_c}} \qquad [1.6.4.4(h)]$$

Substitution of Equations 1.6.4.4(g) and 1.6.4.4(h) for their respective terms in Equation 1.6.4.4(b) and simplifying provides the following relationship:

$$\frac{F_c}{E_c} + 0.002n_c\left(\frac{F_c}{F_{cy}}\right)^{n_c} = \frac{f_c'}{E_c} + 0.002n_c\left(\frac{f_c'}{f_{cy}'}\right)^{n_c} \qquad [1.6.4.4(i)]$$

The only unknown in the above equation is the term F_c, the allowable column compression stress. This property can be solved by an iterative process.

This method is also applicable at other than room temperature, having made adjustments for the effect of temperature on each of the properties. It is critical that the test material be the same in all respects as that for which allowables are selected from the Handbook. Otherwise, the assumption made in Equation 1.6.4.4(c) above is not valid. Equation 1.6.4.4(i) must account for such differences in moduli and shape factors when applicable.

1.7 THIN-WALLED AND STIFFENED THIN-WALLED SECTIONS

A bibliography of information on thin-walled and stiffened thin-walled sections is contained in References 1.7(a) and (b).

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CHAPTER 2

STEEL

This chapter contains the engineering properties and related characteristics of steels used in aircraft and missile structural applications. General comments on engineering properties and other considerations related to alloy selection are presented in Section 2.1. Mechanical and physical property data and characteristics pertinent to specific steel groups or individual steels are reported in Sections 2.2 through 2.7. Element properties are presented in Section 2.8.

2.1 GENERAL

The selection of the proper grade of steel for a specific application is based on material properties and on manufacturing, environmental, and economic considerations. Some of these considerations are outlined in the sections that follow.

2.1.1 ALLOY INDEX — The steel alloys listed in this chapter are arranged in major sections that identify broad classifications of steel partly associated with major alloying elements, partly associated with processing, and consistent generally with steel-making technology. Specific alloys are identified as shown in Table 2.1.1.

Table 2.1.1. Steel Alloy Index

Section	Alloy Designation
2.2	**Carbon steels**
2.2.1	AISI 1025
2.3	**Low-alloy steels (AISI and proprietary grades)**
2.3.1	Specific alloys
2.4	**Intermediate alloy steels**
2.4.1	5Cr-Mo-V
2.4.2	9Ni-4Co-0.20C
2.4.3	9Ni-4Co-0.30C
2.5	**High alloy steels**
2.5.1	18 Ni maraging steels
2.5.2	AF1410
2.5.3	AerMet 100
2.6	**Precipitation and transformation hardening steel (stainless)**
2.6.1	AM-350
2.6.2	AM-355
2.6.3	Custom 450
2.6.4	Custom 455
2.6.5	Custom 465
2.6.6	PH13-8Mo
2.6.7	15-5PH
2.6.8	PH15-7Mo
2.6.9	17-4PH
2.6.10	17-7PH

Table 2.1.1(Continued). Steel Alloy Index

Section	Alloy Designation
2.7	**Austenitic stainless steels**
2.7.1	AISI 301 and Related 300 Series Stainless Steels

2.1.2 MATERIAL PROPERTIES — One of the major factors contributing to the general utility of steels is the wide range of mechanical properties which can be obtained by heat treatment. For example, softness and good ductility may be required during fabrication of a part and very high strength during its service life. Both sets of properties are obtainable in the same material.

All steels can be softened to a greater or lesser degree by annealing, depending on the chemical composition of the specific steel. Annealing is achieved by heating the steel to an appropriate temperature, holding, then cooling it at the proper rate.

Likewise, steels can be hardened or strengthened by means of cold working, heat treating, or a combination of these.

Cold working is the method used to strengthen both the low-carbon unalloyed steels and the highly alloyed austenitic stainless steels. Only moderately high strength levels can be attained in the former, but the latter can be cold rolled to quite high strength levels, or "tempers". These are commonly supplied to specified minimum strength levels.

Heat treating is the principal method for strengthening the remainder of the steels (the low-carbon steels and the austenitic steels cannot be strengthened by heat treatment). The heat treatment of steel may be of three types: martensitic hardening, age hardening, and austempering. Carbon and alloy steels are martensitic-hardened by heating to a high temperature, or "austenitizing", and cooling at a recommended rate, often by quenching in oil or water. This is followed by "tempering", which consists of reheating to an intermediate temperature to relieve internal stresses and to improve toughness.

The maximum hardness of carbon and alloy steels, quenched rapidly to avoid the nose of the isothermal transformation curve, is a function in general of the alloy content, particularly the carbon content. Both the maximum thickness for complete hardening or the depth to which an alloy will harden under specific cooling conditions, and the distribution of hardness can be used as a measure of a material's hardenability.

A relatively new class of steels is strengthened by age hardening. This heat treatment is designed to dissolve certain constituents in the steel, then precipitate them in some preferred particle size and distribution. Since both the martensitic hardening and the age-hardening treatments are relatively complex, specific details are presented for individual steels elsewhere in this chapter.

Recently, special combinations of working and heat treating have been employed to further enhance the mechanical properties of certain steels. At the present time, the use of these specialized treatments is not widespread.

Another method of heat treatment for steels is austempering. In this process, ferrous steels are austenitized, quenched rapidly to avoid transformation of the austenite to a temperature below the pearlite and above the martensite formation ranges, allowed to transform isothermally at that temperature to a completely bainitic structure, and finally cooled to room temperature. The purpose of austempering is to obtain increased ductility or notch toughness at high hardness levels, or to decrease the likelihood of cracking and distortion that might occur in conventional quenching and tempering.

2.1.2.1 *Mechanical Properties* —

2.1.2.1.1 *Strength (Tension, Compression, Shear, Bearing)* — The strength properties presented are those used in structural design. The room-temperature properties are shown in tables following the comments for individual steels. The variations in strength properties with temperature are presented graphically as percentages of the corresponding room-temperature strength property, also described in Section 9.3.1 and associated subsections. These strength properties may be reduced appreciably by prolonged exposure at elevated temperatures.

The strength of steels is temperature-dependent, decreasing with increasing temperature. In addition, steels are strain rate-sensitive above about 600 to 800°F, particularly at temperatures at which creep occurs. At lower strain rates, both yield and ultimate strengths decrease.

The modulus of elasticity is also temperature-dependent and, when measured by the slope of the stress-strain curve, it appears to be strain rate-sensitive at elevated temperatures because of creep during loading. However, on loading or unloading at high rates of strain, the modulus approaches the value measured by dynamic techniques.

Steel bars, billets, forgings, and thick plates, especially when heat treated to high strength levels, exhibit variations in mechanical properties with location and direction. In particular, elongation, reduction of area, toughness, and notched strength are likely to be lower in either of the transverse directions than in the longitudinal direction. This lower ductility and/or toughness results both from the fibering caused by the metal flow and from nonmetallic inclusions which tend to be aligned with the direction of primary flow. Such anisotropy is independent of the depth-of-hardening considerations discussed elsewhere. It can be minimized by careful control of melting practices (including degassing and vacuum-arc remelting) and of hot-working practices. In applications where transverse properties are critical, requirements should be discussed with the steel supplier and properties in critical locations should be substantiated by appropriate testing.

2.1.2.1.2 *Elongation* — The elongation values presented in this chapter apply in both the longitudinal and long transverse directions, unless otherwise noted. Elongation in the short transverse (thickness) direction may be lower than the values shown.

2.1.2.1.3 *Fracture Toughness* — Steels (as well as certain other metals), when processed to obtain high strength, or when tempered or aged within certain critical temperature ranges, may become more sensitive to the presence of small flaws. Thus, as discussed in Section 1.4.12, the usefulness of high-strength steels for certain applications is largely dependent on their toughness. It is generally noted that the fracture toughness of a given alloy product decreases relative to increase in the yield strength. The designer is cautioned that the propensity for brittle fracture must be considered in the application of high-strength alloys for the purpose of increased structural efficiency.

Minimum, average, and maximum values, as well as coefficient of variation of plane-strain fracture toughness for several steel alloys, are presented in Table 2.1.2.1.3. These values are presented as indicative information and do not have the statistical reliability of room-temperature mechanical properties. Data showing the effect of temperature are presented in the respective alloy sections where the information is available.

Table 2.1.2.1.3. Values of Room Temperature Plane-Strain Fracture Toughness of Steel Alloys[a]

Alloy	Heat Treat Condition	Product Form	Orientation[b]	Yield Strength Range, ksi	Product Thickness Range, inches	Number of Sources	Sample Size	Specimen Thickness Range, inches	K_{IC}, ksi √in. Max.	K_{IC}, ksi √in. Avg.	K_{IC}, ksi √in. Min.	K_{IC}, ksi √in. Coefficient of Variation
AerMet 100	Anneal, HT to 280ksi	Bar	L-R	236-281	2.75-10	1	183	1	146	121	100	7.9
AerMet 100	Anneal, HT to 280ksi	Bar	C-R	223-273	2.75-10	1	156	1	137	112	90	8.5
AerMet 100	Anneal, HT to 290ksi	Bar	L-R	251-265	3-10	1	29	1	110	99	88	6.5
AerMet 100	Anneal, HT to 290ksi	Bar	C-R	250-268	3-10	1	24	1	101	88	73	9.7
Custom 465	H950	Bar	L-R[c]	229-249	3-12	1	40	1-1.5	104	89	76	7.4
Custom 465	H950	Bar	R-L[c]	231-246	3-12	1	40	1-1.5	94	82	73	6.4
Custom 465	H1000	Bar	L-R[c]	212-227	3-12	1	40	1-1.5	131	120	108	5.2
Custom 465	H1000	Bar	R-L[c]	212-225	3-12	1	40	1-1.5	118	109	100	3.7
D6AC	1650°F, Aus-Bay Quench 975°F, SQ 375°F, 1000°F 2 + 2	Plate	L-T	217	1.5	1	19	0.6	88	62	40	22.5
D6AC	1650°F, Aus-Bay Quench 975°F, SQ 400°F, 1000°F 2 + 2	Plate	L-T	217	0.8	1	103	0.6-0.8	92	64	44	18.9
D6AC	1650°F, Aus-Bay Quench 975°F, SQ 400°F, 1000°F 2 + 2	Forging	L-T	214	0.8-1.5	1	53	0.6-0.8	96	66	39	18.6
D6AC	1700°F, Aus-Bay Quench 975°F, OQ 140°F, 1000°F 2 + 2	Plate	L-T	217	0.8-1.5	1	30	0.6-0.8	101	92	64	8.9
D6AC	1700°F, Aus-Bay Quench 975°F, OQ 140°F, 1000°F 2 + 2	Forging	L-T	214	0.8-1.5	1	34	0.7	109	95	81	6.7
9Ni-4Co-.20C	Quench and Temper	Hand Forging	L-T	185-192	3.0	2	27	1.0-2.0	147	129	107	8.3
9Ni-4Co-.20C	1650°F, 1-2 Hr, AC, 1525°F, 1-2 Hr, OQ, -100°F, Temp	Forging	L-T	186-192	3.0-4.0	3	17	1.5-2.0	147	134	120	8.5
PH13-8Mo	H1000	Forging	L-T	205-212	4.0-8.0	3	12	0.7-2.0	104	90	49	21.5

a These values are for information only.

b Refer to Figures 1.4.12.3(a) and 1.4.12.3(b) for definition of symbols.

c L-R also includes some L-T, R-L also includes some T-L.

2.1.2.1.4 *Stress-Strain Relationships* — The stress-strain relationships presented in this chapter are prepared as described in Section 9.3.2.

2.1.2.1.5 *Fatigue* — Axial-load fatigue data on unnotched and notched specimens of various steels at room temperature and at other temperatures are shown as S/N curves in the appropriate section. Surface finish, surface finishing procedures, metallurgical effects from heat treatment, environment and other factors influence fatigue behavior. Specific details on these conditions are presented as correlative information for the S/N curve.

2.1.2.2 *Physical Properties* — The physical properties (ω, C, K, and α) of steels may be considered to apply to all forms and heat treatments unless otherwise indicated.

2.1.3 ENVIRONMENTAL CONSIDERATIONS — The effects of exposure to environments such as stress, temperature, atmosphere, and corrosive media are reported for various steels. Fracture toughness of high-strength steels and the growth of cracks by fatigue may be detrimentally influenced by humid air and by the presence of water or saline solutions. Some alleviation may be achieved by heat treatment and all high-strength steels are not similarly affected.

In general, these comments apply to steels in their usual finished surface condition, without surface protection. It should be noted that there are available a number of heat-resistant paints, platings, and other surface coatings that are employed either to improve oxidation resistance at elevated temperature or to afford protection against corrosion by specific media. In employing electrolytic platings, special consideration should be given to the removal of hydrogen by suitable baking. Failure to do so may result in lowered fracture toughness or embrittlement.

2.2 CARBON STEELS

2.2.0 COMMENTS ON CARBON STEELS

2.2.0.1 *Metallurgical Considerations* — Carbon steels are those steels containing carbon up to about 1 percent and only residual quantities of other elements except those added for deoxidation.

The strength that carbon steels are capable of achieving is determined by carbon content and, to a much lesser extent, by the content of the residual elements. Through cold working or proper choice of heat treatments, these steels can be made to exhibit a wide range of strength properties.

The finish conditions most generally specified for carbon steels include hot-rolled, cold-rolled, cold-drawn, normalized, annealed, spheroidized, stress-relieved, and quenched-and-tempered. In addition, the low-carbon grades (up to 0.25 percent C) may be carburized to obtain high surface hardness and wear resistance with a tough core. Likewise, the higher carbon grades are amenable to selective flame hardening to obtain desired combinations of properties.

2.2.0.2 *Manufacturing Considerations* —

Forging — All of the carbon steels exhibit excellent forgeability in the austenitic state provided the proper forging temperatures are used. As the carbon content is increased, the maximum forging temperature is decreased. At high temperatures, these steels are soft and ductile and exhibit little or no tendency to work harden. The resulfurized grades (free-machining steels) exhibit a tendency to rupture when deformed in certain high-temperature ranges. Close control of forging temperatures is required.

Cold Forming — The very low-carbon grades have excellent cold-forming characteristics when in the annealed or normalized conditions. Medium-carbon grades show progressively poorer formability with higher carbon content, and more frequent annealing is required. The high-carbon grades require special softening treatments for cold forming. Many carbon steels are embrittled by warm working or prolonged exposure in the temperature range from 300 to 700°F.

Machining — The low-carbon grades (0.30 percent C and less) are soft and gummy in the annealed condition and are preferably machined in the cold-worked or the normalized condition. Medium-carbon (0.30 to 0.50 percent C) grades are best machined in the annealed condition, and high-carbon grades (0.50 to 0.90 percent C) in the spheroidized condition. Finish machining must often be done in the fully heat-treated condition for dimensional accuracy. The resulfurized grades are well known for their good machinability. Nearly all carbon steels are now available with 0.15 to 0.35 percent lead, added to improve machinability. However, resulfurized and leaded steels are not generally recommended for highly stressed aircraft and missile parts because of a drastic reduction in transverse properties.

Welding — The low-carbon grades are readily welded or brazed by all techniques. The medium-carbon grades are also readily weldable but may require preheating and postwelding heat treatment. The high-carbon grades are difficult to weld. Preheating and postwelding heat treatment are usually mandatory for the latter, and special care must be taken to avoid overheating. Furnace brazing has been used successfully with all grades.

Heat Treatment — Due to the poor oxidation resistance of carbon steels, protective atmospheres must be employed during heat treatment if scaling of the surface cannot be tolerated. Also, these steels are subject to decarburization at elevated temperatures and, where surface carbon content is critical, should be heated in reducing atmospheres.

2.2.0.3 ***Environmental Considerations*** — Carbon steels have poor oxidation resistance above about 900 to 1000°F. Strength and oxidation-resistance criteria generally preclude the use of carbon steels above 900°F.

Carbon steels may undergo an abrupt transition from ductile to brittle behavior. This transition temperature varies widely for different carbon steels depending on many factors. Cautions should be exercised in the application of carbon steels to assure that the transition temperature of the selected alloy is below the service temperature. Additional information is contained in References 2.2.0.3(a) and (b).

The corrosion resistance of carbon steels is relatively poor; clean surfaces rust rapidly in moist atmospheres. Simple oil film protection is adequate for normal handling. For aerospace applications, the carbon steels are usually plated to provide adequate corrosion protection.

2.2.1 AISI 1025

2.2.1.0 ***Comments and Properties*** — AISI 1025 is an excellent general purpose steel for the majority of shop requirements, including jigs, fixtures, prototype mockups, low torque shafting, and other applications. It is not generally classed as an airframe structural steel. However, it is available in aircraft quality as well as commercial quality.

Manufacturing Considerations — Cold-finished flat-rolled products are supplied principally where maximum strength, good surface finish, or close tolerance is desirable. Reasonably good forming properties are found in AISI 1025. The machinability of bar stock is rated next to these sulfurized types of free-machining steels, but the resulting surface finish is poorer.

Specifications and Properties — Material specifications for AISI 1025 steel are presented in Table 2.2.1.0(a). The room-temperature mechanical and physical properties are shown in Table 2.2.1.0(b). The effect of temperature on thermal expansion is shown in Figure 2.2.1.0.

Table 2.2.1.0(a). Material Specifications for AISI 1025 Carbon Steel

Specification	Form
ASTM A 108	Bar
AMS 5075	Seamless tubing
AMS-T-5066[a]	Tubing
AMS 5077	Tubing
AMS 5046	Sheet, strip, and plate
AMS-S-7952	Sheet and strip

a Noncurrent specification

Table 2.2.1.0(b). Design Mechanical and Physical Properties of AISI 1025 Carbon Steel

Specification	AMS 5046 and AMS-S-7952	AMS 5075, AMS 5077 and AMS-T-5066[a]	ASTM A 108
Form	Sheet, strip, and plate	Tubing	Bar
Condition	Annealed	Normalized	All
Thickness, in.	...	...	...
Basis	S	S	S[b]
Mechanical Properties:			
F_{tu}, ksi:			
L	55	55	55
LT	55	55	55
ST	...	...	55
F_{ty}, ksi:			
L	36	36	36
LT	36	36	36
ST	...	...	36
F_{cy}, ksi:			
L	36	36	36
LT	36	36	36
ST	...	...	36
F_{su}, ksi	35	35	35
F_{bru}, ksi:			
(e/D = 1.5)	...	...	...
(e/D = 2.0)	90	90	90
F_{bry}, ksi:			
(e/D = 1.5)	...	...	...
(e/D = 2.0)	...	...	...
e, percent:			
L	...	c	c
LT	c	...	...
E, 10^3 ksi	29.0		
E_c, 10^3 ksi	29.0		
G, 10^3 ksi	11.0		
μ	0.32		
Physical Properties:			
ω, lb/in.^{3}	0.284		
C, Btu/(lb)(°F)	0.116 (122 to 212°F)		
K, Btu/[(hr)(ft^2)(°F)/ft]	30.0 (at 32°F)		
α, 10^{-6} in./in./°F	See Figure 2.2.1.0		

a Noncurrent specification.
b Design values are applicable only to parts for which the indicated F_{tu} has been substantiated by adequate quality control testing.
c See applicable specification for variation in minimum elongation with ultimate strength.

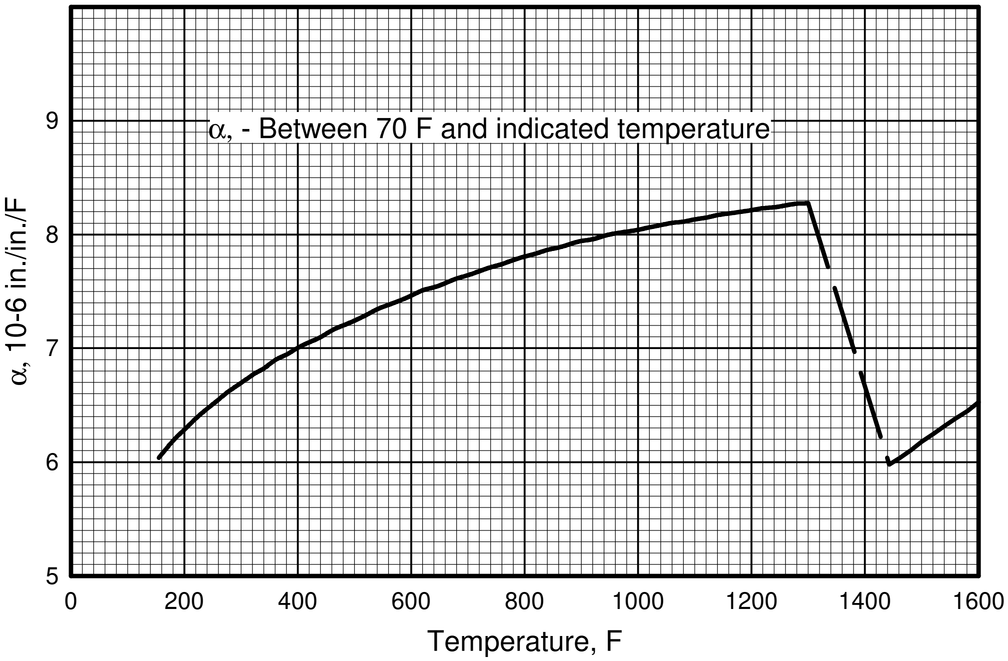


Figure 2.2.1.0. Effect of temperature on the thermal expansion of 1025 steel.

2.3 LOW-ALLOY STEELS (AISI GRADES AND PROPRIETARY GRADES)

2.3.0 COMMENTS ON LOW-ALLOY STEELS (AISI AND PROPRIETARY GRADES)

2.3.0.1 *Metallurgical Considerations* — The AISI or SAE alloy steels contain, in addition to carbon, up to about 1 percent (up to 0.5 percent for most airframe applications) additions of various alloying elements to improve their strength, depth of hardening, toughness, or other properties of interest. Generally, alloy steels have better strength-to-weight ratios than carbon steels and are somewhat higher in cost on a weight, but not necessarily strength, basis. Their applications in airframes include landing-gear components, shafts, gears, and other parts requiring high strength, through hardening, or toughness.

Some alloy steels are identified by the AISI four-digit system of numbers. The first two digits indicate the alloy group and the last two the approximate carbon content in hundredths of a percent. The alloying elements used in these steels include manganese, silicon, nickel, chromium, molybdenum, vanadium, and boron. Other steels in this section are proprietary steels which may be modifications of the AISI grades. The alloying additions in these steels may provide deeper hardening, higher strength and toughness.

These steels are available in a variety of finish conditions, ranging from hot- or cold-rolled to quenched-and-tempered. They are generally heat treated before use to develop the desired properties. Some steels in this group are carburized, then heat treated to produce a combination of high surface hardness and good core toughness.

2.3.0.2 *Manufacturing Conditions* —

Forging — The alloy steels are only slightly more difficult to forge than carbon steels. However, maximum recommended forging temperatures are generally about 50°F lower than for carbon steels of the same carbon content. Slower heating rates, shorter soaking period, and slower cooling rates are also required for alloy steels.

Cold Forming — The alloy steels are usually formed in the annealed condition. Their formability depends mainly on the carbon content and is generally slightly poorer than for unalloyed steels of the same carbon content. Little cold forming is done on these steels in the heat-treated condition because of their high strength and limited ductility.

Machining — The alloy steels are generally harder than unalloyed steels of the same carbon content. As a consequence, the low-carbon alloy steels are somewhat easier to finish machine than their counterparts in the carbon steels. It is usually desirable to finish machine the carburizing and through-hardening grades in the final heat-treated condition for better dimensional accuracy. This often leads to two steps in machining: rough machining in the annealed or hot-finished condition, then finish machining after heat treating. The latter operation, because of the relatively high hardness of the material, necessitates the use of sharp, well-designed, high-speed steel cutting tools, proper feeds, speeds, and a generous supply of coolant. Medium- and high-carbon grades are usually spheroidized for optimum machinability and, after heat treatment, may be finished by grinding. Many of the alloy steels are available with added sulfur or lead for improved machinability. However, resulfurized and leaded steels are not recommended for highly stressed aircraft and missile parts, because of drastic reductions in transverse properties.

Welding — The low-carbon grades are readily welded or brazed by all techniques. Alloy welding rods comparable in strength to the base metal are used, and moderate preheating (200 to 600°F) is usually necessary. At higher carbon levels, higher preheating temperatures, and often postwelding stress relieving, are required. Certain alloy steels can be welded without loss of strength in the heat-affected zone provided that the welding heat input is carefully controlled. If the composition and strength level are such that the strength of the welded joint is reduced, the strength of the joint may be restored by heat treatment after welding.

Heat Treatment — For the low alloy steels, there are various heat treatment procedures that can be applied to a particular alloy to achieve any one of a number of specific mechanical (for example tensile) properties. Within this chapter, there are mechanical properties for three thermal processing conditions: annealed, normalized, and quenched and tempered. The specific details of these three thermal processing conditions are reviewed in Reference 2.3.0.2.5. In general, the annealed condition is achieved by heating to a suitable temperature and holding for a specified period of time. Annealing generally softens the material, producing the lowest mechanical properties. The normalized condition is achieved by holding to a slightly higher temperature than annealing, but for a shorter period of time. The purpose of normalizing varies depending on the desired properties; it can be used to increase or decrease mechanical properties. The quenched and tempered condition, discussed in more detail below, is used to produce the highest mechanical properties while providing relatively high toughness. The mechanical properties for these three processing conditions for specific steels are as shown in Tables 2.3.1.0(c), (f), and (g).

Maximum hardness in these steels is obtained in the as-quenched condition, but toughness and ductility in this condition are comparatively low. By means of tempering, their toughness is improved, usually accompanied by a decrease in strength and hardness. In general, tempering temperatures to achieve very high strength should be avoided when toughness is an important consideration.

In addition, these steels may be embrittled by tempering or by prolonged exposure under stress within the “blue brittle” range (approximately 500 to 700°F). Strength levels that necessitate tempering within this range should be avoided.

The mechanical properties presented in this chapter represent steels heat treated to produce a quenched structure containing 90 percent martensite at the center and tempered to the desired F_{tu} level. This degree of through hardening is necessary (regardless of strength level) to insure the attainment of reasonably uniform mechanical properties throughout the cross section of the heat-treated part. The maximum diameter of round bars of various alloy steels capable of being through hardened consistently are given in Table 2.3.0.2. Limiting dimensions for common shapes other than round are determined by means of the “equivalent round” concept in Figure 2.3.0.2. This concept is essentially a correlation between the significant dimensions of a particular shape and the diameter of a round bar, assuming in each instance that the material, heat treatment, and the mechanical properties at the centers of both the respective shape and the equivalent round are substantially the same.

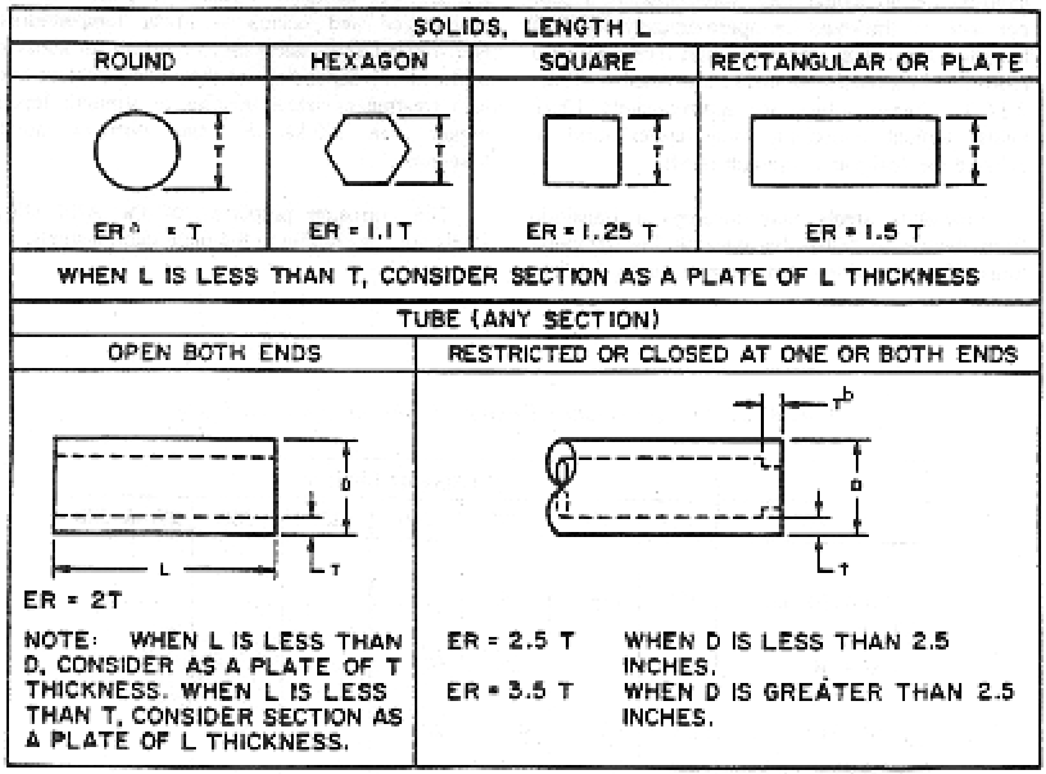
For the quenched and tempered condition, a large range of mechanical property values can be achieved as indicated in Table 2.3.0.2. Various quench media (rates), tempering temperatures, and times can be employed allowing any number of processing routes to achieve these values. As a result of these processing routes, there are a large range of mechanical properties that can be obtained for a specific alloy. Therefore, the properties of a steel can be tailored to meet the needs for a specific component/application.

Because of the potential for several different processing methods for these three conditions, the MIL, Federal, and AMS specifications do not always contain minimum mechanical property values (S-basis). They may contain minimum mechanical property values for one specific quenched and tempered condition. Those specifications cited in this Handbook that do not contain mechanical properties are identified with a footnote in Tables 2.3.1.0(a) and (b). The possible mechanical properties for these alloys covered in the specifications for the normalized, and quenched and tempered conditions in Table 2.3.0.2 are presented in Tables 2.3.1.0 (g_1) and (g_2). Users must rely on their own in-house specifications or appropriate industry specifications to validate that the required strength was achieved. Therefore, no statistical basis (A, B, S) for these values are indicated in Tables 2.3.1.0 (g_1) and (g_2).

Table 2.3.0.2. Maximum Round Diameters for Low-Alloy Steel Bars (Through Hardening to at Least 90 Percent Martensite at Center)

	Maximum Diameter of Round or Equivalent Round, in.[a]						
F_{tu}, ksi	0.5	0.8	1.0	1.7	2.5	3.5	5.0
270 & 280	. . .	. . .	. . .	. . .	. . .	. . .	300M[c]
260	. . .	. . .	. . .	AISI 4340[b]	AISI 4340[c]	AISI 4340[d]	. . .
220	. . .	. . .	. . .	AMS Grades[b,e]	AMS Grades[c,e]	D6AC[b]	D6AC[c]
200	. . .	AISI 8740	AISI 4140	AISI 4340[b] AMS Grades[b,e]	AISI 4340[c] AMS Grades[c,e]	AISI 4340[d]	D6AC[c]
≤180	AISI 4130 and 8630	AISI 8735 4135 and 8740	AISI 4140	AISI 4340[b] AMS Grades[b,e]	AISI 4340[c] AMS Grades[c,e]	AISI 4340[d] D6AC[b]	D6AC[c]

a This table indicates the maximum diameters to which these steels may be through hardened consistently by quenching as indicated. Any steels in this table may be used at diameters less than those indicated. The use of steels at diameters greater than those indicated should be based on hardenability data for specific heats of steel.
b Quenched in molten salt at desired tempering temperature ("martempering").
c Quenched in oil at a flow rate of 200 feet per minute.
d Quenched in water at a flow rate of 200 feet per minute.
e 4330V, 4335V, and Hy-Tuf.



WHEN L IS LESS THAN T, CONSIDER SECTION AS A PLATE OF L THICKNESS

NOTE: WHEN L IS LESS THAN D, CONSIDER AS A PLATE OF T THICKNESS. WHEN L IS LESS THAN T, CONSIDER SECTION AS A PLATE OF L THICKNESS.

ER = 2.5 T WHEN D IS LESS THAN 2.5 INCHES.

ER = 3.5 T WHEN D IS GREATER THAN 2.5 INCHES.

[a] ER = equivalent round. (Illustration after MIL-H-6875.)
[b] Use maximum thickness for calculation.

Figure 2.3.0.2. Correlation between significant dimensions of common shapes other than round, and the diameters of round bars.

2.3.0.3 *Environmental Considerations* — Alloy steels containing chromium or high percentages of silicon have somewhat better oxidation resistance than the carbon or other alloy steels. Elevated-temperature strength for the alloy steels is also higher than that of corresponding carbon steels. The mechanical properties of all alloy steels in the heat-treated condition are affected by extended exposure to temperatures near or above the temperature at which they were tempered. The limiting temperatures to which each alloy may be exposed for no longer than approximately 1 hour per inch of thickness or approximately one-half hour for thicknesses under one-half inch without a reduction in strength occurring are listed in Table 2.3.0.3. These values are approximately 100°F below typical tempering temperatures used to achieve the designated strength levels.

Table 2.3.0.3. Temperature Exposure Limits for Low-Alloy Steels

	Exposure Limit, °F						
F_{tu}, ksi	125	150	180	200	220	260	270 & 280
Alloy:							
AISI 4130 and 8630	925	775	575	...	...	...	...
AISI 4140 and 8740	1025	875	725	625	...	...	...
AISI 4340	1100	950	800	700	...	350	...
AISI 4135 and 8735	975	825	675	...	...	...	...
D6AC	1150	1075	1000	950	900	500	...
Hy-Tuf	875	750	650	550	450	...	...
4330V	925	850	775	700	500	...	...
4335V	975	875	775	700	500	...	...
300M	...	...	...	...	...	...	475

a Quenched and tempered to F_{tu} indicated. If the material is exposed to temperatures exceeding those listed, a reduction in strength is likely to occur.

Low-alloy steels may undergo a transition from ductile to brittle behavior at low temperatures. This transition temperature varies widely for different alloys. Caution should be exercised in the application of low-alloy steels at temperatures below -100°F. For use at a temperature below -100°F, an alloy with a transition temperature below the service temperature should be selected. For low temperatures, the steel should be heat treated to a tempered martensitic condition for maximum toughness.

Heat-treated alloy steels have better notch toughness than carbon steels at equivalent strength levels. The decrease in notch toughness is less pronounced and occurs at lower temperatures. Heat-treated alloy steels may be useful for subzero applications, depending on their alloy content and heat treatment. Heat treating to strength levels higher than 150 ksi F_{ty} may decrease notch toughness.

The corrosion properties of the AISI alloy steels are comparable to the plain carbon steels.

2.3.1 SPECIFIC ALLOYS

2.3.1.0 *Comments and Properties* — AISI 4130 is a chromium-molybdenum steel that is in general use due to its well-established heat-treating practices and processing techniques. It is available in all sizes of sheet, plate, and tubing. Bar stock of this material is also used for small forgings under one-half inch in thickness. AISI 4135, a slightly higher carbon version of AISI 4130, is available in sheet, plate, and tubing.

AISI 4140 is a chromium-molybdenum steel that can be heat treated in thicker sections and to higher strength levels than AISI 4130. This steel is generally used for structural machined and forged parts one-half inch and over in thickness. It can be welded but it is more difficult to weld than the lower carbon grade AISI 4130.

AISI 4340 is a nickel-chromium-molybdenum steel that can be heat treated in thicker sections and to higher strength levels than AISI 4140.

AISI 8630, 8735, and 8740 are nickel-chromium-molybdenum steels that are considered alternates to AISI 4130, 4135, and 4140, respectively.

There are a number of steels available with compositions that represent modifications to the AISI grades described above. Four of the steels that have been used rather extensively at F_{tu} = 220 ksi are D6AC, Hy-Tuf, 4330V, and 4335V. It should be noted that this strength level is not used for AISI 4340 due to embrittlement encountered during tempering in the range of 500 to 700°F. In addition, AISI 4340 and 300M are utilized at strength levels of F_{tu} = 260 ksi or higher. The alloys, AISI 4340, D6AC, 4330V, 4335V, and 300M, are available in the consumable electrode melted grade. Material specifications for these steels are presented in Tables 2.3.1.0(a) and (b).

The room-temperature mechanical and physical properties for these steels are presented in Tables 2.3.1.0(c) through 2.3.1.0(g). Mechanical properties for heat-treated materials are valid only for steel heat treated to produce a quenched structure containing 90 percent or more martensite at the center. Figure 2.3.1.0 contains elevated temperature curves for the physical properties of AISI 4130 and AISI 4340 steels.

2.3.1.1 *AISI Low-Alloy Steels* — Elevated temperature curves for heat-treated AISI low-alloy steels are presented in Figures 2.3.1.1.1 through 2.3.1.1.4. These curves are considered valid for each of these steels in each heat-treated condition but only up to the maximum temperatures listed in Table 2.3.0.1(b).

2.3.1.2 *AISI 4130 and 8630 Steels* — Typical stress-strain and tangent-modulus curves for AISI 8630 are shown in Figures 2.3.1.2.6(a) through (c). Best-fit S/N curves for AISI 4130 steel are presented in Figures 2.3.1.2.8(a) through (h).

2.3.1.3 *AISI 4340 Steel* — Typical stress-strain and tangent-modulus curves for AISI 4340 are shown in Figures 2.3.1.3.6(a) through (c). Typical biaxial stress-strain curves and yield-stress envelopes for AISI 4340 alloy steel are presented in Figures 2.3.1.3.6(d) through (g). Best-fit S/N curves for AISI 4340 are presented in Figures 2.3.1.3.8(a) through (o).

2.3.1.4 *300M Steel* — Best-fit S/N curves for 300M steel are presented in Figures 2.3.1.4.8(a) through (d). Fatigue-crack-propagation data for 300M are shown in Figure 2.3.1.4.9.

2.3.1.5 *D6AC Steel* — Fatigue-crack-propagation data for D6AC steel are presented in Figure 2.3.1.5.9.

Table 2.3.1.0(a). Material Specifications for Air Melted Low-Alloy Steels

Alloy	Form		
	Sheet, strip, and plate	Bars and forgings	Tubing
4130	AMS-S-18729, AMS 6350[a], AMS 6351[a]	AMS-S-6758[a], AMS 6348[a], AMS 6370[a], AMS 6528[a]	AMS-T-6736, AMS 6371[a], AMS 6360, AMS 6361, AMS 6362, AMS 6373, AMS 6374
8630	AMS-S-18728[b], AMS 6350[a]	AMS-S-6050, AMS 6280[a]	AMS 6281[a]
4135	AMS 6352[a]	...	AMS 6372[a], AMS 6365, AMS-T-6735[b]
8735	AMS 6357[a]	AMS 6320[a]	AMS 6282[a]
4140	AMS 6395[a]	AMS-S-5626[a], AMS 6382[a], AMS 6349[a], AMS 6529[a]	AMS 6381[a]
4340	AMS 6359[a]	AMS-S-5000[a], AMS 6415[a]	AMS 6415[a]
8740	AMS 6358[a]	AMS-S-6049[b], AMS 6327, AMS 6322[a]	AMS 6323[a]
4330V	...	AMS 6427[a]	AMS 6427[a]
4335V	AMS 6433	AMS 6430	AMS 6430

a Specification does not contain minimum mechanical properties.
b Noncurrent specification.

Table 2.3.1.0(b). Material Specifications for Consumable Electrode Melted Low-Alloy Steels

Alloy	Form		
	Sheet, strip, and plate	Bar and forgings	Tubing
4340	AMS 6454[a]	AMS 6414	AMS 6414
D6AC	AMS 6439	AMS 6431, AMS 6439	AMS 6431
4330V	...	AMS 6411	AMS 6411
Hy-Tuf	...	AMS 6425	AMS 6425
4335V	AMS 6435	AMS 6429	AMS 6429
300M (0.40C)	...	AMS 6417	AMS 6417
300M (0.42C)	...	AMS 6419, AMS 6257	AMS 6419, AMS 6257

a Specification does not contain minimum mechanical properties.

Table 2.3.1.0(c_1). Design Mechanical and Physical Properties of Air Melted Low-Alloy Steels

Alloy	AISI 4130		AISI 4135		AISI 8630	
Specification [see Tables 2.3.1.0(a) and (b)]	AMS 6360 AMS 6373 AMS 6374 AMS-T-6736 AMS-S-18729		AMS 6365 AMS-T-6735[a]		AMS-S-18728[a]	
Form	Sheet, strip, plate, and tubing		Tubing		Sheet, strip, and plate	
Condition	Normalized and tempered, stress relieved[b]					
Thickness or diameter, in.	≤0.188	>0.188	≤0.188	≤0.188	≤0.188	≤0.188
Basis	S	S	S	S	S	S
Mechanical Properties:						
F_{tu}, ksi	95	90	100	95	95	90
F_{ty}, ksi	75	70	85	80	75	70
F_{cy}, ksi	75	70	89	84	75	70
F_{su}, ksi	57	54	60	57	57	54
F_{bru}, ksi:						
(e/D = 1.5)	...	...	...	...	...	...
(e/D = 2.0)	200	190	190	180	200	190
F_{bry}, ksi:						
(e/D = 1.5)	...	...	...	...	...	...
(e/D = 2.0)	129	120	146	137	129	120
e, percent	See Table 2.3.1.0(d)					
E, 10^3 ksi	29.0					
E_c, 10^3 ksi	29.0					
G, 10^3 ksi	11.0					
μ	0.32					
Physical Properties:						
ω, lb/in.^{3}	0.283					
C, K, and α	See Figure 2.3.1.0					

[a] Noncurrent specification.

[b] Design values are applicable only to parts for which the indicated F_{tu} has been substantiated by adequate quality control testing.

Table 2.3.1.0(c_2). Design Mechanical and Physical Properties of Air Melted Low-Alloy Steels

Alloy	AISI 4130		
Specification [see Tables 2.3.1.0(a) and (b)]	AMS 6361 AMS-T-6736	AMS 6362 AMS-T-6736	AMS-T-6736
Form	Tubing		
Condition	Quenched and tempered[a]		
Thickness or diameter, in.	≤0.188	≤0.188	All Walls
Basis	S	S	S
Mechanical Properties:			
F_{tu}, ksi	125	150	180
F_{ty}, ksi	100	135	165
F_{cy}, ksi	109	141	173
F_{su}, ksi	75	90	108
F_{bru}, ksi:			
(e/D = 1.5)	194	231	277
(e/D = 2.0)	251	285	342
F_{bry}, ksi:			
(e/D = 1.5)	146	210	257
(e/D = 2.0)	175	232	284
e, percent	See Table 2.3.1.0(e)		
E, 10^3 ksi	29.0		
E_c, 10^3 ksi	29.0		
G, 10^3 ksi	11.0		
μ	0.32		
Physical Properties:			
ω, lb/in.^{3}	0.283		
C, K, and α	See Figure 2.3.1.0		

[a] Design values are applicable only to parts for which the indicated F_{tu} has been substantiated by adequate quality control testing.

Table 2.3.1.0(c_3). Design Mechanical and Physical Properties of Air Melted Low-Alloy Steels

Alloy	AISI 8630	AISI 8740	
Specification [see Tables 2.3.1.0(a) and (b)]	AMS-S-6050	AMS-S-6049[a]	AMS 6327
Form	Bars and forgings		
Condition	Quenched and tempered[b]		
Thickness or diameter, in.	≤1.500	≤1.750	
Basis	S	S	
Mechanical Properties:			
F_{tu}, ksi	125	125	125
F_{ty}, ksi	100	103	100
F_{cy}, ksi	109	108	109
F_{su}, ksi	75	75	75
F_{bru}, ksi:			
(e/D = 1.5)	194	192	194
(e/D = 2.0)	251	237	251
F_{bry}, ksi:			
(e/D = 1.5)	146	160	146
(e/D = 2.0)	175	177	175
e, percent	See Table 2.3.1.0(e)		
E, 10^3 ksi	29.0		
E_c, 10^3 ksi	29.0		
G, 10^3 ksi	11.0		
μ	0.32		
Physical Properties:			
ω, lb/in.^{3}	0.283		
C, K, and α	See Figure 2.3.1.0		

[a] Noncurrent specification

[b] Design values are applicable only to parts for which the indicated F_{tu} has been substantiated by adequate quality control testing.

Table 2.3.1.0(c_4). Design Mechanical and Physical Properties of Air Melted Low-Alloy Steels

Alloy	AISI 4135			
Specification [see Tables 2.3.1.0(a) and (b)]	AMS-T-6735			
Form	Tubing			
Condition	Quenched and tempered[a]			
Wall thickness, in.	≤ 0.8			< 0.5[b]
Basis	S	S	S	S
Mechanical Properties:				
F_{tu}, ksi	125	150	180	200
F_{ty}, ksi	100	135	165	165
F_{cy}, ksi	109	141	173	181
F_{su}, ksi	75	90	108	120
F_{bru}, ksi:				
(e/D = 1.5)	194	231	277	308
(e/D = 2.0)	251	285	342	380
F_{bry}, ksi:				
(e/D = 1.5)	146	210	257	274
(e/D = 2.0)	175	232	284	302
e, percent	See Table 2.3.1.0(e)			
E, 10^3 ksi	29.0			
E_c, 10^3 ksi	29.0			
G, 10^3 ksi	11.0			
μ	0.32			
Physical Properties:				
ω, lb/in.^{3}	0.283			
C, K, and α	See Figure 2.3.1.0			

a Design values are applicable only to parts for which the indicated F_{tu} and through hardening has been substantiated by adequate quality control testing.
b Wall thickness at which through hardening is achieved and verified through quality control testing.
b The S-basis value in MIL-T-6735 is 165 ksi.

Table 2.3.1.0(d). Minimum Elongation Values for Low-Alloy Steels in Condition N

Form	Thickness, in.	Elongation, percent: Full tube	Elongation, percent: Strip
Sheet, strip, and plate (T)	Less than 0.062	--	8
	Over 0.062 to 0.125 incl.	--	10
	Over 0.125 to 0.187 incl.	--	12
	Over 0.187 to 0.249 incl.	--	15
	Over 0.249 to 0.749 incl.	--	16
	Over 0.749 to 1.500 incl.	--	18
Tubing (L)	Up to 0.035 incl. (wall)	10	5
	Over 0.035 to 0.188 incl.	12	7
	Over 0.188	15	10

Table 2.3.1.0(e). Minimum Elongation Values for Heat-Treated Low-Alloy Steels

	Round specimens (L)		Elongation in 2 in., percent				
			Sheet specimens			Tubing (L)	
F_{tu}, ksi	Elongation in 4D, percent	Reduction of area, percent	Less than 0.032 in. thick	0.032 to 0.060 in. thick	Over 0.060 in. thick	Full tube	Strip
125	17	55	5	7	10	12	7
140	15	53	4	6	9	10	6
150	14	52	4	6	9	10	6
160	13	50	3	5	8	9	6
180	12	47	3	5	7	8	5
200	10	43	3	4	6	6	5

Table 2.3.1.0(f_1). Design Mechanical and Physical Properties of Low-Alloy Steels

Alloy	Hy-Tuf	4330V	4335V	4335V	D6AC	AISI 4340[a]	0.40C 300M	0.42C 300M
Specification	AMS 6425	AMS 6411	AMS 6430	AMS 6429	AMS 6431	AMS 6414	AMS 6417	AMS 6257 AMS 6419
Form	Bar, forging, tubing							
Condition	Quenched and tempered[b]							
Thickness or diameter, in.	c				d	e	f	
Basis	S	S	S	S	S	S	S	S
Mechanical Properties:								
F_{tu}, ksi	220	220	205	240	220	260	270	280
F_{ty}, ksi	185	185	190	210	190	217	220	230
F_{cy}, ksi	193	193	199	220	198	235	236	247
F_{su}, ksi	132	132	123	144	132	156	162	168
F_{bru}, ksi:								
(e/D = 1.5)	297	297	315	369	297	347	414[g]	430[g]
(e/D = 2.0)	385	385	389	465	385	440	506[g]	525[g]
F_{bry}, ksi:								
(e/D = 1.5)	267	267	296	327	274	312	344[c]	360[c]
(e/D = 2.0)	294	294	327	361	302	346	379[c]	396[c]
e, percent:								
L	10	10	10	10	12	10	8	7
LT	5[a]	5[a]	7	7	9	...	...	...
E, 10^3 ksi	29.0							
E_c, 10^3 ksi	29.0							
G, 10^3 ksi	11.0							
μ	0.32							
Physical Properties:								
ω, lb/in.^{3}	0.283							
C, K, and α	See Figure 2.3.1.0							

a Applicable to consumable-electrode vacuum-melted material only.

b Design values are applicable only to parts for which the indicated F_{tu} has been substantiated by adequate quality control testing.

c Thickness≤ 1.70 in. for quenching in molten salt at desired tempering temperature (martempering); ≤2.50 in. for quenching in oil at flow rate of 200 feet/min.

d Thickness≤ 3.50 in. for quenching in molten salt at desired tempering temperature (martempering); ≤5.00 in. for quenching in oil at flow rate of 200 feet/min.

e Thickness≤ 1.70 in. for quenching in molten salt at desired tempering temperature (martempering); ≤2.50 in. for quenching in oil at flow rate of 200 feet/min.; ≤3.50 in. for quenching in water at a flow rate of 200 feet/min.

f Thickness ≤5.00 in. for quenching in oil at a flow rate of 200 feet/min.

g Bearing values are "dry pin" values per Section 1.4.7.1.

Table 2.3.1.0(f_2). Design Mechanical and Physical Properties of Low-Alloy Steels

Alloy	4335V	D6AC	
Specification	AMS 6435	AMS 6439	
Form	Sheet, strip, and plate		
Condition	Quenched and tempered[a]		
Thickness or diameter, in.	b	≤0.250	≥0.251
Basis	S	S	S
Mechanical Properties:			
F_{tu}, ksi	220	215	224
F_{ty}, ksi	190	190	195
F_{cy}, ksi	198	198	203
F_{su}, ksi	132	129	134
F_{bru}, ksi:[c]			
(e/D = 1.5)	297	290	302
(e/D = 2.0)	385	376	392
F_{bry}, ksi:[c]			
(e/D = 1.5)	274	274	281
(e/D = 2.0)	302	302	310
e, percent:			
L	10	...	...
LT	7	7	7
E, 10^3 ksi	29.0		
E_c, 10^3 ksi	29.0		
G, 10^3 ksi	11.0		
μ	0.32		
Physical Properties:			
ω, lb/in.^{3}	0.283		
C, K, and α	See Figure 2.3.1.0		

a Design values are applicable only to parts for which the indicated F_{tu} has been substantiated by adequate quality control testing.

b Thickness ≤1.70 in. for quenching in molten salt at desired tempering temperature (martempering); ≤2.50 in. for quenching in oil at a flow rate of 200 feet/min.

c Bearing values are "dry pin" values per Section 1.4.7.1.

Table 2.3.1.0(g_1). Design Mechanical and Physical Properties of Low-Alloy Steels

Alloy	AISI 4130		AISI 4135		AISI 8630		AISI 8735	
Specification [see Tables 2.3.1.0(a) and (b)]	AMS 6350 AMS 6528 AMS-S-6758		AMS 6352 AMS 6372		AMS 6281		AMS 6357	
Form	Sheet, strip, plate, bars, and forgings		Sheet, strip, plate, and tubing		Tubing		Sheet, strip, and plate	
Condition	Normalized and tempered, stress relieved[a]							
Thickness or diameter, in.	≤0.188	>0.188	≤0.188	>0.188	≤0.188	>0.188	≤0.188	>0.188
Basis	[b]							
Mechanical Properties:								
F_{tu}, ksi	95	90	95	90	95	90	95	90
F_{ty}, ksi	75	70	75	70	75	70	75	70
F_{cy}, ksi	75	70	75	70	75	70	75	70
F_{su}, ksi	57	54	57	54	57	54	57	54
F_{bru}, ksi:								
(e/D = 1.5)	...	...	...	...	...	...	...	...
(e/D = 2.0)	200	190	200	190	200	190	200	190
F_{bry}, ksi:								
(e/D = 1.5)	...	...	...	...	...	...	...	...
(e/D = 2.0)	129	120	129	120	129	120	129	120
e, percent	See Table 2.3.1.0(d)							
E, 10^3 ksi	29.0							
E_c, 10^3 ksi	29.0							
G, 10^3 ksi	11.0							
μ	0.32							
Physical Properties:								
ω, lb/in.^{3}	0.283							
C, K, and α	See Figure 2.3.1.0							

[a] Design values are applicable only to parts for which the indicated F_{tu} has been substantiated by adequate quality control testing.

[b] There is no statistical basis (T_{99} or T_{90}) or specification basis (S) to support the mechanical property values in this table. See Heat Treatment in Section 2.3.0.2.

Table 2.3.1.0(g_2). Design Mechanical and Physical Properties of Low-Alloy Steels

Alloy	4330V	See steels listed in Table 2.3.0.2 for the applicable strength levels					
Specification	AMS 6427	See Tables 2.3.1.0(a) and (b)					
Form	All wrought forms						
Condition	Quenched and tempered[a]						
Thickness or diameter, in.	≤ 2.5	b					c
Basis	d						
Mechanical Properties:							
F_{tu}, ksi	220	125	140	150	160	180	200
F_{ty}, ksi	185	100	120	132	142	163	176
F_{cy}, ksi	193	109	131	145	154	173	181
F_{su}, ksi	132	75	84	90	96	108	120
F_{bru}, ksi:							
(e/D = 1.5)	297	209	209	219	230	250	272
(e/D = 2.0)	385	251	273	287	300	326	355
F_{bry}, ksi:							
(e/D = 1.5)	267	146	173	189	202	230	255
(e/D = 2.0)	294	175	203	218	231	256	280
e, percent:	10	See Table 2.3.1.0(e)					
L	5[a]						
LT							
E, 10^3 ksi	29.0						
E_c, 10^3 ksi	29.0						
G, 10^3 ksi	11.0						
μ	0.32						
Physical Properties:							
ω, lb/in.^{3}	0.283						
C, K, and α	See Figure 2.3.1.0						

a Design values are applicable only to parts for which the indicated F_{tu} has been substantiated by adequate quality control testing.

b For F_{tu} ≤ 180 ksi, thickness ≤ 0.50 in. for AISI 4130 and 8630; ≤ 0.80 in. for AISI 8735, 4135, and 8740; ≤ 1.00 in. for AISI 4140; ≤ 1.70 in. for AISI 4340, 4330V, 4335V, and Hy-Tuf [Quenched in molten salt at desired tempering temperature (martempering)]; ≤ 2.50 in. for AISI 4340, 4330V, 4335V, and Hy-Tuf (Quenched in oil at a flow rate of 200 feet/min.); ≤ 3.50 in. for AISI 4340 (Quenched in water at a flow rate of 200 feet/min.); ≤ 5.00 in. for D6AC (Quenched in oil at a flow rate of 200 feet/min.)

c For F_{tu} = 200 ksi AISI 4130, 8630, 4135, 8740 not available; thickness ≤ 0.80 in. for AISI 8740; ≤ 1.00 in. for AISI 4140; ≤ 1.70 in. for AISI 4340, 4330V, 4335V, and Hy-Tuf [Quenched in molten salt at desired tempering temperature (martempering)]; ≤ 2.50 in. for AISI 4340, 4330V, 4335V, and Hy-Tuf (Quenched in oil at a flow rate of 200 feet/min.); ≤ 3.50 in. for AISI 4340 (Quenched in water at a flow rate of 200 feet/min.); ≤ 5.00 in. for D6AC (Quenched in oil at a flow rate of 200 feet/min.)

d There is no statistical basis (T_{99} or T_{90}) or specification basis (S) to support the mechanical property values in this table. See Heat Treatment in Section 2.3.0.2.

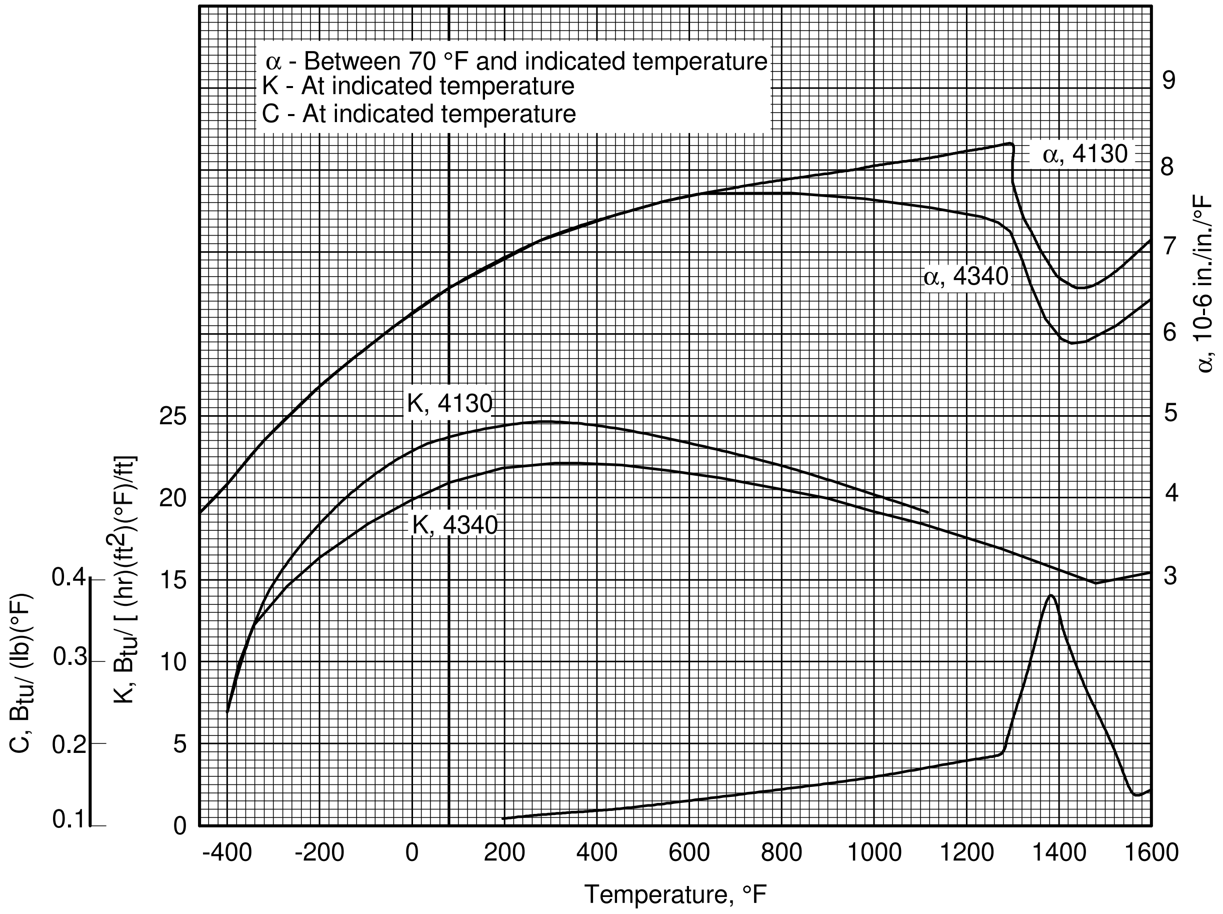


Figure 2.3.1.0. Effect of temperature on the physical properties of 4130 and 4340 alloy steels.

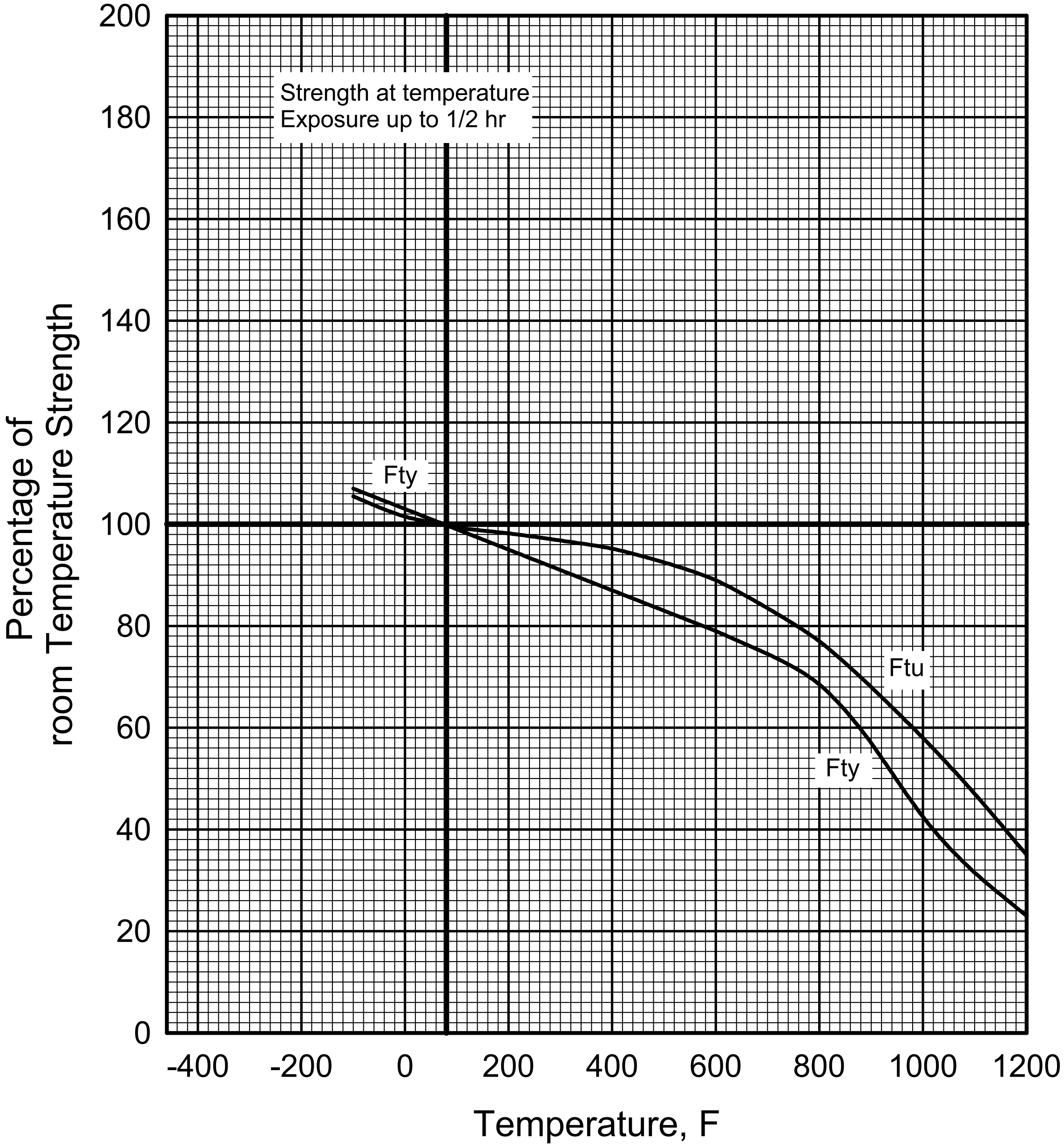


Figure 2.3.1.1.1. Effect of temperature on the tensile ultimate strength (F_{tu}) and tensile yield strength (F_{ty}) of AISI low-alloy steels (all products).

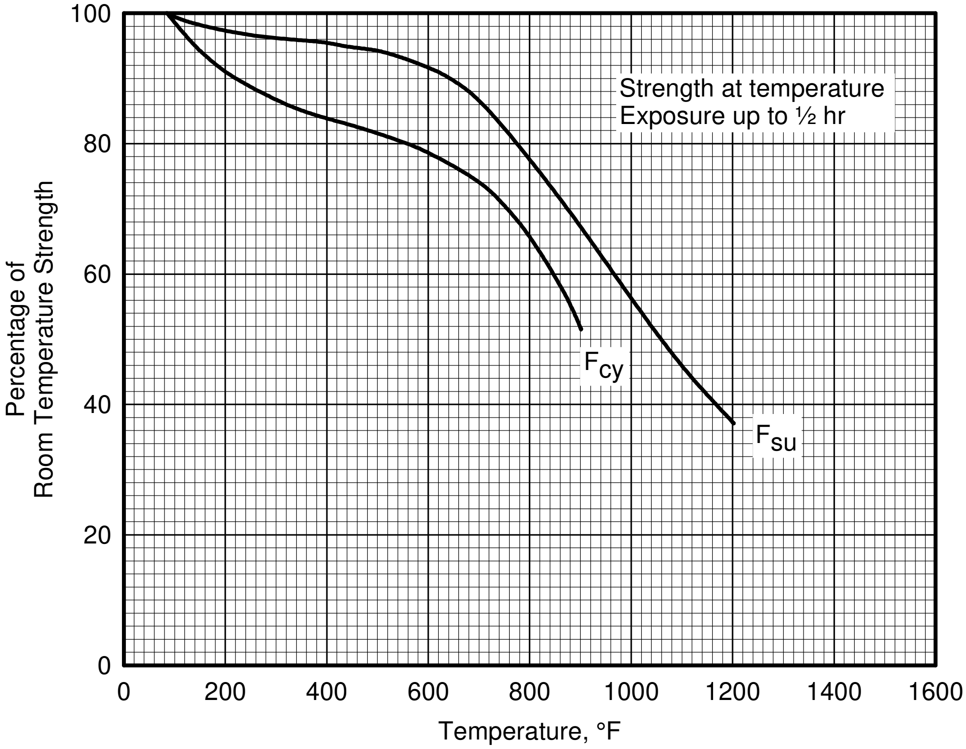


Figure 2.3.1.1.2. Effect of temperature on the compressive yield strength (F_{cy}) and the shear ultimate strength (F_{su}) of heat-treated AISI low-alloy steels (all products).

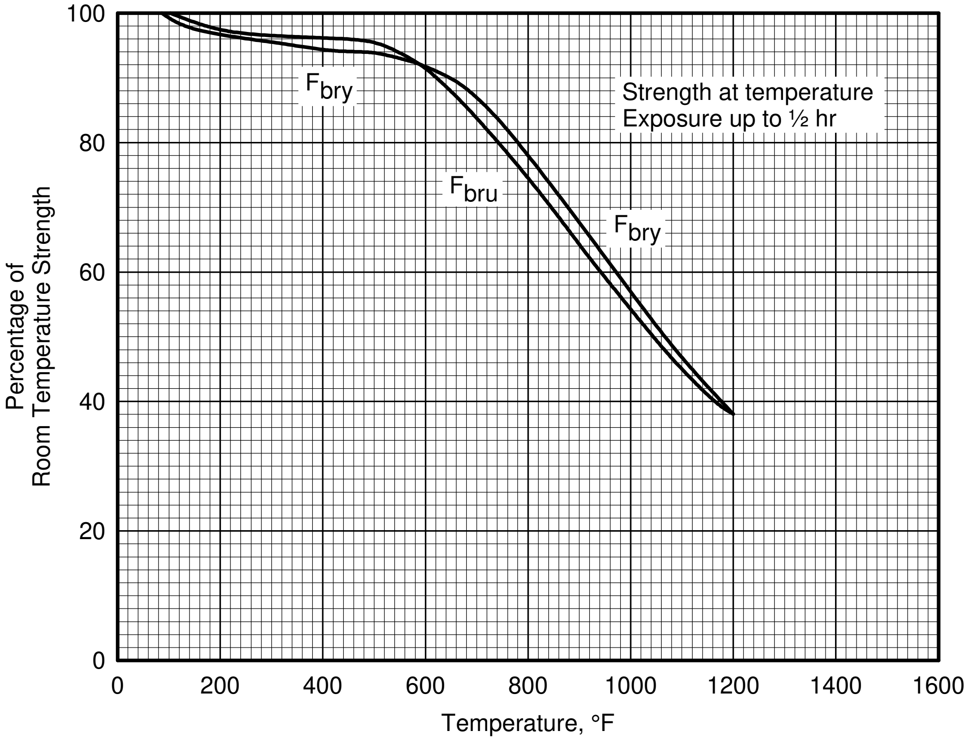


Figure 2.3.1.1.3. Effect of temperature on the bearing ultimate strength (F_{bru}) and the bearing yield strength (F_{bry}) of heat-treated AISI low-alloy steels (all products).

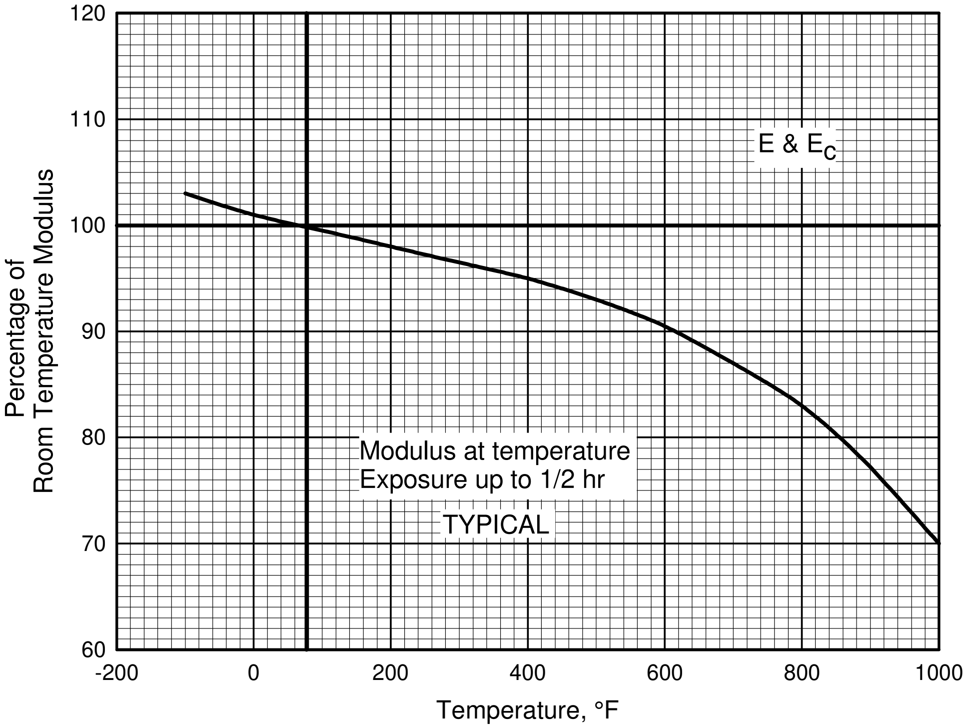


Figure 2.3.1.1.4. Effect of temperature on the tensile and compressive modulus (E and E$_c$) of AISI low-alloy steels.

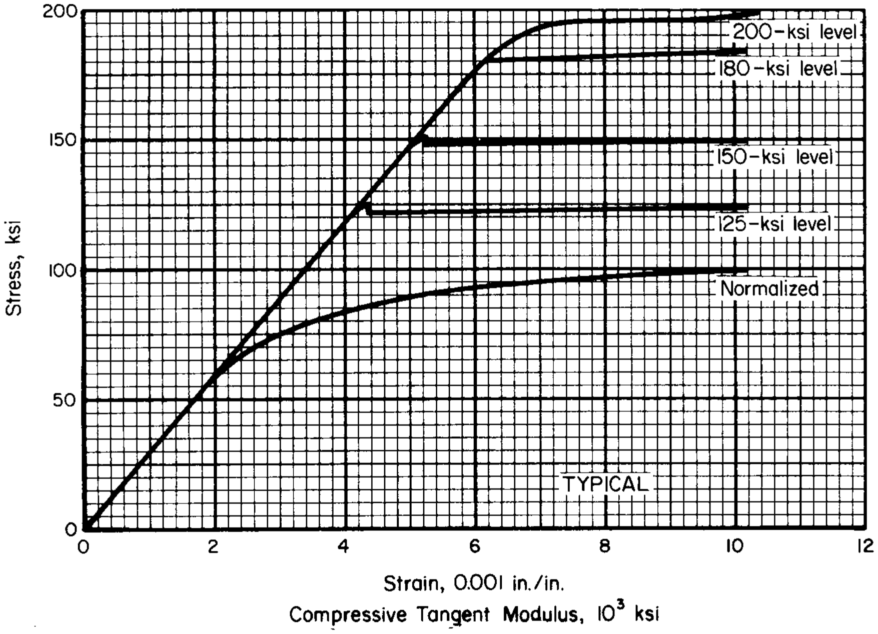


Figure 2.3.1.2.6(a). Typical tensile stress-strain curves at room temperature for heat-treated AISI 8630 alloy steel (all products).

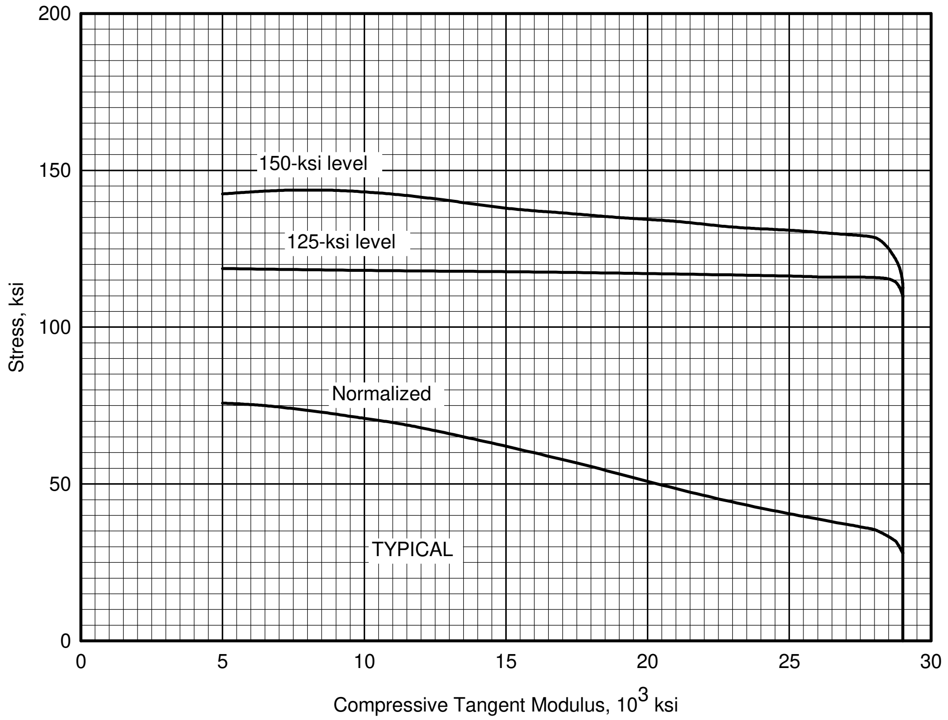


Figure 2.3.1.2.6(b). Typical compressive tangent-modulus curves at room temperature for heat-treated AISI 8630 alloy steel (all products).

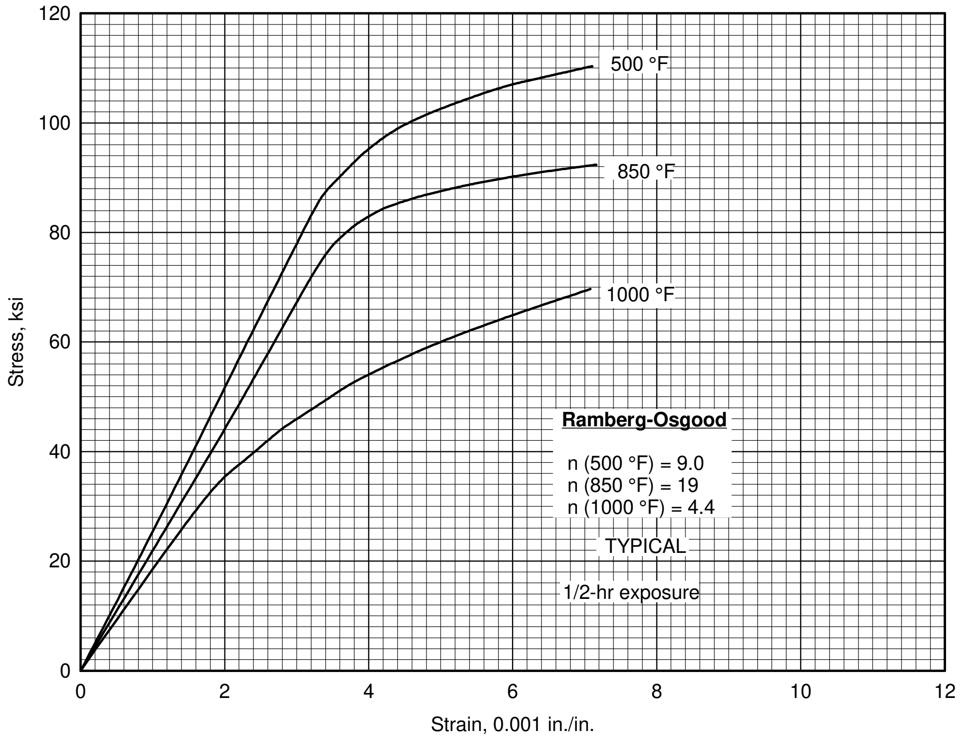


Figure 2.3.1.2.6(c). Typical tensile stress-strain curves at elevated temperatures for heat-treated AISI 8630 alloy steel, F_{tu} = 125 ksi (all products).

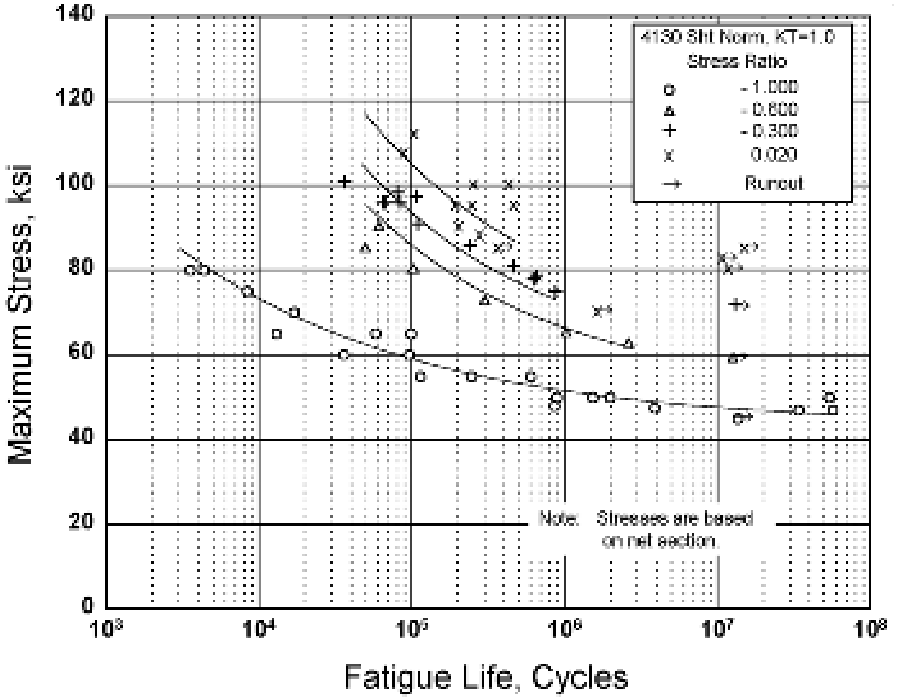


Figure 2.3.1.2.8(a). Best-fit S/N curves for unnotched 4130 alloy steel sheet, normalized, longitudinal direction.

Correlative Information for Figure 2.3.1.2.8(a)

Product Form: Sheet, 0.075 inch thick

Properties:

TUS, ksi	TYS, ksi	Temp., °F
117	99	RT

Specimen Details: Unnotched
2.88-3.00 inches gross width
0.80-1.00 inch net width
12.0 inch net section radius

Surface Condition: Electropolished

References: 3.2.3.1.8(a) and (f)

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

Test Parameters:
Loading - Axial
Frequency - 1100-1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equations:

For stress ratios of -0.60 to +0.02
$\text{Log } N_f = 9.65 - 2.85 \log (S_{eq} - 61.3)$
$S_{eq} = S_{max} (1-R)^{0.41}$
Std. Error of Estimate, Log (Life) = 0.21
Standard Deviation, Log (Life) = 0.45
$R^2 = 78\%$

Sample Size = 23

For a stress ratio of -1.0
$\text{Log } N_f = 9.27 - 3.57 \log (S_{max} - 43.3)$

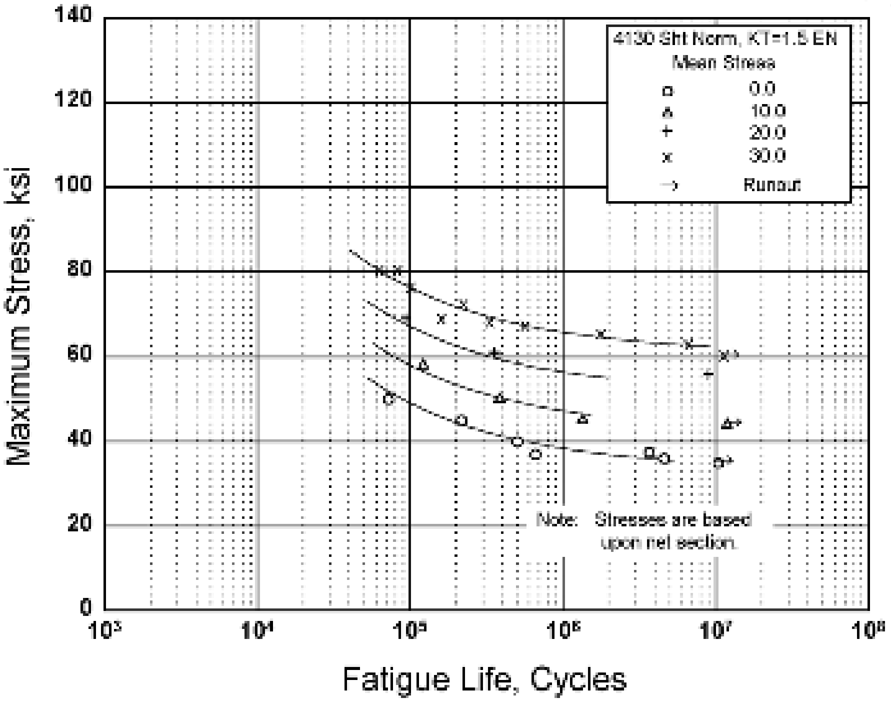


Figure 2.3.1.2.8(b). Best-fit S/N curves for notched, K_t = 1.5, 4130 alloy steel sheet, normalized, longitudinal direction.

Correlative Information for Figure 2.3.1.2.8(b)

Product Form: Sheet, 0.075 inch thick

Properties:

TUS, ksi	TYS, ksi	Temp., °F
117	99	RT (unnotched)
123	--	RT (notched) K_t 1.5

Specimen Details: Edge Notched, K_t = 1.5
3.00 inches gross width
1.50 inches net width
0.76 inch notch radius

Surface Condition: Electropolished

Reference: 3.2.3.1.8(d)

Test Parameters:
Loading - Axial
Frequency - 1100-1500 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equations:
$\text{Log } N_f = 7.94 - 2.01 \log (S_{eq} - 61.3)$
$S_{eq} = S_{max} (1-R)^{0.88}$
Std. Error of Estimate, Log (Life) = 0.27
Standard Deviation, Log (Life) = 0.67
R^2 = 84%

Sample Size = 21

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

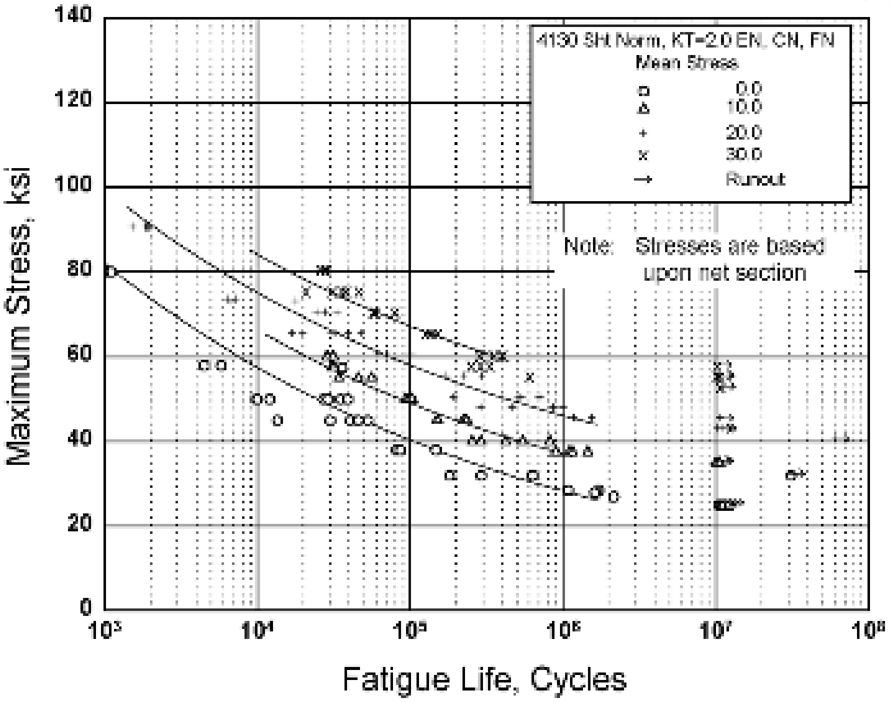


Figure 2.3.1.2.8(c). Best-fit S/N curves for notched, K_t = 2.0, 4130 alloy steel sheet, normalized, longitudinal direction.

<u>Correlative Information for Figure 2.3.1.2.8(c)</u>

<u>Product Form</u>: Sheet, 0.075 inch thick

<u>Properties</u>:

TUS, ksi	TYS, ksi	Temp., °F
117	99	RT (unnotched)
120	--	RT (notched) K_t 2.0

<u>Specimen Details</u>: Notched, K_t = 2.0

Notch Type	Gross Width	Net Width	Notch Radius
Edge	2.25	1.500	0.3175
Center	4.50	1.500	1.500
Fillet	2.25	1.500	0.1736

<u>Surface Condition</u>: Electropolished

<u>References</u>: 3.2.3.1.8(b) and (f)

<u>Test Parameters</u>:
Loading - Axial
Frequency - 1100-1800 cpm
Temperature - RT
Environment - Air

<u>No. of Heats/Lots</u>: Not specified

<u>Equivalent Stress Equation</u>:
$\text{Log } N_f = 17.1 - 6.49 \log (S_{eq})$
$S_{eq} = S_{max} (1-R)^{0.86}$
Std. Error of Estimate, Log (Life) = 0.19
Standard Deviation, Log (Life) = 0.78
R^2 = 94%

<u>Sample Size</u> = 107

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

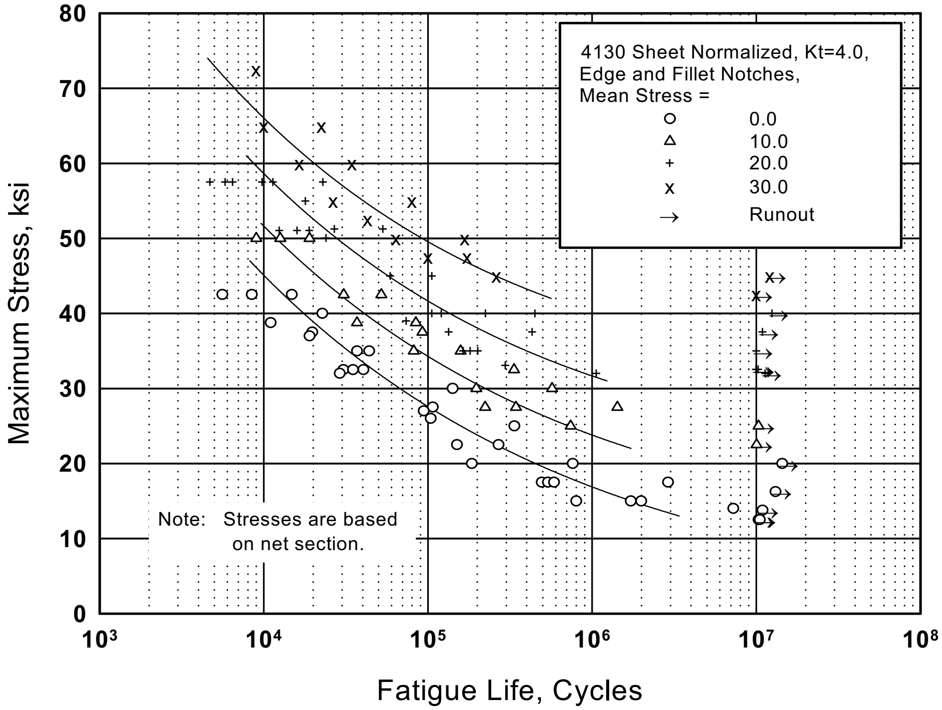


Figure 2.3.1.2.8(d). Best-fit S/N curves diagram for notched, K_t = 4.0, 4130 alloy steel sheet, normalized, longitudinal direction.

Correlative Information for Figure 2.3.1.2.8(d)

Product Form: Sheet, 0.075 inch thick

Properties:

TUS, ksi	TYS, ksi	Temp., °F
117	99	RT (unnotched)
120	—	RT (notched) K_t = 4.0

Specimen Details: Notched, K_t = 4.0

Notch Type	Gross Width	Net Width	Notch Radius
Edge	2.25	1.500	0.057
Edge	4.10	1.496	0.070
Fillet	2.25	1.500	0.0195

Surface Condition: Electropolished

References: 3.2.3.1.8(b), (f), and (g)

Test Parameters:
Loading - Axial
Frequency - 1100-1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
Log N_f = 12.6-4.69 log (S_{eq})
$S_{eq} = S_{max} (1-R)^{0.63}$
Std. Error of Estimate, Log (Life) = 0.24
Standard Deviation, Log (Life) = 0.70
R^2 = 88%

Sample Size = 87

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

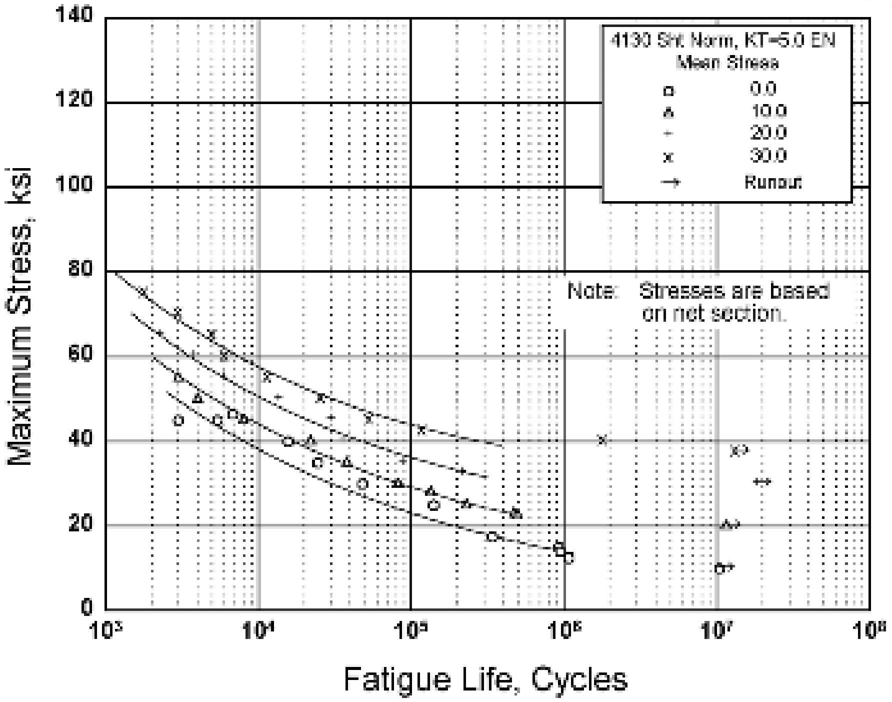


Figure 2.3.1.2.8(e). Best-fit S/N curves diagram for notched, K_t = 5.0, 4130 alloy steel sheet, normalized, longitudinal direction.

Correlative Information for Figure 2.3.1.2.8(e)

Product Form: Sheet, 0.075 inch thick

Properties:

TUS, ksi	TYS, ksi	Temp., °F
117	99	RT (unnotched)
120	—	RT (notched) K_t = 5.0

Specimen Details: Edge Notched, K_t = 5.0
2.25 inches gross width
1.50 inches net width
0.075 inch notch radius

Surface Condition: Electropolished

Reference: 3.2.3.1.8(c)

Test Parameters:
Loading - Axial
Frequency - 1100-1500 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
$\text{Log } N_f = 12.0 - 4.57 \log (S_{eq})$
$S_{eq} = S_{max} (1-R)^{0.56}$
Std. Error of Estimate, Log (Life) = 0.18
Standard Deviation, Log (Life) = 0.87
R^2 = 96%

Sample Size = 38

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

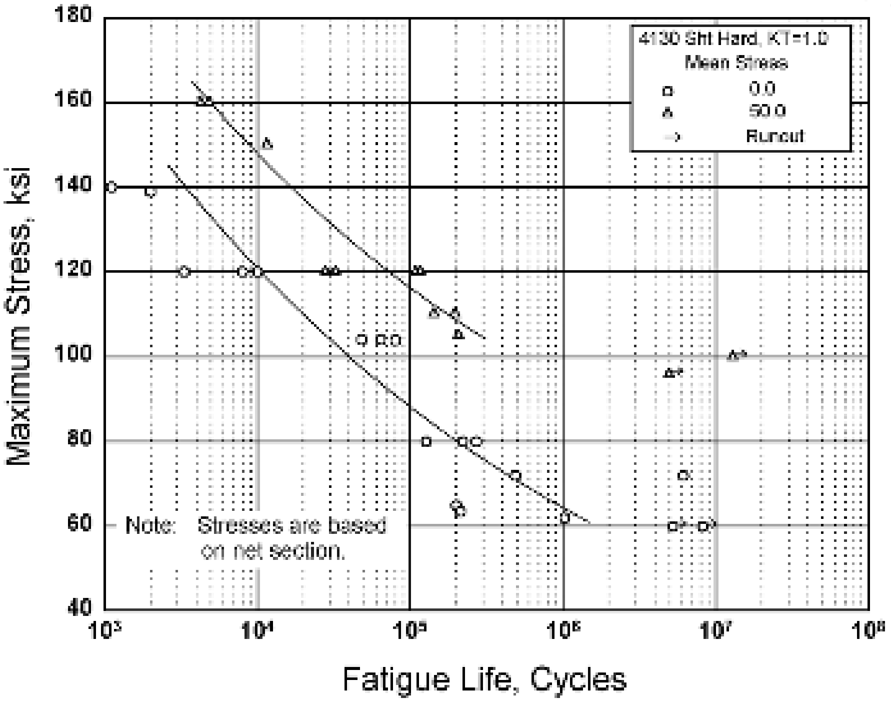


Figure 2.3.1.2.8(f). Best-fit S/N curves for unnotched 4130 alloy steel sheet, F_{tu} = 180 ksi, longitudinal direction.

Correlative Information for Figure 2.3.1.2.8(f)

Product Form: Sheet, 0.075 inch thick

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	180	174	RT

Specimen Details: Unnotched
2.88 inches gross width
1.00 inch net width
12.0 inch net section radius

Surface Condition: Electropolished

Reference: 3.2.3.1.8(f)

Test Parameters:
Loading - Axial
Frequency - 20-1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
$\text{Log } N_f = 20.3 - 7.31 \log (S_{eq})$
$S_{eq} = S_{max} (1-R)^{0.49}$
Std. Error of Estimate, Log (Life) = 0.39
Standard Deviation, Log (Life) = 0.89
R^2 = 81%

Sample Size = 27

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

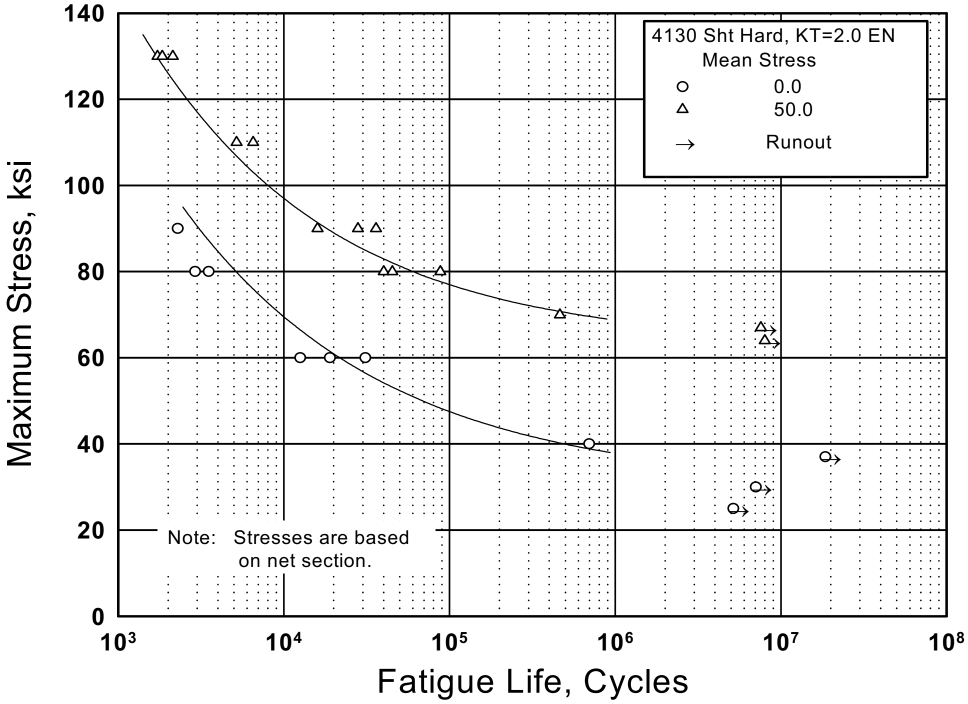


Figure 2.3.1.2.8(g). Best-fit S/N curves for notched, K_t = 2.0, 4130 alloy steel sheet, F_{tu} = 180 ksi, longitudinal direction.

Correlative Information for Figure 2.3.1.2.8(g)

Product Form: Sheet, 0.075 inch thick

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	180	174	RT

Specimen Details: Edge Notched
2.25 inches gross width
1.50 inches net width
0.3175 inch notch radius

Surface Condition: Electropolished

Reference: 3.2.3.1.8(f)

Test Parameters:
Loading - Axial
Frequency - 21-1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
Log N_f = 8.87-2.81 log (S_{eq} - 41.5)
$S_{eq} = S_{max} (1-R)^{0.46}$
Std. Error of Estimate, Log (Life) = 0.18
Standard Deviation, Log (Life) = 0.77
R^2 = 94%

Sample Size = 19

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

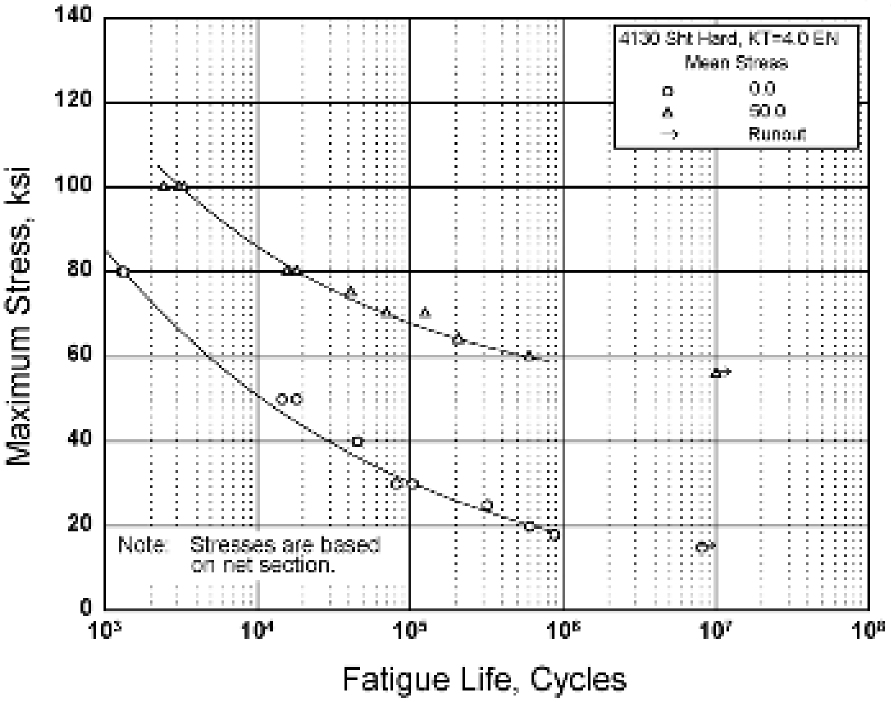


Figure 2.3.1.2.8(h). Best-fit S/N curves for notched, K_t = 4.0, 4130 alloy steel sheet, F_{tu} = 180 ksi, longitudinal direction.

Correlative Information for Figure 2.3.1.2.8(h)

Product Form: Sheet, 0.075 inch thick

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	180	174	RT

Specimen Details: Edge Notched
2.25 inches gross width
1.50 inches net width
0.057 inch notch radius

Surface Condition: Electropolished

Reference: 3.2.3.1.8(f)

Test Parameters:
Loading - Axial
Frequency - 23-1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
Log N_f = 12.4-4.45 log (S_{eq})
$S_{eq} = S_{max}$ (1-R)$^{0.60}$
Std. Error of Estimate, Log (Life) = 0.11
Standard Deviation, Log (Life) = 0.90
R^2 = 98%

Sample Size = 20

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

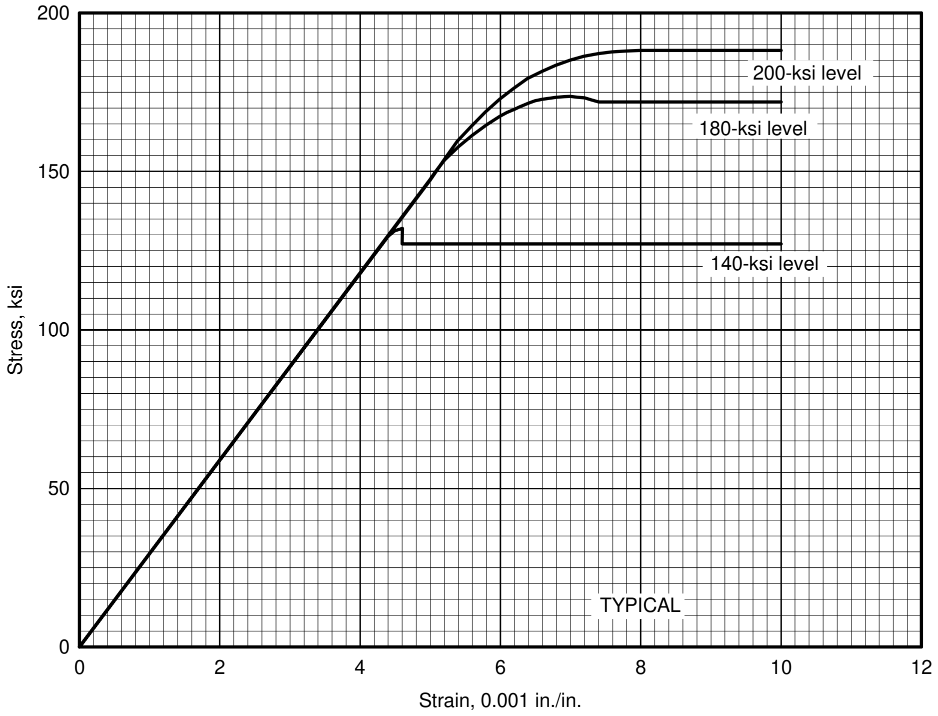


Figure 2.3.1.3.6(a). Typical tensile stress-strain curves at room temperature for heat-treated AISI 4340 alloy steel (all products).

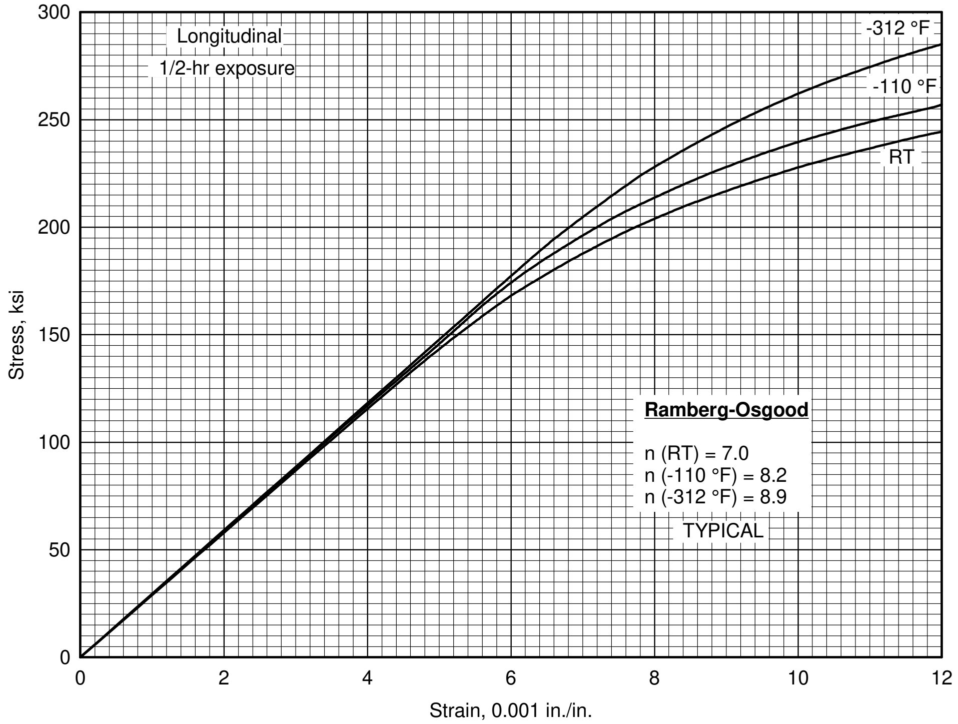


Figure 2.3.1.3.6(b). Typical tensile stress-strain curves at cryogenic and room temperature for AISI 4340 alloy steel bar, F_{tu} = 260 ksi.

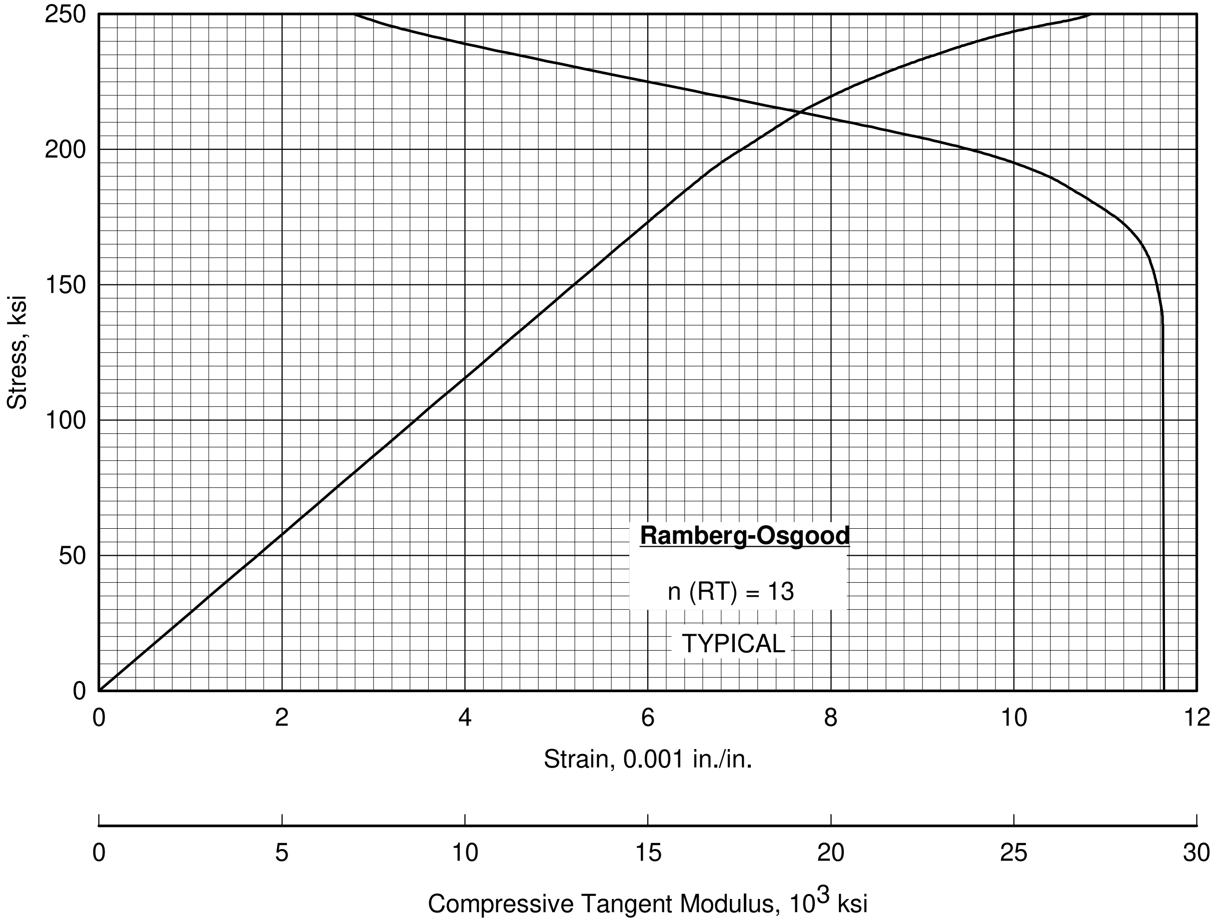


Figure 2.3.1.3.6(c). Typical compressive stress-strain and compressive tangent-modulus curves at room temperature for AISI 4340 alloy steel bar, F_{tu} = 260 ksi.

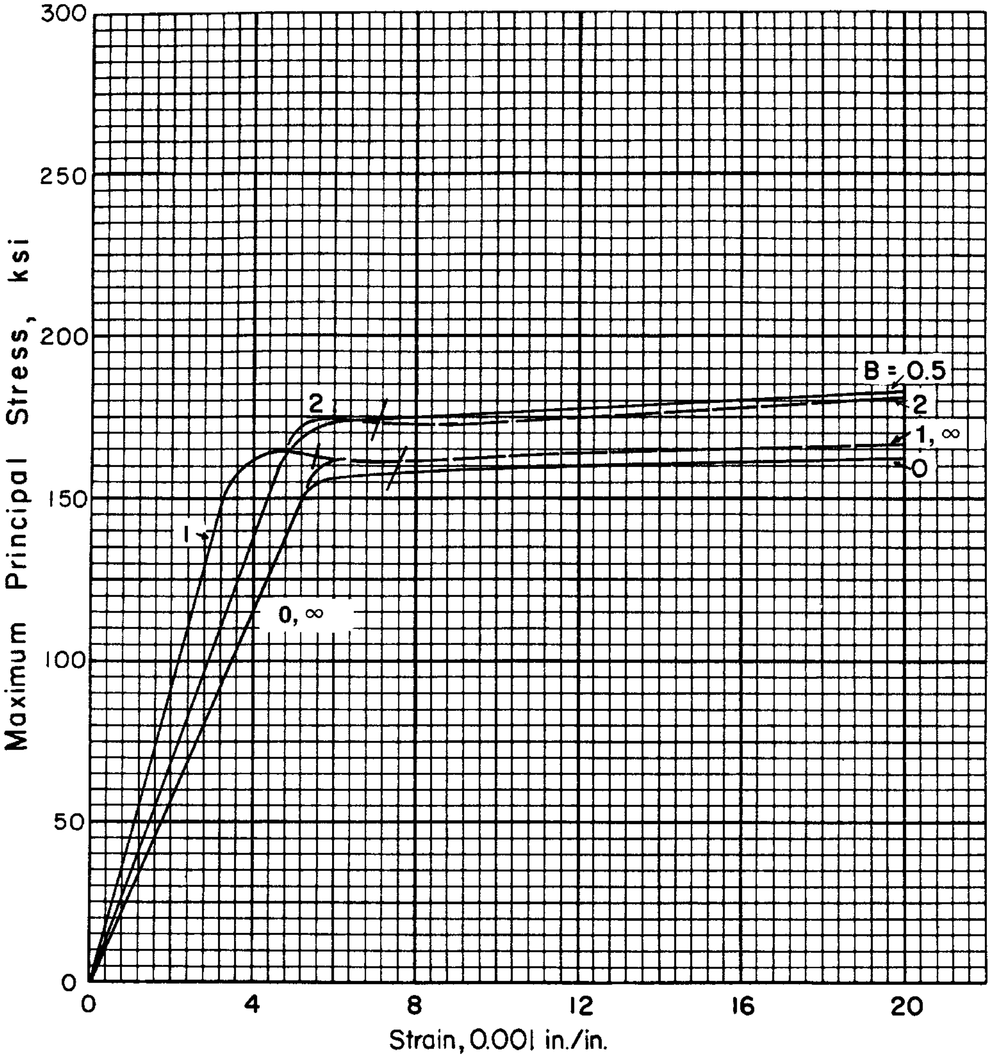


Figure 2.3.1.3.6(d). Typical biaxial stress-strain curves at room temperature for AISI 4340 alloy steel (machined thin-wall cylinders, axial direction = longitudinal direction of bar stock), F_{tu} = 180 ksi. A biaxial ratio, B, denotes the ratio of hoop stresses to axial stresses.

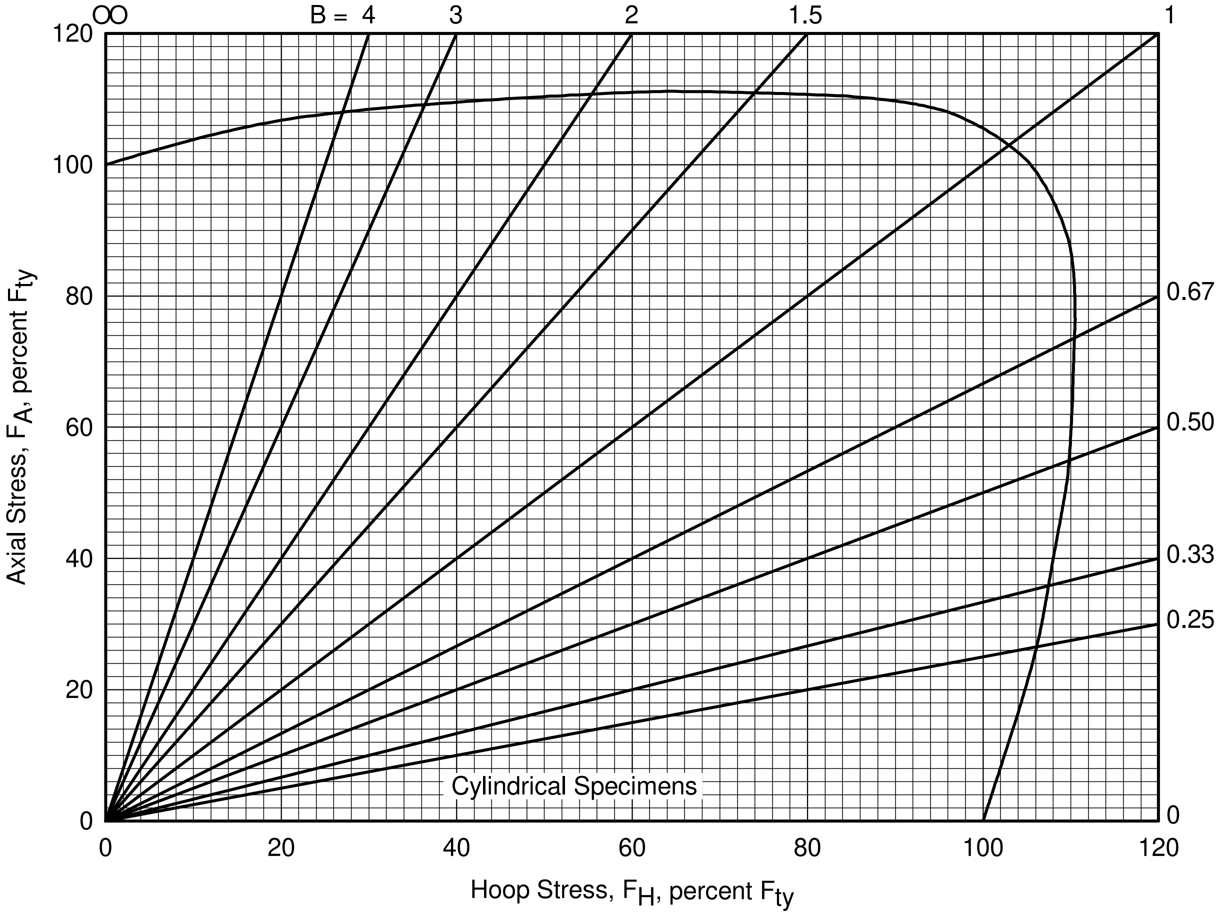


Figure 2.3.1.3.6(e). Biaxial yield-stress envelope at room temperature for AISI 4340 alloy steel (machined thin-wall cylinders, axial direction = longitudinal direction of bar stock), F_{tu} = 180 ksi, F_{ty} measured in the hoop direction.

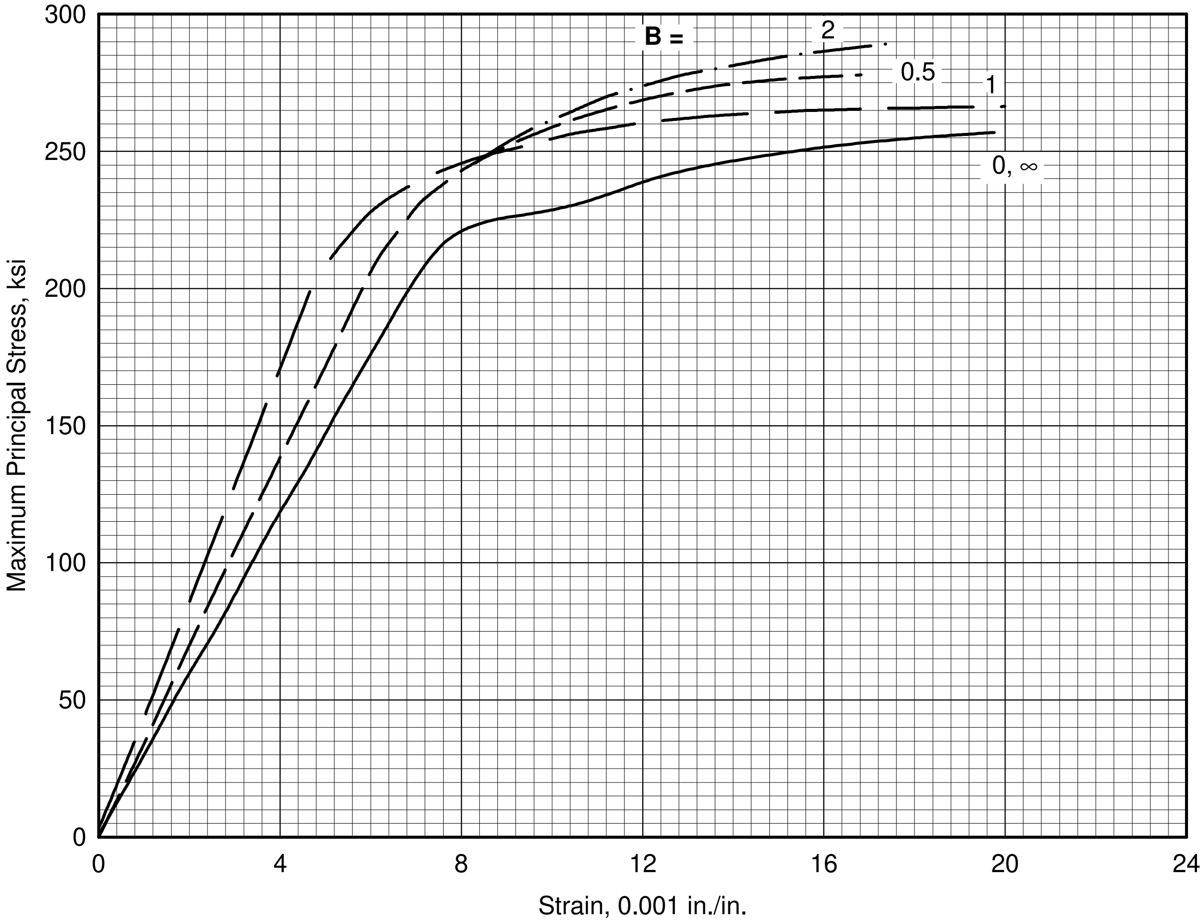


Figure 2.3.1.3.6(f). Typical biaxial stress-strain curves at room temperature for AISI 4340 alloy steel (machined thin-wall cylinders, axial direction = longitudinal direction of bar stock), F_{tu} = 260 ksi. A biaxial ratio B of zero corresponds to the hoop direction.

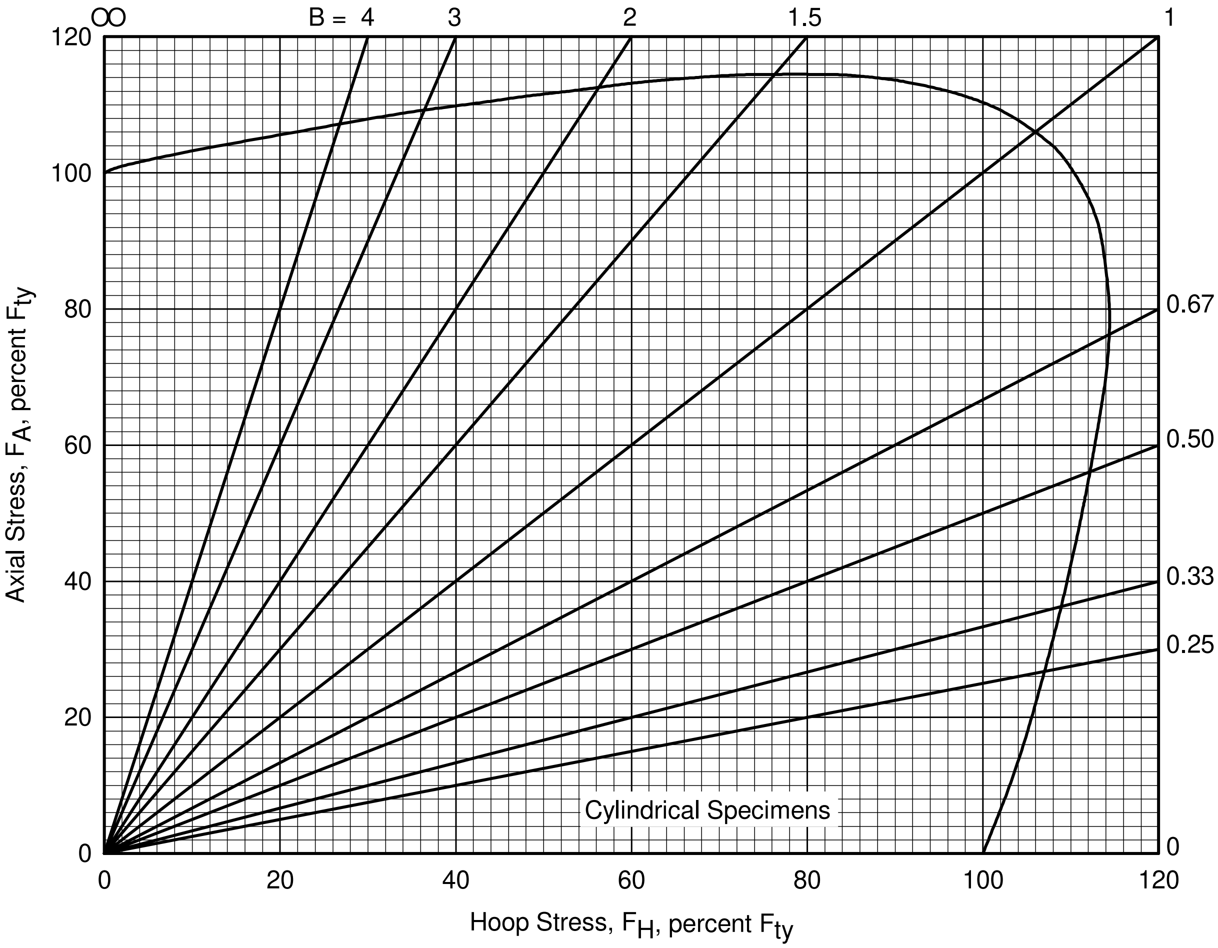


Figure 2.3.1.3.6(g). Biaxial yield-stress envelope at room temperature for AISI 4340 alloy steel (machined thin-wall cylinders, axial direction = longitudinal direction of bar stock), F_{tu} = 260 ksi, F_{ty} measured in the hoop direction.

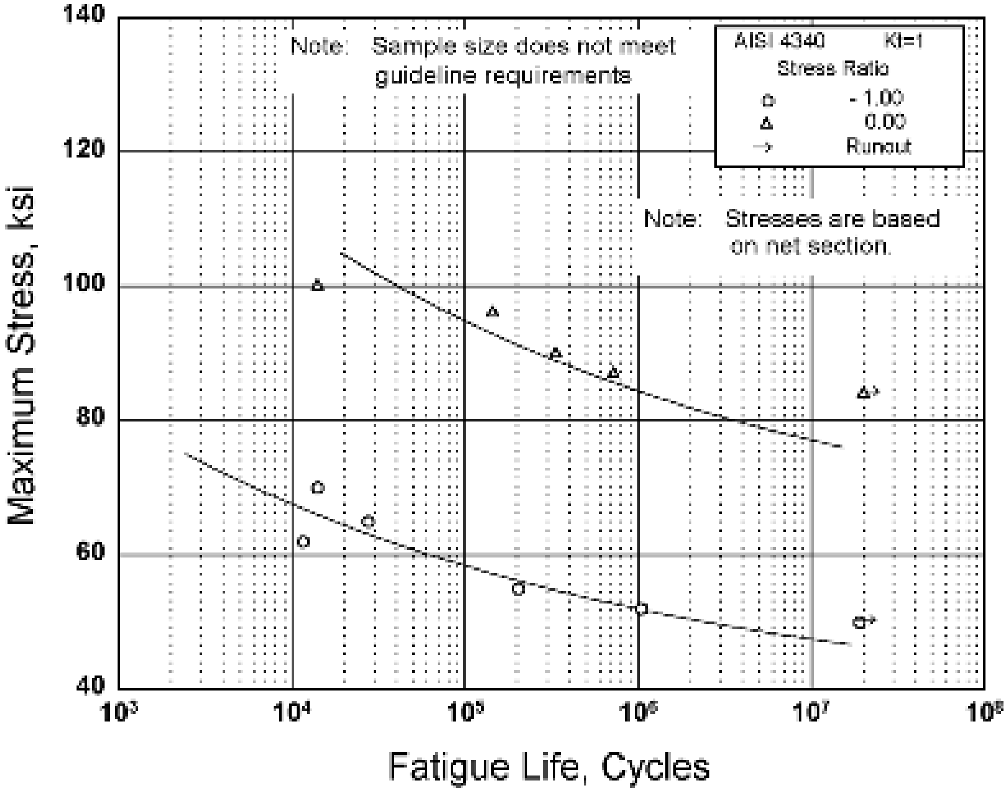


Figure 2.3.1.3.8(a). Best-fit S/N curves for unnotched AISI 4340 alloy steel bar, F_{tu} = 125 ksi, longitudinal direction.

Correlative Information for Figure 2.3.1.3.8(a)

Product Form: Rolled bar, 1.125 inch diameter, air melted

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	125	—	RT (unnotched)
	150	—	RT (notched)

Specimen Details: Unnotched
0.400 inch diameter

Surface Condition: Hand polished to RMS 10

Reference: 2.3.1.3.8(a)

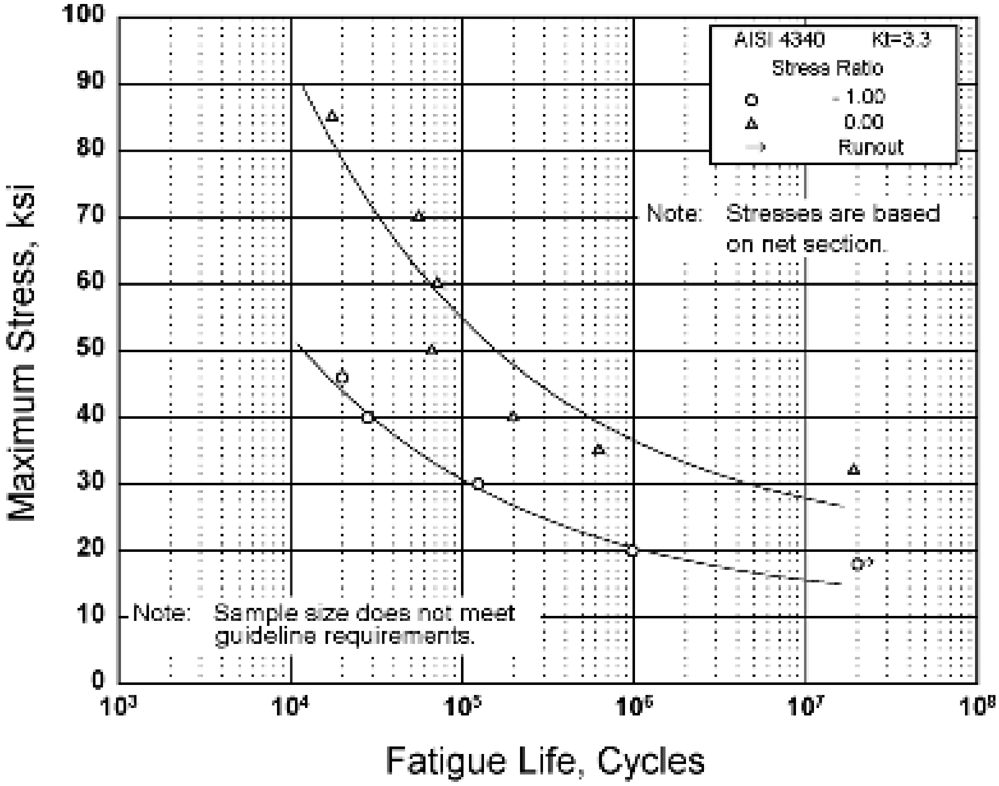
Test Parameters:
Loading - Axial
Frequency - 2000 to 2500 cpm
Temperature - RT
Atmosphere - Air

No. of Heat/Lots: 1

Equivalent Stress Equation:
Log N_f = 14.96-6.46 log (S_{eq}-60)
$S_{eq} = S_{max}\ (1-R)^{0.70}$
Std. Error of Estimate, Log (Life) = 0.35
Standard Deviation, Log (Life) = 0.77
R^2 = 75%

Sample Size = 9

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]



Note: Stresses are based on net section.

Note: Sample size does not meet guideline requirements.

Figure 2.3.1.3.8(b). Best-fit S/N curves for notched, K_t = 3.3, AISI 4340 alloy steel bar, F_{tu} = 125 ksi, longitudinal direction.

Correlative Information for Figure 2.3.1.3.8(b)

Product Form: Rolled bar, 1.125 inch diameter, air melted

Properties:

TUS, ksi	TYS, ksi	Temp., °F
125	—	RT (unnotched)
150	—	RT (notched)

Specimen Details: Notched, V-Groove, K_t=3.3
0.450 inch gross diameter
0.400 inch net diameter
0.010 inch root radius, r
60° flank angle, ω

Surface Condition: Lathe turned to RMS 10

Reference: 2.3.1.3.8(a)

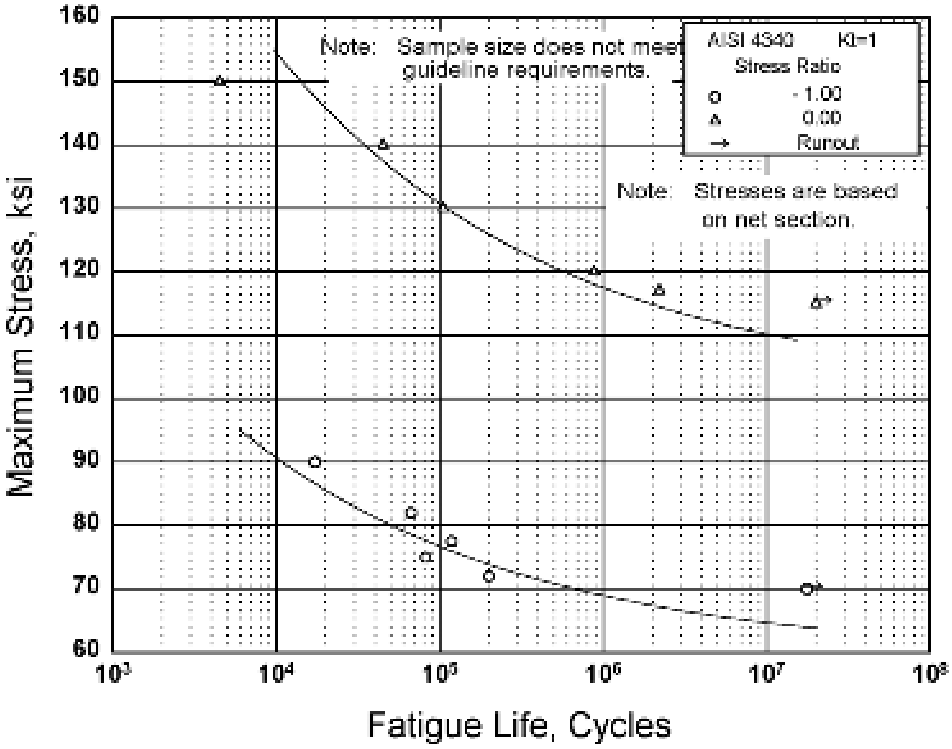
Test Parameters:
Loading - Axial
Frequency - 2000 to 2500 cpm
Temperature - RT
Atmosphere - Air

No. of Heat/Lots: 1

Equivalent Stress Equation:
$\log N_f = 9.75 - 3.08 \log (S_{eq} - 20.0)$
$S_{eq} = S_{max} (1-R)^{0.84}$
Std. Error of Estimate, Log (Life) = 0.40
Standard Deviation, Log (Life) = 0.90
R^2 = 80%

Sample Size = 11

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]



Note: Sample size does not meet guideline requirements.

Note: Stresses are based on net section.

Figure 2.3.1.3.8(c). Best-fit S/N curves for unnotched AISI 4340 alloy steel bar, F_{tu} = 150 ksi, longitudinal direction.

Correlative Information for Figure 2.3.1.3.8(c)

Product Form: Rolled bar, 1.125 inch diameter, air melted

Properties:

TUS, ksi	TYS, ksi	Temp., °F
158	147	RT (unnotched)
190	—	RT (notched)

Specimen Details: Unnotched 0.400 inch diameter

Surface Condition: Hand polished to RMS 10

Reference: 2.3.1.3.8(b)

Test Parameters:
Loading - Axial
Frequency - 2000 to 2500 cpm
Temperature - RT
Atmosphere - Air

No. of Heat/Lots: 1

Equivalent Stress Equation:
Log N_f = 10.76-3.91 log (S_{eq} - 101.0)
$S_{eq} = S_{max} (1-R)^{0.77}$
Std. Error of Estimate, Log (Life) = 0.17
Standard Deviation, Log (Life) = 0.33
Adjusted R^2 Statistic = 73%

Sample Size = 9

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

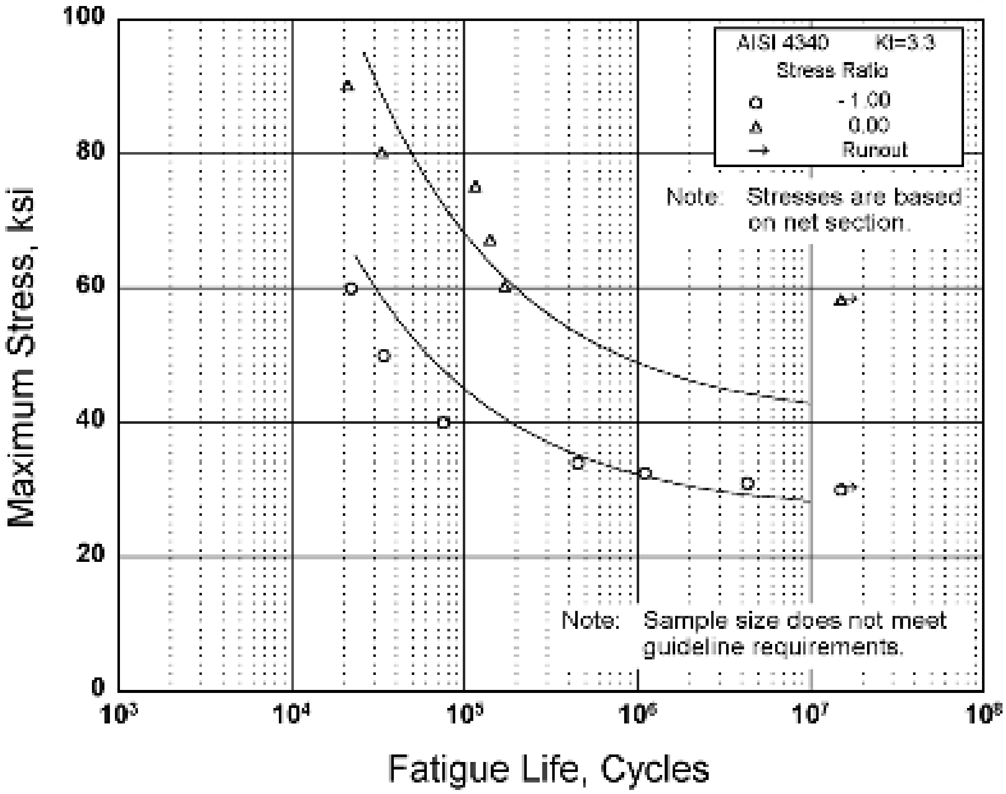


Figure 2.3.1.3.8(d). Best-fit S/N curves for notched AISI 4340 alloy steel bar, F_{tu} = 150 ksi, longitudinal direction.

Correlative Information for Figure 2.3.1.3.8(d)

Product Form: Rolled bar, 1.125 inch diameter, air melted

Properties:

TUS, ksi	TYS, ksi	Temp., °F
158	147	RT (unnotched)
190	—	RT (notched)

Specimen Details: Notched, V-Groove, K_t = 3.3
0.450 inch gross diameter
0.400 inch net diameter
0.010 inch root radius, r
60° flank angle, ω

Surface Condition: Lathe turned to RMS 10

Reference: 2.3.1.3.8(a)

Test Parameters:
Loading - Axial
Frequency - 2000 to 2500 cpm
Temperature - RT
Atmosphere - Air

No. of Heat/Lots: 1

Equivalent Stress Equation:
$\text{Log } N_f = 7.90 - 2.00 \log (S_{eq} - 40.0)$
$S_{eq} = S_{max} (1-R)^{0.60}$
Std. Error of Estimate, Log (Life) = 0.27
Standard Deviation, Log (Life) = 0.74
$R^2 = 86\%$

Sample Size = 11

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

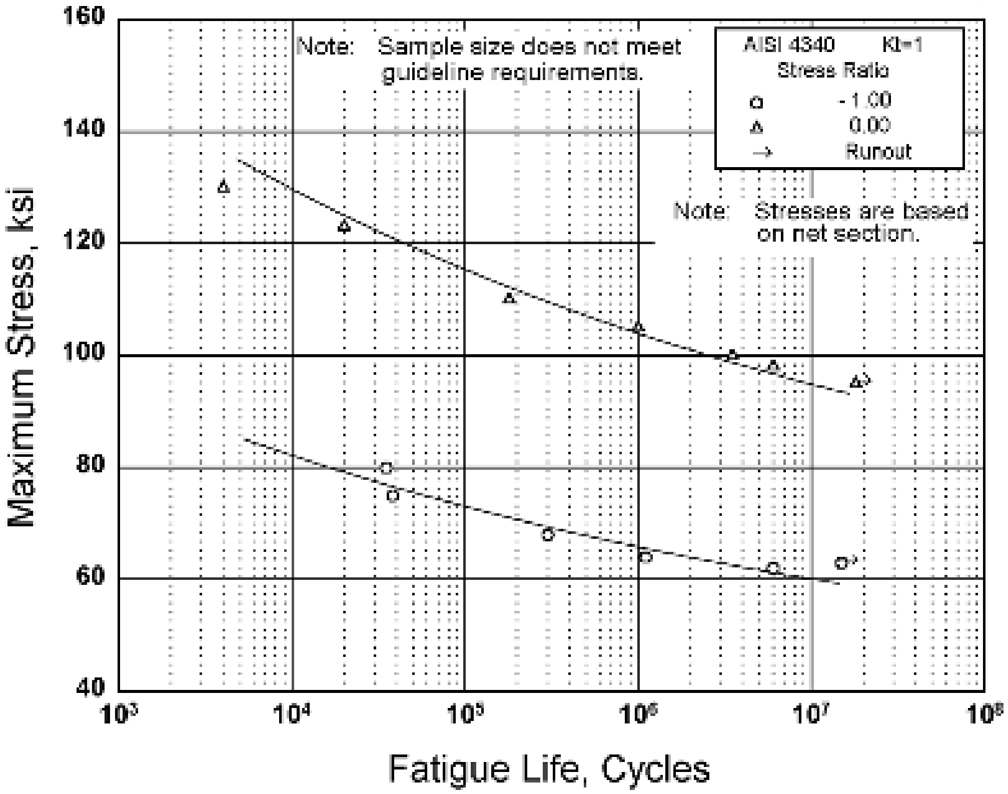


Figure 2.3.1.3.8(e). Best-fit S/N curves for unnotched AISI 4340 alloy steel bar at 600°F, F_{tu} = 150 ksi, longitudinal direction.

Correlative Information for Figure 2.3.1.3.8(e)

Product Form: Rolled bar, 1.125 inch diameter, air melted

Properties:

TUS, ksi	TYS, ksi	Temp., °F
158	147	RT (unnotched)
153	121	600 (unnotched)
190	—	RT (notched)
176	—	600 (notched)

Specimen Details: Unnotched
0.400 inch diameter

Surface Condition: Hand polished to RMS 10

Reference: 2.3.1.3.8(b)

Test Parameters:
Loading - Axial
Frequency - 2000 to 2500 cpm
Temperature - 600°F
Atmosphere - Air

No. of Heat/Lots: 1

Equivalent Stress Equation:
Log N_f = 22.36-9.98 log (S_{eq}-60.0)
$S_{eq} = S_{max}\,(1\text{-}R)^{0.66}$
Std. Error of Estimate Log (Life) = 0.24
Standard Deviation, Log (Life) = 1.08
R^2 = 95%

Sample Size = 11

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

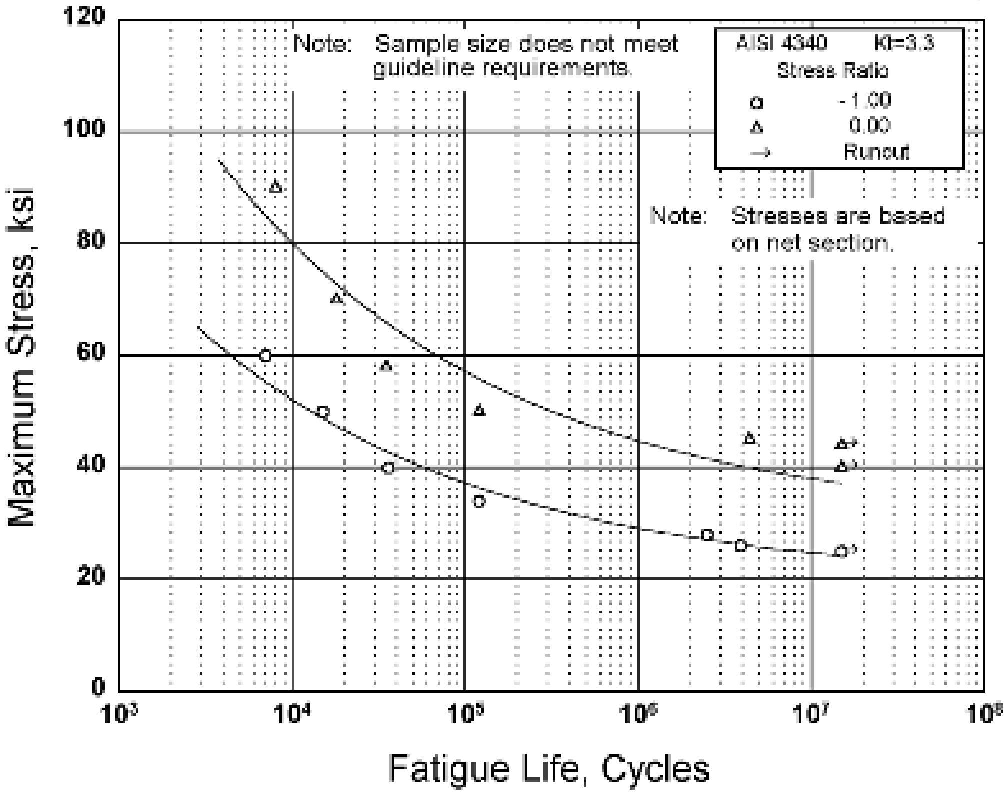


Figure 2.3.1.3.8(f). Best-fit S/N curves for notched, K_t = 3.3, AISI 4340 alloy steel bar at 600°F, F_{tu} = 150 ksi, longitudinal direction.

Correlative Information for Figure 2.3.1.3.8(f)

Product Form: Rolled bar, 1.125 inch diameter, air melted

Properties:

TUS, ksi	TYS, ksi	Temp., °F
158	147	RT (unnotched)
153	121	600 (unnotched)
190	—	RT (notched)
176	—	600 (notched)

Specimen Details: Notched, V-Groove, K_t = 3.3
0.450 inch gross diameter
0.400 inch net diameter
0.010 inch root radius, r
60° flank angle, ω

Surface Condition: Lathe turned to RMS 10

Reference: 2.3.1.3.8(b)

Test Parameters:
Loading - Axial
Frequency - 2000 to 2500 cpm
Temperature - RT
Atmosphere - Air

No. of Heat/Lots: 1

Equivalent Stress Equation:
Log N_f = 10.39-3.76 log (S_{eq}-30.0)
$S_{eq} = S_{max} (1-R)^{0.62}$
Std. Error of Estimate, Log (Life) = 0.36
Standard Deviation, Log (Life) = 1.06
R^2 = 89%

Sample Size = 11

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

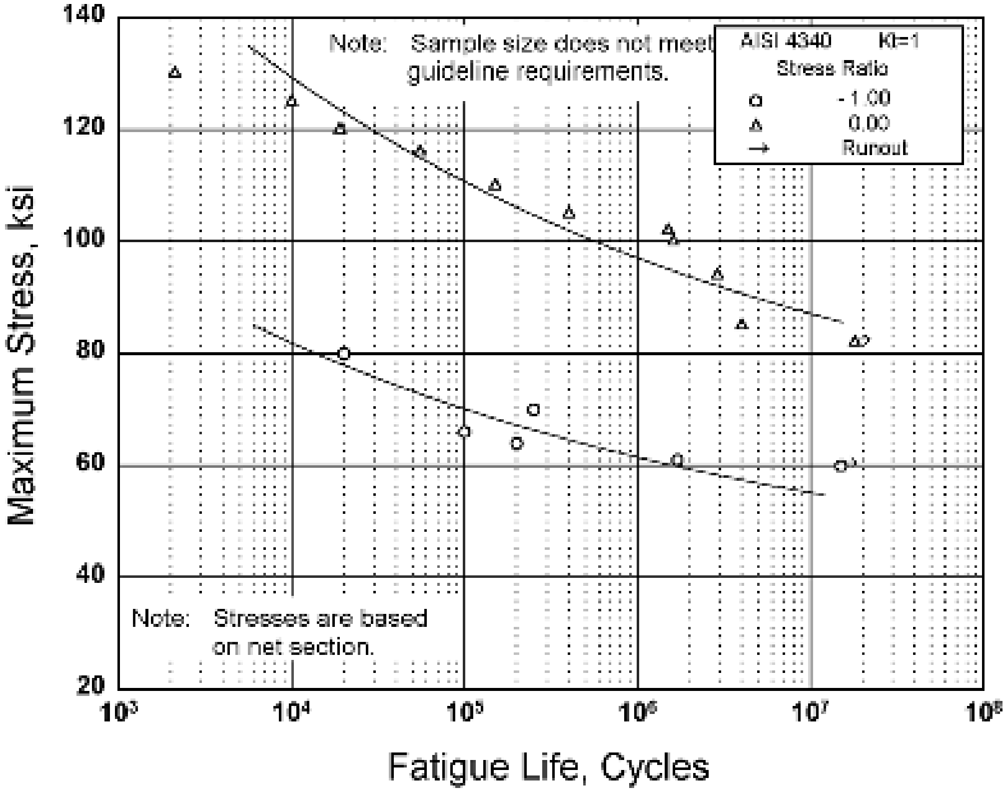


Figure 2.3.1.3.8(g). Best-fit S/N curves for unnotched AISI 4340 alloy steel bar at 800°F, F_{tu} = 150 ksi, longitudinal direction.

Correlative Information for Figure 2.3.1.3.8(g)

Product Form: Rolled bar, 1.125 inch diameter, air melted

Properties:

TUS, ksi	TYS, ksi	Temp., °F
158	147	RT (unnotched)
125	101	800 (unnotched)
190	—	RT (notched)
154	—	800 (notched)

Specimen Details: Unnotched
0.400 inch diameter

Surface Condition: Hand polished to RMS 10

Reference: 2.3.1.3.8(b)

Test Parameters:
Loading - Axial
Frequency - 2000 to 2500 cpm
Temperature - 800°F
Atmosphere - Air

No. of Heat/Lots: 1

Equivalent Stress Equation:
Log N_f = 17.53-7.35 log (S_{eq}-60.0)
$S_{eq} = S_{max} (1-R)^{0.66}$
Std. Error of Estimate, Log (Life) = 0.42
Standard Deviation, Log (Life) = 0.99
R^2 = 82%

Sample Size = 15

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

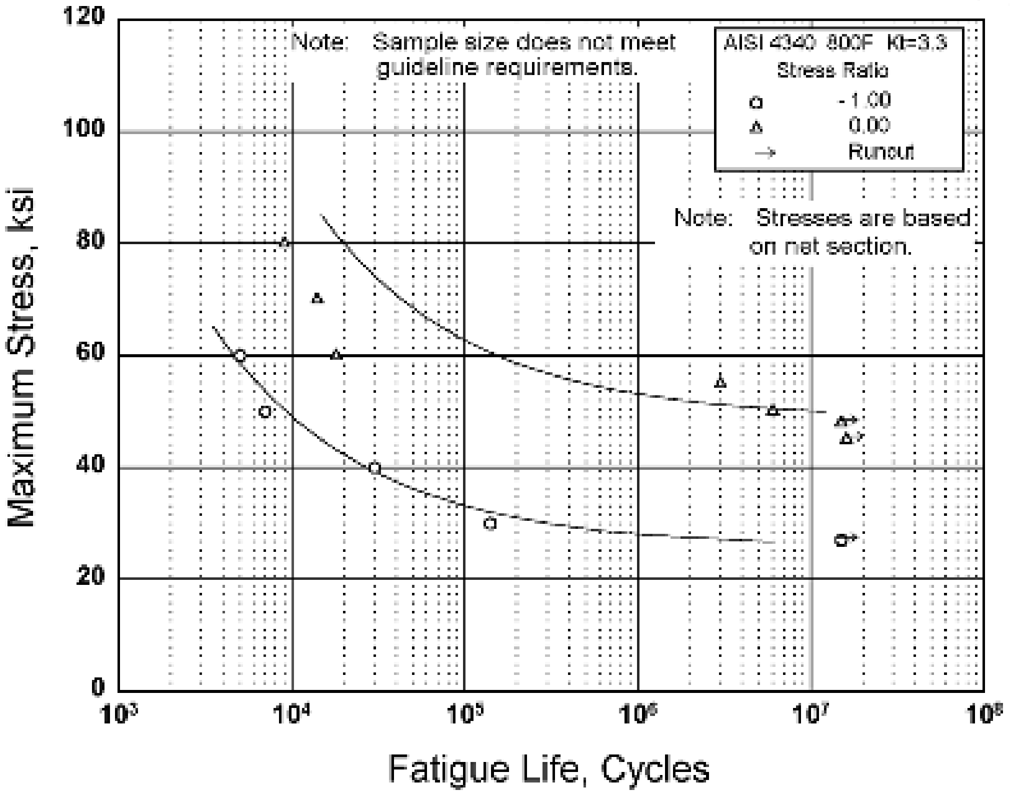


Figure 2.3.1.3.8(h). Best-fit S/N curves for notched, K_t = 3.3, AISI 4340 alloy steel bar at 800°F, F_{tu} = 150 ksi, longitudinal direction.

Correlative Information for Figure 2.3.1.3.8(h)

Product Form: Rolled bar, 1.125 inch diameter, air melted

Properties:

TUS, ksi	TYS, ksi	Temp., °F
158	147	RT (unnotched)
125	101	800 (unnotched)
190	—	RT (notched)
154	—	800 (notched)

Specimen Details: Notched, V-Groove, K_t = 3.3
0.450 inch gross diameter
0.400 inch net diameter
0.010 inch root radius, r
60° flank angle, ω

Surface Condition: Lathe turned to RMS 10

Reference: 2.3.1.3.8(b)

Test Parameters:
Loading - Axial
Frequency - 2000 to 2500 cpm
Temperature - 800°F
Atmosphere - Air

No. of Heat/Lots: 1

Equivalent Stress Equation:
$\text{Log } N_f = 7.31 - 2.01 \log (S_{eq} - 48.6)$
$S_{eq} = S_{max} (1-R)^{0.92}$
Std. Error of Estimate, Log (Life) = 0.60
Standard Deviation, Log (Life) = 1.14
R^2 = 72%

Sample Size = 9

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

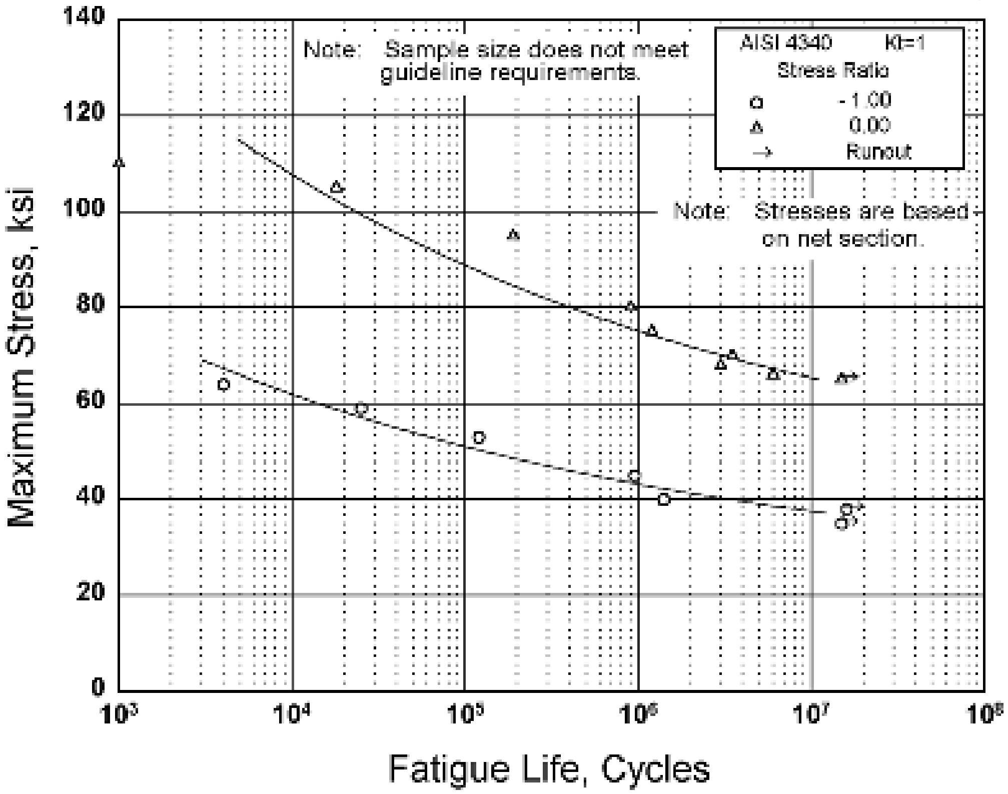


Figure 2.3.1.3.8(i). Best-fit S/N curves for unnotched AISI 4340 alloy steel bar at 1000°F, F_{tu} = 150 ksi, longitudinal direction.

Correlative Information for Figure 2.3.1.3.8(i)

Product Form: Rolled bar, 1.125 inch diameter, air melted

Properties:

TUS, ksi	TYS, ksi	Temp., °F
158	147	RT (unnotched)
81	63	1000°F (unnotched)
190	—	RT (notched)
98	—	1000°F (notched)

Specimen Details: Unnotched
0.400 inch diameter

Surface Condition: Hand polished to RMS 10

Reference: 2.3.1.3.8(b)

Test Parameters:
Loading - Axial
Frequency - 2000 to 2500 cpm
Temperature - 1000°F
Atmosphere - Air

No. of Heat/Lots: 1

Equivalent Stress Equation:
Log N_f = 16.85-7.02 log (S_{eq}-40.0)
$S_{eq} = S_{max} (1-R)^{0.80}$
Std. Error of Estimate, Log (Life) = 0.42
Standard Deviation, Log (Life) = 1.20
R^2 = 88%

Sample Size = 13

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

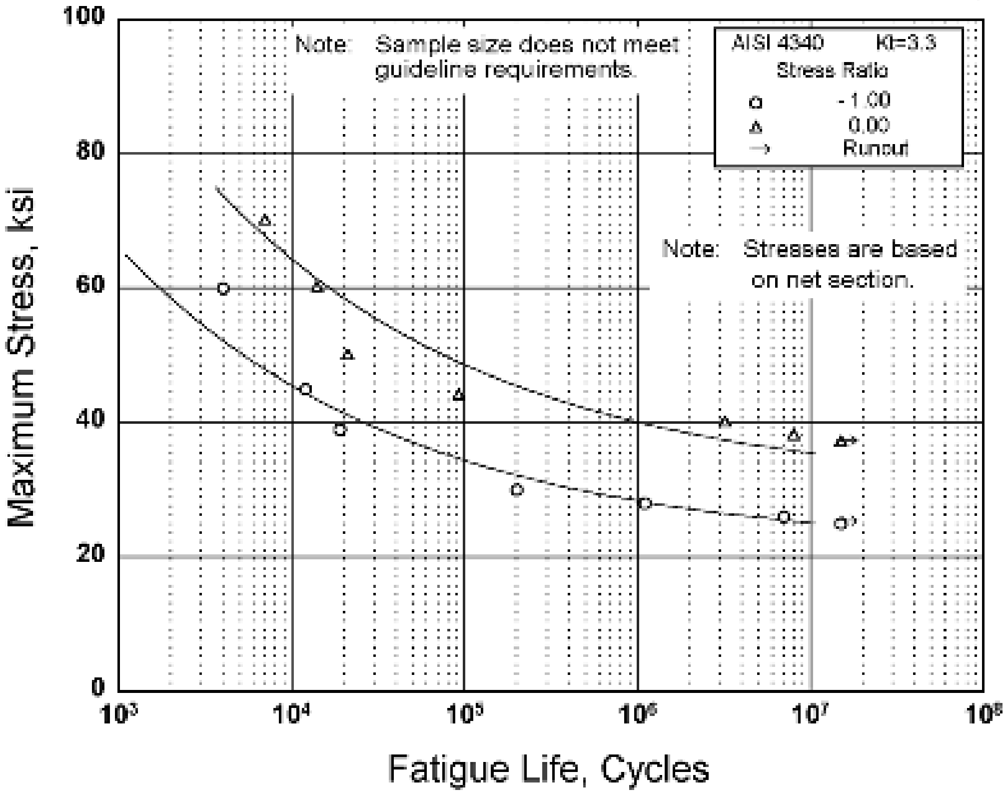


Figure 2.3.1.3.8(j). Best-fit S/N curves for notched, K_t = 3.3, AISI 4340 alloy steel bar at 1000°F, F_{tu} = 150 ksi, longitudinal direction.

Correlative Information for Figure 2.3.1.3.8(j)

Product Form: Rolled bar, 1.125 inch diameter, air melted

Properties:

TUS, ksi	TYS, ksi	Temp., °F
158	147	RT (unnotched)
81	63	1000°F (unnotched)
190	—	RT (notched)
98	—	1000°F (notched)

Specimen Details: Notched, V-Groove, K_t = 3.3
0.450 inch gross diameter
0.400 inch net diameter
0.010 inch root radius, r
60° flank angle, ω

Surface Condition: Lathe turned to RMS 10

Reference: 2.3.1.3.8(b)

Test Parameters:
Loading - Axial
Frequency - 2000 to 2500 cpm
Temperature - 1000°F
Atmosphere - Air

No. of Heat/Lots: 1

Equivalent Stress Equation:
$\text{Log } N_f = 9.76\text{-}3.75 \log (S_{eq}\text{-}30.0)$
$S_{eq} = S_{max} (1\text{-}R)^{0.50}$
Std. Error of Estimate, Log (Life) = 0.40
Standard Deviation, Log (Life) = 1.22
R^2 = 89%

Sample Size = 12

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

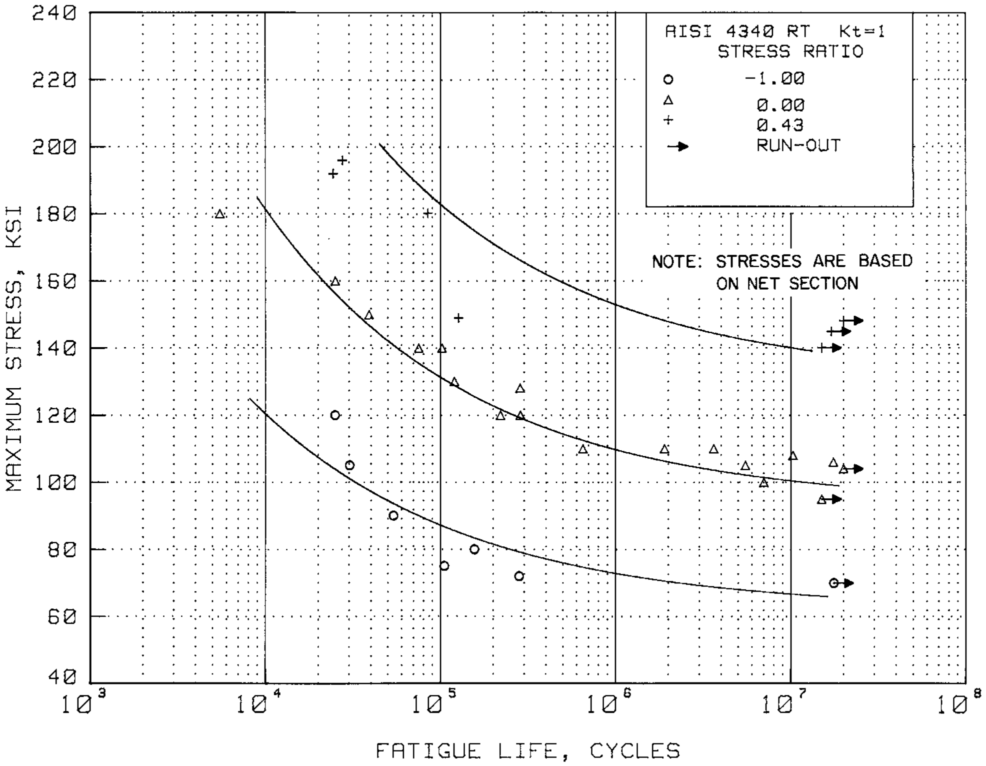


Figure 2.3.1.3.8(k). Best-fit S/N curves for unnotched AISI 4340 alloy steel bar and die forging, F_{tu} = 200 ksi, longitudinal direction.

<u>Correlative Information for Figure 2.3.1.3.8(k)</u>

<u>Product Form</u>: Rolled bar, 1.125 inch diameter, air melted
Die forging (landing gear-B-36 aircraft), air melted

<u>Properties</u>:

TUS, ksi	TYS, ksi	Temp., °F
208, 221	189, 217	RT (unnotched)
251	—	RT (notched)

<u>Specimen Details</u>: Unnotched
0.300 and 0.400inch diameter

<u>Surface Condition</u>: Hand polished to RMS 5-10

<u>References</u>: 2.3.1.3.8(a) and (c)

<u>Test Parameters</u>:
Loading - Axial
Frequency - 2000 to 2500 cpm
Temperature - RT
Atmosphere - Air

<u>No. of Heat/Lots</u>: 2

<u>Equivalent Stress Equation</u>:
Log N_f = 9.31-2.73 log (S_{eq}-93.4)
$S_{eq} = S_{max} (1-R)^{0.59}$
Std. Error of Estimate, Log (Life) = 0.49
Standard Deviation, Log (Life) = 0.93
R^2 = 72%

<u>Sample Size</u> = 26

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

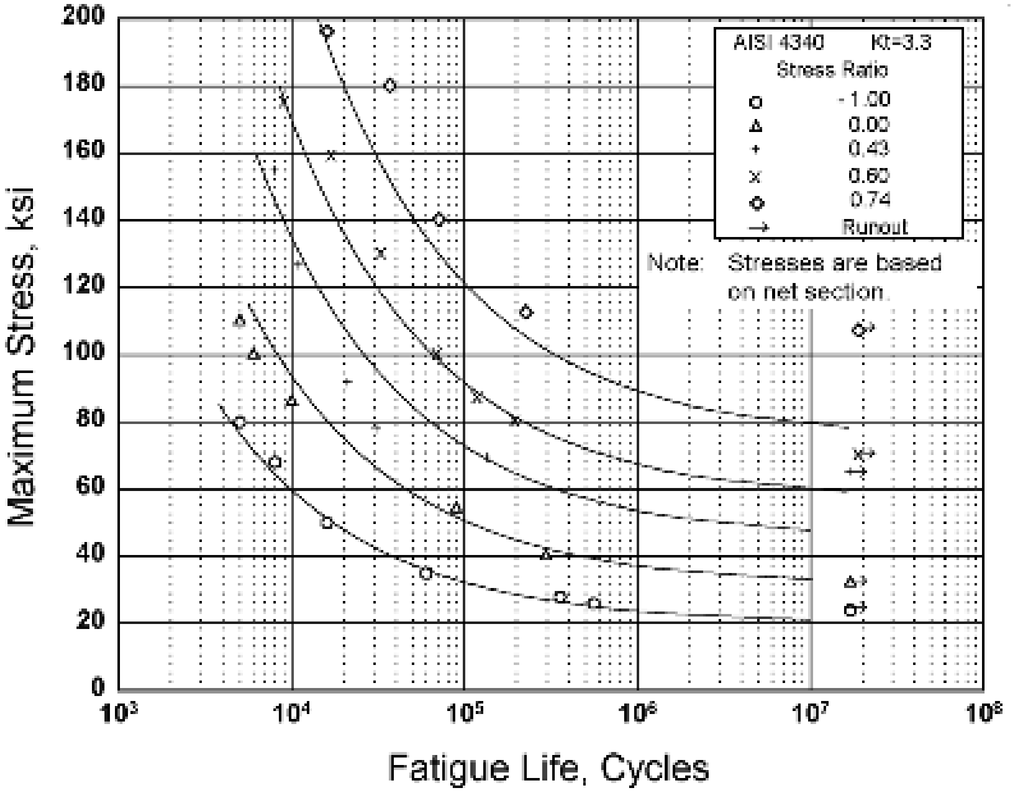


Figure 2.3.1.3.8(l). Best-fit S/N curves for notched, K_t = 3.3, AISI 4340 alloy steel bar, F_{tu} = 200 ksi, longitudinal direction.

Correlative Information for Figure 2.3.1.3.8(l)

Product Form: Rolled bar, 1.125 inch diameter, air melted

Properties:

TUS, ksi	TYS, ksi	Temp., °F
208	—	RT (unnotched)
251	—	RT (notched)

Specimen Details: Notched, V-Groove, K_t = 3.3
0.450 inch gross diameter
0.400 inch net diameter
0.010 inch root radius, r
60° flank angle, ω

Surface Condition: Lathe turned to RMS 10

Reference: 2.3.1.3.8(a)

Test Parameters:
Loading - Axial
Frequency - 2000 to 2500 cpm
Temperature - RT
Atmosphere - Air

No. of Heat/Lots: 1

Equivalent Stress Equation:
$\text{Log } N_f = 7.52-1.96 \log (S_{eq}-31.2)$
$S_{eq} = S_{max} (1-R)^{0.65}$
Std. Error of Estimate, Log (Life) = 0.16
Standard Deviation, Log (Life) = 0.62
R^2 = 93%

Sample Size = 26

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

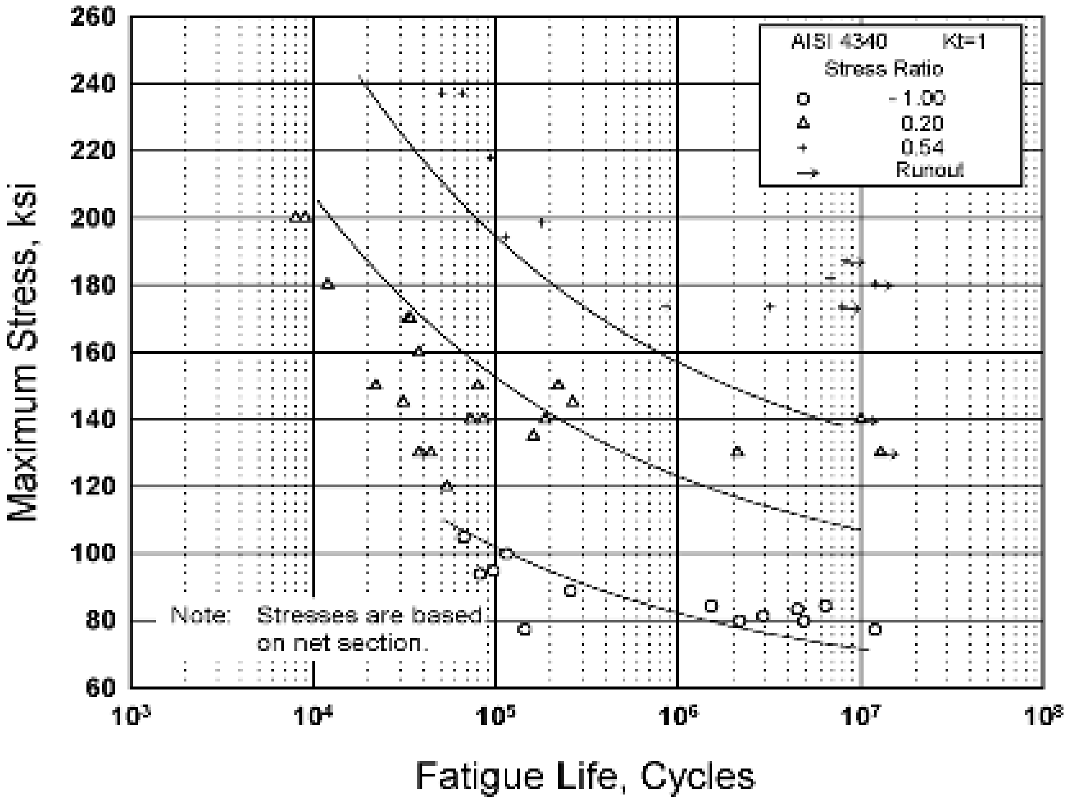


Figure 2.3.1.3.8(m). Best-fit S/N curves for unnotched AISI 4340 alloy steel bar and billet, F_{tu} = 260 ksi, longitudinal direction.

Correlative Information for Figure 2.3.1.3.8(m)

Product Form: Rolled bar, 1.125 inch diameter, air melted
Billet, 6 inches RCS air melted

Properties:

TUS, ksi	TYS, ksi	Temp., °F
266, 291	232	RT (unnotched)
352	—	RT (notched)

Specimen Details: Unnotched
0.200 and 0.400 inch diameter

Surface Condition: Hand polished to RMS 10

References: 2.3.1.3.8(a) and (b)

Test Parameters:
Loading - Axial
Frequency - 1800 to 2500 cpm
Temperature - RT
Atmosphere - Air

No. of Heat/Lots: 2

Equivalent Stress Equation:
Log $N_f = 11.62 - 3.75 \log (S_{eq} - 80.0)$
$S_{eq} = S_{max} (1-R)^{0.44}$
Std. Error of Estimate, Log (Life) = 0.64
Standard Deviation, Log (Life) = 0.86
$R^2 = 45\%$

Sample Size = 41

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

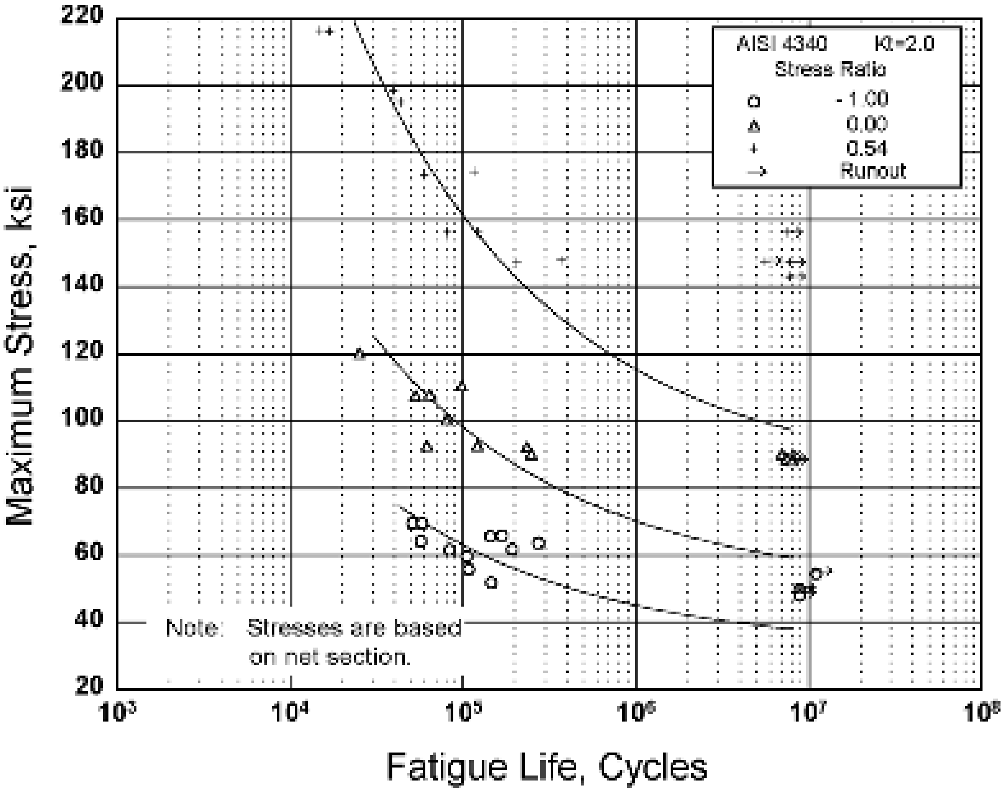


Figure 2.3.1.3.8(n). Best-fit S/N curves for notched, K_t = 2.0, AISI 4340 alloy steel bar, F_{tu} = 260 ksi, longitudinal direction.

Correlative Information for Figure 2.3.1.3.8(n)

Product Form: Rolled bar, 1.125 inch diameter, air melted

Properties:

TUS, ksi	TYS, ksi	Temp., °F
266	232	RT (unnotched)
390	—	RT (notched)

Specimen Details: Notched, V-Groove, K_t = 2.0
0.300 inch gross diameter
0.220 inch net diameter
0.030 inch root radius, r
60° flank angle, ω

Surface Condition: Lathe turned to RMS 10

Reference: 2.3.1.3.8(a)

Test Parameters:
Loading - Axial
Frequency - 2000 to 2500 cpm
Temperature - RT
Atmosphere - Air

No. of Heat/Lots: 1

Equivalent Stress Equation:
$\text{Log } N_f = 9.46 - 2.65 \log (S_{eq} - 50.0)$
$S_{eq} = S_{max} (1-R)^{0.64}$
Std. Error of Estimate, Log (Life) = 0.22
Standard Deviation, Log (Life) = 0.34
R^2 = 58%

Sample Size = 30

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

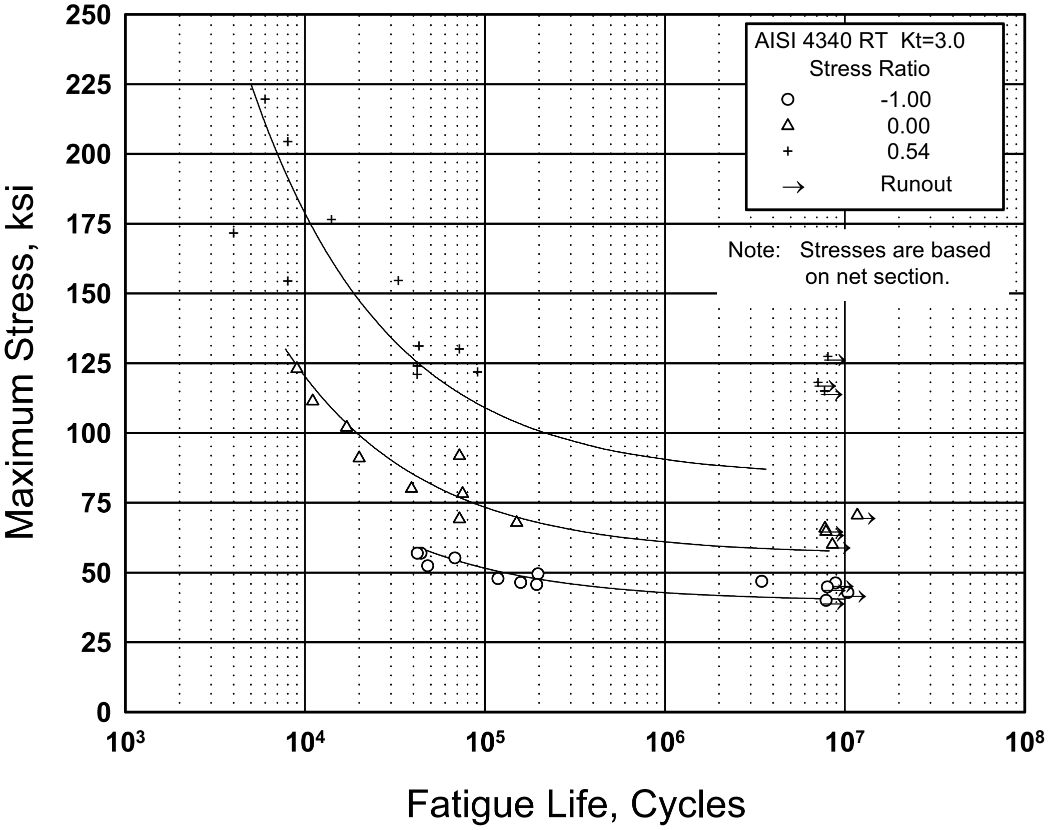


Figure 2.3.1.3.8(o). Best-fit S/N curves for notched, K_t = 3.0, AISI 4340 alloy steel bar, F_{tu} = 260 ksi, longitudinal direction.

Correlative Information for Figure 2.3.1.3.8(o)

Product Form: Rolled bar, 1.125 inch diameter, air melted

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	266	232	RT (unnotched)
	352	—	RT (notched)

Specimen Details: Notched, V-Groove, $K_t = 3.0$
0.270 inch gross diameter
0.220 inch net diameter
0.010 inch root radius, r
60° flank angle, ω

Surface Condition: Lathe turned to RMS 10

Reference: 2.3.1.3.8(a)

Test Parameters:
Loading—Axial
Frequency—2000 to 2500 cpm
Temperature—RT
Atmosphere—Air

No. of Heats/Lots: 1

Equivalent Stress Equation:
$\text{Log } N_f = 7.14 - 1.74 \log (S_{eq} - 56.4)$
$S_{eq} = S_{max} (1-R)^{0.51}$
Std. Error of Estimate, Log (Life) = 0.32
Standard Deviation, Log (Life) = 0.59
$R^2 = 71\%$

Sample Size = 29

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

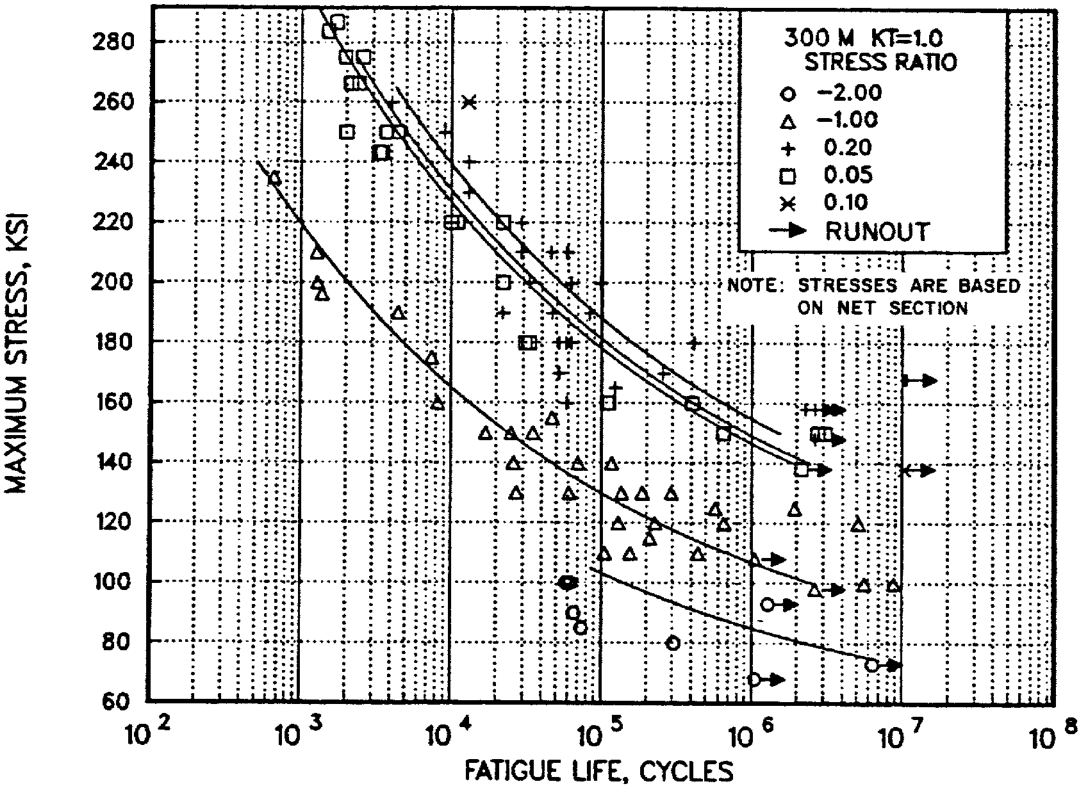


Figure 2.3.1.4.8(a). Best-fit S/N curves for unnotched 300M alloy forging, F_{tu} = 280 ksi, longitudinal and transverse directions.

Correlative Information for Figure 2.3.1.4.8(a)

Product Forms: Die forging, 10 x 20 inches CEVM
Die forging, 6.5 x 20 inches CEVM
RCS billet, 6 inches CEVM
Forged Bar, 1.25 x 8 inches CEVM

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	274-294	227-247	RT

Specimen Details: Unnotched
0.200 - 0.250 inch diameter

Surface Condition: Heat treat and finish grind to a surface finish of RMS 63 or better with light grinding parallel to specimen length, stress relieve

References: 2.3.1.4.8(a), (c), (d), (e)

Test Parameters:
Loading - Axial
Frequency - 1800 to 2000 cpm
Temperature - RT
Atmosphere - Air

No. of Heat/Lots: 6

Equivalent Stress Equation:
Log N_f = 14.8-5.38 log (S_{eq}-63.8)
$S_{eq} = S_a + 0.48\ S_m$
Std. Error of Estimate, Log (Life) = 55.7 ($1/S_{eq}$)
Standard Deviation, Log (Life) = 1.037
R^2 = 82.0

Sample Size = 104

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

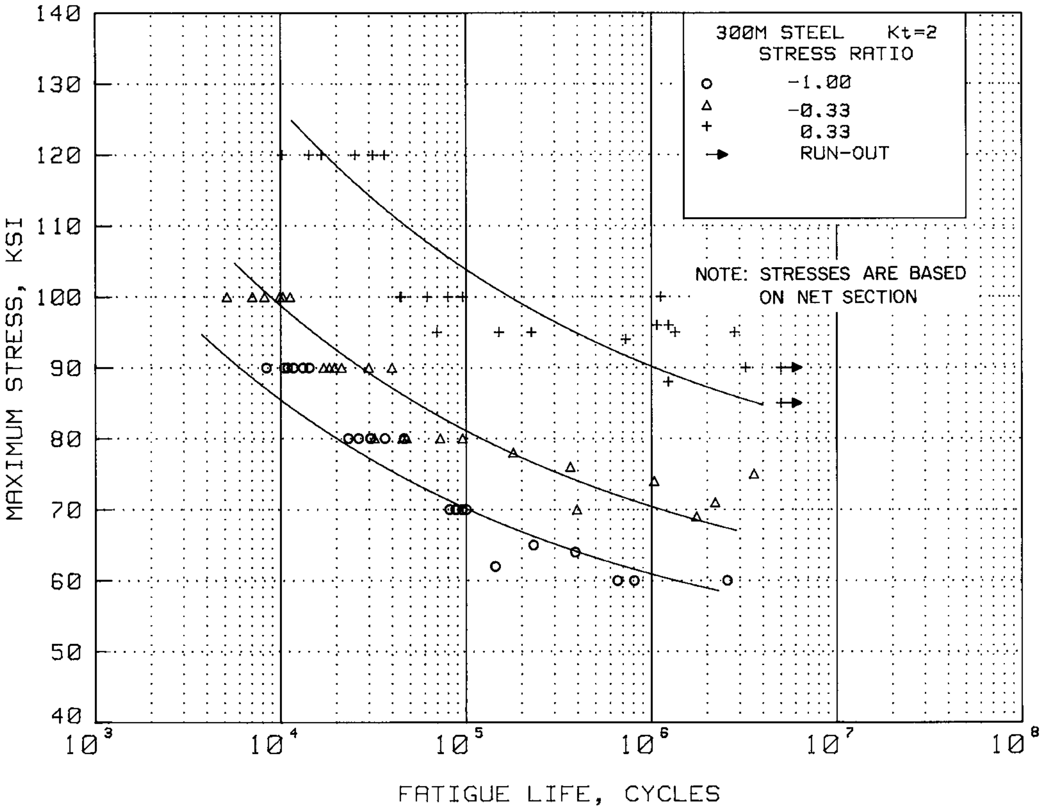


Figure 2.3.1.4.8(b). Best-fit S/N curves for unnotched, K_t = 2.0, 300M alloy forged billet, F_{tu} = 280 ksi, longitudinal direction.

Correlative Information for Figure 2.3.1.4.8(b)

Product Form: Forged billet, unspecified size, CEVM

Properties:

TUS, ksi	TYS, ksi	Temp., °F
290	242	RT (unnotched)
456	—	RT (notched)

Specimen Details: Notched, 60° V-Groove, K_t=2.0
0.500 inch gross diameter
0.250 inch net diameter
0.040 inch root radius, r
60° flank angle, ω

Surface Condition: Heat treat and finish grind notch to RMS 63 ± 5; stress relieve

Reference: 2.3.1.4.8(b)

Test Parameters:
Loading - Axial
Frequency -
Temperature - RT
Atmosphere - Air

No. of Heats/Lots: 3

Equivalent Stress Equation:
Log N_f = 12.87-5.08 log (S_{eq}-55.0)
$S_{eq} = S_{max} (1-R)^{0.36}$
Std. Error of Estimate, Log (Life) = 0.79
Standard Deviation, Log (Life) = 1.72
R^2 = 79%

Sample Size = 70

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

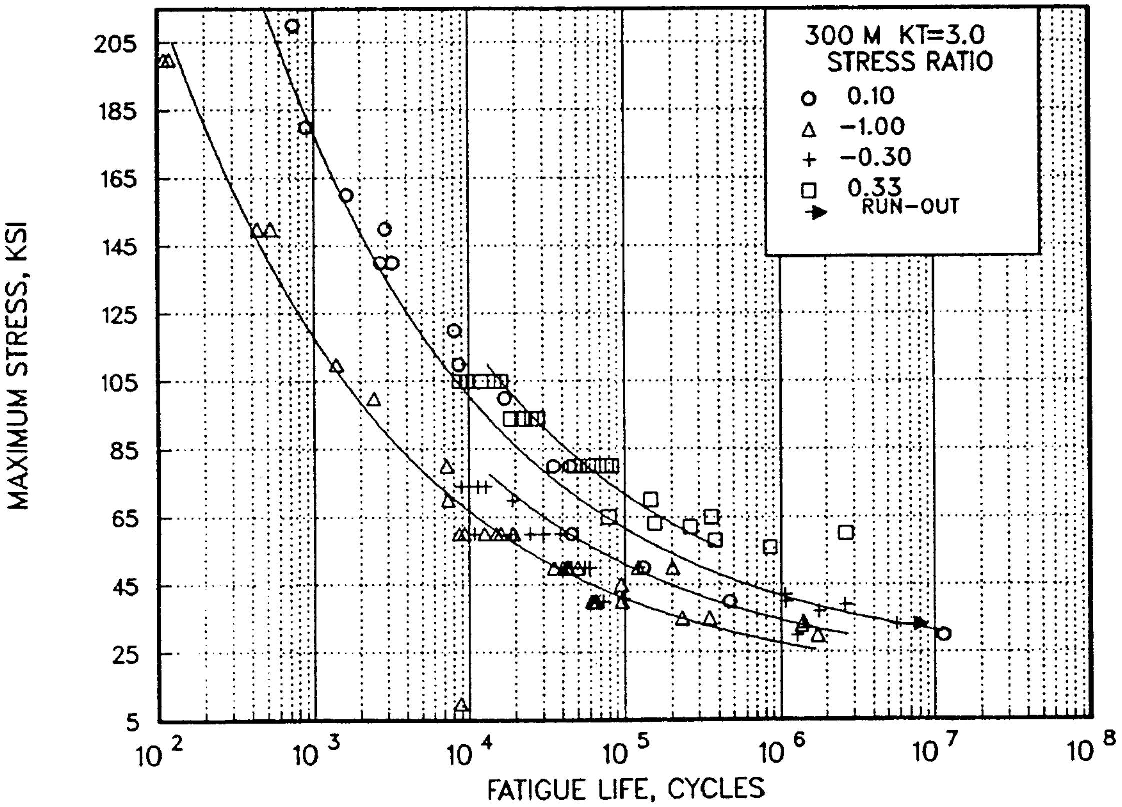


Figure 2.3.1.4.8(c). Best-fit S/N curves for notched, K_t = 3.0, 300M alloy forging, F_{tu} = 280 ksi, longitudinal and transverse directions.

Correlative Information for Figure 2.3.1.4.8(c)

Product Forms: Forged billet, unspecified size, CEVM
Die forging, 10 x 20 inches, CEVM
Die forging, 6.50 x 20 inches, CEVM

Properties:

	TUS, ksi	TYS, ksi	Temp., °F
	290-292	242-247	RT (unnotched)
	435	—	RT (notched)

Specimen Details: Notched 60° V-Groove, K_t = 3.0
0.500 inch gross diameter
0.250 inch net diameter
0.0145 inch root radius, r
60° flank angle, ω

Surface Condition: Heat treat and finish grind notch to RMS 63 or better; stress relieve

References: 2.3.1.4.8(a), (b), (c)

Test Parameters:
Loading - Axial
Frequency -
Temperature - RT
Atmosphere - Air

No. of Heats/Lots: 5

Equivalent Stress Equation:
Log N_f = 10.40-3.41 log (S_{eq}-20.0)
$S_{eq} = S_{max} (1-R)^{0.51}$
Std. Error of Estimate, Log (Life) = 18.3 ($1/S_{eq}$)
Standard Deviation, Log (Life) = 2.100
R^2 = 97.4

Sample Size = 99

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

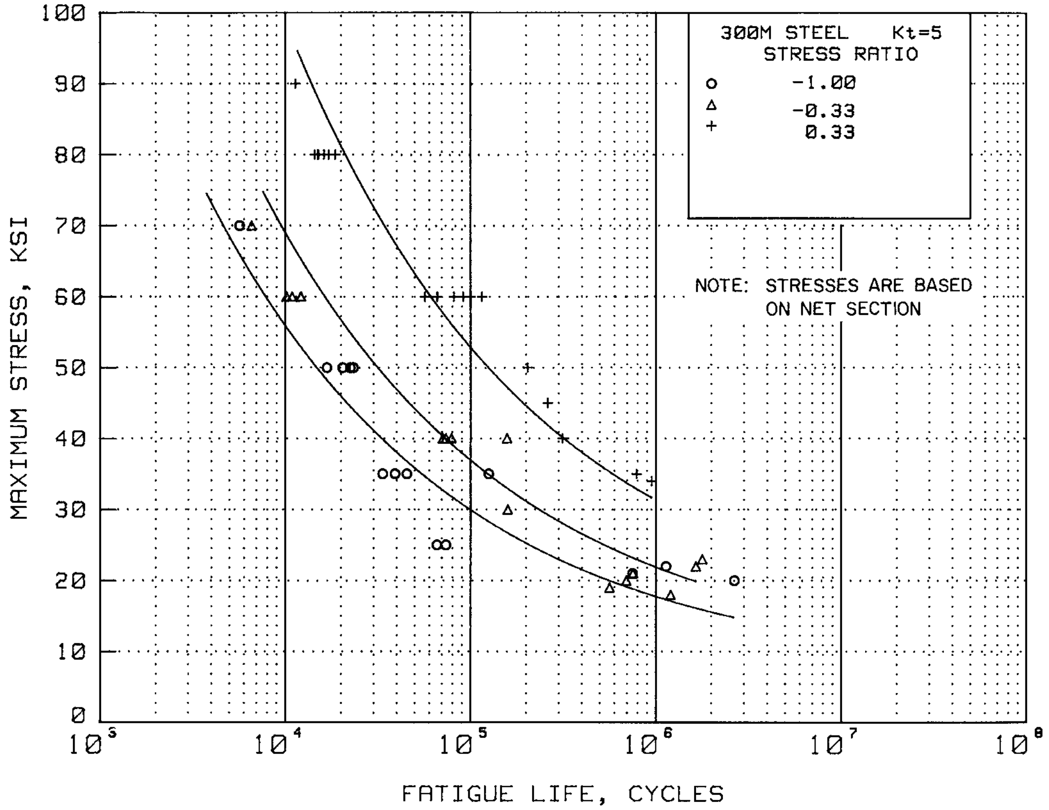


Figure 2.3.1.4.8(d). Best-fit S/N curves for notched, K_t = 5.0, 300M alloy forged billet, F_{tu} = 280 ksi, longitudinal direction.

Correlative Information for Figure 2.3.1.4.8(d)

Product Forms: Forged billet, unspecified size, CEVM

Properties:

TUS, ksi	TYS, ksi	Temp., °F
290	242	RT (unnotched)
379	—	RT (notched)

Specimen Details: Notched, 60° V-Groove, K_t=5.0
0.500 inch gross diameter
0.250 inch net diameter
0.0042 inch root radius, r
60° flank angle, ω

Surface Condition: Heat treat and finish grind notch to RMS 63 maximum; stress relieve

Reference: 2.3.1.4.8(b)

Test Parameters:
Loading - Axial
Frequency -
Temperature - RT
Atmosphere - Air

No. of Heat/Lots: 2

Equivalent Stress Equation:
Log N_f = 9.61-3.04 log (S_{eq}-10.0)
$S_{eq} = S_{max}\ (1-R)^{0.52}$
Std. Error of Estimate, Log (Life) = 0.28
Standard Deviation, Log (Life) = 0.81
R^2 = 88%

Sample Size = 48

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

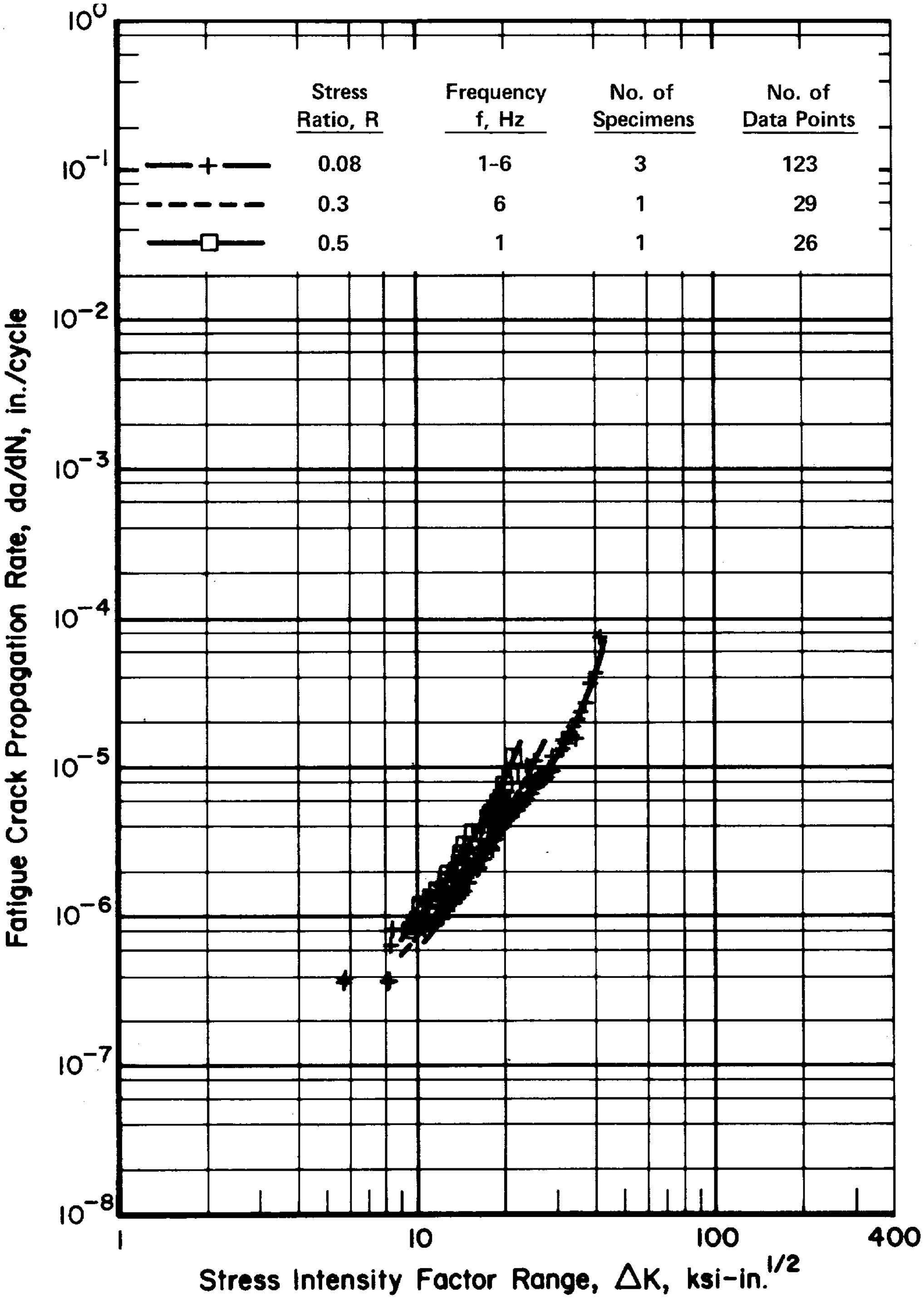


Figure 2.3.1.4.9. Fatigue-crack-propagation data for 3.00-inch hand forging and 1.80-inch thick, 300M steel alloy plate (TUS: 280-290 ksi). [References - 2.3.1.4.9(a) and (b).]

Specimen Thickness:	*0.900-1.000 inches*	*Environment:*	*Low-humidity air*
Specimen Width:	*3.09-7.41 inches*	*Temperature:*	*RT*
Specimen Type:	*CT*	*Orientation:*	*L-T and T-L*

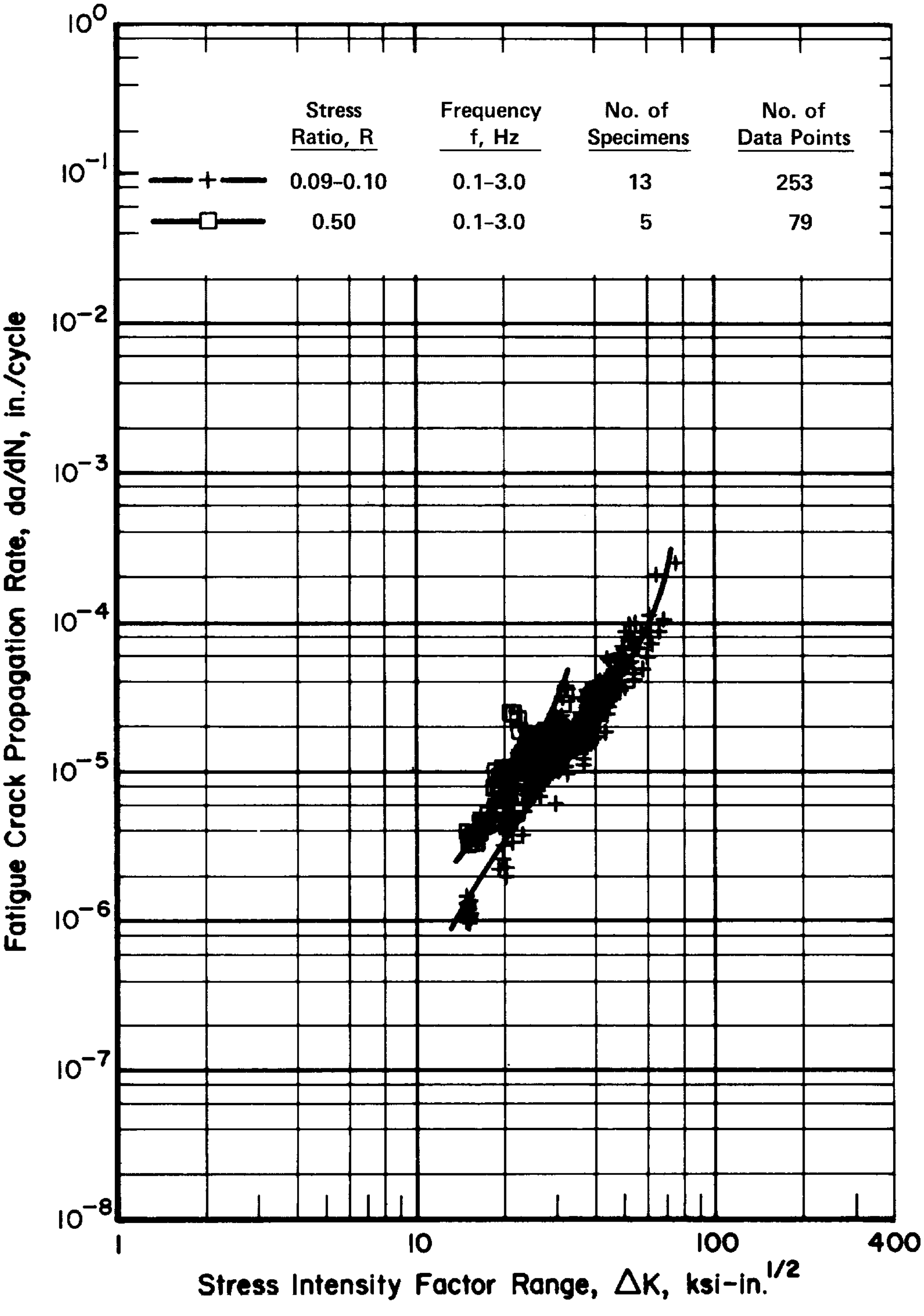


Figure 2.3.1.5.9. Fatigue-crack-propagation data for 0.80-inch D6AC steel alloy plate. Data include material both oil quenched and salt quenched (TUS: 230-240 ksi). [Reference - 2.3.1.5.9.]

Specimen Thickness:	*0.70-0.75 inch*	*Environment:*	*Dry air and lab air*
Specimen Width:	*1.5-5.0 inches*	*Temperature:*	*RT*
Specimen Type:	*CT*	*Orientation:*	*L-T*

2.4 INTERMEDIATE ALLOY STEELS

2.4.0 COMMENTS ON INTERMEDIATE ALLOY STEELS — The intermediate alloy steels in this section are those steels that are substantially higher in alloy content than the alloy steels described in Section 2.3, but lower in alloy content than the stainless steels. Typical of the intermediate alloy steels is the 5Cr-Mo-V aircraft steel and the 9Ni-4Co series of steels.

2.4.0.1 Metallurgical Considerations — The alloying elements added to these steels are similar to those used in the lower alloy steels and, in general, have the same effects. The difference lies in the quantity of alloying additions and the extent of these effects. Thus, higher chromium contents provide improved oxidation resistance. Additions of molybdenum, vanadium, and tungsten, together with the chromium, provide deep air-hardening properties and improve the elevated-temperature strength by retarding the rate of tempering at high temperatures. Additions of nickel to nonsecondary hardening steels lower the transition temperature and improve low-temperature toughness.

2.4.1 5CR-MO-V

2.4.1.0 Comments and Properties — Alloy 5Cr-Mo-V aircraft steel exhibits high strength in the temperature range up to 1000°F. Its characteristics also include air hardenability in thick sections; consequently, little distortion is encountered in heat treatment. This steel is available either as air-melted or consumable electrode vacuum-melted quality although only consumable electrode vacuum-melted quality is recommended for aerospace applications.

The heat treatment recommended for this steel consists of heating to 1850°F ± 50, holding 15 to 25 minutes for sheet or 30 to 60 minutes for bars depending on section size, cooling in air to room temperature, tempering three times by heating to the temperature specified in Table 2.4.1.0(a) for the strength level desired, holding at temperature for 2 to 3 hours, and cooling in air.

Table 2.4.1.0(a). Tempering Temperatures for 5Cr-Mo-V Aircraft Steel

F_{tu}, ksi	Temperature, °F	Hardness, R_c
280	1000 ± 10	54-56
260	1030 ± 10	52-54
240	1050 ± 10	49-52
220	1080 ± 10	46-49

Material specifications for 5Cr-Mo-V aircraft steel are presented in Table 2.4.1.0(b). The room-temperature mechanical and physical properties are shown in Tables 2.4.1.0(c) and (d). The mechanical properties are for 5Cr-Mo-V steel heat treated to produce a structure containing 90 percent or more martensite at the center prior to tempering.

Table 2.4.1.0(b). Material Specifications for 5Cr-Mo-V Aircraft Steel

Specification	Form
AMS 6437	Sheet, strip, and plate (air melted)
AMS 6488	Bar and forging (air melted, premium quality)
AMS 6487	Bar and forging (CEVM)

The room-temperature properties of 5Cr-Mo-V aircraft steel are affected by extended exposure to temperatures near or above the tempering temperature. The limiting temperature to which the alloy may be exposed for extended periods without significantly affecting its room-temperature properties may be estimated at 100°F below the tempering temperature for the desired strength level. The effect of temperature on the physical properties is shown in Figure 2.4.1.0.

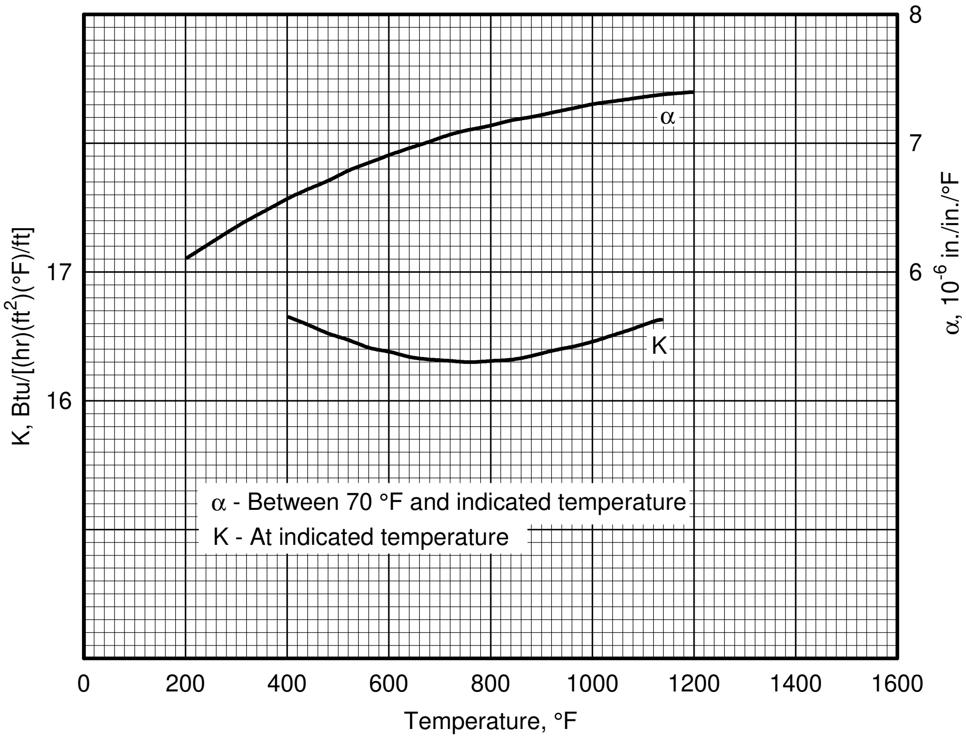


Figure 2.4.1.0. Effect of temperature on the physical properties of 5Cr-Mo-V aircraft steel.

2.4.1.1 ***Heat-Treated Condition*** — The effect of temperature on various mechanical properties for heat-treated 5Cr-Mo-V aircraft steel is presented in Figures 2.4.1.1.1(a) through 2.4.1.1.4.

Table 2.4.1.0(c). Design Mechanical and Physical Properties of 5Cr-Mo-V Aircraft Steel Bar and Forging

Specification	AMS 6487 and AMS 6488		
Form	Bars and forgings		
Condition	Quenched and tempered		
Cross-sectional area, in.^{2}	a,b		
Basis	S[c]	S[c]	S[c]
Mechanical Properties:			
F_{tu}, ksi:			
L	...	260[a]	...
T	240	260[b]	280
F_{ty}, ksi:			
L	...	215[a]	...
T	200	215[b]	240
F_{cy}, ksi:			
L	...	...	...
T	220	234	260
F_{su}, ksi	144	156	168
F_{bru}, ksi:			
(e/D = 1.5)	...	...	...
(e/D = 2.0)	400	435	465
F_{bry}, ksi:			
(e/D = 1.5)	...	...	...
(e/D = 2.0)	315	333	365
e, percent:			
L	9	8[a]	7
T	...	...	...
RA, percent:			
L	...	30[a]	...
T	...	6[b]	...
E, 10^3 ksi	30.0		
E_c, 10^3 ksi	30.0		
G, 10^3 ksi	11.0		
μ	0.36		
Physical Properties:			
ω, lb/in.^{3}	0.281		
C, Btu/(lb)(°F)	0.11 (32°F)[d]		
K and α	See Figure 2.4.1.0		

[a] Longitudinal properties applicable to cross-sectional area ≤ 25 sq. in.

[b] Transverse properties applicable only to product sufficiently large to yield tensile specimens not less than 4.50 inches in length.

[c] Design values are applicable only to parts for which the indicated F_{tu} has been substantiated by adequate quality control testing.

[d] Calculated value.

Table 2.4.1.0(d). Design Mechanical and Physical Properties of 5Cr-Mo-V Aircraft Steel Sheet, Strip, and Plate

Specification	AMS 6437		
Form	Sheet, strip, and plate		
Condition	Quenched and tempered		
Thickness, in.	...		
Basis	S[a]	S[a]	S[a]
Mechanical Properties:			
F_{tu}, ksi:			
L	...	...	...
LT	240	260	280
F_{ty}, ksi:			
L	...	...	...
LT	200	220	240
F_{cy}, ksi:			
L	...	...	...
LT	220	240	260
F_{su}, ksi	144	156	168
F_{bru}, ksi:			
(e/D = 1.5)	...	...	...
(e/D = 2.0)	400	435	465
F_{bry}, ksi:			
(e/D = 1.5)	...	...	...
(e/D = 2.0)	315	340	365
e, percent:			
L	...	...	...
LT, in 2 inches[b]	6	5	4
LT, in 1 inch	8	7	6
E, 10^3 ksi	30.0		
E_c, 10^3 ksi	30.0		
G, 10^3 ksi	11.0		
μ	0.36		
Physical Properties:			
ω, lb/in.^{3}	0.281		
C, Btu/(lb)(°F)	0.11[c] (32°F)		
K and α	See Figure 2.4.1.0		

a Design values are applicable only to parts for which the indicated F_{tu} has been substantiated by adequate quality control testing.
b For sheet thickness greater than 0.050 inch.
c Calculated value.

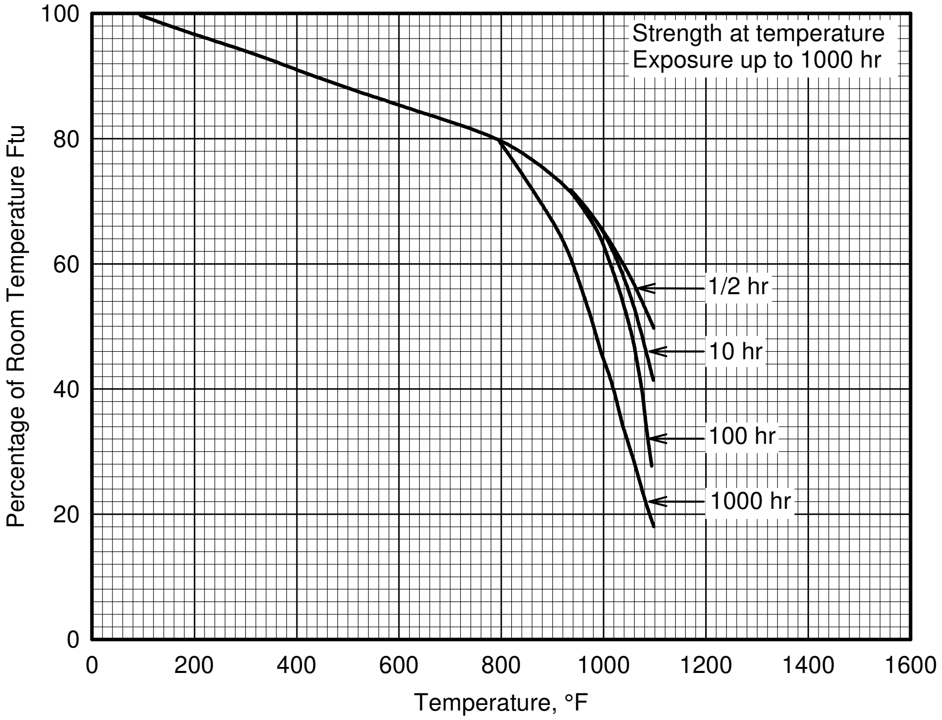


Figure 2.4.1.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of 5Cr-Mo-V aircraft steel.

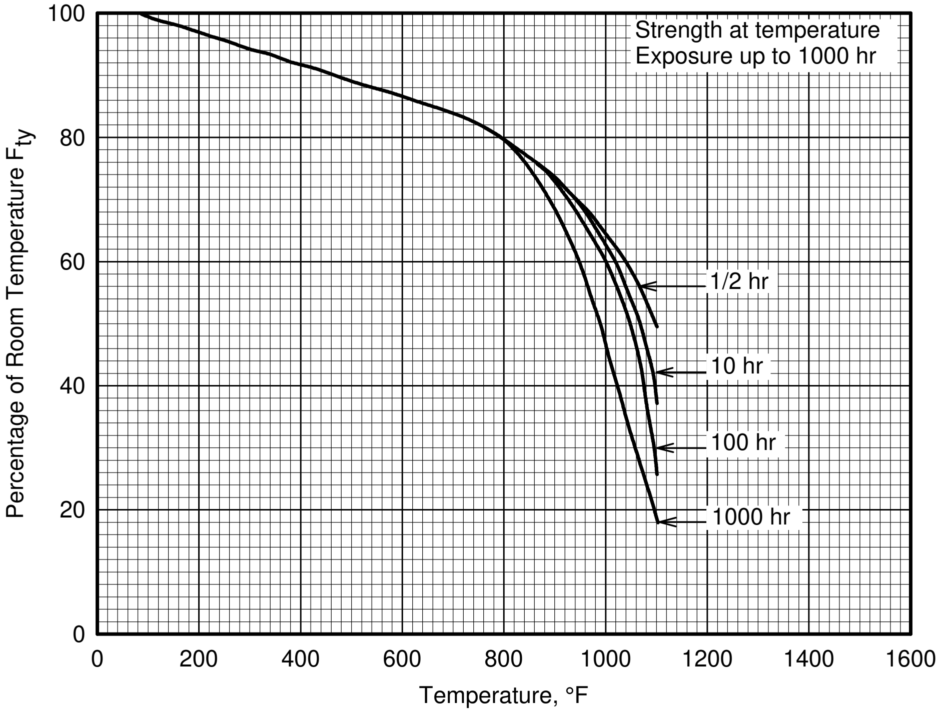


Figure 2.4.1.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of 5Cr-Mo-V aircraft steel.

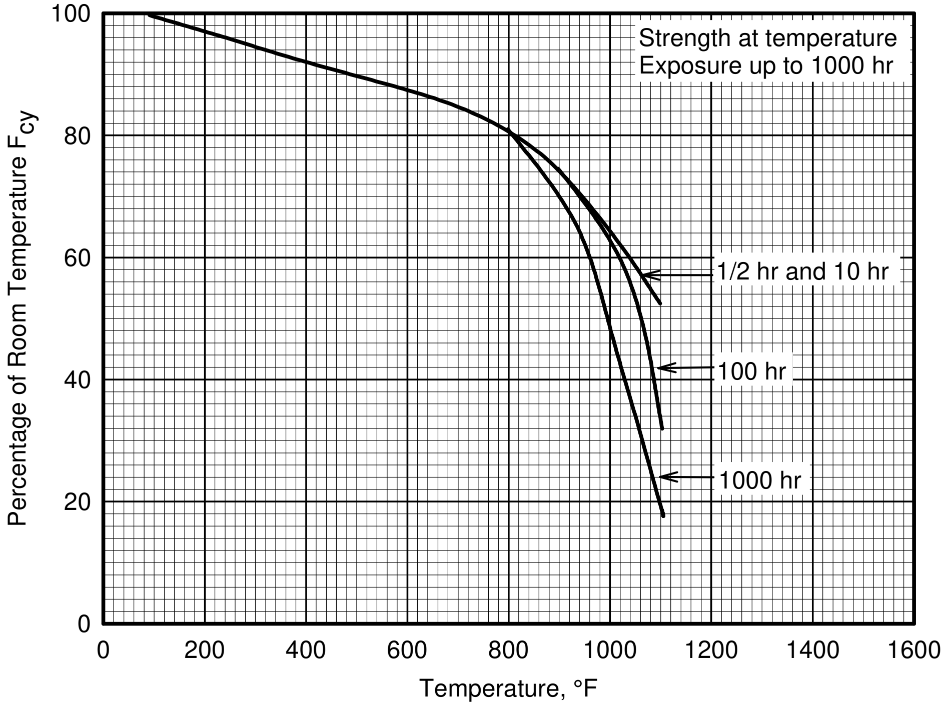


Figure 2.4.1.1.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of 5Cr-Mo-V aircraft steel.

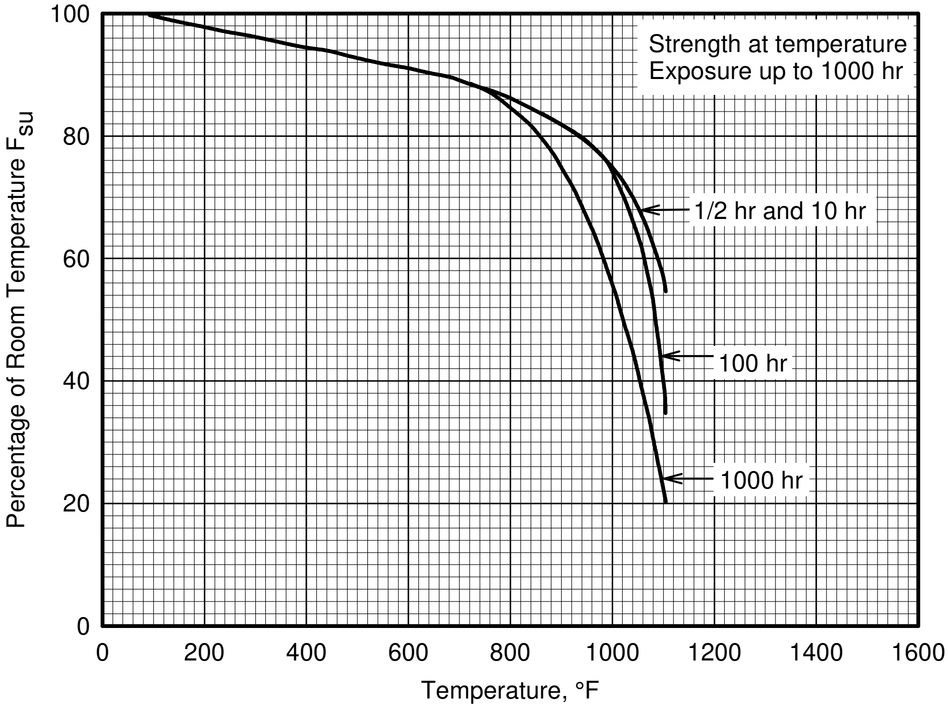


Figure 2.4.1.1.2(b). Effect of temperature on the ultimate shear strength (F_{su}) of 5Cr-Mo-V aircraft steel.

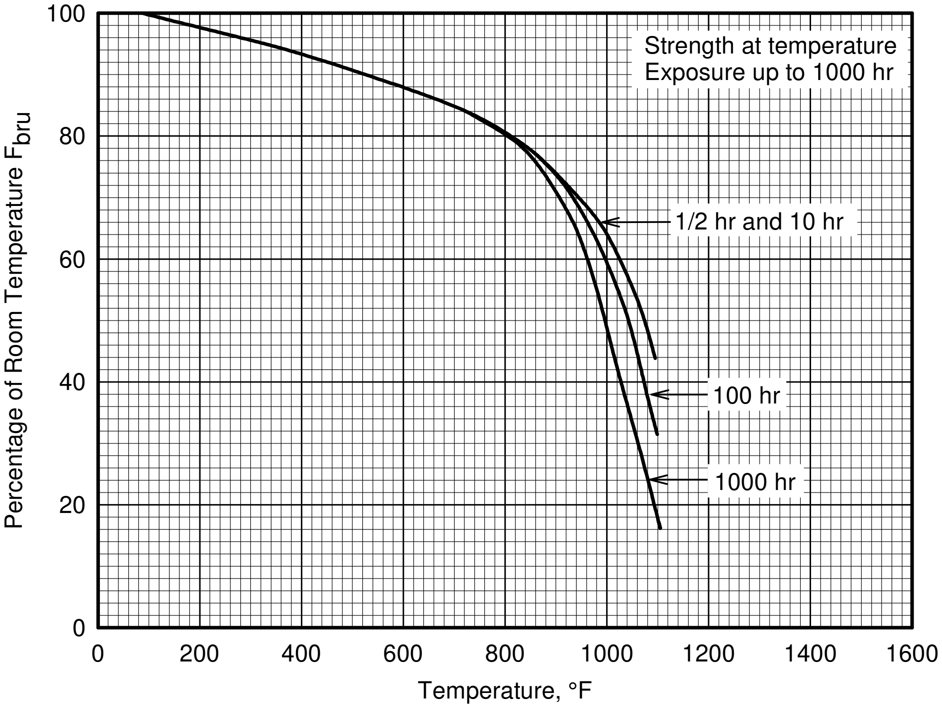


Figure 2.4.1.1.3(a). Effect of temperature on the ultimate bearing strength (F_{bru}) of 5 Cr-Mo-V aircraft steel.

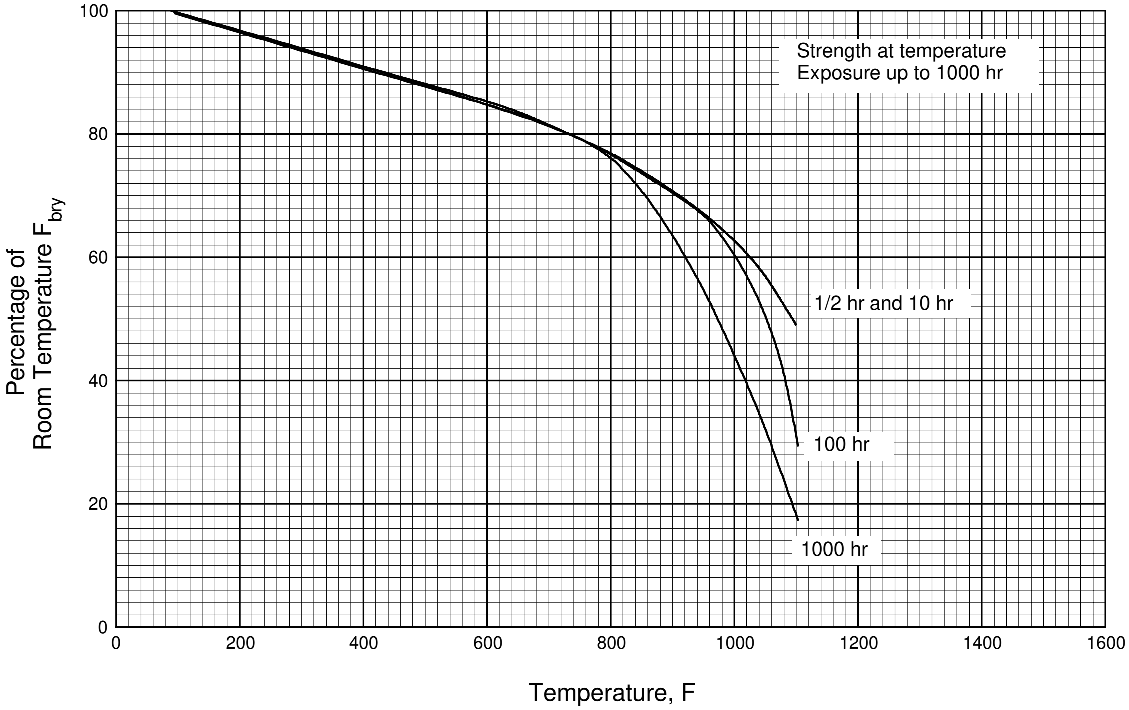


Figure 2.4.1.1.3(b). Effect of temperature on the bearing yield strength (F_{bry}) of 5Cr-Mo-V aircraft steel.

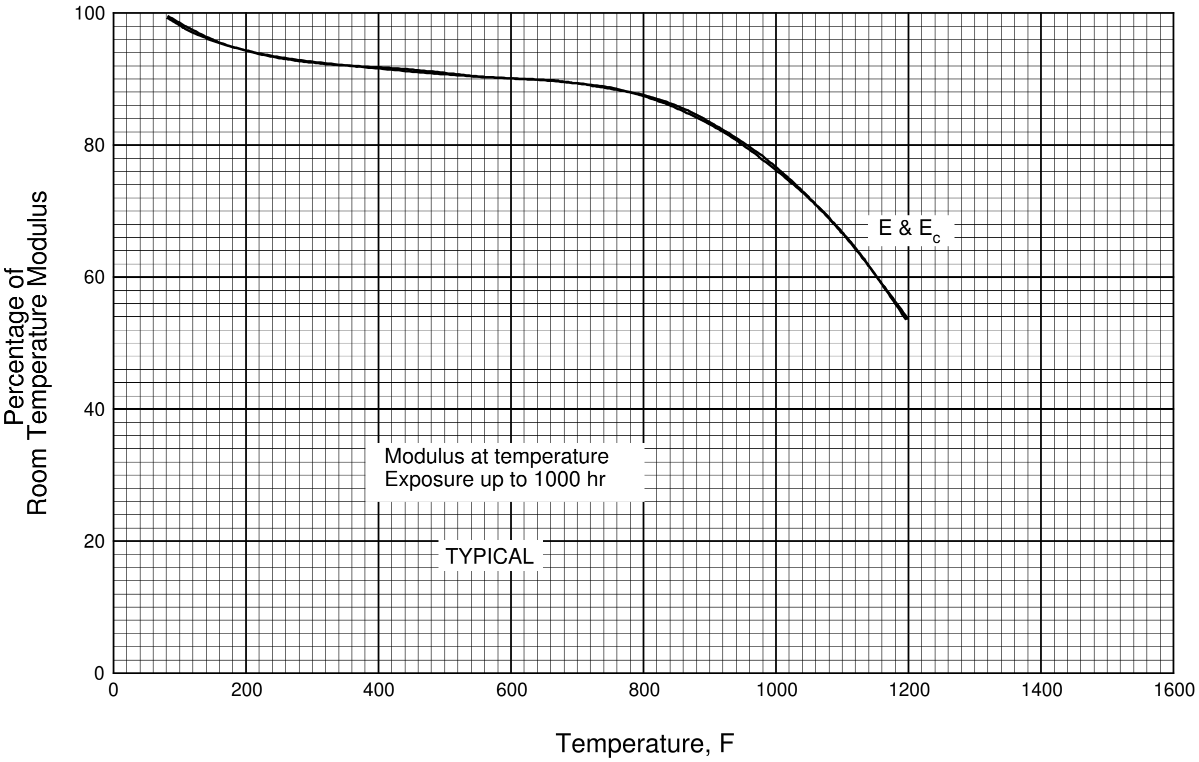


Figure 2.4.1.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of 5Cr-Mo-V aircraft steel.

2.4.2 9NI-4CO-0.20C

2.4.2.0 *Comments and Properties* — The 9Ni-4Co-0.20C alloy was developed specifically to have excellent fracture toughness, excellent weldability, and high hardenability when heat-treated to 190 to 210 ksi ultimate tensile strength. The alloy can be readily welded in the heat-treated condition with preheat and post-heat usually not required. The alloy is through hardening in section sizes up to at least 8 inches thick. The alloy may be exposed to temperatures up to 900°F (approximately 100°F below typical tempering temperature) without microstructural changes which degrade room temperature strength.

The heat treatment for this alloy consists of normalizing at 1650 ± 25°F for 1 hour per inch of cross section, cooling in air to room temperature, heating to 1525 ± 25°F for 1 hour per inch of cross section, quenching in oil or water, hold at -100 ± 20°F for 2 hours within 2 hours after quenching, and double tempering at 1035 ± 10°F for 2 hours.

A material specification for 9Ni-4Co-0.20C steel is presented in Table 2.4.2.0(a). Room temperature mechanical and physical properties are shown in Table 2.4.2.0(b). The effect of temperature on thermal expansion is shown in Figure 2.4.2.0.

Table 2.4.2.0(a). Material Specification for 9Ni-4Co-0.20C Steel

Specification	Form
AMS 6523	Sheet, strip, and plate

2.4.2.1 *Heat-Treated Condition* — Effect of temperature on various mechanical properties is presented in Figures 2.4.2.1.1, 2.4.2.1.2, and 2.4.2.1.4. Typical tensile stress-strain curves at room and elevated temperatures are shown in Figure 2.4.2.1.6(a). Typical compression stress-strain and tangent-modulus curves are presented in Figure 2.4.2.1.6(b).

Table 2.4.2.0(b). Design Mechanical and Physical Properties of 9Ni-4Co-0.20C Steel Plate

Specification	AMS 6523	
Form	Plate	
Condition	Quenched and tempered	
Thickness, in.	<0.250	≥0.250
Basis	S[a]	S[a]
Mechanical Properties:		
F_{tu}, ksi:		
L	186	186
LT	190	190
F_{ty}, ksi:		
L	173	173
LT	175	175
F_{cy}, ksi:		
L	188	188
LT	187	187
F_{su}, ksi	114	114
F_{bru}, ksi:		
(e/D = 1.5)	...	...
(e/D = 2.0)	...	...
F_{bry}, ksi:		
(e/D = 1.5)	...	...
(e/D = 2.0)	...	...
e, percent:		
LT	5	10
RA, percent:		
LT	45	45
E, 10^3 ksi	28.8	
E_c, 10^3 ksi	28.8	
G, 10^3 ksi	11.1	
μ	0.30	
Physical Properties:		
ω, lb/in.^{3}	0.283	
C, Btu/(lb)(°F)	...	
K, Btu/[(hr)(ft^2)(°F)/ft]	14.2 (75°F)	
α, 10^{-6} in./in./°F	See Figure 2.4.2.0	

a Design values are applicable only to parts for which the indicated F_{tu} has been substantiated by adequate quality control testing.

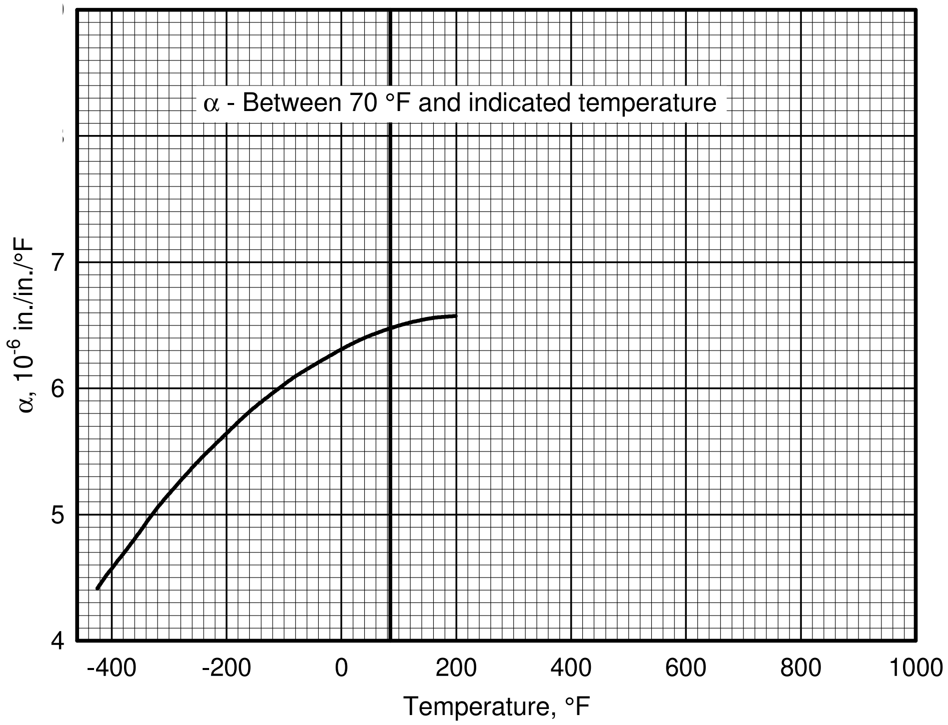


Figure 2.4.2.0. Effect of temperature on the thermal expansion of 9Ni-4Co-0.20C steel.

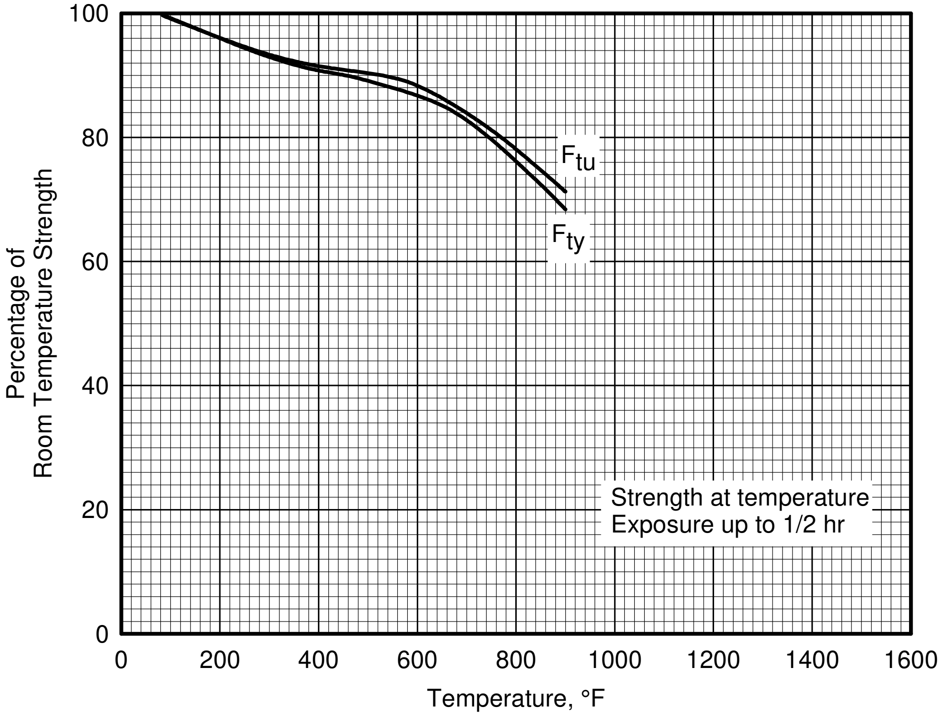


Figure 2.4.2.1.1. Effect of temperature on the tensile ultimate strength (F_{tu}) and tensile yield strength (F_{ty}) of 9Ni-4Co-0.20C steel plate.

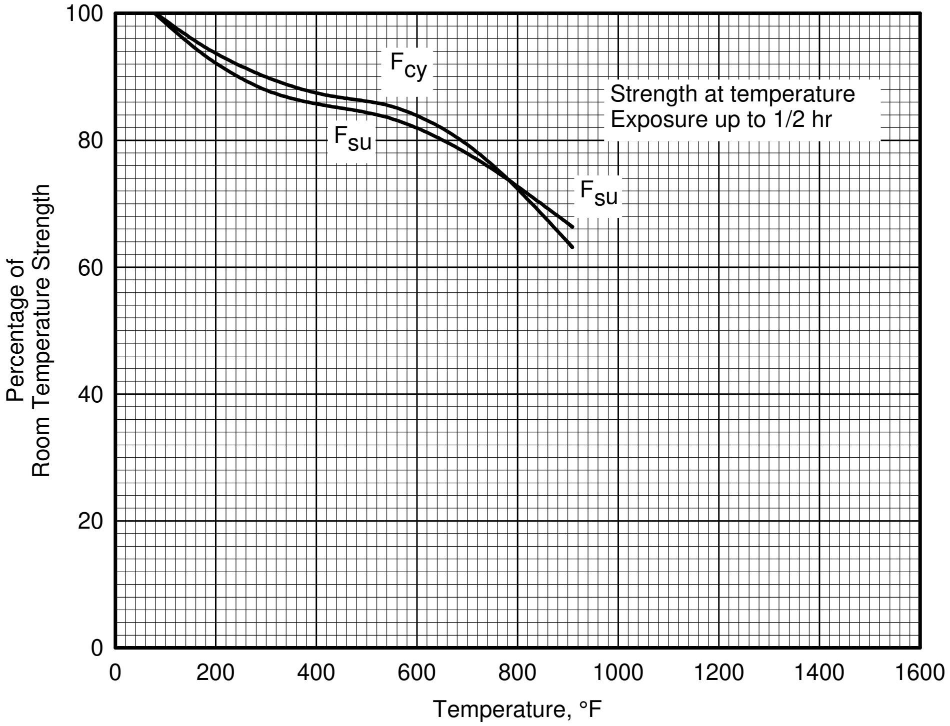


Figure 2.4.2.1.2. Effect of temperature on the compressive yield strength (F_{cy}) and the shear ultimate strength (F_{su}) of 9Ni-4Co-0.20C steel plate.

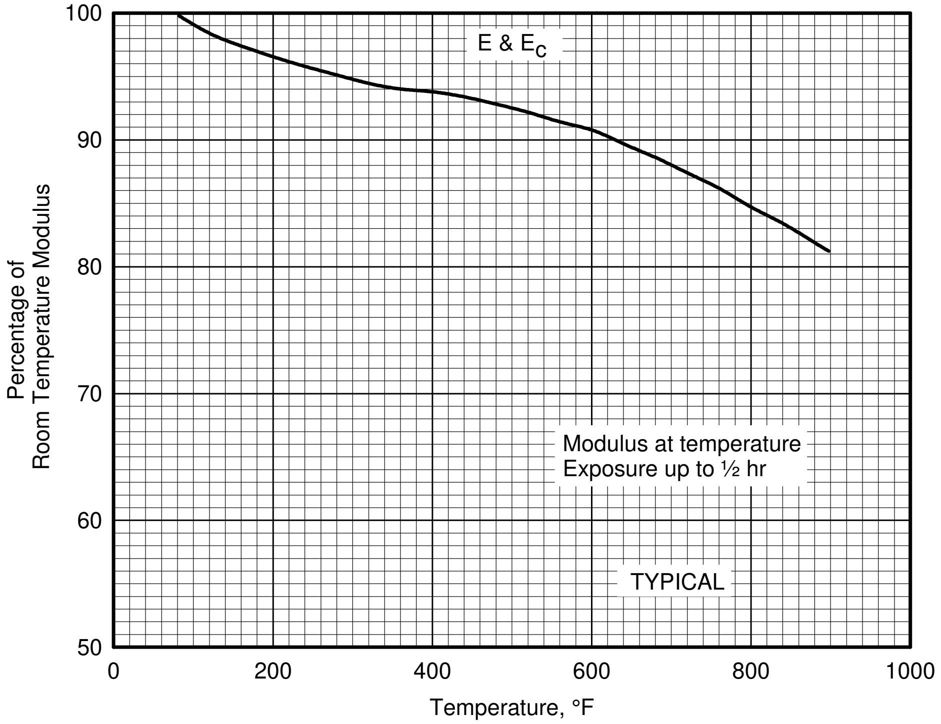


Figure 2.4.2.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of 9Ni-4Co-0.20C steel plate.

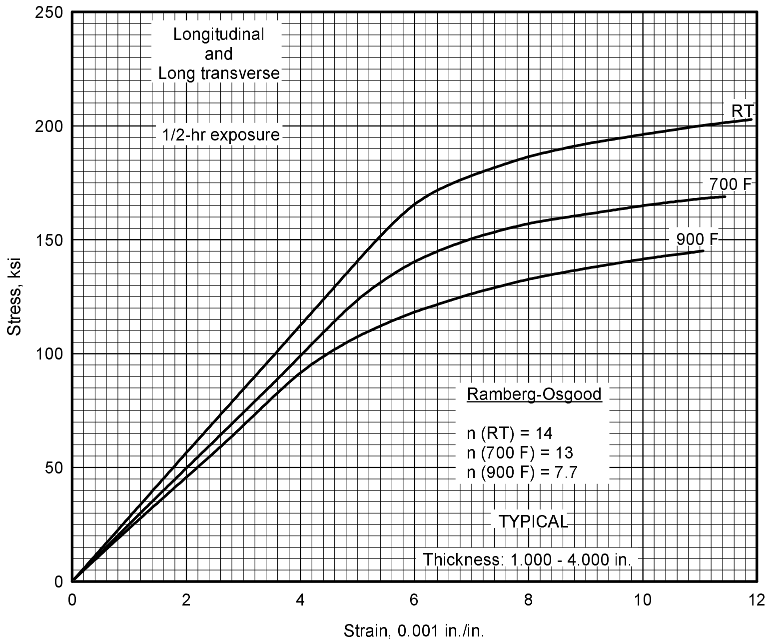


Figure 2.4.2.1.6(a). Typical tensile stress-strain curves for 9Ni-4Co-0.20C steel plate at various temperatures.

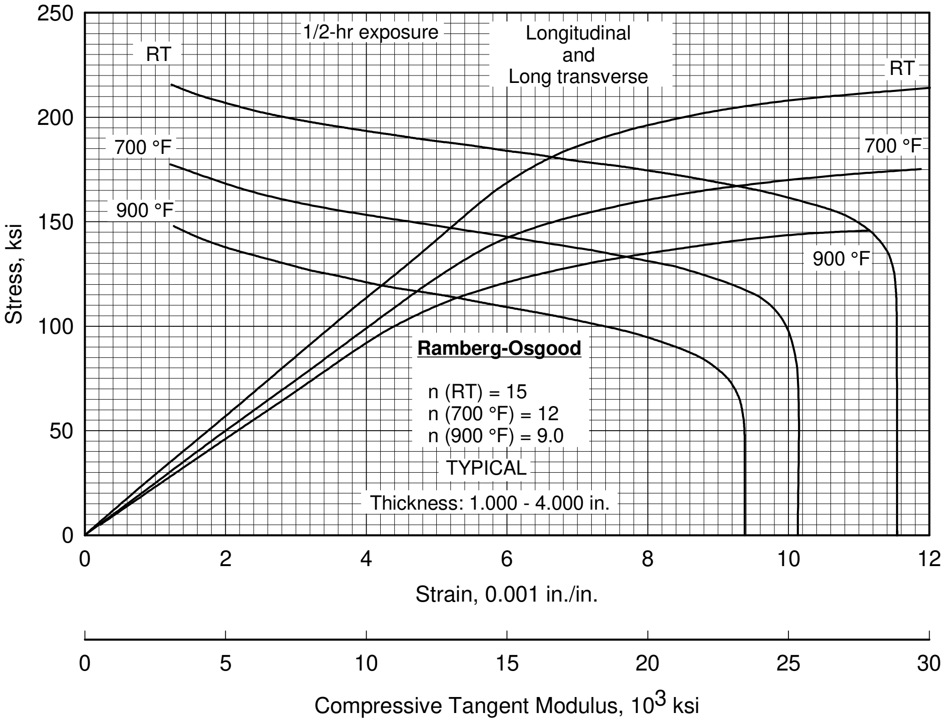


Figure 2.4.2.1.6(b). Typical compressive stress-strain and compressive tangent-modulus curves for 9Ni-4Co-0.20C steel plate at various temperatures.

2.4.3 9Ni-4Co-0.30C

2.4.3.0 *Comments and Properties* — The 9Ni-4Co-0.30C alloy was developed specifically to have high hardenability and good fracture toughness when heat treated to 220 to 240 ksi ultimate tensile strength. The alloy is through hardening in section sizes up to 4 inches thick. The alloy may be exposed to temperatures up to 900°F (approximately 100°F below typical tempering temperature) without microstructural changes which degrade room temperature strength. This grade must be formed and welded in the annealed condition. Preheat and post-heat of the weldment is required. The steel is produced by consumable electrode vacuum melting.

The heat treatment for this alloy consists of normalizing at 1650 ± 25°F for 1 hour per inch of cross section, cooling in air to room temperature, heating to 1550 ± 25°F for 1 hour per inch of cross section but not less than 1 hour, quenching in oil or water, subzero treating at -100°F for 1 to 2 hours, and double tempering at 975 ± 10°F (sheet, strip, and plate) or 1000 ± 10°F (bars, forgings, and tubings) for 2 hours.

Material specifications for 9Ni-4Co-0.30C steel are presented in Table 2.4.3.0(a). The room temperature mechanical and physical properties are shown in Table 2.3.4.0(b). The effect of temperature on thermal expansion is shown in Figure 2.4.3.0.

Table 2.4.3.0(a). Material Specifications for 9Ni-4Co-0.30C Steel

Specification	Form
AMS 6524[a]	Sheet, strip, and plate
AMS 6526	Bar, forging, and tubing

a Noncurrent specification.

2.4.3.1 *Heat-Treated Condition* — Effect of temperature on various mechanical properties is presented in Figures 2.4.3.1.1. through 2.4.3.1.4. Typical stress-strain and tangent-modulus curves are presented in Figures 2.4.3.1.6(a) through (d). Notched fatigue data at room temperature are illustrated in Figure 2.4.3.1.8.

Table 2.4.3.0(b). Design Mechanical and Physical Properties of 9Ni-4Co-0.30C Steel

Specification	AMS 6524[a]		AMS 6526
Form	Sheet, strip, and plate		Bar, forging, and tubing
Condition	Quenched and tempered		Quenched and tempered
Thickness, in.	≤0.249	≥0.250	≤4.000
Basis	S[b]	S[b]	S[b]
Mechanical Properties:			
F_{tu}, ksi:			
L	...	...	220
LT	220	220	...
F_{ty}, ksi:			
L	...	...	190
LT	185	190	...
F_{cy}, ksi:			
L	...	...	209
LT	...	209	...
F_{su}, ksi	...	137	137
F_{bru}[c], ksi:			
(e/D = 1.5)	...	346	346
(e/D = 2.0)	...	440	440
F_{bry}[c], ksi:			
(e/D = 1.5)	...	291	291
(e/D = 2.0)	...	322	322
e, percent:			
L	...	...	10
LT	6	10	...
RA, percent:			
L	...	...	40
LT	...	35	...
E, 10^3 ksi	28.5		
E_c, 10^3 ksi	29.8		
G, 10^3 ksi	...		
μ	...		
Physical Properties:			
ω, lb/in.^{3}	0.28		
C, Btu/(lb)(°F)	...		
K, Btu/[(hr)(ft^2)(°F)/ft]	13.3 (75°F)		
α, 10^{-6} in./in./°F	See Figure 2.4.3.0		

a Noncurrent specification.

b Design values are applicable only to parts for which the indicated F_{tu} has been substantiated by adequate quality control testing.

c Bearing values are "dry pin" values per Section 1.4.7.1.

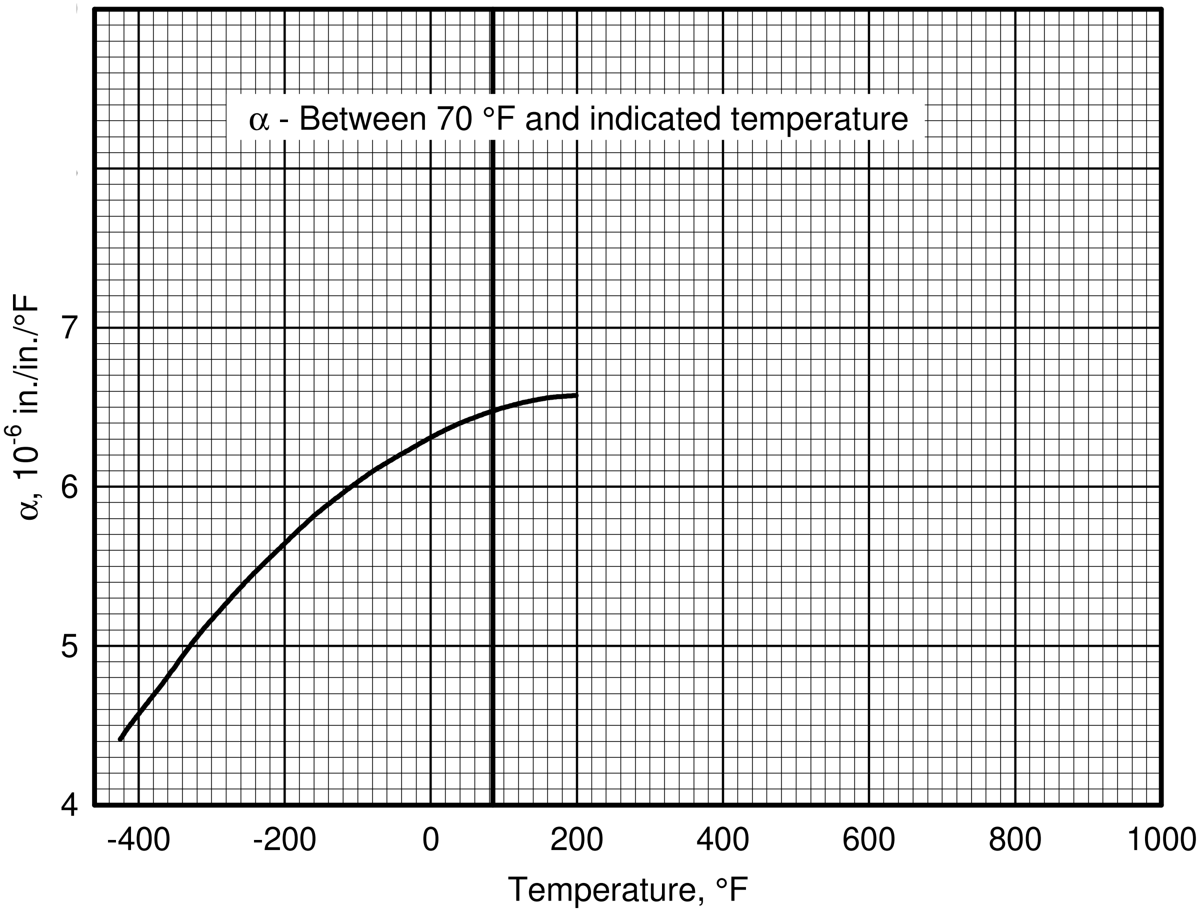


Figure 2.4.3.0. Effect of temperature on the thermal expansion of 9Ni-4Co-0.30C steel.

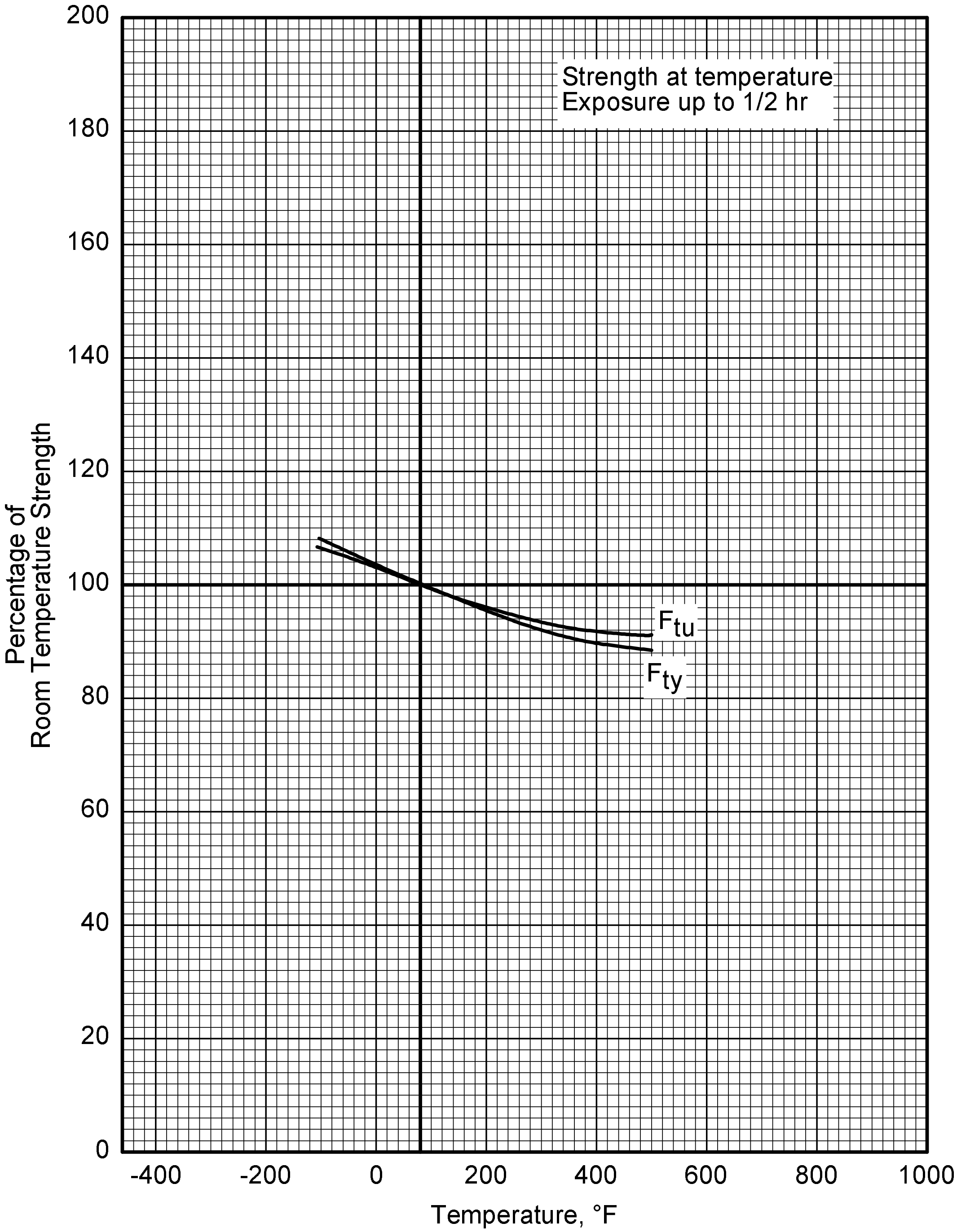


Figure 2.4.3.1.1. Effect of temperature on the tensile yield strength (F_{ty}) and the tensile ultimate strength of 9Ni-4Co-0.30C steel hand forging.

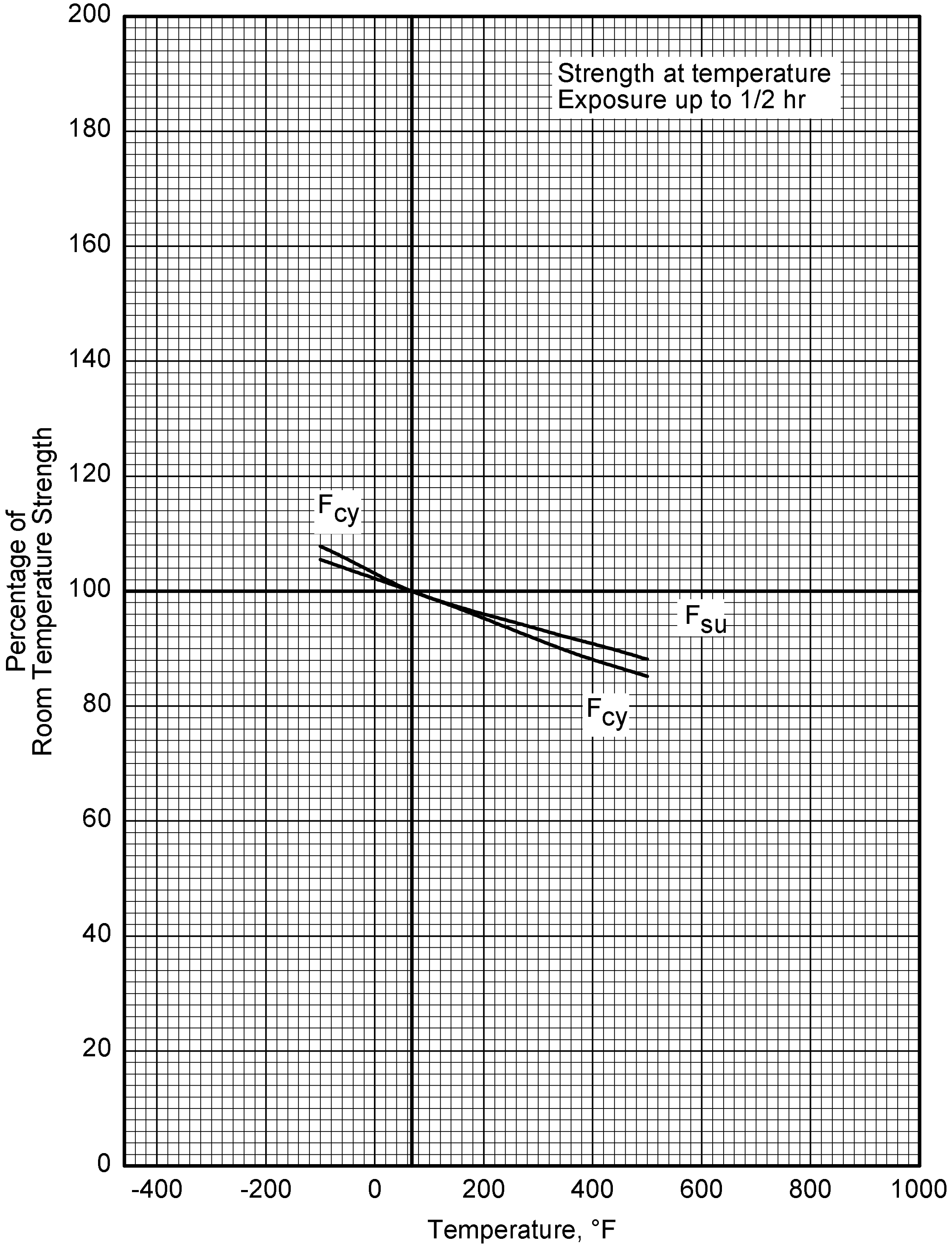


Figure 2.4.3.1.2. Effect of temperature on the compressive yield strength (F_{cy}) and the shear ultimate strength (F_{su}) of 9Ni-4Co-0.30C steel hand forging.

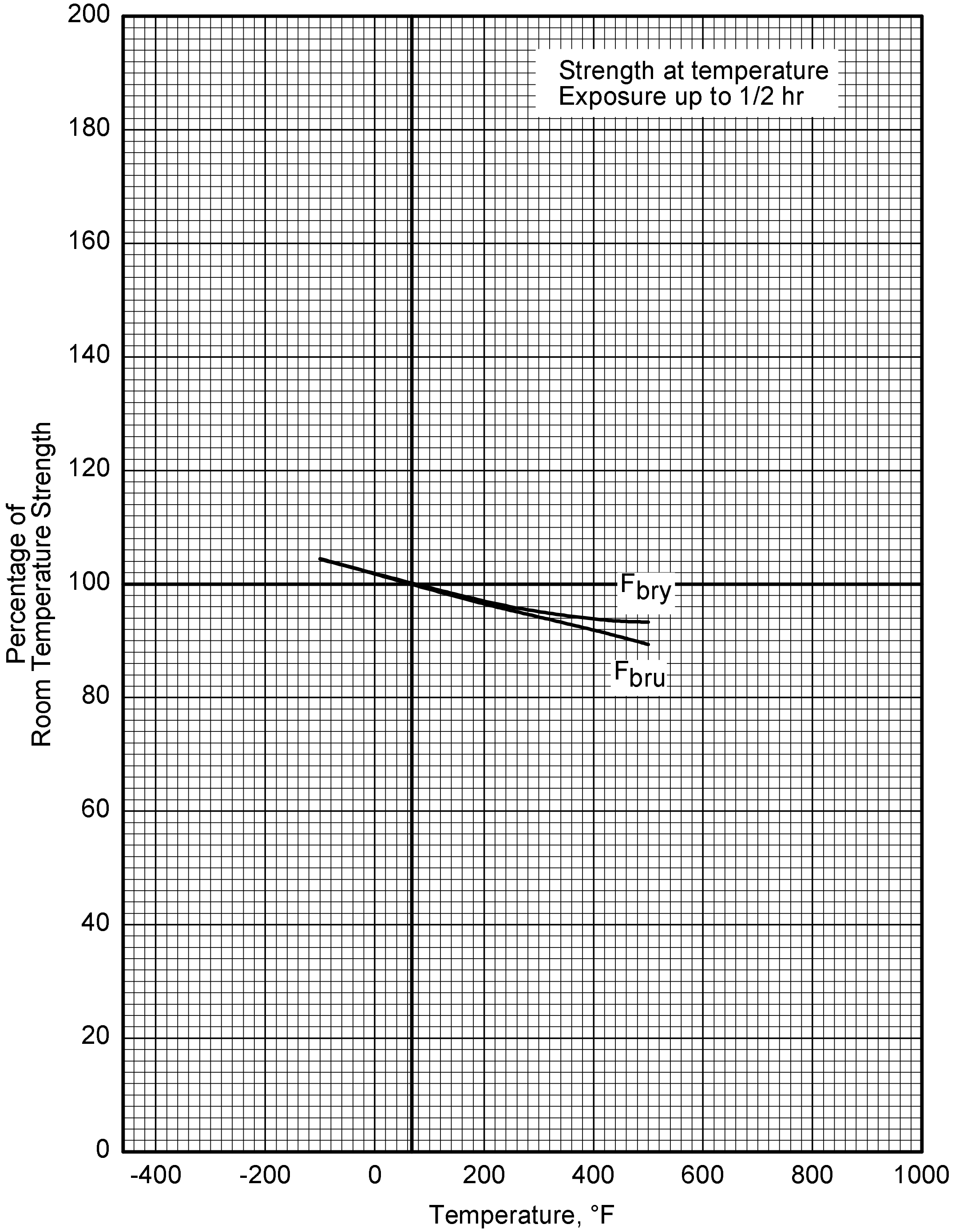


Figure 2.4.3.1.3. Effect of temperature on the bearing ultimate strength (F_{bru}) and the bearing yield strength (F_{bry}) of 9Ni-4Co-0.30C steel hand forging.

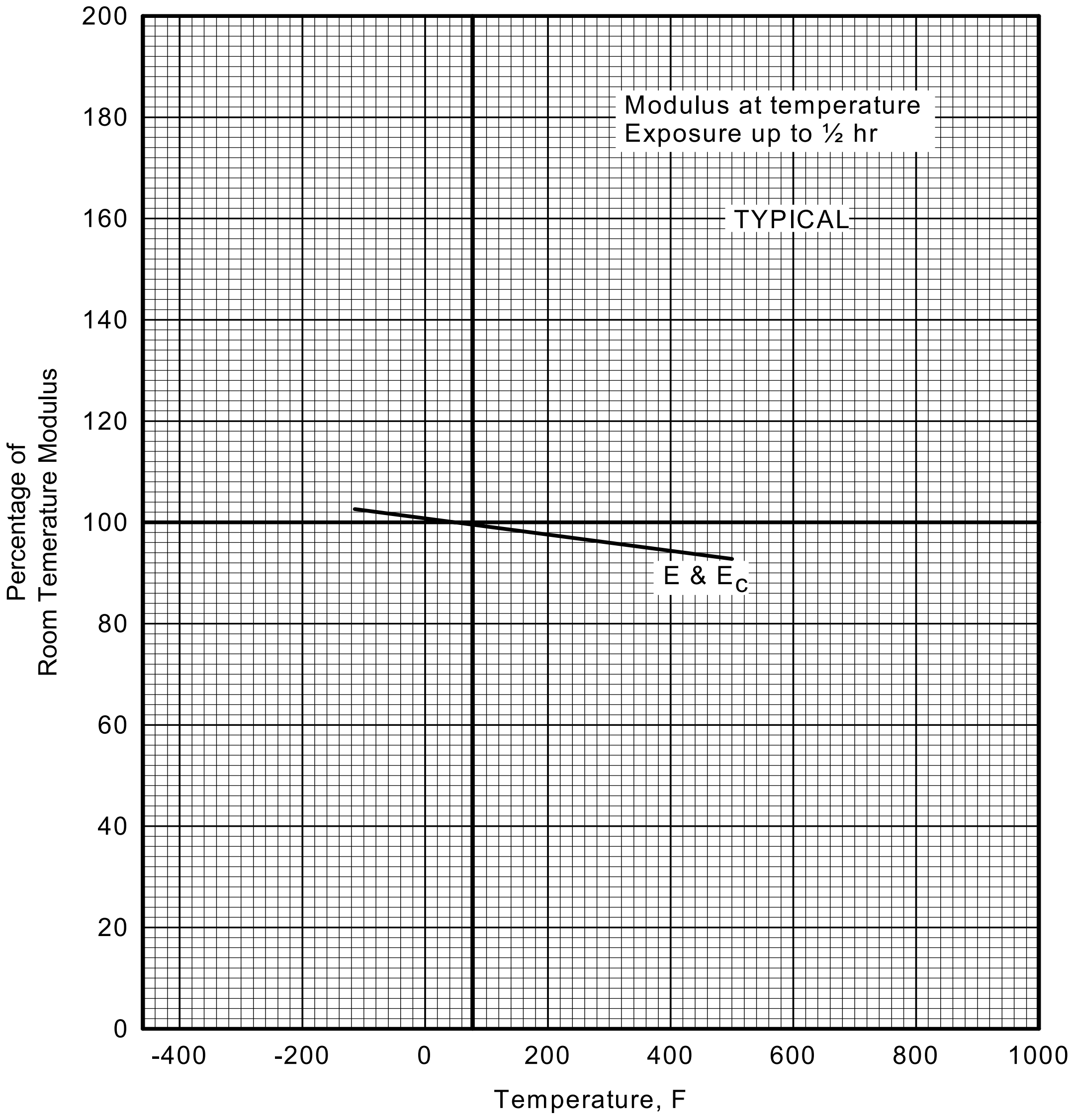


Figure 2.4.3.1.4 Effect of temperature on the tensile and compressive moduli (E and E_c) of 9Ni-4Co-0.30C steel.

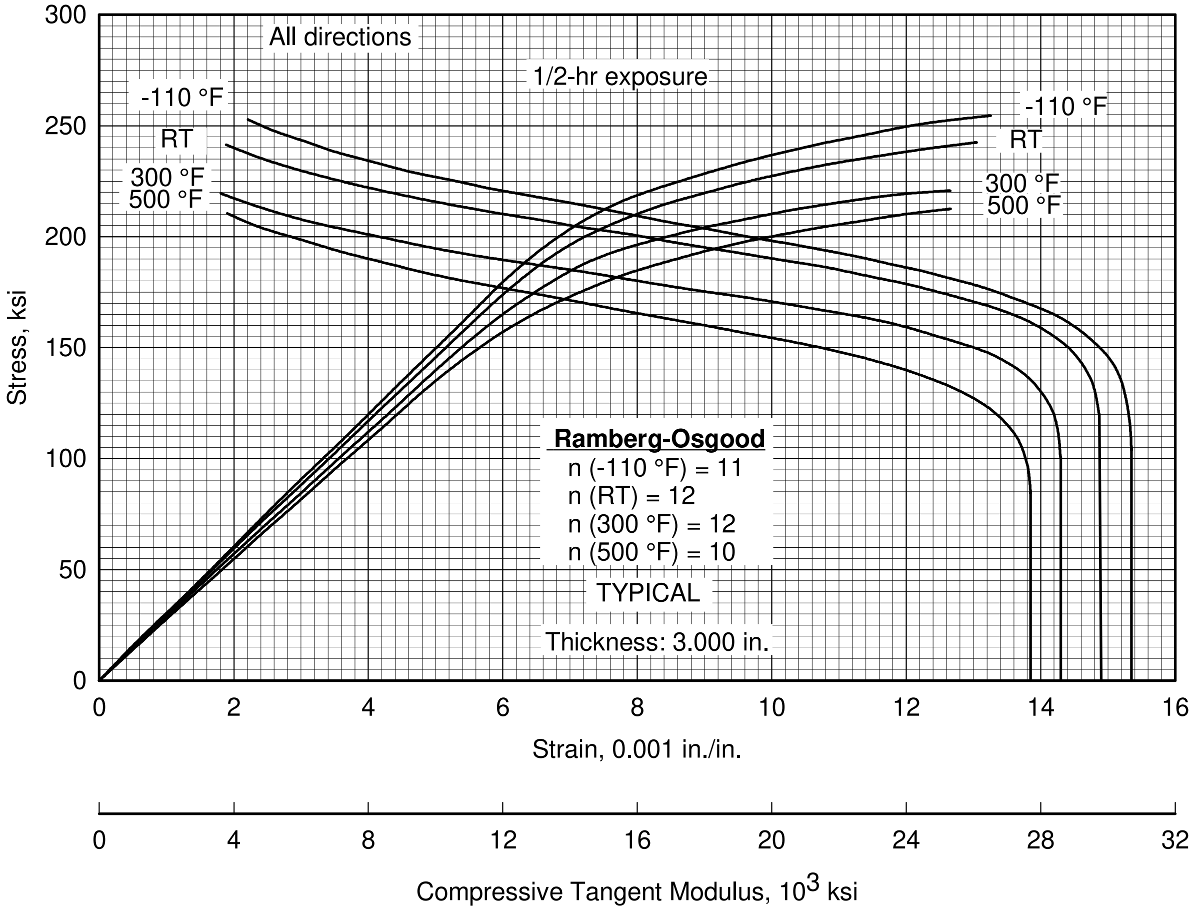


Figure 2.4.3.1.6(a). Typical compressive stress-strain and compressive tangent-modulus curves for 9Ni-4Co-0.30C steel hand forging at various temperatures.

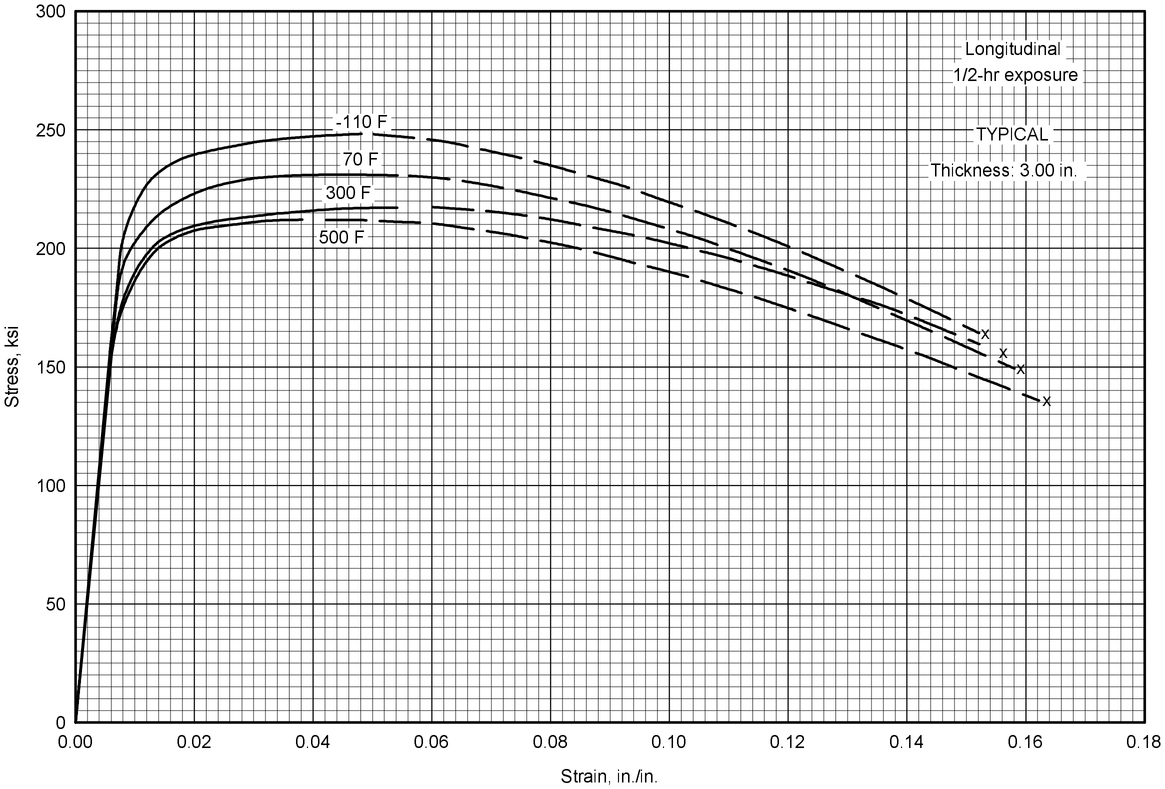


Figure 2.4.3.1.6(b). Typical tensile stress-strain curves (full range) for 9Ni-4Co-0.30C hand forging at various temperatures.

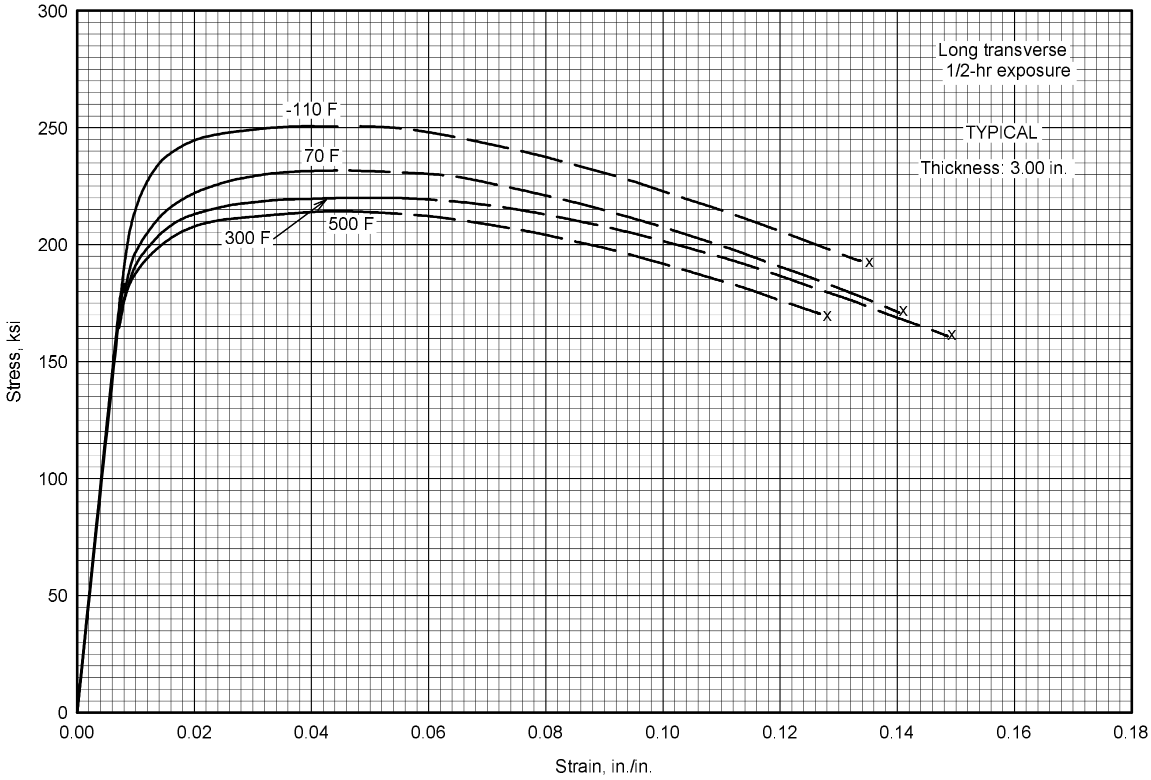


Figure 2.4.3.1.6(c). Typical tensile stress-strain curves (full range) for 9Ni-4Co-0.30C hand forging at various temperatures.

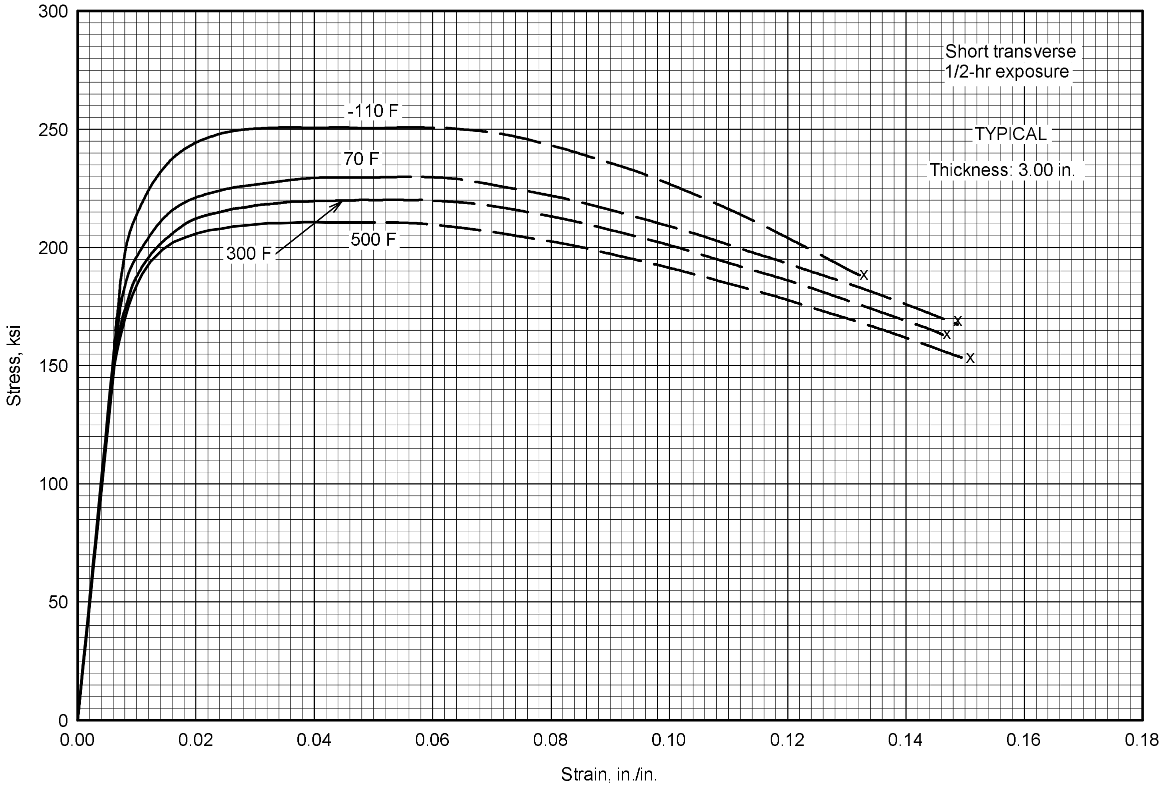
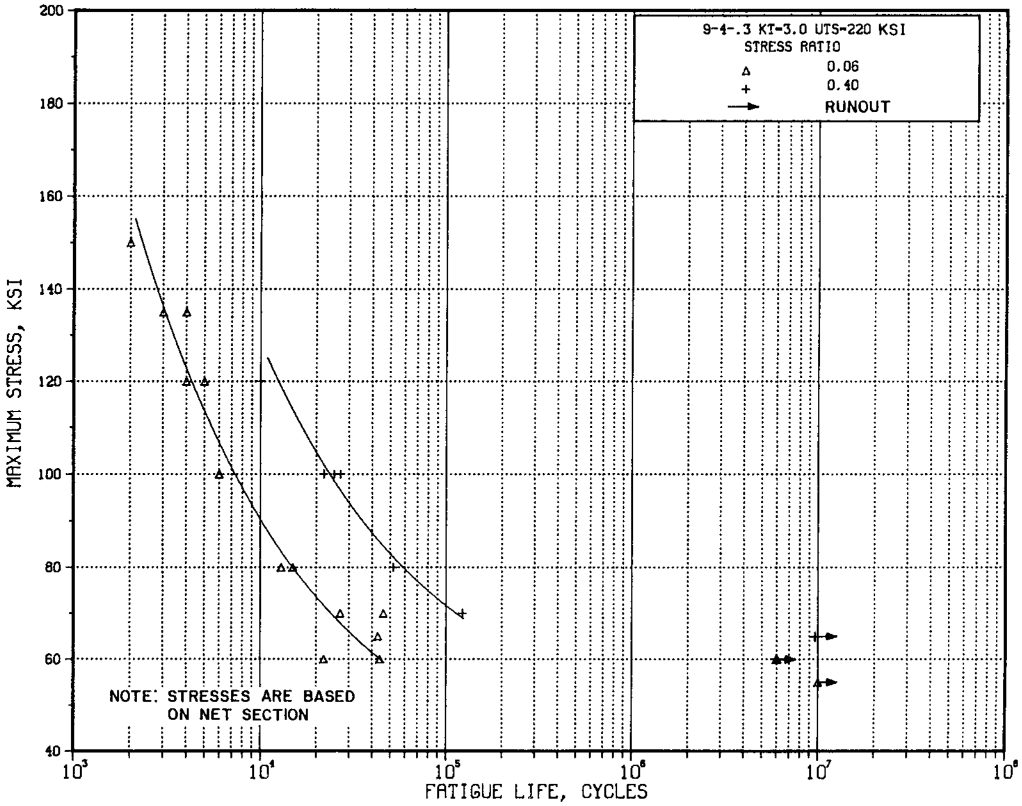


Figure 2.4.3.1.6(d). Typical tensile stress-strain curves (full range) for 9Ni-4Co-0.30C hand forging at various temperatures.



NOTE: STRESSES ARE BASED ON NET SECTION

Figure 2.4.3.1.8. Best-fit S/N curves for notched, K_t = 3.0, 9Ni-4Co-0.30C steel hand forging, long and short transverse directions.

Correlative Information for Figure 2.4.3.1.8

Product Form: Hand forging, 3 x 9 inches

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	231	197	RT (LT)

Specimen Details: Notched, V-Groove K_t=3.0
0.354 inch gross diameter
0.250 inch net diameter
0.01 inch root radius
60° flank angle, ω

Surface Condition: Not specified

Reference: 2.4.3.1.8

Test Parameters:
Loading - Axial
Frequency - 1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 3

Equivalent Stress Equation:
$\text{Log } N_f = 7.77 - 2.15 \log (S_{eq} - 28.32)$
$S_{eq} = S_{max} (1-R)^{0.79}$
Std. Error of Estimate, Log (Life) = 0.12
Standard Deviation, Log (Life) = 0.47
R^2 = 93%

Sample Size = 22

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

2.5 HIGH-ALLOY STEELS

2.5.0 COMMENTS ON HIGH-ALLOY STEELS — The high-alloy steels in this section are those steels that are substantially higher in alloy content than the intermediate alloy steels described in Section 2.4 but are not stainless steels. The 18 Ni maraging and AF1410 steels are in this category.

2.5.0.1 Metallurgical Considerations — The 18 Ni maraging steels are iron base alloys with nominally 18 percent nickel, 7 to 9 percent cobalt, 3 to 5 percent molybdenum, less than 1 percent titanium, and very low carbon content, below 0.03 percent. Upon cooling from the annealing or hot-working temperature, these steels transform to a soft martensite which can be easily machined or formed. The steels can be subsequently aged (maraged) to high strengths by heating to a lower temperature, 900°F.

AF1410 is an iron base alloy with nominally 14 percent cobalt, 10 percent nickel, 2 percent chromium, 1 percent molybdenum, and 0.15 percent carbon. When quenched from austenitizing temperatures, AF1410 forms a highly dislocated lath martensitic structure with very little twinning or retained austenite. At aging temperatures ranging from 900 to 1000°F, a precipitation of extremely fine alloy carbide containing chromium and molybdenum occurs, which simultaneously develops strength and toughness properties.

2.5.0.2 Environmental Considerations — The stress corrosion cracking resistance of high strength steels is of concern for highly loaded structural components such as landing gears and wing attach fittings that are subjected to corrosive environments such as sea spray or water. Figure 2.5.0.2(a) indicates the relative stress corrosion cracking resistance of several high-strength steel alloys. The data in this figure were obtained from Reference (2.5.0.2). The stress corrosion cracking threshold stress intensity (K_{Issc}) for each steel was defined as the value at which cracking did not occur. For most of these alloys, this value is about 20 ksi$\sqrt{\text{in}}$. As indicated, there is a definite difference in the stress corrosion resistance between the alloys.

In general, the high-strength steels do not reach a true threshold stress intensity until after 1000 hours of exposure. The highest stress corrosion cracking resistance in high-strength steels is associated with low carbon levels and lath martensite microstructure containing a fine distribution of M_2C type carbides; alloys AF1410 and AerMet 100. The effect of low carbon is indicated between the AF1410 and 0.20AF1410 where the carbon levels are 0.15 and 0.20%, respectively. The lower stress cracking corrosion resistance is associated with higher carbon and the martensite is of plate morphology that exhibits a twinned structure; alloys 4340 and 300M. A slight anisotropic effect was observed for Hy-Tuf (TL vs LT); however, the effect was not apparent for AF1410. The differences in anisotropic properties may be due to differences in the cleanliness of the steels since Hy-Tuf was an air melted product and the others were either vacuum induction melted (VIM) or electroslag remelted (ESR).

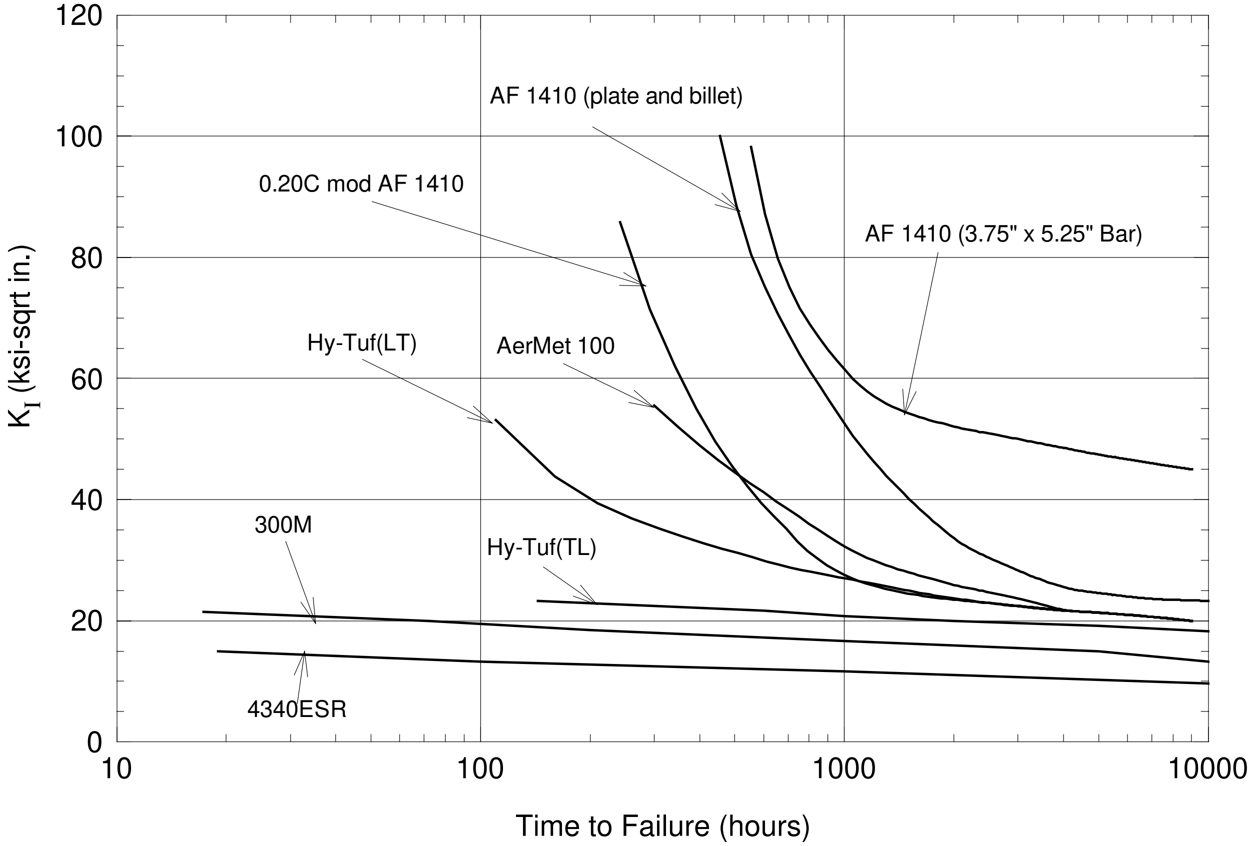


Figure 2.5.0.2(a). The relative stress corrosion cracking resistance of several high-strength steels tested in an environment of 3.5% NaCl (Reference 2.5.0.2).

2.5.1 18 NI MARAGING STEELS

2.5.1.0 *Comments and Properties* — The 250 and 280 (300) maraging steels are normally supplied in the annealed condition and are heat treated to high strengths, without quenching, by aging at 900°F. The steels are characterized by high hardenability and high strength combined with good toughness. The 250 and 280 (300) designation refers to the nominal yield strengths of the two alloys. The two alloys are available in the form of sheet, plate, bar, and die forgings. Only the consumable electrode-vacuum-melted quality grades are considered in this section.

Manufacturing Considerations — The 250 and 280 grades are readily hot worked by conventional rolling and forging operations. These grades also have good cold forming characteristics in spite of the relatively high hardness in the annealed (martensitic) condition. The machinability of the 250 and 280 grades is not unlike 4330 steel at equivalent hardness. The 18 Ni maraging steels can be readily welded in either the annealed or aged conditions without preheating. Welding of aged material should be followed by aging at 900°F to strengthen the weld area.

Environmental Considerations — Although the 18 Ni maraging steels are high in alloy content, these grades are not corrosion resistant. Since the general corrosion resistance is similar to the low-alloy steels, these steels require protective coatings. The 250 grade reportedly has better resistance to stress corrosion cracking than the low-alloy steels at the same strength.

Specifications and Properties — Material specifications for these steels are shown in Table 2.5.1.0(a). The room temperature properties for material aged at 900°F are shown in Tables 2.5.1.0(b) and (c), and the effect of temperature on physical properties is shown in Figure 2.5.1.0.

Table 2.5.1.0(a). Material Specifications for 18 Ni Maraging Steels

Grade	Specification	Form
250	AMS 6520	Sheet and plate
250	AMS 6512	Bar
280 (300)	AMS 6521[a]	Sheet and plate
280 (300)	AMS 6514	Bar

[a] Noncurrent specification.

2.5.1.1 *Maraged Condition (aged at 900 ° F)* — Effect of temperature on 250 and 280 grade maraging steel is presented in Figures 2.5.1.1.1 through 2.5.1.1.4. Figures 2.5.1.1.6(a) and (b) are room and elevated temperature tensile stress-strain curves. Typical compressive stress-strain and tangent-modulus curves at room temperature are presented in Figures 2.5.1.1.6(c) and (d). Figure 2.5.1.1.6(e) is a full-range stress-strain curve at room temperature for 280 grade maraging steel.

Table 2.5.1.0(b). Design Mechanical and Physical Properties of 250 Maraging Steel

Specification	AMS 6520			AMS 6512	
Form	Sheet	Plate		Bar	
Condition	Maraged at 900°F			Maraged at 900°F	
Thickness or diameter, in.	≤0.187	0.187-0.250	>0.250	<4.000	4.000-10.000
Basis	S	S	S	S	S
Mechanical Properties:					
F_{tu} ksi:					
L	247	252	...	255	245
T	255	255	255	255	245
F_{ty}, ksi:					
L	238	242	...	250	240
T	245	245	245	250	240
F_{cy}, ksi:					
L	221	...	...	260	...
T	225	255	...	...	...
F_{su}, ksi	148	155	...	148	...
F_{bru}, ksi:					
(e/D = 1.5)	327	352	...	...	...
(e/D = 2.0)	444	448	...	...	...
F_{bry}, ksi:					
(e/D = 1.5)	278	324	...	...	...
(e/D = 2.0)	353	354	...	...	...
e, percent:					
L	...[a]	...[a]	...[a]	6	5
T				4	3
RA, percent:					
L	...	...	...	45	30
T	...	...	...	35	20
E, 10^3 ksi	26.5				
E_c, 10^3 ksi:					
L	28.2				
T	29.4				
G, 10^3 ksi	...				
μ	0.31				
Physical Properties:					
ω, lb/in.^{3}	0.286				
C, K, and α	See Figure 2.5.1.0				

[a] Elongation properties vary with thickness as follows:

≤0.090	2.5%
0.091-0.125	3.0%
0.126-0.250	4.0%
0.251-0.375	5.0%
≥0.376	6.0%

Table 2.5.1.0(c). Design Mechanical and Physical Properties of 280 Maraging Steel

Specification	AMS 6521[a]			AMS 6514	
Form	Sheet	Plate		Bar	
Condition	Maraged at 900°F			Maraged at 900°F	
Thickness or diameter, in.	≤0.187	0.188-0.250	>0.250	<4.000	4.000-10.000
Basis	S	S	S	S	S
Mechanical Properties:					
F_{tu} ksi:					
L	271	276	...	280	275
T	280	280	280	280	275
F_{ty}, ksi:					
L	262	267	...	270	270
T	270	270	270	270	270
F_{cy}, ksi:					
L	244	...	...	281	...
T	248	281	...	...	...
F_{su}, ksi	163	170	...	162	...
F_{bru}, ksi:					
(e/D = 1.5)	359	386	...	...	...
(e/D = 2.0)	487	492	...	...	...
F_{bry}, ksi:					
(e/D = 1.5)	306	357	...	...	...
(e/D = 2.0)	389	390	...	...	...
e, percent:					
L	...[b]	...[b]	...[b]	5	4
T				4	2
RA, percent:					
L	...	...	...	30	25
T	...	...	...	25	20
$E, 10^3$ ksi	26.5				
E_c, 10^3 ksi:					
L	28.6				
T	29.6				
G, 10^3 ksi	...				
μ	0.31				
Physical Properties:					
ω, lb/in.^{3}	0.286				
C, *K*, and *α*	See Figure 2.5.1.0				

a Noncurrent specification.

b Elongation properties vary with thickness as follows:

≤0.090	2.5%
0.091-0.125	3.0%
0.126-0.250	4.0%
0.251-0.375	5.0%
≥0.376	6.0%

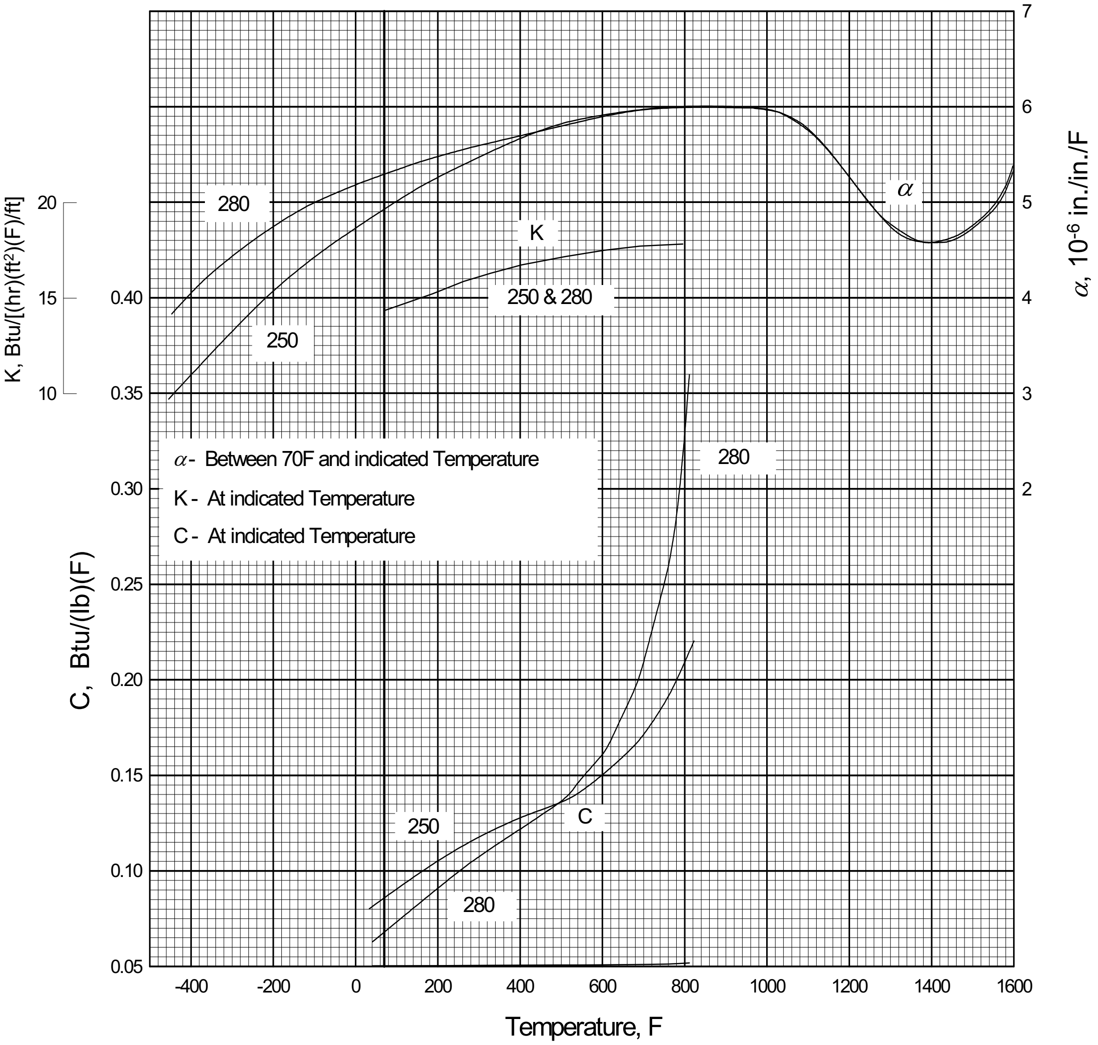


Figure 2.5.1.0. Effect of temperature on the physical properties of 250 and 280 maraging steels.

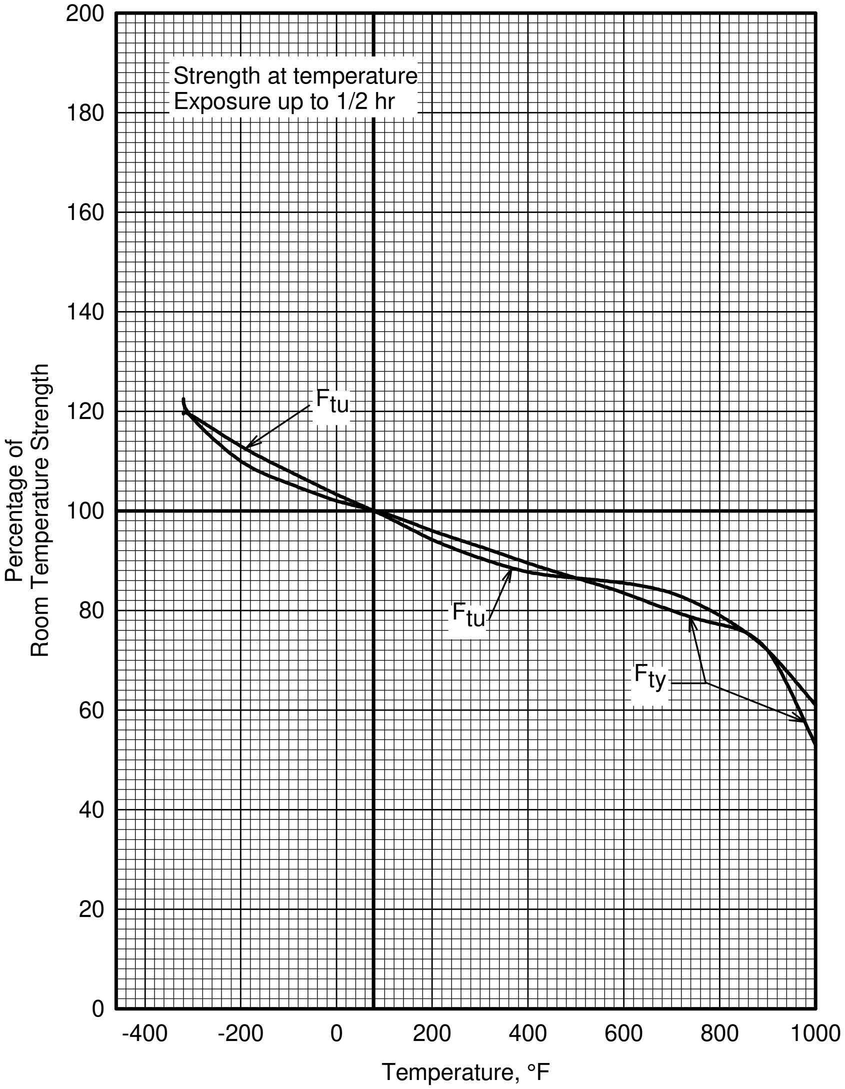


Figure 2.5.1.1.1. Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of 250 and 280 maraging steel sheet and plate.

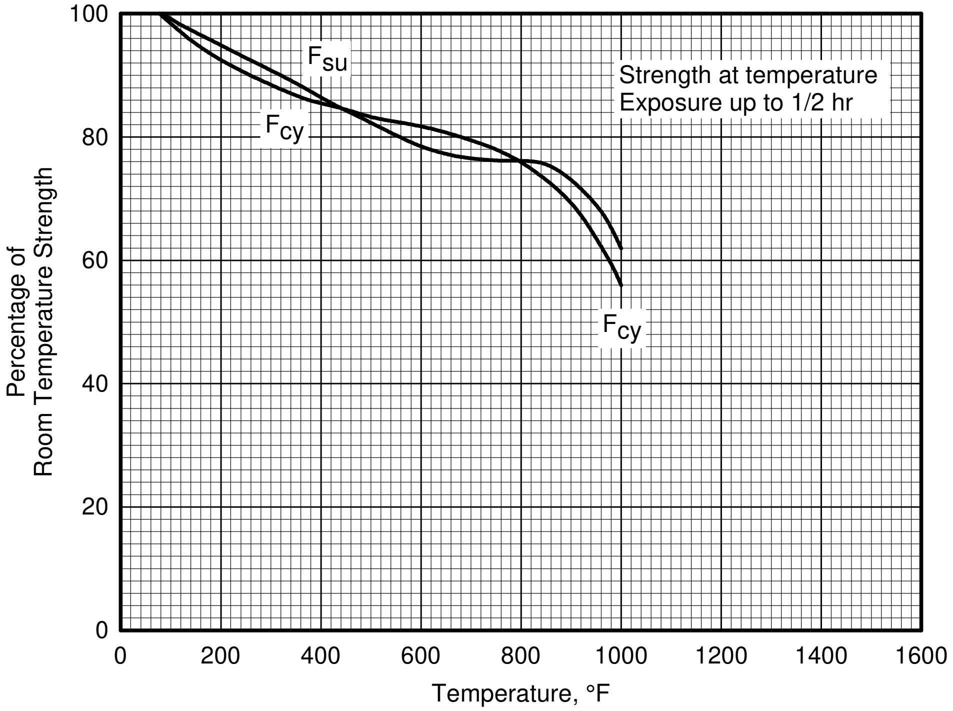


Figure 2.5.1.1.2. Effect of temperature on the compressive yield strength (F_{cy}) and the shear ultimate strength (F_{su}) of 250 and 280 maraging steel sheet and plate.

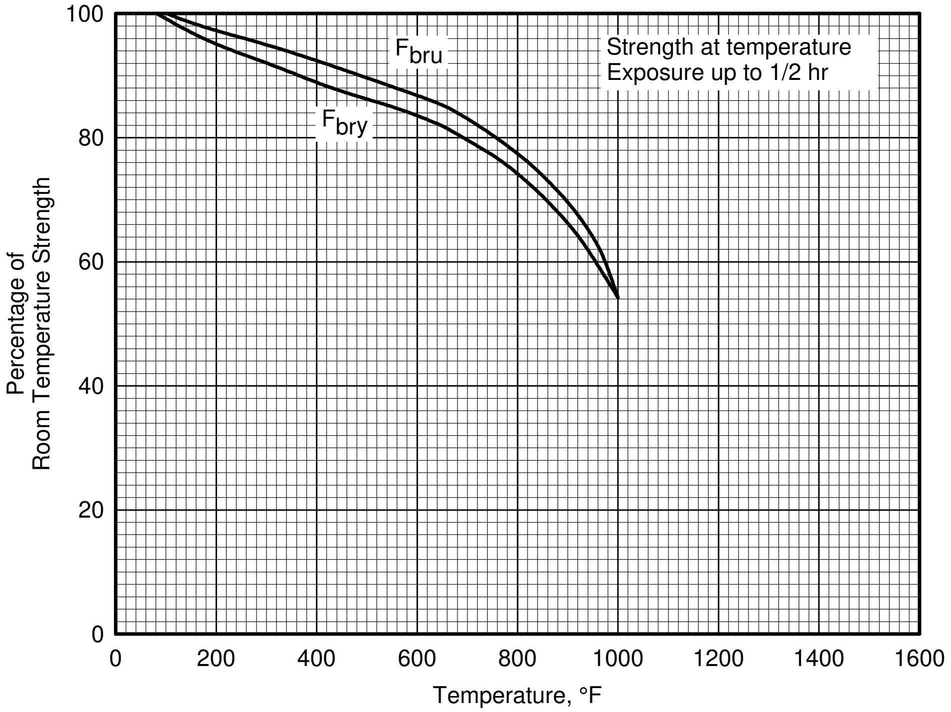


Figure 2.5.1.1.3. Effect of temperature on the bearing ultimate strength (F_{bru}) and the bearing yield strength (F_{bry}) of 250 and 280 maraging steel sheet and plate.

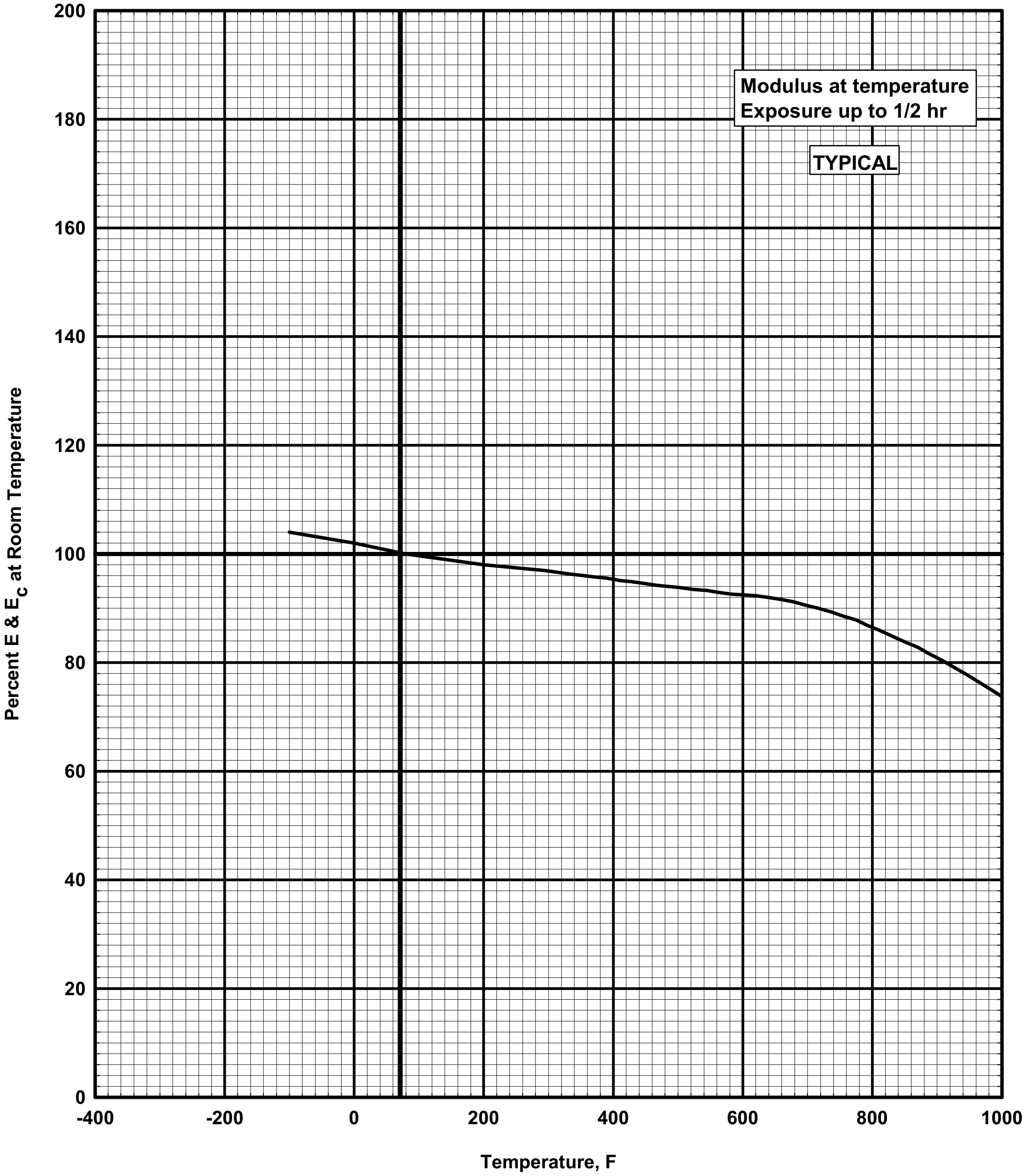


Figure 2.5.1.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of 250 and 280 maraging steel.

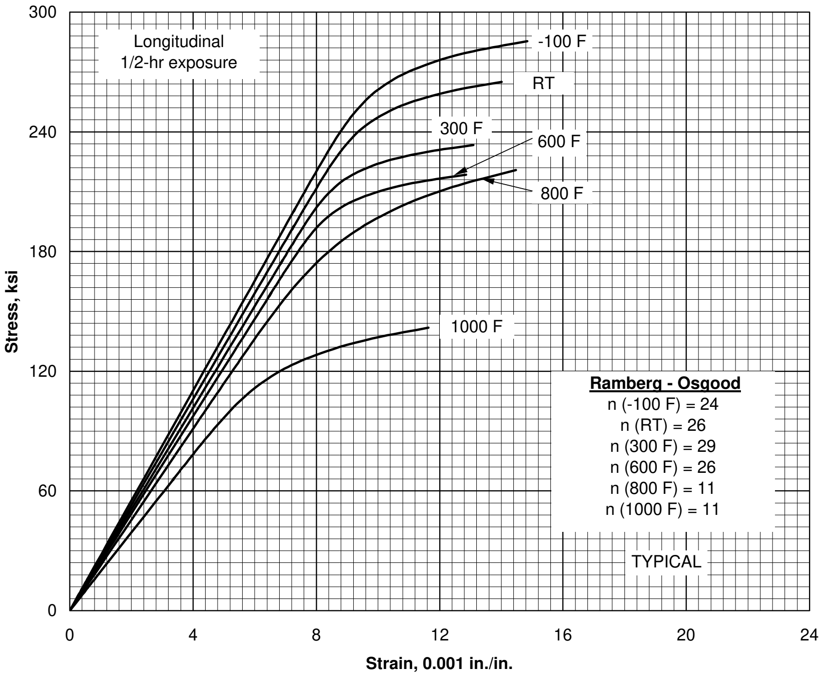


Figure 2.5.1.1.6(a). Typical tensile stress-strain curves at room and elevated temperatures for 250 maraging steel bar.

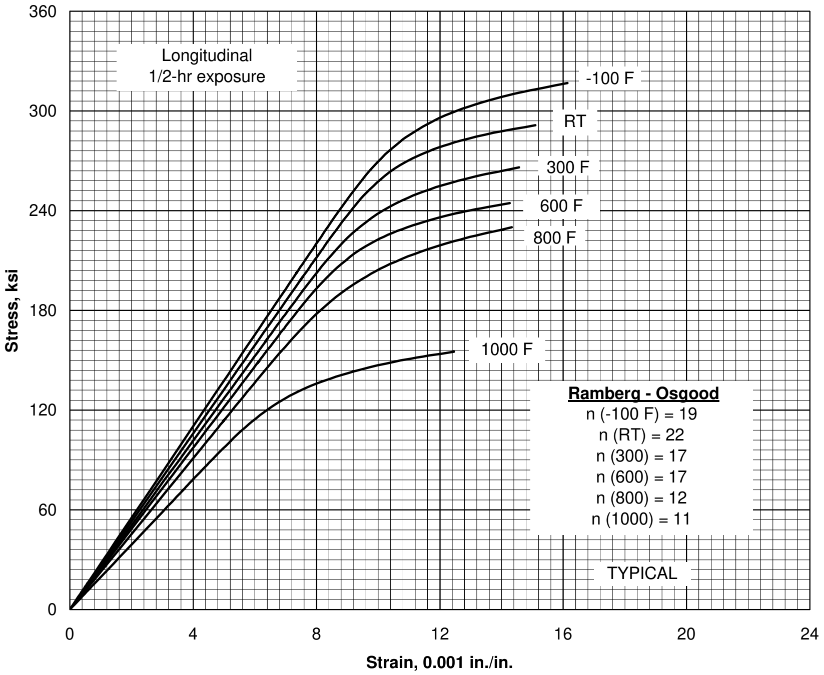


Figure 2.5.1.1.6(b). Typical tensile stress-strain curves at room and elevated temperatures for 280 maraging steel bar.

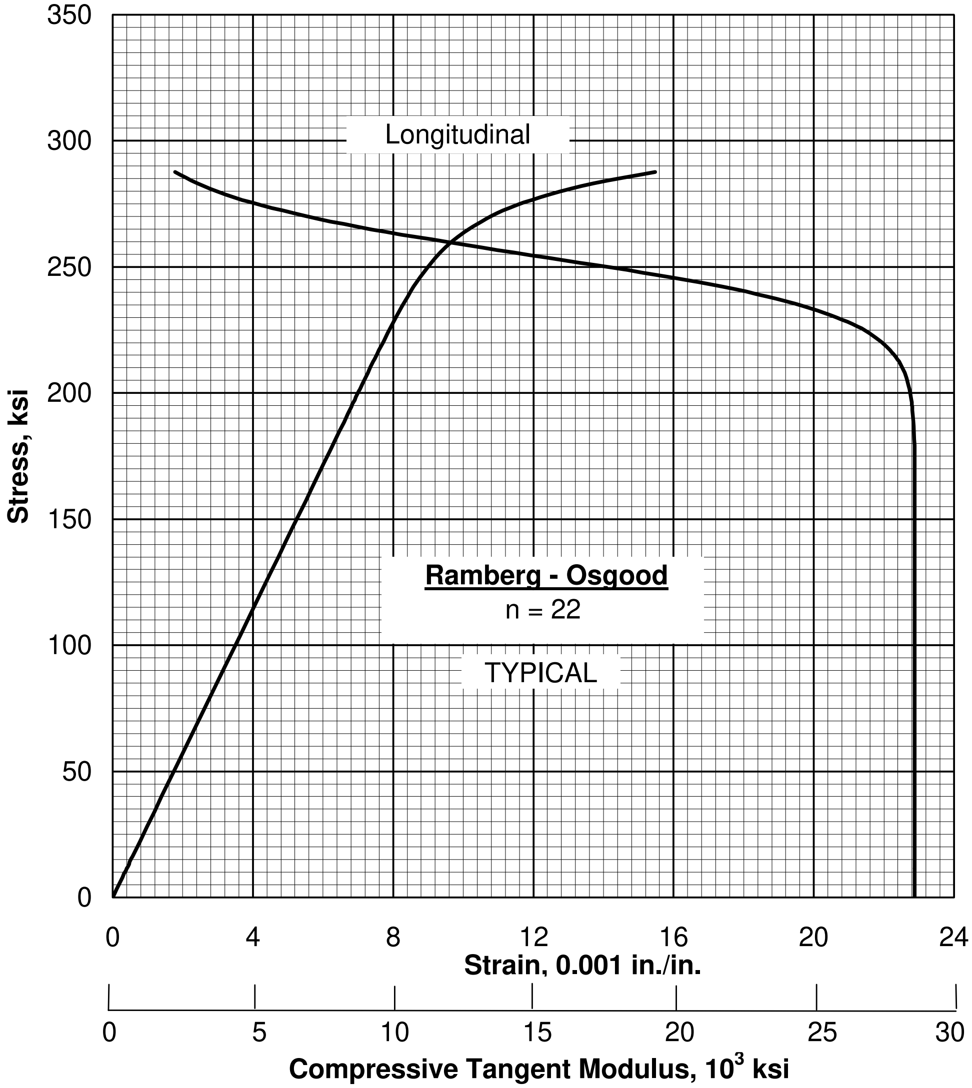


Figure 2.5.1.1.6(c). Typical compressive stress-strain and compressive tangent-modulus curves for 250 maraging steel bar at room temperature.

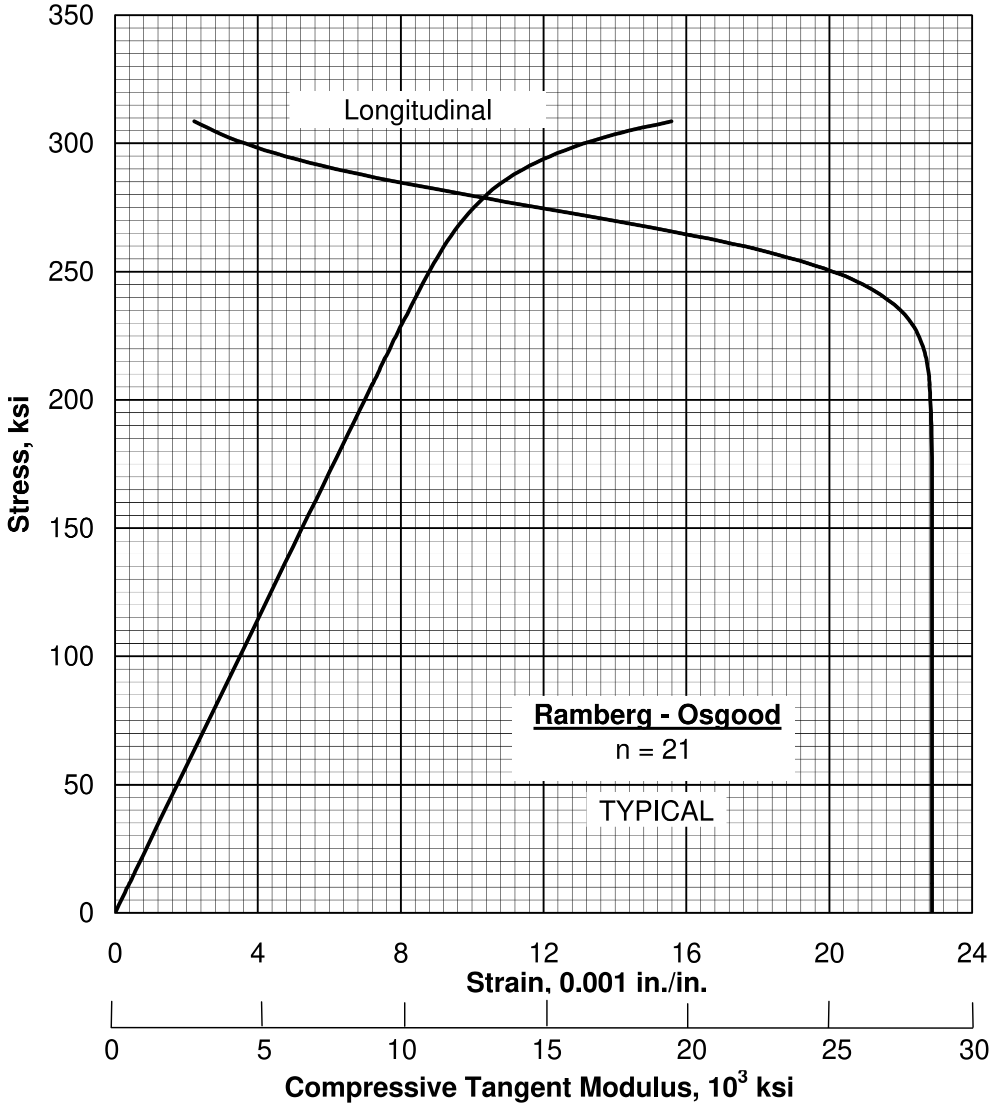


Figure 2.5.1.1.6(d). Typical compressive stress-strain and compressive tangent-modulus curves for 280 maraging steel bar at room temperature.

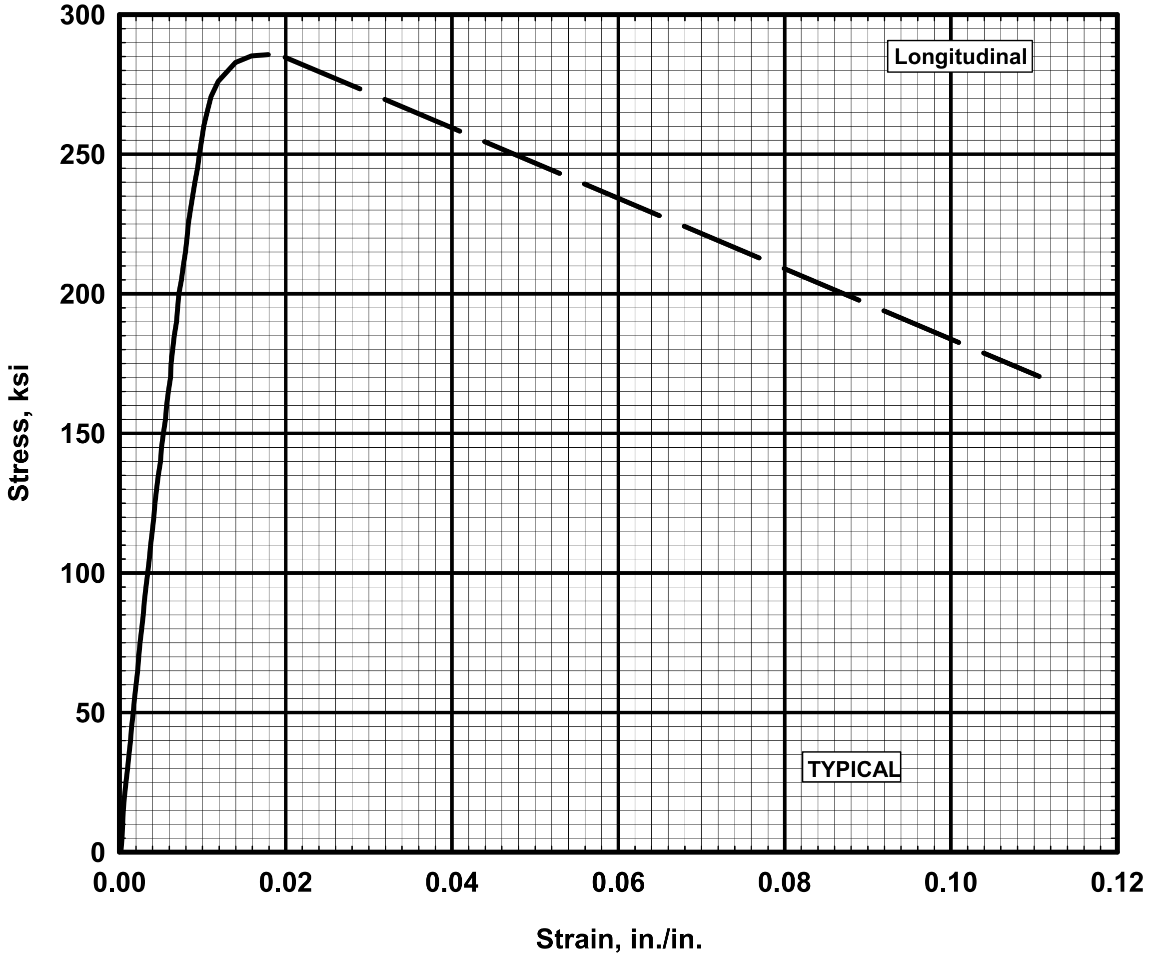


Figure 2.5.1.1.6(e). Typical tensile stress-strain curve (full range) for 280 maraging steel bar at room temperature.

2.5.2 AF1410

2.5.2.0 *Comments and Properties* — AF1410 alloy was developed specifically to have high strength, excellent fracture toughness, and excellent weldability when heat treated to 235 to 255 ksi ultimate tensile strength. AF1410 has good weldability and does not require preheating prior to welding. The alloy maintains good toughness at cryogenic temperatures, as well as high strength and stability at temperatures up to 800°F. The alloy is available in a wide variety of sizes and forms, including billet, bar, plate, and die forgings. The alloy is produced by vacuum induction melting followed by vacuum remelting.

Heat Treatment — The heat treatment for this alloy consists of heating to 1650 ± 25°F for 1 hour, forced-air cooling to room temperature, reheating to 1525 ± 25°F for 1 hour, forced-air cooling to room temperature, cooling to -100 ± 15°F, holding at temperature for 1 hour, warming to room temperature, and aging at 950 ± 10°F for 5 hours, and air cooling. A forced-air cool from austenitizing temperatures should be used for section thicknesses up to 2 inches. For sections of greater thickness, an oil quench should be utilized. A single austenitizing treatment (1525 ± 25°F) can be used to minimize heat treating distortion with a resulting slight decrease in fracture toughness.

Environmental Considerations — AF1410 has general corrosion resistance similar to the maraging steels. It should not be used in the unprotected condition. The alloy is highly resistant to stress-corrosion cracking compared to other high-strength steels.

Specification and Properties — A material specification for AF1410 is presented in Table 2.5.2.0(a). Room temperature mechanical properties are shown in Table 2.5.2.0(b).

Table 2.5.2.0(a). Material Specification for AF1410 Steel

Specification	Form
AMS 6527	Bar and forging

2.5.2.1 *Heat-Treated Condition* — Typical stress-strain curves at room temperature are shown in Figures 2.5.2.1.6(a) and (b).

Table 2.5.2.0(b). Design Mechanical and Physical Properties of AF1410 Steel Bar

Specification	AMS 6527
Form	Bar
Condition	[a]
Cross-sectional area, sq. in.	≤100[b]
Thickness or diameter, in.	≤4.25[b]
Basis	S
Mechanical Properties:	
F_{tu}, ksi:	
L	235
LT[c]	235
ST[c]	235
F_{ty}, ksi:	
L	215
LT[c]	215
ST[c]	215
F_{cy}, ksi:	
L	223
ST[c]	225
F_{su}, ksi	141
F_{bru}, ksi:	
(e/D = 1.5)	334
(e/D = 2.0)	435
F_{bry}, ksi:	
(e/D = 1.5)	269
(e/D = 2.0)	300
e, percent:	
L	12
LT[c]	12
ST[c]	12
RA, percent:	
L	60
LT[c]	55
ST[c]	55
E, 10^3 ksi	29.4
E_c, 10^3 ksi	30.9
G, 10^3 ksi	...
μ	...
Physical Properties:	
ω, lb/in.^{3}	0.283
C, K, and α	...

[a] Heat at 1650 ± 25°F for one hour, forced-air cool to room temperature, heat at 1525 ± 25°F for one hour, forced-air cool to room temperature, cool at -100 ± 15°F for one hour, age at 950 ± 10°F for 5 hours, and air cool.

[b] Maximum size from which test specimens were rough machined prior to heat treatment.

[c] Applicable providing LT or ST dimension is ≥2.500 inches.

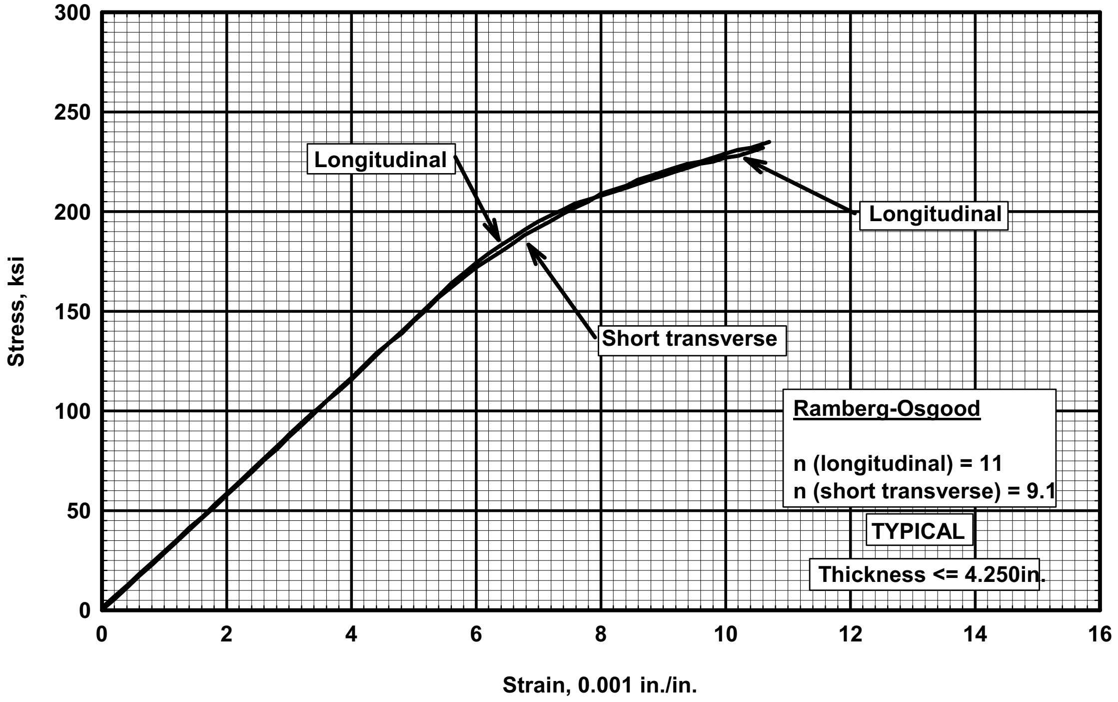


Figure 2.5.2.1.6(a). **Typical tensile stress-strain curves at room temperature for heat-treated AF1410 steel bar.**

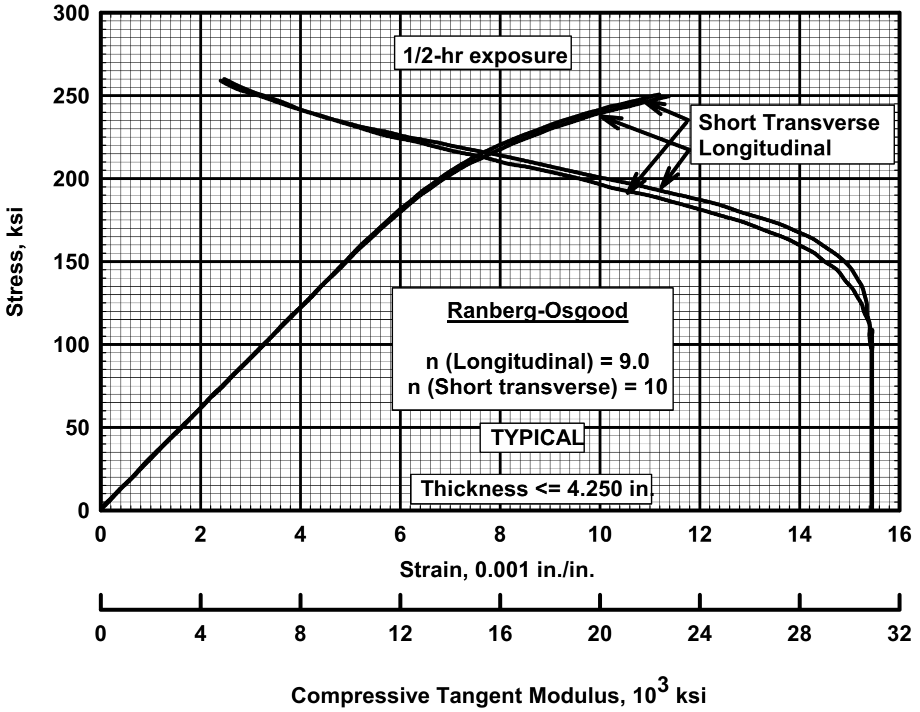


Figure 2.5.2.1.6(b). **Typical compressive stress-strain and compressive tangent-modulus curves at room temperature for heat-treated AF1410 steel bar.**

2.5.3 AERMET 100

2.5.3.0 *Comments and Properties* — AerMet 100 is a higher strength derivative of AF1410. The Ni-Co-Fe alloy can be heat treated to 280-300 ksi or to 290-310 ksi tensile strength while exhibiting excellent fracture toughness and high resistance to stress-corrosion cracking. AerMet 100 has good weldability and does not require preheating prior to welding. AerMet 100 is available in a wide variety of sizes and forms including billet, bar, sheet, strip, plate, wire, and die forgings. The alloy is produced by vacuum induction melting followed by vacuum-arc remelting.

Heat Treatment — This alloy can be heat treated to several strength levels. Consult the applicable materials specification for specific procedures.

Environmental Considerations — AerMet 100 is not considered corrosion resistant; consequently, parts should be protected with a corrosion resistant coating. The alloy is highly resistant to stress corrosion cracking compared to other high-strength steels of the same strength level.

This alloy displays good toughness at cryogenic temperatures as well as high strength and stability at temperatures up to 800°F.

Specification and Properties — A material specification for AerMet 100 is shown in Table 2.5.3.0(a). Room temperature mechanical properties are presented in Table 2.5.3.0(b) for both heat treated conditions.

Table 2.5.3.0(a). Material Specification for AerMet 100 Steel

Specification	Form
AMS 6532	Bar and forging
AMS 6478	Bar and forging

2.5.3.1 *280-300 ksi Heat-Treated Condition* — Typical stress-strain curves at room temperature are shown in Figures 2.5.3.1.6(a) and (b). A full-range tensile stress-strain curve is presented in Figure 2.5.3.1.6(c).

2.5.3.2 *290-310 ksi Heat-Treated Condition* — Typical tensile and compression stress-strain curves and compression tangent-modulus curves at room temperature are shown in Figures 2.5.3.2.6(a) and (b). A full-range tensile stress-strain curve is presented in Figure 2.5.3.2.6(c).

Table 2.5.3.0(b). Design Mechanical and Physical Properties of AerMet 100 Steel Bar

Specification	AMS 6532		AMS 6478
Form	Bar and forging		
Condition	Solution treated and aged		
Cross-sectional area, in.^{2}.	≤ 100		
Thickness or diameter, in.	≤ 10.000		
Basis	A	B	S
Mechanical Properties:			
F_{tu}, ksi:			
L	275	284	290
LT[a]	280	284	290
ST[a]	280[b]	...	290
F_{ty}, ksi:			
L	235	247	245
LT[a]	235	246	245
ST[a]	235[b]	...	245
F_{cy}, ksi:			
L	262	276	281
ST[a]	263	277	279
F_{su}, ksi	174	177	182
F_{bru}[c], ksi:			
(e/D = 1.5)	432	440	448
(e/D = 2.0)	569	579	581
F_{bry}[c], ksi:			
(e/D = 1.5)	361	380	378
(e/D = 2.0)	411	432	442
e, percent: (S-basis)			
L	10	...	10
LT[a]	8	...	8
ST[a]	8	...	8
RA, percent: (S-basis)			
L	55	...	50
LT[a]	45[d]	...	35
ST[a]	45	...	35
E, 10^3 ksi	28.0		
E_c, 10^3 ksi	28.1		
G, 10^3 ksi	...		
μ	0.305		
Physical Properties:			
ω, lb/in.^{3}	0.285		
C, K, and α	...		

a Applicable providing LT or ST dimension is ≤2.500 inches.
b S-Basis value
c Bearing values are "dry pin" values per Section 1.4.7.1.
d Rounded T_{99} value is 41%.

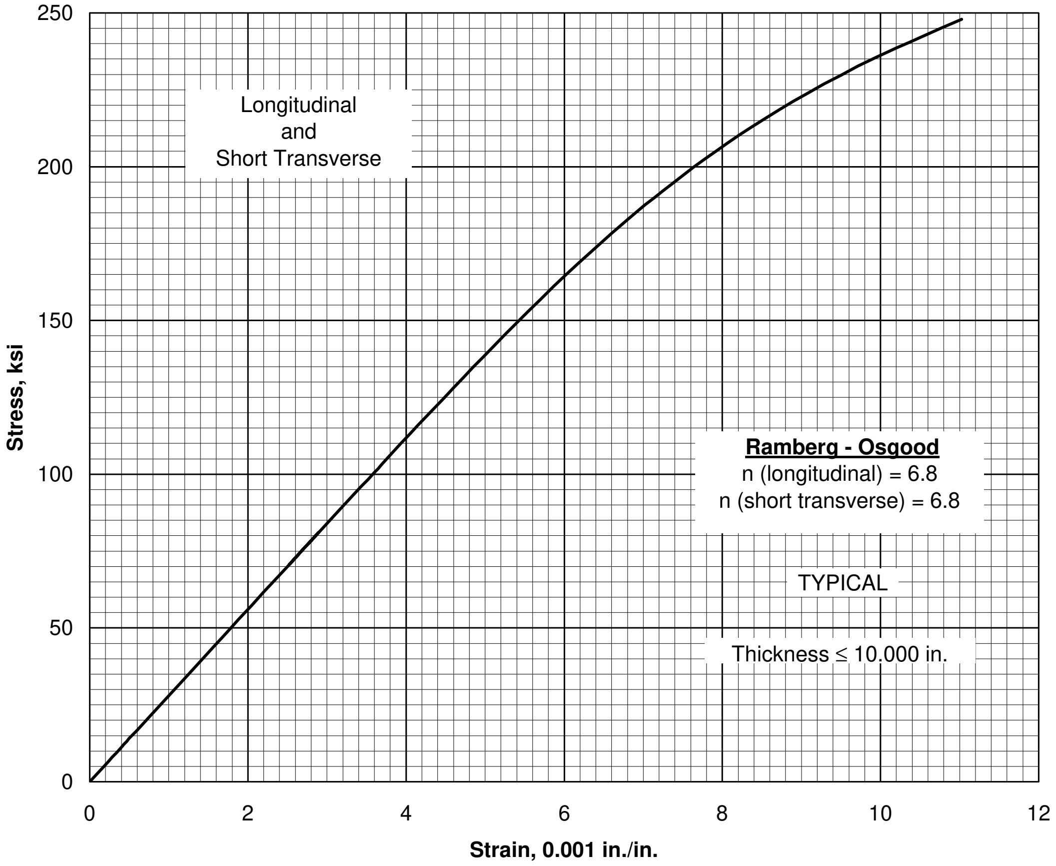


Figure 2.5.3.1.6(a). Typical tensile stress-strain curve at room temperature for AerMet 100 steel bar, heat treated to 280-300 ksi.

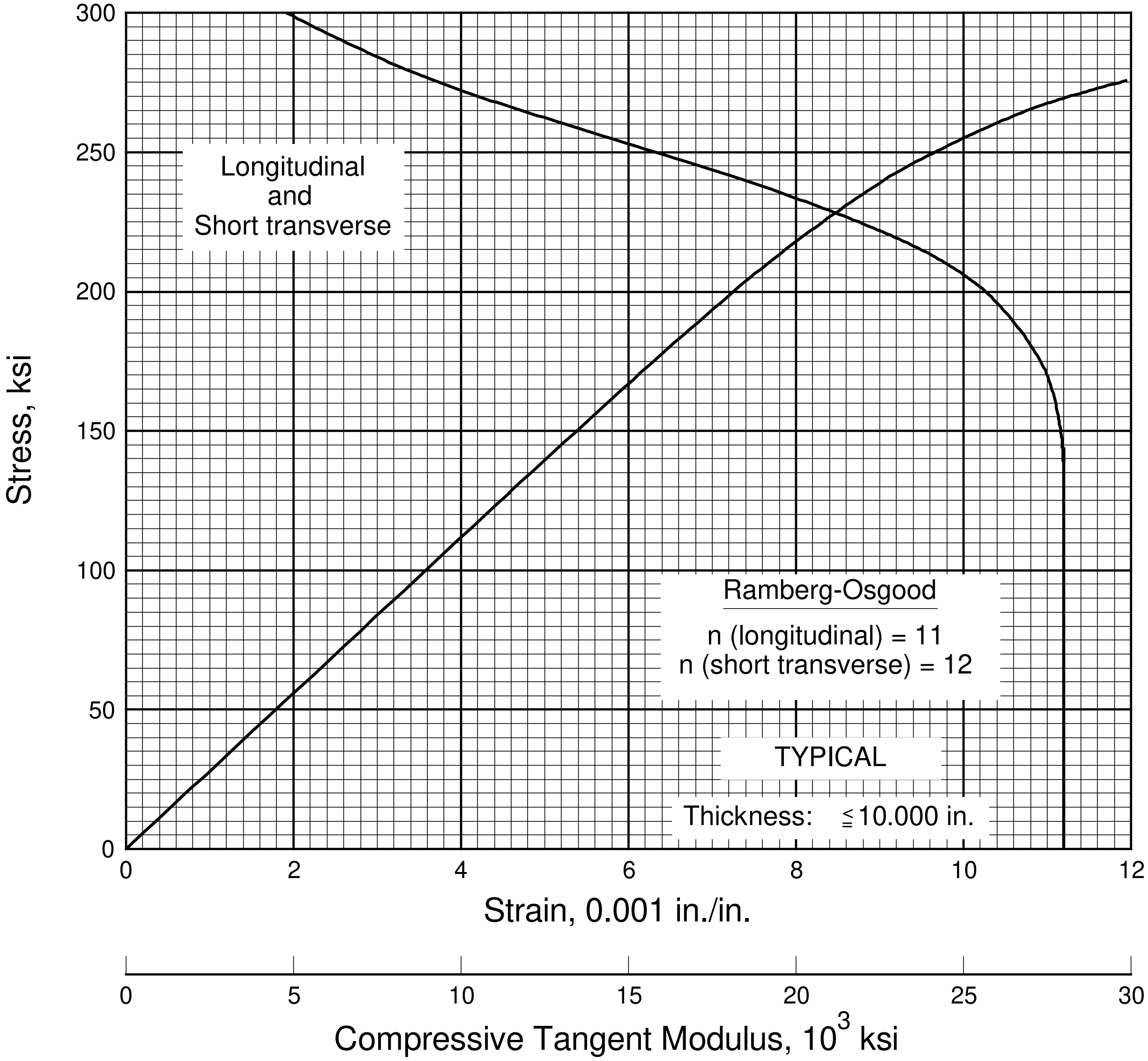


Figure 2.5.3.1.6(b). Typical compressive stress-strain and compressive tangent-modulus curves at room temperature for AerMet 100 steel bar, heat treated to 280-300 ksi.

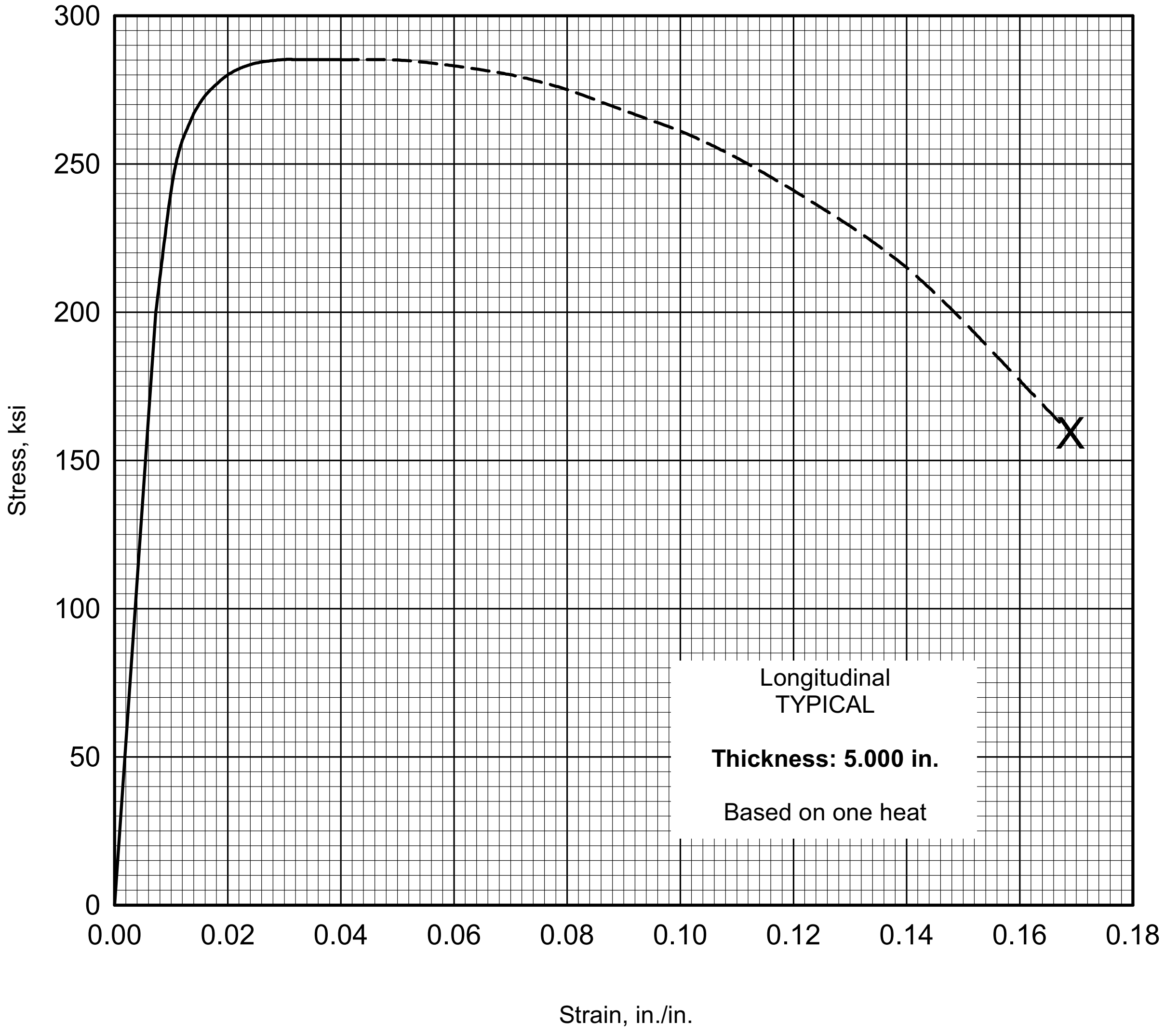


Figure 2.5.3.1.6(c). Typical tensile stress-strain curve (full range) at room temperature for AerMet 100 steel bar, heat treated to 280-300 ksi.

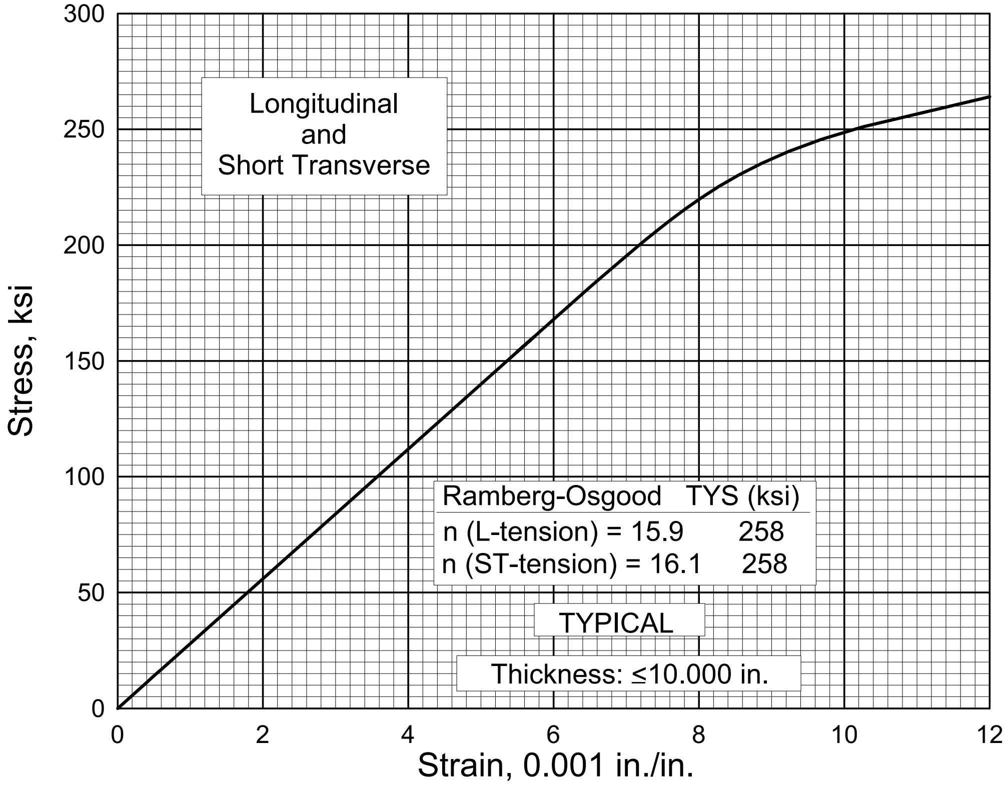


Figure 2.5.3.2.6(a). Typical tensile stress-strain curve at room temperature for AerMet 100 steel bar, heat treated to 290-310 ksi.

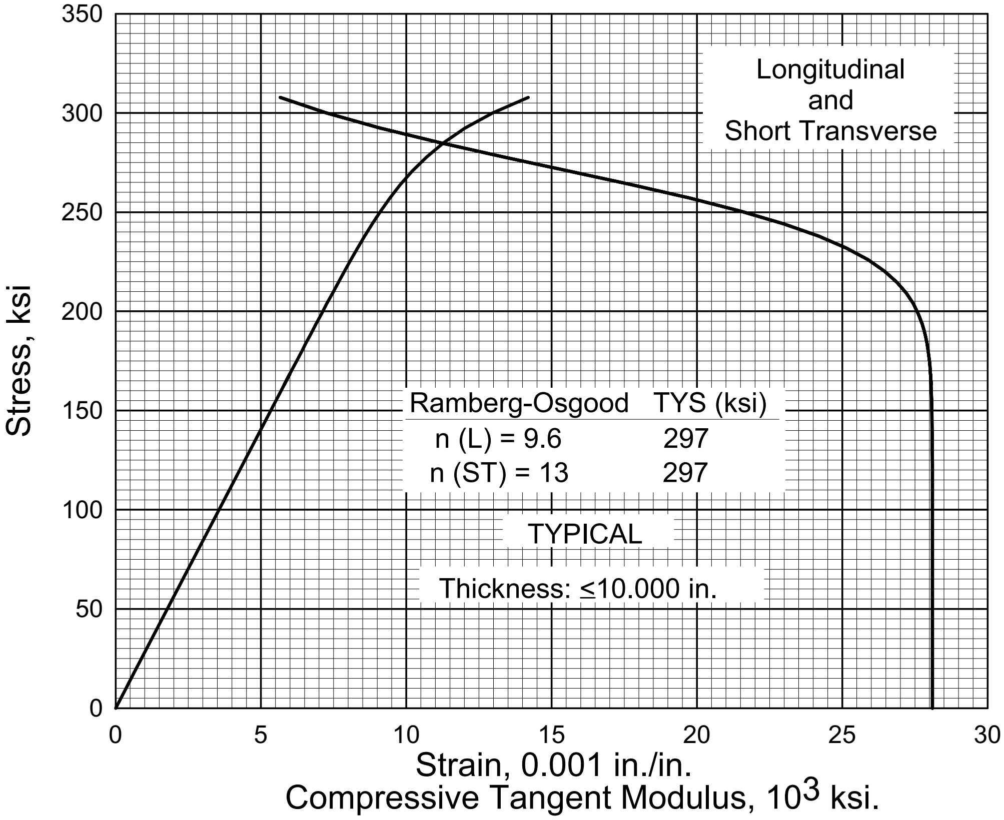


Figure 2.5.3.2.6(b). Typical compressive stress-strain and compressive tangent-modulus curves at room temperature for AerMet 100 steel bar, heat treated to 290-310 ksi.

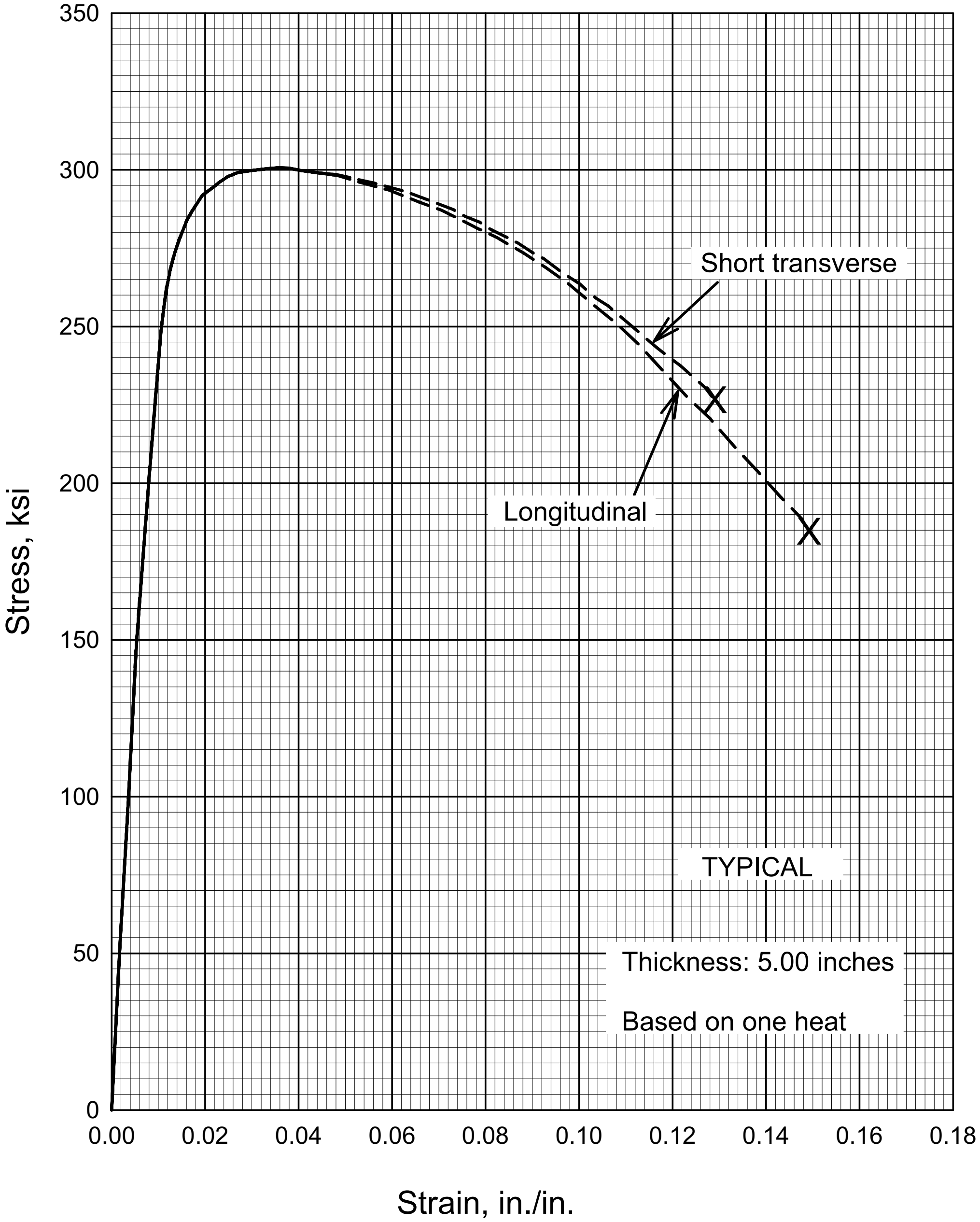


Figure 2.5.3.2.6(c). Typical tensile stress-strain curve (full range) at room temperature for AerMet 100 steel bar, heat treated to 290-310 ksi.

2.6 PRECIPITATION AND TRANSFORMATION-HARDENING STEELS (STAINLESS)

2.6.0 COMMENTS ON PRECIPITATION AND TRANSFORMATION-HARDENING STEELS (STAINLESS)

2.6.0.1 *Metallurgical Considerations* — The transformation and precipitation-hardening stainless steels are martensitic or semiaustenitic stainless steels that are hardenable by heat treatment.* The martensitic alloys require only a single step heat treatment to develop maximum strength. The others are austenitic in the fully annealed condition but become martensitic during subsequent heat treatment or as a result of extensive cold working. During a final heat treatment designed to temper the martensite, several of these steels are hardened further by the precipitation of copper, aluminum, or titanium.

Some dimensional change may be experienced during the heat treatment of the semiaustenitic steels. A dimensional expansion of approximately 0.0045-in./in. occurs during the transformation from the austenitic to the martensitic condition; during aging, a contraction of about 0.0005-in./in. takes place.

2.6.0.2. *Manufacturing Considerations* — The martensitic precipitation-hardening steels, before age hardening, are similar to the straight-chromium martensitic stainless steels (Type 410 or 431) in their general fabricating characteristics. The semiaustenitic grades, in the annealed condition, are similar to the austenitic stainless steels (Types 301, etc.) in this respect, and are readily cold formed. Forming of hardened steels after final heat treatment should be avoided.

These alloys can be welded by the conventional methods used for the austenitic stainless steels. Inert-gas-shielded welding is recommended to prevent the loss of titanium or aluminum in certain of these alloys. Postweld annealing is recommended for some grades.

The heat treatments for these steels are compatible with the cycles used for honeycomb panel brazing. Vapor blasting of scaled parts, after final heat treatment, is recommended because of the hazards of intergranular corrosion in inadequately controlled acids pickling operations.

2.6.0.3 *Environmental Considerations* — The precipitation-hardening stainless steels have good strength and oxidation and corrosion resistance in their service range. Prolonged exposures above 600°F and below the tempering range may cause further hardening, with possible decrease in ductility. Prolonged exposures in or above the temperature range result in loss of strength due to overtempering, overaging, or reaustenizing.

2.6.1 AM-350

2.6.1.0 *Comments and Properties* — AM-350 has high strength up to 800°F and good oxidation resistance up to about 1000°F. The alloy can be hardened by subzero cooling and tempering (Condition SCT).

Manufacturing Considerations — AM-350 is readily formed, welded, and brazed. Its forming characteristics are similar to the AISI 300 series stainless steels; however, it does have a higher rate of strain hardening. When fabricating AM-350 in the annealed condition, proper design allowance must be made for growth which occurs upon hardening. To obtain proper response to the SCT treatment after welding, the alloy must be reannealed.

Environmental Considerations — AM-350 shows good corrosion-resisting properties in ordinary atmospheres and also in a number of chemical environments. Exposure in the 600 to 800°F range for 1,000

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* Heat treating procedures for these steels are specified in MIL-H-6875 and are further described in producers' literature.

hours at stress levels below the short-time yield strength tends to increase room-temperature yield strength and room-temperature tensile strength slightly. Exposure to 800°F results in a decrease in elongation. Typical data are presented in Table 2.6.1.0(a).

Table 2.6.1.0(a). Effect of Elevated Temperature Exposure on Typical Tensile Properties of AM-350 Alloy in the SCT 850 Condition

Exposure temperature, °F	Exposure stress, ksi	Exposure time, hr	Room-temperature properties		
			TUS, ksi	TYS, ksi	e, %
RT	...	...	201	158	12.0
600	60	1,000	198	162	14.0
700	60	1,000	204	169	11.0
800	60	1,000	220	190	7.0
600	90	1,000	202	177	13.0
700	90	1,000	206	180	11.0
800	90	1,000	214	192	7.0

Specifications and Properties — A material specification for AM-350 stainless steel is presented in Table 2.6.1.0(b). The room-temperature properties of AM-350 in the SCT 850 condition are shown in Table 2.6.1.0(c). Figure 2.6.1.0 presents elevated temperature physical property information.

Table 2.6.1.0(b). Material Specifications for AM-350 Stainless Steel

Specification	Form
AMS 5548	Sheet and strip

2.6.1.1 ***SCT 850 Condition*** — Effect of temperature on various mechanical properties of AM-350 is presented in Figures 2.6.1.1.1 through 2.6.1.1.4. Typical stress-strain and tangent-modulus curves at several temperatures are shown in Figures 2.6.1.1.6(a) and (b).

Table 2.6.1.0(c). Design Mechanical and Physical Properties of AM-350 Stainless Steel Sheet and Strip

Specification	AMS 5548
Form	Sheet and strip[a]
Condition	SCT 850
Thickness, in.	≤ 0.187
Basis	S
Mechanical Properties:	
F_{tu}, ksi:	
L	183
LT	185
F_{ty}, ksi:	
L	147
LT	150
F_{cy}, ksi:	
L	163
LT	...
F_{su}, ksi	121
F_{bru}, ksi:	
(e/D = 1.5)	...
(e/D = 2.0)	373
F_{bry}, ksi:	
(e/D = 1.5)	...
(e/D = 2.0)	252
e, percent:	
LT	10[b]
E, 10^3 ksi	29.0
E_c, 10^3 ksi	30.0
G, 10^3 ksi	11.0
μ	0.32
Physical Properties:	
ω, lb/in.^{3}	0.282
C, Btu/(lb)(°F)	0.12 (32 to 212°F)
K and α	See Figure 2.6.1.0

[a] Test direction longitudinal for widths less than 9 in.; transverse for widths 9 in. and over.

[b] Elongation is 8 percent for sheet thickness in the range 0.010 to 0.050 inch. Listed value is for thickness > 0.050 inch.

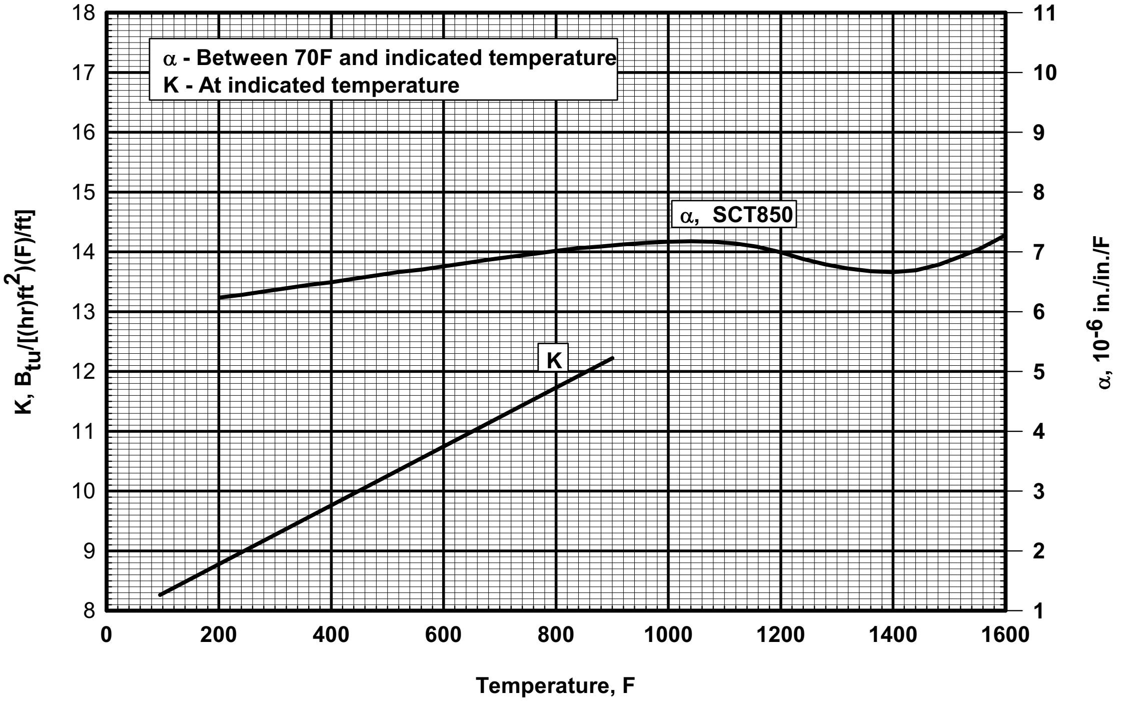

Figure 2.6.1.0. Effect of temperature on the physical properties of AM-350 stainless steel.

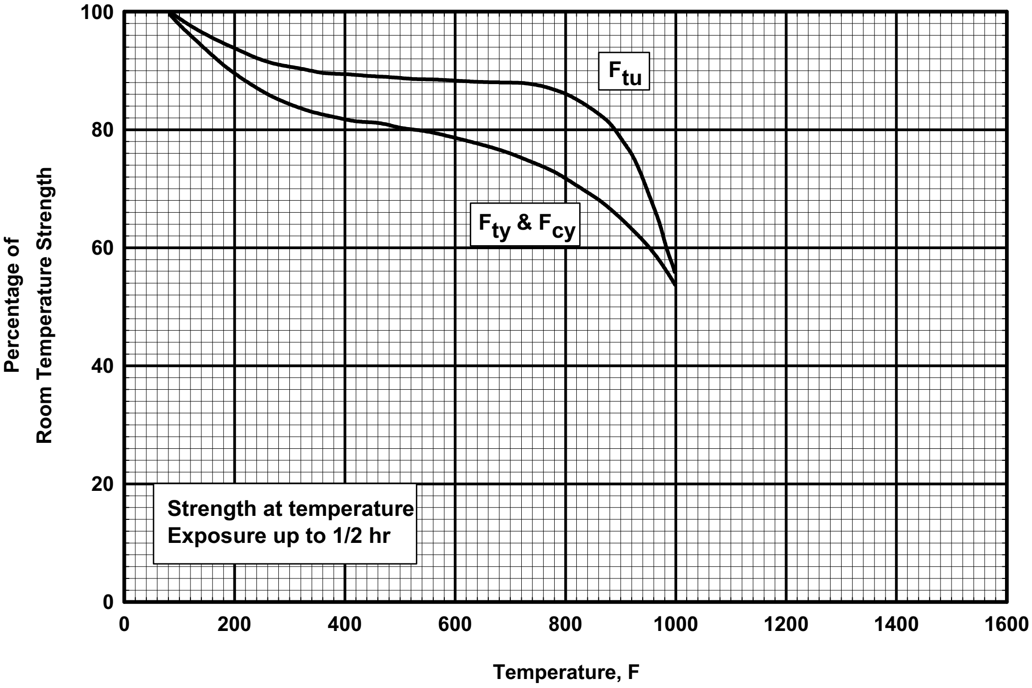

Figure 2.6.1.1.1. Effect of temperature on the tensile ultimate strength (F_{tu}), the tensile yield strength (F_{ty}), and the compressive yield strength (F_{cy}) of AM-350 (SCT 850) stainless steel sheet.

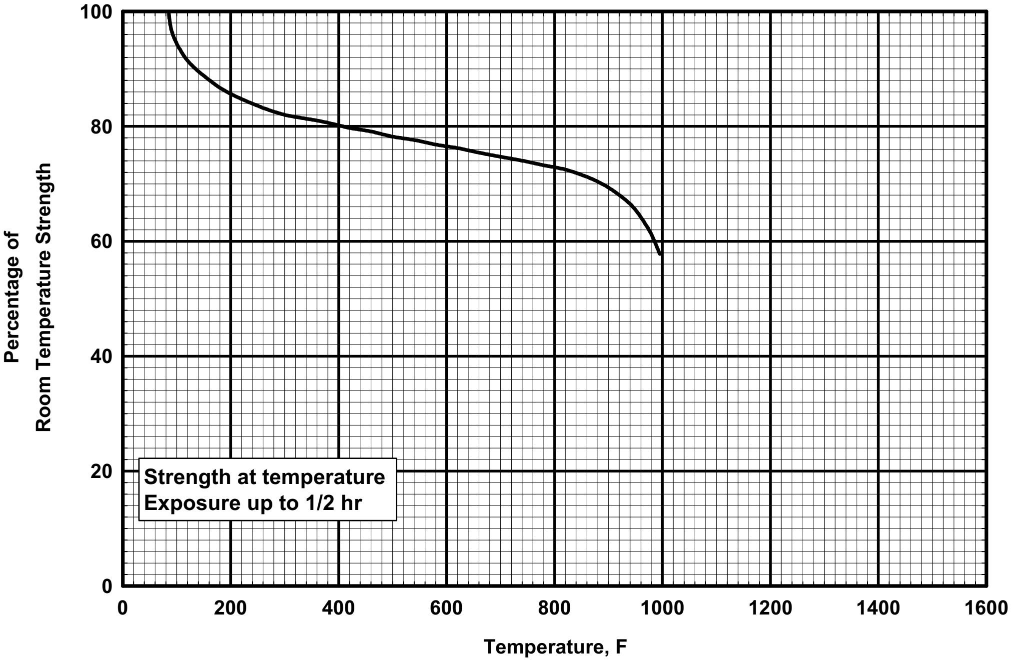

Figure 2.6.1.1.2. Effect of temperature on the shear ultimate strength (F_{su}) of AM-350 (SCT 850) stainless steel sheet.

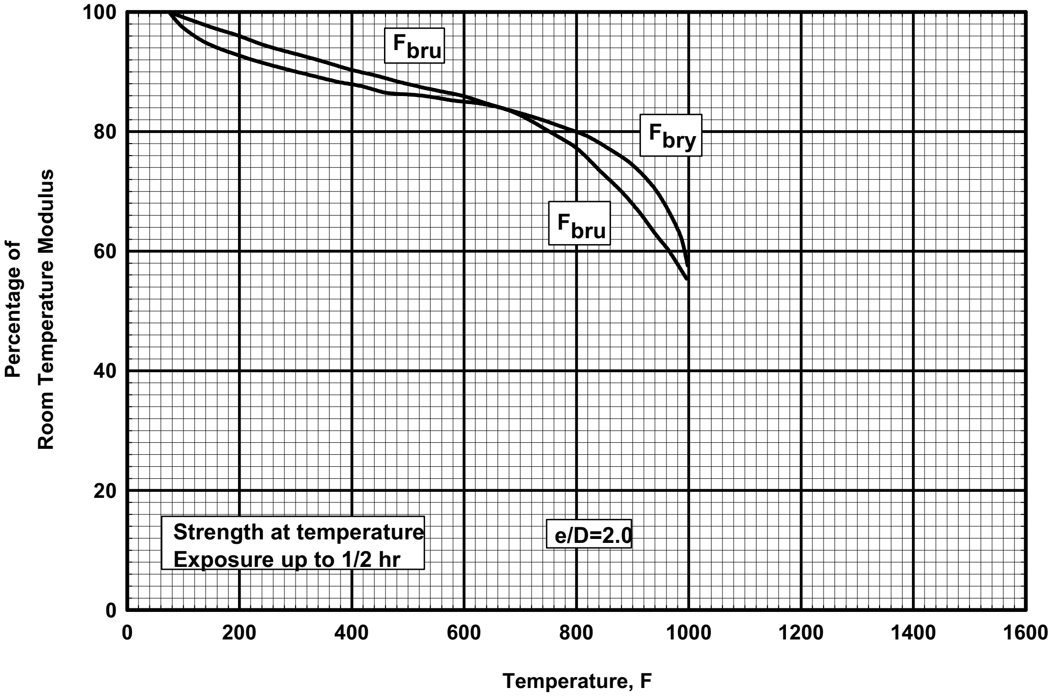

Figure 2.6.1.1.3. Effect of temperature on the bearing ultimate strength (F_{bru}) and the bearing yield strength (F_{bry}) of AM-350 (SCT 850) stainless steel sheet.

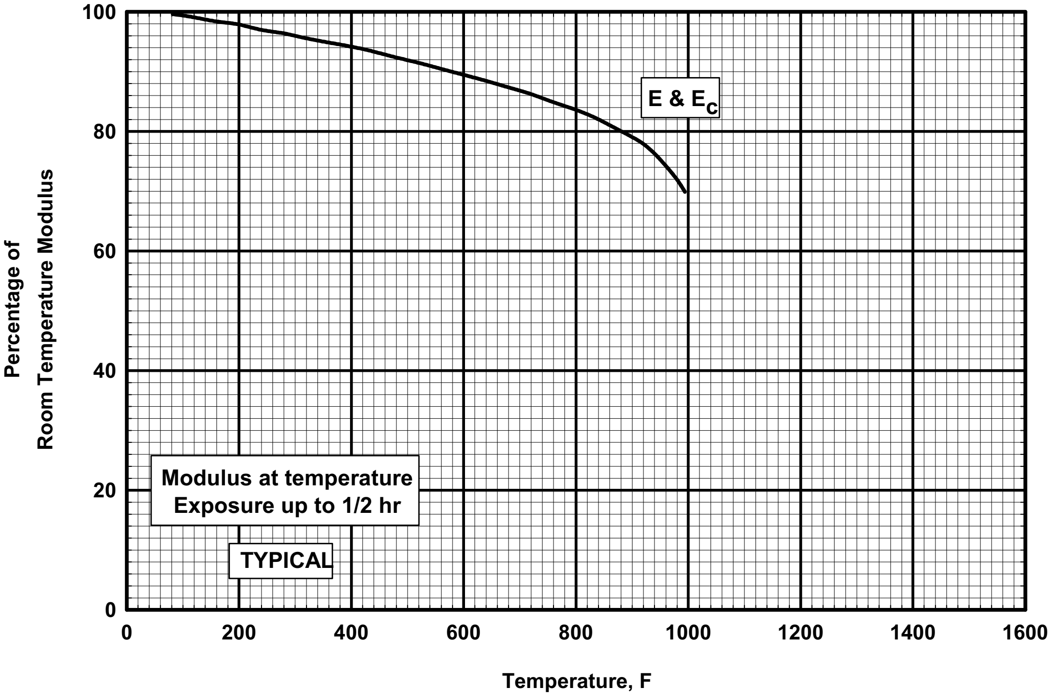

Figure 2.6.1.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of AM-350 (SCT 850) stainless steel sheet.

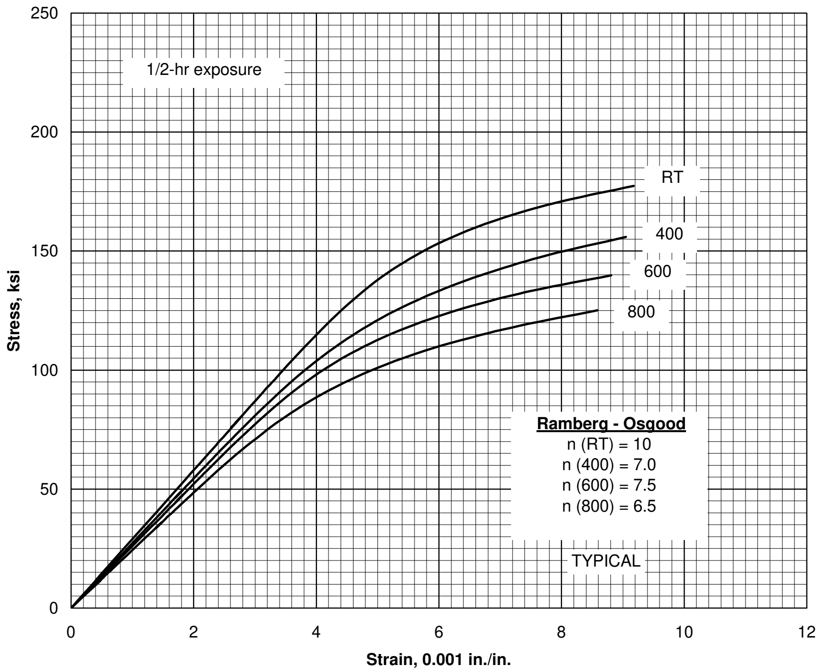

Figure 2.6.1.1.6(a). Typical tensile stress-strain curves at various temperature for AM-350 (SCT 850) stainless steel sheet.

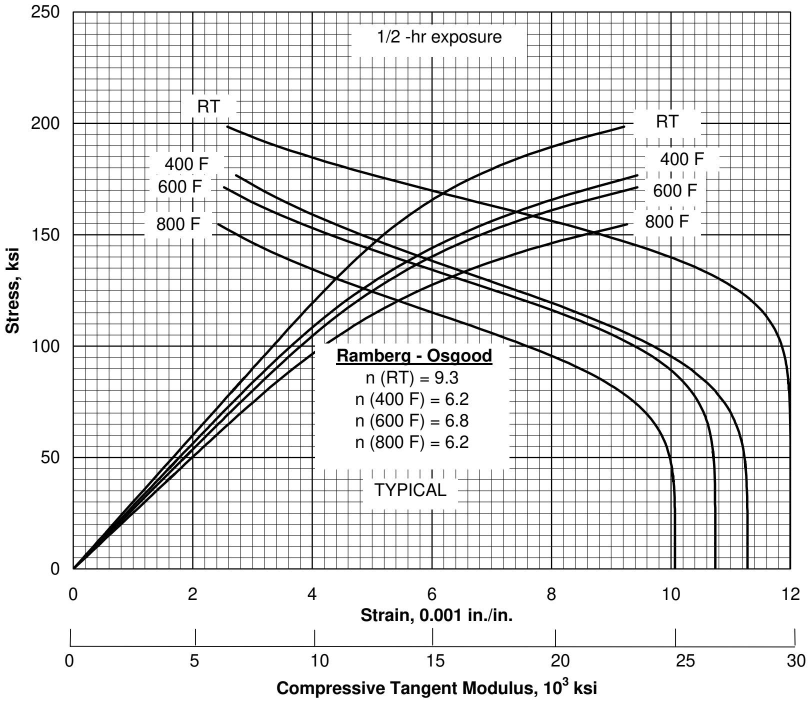

Figure 2.6.1.1.6(b). Typical compressive stress-strain compressive tangent-modulus curves at various temperatures for AM-350 (SCT 850) stainless steel sheet.

2.6.2 AM-355

2.6.2.0 *Comments and Properties* — AM-355, like AM-350, has high strength up to 800°F and good oxidation resistance up to 1000°F. The AM-355 alloy is generally hardened by subzero cooling and tempering (Condition SCT).

AM-355 is available in all mill products. The manufacturing considerations for AM-355 are similar to those for AM-350. Machining of AM-355 bars and forgings is best accomplished after overtempering at 1000°F to 1100°F.

The differences between AM-350 and AM-355 are a result of higher carbon, lower chromium, and reduced delta ferrite in AM-355. This difference in composition makes AM-355 slightly stronger but slightly less corrosion resistant than AM-350.

Environmental Considerations — Exposure in the 600°F to 800°F range for 100 hours at stress levels below the short time yield strength tends to increase room-temperature yield strength and room-temperature tensile strength slightly, with little change in elongation. Typical data are shown in Table 2.6.2.0(a).

Table 2.6.2.0(a). Effect of Elevated Temperature Exposure on Typical Tensile Properties of AM-355 Alloy in the SCT 850 Condition

Exposure temperature, °F	Exposure stress, ksi	Exposure time, hr	Room-temperature properties		
			TUS, ksi	TYS, ksi	e, %
RT	...	...	211	170	11.5
600	66	1,000	213	172	12.0
700	65	1,000	218	178	10.5
800	62	1,000	227	200	12.5
600	99	1,000	214	180	10.5
700	97	1,000	218	189	11.5
800	93	1,000	224	204	12.5

Specifications and Properties — Material specifications for AM-355 are presented in Table 2.6.2.0(b). The room temperature properties of AM-355 SCT are shown in Table 2.6.2.0(c) through (e). The physical properties of this alloy are presented in Figure 2.6.2.0.

Table 2.6.2.0(b). Material Specifications for AM-355 Stainless Steel

Specification	Form
AMS 5547	Sheet and strip
AMS 5549[a]	Plate
AMS 5743	Bar, forging, and forging stock

[a] Noncurrent specification.

2.6.2.1 *SCT Condition* — Elevated-temperature properties for AM-355 in the SCT (subzero cooled and tempered) condition are presented in Figures 2.6.2.1.1 through 2.6.2.1.4.

Table 2.6.2.0(c). Design Mechanical and Physical Properties of AM-355 Stainless Steel

Specification	AMS 5547		AMS 5743	
Form	Sheet and strip[a]		Bar and forging	
Condition	SCT850[b]	SCT1000	SCT850[b]	SCT1000
Thickness or diameter, in.	0.0005-0.187	0.010-0.187	...	...
Basis	S	S	S	S
Mechanical Properties:				
F_{tu}, ksi:				
L	188	...	200	170
LT	190	165	...	...
F_{ty}, ksi:				
L	162	...	165	155
LT	165	140	...	...
F_{cy}, ksi:				
L	180	...	...	...
LT	...	...	...	...
F_{su}, ksi	124	...	...	...
F_{bru}, ksi:				
(e/D = 1.5)	...	...	...	...
(e/D = 2.0)	383	...	...	...
F_{bry}, ksi:				
(e/D = 1.5)	...	...	...	...
(e/D = 2.0)	278	...	...	...
e, percent:				
L	...	...	10	12
LT	[c]	10	...	...
RA, percent:				
L	...	...	20	25
E, 10^3 ksi	29.0			
E_c, 10^3 ksi	29.0			
G, 10^3 ksi	11.0			
μ	0.32			
Physical Properties:				
ω, lb/in.^{3}	0.282			
C, K, and α	See Figure 2.6.2.0			

[a] Test direction longitudinal for widths less than 9 inches; transverse for widths 9 inches and over.

[b] Note: Condition SCT850 has been superseded by Condition SCT1000 in the applicable specifications. The tensile properties in these columns are the values previously specified for Condition SCT850.

[c] See Table 2.6.2.0(e).

Table 2.6.2.0(d). Design Mechanical and Physical Properties of AM-355 Stainless Steel Plate

Specification	AMS 5549[a]			
Form	Plate[b]			
Condition	SCT850[c]			SCT 1000
Thickness, in.	<0.375	0.375-1.000	>1.000	<0.187
Basis	S	S	S	S
Mechanical Properties:				
F_{tu}, ksi:				
L	188	...	...	...
LT	190	190	190	165
F_{ty}, ksi:				
L	162	...	...[d]	...
LT	165	150		140
F_{cy}, ksi:				
L	180	...	...	...
LT	...	...	...	...
F_{su}, ksi	124	...	...	...
F_{bru}, ksi:				
(e/D = 1.5)	...	...	...	...
(e/D = 2.0)	383	...	...	...
F_{bry}, ksi:				
(e/D = 1.5)	...	...	...	...
(e/D = 2.0)	278	...	...	...
e, percent:				
LT	10	10	10	12
E, 10^3 ksi	29.0			
E_c, 10^3 ksi	29.0			
G, 10^3 ksi	11.0			
μ	0.32			
Physical Properties:				
ω, lb/in.^{3}	0.282			
C, K, and α	See Figure 2.6.2.0			

a Noncurrent specification.
b Test direction longitudinal for widths less than 9 inches; transverse for widths 9 inches and over.
c Note: Condition SCT850 has been superseded by Condition SCT1000 in the applicable specifications. The tensile properties in these columns are the values previously specified for Condition SCT850.
d As agreed upon by purchaser and vendor.

Table 2.6.2.0(e). Minimum Elongation Values for AM-355 (SCT 850) Stainless Steel Sheet and Strip

Thickness, inches	e (LT), percent in 2 inches
0.0005 to 0.0015	2
Over 0.0015 to 0.0020	3
Over 0.0020 to 0.0050	5
Over 0.0050 to 0.0100	7
Over 0.0100 to 0.1875	8

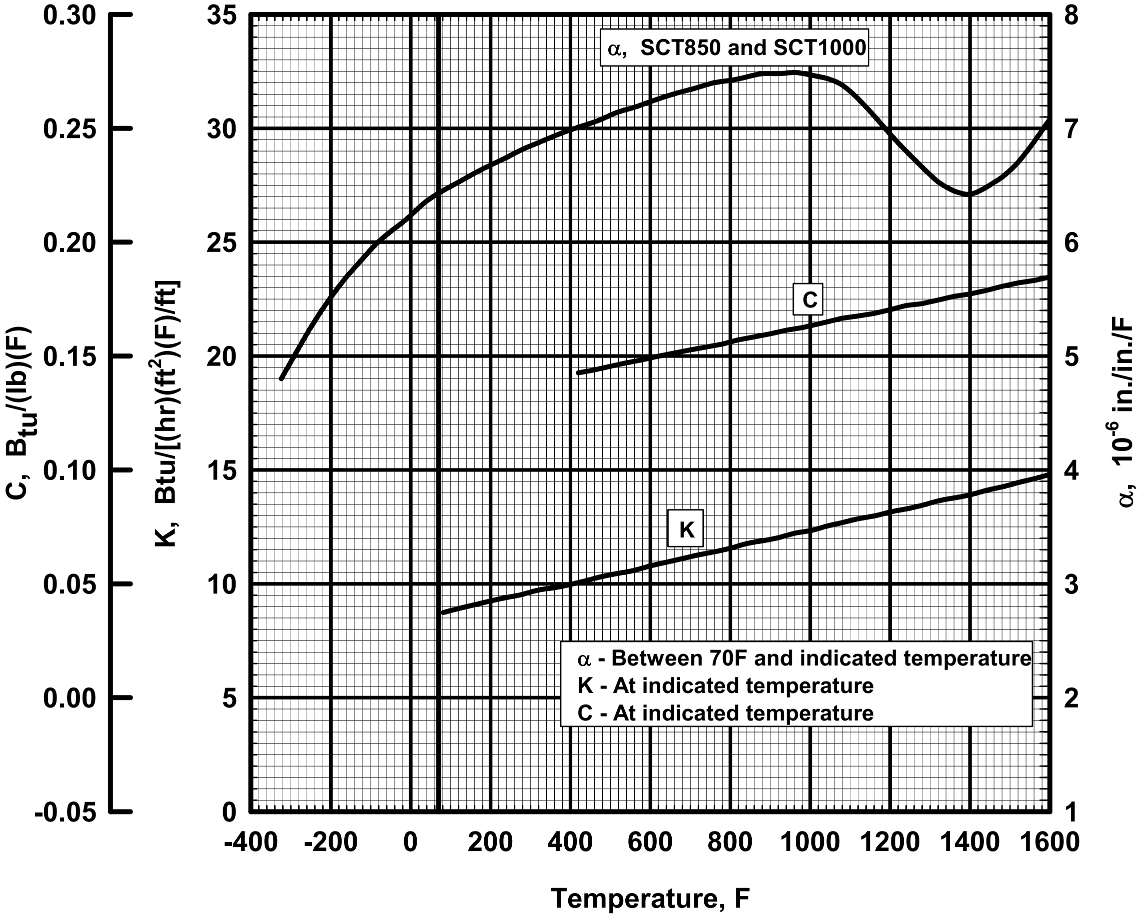

Figure 2.6.2.0. Effect of temperature on the physical properties of AM-355 stainless steel.

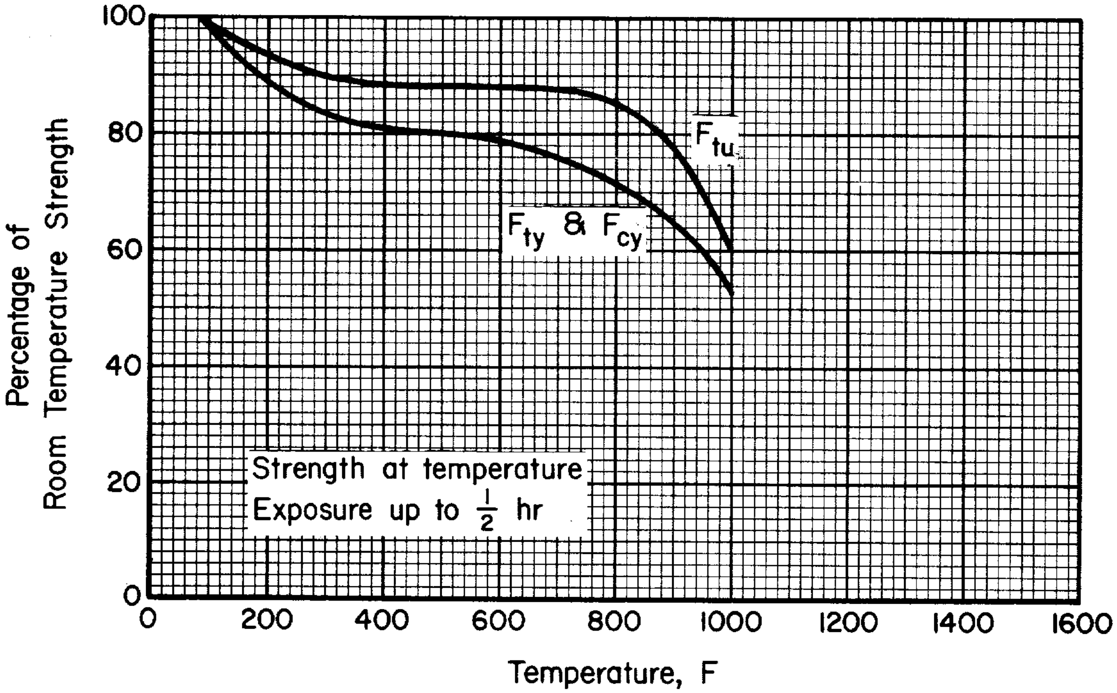

Figure 2.6.2.1.1. Effect of temperature on the tensile ultimate strength (F_{tu}), the tensile yield strength (F_{ty}), and the compressive yield strength (F_{cy}) of AM-355 (SCT 850) stainless steel (all products).

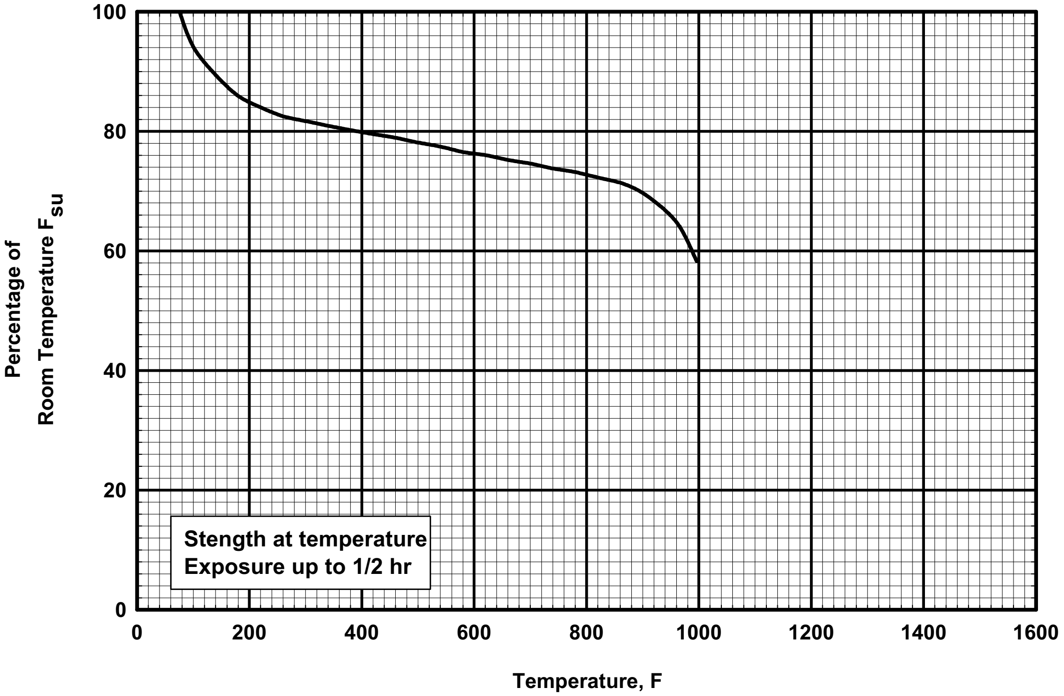

Figure 2.6.2.1.2. Effect of temperature on the shear ultimate strength (F_{su}) of AM-355 (SCT 850) stainless steel (all products).

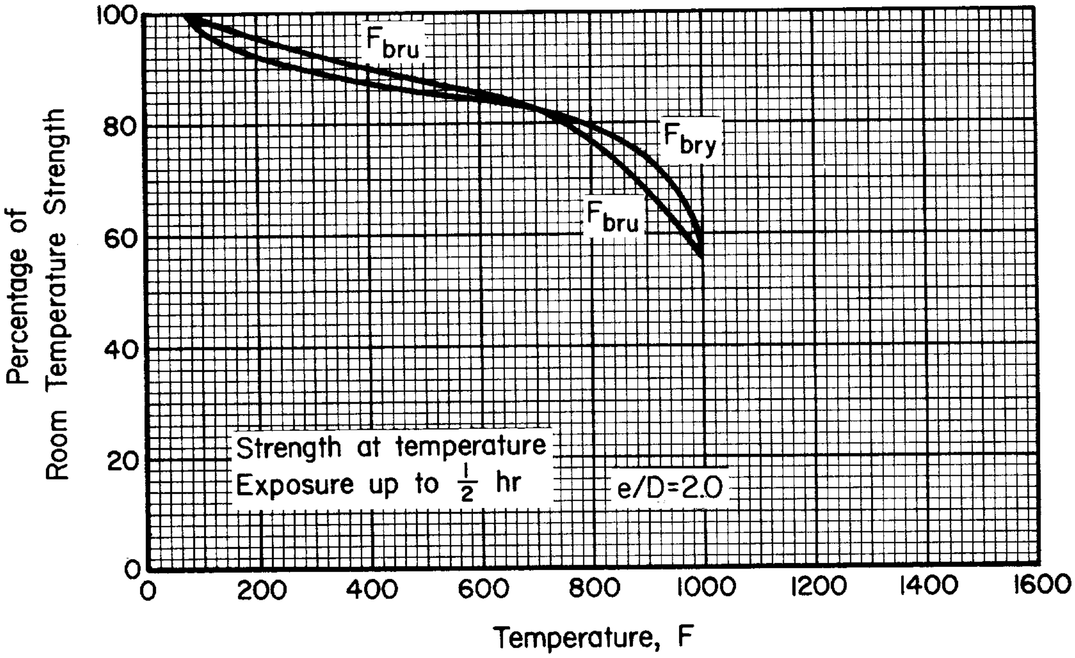

Figure 2.6.2.1.3. Effect of temperature on the bearing ultimate strength (F_{bru}) and the bearing yield strength (F_{bry}) of AM-355 (SCT 850) stainless steel sheet.

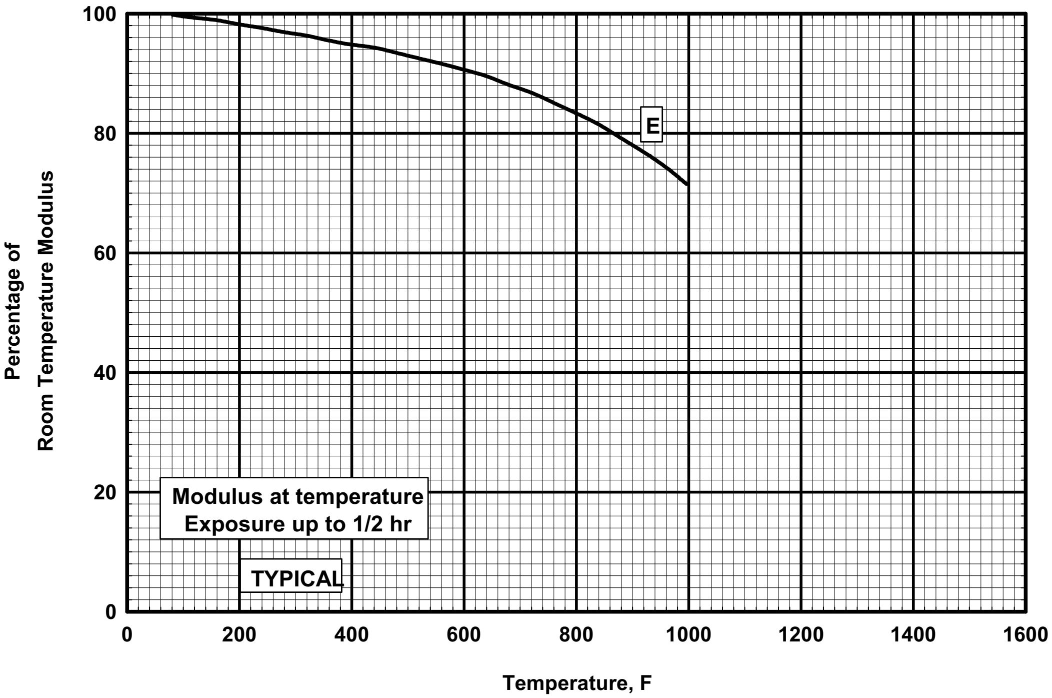

Figure 2.6.2.1.4. Effect of temperature on the tensile modulus (E) of AM-355 (SCT 850) stainless steel (all products).

2.6.3 CUSTOM 450

2.6.3.0 *Comments and Properties* — Custom 450 is a martensitic, precipitation-hardening stainless steel used for parts requiring corrosion resistance and high strength at temperatures up to 800°F for aged conditions. It is available in the form of forgings, billet, bar, wire, strip, and welded tubing.

Manufacturing Considerations — Custom 450 is normally supplied and fabricated in the solution-treated condition except wire for cold heading is supplied in the H1150M condition. Forming, machining, and joining operations are similar to those employed for other precipitation hardening stainless steels.

Heat Treatment — Among the alloys of its type, Custom 450 is the only one recommended for use in the solution-treated condition at temperatures up to 500°F. The alloy can also be heat treated to various strength levels having a wide range of properties. Consult the applicable material specification or MIL-H-6875 for specific heat treatment procedures.

In all heat treat conditions, Custom 450 has excellent ductility and toughness. Cryogenic properties are optimum in the H1150 condition. Maximum strength is achieved with the 900°F aging treatment while optimum fatigue life is exhibited with a 1050°F age.

When the as-supplied solution-treated condition is altered during processing by hot working, severe cold working, or welding, parts should be resolution annealed prior to aging. A dimensional contraction of about 0.0002 in./in. with the 900°F age and about 0.001 in./in. for the 1050°F aging treatment can be expected.

Environmental Considerations — The general corrosion resistance of Custom 450 is similar to AISI Type 304 stainless steel. Custom 450 shows excellent resistance to atmosphere corrosion and mild chemical environments. It has good resistance to stress corrosion cracking in the solution-treated condition. Like all martensitic precipitation hardening alloys, if stress corrosion is of concern, it should be aged at the highest temperature compatible with strength requirements. It offers the best resistance to stress corrosion cracking and hydrogen embrittlement when aged at 1150°F. The general corrosion resistance is very slightly decreased by the higher aging temperatures.

Material specifications for Custom 450 are shown in Table 2.6.3.0(a). The room-temperature mechanical properties are presented in Tables 2.6.3.0(b) and (c). The effect of temperature on thermal expansion is shown in Figure 2.6.3.0.

Table 2.6.3.0(a). Material Specifications for Custom 450 Stainless Steel

Specification	Form
AMS 5763	Bar, forging, tubing, wire, and ring (air melted)
AMS 5773	Bar, forging, tubing, wire, and ring (CEM)

2.6.3.1 *H900 Condition* — Elevated temperature curves are presented in Figures 2.6.3.1.1, 2.6.3.1.2, and 2.6.3.1.5. A tensile stress-strain curve at room temperature is shown in Figure 2.6.3.1.6. Fatigue data at room temperature are presented in Figure 2.6.3.1.8.

2.6.3.2 *H1050 Condition* — Elevated temperature curves are presented in Figures 2.6.3.2.1, 2.6.3.2.2, and 2.6.3.2.5. A tensile stress-strain curve at room temperature is shown in Figure 2.6.3.2.6. Fatigue data at room temperature are presented in Figure 2.6.3.2.8.

Table 2.6.3.0(b). Design Mechanical and Physical Properties of Custom 450 Stainless Steel Bar

Specification	AMS 5763		
Form	Bar		
Condition	Solution Treated	H900	H1050
Thickness or diameter, in.	≤8.000	≤8.000	≤8.000
Basis	S	S	S[a]
Mechanical Properties:			
F_{tu}, ksi:			
L	125	180	145
ST	...	179	144
F_{ty}, ksi:			
L	95	170	135
ST	...	168	133
F_{cy}, ksi:			
L	...	175	143
ST	...	173	141
F_{su}, ksi	...	114	93
F_{bru}, ksi:			
(e/D = 1.5)	...	298	239
(e/D = 2.0)	...	381	307
F_{bry}, ksi:			
(e/D = 1.5)	...	265	204
(e/D = 2.0)	...	326	257
e, percent:			
L	10	10	12
RA, percent:			
L	40	40	45
E, 10^3 ksi	28.0	29.0	
E_c, 10^3 ksi	...	31.0	
G, 10^3 ksi	...	11.2	
μ	...	0.29	
Physical Properties:			
ω, lb/in.^{3}	0.28		
C, Btu/(lb)(°F)	...		
K, Btu/[(hr)(ft^2)(°F)/ft]	...		
α, 10^{-6} in./in./°F	See Figure 2.6.3.0		

[a] Suppliers guaranteed minimum properties.

Table 2.6.3.0(c). Design Mechanical and Physical Properties of Custom 450 Stainless Steel Bar

Specification	AMS 5773						
Form	Bar						
Condition	Solution treated	H900	H950	H1000	H1050	H1100	H1150
Thickness or diameter, in.	≤12.000						
Basis	S	S	S	S	S	S	S
Mechanical Properties:							
F_{tu}, ksi:							
L	125	180	170	160	145	130	125
T	. . .	180	170	160	145	130	125
F_{ty}, ksi:							
L	95	170	160	150	135	105	75
T	. . .	170	160	150	135	105	75
F_{cy}, ksi:							
L	. . .	175	. . .	. . .	143	. . .	. . .
T	. . .	173	. . .	. . .	141	. . .	. . .
F_{su}, ksi	. . .	114	. . .	. . .	93	. . .	. . .
F_{bru}, ksi:							
(e/D = 1.5)	. . .	298	. . .	. . .	239	. . .	. . .
(e/D = 2.0)	. . .	381	. . .	. . .	307	. . .	. . .
F_{bry}, ksi:							
(e/D = 1.5)	. . .	265	. . .	. . .	204	. . .	. . .
(e/D = 2.0)	. . .	326	. . .	. . .	257	. . .	. . .
e, percent:							
L	10	10	10	12	12	16	18
T	...	6	7	8	9	11	12
R, percent:							
L	40	40	40	45	45	50	55
T	. . .	20	22	27	30	30	35
E, 10^3 ksi	28.0	29.0					
E_c, 10^3 ksi	. . .	31.0					
G, 10^3 ksi	. . .	11.2					
μ	. . .	0.29					
Physical Properties:							
ω, lb/in.^{3}	0.28						
C, Btu/(lb)(°F)	. . .						
K, Btu/[(hr)(ft^2)(°F)/ft]	. . .						
α, 10^{-6} in./in./°F	See Figure 2.6.3.0						

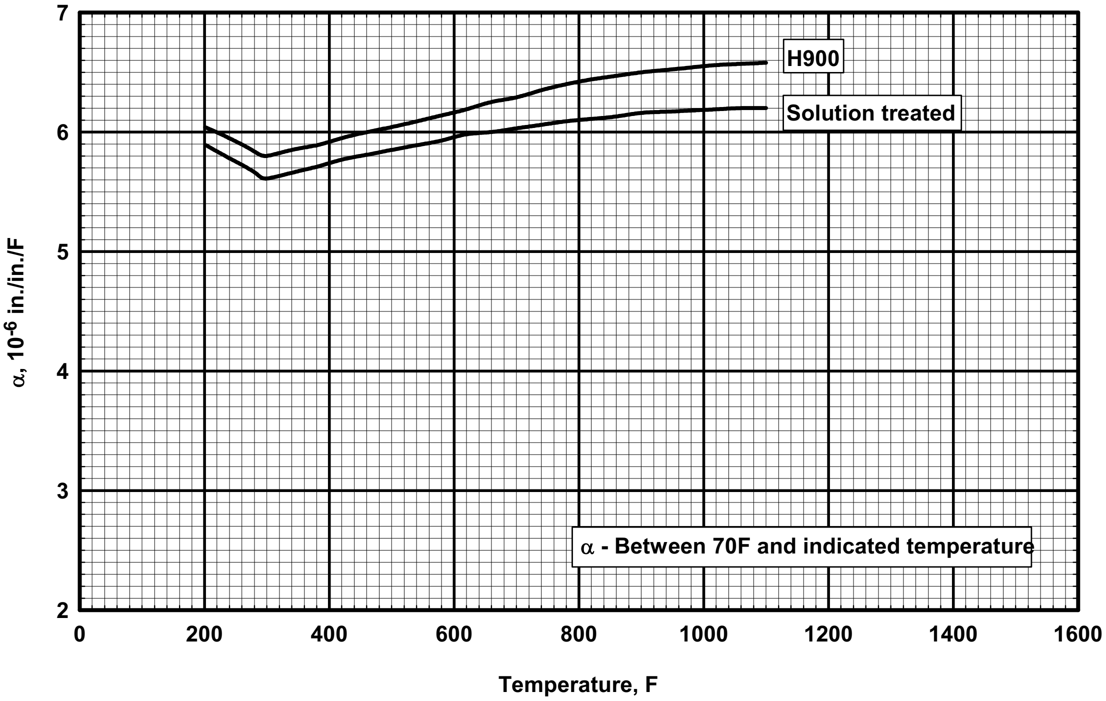

Figure 2.6.3.0. Effect of temperature on the physical properties of Custom 450 stainless steel.

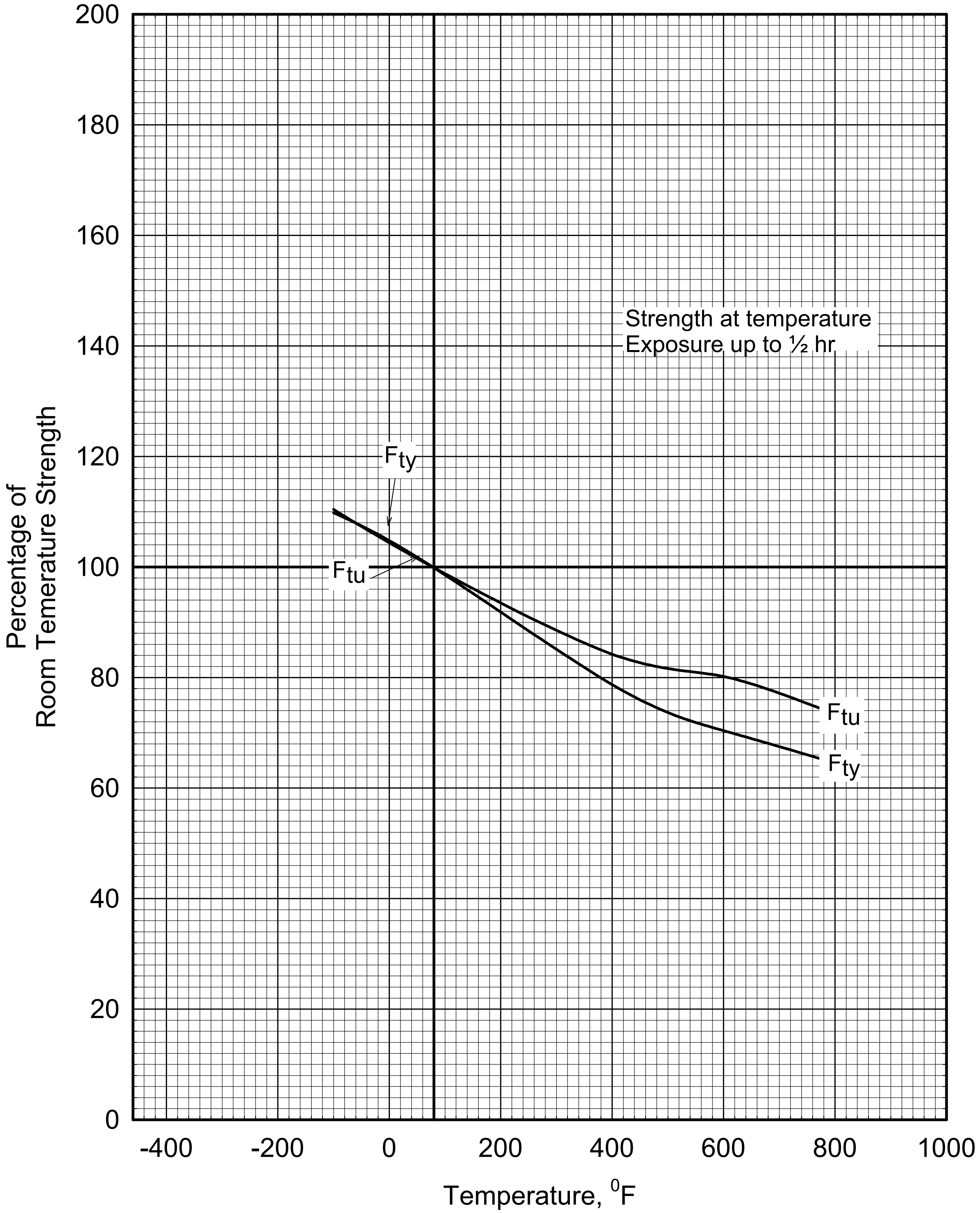

Figure 2.6.3.1.1. Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of Custom 450 (H900) stainless steel bar.

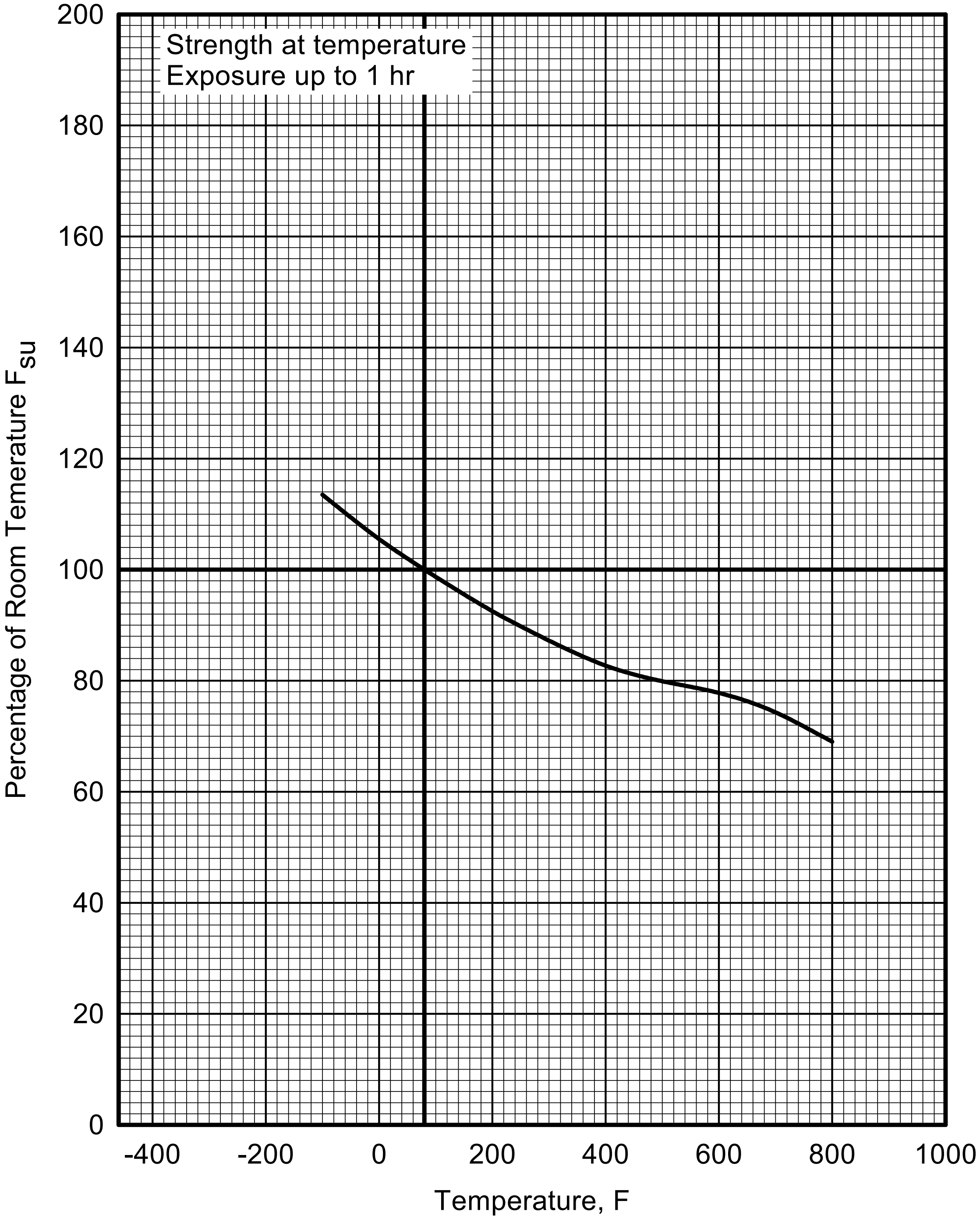

Figure 2.6.3.1.2. Effect of temperature on the ultimate shear strength (F_{su}) of Custom 450 (H900) stainless steel bar.

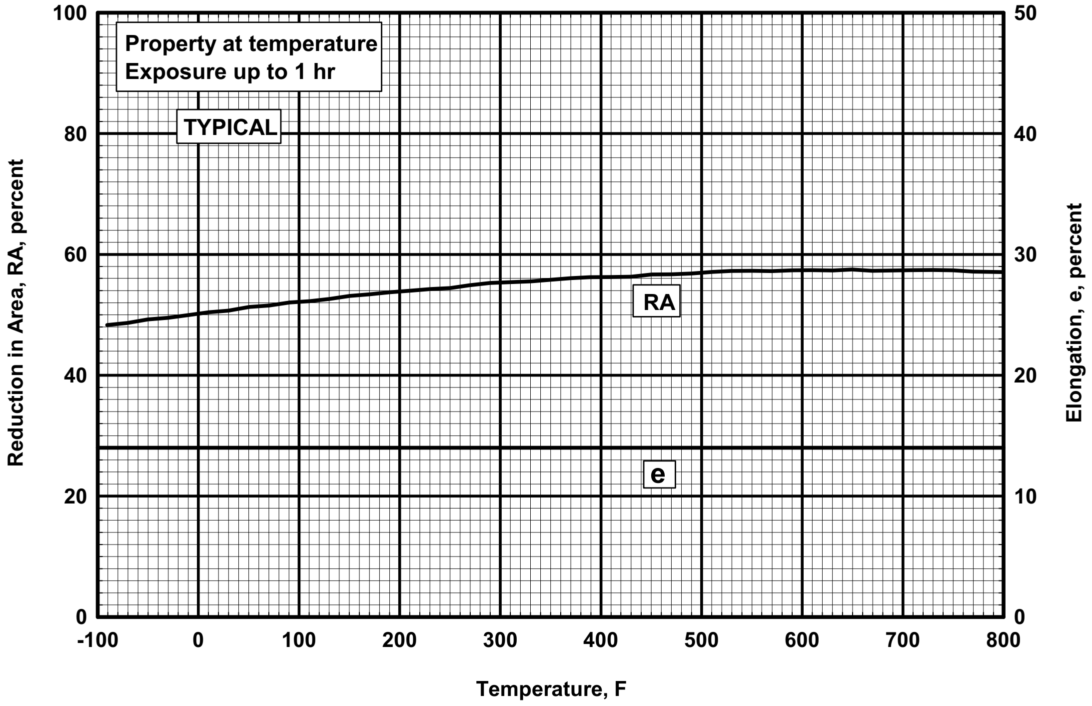

Figure 2.6.3.1.5. Effect of temperature on the elongation (e) and the reduction of area (RA) of Custom 450 (H900) stainless steel bar.

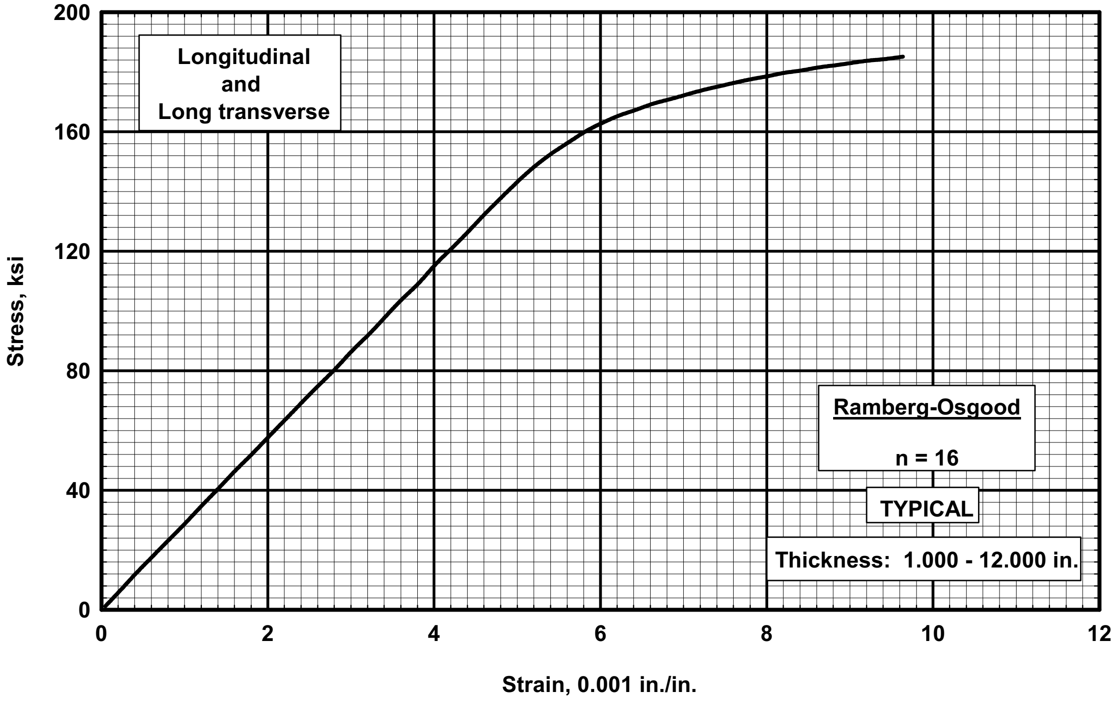

Figure 2.6.3.1.6. Typical tensile stress-strain curve for Custom 450 (H900) stainless steel bar at room temperature.

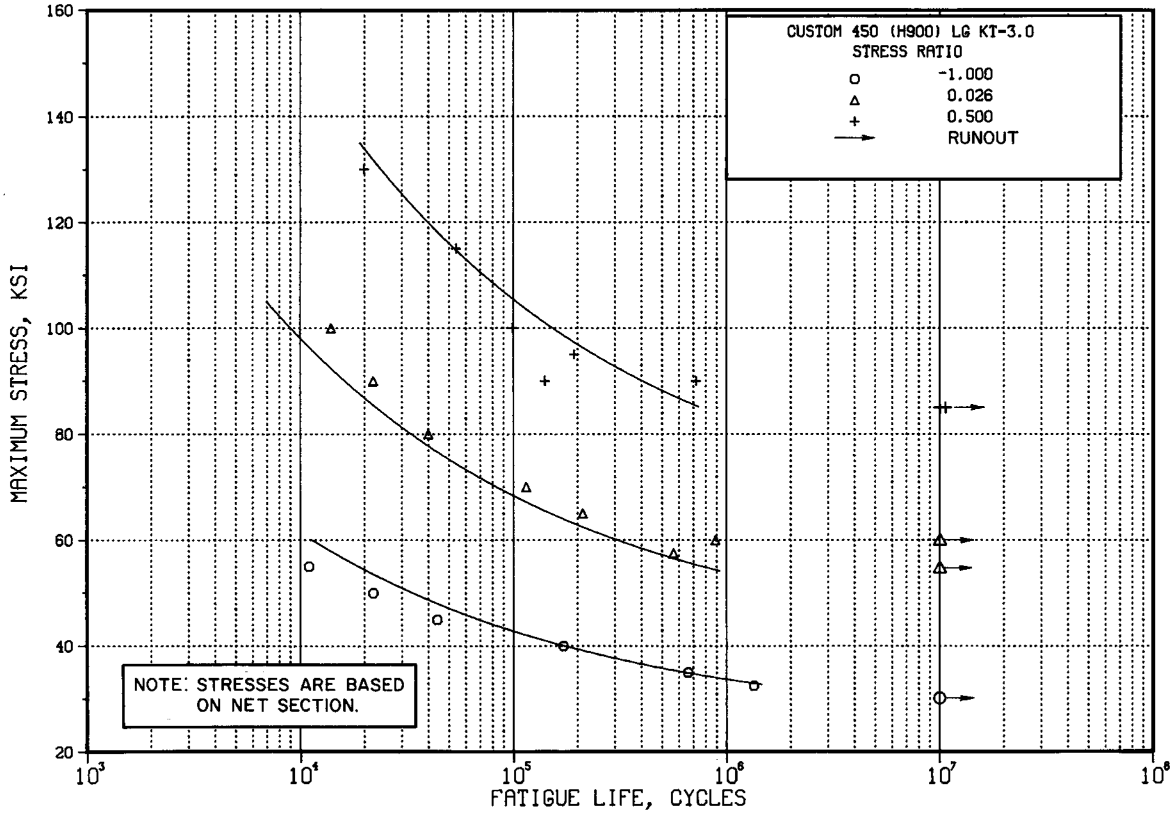

Figure 2.6.3.1.8. Best-fit S/N curves for notched, K_t = 3.0, Custom 450 (H900) stainless steel (ESR) bar, longitudinal direction.

Correlative Information for Figure 2.6.3.1.8

Product Form: Bar, 1.0625 inch diameter

Properties:

TUS, ksi	TYS, ksi	Temp., °F
192	188	RT (unnotched)
304	—	RT (notched)

Specimen Details: Notched, V-Groove, K_t=3.0
0.283 inch gross diameter
0.200 inch net diameter
0.010 inch root radius, r
60° flank angle, ω

Surface Condition: Polished with abrasive nylon cord

Reference: 2.6.3.1.8

Test Parameters:
Loading - Axial
Frequency - 1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 1

Equivalent Stress Equation:
$\text{Log } N_f = 9.64-3.21 \log (S_{eq}-39.28)$
$S_{eq} = S_{max} (1-R)^{0.65}$
Std. Error of Estimate, Log (Life) = 0.228
Standard Deviation, Log (Life) = 0.656
R^2 = 88%

Sample Size = 19

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

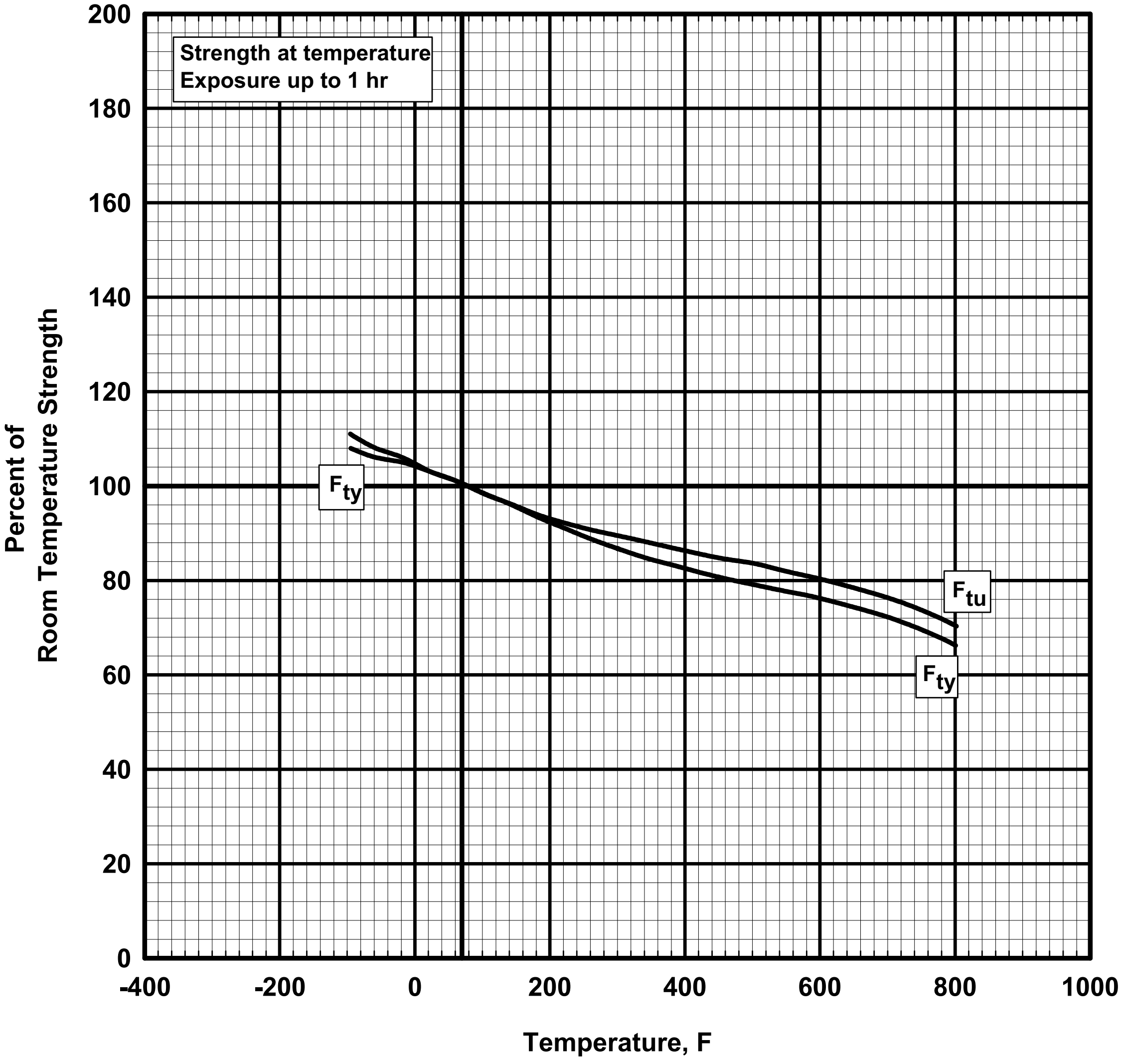

Figure 2.6.3.2.1. Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of Custom 450 (H1050) stainless steel bar.

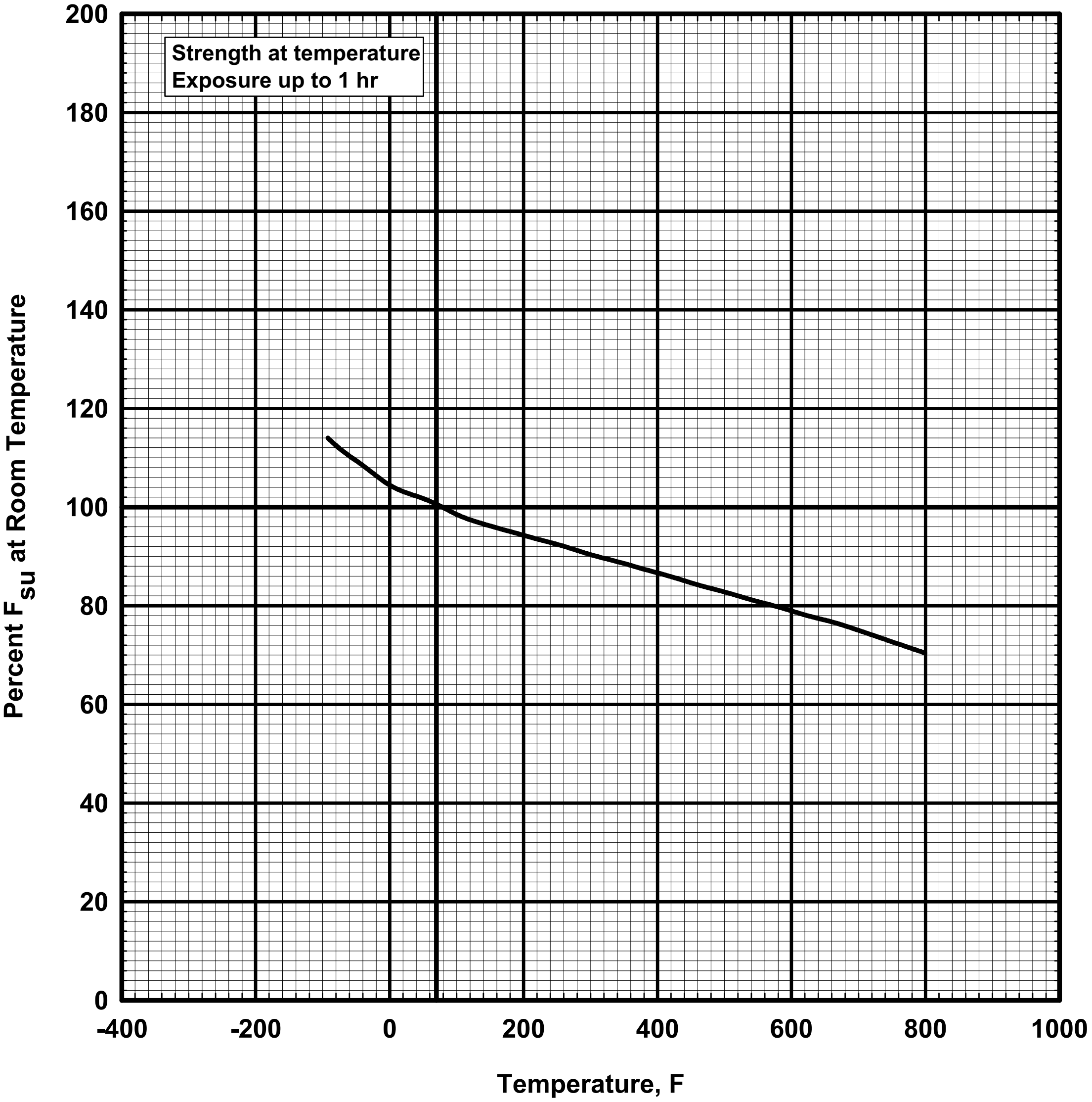

Figure 2.6.3.2.2. Effect of temperature on the ultimate shear strength (F_{su}) of Custom 450 (H1050) stainless steel bar.

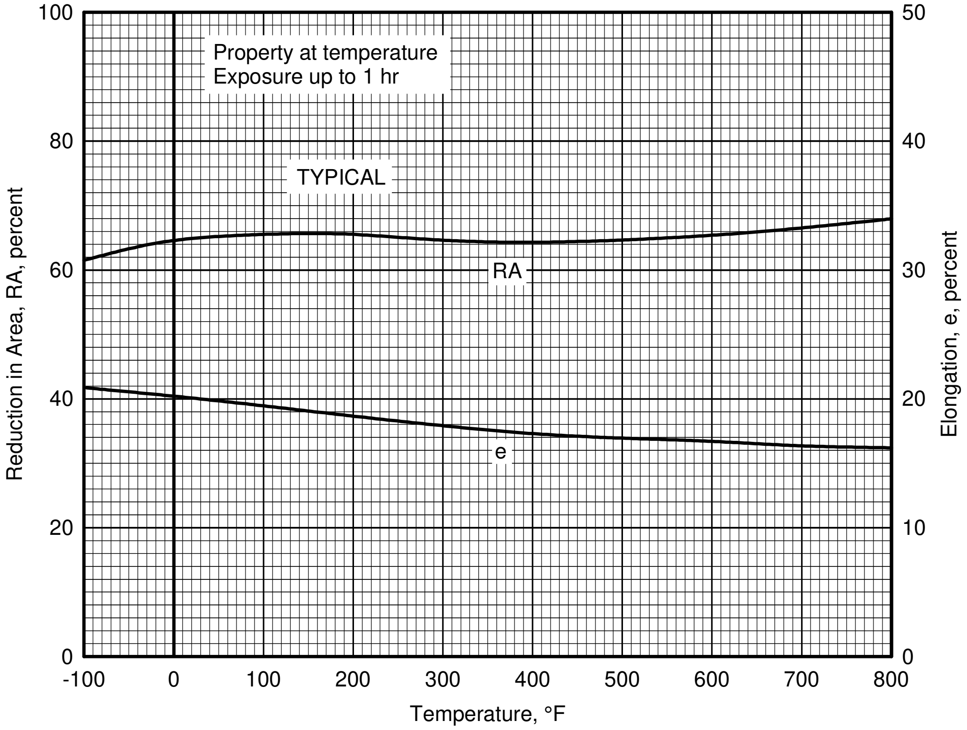

Figure 2.6.3.2.5. Effect of temperature on the elongation (e) and the reduction of area (RA) of Custom 450 (H1050) stainless steel bar.

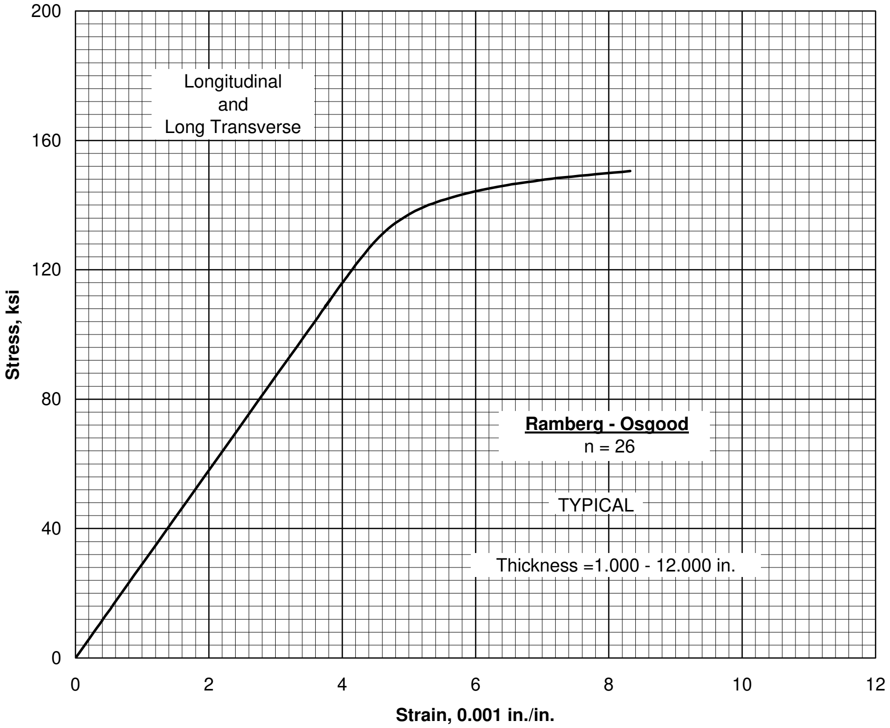

Figure 2.6.3.2.6. Typical tensile stress-strain curve for Custom 450 (H1050) stainless steel bar at room temperature.

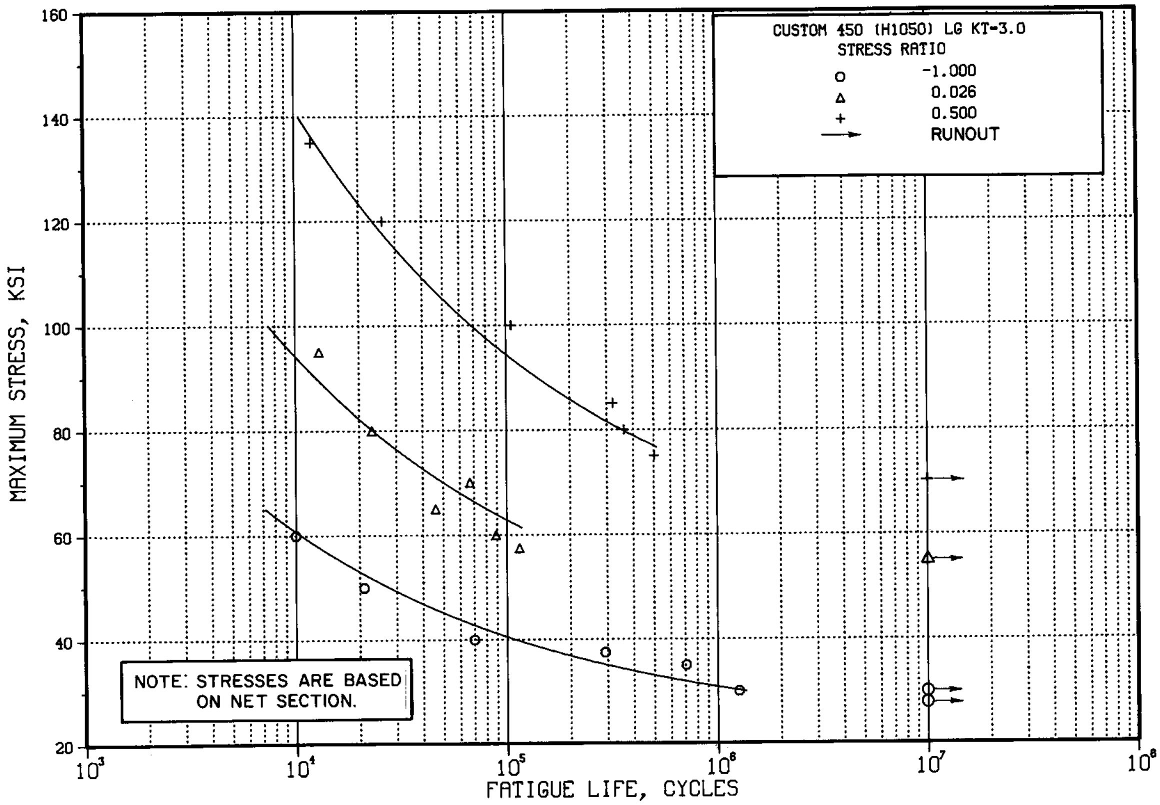

Figure 2.6.3.2.8. Best-fit S/N curves for notched, K_t = 3.0, Custom 450 (H1050) stainless steel (ESR) bar, longitudinal direction.

Correlative Information for Figure 2.6.3.2.8

Product Form: Bar, 1.0625 inch diameter

Properties:

TUS, ksi	TYS, ksi	Temp.,°F
156	151	RT (unnotched)
244	—	RT (notched)

Specimen Details: Notched, V-Groove, K_t=3.0
0.283 inch gross diameter
0.200 inch net diameter
0.010 inch root radius, r
60° flank angle, ω

Surface Condition: Polished with abrasive nylon cord

Reference: 2.6.3.1.8

Test Parameters:
Loading - Axial
Frequency - 1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 1

Equivalent Stress Equation:
$\text{Log } N_f = 9.59 - 3.15 \log (S_{eq} - 33.23)$
$S_{eq} = S_{max} (1-R)^{0.607}$
Std. Error of Estimate, Log (Life) = 0.188
Standard Deviation, Log (Life) = 0.649
R^2 = 92%

Sample Size = 18

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

2.6.4 CUSTOM 455

2.6.4.0 *Comments and Properties* — Custom 455 is a precipitation hardenable stainless steel with a martensitic structure in both the solution annealed and hardened conditions. It is used for parts requiring corrosion resistance and high strength at temperatures up to 800°F. It is produced by consumable electrode remelting and is available in the form of forgings, billet, bar, wire, strip, and welded tubing.

Manufacturing Considerations — Custom 455 is normally supplied and fabricated in the solution annealed condition. Forming, machining, and joining operations are similar to those employed for other precipitation hardening stainless steels. Optimum weld ductility is obtained by postweld solution annealing prior to aging.

Heat Treatment — The alloy can be heat treated to several strength levels. Consult the applicable materials specification or MIL-H-6875 for specific procedures. The minimum recommended hardening temperature to produce the optimum combination of strength, fracture toughness, and stress corrosion cracking resistance is 950°F. Higher strength is attainable with the 900°F aging treatment but at a sacrifice of fracture toughness and stress corrosion cracking resistance. Like other precipitation hardening stainless steels, the fracture toughness and stress intensity below which stress corrosion cracking does not occur improve with increasing aging temperature within the range of 900°F to 1000°F.

Usually parts are aged directly from the as-supplied solution annealed condition. When this condition has been altered during processing by hot working, severe cold working, or welding, the parts should be resolution annealed prior to aging. A dimensional contraction of about 0.0009 in./in. should be expected with the 950°F aging treatment.

Environmental Considerations — The general corrosion resistance of Custom 455 is about equivalent to that of AISI Type 430 stainless steel.

Hydrogen embrittlement tests in 5 percent by weight acid saturated with H_2S at room temperature show the same degree of susceptibility as other high-strength martensitic stainless steels.

When stress-corrosion cracking is of concern, one should use the highest aging temperature consistent with the strength properties required. The 900°F aging treatment should not be employed when stress corrosion cracking is a consideration. Consult the material producers literature for available stress corrosion data.

Like other precipitation hardening stainless steels, Custom 455 increases slightly in tensile strength and loses some toughness when exposed for long periods of time at temperatures around 700°F. For most applications, the loss in toughness which occurs is not detrimental to performance.

Specifications and Properties — Material specifications for Custom 455 are presented in Table 2.6.4.0(a). The room-temperature mechanical properties of Custom 455 are presented in Table 2.6.4.0(b). Physical properties at elevated temperatures are presented in Figure 2.6.4.0.

Table 2.6.4.0(a). Material Specifications for Custom 455 Stainless Steel

Specification	Form
AMS 5578	Tubing (welded)
AMS 5617	Bar and forging

Table 2.6.4.0(b). Design Mechanical and Physical Properties of Custom 455 Stainless Steel

Specification	AMS 5578		AMS 5617		
Form	Tubing (Welded)		Bar		
Condition	H950		H950		H1000
Thickness or diameter, in.[a]	0.020-0.062	>0.062	≤4.000	4.001-6.000	≤8.000
Basis	S	S	S	S	S
Mechanical Properties:					
F_{tu}, ksi:					
L	220	220	225	220	200
LT	...	...	225[b]	220[b]	...
ST	...	...	225[b]	220[b]	...
F_{ty}, ksi:					
L	205	205	210	205	185
LT	...	...	210[b]	205[b]	...
ST	...	...	210[b]	205[b]	...
F_{cy}, ksi:					
L	...	...	219	214	193
LT	...	...	219	214	193
ST	...	...	219	214	193
F_{su}, ksi	...	...	133	130	124
F_{bru}, ksi:					
(e/D = 1.5)	...	...	355	347	324
(e/D = 2.0)	...	...	450	440	409
F_{bry}, ksi:					
(e/D = 1.5)	...	...	311	303	285
(e/D = 2.0)	...	...	366	358	343
e, percent:					
L	3	4	10	10	10
LT	...	...	5[b]	5[b]	...
ST	...	...	5[b]	5[b]	...
RA, percent:					
L	...	...	40	40	40
LT	...	...	20[b]	20[b]	...
ST	...	...	20[b]	20[b]	...
E, 10^3 ksi	28.5				28.9
E_c, 10^3 ksi	30.0				30.0
G, 10^3 ksi	11.3				11.5
μ	0.27				0.26
Physical Properties:					
ω, lb/in.^{3}	0.28				
C, Btu/(lb)(°F)	...				
K, Btu/[(hr)(ft^2)(°F)/ft]	See Figure 2.6.4.0				
α, 10^{-6} in./in./°F	See Figure 2.6.4.0				

a Wall thickness for tubing.
b For Grade 2 material only.

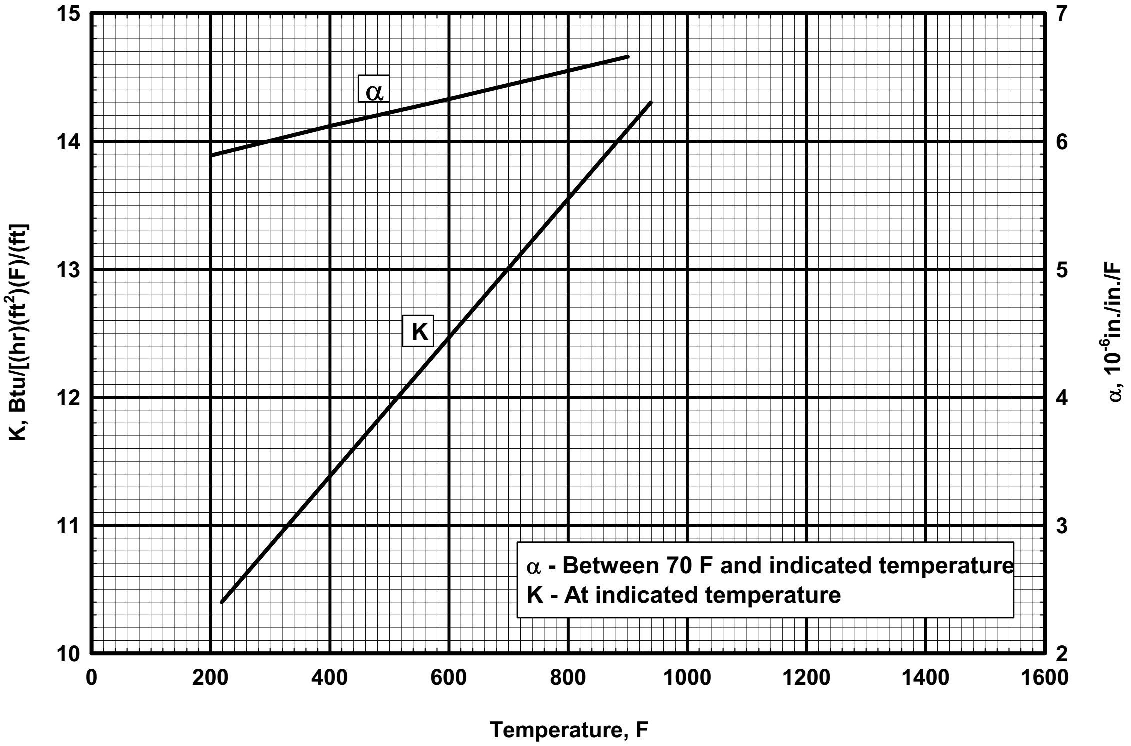

Figure 2.6.4.0. Effect of temperature on the physical properties of Custom 455 (H950) stainless steel.

2.6.4.1 ***H950 Condition*** — Elevated temperature curves are presented in Figure 2.6.4.1.1, 2.6.4.1.2, and 2.6.4.1.5. A tensile stress-strain curve at room temperature is shown in Figure 2.6.4.1.6. Fatigue data at room temperature are presented in Figure 2.6.4.1.8(a) and (b).

2.6.4.2 ***H1000 Condition*** — Elevated temperature curves are shown in Figures 2.6.4.2.1, 2.6.4.2.2, and 2.6.4.2.5. A tensile stress-strain curve at room temperature is presented in Figure 2.6.4.2.6. Fatigue data at room temperature are shown in Figure 2.6.4.2.8.

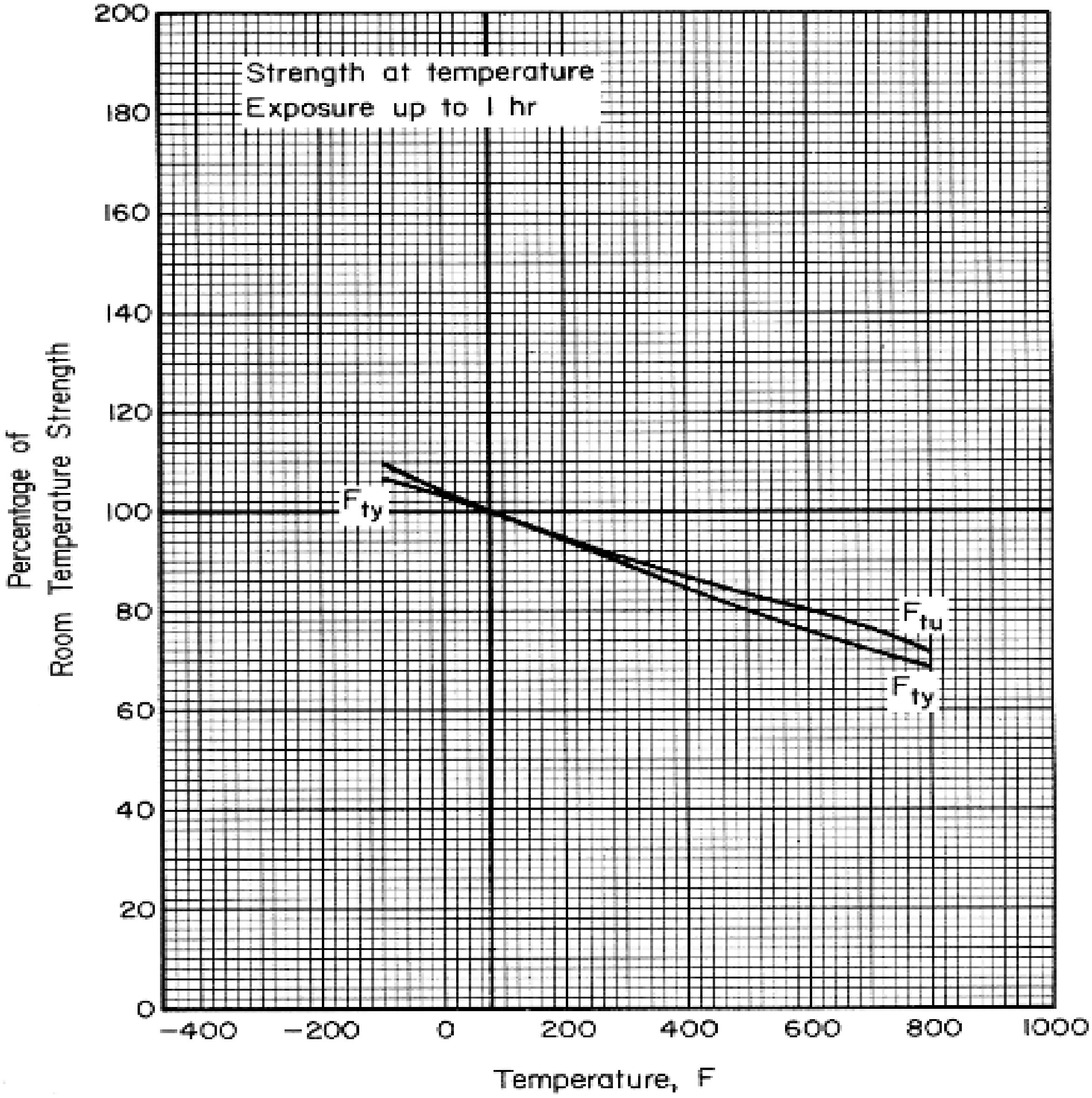

Figure 2.6.4.1.1. Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of Custom 455 (H950) stainless steel bar.

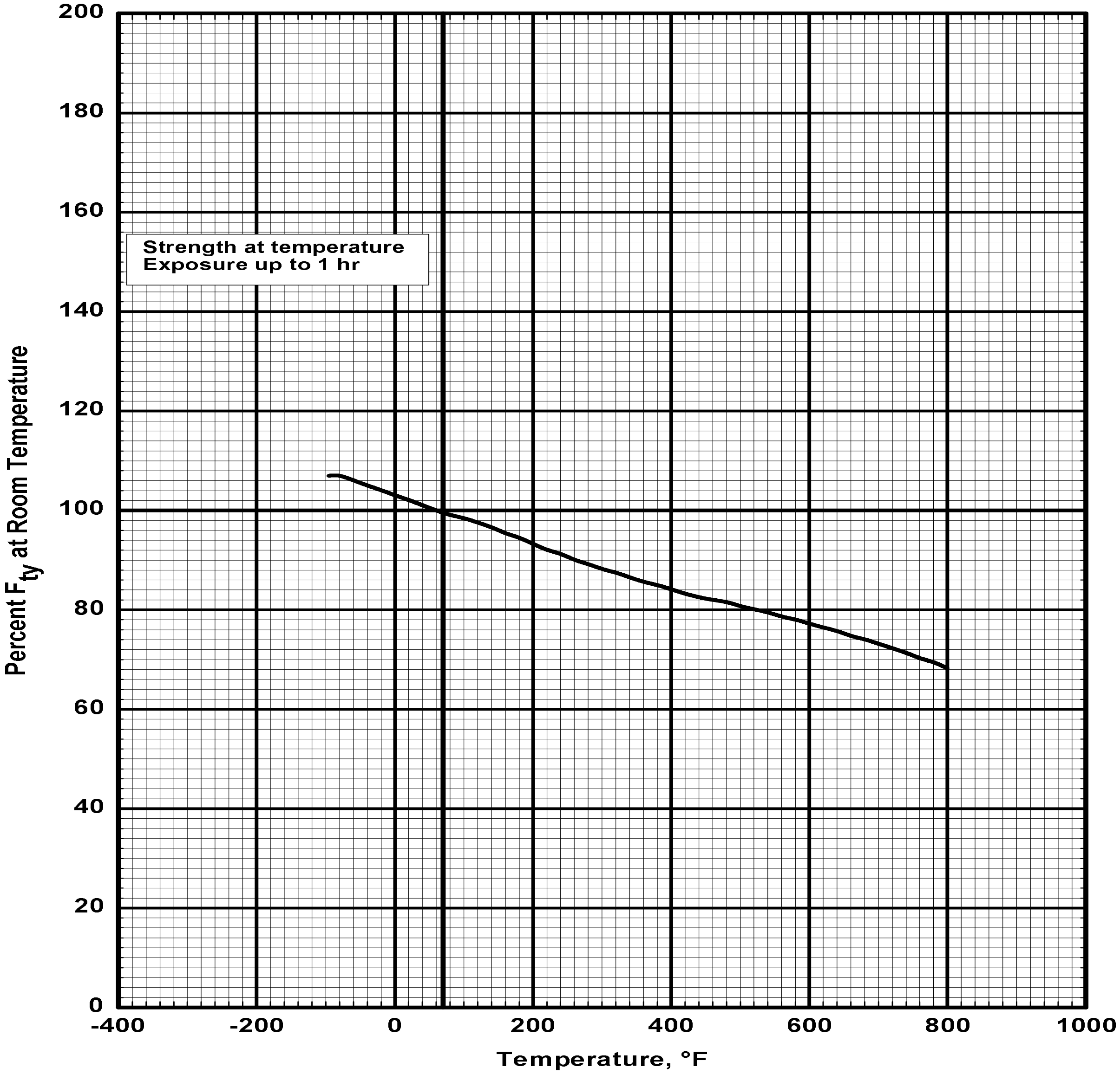

Figure 2.6.4.1.2. Effect of temperature on the ultimate shear strength (F_{su}) of Custom 455 (H950) stainless steel bar.

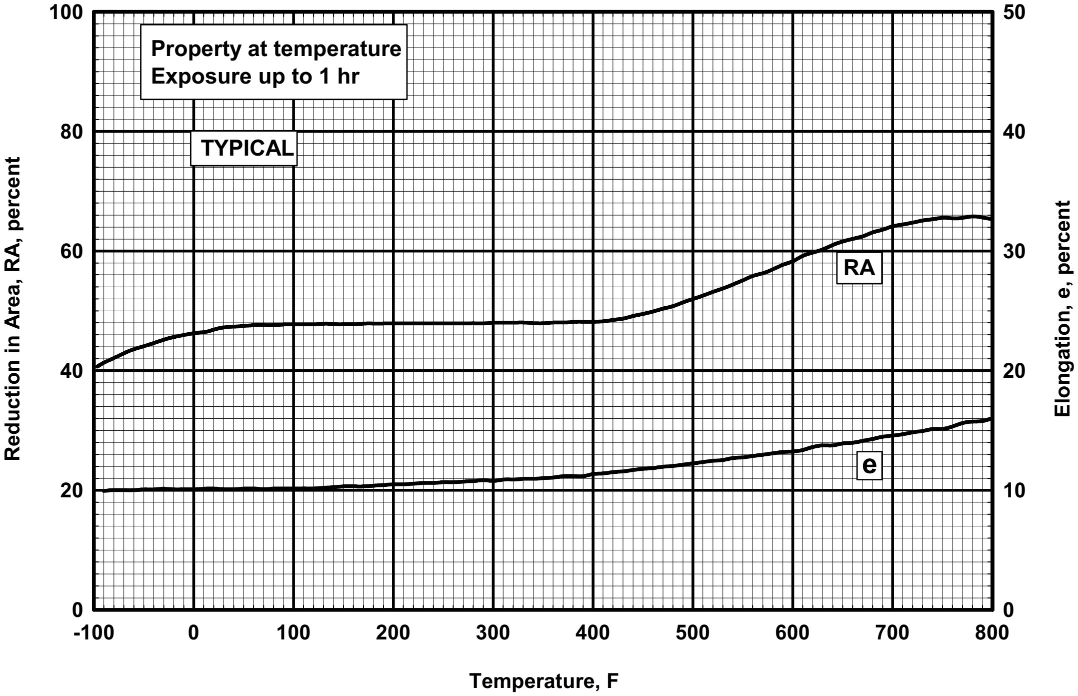

Figure 2.6.4.1.5. Effect of temperature on the elongation (e) and reduction of area (RA) of Custom 455 (H950) stainless steel bar.

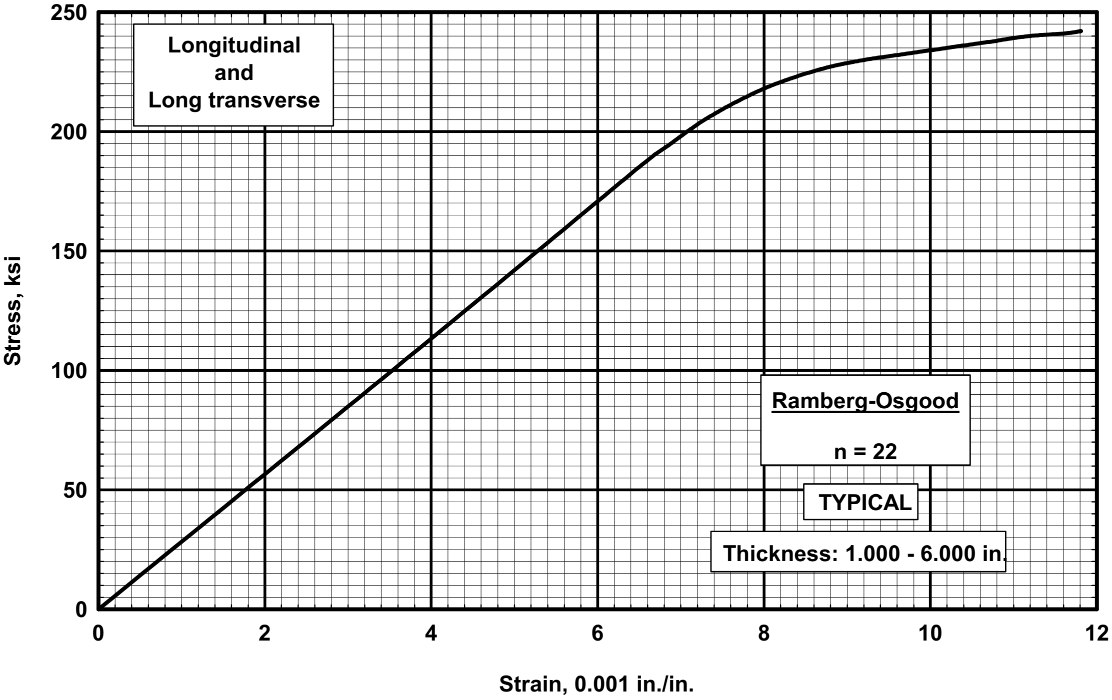

Figure 2.6.4.1.6. Typical tensile stress-strain curve for Custom 455 (H950) stainless steel bar at room temperature.

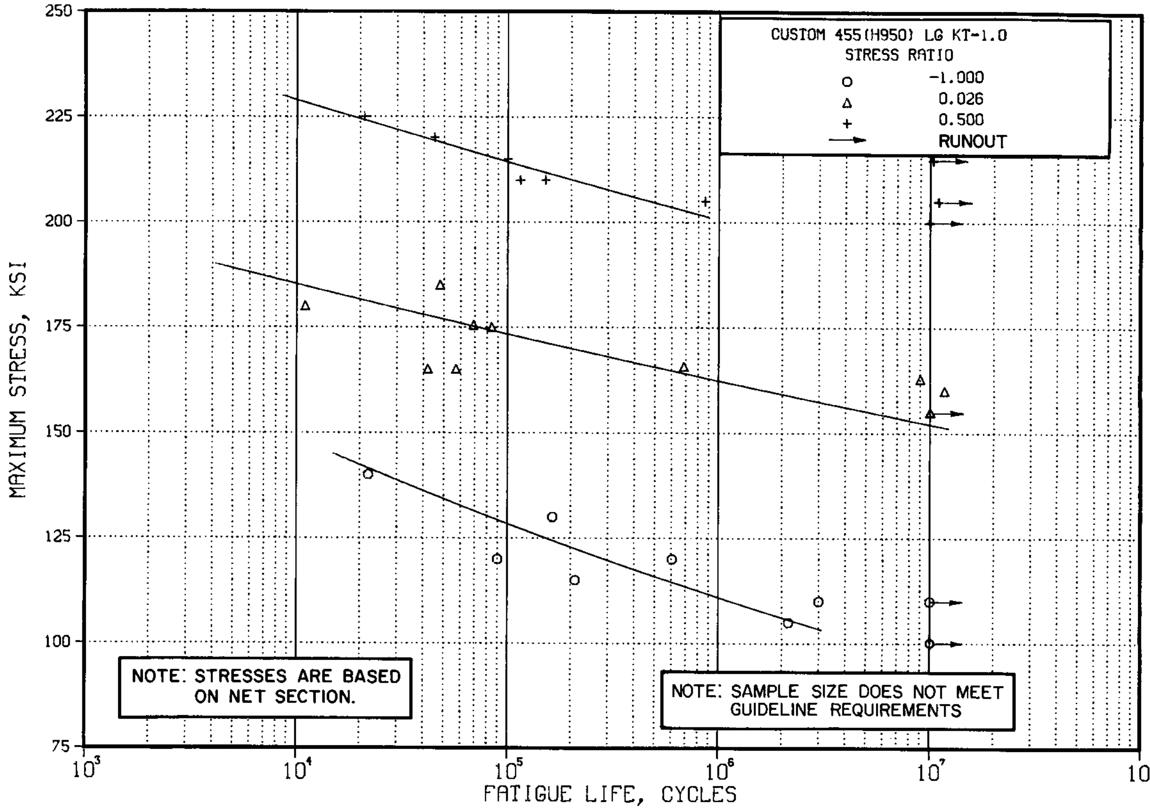

Figure 2.6.4.1.8(a). Best-fit S/N curves for unnotched, Custom 455 (H950) stainless steel bar, longitudinal direction.

Correlative Information for Figure 2.6.4.1.8(a)

Product Form: Bar, 1.0625 inch diameter

Properties:

TUS, ksi	TYS, ksi	Temp.,°F
245	242	RT (unnotched)

Specimen Details: Unnotched
0.200-inch diameter

Surface Condition: Hand polished in longitudinal direction, finishing with 3 μ diamond paste

Reference: 2.6.3.1.8

Test Parameters:
Loading - Axial
Frequency - 1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 1

Equivalent Stress Equation:
Log N_f = 38.1-15.7 log S_{max}, R = -1.0
= 82.9-34.8 log S_{max}, R = 0.026
= 85.9-34.7 log S_{max}, R = 0.50

Sample Size = 22

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

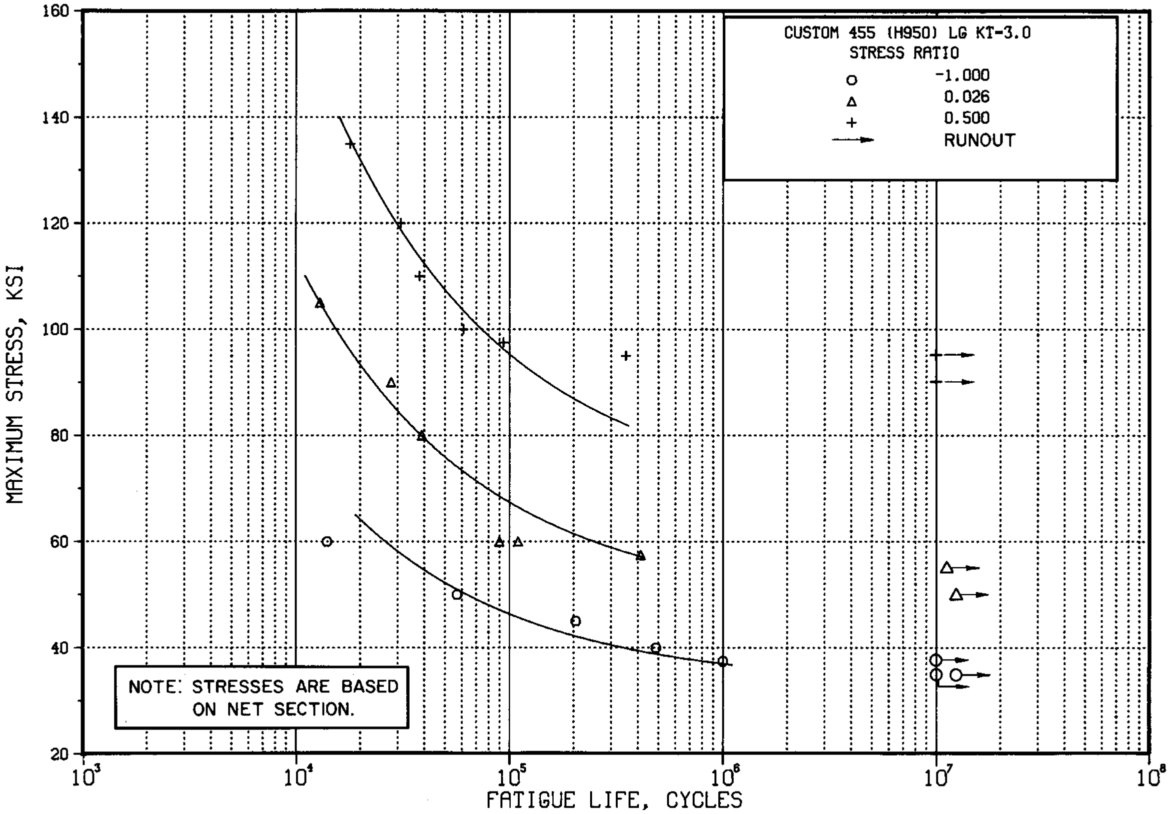

Figure 2.6.4.1.8(b). Best-fit S/N curves for notched, K_t = 3.0, Custom 455 (H950) stainless steel bar, longitudinal direction.

Correlative Information for Figure 2.6.4.1.8(b)

Product Form: Bar, 1.0625 inch diameter

Properties:

TUS, ksi	TYS, ksi	Temp.,°F
245	242	RT (unnotched)
361	—	RT (notched)

Specimen Details: Notched, V-Groove, $K_t = 3.0$
0.283 inch gross diameter
0.200 inch net diameter
0.010 inch root radius, r
60° flank angle, ω

Surface Condition: Polished with abrasive nylon cord

Reference: 2.6.3.1.8

Test Parameters:
Loading - Axial
Frequency - 1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 1

Equivalent Stress Equation:
$\text{Log } N_f = 7.42-1.90 \log (S_{eq}-47.34)$
$S_{eq} = S_{max} (1-R)^{0.515}$
Std. Error of Estimate, Log (Life) = 0.246
Standard Deviation, Log (Life) = 0.568
$R^2 = 81\%$

Sample Size = 17

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

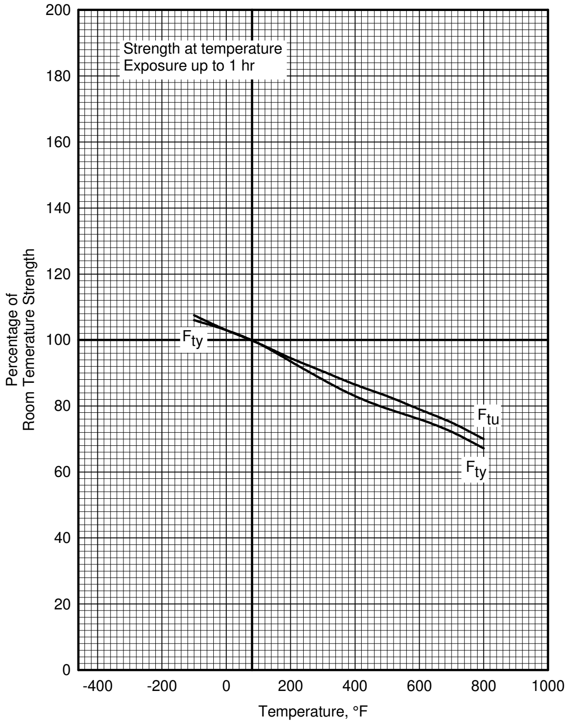

Figure 2.6.4.2.1. Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of Custom 455 (H1000) stainless steel bar.

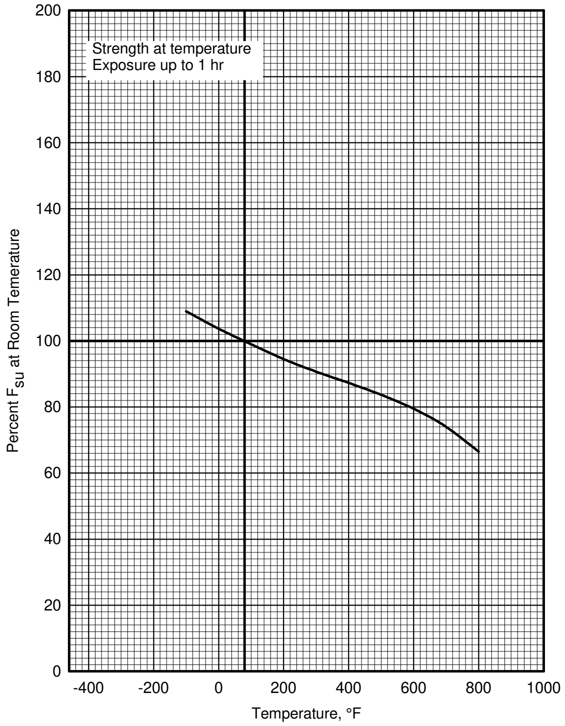

Figure 2.6.4.2.2. Effect of temperature on the ultimate shear strength (F_{su}) of Custom 455 (H1000) stainless steel bar.

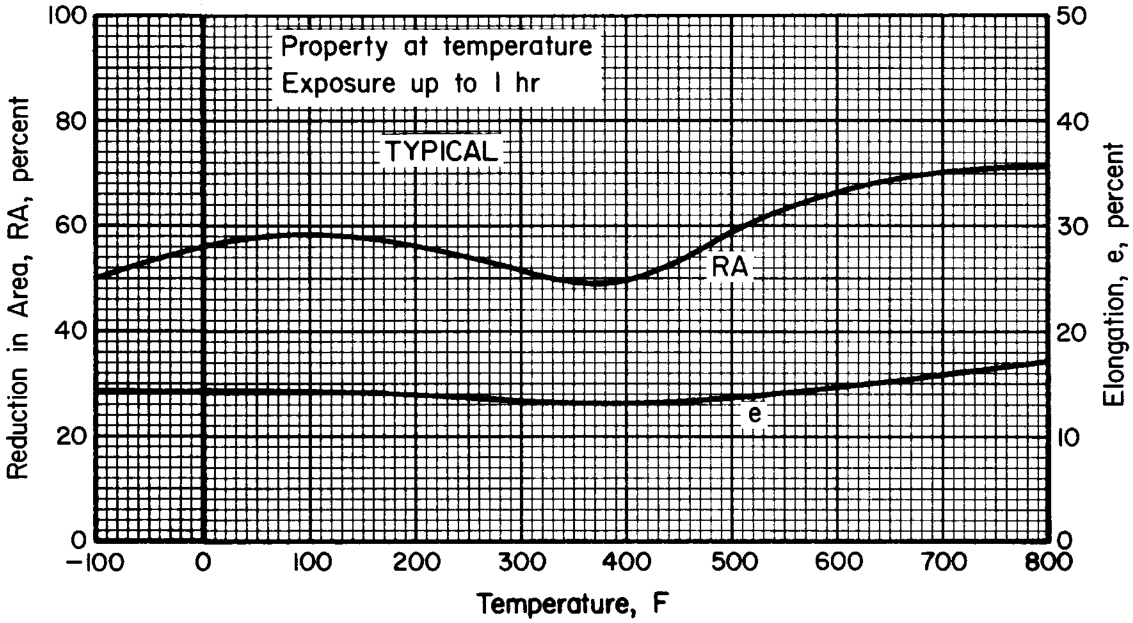

Figure 2.6.4.2.5. Effect of temperature on the elongation (e) and the reduction of area (RA) of Custom 455 (H1000) stainless steel bar.

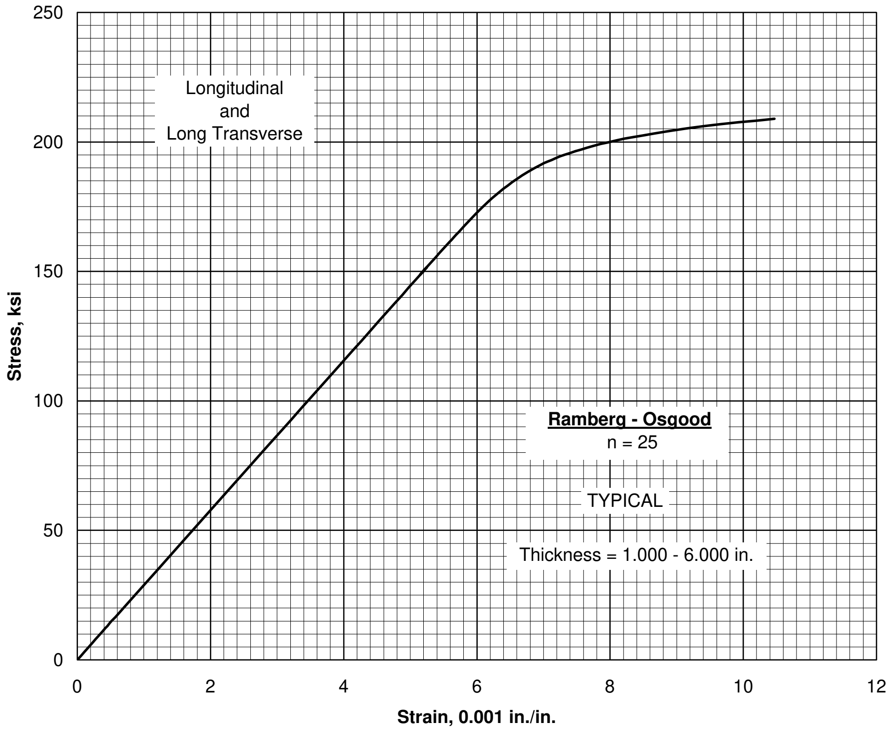

Figure 2.6.4.2.6. Typical tensile stress-strain curve for Custom 455 (H1000) stainless steel bar at room temperature.

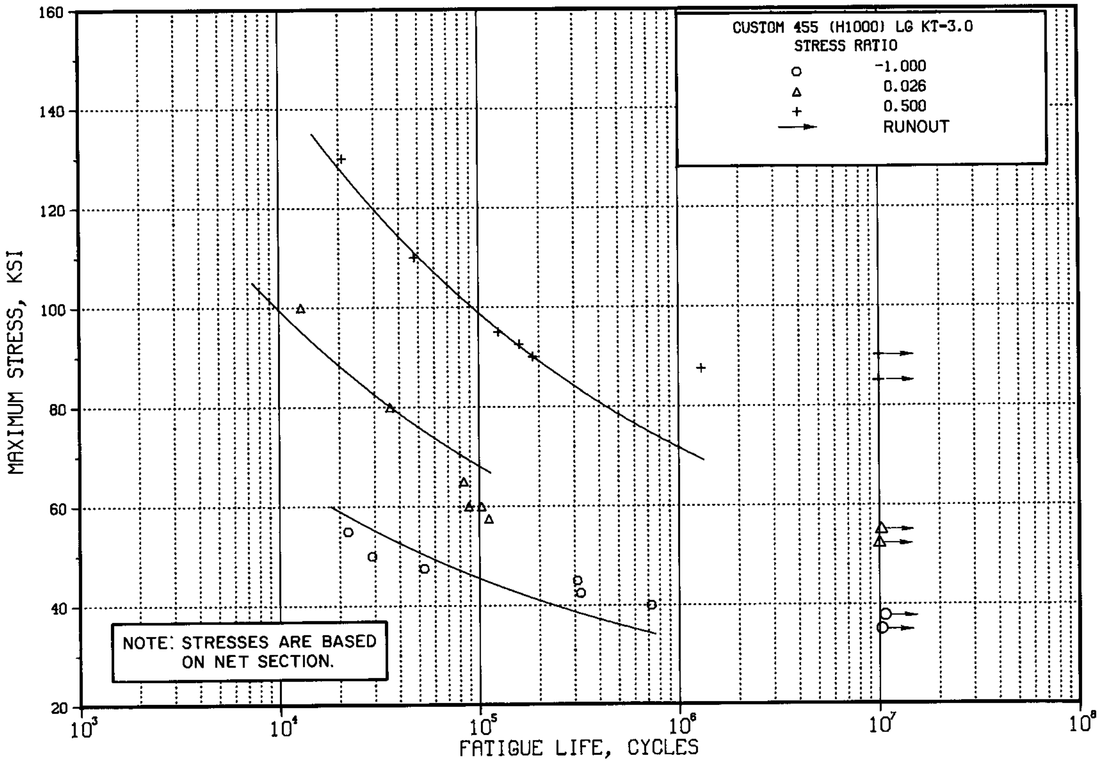

Figure 2.6.4.2.8. Best-fit S/N curves for notched, K_t = 3.0, Custom 455 (H1000) stainless steel bar, longitudinal direction.

Correlative Information for Figure 2.6.4.2.8

Product Form: Bar, 1.0625 inch diameter

Properties:

TUS, ksi	TYS, ksi	Temp., °F
214	209	RT (unnotched)
335	—	RT (notched)

Specimen Details: Notched, V-Groove, K_t=3.0
0.283 inch gross diameter
0.200 inch net diameter
0.010 inch root radius, r
60° flank angle, ω

Surface Condition: Polished with abrasive nylon cord

Reference: 2.6.3.1.8

Test Parameters:
Loading - Axial
Frequency - 1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 1

Equivalent Stress Equation:
$\text{Log } N_f = 12.37 - 4.44 \log (S_{eq} - 21.43)$
$S_{eq} = S_{max} (1-R)^{0.561}$
Std. Error of Estimate, Log (Life) = 0.359
Standard Deviation, Log (Life) = 0.540
R^2 = 56%

Sample Size = 18

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

2.6.5 CUSTOM 465

2.6.5.0 *Comments and Properties* — Custom 465® stainless is a double-vacuum melted, martensitic, age-hardenable alloy. This alloy was designed to have excellent notch tensile strength and fracture toughness over a wide range of section sizes. In the H950 condition, the alloy achieves a minimum ultimate tensile strength of 240 ksi while retaining good toughness and resistance to stress-corrosion cracking. Overaging to the H1000 condition provides a greater level of toughness at a minimum ultimate tensile strength of 220 ksi. Custom 465 stainless provides a superior combination of strength, toughness and stress corrosion cracking resistance compared with other high-strength PH stainless alloys such as Custom 455® stainless or PH13-8Mo® stainless. Other combinations of strength and toughness are possible employing age-hardening temperatures between 900°F and 1150°F. Custom 465 stainless is available in the form of forgings, billet, bar, wire and strip.

Manufacturing Considerations —Custom 465 stainless normally is supplied and fabricated in the solution-annealed condition. Billet products will be provided in the hot finished condition. Forming, machining, and joining operations are similar to those employed for other precipitation-hardening stainless steels. Optimum weld strength and ductility are obtained by postweld solution annealing and subzero cooling prior to aging. Pyromet®X23 stainless filler metal should be considered under multi-bead GMA welding conditions.

Heat Treatment —Among the corrosion-resistant alloys of its type, Custom 465 stainless provides the highest minimum combinations of strength and toughness in the H950 and H1000 conditions. Usually, parts are aged directly from the mill-supplied, solution-annealed condition. However, if material has been hot worked or welded, components should be reannealed (1800°F/982°C) and subzero cooled (-100°F/-73°C, 8-hour hold) prior to age hardening. Components should be cooled rapidly from the annealing temperature. Section sizes up to 12" (305 mm) can be cooled in a suitable liquid quench medium. The subsequent subzero treatment should be applied within 24-hours of solution annealing. The refrigeration treatment after annealing is important for achieving optimum aging response by eliminating small amounts of retained austenite from the microstructure. The mill-supplied solution anneal includes the subzero treatment.

Aging treatments are performed by heating components to the specified temperature, holding for four hours, followed by cooling in air, oil or other suitable liquid quench medium. The 4-hour aging cycle is important developing optimum toughness and ductility at the specified strength levels. Increased cooling rates from the aging temperature tend to improve toughness and ductility and may be beneficial for 3" (76mm) section sizes and greater.

Environmental Considerations — The general corrosion resistance of Custom 465 stainless approaches that of Type 304 stainless. Exposure to 5% neutral salt spray at 95°F (35°C) (per ASTM B117) caused little or no corrosion after 200 hours regardless of condition (i.e., annealed or H900-H1100 conditions).

Double cantilever beam tests conducted in 3.5% NaCl (pH 6) show Custom 465 stainless to possess inherently good resistance to stress corrosion cracking which improves with increasing aging temperature. Typical results for 1/2" thick double cantilever beam specimens (T-L orientation) from 4-1/2" x 2-3/4" forged bar exposed to 3.5 wt. % NaCl (pH 6) for 1270 hours by constant immersion per NACE Standard TM0177-96 (Reference 2.6.5.0), are shown in Table 2.6.5.0(a).

Table 2.6.5.0(a). Typical Stress Corrosion Cracking Resistance[a]

Condition	TYS (T), ksi	K_{Iscc}, ksi$\sqrt{}$in.	Remarks
H950	226	68	No cracking
H1000	213	98	No cracking

[a] Double-cantilever-beam, wedge loaded, constant immersion in 3.5% NaCl (pH 6) per NACE Standard TM0177-96. See Reference 2.6.5.0.

Typical tensile properties following exposure to elevated temperatures for 200 and 1000 hours are shown in Table 2.6.5.0(b).

Table 2.6.5.0(b). Effect of Elevated Temperature Exposure on Typical Tensile Properties of Custom 465 Alloy[a]

Condition	Exposure Temp., °F	Exposure Time, Hours	Room-temperature properties			
			UTS, ksi	TYS, ksi	e, %	RA, %
H950	Room Temp.	Unexposed	255	238	14	62
	600	200	258	240	14	61
	700	200	266	249	13	59
	800	200	266	249	14	58
	900	200	236	223	15	64
	600	1000	259	242	16	59
	700	1000	268	250	14	56
	800	1000	272	253	13	54
	900	1000	223	211	19	67
H1000	Room Temp.	Unexposed	231	218	16	66
	600	200	234	220	14	66
	700	200	241	226	15	64
	800	200	240	226	14	66
	900	200	230	218	16	66
	600	1000	232	219	18	65
	700	1000	240	226	16	64
	800	1000	245	229	15	62
	900	1000	222	210	20	66

[a] Data from 1 heat, 4.5" x1.5" forged bar, duplicate tests

Specifications and Properties — Material specifications for Custom 465 are shown in Table 2.6.5.0(c). The room-temperature mechanical properties are presented in Tables 2.6.5.0(b).

Table 2.6.5.0(c). Material Specifications for Custom 465 Stainless Steel

Specification	Form
AMS 5936	Bars, Wires, and Forgings

2.6.5.1 *H950 and H1000 Condition* — Figure 2.6.5.1(a) presents the typical tensile stress-strain curves at room temperature. Figures 2.6.5.1(b) and (c) present the full-range tensile stress-strain curves at room temperature for the H950 and H1000 conditions.

Table 2.6.5.0(d). Design Mechanical and Physical Properties of Custom 465 Stainless Steel Bar

Specification	AMS 5936			
Form	Bar			
Condition	H950		H1000	
Thickness or diameter, in.	≤12.000		≤12.000	
Basis	A	B	A	B
Mechanical Properties:				
F_{tu}, ksi:				
L	240[a]	251	220[b]	226
T	240[a]	251	220[b]	226
F_{ty}, ksi:				
L	220[a]	236	200[b]	212
T	220[a]	236	200[b]	213
F_{cy}, ksi:				
L	233	249	210	223
T	233	250	211	224
F_{su}, ksi	134	140	129	132
F_{bru}[c], ksi:				
(e/D = 1.5)	359	375	333	342
(e/D = 2.0)	462	484	428	440
F_{bry}[c], ksi:				
(e/D = 1.5)	321	344	294	312
(e/D = 2.0)	365	391	353	374
e, percent: (S-basis)				
L	10	...	10	...
T	8	...	10	...
RA, percent: (S-basis)				
L	45	...	50	...
T	35	...	40	...
E, 10^3 ksi	28.7		28.4	
E_c, 10^3 ksi	28.9		29.4	
G, 10^3 ksi	11.2		11.3	
μ	0.28		0.28	
Physical Properties:				
ω, lb/in.^{3}	0.28		0.28	
C, Btu/(lb)(°F)	...		see Figure 2.6.5.0(a)	
K, Btu/[(hr)(ft^2)(°F)/ft]	...		see Figure 2.6.5.0(a)	
α, 10^{-6} in./in./°F	...		see Figure 2.6.5.0(a)	

a S-basis. The rounded T99 value for F_{tu} (L) = 246 ksi, F_{tu} (T) = 249, F_{ty} (L) = 230 ksi, and F_{ty} (T) = 231 ksi

b S-basis. The rounded T99 value for F_{tu} (L) = 221 ksi, F_{tu} (T) = 221, F_{ty} (L) = 206 ksi, and F_{ty} (T) = 208 ksi

c Bearing values are "dry pin" values per Section 1.4.7.1

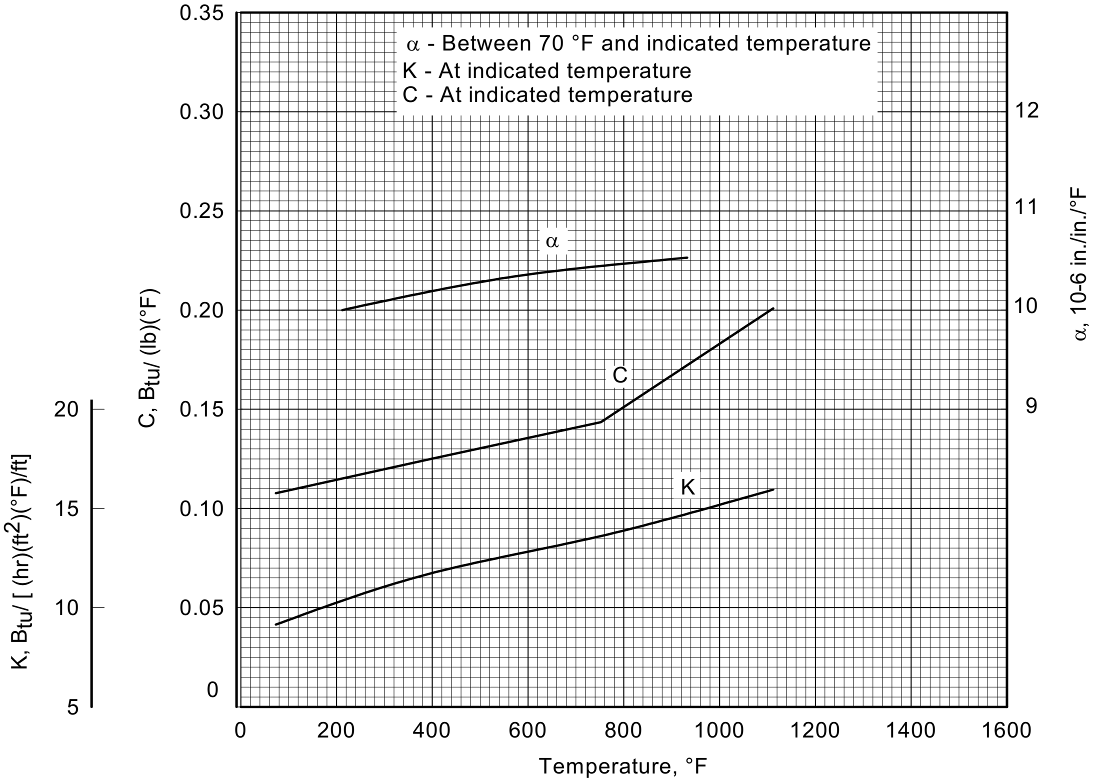

Figure 2.6.5.0(a). Effect of temperature on the physical properties of Custom 465 H1000 stainless steel bar.

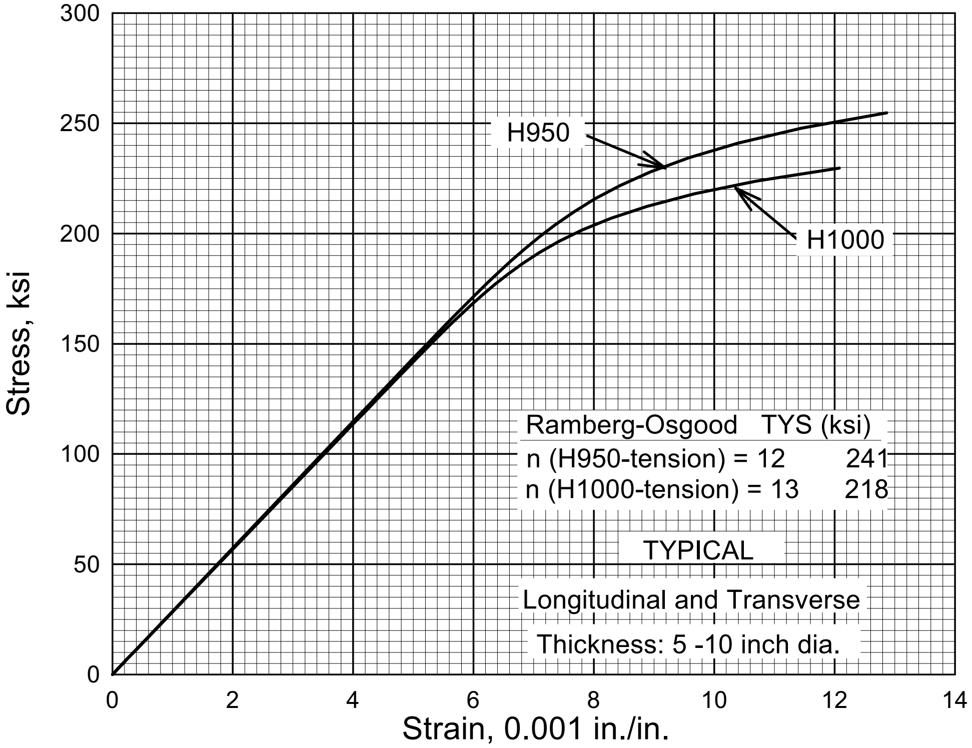

Figure 2.6.5.1(a). Typical tensile stress-strain curves for Custom 465, H950 and H1000 condition bar at room temperature.

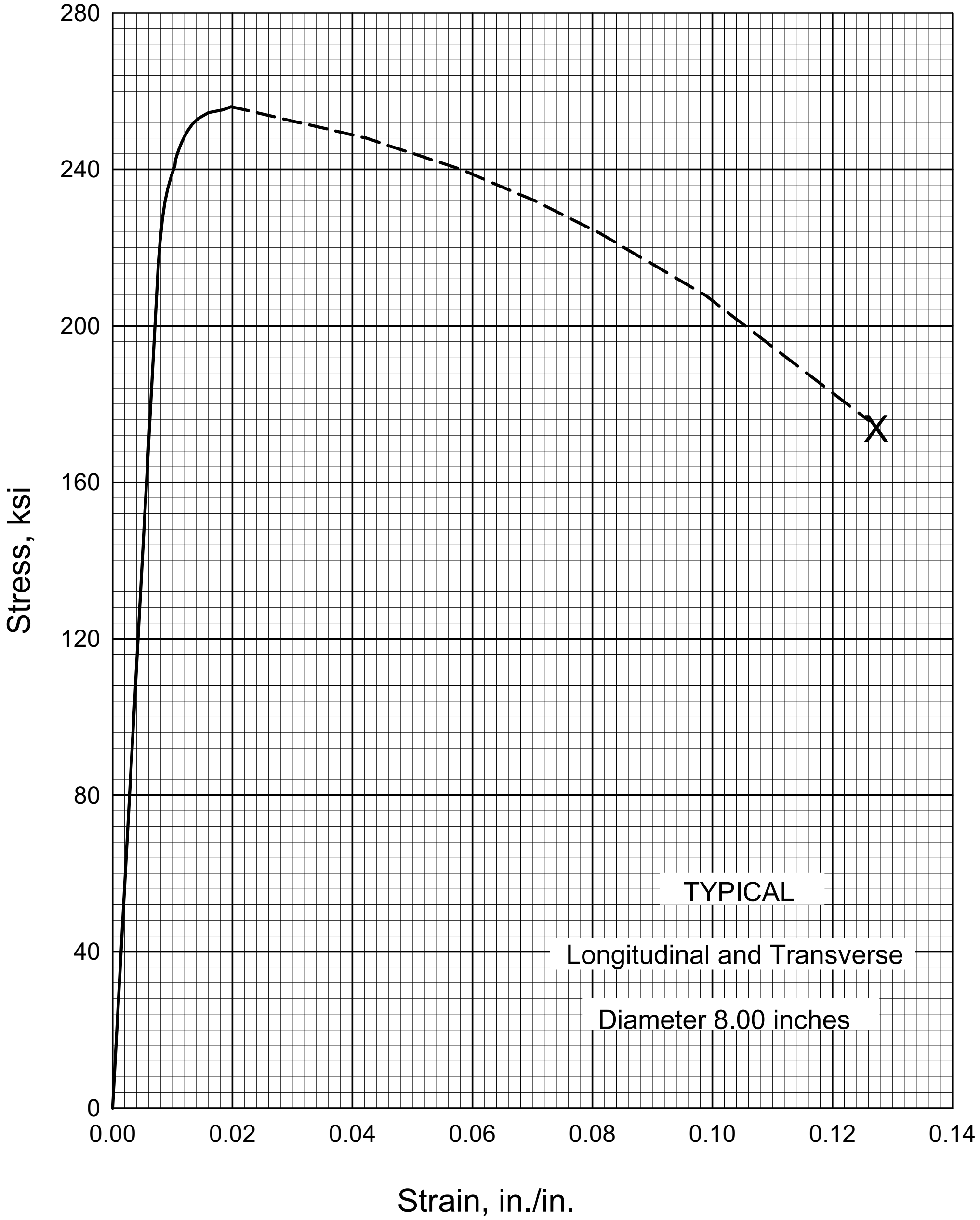

Figure 2.6.5.1(b). Typical tensile stress-strain curves (full range) for Custom 465 H950 bar at room temperature.

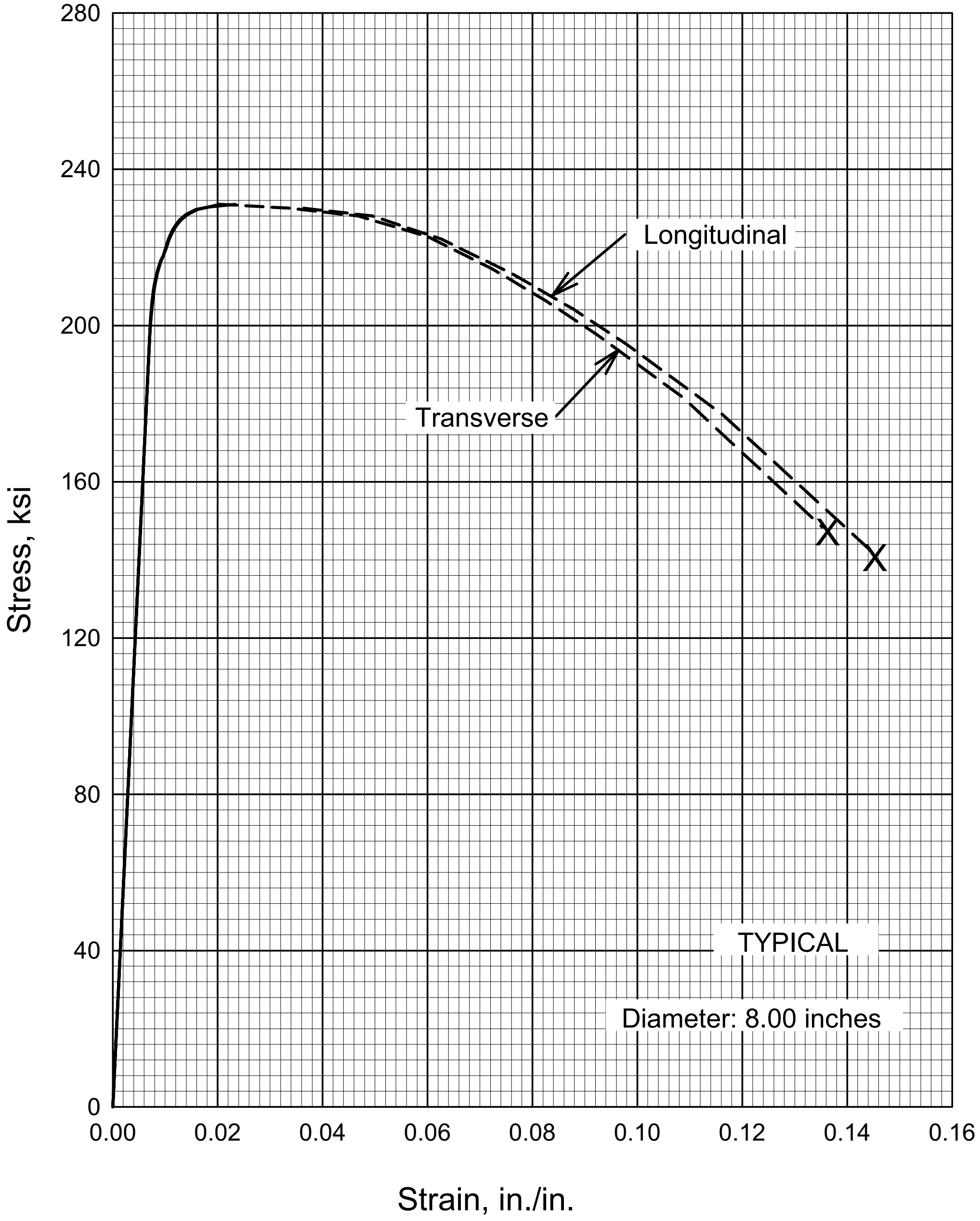

Figure 2.6.5.1(c). Typical tensile stress-strain curves (full range) for Custom 465, H1000 bar at room temperature.

2.6.6 PH13-8Mo

2.6.6.0 *Comments and Properties* — PH13-8Mo is a martensitic precipitation-hardening stainless steel used for parts requiring corrosion resistance, high strength, high fracture toughness, and oxidation resistance up to 800°F. When used at temperatures between 600°F and 800°F, some loss in notch toughness will occur. The loss is time-temperature dependent and will occur gradually over thousands of hours at 600°F and hundreds of hours at 800°F. Depending upon the application, this loss in notch toughness may not be important and useful engineering properties may still be available. Good transverse mechanical properties are one of the major advantages of PH13-8Mo. PH13-8Mo is produced by double vacuum melting and is available in the form of forgings, plate, bar, and wire, normally furnished in the solution-treated (A) condition.

Manufacturing Considerations — Forming, joining, and machining operations are usually performed on material in Condition A, using similar procedures and equipment to those employed for other precipitation-hardening stainless steels. Best machinability is exhibited by Conditions H1150 and H1150M. A dimensional contraction of 0.0004 to 0.0006 and 0.0008 to 0.0012 in./in. occurs upon hardening to the H1000 and H1100 conditions, respectively.

Heat Treatment — PH13-8Mo must be used in the heat-treated condition and should not be placed in service in Condition A. The alloy can be heat treated to various strength levels having a wide range of properties. Consult the applicable material specification or MIL-H-6875 for specific heat treatment procedures.

Environmental Considerations — PH13-8Mo is nearly equal to 17-4PH in general corrosion resistance and surpasses the other hardenable stainless steels in stress-corrosion resistance. However, for tensile application where stress corrosion is a possibility, PH13-8Mo should be aged at the highest temperature compatible with strength requirements and at a temperature not lower than 1000°F for 4 hours minimum aging time.

Specification and Properties — A material specification for PH13-8Mo is presented in Table 2.6.6.0(a). The room-temperature mechanical and physical properties for PH13-8Mo are presented in Table 2.6.6.0(b) and (c). The physical properties of this alloy at elevated temperatures are presented in Figure 2.6.6.0.

Table 2.6.6.0(a). Material Specification for PH13-8Mo Stainless Steel

Specification	Form
AMS 5629	Bar, forging, ring, and extrusion (VIM plus CEVM)

2.6.6.1 *H950 and H1000 Conditions* — Elevated temperature curves for tensile yield and ultimate strengths are presented in Figure 2.6.6.1.1. Typical tensile and compressive stress-strain and tangent-modulus curves for the H1000 condition at room temperature are depicted in Figures 2.6.6.1.6(a) and (b). Figure 2.6.6.1.6(c) contains typical full-range stress-strain curves at room temperature for various heat-treated conditions. Unnotched and notched fatigue information for H1000 condition at room temperature is presented in Figures 2.6.6.1.8(a) through (c).

Table 2.6.6.0(b). Design Mechanical and Physical Properties of PH13-8Mo Stainless Steel

Specification	AMS 5629							
Form	Round, hex, square and flat bar							
Condition	H950		H1000		H1025	H1050	H1100	H1150
Thickness or diameter, in.	<9.0		<8.0		≤12.0			
Basis	A	B	A	B	S	S	S	S
Mechanical Properties:[a]								
F_{tu}, ksi:								
L	217	221	201	208	185	175	150	135
T	217	221	201	208	185	175	150	135
F_{ty}, ksi:								
L	198	205	190[b]	200	175	165	135	90
T	198	205	190[b]	200	175	165	135	90
F_{cy}, ksi:								
L	...	...	200	211	...	...	...	...
T	...	...	200	211	...	...	...	...
F_{su}, ksi	...	...	117	122	...	...	...	...
F_{bru}, ksi:								
(e/D = 1.5)	...	...	302	313	...	...	...	...
(e/D = 2.0)	...	...	402	416	...	...	...	...
F_{bry}, ksi:								
(e/D = 1.5)	...	...	263	277	...	...	...	...
(e/D = 2.0)	...	...	338	356	...	...	...	...
e, percent (S-basis):								
L	10	...	10	...	11	12	14	14
T	10	...	10	...	11	12	14	14
RA, percent (S-basis):								
L	45	...	50	...	50	50	50	50
T	35	...	40	...	45	45	50	50
E, 10^3 ksi	28.3							
E_c, 10^3 ksi	29.4							
G, 10^3 ksi	11.0							
μ	0.28							
Physical Properties:								
ω, lb/in.^{3}	0.279							
C, Btu/(lb)(°F)	0.11 (32 to 212°F) (Est.)							
K and α	See Figure 2.6.6.0							

[a] Design allowables were based mainly upon data from samples of material, supplied in the solution treated condition, which were aged to demonstrate response to heat treatment by suppliers.

[b] S-basis. Rounded T_{99} value = 193 ksi.

Table 2.6.6.0(c). Design Mechanical and Physical Properties of PH13-8Mo Stainless Steel

Specification	AMS 5629					
Form	Forging, flash welded ring, and extrusion					
Condition	H950	H1000	H1025	H1050	H1100	H1150
Thickness or diameter, in.	≤12					
Basis	S	S	S	S	S	S
Mechanical Properties:						
F_{tu}, ksi:						
L	220	205	185	175	150	135
T	220	205	185	175	150	135
F_{ty}, ksi:						
L	205	190	175	165	135	90
T	205	190	175	165	135	90
F_{cy}, ksi:						
L	...	...	...	...	...	...
T	...	...	...	...	...	...
F_{su}, ksi	...	...	...	...	...	...
F_{bru}, ksi:						
(e/D = 1.5)	...	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...	...
F_{bry}, ksi:						
(e/D = 1.5)	...	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...	...
e, percent:						
L	10	10	11	12	14	14
T	10	10	11	12	14	14
RA, percent:						
L	45	50	50	50	50	50
T	35	40	45	45	50	50
E, 10^3 ksi	28.3					
E_c 10^3 ksi	29.4					
G, 10^3 ksi	11.0					
μ	0.28					
Physical Properties:						
ω, lb/in.^{3}	0.279					
C, Btu/(lb)(°F)	0.11 (32 to 212°F) (Est.)					
K and α	See Figure 2.6.6.0					

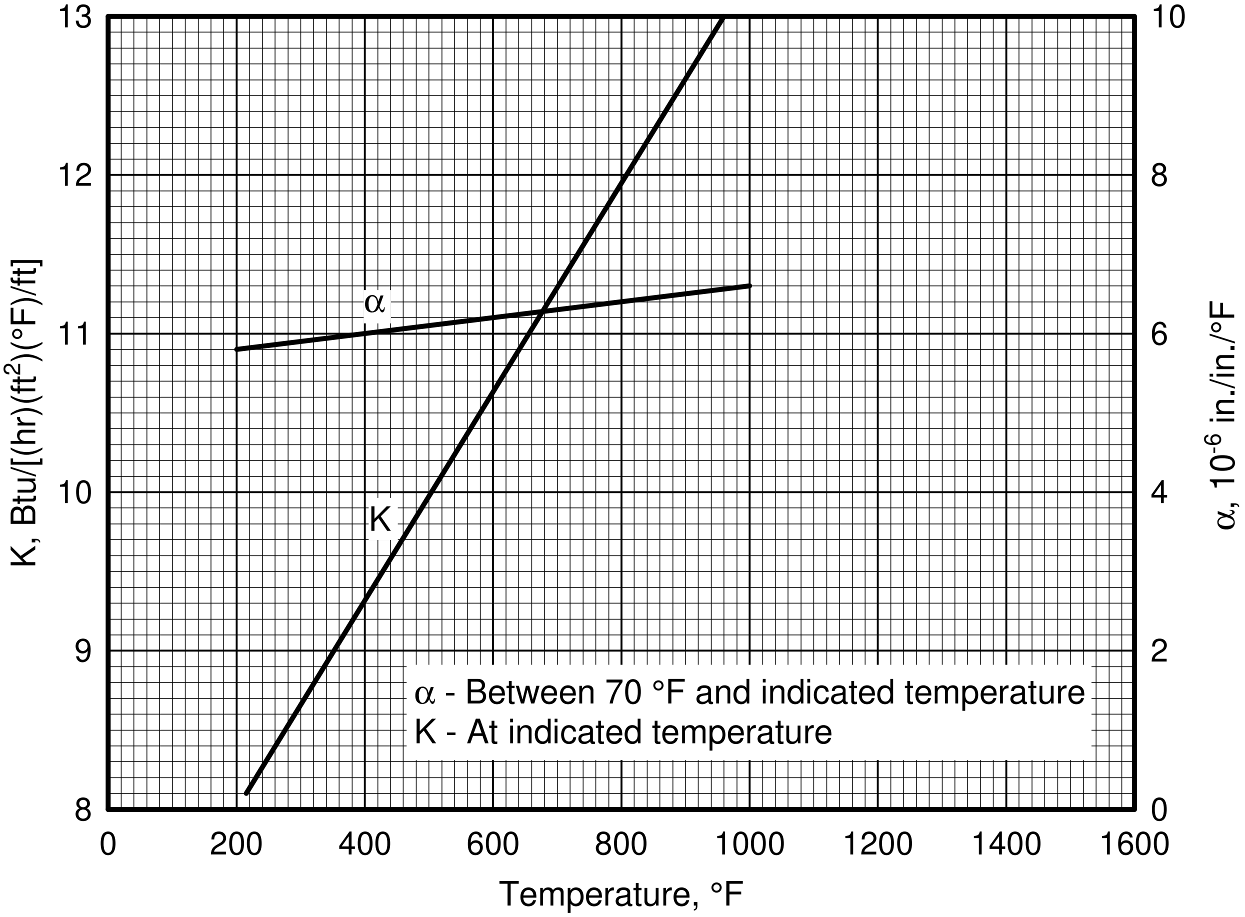

Figure 2.6.6.0. Effect of temperature on the physical properties of PH13-8Mo stainless steel.

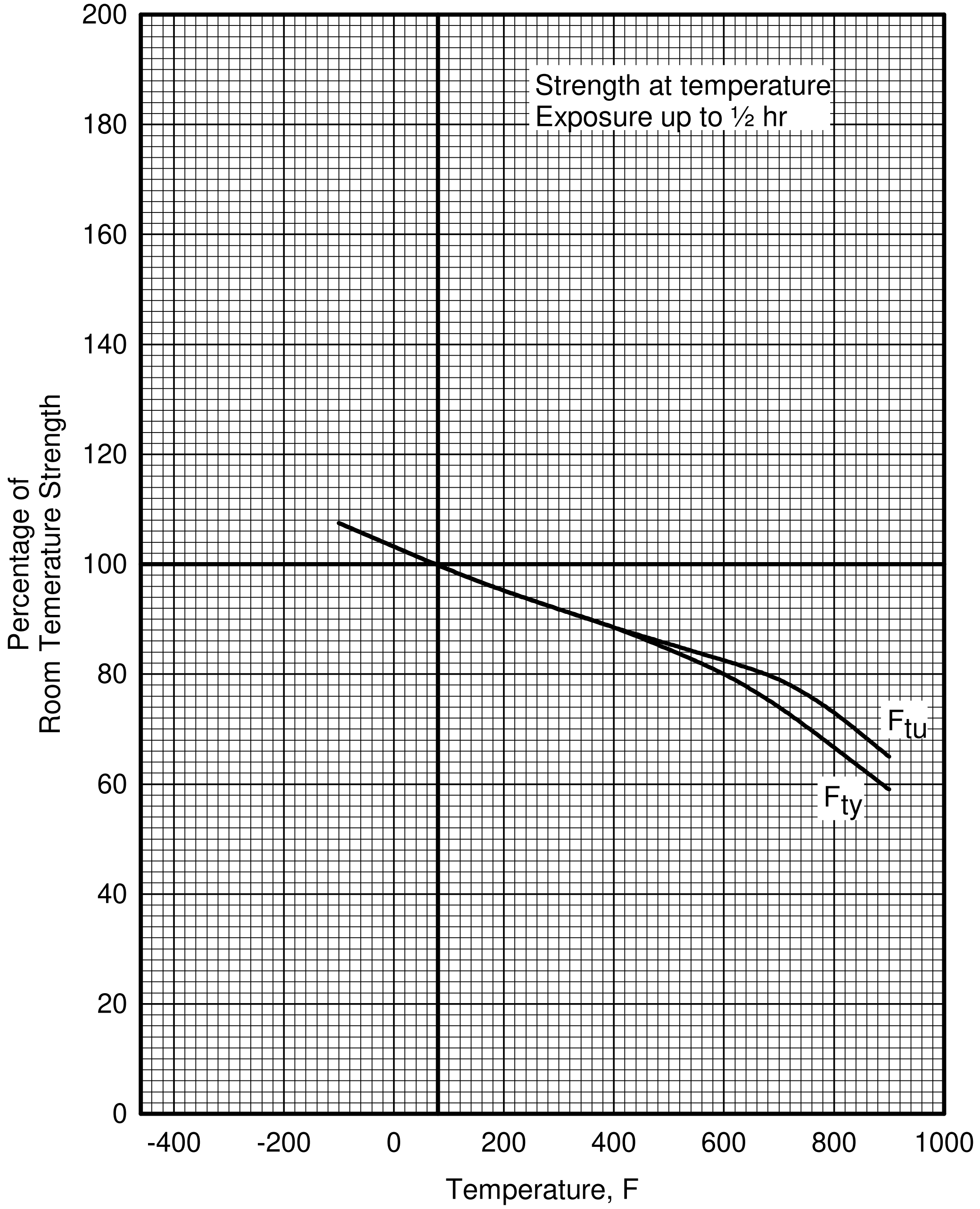

Figure 2.6.6.1.1. Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of PH13-8Mo (H950 and H1000) stainless steel bar.

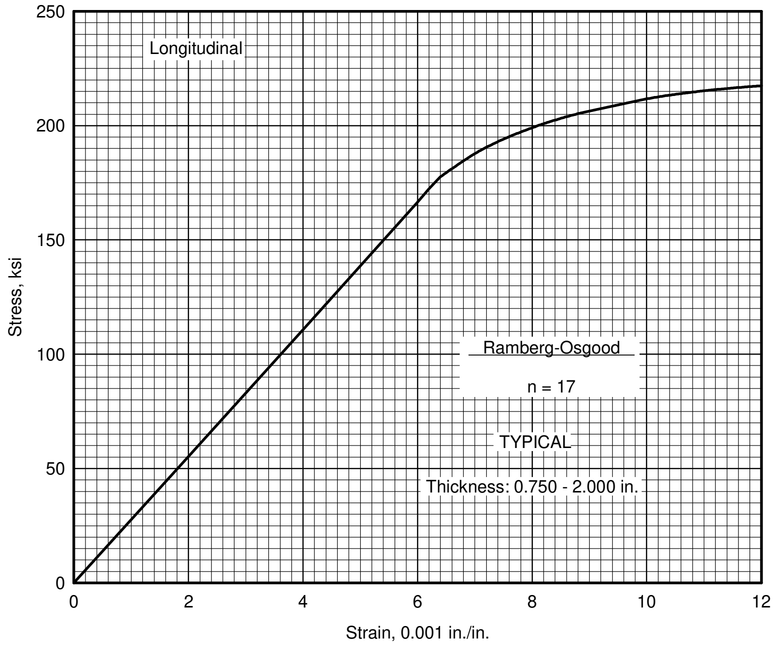

Figure 2.6.6.1.6(a). Typical tensile stress-strain curve at room temperature for PH13-8Mo (H1000) stainless steel bar.

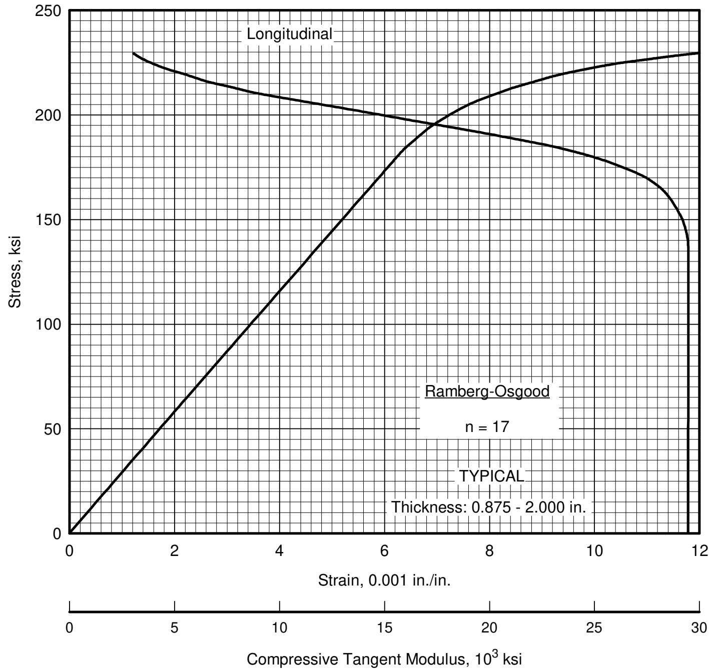

Figure 2.6.6.1.6(b). Typical compressive stress-strain and compressive tangent-modulus curves at room temperature for PH13-8Mo (H1000) stainless steel bar.

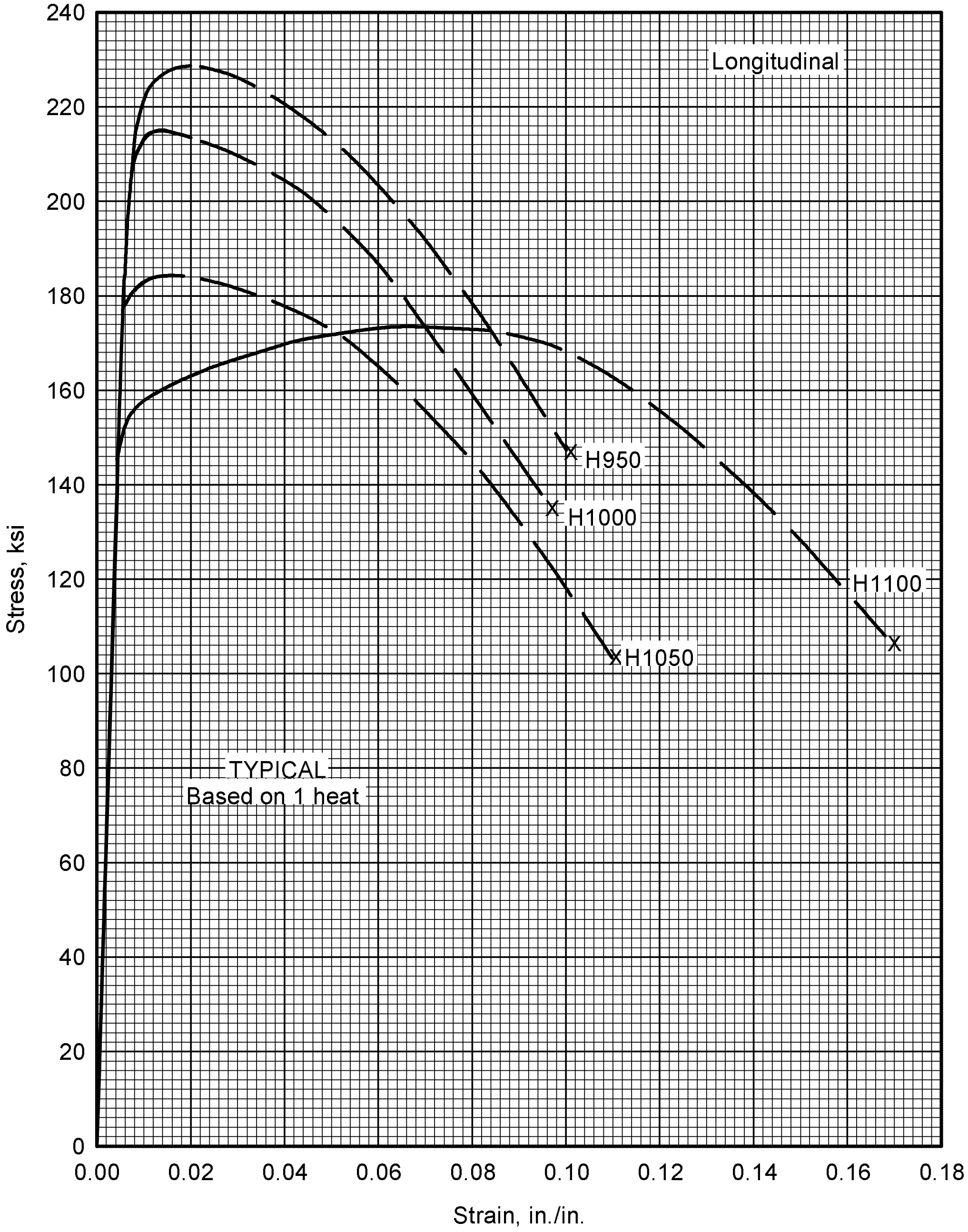

Figure 2.6.6.1.6(c). Typical tensile stress-strain curves (full range) at room temperature for various heat treated conditions of PH13-8Mo stainless steel bar.

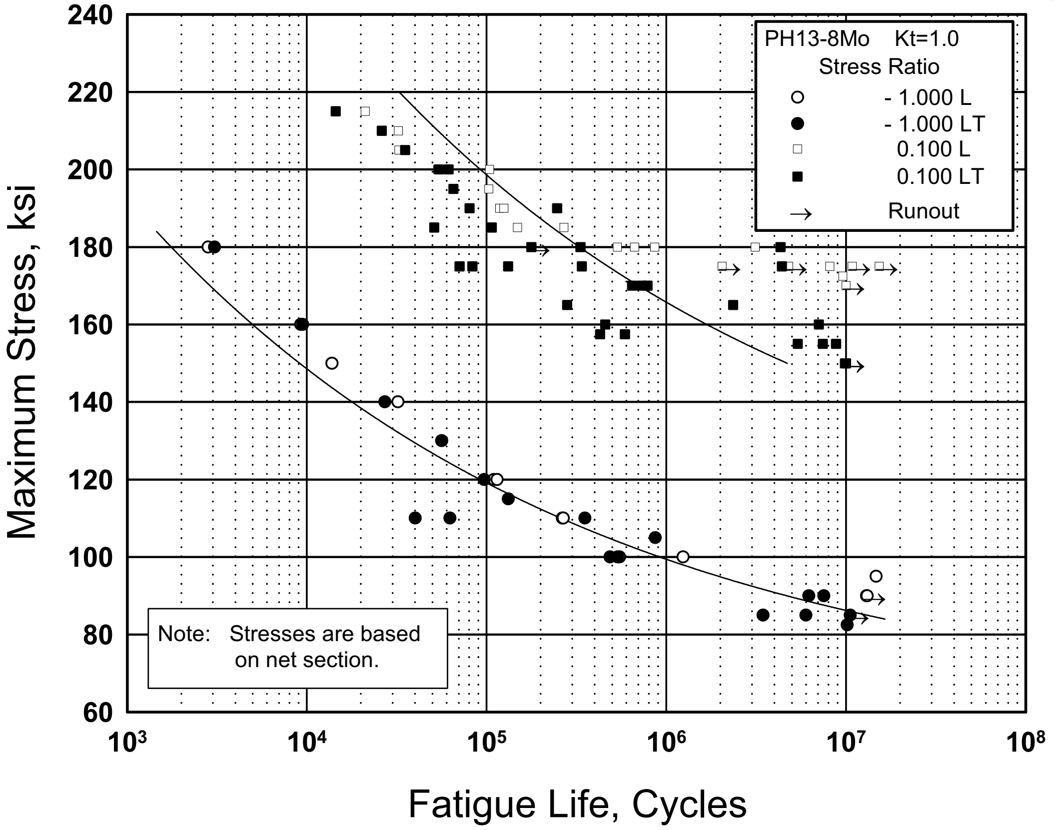

Figure 2.6.6.1.8(a). Best-fit S/N curves for unnotched PH13-8Mo (H1000) forged bar, longitudinal and transverse directions.

Correlative Information for Figure 2.6.6.1.8(a)

Product Form: Forged bar, 4 x 5 and 2 x 6 inches

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	205	197	RT

Specimen Details: Unnotched

Gross Diameter	Net Diameter
0.50 - 0.75	0.25

Surface Condition: Polished to RMS 10

References: 2.6.6.1.8(a), (b), (d)

Test Parameters:
Loading - Axial
Frequency - Not Specified
Temperature - RT
Environment - Air

No. of Heats/Lots: 4

Equivalent Stress Equation:
$\text{Log } N_f = 16.32 - 5.75 \log (S_{eq} - 92.6)$
$S_{eq} = S_{max} (1 - R)^{0.64}$
Std. Error of Estimate, Log (Life) = 0.461
Standard Deviation, Log (Life) = 0.919
$R^2 = 75\%$

Sample Size: 86

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

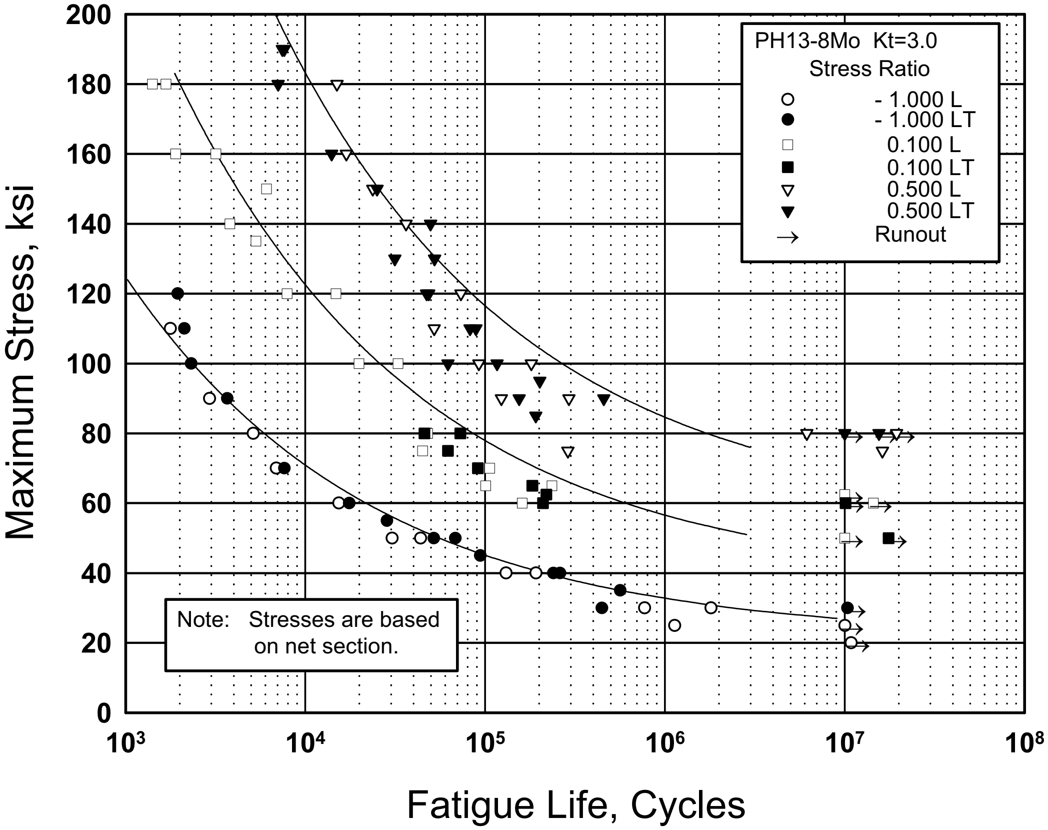

Figure 2.6.6.1.8(b). Best-fit S/N curves for notched, K_t = 3.0, PH13-8Mo (H1000) forged bar, longitudinal and long transverse directions.

Correlative Information for Figure 2.6.6.1.8(b)

Product Form: Forged bar, 4 x 5 and 2 x 6 inches

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	205	197	RT

Specimen Details: Notched, K_t = 3.0

Gross Diameter	Net Diameter	Notch Root Radius
0.750	0.252	0.013
0.500	0.250	0.013

60° flank angle

Surface Condition: Notch was polished with abrasively charged wire and rotating wire with oil and aluminum grit

References: 2.6.6.1.8(a), (b), (d)

Test Parameters:

Loading - Axial
Frequency - Not Specified
Temperature - RT
Environment - Air

No. of Heats/Lots: 4

Equivalent Stress Equation:
Log N_f = 9.90 - 3.13 log (S_{eq} - 34.4)
$S_{eq} = S_{max} (1 - R)^{0.68}$
Std. Error of Estimate, Log (Life) = 23.1 (1/S_{eq})
Standard Deviation, Log (Life) = 1.15
R^2 = 92%

Sample Size: 104

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

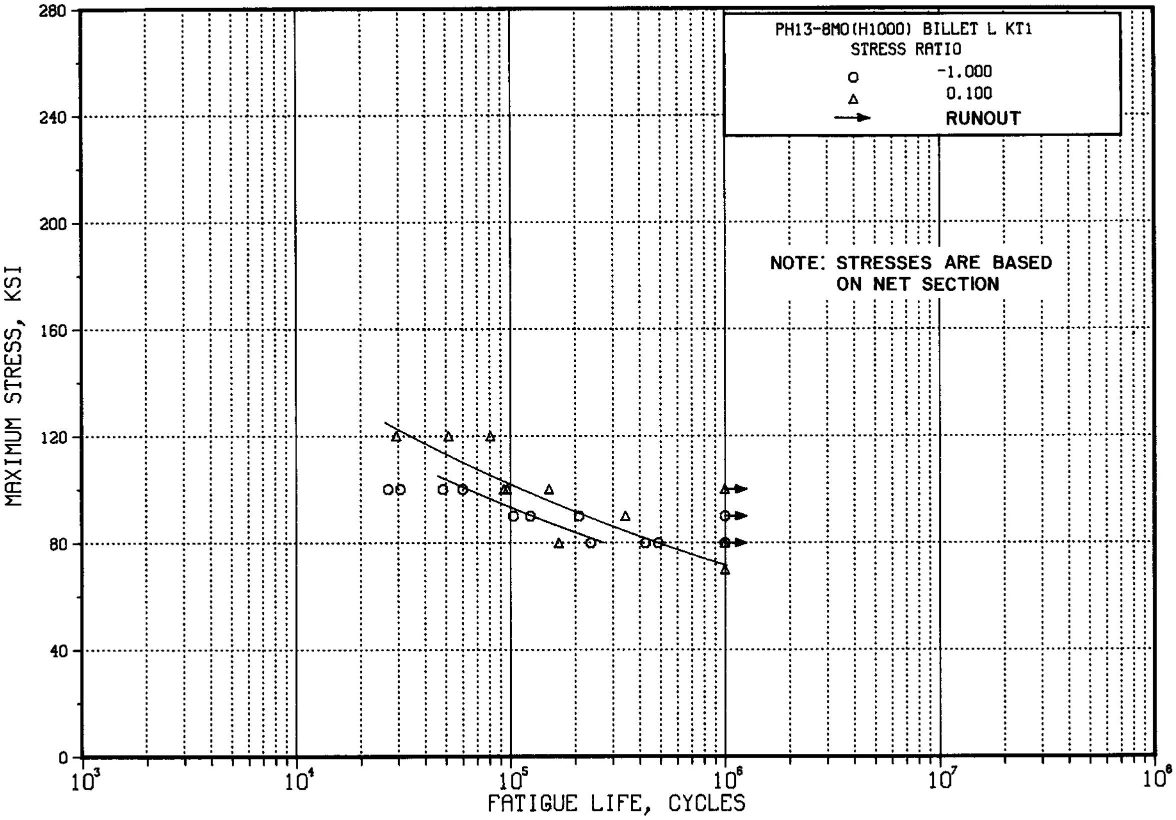

Figure 2.6.6.1.8(c). Best-fit S/N curves for unnotched PH13-8Mo (H1000) hand forging, longitudinal direction.

Correlative Information for Figure 2.6.6.1.8(c)

Product Form: Forged bar, 7 x 7 inches

Properties:

TUS, ksi	TYS, ksi	Temp., °F
210	204	RT

Specimen Details: Unnotched
0.500 inch gross diameter
0.250 inch net diameter

Surface Condition: Machined to RMS 63-270, solution treated and aged, grit blasted

Reference: 2.6.6.1.8(c)

Test Parameters:
Loading - Axial
Frequency - Not Specified
Temperature - RT
Environment - Air

No. of Heats/Lots: 2

Equivalent Stress Equation:
$\text{Log } N_f = 18.12 - 6.54 \log (S_{eq})$
$S_{eq} = S_{max} (1-R)^{0.11}$
Std. Error of Estimate, Log (Life) = 0.263
Standard Deviation, Log (Life) = 0.475
$R^2 = 69\%$

Sample Size: 20

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

2.6.7 15-5PH

2.6.7.0 *Comments and Properties* — 15-5PH is a precipitation-hardening, martensitic stainless steel used for parts requiring corrosion resistance and high strength at temperatures up to 600°F. Alloy 15-5PH has good transverse ductility and strength in large section sizes. This material is supplied in either the annealed or overaged condition and is heat treated after fabrication. Parts should never be used in Condition A. When good fracture toughness or impact properties are required, both at or below room temperature, conditions H900 and H925 should not be used. Conditions H1025, H1075, H1100, and H1150 provide lower transition temperatures and more useful levels of fracture toughness than the H900 and H925 conditions. The H1150M condition has the best notch toughness and is recommended for cryogenic applications.

Manufacturing Considerations — 15-5PH is readily forged and welded. Forging procedures are similar to those used for 17-4PH, the forgeability of 15-5PH being superior to that of 17-4PH in critical types of upset-forging and hot-flattening operations. Machining in the solution-treated condition is done at rates similar to Type 304 and 60 percent of these rates work well for Condition H900. Highest machining rates are possible with Conditions H1150 and H1150M. Material which is hot worked must be solution-treated before hardening. A dimensional contraction of 0.0004 to 0.0006 and 0.0008 to 0.0010 in./in. will occur on hardening to the H900 and H1150 conditions, respectively.

Heat Treatment — 15-5PH must be used in the heat-treated condition and should not be placed in service in Condition A. The alloy can be heat treated to various strength levels having a wide range of properties. Consult the applicable material specification or MIL-H-6875 for specific heat treatment procedures.

Environmental Considerations — The corrosion resistance of 15-5PH is comparable to that of 17-4PH. For tensile applications where stress corrosion is a possibility, 15-5PH should be aged at the highest temperature compatible with strength requirements and at a temperature not lower than 1025°F for 4 hours minimum aging time.

Specifications and Properties — Material specifications for 15-5PH are presented in Table 2.6.7.0(a). Room-temperature mechanical and physical properties of 15-5PH are shown in Tables 2.6.7.0(b) through (d). The effect of temperature on physical properties is depicted in Figure 2.6.7.0.

Table 2.6.7.0(a). Material Specifications for 15-5PH Stainless Steel

Specification	Form
AMS 5659	Bar, forging, ring, and extrusion (CEVM)
AMS 5862	Sheet, strip, and plate (CEVM)
AMS 5400	Investment casting

2.6.7.1 *Various Heat-Treated Conditions* — Elevated temperature curves for the various mechanical properties are shown in Figures 2.6.7.1.1 and 2.6.7.1.4. Typical stress-strain and tangent-modulus curves are shown in Figures 2.6.7.1.6(a) through (c).

2.6.7.2 *H1025 Condition* — An elevated temperature curve for compressive yield strength is presented in Figure 2.6.7.2.2. Stress-strain and tangent-modulus curves are shown in Figures 2.6.7.2.6(a) and (b). Fatigue data at room temperature are illustrated in Figures 2.6.7.2.8(a) through (c).

2.6.7.3 *H1150 Condition* — An elevated temperature curve for compressive yield strength is presented in Figure 2.6.7.3.2. Compressive stress-strain and tangent-modulus curves at various temperatures are shown in Figure 2.6.7.3.6.

Table 2.6.7.0(b). Design Mechanical and Physical Properties of 15-5PH Stainless Steel Bar and Forging

Specification	AMS 5659					
Form	Bar[a]					
Condition	H900	H925	H1025	H1075	H1100	H1150
Thickness or diam., in.	≤12	≤12	≤12	≤12	≤12	≤12
Basis	S	S	S	S	S	S
Mechanical Properties:						
F_{tu}, ksi:						
L	190	170	155	145	140	135
T	190	170	155	145	140	135
F_{ty}, ksi:						
L	170	155	145	125	115	105
T	170	155	145	125	115	105
F_{cy}, ksi:						
L	...	...	143	...	...	99
T	...	...	143	...	...	99
F_{su}, ksi	...	...	97	...	...	85
$F_{bru}{}^{b}$, ksi:						
(e/D = 1.5)	...	...	263	...	...	230
(e/D = 2.0)	...	...	332	...	...	293
$F_{bry}{}^{b}$, ksi:						
(e/D = 1.5)	...	...	211	...	...	166
(e/D = 2.0)	...	...	250	...	...	201
e, percent:						
L	10	10	12	13	14	16
T	6	7	8	9	10	11
RA, percent:						
L	35	38	45	45	45	50
T	20	25	32	33	34	35
E, 10^3 ksi	28.5					
E_c, 10^3 ksi	29.2					
G, 10^3 ksi	11.2					
μ	0.27					
Physical Properties:						
ω, lb/in.^{3}	0.283					
C, Btu/(lb)(°F)	...					
K and α	See Figure 2.6.7.0					

a Forging, ring, and extrusion product forms are also covered by AMS 5659.
b Bearing values are "dry pin" values per Section 1.4.7.1.

Table 2.6.7.0(c). Design Mechanical and Physical Properties of 15-5PH Stainless Steel Plate

Specification	AMS 5862			
Form	Plate			
Condition	H1025[a]			
Thickness, in.	0.187-0.625	0.626-2.000	2.001-3.000	3.001-4.000
Basis	S	S	S	S
Mechanical Properties:				
F_{tu}, ksi:				
L	154	154	154	...
LT	155	155	155	155
F_{ty}, ksi:				
L	143	143	143	...
LT	145	145	145	145
F_{cy}, ksi:				
L	150	150	150	...
LT	152	149	146	...
F_{su}, ksi	97	97	96	...
$F_{bru}{}^{b}$, ksi:				
(e/D = 1.5)	257	257	257	...
(e/D = 2.0)	331	331	331	...
$F_{bry}{}^{b}$, ksi:				
(e/D = 1.5)	211	211	211	...
(e/D = 2.0)	246	246	246	...
e, percent:				
LT	8	12	12	12
RA, percent:				
LT	35	40	40	40
E, 10^3 ksi	28.5			
E_c, 10^3 ksi	29.2			
G, 10^3 ksi	11.2			
μ	0.27			
Physical Properties:				
ω, lb/in.^{3}	0.283			
C, Btu/(lb)(°F)	...			
K and α	See Figure 2.6.7.0			

a The H900, H925, H1075, H1100, and H1150 conditions are included in AMS 5862.
b Bearing values are "dry pin" values per Section 1.4.7.1.

Table 2.6.7.0(d). Design Mechanical and Physical Properties of 15-5PH Stainless Steel Investment Casting

Specification	AMS 5400
Form	Investment casting
Condition	H935
Location within casting	Any area
Basis	S
Mechanical Properties:[a]	
F_{tu}, ksi	170
F_{ty}, ksi	150
F_{cy}, ksi	155
F_{su}, ksi	107
$F_{bru}{}^{b}$, ksi:	
(e/D = 1.5)	269
(e/D = 2.0)	349
$F_{bry}{}^{b}$, ksi:	
(e/D = 1.5)	209
(e/D = 2.0)	240
e, percent	6
RA, percent	14
E, 10^3 ksi	28.5
E_c, 10^3 ksi	29.2
G, 10^3 ksi	11.2
μ	0.27
Physical Properties:	
ω, lb/in.^{3}	0.283
C, Btu/(lb)(°F)	...
K, and α	See Figure 2.6.7.0

a Properties apply only when drawing specifies that conformance to tensile property requirements will be determined from specimens cut from castings or integrally cast specimens.

b Bearing values are "dry pin" values per Section 1.4.7.1.

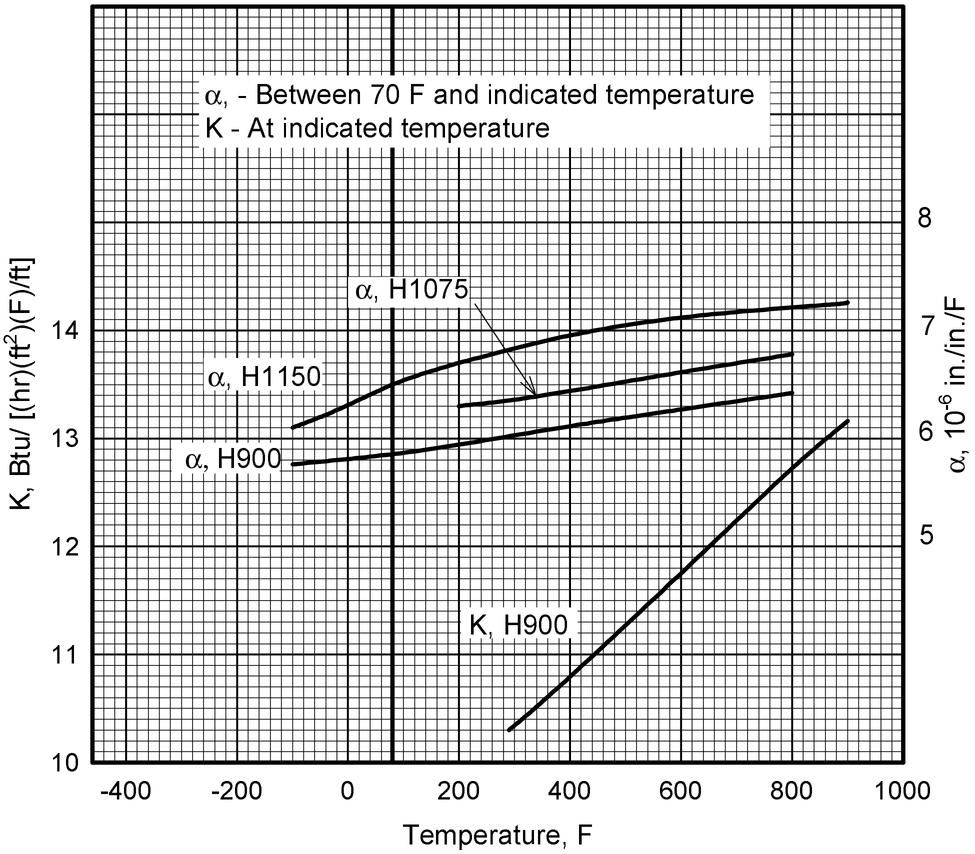

Figure 2.6.7.0. Effect of temperature on the physical properties of 15-5PH stainless steel.

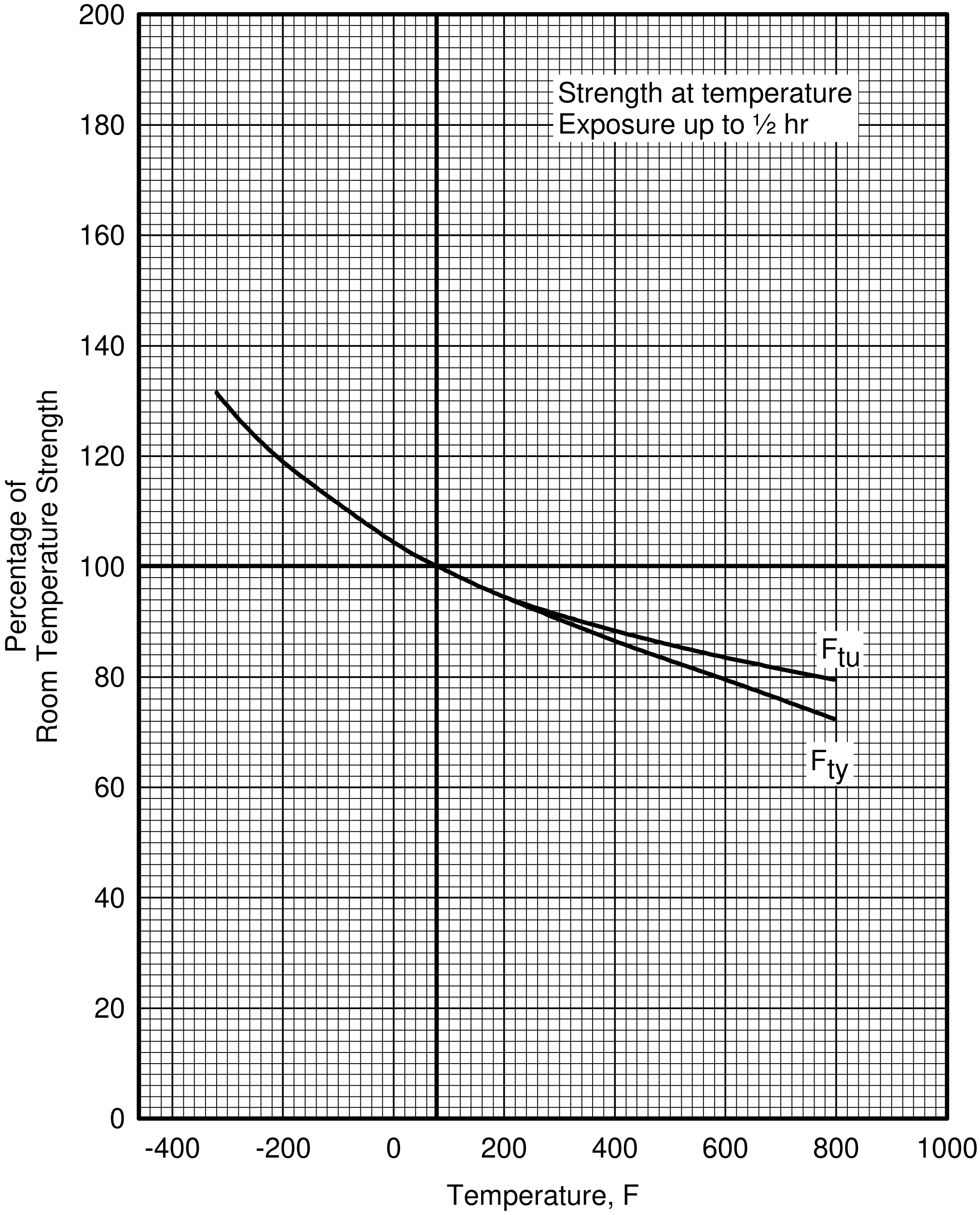

Figure 2.6.7.1.1. Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of 15-5PH (H925, H1025, and H1100) stainless steel bar.

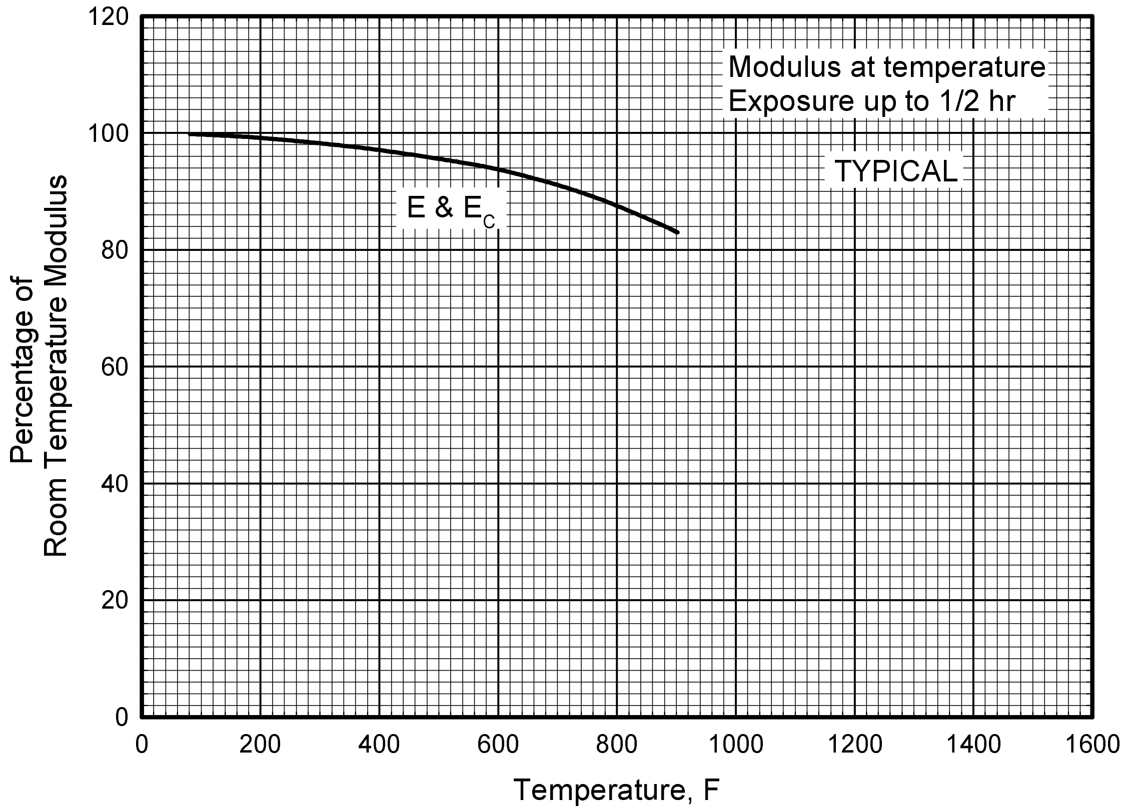

Figure 2.6.7.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of 15-5PH stainless steel.

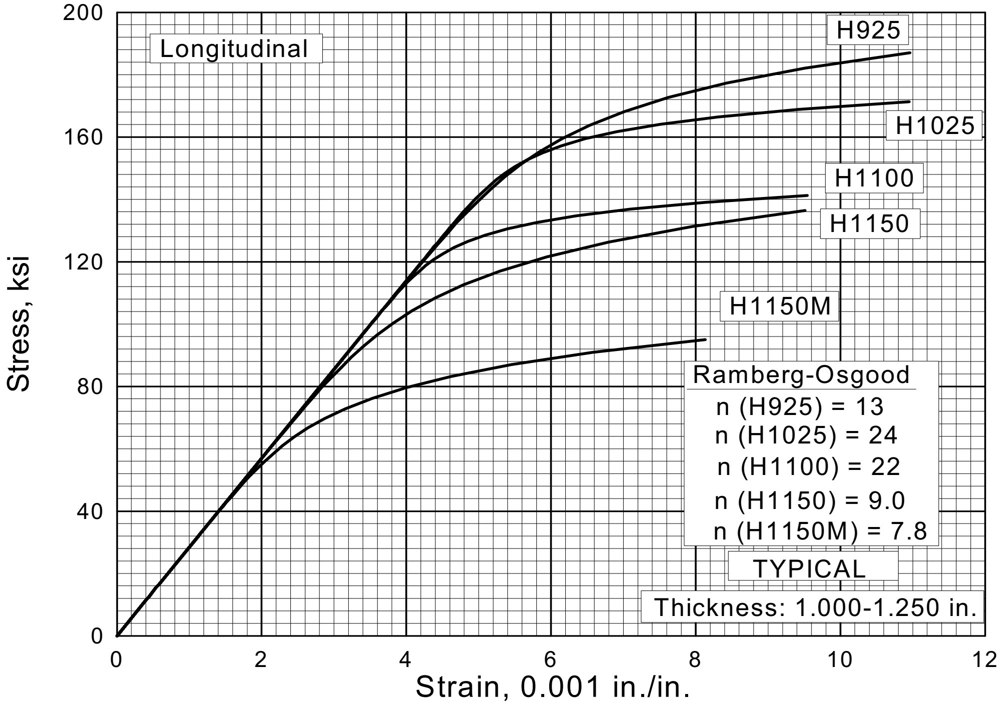

Figure 2.6.7.1.6(a). Typical tensile stress-strain curves at room temperature for various heat-treated conditions of 15-5PH stainless steel bar.

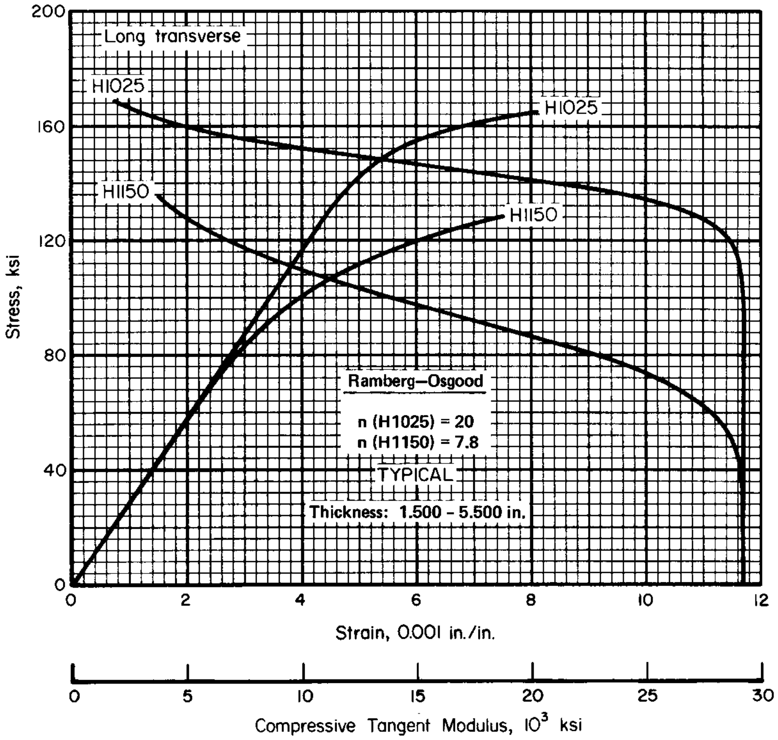

Figure 2.6.7.1.6(b). Typical compressive stress-strain and compressive tangent-modulus curves at room temperature for various heat-treated conditions of 15-5PH stainless steel bar.

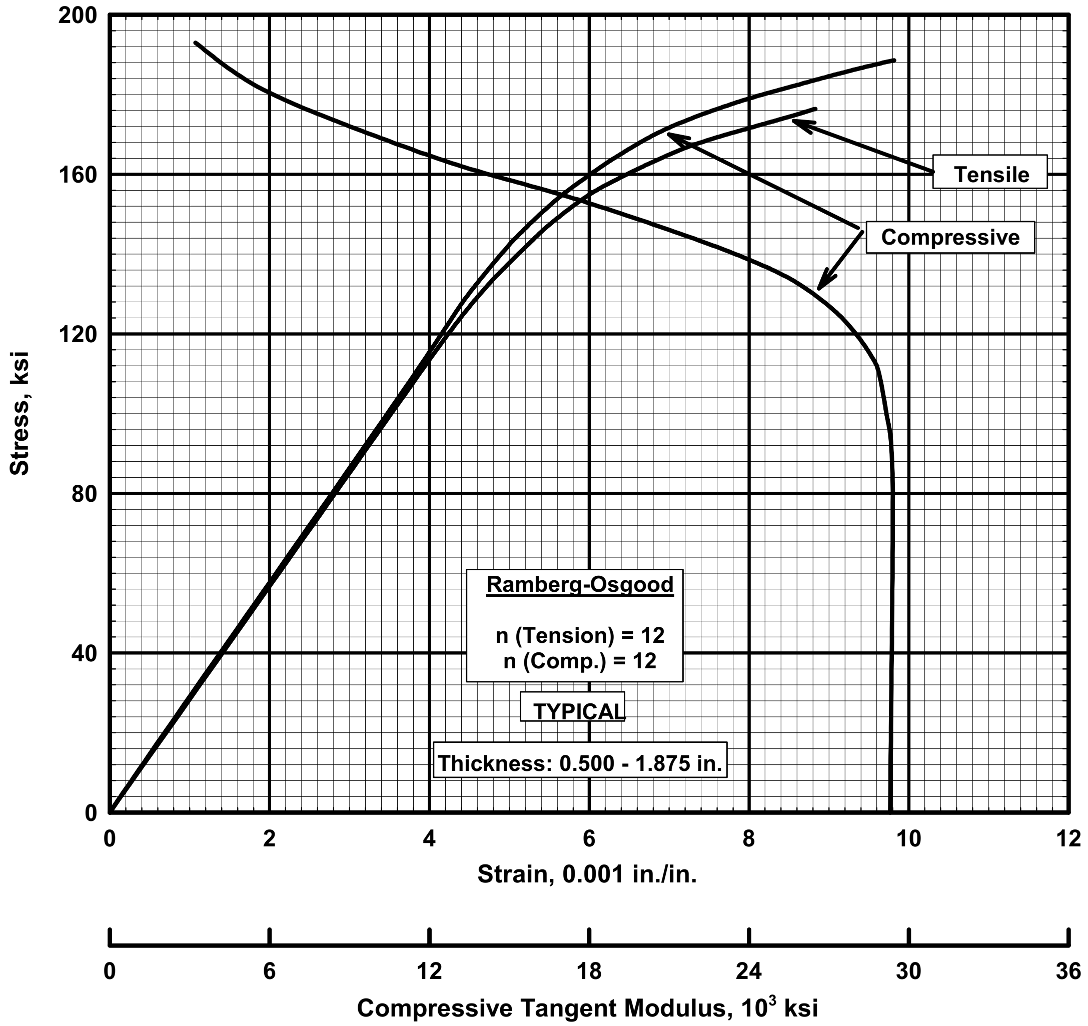

Figure 2.6.7.1.6(c). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 15-5PH (H935) stainless steel casting.

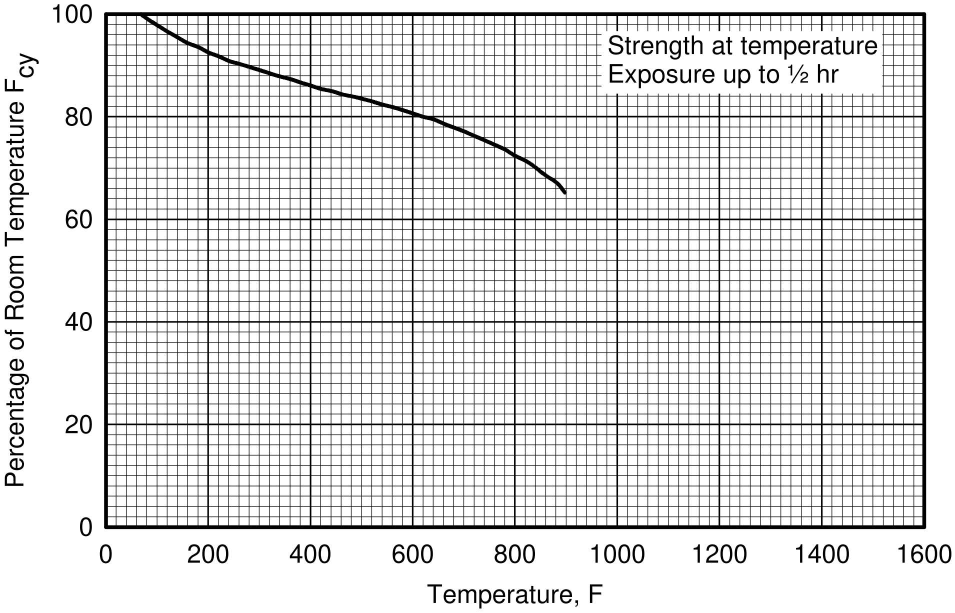

Figure 2.6.7.2.2. Effect of temperature on the compressive yield strength (F_{cy}) of 15-5PH (H1025) stainless steel bar.

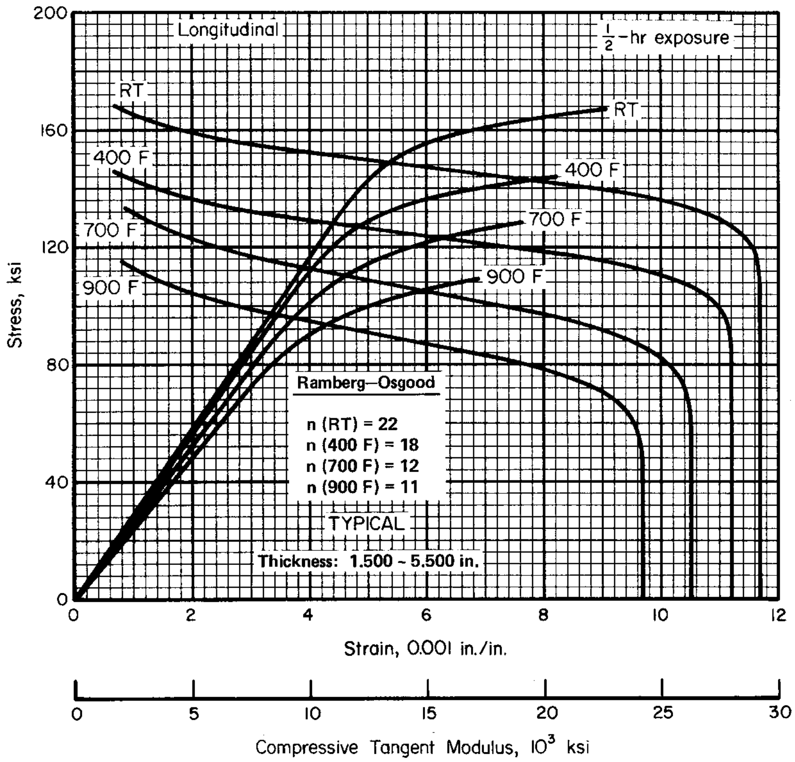

Figure 2.6.7.2.6(a). Typical compressive stress-strain and compressive tangent-modulus curves at various temperatures for 15-5PH (H1025) stainless steel bar.

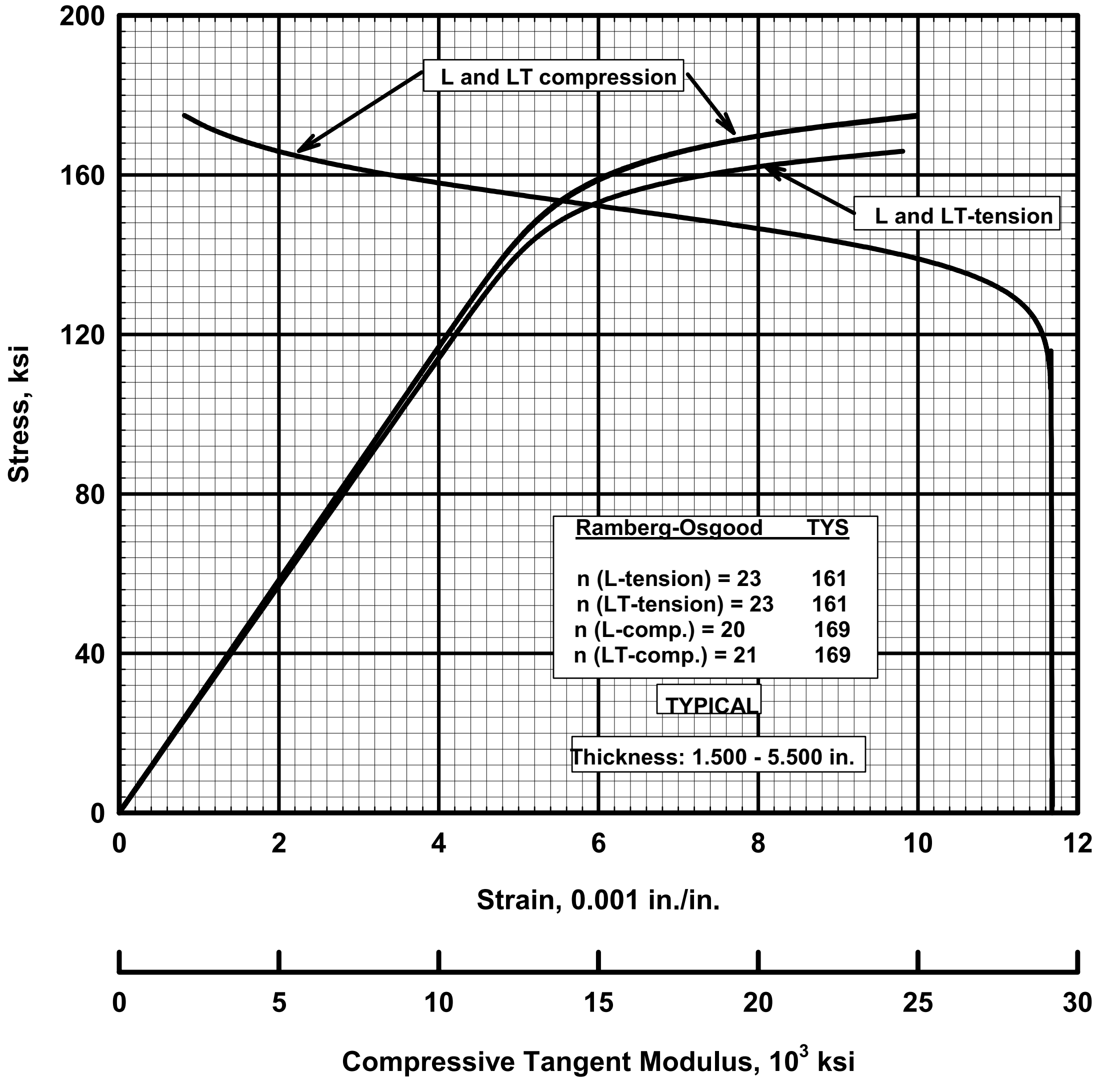

Figure 2.6.7.2.6(b). Tensile and compressive stress-strain and compressive tangent-modulus curves for 15-5PH (H1025) stainless steel plate.

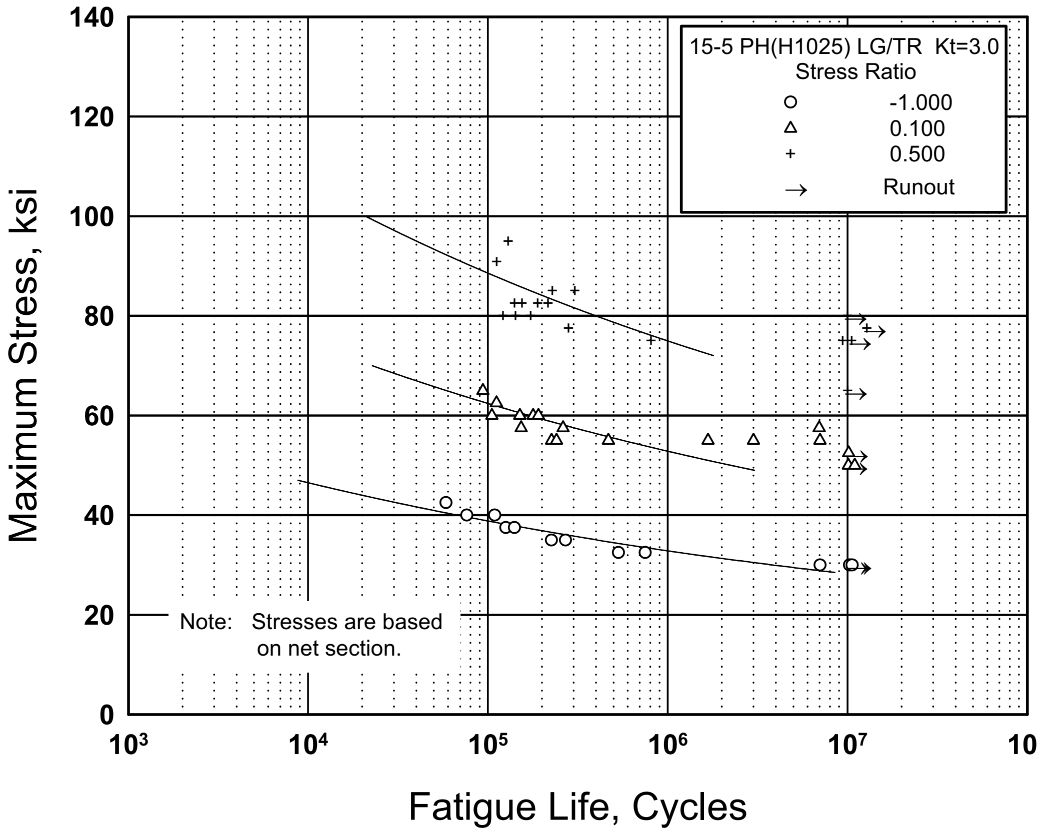

Figure 2.6.7.2.8(a). Best-fit S/N curve for notched, K_t = 3.0, 15-5PH (H1025) stainless steel bar, longitudinal and long transverse directions.

Correlative Information for Figure 2.6.7.2.8(a)

Product Form: Bar, 2 x 6 inches

Properties:	TUS, ksi	TYS, ksi	Temp, °F
Longitudinal	163	159	RT
Long Transverse	164	160	RT
Longitudinal	278	—	RT (notched)
Long Transverse	277	—	RT (notched)

Specimen Details: Notched, V-Groove, K_t = 3.0
0.375 inch gross diameter
0.250 inch net diameter
0.013 inch root radius, *r*
60° flank angle, *ω*

Surface Condition: Ground notch

Reference: 2.6.7.2.8(a)

Test Parameters:
Loading - Axial
Frequency - 1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 3

Equivalent Stress Equation:
$\text{Log } N_f = 19.69 - 9.14 \log (S_{eq} - 18.16)$
$S_{eq} = S_{max} (1 - R)^{0.595}$
Std. Error of Estimate, Log (Life) = 0.449
Standard Deviation, Log (Life) = 0.627
R^2 = 49%

Sample Size: 40

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

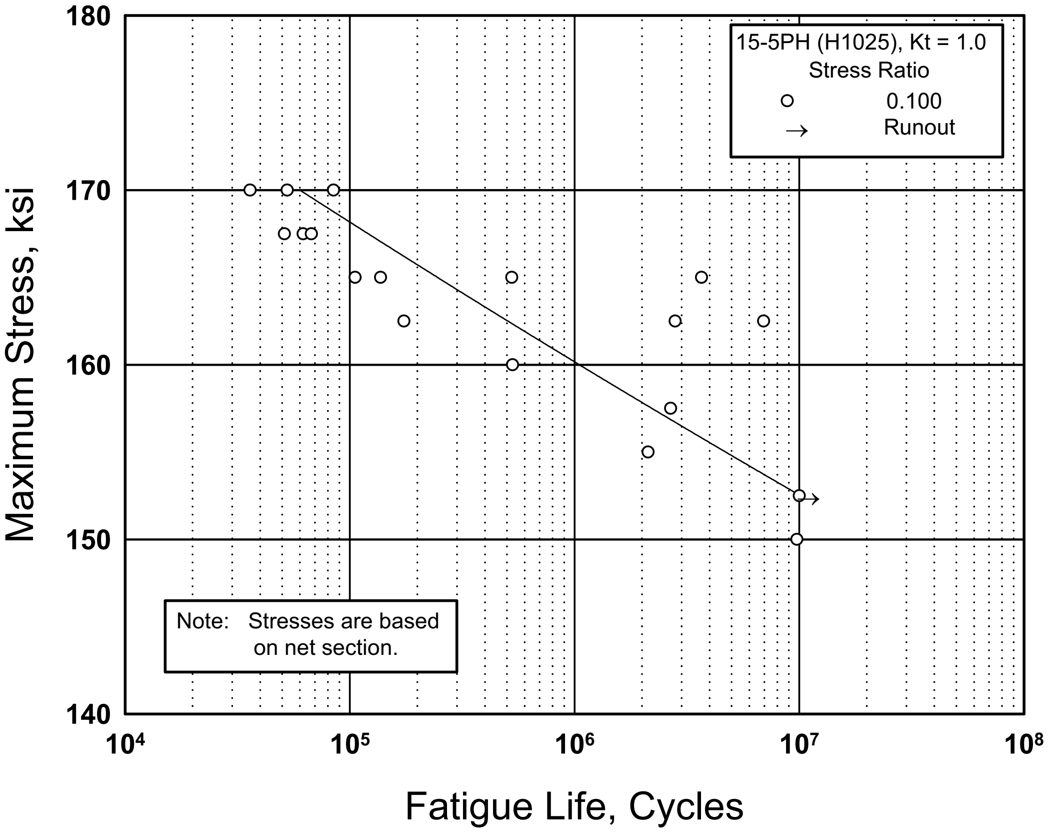

Figure 2.6.7.2.8(b). Best-fit S/N curve for unnotched, K_t = 1.0, 15-5PH (H1025) stainless steel plate, longitudinal and long transverse directions.

Correlative Information for Figure 2.6.7.2.8(b)

Product Form: Plate, 0.808 inch, 2.024 inch, and 2.579 inch thick

Properties:	TUS, ksi	TYS, ksi	Temp, °F
Longitudinal	169.9	165.7	RT
Long Transverse	170.2	166.1	RT

Specimen Details: Unnotched
0.250 inch diameter

Surface Condition: Axial, ground RMS 8

Reference: 2.6.7.2.8(b)

Test Parameters:
Loading - Axial
Frequency - 30 Hz
Temperature - RT
Atmosphere - Air

No. of Heats/Lots: 4

Fatigue Life Equation:
Log N_f = 110.1 - 47.22 log (S_{max})
Std. Error of Estimate, Log (Life) = 0.58
Standard Deviation, Log (Life) = 0.84
R^2 = 52.8%

Sample Size = 19

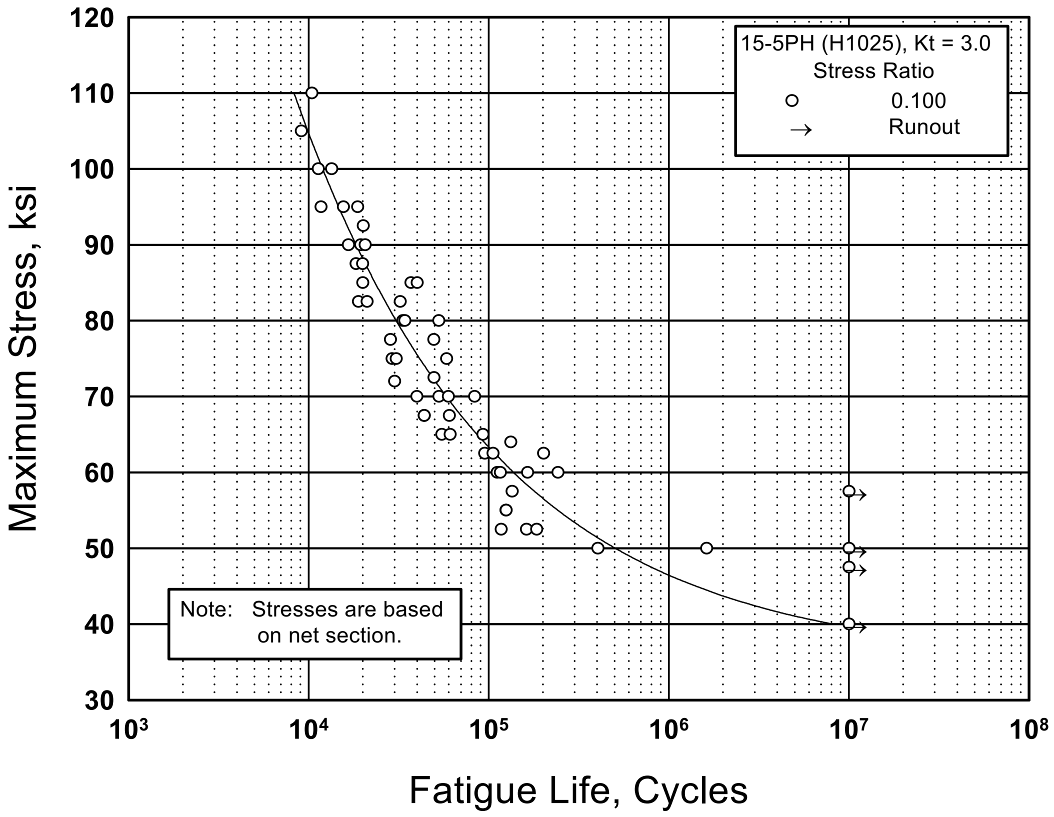

Figure 2.6.7.2.8(c). Best-fit S/N curve for notched, K_t = 3.0, 15-5PH (H1025) stainless steel plate, longitudinal and long transverse directions.

Correlative Information for Figure 2.6.7.2.8(c)

Product Form: Plate, 0.215 inch, 0.269 inch, 0.277 inch, 0.394 inch, 0.524 inch, 0.908 inch, 2.024 inch, and 2.579 inch

Properties:	TUS, ksi	TYS, ksi	Temp, °F
Longitudinal	170.8	165.6	RT
Long Transverse	170.2	166.1	RT

Specimen Details: Notched, V-Groove, K_t = 3.0

Flat, 0.590-inch gross width
0.500-inch net width
0.025-inch root radius
60° flank angle, ω

Round, 0.374-inch gross diameter
0.252-inch net diameter
0.013-inch root radius
60° flank angle, ω

Surface Condition: RMS 32 notch

Reference: 2.6.7.2.8(b)

Test Parameters:
Loading - Axial
Frequency - 30 Hz
Temperature - RT
Atmosphere - Air

No. of Heats/Lots: 10

Fatigue Life Equation:
Log N_f = 8.72 - 2.56 log (S_{max} - 34.9)
Std. Error of Estimate, Log (Life) =10.9 (l/S_{max})

R^2 = 88.2%

Sample Size = 55

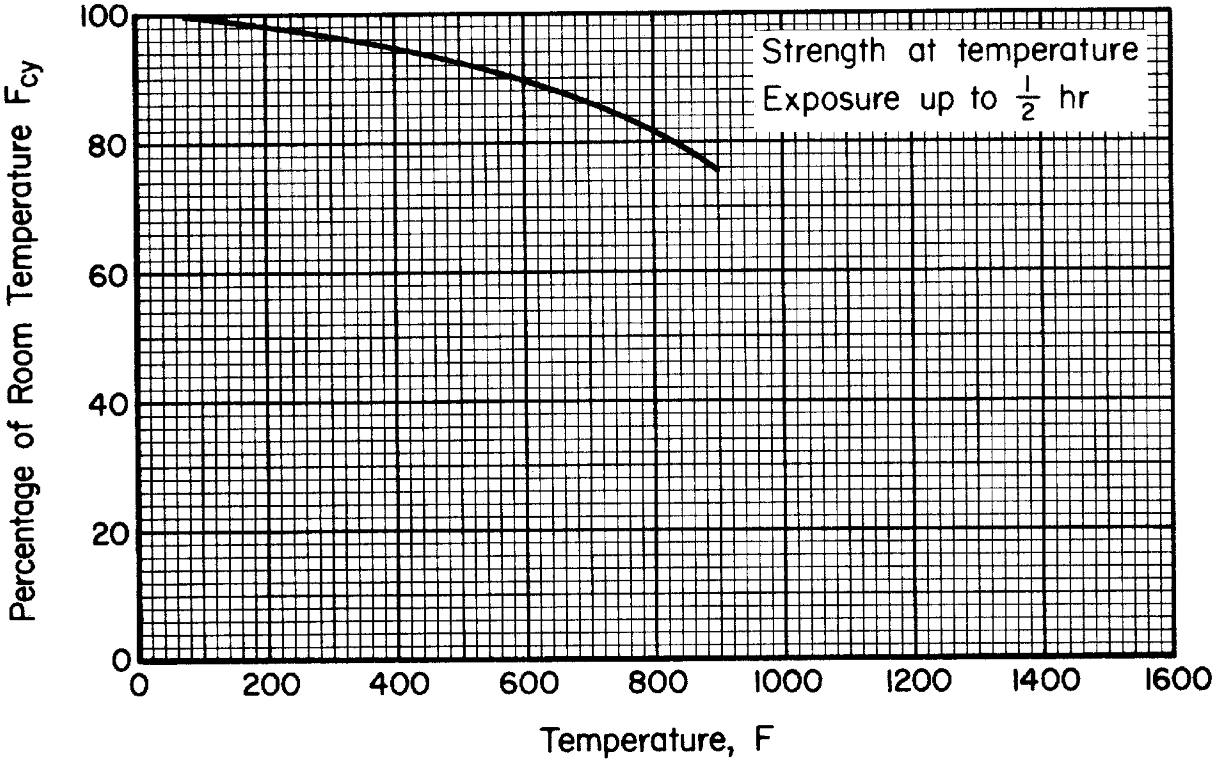

Figure 2.6.7.3.2. Effect of temperature on the compressive yield strength (F_{cy}) of 15-5PH (H1150) stainless steel bar.

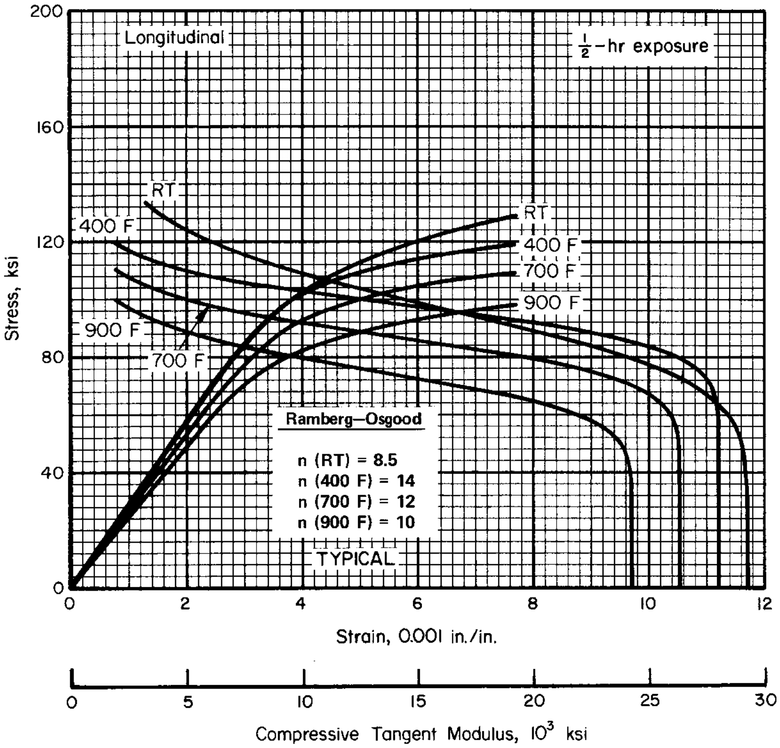

Figure 2.6.7.3.6. Typical compressive stress-strain and tangent-modulus curves at various temperatures for 15-5PH (H1150) stainless steel bar.

2.6.8 PH15-7Mo

2.6.8.0 *Comments and Properties* — PH15-7Mo is a semiaustenitic stainless steel used where high strength and good corrosion and oxidation resistance are needed up to 600°F. This steel is supplied in Condition A for ease of forming or in Condition C when highest strength is required.

Manufacturing Considerations — PH15-7Mo in Condition A is readily cold formed. Conventional inert-gas shielded arc and resistance techniques are generally used for welding. The heat treatments for this steel are compatible with the cycles used for honeycomb panel brazing. Vapor blasting of scaled Condition TH1050 parts is recommended because of the hazards of intergranular corrosion in adequately controlled pickling operations.

In hardening this steel from Condition A to Condition TH1050 a net dimensional growth of 0.004 in./in. should be anticipated. Use of this steel in Conditions T and T-100 is not recommended.

Environmental Considerations — The resistance of PH15-7Mo to stress-corrosion cracking in chloride environments has been evaluated and found to be superior to that of the alloy steels and the hardenable chromium steels. Conditions C and CH 900 provide maximum resistance to stress corrosion.

Specification and Properties — A material specification for PH15-7Mo stainless steel is presented in Table 2.6.8.0(a). The room-temperature properties of PH15-7Mo are shown in Tables 2.6.8.0(b) and (c). The physical properties of this alloy at room and elevated temperatures are presented in Figure 2.6.8.0.

Table 2.6.8.0(a). Material Specification for PH15-7Mo Stainless Steel

Specification	Form
AMS 5520	Plate, sheet, and strip

2.6.8.1 *TH1050 Condition* — Effect of temperature on various mechanical properties for this condition is presented in Figures 2.6.8.1.1 and 2.6.8.1.4. Typical stress-strain and tangent-modulus curves at room temperature and elevated temperature are presented in Figures 2.6.8.1.6(a) through (c). Unnotched and notched fatigue information at room and elevated temperatures are illustrated in Figures 2.6.8.1.8(a) through (f).

Table 2.6.8.0(b). Design Mechanical and Physical Properties of PH15-7Mo Stainless Steel Sheet, Strip, and Plate

Specification	AMS 5520
Form	Sheet, strip, and plate
Condition	TH1050
Thickness, in.	0.0015-0.500
Basis	S
Mechanical Properties:	
F_{tu}, ksi:	
L	185
LT	190
F_{ty}, ksi:	
L	165
LT	170
F_{cy}, ksi:	
L	182
LT	188
F_{su}, ksi	120
F_{bru}, ksi:	
(e/D = 1.5)	327
(e/D = 2.0)	377
F_{bry}, ksi:	
(e/D = 1.5)	259
(e/D = 2.0)	272
e, percent:	
LT	[a]
E, 10^3 ksi	29.0
E_c, 10^3 ksi	30.0
G, 10^3 ksi	11.4
μ	0.28
Physical Properties:	
ω, lb/in.^{3}	0.277
C, Btu/(lb)(°F)	...
K and α	See Figure 2.6.8.0

[a] See Table 2.6.8.0(c).

Table 2.6.8.0(c). Minimum Elongation Values for PH15-7Mo (TH1050) Stainless Steel Sheet

Thickness, inches	e (LT), percent
0.0015 to 0.0049	2
0.0050 to 0.0099	3
0.010 to 0.019	4
0.020 to 0.1874	5
0.1875 to 0.500	6

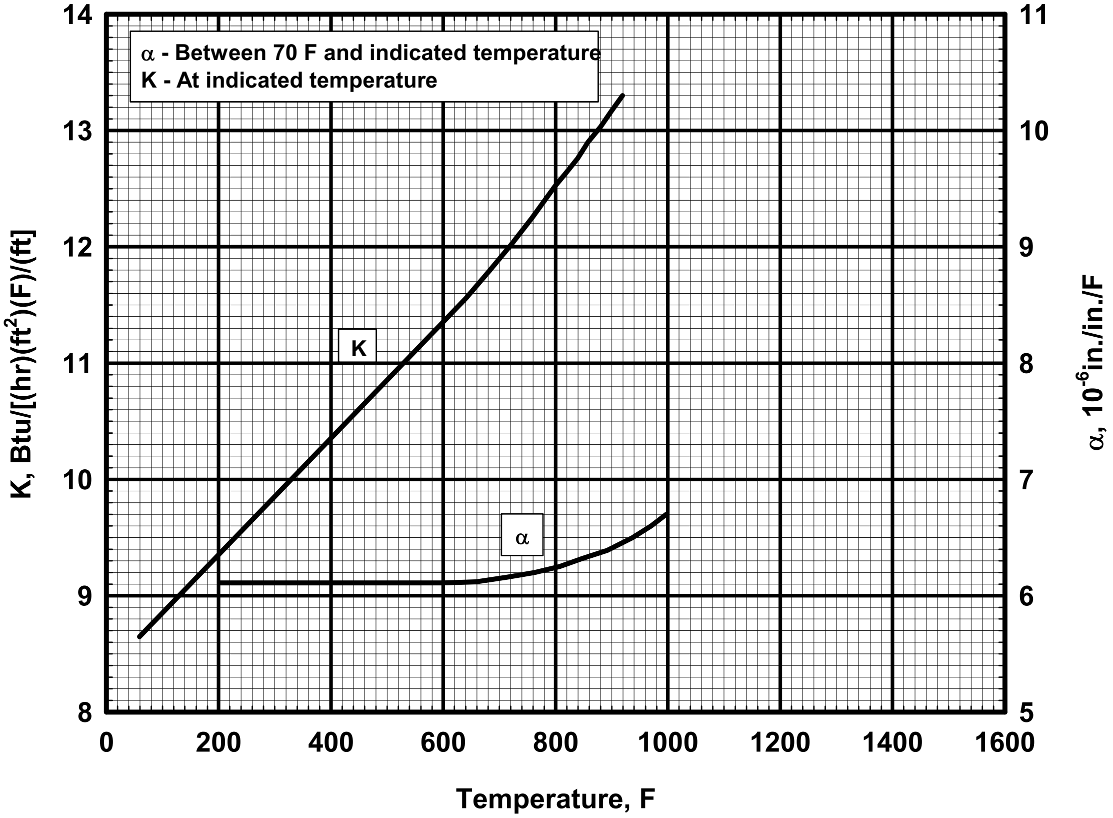

Figure 2.6.8.0. Effect of temperature on the physical properties of PH15-7Mo (TH1050) stainless steel.

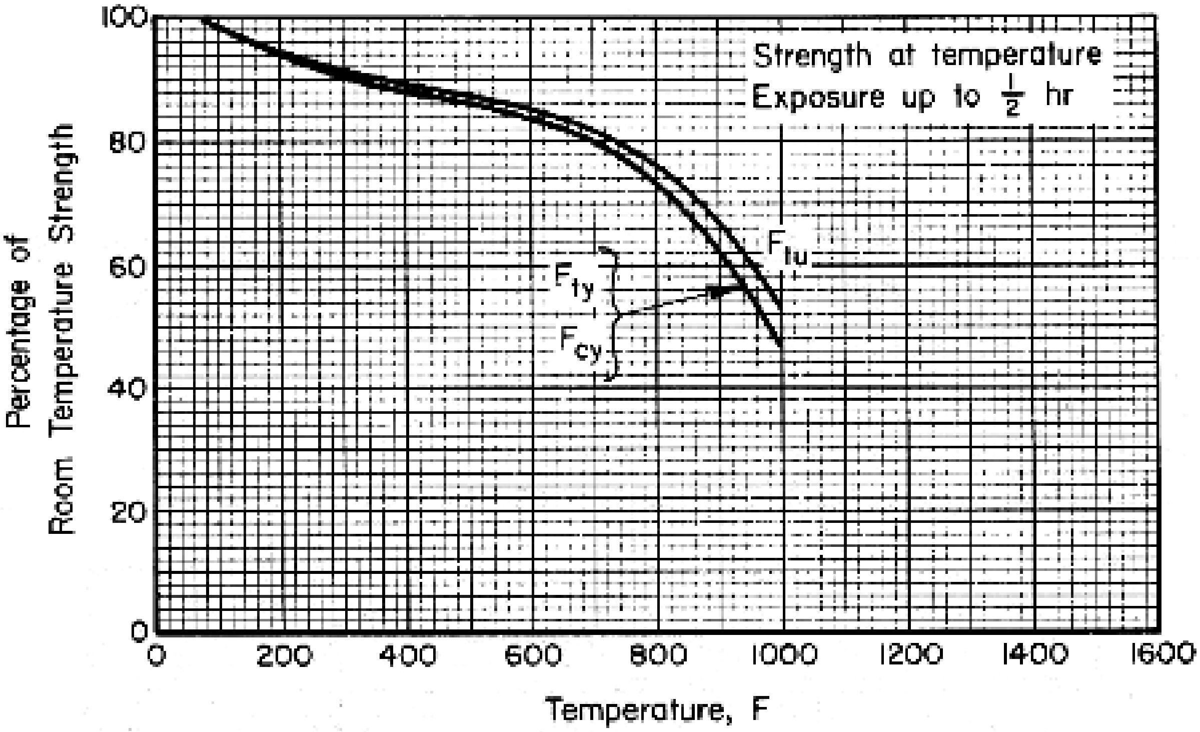

Figure 2.6.8.1.1. Effect of temperature on the tensile ultimate strength (F_{tu}), tensile yield strength (F_{ty}), and compressive yield strength (F_{cy}) of PH15-7Mo (TH1050) stainless steel sheet.

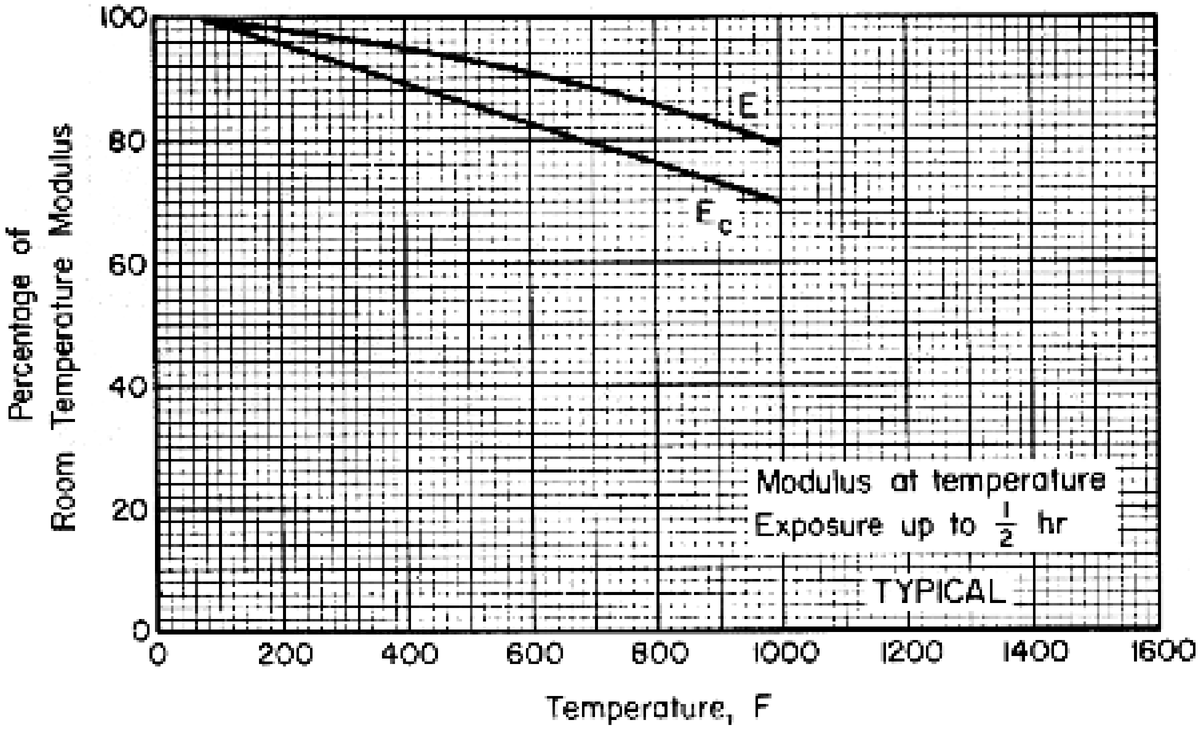

Figure 2.6.8.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of PH15-7Mo (TH1050) stainless steel sheet.

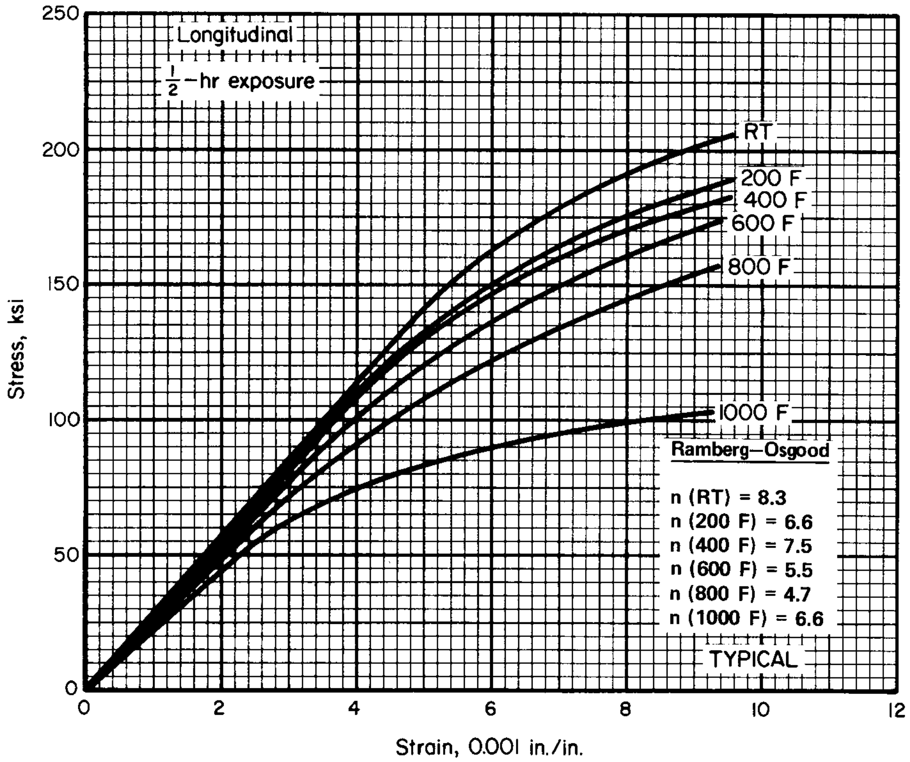

Figure 2.6.8.1.6(a). Typical tensile stress-strain curves at various temperatures for PH15-7Mo (TH1050) stainless steel sheet.

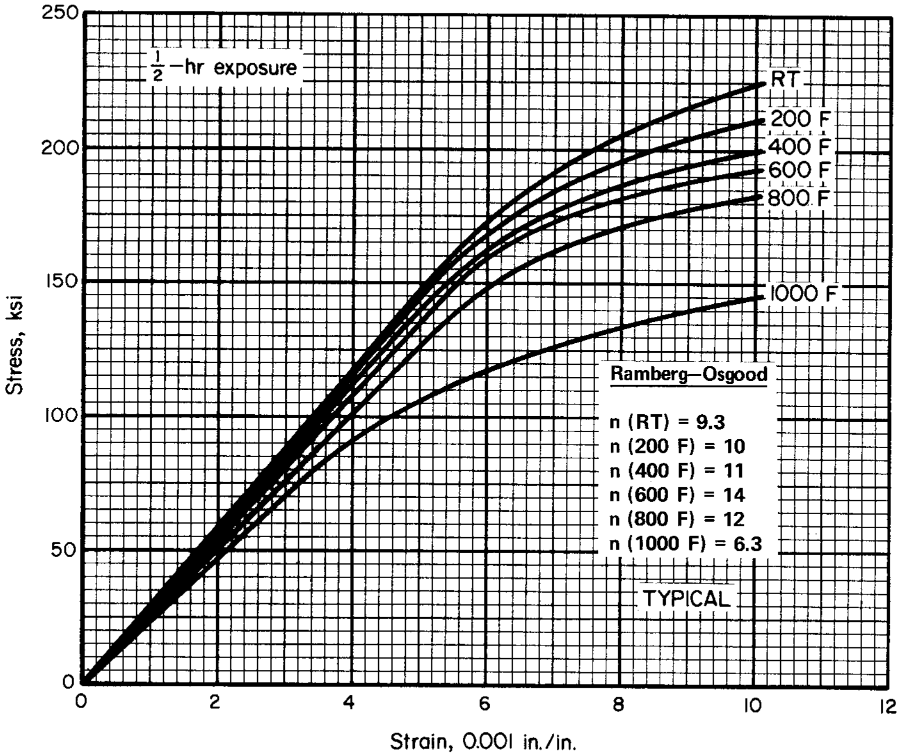

Figure 2.6.8.1.6(b). Typical compressive stress-strain curves at various temperatures for PH15-7Mo (TH1050) stainless steel sheet.

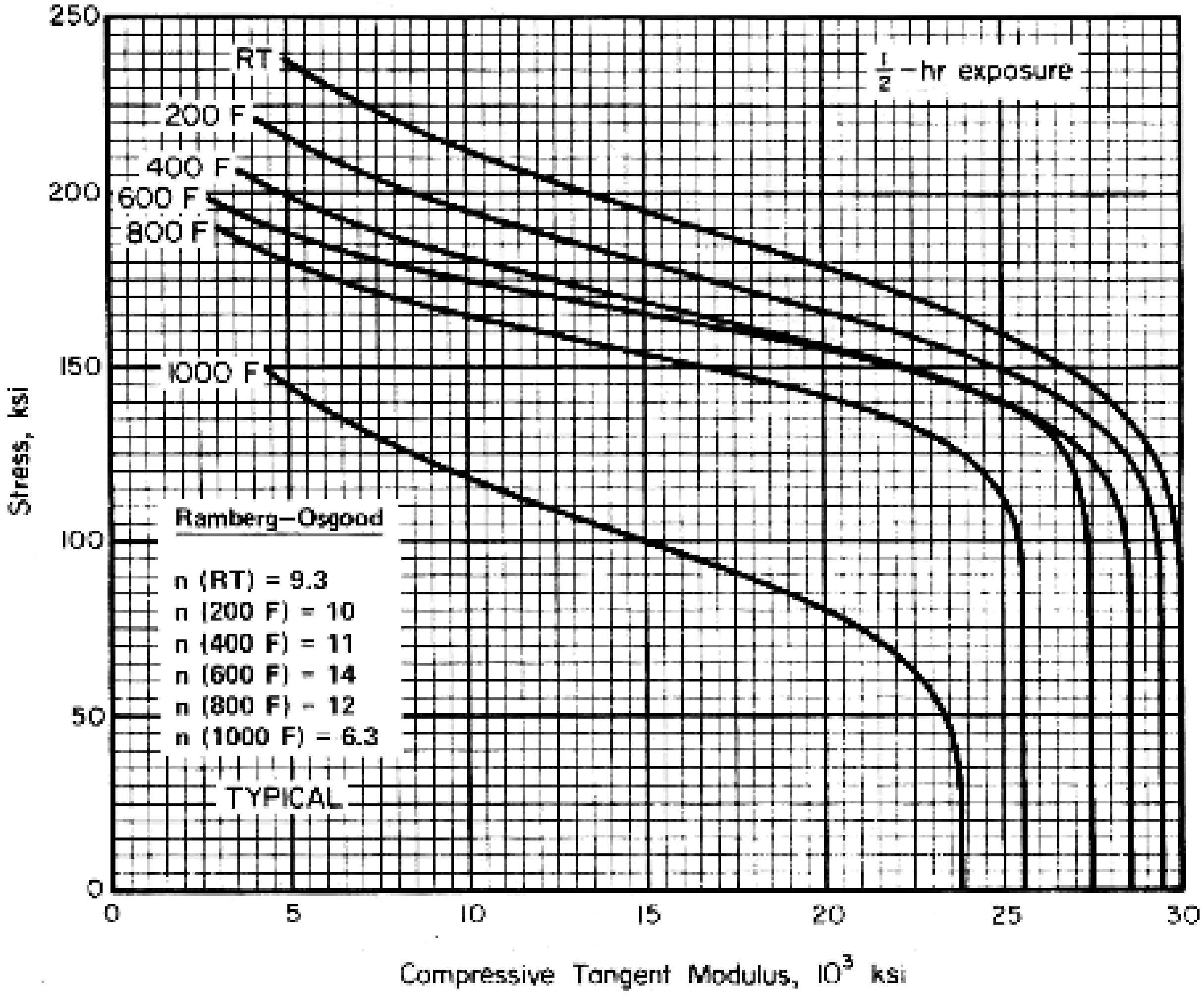

Figure 2.6.8.1.6(c). Typical compressive tangent-modulus curves at various temperatures for PH15-7Mo (TH1050) stainless steel sheet.

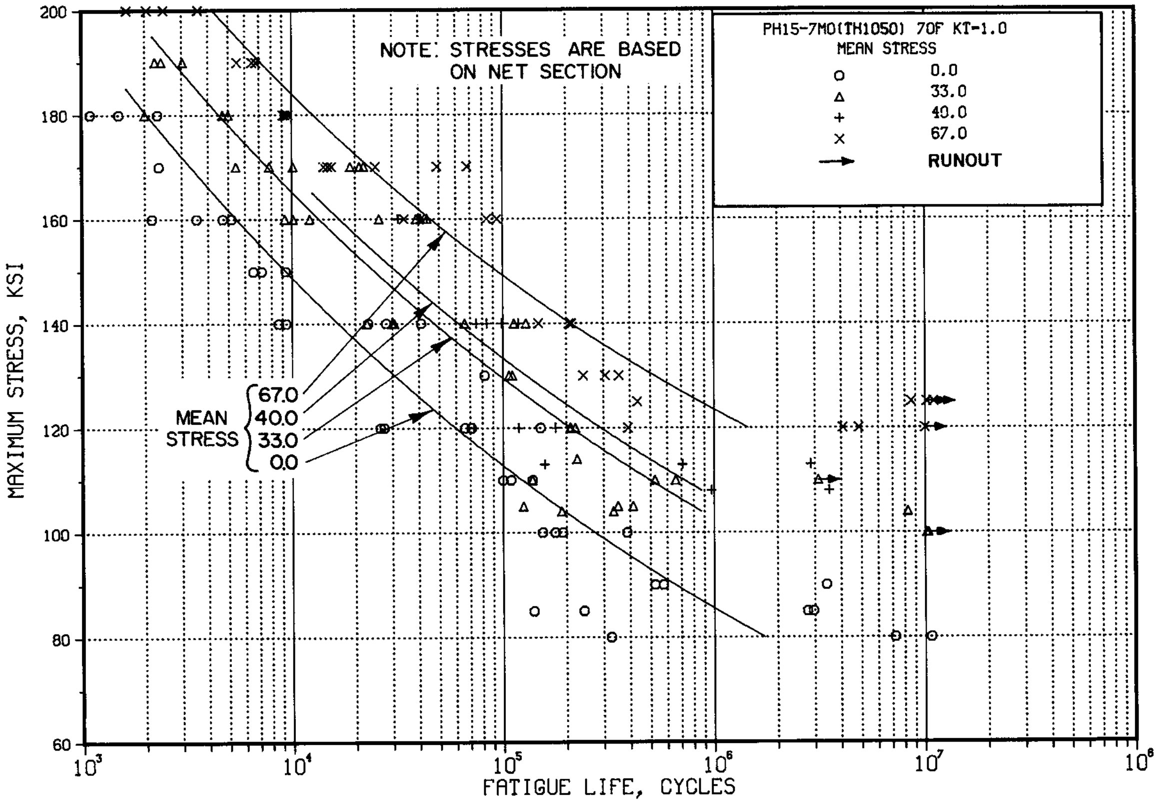

Figure 2.6.8.1.8(a). Best-fit S/N curves for unnotched PH15-7Mo (TH1050) sheet, longitudinal direction.

Correlative Information for Figure 2.6.8.1.8(a)

Product Form: Sheet, 0.025 inch

Properties:

TUS, ksi	TYS, ksi	Temp., °F
201	196	RT

Specimen Details: Unnotched
2.0 inch gross width
0.75 inch net width

Surface Condition: Specimen edges machined in longitudinal direction, edges polished with 320 grit emery paper

References: 2.6.8.1.8(a) and (b)

Test Parameters:
Loading - Axial
Frequency - 24 and 1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
$\text{Log } N_f = 23.24\text{-}8.32 \log S_{eq}$
$S_{eq} = S_{max} (1\text{-}R)^{0.47}$
Std. Error of Estimate, Log (Life) = 0.35
Standard Deviation, Log (Life) = 0.94
$R^2 = 86\%$

Sample Size: 124

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

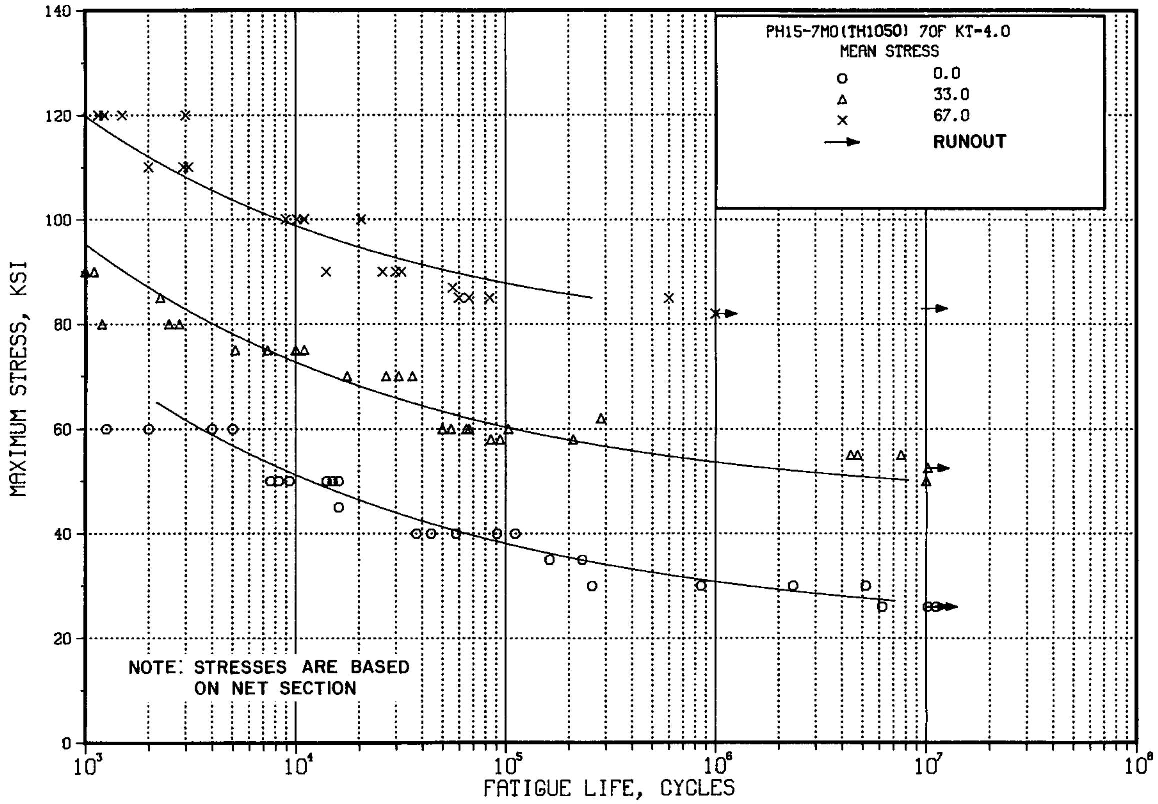

Figure 2.6.8.1.8(b). Best-fit S/N curves for notched, K_t = 4.0, PH15-7Mo (TH1050) sheet, longitudinal direction.

Correlative Information for Figure 2.6.8.1.8(b)

Product Form: Sheet, 0.025-inch

Properties:

TUS, ksi	TYS, ksi	Temp., °F
201	196	RT

Specimen Details: Edge Notched, K_t = 4.0
2.25 inch gross width
1.50 inch net width
0.058 inch notch radius
0° flank angle, ω

Surface Condition: Drilled holes near edges and slots milled from edge, corners of notch were beveled with rubber abrasive

Reference: 2.6.8.1.8(b)

Test Parameters:
Loading - Axial
Frequency - 24 and 1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
Log N_f = 10.42-3.91 log (S_{eq}-32)
$S_{eq} = S_{max} (1-R)^{0.58}$
Std. Error of Estimate, Log (Life) = 0.36
Standard Deviation, Log (Life) = 1.07
R^2 = 89%

Sample Size: 74

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

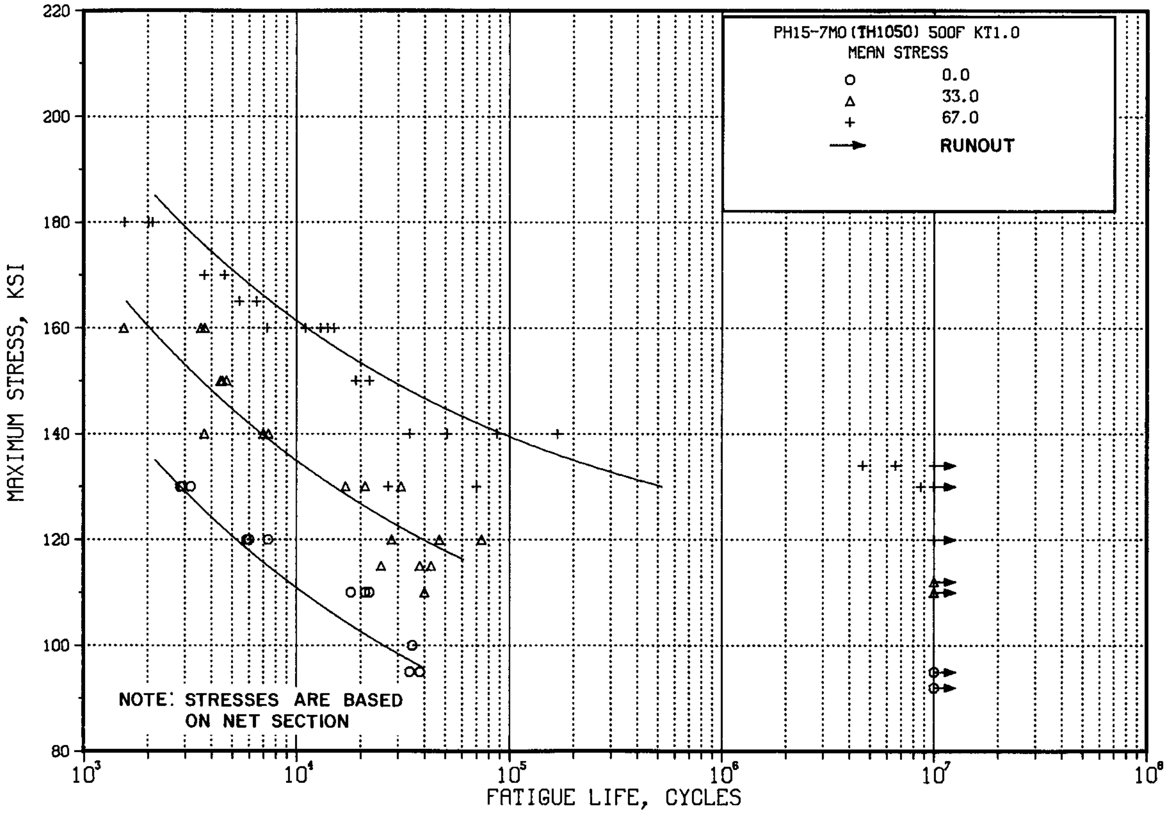

Figure 2.6.8.1.8(c). Best-fit S/N curves for unnotched PH15-7Mo (TH1050) sheet at 500°F, longitudinal direction.

<u>Correlative Information for Figure 2.6.8.1.8(c)</u>

<u>Product Form:</u> Sheet, 0.025 inch

<u>Properties:</u>

TUS, ksi	TYS, ksi	Temp., °F
201	196	RT
179	173	500

<u>Specimen Details:</u> Unnotched
2.0 inch gross width
0.75 inch net width

<u>Surface Condition:</u> Machined in longitudinal direction, edges polished with 320 grit emery paper

<u>Reference:</u> 2.6.8.1.8(b)

<u>Test Parameters</u>:
Loading - Axial
Frequency - 24 and 1800 cpm
Temperature - 500°F
Environment - Air

<u>No. of Heats/Lots:</u> Not specified

<u>Equivalent Stress Equation</u>:
$\text{Log } N_f = 11.71 - 4.00 \log (S_{eq} - 96)$
$S_{eq} = S_{max} (1-R)^{0.70}$
Std. Error of Estimate, Log (Life) = 0.44
Standard Deviation, Log (Life) = 0.79
$R^2 = 69\%$

<u>Sample Size:</u> 55

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

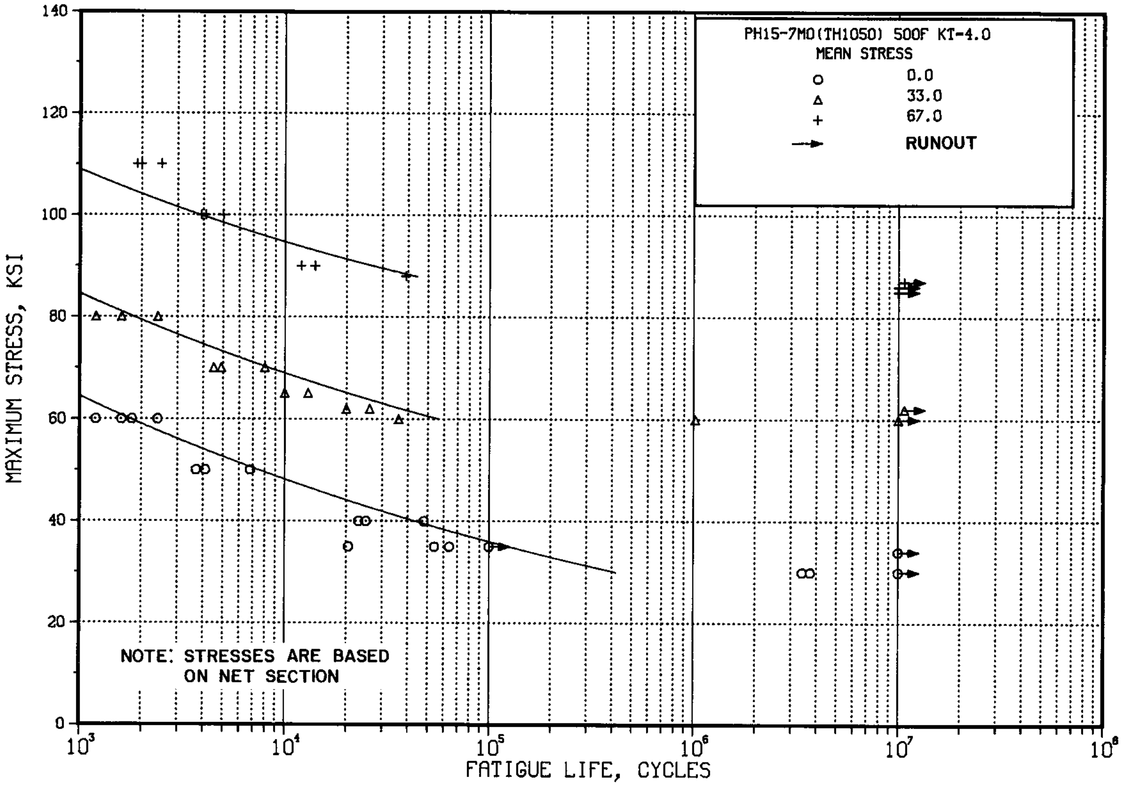

Figure 2.6.8.1.8(d). Best-fit S/N curves for notched, K_t = 4.0, PH15-7Mo (TH1050) sheet at 500°F, longitudinal direction.

Correlative Information for Figure 2.6.8.1.8(d)

Product Form: Sheet, 0.025 inch

Properties:

TUS, ksi	TYS, ksi	Temp., °F
201	196	RT
179	173	500

Specimen Details: Edge Notched, K_t = 4.0
2.25 inch gross width
1.50 inch net width
0.058 inch notch radius
0° flank angle, ω

Surface Condition: Drilled holes near edges and slots milled from edge, corners of notch were beveled with rubber abrasive

Reference: 2.6.8.1.8(b)

Test Parameters:
Loading - Axial
Frequency - 24 and 1800 cpm
Temperature - 500°F
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
Log N_f = 18.60-7.92 log (S_{eq})
$S_{eq} = S_{max} (1-R)^{0.55}$
Std. Error of Estimate, Log (Life) = 0.41
Standard Deviation, Log (Life) = 0.86
R^2 = 77%

Sample Size: 37

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

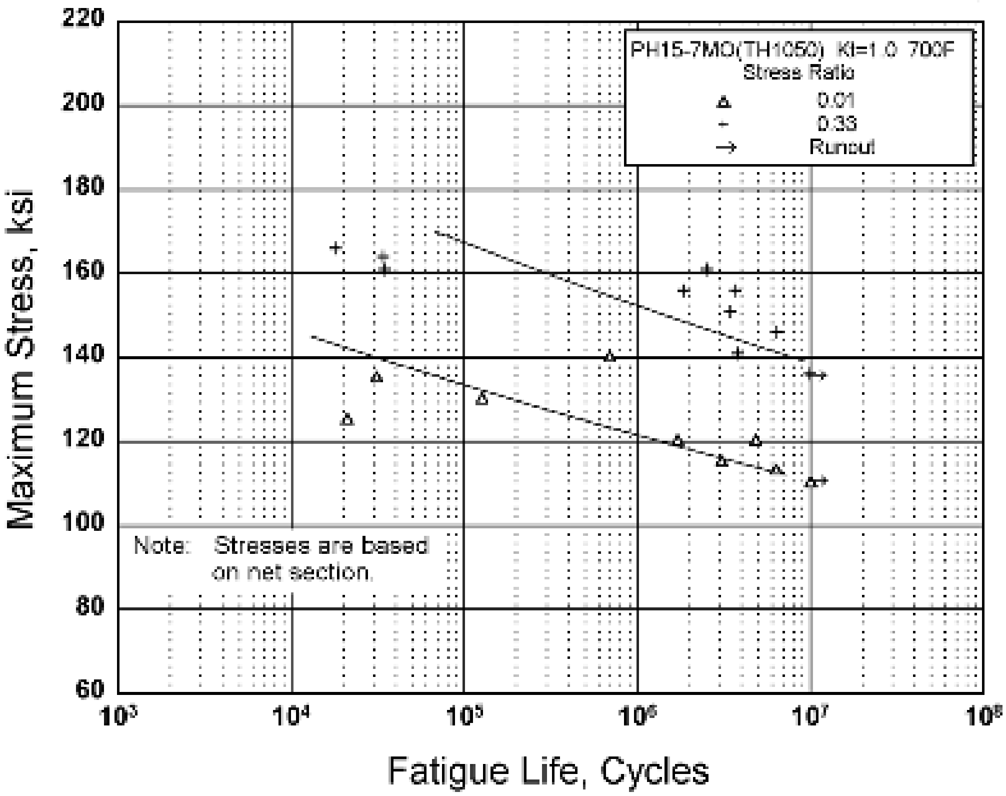

Figure 2.6.8.1.8(e). Best-fit S/N curves for PH15-7Mo (TH1050) sheet at 700°F, transverse direction.

Correlative Information for Figure 2.6.8.1.8(e)

Product Form: Sheet, 0.050 inch

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	175	161	700 (LT)

Specimen Details: Unnotched
2.0 inch gross width
0.375 inch net width

Surface Condition: Polished in longitudinal direction with wet 600 grit silicon carbide paper

Reference: 2.6.8.1.8(c)

Test Parameters:
Loading - Axial
Frequency - 1200 cpm
Temperature - 700°F
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
Log N_f = 56.92-24.46 log (S_{eq})
$S_{eq} = S_{max}\ (1\text{-}R)^{0.58}$
Std. Error of Estimate, Log (Life) = 0.77
Standard Deviation, Log (Life) = 0.99
R^2 = 39%

Sample Size: 17

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

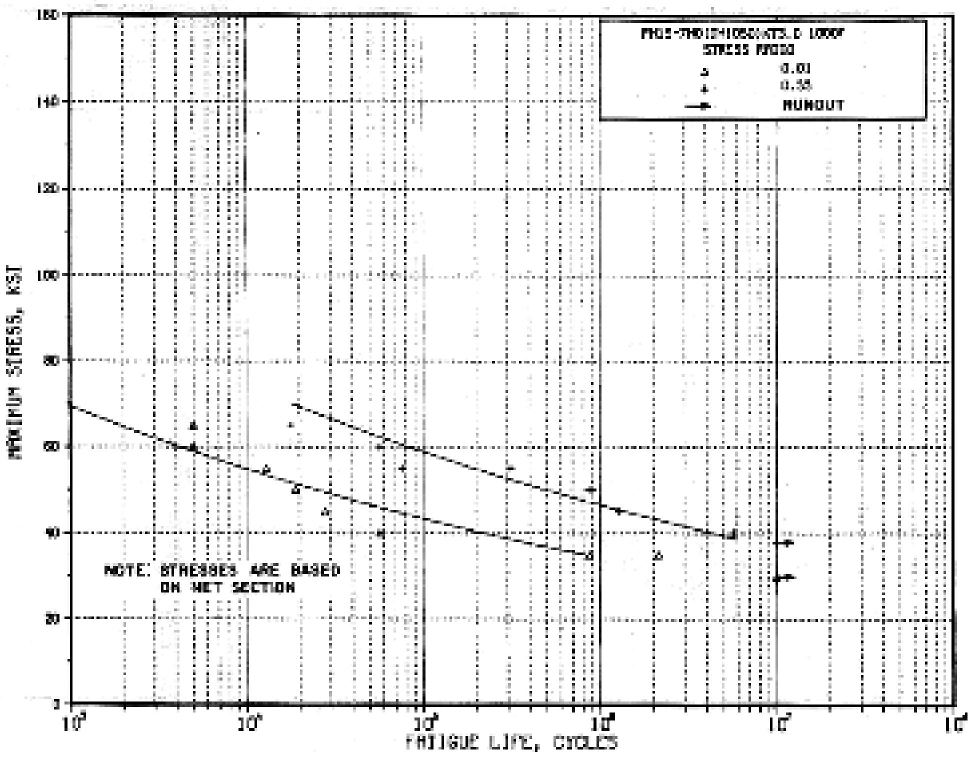

Figure 2.6.8.1.8(f). Best-fit S/N curves for notched, K_t = 3.0, PH15-7Mo (TH1050) sheet at 1000°F, transverse direction.

Correlative Information for Figure 2.6.8.1.8(f)

Product Form: Sheet, 0.050 inch

Properties:

TUS, ksi	TYS, ksi	Temp., °F
107	92	1000 (LT)

Specimen Details: Edge Notched, K_t = 3.0
0.535 inch gross width
0.375 inch net width
0.021 inch notch radius
60° flank angle, ω

Surface Condition: Polished longitudinally

Reference: 2.6.8.1.8(c)

Test Parameters:
Loading - Axial
Frequency - 1200 cpm
Temperature - 1000°F
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
$\text{Log } N_f = 21.00\text{-}9.80 \log (S_{eq})$
$S_{eq} = S_{max} (1\text{-}R)^{0.78}$
Std. Error of Estimate, Log (Life) = 0.33
Standard Deviation, Log (Life) = 0.99
R^2 = 89%

Sample Size: 16

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

2.6.9 17-4PH

2.6.9.0 *Comments and Properties* — Alloy 17-4PH is a precipitation-hardening, martensitic stainless steel used for parts requiring high strength and good corrosion and oxidation resistance up to 600°F. The alloy is available in all product forms.

Manufacturing Considerations — 17-4PH is readily forged, machined, welded, and brazed. Machining requires the same precautions as the austenitic stainless steels except that work-hardening is not a problem. Best machinability is exhibited by Conditions H1150 and H1150M. A dimensional contraction of 0.0004 to 0.0006 and 0.0008 to 0.0010 in./in. occurs upon hardening to the H900 and H1150 conditions, respectively. This fact should be considered before finish machining prior to aging treatment.

When permanent deformation is performed, such as cold straightening of hardened parts, reaging is recommended to minimize internal stresses.

Alloy 17-4PH can be fusion welded with any of the normal processes using 17-4PH filler metal without preheat. For details up to ½-inch thickness, Condition A is satisfactory prior to welding, but for heavy sections, an overaged condition (H1150) is recommended to preclude cracking. After welding, weldments should be aged or solution treated and aged.

Alloy 17-4PH castings are produced in sand molds, investment molds, and by centrifugal casting. While 17-4PH has good castability, it is subject to hot-tearing, so heavy X or T sections, sharp corners, and abrupt changes in section size should be avoided. Alloy 17-4PH castings are susceptible to microshrinkage which will decrease the ductility but have no effect on the yield or ultimate strength. During heat treatment, care must be exercised to avoid carbon or nitrogen contamination from furnace atmospheres. Combusted hydrocarbon and dissociated ammonia atmospheres have been sources of contamination. Air is commonly used and both vacuum and dry argon are effective for minimizing scaling. Oxides formed during solution treating in air may be removed by grit blasting or abrasive tumbling.

Alloy 17-4PH can be heat treated to develop a wide range of properties. Heat treatment procedures are specified in applicable material specifications and MIL-H-6875.

Design and Environmental Considerations — For tensile applications where stress corrosion is a possibility, 17-4PH should be aged at the highest temperature compatible with strength requirements and at a temperature not lower than 1025°F for 4 hours minimum.

The impact strength of 17-4PH, especially large size bar in the H900 and H925 conditions, may be very low at subzero temperatures; consequently, the use of 17-4PH for critical applications at low temperatures should be avoided. For non-impact applications, such as valve seats, parts in the H925 condition have performed satisfactorily down to -320°F. The H1100 and H1150 conditions have improved impact strength so that parts made from small diameter bar can be used down to -100°F with low risk. For critical low temperature applications, a similar alloy, 15-5PH (consumable electrode vacuum melted), should be used instead of 17-4PH because of its superior impact strength at low temperature.

Specifications and Properties — Material specifications for 17-4PH are presented in Table 2.6.9.0(a). Room temperature mechanical and physical properties for various conditions of 17-4PH products are presented in Table 2.6.9.0(b) through (f). The physical properties of this alloy at room and elevated temperatures are presented in Figure 2.6.9.0.

Table 2.6.9.0(a). Material Specifications for 17-4PH Stainless Steel

Specification	Form
AMS 5604	Sheet, strip, and plate
AMS 5643	Bar, forging, and ring
AMS 5342	Investment casting (H1100)
AMS 5343	Investment casting (H1000)
AMS 5344	Investment casting (H900)

2.6.9.1 ***H900 Condition*** — Elevated temperature curves for various mechanical properties are presented in Figures 2.6.9.1.2 through 2.6.9.1.4. Unnotched and notched fatigue information at room temperature is presented in Figures 2.6.9.1.8(a) through (c).

2.6.9.2 ***Various Heat Treat Conditions*** — Elevated temperature curves for tensile yield and ultimate strengths are depicted in Figure 2.6.9.2.1. Room temperature stress-strain and tangent-modulus curves are shown in Figures 2.6.9.2.6(a) and (b).

2.6.9.3 ***H1000 Condition*** — Room temperature stress-strain and tangent-modulus curves for castings are shown in Figures 2.6.9.3.6(a) and (b).

2.6.9.4 ***H1025 Condition*** — Notched fatigue information is presented in Figure 2.6.9.4.8 for bar.

2.6.9.5 ***H1100 Condition*** — Notched fatigue information is presented in Figure 2.6.9.5.8 for bar.

2.6.9.6 ***H1150 Condition*** — Elevated temperature curves for tensile yield and ultimate strengths are shown in Figure 2.6.9.6.1.

Table 2.6.9.0(b). Design Mechanical and Physical Properties of 17-4PH Stainless Steel Sheet, Strip, and Plate

Specification	AMS 5604					
Form	Sheet, strip[a], and plate					
Condition	H900	H925	H1025	H1075	H1100	H1150
Thickness, in.	≤ 4.000					
Basis	S	S	S	S	S	S
Mechanical Properties:						
F_{tu}, ksi:						
L	...	...	...	...	...	...
LT	190	170	155	145	140	135
F_{ty}, ksi:						
L	...	...	...	...	...	...
LT	170	155	145	125	115	105
F_{cy}, ksi:						
L	...	...	...	...	...	...
LT	...	...	...	...	...	...
F_{su}, ksi	...	...	...	...	...	...
F_{bru}, ksi:						
(e/D = 1.5)	...	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...	...
F_{bry}, ksi:						
(e/D = 1.5)	...	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...	...
e, percent:						
LT	[b]	[b]	[b]	[b]	[b]	[b]
E, 10^3 ksi	28.5					
E_c, 10^3 ksi	30.0					
G, 10^3 ksi	11.2					
μ	0.27					
Physical Properties:						
ω, lb/in.^{3}	0.282 (H900), 0.283 (H1075), 0.284 (H1150)					
C, K, and α	See Figure 2.6.9.0					

[a] Test direction longitudinal for widths less than 9 inches; long transverse for widths 9 inches and over.
[b] See Table 2.6.9.0(c).

Table 2.6.9.0(c). Minimum Elongation Values for 17-4PH Sheet, Strip, and Plate

	e, percent (LT)					
Thickness	H900	H925	H1025	H1075	H1100	H1150
0.015 through 0.186	5	5	5	5	5	8
0.187 through 0.625	8	8	8	9	10	10
0.626 through 4.000	10	10	12	13	14	16

Table 2.6.9.0(d). Design Mechanical and Physical Properties of 17-4PH Stainless Steel Forging, Tubing, and Rings

Specification	AMS 5643						
Form	Forging, tubing, and rings						
Condition	H900	H925	H1025	H1075	H1100	H1150	H1150M[a]
Thickness, in.	<8.000						
Basis	S	S	S	S	S	S	S
Mechanical Properties:							
F_{tu}, ksi:							
L	190	170	155	145	140	135	115
T	...	...	...	...	...	...	...
F_{ty}, ksi:							
L	170	155	145	125	115	105	75
T	...	...	...	...	...	...	...
F_{cy}, ksi:							
L	...	...	...	...	...	...	...
T	...	...	...	...	...	...	...
F_{su}, ksi	...	...	...	...	...	...	...
F_{bru}, ksi:							
(e/D = 1.5)	...	...	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...	...	...
F_{bry}, ksi:							
(e/D = 1.5)	...	...	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...	...	...
e, percent:							
L	10	10	12	13	14	16	18
E, 10^3 ksi	28.5						
E_c, 10^3 ksi	30.0						
G, 10^3 ksi	11.2						
μ	0.27						
Physical Properties:							
ω, lb/in.^{3}	0.282 (H900), 0.283 (H1075), 0.284 (H1150)						
C, K, and α	See Figure 2.6.9.0						

[a] Not covered by AMS 5643. S values are producers' guaranteed minimum tensile properties.

Table 2.6.9.0(e). Design Mechanical and Physical Properties of 17-4PH Stainless Steel Bar

Specification	AMS 5643										
Form	Bar										
Condition	H900		H925		H1025	H1075		H1100	H1150		H1150M[a]
Thickness or diameter, in.	<8.000										
Basis	A	B	A	B	S	A	B	S	A	B	S[a]
Mechanical Properties:[b]											
F_{tu}, ksi:											
L	190	195	170	178	155	143	150	140	125	134	115
T	...	...	...	...	...	...	...	...	...	...	...
F_{ty}, ksi:											
L	170	175	155[c]	167	145	125[d]	143	115	100	115	75
T	...	...	...	...	...	...	...	...	...	...	...
F_{cy}, ksi:											
L	170	175	...	...	139	...	...	...	90	104	...
T	...	...	...	...	...	...	...	...	...	...	...
F_{su}, ksi	123	126	...	...	95	...	...	...	79	85	...
F_{bru}, ksi:											
(e/D = 1.5)	313	322	...	...	263[e]	...	...	...	213[e]	228[e]	...
(e/D = 2.0)	380	390	...	...	332[e]	...	...	...	270[e]	289[e]	...
F_{bry}, ksi:											
(e/D = 1.5)	255	262	...	...	211[e]	...	...	...	152[e]	175[e]	...
(e/D = 2.0)	280	288	...	...	250[e]	...	...	...	181[e]	208[e]	...
e, percent (S-basis):											
L	10	...	10	...	12	13	...	14	16	...	18
E, 10^3 ksi	28.5										
E_c, 10^3 ksi	30.0										
G, 10^3 ksi	11.2										
μ	0.27										
Physical Properties:											
ω, lb/in.^{3}	0.282 (H900), 0.283 (H1075), 0.284 (H1150)										
C, K, and α	See Figure 2.6.9.0										

[a] Not covered by AMS 5643. S values are producer's guaranteed minimum tensile properties.

[b] Design allowables were based upon data from samples of material, supplied in the solution treated condition, which were aged to demonstrate response to heat treatment by suppliers.

[c] S-basis. Rounded T_{99} value = 157 ksi.

[d] S-basis. Rounded T_{99} value = 136 ksi.

[e] Bearing values are "dry pin" values per Section 1.4.7.1.

Table 2.6.9.0(f). Design Mechanical and Physical Properties of 17-4PH Stainless Steel Investment Casting

Specification	AMS 5344	AMS 5343	AMS 5342
Form	Investment Casting		
Condition	[a]	H1000[b]	H1100[c]
Location within casting	Any area		
Basis	S	S	S
Mechanical Properties[d]:			
F_{tu}, ksi	180	150	130
F_{ty}, ksi	160	130	120
F_{cy}, ksi	...	132	...
F_{su}, ksi	...	98	...
F_{bru}[e], ksi:			
(e/D = 1.5)	...	254	...
(e/D = 2.0)	...	329	...
F_{bry}[e], ksi:			
(e/D = 1.5)	...	189	...
(e/D = 2.0)	...	222	...
e, percent	4	4	6
RA, percent	12	12	15
E, 10^3 ksi	28.5		
E_c, 10^3 ksi	30.0		
G, 10^3 ksi	12.7		
μ	0.27		
Physical Properties:			
ω, lb/in.^{3}	0.282 (H900)		
C, K, and α	See Figure 2.6.9.0		

a Aged at 900 to 925°F for 90 minutes.
b Aged at 985 to 1015°F for 90 minutes.
c Aged at 1085 to 1115°F for 90 minutes.
d Properties apply only when drawing specifies that conformance to tensile property requirements will be determined from specimens cut from casting or integrally cast specimens.
e Bearing values are "dry pin" values per Section 1.4.7.1.

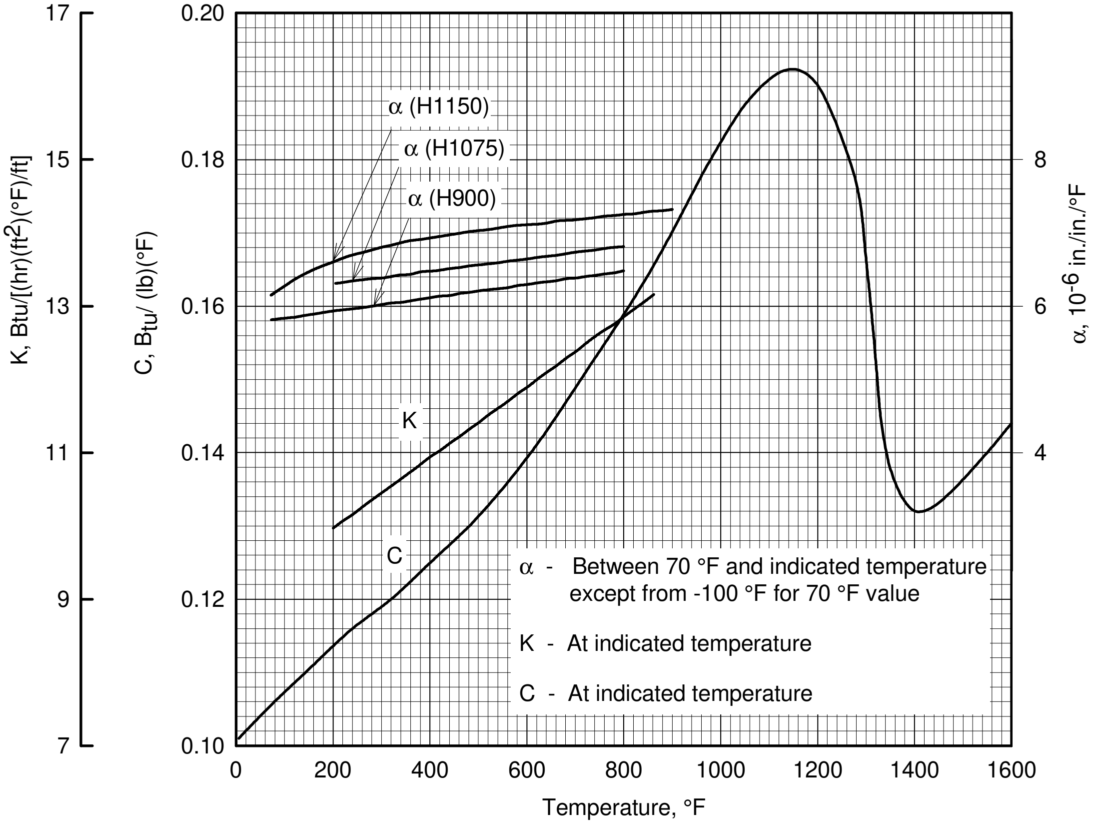

Figure 2.6.9.0. Effect of temperature on the physical properties of 17-4PH stainless steel.

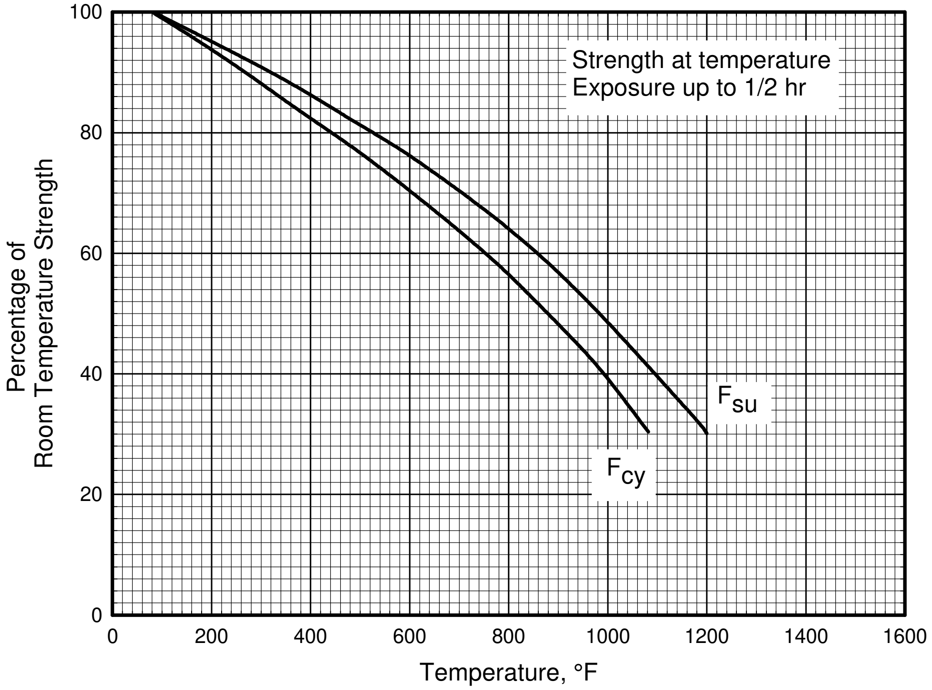

Figure 2.6.9.1.2. Effect of temperature on the compressive yield strength (F_{cy}) and the shear ultimate strength (F_{su}) of 17-4PH (H900) stainless steel bar and forging.

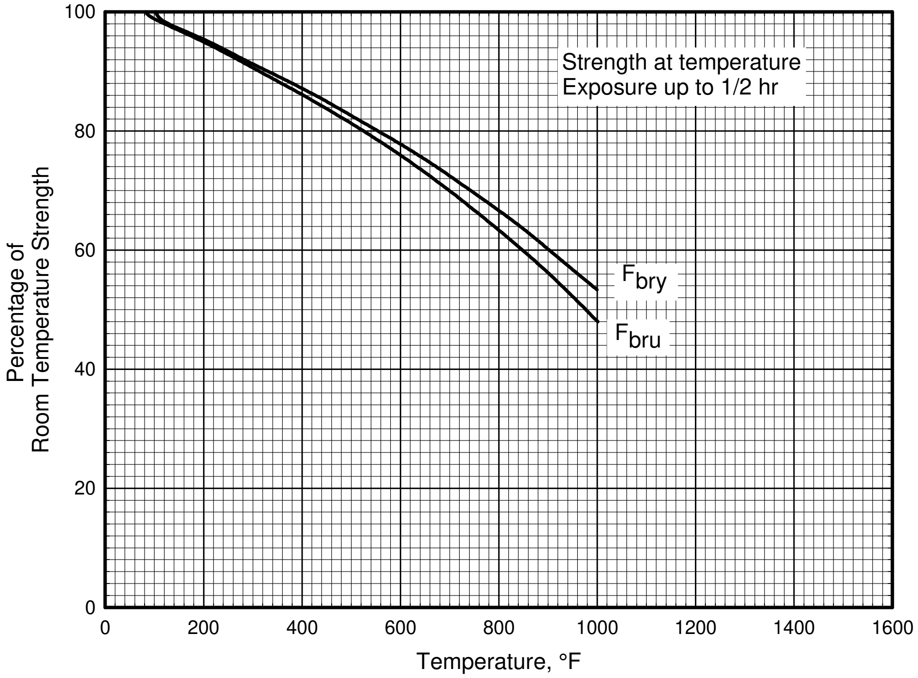

Figure 2.6.9.1.3. Effect of temperature on the bearing ultimate strength (F_{bru}) and the bearing yield strength (F_{bry}) of 17-4PH (H900) stainless steel bar and forging.

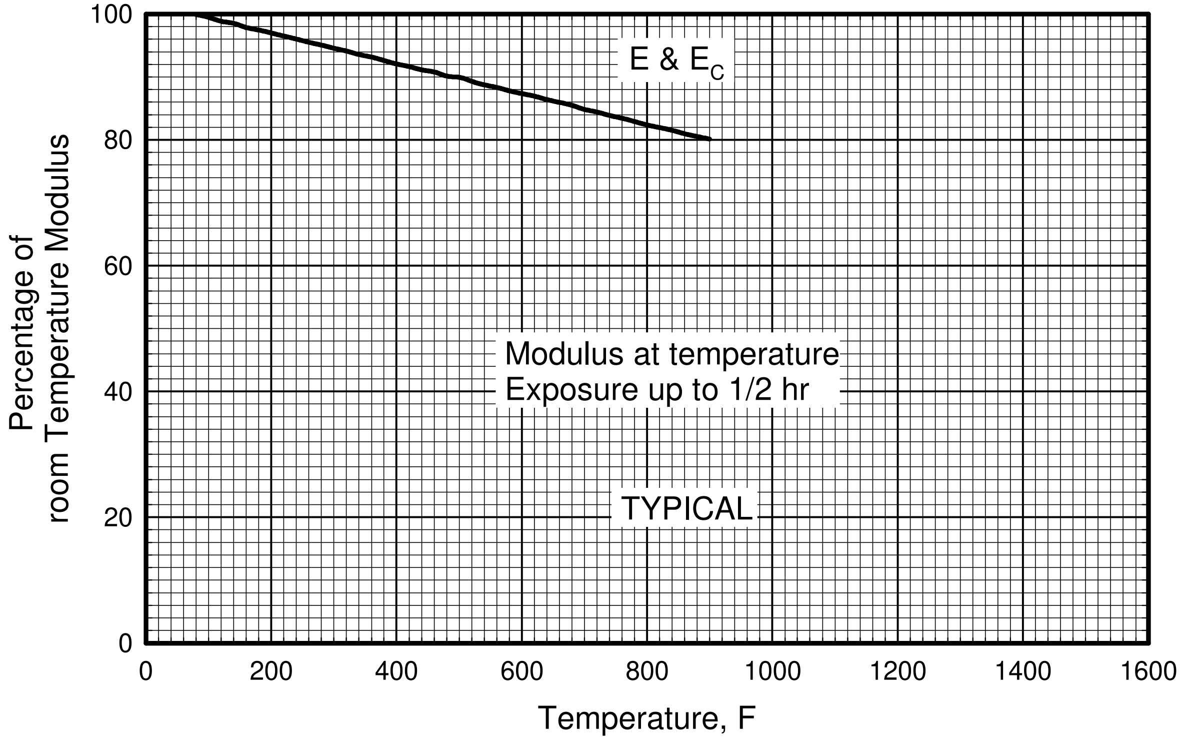

Figure 2.6.9.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of 17-4PH (H900) stainless steel bar and forging.

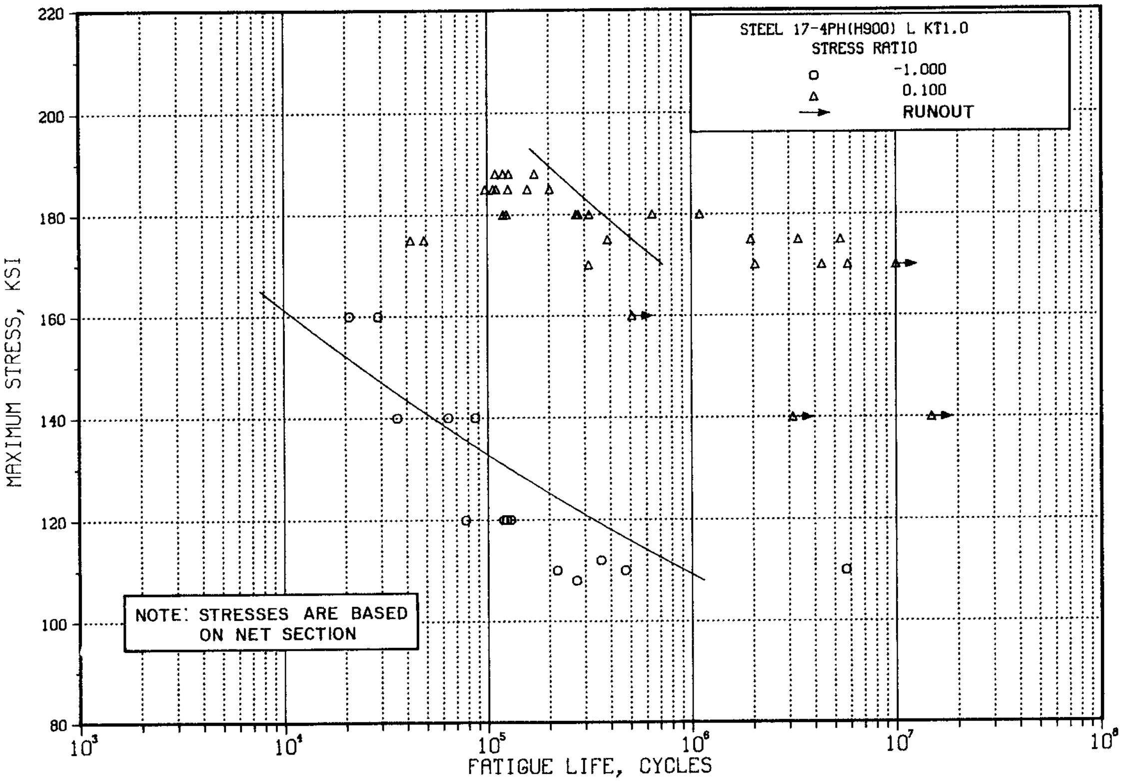

Figure 2.6.9.1.8(a). Best-fit S/N curves for unnotched 17-4PH (H900) bar, longitudinal direction.

Correlative Information for Figure 2.6.9.1.8(a)

Product Form: Bar, 1 inch and 1.125 inch diameter

Properties:

TUS, ksi	TYS, ksi	Temp., °F
202	195	RT

Specimen Details: Unnotched
1.25 inch gross diameter
0.252 inch net diameter

Surface Condition: Polished

References: 2.6.9.1.8(a)

Test Parameters:
Loading - Axial
Frequency - 1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
$\text{Log } N_f = 30.6 - 11.2 \log (S_{eq})$
$S_{eq} = S_{max} (1-R)^{0.52}$
Std. Error of Estimate, Log (Life) = 0.531
Standard Deviation, Log (Life) = 0.672
$R^2 = 38\%$

Sample Size: = 42

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

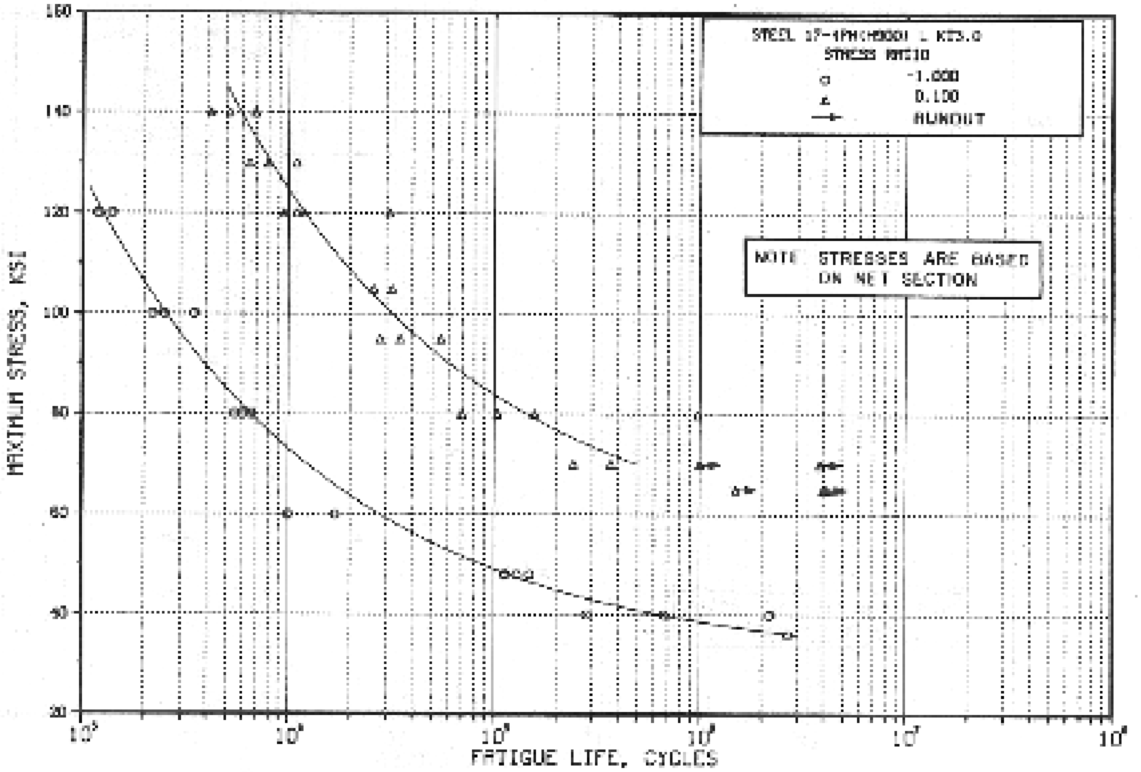

Figure 2.6.9.1.8(b). Best-fit S/N curves for notched, K_t = 3.0, 17-4PH (H900) bar, longitudinal direction.

Correlative Information for Figure 2.6.9.1.8(b)

Product Form: Bar, 1 inch and 1.125 inch diameter

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	202	195	RT

Specimen Details: Circumferential V-Groove, K_t = 3.0

Gross diameter inches	Net diameter inches	Notch radius inches
0.430	0.300	0.016
0.357	0.252	0.013

60° flank angle, ω

Surface Condition: Polished

Reference: 2.6.9.1.8(a)

Test Parameters:
Loading - Axial
Frequency - Not specified
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
$\text{Log } N_f = 9.10 - 2.79 \log (S_{eq} - 48.4)$
$S_{eq} = S_{max} (1-R)^{0.67}$
Std. Error of Estimate, Log (Life) = 0.235
Standard Deviation, Log (Life) = 0.897
R^2 = 93%

Sample Size: 39

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

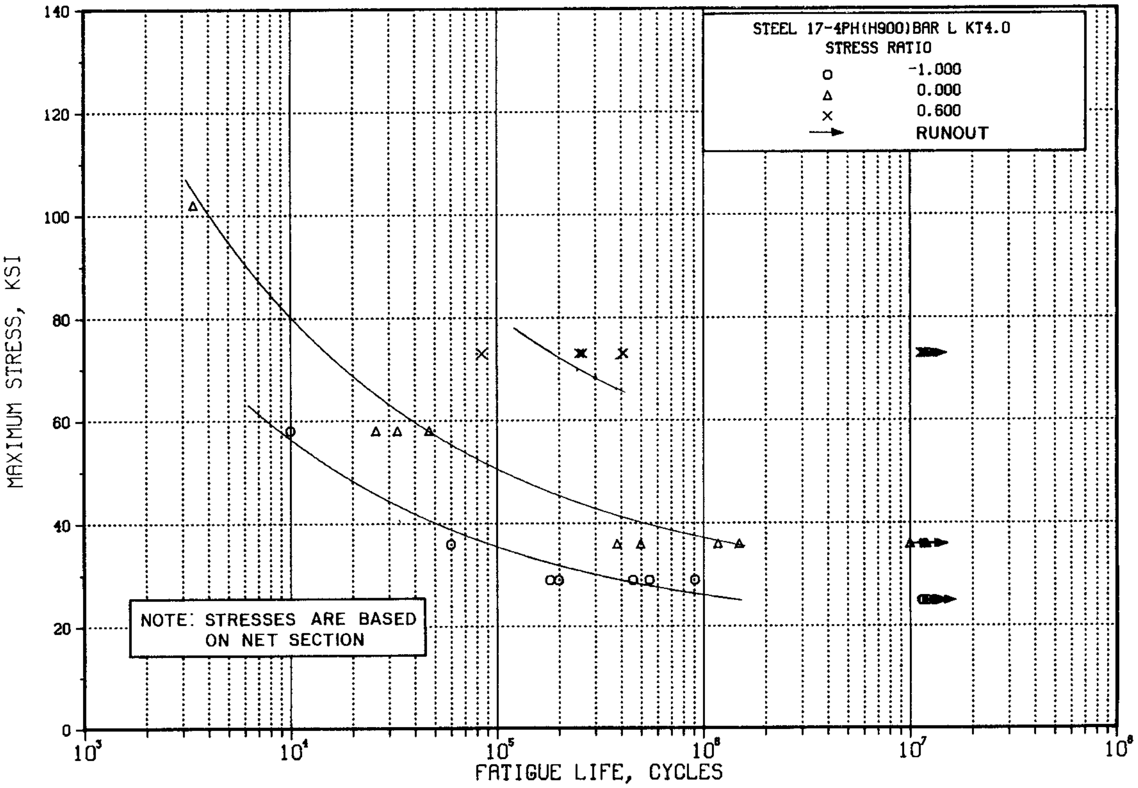

Figure 2.6.9.1.8(c). Best-fit S/N curves for notched, K_t = 4.0, 17-4PH (H900) bar, longitudinal direction.

Correlative Information for Figure 2.6.9.1.8(c)

Product Form: Bar, 0.787 inch diameter, vacuum melted

Properties:

TUS, ksi	TYS, ksi	Temp., °F
207	—	RT

Specimen Details: Circumferential
V-Groove, K_t = 4.0
0.492 inch gross diameter
0.256 inch net diameter
0.008 inch notch radius, n
60° flank angle, ω

Surface Condition: Machined and aged

Reference: 2.6.9.1.8(b)

Test Parameters:
Loading - Axial
Frequency - 2000 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 1

Equivalent Stress Equation:
$\text{Log } N_f = 9.03 - 2.91 \log (S_{eq} - 26.1)$
$S_{eq} = S_{max} (1-R)^{0.51}$
Std. Error of Estimate, Log (Life) = 0.345
Standard Deviation, Log (Life) = 0.812
$R^2 = 82\%$

Sample Size: = 22

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

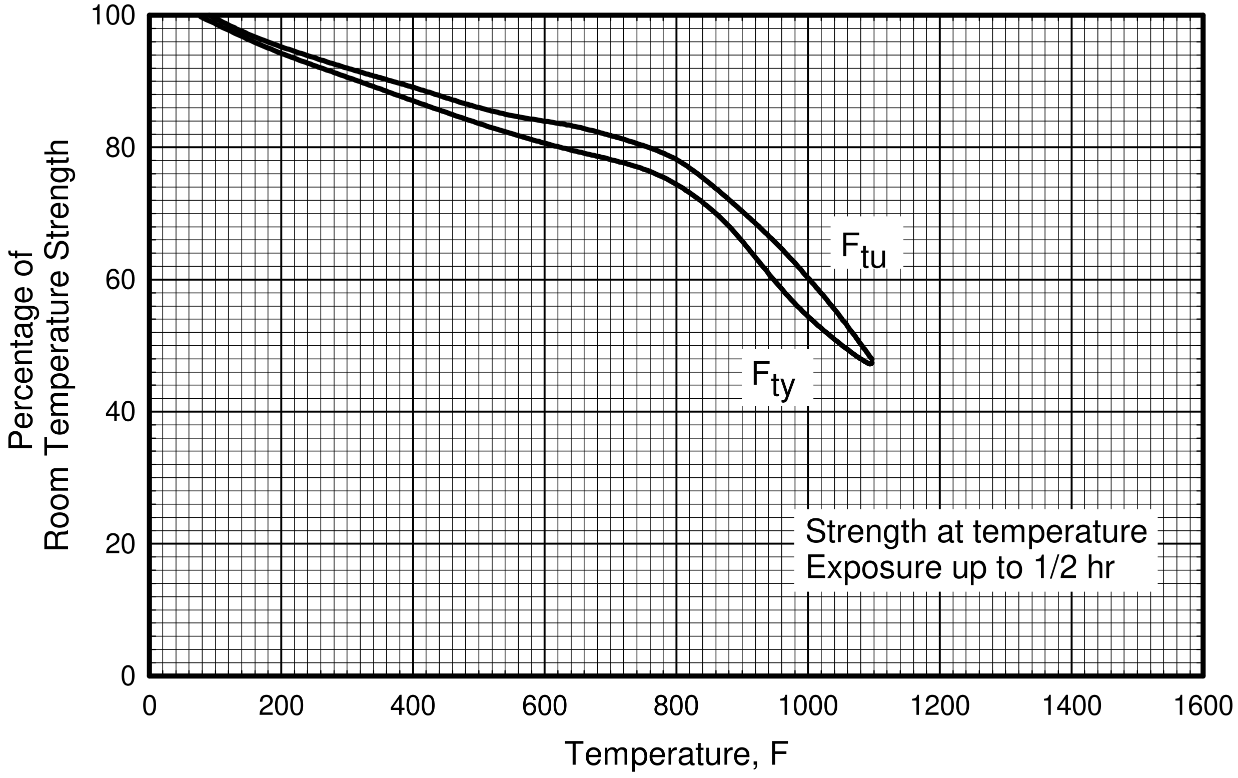

Figure 2.6.9.2.1. Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of 17-4PH (H900, H925, H1025, and H1075) stainless steel bar.

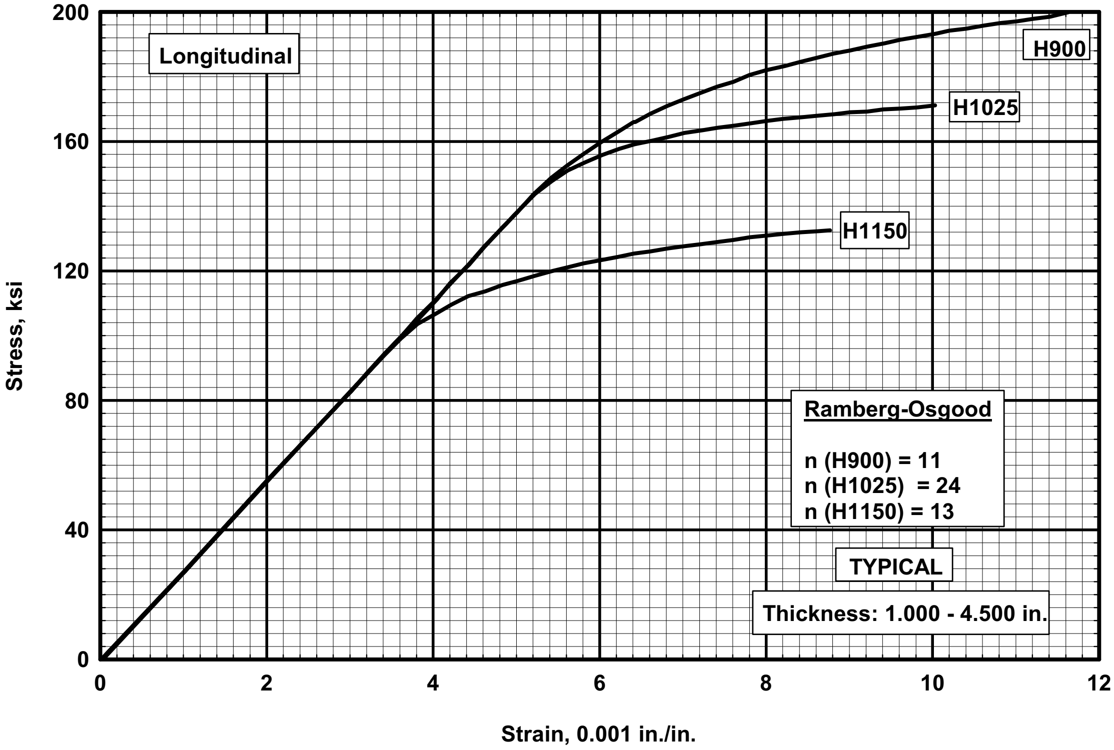

Figure 2.6.9.2.6(a). Typical tensile stress-strain curves at room temperature for various heat treated conditions of 17-4PH stainless steel bar.

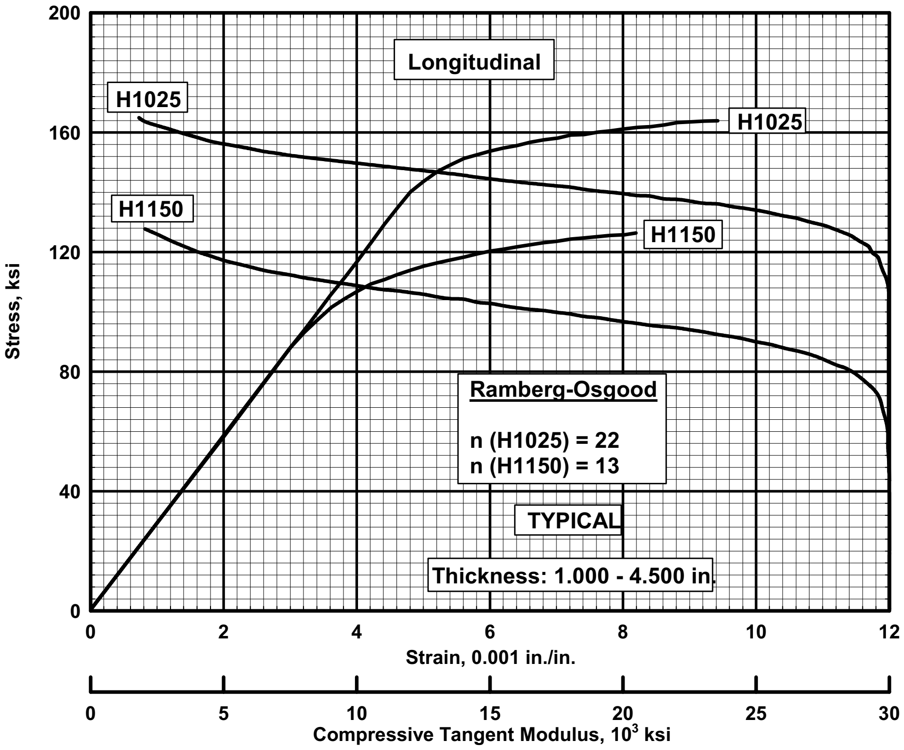

Figure 2.6.9.2.6(b). Typical compressive stress-strain and compressive tangent-modulus curves at room temperature for various heat treated conditions of 17-4PH stainless steel bar.

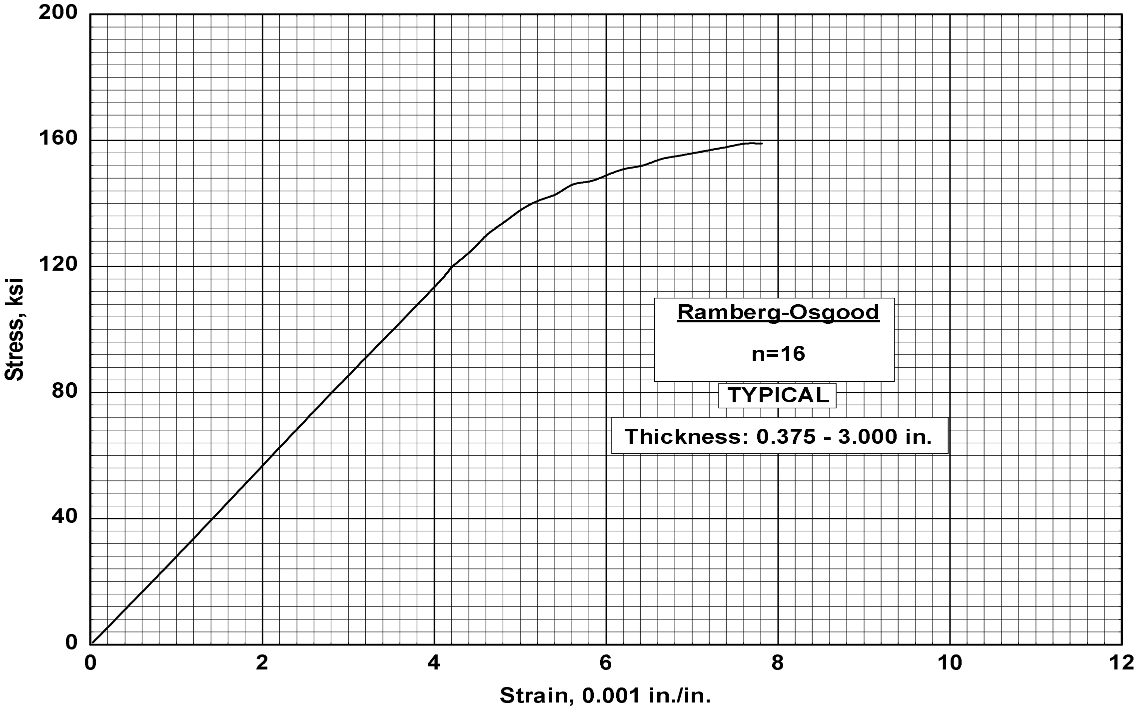

Figure 2.6.9.3.6(a). Typical tensile stress-strain curve for 17-4PH (H1000) stainless steel casting at room temperature.

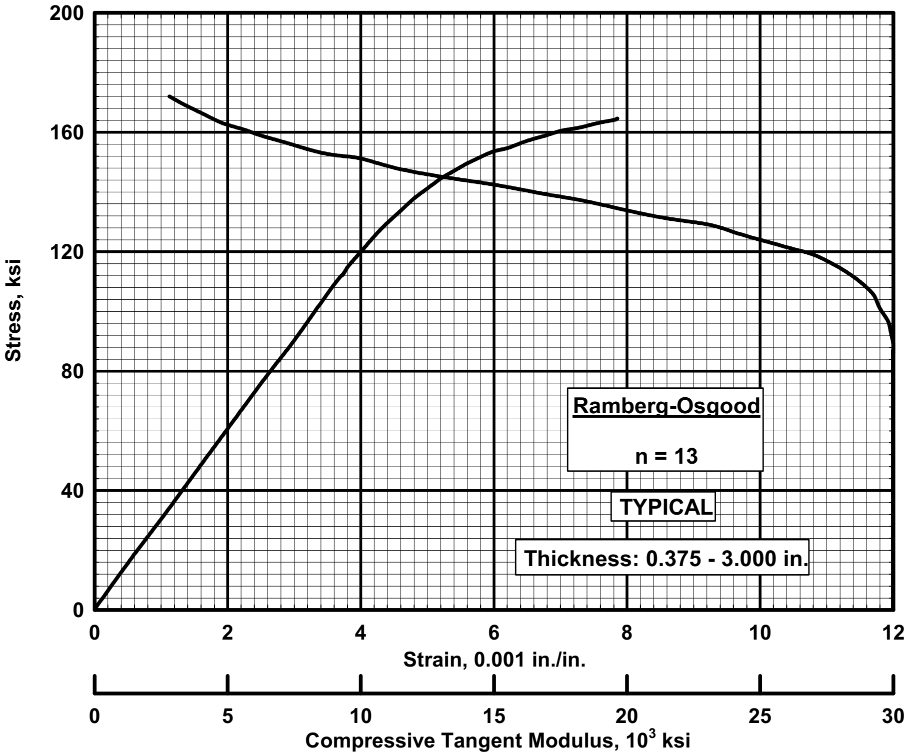

Figure 2.6.9.3.6(b). Typical compressive stress-strain and compressive tangent-modulus curves for 17-4PH (H1000) stainless steel casting at room temperature.

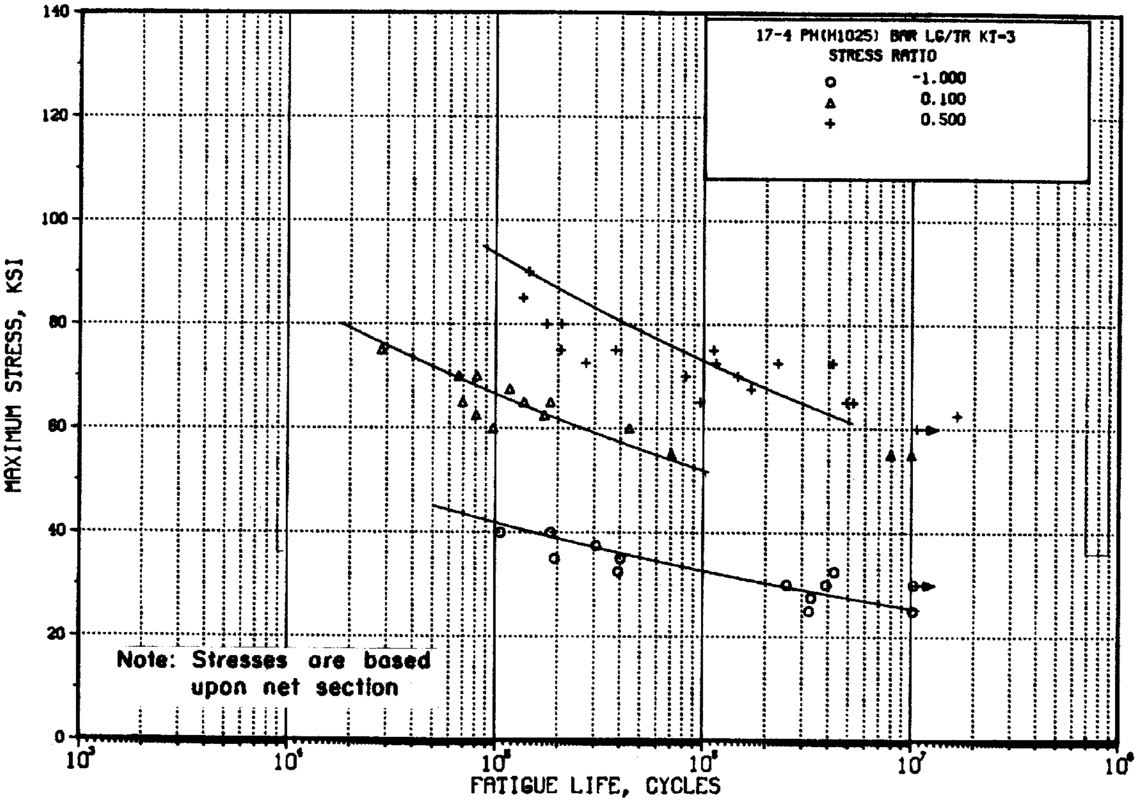

Figure 2.6.9.4.8. Best-fit S/N curves for notched, K_t = 3.0, fatigue behavior of 17-4PH (H1025) stainless steel bar, longitudinal and long transverse directions.

Correlative Information for Figure 2.6.9.4.8

Product Form: Bar, 2 x 6 inches

Properties:	TUS, ksi	TYS, ksi	Temp, °F
Longitudinal	165	161	RT
Long Transverse	164	158	RT
Longitudinal	280	—	RT (notched)
Long Transverse	275	—	RT (notched)

Specimen Details: Notched V-Groove, K_t = 3.0
0.375 inch gross diameter
0.250 inch net diameter
0.013 inch root radius, r
60° flank angle, ω

Surface Condition: Notched: Ground notch

Reference: 2.6.6.2.8

Test Parameters:
Loading - Axial
Frequency - 1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 3

Equivalent Stress Equation:
$\text{Log } N_f = 21.60 - 9.24 \log (S_{eq})$
$S_{eq} = S_{max} (1-R)^{0.581}$
Std. Error of Estimate, Log (Life) = 0.413
Standard Deviation, Log (Life) = 0.724
$R^2 = 67\%$

Sample Size: = 44

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

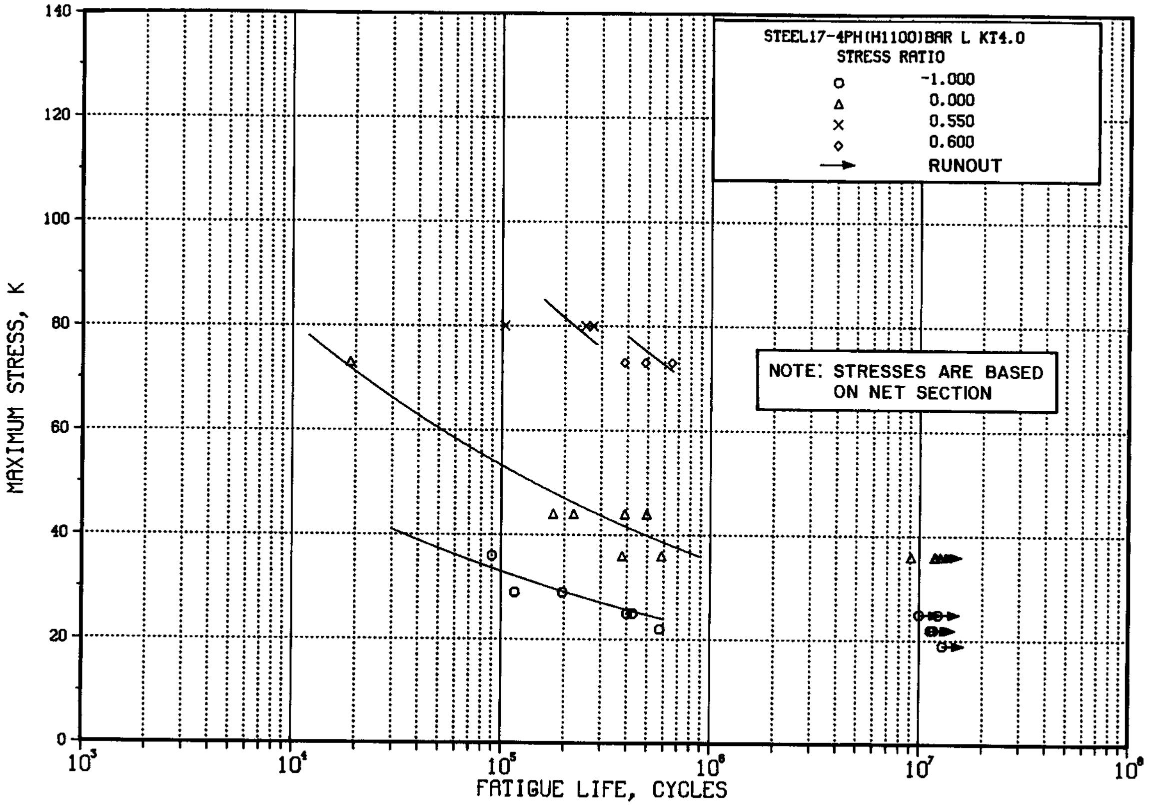

Figure 2.6.9.5.8. Best-fit S/N curves for notched, K_t = 4.0, 17-4PH (H1100) bar, longitudinal direction.

Correlative Information for Figure 2.6.9.5.8

Product Form: Bar, 0.787 inch diameter

Properties:	TUS, ksi	TYS, ksi	Temp, °F
	151	—	RT

Specimen Details: Circumferential V-Groove, K_t=4.0
0.492 inch gross diameter
0.256 inch net diameter
0.008 inch notch radius, r
60° flank angle, ω

Surface Condition: Machined then aged

Reference: 2.6.9.1.8(b)

Test Parameters:
Loading - Axial
Frequency - 2000 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not Specified

Equivalent Stress Equation:
$\text{Log } N_f = 14.6 - 5.56 \log (S_{eq})$
$S_{eq} = S_{max} (1-R)^{0.69}$
Std. Error of Estimate, Log (Life) = 0.301
Standard Deviation, Log (Life) = 0.556
R^2 = 71%

Sample Size: = 21

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

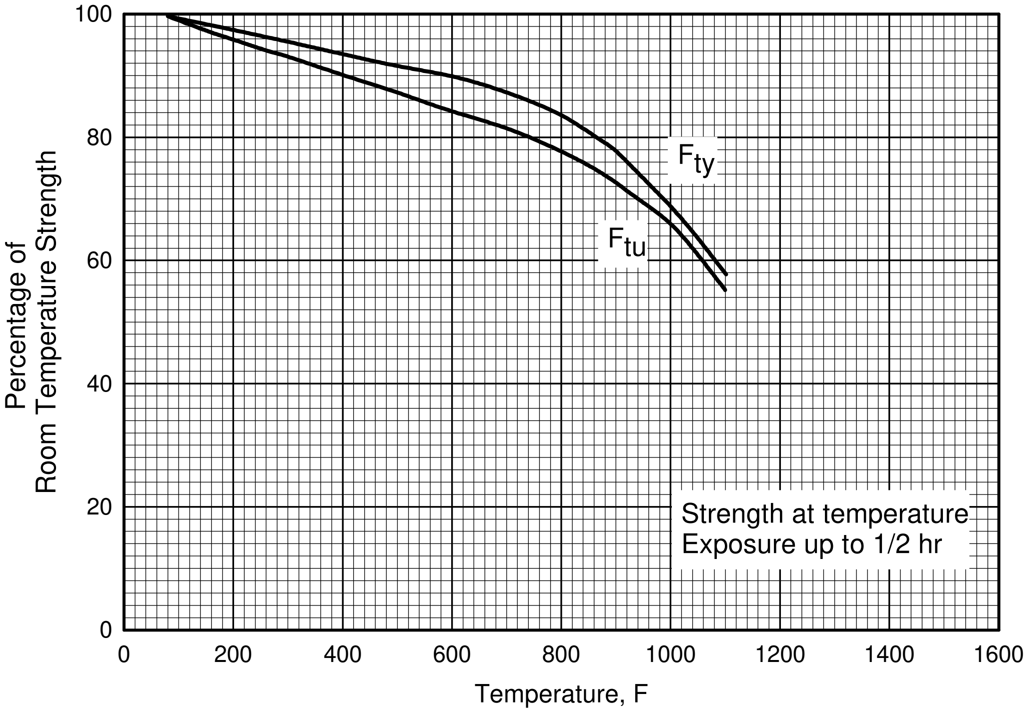

Figure 2.6.9.6.1. Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of 17-4PH (H1150) stainless steel bar.

2.6.10 17-7PH

2.6.10.0 *Comments and Properties* — 17-7PH is a semiaustenitic stainless steel used where high strength and good corrosion and oxidation resistance are needed up to 600°F. This steel is supplied in Condition A for ease of forming.

Manufacturing Considerations — 17-7PH in Condition A is readily cold formed. Conventional inert-gas shielded arc and resistance techniques are generally used for welding. Vapor blasting of scaled Condition TH1050 parts is recommended because of the hazards of intergranular corrosion during pickling operations.

Heat Treatment — 17-7PH must be used in the heat-treated condition and should not be placed in service in Condition A or T. Condition A should be restored by resolution treating when this condition has been altered during processing operations such as hot working, welding, or brazing. The heat-treatment procedures for this steel are compatible with the cycles used for honeycomb panel brazing. In hardening this steel from Condition A to Condition TH1050 a net dimensional growth of 0.0045 in./in. will occur.

The heat treatment to anneal is:

Treatment	Designation
1950 ± 25°F and air cool	Condition A

The transformation treatment from Condition A is as follows:

Treatment	Designation
1400 ± 25°F - 90 minutes and cool to 55 ± 5°F for 30 minutes	Condition T

The aging treatment is:

Treatment	Designation
1050 ± 10°F - 90 minutes and air cool	TH1050

Environmental Considerations — The resistance of 17-7PH to stress-corrosion cracking in chloride environs has been evaluated and found to be superior to that of the alloy steels and the hardenable chromium steels. Strength properties are lowered by exposure to temperatures above about 975°F for periods longer than one-half hour.

Specifications and Properties — Material specifications for 17-7PH stainless steel is presented in Table 2.6.10.0(a). The room-temperature properties of 17-7PH are shown in Tables 2.6.10.0(b) and (c). The effect of temperature on the physical properties of this alloy are presented in Figure 2.6.10.0.

Table 2.6.10.0(a). Material Specification for 17-7PH Stainless Steel

Specification	Form
AMS 5528	Plate, sheet, and strip

Table 2.6.10.0(b). Design Mechanical and Physical Properties of 17-7PH Stainless Steel Sheet and Plate

Specification	AMS 5528			
Form	Sheet		Plate	
Condition	TH1050			
Thickness, in.	0.015-0.187		0.188-0.500	0.501-1.000
Basis	A	B	S	S
Mechanical Properties:[a]				
F_{tu}, ksi:				
L	177	183	...	...
LT	177	184	180	180
F_{ty}, ksi:				
L	150[b]	167	...	...
LT	150[c]	167	150	150
F_{cy}, ksi:				
L	160	179	160	...
LT	166	185	166	...
F_{su}, ksi	112	117	114	...
F_{bru}, ksi:				
(e/D = 1.5)	305	317	310	...
(e/D = 2.0)	351	365	357	...
F_{bry}, ksi:				
(e/D = 1.5)	228	254	228	...
(e/D = 2.0)	240	267	240	...
e, percent (S-basis):				
LT	[d]	...	6	6
E, 10^3 ksi	29.0			
E_c, 10^3 ksi	30.0			
G, 10^3 ksi	11.5			
μ	0.28			
Physical Properties:				
ω, lb/in.^{3}	0.276			
C, K, and α	See Figure 2.6.10.0			

[a] Design allowables were based upon data from samples of material, supplied in the solution treated condition, which were austenite conditioned and aged to demonstrate response to heat treatment by suppliers. Properties obtained by the user may be different if the material has been formed or otherwise cold worked.

[b] The rounded T_{99} value of 158 ksi was reduced to agree with transverse specification value.

[c] S-Basis. The rounded T_{99} value equals 159 ksi.

[d] See Table 2.6.10.0(c).

2.6.10.1 ***TH1050 Condition*** — Elevated temperature curves for various mechanical properties are presented in Figures 2.6.10.1.1, 2.6.10.1.2, and 2.6.10.1.4(a) and (b). Tensile and compression stress-strain curves at room temperature and at several elevated temperatures are presented in Figures 2.6.10.1.6(a) and (b). Typical compressive tangent-modulus curves at various temperatures are presented in Figure 2.6.10.1.6(c).

Table 2.6.10.0(c). Minimum Elongation Values for 17-7PH (TH1050) Stainless Steel Sheet

Thickness, in.	Elongation (LT), percent
0.005 to 0.010	4
0.011 to 0.019	5
0.020 to 0.187	6

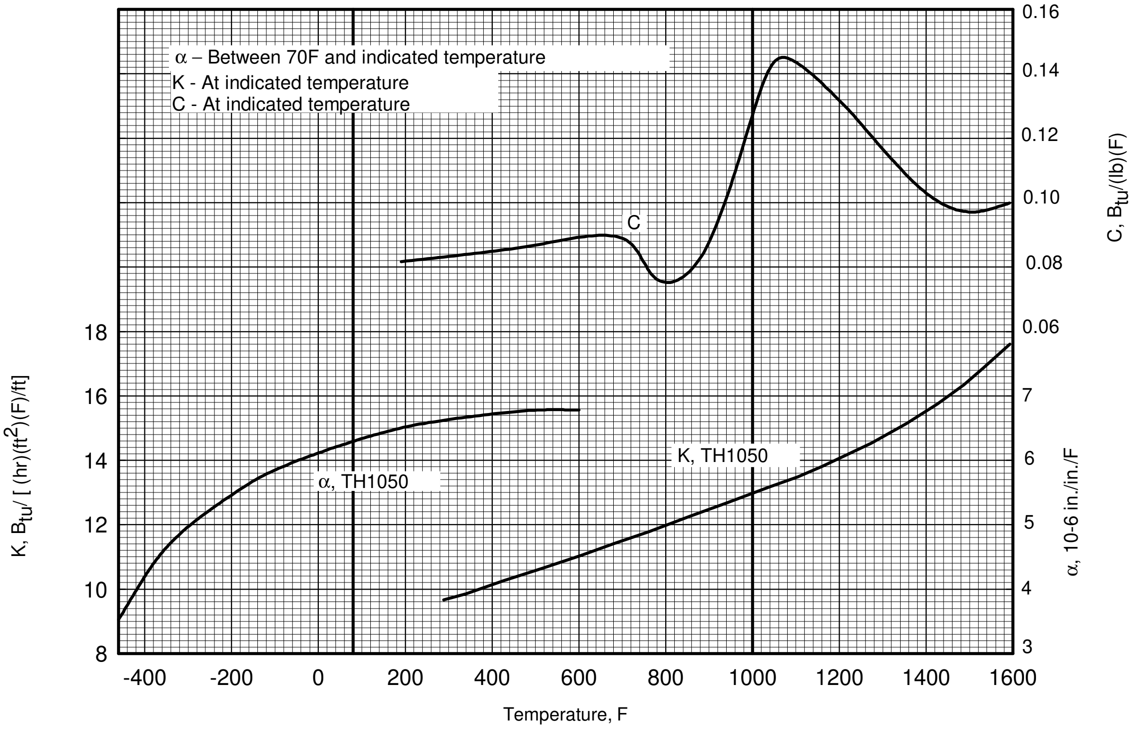

Figure 2.6.10.0. Effect of temperature on the physical properties of 17-7PH stainless steel.

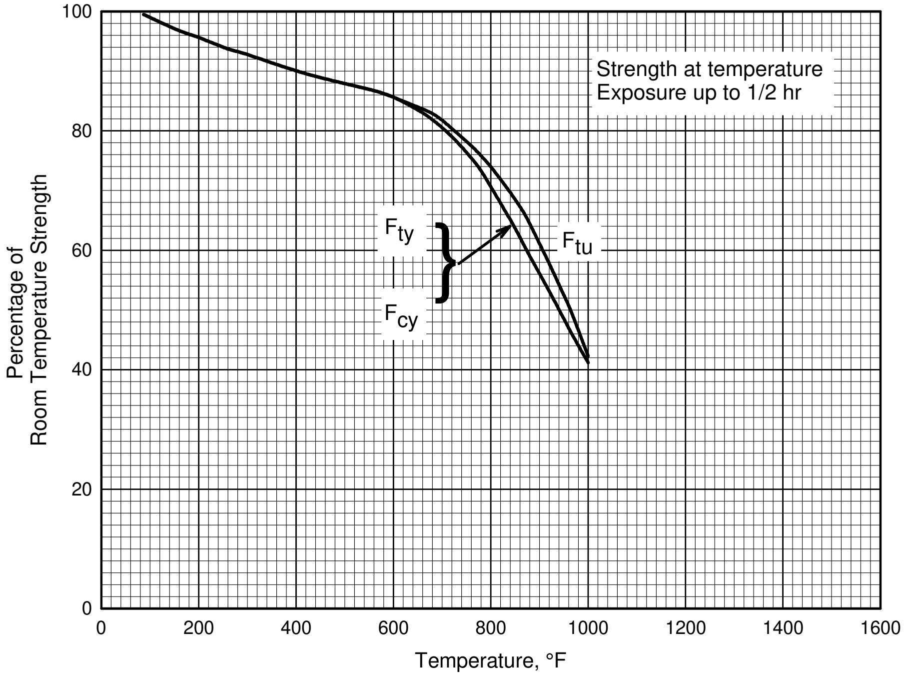

Figure 2.6.10.1.1. Effect of temperature on the tensile ultimate strength (F_{tu}), tensile yield strength (F_{ty}), and compressive yield strength (F_{cy}) of 17-7PH (TH1050) stainless steel sheet.

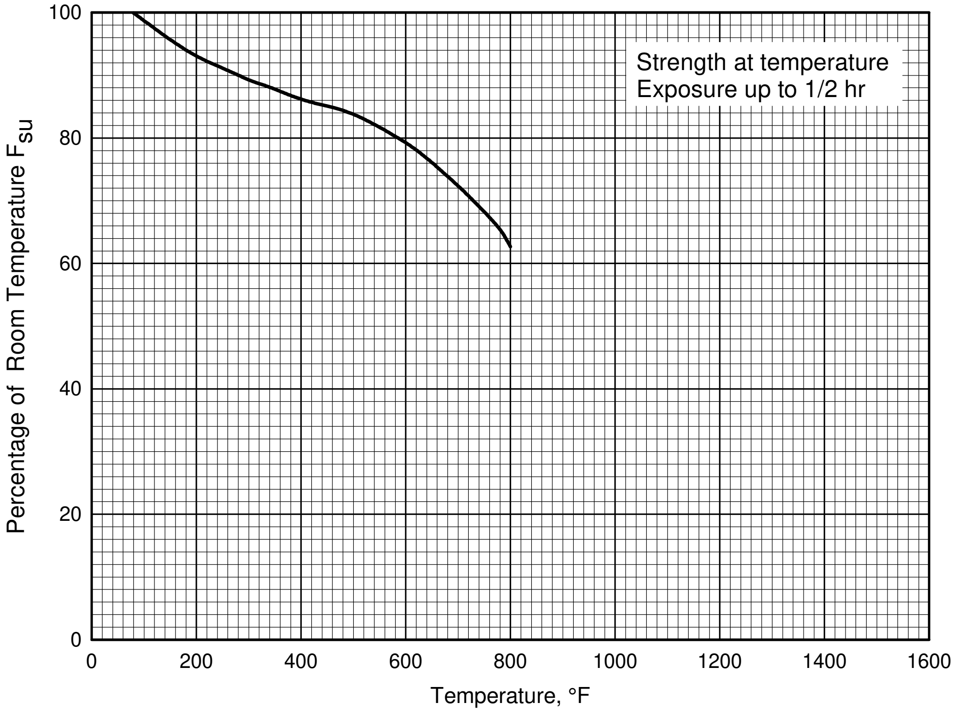

Figure 2.6.10.1.2. Effect of temperature on the ultimate shear strength (F_{su}) of 17-7PH (TH1050) stainless steel sheet.

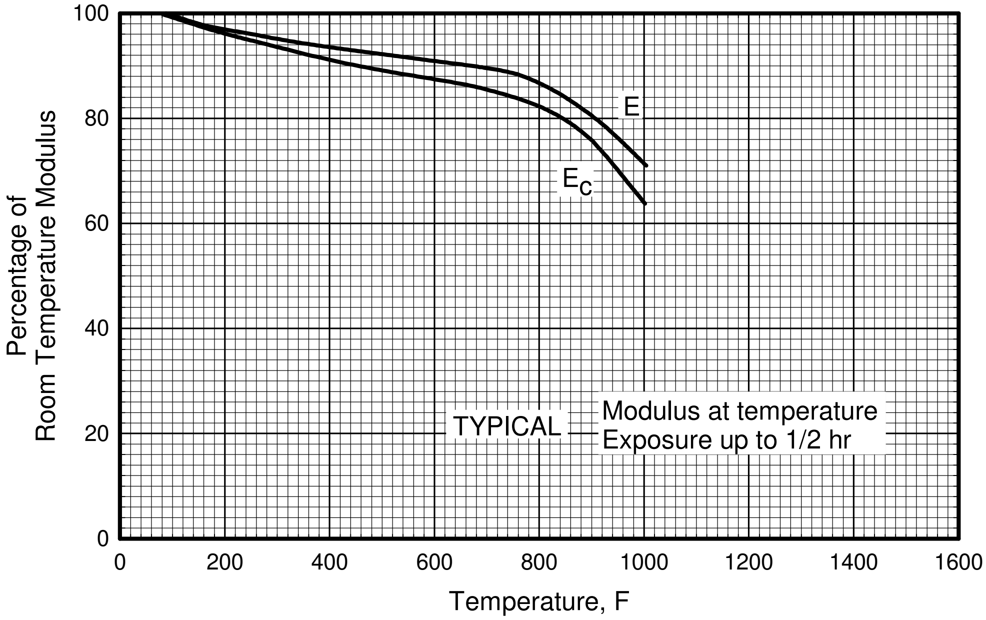

Figure 2.6.10.1.4(a). Effect of temperature on the tensile and compressive moduli (E and E_c) of 17-7PH (TH1050) stainless steel sheet.

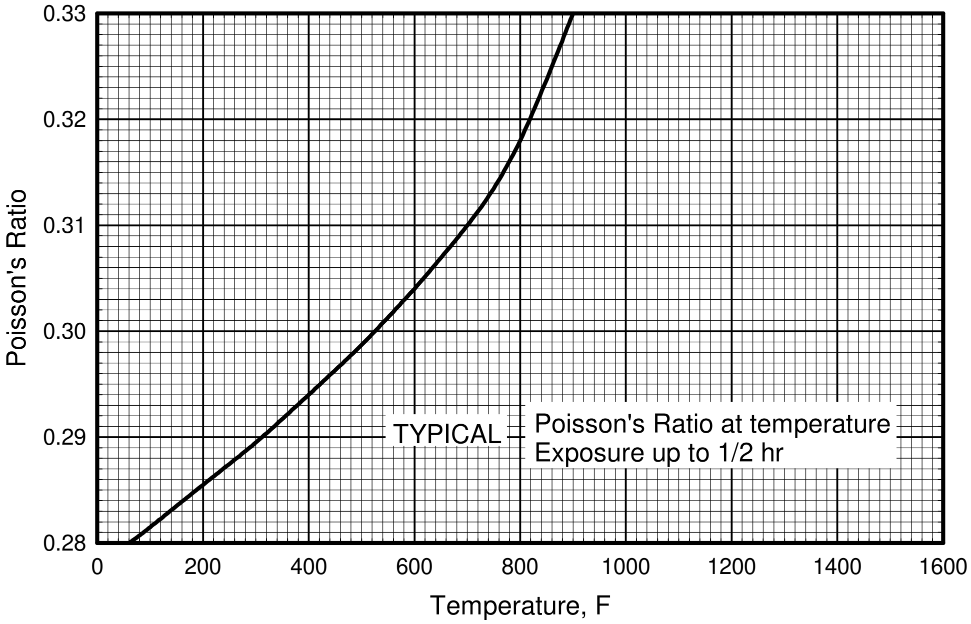

Figure 2.6.10.1.4(b). Effect of temperature on Poisson's ratio (μ) for 17-7PH (TH1050) stainless steel sheet.

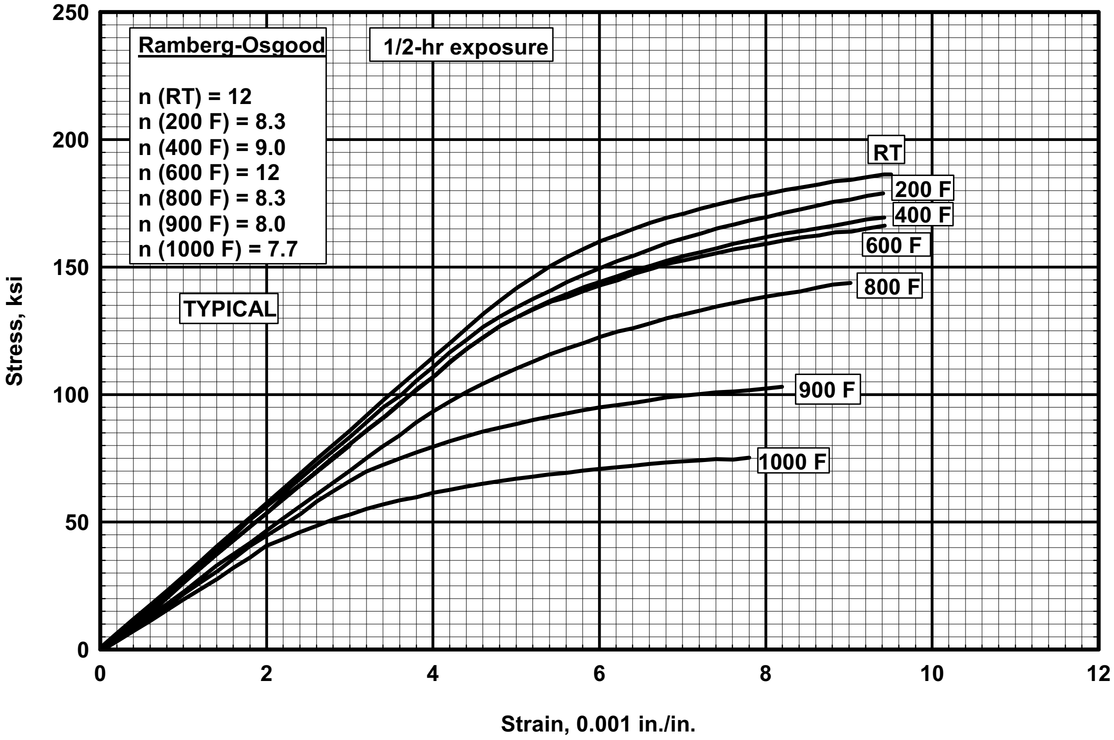

Figure 2.6.10.1.6(a). Typical tensile stress-strain curves at various temperatures for 17-7PH (TH1050) stainless steel sheet.

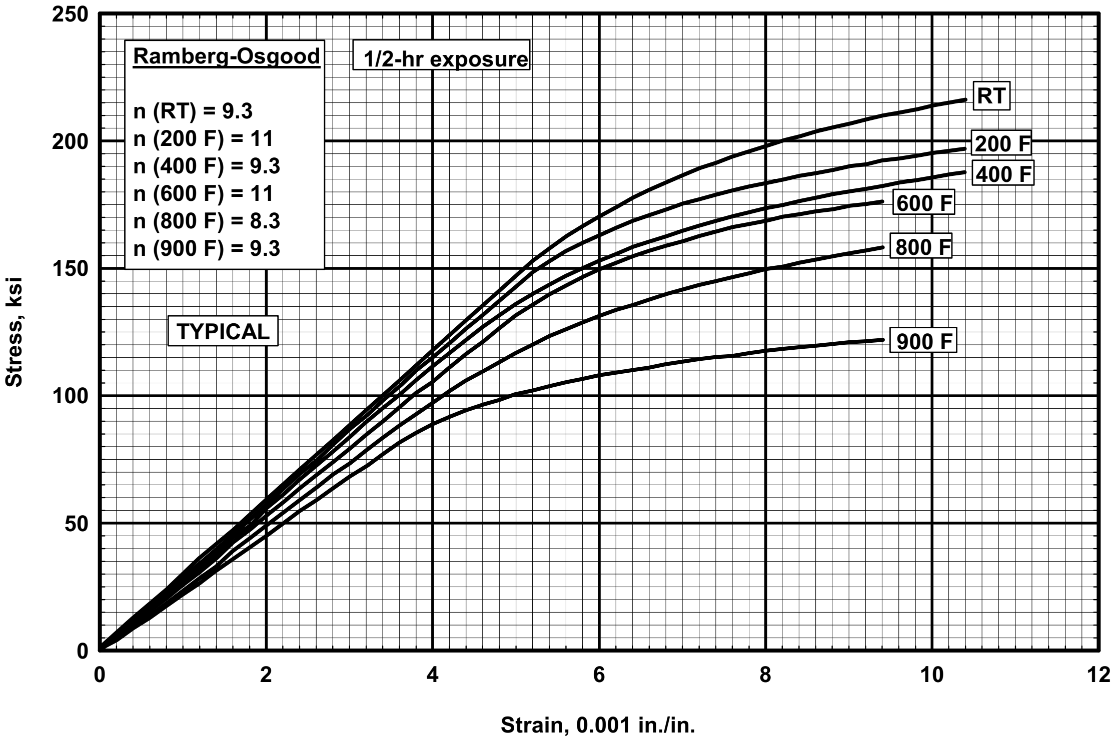

Figure 2.6.10.1.6(b). Typical compressive stress-strain curves at various temperatures for 17-7PH (TH1050) stainless steel sheet.

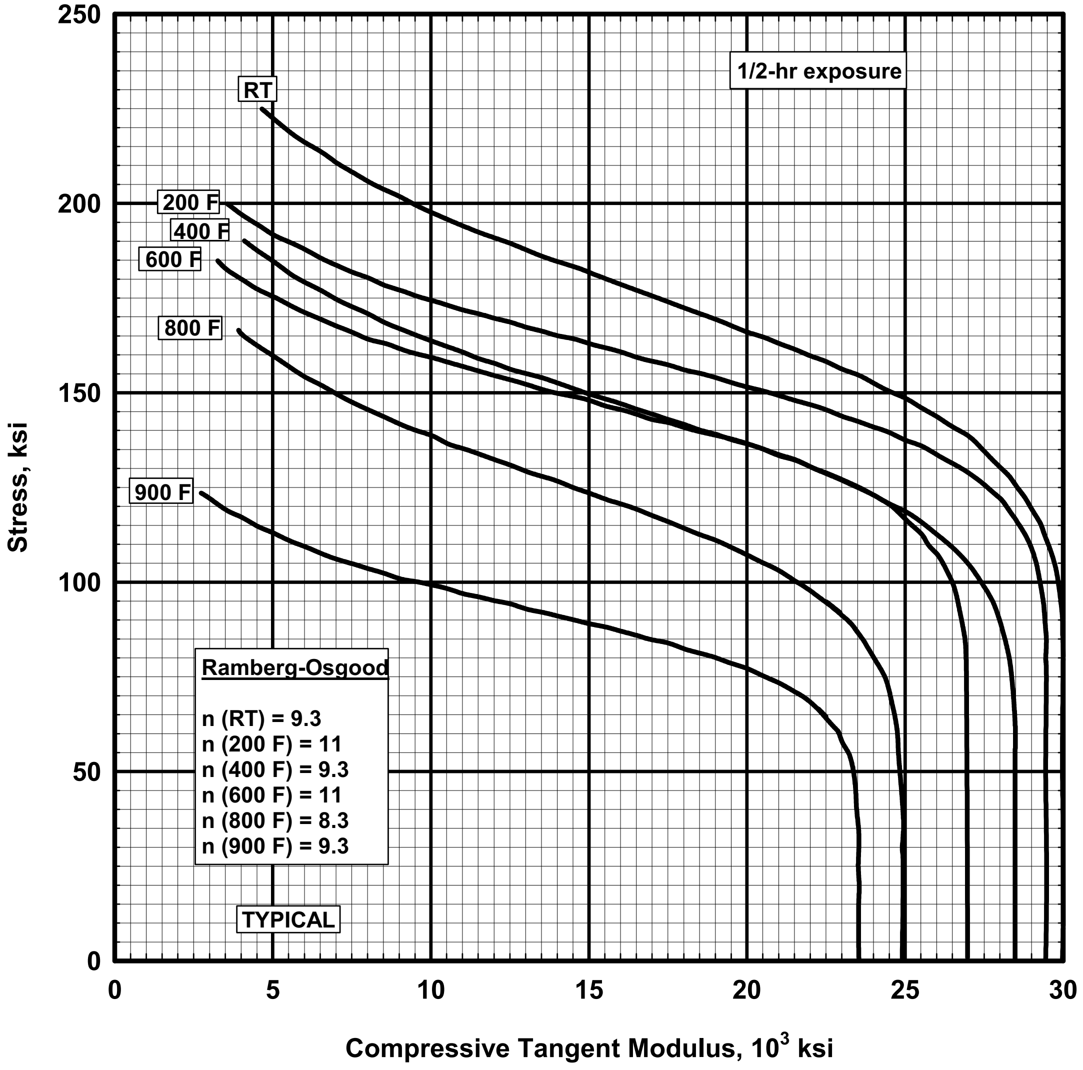

Figure 2.6.10.1.6(c). Typical compressive tangent-modulus curves at various temperatures for 17-7PH (TH1050) stainless steel sheet.

2.7 AUSTENITIC STAINLESS STEELS

2.7.0 COMMENTS ON AUSTENITIC STAINLESS STEEL

2.7.0.1 *Metallurgical Considerations* — The austenitic ("18-8") stainless steels were developed as corrosion-resistant alloys. However, they possess excellent oxidation resistance and good creep strength at elevated temperatures, along with good cold formability and other properties in airframe and missile applications. They are used in sheet form for portions of the airframe having ambient temperatures too high for aluminum alloys and, with the development of sandwich structures, are gaining additional uses. These steels are also used extensively at cryogenic temperatures.

The two alloying elements in the austenitic stainless steels are chromium and nickel. Chromium adds corrosion and oxidation resistance and high-temperature strength, and nickel gives an austenitic structure, with its associated toughness and ductility. The AISI 300 series stainless steels constitute a wide variety of compositions designed for different applications. The basic grade, Type 302, contains 18 percent chromium and 8 percent nickel. Varying one or both of these elements creates special characteristics. Type 301 (17 percent chromium and 7 percent nickel) work hardens to very high strengths. Type 310 (25 percent chromium and 20 percent nickel) has higher elevated temperature strength and greater oxidation resistance than Type 302. Sulfur and selenium additions promote free machining. Low carbon and/or columbium or titanium additions minimize intergranular corrosion for elevated temperature applications and welded construction. The addition of molybdenum improves corrosion resistance in reducing environments and gives improved creep resistance over Type 302. The characteristics of some of the AISI 300 series stainless steels are presented in Table 2.7.0.1.

These alloys are not hardenable by heat treatment but can achieve high-strength levels through cold working. The strength imparted by cold working is decreased by exposure to temperatures above about 900°F.

2.7.0.2 *Manufacturing Considerations* —

Forging — The stainless steels have lower thermal conductivity than lower alloy steels and are susceptible to grain growth at forging temperatures. Hence, soaking times must be adequate to permit thorough heating of the billet but must be controlled carefully to limit grain growth when small reductions are involved during forging. At forging temperatures, the stainless steels are stronger than alloy steels, and forging must be conducted at higher temperatures and heavier forging equipment and more frequent reheating are required. The stainless steel billets forge much better when the surface is free of defects, and machine turning of the billets is advisable.

Cold Forming — Because of their austenitic structure at room temperature, the stainless steels have excellent ductility for cold-forming operations when in the annealed condition. These steels work harden rapidly, and intermediate anneals may be required in deep drawing.

Machining — The machining of the austenitic stainless steels is not difficult if proper steps are taken to combat the work-hardening tendencies of these steels. The use of heavy machines, slow speeds, deep cuts, and properly designed cutting tools with a fairly steep top rake produces the best results. Cold-worked material possesses somewhat better machinability than hot-finished, annealed material. These steels also are available in free-machining grades, containing sulfur or selenium.

Welding — The austenitic stainless steels can be welded by almost any usual technique except carbon arc, provided adequate steps are taken to prevent oxidation or carburization of the weldment. The stabilized grades are preferred for welded parts that are used in the as-welded condition under corrosive conditions. The free-machining grades are not recommended for welding. Filler rods should be the same composition, or slightly higher in alloy content, as the material to be welded. Special fluxes designed for use with stainless

Table 2.7.0.1. Characteristics of Some AISI 300 Series Stainless Steels

AISI	Characteristics
301	High work-hardening rate; applications requiring high strength and ductility.
302	Higher carbon modification of Type 304 for higher strength on cold rolling.
303	Free machining sulfur modification of Type 302.
303Se	Free machining selenium modification of Type 302.
304	General purpose austenitic grade for enhanced corrosion resistance.
304L	Low-carbon modification of Type 304 for welding applications.
305	Low work-hardening rate; spin forming and severe spin drawing operations.
309	High-temperature strength and oxidation resistance.
309S	Low-carbon modification of Type 309 for welded construction.
310	High-temperature strength and oxidation resistance greater than Type 309.
310S	Low-carbon modification of Type 310 for welded construction.
314	Increased oxidation resistance over Type 310.
316	Mo added to improve corrosion resistance in reducing environments; improved creep resistance over Type 302.
316L	Low-carbon modification of Type 316 for welded construction.
317	Increased Mo to improve corrosion resistance over Type 316 in reducing media.
321	Titanium stabilized for service in 800 to 1600°F range and to minimize carbide precipitation when welding for resistance to intergranular corrosion.
347	Columbium stabilized for service in 800 to 1600°F range and to minimize carbide precipitation when welding for resistance to intergranular corrosion.

steels should be employed, except in atomic hydrogen or inert-gas-shielded arc welding. Spot and roll seam welding also are used to a considerable extent.

Brazing — Special techniques have been developed for silver-soldering and brazing these steels. Solders and fluxes especially designed should be used, surfaces must be thoroughly cleaned, and close control of temperature must be followed.

2.7.0.3 *Environmental Considerations* — The austenitic stainless steels have excellent oxidation resistance at high temperatures, and their elevated-temperature service is usually limited by strength criteria. They also possess unusually good resistance to corrosion by most media. Prolonged exposure of the nonstabilized grades to temperatures between 700 and 1650°F makes them susceptible to intergranular corrosion.

2.7.1 AISI 301 and Related 300 Series Stainless Steels

2.7.1.0 ***Comments and Properties*** — Of the austenitic stainless steels, AISI 301 is the one most frequently used at high-strength levels in aircraft, mainly because of its greater work-hardening characteristics.

Type 301 is strengthened by cold working. If cold-worked Type 301 is subjected to temperatures above 900°F, its room-temperature strength is reduced.

Type 301 should not be used for extended periods at temperatures of 750 to 1650°F and should not be cooled slowly from higher temperatures through this range.

Material specifications for AISI 301 stainless steel are presented in Table 2.7.1.0(a). The room-temperature mechanical and physical properties for AISI 301 stainless steel are presented in Tables 2.7.1.0(b) and (c). The physical properties of this alloy at room and elevated temperatures are presented in Figure 2.7.1.0. Specifications for related 300 series alloys for which the properties are applicable are footnoted in Table 2.7.1.0(b).

Table 2.7.1.0(a). Material Specifications for AISI 301 Stainless Steel

Specification	Form
AMS 5517	Sheet and strip
AMS 5518	Sheet and strip
AMS 5519	Sheet and strip
AMS 5901	Plate, sheet, and strip
AMS 5902	Sheet and strip

2.7.1.1 ***Annealed Condition*** — Elevated temperature curves for tensile yield and ultimate strengths are presented in Figures 2.7.1.1.1(a) and (b).

2.7.1.2 ***¼ Hard Condition*** — Typical room-temperature stress-strain and tangent-modulus curves are presented in Figures 2.7.1.2.6(a) and (b).

2.7.1.3 ***½ Hard Condition*** — Elevated temperature curves for various mechanical properties are presented in Figures 2.7.1.3.1 through 2.7.1.3.4. Typical stress-strain and tangent-modulus curves are presented in Figures 2.7.1.3.6(a) and (b).

2.7.1.4 ***¾ Hard Condition*** — Typical room-temperature stress-strain and tangent-modulus curves are presented in Figures 2.7.1.4.6(a) and (b).

2.7.1.5 ***Full-Hard Condition*** — The full-hard condition is a standard AISI temper and is developed by cold rolling 40 to 50 percent. Elevated temperature curves for various mechanical properties are presented in Figure 2.7.1.5.1 through 2.7.1.5.4. Tensile and compressive stress-strain as well as tangent-modulus curves at room temperature and several elevated temperatures are presented in Figures 2.7.1.5.6(a) through (d).

Table 2.7.1.0(b). Design Mechanical and Physical Properties of AISI 301and Related[a,b,c] Stainless Steels

Specification	AMS 5901	AMS 5517		AMS 5518		AMS 5902		AMS 5519	
Form	Sheet and strip								
Condition	Annealed	¼ Hard		½ Hard		¾ Hard		Full Hard	
Thickness, in.	≤0.187	...		...		...		...	
Basis	S	A	B	A	B	A	B	A	B
Mechanical Properties:									
F_{tu}, ksi:									
L	73	124	129	141	151	157	168	174	185
LT	75	122	127	142	152	163	173	175	186
F_{ty}, ksi:									
L	26	69	83	93	110	118	135	137	153
LT	30	67	82	92	105	113	133	125	142
F_{cy}, ksi:									
L	23	44	54	61	69	75	88	83	94
LT	29	71	88	100	116	127	152	142	164
F_{su}, ksi	50	66	69	77	82	88	93	95	100
F_{bru}, ksi:									
(e/D = 1.5)	...	...	...	...	...	...	...	...	...
(e/D = 2.0)	162	262	273	292	310	327	342	346	361
F_{bry}, ksi:									
(e/D = 1.5)	...	...	...	...	...	...	...	...	...
(e/D = 2.0)	55	123	149	167	189	202	234	222	249
e, percent (S basis):									
LT	40	25	...	[d]	...	[d]	...	[d]	...
E, 10^3 ksi:									
L	29.0	27.0		26.0		26.0		26.0	
LT	29.0	28.0		28.0		28.0		28.0	
E_c, 10^3 ksi:									
L	28.0	26.0		26.0		26.0		26.0	
LT	28.0	27.0		27.0		27.0		27.0	
G, 10^3 ksi	11.2	10.6		10.5		10.5		10.5	
μ	0.27	0.27		0.27		0.27		0.27	
Physical Properties:									
ω, lb/in.^{3}	0.286								
C, K, and α	See Figure 2.7.1.0								

a Properties also applicable to AISI 302 for the following; AMS 5516 for annealed condition, AMS 5903 for 1/4H condition, AMS 5904 for 1/2H condition, AMS 5905 for 3/4H condition, and AMS 5906 for full hard condition.

b Properties also applicable to AISI 304 for the following; AMS 5513 for annealed condition, AMS 5910 for 1/4H condition, AMS 5911 for 1/2H condition, AMS 5912 for 3/4H condition, and AMS 5913 for full hard condition.

c Properties also applicable to AISI 316 for the following; AMS 5524 for annealed condition and AMS 5907 for 1/4H condition.

d See Table 2.7.1.0(c).

Note: Yield strength, particularly in compression, and modulus of elasticity in the longitudinal direction may be raised appreciably by thermal stress-relieving treatment in the range 500 to 800°F.

Table 2.7.1.0(c). Minimum Elongation Values for AISI 301 Stainless Steel Sheet and Strip

Condition	Thickness, inches	Elongation (LT), percent
½ hard	0.015 and under	15
	0.016 and over	18
¾ hard	0.030 and under	10
	0.031 and over	12
Full hard	0.015 and under	8
	0.016 and over	9

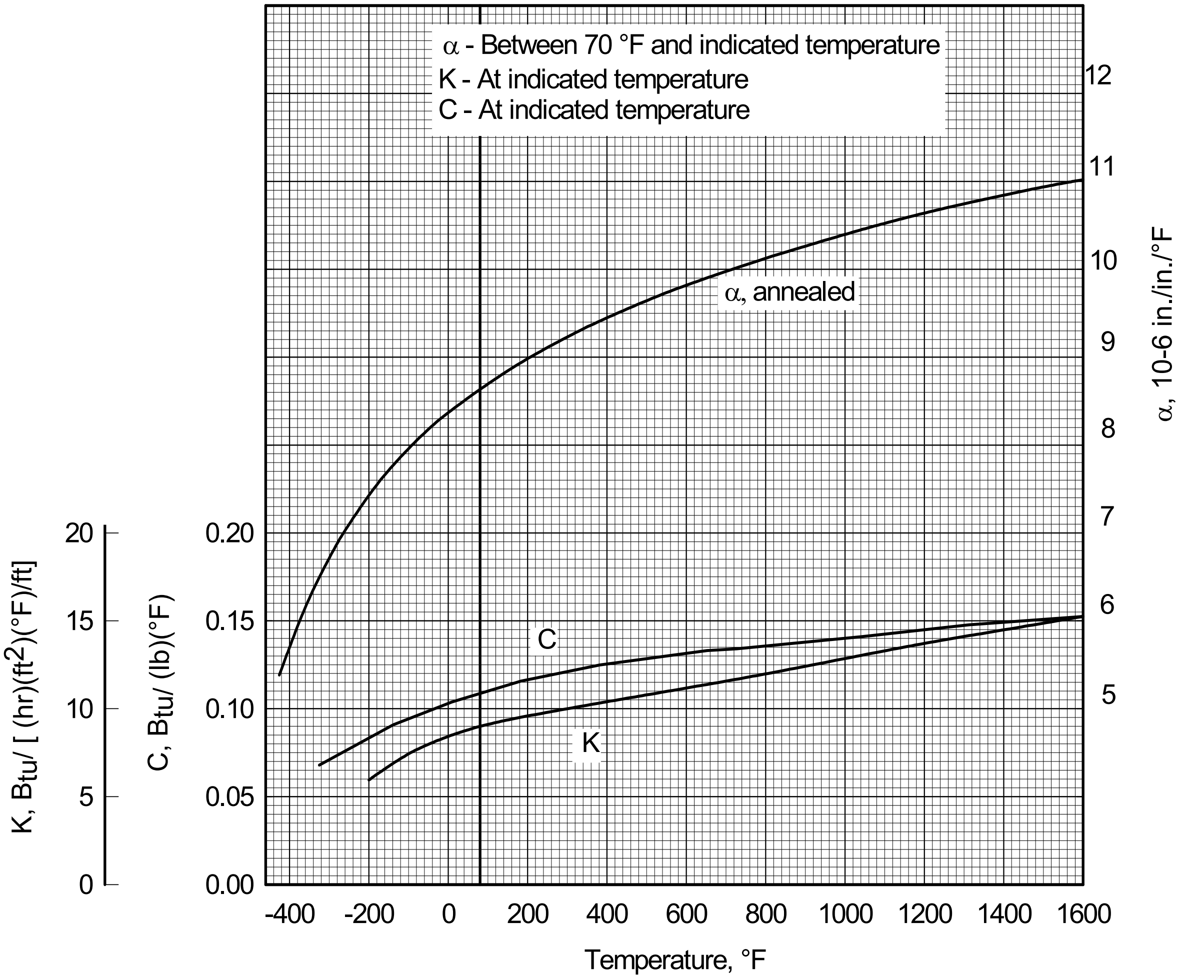

Figure 2.7.1.0. Effect of temperature on the physical properties of AISI 301 stainless steel.

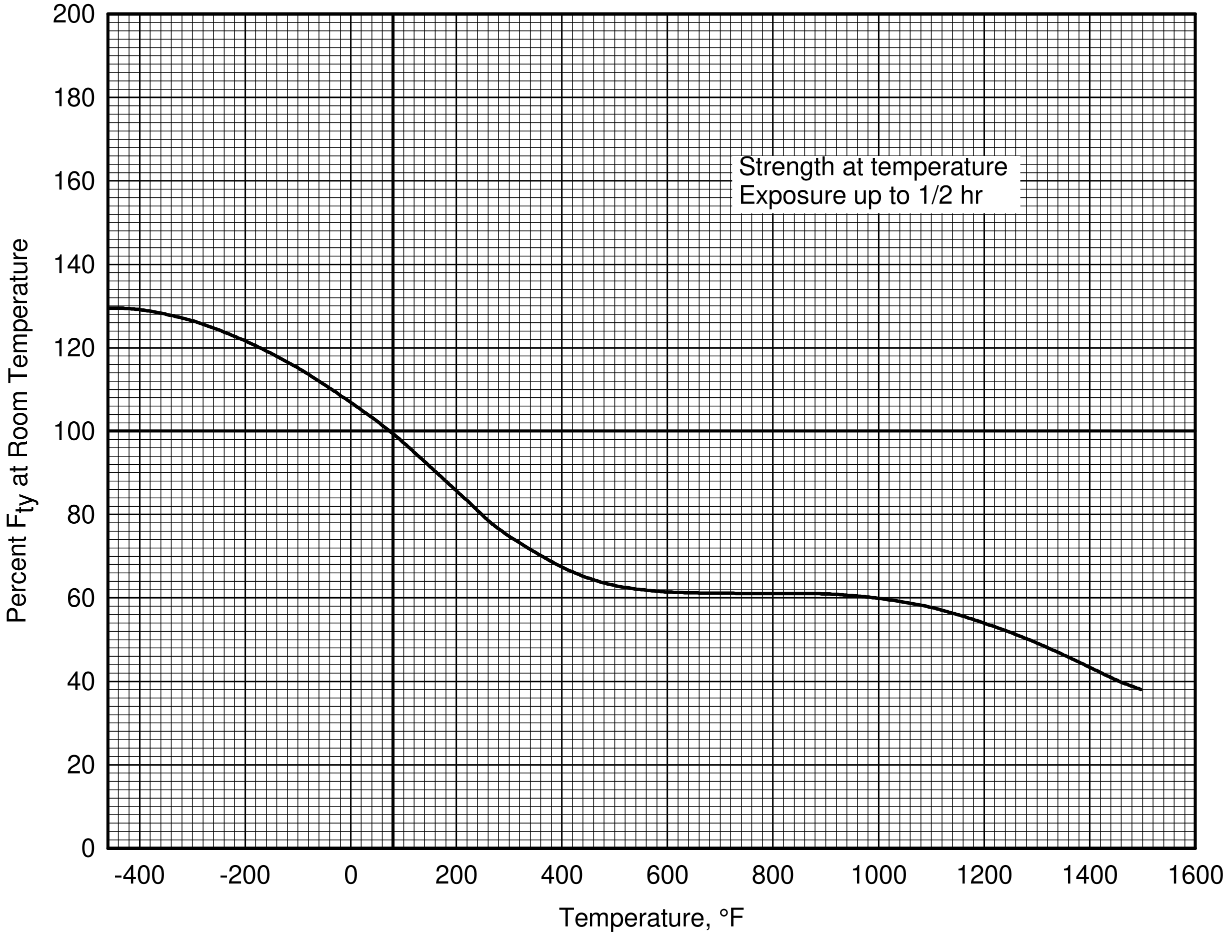

Figure 2.7.1.1.1(a). Effect of temperature on the tensile yield strength (F_{by}) of AISI 301, 302, 304, 304L, 321, and 347 annealed stainless steel.

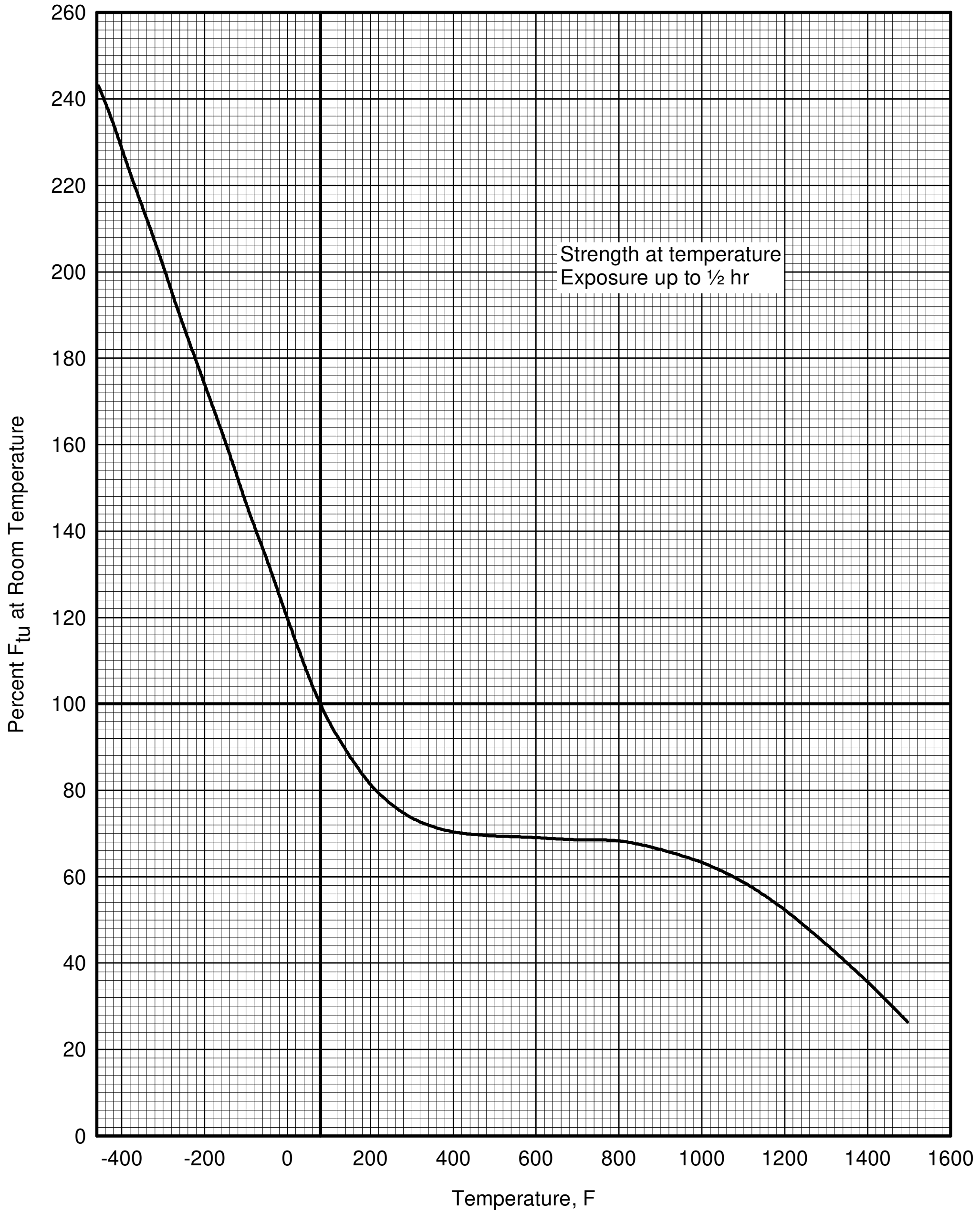

Figure 2.7.1.1.1(b). Effect of temperature on the tensile ultimate strength (F_{tu}) of AISI 301, 302, 304, 304L, 321, and 347 annealed stainless steel.

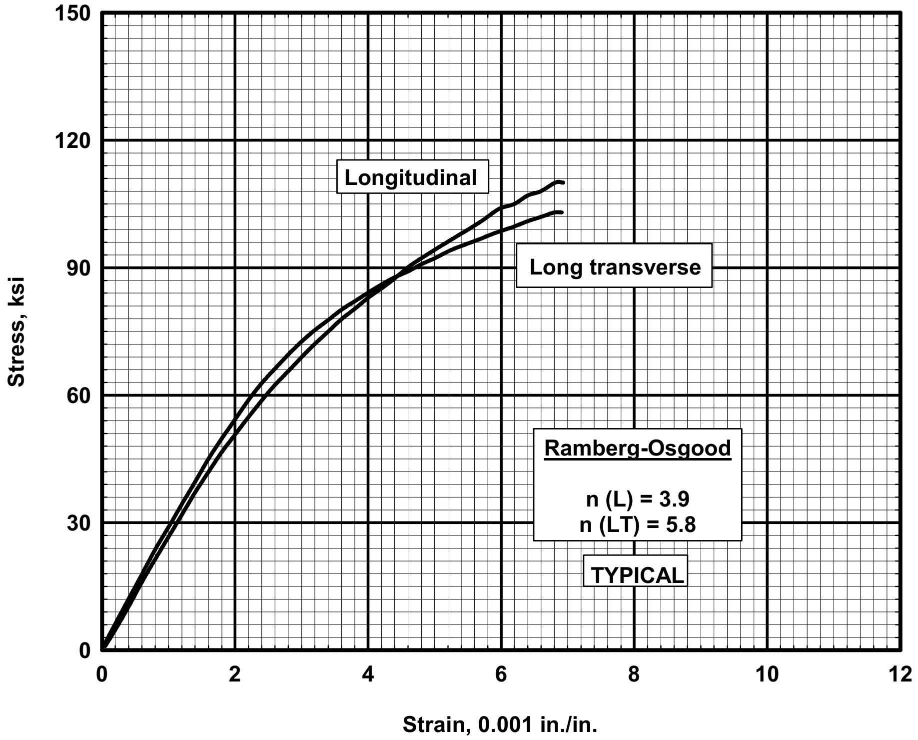

Figure 2.7.1.2.6(a). Typical tensile stress-strain curves at room temperature for AISI 301 1/4-hard stainless steel sheet.

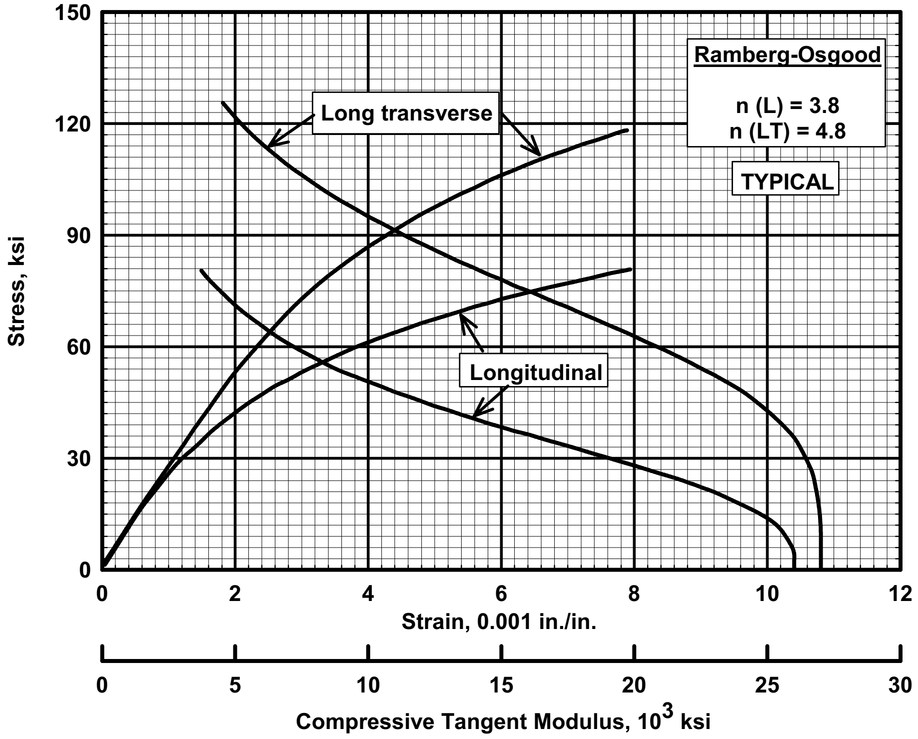

Figure 2.7.1.2.6(b). Typical compressive stress-strain and compressive tangent-modulus curves at room temperature for AISI 301 1/4-hard stainless steel sheet.

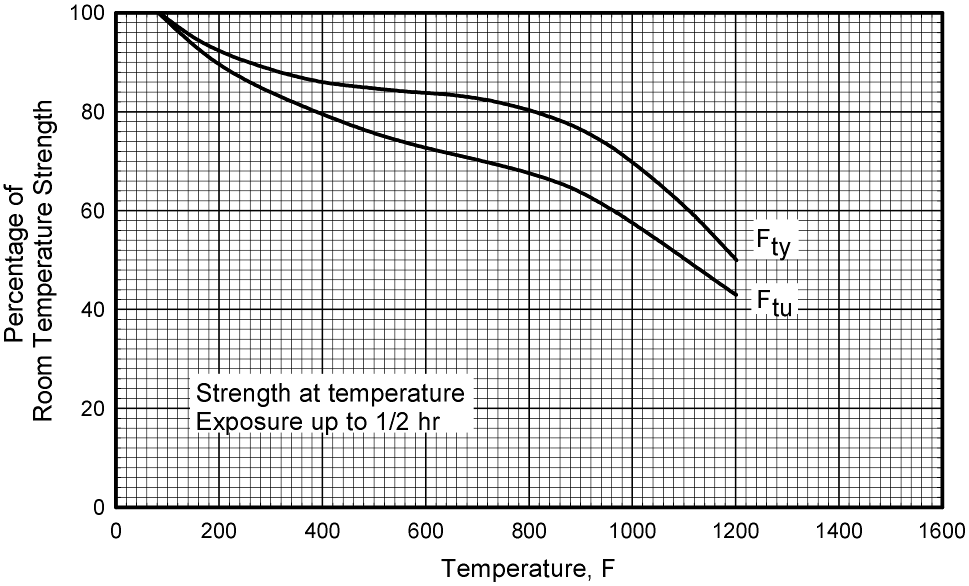

Figure 2.7.1.3.1. Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of AISI 301 1/2-hard stainless steel sheet.

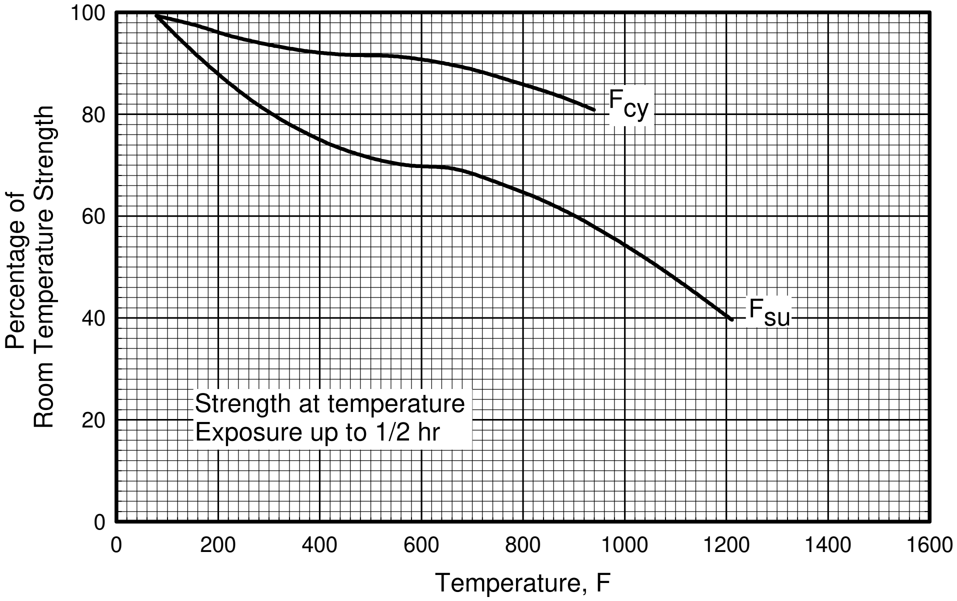

Figure 2.7.1.3.2. Effect of temperature on the compressive yield strength (F_{cy}) and the shear ultimate strength (F_{su}) of AISI 301 1/2-hard stainless steel sheet.

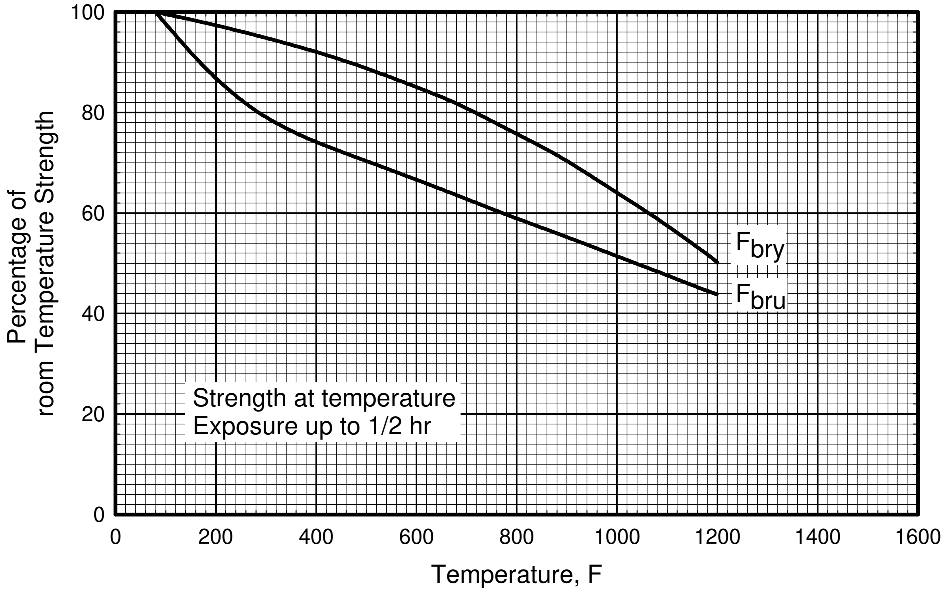

Figure 2.7.1.3.3. Effect of temperature on the bearing ultimate strength (F_{bru}) and the bearing yield strength (F_{bry}) of AISI 301 1/2-hard stainless steel sheet.

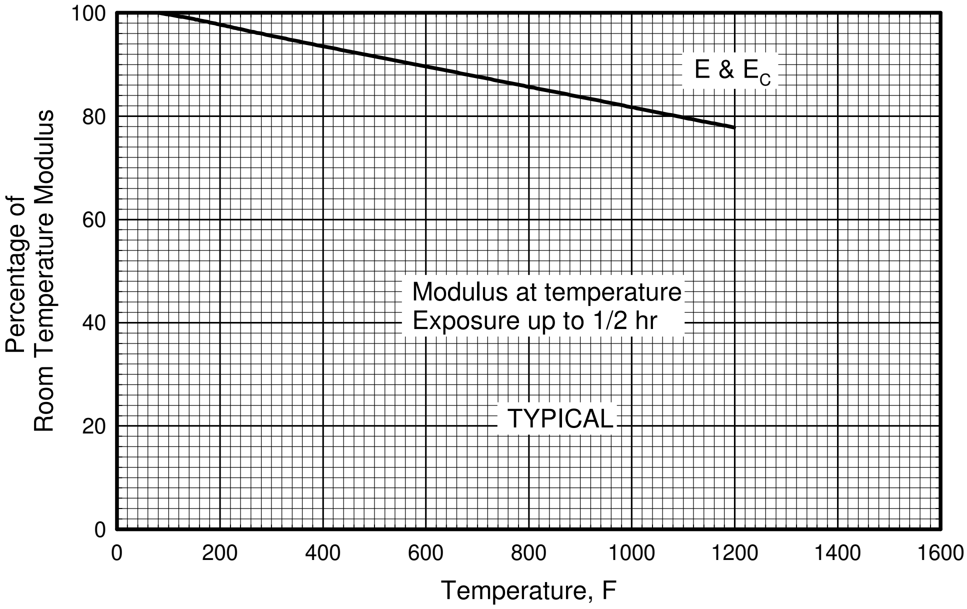

Figure 2.7.1.3.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of AISI 301 1/2-hard stainless steel sheet.

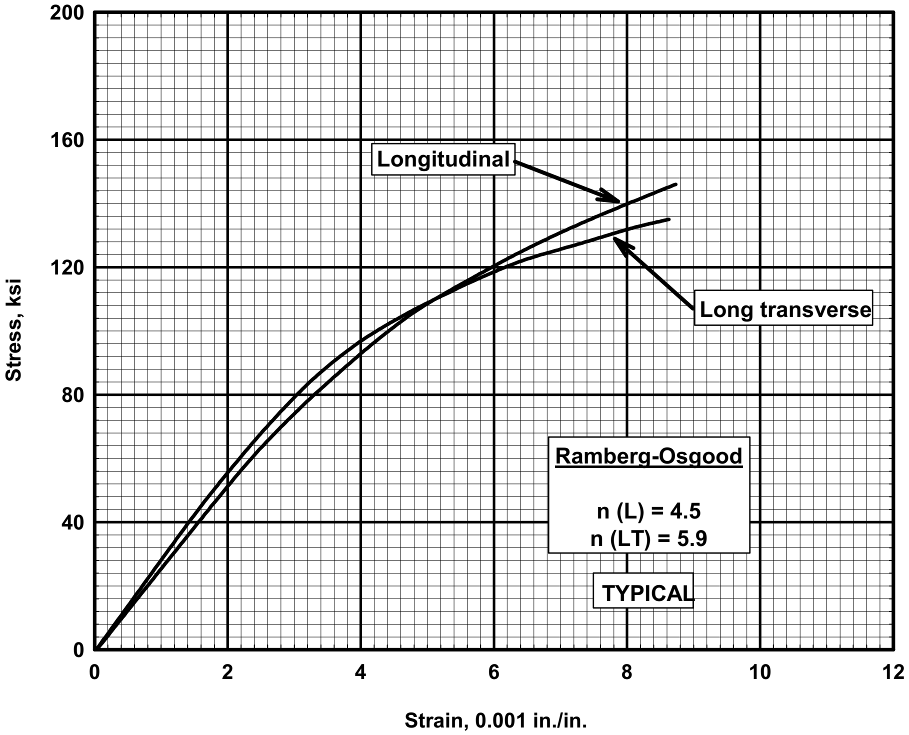

Figure 2.7.1.3.6(a). Typical tensile stress-strain curves at room temperature for AISI 301 1/2-hard stainless steel sheet.

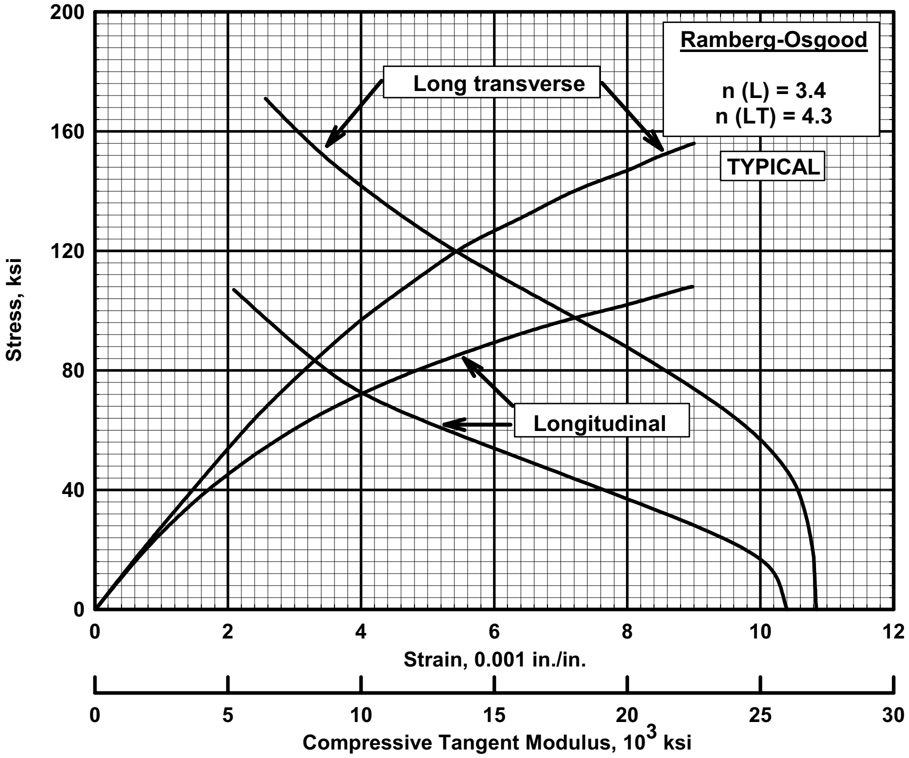

Figure 2.7.1.3.6(b). Typical compressive stress-strain and compressive tangent-modulus curves at room temperature for AISI 301 1/2-hard stainless steel sheet.

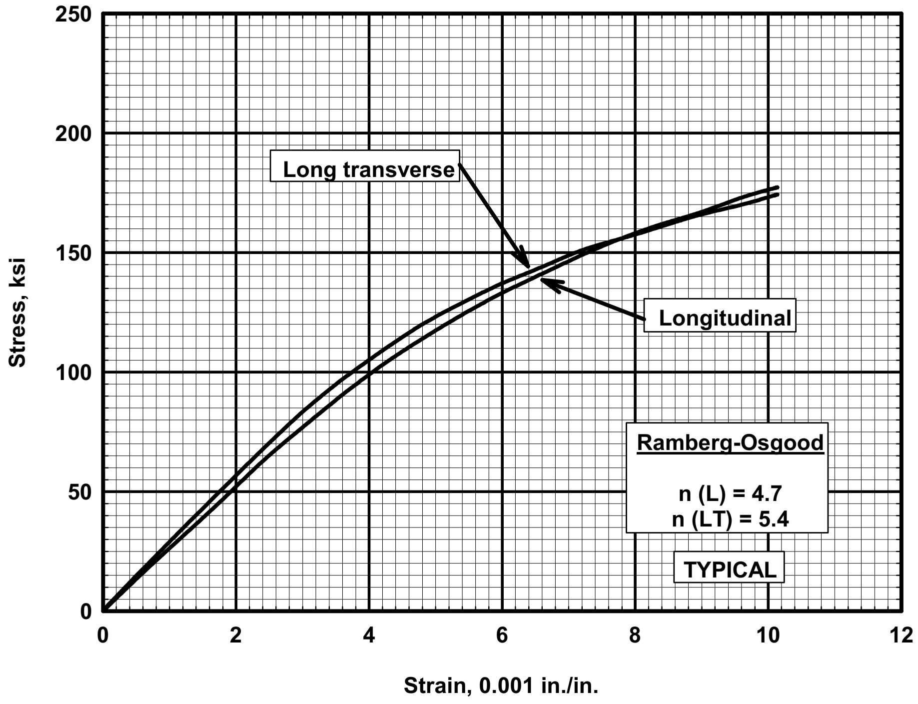

Figure 2.7.1.4.6(a). Typical tensile stress-strain curves at room temperature for AISI 301 3/4-hard stainless steel sheet.

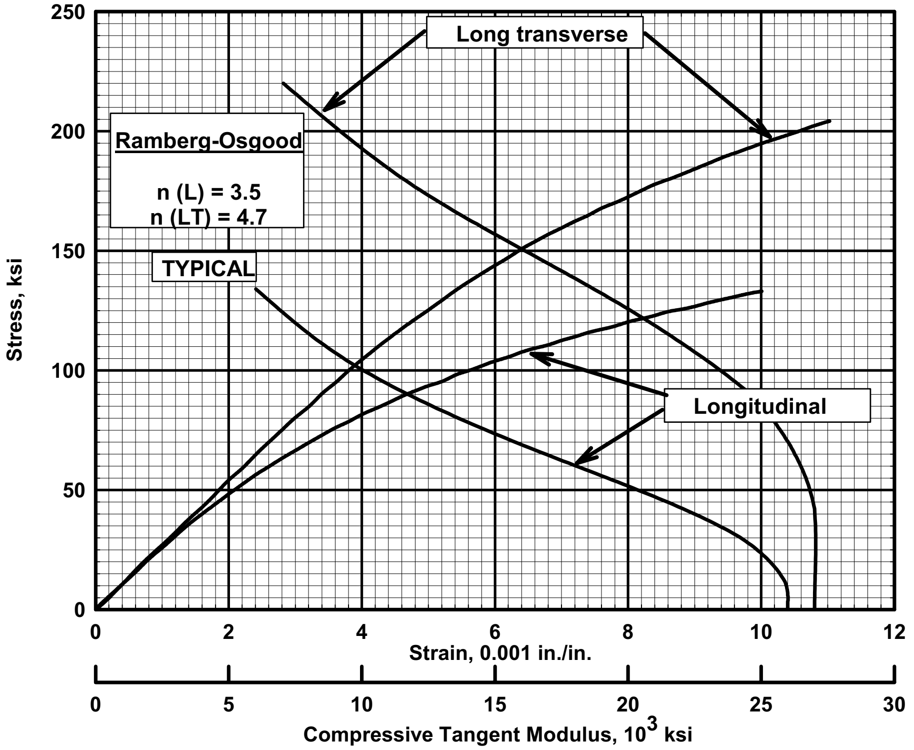

Figure 2.7.1.4.6(b). Typical compressive stress-strain and compressive tangent-modulus curves at room temperature for AISI 301 3/4-hard stainless steel sheet.

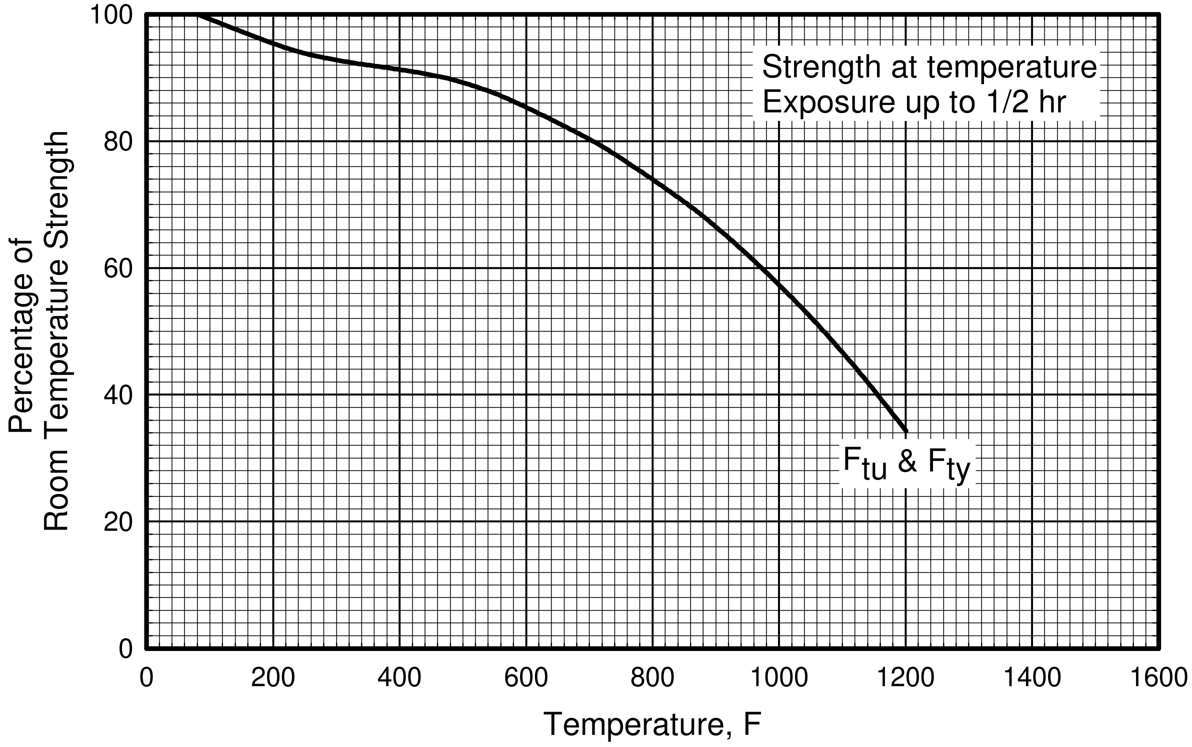

Figure 2.7.1.5.1. Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of AISI 301 full-hard stainless steel sheet.

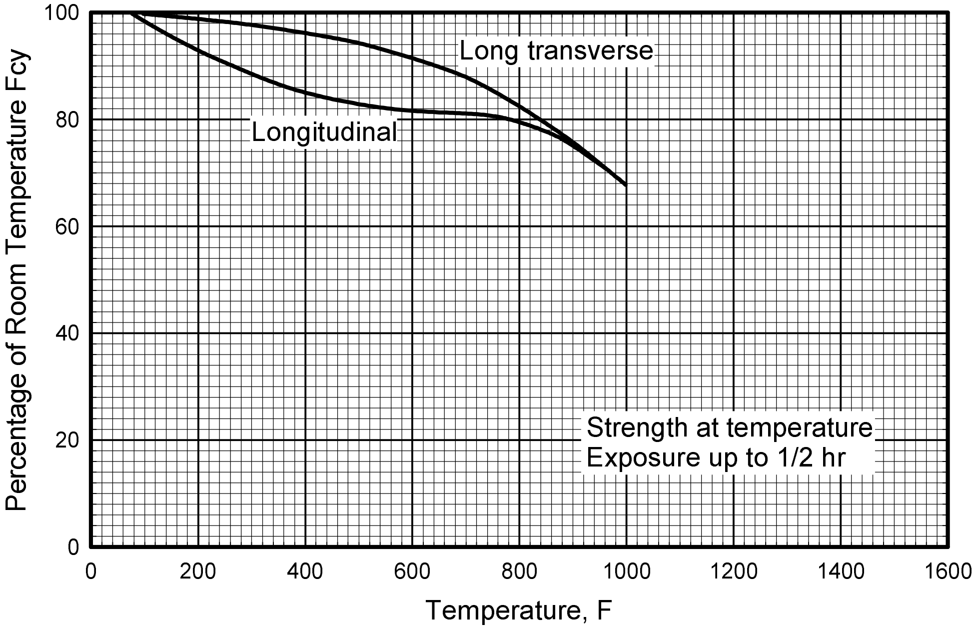

Figure 2.7.1.5.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of AISI 301 (full-hard) stainless steel sheet.

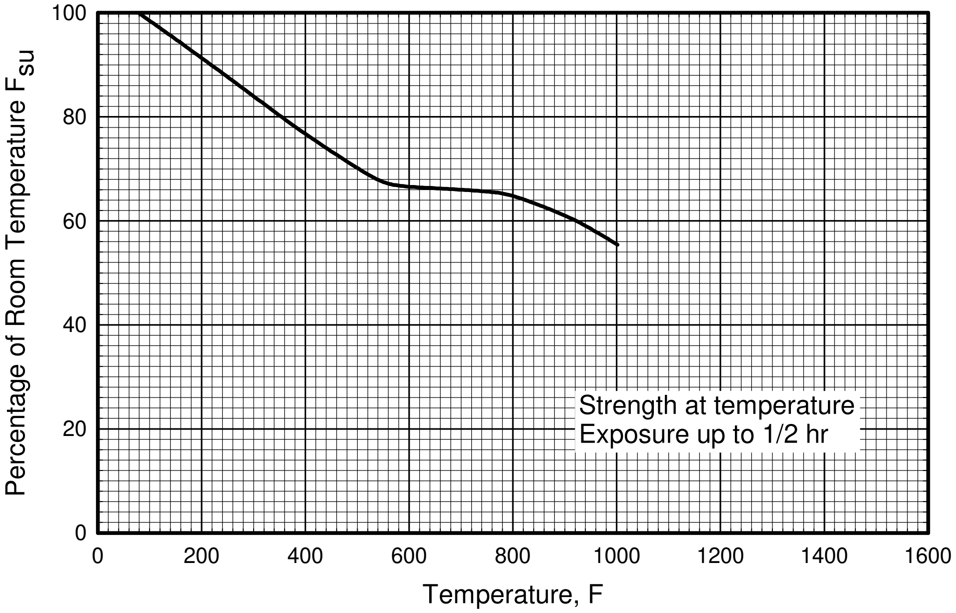

Figure 2.7.1.5.2(b). Effect of temperature on the ultimate shear strength (F_{su}) of AISI 301 (full-hard) stainless steel sheet.

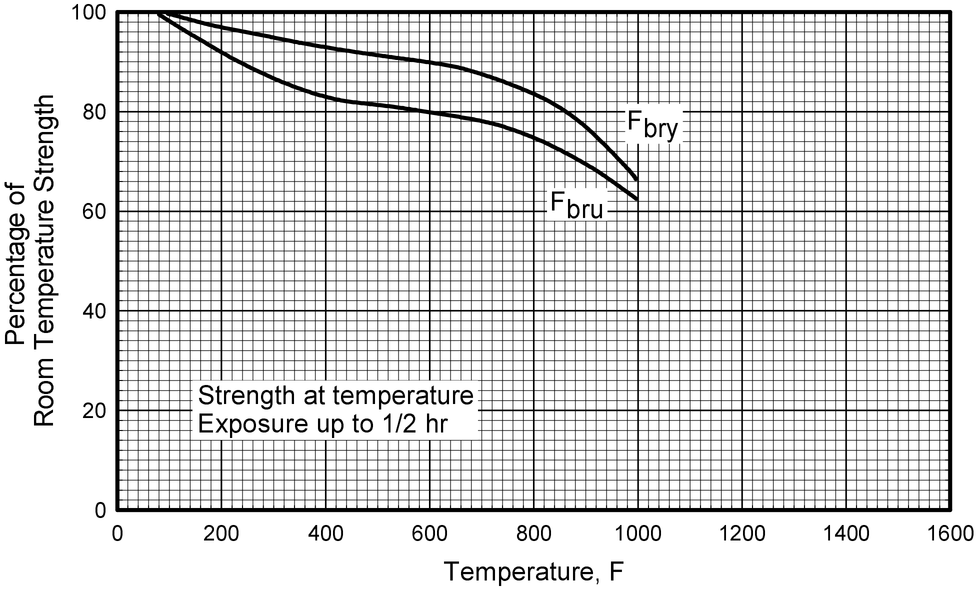

Figure 2.7.1.5.3. Effect of temperature on the bearing ultimate strength (F_{bru}) and the bearing yield strength (F_{bry}) of AISI 301 (full-hard) stainless steel sheet.

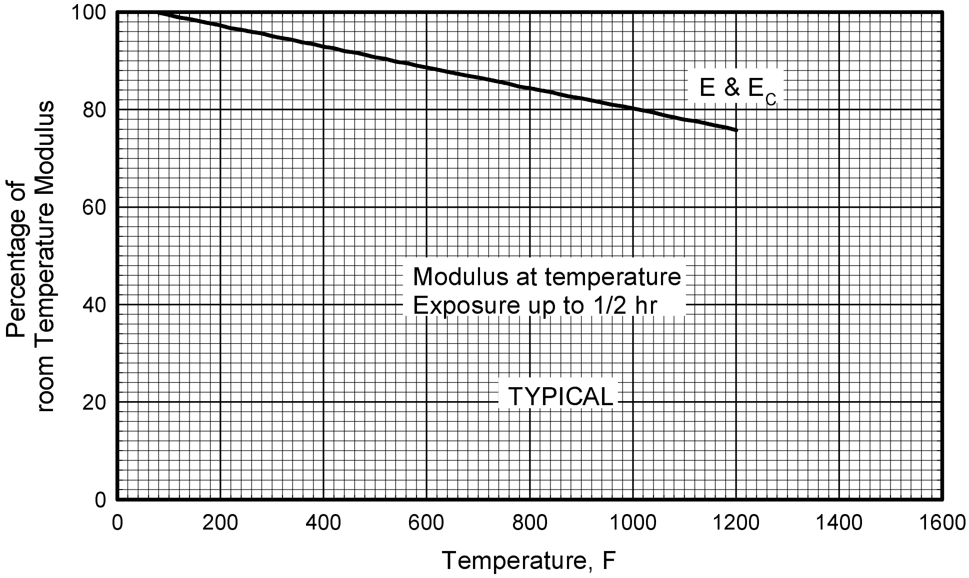

Figure 2.7.1.5.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of AISI 301 (full-hard) stainless steel sheet.

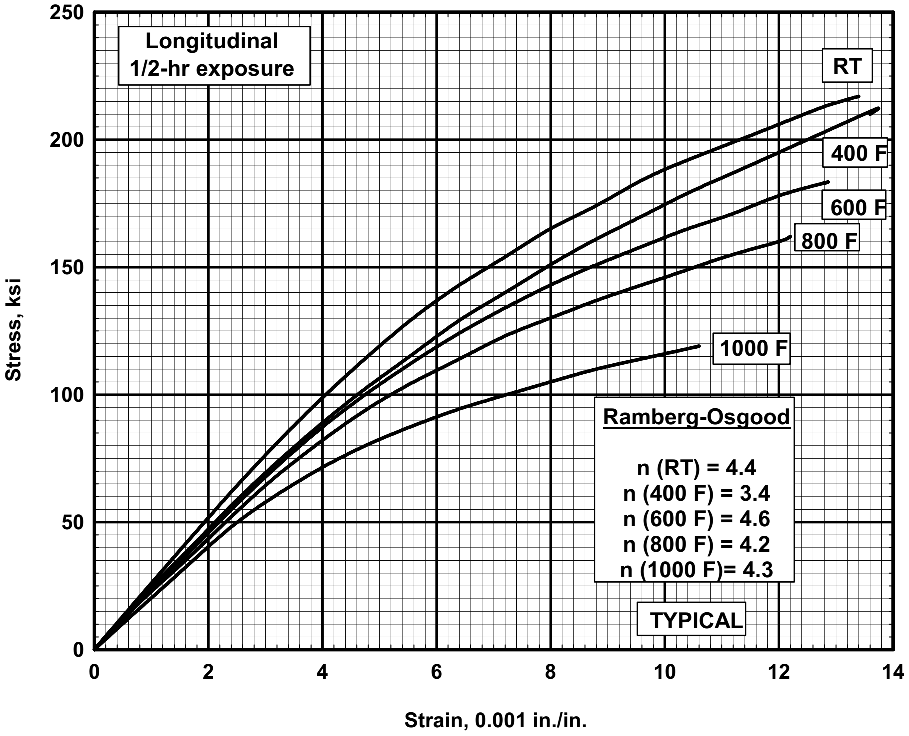

Figure 2.7.1.5.6(a). Typical tensile stress-strain curves at room and elevated temperatures for AISI 301 (full-hard) stainless steel sheet.

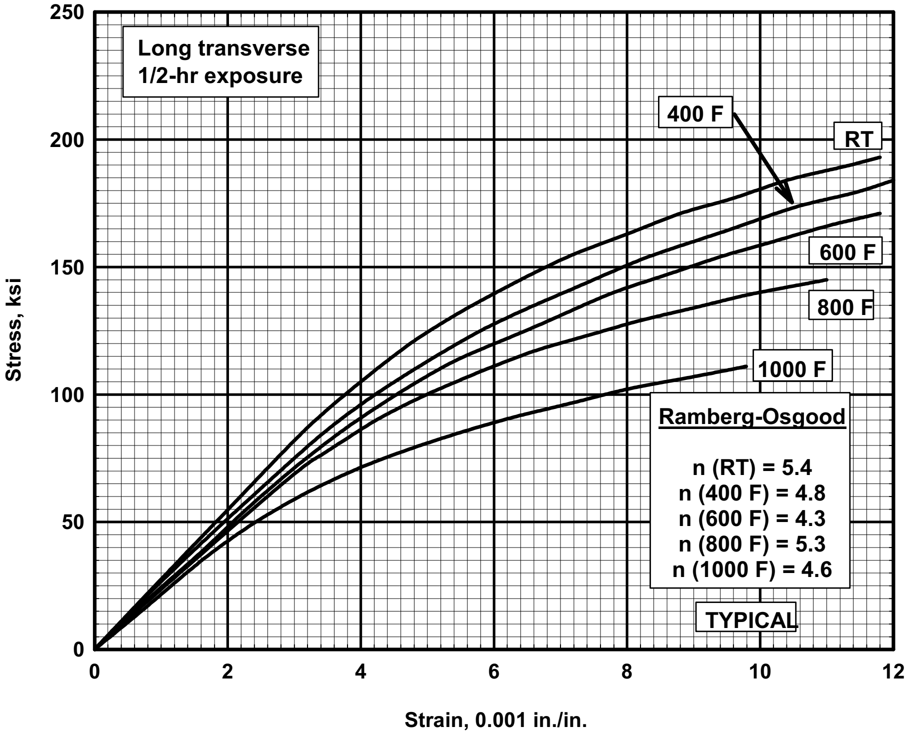

Figure 2.7.1.5.6(b). Typical tensile stress-strain curves at room and elevated temperatures for AISI 301 (full-hard) stainless steel sheet.

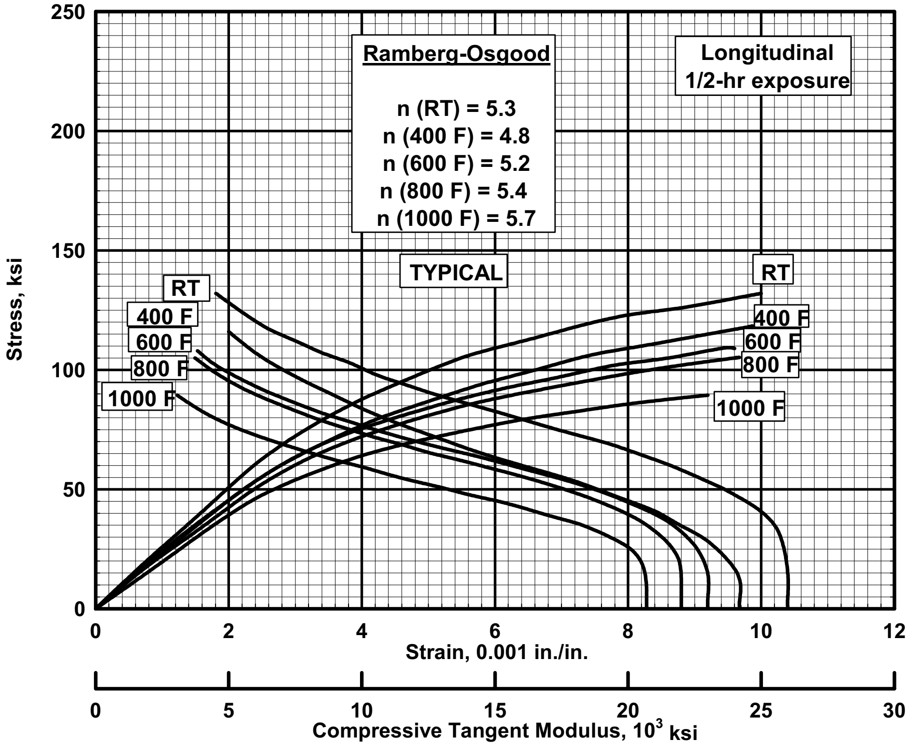

Figure 2.7.1.5.6(c). Typical compressive stress-strain and compressive tangent-modulus curves at room and elevated temperatures for AISI 301 (full-hard) stainless steel sheet.

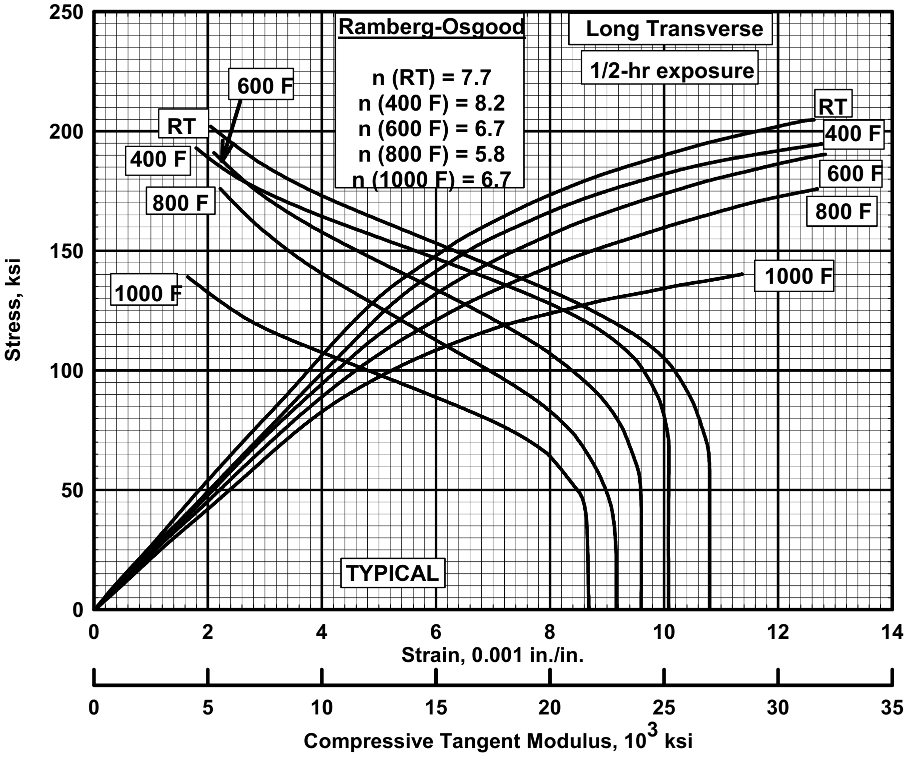

Figure 2.7.1.5.6(d). Typical compressive stress-strain and compressive tangent-modulus curves at room and elevated temperatures for AISI 301 (full-hard) stainless steel sheet.

2.8 ELEMENT PROPERTIES

2.8.1 BEAMS

See Equation 1.3.2.3, Section 1.5.2.5, and References 1.7.1(a) and (b) for general information on stress analysis of beams.

2.8.1.1 *Simple Beams* — Beams of solid, tubular, or similar cross sections, not subject to instability (buckling, crippling, column, lateral bending) can be assumed to fail through exceeding an allowable modulus of rupture in bending, F_b, the value of which will depend upon beam cross-section geometry and beam material stress-strain characteristics. The modulus of rupture in bending is further discussed in Section 1.5.2.5. See Reference 2.8.1.1.

Round Tubes — For round tubes, the value of F_b will depend on the D/t ratio, as well as the ultimate tensile stress. Figures 2.8.1.1(a) and (b) give the bending modulus of rupture for round alloy-steel tubing.

Unconventional Cross Sections — Sections other than solid or tubular should be tested to determine the allowable bending stress.

2.8.1.2 *Built-Up Beams* — Built-up beams usually fail because of local failures of the component parts. In welded steel tube beams, the allowable tensile stresses should be reduced properly for the effects of welding.

2.8.1.3 *Thin-Web Beams* — The allowable stresses for thin-web beams will depend on the nature of the failure and are determined from the allowable stresses of the web in tension and of the flanges and stiffeners in compression.

2.8.2 COLUMNS

2.8.2.1 *General* — The general formula for primary instability is given in Section 1.3.8. Both primary and local instability are discussed in Section 1.6.

2.8.2.2 *Effects of Welding* — The primary failure stress of a column having welded ends can be determined from column curves or the column formula with the restriction that the column stress will not exceed a “cut-off” stress which accounts for the effect of welding on the local failure of the column.

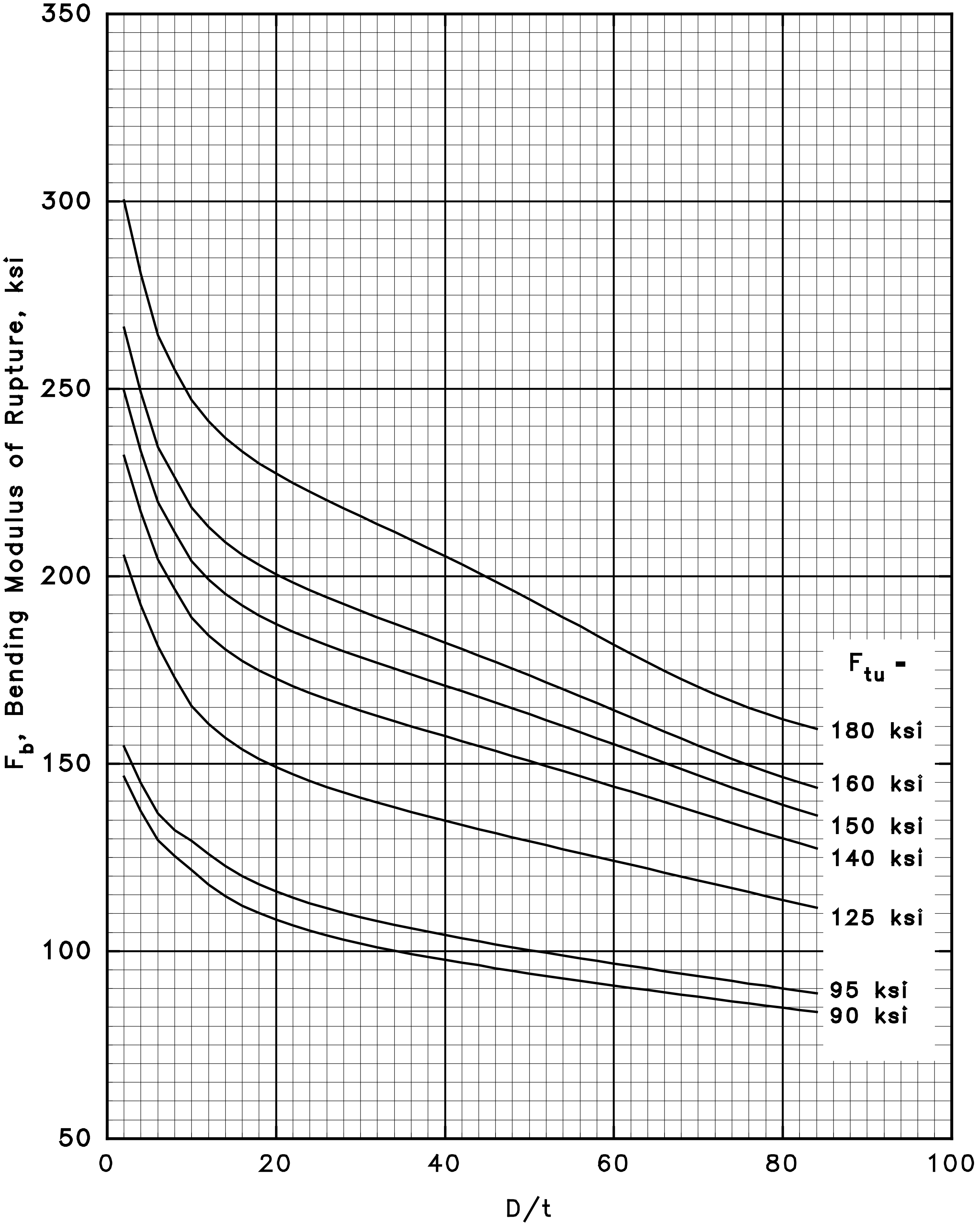

Figure 2.8.1.1(a). Bending modulus of rupture for round low-alloy steel tubing.

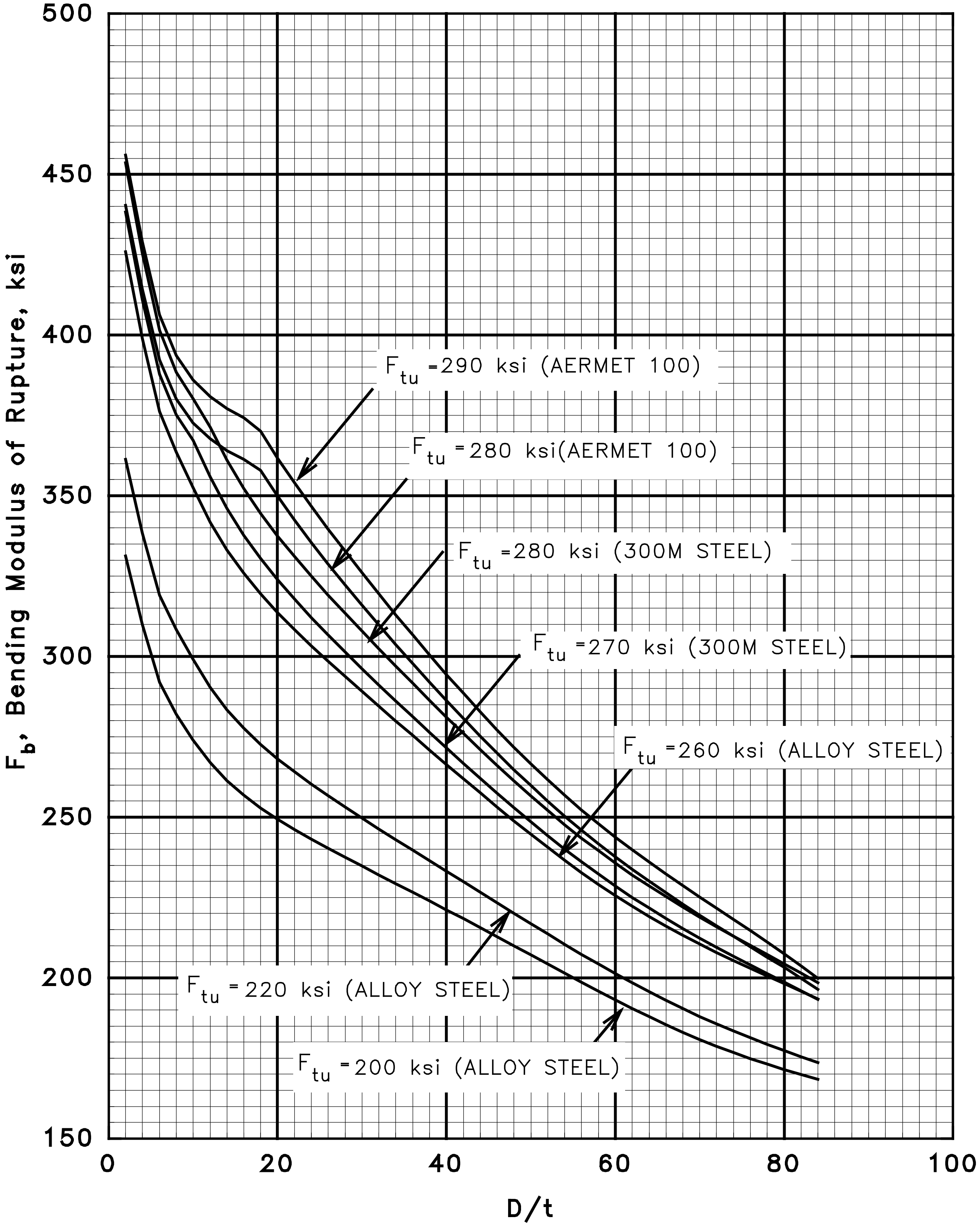

Figure 2.8.1.1(b). Bending modulus of rupture for round high-alloy steel tubing.

2.8.3 TORSION

2.8.3.1 *General* — The torsion failure of steel tubes may be due to material failure, or to elastic or plastic buckling. Pure shear failure usually will not occur within the range of wall thickness commonly used for aircraft tubing.

2.8.3.2 *Torsion Properties* — The curves of Figures 2.8.3.2(a) through (j) are derived from the method outlined in Reference 2.8.3.2 and take into account the parameter L/D; the theoretical results set forth in Reference 2.8.3.2 have been found to be in good agreement with the experimental results.

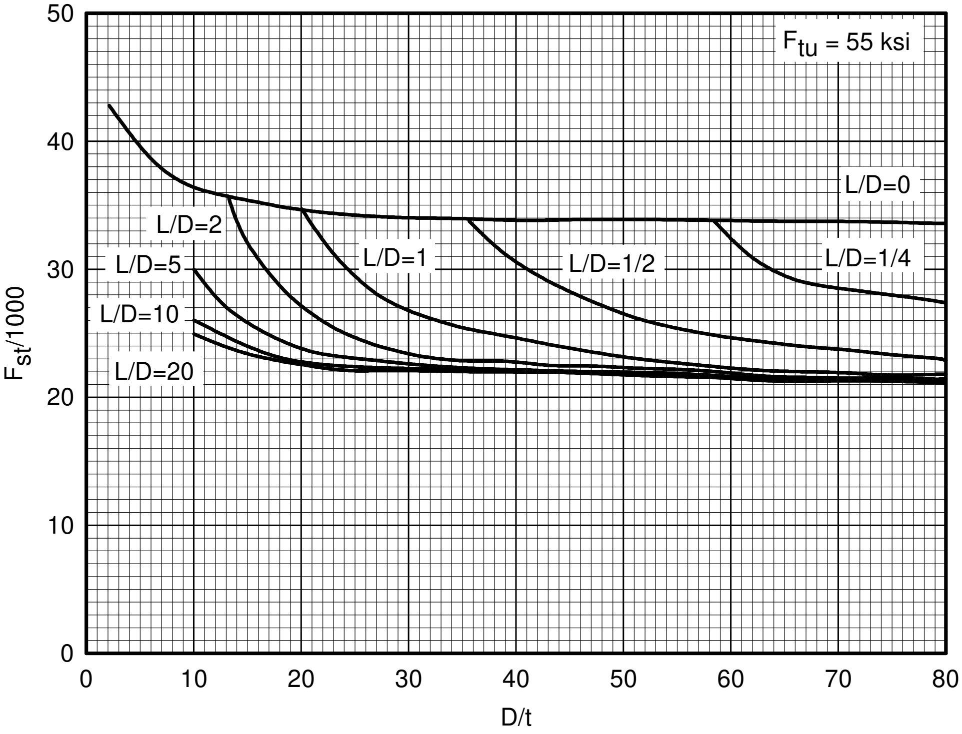

Figure 2.8.3.2(a). Torsional modulus of rupture—plain carbon steels F_{tu} = 55 ksi.

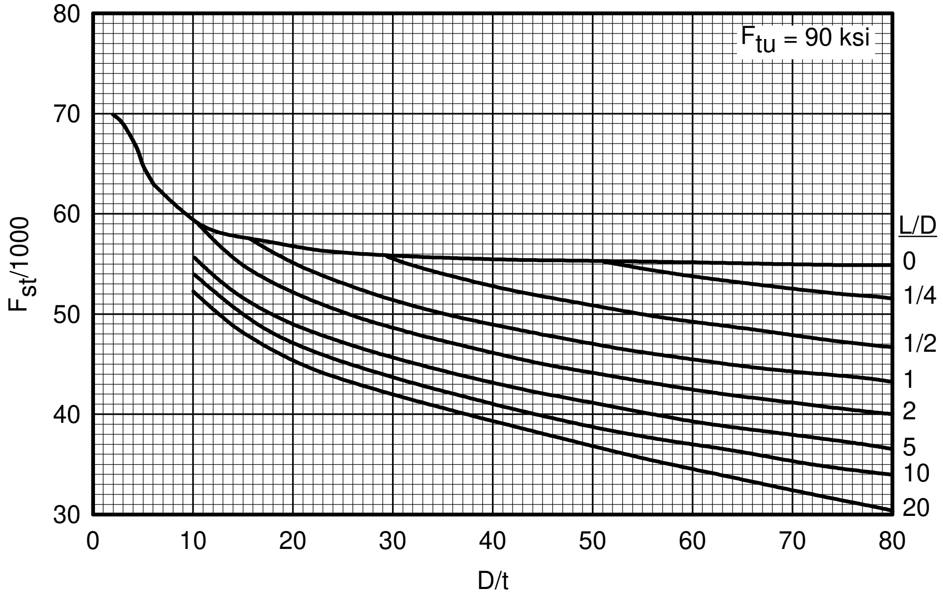

Figure 2.8.3.2(b). Torsional modulus of rupture—low-alloy steels treated to F_{tu} = 90 ksi.

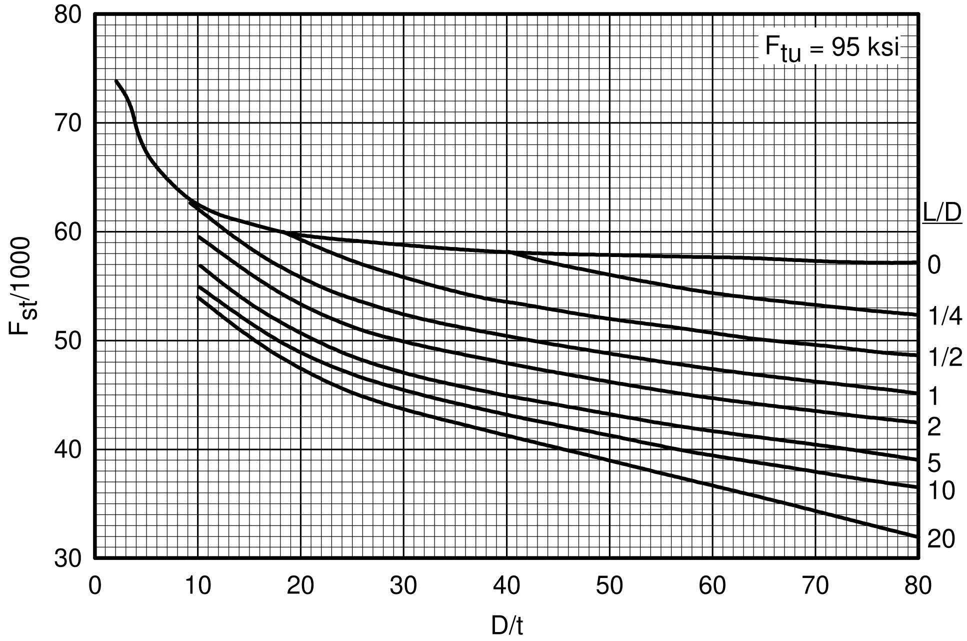

Figure 2.8.3.2(c). Torsional modulus of rupture—low-alloy steels heat treated to F_{tu} = 95 ksi.

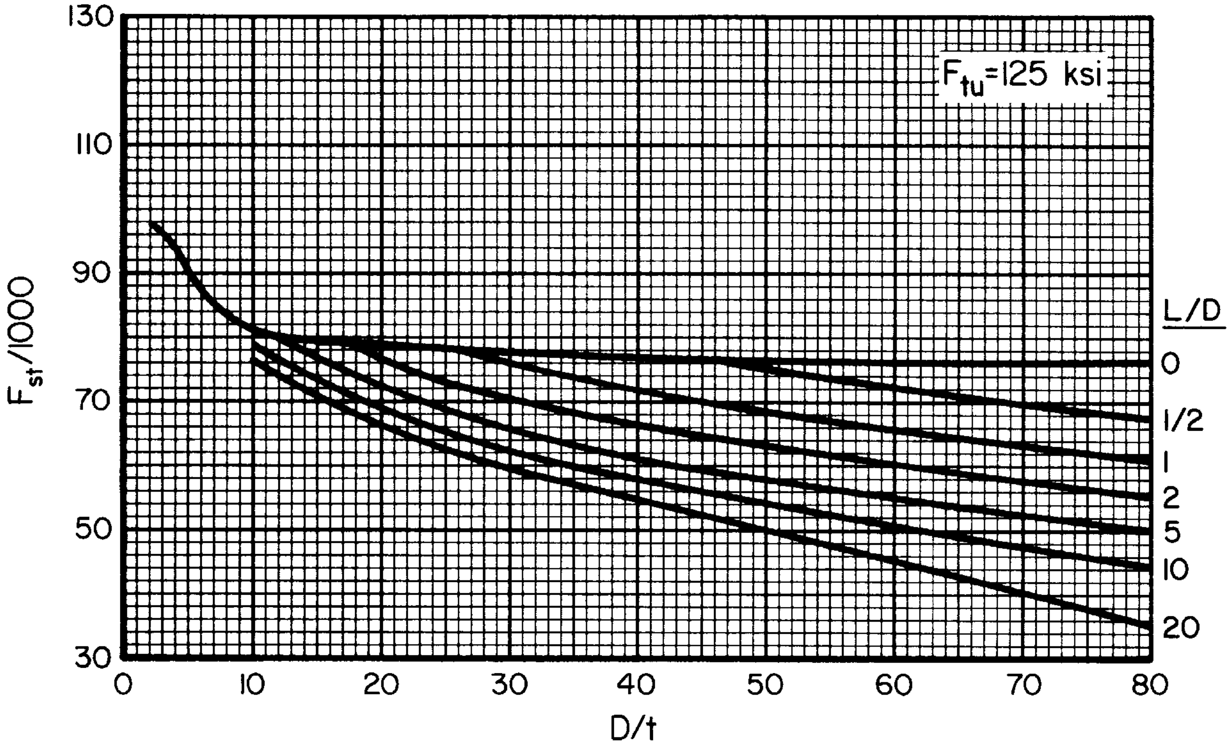

Figure 2.8.3.2(d). Torsional modulus of rupture—low-alloy steels, heat treated to F_{tu} = 125 ksi.

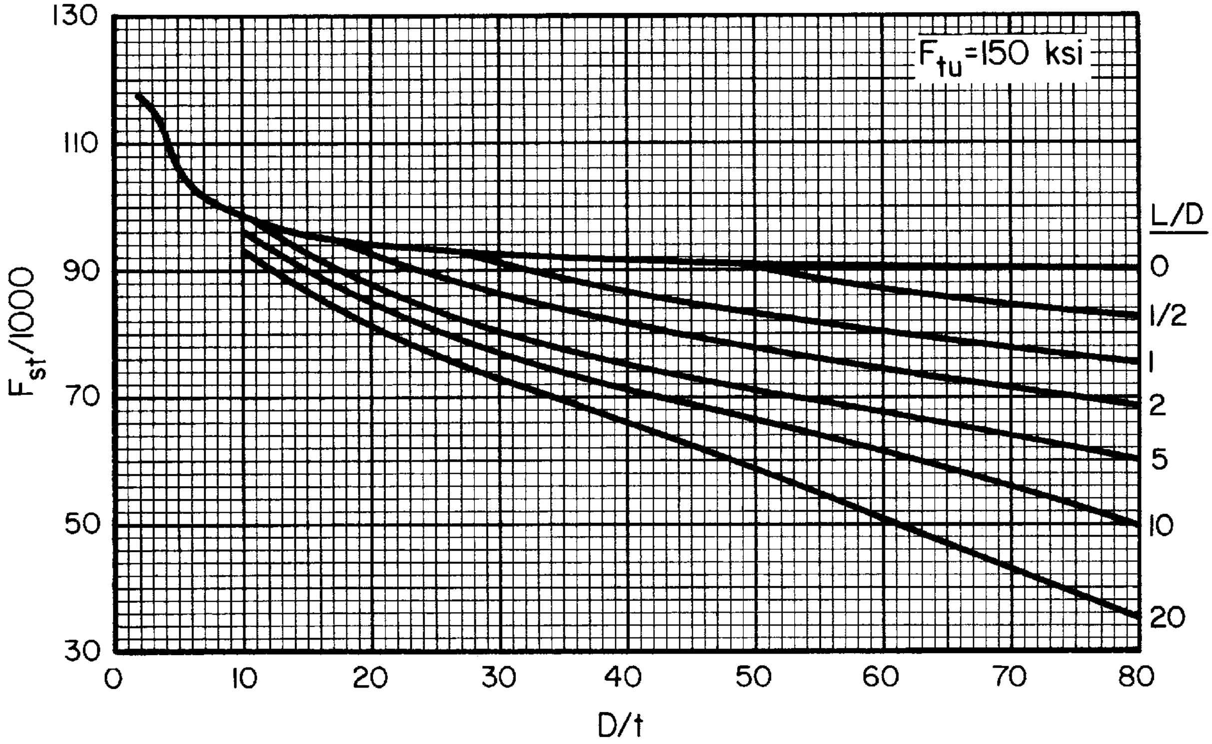

Figure 2.8.3.2(e). Torsional modulus of rupture—low-alloy steels heat treated to F_{tu} = 150 ksi.

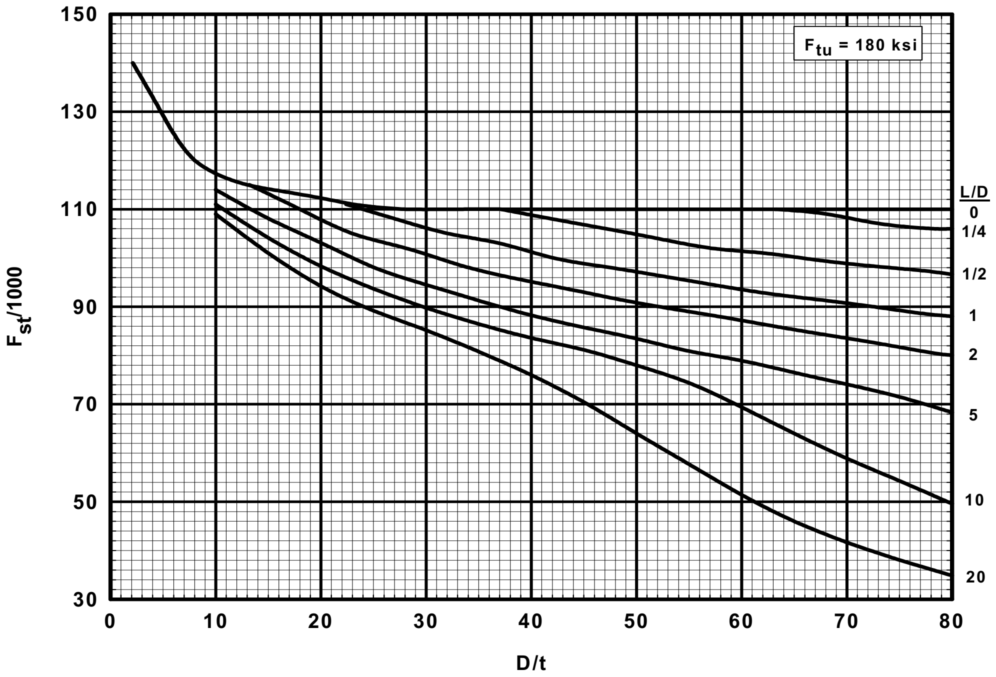

Figure 2.8.3.2(f). Torsional modulus of rupture—alloy steels heat treated to F_{tu} = 180 ksi.

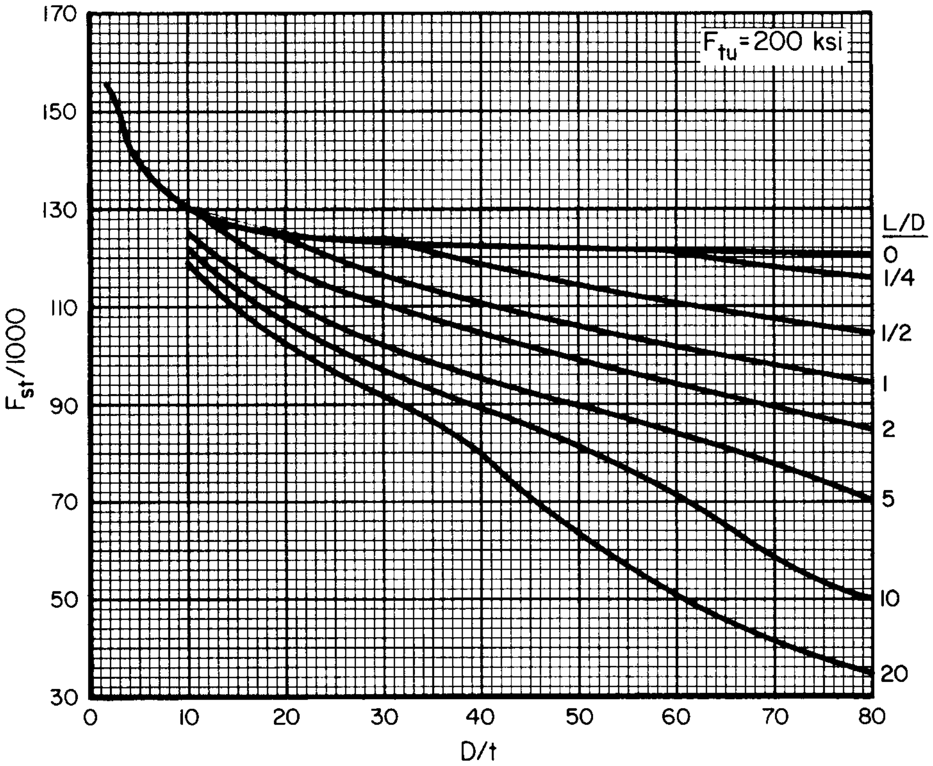

Figure 2.8.3.2(g). Torsional modulus of rupture—alloy steels heat treated to F_{tu} = 200 ksi.

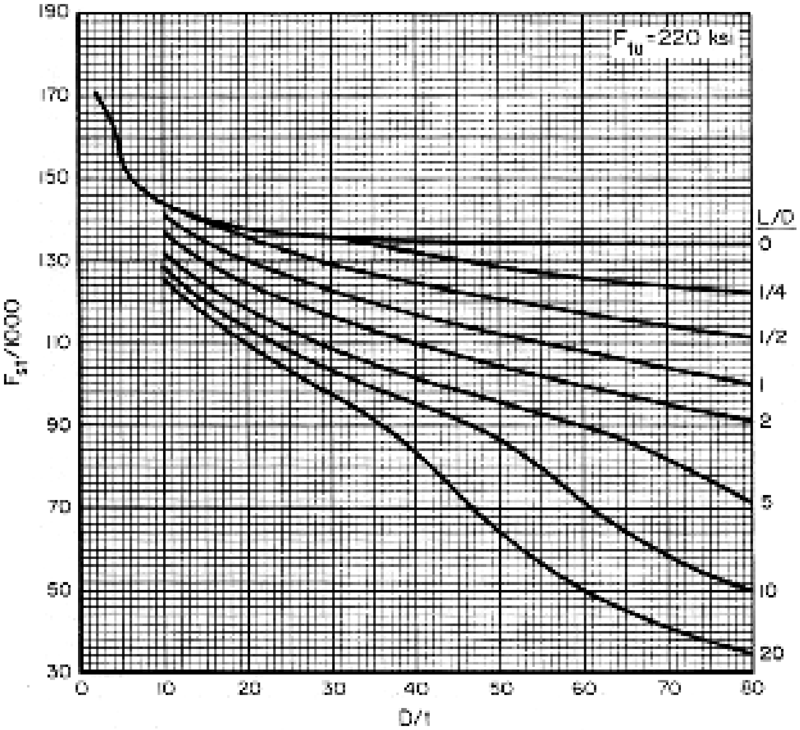

Figure 2.8.3.2(h). Torsional modulus of rupture—alloy steels heat treated to F_{tu} = 220 ksi.

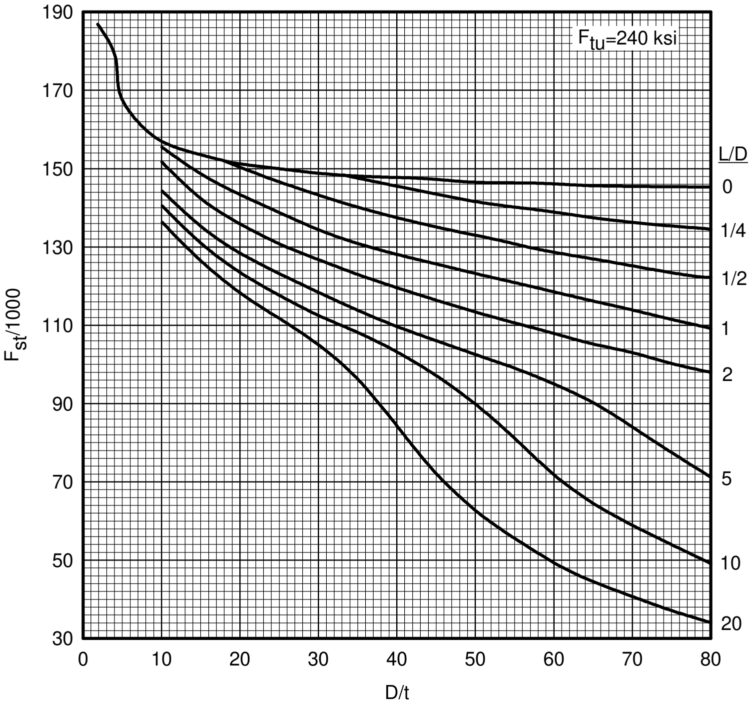

Figure 2.8.3.2(i). Torsional modulus of rupture—alloy steels heat treated to F_{tu} = 240 ksi.

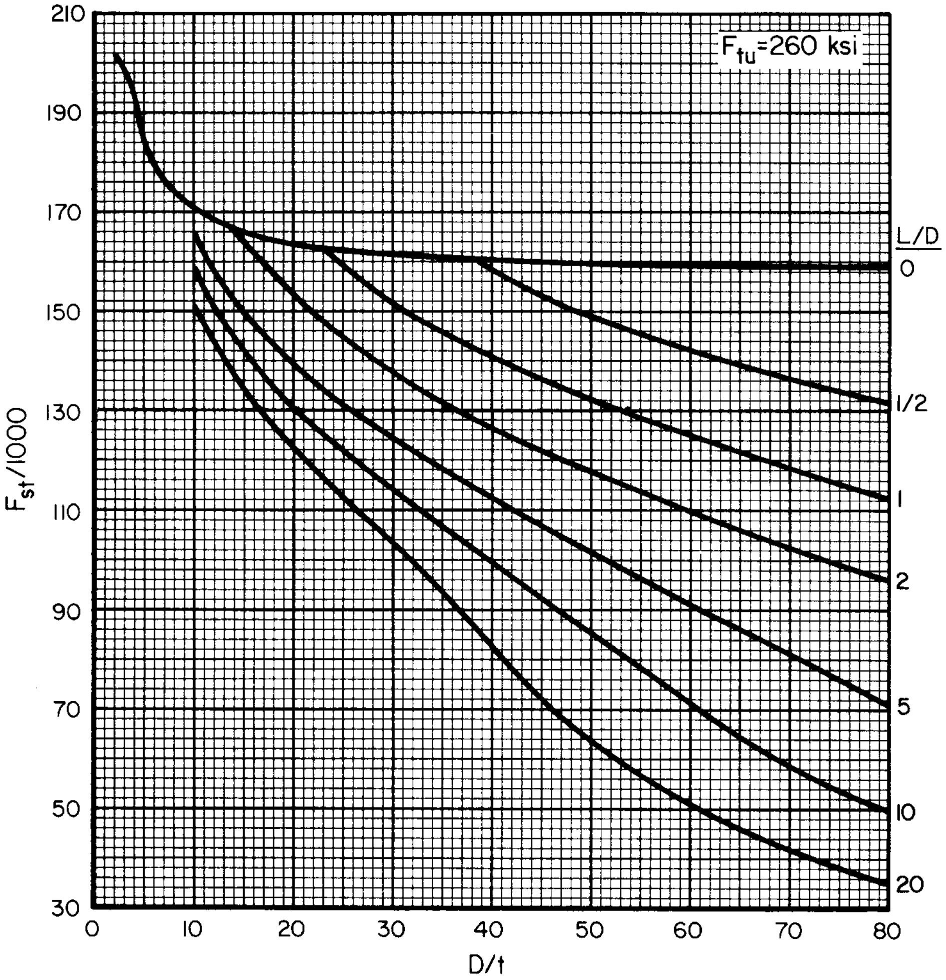

Figure 2.8.3.2(j). Torsional modulus of rupture—alloy steels heat treated to F_{tu} = 260 ksi.

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2.8.3.2 Lee, L.H.N., and Ades, C. S., "Plastic Torsional Buckling Strength of Cylinders Including the Effects of Imperfections," Journal of the Aeronautical Sciences, Vol. 24, No. 4, pp 241-248 (April 1957).

CHAPTER 3

ALUMINUM

3.1 GENERAL

This chapter contains the engineering properties and related characteristics of wrought and cast aluminum alloys used in aircraft and missile structural applications.

General comments on engineering properties and the considerations relating to alloy selection are presented in Section 3.1. Mechanical and physical property data and characteristics pertinent to specific alloy groups or individual alloys are reported in Sections 3.2 through 3.9. Element properties are presented in Section 3.10.

Aluminum is a lightweight, corrosion-resistant structural material that can be strengthened through alloying and, dependent upon composition, further strengthened by heat treatment and/or cold working [Reference 3.1(a)]. Among its advantages for specific applications are: low density, high strength-to-weight ratio, good corrosion resistance, ease of fabrication and diversity of form.

Wrought and cast aluminum and aluminum alloys are identified by a four-digit numerical designation, the first digit of which indicates the alloy group as shown in Table 3.1. For structural wrought aluminum alloys the last two digits identify the aluminum alloy. The second digit indicates modifications of the original alloy or impurity limits. For cast aluminum and aluminum alloys the second and third digits identify the aluminum alloy or indicate the minimum aluminum percentage. The last digit, which is to the right of the decimal point, indicates the product form: XXX.0 indicates castings, and XXX.1 and XXX.2 indicate ingot.

Table 3.1. Basic Designation for Wrought and Cast Aluminum Alloys [Reference 3.1(b)]

Alloy Group	Major Alloying Elements	Alloy Group	Major Alloying Groups
	Wrought Alloys		Cast Alloys
1XXX	99.00 percent minimum aluminum	1XX.0	99.00 percent minimum aluminum
2XXX	Copper	2XX.0	Copper
3XXX	Manganese	3XX.0	Silicon with added copper and/or magnesium
4XXX	Silicon	4XX.0	Silicon
5XXX	Magnesium	5XX.0	Magnesium
6XXX	Magnesium and Silicon	6XX.0	Unused Series
7XXX	Zinc	7XX.0	Zinc
8XXX	Other Elements	8XX.0	Tin
9XXX	Unused Series	9XX.0	Other Elements

3.1.1 ALUMINUM ALLOY INDEX — The layout of this chapter is in accordance with this four-digit number system for both wrought and cast alloys [Reference 3.1(b)]. Table 3.1.1 is the aluminum alloy index that illustrates both the general section layout as well as details of those specific aluminum alloys presently contained in this chapter. The wrought alloys are in Sections 3.2 through 3.7; whereas the cast alloys are in Sections 3.8 and 3.9.

Table 3.1.1. Aluminum Alloy Index

Section	Alloy Designation	Section	Alloy Designation
3.2	2000 series wrought alloys	3.6.2.	6061
3.2.1	2014	3.6.3	6151
3.2.2	2107	3.7	7000 series wrought alloys
3.2.3	2024	3.7.1	7010
3.2.4	2025	3.7.2	7040
3.2.5	2026	3.7.3	7049/7149
3.2.6	2090	3.7.4	7050
3.2.7	2124	3.7.5	7055
3.2.8	2219	3.7.6	7075
3.2.9	2297	3.7.7	7150
3.2.10	2424	3.7.8	7175
3.2.11	2519	3.7.9	7249
3.2.12	2524	3.7.10	7475
3.2.13	2618	3.8	200.0 series cast alloys
3.3	3000 series wrought alloys	3.8.1	A201.0
3.4	4000 series wrought alloys	3.9	300.0 series cast alloys
3.5	5000 series wrought alloys	3.9.1	354.0
3.5.1	5052	3.9.2	355.0
3.5.2	5083	3.9.3	C355.0
3.5.3	5086	3.9.4	356.0
3.5.4	5454	3.9.5	A356.0
3.5.5	5456	3.9.6	A357.0
3.6	6000 series wrought alloys	3.9.7	D357.0
3.6.1	6013	3.9.8	359.0

3.1.2 MATERIAL PROPERTIES — The properties of the aluminum alloys are determined by the alloy content and method of fabrication. Some alloys are strengthened principally by cold work, while others are strengthened principally by solution heat treatment and precipitation hardening [Reference 3.1(a)]. The temper designations, shown in Table 3.1.2 (which is based on Reference 3.1.2), are indicative of the type of strengthening mechanism employed.

Among the properties presented herein, some, such as the room-temperature, tensile, compressive, shear and bearing properties, are either specified minimum properties or derived minimum properties related directly to the specified minimum properties. They may be directly useful in design. Data on the effect of temperature on properties are presented so that percentages may be applied directly to the room-temperature minimum properties. Other properties, such as the stress-strain curve, fatigue and fracture toughness data, and modulus of elasticity values, are presented as average or typical values, which may be used in assessing the usefulness of the material for certain applications. Comments on the effect of temperature on properties are given in Sections 3.1.2.1.7 and 3.1.2.1.8; comments on the corrosion resistance are given in Section 3.1.2.3; and comments on the effects of manufacturing practices on these properties are given in Section 3.1.3.

Table 3.1.2. Temper Designation System for Aluminum Alloys

Temper Designation System[a,b]

The temper designation system is used for all forms of wrought and cast aluminum and aluminum alloys except ingot. It is based on the sequences of basic treatments used to produce the various tempers. The temper designation follows the alloy designation, the two being separated by a hyphen. Basic temper designations consist of letters. Subdivisions of the basic tempers, where required, are indicated by one or more digits following the letter. These designate specific sequences of basic treatments, but only operations recognized as significantly influencing the characteristics of the product are indicated. Should some other variation of the same sequence of basic operations be applied to the same alloy, resulting in different characteristics, then additional digits are added to the designation.

Basic Temper Designations

F **as fabricated**. Applies to the products of shaping processes in which no special control over thermal conditions or strain-hardening is employed. For wrought products, there are no mechanical property limits.

O **annealed**. Applies to wrought products which are annealed to obtain the lowest strength temper, and to cast products which are annealed to improve ductility and dimensional stability. The O may be followed by a digit other than zero.

H **strain-hardened (wrought products only)**. Applies to products which have their strength increased by strain-hardening, with or without supplementary thermal treatments to produce some reduction in strength. The H is always followed by two or more digits.

W **solution heat-treated**. An unstable temper applicable only to alloys which spontaneously age at room temperature after solution heat-treatment. This designation is specific only when the period of natural aging is indicated: for example, W ½ hr.

T **thermally treated to produce stable tempers other than F, O, or H**. Applies to products which are thermally treated, with or without supplementary strain-hardening, to produce stable tempers. The T is always followed by one or more digits.

Subdivisions of H Temper: Strain-hardened.

The first digit following H indicates the specific combination of basic operations, as follows:

H1 **strain-hardened only**. Applies to products which are strain-hardened to obtain the desired strength without supplementary thermal treatment. The number following this designation indicates the degree of strain-hardening.

H2 **strain-hardened and partially annealed**. Applies to products which are strain-hardened more than the desired final amount and then reduced in strength to the desired level by partial annealing. For alloys that age-soften at room temperature, the H2 tempers have the same minimum ultimate tensile strength as the corresponding H3 tempers. For other alloys, the H2 tempers have the same minimum ultimate tensile strength as the corresponding H1 tempers and slightly higher elongation. The number following this designation indicates the degree of strain-hardening remaining after the product has been partially annealed.

H3 **strain-hardened and stabilized**. Applies to products which are strain-hardened and whose mechanical properties are stabilized either by a low temperature thermal treatment or as a result of heat introduced during fabrication. Stabilization usually improves ductility. This designation is applicable only to those alloys which, unless stabilized, gradually age-soften at room temperature. The number following this designation indicates the degree of strain-hardening remaining after the stabilization treatment.

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[a] From reference 3.1.2.

[b] Temper designations conforming to this standard for wrought aluminum and wrought aluminum alloys, and aluminum alloy castings may be registered with the Aluminum Association provided: (1) the temper is used or is available for use by more than one user, (2) mechanical property limits are registered, (3) characteristics of the temper are significantly different from those of all other tempers which have the same sequence of basic treatments and for which designations already have been assigned for the same alloy and product, and (4) the following are also registered if characteristics other than mechanical properties are considered significant: (a) test methods and limits for the characteristics or (b) the specific practices used to produce the temper.

Table 3.1.2. Temper Designation System for Aluminum Alloys — Continued

The digit following the designations H1, H2, and H3 indicates the degree of strain hardening. Numeral 8 has been assigned to indicate tempers having an ultimate tensile strength equivalent to that achieved by a cold reduction (temperature during reduction not to exceed 120°F) of approximately 75 percent following a full anneal. Tempers between O (annealed) and 8 are designated by numerals 1 through 7. Material having an ultimate tensile strength about midway between that of the O temper and that of the 8 temper is designated by the numeral 4; about midway between the O and 4 tempers by the numeral 2; and about midway between 4 and 8 tempers by the numeral 6. Numeral 9 designates tempers whose minimum ultimate tensile strength exceeds that of the 8 temper by 2.0 ksi or more. For two-digit H tempers whose second digit is odd, the standard limits for ultimate tensile strength are exactly midway between those of the adjacent two digit H tempers whose second digits are even.

NOTE: For alloys which cannot be cold reduced an amount sufficient to establish an ultimate tensile strength applicable to the 8 temper (75 percent cold reduction after full anneal), the 6 temper tensile strength may be established by a cold reduction of approximately 55 percent following a full anneal, or the 4 temper tensile strength may be established by a cold reduction of approximately 35 percent after a full anneal.

The third digit[c], when used, indicates a variation of a two-digit temper. It is used when the degree of control of temper or the mechanical properties or both differ from, but are close to, that (or those) for the two-digit H temper designation to which it is added, or when some other characteristic is significantly affected.

NOTE: The minimum ultimate tensile strength of a three-digit H temper must be at least as close to that of the corresponding two-digit H temper as it is to the adjacent two-digit H tempers. Products of the H temper whose mechanical properties are below H_1 will be variations of H_1.

Three-digit H Tempers

H_11 Applies to products which incur sufficient strain hardening after the final anneal that they fail to qualify as annealed but not so much or so consistent an amount of strain hardening that they qualify as H_1.

H112 Applies to products which may acquire some temper from working at an elevated temperature and for which there are mechanical property limits.

Subdivisions of T Temper: Thermally Treated

Numerals 1 through 10 following the T indicate specific sequences of basic treatments, as follows.[d]

T1 **cooled from an elevated temperature shaping process and naturally aged to a substantially stable condition**. Applies to products which are not cold worked after cooling from an elevated temperature shaping process, or in which the effect of cold work in flattening or straightening may not be recognized in mechanical property limits.

T2 **cooled from an elevated temperature shaping process, cold worked and naturally aged to a substantially stable condition**. Applies to products which are cold worked to improve strength after cooling from an elevated temperature shaping process, or in which the effect of cold work in flattening or straightening is recognized in mechanical property limits.

T3 **solution heat-treated[e], cold worked, and naturally aged to a substantially stable condition**. Applies to products which are cold worked to improve strength after solution heat-treatment, or in which the effect of cold work in flattening or straightening is recognized in mechanical property limits.

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[c] Numerals 1 through 9 may be arbitrarily assigned as the third digit and registered with The Aluminum Association for an alloy and product to indicate a variation of a two-digit H temper (see footnote b).

[d] A period of natural aging at room temperature may occur between or after the operations listed for the T tempers. Control of this period is exercised when it is metallurgically important.

[e] Solution heat treatment is achieved by heating cast or wrought products to a suitable temperature, holding at that temperature long enough to allow constituents to enter into solid solution and cooling rapidly enough to hold the constituents in solution. Some 6000 series alloys attain the same specified mechanical properties whether furnace solution heat-treated or cooled from an elevated temperature shaping process at a rate rapid enough to hold constituents in solution. In such cases the temper designations T3, T4, T6, T7, T8, and T9 are used to apply to either process and are appropriate designations.

Table 3.1.2. Temper Designation System for Aluminum Alloys — Continued

T4 solution heat-treated[e] and naturally aged to a substantially stable condition. Applies to products which are not cold worked after solution heat-treatment, or in which the effect of cold work in flattening or straightening may not be recognized in mechanical property limits.

T5 cooled from an elevated temperature shaping process and artificially aged. Applies to products which are not cold worked after cooling from an elevated temperature shaping process, or in which the effect of cold work in flattening or straightening may not be recognized in mechanical property limits.

T6 solution heat-treated[e] and artificially aged. Applies to products which are not cold worked after solution heat-treatment or in which the effect of cold work in flattening or straightening may not be recognized in mechanical property limits.

T7 solution heat-treated[e] and overaged/stabilized. Applies to wrought products that are artificially aged after solution heat-treatment to carry them beyond a point of maximum strength to provide control of some significant characteristic. Applies to cast products that are artificially aged after solution heat-treatment to provide dimensional and strength stability.

T8 solution heat-treated[e], cold worked, and artificially aged. Applies to products which are cold worked to improve strength, or in which the effect of cold work in flattening or straightening is recognized in mechanical property limits.

T9 solution heat-treated[e], artificially aged, and cold worked. Applies to products which are cold worked to improve strength.

T10 cooled from an elevated temperature shaping process, cold worked, and artificially aged. Applies to products which are cold worked to improve strength, or in which the effect of cold work in flattening or straightening is recognized in mechanical property limits.

Additional digits[f], the first of which will not be zero, may be added to designations T1 through T10 to indicate a variation in treatment which significantly alters the product characteristics[g] that are or would be obtained using the basic treatment.

The following specific additional digits have been assigned for stress-relieved tempers of wrought products:

Stress Relieved by Stretching

T_51 Applies to plate and rolled or cold-finished rod and bar when stretched the indicated amounts after solution heat-treatment or after cooling from an elevated temperature shaping process. The products receive no further straightening after stretching.

Plate .... 1½ to 3% permanent set.
Rolled or Cold-Finished
Rod and Bar .... 1 to 3% permanent set.
Die or Ring Forgings
and Rolled Rings .... 1 to 5% permanent set.

T_510 Applies to extruded rod, bar, shapes and tube and to drawn tube when stretched the indicated amounts after solution heat-treatment or after cooling from an elevated temperature shaping process. These products receive no further straightening after stretching.

Extruded Rod, Bar, Shapes
and Tube .... 1 to 3% permanent set.
Drawn Tube .... ½ to 3% permanent set.

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[e] Solution heat treatment is achieved by heating cast or wrought products to a suitable temperature, holding at that temperature long enough to allow constituents to enter into solid solution and cooling rapidly enough to hold the constituents in solution. Some 6000 series alloys attain the same specified mechanical properties whether furnace solution heat-treated or cooled from an elevated temperature shaping process at a rate rapid enough to hold constituents in solution. In such cases the temper designations T3, T4, T6, T7, T8, and T9 are used to apply to either process and are appropriate designations.

[f] Additional digits may be arbitrarily assigned and registered with the Aluminum Association for an alloy and product to indicate a variation of tempers T1 through T10 even though the temper representing the basic treatment has not been registered (see footnote b). Variations in treatment which do not alter the characteristics of the product are considered alternate treatments for which additional digits are not assigned.

[g] For this purpose, characteristic is something other than mechanical properties. The test method and limit used to evaluate material for this characteristic are specified at the time of the temper registration.

Table 3.1.2. Temper Designation System for Aluminum Alloys — Continued

T_511

Applies to extruded rod, bar, shapes and tube and to drawn tube when stretched the indicated amounts after solution heat-treatment or after cooling from an elevated temperature shaping process. These products may receive minor straightening after stretching to comply with standard tolerances.

Stress Relieved by Compressing

T_52

Applies to products which are stress-relieved by compressing after solution heat-treatment or cooling from an elevated temperature shaping process to produce a set of 1 to 3 percent.

Stress Relieved by Combined Stretching and Compressing

T_54

Applies to die forgings which are stress relieved by restriking cold in the finish die.

NOTE: The same digits (51, 52, 54) may be added to the designation W to indicate unstable solution heat-treated and stress-relieved treatment.

The following temper designations have been assigned for wrought product test material heat-treated from annealed (O, O1, etc.) or F temper.[h]

T42 Solution heat-treated from annealed or F temper and naturally aged to a substantially stable condition.

T62 Solution heat-treated from annealed or F temper and artificially aged.

Temper designations T42 and T62 may also be applied to wrought products heat-treated from any temper by the user when such heat-treatment results in the mechanical properties applicable to these tempers.

Variations of O Temper: Annealed

A digit following the O, when used, indicates a product in the annealed condition have special characteristics. NOTE: As the O temper is not part of the strain-hardened (H) series, variations of O temper will not apply to products which are strain-hardened after annealing and in which the effect of strain-hardening is recognized in the mechanical properties or other characteristics.

Assigned O Temper Variations

The following temper designation has been assigned for wrought products high temperature annealed to accentuate ultrasonic response and provide dimensional stability.

O1 Thermally treated at approximately same time and temperature required for solution heat treatment and slow cooled to room temperature. Applicable to products which are to be machined prior to solution heat treatment by the user. Mechanical Property limits are not applicable.

Designation of Unregistered Tempers

The letter P has been assigned to denote H, T and O temper variations that are negotiated between manufacturer and purchaser. The letter P immediately follows the temper designation that most nearly pertains. Specific examples where such designation may be applied include the following:

The use of the temper is sufficiently limited so as to preclude its registration. (Negotiated H temper variations were formerly indicated by the third digit zero.)

The test conditions (sampling location, number of samples, test specimen configuration, etc.) are different from those required for registration with the Aluminum Association.

The mechanical property limits are not established on the same basis as required for registration with the Aluminum Association.

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[h] When the user requires capability demonstrations from T-temper, the seller will note "capability compliance" adjacent to the specified ending tempers. Some examples are: "-T4 to -T6 Capability Compliance as for aging" or "-T351 to -T4 Capability Compliance as for resolution heat treating."

It should be recognized not all combinations of stress and environment have been investigated, and it may be necessary to evaluate an alloy under the specific conditions involved for certain critical applications.

3.1.2.1 *Mechanical Properties* —

3.1.2.1.1 *Strength (Tension, Compression, Shear, Bearing)* — The design strength properties at room temperature are listed at the beginning of the section covering the properties of an alloy. The effect of temperature on these properties is indicated in figures which follow the tables.

The A- and B-basis values for tensile properties for the direction associated with the specification requirements are based upon a statistical analysis of production quality control data obtained from specimens tested in accordance with procurement specification requirements. For sheet and plate of heat-treatable alloys, the specified minimum values are for the long-transverse (LT) direction, while for sheet and plate of nonheat treatable alloys and for rolled, drawn, or extruded products, the specified minimum values are for the longitudinal (L) direction. For forgings, the specified minimum values are stated for at least two directions. The design tensile properties in other directions and the compression, shear, and bearing properties are "derived" properties, based upon the relationships among the properties developed by tests of at least ten lots of material and applied to the appropriate established A, B, or S properties. All of these properties are representative of the regions from which production quality control specimens are taken, but may not be representative of the entire cross section of products appreciably thicker than the test specimen or products of complex cross sections.

Tensile and compressive strengths are given for the longitudinal, long-transverse, and short-transverse directions wherever data are available. Short-transverse strengths may be relatively low, and transverse properties should not be assumed to apply to the short-transverse direction unless so stated. In those instances where the direction in which the material will be used is not known, the lesser of the applicable longitudinal or transverse properties should be used.

Bearing strengths are given without reference to direction and may be assumed to be about the same in all directions, with the exception of plate, die forging, and hand forging. A reduction factor is used for edgewise bearing load in thick bare and clad plate of 2000 and 7000 series alloys. The results of bearing tests on longitudinal and long-transverse specimens taken edgewise from plate, die forging, and hand forging have shown that the edgewise bearing strengths are substantially lower than those of specimens taken parallel to the surface. The bearing specimen orientations in thick plate are shown in Figure 3.1.2.1.1(a). For plate, bearing specimens are oriented so that the width of the specimen is parallel to the surfaces of the plate (flatwise); consequently, in cases where the stress condition approximates that of the longitudinal or long-transverse edgewise orientations, the reductions in design values shown in Table 3.1.2.1.1 should be made.

It should be noted that in recent years, bearing data have been presented from tests made in accordance with ASTM E 238 which requires clean pins and specimens. See Reference 3.1.2.1.1 for additional information. Designers should consider a reduction factor in applying these values to structural analyses.

For die and hand forgings, bearing specimens are taken edgewise so that no reduction factor is necessary. In the case of die forgings, the location of bearing specimens is shown in Figures 3.1.2.1.1(b) and (c). For die forgings with cross-sectional shapes in the form of an I-beam or a channel, longitudinal

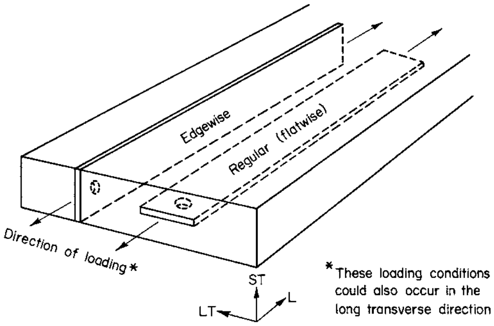

Figure 3.1.2.1.1(a). Bearing specimen orientation in thick plate.

Table 3.1.2.1.1. Bearing Property Reductions for Thick Plate of 2000 and 7000 Series Alloys

	Bearing Property Reduction, percent
Thickness (in.) ...	1.001-6.000
F_{bru} (e/D = 1.5)	15
F_{bru} (e/D = 2.0)	10
F_{bry} (e/D = 1.5)	5
F_{bry} (e.D = 2.0)	5

bearing specimens are oriented so the width of the specimens is normal to the parting plane (edgewise). The specimens are positioned so the bearing test holes are midway between the parting plane and the top of the flange. The severity of metal flow at the parting plane near the flash can be expected to vary considerably for web-flange type die forgings; therefore, for consistency, the bearing test hole should not be located on the parting plane. However, in the case of large, bulky-type die forgings, with a cross-sectional shape similar to a square, rectangle, or trapezoid, as shown in Figure 3.1.2.1.1(c), longitudinal bearing specimens are oriented edgewise to the parting plane, but the specimens are positioned so the bearing test holes are located on the parting plane. Similarly, for hand forgings, bearing specimens are oriented edgewise and the specimens are positioned at the ½ thickness location.

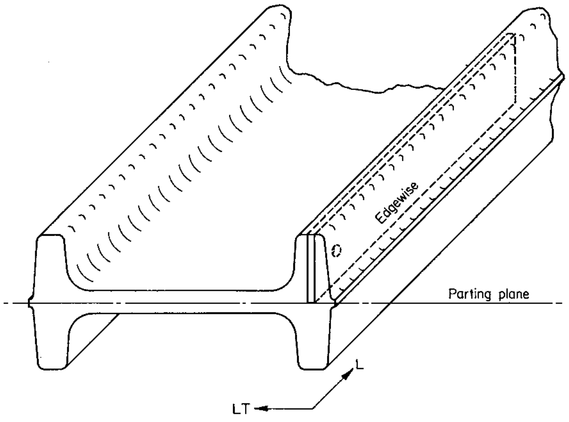

Figure 3.1.2.1.1(b). Bearing specimen orientation for web-flange type die forging.

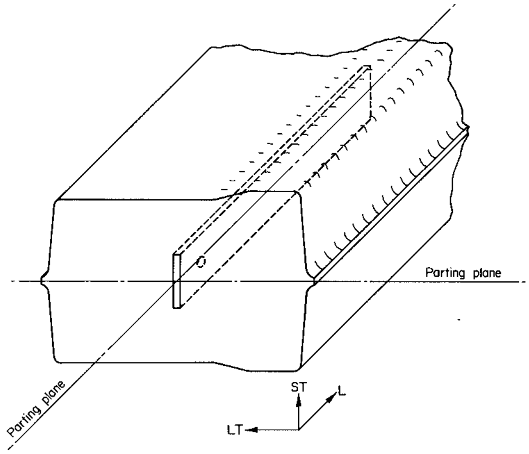

Figure 3.1.2.1.1(c). Bearing specimen orientation for thick cross-section die forging.

Shear strengths also vary to some extent with plane of shear and direction of loading but the differences are not so consistent [Reference 3.1.2.1.1(c)]. The standard test method for the determination of shear strength of aluminum alloy products, 3/16 inch and greater in thickness, is contained in ASTM B 769.

Shear strength values are presented without reference to grain direction, except for hand forgings. For products other than hand forgings, the lowest shear strength exhibited by tests in the various grain directions is the design value. For hand forgings, the shear strength in short-transverse direction may be significantly lower than for the other two grain directions. Consequently, the shear strength for hand forgings is presented for each grain direction.

For clad sheet and plate (i.e., containing thin surface layers of material of a different composition for added corrosion protection), the strength values are representative of the composite (i.e., the cladding and the core). For sheet and thin plate (≤0.499 inch), the quality-control test specimens are of the full thickness, so that the guaranteed tensile properties and the associated derived values for these products directly represent the composite. For plate ≥0.500 inch in thickness, the quality-control test specimens are machined from the core so the guaranteed tensile properties in specifications reflect the core material only, not the composite. Therefore, the design tensile properties for the thicker material are obtained by adjustment of the specification tensile properties and the other related properties to represent the composite, using the nominal total cladding thickness and the typical tensile properties of the cladding material.

For clad aluminum sheet and plate products, it is also important to distinguish between primary and secondary modulus values. The initial, or primary, modulus represents an average of the elastic moduli of the core and cladding; it applies only up to the proportional limit of the cladding. For example, the primary modulus of 2024-T3 clad sheet applies only up to about 6 ksi. Similarly, the primary modulus of 7075-T6 clad sheet applies only up to approximately 12 ksi. A typical use of primary moduli is for low amplitude, high frequency fatigue.

3.1.2.1.2 *Elongation* — Elongation values are included in the tables of room-temperature mechanical properties. In some cases where the elongation is a function of material thickness, a supplemental table is provided. Short-transverse elongations may be relatively low, and long-transverse values should not be assumed to apply to the short-transverse direction.

3.1.2.1.3 *Stress-Strain Relationship* — The stress-strain relationships presented, which include elastic and compressive tangent moduli, are typical curves based on three or more lots of test data. Being typical, these curves will not correspond to yield strength data presented as design allowables (minimum values). However, the stress-strain relationships are no less useful, since there are well-known methods for using these curves in design by reducing them to a minimum curve scaled down from the typical curve or by using Ramberg-Osgood parameters obtained from the typical curves.

3.1.2.1.4 *Creep and Stress Rupture* — Sustained stressing at elevated temperature sufficient to result in appreciable amounts of creep deformation (e.g., more than 0.2 percent) may result in decreased strength and ductility. It may be necessary to evaluate an alloy under its stress-temperature environment for critical applications where sustained loading is anticipated (see Reference 3.1.2.1.4).

3.1.2.1.5 *Fatigue* — Fatigue S/N curves are presented for those alloys for which sufficient data are available. Data for both smooth and notched specimens are presented. The data from which the curves were developed were insufficient to establish scatter bands and do not have the statistical reliability of the room-temperature mechanical properties; the values should be considered to be representative for the respective alloys.

The fatigue strengths of aluminum alloys, with both notched and unnotched specimens, are at least as high or higher at subzero temperatures than at room temperature [References 3.1.2.1.5(a) through (c)].

At elevated temperatures, the fatigue strengths are somewhat lower than at room temperature, the difference increasing with increase in temperature.

The data presented do not apply directly to the design of structures because they do not take into account the effect of stress raisers such as reentrant corners, notches, holes, joints, rough surfaces, and other similar conditions which are present in fabricated parts. The localized high stresses induced in fabricated parts by such stress raisers are of much greater importance for repeated loading than they are for static loading and may reduce the fatigue life of fabricated parts far below that which would be predicted by comparing the smooth-specimen fatigue strength directly with the nominal calculated stresses for the parts in question. See References 3.1.2.1.5 (d) through (q) for information on how to use high-strength aluminum alloys, Reference 3.1.2.1.5(r) for details on the static and fatigue strengths of high-strength aluminum-alloy bolted joints, Reference 3.1.2.1.5(s) for single-rivet fatigue-test data, and Reference 1.4.9.3(b) for a general discussion of designing for fatigue. Fatigue-crack-growth data are presented in the various alloy sections.

3.1.2.1.6 *Fracture Toughness* — Typical values of plane-strain fracture toughness, K_{Ic}, [Reference 3.1.2.1.6(a)] for the high-strength aluminum alloy products are presented in Table 3.1.2.1.6. Minimum, average, and maximum values as well as coefficient of variation are presented for the alloys and tempers for which valid data are available [References 3.1.2.1.6(b) through (j)]. Although representative, these values do not have the statistical reliability of the room-temperature mechanical properties.

Graphic displays of the residual strength behavior of middle tension panels are presented in the various alloy sections. The points denote the experimental data from which the curve of fracture toughness was derived.

3.1.2.1.7 *Cryogenic Temperatures* — In general, the strengths (including fatigue strengths) of aluminum alloys increase with decrease in temperature below room temperature [References 3.1.2.1.7(a) and (b)]. The increase is greatest over the range from about -100 to -423°F (liquid hydrogen temperature); the strengths at -452°F (liquid helium temperature) are nearly the same as at -423°F [References 3.1.2.1.7(c) and (d)]. For most alloys, elongation and various indices of toughness remain nearly constant or increase with decrease in temperature, while for the 7000 series, modest reductions are observed [References 3.1.2.1.7(d) and (e)]. None of the alloys exhibit a marked transition in fracture resistance over a narrow range of temperature indicative of embrittlement.

The tensile and shear moduli of aluminum alloys also increase with decreasing temperature so that at -100, -320, and -423°F, they are approximately 5, 12, and 16 percent, respectively, above the room temperature values [Reference 3.1.2.1.7(f)].

3.1.2.1.8 *Elevated Temperatures* — In general, the strengths of aluminum alloys decrease and toughness increases with increase in temperature and with time at temperature above room temperature; the effect is generally greatest over the temperature range from 212 to 400°F. Exceptions to the general trends are tempers developed by solution heat treatment without subsequent aging, for which the initial elevated temperature exposure results in some age hardening and reduction in toughness; further time at temperature beyond that required to achieve peak hardness results in the aforementioned decrease in strength and increase in toughness [Reference 3.1.2.1.8].

Table 3.1.2.1.6. Values of Room-Temperature Plane-Strain Fracture Toughness of Aluminum Alloys[a]

Alloy/Temper[b]	Product Form	Orientation[c]	Product Thickness Range, inches	Number of Sources	Sample Size	Specimen Thickness Range, inches	K_{IC}, ksi $\sqrt{in.}$				
							Max.	Avg.	Min.	Coefficient of Variation	Minimum Specification Value
2014-T651	Plate	L-T	≥0.5	1	24	0.5-1.0	25	22	19	8.4	
2014-T651	Plate	T-L	≥0.5	2	34	0.5-1.0	23	21	18	6.5	
2014-T652	Hand Forging	L-T	≥0.5	2	15	0.8-2.0	48	31	24	21.8	
2014-T652	Hand Forging	T-L	≥0.8	2	15	0.8-2.0	30	21	18	14.4	
2024-T351	Plate	L-T	≥1.0	2	11	0.8-2.0	43	31	27	16.5	
2024-T851	Plate	L-S	1.4-3.0	4	11	0.5-0.8	32	25	20	17.8	
2024-T851	Plate	L-T	≥0.5	11	102	0.4-1.4	32	23	15	10.1	
2024-T851	Plate	T-L	0.4-4.0	9	80	0.4-1.4	25	20	18	8.8	
2024-T852	Forging	T-L	2.0-7.0	3	20	0.7-2.0	25	19	15	15.5	
2024-T852	Hand Forging	L-T	----	4	35	0.8-2.0	38	28	19	18.4	
2024-T852	Hand Forging	T-L	----	2	17	0.7-2.0	22	18	14	14.4	
2124-T851	Plate	L-T	≥0.8	13	497	0.5-2.5	38	29	18	10.4	24
2124-T851	Plate	T-L	0.6-6.0	10	509	0.5-2.0	32	25	19	9.7	20
2124-T851	Plate	S-L	≥0.5	6	489	0.3-1.5	27	21	16	9.8	18
2219-T851	Plate	L-T	----	4	67	1.0-2.5	38	33	30	7.2	
2219-T851	Plate	T-L	≥1.0	6	108	0.8-2.5	37	29	20	10.1	
2219-T851	Plate	S-L	≥0.8	3	24	0.5-1.5	26	22	20	9.6	
2219-T851	Forging	S-L	----	1	85	1.0-1.5	34	25	19	12.1	
2219-T8511	Extrusion	T-L	----	1	19	1.8-2.0	34	29	23	12.3	
2219-T852	Forging	S-L	----	2	60	0.8-2.0	35	25	20	12.1	
2219-T852	Hand Forging	L-T	----	2	32	1.5-2.5	46	38	30	9.7	
2219-T852	Hand Forging	T-L	≥1.5	2	28	1.5-2.5	30	27	22	8.4	
2219-T87	Plate	L-T	≥1.5	3	11	0.8-2.0	34	27	25	9.3	
2219-T87	Plate	T-L	----	1	11	1.0	22	22	19	3.9	31
2297-T87	Plate	L-T	3-4	1	16	1.5	50	40	33	11.3	31
2297-T87	Plate	T-L	3-4	1	18	1.5	41	32	28	9.4	27
2297-T87	Plate	S-L	3-4	1	17	1.0	32	25	20	11.0	20
2297-T87	Plate	L-T	4-5	1	51	1.5	46	38	32	8.0	30
2297-T87	Plate	T-L	4-5	1	51	1.5	37	30	26	7.1	26
2297-T87	Plate	S-L	4-5	1	52	1.0	30	24	19	8.7	18
2297-T87	Plate	L-T	5-6	1	17	1.5	42	36	31	7.7	29
2297-T87	Plate	T-L	5-6	1	17	1.5	30	27	25	6.2	25
2297-T87	Plate	S-L	5-6	1	14	1.0	27	23	19	8.7	18

[a] These values are for information only.

[b] Products that do not receive a mechanical stress-relieving process (e.g. -T73 & -T74 tempers) have the potential for induced residual stresses. As a result, care must be taken to prevent fracture toughness properties from bias resulting from residual stresses.

[c] Refer to Figure 1.4.12.3 for definition of symbols.

[d] Varies with thickness.

Table 3.1.2.1.6. Values of Room-Temperature Plane-Strain Fracture Toughness of Aluminum Alloys[a]—Continued

Alloy/Temper[b]	Product Form	Orientation[c]	Product Thickness Range, inches	Number of Sources	Sample Size	Specimen Thickness Range, inches	K_{IC}, ksi$\sqrt{\text{in.}}$				
							Max.	Avg.	Min.	Coefficient of Variation	Minimum Specification Value
7040-T7451	Plate	L-T	3-4	1	16	2	39	37	34	5.2	26
7040-T7451	Plate	T-L	3-4	1	16	2	31	30	28	2.8	24
7040-T7451	Plate	S-L	3-4	1	14	2	33	31	29	4.2	30
7040-T7451	Plate	L-T	4-5	1	17	2	34	32	31	2.0	25
7040-T7451	Plate	T-L	4-5	1	17	2	27	26	26	1.5	24
7040-T7451	Plate	S-L	4-5	1	17	2	28	26	26	2.2	29
7040-T7451	Plate	L-T	5-6	1	17	2	34	32	30	2.7	23
7040-T7451	Plate	T-L	5-6	1	14	2	28	25	25	3.5	24
7040-T7451	Plate	S-L	5-6	1	16	2	28	27	26	2.7	27
7040-T7451	Plate	L-T	6-7	1	21	2	37	34	30	5.9	22
7040-T7451	Plate	T-L	6-7	1	21	2	29	27	25	2.8	23
7040-T7451	Plate	S-L	6-7	1	21	2	30	29	27	4.0	26
7040-T7451	Plate	L-T	7-8	1	18	2	33	32	30	3.2	22
7040-T7451	Plate	T-L	7-8	1	16	2	29	28	26	2.7	23
7040-T7451	Plate	S-L	7-8	1	13	2	31	29	26	4.6	26
7040-T7451	Plate	L-T	8-8.5	1	17	2	34	31	28	4.6	22
7040-T7451	Plate	T-L	8-8.5	1	13	2	26	24	23	5.0	22
7040-T7451	Plate	S-L	8-8.5	1	17	2	27	26	25	2.1	
7049-T73	Die Forging	L-T	1.4	3	21	0.5-1.0	34	30	27	7.4	
7049-T73	Die Forging	S-L	≥0.5	3	46	0.5-1.0	26	22	18	9.7	
7049-T73	Hand Forging	L-T	≥0.5	2	28	0.5-1.0	37	30	23	12.1	
7049-T73	Hand Forging	T-L	2.0-7.1	2	27	1.0	28	22	18	12.5	
7049-T73	Hand Forging	S-L	1.0	2	24	0.8-1.0	22	19	14	14.2	
7050-T7351	Plate	L-T	1.0-6.0	2	31	1.0-2.0	43	35	28	11.3	
7050-T7351	Plate	T-L	2.0-6.0	1	29	1.5-2.0	35	30	25	8.5	
7050-T7351	Plate	S-L	2.0-6.0	1	30	0.8-1.5	30	28	25	4.6	
7050-T74	Die Forging	S-L	0.6-7.1	3	12	0.6-2.0	27	24	21	8.8	d
7050-T7451	Plate	L-T	----	13	96	1.0-2.0	39	32	25	11.7	d
7050-T7451	Plate	T-L	≥1.0	9	97	0.5-2.0	38	28	21	15.6	d
7050-T7451	Plate	S-L	≥1.0	6	44	0.7-2.0	28	23	21	6.3	d

a These values are for information only.

b Products that do not receive a mechanical stress-relieving process (e.g. -T73 & -T74 tempers) have the potential for induced residual stresses. As a result, care must be taken to prevent fracture toughness properties from bias resulting from residual stresses.

c Refer to Figure 1.4.12.3 for definition of symbols.

d Varies with thickness.

Table 3.1.2.1.6. Values of Room-Temperature Plane-Strain Fracture Toughness of Aluminum Alloys[a]—Continued

Alloy/Temper[b]	Product Form	Orientation[c]	Product Thickness Range, inches	Number of Sources	Sample Size	Specimen Thickness Range, inches	K_{IC}, ksi$\sqrt{in.}$				
							Max.	Avg.	Min.	Coefficient of Variation	Minimum Specification Value
7050-T7452	Hand Forging	L-T	3.5-5.5	1	11	1.5	34	31	26	8.0	d
7050-T7452	Hand Forging	T-L	3.5-7.5	1	13	1.5	22	21	18	6.7	d
7050-T7452	Hand Forging	S-L	3.5-7.5	1	17	0.8-1.5	21	19	16	7.5	
7050-T76511	Extrusion	L-T	----	2	38	0.6-2.0	40	31	27	7.8	
7075-T651	Plate	L-T	≥0.6	7	99	0.5-2.0	30	26	20	7.6	
7075-T651	Plate	T-L	≥0.5	5	135	0.4-2.0	27	22	18	8.9	
7075-T651	Plate	S-L	----	2	37	0.5-1.5	22	18	14	10.4	
7075-T6510	Extrusion	L-T	0.7-3.5	1	26	0.5-1.2	32	27	23	7.8	
7075-T6510	Extrusion	T-L	0.7-3.5	1	25	0.5-1.2	28	24	21	8.0	
7075-T6510	Forged Bar	L-T	0.7-5.0	1	13	0.6-2.0	35	29	24	11.6	
7075-T6510	Forged Bar	T-L	0.7-5.0	1	13	0.5-2.5	24	21	17	8.2	
7075-T73	Die Forging	T-L	≥0.5	1	22	0.5-0.8	25	21	18	9.9	
7075-T73	Hand Forging	L-T	----	2	10	1.0-1.5	39	31	29	8.8	
7075-T73	Hand Forging	T-L	≥1.0	2	14	1.0-1.5	27	23	20	9.0	
7075-T7351	Plate	L-T	≥1.0	8	65	0.5-2.0	36	30	25	8.2	
7075-T7351	Plate	T-L	≥0.5	6	56	0.5-2.0	47	27	21	20.1	
7075-T7351	Plate	S-L	≥0.5	3	20	0.5-1.5	38	22	17	32.5	
7075-T73511	Extrusion	T-L	1.0-7.0	1	19	0.9-1.0	22	20	19	3.7	
7075-T73511	Extrusion	L-T	≥0.9	3	28	0.7-2.0	43	35	31	9.4	
7075-T73511	Extrusion	T-L	≥0.7	3	35	0.5-1.8	35	23	12	20.3	
7075-T73511	Extrusion	S-L	≥0.5	3	15	0.4-1.0	22	20	17	9.0	
7075-T7352	Hand Forging	L-T	----	2	27	0.8-2.0	39	33	30	9.2	
7075-T7352	Hand Forging	T-L	≥0.8	3	20	0.8-2.0	33	26	23	9.9	
7075-T7651	Plate	L-T	≥0.8	6	82	0.5-2.0	43	29	22	17.8	
7075-T7651	Plate	T-L	≥0.5	7	96	0.5-2.0	28	23	20	7.6	
7075-T7651	Plate	S-L	≥0.5	5	28	0.4-0.8	20	18	15	7.7	
7075-T7651	Clad Plate	L-T	0.5-0.6	2	30	0.5-0.6	30	25	22	7.1	
7075-T7651	Clad Plate	T-L	0.5-0.6	2	56	0.5-0.6	28	24	21	7.7	

[a] These values are for information only.

[b] Products that do not receive a mechanical stress-relieving process (e.g. -T73 & -T74 tempers) have the potential for induced residual stresses. As a result, care must be taken to prevent fracture toughness properties from bias resulting from residual stresses.

[c] Refer to Figure 1.4.12.3 for definition of symbols.

[d] Varies with thickness.

Table 3.1.2.1.6. Values of Room-Temperature Plane-Strain Fracture Toughness of Aluminum Alloys[a]—Concluded

Alloy/Temper[b]	Product Form	Orientation[c]	Product Thickness Range, inches	Number of Sources	Sample Size	Specimen Thickness Range, inches	K_{IC}, ksi$\sqrt{in.}$				
							Max.	Avg.	Min.	Coefficient of Variation	Minimum Specification Value
7075-T76511	Extrusion	L-T	1.3-7.0	4	11	1.2-2.0	41	35	31	11.0	
7075-T76511	Extrusion	T-L	1.2	3	42	0.6-2.0	36	23	20	15.5	
7150-T77511	Extrusion	L-T	0.76	1	52	0.5	36	31	26	7.7	24
7150-T77511	Extrusion	T-L	0.76	1	52	0.5	27	24	21	5.1	20
7175-T6/T6511	Extrusion	T-L	----	2	25	0.8-1.0	24	21	18	7.9	
7175-T651	Plate	L-T	----	1	17	0.7-0.8	30	26	24	9.2	
7175-T651	Plate	T-L	----	1	10	0.7-0.8	26	22	20	9.8	
7175-T6511	Extrusion	L-T	----	2	14	0.8-1.0	36	32	24	13.8	
7175-T7351	Plate	L-T	----	2	30	0.7-1.6	36	33	32	3.3	
7175-T7351	Plate	T-L	----	2	32	0.7-1.6	30	27	25	4.5	
7175-T73511	Extrusion	L-T	≥0.7	5	43	0.5-1.5	47	33	23	16.0	30
7175-T73511	Extrusion	T-L	≥0.5	5	43	0.5-1.5	35	25	20	10.9	22
7175-T74	Die Forging	L-T	≥0.5	3	14	0.5-1.0	38	30	22	15.0	27
7175-T74	Die Forging	T-L	≥0.5	2	13	0.5-1.0	33	24	21	15.7	21
7175-T74	Die Forging	S-L	≥0.5	4	41	0.5-0.8	31	26	20	8.6	21
7175-T74	Hand Forging	T-L	3.0-5.0	2	10	1.0-1.5	29	26	24	4.8	25
7175-T7651	Clad Plate	L-T	----	1	53	1.5	33	32	30	4.3	
7175-T7651	Clad Plate	T-L	----	1	50	0.6	28	27	25	3.1	
7175-T7651	Plate	L-T	----	1	12	1.5	32	32	31	1.7	
7175-T7651	Plate	T-L	----	1	11	1.5	26	25	24	3.3	
7175-T76511	Extrusion	L-T	1.4-3.8	2	48	0.6-2.0	39	33	27	10.7	
7175-T76511	Extrusion	T-L	≥0.6	4	49	0.6-1.8	31	22	20	9.8	
7475-T651	Plate	L-T	----	3	34	0.9-2.0	49	38	33	9.2	30
7475-T651	Plate	T-L	0.6-2.0	2	143	0.6-2.0	43	34	27	9.8	28
7475-T651	Plate	S-L	≥0.6	1	23	0.5-1.0	36	28	20	14.9	
7475-T7351	Plate	L-T	1.3-4.0	8	151	1.3-3.0	60	47	34	10.4	d
7475-T7351	Plate	T-L	≥1.3	7	132	0.7-3.0	50	37	29	10.4	d
7475-T7351	Plate	S-L	≥0.7	7	74	0.5-1.5	36	30	25	8.7	25
7475-T7651	Plate	L-T	1.0-2.0	4	10	1.0-2.0	46	41	36	6.2	33
7475-T7651	Plate	T-L	≥1.0	2	15	0.9-2.0	50	36	29	14.5	30

a These values are for information only.

b Products that do not receive a mechanical stress-relieving process (e.g. -T73 & -T74 tempers) have the potential for induced residual stresses. As a result, care must be taken to prevent fracture toughness properties from bias resulting from residual stresses.

c Refer to Figure 1.4.12.3 for definition of symbols.

d Varies with thickness.

3.1.2.2 *Physical Properties* — Where available from the literature, the average values of certain physical properties are included in the room-temperature tables for each alloy. These properties include density, ω, in lb/in.^{3}; the specific heat, C, in Btu/(lb)(°F); the thermal conductivity, K, in Btu/[(hr)(ft^2)(°F)/ft]; and the mean coefficient of thermal expansion, α, in in./in./°F. Where more extensive data are available to show the effect of temperature on these physical properties, graphs of physical property as a function of temperature are presented for the applicable alloys.

3.1.2.3 *Corrosion Resistance* —

3.1.2.3.1 *Resistance to Stress-Corrosion Cracking [see References 3.1.2.3.1(a) through (d)]* — In-service stress-corrosion cracking failures can be caused by stresses produced from a wide variety of sources, including solution heat treatment, straightening, forming, fit-up, clamping, and sustained service loads. These stresses may be tensile or compressive, and the stresses due to Poisson effects should not be ignored because SCC failures can be caused by sustained shear stresses. Pin-hole flaws in some corrosion protection coatings may also be sufficient to allow SCC to occur. The high-strength heat treatable wrought aluminum alloys in certain tempers are susceptible to stress-corrosion cracking, depending upon product, section size, direction and magnitude of stress. These alloys include 2014, 2025, 2618, 7075, 7150, 7175, and 7475 in the T6-type tempers and 2014, 2024, 2124, and 2219 in the T3 and T4-type tempers. Other alloy-temper combinations, notably 2024, 2124, 2219, and 2519 in the T6- or T8-type tempers and 7010, 7049, 7050, 7075, 7149, 7175, and 7475 in the T73-type tempers, are decidedly more resistant and sustained tensile stresses of 50 to 75 percent of the minimum yield strength may be permitted without concern about stress corrosion cracking. The T74 and T76 tempers of 7010, 7075, 7475, 7049, 7149, and 7050 provide an intermediate degree of resistance to stress-corrosion cracking, i.e., superior to that of the T6 temper, but not as good as that of the T73 temper of 7075. To assist in the selection of materials, letter ratings indicating the relative resistance to stress-corrosion cracking of various mill product forms of the wrought 2000, 6000, and 7000 series heat-treated aluminum alloys are presented in Table 3.1.2.3.1(a). This table is based upon ASTM G 64 which contains more detailed information regarding this rating system and the procedure for determining the ratings. In addition, more quantitative information in the form of the maximum specified tension stresses at which test specimens will not fail when subjected to the alternate immersion stress-corrosion test described in ASTM G 47 are shown in Tables 3.1.2.3.1(b) through (e) for various heat-treated aluminum product forms, alloys, and tempers.

Where short times at elevated temperatures of 150 to 500°F may be encountered, the precipitation heat-treated tempers of 2024 and 2219 alloys are recommended over the naturally aged tempers.

Alloys 5083, 5086, and 5456 should not be used under high constant applied stress for continuous service at temperatures exceeding 150°F, because of the hazard of developing susceptibility to stress-corrosion cracking. In general, the H34 through H38 tempers of 5086, and the H32 through H38 tempers of 5083 and 5456 are not recommended, because these tempers can become susceptible to stress-corrosion cracking.

For the cold forming of 5083 sheet and plate in the H112, H321, H323, and H343 tempers and 5456 sheet and plate in the H112 and H321 tempers, a minimum bend radius of 5T should be used. Hot forming of the O temper for alloys 5083 and 5456 is recommended, and is preferred to the cold worked tempers to avoid excessive cold work and high residual stress. If the cold worked tempers are heat-treatable alloys are heated for hot forming, a slight decrease in mechanical properties, particularly yield strength, may result.

Table 3.1.2.3.1(a). Resistance to Stress-Corrosion Ratings[a] for High-Strength Aluminum Alloy Products

Alloy and Temper[b]	Test Direction[c]	Rolled Plate	Rod and Bar[d]	Extruded Shapes	Forging
2014-T6	L	A	A	A	B
	LT	B[e]	D	B[e]	B[e]
	ST	D	D	D	D
2024-T3, T4	L	A	A	A	[f]
	LT	B[e]	D	B[e]	[f]
	ST	D	D	D	[f]
2024-T6	L	[f]	A	[f]	A
	LT	[f]	B	[f]	A[e]
	ST	[f]	B	[f]	D
2024-T8	L	A	A	A	A
	LT	A	A	A	A
	ST	B	A	B	C
2124-T8	L	A	[f]	[f]	[f]
	LT	A	[f]	[f]	[f]
	ST	B	[f]	[f]	[f]
2219-T351X, T37	L	A	[f]	A	[f]
	LT	B	[f]	B	[f]
	ST	D	[f]	D	[f]
2219-T6	L	A	A	A	A
	LT	A	A	A	A
	ST	A	A	A	A
2219-T85XX, T87	L	A	[f]	A	A
	LT	A	[f]	A	A
	ST	A	[f]	A	A
6061-T6	L	A	A	A	A
	LT	A	A	A	A
	ST	A	A	A	A
7040-T7451	L	A	[f]	[f]	[f]
	LT	A	[f]	[f]	[f]
	ST	B	[f]	[f]	[f]
7049-T73	L	A	[f]	A	A
	LT	A	[f]	A	A
	ST	A	[f]	B	A
7049-T76	L	[f]	[f]	A	[f]
	LT	[f]	[f]	A	[f]
	ST	[f]	[f]	C	[f]
7050-T74	L	A	[f]	A	A
	LT	A	[f]	A	A
	ST	B	[f]	B	B
7050-T76	L	A	A	A	[f]
	LT	A	B	A	[f]
	ST	C	B	C	[f]
7075-T6	L	A	A	A	A
	LT	B[e]	D	B[e]	B[e]
	ST	D	D	D	D
7075-T73	L	A	A	A	A
	LT	A	A	A	A
	ST	A	A	A	A

Table 3.1.2.3.1(a). Resistance to Stress-Corrosion Ratings[a] for High-Strength Aluminum Alloy Products—Continued

Alloy and Temper[b]	Test Direction[c]	Rolled Plate	Rod and Bar[d]	Extruded Shapes	Forging
7075-T74	L	f	f	f	A
	LT	f	f	f	A
	ST	f	f	f	B
7075-T76	L	A	f	A	f
	LT	A	f	A	f
	ST	C	f	C	f
7149-T73	L	f	f	A	A
	LT	f	f	A	A
	ST	f	f	B	A
7175-T74	L	f	f	f	A
	LT	f	f	f	A
	ST	f	f	f	B
7475-T6	L	A	f	f	f
	LT	B[e]	f	f	f
	ST	D	f	f	f
7475-T73	L	A	f	f	f
	LT	A	f	f	f
	ST	A	f	f	f
7475-T76	L	A	f	f	f
	LT	A	f	f	f
	ST	C	f	f	f

a Ratings were determined from stress corrosion tests performed on at least ten random lots for which test results showed 90% conformance with 95% confidence when tested at the following stresses.

A - Equal to or greater than 75% of the specified minimum yield strength. A very high rating. SCC not anticipated in general applications if the total sustained tensile stress* is less than 75% of the minimum specified yield stress for the alloy, heat treatment, product form, and orientation.

B - Equal to or greater than 50% of the specified minimum yield strength. A high rating. SCC not anticipated if the total sustained tensile stress* is less than 50% of the specified minimum yield stress.

C - Equal to or greater than 25% of the specified minimum yield stress or 14.5 ksi, whichever is higher. An intermediate rating. SCC not anticipated if the total sustained tensile stress* is less than 25% of the specified minimum yield stress. This rating is designated for the short transverse direction in improved products used primarily for high resistance to exfoliation corrosion in relatively thin structures where applicable short transverse stresses are unlikely.

D - Fails to meet the criterion for the rating C. A low rating. SCC failures have occurred in service or would be anticipated if there is any sustained tensile stress* in the designated test direction. This rating currently is designated only for the short transverse direction in certain materials.

NOTE - The above stress levels are not to be interpreted as “threshold” stresses, and are not recommended for design. Other documents, such as MIL-STD-1568, NAS SD-24, and MSFC-SPEC-522A, should be consulted for design recommendations.

b The ratings apply to standard mill products in the types of tempers indicated, including stress-relieved tempers, and could be invalidated in some cases by application of nonstandard thermal treatments of mechanical deformation at room temperature by the user.

* The sum of all stresses, including those from service loads (applied), heat treatment, straightening, forming, etc.

Table 3.1.2.3.1(a). Resistance to Stress-Corrosion Ratings[a] for High Strength Aluminum Alloy Products—Continued

c Test direction refers to orientation of the stressing direction relative to the directional grain structure typical of wrought materials, which in the case of extrusions and forgings may not be predictable from the geometrical cross section of the product.
L—Longitudinal: parallel to the direction of principal metal extension during manufacture of the product.
LT—Long Transverse: perpendicular to direction of principal metal extension. In products whose grain structure clearly shows directionality (width to thickness ratio greater than two) it is that perpendicular direction parallel to the major grain dimension.
ST—Short Transverse: perpendicular to direction of principal metal extension and parallel to minor dimension of grains in products with significant grain directionality.

d Sections with width-to-thickness ratio equal to or less than two for which there is no distinction between LT and ST.

e Rating is one class lower for thicker sections: extrusion, 1 inch and over; plate and forgings, 1.5 inches and over.

f Ratings not established because the product is not offered commercially.

NOTE: This table is based upon ASTM G 64.

3.1.2.3.2 *Resistance to Exfoliation [Reference 3.1.2.3.2]* — The high-strength wrought aluminum alloys in certain tempers are susceptible to exfoliation corrosion, dependent upon product and section size. Generally those alloys and tempers that have the lowest resistance to stress-corrosion cracking also have the lowest resistance to exfoliation. The tempers that provide improved resistance to stress-corrosion cracking also provide improved resistance or immunity to exfoliation. For example, the T76 temper of 7075, 7049, 7050, and 7475 provides a very high resistance to exfoliation, i.e., decidedly superior to the T6 temper, and almost the immunity provided by the T73 temper of 7075 alloy (see Reference 3.1.2.3.2).

3.1.3 MANUFACTURING CONSIDERATIONS

3.1.3.1 ***Avoiding Stress-Corrosion Cracking*** — In order to avoid stress-corrosion cracking (see Section 3.1.2.3), practices, such as the use of press or shrink fits; taper pins; clevis joints in which tightening of the bolt imposes a bending load on female lugs; and straightening or assembly operations; which result in sustained surface tensile stresses (especially when acting in the short-transverse grain orientation), should be avoided in these high-strength alloys: 2014-T451, T4, T6, T651, T652; 2024-T3, T351, T4; 7075-T6, T651, T652; 7150-T6151, T61511; and 7475-T6, T651.

Where straightening or forming is necessary, it should be performed when the material is in the freshly quenched condition or at an elevated temperature to minimize the residual stress induced. Where elevated temperature forming is performed on 2014-T4 T451, or 2024-T3 T351, a subsequent precipitation heat treatment to produce the T6 or T651, T81 or T851 temper is recommended.

It is good engineering practice to control sustained short-transverse tensile stress at the surface of structural parts at the lowest practicable level. Thus, careful attention should be given in all stages of manufacturing, starting with design of the part configuration, to choose practices in the heat treatment, fabrication, and assembly to avoid unfavorable combinations of end grain microstructure and sustained tensile stress. The greatest danger arises when residual, assembly, and service stress combine to produce high sustained tensile stress at the metal surface. Sources of residual and assembly stress have been the most contributory to stress-corrosion-cracking problems because their presence and magnitude were not recognized. In most cases, the design stresses (developed by functional loads) are not continuous and would not be involved in the summation of sustained tensile stress. It is imperative that, for materials with low resistance to stress-corrosion cracking in the short-transverse grain orientation, every effort be taken to keep the level of sustained tensile stress close to zero.

Table 3.1.2.3.1(b). Maximum Specified Tension Stress at Which Test Specimens Will Not Fail in 3½% NaCl Alternate Immersion Test[a] for Various Stress Corrosion Resistant Aluminum Alloy Plate

Alloy and Temper	Test Direction	Thickness, inches	Stress, ksi	Referenced Specifications
2024-T851	ST	1.001-4.000	28[b]	Company specification
		4.001-6.000	27[b]	
2090-T81[c]	ST	0.750-1.500	20	AMS 4303
2124-T851	ST	1.500-1.999	28[b]	AMS 4101
		2.000-4.000	28[b]	AMS-QQ-A-0025/29, ASTM B 209, AMS 4101
		4.001-6.000	27[b]	
2124-T8151[c]	ST	1.500-3.000	30[b]	AMS 4221
		3.001-5.000	29[b]	
		5.001-6.000	28[b]	
2219-T851	ST	0.750-2.000	34[d]	AMS-QQ-A-250/30
		2.001-4.000	33[d]	
		4.001-5.000	32[d]	
		5.001-6.000	31[d]	
2219-T87	ST	0.750-3.000	38[d]	AMS-QQ-A-250/30
		3.001-4.000	37[d]	
		4.001-5.000	36[d]	
2519-T87	ST	0.750-4.000	43[d]	MIL-A-46192
7010-T7351[c]	ST	0.750-3.000	41[d]	AMS 4203
		3.001-5.000	40[d]	
		5.001-5.500	39[d]	
7010-T7451	ST	0.750-3.000	31[b]	AMS 4205
		3.001-5.500	35	
7010-T7651	ST	0.750-5.500	25	AMS 4204
7049-T7351	ST	0.750-5.000	45	AMS 4200
7050-T7451	ST	0.750-6.000	35	AMS 4050
7050-T7651	ST	0.750-3.000	25	AMS 4201
7075-T7351	ST	0.750-2.000	42[d]	AMS-QQ-A-250/12, AMS 4078, ASTM B 209
		2.001-2.500	39[d]	
		2.501-4.000	36[d]	
7075-T7651	ST	0.750-1.000	25	AMS-QQ-A-00250/24, ASTM B 209
Clad 7075-T7651	ST	0.750-1.000	25	AMS-QQ-A-00250/25, ASTM B 209
7150-T7751	ST	0.750-3.000	25	AMS 4252
7475-T7351	ST	0.750-4.000	40	AMS 4202
7475-T7651	ST	0.750-1.500	25	AMS 4089

[a] Most specifications reference ASTM G 47, which requires exposures of 10 days for 2XXX alloys and 20 days for 7XXX alloys in ST test direction.

[b] 50% of specified minimum long transverse yield strength.

[c] Design values are not included in MIL-HDBK-5.

[d] 75% of specified minimum long transverse yield strength.

DO NOT USE STRESS VALUES FOR DESIGN

Table 3.1.2.3.1(c). Maximum Specified Tension Stress at Which Test Specimens Will Not Fail in 3½% NaCl Alternate Immersion Test[a] for Various Stress Corrosion Resistant Aluminum Alloy Rolled Bars, Rods, and Extrusions

Alloy and Temper	Product Form	Test Direction	Thickness, inches	Stress, ksi	Referenced Specifications
7075-T73-T7351	Rolled Bar and Rod	ST	0.750-3.000	42[b]	AMS-QQ-A-225/9, AMS 4124, ASTM B211
2219-T8511	Extrusion	ST	0.750-3.000	30	AMS 4162, AMS 4163
7049-T73511	Extrusion	ST	0.750-2.999	41[c]	AMS 4157
			3.000-5.000	40[c]	
7049-T76511[d]	Extrusion	ST	0.750-5.000	20	AMS 4159
7050-T73511	Extrusion	ST	0.750-5.000	45	AMS 4341
7050-T74511	Extrusion	ST	0.750-5.000	35	AMS 4342
7050-T76511	Extrusion	ST	0.750-5.000	17	AMS 4340
7075-T73-T73510-T73511	Extrusion	ST	0.750-1.499	45[b]	AMS-QQ-A-200/11, AMS 4166, AMS 4167, ASTM B 211
			1.500-2.999	44[b]	
			3.000-4.999	42[b]	
			3.000-4.999	41[b,e]	
7075-T76-T76510-T76511	Extrusion	ST	0.750-1.000	25	AMS-QQ-A-200/15, ASTM B 221
7149-T73511[d]	Extrusion	ST	0.750-2.999	41[c]	AMS 4543
			3.000-5.000	40[c]	
7150-T77511	Extrusion	ST	0.750-2.000	25	AMS 4345
7175-T73511	Extrusion	ST	0.750-2.000	44	AMS 4344

[a] Most specifications reference ASTM G 47, which requires exposures of 10 days for 2XXX alloys and 20 days for 7XXX alloys in ST test direction.
[b] 75% of specified minimum longitudinal yield strength.
[c] 65% of specified minimum longitudinal yield strength.
[d] Design values are not included in MIL-HDBK-5.
[e] Over 20 square inches cross-sectional area.

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Alloy and Temper	Test Direction	Thickness, inches	Stress, ksi	Referenced Specifications
7049-T73	ST	0.750-2.000	46[b]	AMS-QQ-A-367, AMS 4111, ASTM B 247
		2.001-5.000	45[b]	
7050-T74	ST	0.750-6.000	35	AMS 4107
7050-T7452	ST	0.750-4.000	35	AMS 4333
7075-T73	ST	0.750-3.000	42[b]	AMS-A-22771, AMS-QQ-A-367
		3.001-4.000	41[b]	AMS 4241, ASTM B 247
		4.001-5.000	39[b]	AMS 4141
		5.001-6.000	38[b]	
7075-T7352	ST	0.750-4.000	42[b]	AMS-A-22771, AMS-QQ-A-367, AMS 4147, ASTM B 247
		3.001-4.000	39[b]	
7075-T7354[c]	ST	0.750-3.000	42	Company Specification
7075-T74[c]	ST	0.750-3.000	35	AMS 4131
		3.001-4.000	31[d]	
		4.001-5.000	30[d]	
		5.001-6.000	29[d]	
7149-T73	ST	0.750-2.000	46[b]	AMS 4320
		2.001-5.000	45[b]	
7175-T74	ST	0.750-3.000	35	AMS 4149, ASTM B 247
		3.001-4.000	31[d]	AMS 4149
		4.001-5.000	30[d]	
		5.001-6.000	29[d]	
7175-T7452[c]	ST	0.750-3.000	35	AMS 4179

a Most specifications Reference ASTM G 47, which requires 20 days of exposure for 7XXX alloys in ST test direction.
b 75% of specified minimum longitudinal yield strength.
c Design values are not included in MIL-HDBK-5.
d 50% of specified minimum longitudinal yield strength.

DO NOT USE STRESS VALUES FOR DESIGN

Table 3.1.2.3.1(e). Maximum Specified Tension Stress at Which Test Specimens Will Not Fail in 3½% NaCl Alternate Immersion Test[a] for Various Stress Corrosion Resistant Aluminum Hand Forgings

Alloy and Temper	Test Direction	Thickness, inches	Stress, ksi	Referenced Specifications
7049-T73	ST	2.001-3.000	45[b]	AMS-QQ-A-367, AMS 4111, ASTM B 247
		3.001-4.000	44[b]	
		4.001-5.000	42[b]	
7049-T7352[c]	ST	0.750-3.000	44[b]	AMS 4247
		3.001-4.000	43[b]	
		4.001-5.000	40[b]	
7050-T7452	ST	0.750-8.000	35	AMS 4108
7075-T73	ST	0.750-3.000	42[b]	AMS-A-22771, AMS-QQ-A-367, ASTM B 247
		3.001-4.000	41[b]	
		4.001-4.000	39[b]	
		5.001-6.000	38[b]	
7075-T7352	ST	0.750-3.000	39[d]	AMS 4147
		3.001-4.000	37[d]	
		4.001-5.000	36[d]	
		5.001-6.000	34[d]	
7075-T74[c]	ST	0.750-3.000	35	AMS 4131
		3.001-4.000	30[e]	
		4.001-5.000	28[e]	
		5.001-6.000	27[e]	
7075-T7452[c]	ST	0.750-2.000	35	AMS 4323
		2.001-3.000	29[f]	
		3.001-4.000	28[f]	
		4.001-5.000	26[f]	
		5.001-6.000	24[f]	
7149-T73	ST	2.000-3.000	44[d]	AMS 4320
		3.001-4.000	43[d]	
		4.001-5.000	42[d]	
7175-T74	ST	0.750-3.000	35	AMS 4149
		3.001-4.000	29[f]	
		4.001-5.000	28[f]	
		4.001-6.000	26[f]	
7175-T7452	ST	0.750-3.000	35	AMS 4179
		3.001-4.000	27[f]	
		4.001-5.000	26[f]	
		5.001-6.000	24[f]	

[a] Most specifications Reference ASTM G 47, which requires 20 days of exposure for 7XXX alloys in ST test direction.
[b] 75% of specified minimum longitudinal yield strength.
[c] Design values are not included in MIL-HDBK-5.
[d] 75% of specified minimum long transverse yield strength.
[e] 50% of specified minimum longitudinal yield strength.
[f] 50% of specified minimum long transverse yield strength.

DO NOT USE STRESS VALUES FOR DESIGN

3.1.3.2 ***Cold-Formed Heat-Treatable Aluminum Alloys*** — Cold working such as stretch forming of aluminum alloy prior to solution heat treatment may result in recrystallization or grain growth during heat treatment. The resulting strength, particularly yield strength, may be significantly below the specified minimum values. For critical applications, the strength should be determined on the part after forming and heat treating including straightening operations. To minimize recrystallization during heat treatment, it is recommended that forming be done after solution heat treatment in the as-quenched condition whenever possible, but this may result in compressive yield strength in the direction of stretching being lower than MIL-HDBK-5 design allowables for user heat treat tempers.

3.1.3.3 ***Dimensional Changes*** — The dimensional changes that occur in aluminum alloy during thermal treatment generally are negligible, but in a few instances these changes may have to be considered in manufacturing. Because of many variables involved, there are no tabulated values for these dimensional changes. In the artificial aging of alloy 2219 from the T42, T351, and T37 tempers to the T62, T851, and T87 tempers, respectively, a net dimensional growth of 0.00010 to 0.0015 in./in. may be anticipated. Additional growth of as much as 0.0010 in./in. may occur during subsequent service of a year or more at 300°F or equivalent shorter exposures at higher temperatures. The dimensional changes that occur during the artificial aging of other wrought heat-treatable alloys are less than one-half that for alloy 2219 under the same conditions.

3.1.3.4 ***Welding*** — The ease with which aluminum alloys may be welded is dependent principally upon composition, but the ease is also influenced by the temper of the alloy, the welding process, and the filler metal used. Also, the weldability of wrought and cast alloys is generally considered separately.

Several weldability rating systems are established and may be found in publications by the Aluminum Association, American Welding Society, and the American Society for Metals. Handbooks from these groups can be consulted for more detailed information. Specification AA-R-566 also contains useful information. This document follows most of these references in adopting a four level rating system. An “A” level, or readily weldable, means that the alloy (and temper) is routinely welded by the indicated process using commercial procedures. A “B” level means that welding is accomplished for many applications, but special techniques are required, and the application may require preliminary trials to develop procedures and tests to demonstrate weld performance. A “C” level refers to limited weldability because crack sensitivity, loss of corrosion resistance, and/or loss of mechanical properties may occur. A “D” level indicates that the alloy is not commercially weldable.

The weldability of aluminum alloys is rated by alloy, temper, and welding process (arc or resistance). Tables 3.1.3.4(a) and (b) list the ratings in the alloy section number order in which they appear in Chapter 3.

When heat-treated or work-hardened materials of most systems are welded, a loss of mechanical properties generally occurs. The extent of the loss (if not reheat treated) over the table strength allowables will have to be established for each specific situation.

Table 3.1.3.4(a). Fabrication Weldability of Wrought Aluminum Alloys

MIL-HDBK-5 Section No.	Alloy	Tempers	Weldability[a,b]	
			Inert Gas Metal or Tungsten Arc	Resistance Spot[c]
3.2.1	2014	O	C	D
		T6, T62, T651, T652, T6510, T6511	B	B
3.2.2	2017	T4, T42, T451	C	B
3.2.3	2024	O	D	D
		T3, T351, T361, T4, T42	C	B
		T6, T62, T81, T851, T861	C	B
		T8510, T8511, T3510, T3511	C	B
3.2.4	2025	T6	C	B
3.2.5	2090	T83	B	B
3.2.6	2124	T851	C	B
3.2.7	2219	O	A	B-D
		T62, T81, T851, T87, T8510, T8511	A	A
3.2.8	2618	T61	C	B
3.2.9	2519	T87	A	...
3.5.1	5052	O	A	B
		H32, H34, H36, H38	A	A
3.5.2	5083	O	A	B
		H321, H323, H343, H111, H112	A	A
3.5.3	5086	O	A	B
		H32, H34, H36, H38, H111, H112	A	A
3.5.4	5454	O	A	B
		H32, H34, H111, H112	A	A
3.5.5	5456	O	A	B
		H111, H321, H112	A	A
3.6.1	6013	T6	A	A
3.6.2	6061	O	A	B
		T4, T42, T451, T4510, T4511, T6	A	A
		T62, T651, T652, T6510, T6511	A	A
3.6.3	6151	T6	A	A
3.7.1	7010	All	C	B
3.7.2	7040	All	C	B
3.7.3	7049	All	C	B
	7149			
3.7.4	7050	All	C	B
3.7.5	7055			
3.7.6	7075	All	C	B
3.7.7	7150	All	C	B
3.7.8	7175	All	C	B
3.7.9	7249			
3.7.10	7475	All	C	B

a Ratings A through D are relative ratings defined as follows:
A - Generally weldable by all commercial procedures and methods.
B - Weldable with special techniques or for specific applications which justify preliminary trials or testing to develop welding procedures and weld performance.
C - Limited weldability because of crack sensitivity or loss in resistance to corrosion and mechanical properties.
D - No commonly used welding methods have been developed.

b When using filler wire, the wire should contain less than 0.0008 percent beryllium to avoid toxic fumes.

c See AMS-W-6858 for permissible combinations.

Table 3.1.3.4(b). Fabrication Weldability[a] of Cast Aluminum Alloys

MIL-HDBK-5 Section No.	Alloy	Weldability[b,c]	
		Inert Gas Metal or Tungsten Arc	Resistance Spot
3.8.1	A201.0	C	C
3.9.1	354.0	B	B
3.9.2	355.0	B	B
3.9.3	C355.0	B	B
3.9.4	356.0	A	A
3.9.5	A356.0	A	A
3.9.6	A357.0	A	B
3.9.7	D357.0	A	A
3.9.8	359.0	A	B

a Weldability related to joining a casting to another part of same composition. The weldability ratings are not applicable to minor weld repairs. Such repairs will be governed by the contractors procedure for in-process welding of castings, after approval by the procuring agency.

b Ratings A through D are relative ratings defined as follows:
- A - Generally weldable by all commercial procedures and methods.
- B - Weldable with special techniques or for specific applications which justify preliminary trials or testing to develop welding procedure and weld performance.
- C - Limited weldability because of crack sensitivity or loss in resistance to corrosion and mechanical properties.
- D - No commonly used welding methods have been developed.

c When using filler wire, the wire should contain less than 0.0008 percent beryllium to avoid toxic fumes.

3.2 2000 SERIES WROUGHT ALLOYS

Alloys of the 2000 series contain copper as the principal alloying element and are strengthened by solution heat treatment and aging. As a group, these alloys are noteworthy for their excellent strengths at elevated and cryogenic temperatures, and creep resistance at elevated temperatures.

3.2.1 2014 ALLOY

3.2.1.0 *Comments and Properties* — 2014 is an Al-Cu alloy available in a wide variety of product forms. As shown in Table 3.1.2.3.1(a), 2014-T6 rolled plate, rod and bar, extruded shapes, and forgings have a 'D' SCC rating. This is the lowest rating and means that SCC failures have occurred in service or would be anticipated if there is any sustained stress. In-service failures are caused by stresses produced by any combination of sources including solution heat treatment, straightening, forming, fit-up, clamping, sustained service loads, or high service compression stresses that produce residual tensile stresses. These stresses may be tension or compression as well as the stresses due to the Poisson effect, because the actual failures are caused by the resulting sustained shear stresses. Pin-hole flaws in corrosion protection are sufficient for SCC. Refer to Section 3.1.2.3 for comments regarding the resistance of the alloy to stress-corrosion cracking, and to Section 3.1.3.4 for comments regarding the weldability of the alloy.

The properties of extrusions should be based upon the thickness at the time of quenching prior to machining. Selection of the mechanical properties based upon its final machined thickness may be unconservative; therefore, the thickness at the time of quenching to achieve properties is an important factor in the selection of the proper thickness column. For extrusions having sections with various thicknesses, consideration should be given to the properties as a function of thickness.

Material specifications for 2014 aluminum alloy are presented in Table 3.2.1.0(a). Room-temperature mechanical and physical properties are shown in Tables 3.2.1.0(b) through (g). Stress-strain parameters in accordance with Section 9.3.2.5 are given in Table 3.2.1.0(h). Figure 3.2.1.0 shows the effect of temperature on the physical properties of 2014 alloy.

Table 3.2.1.0(a). Material Specifications for 2014 Aluminum Alloy

Specification	Form
AMS 4028	Bare sheet and plate
AMS 4029	Bare sheet and plate
AMS-QQ-A-250/3	Clad sheet and plate
AMS-QQ-A-225/4	Rolled or drawn bar, rod, and shapes
AMS 4121	Bar and rod, rolled or cold finished
AMS-QQ-A-200/2	Extruded bar, rod, and shapes
AMS 4153	Extrusion
AMS-A-22771	Forging
AMS - QQ-A-367	Forging
AMS 4133	Forging

The temper index for 2014 is as follows:

Section	Temper
3.2.1.1	T6, T62, T651, T652, T6510, and T6511

3.2.1.1 ***T6, T62, T651, T652, T6510, and T6511 Temper***— Figures 3.2.1.1.1(a) through 3.2.1.1.5(b) present elevated-temperature curves for various mechanical properties. Figures 3.2.1.1.6(a) through (r) present tensile and compressive stress-strain and tangent-modulus curves for various tempers, product forms, and temperatures. Figures 3.2.1.1.6(s) through (v) are full-range tensile stress-strain curves for various products and tempers. Figures 3.2.1.1.8(a) through (e) contain S/N fatigue curves for various wrought products in the T6 temper.

Table 3.2.1.0(b$_1$). Design Mechanical and Physical Properties of 2014 Aluminum Alloy Sheet and Plate

Specification	AMS 4029															
Form	Sheet				Plate											
Temper	T6				T651[a]											
Thickness, in.	0.020-0.039		0.040-0.249		0.250-0.499		0.500-1.000		1.001-2.000		2.001-2.500		2.501-3.000		3.001-4.000	
Basis	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
Mechanical Properties:																
F_{tu}, ksi:																
L	65	67	67	68	66	68	66	67	66	67	64	65	...	...	...	...
LT	64	66	66	67	67	69	67	68	67	68	65	66	63	64	59	60
ST	...	...	...	...	...	...	...	...	...	...	59[b]	60[b]	...	...	...	...
F_{ty}, ksi:																
L	58	60	59	60	60	62	60	61	60	62	59	61	...	...	...	...
LT	57	59	58	59	59	61	59	60	59	61	58	60	57	59	55	57
ST	...	...	...	...	...	...	...	...	...	...	54[b]	56[b]	...	...	...	...
F_{cy}, ksi:																
L	58	60	59	60	58	60	58	59	58	60	57	59	...	...	...	...
LT	59	61	60	61	61	63	61	62	61	63	60	62	...	...	...	...
ST	...	...	...	...	...	...	...	...	...	...	59	61	...	...	...	...
F_{su}, ksi	39	40	40	41	40	41	40	41	40	41	38	39	...	...	...	...
F_{bru}, ksi:																
(e/D = 1.5)	97	100	100	102	105	108	105	107	105	107	102	104	...	...	...	...
(e/D = 2.0)	123	127	127	129	134	138	134	136	134	136	130	132	...	...	...	...
F_{bry}, ksi:																
(e/D = 1.5)	81	84	83	84	90	93	90	92	90	93	88	92	...	...	...	...
(e/D = 2.0)	93	96	94	96	106	110	106	109	106	110	104	109	...	...	...	...
e, percent (S-basis):																
LT	6	...	7	...	7	...	6	...	4	...	2	...	2	...	1	...
E, 10^3 ksi	10.5				10.7											
E_c, 10^3 ksi	10.7				10.9											
G, 10^3 ksi	4.0				4.0											
μ	0.33				0.33											
Physical Properties:																
ω, lb/in.^{3}	0.101															
C, K, and α	See Figure 3.2.1.0															

a Bearing values are "dry pin" values per Section 1.4.7.1. See Table 3.1.2.1.1.

b Caution: This specific alloy, temper, and product form exhibits poor stress-corrosion cracking resistance in this grain direction. It corresponds to an SCC resistance rating of D, as indicated in Table 3.1.2.3.1(a).

Table 3.2.1.0(b_2). Design Mechanical and Physical Properties of 2014 Aluminum Alloy Sheet and Plate —Continued

Specification	AMS 4028							
Form	Sheet				Plate[a]			
Temper	T62[b]							
Thickness, in.	0.020-0.039		0.040-0.249		0.250-0.499		0.500-1.000	
Basis	A	B	A	B	A	B	A	B
Mechanical Properties:								
F_{tu}, ksi:								
L	65	67	67	68	65	67	65	67
LT	64	66	66	67	67	69	67	69
F_{ty}, ksi:								
L	58	60	59	60	57	59	57	59
LT	57	59	58	59	59	61	59	61
F_{cy}, ksi:								
L	58	60	59	60	59	61	59	61
LT	59	61	60	61	60	62	60	62
F_{su}, ksi	39	40	40	41	37	39	37	39
F_{bru}, ksi:								
(e/D = 1.5)	97	100	100	102	100	103	100	103
(e/D = 2.0)	123	127	127	129	127	131	127	131
F_{bry}, ksi:								
(e/D = 1.5)	81	84	83	84	84	87	84	87
(e/D = 2.0)	93	96	95	96	99	103	99	103
e, percent (S-basis):								
LT	6	...	7	...	7	...	6	...
E, 10^3 ksi	10.5				10.7			
E_c, 10^3 ksi	10.7				10.9			
G, 10^3 ksi	4.0				4.0			
μ	0.33				0.33			
Physical Properties:								
ω, lb/in.^{3}	0.101							
C, K, and α	See Figure 3.2.1.0							

[a] Bearing values are “dry pin” values per Section 1.4.7.1.

[b] Design allowables were based upon data obtained from testing samples of material, supplied in the O or F temper, which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained by the user may be lower than those listed if the material has been formed or otherwise cold or hot worked, particularly in the annealed temper, prior to solution heat treatment.

Table 3.2.1.0(c_1). Design Mechanical and Physical Properties of Clad 2014 Aluminum Alloy Sheet and Plate

Specification	AMS-QQ-A-250/3															
Form	Sheet				Plate											
Temper	T6				T651[a]											
Thickness, in.	0.020-0.039		0.040-0.249		0.250-0.499		0.500-1.000[b]		1.001-2.000[b]		2.001-2.500[b]		2.501-3.000[b]		3.001-4.000[b]	
Basis	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
Mechanical Properties:																
F_{tu}, ksi:																
L	62	64	65	67	63	65	63	64	63	64	61	62	...	...	...	...
LT	61	63	64	66	64	66	64	65	64	65	62	63	60	61	56	57
ST	...	...	...	...	...	...	...	...	...	...	59[c]	60[c]	...	...	...	...
F_{ty}, ksi:																
L	54	56	57	59	58	60	57	58	57	59	56	58	...	...	...	...
LT	53	55	56	58	57	59	56	57	56	58	55	57	54	56	52	54
ST	...	...	...	...	...	...	...	...	...	...	54[c]	56[c]	...	...	...	...
F_{cy}, ksi:																
L	54	56	57	59	56	58	55	56	55	57	54	56	...	...	...	...
LT	55	57	58	60	59	61	58	59	58	60	57	59	...	...	...	...
ST	...	...	...	...	...	...	...	...	...	...	59	61	...	...	...	...
F_{su}, ksi	37	38	39	40	38	39	38	38	38	38	37	37	...	...	...	...
F_{bru}, ksi:																
(e/D = 1.5)	93	96	97	100	101	104	101	102	101	102	97	99	...	...	...	...
(e/D = 2.0)	117	121	123	127	128	132	128	130	128	130	124	126	...	...	...	...
F_{bry}, ksi:																
(e/D = 1.5)	76	78	80	83	87	90	85	87	85	88	84	87	...	...	...	...
(e/D = 2.0)	86	89	91	94	102	106	100	102	100	104	98	102	...	...	...	...
e, percent (S-basis):																
LT	7	...	8	...	8	...	6	...	4	...	2	...	2	...	1	...
E, 10^3 ksi	10.5				10.7											
E_c, 10^3 ksi	10.7				10.9											
G, 10^3 ksi	4.0				4.0											
μ	0.33				0.33											
Physical Properties:																
ω, lb/in.^{3}	0.101															
C, K, and α	...															

[a] Bearing values are “dry pin” values per Section 1.4.7.1. See Table 3.1.2.1.1.

[b] These values, except in the ST direction, have been adjusted to represent the average properties across the whole section, including the 2-½ percent per side nominal cladding thickness.

[c] Caution: This specific alloy, temper, and product form exhibits poor stress-corrosion cracking resistance in this grain direction. It corresponds to an SCC resistance rating of D, as indicated in Table 3.1.2.3.1(a).

Table 3.2.1.0(c_2). Design Mechanical and Physical Properties of Clad 2014 Aluminum Alloy Sheet and Plate—Continued

Specification	AMS-QQ-A-250/3									
Form	Sheet				Plate[a]					
Temper	T62[b]									
Thickness, in.	0.020-0.039		0.040-0.249		0.250-0.499	0.500-1.000[c]	1.001-2.000[c]	2.001-2.500[c]	2.501-3.000[c]	3.001-4.000[c]
Basis	A	B	A	B	S	S	S	S	S	S
Mechanical Properties:										
F_{tu}, ksi:										
L	62	64	65	67	62	62	62	60	...	...
LT	61	63	64	66	64	64	64	62	60	56
F_{ty}, ksi:										
L	54	56	57	59	55	54	54	53	...	...
LT	53	55	56	58	57	56	56	55	54	52
F_{cy}, ksi:										
L	54	56	57	59	57	56	56	55	...	...
LT	55	57	58	60	58	57	56	55	...	...
F_{su}, ksi	37	38	39	40	36	36	36	35	...	...
F_{bru}, ksi:										
(e/D = 1.5)	93	96	97	100	96	96	96	93	...	...
(e/D = 2.0)	117	121	123	127	121	121	121	118	...	...
F_{bry}, ksi:										
(e/D = 1.5)	76	78	80	83	81	79	79	78	...	...
(e/D = 2.0)	86	89	91	94	96	94	94	92	...	...
e, percent (S-basis):										
LT	7	...	8	...	8	6	4	2	2	1
E, 10^3 ksi	10.5				10.7					
E_c, 10^3 ksi	10.7				10.9					
G, 10^3 ksi	4.0				4.0					
μ	0.33				0.33					
Physical Properties:										
ω, lb/in.^{3}	0.101									
C, K, and α	...									

a Bearing values are “dry pin” values per Section 1.4.7.1. See Table 3.1.2.1.1.

b Design allowables were based upon data obtained from testing samples of material, supplied in the O or F temper, which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained by the user may be lower than those listed if the material has been formed or otherwise cold or hot worked, particularly in the annealed temper, prior to solution heat treatment.

c These values have been adjusted to represent the average properties across the whole section, including the 2-½ percent per side nominal cladding thickness.

Table 3.2.1.0(d). Design Mechanical and Physical Properties of 2014 Aluminum Alloy Bar, Rod, and Shapes; Rolled, Drawn, or Cold-Finished

Specification	AMS 4121 and AMS-QQ-A-225/4							AMS-QQ-A-225/4
Form	Bar, rod, and shapes, rolled, drawn, or cold-finished							
Temper	T6 and T651							T62[a]
Thickness, in.	Up to 1.000	1.001-2.000	2.001-3.000	3.001-4.000	4.001-5.000[b]	5.001-6.000[b]	6.001-8.000[b]	≤8.000[b]
Basis	S	S	S	S	S	S	S	S
Mechanical Properties:								
F_{tu}, ksi:								
L	65	65	65	65	65	65	65	65
LT	64[c]	63[c]	62[c]	61[c]	60[c]	59[c]	...	...
F_{ty}, ksi:								
L	55	55	55	55	55	55	55	55
LT	53[c]	52[c]	51[c]	50[c]	49[c]	48[c]	...	...
F_{cy}, ksi:								
L	53	53	53	53	53	53	53	...
LT	...	...	...	...	...	...	...	...
F_{su}, ksi	38	38	38	38	38	38	38	...
F_{bru}, ksi:								
(e/D = 1.5)	98	...	...	...	...	...	...	...
(e/D = 2.0)	124	...	...	...	...	...	...	...
F_{bry}, ksi:								
(e/D = 1.5)	77	...	...	...	...	...	...	...
(e/D = 2.0)	88	...	...	...	...	...	...	...
e, percent:								
L	8	8	8	8	8	8	8	8
E, 10^3 ksi	10.5							
E_c, 10^3 ksi	10.7							
G, 10^3 ksi	4.0							
μ	0.33							
Physical Properties:								
ω, lb/in.^{3}	0.101							
C, K, and α	See Figure 3.2.1.0							

[a] Design allowables were based upon data obtained from testing samples of material, supplied in the O or F temper, which were heat treated to demonstrate response to heat treatment by suppliers.

[b] For square, rectangular, hexagonal, or octagonal bar, maximum thickness is 4 in., and maximum cross-sectional area is 36 sq. in.

[c] Caution: This specific alloy, temper, and product form exhibits poor stress-corrosion cracking resistance in this grain direction. It corresponds to an SCC resistance rating of D, as indicated in Table 3.1.2.3.1(a).

Table 3.2.1.0(e). Design Mechanical and Physical Properties of 2014 Aluminum Alloy Die Forging

Specification	AMS 4133, AMS-A-22771, and AMS-QQ-A-367							AMS-A-22771 and AMS-QQ-A-367						
Form	Die forging													
Temper	T6^{a}							T652						
Thickness^{b}, in.	≤ 1.000		1.001-2.000		2.001-3.000		3.001-4.000	≤ 1.000		1.001-2.000		2.001-3.000		3.001-4.000
Basis	A	B	A	B	A	B	S	A	B	A	B	A	B	S
Mechanical Properties:														
F_{tu}, ksi:														
L	65	67	65	67	65	67	63	65	67	65	67	65	67	63
T^{c}	64^{d}	...	64^{d}	...	63^{d}	...	63	64^{d}	...	64^{d}	...	63^{d}	...	63
F_{ty}, ksi:														
L	56	59	56	59	55	58	55	56	59	56	59	55	58	55
T^{c}	55^{d}	...	55^{d}	...	54^{d}	...	54	55^{d}	...	55^{d}	...	54^{d}	...	54
F_{cy}, ksi:														
L	59	62	59	62	58	61	58	56	59	56	59	55	58	55
ST	56	59	56	59	55	58	55	59	62	59	62	58	61	58
F_{su}, ksi	40	41	40	41	39	40	39	40	41	40	41	39	40	39
$F_{bru}{}^{e}$, ksi:														
(e/D = 1.5)	91	94	91	94	91	94	88	91	94	91	94	91	94	88
(e/D = 2.0)	123	127	123	127	123	127	120	123	127	123	127	123	127	120
$F_{bry}{}^{e}$, ksi:														
(e/D = 1.5)	73	77	73	77	71	75	71	73	77	73	77	71	75	71
(e/D = 2.0)	90	94	90	94	88	93	88	90	94	90	94	88	93	88
e, percent (S-basis):														
L	6	...	6	...	6	...	6	6	...	6	...	6	...	6
T^{c}	3	...	2	...	2	...	2	3	...	2	...	2	...	2
E, 10^3 ksi	10.5													
E_c, 10^3 ksi	10.8													
G, 10^3 ksi	4.0													
μ	0.33													
Physical Properties:														
ω, lb/in.^{3}	0.101													
C, K, and α	See Figure 3.2.1.0													

a When die forgings are machined before heat treatment, the mechanical properties are applicable, provided the as-forged thickness is not greater than twice the thickness at the time of heat treatment.
b Thickness at time of heat treatment.
c T indicates any grain direction not within ±15° of being parallel to the forging flow lines. F_{cy}(T) values are based upon short transverse (ST) test data.
d Specification value. T tensile properties are presented on S basis only.
e Bearing values are "dry pin" values per Section 1.4.7.1.

Table 3.2.1.0(f). Design Mechanical and Physical Properties of 2014 Aluminum Alloy Hand Forging

Specification	AMS 4133, AMS-A-22771, and AMS-QQ-A-367							AMS-A-22771 and AMS-QQ-A-367						
Form	Hand forging													
Temper	T6[a]							T652[b]						
Cross-Sectional Area, in.^{2}	≤ 256													
Thickness, in.	≤2.000	2.001-3.000	3.001-4.000	4.001-5.000	5.001-6.000	6.001-7.000	7.001-8.000	≤2.000	2.001-3.000	3.001-4.000	4.001-5.000	5.001-6.000	6.001-7.000	7.001-8.000
Basis	S	S	S	S	S	S	S	S	S	S	S	S	S	S
Mechanical Properties:														
F_{tu}, ksi:														
L	65	64	63	62	61	60	59	65	64	63	62	61	60	59
LT	65	64	63	62	61	60	59	65	64	63	62	61	60	59
ST	...	62[c]	61[c]	60[c]	59[c]	58[c]	57[c]	...	62[c]	61[c]	60[c]	59[c]	58[c]	57[c]
F_{ty}, ksi:														
L	56	56	55	54	53	52	51	56	56	55	54	53	52	51
LT	56	55	55	54	53	52	51	56	55	55	54	53	52	51
ST	...	55[c]	54[c]	53[c]	53[c]	52[c]	51[c]	...	52[c]	51[c]	50[c]	50[c]	49[c]	48[c]
F_{cy}, ksi:														
L	56	56	55	54	53	...	...	56	56	55	54	53	...	...
LT	56	55	55	54	53	...	...	57	56	56	55	54	...	...
ST	...	...	...	...	...	...	...	...	57	56	55	55	...	...
F_{su}, ksi	40	39	39	38	38	...	...	38	37	37	36	36	...	...
F_{bru}, ksi:														
(e/D = 1.5)	91	90	88	87	85	...	...	88	87	85	84	83	...	...
(e/D = 2.0)	117	115	113	112	110	...	...	115	113	111	110	108	...	...
F_{bry}, ksi:														
(e/D = 1.5)	78	78	77	76	74	...	...	77	76	76	74	73	...	...
(e/D = 2.0)	90	90	88	87	85	...	...	91	89	89	87	86	...	...
e, percent:														
L	8	8	8	7	7	6	6	8	8	8	7	7	6	6
LT	3	3	3	2	2	2	2	3	3	3	2	2	2	2
ST	...	2	2	1	1	1	1	...	2	2	1	1	1	1
E, 10^3 ksi	10.5													
E_c, 10^3 ksi	10.8													
G, 10^3 ksi	4.0													
μ	0.33													
Physical Properties:														
ω, lb/in.^{3}	0.101													
C, K, and α	See Figure 3.2.1.0													

a When hand forgings are machined before heat treatment, the section thickness at time of heat treatment will determine the minimum mechanical properties as long as the original (as-forged) thickness does not exceed the maximum thickness for the alloy as shown in the table.

b Bearing values are “dry pin” values per Section 1.4.7.1.

c Caution: This specific alloy, temper, and product form exhibits poor stress-corrosion cracking resistance in this grain direction. It corresponds to an SCC resistance rating of D, as indicated in Table 3.1.2.3.1(a).

Table 3.2.1.0(g). Design Mechanical and Physical Properties of 2014 Aluminum Alloy Extrusion

Specification	AMS 4153 and AMS-QQ-A-200/2											AMS-QQ-A-200/2		
Form	Extruded bar, rod, and shapes													
Temper	T6, T6510, and T6511											T62[a]		
Cross-Sectional Area, in.^{2}	≤25										>25-≤32	All	≤25	>25-≤32
Thickness or Dia., in.[b]	0.125-0.499		0.500-0.749		0.750-1.499		1.500-1.750		1.751-2.999	3.000-4.499	≥0.750	≤0.749	≥0.750	≥0.750
Basis	A	B	A	B	A	B	A	B	S	S	S	S	S	S
Mechanical Properties:														
F_{tu}, ksi:														
L	60	62	64	68	68	70	68	71	68	68	68	60	60	60
LT (S-basis)	60[c]	...	64[c]	...	63[c]	...	61[c]	...	61	58	56	...	...	...
F_{ty}, ksi:														
L	53	57	58	62	60	63	60	63	60	60	58	53	53	53
LT (S-basis)	53[c]	...	55[c]	...	54[c]	...	52[c]	...	52	49	47	...	...	...
F_{cy}, ksi:														
L	52	56	57	61	59	62	59	62	...	...	...	...	...	...
LT	...	...	...	...	...	...	...	...	...	...	...	...	...	...
F_{su}, ksi	35	36	37	39	39	41	39	41	...	...	...	...	...	...
F_{bru}[d], ksi:														
(e/D = 1.5)	90	93	96	102	102	105	102	106	...	...	...	...	...	...
(e/D = 2.0)	116	120	124	132	132	136	132	138	...	...	...	...	...	...
F_{bry}[d], ksi:														
(e/D = 1.5)	73	78	80	85	82	86	82	86	...	...	...	...	...	...
(e/D = 2.0)	85	91	93	99	96	101	96	101	...	...	...	...	...	...
e, percent (S-basis):														
L	7	...	7	...	7	...	7	...	7	7	6	7	7	6
LT	5[e]	...	5	...	2	...	2	...	2	1	1	...	...	...
E, 10^3 ksi	10.8													
E_c, 10^3 ksi	11.0													
G, 10^3 ksi	4.1													
μ	0.33													
Physical Properties:														
ω, lb/in.^{3}	0.101													
C, K, and α	See Figure 3.2.1.0													

a Design allowables were based upon data obtained from testing samples of material, supplied in O or F temper, which were heat treated to demonstrate response to heat treatment by suppliers.

b The mechanical properties are to be based upon the thickness at the time of quench.

c S-basis.

d Bearing values are "dry pin" values per Section 1.4.7.1.

e For 0.375-0.499 in.

Table 3.2.1.0(h). Typical Stress-Strain Parameters for 2014 Aluminum Alloy

Temper/Product Form	Condition	Temperature, °F	Grain Direction	Tension, ksi			Compression, ksi	
				n	TYS	TUS	n_c	CYS
T6 Clad Sheet	0.02-0.039 in. thickness	RT	L	32	57		17	57
			LT	17	57		13	60
	0.04-0.249 in. thickness		L	27	62		15	62
			LT	20	60		17	65
	½ hr. exposure	200°F	LT				9.5	60
	100 hr. exposure						8.0	62
	½ and 2 hr. exposure	300°F					4.0	54
	1000 hr. exposure						6.4	46
	½ hr. exposure	400°F					8.2	47
	100 hr. exposure						10	20
	1000 hr. exposure						6.0	16
	½ hr. exposure	500°F					7.0	22
	½ hr. exposure	600 °F					4.3	9
	10 hr. exposure						6.0	8
	100 hr. exposure						13	7
T62 Clad Plate	0.250 - 2.000 in. thickness	RT	L	29	64		27	69
			LT	29	64		27	70
T651 Plate	0.250 - 2.000 in. thickness	RT	L	30	66		15	68
			LT	19	65		18	66
T6 Bar, Rod and Shapes	> 3 in. thickness	RT	L	31	62		25	60
T6 Forging		RT	L			70		
			LT			68		
T652 Hand Forging	2.001 - 3.000 in. thickness	RT	L	18	62	67	17	63
			LT	18	62	66	18	65
			ST	13	60		22	67
T6 Extrusion	0.125 - 0.499 in. thickness	RT	L	23	62		15	64
	> 0.500 in. thickness			26	68		14	72
T62 Extrusion	< 0.499 in. thickness	RT	L	29	64	71	17	68
			LT	29	64		32	68
T651X Extrusion	0.500 - 0.749 in. thickness	RT	L	32	64	74	16	68
			LT	18	64	70	18	68

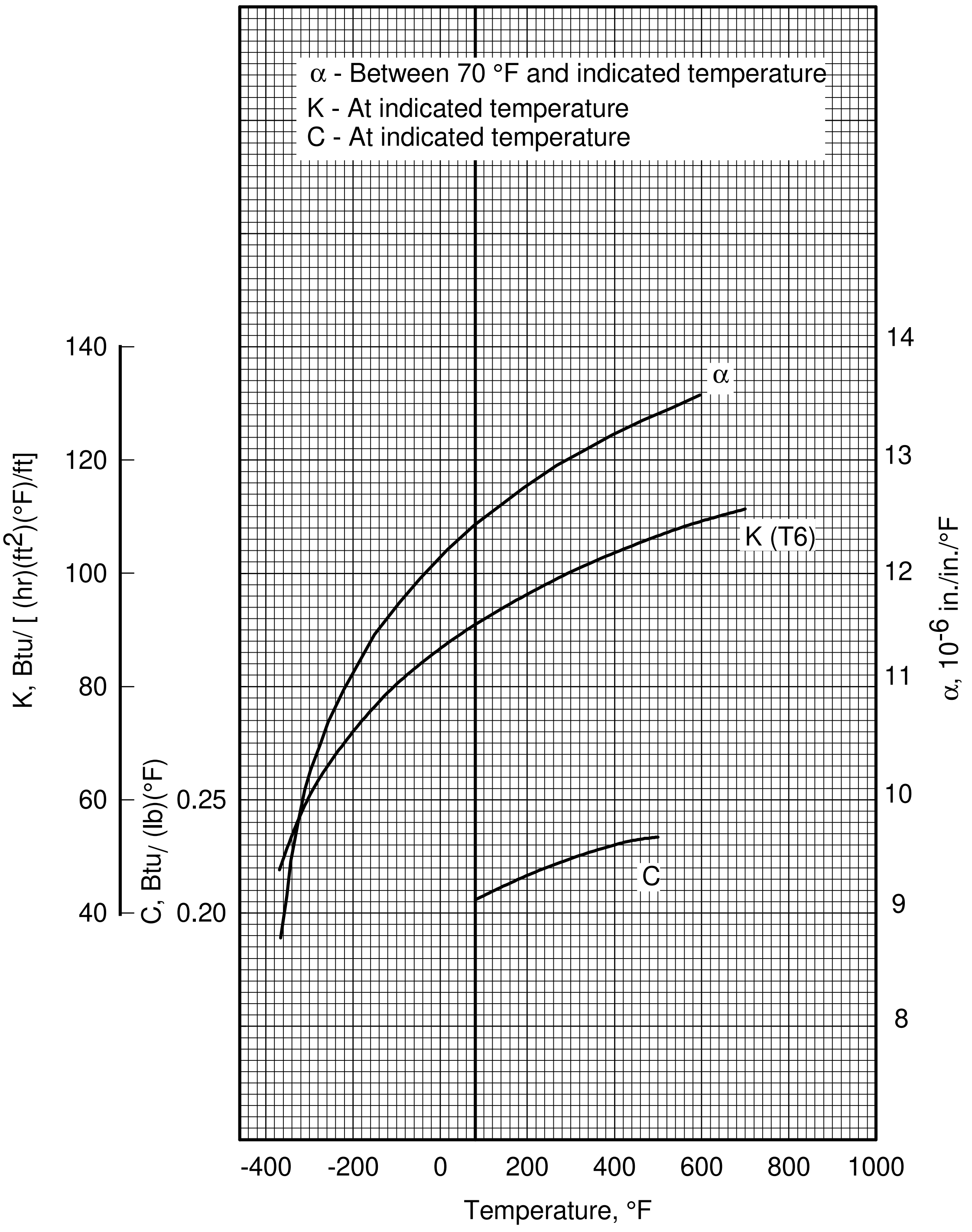


Figure 3.2.1.0. Effect of temperature on the physical properties of 2014 aluminum alloy.

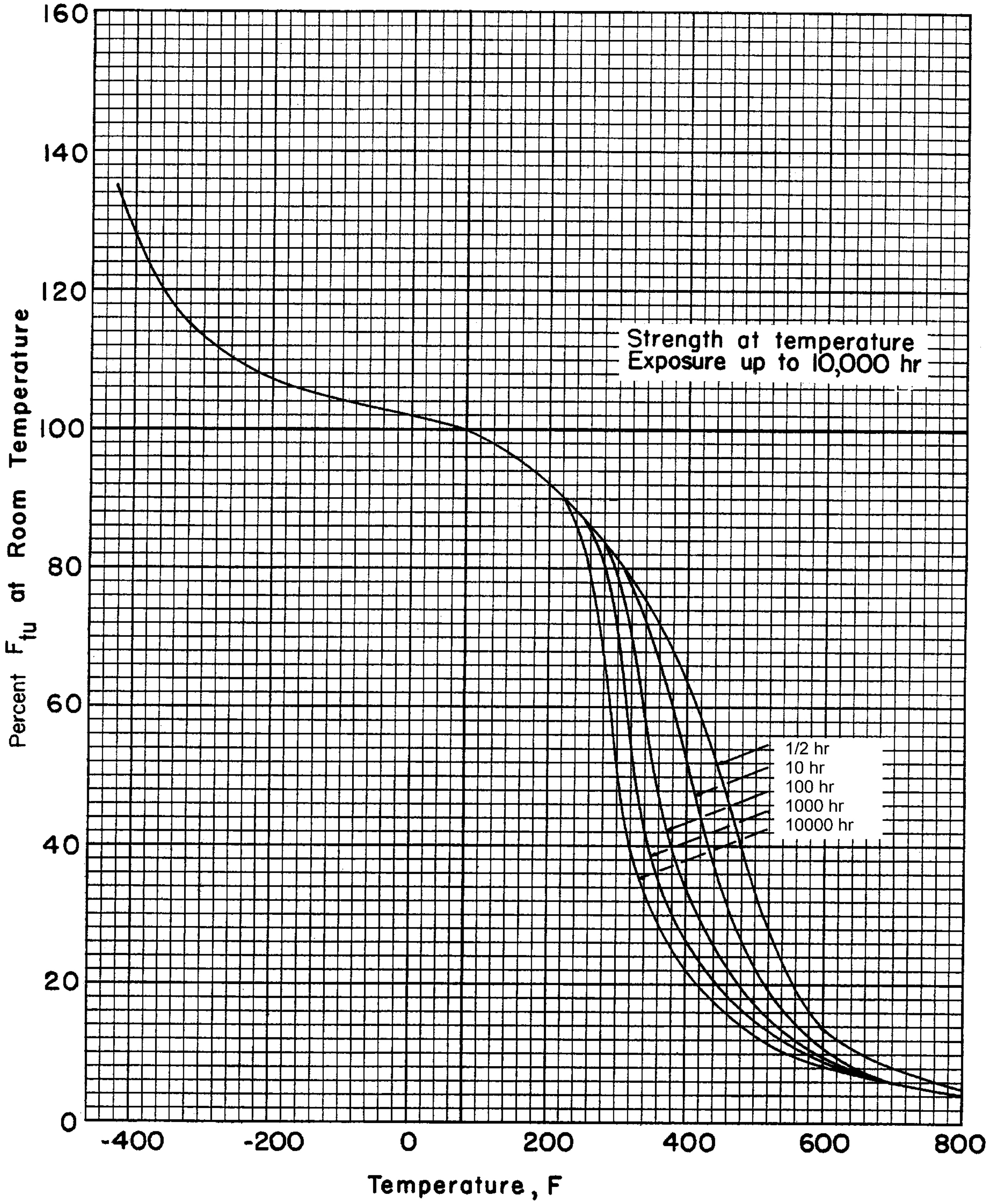


Figure 3.2.1.1.1(a). Effect of temperature on the tensile ultimate strength (F_{tu}) of 2014-T6, T651, T6510 and T6511 aluminum alloy (bare and clad sheet and plate 0.040-1.500 in. thick; extruded bar, rod and shapes ≥ 0.750 in. thick with cross-sectional area ≤ 32 sq. in.).

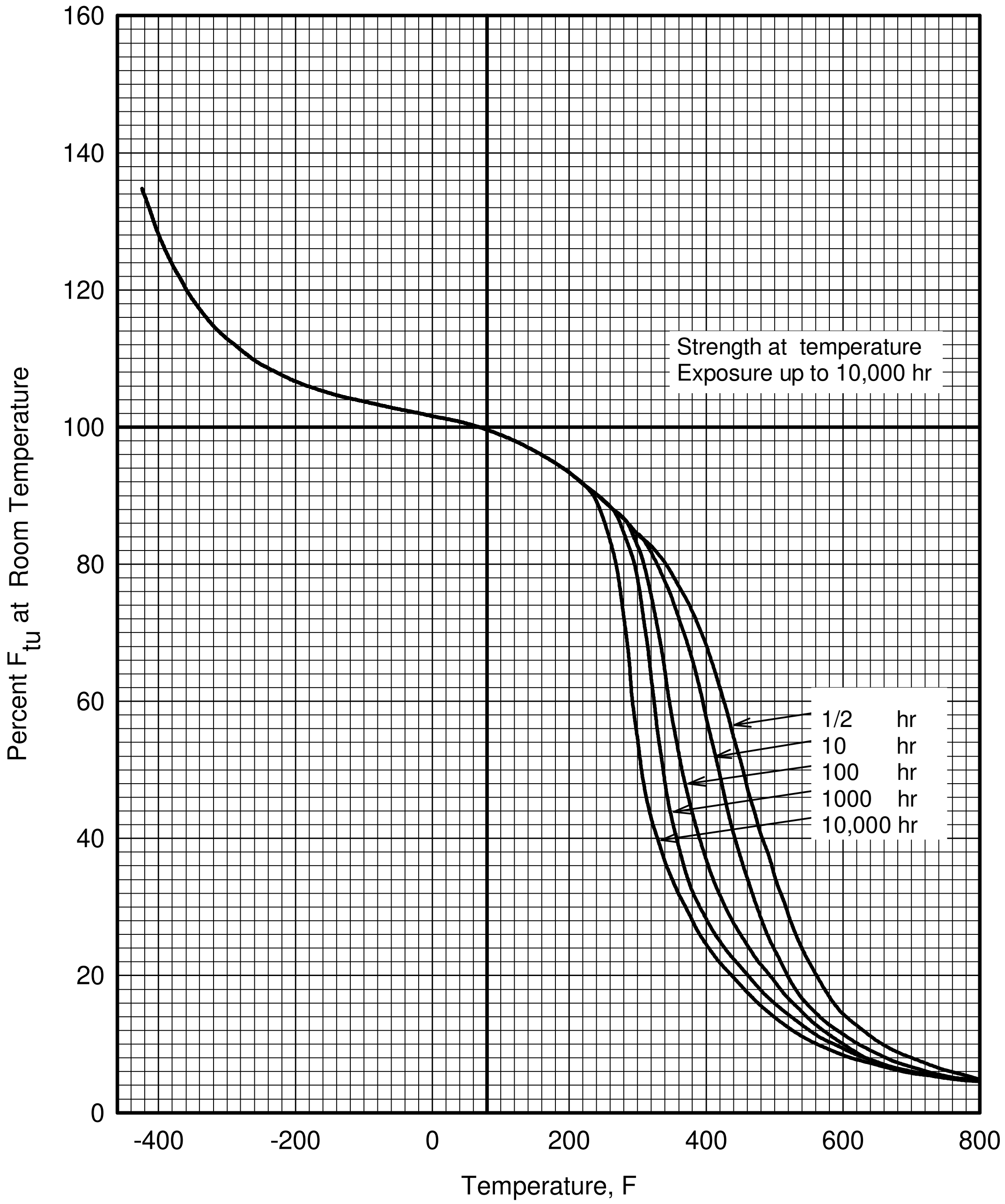


Figure 3.2.1.1.1(b). Effect of temperature on the ultimate strength (F_{tu}) of 2014-T6, T651, T6510 and T6511 aluminum alloy (bare and clad sheet 0.020-0.039 in. thick; bare and clad plate 1.501-4.000 in. thick; rolled bar, rod and shapes; hand and die forgings; extruded bar, rod and shapes 0.125-0.749 in. thick with cross-sectional area ≤ 25 sq. in.).

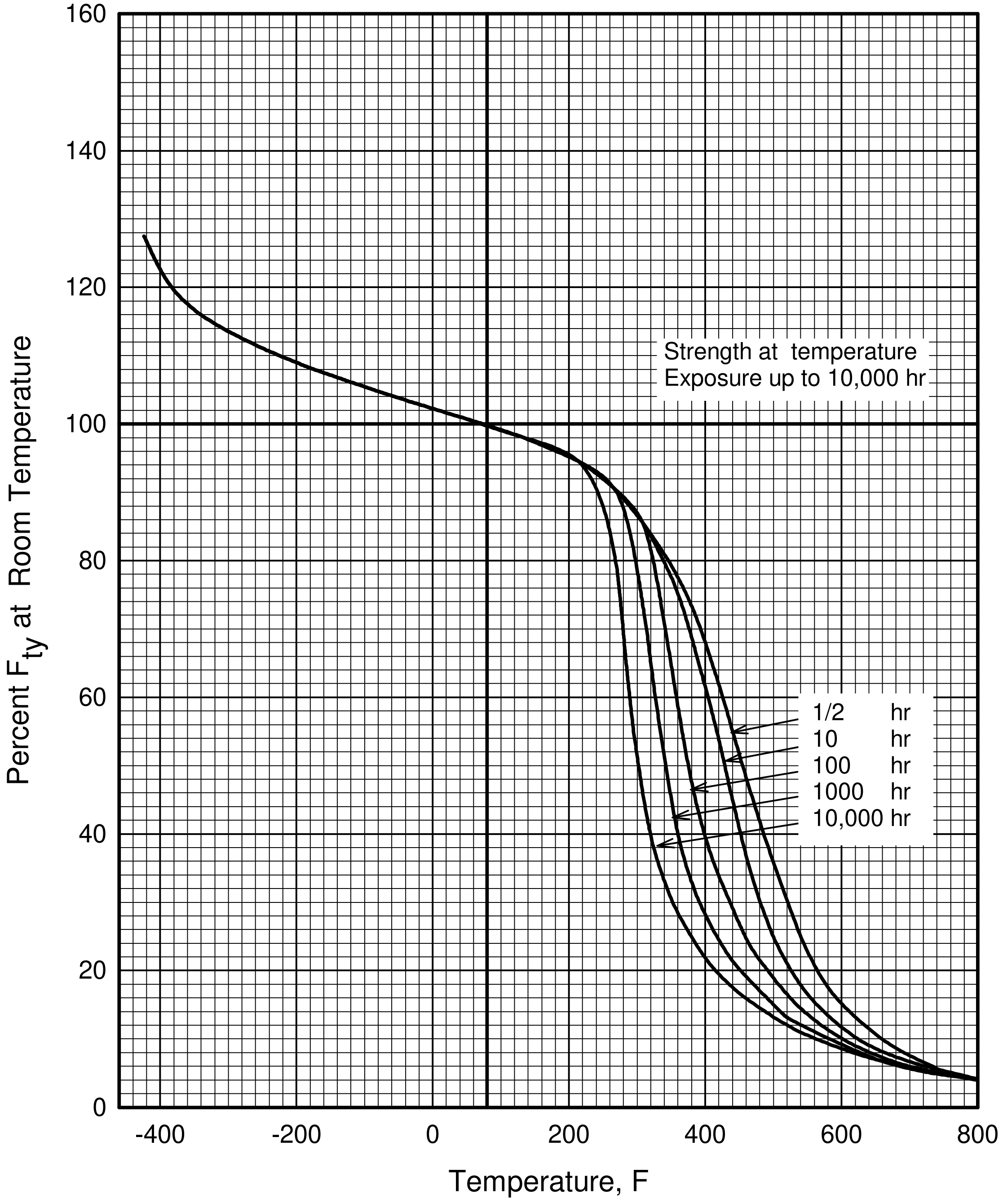


Figure 3.2.1.1.1(c). Effect of temperature on the tensile yield strength (F_{ty}) of 2014-T6, T651, T6510 and T6511 aluminum alloy (bare and clad plate 3.001-4.000 in. thick; rolled bar, rod and shapes; hand and die forgings; extruded bar, rod and shapes 0.125-0.499 in. thick with cross-sectional area ≤ 25 sq. in.).

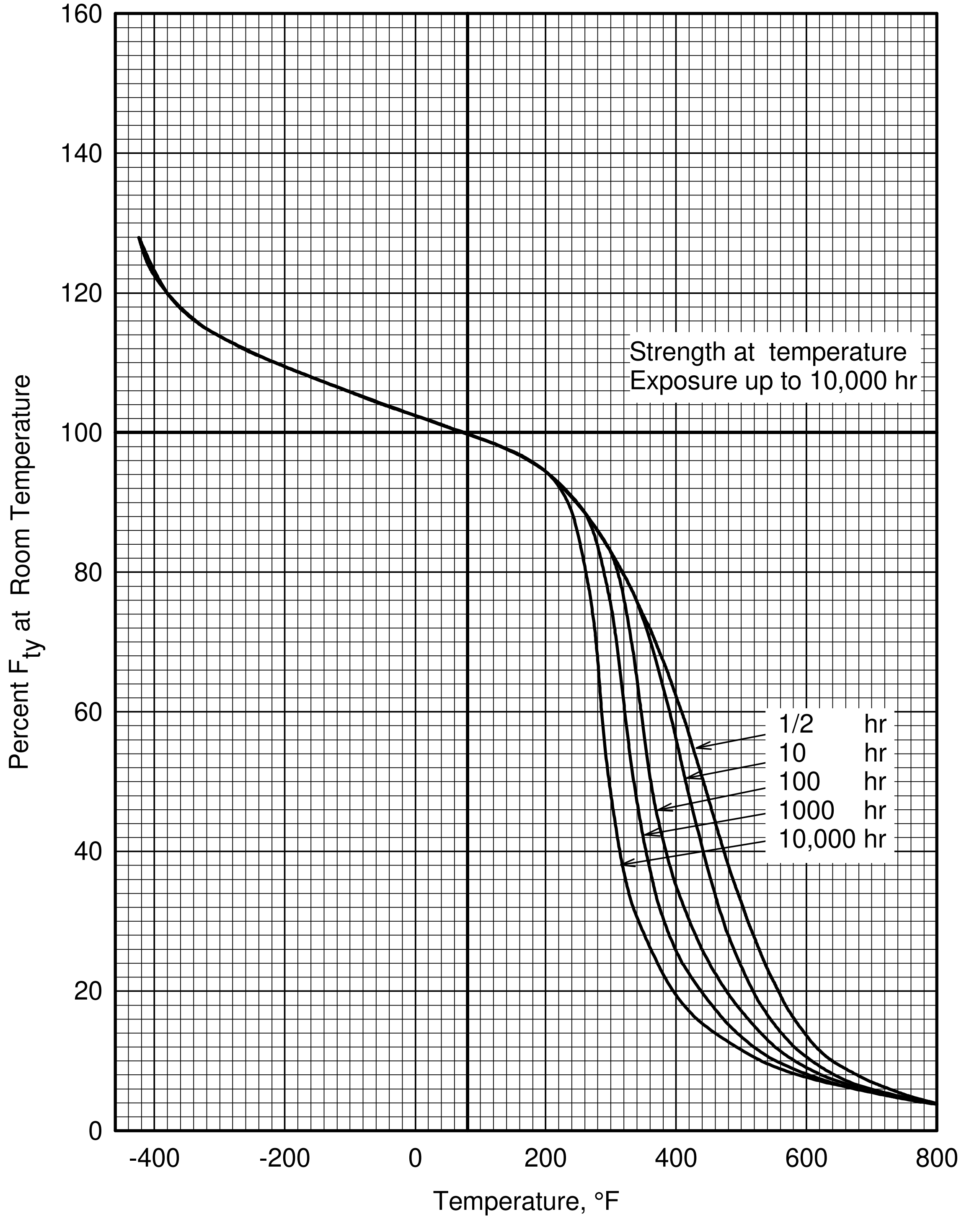


Figure 3.2.1.1.1(d). Effect of temperature on the tensile yield strength (F_{ty}) of 2014-T6, T651, T6510, and T6511 aluminum alloy (bare and clad sheet and plate 0.020-3.000 in. thick; extruded bar, rod and shapes 0.500-0.749 in. thick with cross-sectional area ≤ 25 sq. in. and ≥ 0.750 in. thick with cross-sectional area ≤ 32 sq. in.).

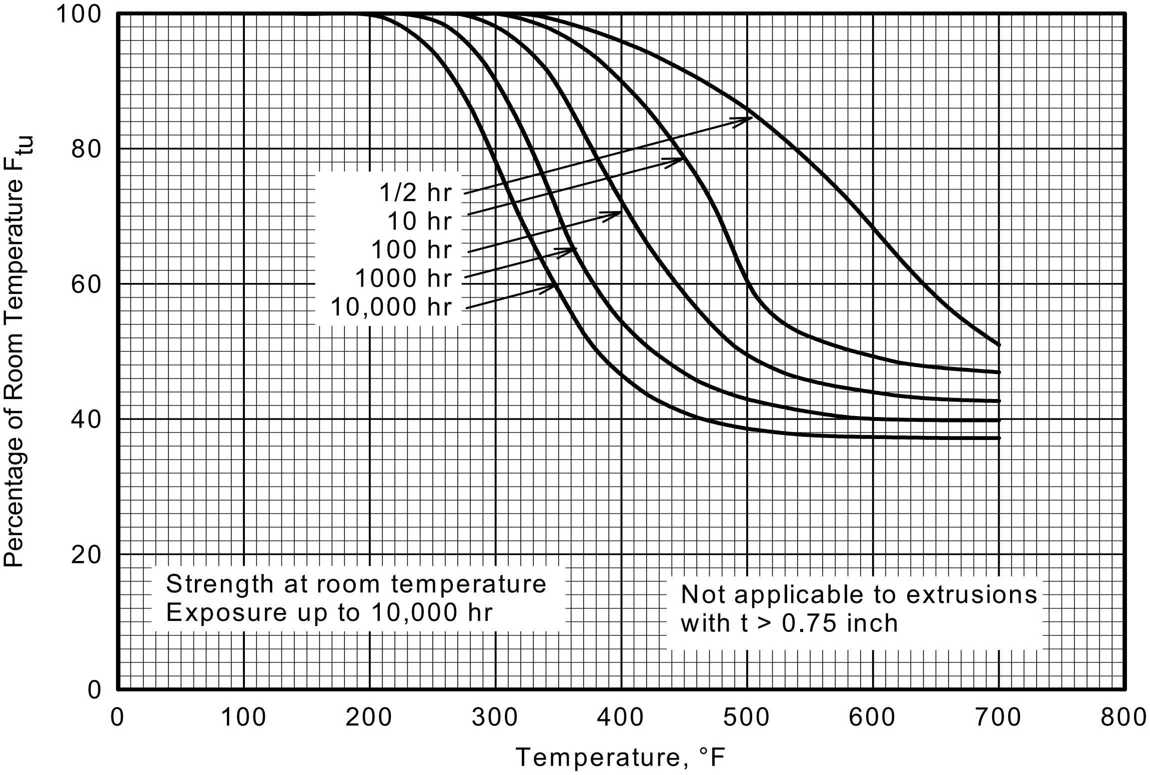


Figure 3.2.1.1.1(e). Effect of exposure at elevated temperatures on the room-temperature tensile ultimate strength (F_{tu}) of 2014-T6, T651, T6510, and T6511 aluminum alloy (all products except thick extrusions).

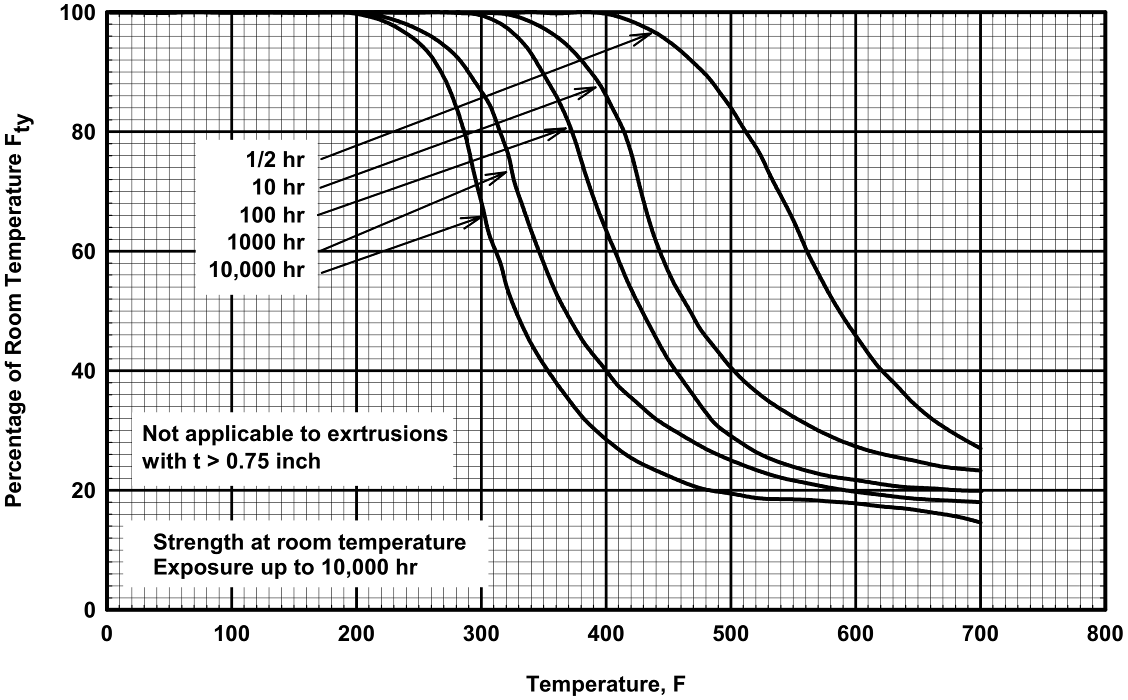


Figure 3.2.1.1.1(f). Effect of exposure at elevated temperature on the room-temperature tensile yield strength (F_{ty}) of 2014-T6, T651, T6510, and T6511 aluminum alloy (all products except thick extrusions).

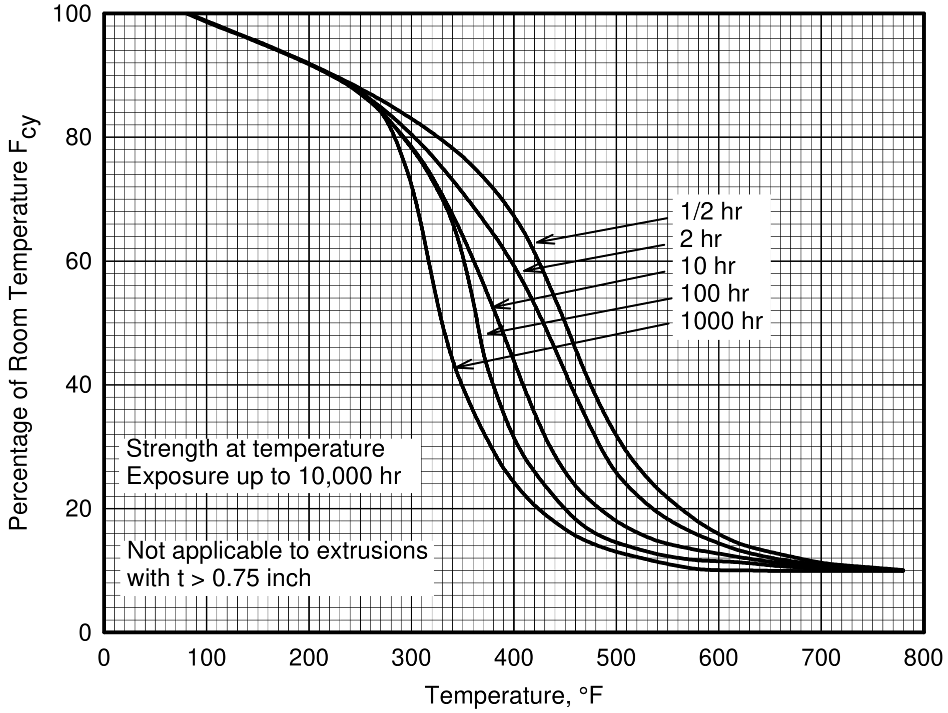


Figure 3.2.1.1.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of 2014-T6, T651, T6510 and T6511 aluminum alloy (all products except thick extrusions).

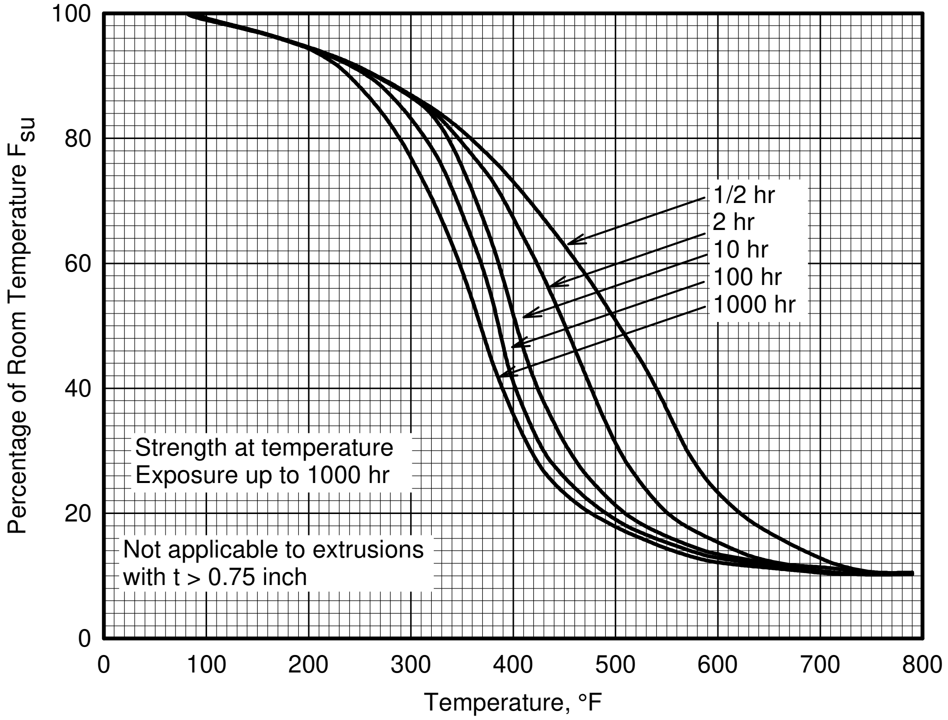


Figure 3.2.1.1.2(b). Effect of temperature on the shear ultimate strength (F_{su}) of 2014-T6, T651, T6510 and T6511 aluminum alloy (all products except thick extrusions).

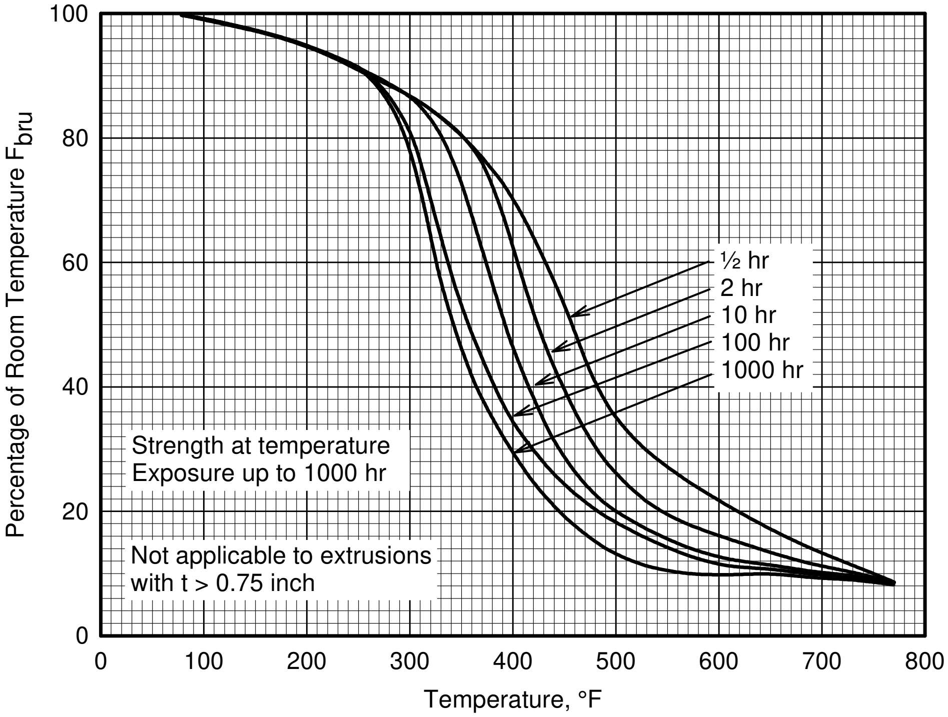


Figure 3.2.1.1.3(a). Effect of temperature on the bearing ultimate strength (F_{bru}) of 2014-T6, T651, T6510 and T6511 aluminum alloy (all products except thick extrusions).

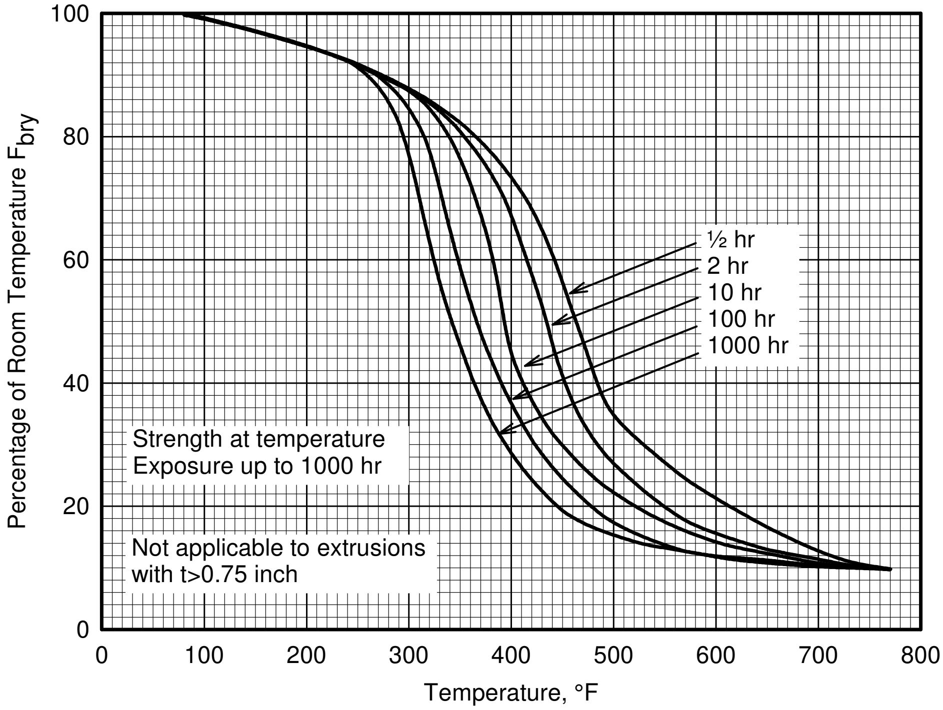


Figure 3.2.1.1.3(b). Effect of temperature on the bearing yield strength (F_{bry}) of 2014-T6, T651, T6510 and T6511 aluminum alloy (all products except thick extrusions).

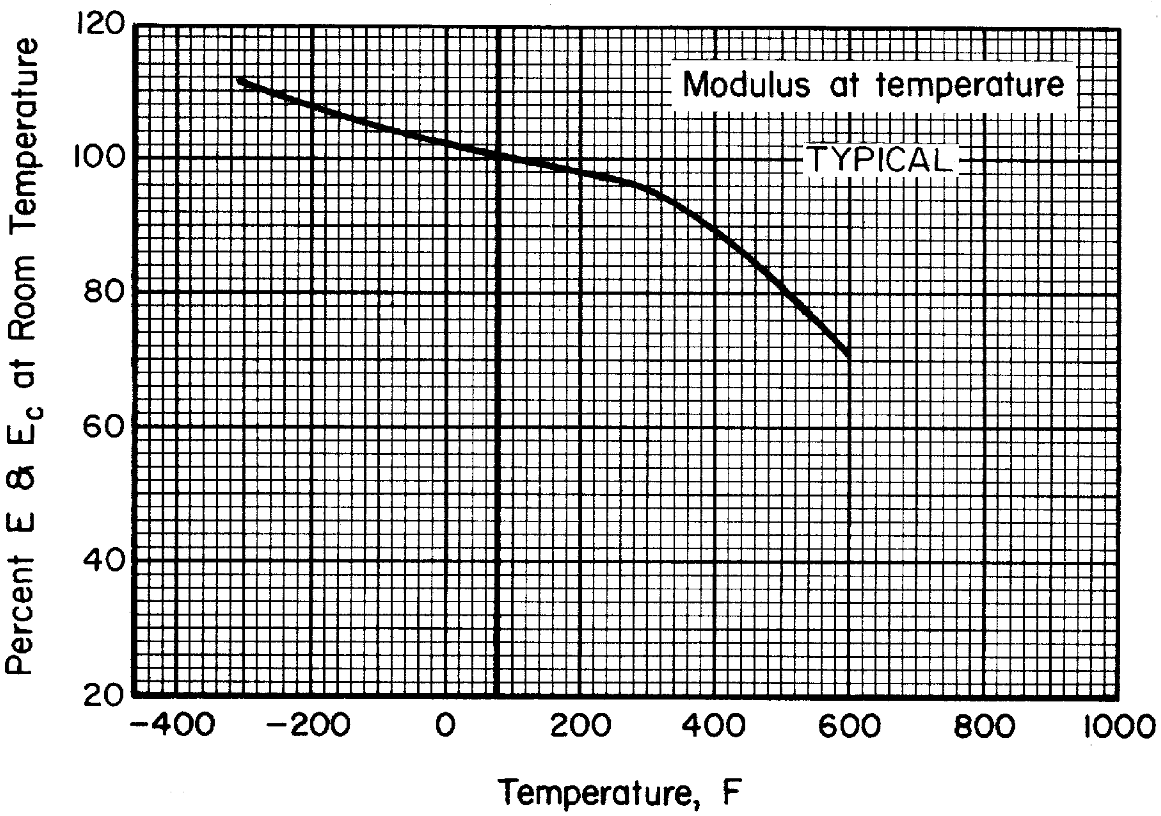


Figure 3.2.1.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of 2014 aluminum alloy.

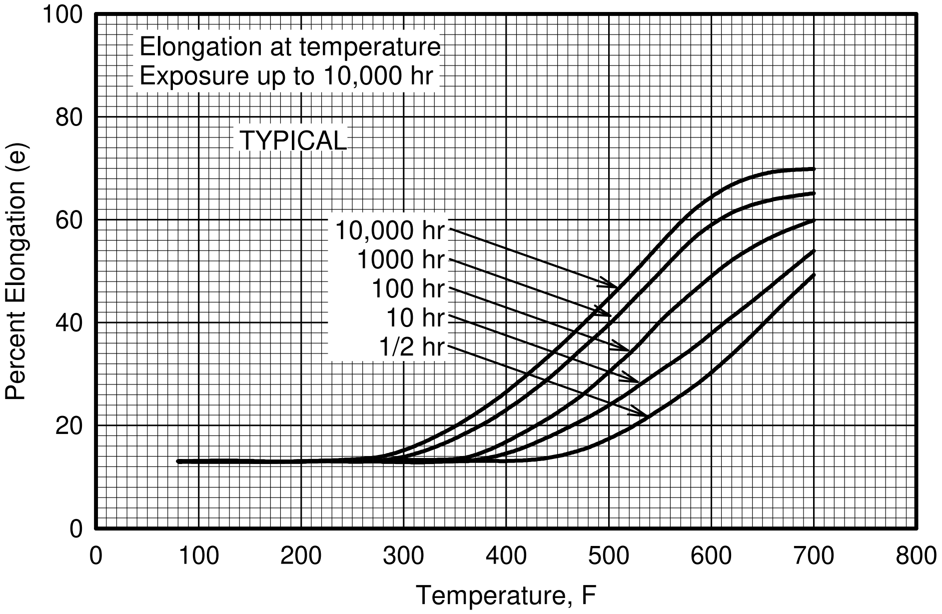


Figure 3.2.1.1.5(a). Effect of temperature on the elongation of 2014-T6, T651, T6510 and T6511 aluminum alloy (all products except thick extrusions).

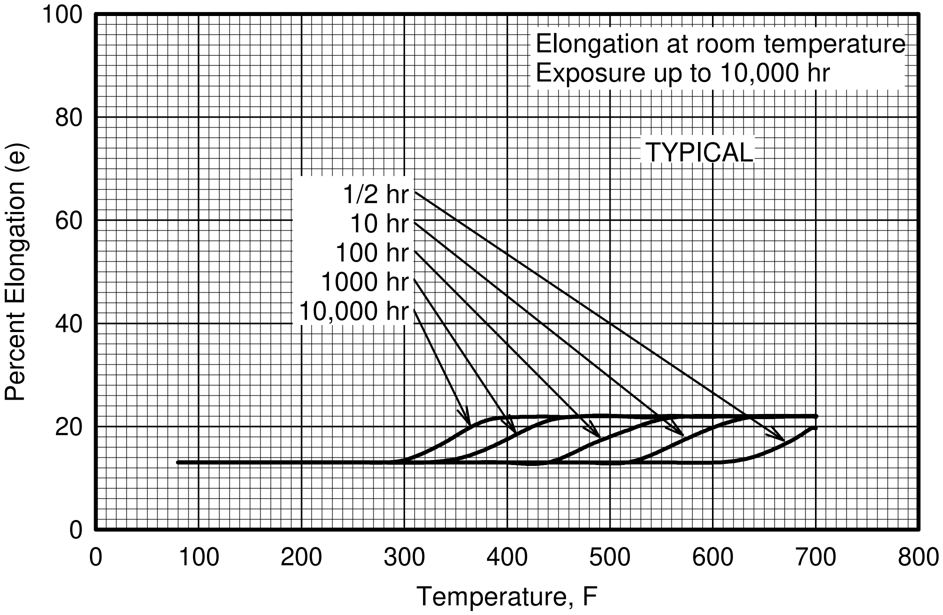


Figure 3.2.1.1.5(b). Effect of exposure at elevated temperatures on the room-temperature elongation of 2014-T6, T651, T6510 and T6511 aluminum alloy (all products except thick extrusions).

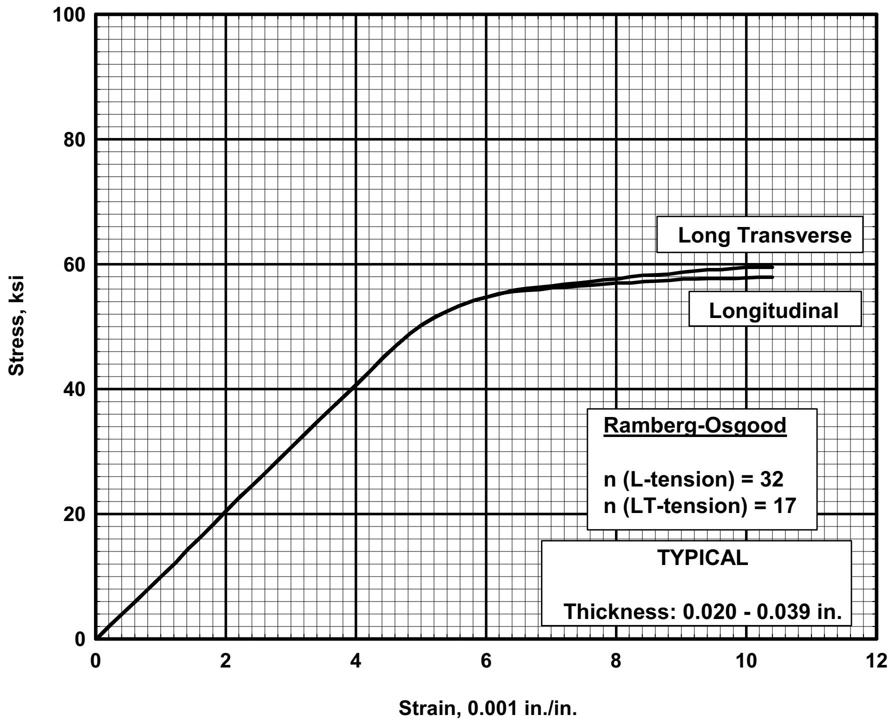


Figure 3.2.1.1.6(a). Typical tensile stress-strain curves for clad 2014-T6 aluminum alloy sheet at room temperature.

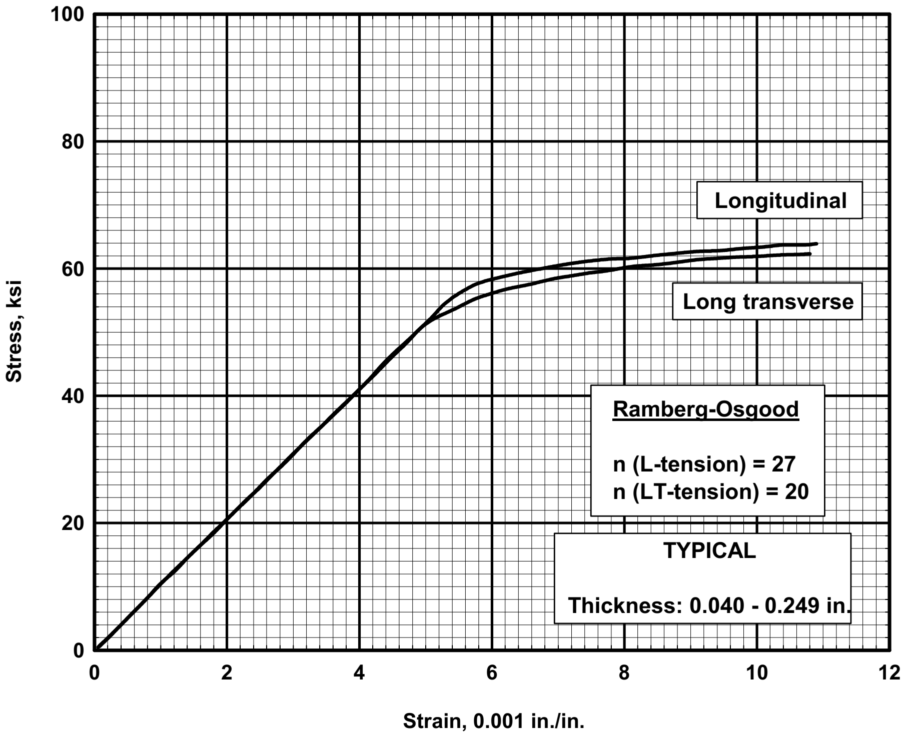


Figure 3.2.1.1.6(b). Typical tensile stress-strain curves for clad 2014-T6 aluminum alloy sheet at room temperature.

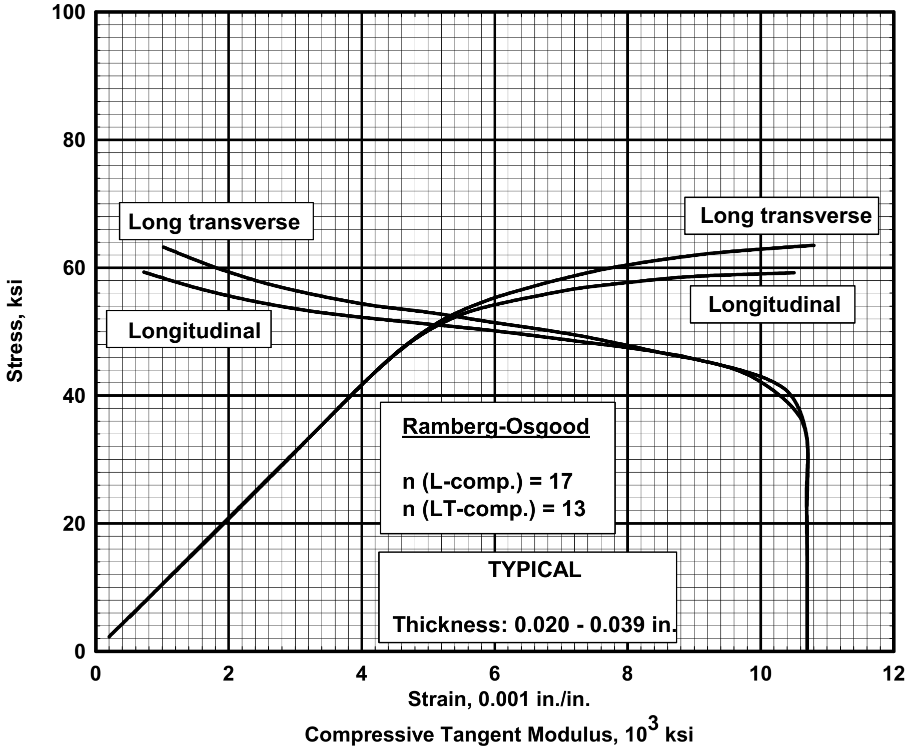


Figure 3.2.1.1.6(c). Typical compressive stress-strain and compressive tangent-modulus curves for clad 2014-T6 aluminum alloy sheet at room temperature.

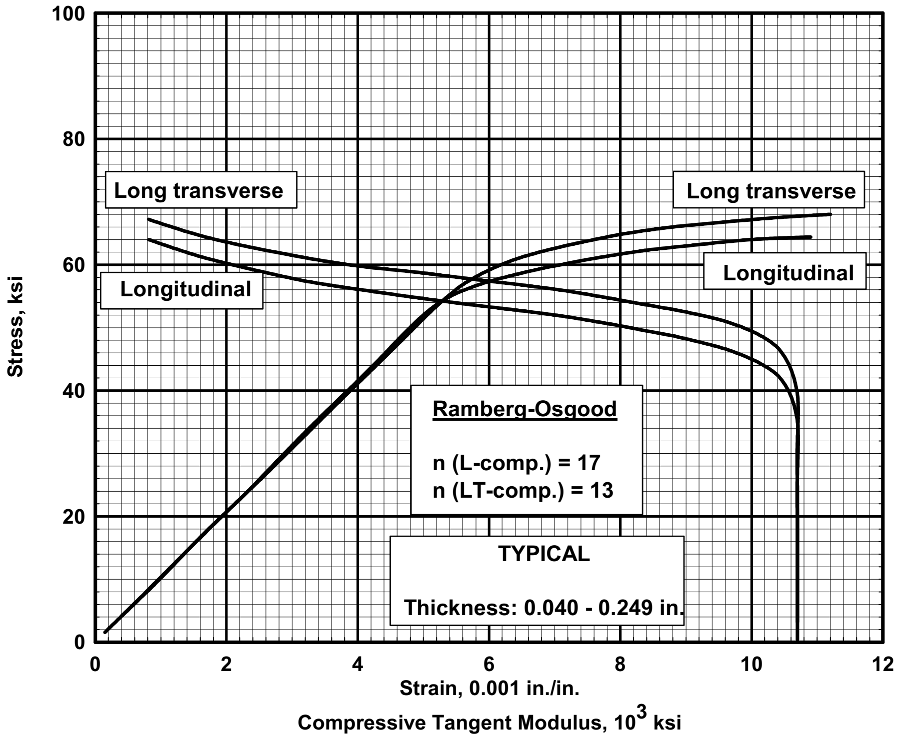


Figure 3.2.1.1.6(d). Typical compressive stress-strain and compressive tangent-modulus curves for clad 2014-T6 aluminum alloy sheet at room temperature.

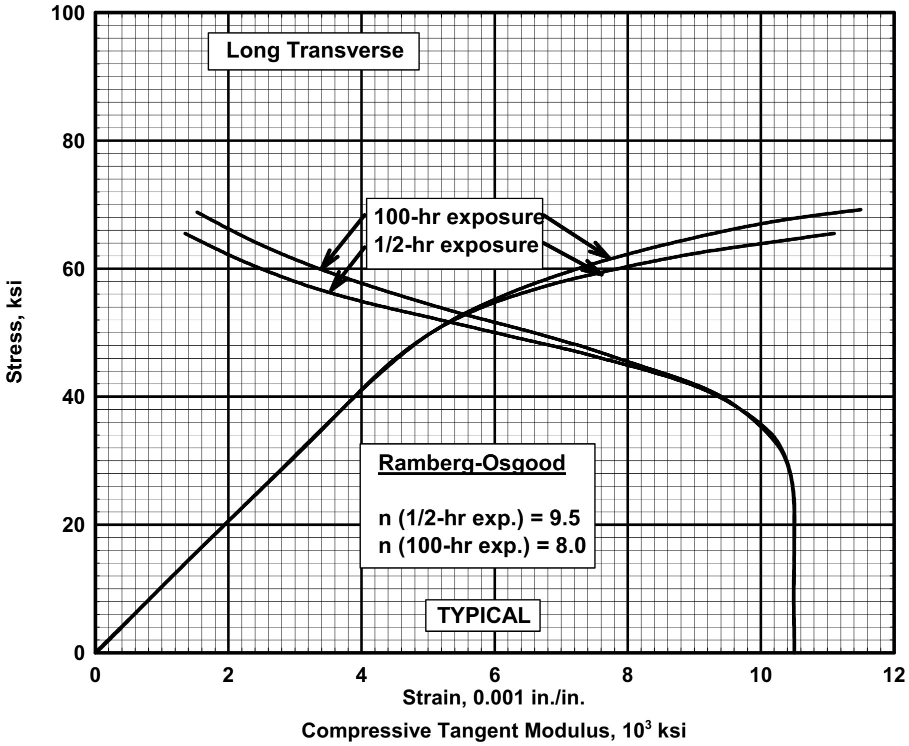


Figure 3.2.1.1.6(e). Typical compressive stress-strain and compressive tangent-modulus curves for clad 2014-T6 aluminum alloy sheet at 200°F.

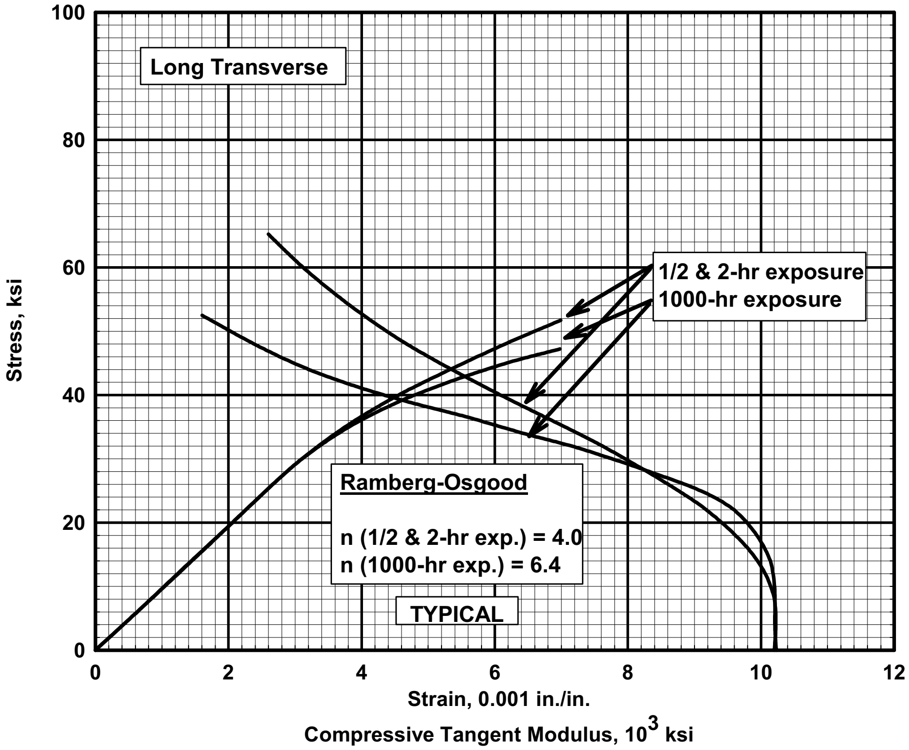


Figure 3.2.1.1.6(f). Typical compressive stress-strain and compressive tangent-modulus curves for clad 2014-T6 aluminum alloy sheet at 300°F.

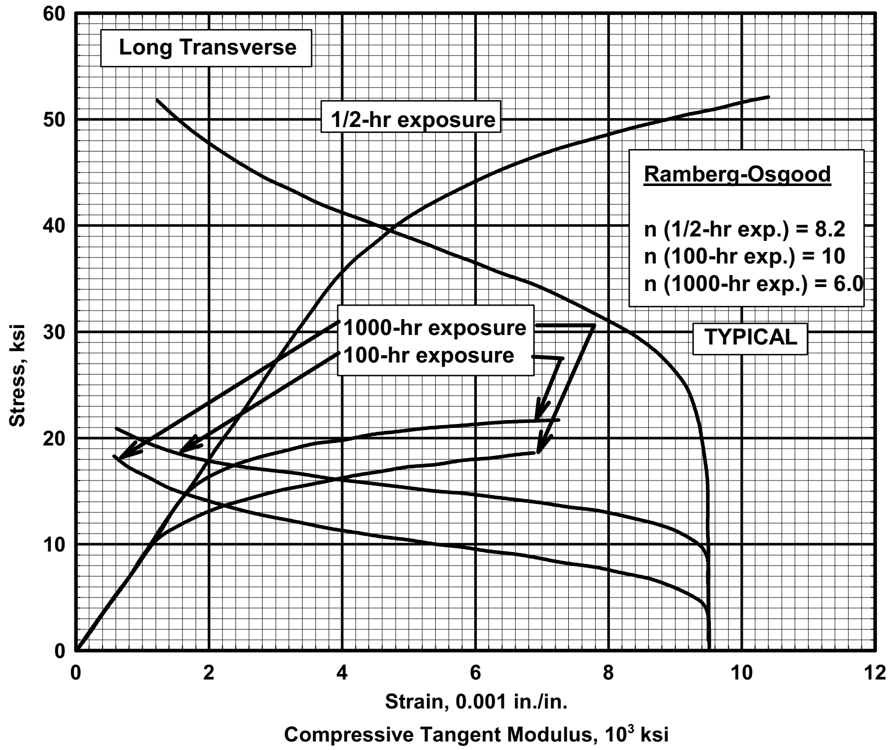


Figure 3.2.1.1.6(g). Typical compressive stress-strain and compressive tangent-modulus curves for clad 2014-T6 aluminum alloy sheet at 400°F.

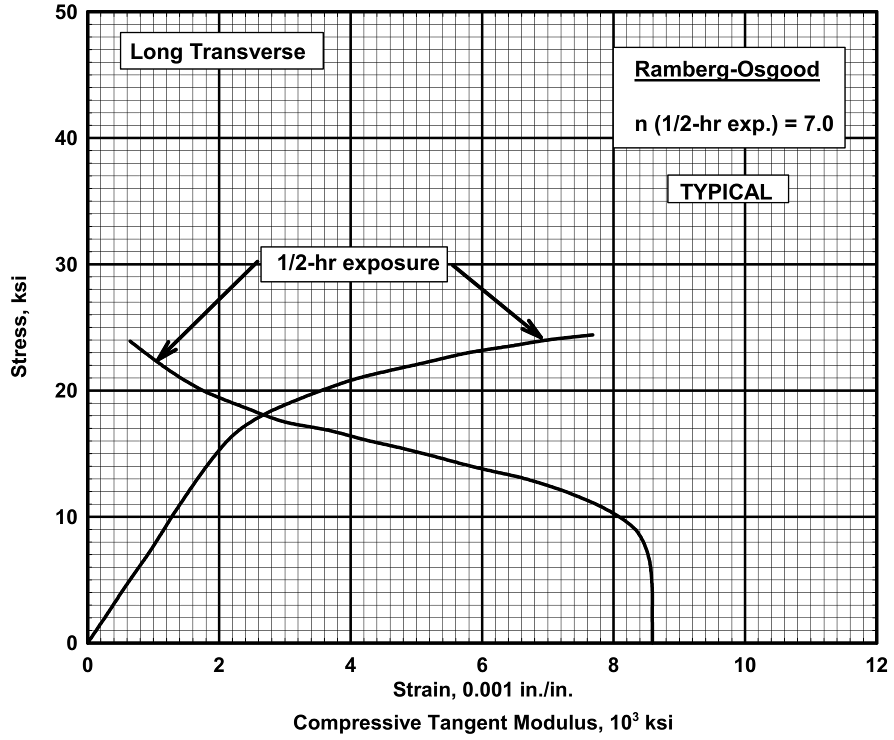


Figure 3.2.1.1.6(h). Typical compressive stress-strain and compressive tangent-modulus curves for clad 2014-T6 aluminum alloy sheet at 500°F.

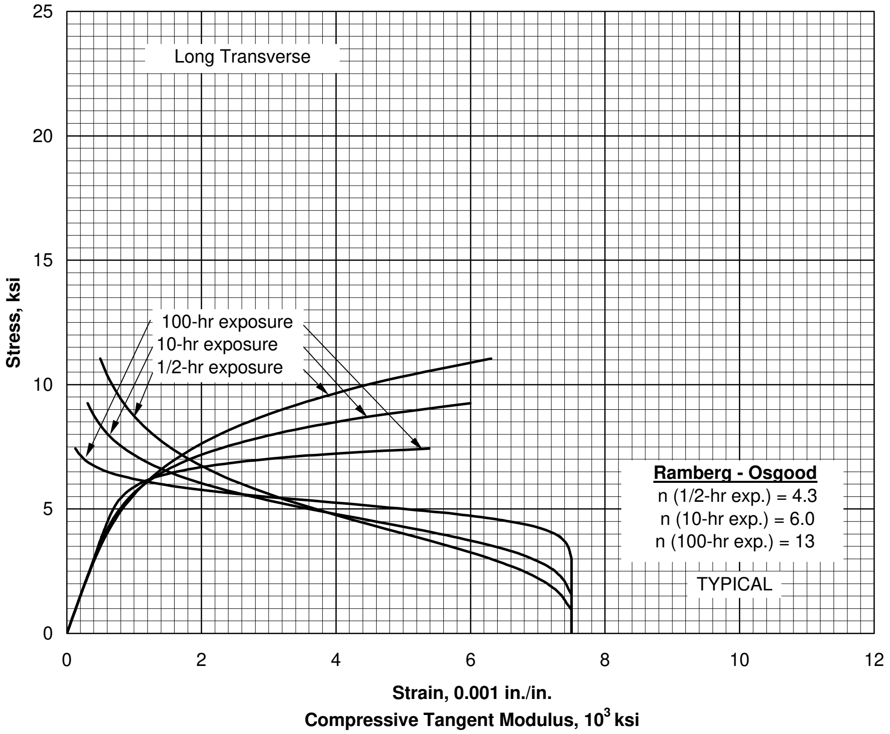


Figure 3.2.1.1.6(i). Typical compressive stress-strain and compressive tangent-modulus curves for clad 2014-T6 aluminum alloy sheet at 600°F.

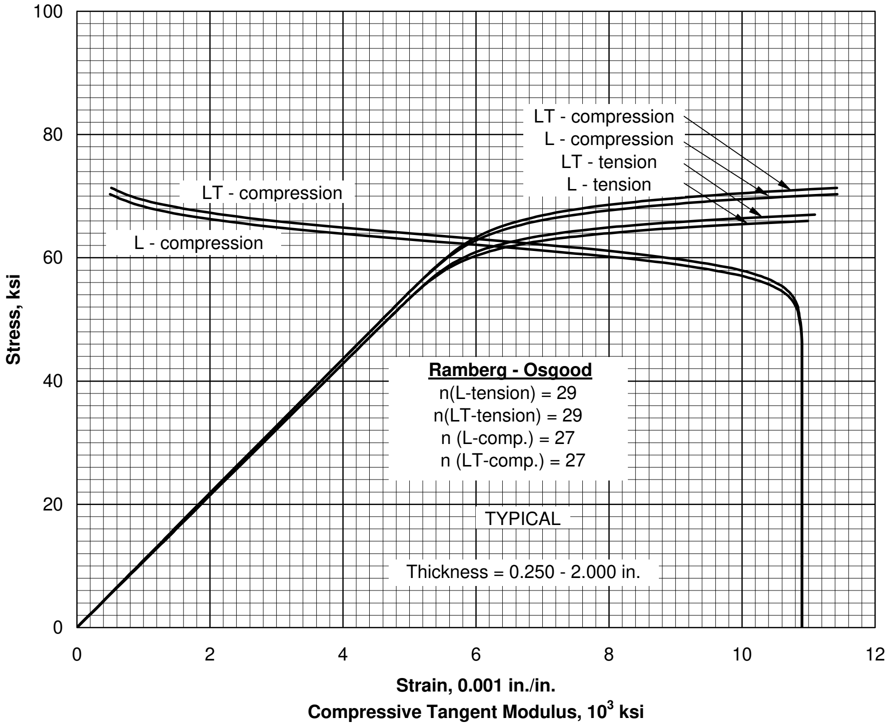


Figure 3.2.1.1.6(j). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for clad 2014-T62 aluminum alloy plate at room temperature.

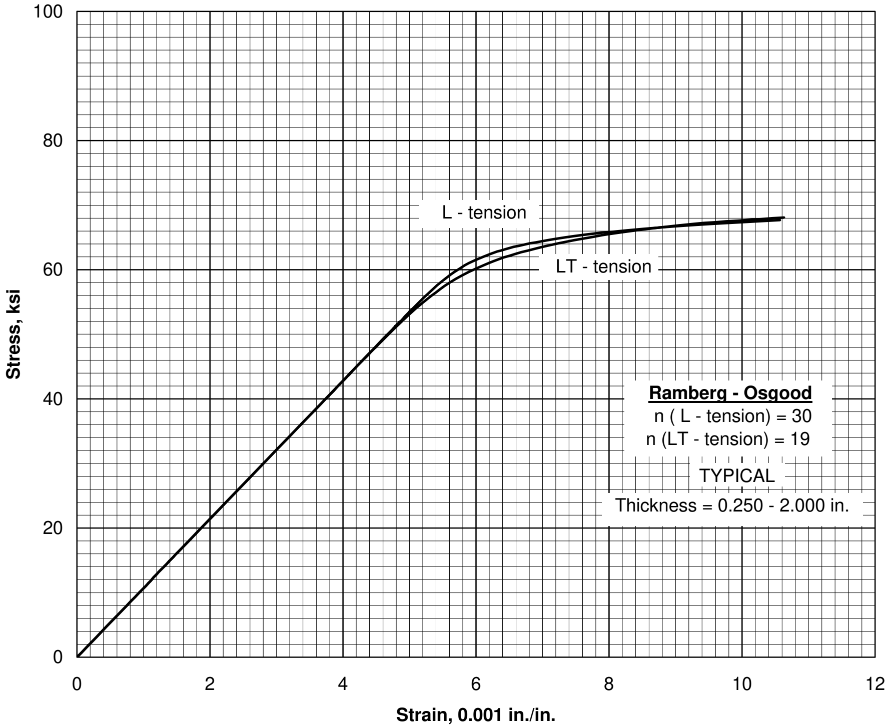


Figure 3.2.1.1.6(k). Typical tensile stress-strain curves for 2014-T651 aluminum alloy plate at room temperature.

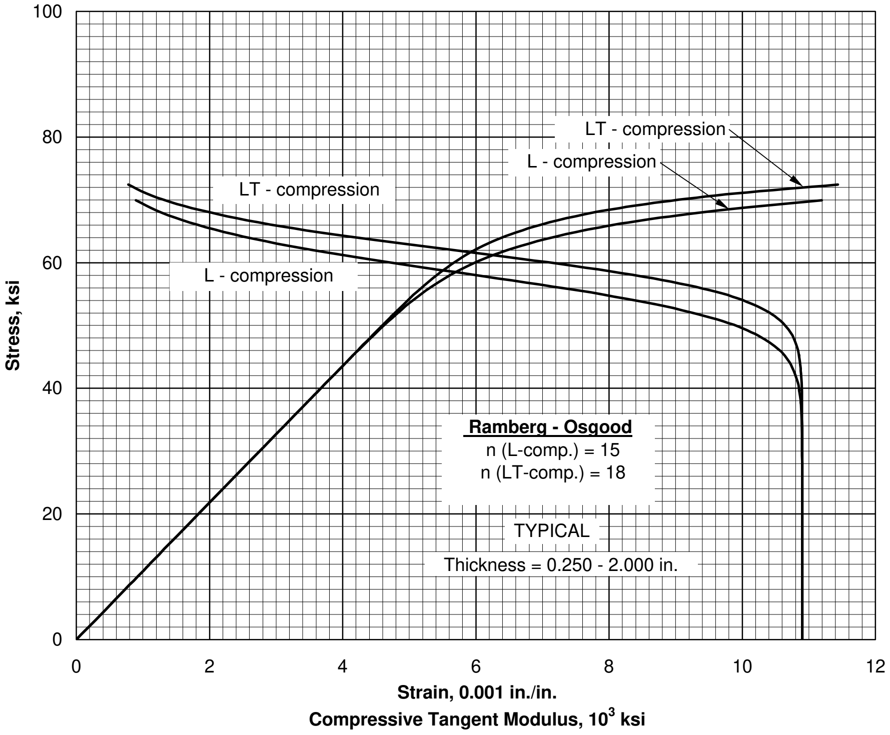


Figure 3.2.1.1.6(l). Typical compressive stress-strain and compressive tangent-modulus curves for 2014-T651 aluminum alloy plate at room temperature.

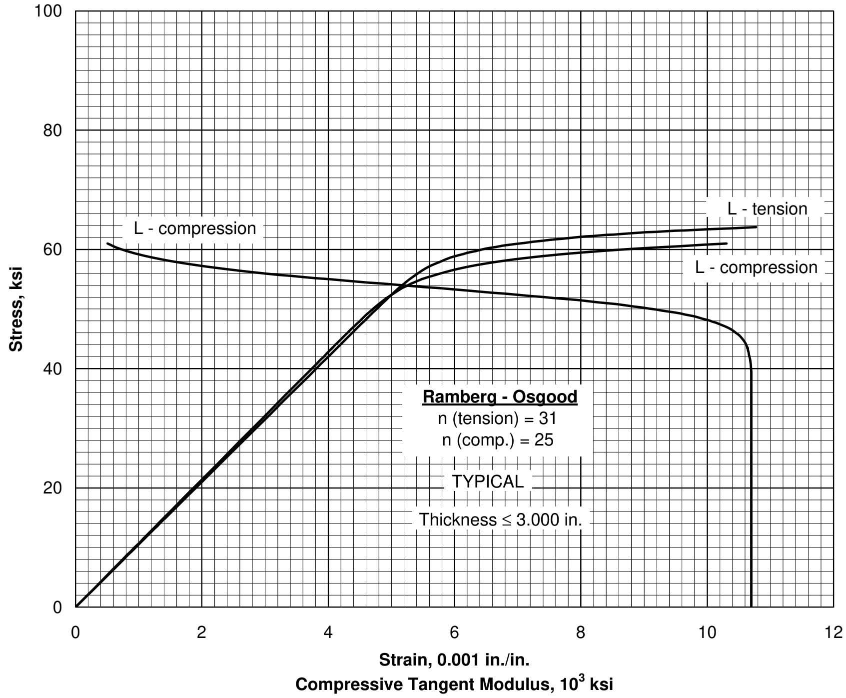


Figure 3.2.1.1.6(m). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 2014-T6 aluminum alloy rolled bar, rod, and shapes at room temperature.

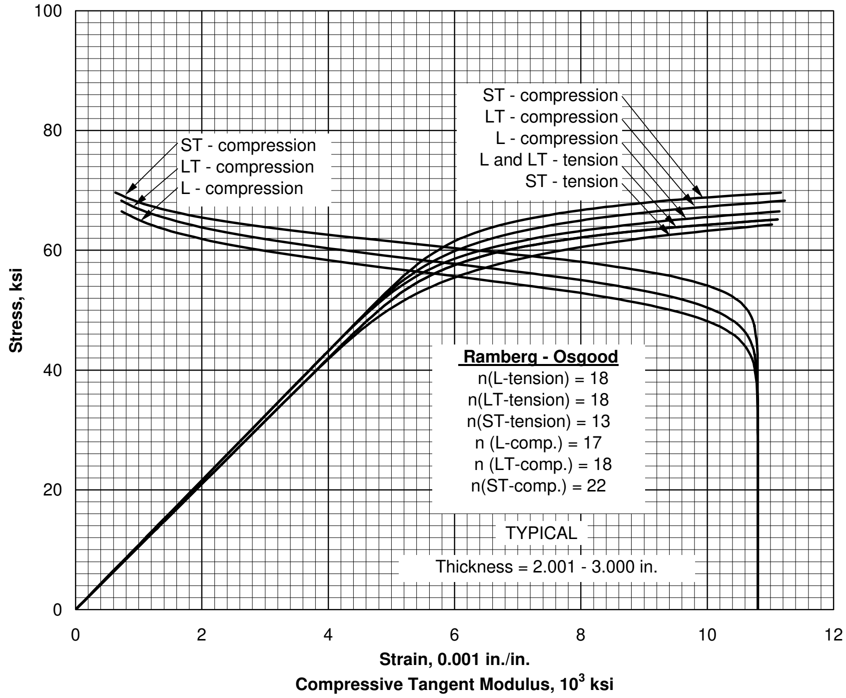


Figure 3.2.1.1.6(n). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 2014-T652 aluminum alloy hand forging at room temperature.

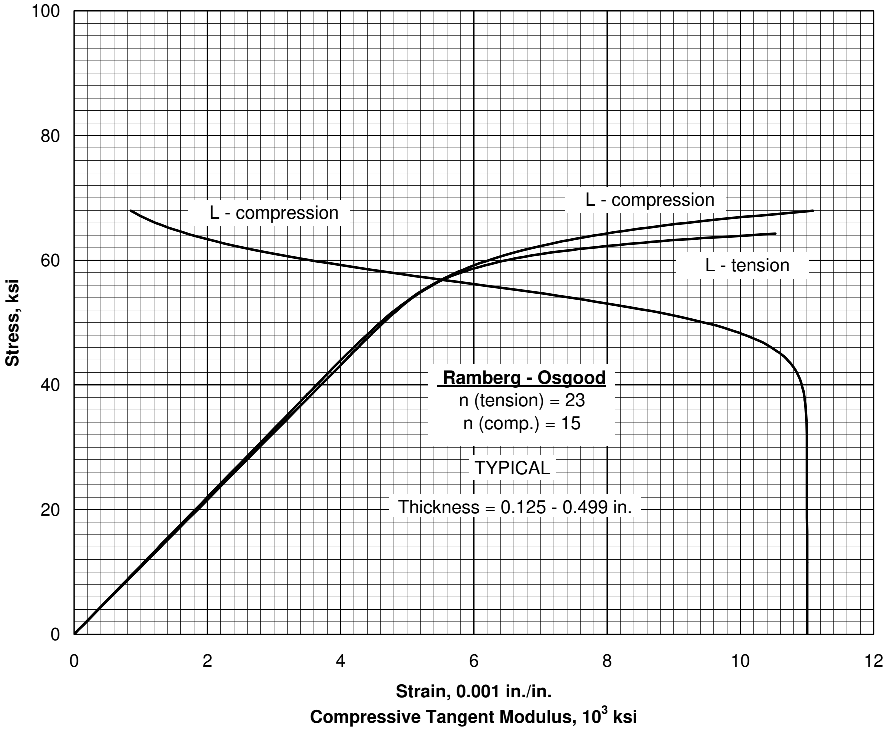


Figure 3.2.1.1.6(o). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 2014-T6 aluminum alloy extrusion at room temperature.

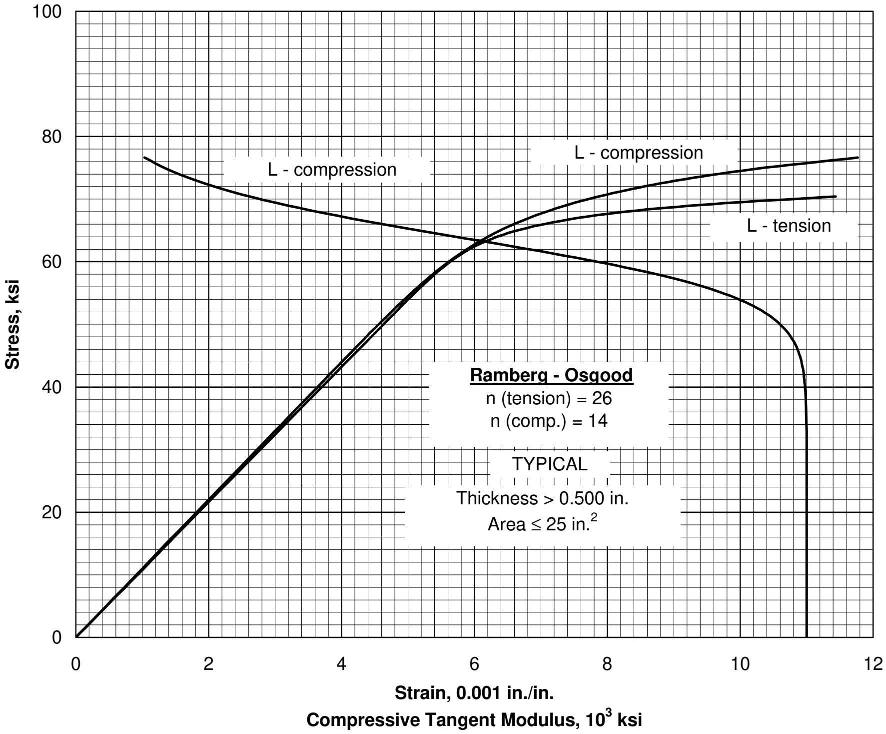


Figure 3.2.1.1.6(p). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 2014-T6 aluminum alloy extrusion at room temperature.

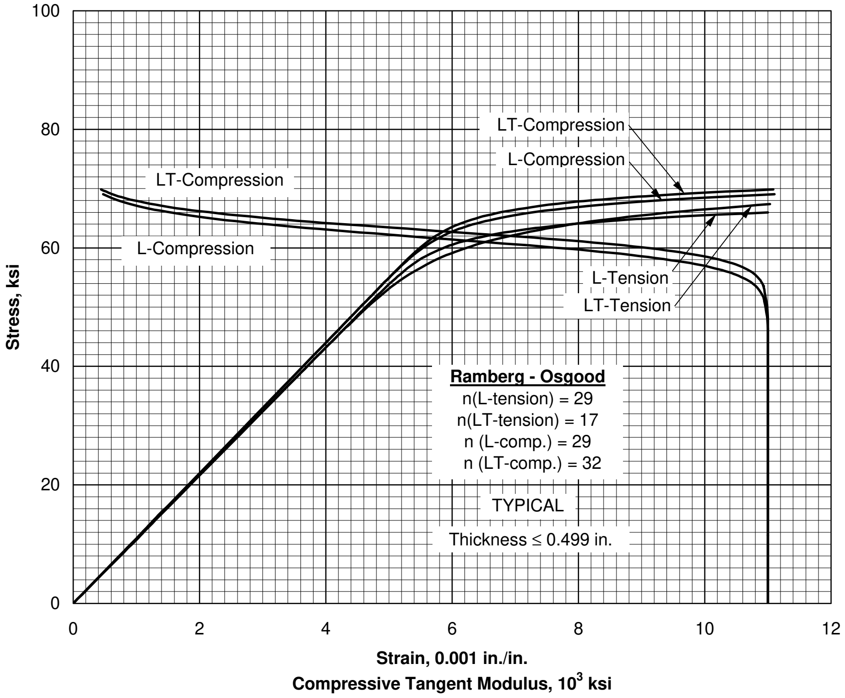


Figure 3.2.1.1.6(q). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 2014-T62 aluminum alloy extrusion at room temperature.

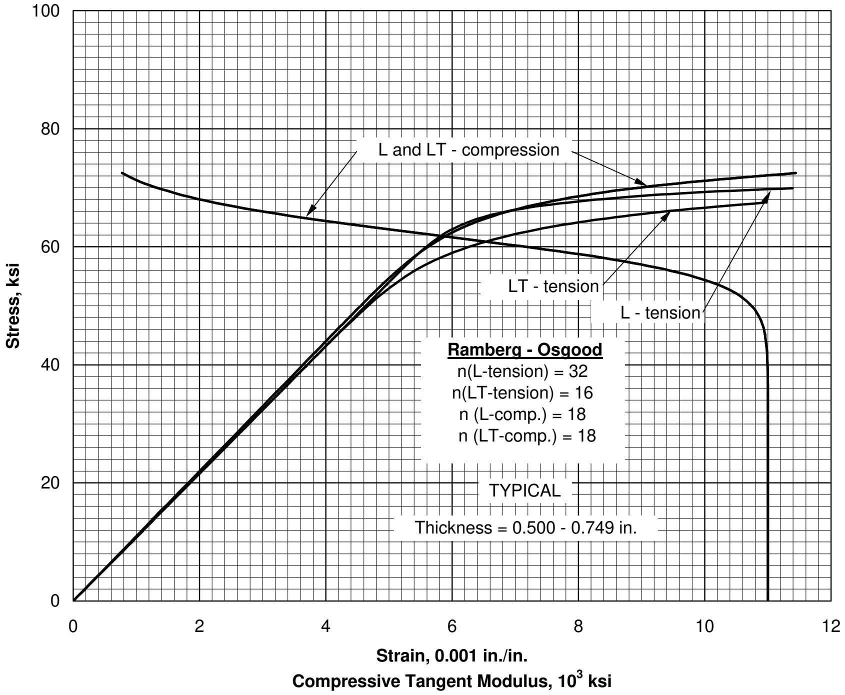


Figure 3.2.1.1.6(r). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 2014-T651X aluminum alloy extrusion at room temperature.

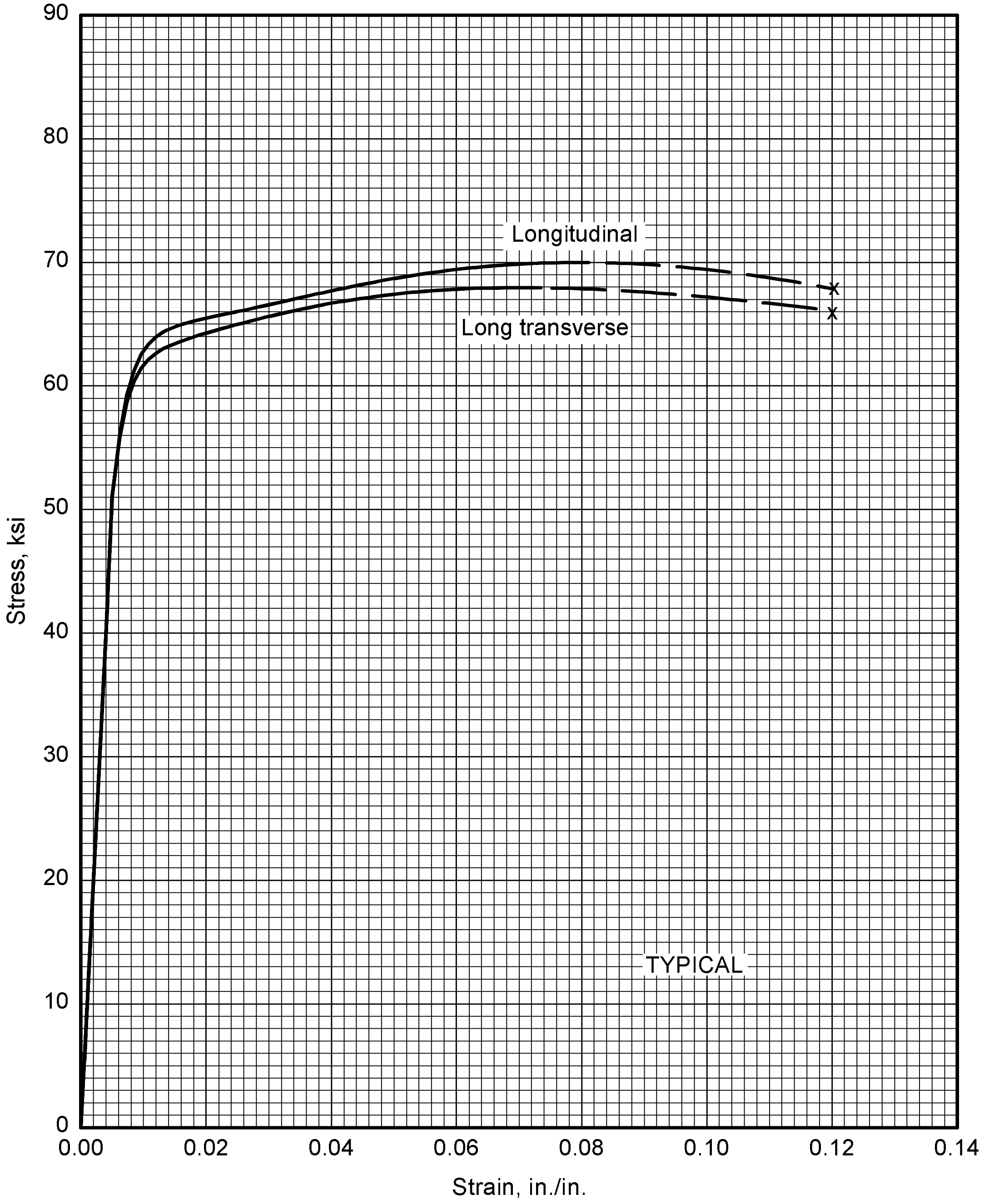


Figure 3.2.1.1.6(s). Typical tensile stress-strain curves (full range) for 2014-T6 aluminum alloy forging at room temperature.

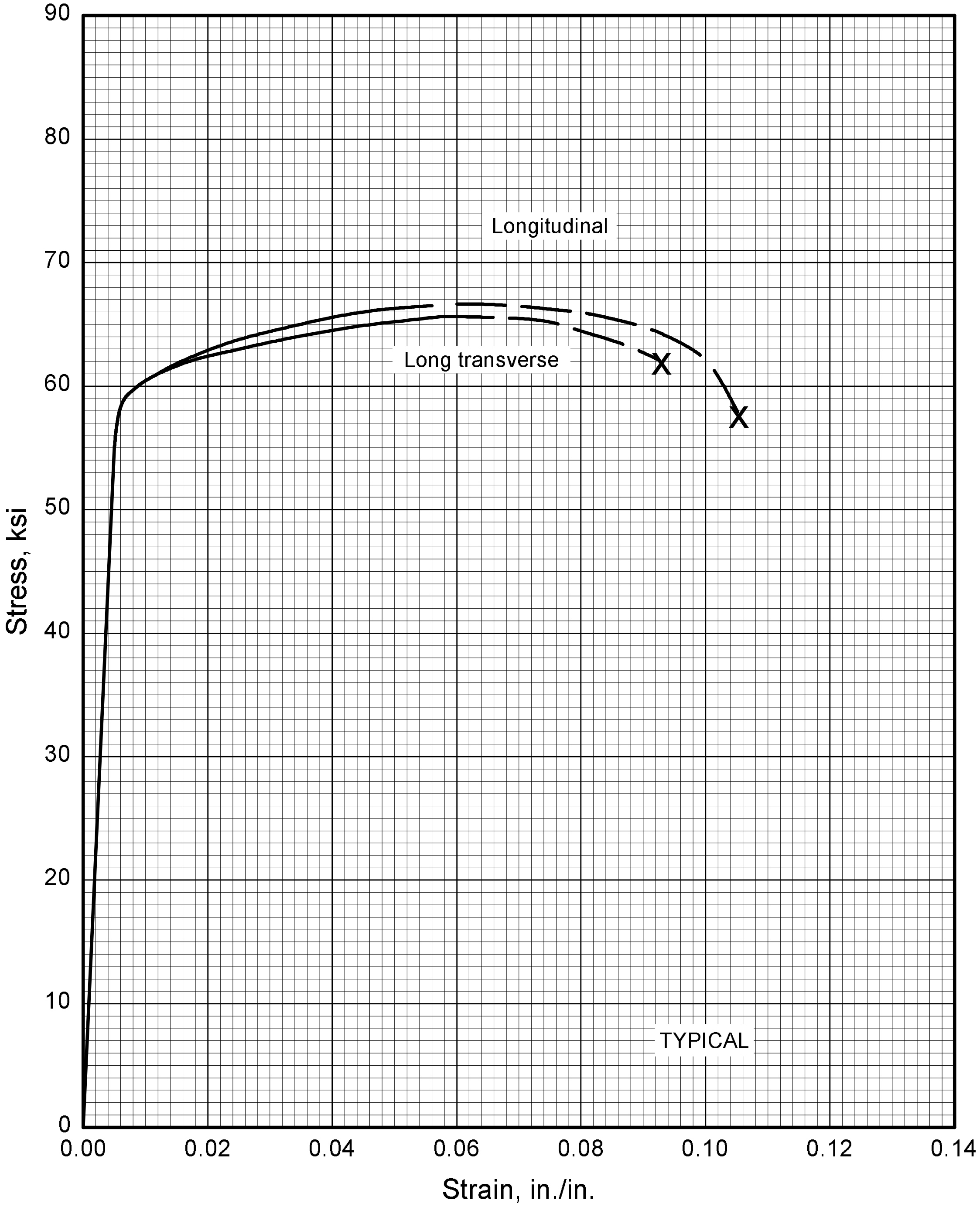


Figure 3.2.1.1.6(t). Typical tensile stress-strain curves (full range) for 2014-T652 aluminum alloy forging at room temperature.

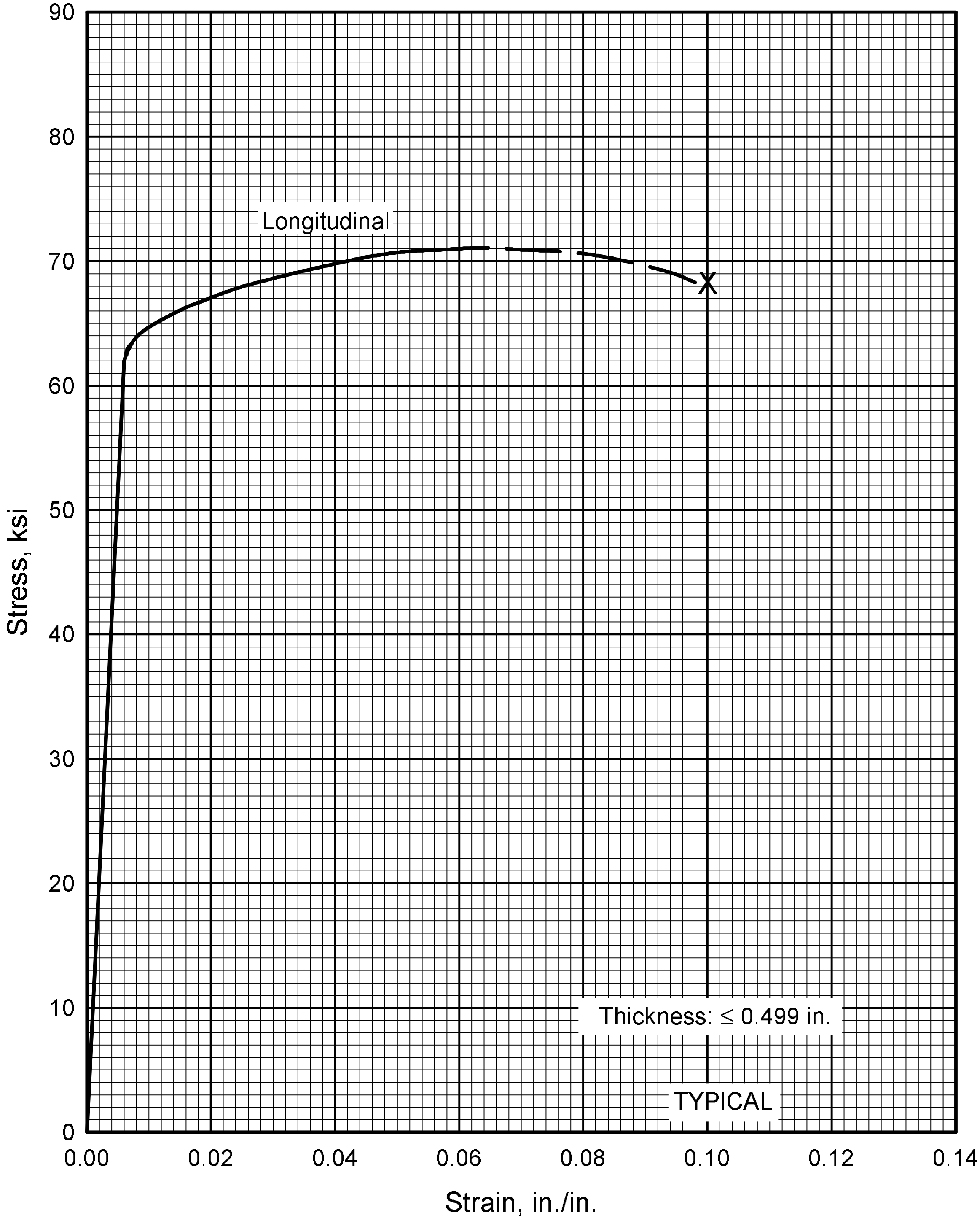


Figure 3.2.1.1.6(u). Typical tensile stress-strain curves (full range) for 2014-T62 aluminum alloy extrusion at room temperature.

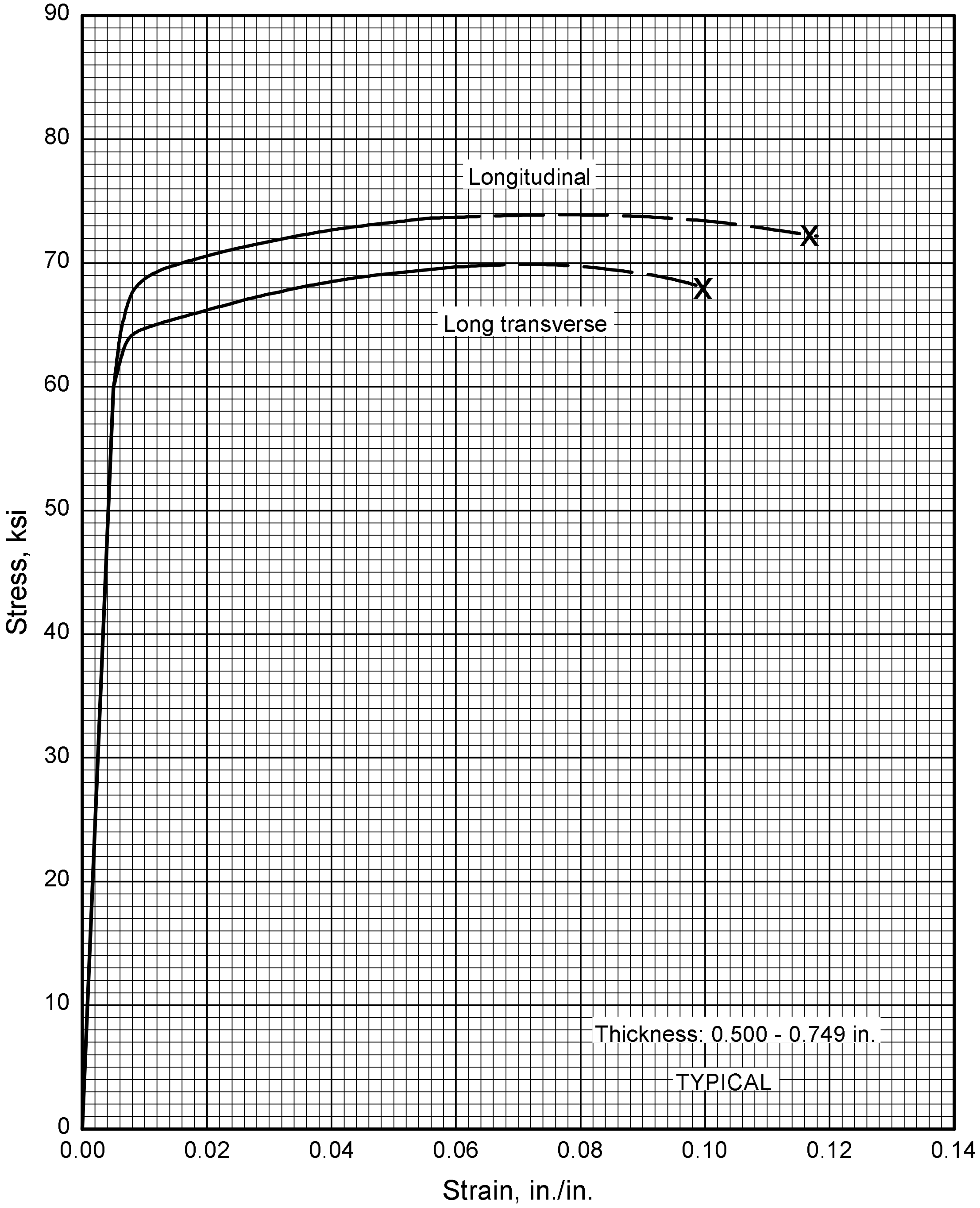


Figure 3.2.1.1.6(v). Typical tensile stress-strain curves (full range) for 2014-T651X aluminum alloy extrusion at room temperature.

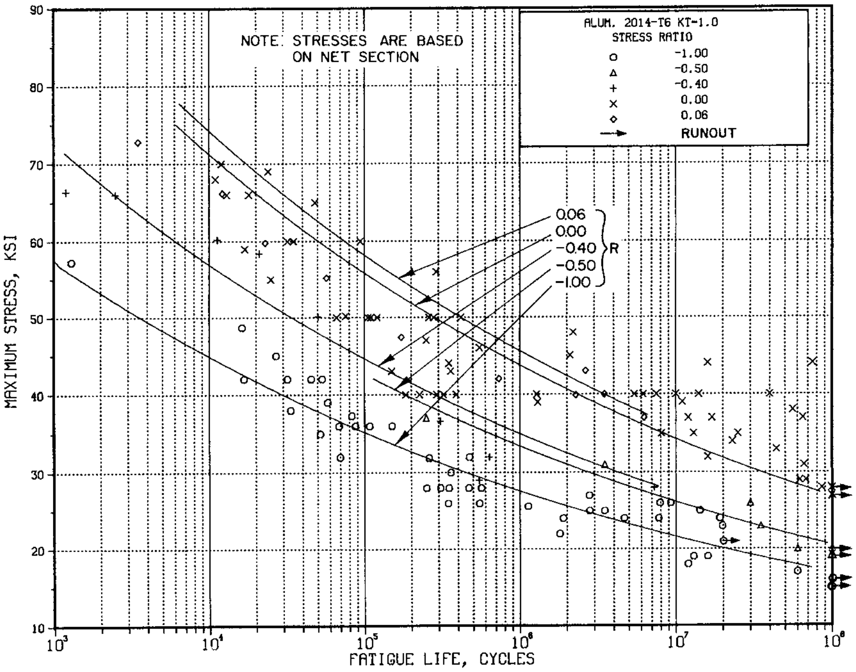


Figure 3.2.1.1.8(a). Best-fit S/N curves for unnotched 2014-T6 aluminum alloy, various wrought products, longitudinal direction.

Correlative Information for Figure 3.2.1.1.8(a)

Product Form: Drawn rod, 0.75 inch diameter
Rolled bar, 1 x 7.5 inch and 1.125 inch diameter
Rolled rod, 4.5 inch diameter
Extruded rod, 1.25 inch diameter
Extruded bar, 1.25 x 4 inch
Hand forging, 3 x 6 inch
Die forging, 4.5 inch diameter
Forged slab, 0.875 inch

Properties:

TUS, ksi	TYS, ksi	Temp., °F
67-78	60-72	RT

Specimen Details: Unnotched

Gross Diameter, inches	Net Diameter, inches
1.00	0.400
0.273	0.100
---	0.200
---	0.160
1.00	0.500

Surface Condition:
Mechanically polished and as-machined

References: 3.2.1.1.8(a), (b), (d), and (e)

Test Parameters:
Loading - Axial
Frequency - 1100 to 3600 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
$\text{Log } N_f = 21.49 - 9.44 \log (S_{eq})$
$S_{eq} = S_{max} (1-R)^{0.67}$
Std. Error of Estimate, Log (Life) = 0.51
Standard Deviation, Log (Life) = 1.25
$R^2 = 83\%$

Sample Size = 127

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

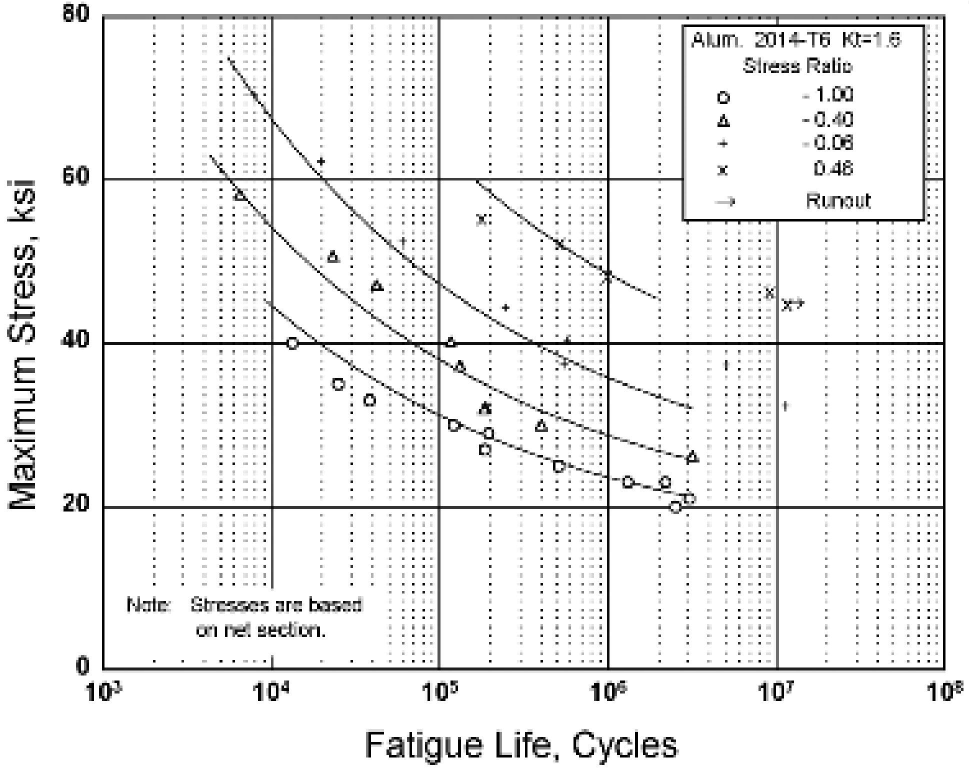


Figure 3.2.1.1.8(b). Best-fit S/N curves for notched, K_t = 1.6, 2014-T6 aluminum alloy rolled bar, longitudinal direction.

Correlative Information for Figure 3.2.1.1.8(b)

Product Form: Rolled bar, 1.125 inch diameter

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	72	64	RT

Specimen Details: Semicircular circumferential notch, K_t = 1.6
0.45 inch gross diameter
0.4 inch net diameter
0.01 inch root radius
60° flank angle, ω

Surface Condition: Polished

Reference: 3.2.1.1.8(b)

Test Parameters:
Loading - Axial
Frequency - 3600 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
$\text{Log } N_f = 10.65 - 4.02 \log (S_{eq} - 20.2)$
$S_{eq} = S_{max} (1-R)^{0.55}$
Std. Error of Estimate, Log (Life) = 0.33
Standard Deviation, Log (Life) = 0.87
R^2 = 86%

Sample Size = 33

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

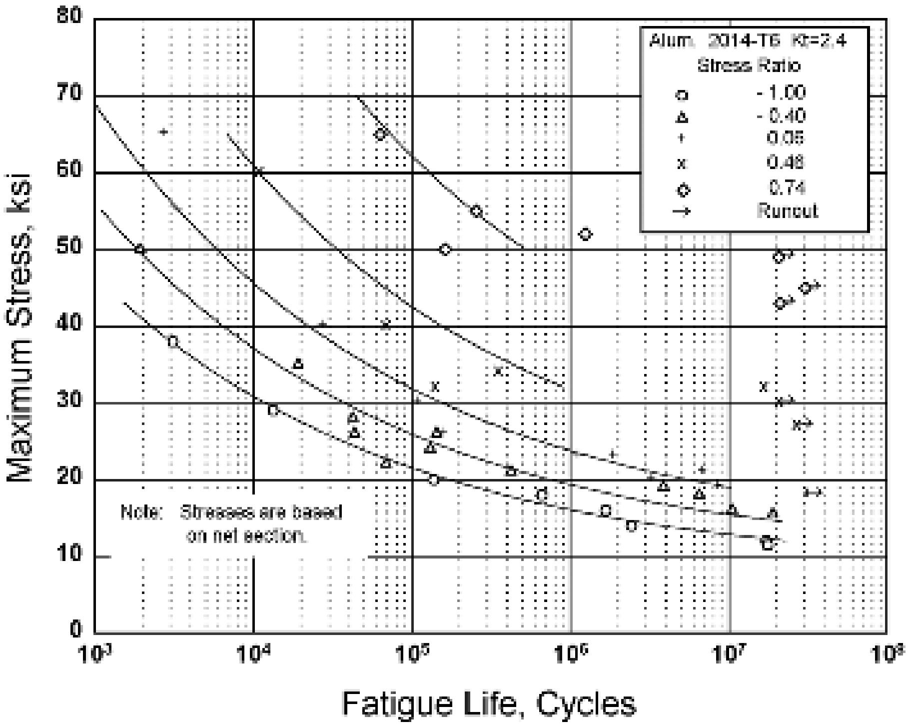


Figure 3.2.1.1.8(c). Best-fit S/N curves for notched, K_t = 2.4, 2014-T6 aluminum alloy rolled bar, longitudinal direction.

Correlative Information for Figure 3.2.1.1.8(c)

Product Form: Rolled bar, 1.125 inch diameter

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	72	64	RT

Specimen Details: Circumferential V-notch,
$K_t = 2.4$
0.500 inch gross diameter
0.400 inch net diameter
0.032 inch notch radius
60° flank angle, ω

Surface Condition: Polished

Reference: 3.2.1.1.8(b)

Test Parameters:
Loading - Axial
Frequency - 1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
$\text{Log } N_f = 10.59 - 4.36 \log (S_{eq} - 11.7)$
$S_{eq} = S_{max} (1-R)^{0.52}$
Std. Error of Estimate, Log (Life) = 0.38
Standard Deviation, Log (Life) = 1.18
$R^2 = 90\%$

Sample Size = 39

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

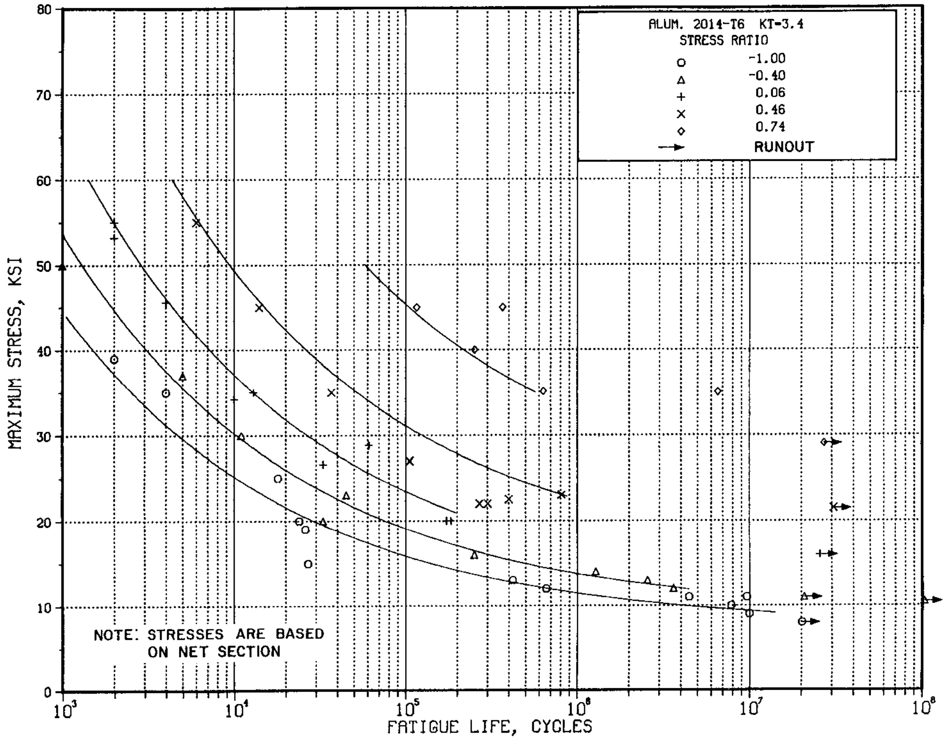


Figure 3.2.1.1.8(d). Best-fit S/N curves for notched, K_t = 3.4, 2014-T6 aluminum alloy rolled and extruded bar, longitudinal direction.

Correlative Information for Figure 3.2.1.1.8(d)

Product Form: Extruded bar, 1.125 inch diameter

Properties:

TUS, ksi	TYS, ksi	Temp.,°F
75	67	RT

Specimen Details: Circumferential V-notch,
K_t = 3.4
0.450 inch gross diameter
0.400 inch net diameter
0.010 inch notch radius
60° flank angle, ω

Surface Condition: Smooth machine finish

References: 3.2.1.1.8(b) and (c)

Test Parameters:
Loading - Axial
Frequency - 3600 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
Log N_f = 8.35-3.10 log (S_{eq}-10.6)
$S_{eq} = S_{max} (1-R)^{0.52}$
Std. Error of Estimate, Log (Life) = 0.34
Standard Deviation, Log (Life) = 1.10
R^2 = 90%

Sample Size = 45

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

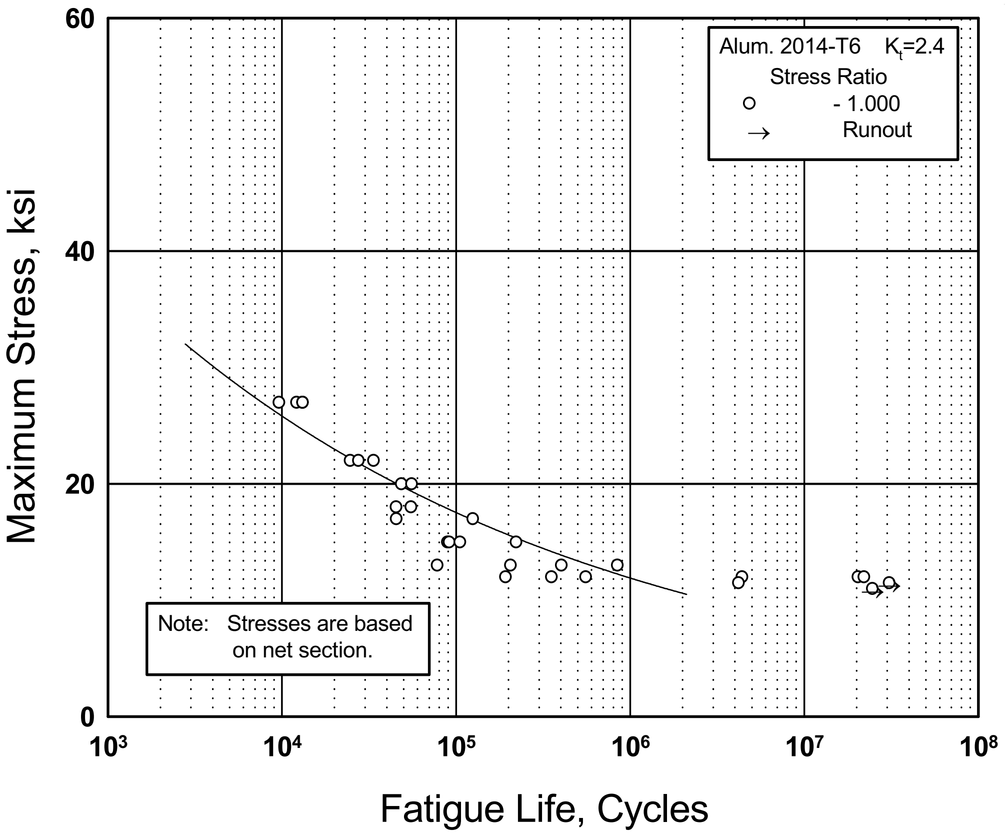


Figure 3.2.1.1.8(e). Best-fit S/N curves for notched, K_t = 2.4, 2014-T6 aluminum alloy hand forging, longitudinal and short transverse directions.

Correlative Information for Figure 3.2.1.1.8(e)

Product Form: Hand forging, 3 x 6 inch

Properties:	TUS, ksi	TYS, ksi	Temp.,°F
	Not specified		RT

Specimen Details: Circumferential V-notch,
K_t = 2.4
0.273 inch gross diameter
0.100 inch net diameter
0.010 inch notch radius
60° flank angle, ω

Surface Condition: Mechanically polished

Reference: 3.2.1.1.8(d)

Test Parameters:
Loading - Axial
Frequency - Not specified
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Maximum Stress Equation:
Log N_f = 12.4-5.95 log (S_{max})
Std. Error of Estimate, Log (Life) = 0.53
Standard Deviation, Log (Life) = 0.91
R^2 = 66%

Sample Size = 28

3.2.2 2017 ALLOY

3.2.2.0 *Comments and Properties* — 2017 is a heat-treatable Al-Cu alloy available in the form of rolled bar, rod, and wire, and is used principally for fasteners. Refer to Section 3.1.3.4 for comments regarding the weldability of the alloy.

A material specification for 2017 aluminum alloy is presented in Table 3.2.2.0(a). Room-temperature mechanical and physical properties are shown in Table 3.2.2.0(b). Figure 3.2.2.0 shows the effect of temperature on thermal expansion.

Table 3.2.2.0(a). Material Specifications for 2017 Aluminum Alloy

Specification	Form
AMS-QQ-A-225/5	Rolled bar and rod
AMS 4118	Bar and rod, rolled or cold-finished

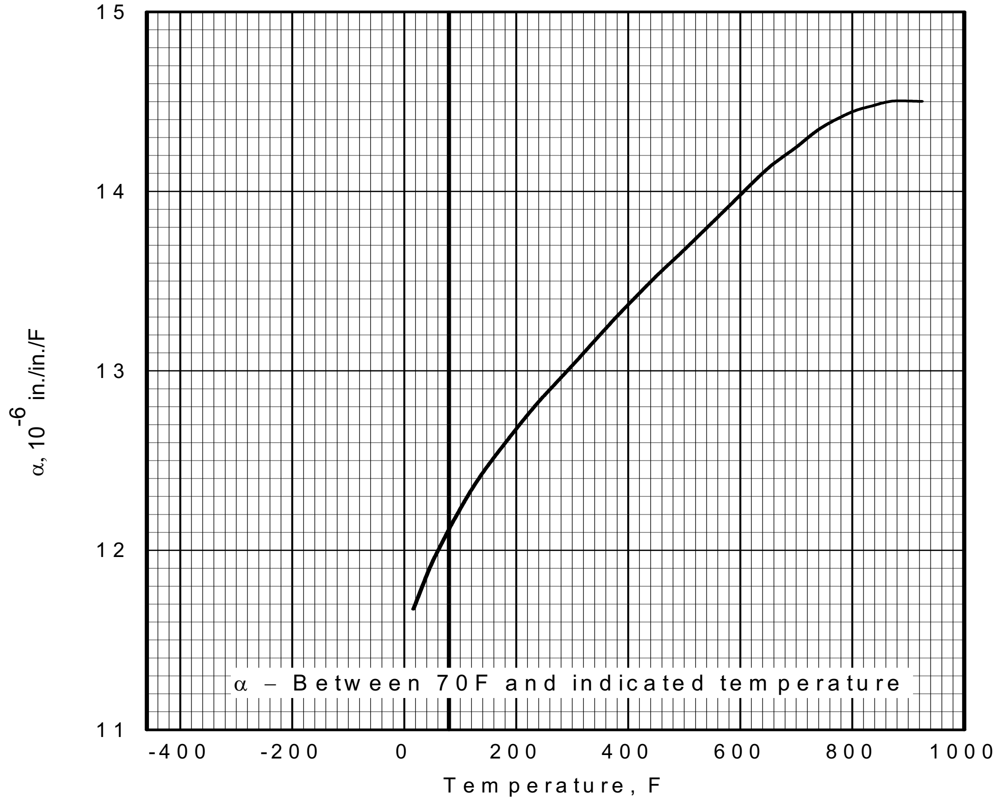


Figure 3.2.2.0. Effect of temperature on the thermal expansion of 2017 aluminum alloy.

The temper index for 2017 is as follows:

Section	Temper
3.2.2.1	T4, T451, and T42

3.2.2.1 *T4, T451, and T42 Temper* — The effect of temperature on modulus elasticity is presented in Figure 3.2.2.1.4.

Table 3.2.2.0(b). Design Mechanical and Physical Properties of 2017 Aluminum Alloy Bar and Rod; Rolled, Drawn, or Cold-Finished

Specification	AMS 4118 and AMS-QQ-A-225/5
Form	Bar and rod; rolled, drawn, or cold-finished
Temper	T4, T451, T42[a]
Cross-Sectional Area, in.^{2}	$\leq$50
Thickness or Diameter, in.	$\leq$8.000
Basis	S
Mechanical Properties:	
F_{tu}, ksi:	
L	55
LT	...
F_{ty}, ksi:	
L	32
LT	...
F_{cy}, ksi:	
L	32[b]
LT	...
F_{su}, ksi	33
F_{bru}, ksi:	
(e/D = 1.5)	83
(e/D = 2.0)	105
F_{bry}, ksi:	
(e/D = 1.5)	45
(e/D = 2.0)	51
e, percent (S-basis):	
L	12
E, 10^3 ksi	10.4
E_c, 10^3 ksi	10.6
G, 10^3 ksi	3.95
μ	0.33
Physical Properties:	
ω, lb/in.^{3}	0.101
C, Btu/(lb)(°F)	0.23 (at 212°F)
K, Btu/[(hr)(ft^2)(°F)/ft]	78 (at 77°F)
α, 10^{-6} in./in./°F	See Figure 3.2.2.0

a Design allowables were based upon data obtained from testing T4 material and from testing samples of bar and rod, supplied in the O or F temper, which were heat treated to T42 temper to demonstrate response to heat treatment by suppliers.

b For the stress-relieved temper T451, the F_{cy} value may be somewhat lower.

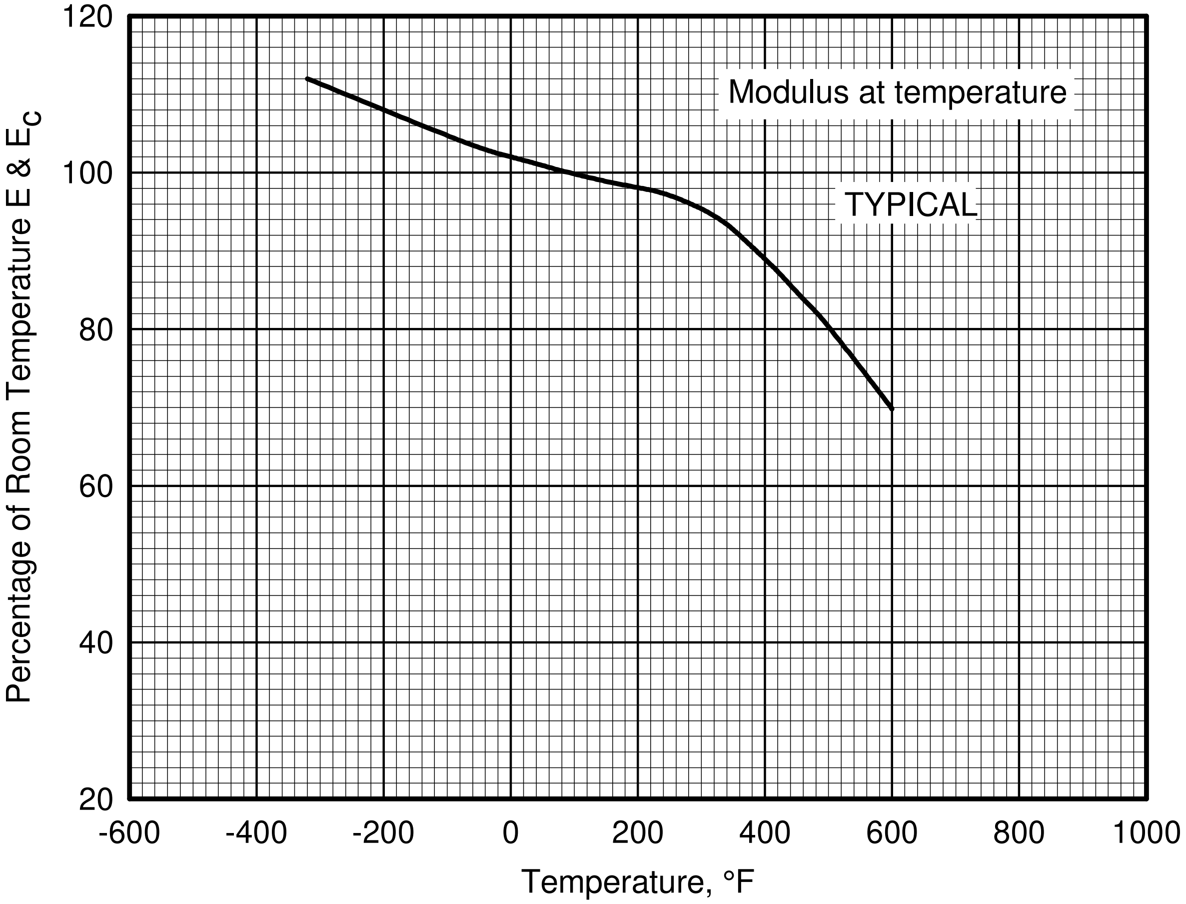


Figure 3.2.2.1.4. Effect of temperature on the tensile and compression moduli (E and E_c) of 2017 aluminum alloy.

3.2.3 2024 ALLOY

3.2.3.0 *Comments and Properties* — 2024 is a heat-treatable Al-Cu alloy which is available in a wide variety of product forms and tempers. The properties vary markedly with temper; those in T3 and T4 type tempers are noteworthy for their high toughness, while T6 and T8 type tempers have very high strength. This alloy has excellent properties and creep resistance at elevated temperatures. The T6 and T8 type tempers have very high resistance to corrosion. However, as shown in Table 3.1.2.3.1(a), 2024-T3, -T4, and -T42 rolled plate, rod and bar, and extruded shapes and 2024-T6 and -T62 forgings have a 'D' SCC rating. This is the lowest rating and means that SCC failures have occurred in service or would be anticipated if there is any sustained stress. In-service failures are caused by stresses produced by any combination of sources including solution heat treatment, straightening, forming, fit-up, clamping, sustained service loads or high service compression stresses that produce residual tensile stresses. These stresses may be tension or compression as well as the stresses due to the Poisson effect, because the actual failures are caused by the resulting sustained shear stresses. Pin-hole flaws in corrosion protection are sufficient for SCC. The weldability of the alloy is discussed in Section 3.1.3.4.

The properties of extrusions should be based upon the thickness at the time of quenching prior to machining. Selection of the mechanical properties based upon its final machined thickness may be unconservative; therefore, the thickness at the time of quenching to achieve properties is an important factor in the selection of the proper thickness column. For extrusions having sections with various thicknesses, consideration should be given to the properties as a function of thickness.

Material specifications for 2024 are presented in Table 3.2.3.0(a). Room-temperature mechanical properties are shown in Tables 3.2.3.0(b) through (j_2). The effect of temperature on the physical properties of this alloy is shown in Figure 3.2.3.0.

Table 3.2.3.0(a). Material Specifications for 2024 Aluminum Alloy

Specification	Form
AMS 4037	Bare sheet and plate
AMS 4035	Bare sheet and plate
AMS-QQ-A-250/4	Bare sheet and plate
AMS-QQ-A-250/5	Clad sheet and plate
AMS 4120	Bar and rod, rolled or cold-finished
AMS-QQ-A-225/6	Rolled or drawn bar, rod, and wire
AMS 4086	Tubing, hydraulic, seamless, drawn
AMS-WW-T-700/3	Tubing
AMS 4152	Extrusion
AMS 4164	Extrusion
AMS 4165	Extrusion
AMS-QQ-A-200/3	Extruded bar, rod, and shapes

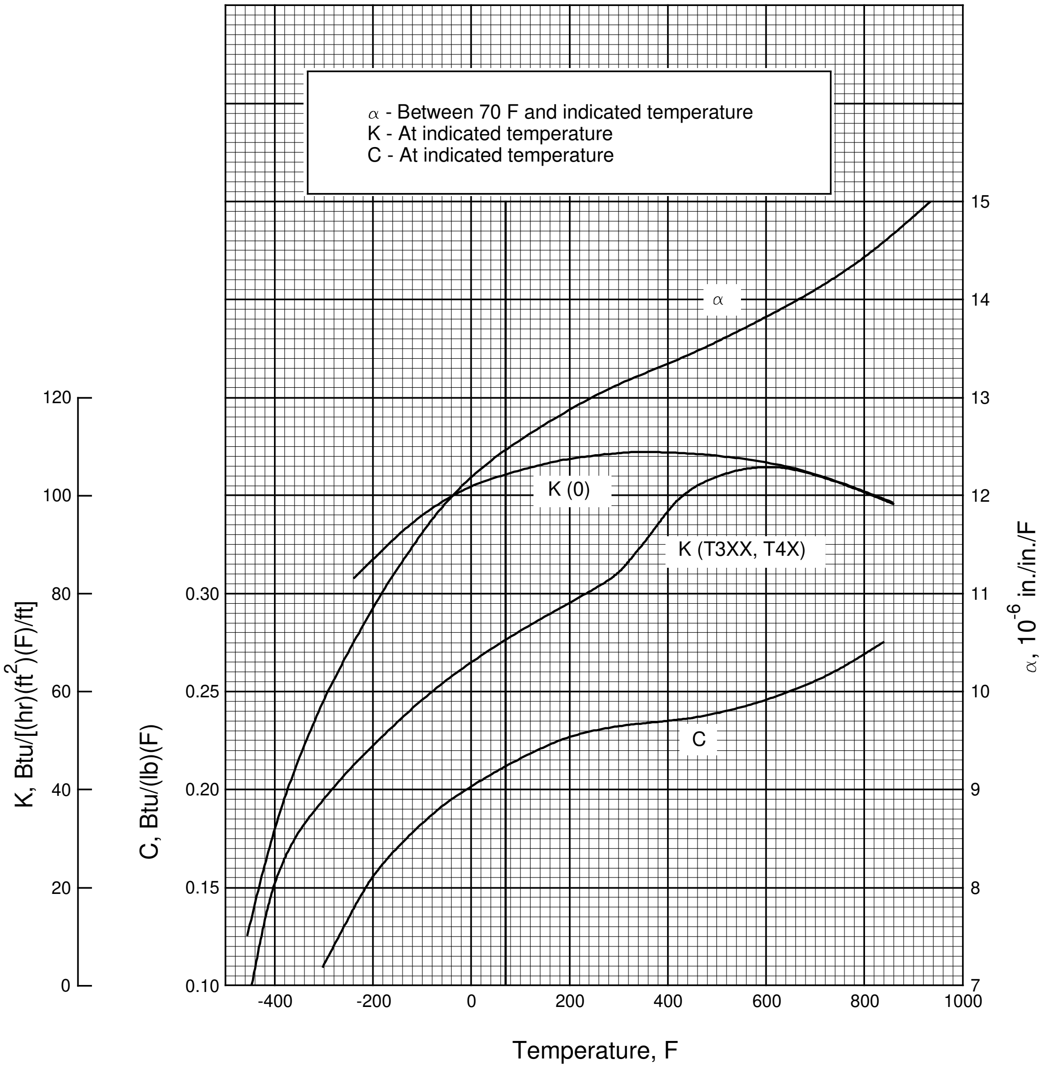


Figure 3.2.3.0. Effect of temperature on the physical properties of 2024 aluminum alloy.

The following temper designations are more specifically described than in Table 3.1.2.:

T81—The applicable designation for 2024-T3 sheet artificially aged to the required strength level.

T361—Solution heat treated and naturally aged followed by cold rolling and natural aging treatment.

T861—Solution heat treated and naturally aged followed by cold rolling and artificial aging treatment.

T72—Solution heat treated and aged by user in accordance with AMS 2770 to provide high resistance to stress-corrosion cracking, applicable only to sheet.

The temper index for 2024 is as follows:

Section	Temper
3.2.3.1	T3, T351, T3510, T3511, T4, and T42
3.2.3.2	T361 (supersedes T36)
3.2.3.3	T62 and T72
3.2.3.4	T81, T851, T8510, and T8511
3.2.3.5	T861 (supersedes T86)

3.2.3.1 ***T3, T351, T3510, T3511, T4, and T42 Temper*** — Figures 3.2.3.1.1(a) through 3.2.3.1.5(b) present elevated temperature curves for various properties. Figures 3.2.3.1.6(a) through (q) present tensile and compressive stress-strain curves and tangent-modulus curves for various product forms and tempers at various temperatures. Figures 3.2.3.1.6(r) through (w) are full-range, stress-strain curves at room temperature for various product forms. Figures 3.2.3.1.8(a) through (i) provide S/N fatigue curves for unnotched and notched specimens for T3 and T4 tempers.

3.2.3.2 ***T361 (supersedes T36) Temper*** —

3.2.3.3 ***T62 and T72 Temper*** — Figures 3.2.3.3.1(a) through (d) and 3.2.3.3.5(a) and (b) show the effect of temperature on the tensile properties of the T62 temper. Figure 3.2.3.1.4 can be used for the elevated temperature curve for elastic moduli for this temper. Tensile and compressive stress-strain and tangent-modulus curves at room temperature are shown in Figure 3.2.3.3.6.

3.2.3.4 ***T81, T851, T852, T8510, and T8511 Temper*** — Figures 3.2.3.4.1(a) through (d), 3.2.3.4.2(a) and (b), 3.2.3.4.3(a) and (b), and 3.2.3.4.5(a) and (b) present elevated temperature curves for various mechanical properties for the T8XXX temper. Figures 3.2.3.4.1(e) and (f) contain graphs for determining tensile properties after complex thermal exposure. See Section 3.7.4.1 for a detailed discussion of their use. Figures 3.2.3.4.6(a) through (g) present tensile and compressive stress-strain and tangent-modulus curves for various products and tempers. Figures 3.2.3.4.6(h) through (j) are full-range stress-strain curves at room temperature for various product forms.

3.2.3.5 ***T861 (T86) Temper*** — Figures 3.2.3.5.1(a) through (d), 3.2.3.5.2(a) and (b), 3.2.3.5.3(a) through (c), and 3.2.3.5.5(a) and (b) present effect-of-temperature curves for various mechanical properties. Figures 3.2.3.5.6(a) through (d) present compressive stress-strain and tangent-modulus curves for sheet material at various temperatures. Graphical displays of the residual strength behavior of center-cracked tension panels are presented in Figures 3.2.3.5.10(a) and (b).

Table 3.2.3.0(b$_1$). Design Mechanical and Physical Properties of 2024 Aluminum Alloy Sheet and Plate

Specification	AMS 4037 and AMS-QQ-A-250/4																	AMS-QQ-A-250/4		
Form	Sheet					Plate												Sheet		Plate
Temper	T3					T351												T361		
Thickness, in.	0.008-0.009	0.010-0.128		0.129-0.249		0.250-0.499		0.500-1.000		1.001-1.500		1.501-2.000		2.001-3.000		3.001-4.000		0.020-0.062	0.063-0.249	0.250-0.500
Basis	S	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	S	S	S
Mechanical Properties:																				
F_{tu}, ksi:																				
L	64	64	65	65	66	64	66	63	65	62	64	62	64	60	62	57	59	68	69	67
LT	63	63	64	64	65	64	66	63	65	62	64	62	64	60	62	57	59	67	68	66
ST	...	...	...	...	...	...	...	...	...	...	...	...	...	52[a]	54[a]	49[a]	51[a]	...	...	...
F_{ty}, ksi:																				
L	47	47	48	47	48	48	50	48	50	47	50	47	49	46	48	43	46	56	56	54
LT	42	42	43	42	43	42	44	42	44	42	44	42	44	42	44	41	43	50	51	49
ST	...	...	...	...	...	...	...	...	...	...	...	...	...	38[a]	40[a]	38[a]	39[a]	...	...	...
F_{cy}, ksi:																				
L	39	39	40	39	40	39	41	39	41	39	40	38	40	37	39	35	37	47	48	46
LT	45	45	46	45	46	45	47	45	47	44	46	44	46	43	45	41	43	53	54	52
ST	...	...	...	...	...	...	...	...	...	...	...	...	...	46	48	44	47	...	...	...
F_{su}, ksi	39	39	40	40	41	38	39	37	38	37	38	37	38	35	37	34	35	42	42	41
F_{bru}[b], ksi:																				
(e/D = 1.5)	104	104	106	106	107	97	100	95	98	94	97	94	97	91	94	86	89	111	112	109
(e/D = 2.0)	129	129	131	131	133	119	122	117	120	115	119	115	119	111	115	106	109	137	139	135
F_{bry}[b], ksi:																				
(e/D = 1.5)	73	73	75	73	75	72	76	72	76	72	76	72	76	72	76	70	74	82	84	81
(e/D = 2.0)	88	88	90	88	90	86	90	86	90	86	90	86	90	86	90	84	88	97	99	96
e, percent (S-basis):																				
LT	10	[c]	...	[c]	...	12	...	8	...	7	...	6	...	4	...	4	...	8	9	9[d]
E, 10^3 ksi	10.5					10.7												10.5		10.7
E_c, 10^3 ksi	10.7					10.9												10.7		10.9
G, 10^3 ksi	4.0					4.0												4.0		4.0
μ	0.33					0.33												0.33		0.33
Physical Properties:																				
ω, lb/in.	0.100																			
C, K, and α	See Figure 3.2.3.0																			

a Caution: This specific alloy, temper, and product form exhibits poor stress-corrosion cracking resistance in this grain direction. It corresponds to an SCC resistance rating of D, as indicated in Table 3.1.2.3.1(a).

b Bearing values are "dry pin" values per Section 1.4.7.1. See Table 3.1.2.1.1.

c See Table 3.2.3.0(c).

d 10% for 0.500 inch.

Table 3.2.3.0(b_2). Design Mechanical and Physical Properties of 2024 Aluminum Alloy Sheet and Plate—Continued

Specification	AMS-QQ-A-250/4		AMS 4035 and AMS-QQ-A-250/4					AMS-QQ-A-250/4				
Form	Coiled Sheet		Flat Sheet and Plate									
Temper	T4		T42[a]					T62[a]				T72[a]
Thickness, in.	0.010-0.249		0.010-0.249	0.250-0.499	0.500-1.000	1.001-2.000	2.001-3.000	0.010-0.249	0.250-0.499	0.500-2.000	2.001-3.000	0.010-0.249
Basis	A	B	S	S	S	S	S	S	S	S	S	S
Mechanical Properties:												
F_{tu}, ksi:												
L	62	64	62	62	61	60	...	63	63	63	...	...
LT	62	64	62	62	61	60	58	64	64	63	63	60
F_{ty}, ksi:												
L	40	42	38	38	38	38	...	50	50	50	...	...
LT	40	42	38	38	38	38	38	50	50	50	50	46
F_{cy}, ksi:												
L	40	42	42	42	40	37	...	52	52	52	...	...
LT	40	42	41	41	41	41	...	53	52	48	...	...
F_{su}, ksi	37	38	37	37	36	36	...	38	38	37	...	...
F_{bru}[b], ksi:												
(e/D = 1.5)	93	96	99	98	94	85[c]	...	103	103	102[c]	...	...
(e/D = 2.0)	118	122	123	123	121	119[c]	...	134	134	132[c]	...	...
F_{bry}[b], ksi:												
(e/D = 1.5)	56	59	67	67	67	67[c]	...	80	80	80[c]	...	...
(e/D = 2.0)	64	67	80	80	80	80[c]	...	95	95	95[c]	...	...
e, percent (S-basis):												
LT	[d]	...	[d]	12	8	[d]	4	5	5	5	5	5
E, 10^3 ksi	See Table 3.2.3.0(d)											
E_c, 10^3 ksi	See Table 3.2.3.0(d)											
G, 10^3 ksi	See Table 3.2.3.0(d)											
μ	See Table 3.2.3.0(d)											
Physical Properties:												
ω, lb/in.^{3}	0.100											
C, Btu/(lb)(°F)	See Figure 3.2.3.0											
K, Btu/[(hr)(ft^2)(°F)/ft]	71 (at 77°F) for T4X and 87 (at 77°F) for T6X, T7X, See Figure 3.2.3.0											
α, 10^{-6} in./in./°F	See Figure 3.2.3.0											

---

[a] Design allowables in some cases were based upon data obtained from testing samples of material, supplied in the O or F temper, which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained by the user may be different than those listed if the material has been formed or otherwise cold or hot worked, particularly in the annealed temper, prior to solution heat treatment.

[b] Bearing values are "dry pin" values per Section 1.4.7.1.

[c] See Table 3.1.2.1.1.

[d] See Table 3.2.3.0(c).

Table 3.2.3.0(b_3). Design Mechanical and Physical Properties of 2024 Aluminum Alloy Sheet and Plate—Continued

Specification	AMS-QQ-A-250/4								
Form	Sheet		Plate				Sheet		Plate
Temper	T81		T851				T861		
Thickness, in.	0.010-0.249		0.250-0.499		0.500-1.000	1.001-1.499	0.020-0.062	0.063-0.249	0.250-0.500
Basis	A	B	A	B	S	S	S	S	S
Mechanical Properties:									
F_{tu}, ksi:									
L	67	68	67	68	66	66	71	72	70
LT	67	68	67	68	66	66	70	71	70
F_{ty}, ksi:									
L	59	61	58	60	58	57	63	67	64
LT	58	60	58	60	58	57	62	66	64
F_{cy}, ksi:									
L	59	61	58	60	58	56	63	67	64
LT	58	60	59	61	58	57	65	69	67
F_{su}, ksi	40	41	38	39	37	37	40	40	40
F_{bru}[a], ksi:									
(e/D = 1.5)	100	102	102	103	100	100[b]	108	110	108
(e/D = 2.0)	127	129	131	133	129	129[b]	140	142	140
F_{bry}[a], ksi:									
(e/D = 1.5)	83	86	86	89	86	85[b]	90	96	93
(e/D = 2.0)	94	97	101	105	101	99[b]	105	112	109
e, percent (S-basis):									
LT	5	...	5	...	5	5	3	4	4
E, 10^3 ksi	See Table 3.2.3.0(d)								
E_c, 10^3 ksi	See Table 3.2.3.0(d)								
G, 10^3 ksi	See Table 3.2.3.0(d)								
μ	See Table 3.2.3.0(d)								
Physical Properties:									
ω, lb/in.^{3}	0.100								
C, Btu/(lb)(°F)	See Figure 3.2.3.0								
K, Btu/[(hr)(ft^2)(°F)/ft]	87 (at 77°F)								
α, 10^{-6} in./in./°F	See Figure 3.2.3.0								

[a] Bearing values are "dry pin" values per Section 1.4.7.1.
[b] See Table 3.1.2.1.1.

Table 3.2.3.0(c). Minimum Elongation Values for Bare 2024 Aluminum Alloy Sheet and Plate

	Elongation (LT), percent
Condition	T3, T4, and T42
Thickness, in.:	
0.010-0.020	12
0.021-0.249	15
0.250-0.499	12
0.500-1.000	8
1.001-1.500	7
1.501-2.000	6

Table 3.2.3.0(d). Modulus Values and Poisson's Ratio for Bare 2024 Aluminum Alloy Sheet and Plate, All Tempers

Property	E	E_c	G	μ
Thickness, in.:				
0.010-0.249	10.5	10.7	4.0	0.33
≥0.250	10.7	10.9	4.0	0.33

Table 3.2.3.0(e_1). Design Mechanical and Physical Properties of Clad 2024 Aluminum Alloy Sheet and Plate

Specification	AMS-QQ-A-250/5																			
Form	Flat sheet and plate																			
Temper	T3								T351											
Thickness, in.	0.008-0.009		0.010-0.062		0.063-0.128		0.129-0.249		0.250-0.499		0.500-1.000[a]		1.001-1.500[a]		1.501-2.000[a]		2.001-3.000[a]		3.001-4.000[a]	
Basis	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
Mechanical Properties:																				
F_{tu}, ksi:																				
L	59	60	60	61	62	63	63	64	62	64	61	63	60	62	60	62	58	60	55	57
LT	58	59	59	60	61	62	62	63	62	64	61	63	60	62	60	62	58	60	55	57
ST	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	52[b]	54[b]	49[b]	51[b]
F_{ty}, ksi:																				
L	44	45	44	45	45	47	45	47	46	48	45	48	45	48	45	47	44	46	39	41
LT	39	40	39	40	40	42	40	42	40	42	40	42	40	42	40	42	40	42	39	41
ST	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	38[b]	40[b]	38[b]	39[b]
F_{cy}, ksi:																				
L	36	37	36	37	37	39	37	39	37	39	37	39	37	39	36	38	35	37	33	35
LT	42	43	42	43	43	45	43	45	43	45	42	45	42	44	42	44	41	43	39	41
ST	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	46	48	44	47
F_{su}, ksi	37	37	37	38	38	39	39	40	37	38	36	37	35	37	35	37	34	35	32	34
F_{bru}[c], ksi:																				
(e/D = 1.5)	96	97	97	99	101	102	102	104	94	97	92	95	91	94	91	94	88	91	83	86
(e/D = 2.0)	119	121	121	123	125	127	127	129	115	119	113	117	111	115	111	115	107	111	102	106
F_{bry}[c], ksi:																				
(e/D = 1.5)	68	70	68	70	70	73	70	73	69	72	69	72	69	72	69	72	69	72	67	70
(e/D = 2.0)	82	84	82	84	84	88	84	88	82	86	82	86	82	86	82	86	82	86	80	84
e, percent (S-basis):																				
LT	10	...	[d]	...	15	...	15	...	12	...	8	...	7	...	6	...	4	...	4	...
E, 10^3 ksi:																				
Primary	10.5								10.7											
Secondary	9.5				10.0				10.2											
E_c, 10^3 ksi:																				
Primary	10.7								10.9											
Secondary	9.7				10.2				10.4											
G, 10^3 ksi	...																			
μ	0.33																			
Physical Properties:																				
ω, lb/in.^{3}	0.100																			
C, K, and α	...																			

[a] These values, except in the ST direction, have been adjusted to represent the average properties across the whole section, including the 2-½ percent nominal cladding thickness.

[b] Caution: This specific alloy, temper, and product form exhibits poor stress-corrosion cracking resistance in this grain direction. It corresponds to an SCC resistance rating of D, as indicated in Table 3.1.2.3.1(a).

[c] Bearing values are "dry pin" values per Section 1.4.7.1. See Table 3.1.2.1.1.

[d] See Table 3.2.3.0(f).

Table 3.2.3.0(e_2). Design Mechanical and Physical Properties of Clad 2024 Aluminum Alloy Sheet and Plate—Continued

Specification	AMS-QQ-A-250/5							
Form	Flat sheet and plate				Coiled sheet			
Temper	T361				T4			
Thickness, in.	0.020-0.062	0.063-0.249	0.250-0.499	0.500[a]	0.010-0.062		0.063-0.128	
Basis	S	S	S	S	A	B	A	B
Mechanical Properties:								
F_{tu}, ksi:								
L	62	65	65	64	58	59	61	62
LT	61	64	64	63	58	59	61	62
F_{ty}, ksi:								
L	53	53	53	52	36	38	38	39
LT	47	48	48	47	36	38	38	39
F_{cy}, ksi:								
L	44	45	45	44	36	38	38	39
LT	50	51	51	50	36	38	38	39
F_{su}, ksi	38	40	40	39	37	37	38	39
F_{bru}[b], ksi:								
(e/D = 1.5)	101	105	105	104	96	97	101	102
(e/D = 2.0)	125	131	131	129	119	121	125	127
F_{bry}[b], ksi:								
(e/D = 1.5)	78	79	79	78	63	66	66	68
(e/D = 2.0)	92	94	94	92	76	80	80	82
e, percent (S-basis):								
LT	8	9	9	10	[c]	...	15	...
E, 10^3 ksi:								
Primary	10.5	10.5	10.7		10.5		10.5	
Secondary	9.5	10.0	10.2		9.5		10.0	
E_c, 10^3 ksi:								
Primary	10.7	10.7	10.9		10.7		10.7	
Secondary	9.7	10.2	10.4		9.7		10.2	
G, 10^3 ksi	...							
μ	0.33							
Physical Properties:								
ω, lb/in.^{3}	0.100							
C, K, and α	...							

[a] These values have been adjusted to represent the average properties across the whole section, including the 2-½ percent nominal cladding thickness.

[b] Bearing values are "dry pin" values per Section 1.4.7.1.

[c] See Table 3.2.3.0(f).

Table 3.2.3.0(e_3). Design Mechanical and Physical Properties of Clad 2024 Aluminum Alloy Sheet and Plate—Continued

Specification	AMS-QQ-A-250/5														
Form	Flat sheet and plate														
Temper	T42[a]										T62[a]			T72[a]	
Thickness, in.	0.008-0.009		0.010-0.062		0.063-0.249		0.250-0.499	0.500-1.000[b]	1.001-2.000[b]	2.001-3.000[b]	0.010-0.062	0.063-0.249	0.250-0.499	0.010-0.062	0.063-0.249
Basis	A	B	A	B	A[c]	B[c]	S[c]	S[c]	S[c,d]	S	S	S[c]	S[c]	S	S
Mechanical Properties:															
F_{tu}, ksi:															
L	55	57	57	59	60	62	60	59	58	...	60	62	62	...	...
LT	55	57	57	59	60	62	60	59	58	56	60	62	62	56	58
F_{ty}, ksi:															
L	34	35	34	35	36	38	36	36	36	...	47	49	49	...	...
LT	34	35	34	35	36	38	36	36	36	36	47	49	49	43	45
F_{cy}, ksi:															
L	38	39	38	39	40	42	39	38	35	...	49	51	51	...	...
LT	37	38	37	38	39	41	39	39	39	...	49	52	51	...	...
F_{su}, ksi	33	34	34	35	36	37	36	35	35	...	35	36	36	...	...
F_{bru}, ksi:															
(e/D = 1.5)	88	91	91	94	96	99	95	90	83	...	97	100	100	...	...
(e/D = 2.0)	109	113	113	117	119	123	119	117	115	...	126	130	130	...	...
F_{bry}, ksi:															
(e/D = 1.5)	60	61	60	61	63	67	63	63	63	...	75	79	79	...	...
(e/D = 2.0)	72	74	72	74	76	80	76	76	76	...	89	93	93	...	...
e, percent (S-basis):															
LT	10	...	[e]	...	15	...	12	8	[e]	4	5	5	5	5	5
E, 10^3 ksi:															
Primary	10.5				10.5		10.7				10.5		10.7	10.5	10.5
Secondary	9.5				10.0		10.2				10.0		10.2	9.5	10.0
E_c, 10^3 ksi:															
Primary	10.7				10.7		10.9				10.7		10.9	10.7	10.7
Secondary	9.7				10.2		10.4				10.2		10.4	9.7	10.2
G, 10^3 ksi	...														
μ	0.33														
Physical Properties:															
ω, lb/in.^{3}	0.100														
C, K, and α	...														

a Design allowables in some cases were based upon data obtained from testing samples of material, supplied in the O or F temper, which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained by the user may be different than those listed if the material has been formed or otherwise cold or hot worked, particularly in the annealed temper, prior to solution heat treatment.

b These values have been adjusted to represent the average properties across the whole section, including 2½ percent per side nominal cladding thickness.

c Bearing values are "dry pin" values per Section 1.4.7.1.

d See Table 3.1.2.1.1.

e See Table 3.2.3.0(f).

Table 3.2.3.0(e_4). Design Mechanical and Physical Properties of Clad 2024 Aluminum Alloy Sheet and Plate—Continued

Specification	AMS-QQ-A-250/5								
Form	Flat sheet and plate								
Temper	T81		T851[a]			T861[a]			
Thickness, in.	0.010-0.062	0.063-0.249	0.250-0.499		0.500-1.000[b]	0.020-0.062	0.063-0.249	0.250-0.499	0.500[b]
Basis	S	S	A	B	S	S	S	S	S
Mechanical Properties:									
F_{tu}, ksi:									
L	64	67	65	66	63	65	70	68	67
LT	62	65	65	66	63	64	69	68	67
F_{ty}, ksi:									
L	57	59	56	58	56	59	65	62	61
LT	54	56	56	58	56	58	64	62	61
F_{cy}, ksi:									
L	55	57	56	58	56	59	65	62	61
LT	55	57	57	59	56	61	67	65	64
F_{su}, ksi	38	39	37	37	36	36	39	39	38
F_{bru}, ksi:									
(e/D = 1.5)	96	100	99	100	96	99	107	105	104
(e/D = 2.0)	122	127	127	129	123	128	138	136	134
F_{bry}, ksi:									
(e/D = 1.5)	78	83	83	86	83	84	93	90	88
(e/D = 2.0)	90	94	98	101	98	99	109	105	104
e, percent (S-basis):									
LT	5	5	5	...	5	3	4	4	4
E, 10^3 ksi:									
Primary	10.5	10.5	10.7			10.5	10.5	10.5	
Secondary	9.5	10.0	10.2			9.5	10.0	10.2	
E_c, 10^3 ksi:									
Primary	10.7	10.7	10.9			10.7	10.7	10.9	
Secondary	9.7	10.2	10.4			9.7	10.2	10.4	
G, 10^3 ksi	...								
μ	0.33								
Physical Properties:									
ω, lb/in.^{3}	0.100								
C, K, and α	...								

[a] Bearing values are "dry pin" values per Section 1.4.7.1.

[b] These values have been adjusted to represent the average properties across the whole section, including the 2-½ percent nominal cladding thickness.

Table 3.2.3.0(f). Minimum Elongation Values for Clad 2024 Aluminum Alloy Sheet and Plate

	Elongation (LT), percent
Temper	T3, T4, T42
Thickness, in.:	
0.010-0.020	12
0.021-0.062	15
1.001-1.500	7
1.501-2.000	6

Table 3.2.3.0(g). Design Mechanical and Physical Properties of 2024 Aluminum Alloy Drawn Tubing

Specification	AMS 4086 and WW-T-700/3		WW-T-700/3	
Form	Drawn tubing			
Temper	T3		T42[a]	T81
Wall Thickness, in.	0.018-0.500		0.018-0.500	0.010-0.249
Basis	A	B	S	S
Mechanical Properties:				
F_{tu}, ksi:				
L	64	66	62	66
LT	...	...	...	...
F_{ty}, ksi:				
L	42	45	38	58
LT	...	...	...	...
F_{cy}, ksi:				
L	42	45	38	...
LT	...	...	...	...
F_{su}, ksi	39	40	38	...
F_{bru}, ksi:				
(e/D = 1.5)	96	99	93	...
(e/D = 2.0)	122	126	118	...
F_{bry}, ksi:				
(e/D = 1.5)	59	63	53	...
(e/D = 2.0)	67	72	61	...
e, percent (S-basis):	[b]		[b]	[b]
L		...		
E, 10^3 ksi	10.5			
E_c, 10^3 ksi	10.7			
G, 10^3 ksi	4.0			
μ	0.33			
Physical Properties:				
ω, lb/in.^{3}	0.100			
C, K, and α	See Figure 3.2.3.0			

a Design allowables were based upon data obtained from testing samples of material supplied in the O or F temper, which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained by the user, however, may be lower than those listed if the material has been formed or otherwise cold or hot worked, particularly in the annealed temper, prior to solution heat treatment.

b See Table 3.2.3.0(h).

Table 3.2.3.0(h). Minimum Elongation Values for 2024 Aluminum Alloy Drawn Tubing

	Elongation (L), percent[a]
Temper	T3, T42
Wall Thickness, in.:	
0.018-0.024	10
0.025-0.049	12
0.050-0.259	14
0.260-0.500	16
Temper	T81
0.010-0.024	...
0.025-0.049	5
0.050-0.249	6

a Full section specimen.

Table 3.2.3.0(i_1). Design Mechanical and Physical Properties of 2024 Aluminum Alloy Bar and Rod; Rolled, Drawn, or Cold-Finished

Specification	AMS 4120 and AMS-QQ-A-225/6							AMS-QQ-A-225/6
Form	Bar and rod; rolled, drawn, or cold-finished							
Temper	T351							T361
Thickness, in.	0.500-1.000	1.001-2.000	2.001-3.000	3.001-4.000	4.001-5.000[a]	5.001-6.000[a]	6.001-6.500[a]	≤0.375
Basis	S	S	S	S	S	S	S	S
Mechanical Properties:								
F_{tu}, ksi:								
L	62	62	62	62	62	62	62	69
LT	61[b]	59[b]	57[b]	55[b]	54[b]	52[b]	...	...
F_{ty}, ksi:								
L	45	45	45	45	45	45	45	52
LT	36[b]	36[b]	36[b]	36[b]	36[b]	36[b]	...	...
F_{cy}, ksi:								
L	34	34	34	34	34	34	...	...
LT	41	41	41	41	41	41	...	...
F_{su}, ksi	37	37	37	37	37	37	...	...
F_{bru}, ksi:								
(e/D = 1.5)	90	90	90	90	90	90	...	...
(e/D = 2.0)	115	115	115	115	115	115	...	...
F_{bry}, ksi:								
(e/D = 1.5)	63	63	63	63	63	63	...	...
(e/D = 2.0)	74	74	74	74	74	74	...	...
e, percent:								
L	10	10	10	10	10	10	10	10
E, 10^3 ksi	10.5							
E_c, 10^3 ksi	10.7							
G, 10^3 ksi	4.0							
μ	0.33							
Physical Properties:								
ω, lb/in.^{3}	0.100							
C, K, and α	See Figure 3.2.3.0							

a For square, rectangular, hexagonal, or octagonal bar, minimum thickness is 4 inches, and maximum cross-sectional area is 36 square inches.

b Caution: This specific alloy, temper, and product form exhibits poor stress-corrosion cracking resistance in this grain direction. It corresponds to an SCC resistance rating of D, as indicated in Table 3.1.2.3.1(a).

Table 3.2.3.0(i_2). Design Mechanical and Physical Properties of 2024 Aluminum Alloy Bar and Rod; Rolled, Drawn, or Cold-Finished—Continued

Specification	AMS 4120 and AMS-QQ-A-225/6										AMS-QQ-A-225/6
Form	Bar and rod; rolled, drawn, or cold-finished										
Temper	T4[a]										T42[b]
Thickness, in.	0.125-0.499	0.500-1.000	1.001-2.000	2.001-3.000	3.001-4.000	4.001-4.500[c]	4.501-5.000[d]	5.001-6.000[c]	6.001-6.500[d]	6.501-8.000[d]	≤6.500[c]
Basis	S	S	S	S	S	S	S	S	S	S	S
Mechanical Properties:											
F_{tu}, ksi:											
L	62	62	62	62	62	62	62	62	62	58	62
LT	61[e]	61[e]	59[e]	57[e]	55[e]	54[e]	54[e]	52[e]	...	...	...
F_{ty}, ksi:											
L	45	42	42	42	42	42	40	40	40	38	40
LT	45[e]	42[e]	41[e]	40[e]	39[e]	39[e]	37[e]	36[e]	...	...	...
F_{cy}, ksi:											
L	36	33	33	33	33	33	32	32	...	...	...
LT	...	...	...	...	...	...	...	...	...	...	...
F_{su}, ksi	37	37	37	37	37	37	37	37	37	...	...
F_{bru}, ksi:											
(e/D = 1.5)	93	93	93	93	93	93	93	93	...	...	...
(e/D = 2.0)	118	118	118	118	118	118	118	118	...	...	...
F_{bry}, ksi:											
(e/D = 1.5)	63	59	59	59	59	59	56	56	...	...	...
(e/D = 2.0)	72	67	67	67	67	67	64	64	...	...	...
e, percent:											
L	10	10	10	10	10	10	10	10	10	10	10
E, 10^3 ksi	10.5										
E_c, 10^3 ksi	10.7										
G, 10^3 ksi	4.0										
μ	0.33										
Physical Properties:											
ω, lb/in.^{3}	0.100										
C and α	See Figure 3.2.3.0										
K, Btu/[(hr)(ft^2)(°F)/ft]	71 (at 77°F) for T4X (See Figure 3.2.3.0)										

[a] The T4 temper is obsolete and should not be specified for new designs.

[b] These properties apply when samples of material supplied in the O or F temper are heat treated to demonstrate response to heat treatment. Properties obtained by the user, however, may be lower than those listed if the material has been formed or otherwise cold or hot worked, particularly in the annealed temper, prior to solution heat treatment.

[c] For square, rectangular, hexagonal, or octagonal bar, maximum thickness is 4 inches, and maximum cross-sectional area is 36 square inches.

[d] Applies to rod only.

[e] Caution: This specific alloy, temper, and product form exhibits poor stress-corrosion cracking resistance in this grain direction. It corresponds to an SCC resistance rating of D, as indicated in Table 3.1.2.3.1(a).

Table 3.2.3.0(i_3). Design Mechanical and Physical Properties of 2024 Aluminum Alloy Bar and Rod; Rolled, Drawn, or Cold-Finished—Continued

Specification	AMS-QQ-A-225/6		
Form	Bar and rod; rolled, drawn, or cold finished		
Temper	T6[a]	T62[b]	T851
Thickness,[c] in.	≤6.500	≤6.500	0.500-6.500
Basis	S	S	S
Mechanical Properties:			
F_{tu}, ksi:			
L	62	60	66
LT	...	...	...
F_{ty}, ksi:			
L	50	46	58
LT	...	...	...
F_{cy}, ksi:			
L	...	...	...
LT	...	...	...
F_{su}, ksi	...	...	...
F_{bru}, ksi:			
(e/D = 1.5)	...	...	...
(e/D = 2.0)	...	...	...
F_{bry}, ksi:			
(e/D = 1.5)	...	...	...
(e/D = 2.0)	...	...	...
e, percent:			
L	5	5	5
E, 10^3 ksi	10.5		
E_c, 10^3 ksi	10.7		
G, 10^3 ksi	4.0		
μ	0.33		
Physical Properties:			
ω, lb/in.^{3}	0.100		
C and α	See Figure 3.2.3.0		
K, Btu/[(hr)(ft^2)(°F)/ft]	87 (at 77°F) for T6X and T8XX		

a The T6 temper is obsolete and should not be specified for new designs.

b These properties apply when samples of material supplied in the O or F temper are heat treated to demonstrate response to heat treatment. Properties obtained by the user, however, may be lower than those listed if the material has been formed or otherwise cold or hot worked, particularly in the annealed temper, prior to solution heat treatment.

c For square, rectangular, hexagonal, or octagonal bar, maximum thickness is 4 inches, and maximum cross-sectional area is 36 square inches.

Table 3.2.3.0(j_1). Design Mechanical and Physical Properties of 2024 Aluminum Alloy Extrusion

Specification	AMS 4152, AMS 4164, AMS 4165, and AMS-QQ-A-200/3														AMS-QQ-A-200/3		
Form	Extruded bar, rod, and shapes																
Temper	T3, T3510, and T3511														T81, T8510, and T8511		
Thickness,[a] in.	≤0.249		0.250-0.499		0.500-0.749		0.750-1.499		1.500-2.999		3.000-4.499		1.500-2.999	3.000-4.499	0.050-0.249	0.250-1.499	1.500-4.500
Cross-Section Area, in.^{2}	≤20								≤25				>25 - ≤32		≤20		≤32
Basis	A	B	A	B	A	B	A	B	A	B	A	B	S	S	S	S	S
Mechanical Properties:																	
F_{tu}, ksi:																	
L	57	61	60	62	60	62	65	70	70	74	70	74	68	68	64	66	66
LT	54	58	56	57	54	56	56	60	55	58	54	57	53	52	64	64	61
F_{ty}, ksi:																	
L	42	47	44	47	44	47	46	54	52	54	52	54	48	48	56	58	58
LT	37	41	38	40	37	39	37	43	39	41	39	41	36	36	55	57	57
F_{cy}, ksi:																	
L	34	38	37	39	38	40	41	48	49	50	49	51	45	45	57	59	59
LT	41	45	41	44	40	43	40	47	42	44	41	43	39	38	57	59	59
F_{su}, ksi	29	31	31	32	30	31	33	35	34	36	33	35	33	32	35	36	36
F_{bru}[b], ksi:																	
(e/D = 1.5)	84	90	78	81	78	80	84	90	88	93	86	91	86	84	94	96	92
(e/D = 2.0)	108	114	98	101	97	101	105	113	111	118	109	115	108	106	123	123	117
F_{bry}[b], ksi:																	
(e/D = 1.5)	61	68	55	59	55	59	57	67	63	66	62	65	59	57	79	82	82
(e/D = 2.0)	71	79	67	71	67	71	69	81	77	80	75	78	71	69	93	96	96
e, percent (S-basis):																	
L	12	...	12	...	12	...	10	...	10	...	10	...	8	8	4	5	5
E, 10^3 ksi	10.8																
E_c, 10^3 ksi	11.0																
G, 10^3 ksi	4.1																
μ	0.33																
Physical Properties:																	
ω, lb/in.^{3}	0.100																
C, K, and α	See Figure 3.2.3.0																

a The mechanical properties are to be based upon the thickness at the time of quench.

b Bearing values are “dry pin” values per Section 1.4.7.1.

Table 3.2.3.0(j_2). Design Mechanical and Physical Properties of 2024 Aluminum Alloy Extrusion—Concluded

Specification	AMS-QQ-A-200/3									
Form	Extruded bar, rod, and shapes									
Temper	T42[a]									
Cross-Sectional Area, in.^{2}	≤ 25									
Thickness or Diameter,[b] in.	≤ 0.249	0.250-0.499	0.500-0.749	0.750-0.999	1.000-1.249	1.250-1.499	1.500-1.749	1.750-1.999	2.000-2.249	2.250-2.499
Basis	S	S	S	S	S	S	S	S	S	S
Mechanical Properties:										
F_{tu}, ksi:										
L	57	57	57	57	57	57	57	57	57	57
LT	55	54	52	51	49	47	45	43	41	39
F_{ty}, ksi:										
L	38	38	38	38	38	38	38	38	38	38
LT	36	35	34	33	32	31	30	29	28	27
F_{cy}, ksi:										
L	38	38	38	38	38	38	38	38	38	38
LT	39	38	37	36	35	34	33	31	30	29
F_{su}, ksi	29	29	29	29	29	29	28	27	26	24
F_{bru}[c], ksi:										
(e/D = 1.5)	81	80	79	77	75	74	71	69	67	64
(e/D = 2.0)	99	98	97	95	93	91	89	86	83	81
F_{bry}[c], ksi:										
(e/D = 1.5)	56	55	53	51	49	47	44	41	39	36
(e/D = 2.0)	69	67	65	63	61	59	56	53	50	47
e, percent:										
L	12	12	12	10	10	10	10	10	10	10
E, 10^3 ksi	10.8									
E_c, 10^3 ksi	11.0									
G, 10^3 ksi	4.1									
μ	0.33									
Physical Properties:										
ω, lb/in.^{3}	0.100									
C, K, and α	See Figure 3.2.3.0									

[a] Design allowables were based upon data obtained from testing samples of material supplied in the O or F temper, which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained by the user, however, may be lower than those listed if the material has been formed or otherwise cold or hot worked, particularly in the annealed temper, prior to solution heat treatment.

[b] The mechanical properties are to be based upon the thickness at the time of quench.

[c] Bearing values are “dry pin” values per Section 1.4.7.1.

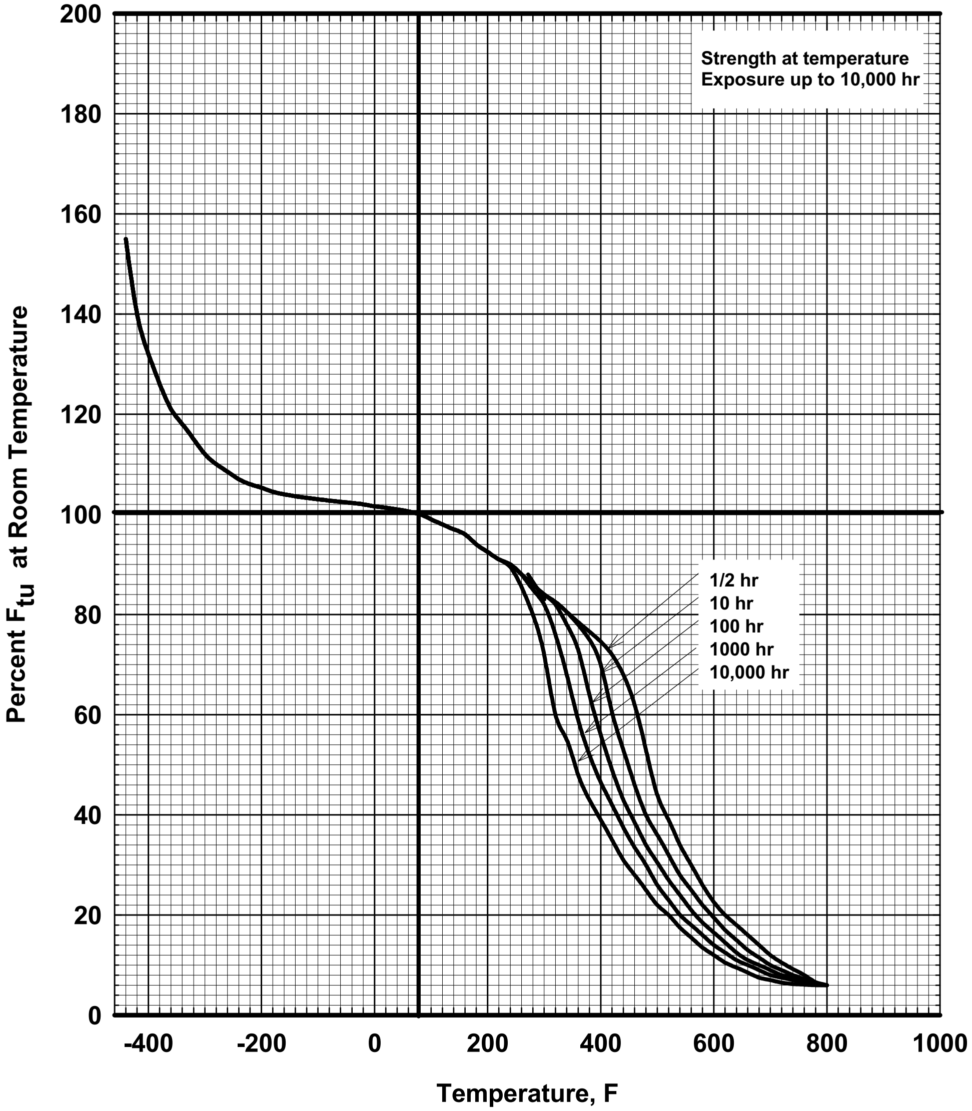


Figure 3.2.3.1.1(a). Effect of temperature on the tensile ultimate strength (F_{tu}) of 2024-T3, T351, and 2024-T4 aluminum alloy (all products except extrusions).

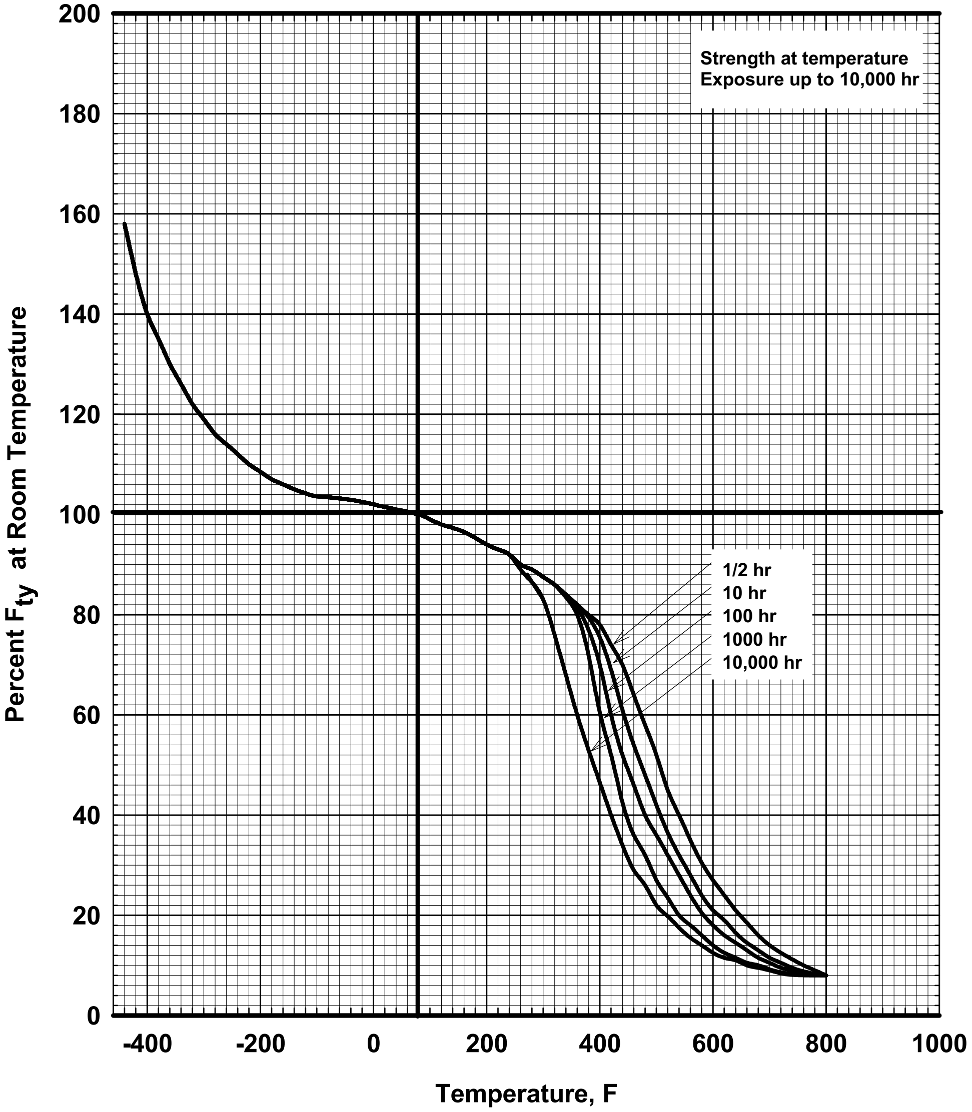


Figure 3.2.3.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of 2024-T3, T351, and 2024-T4 aluminum alloy (all products except extrusions).

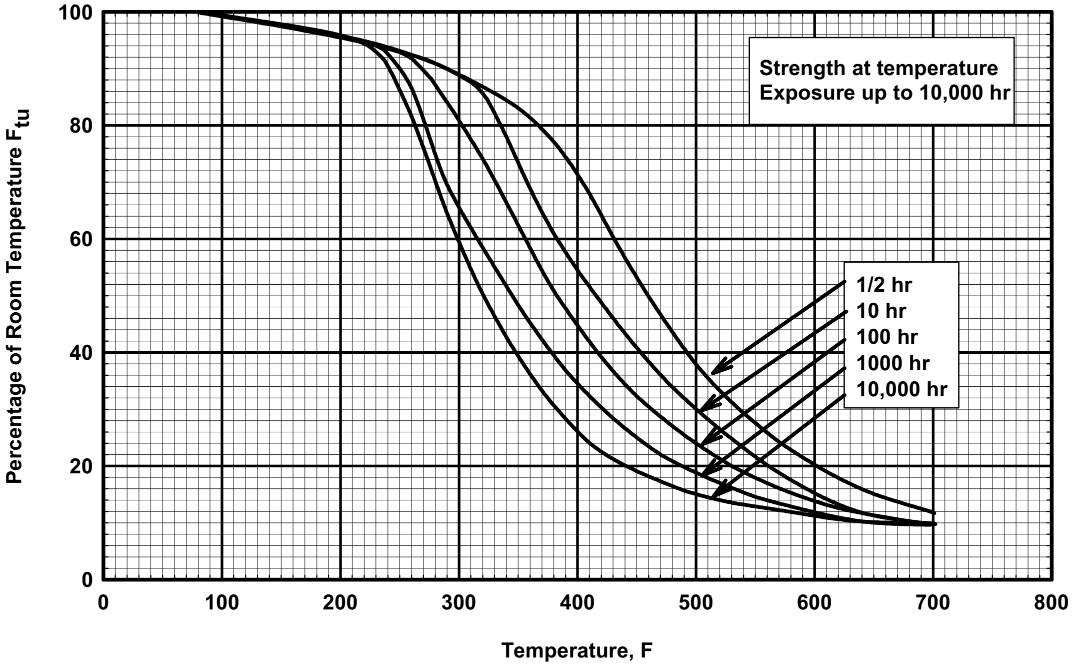


Figure 3.2.3.1.1(c). Effect of temperature on the tensile ultimate strength (F_{tu}) of 2024-T3, T3510, T3511, and T42 aluminum alloy extrusion.

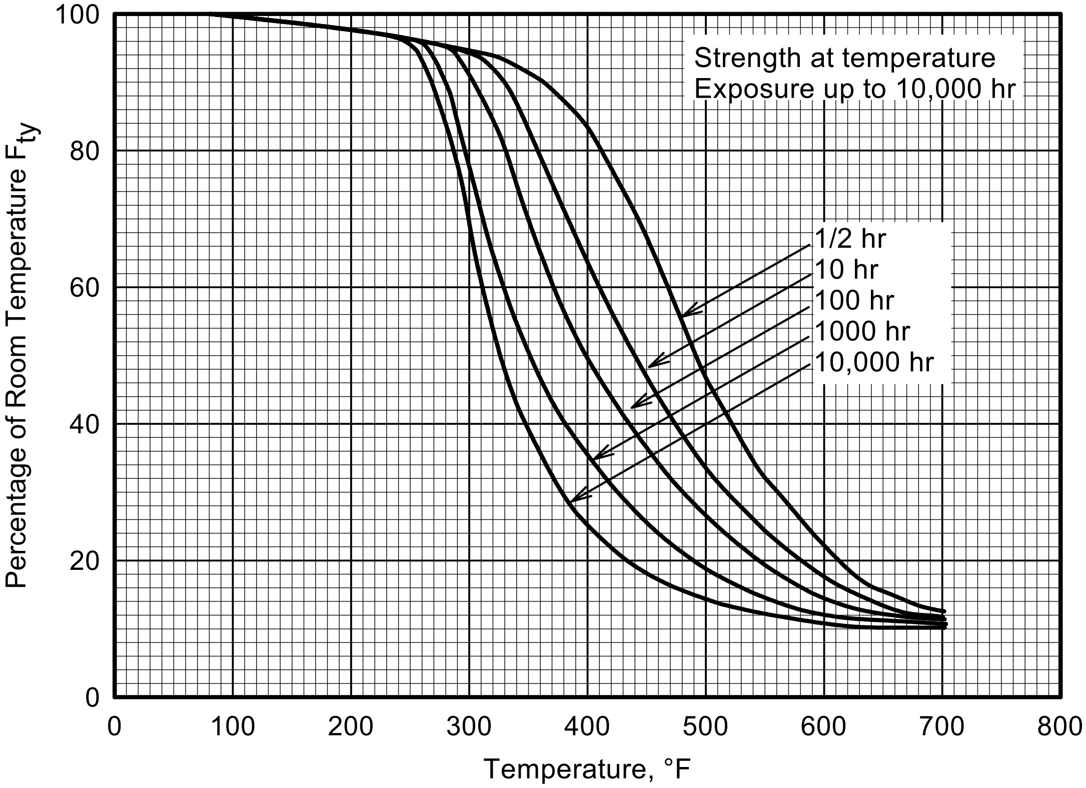


Figure 3.2.3.1.1.(d). Effect of temperature on the tensile yield strength (F_{ty}) of 2024-T3, T3510, T3511, and T42 aluminum alloy extrusion.

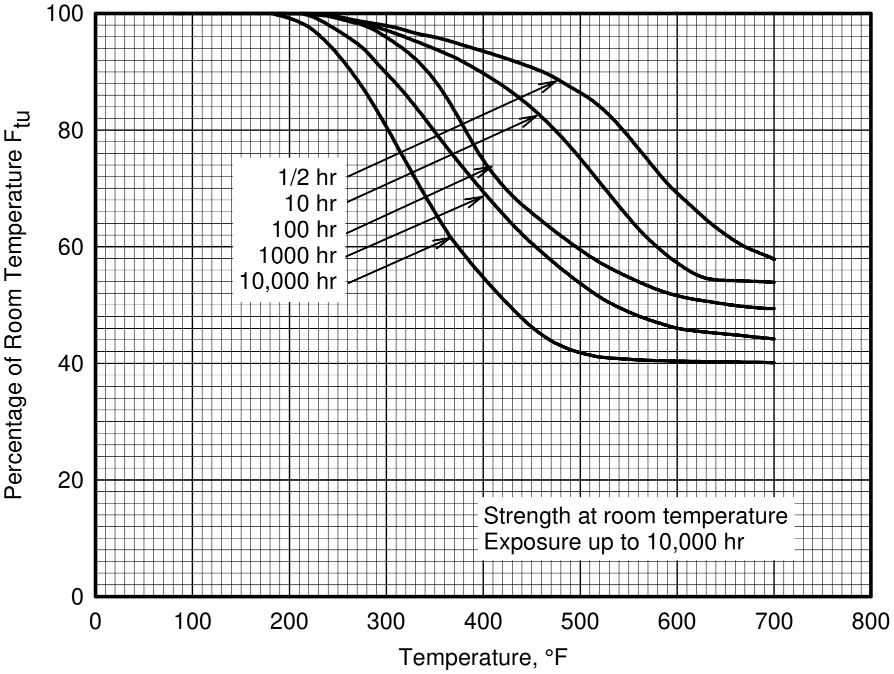


Figure 3.2.3.1.1(e). **Effect of exposure at elevated temperatures on the room-temperature tensile ultimate strength (F_{tu}) of 2024-T3, T351, T3510, T3511, and T42 aluminum alloy (all products except thick extrusions).**

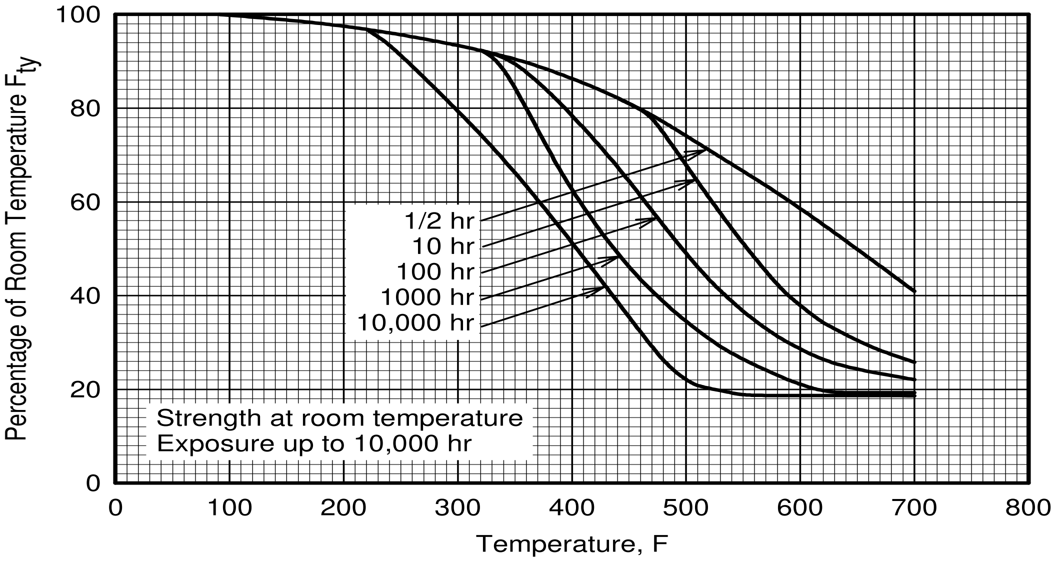


Figure 3.2.3.1.1(f). **Effect of exposure at elevated temperatures on the room-temperature tensile yield strength (F_{ty}) of 2024-T3, T351, T3510, T3511, T4, and T42 aluminum alloy (all products except thick extrusions).**

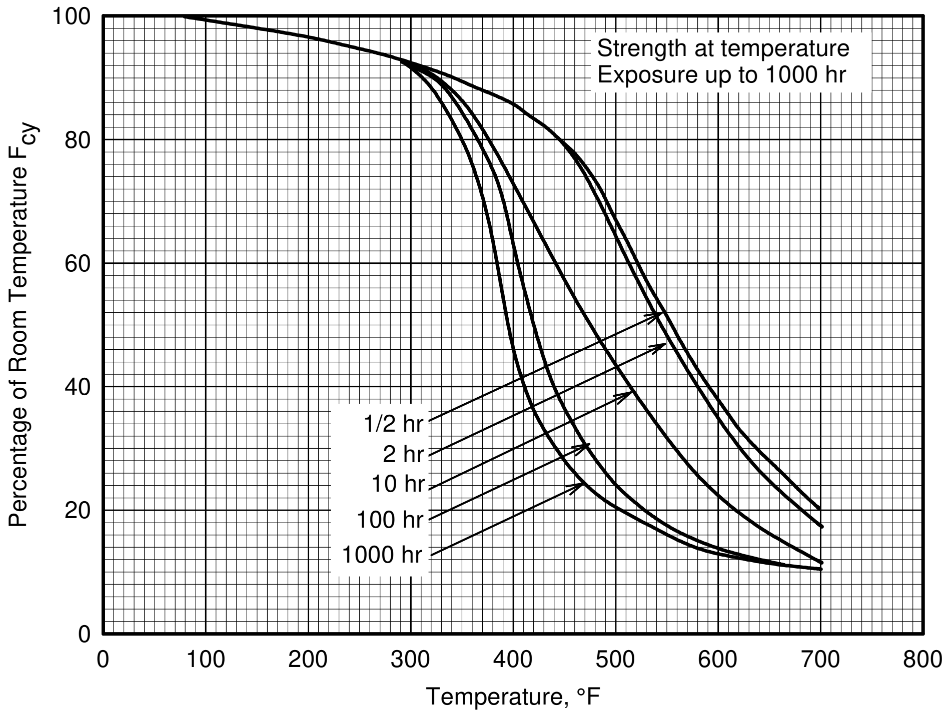


Figure 3.2.3.1.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of flat clad 2024-T3, coiled clad 2024-T4 aluminum alloy sheet, and clad 2024-T351 aluminum alloy plate.

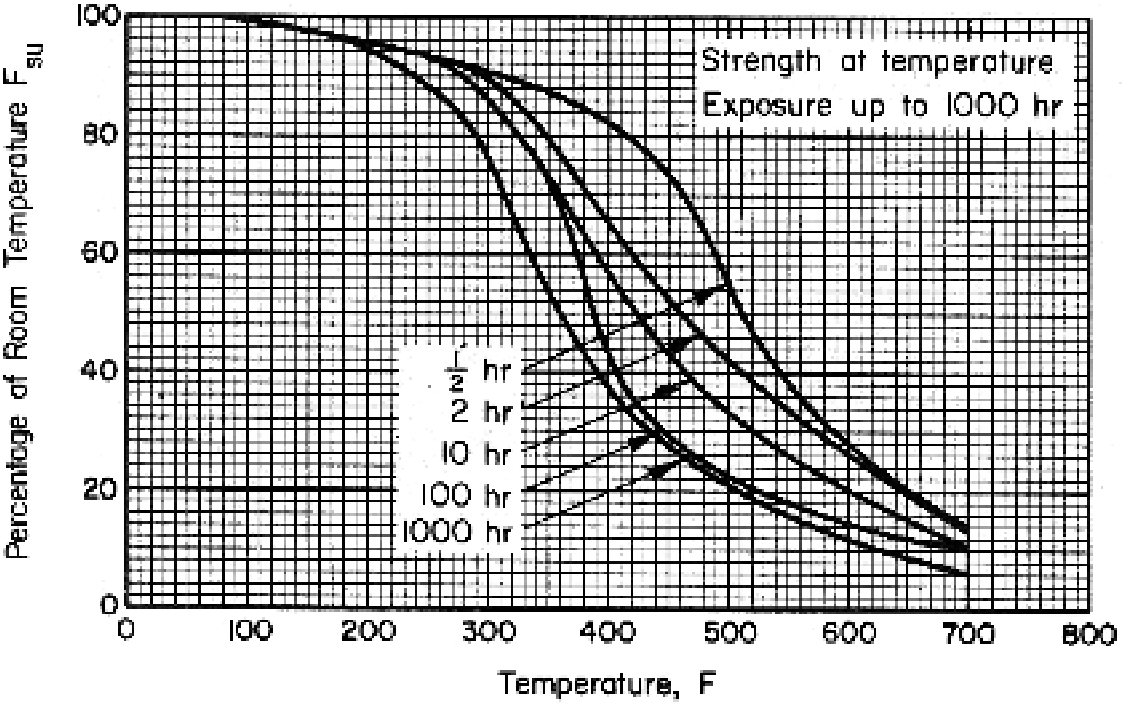


Figure 3.2.3.1.2(b). Effect of temperature on the shear ultimate strength (F_{su}) of flat clad 2024-T3, coiled clad 2024-T4 aluminum alloy sheet, and clad 2024-T351 aluminum alloy plate.

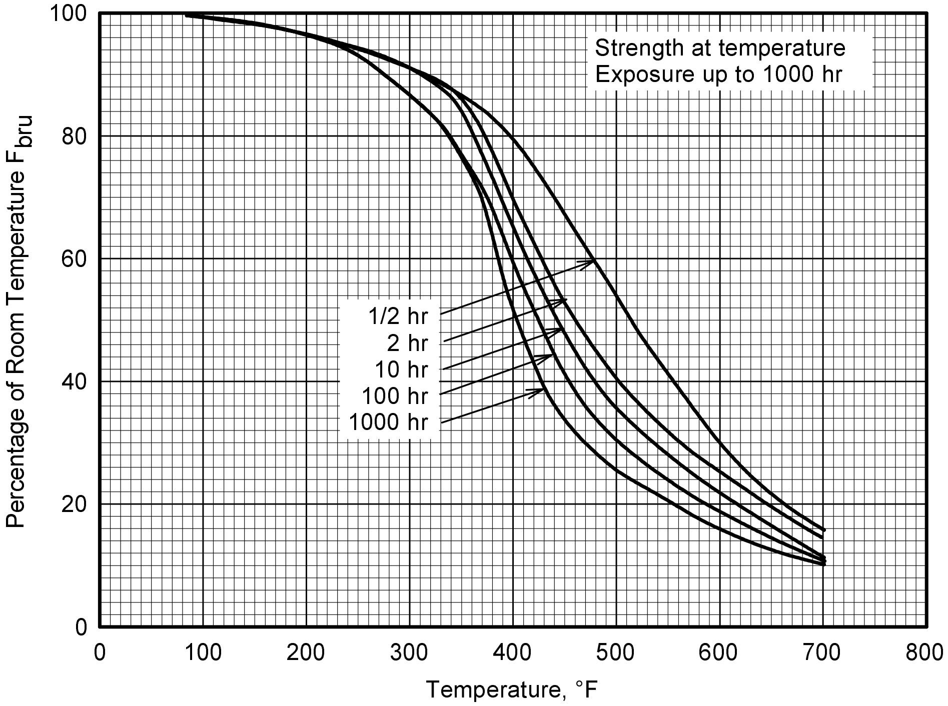


Figure 3.2.3.1.3(a). Effect of temperature on the bearing ultimate strength (F_{bru}) of flat clad 2024-T3, coiled clad 2024-T4 aluminum alloy sheet, and clad 2024-T351 aluminum alloy plate.

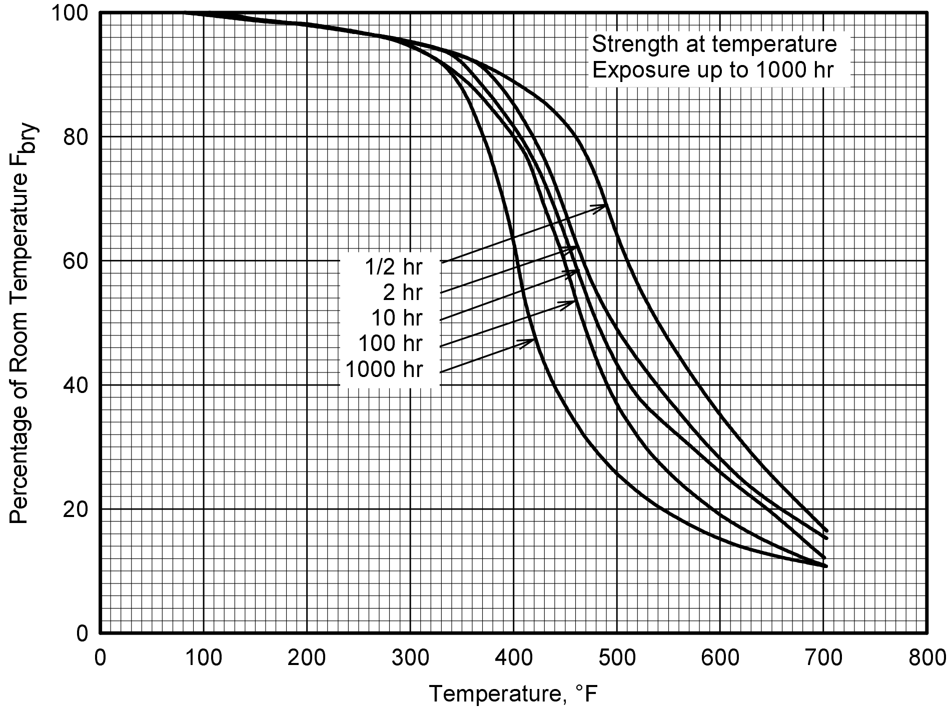


Figure 3.2.3.1.3(b). Effect of temperature on the bearing yield strength (F_{bry}) of flat clad 2024-T3, coiled clad 2024-T4 aluminum alloy sheet, and clad 2024-T351 aluminum alloy plate.

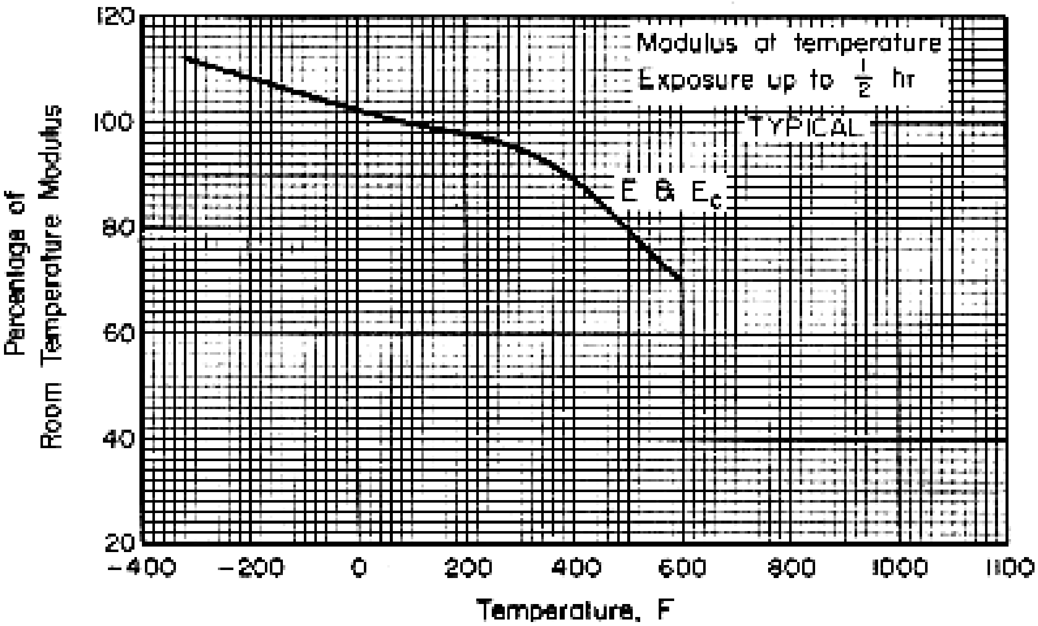


Figure 3.2.3.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of 2024 aluminum alloy.

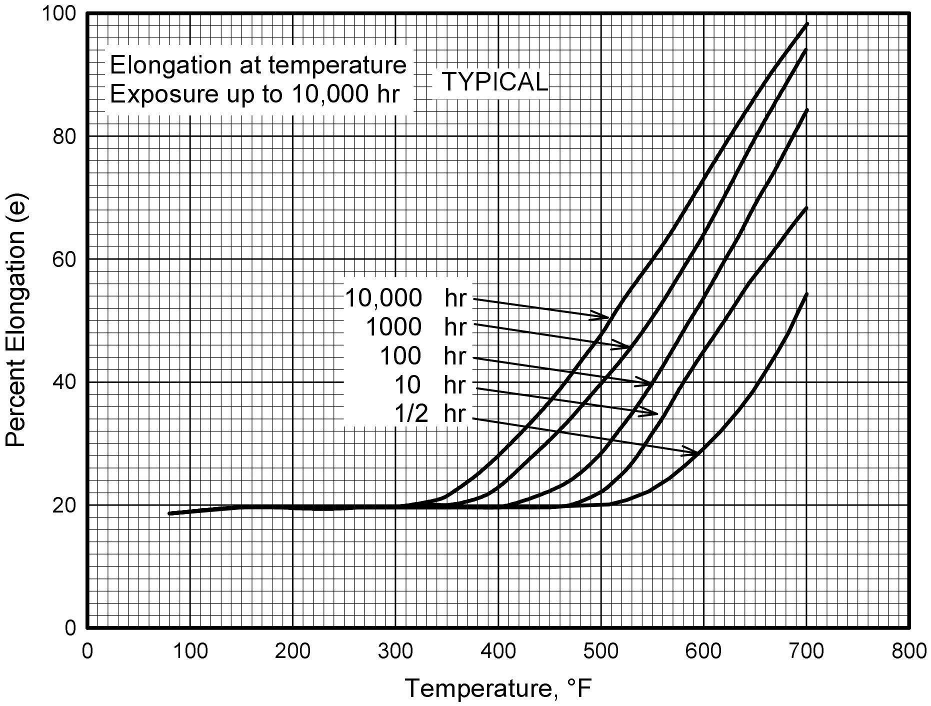


Figure 3.2.3.1.5(a). Effect of temperature on the elongation of 2024-T3, T351, T3510, T3511, T4, and T42 aluminum alloy (all products except thick extrusions).

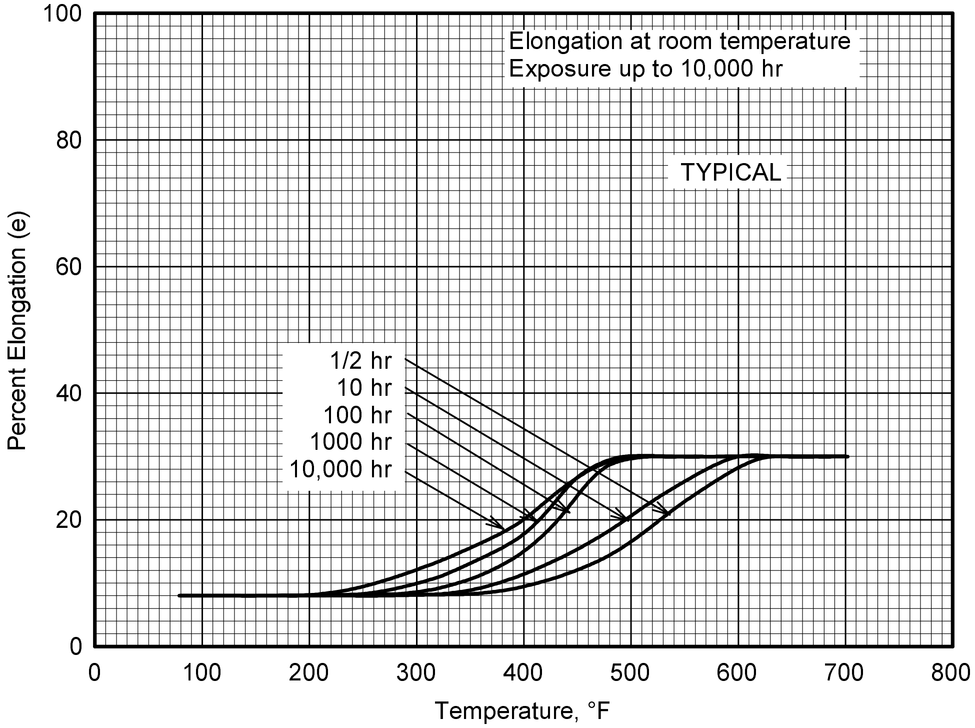


Figure 3.2.3.1.5(b). Effect of exposure at elevated temperature on the elongation (e) of 2024-T3, T351, T3510, T3511, T4, and T42 aluminum alloy (all products except thick extrusions).

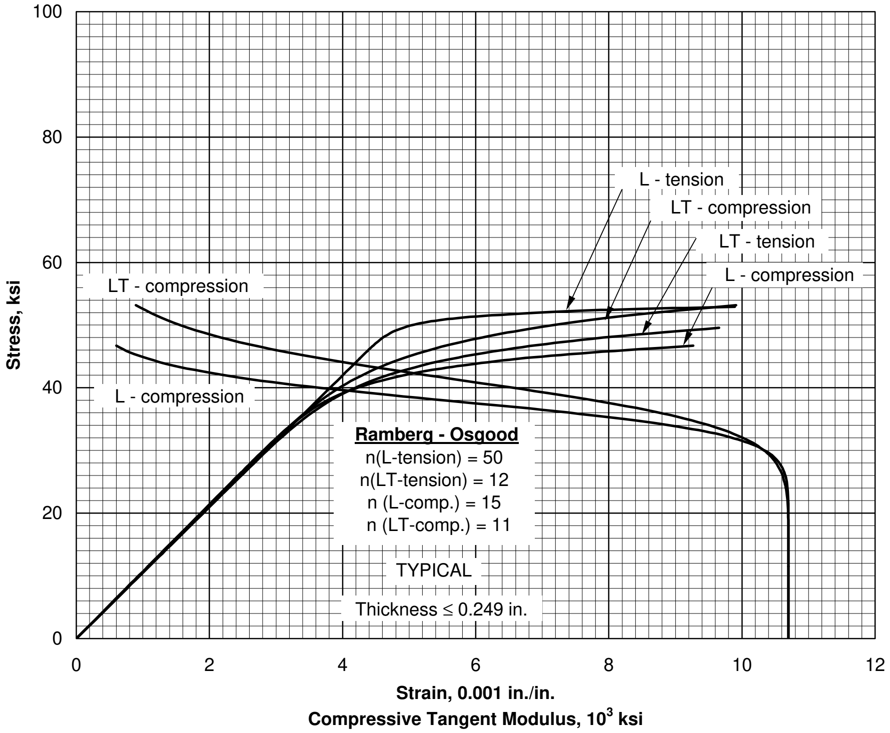


Figure 3.2.3.1.6(a). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 2024-T3 aluminum alloy sheet at room temperature.

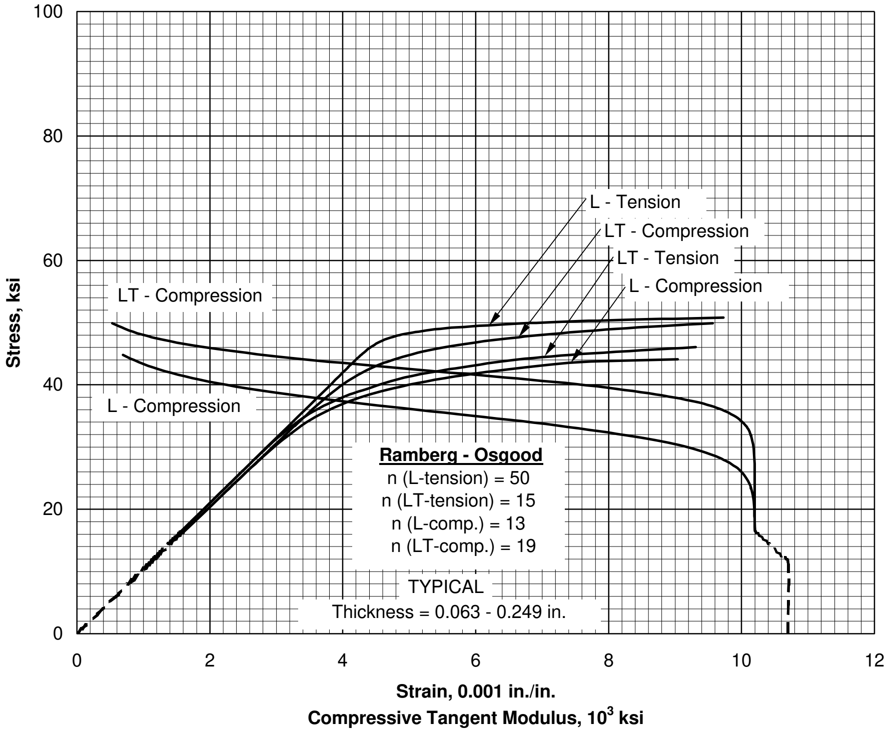


Figure 3.2.3.1.6(b). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for clad 2024-T3 aluminum alloy sheet at room temperature.

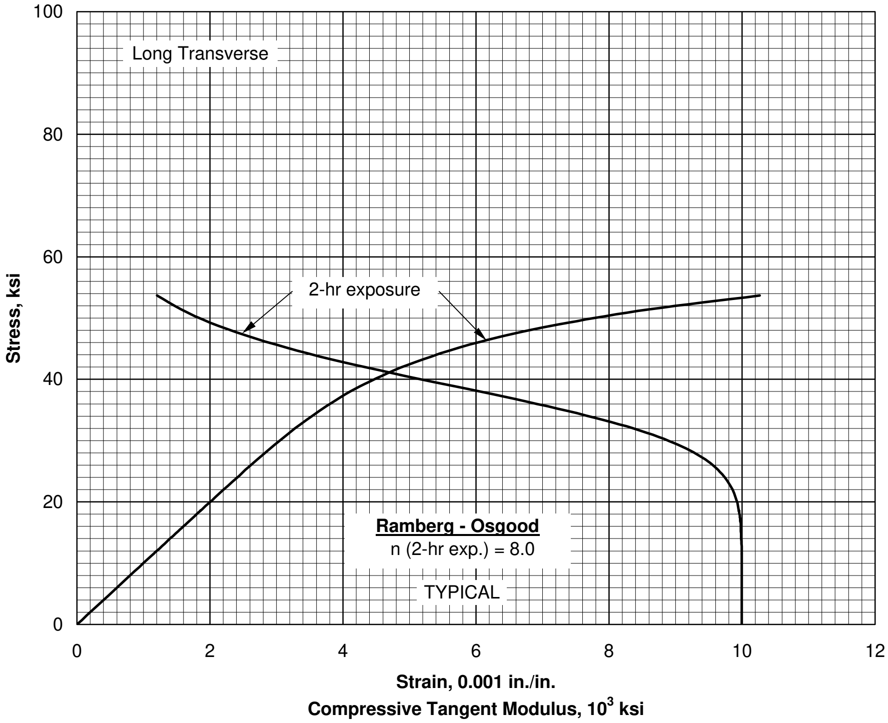


Figure 3.2.3.1.6(c). Typical compressive stress-strain and compressive tangent-modulus curves for clad 2024-T3 aluminum alloy sheet at 212°F.

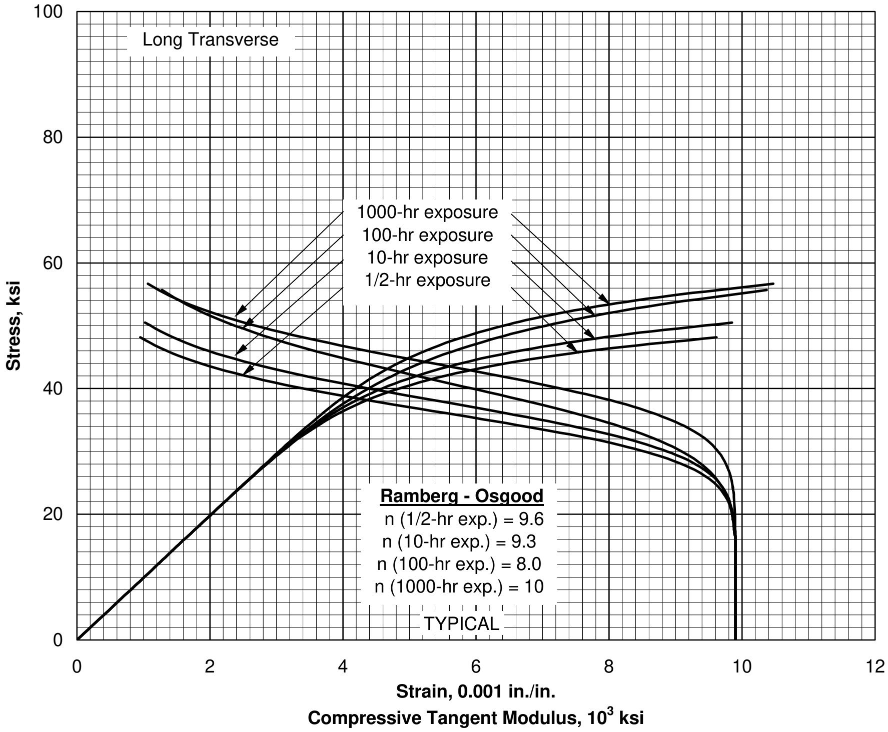


Figure 3.2.3.1.6(d). Typical compressive stress-strain and compressive tangent-modulus curves for clad 2024-T3 aluminum alloy sheet at 300°F.

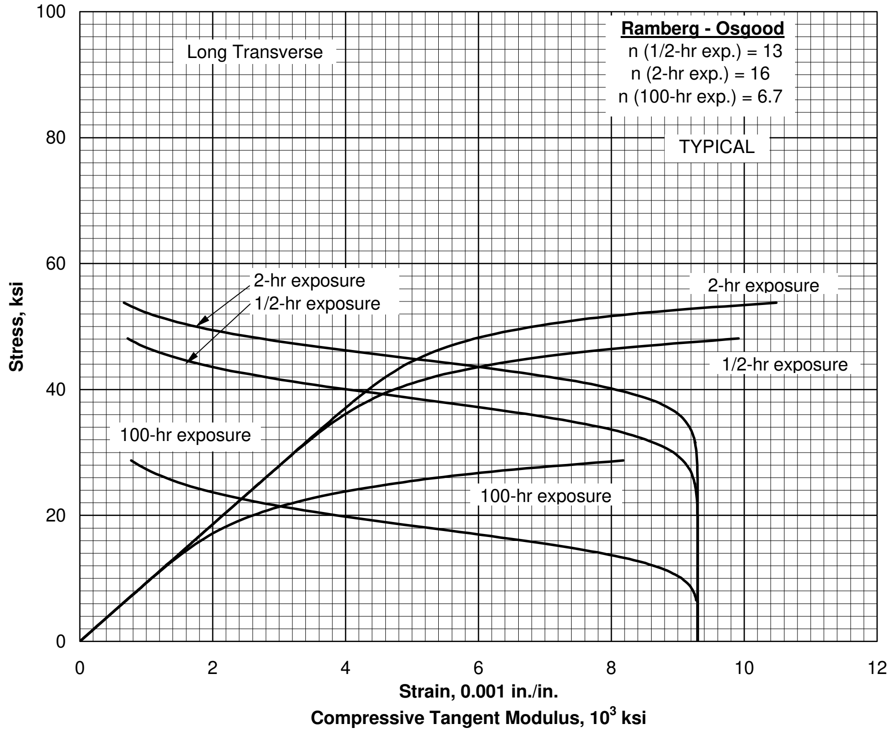


Figure 3.2.3.1.6(e). Typical compressive stress-strain and compressive tangent-modulus curves for clad 2024-T3 aluminum alloy sheet at 400°F.

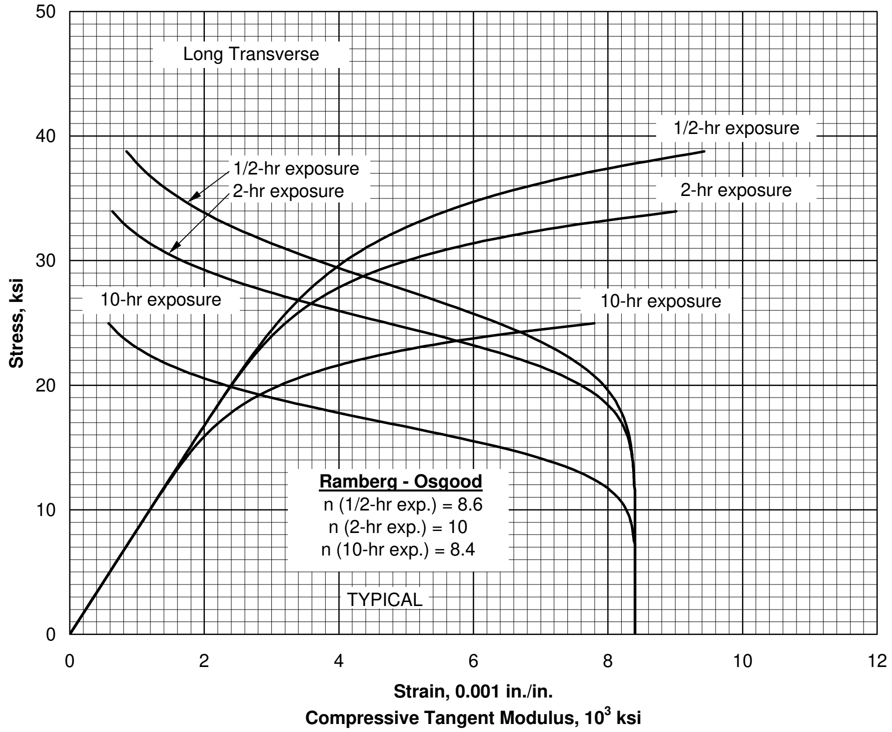


Figure 3.2.3.1.6(f). Typical compressive stress-strain and compressive tangent-modulus curves for clad 2024-T3 aluminum alloy sheet at 500°F.

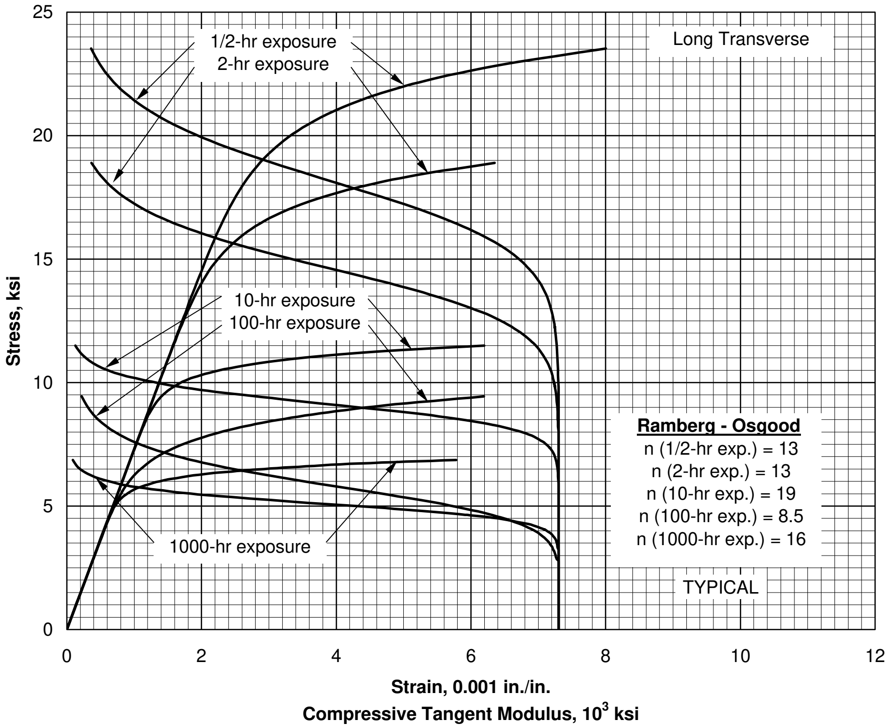


Figure 3.2.3.1.6(g). Typical compressive stress-strain and compressive tangent-modulus curves for clad 2024-T3 aluminum alloy sheet at 600°F.

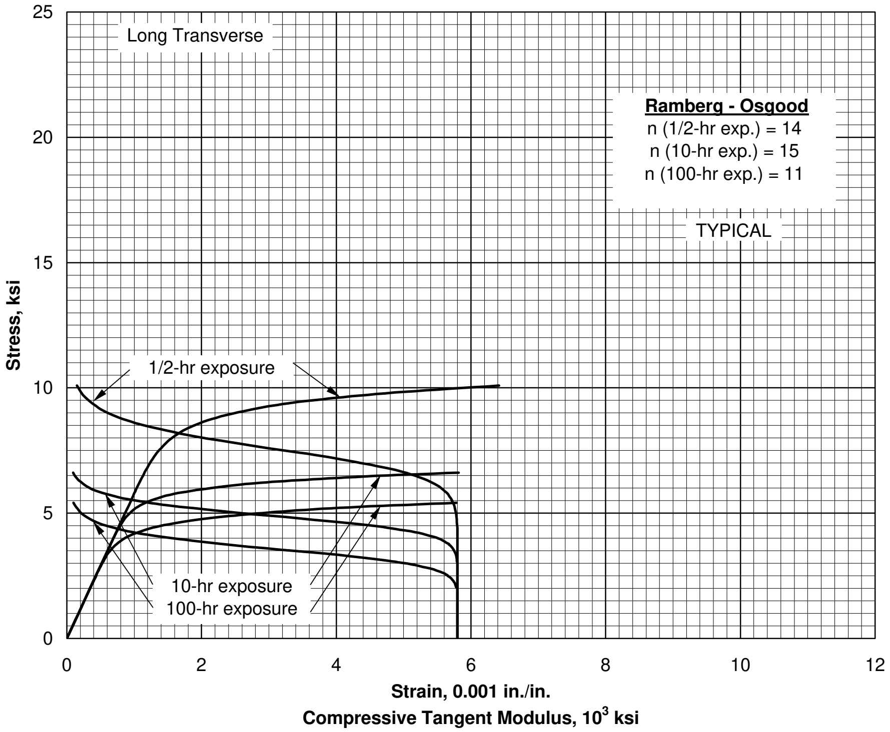


Figure 3.2.3.1.6(h). Typical compressive stress-strain and compressive tangent-modulus curves for clad 2024-T3 aluminum alloy sheet at 700°F.

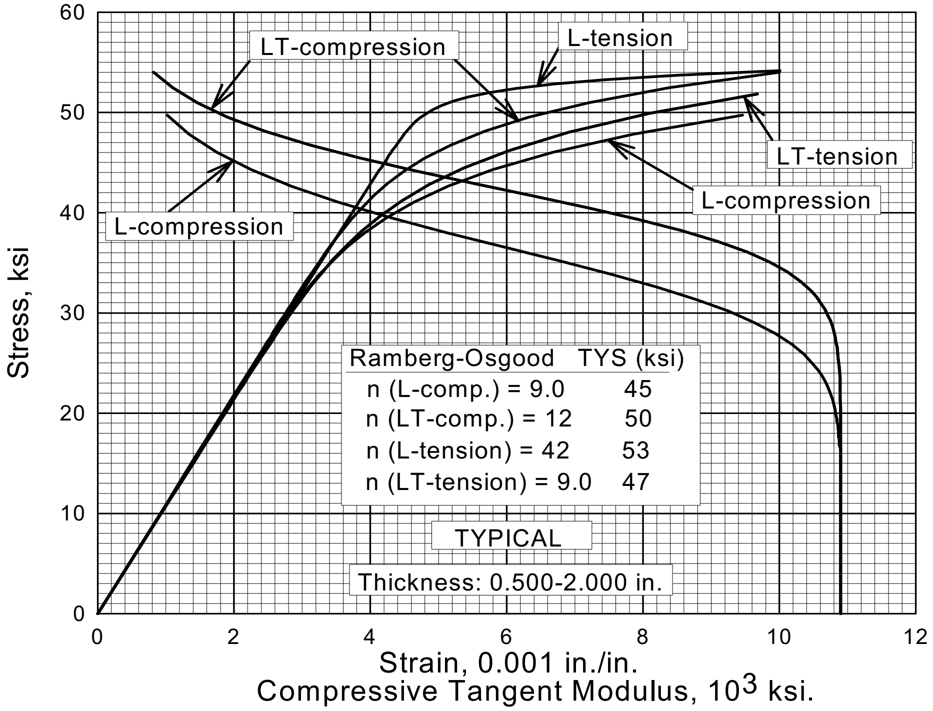


Figure 3.2.3.1.6(i). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 2024-T351 aluminum alloy plate at room temperature.

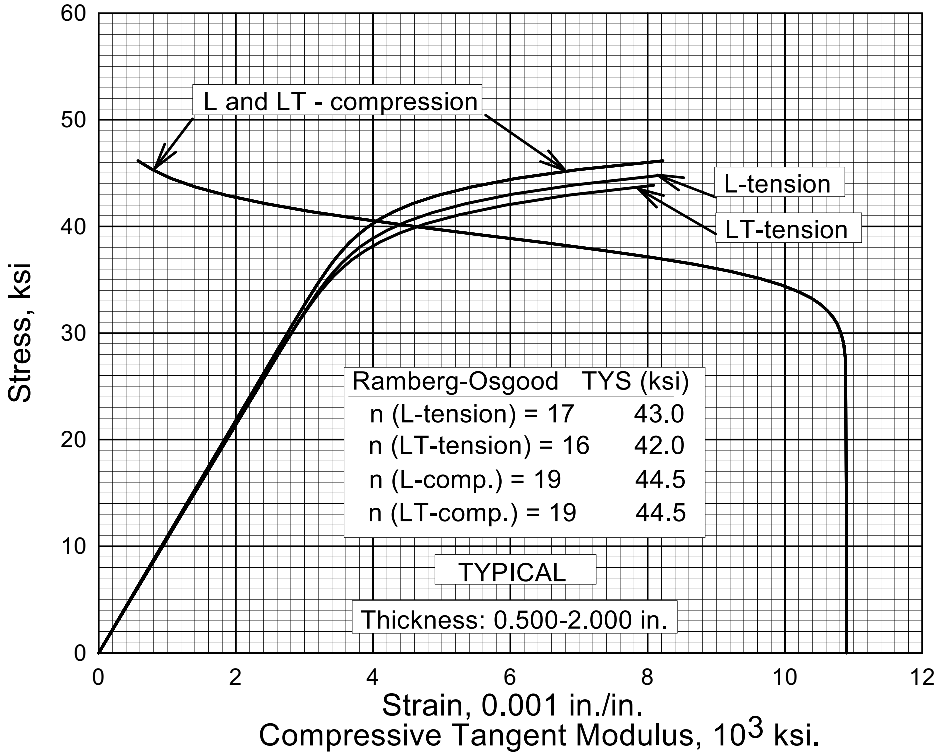


Figure 3.2.3.1.6(j). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 2024-T42 aluminum alloy plate at room temperature.

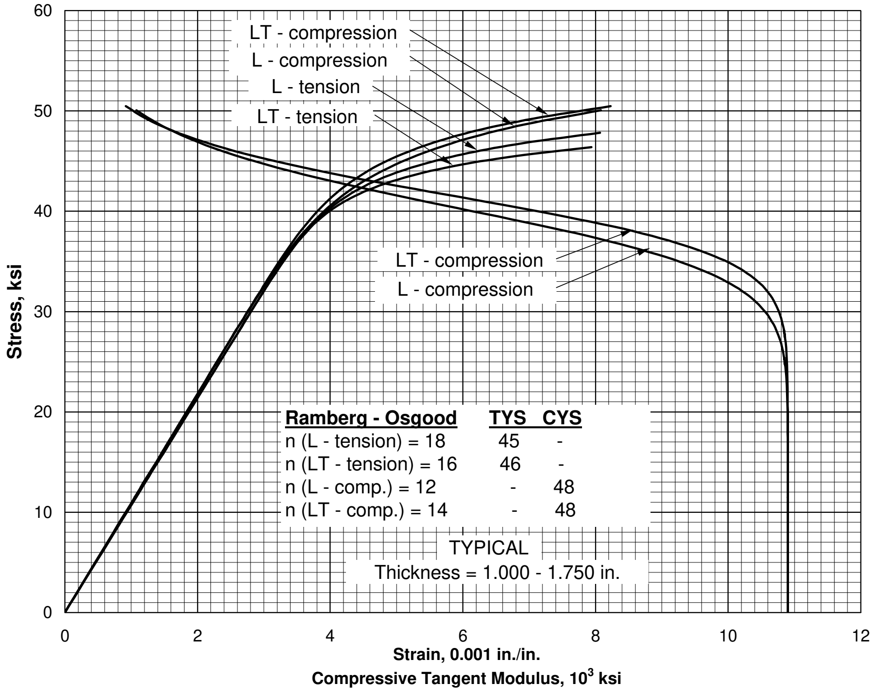


Figure 3.2.3.1.6(k) Typical tension and compression stress-strain and compression tangent modulus curves for 2024-T42 aluminum alloy plate at room temperature. Note, the data to generate these curves may have been from clad product, however, they are shown here without secondary modulus since it could not be positively confirmed the product was cladded.

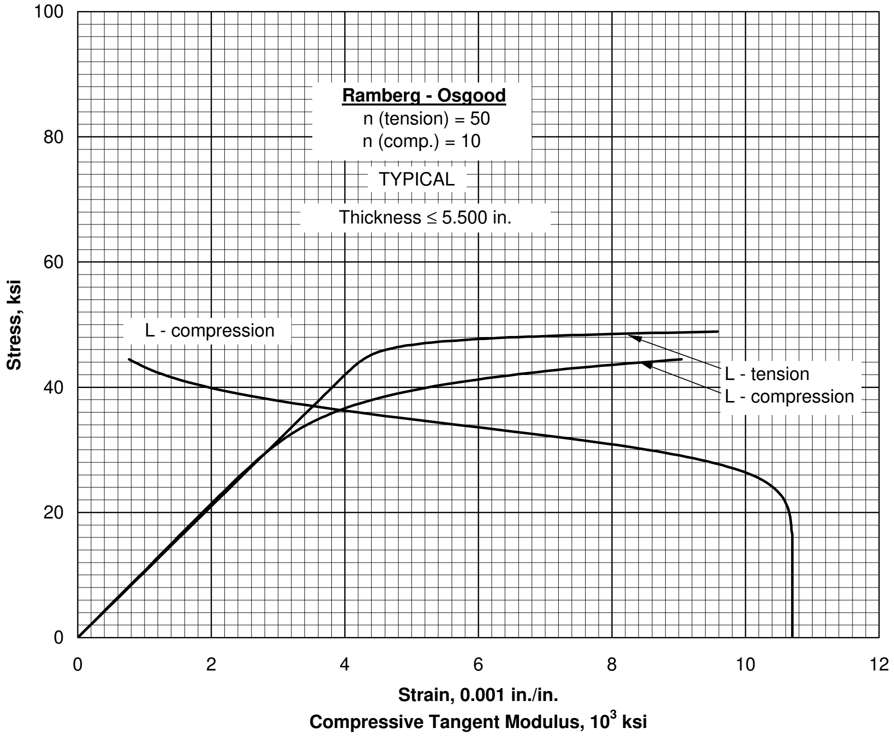


Figure 3.2.3.1.6(l). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 2024-T4 aluminum alloy rolled bar, rod, and shapes at room temperature.

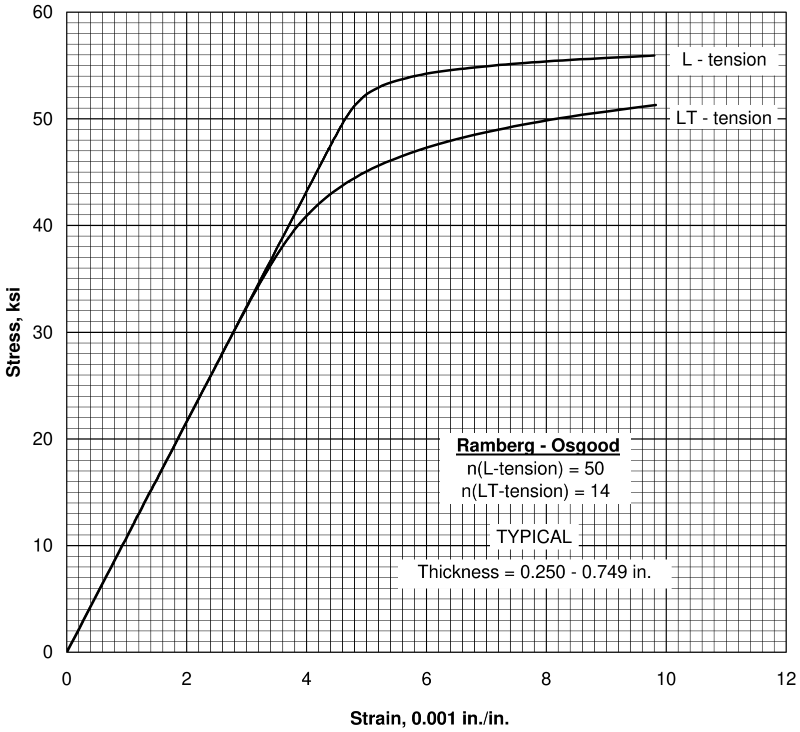


Figure 3.2.3.1.6(m). Typical tensile stress-strain curves for 2024-T351X aluminum alloy extrusion at room temperature.

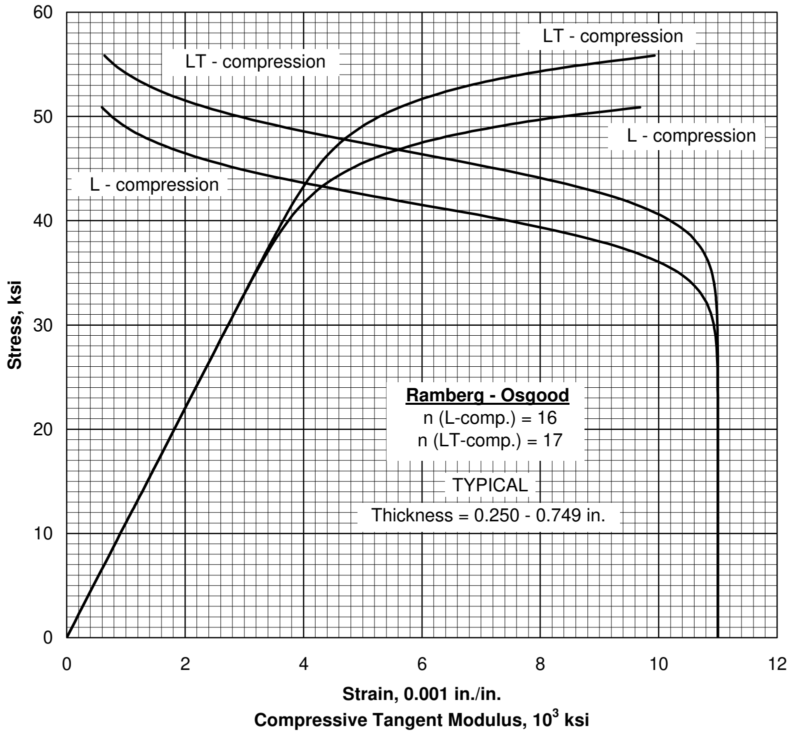


Figure 3.2.3.1.6(n). Typical compressive stress-strain and compressive tangent-modulus curves for 2024-T351X aluminum alloy extrusion at room temperature.

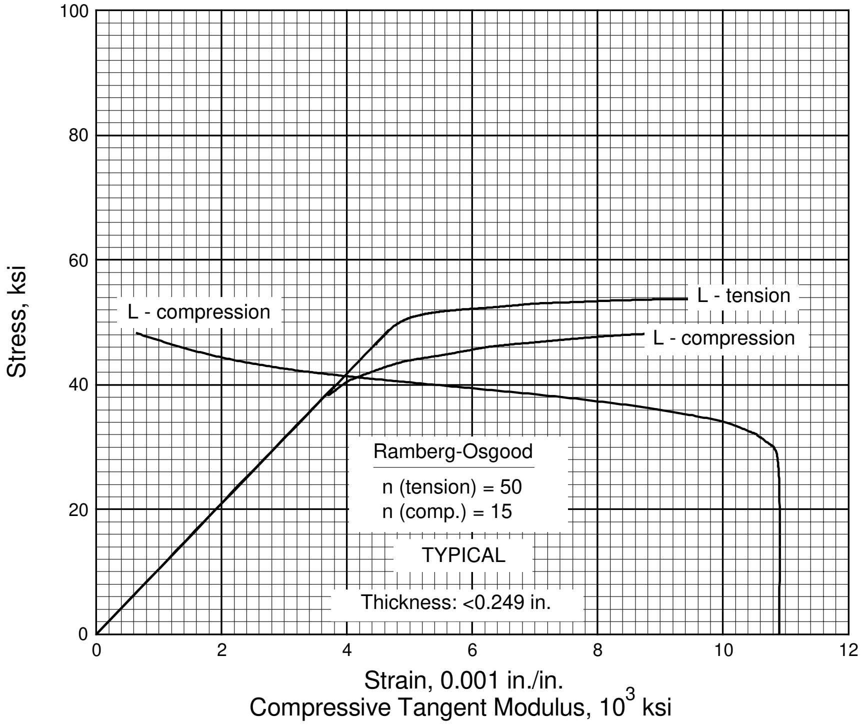


Figure 3.2.3.1.6(o). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 2024-T3 aluminum alloy extrusion at room temperature.

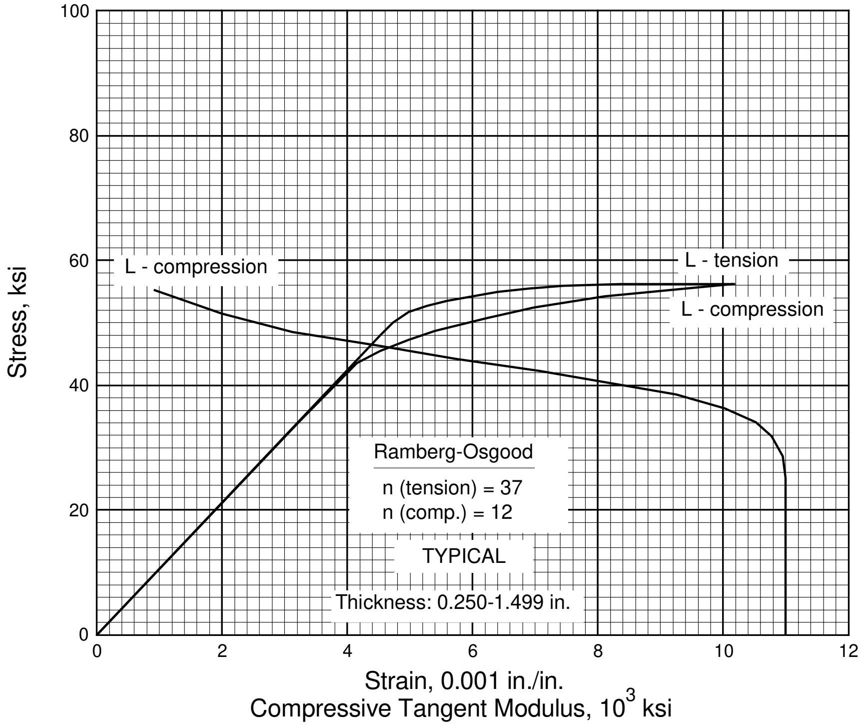


Figure 3.2.3.1.6(p). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 2024-T3 aluminum alloy extrusion at room temperature.

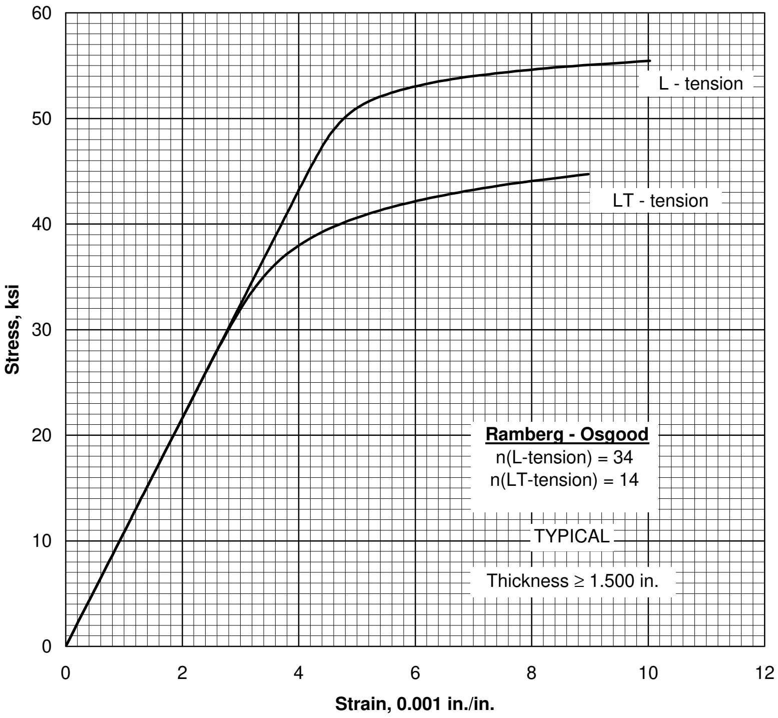


Figure 3.2.3.1.6(q). Typical tensile stress-strain curves for 2024-T42 aluminum alloy extrusion at room temperature.

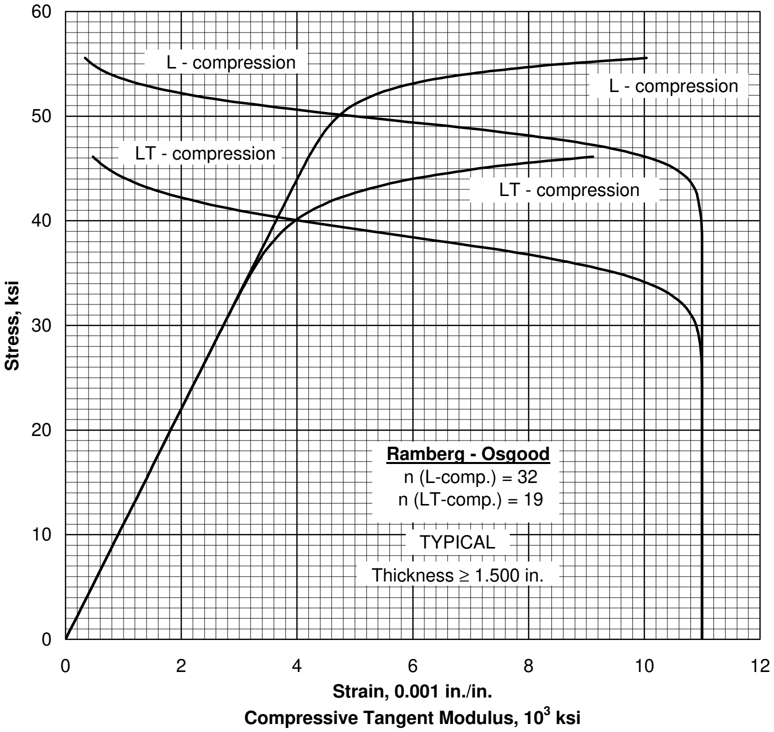
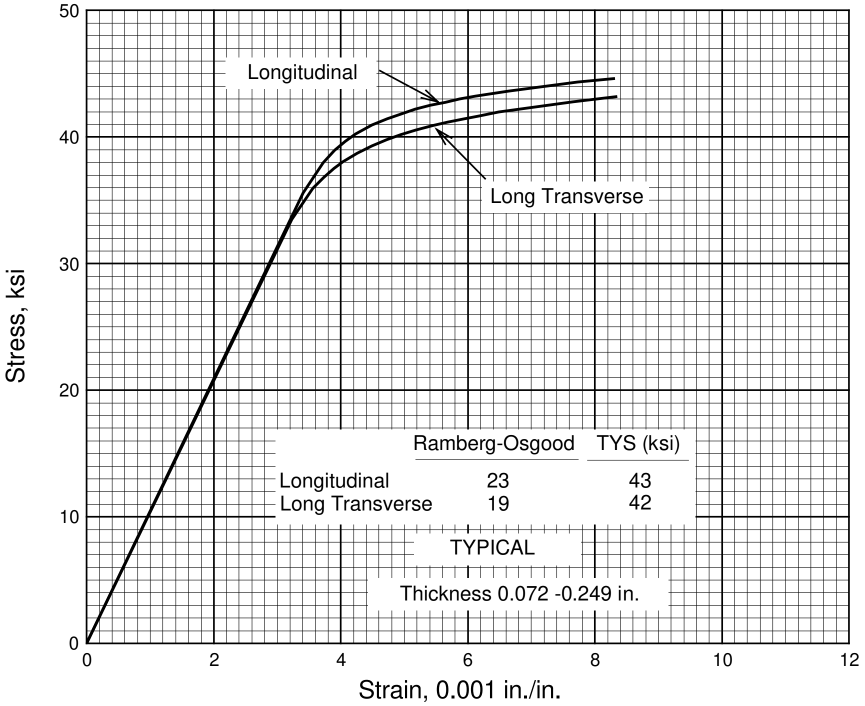
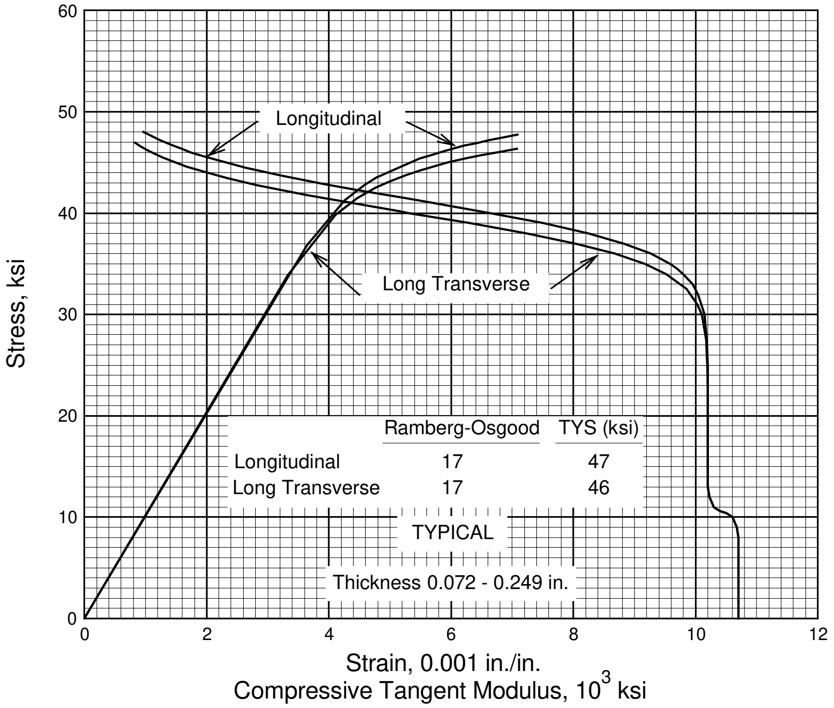


Figure 3.2.3.1.6(r). Typical compressive stress-strain and compressive tangent-modulus curves for 2024-T42 aluminum alloy extrusion at room temperature.



	Ramberg-Osgood	TYS (ksi)
Longitudinal	23	43
Long Transverse	19	42

Figure 3.2.3.1.6(s). Typical tensile stress-strain curves for clad 2024-T42 aluminum alloy sheet at room temperature.



	Ramberg-Osgood	TYS (ksi)
Longitudinal	17	47
Long Transverse	17	46

Figure 3.2.3.1.6(t). Typical compressive stress-strain and compressive tangent-modulus curves for clad 2024-T42 aluminum alloy sheet at room temperature.

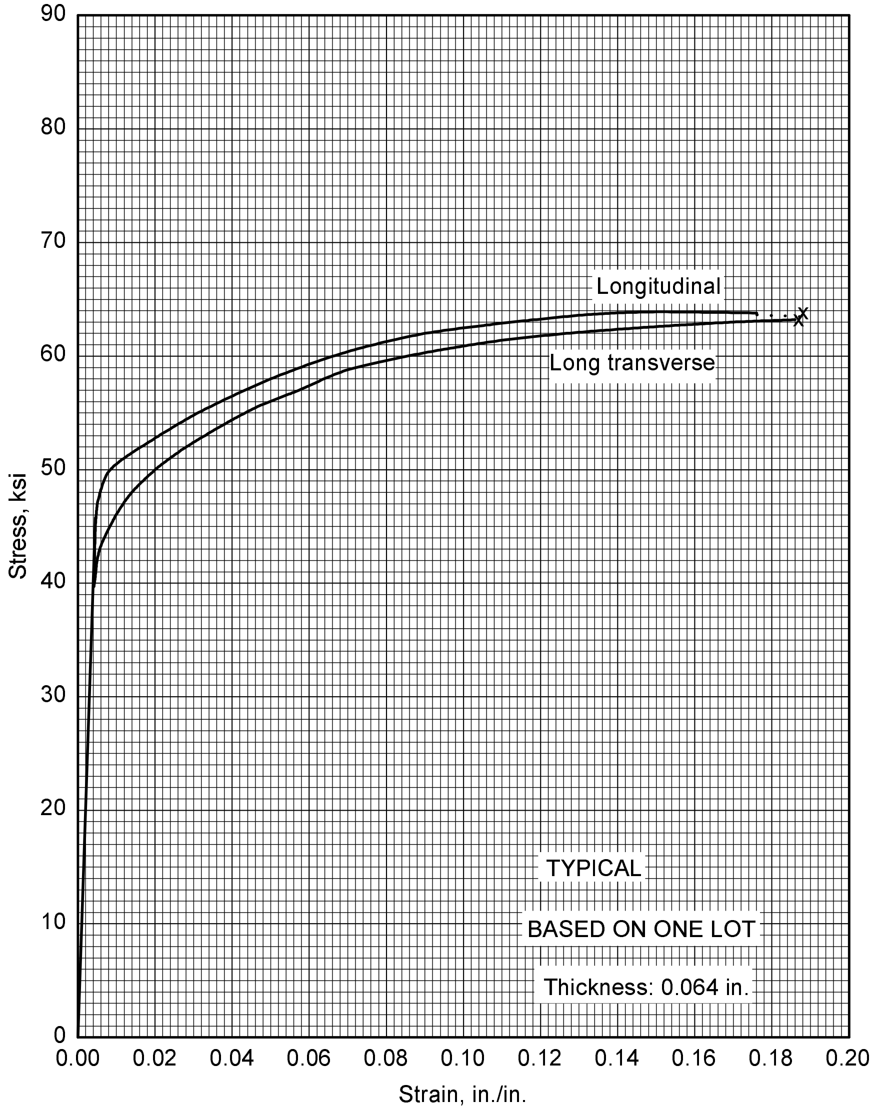


Figure 3.2.3.1.6(u). Typical tensile stress-strain curves (full range) for clad 2024-T3 aluminum alloy sheet at room temperature.

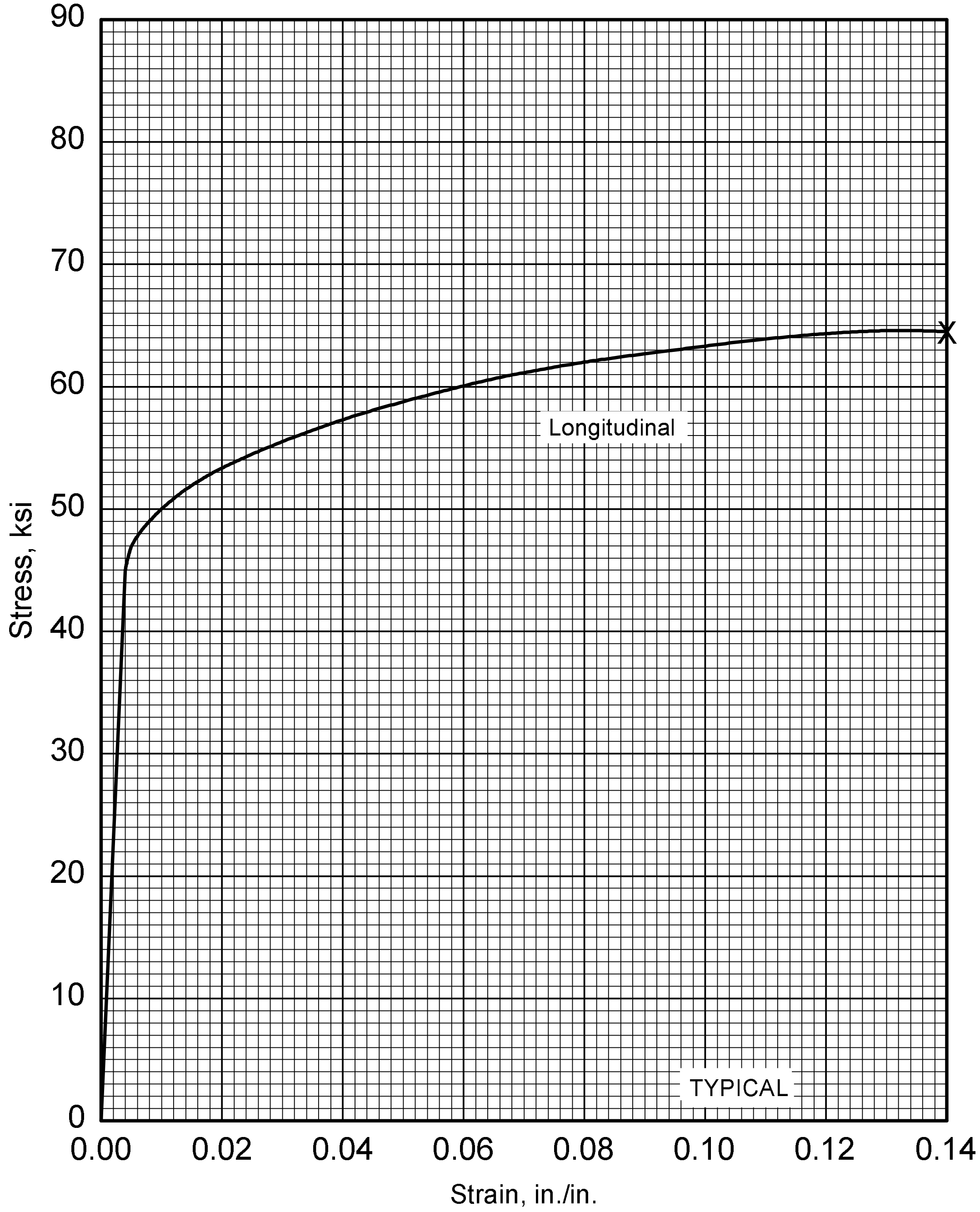


Figure 3.2.3.1.6(v). Typical tensile stress-strain curve (full range) for 2024-T351 aluminum alloy rolled rod at room temperature.

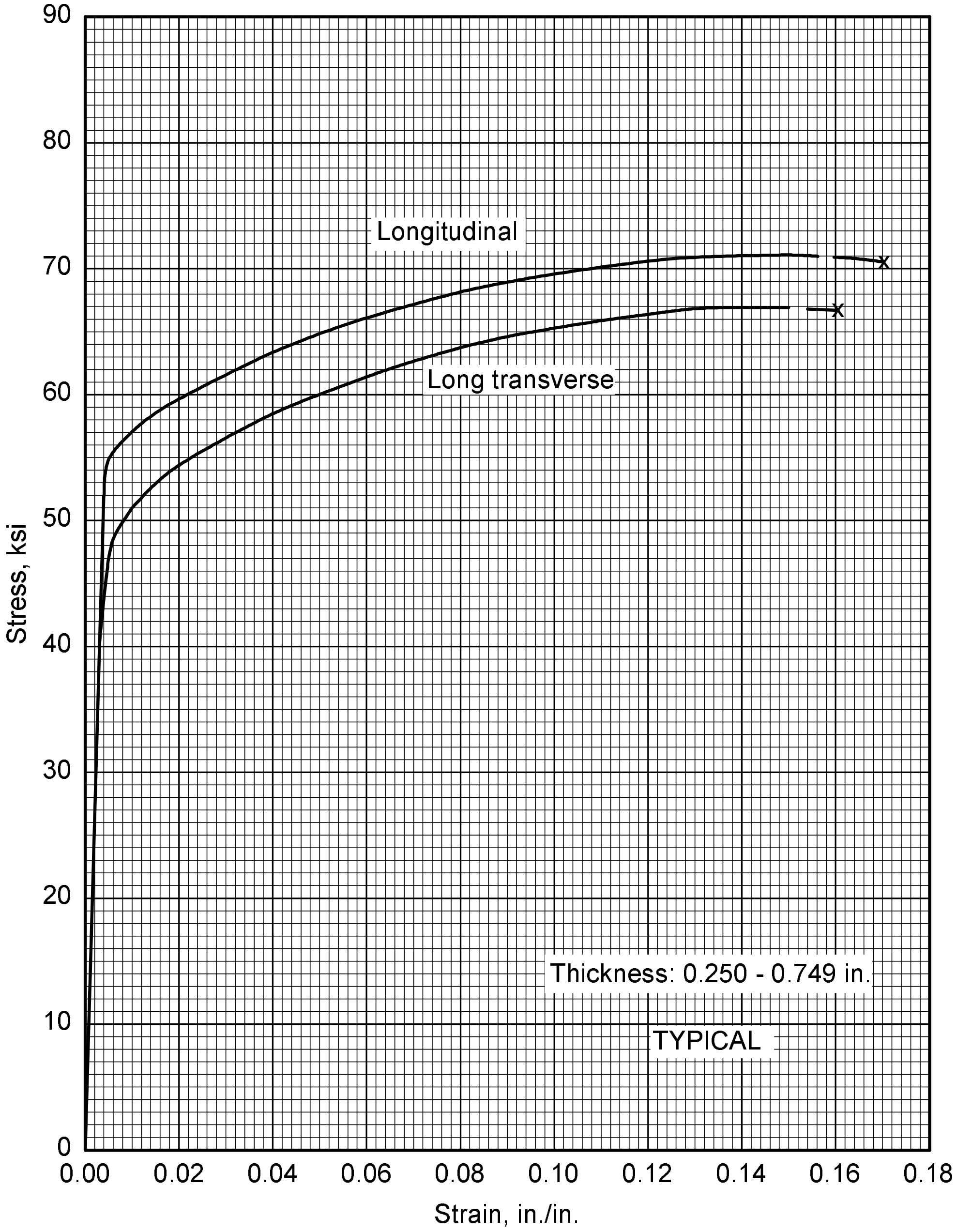


Figure 3.2.3.1.6(w). Typical tensile stress-strain curve (full range) for 2024-T351X aluminum alloy extrusion at room temperature.

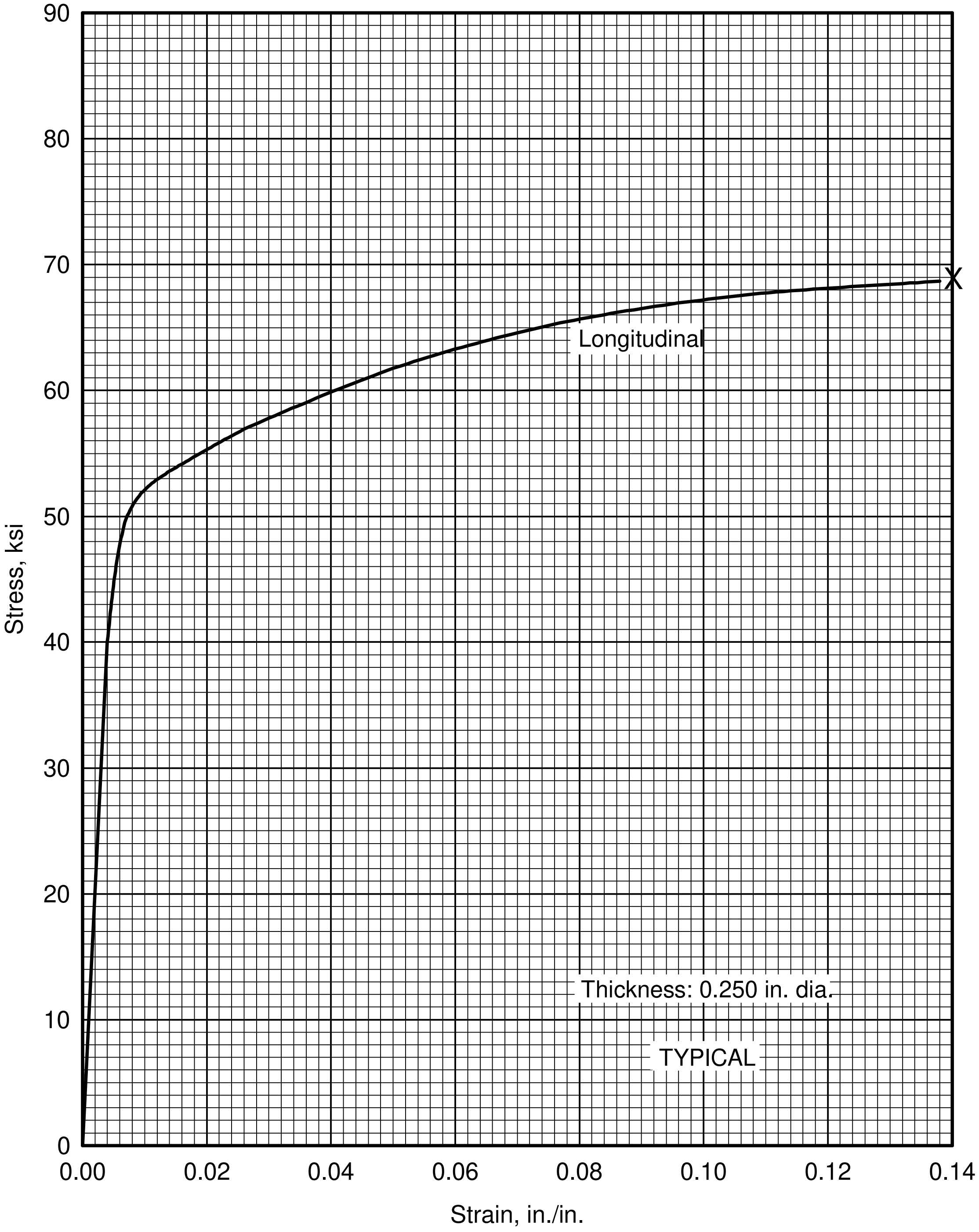


Figure 3.2.3.1.6(x). Typical stress-strain curve (full range) for 2024-T3 aluminum alloy extrusion at room temperature.

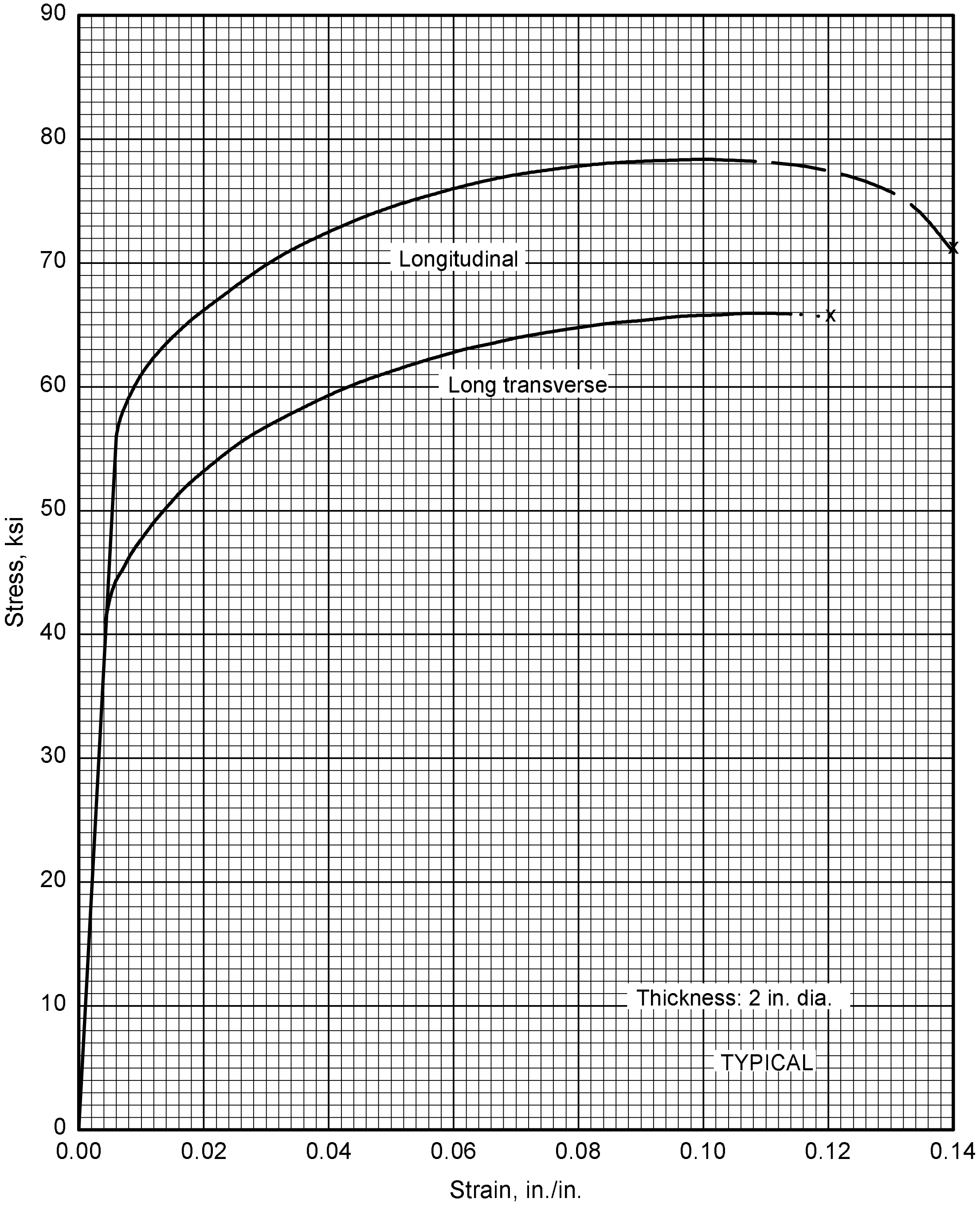


Figure 3.2.3.1.6(y). Typical tensile stress-strain curves (full range) for 2024-T3 aluminum alloy extrusion at room temperature.

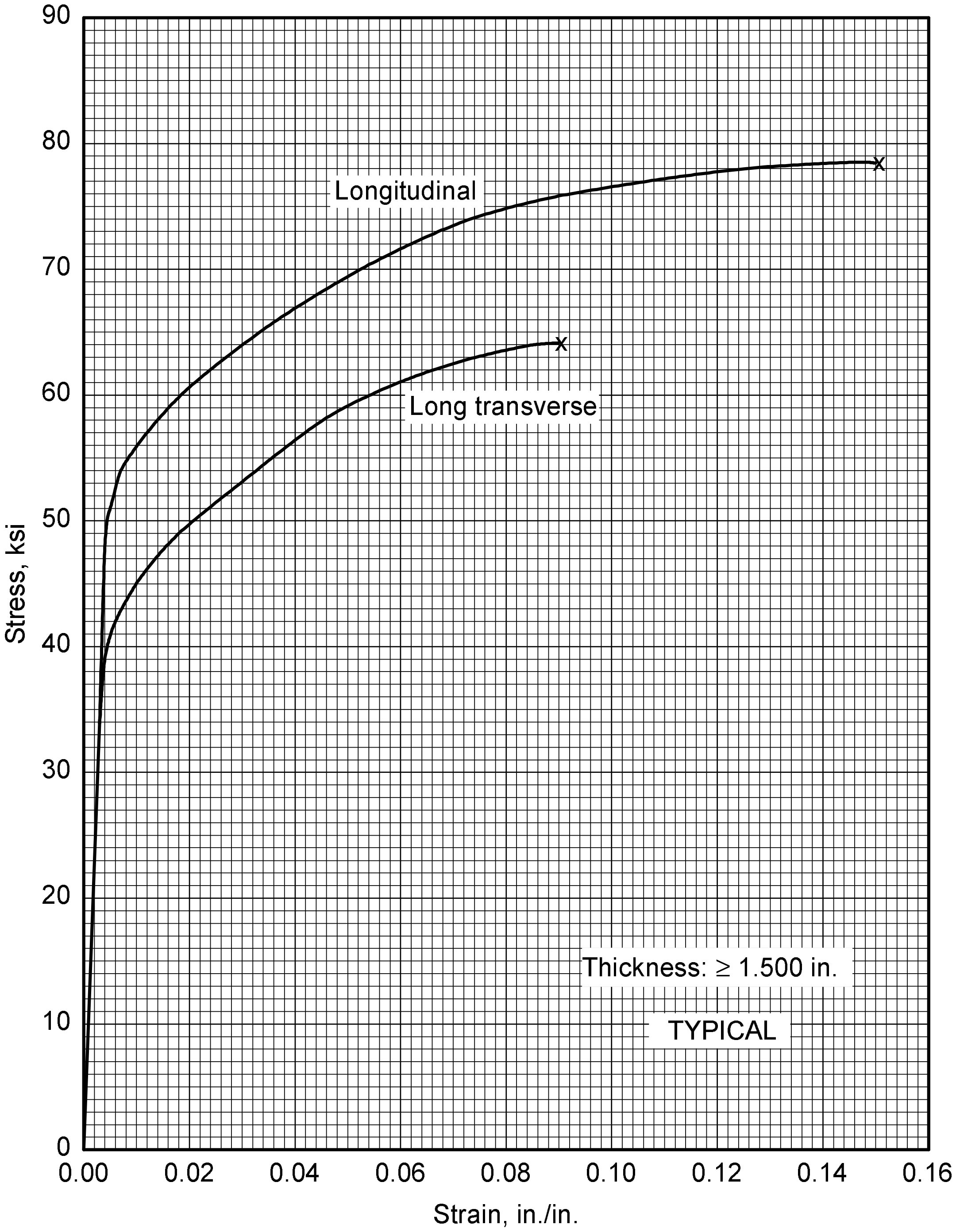


Figure 3.2.3.1.6(z). Typical tensile stress-strain curves (full range) for 2024-T42 aluminum alloy extrusion at room temperature.

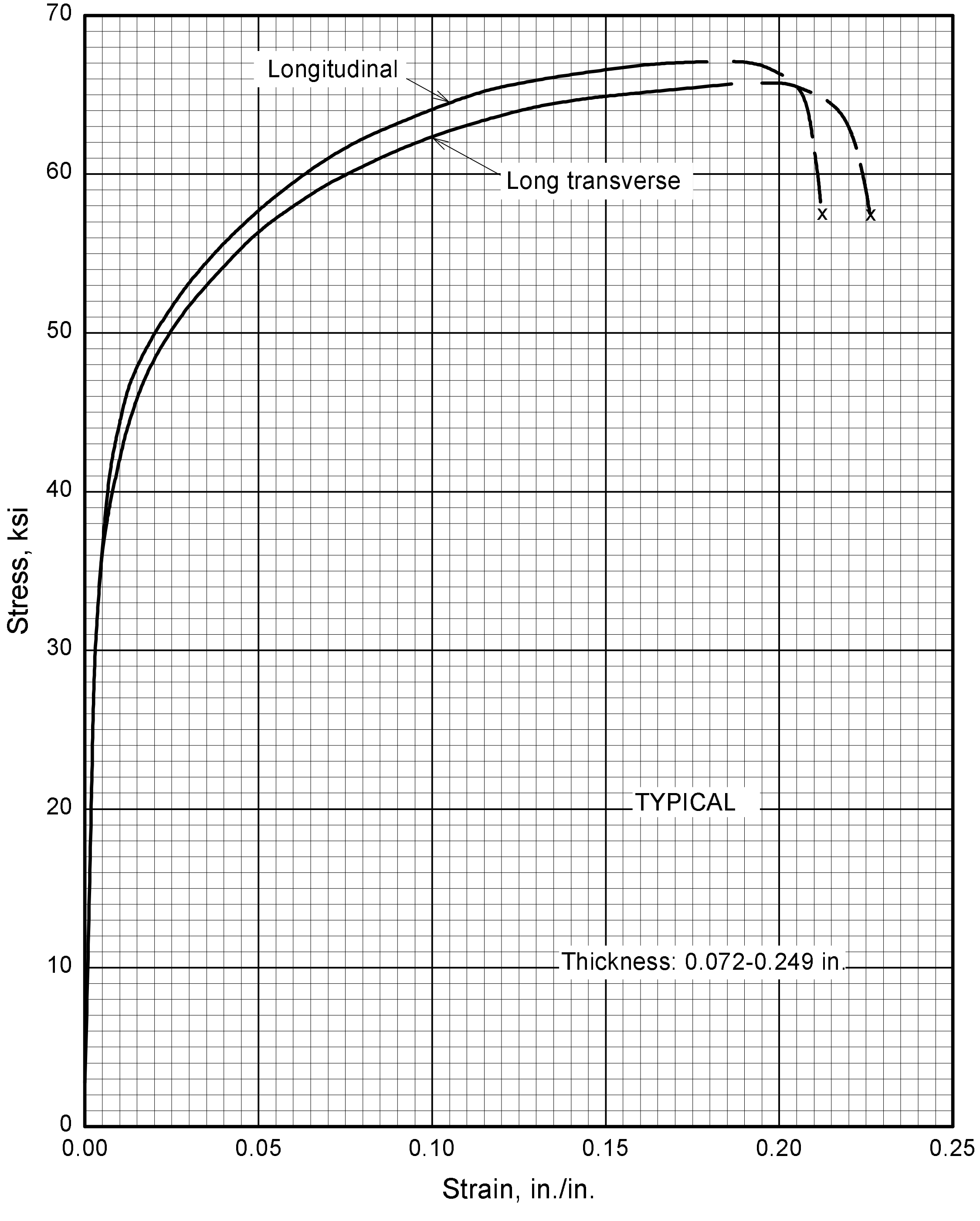


Figure 3.2.3.1.6(aa). Typical stress-strain curves (full range) for clad 2024-T42 aluminum alloy sheet at room temperature.

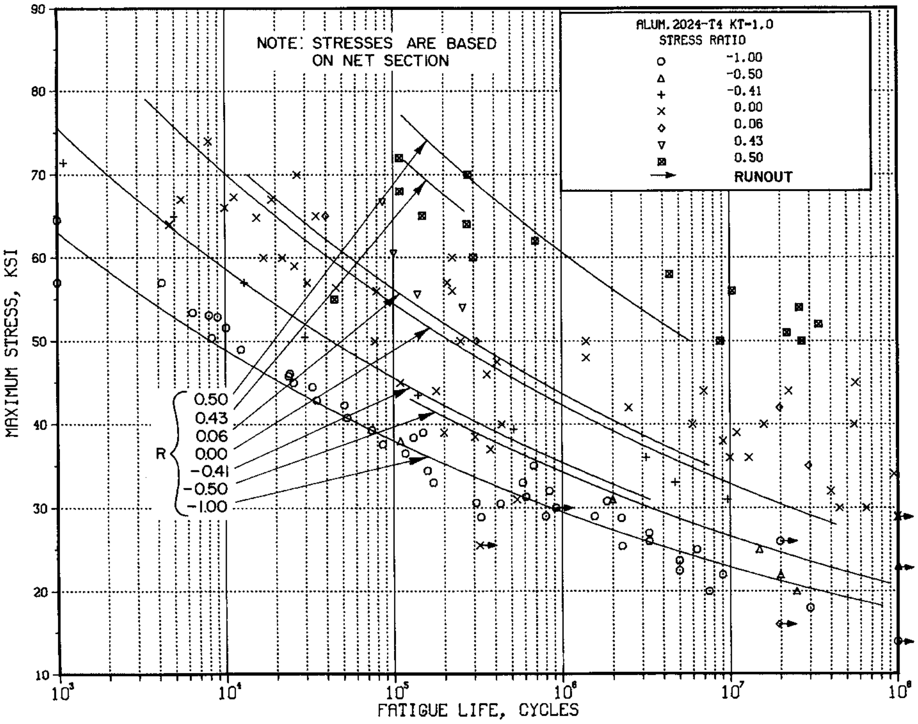


Figure 3.2.3.1.8(a). Best-fit S/N curves for unnotched 2024-T4 aluminum alloy, various wrought products, longitudinal direction.

Correlative Information for Figure 3.2.3.1.8(a)

Product Form: Rolled bar, 0.75 to 0.125 inch diameter
Drawn rod, 0.75 inch diameter
Extruded rod, 1.25 inch diameter
Extruded bar, 1.25 x 4-inch

Properties:

TUS, ksi	TYS, ksi	Temp., °F
69	45	RT (rolled)
71	44	RT (drawn)
85	65	RT (extruded)

Specimen Details: Unnotched
0.160 to 0.400 inch diameter

Surface Condition: Longitudinally polished

References: 3.2.1.1.8(a) through (c) and 3.2.3.1.8(i)

Test Parameters:
Loading - Axial
Frequency - 1800 to 3600 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
Log N_f = 20.83-9.09 log (S_{eq})
$S_{eq} = S_{max} (1-R)^{0.52}$
Std. Error of Estimate, Log (Life) = 0.566
Standard Deviation, Log (Life) = 1.324
R^2 = 82%

Sample Size = 134

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

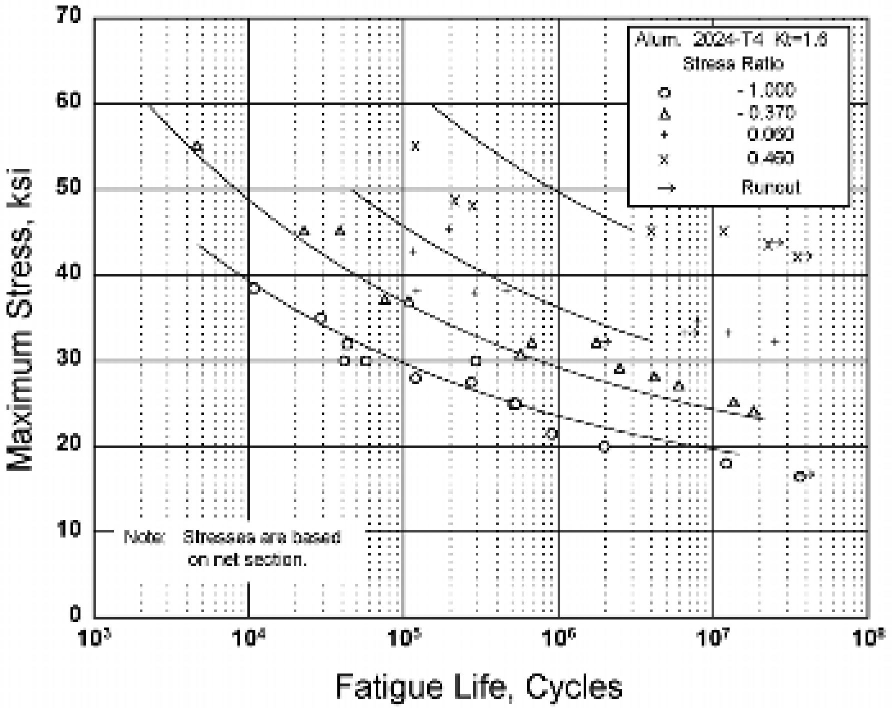


Figure 3.2.3.1.8(b). Best-fit S/N curves for notched, K_t = 1.6, 2024-T4 aluminum alloy bar, longitudinal direction.

Correlative Information for Figure 3.2.3.1.8(b)

Product Form: Rolled bar, 1.125 inch diameter

Properties:

TUS, ksi	TYS, ksi	Temp., °F
73	49	RT

Specimen Details: Semicircular
V-Groove, K_t = 1.6
0.450 inch gross diameter
0.400 inch net diameter
0.100 inch root radius, r
60° flank angle, ω

Surface Condition: As machined

Reference: 3.2.1.1.8(a)

Test Parameters:
Loading - Axial
Frequency - 1800 to 3600 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
Log N_f = 12.25-5.16 log (S_{eq}-18.7)
$S_{eq} = S_{max} (1-R)^{0.57}$
Std. Error of Estimate, Log (Life) = 0.414
Standard Deviation, Log (Life) = 0.989
R^2 = 82%

Sample Size = 38

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

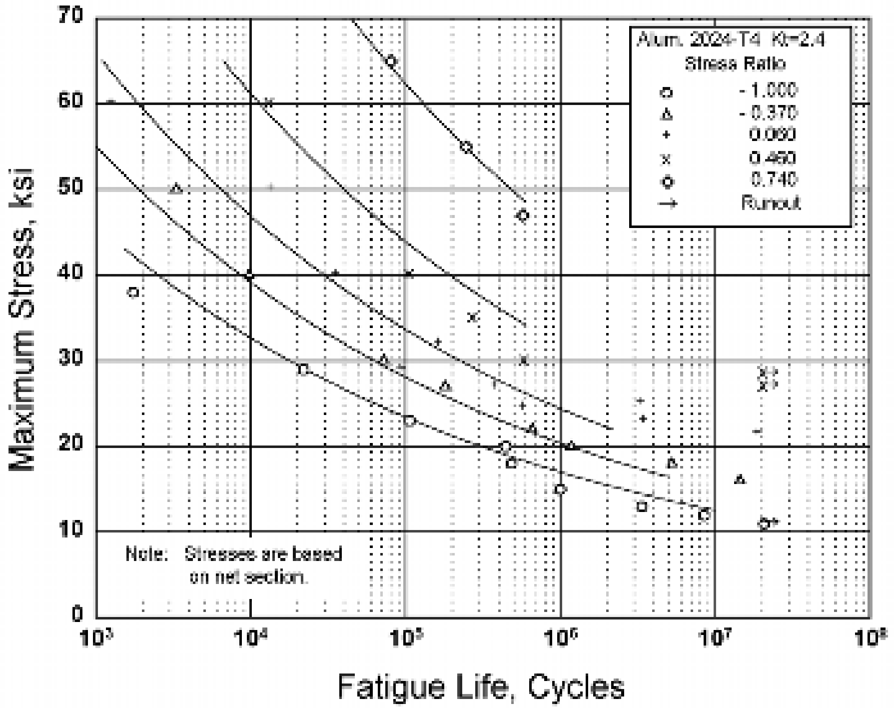


Figure 3.2.3.1.8(c). Best-fit S/N curves for notched, K_t = 2.4, 2024-T4 aluminum alloy bar, longitudinal direction.

Correlative Information for Figure 3.2.3.1.8(c)

Product Form: Rolled bar, 1.125 inch diameter

Properties:

TUS, ksi	TYS, ksi	Temp., °F
73	49	RT

Specimen Details: Circumferential
V-Groove, K_t = 2.4
0.500 inch gross diameter
0.400 inch net diameter
0.032 inch root radius, r
60° flank angle, ω

Surface Condition: As machined

Reference: 3.2.1.1.8(b)

Test Parameters:
Loading - Axial
Frequency - 1800 to 3600 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
$\text{Log } N_f = 14.33-6.35 \log (S_{eq}-3.2)$
$S_{eq} = S_{max} (1-R)^{0.48}$
Std. Error of Estimate, Log (Life) = 0.310
Standard Deviation, Log (Life) = 1.084
R^2 = 92%

Sample Size = 33

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

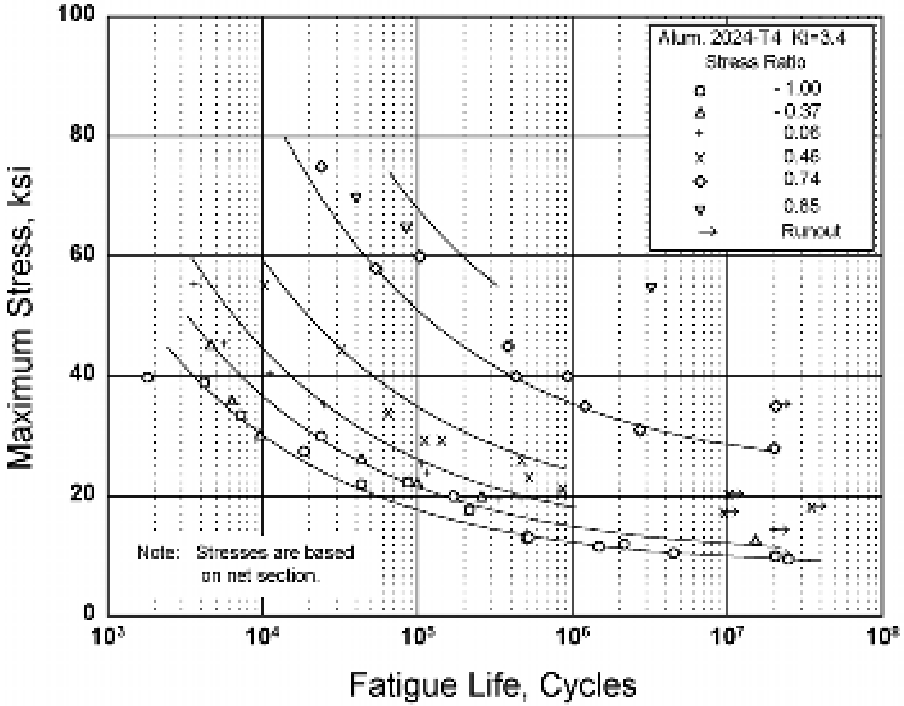


Figure 3.2.3.1.8(d). Best-fit S/N curves for notched, K_t = 3.4, 2024-T4 aluminum alloy, various wrought products, longitudinal direction.

Correlative Information for Figure 3.2.3.1.8(d)

Product Form: Rolled bar, 1.125 inch diameter
Extruded bar, 1.25 inch diameter

Properties:

TUS, ksi	TYS, ksi	Temp., °F
74.2	—	RT (rolled)
84.1	—	RT (extruded)

Specimen Details: Circumferential
V-Groove, K_t = 3.4
0.450 inch gross diameter
0.400 inch net diameter
0.010 inch root radius, r
60° flank angle, ω

Surface Condition: As machined

References: 3.2.1.1.8(b) and (c)

Test Parameters:
Loading - Axial
Frequency - 1800 to 3600 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
$\text{Log } N_f = 8.18 - 2.76 \log (S_{eq} - 11.6)$
$S_{eq} = S_{max} (1-R)^{0.52}$
Std. Error of Estimate, Log (Life) = 0.292
Standard Deviation, Log (Life) = 1.011
R^2 = 92%

Sample Size = 51

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

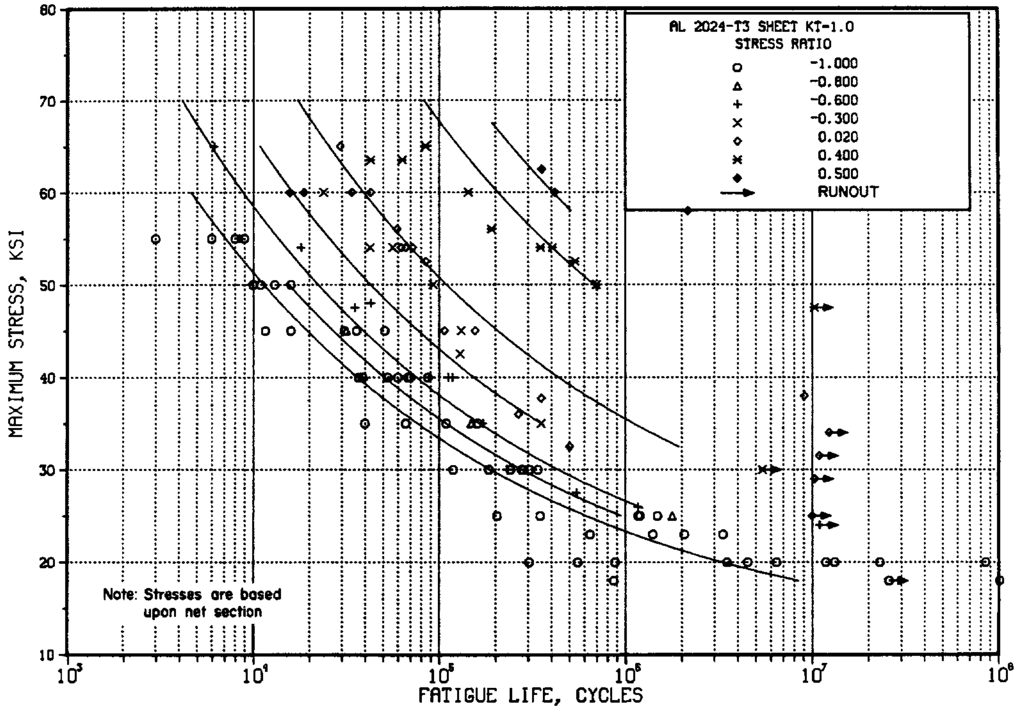


Figure 3.2.3.1.8(e). Best-fit S/N curves for unnotched, 2024-T3 aluminum alloy sheet, longitudinal direction.

Correlative Information for Figure 3.2.3.1.8(e)

Product Form: Bare sheet, 0.090 inch

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	72 - 73	52 - 54	RT

Specimen Details: Unnotched
0.8 to 1.0 inch width

Surface Condition: Electropolished

References: 3.2.3.1.8(a) and (f)

Test Parameters:
Loading - Axial
Frequency - 1100 to 1800 cpm

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
$\text{Log } N_f = 11.1\text{-}3.97 \log (S_{eq}\text{-}15.8)$
$S_{eq} = S_{max} (1\text{-}R)^{0.56}$
Std. Error of Estimate, Log (Life) = 0.38
Standard Deviation, Log (Life) = 0.90
$R^2 = 82\%$

Sample Size = 107

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

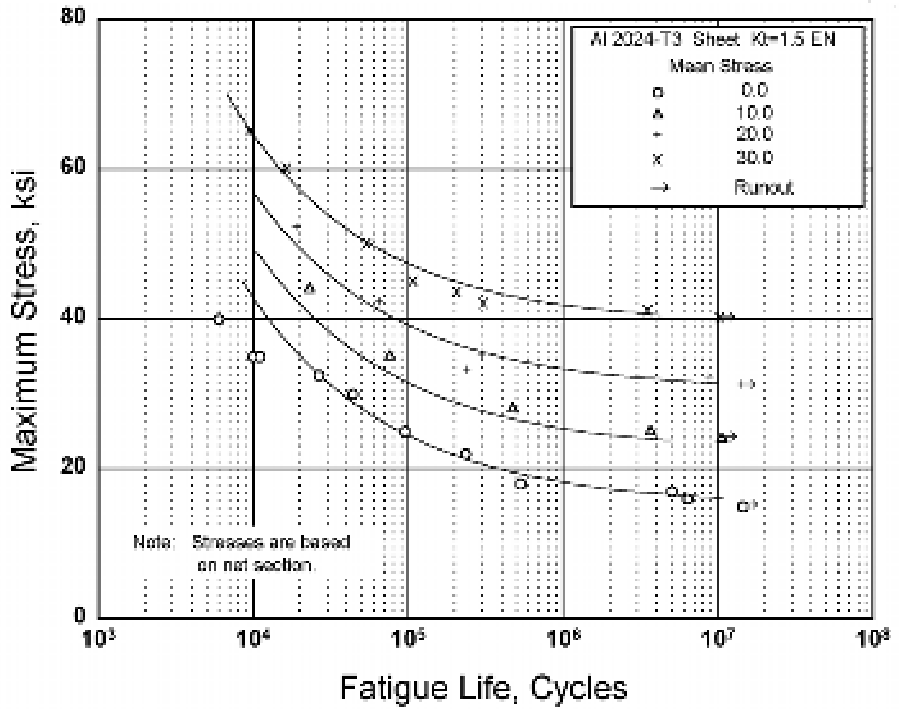


Figure 3.2.3.1.8(f). Best-fit S/N curves for notched, K_t = 1.5, 2024-T3 aluminum alloy sheet, longitudinal direction.

Correlative Information for Figure 3.2.3.1.8(f)

Product Form: Bare sheet, 0.090 inch

Properties:

TUS, ksi	TYS, ksi	Temp., °F
73	54	RT (unnotched)
76	—	RT (notched K_t = 1.5)

Specimen Details: Edge notched, K_t = 1.5
3.00 inches gross width
1.500 inches net width
0.760 inch notch radius
0° flank angle

Surface Condition: Electropolished

Reference: 3.2.3.1.8(d)

Test Parameters:
Loading - Axial
Frequency - 1100 to 1500 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
$\text{Log } N_f = 7.5 - 2.13 \log (S_{eq} - 23.7)$
$S_{eq} = S_{max} (1-R)^{0.66}$
Std. Error of Estimate, Log (Life) = 0.30
Standard Deviation, Log (Life) = 0.95
R^2 = 90%

Sample Size = 26

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

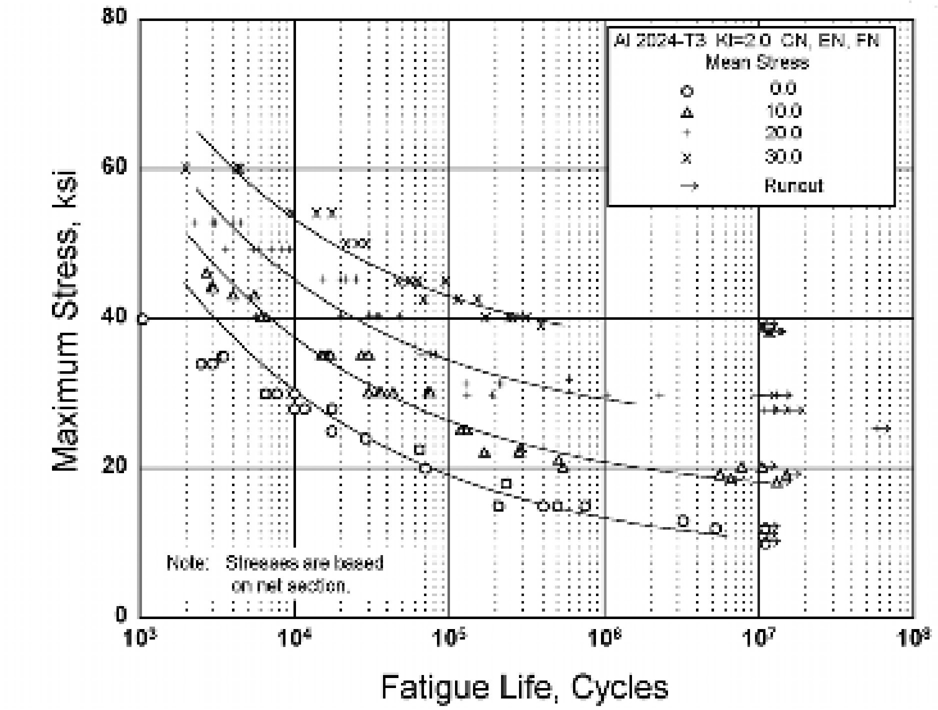


Figure 3.2.3.1.8(g). Best-fit S/N curves for notched, K_t = 2.0, 2024-T3 aluminum alloy sheet, longitudinal direction.

Correlative Information for Figure 3.2.3.1.8(g)

Product Form: Bare sheet, 0.090 inch

Properties:

TUS, ksi	TYS, ksi	Temp., °F
73	54	RT (unnotched)
73	—	RT (notched K_t= 2.0)

Specimen Details: Notched, K_t = 2.0

Notch Type	Gross Width	Net Width	Notch Radius
Center	4.50	1.50	1.50
Edge	2.25	1.50	0.3175
Fillet	2.25	1.50	0.1736

Surface Condition: Electropolished, machined and burrs removed with fine crocus cloth

References: 3.2.3.1.8(b) and (f)

Test Parameters:
Loading - Axial
Frequency - 1100 to 1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
$\text{Log } N_f = 9.2\text{-}3.33 \log (S_{eq}\text{-}12.3)$
$S_{eq} = S_{max} (1\text{-}R)^{0.68}$
Std. Error of Estimate, Log (Life) = 0.27
Standard Deviation, Log (Life) = 0.89
R^2 = 91%

Sample Size = 113

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

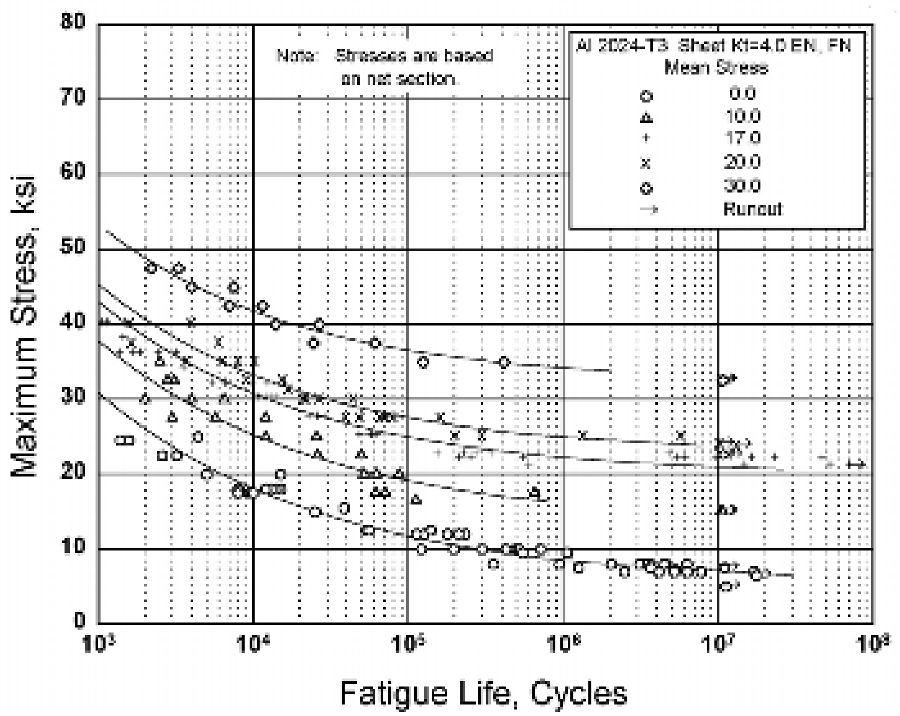


Figure 3.2.3.1.8(h). Best-fit S/N curves for notched, K_t = 4.0 of 2024-T3 aluminum alloy sheet, longitudinal direction.

Correlative Information for Figure 3.2.3.1.8(h)

Product Form: Bare sheet, 0.090-inch

Properties:

TUS, ksi	TYS, ksi	Temp., °F
73	54	RT (unnotched)
67	—	RT (notched K_t = 2.0)

Specimen Details: Notched, K_t = 2.0

Notch Type	Gross Width	Net Width	Notch Radius
Center	2.25	1.50	0.057
Edge	4.10	1.50	0.070
Fillet	2.25	1.50	0.0195

Surface Condition: Electropolished, machined, and burrs removed with fine crocus cloth

References: 3.2.3.1.8(b), (e), (f), (g), and (h)

Test Parameters:
Loading - Axial
Frequency - 1100 to 1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
Log N_f = 8.3-3.30 log (S_{eq}-8.5)
$S_{eq} = S_{max} (1-R)^{0.66}$
Std. Error of Estimate, Log (Life) = 0.39
Standard Deviation, Log (Life) = 1.24
R^2 = 90%

Sample Size = 126

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

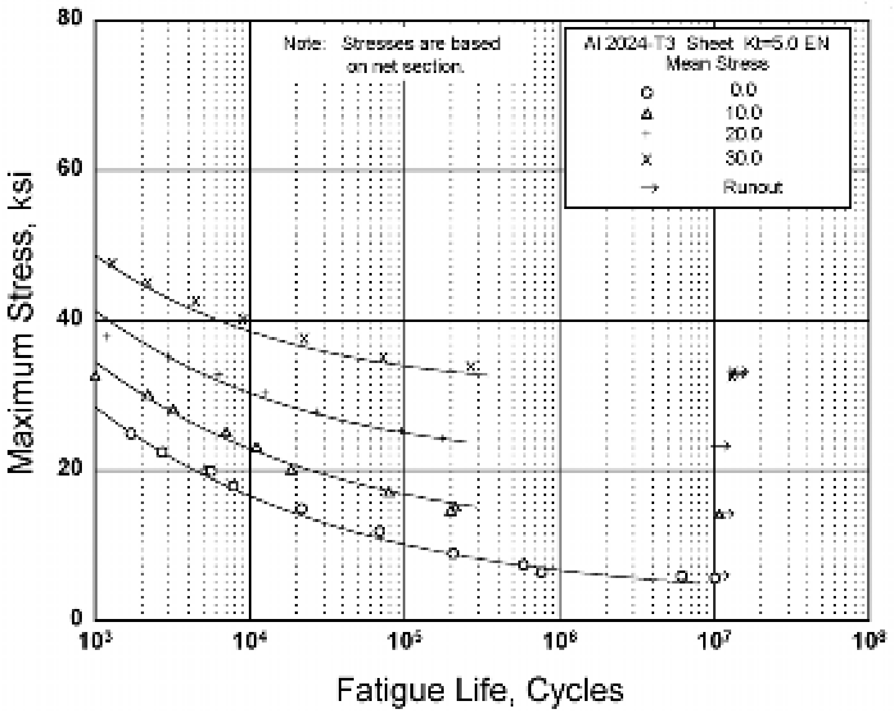


Figure 3.2.3.1.8(i). Best-fit S/N curves for notched, K_t = 5.0, 2024-T3 aluminum alloy sheet, longitudinal direction.

Correlative Information for Figure 3.2.3.1.8(i)

Product Form: Bare sheet, 0.090 inch

Properties:

TUS, ksi	TYS, ksi	Temp., °F
73	54	RT (unnotched)
62	—	RT (notched K_t = 5.0)

Specimen Details: Edge notched, K_t = 5.0
2.25 inch gross width
1.500 inch net width
0.03125 inch notch radius
0° flank angle

Surface Condition: Electropolished

Reference: 3.2.3.1.8(c)

Test Parameters:
Loading - Axial
Frequency - 1100 to 1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
$\text{Log } N_f = 8.9-3.73 \log (S_{eq}-3.9)$
$S_{eq} = S_{max} (1-R)^{0.56}$
Std. Error of Estimate, Log (Life) = 0.39
Standard Deviation, Log (Life) = 1.24
R^2 = 90%

Sample Size = 35

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

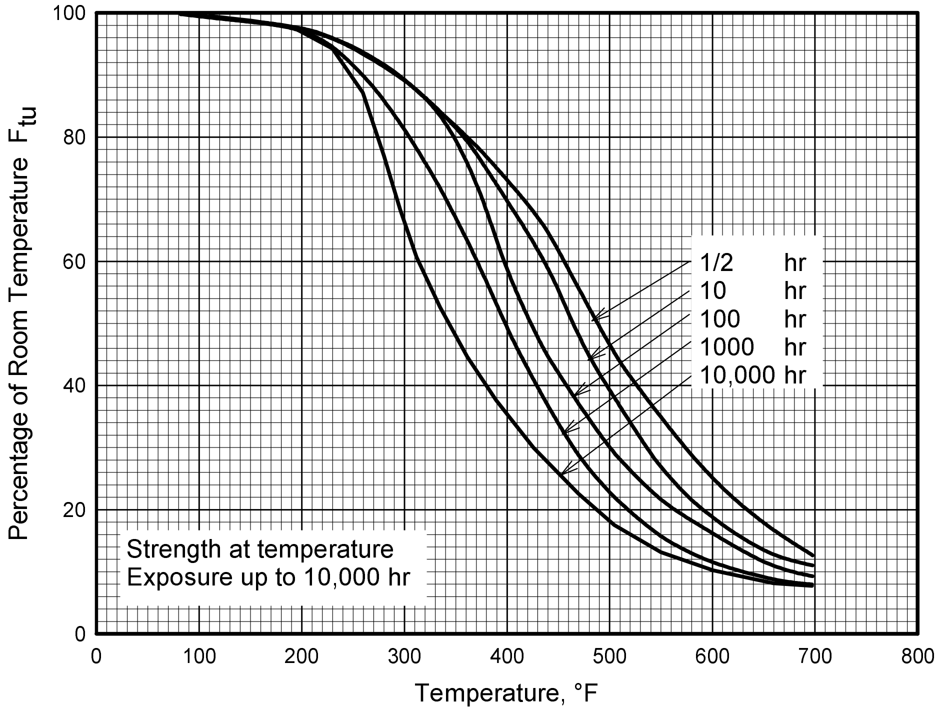


Figure 3.2.3.3.1(a). Effect of temperature on the tensile ultimate strength (F_{tu}) of 2024-T62 aluminum alloy (all products).

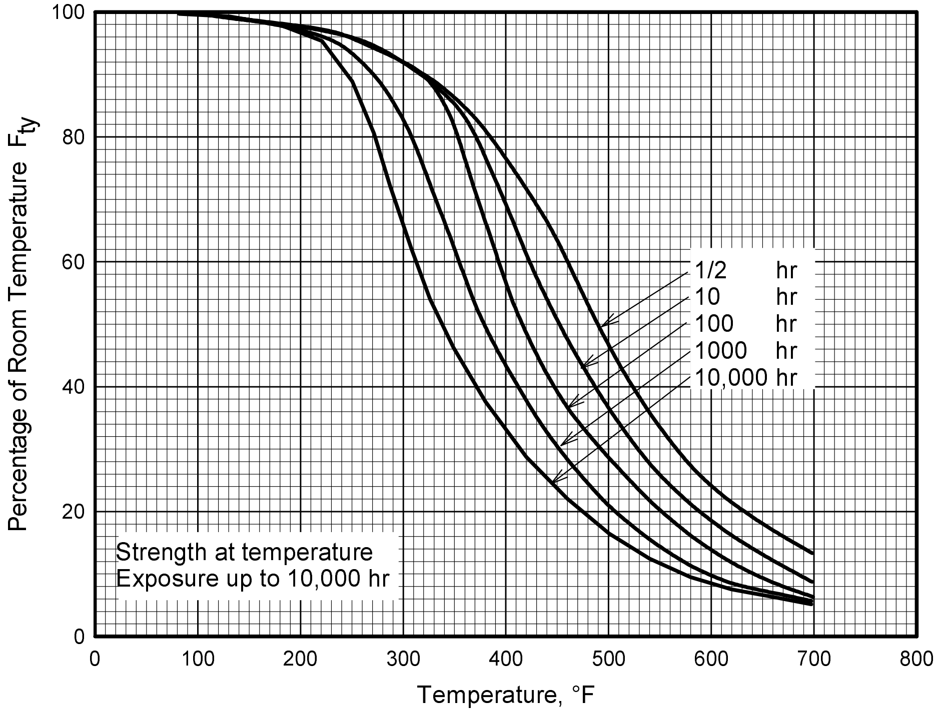


Figure 3.2.3.3.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of 2024-T62 aluminum alloy (all products).

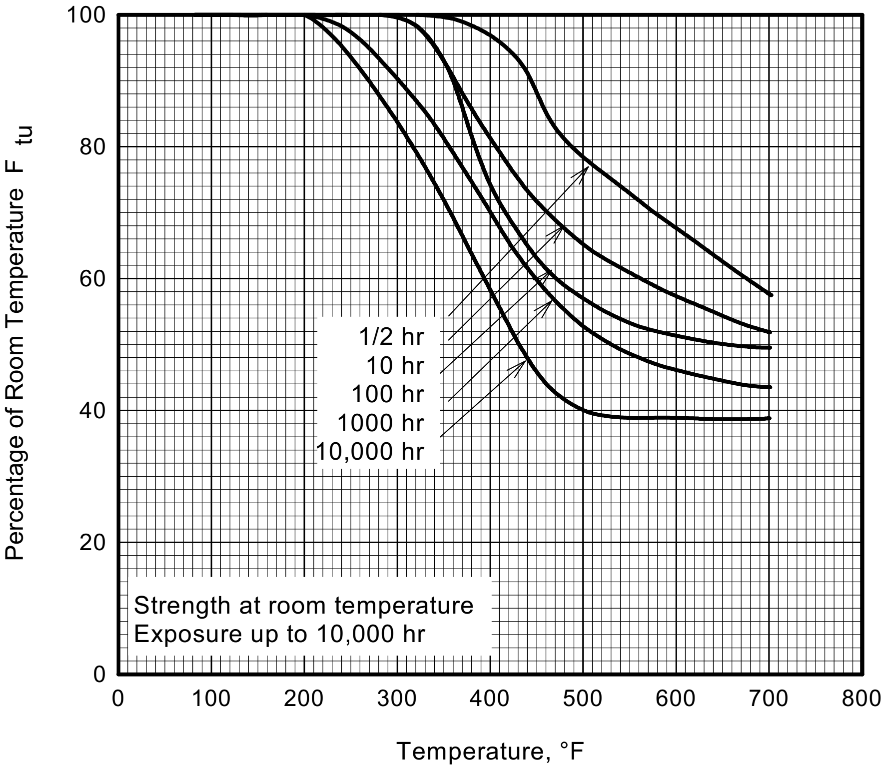


Figure 3.2.3.3.1(c). Effect of exposure at elevated temperatures on the room-temperature tensile ultimate strength (F_{tu}) of 2024-T62 aluminum alloy (all products).

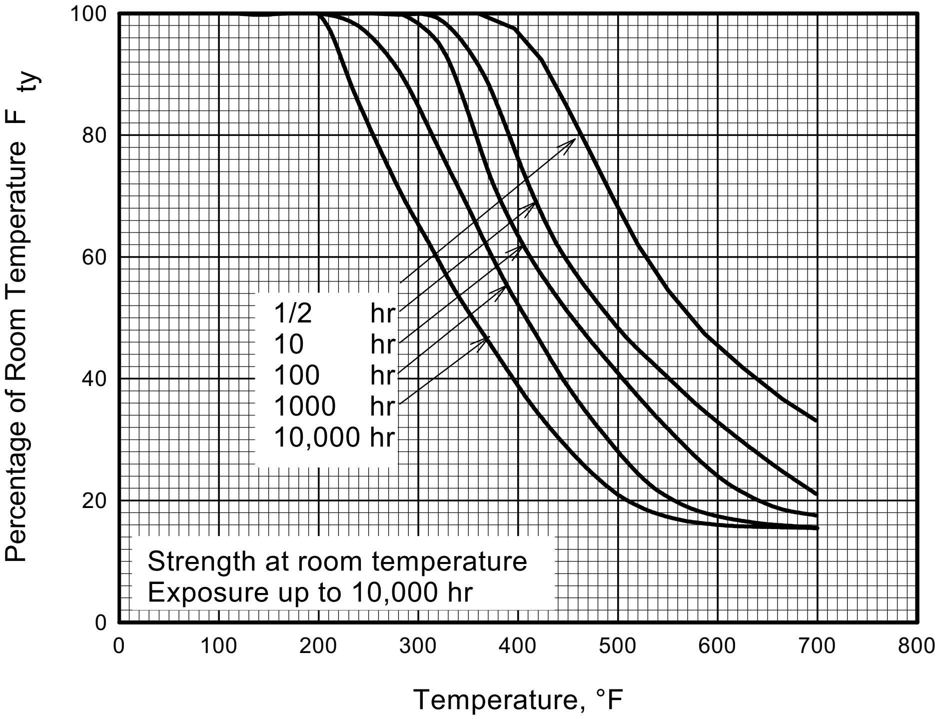


Figure 3.2.3.3.1(d). Effect of exposure at elevated temperatures on the room-temperature tensile yield strength (F_{ty}) of 2024-T62 aluminum alloy (all products).

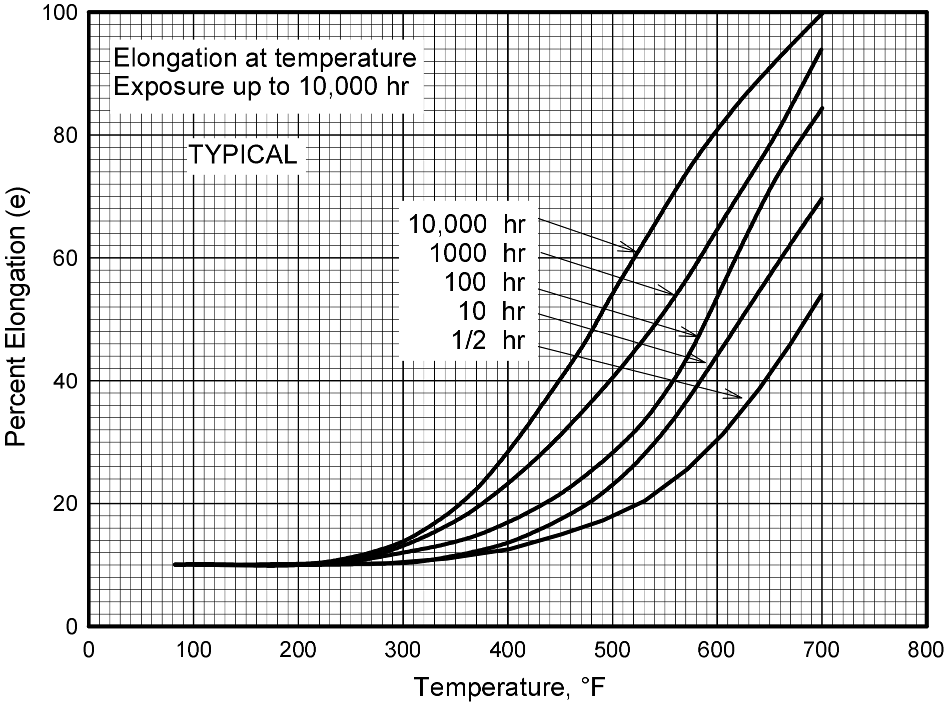


Figure 3.2.3.3.5(a). Effect of temperature on the elongation of 2024-T62 aluminum alloy (all products).

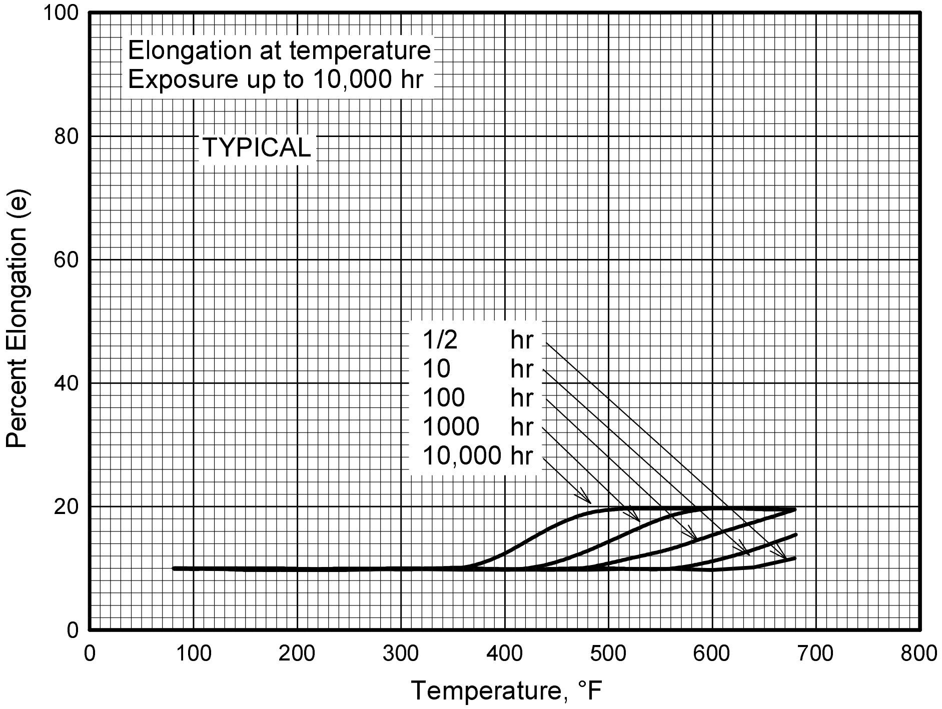


Figure 3.2.3.3.5(b). Effect of exposure at elevated temperatures on the elongation of 2024-T62 aluminum alloy (all products).

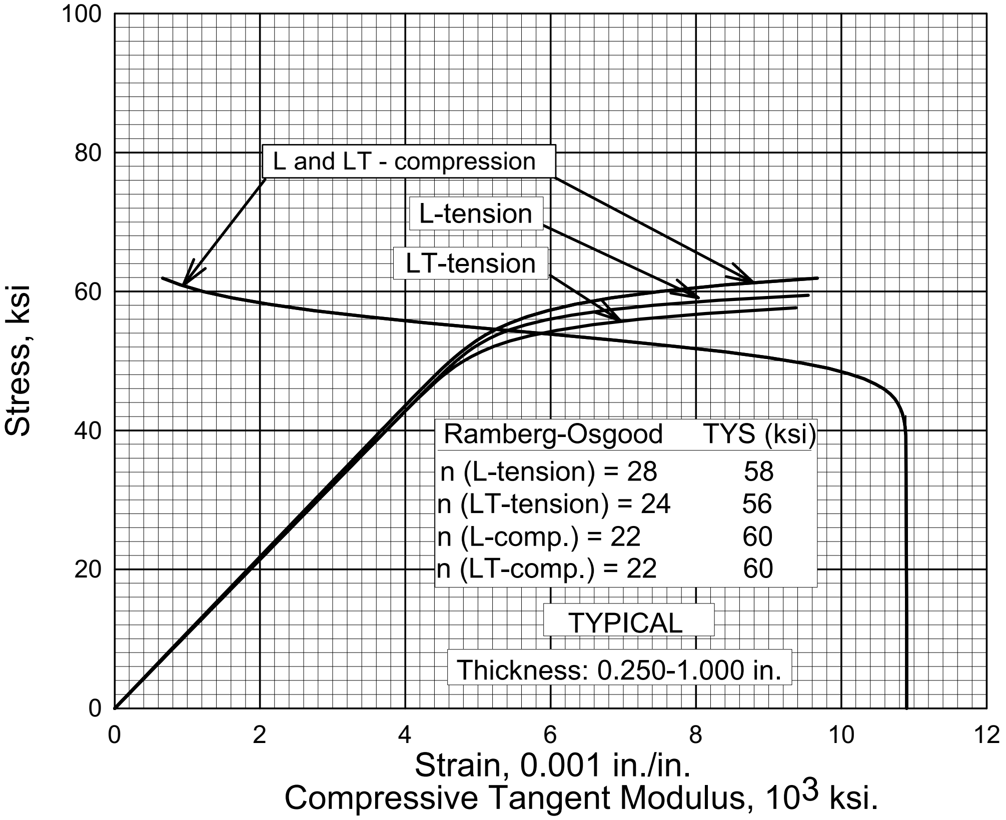


Figure 3.2.3.3.6(a). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 2024-T62 aluminum alloy plate at room temperature.

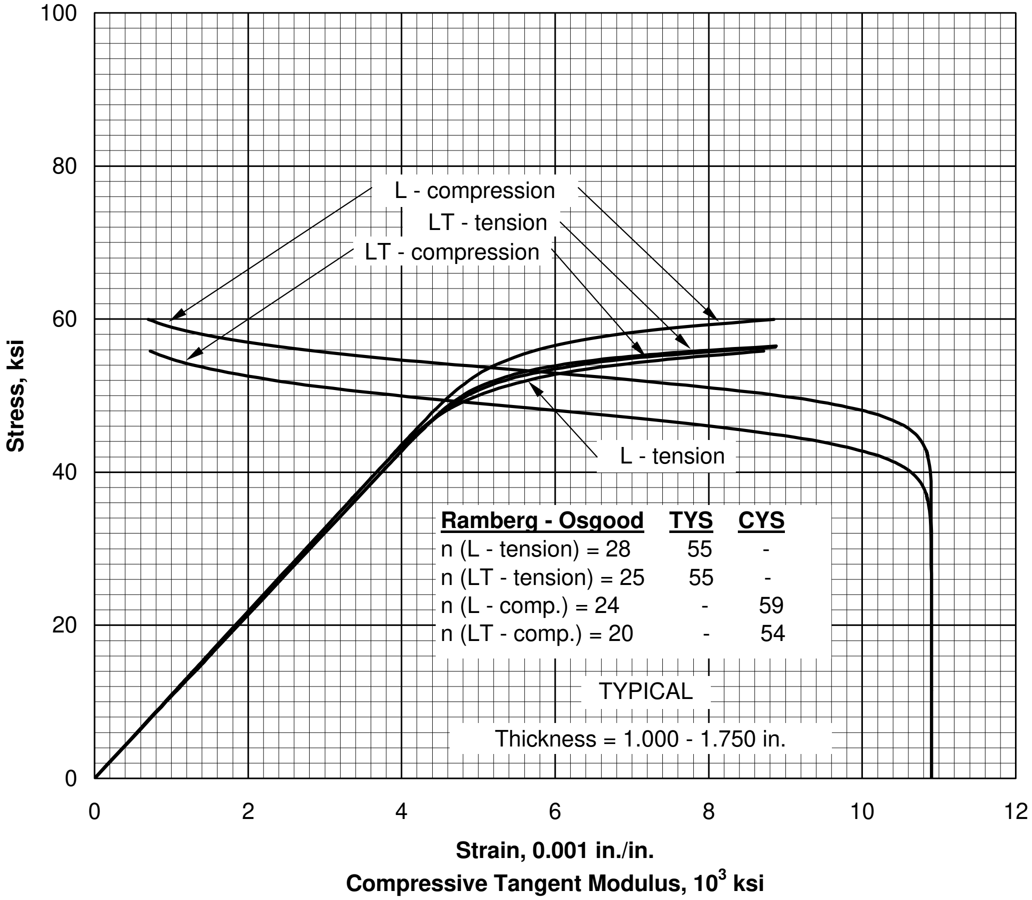


Figure 3.2.3.3.6(b) Typical tension and compression stress-strain and compression tangent modulus curves for 2024-T62 aluminum alloy plate at room temperature. Note, the data to generate these curves may have been from clad product, however, they are shown here without secondary modulus since it could not be positively confirmed the product was clad.

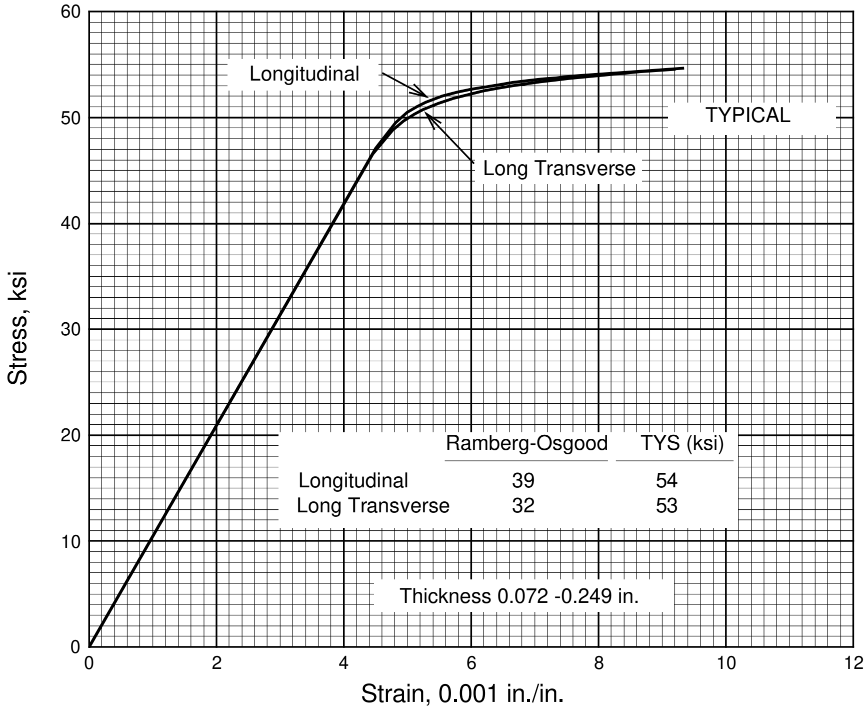


Figure 3.2.3.3.6(c). Typical tensile stress-strain curves for clad 2024-T62 aluminum alloy sheet at room temperature.

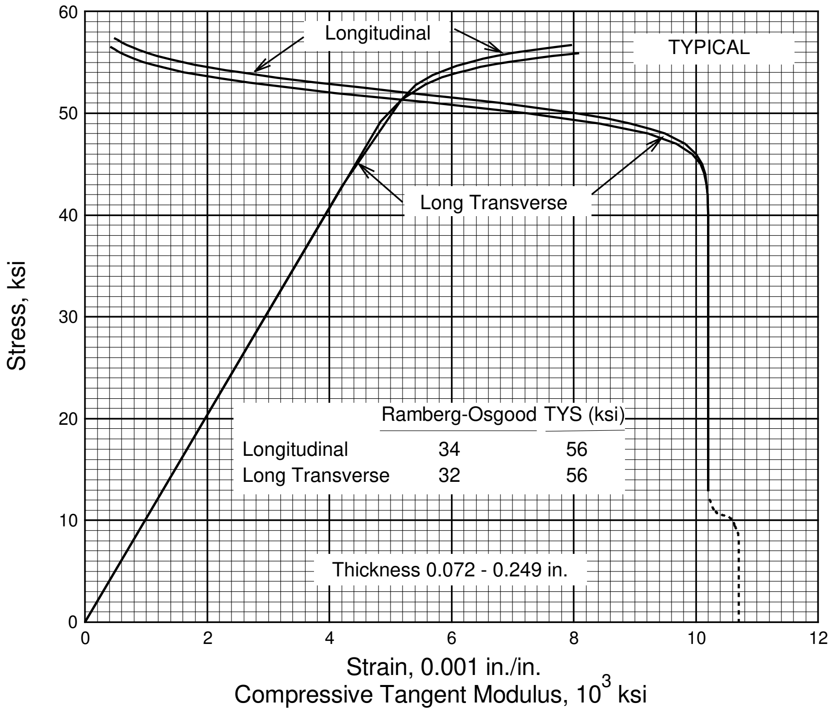


Figure 3.2.3.3.6(d). Typical compressive stress-strain and compressive tangent-modulus curves for clad 2024-T62 aluminum alloy sheet at room temperature.

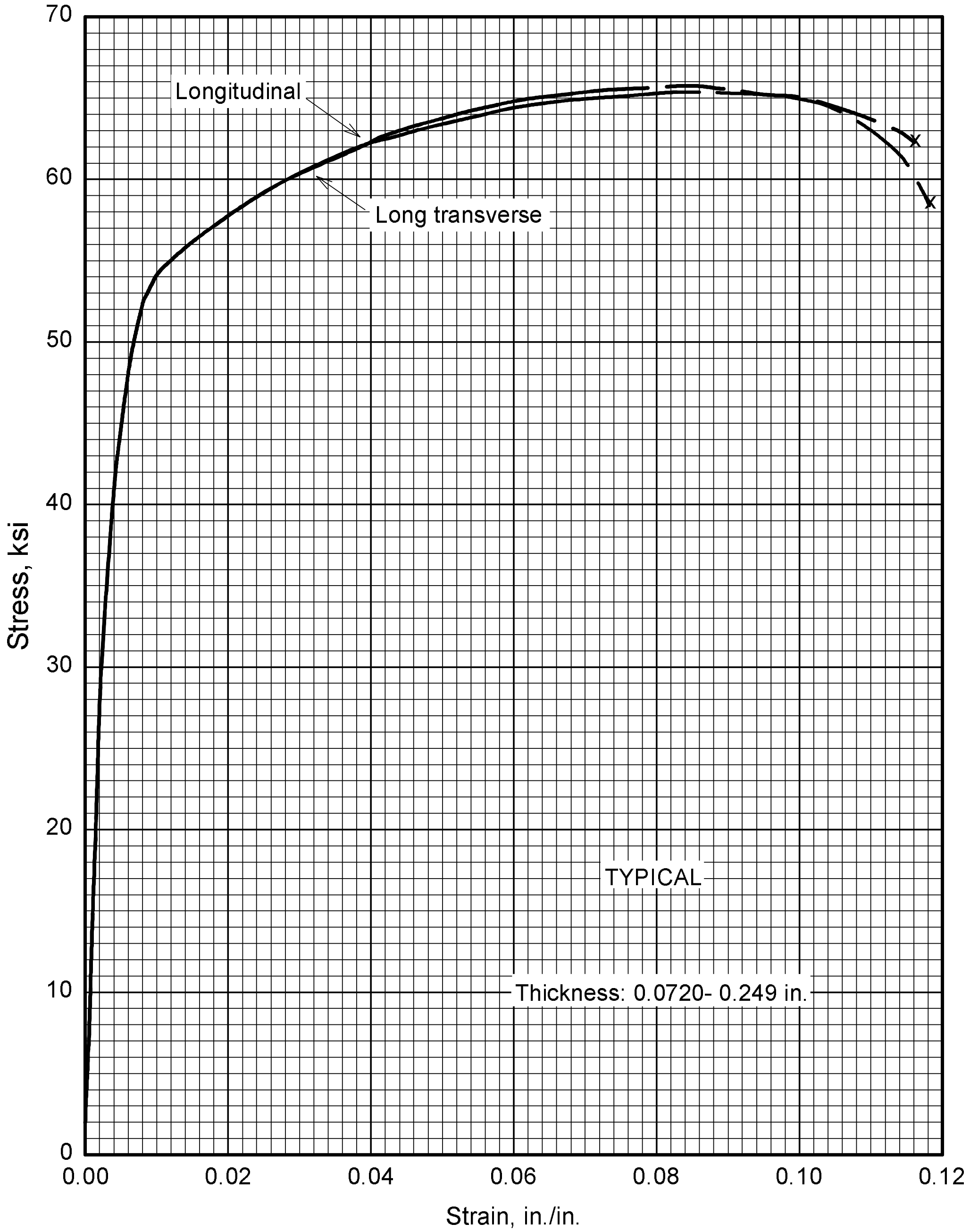


Figure 3.2.3.3.6(e). Typical stress-strain curves (full range) for clad 2024-T62 aluminum alloy sheet at room temperature.

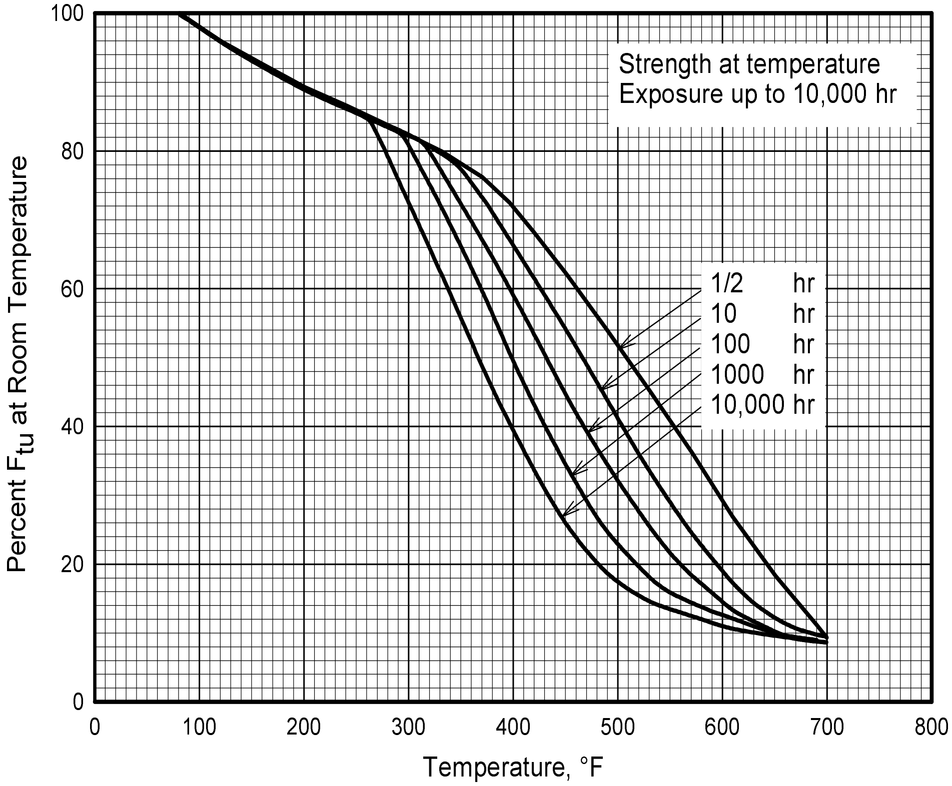


Figure 3.2.3.4.1(a). Effect of temperature on the tensile ultimate strength (F_{tu}) of 2024-T81, T851, T8510, and T8511 aluminum alloy (all products).

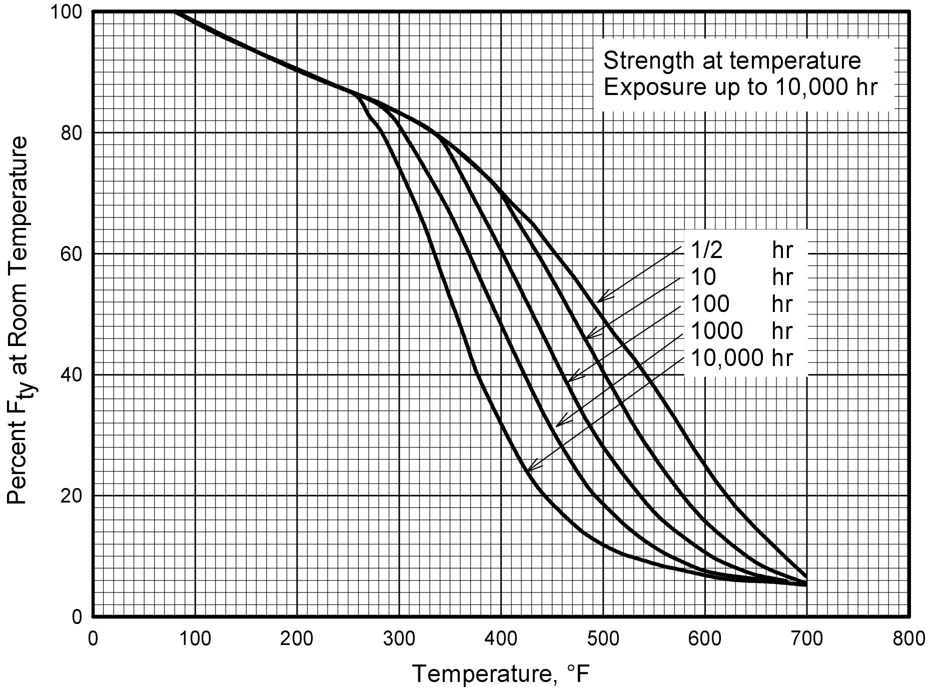


Figure 3.2.3.4.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of 2024-T81, T851, T8510, and T8511 aluminum alloy (all products).

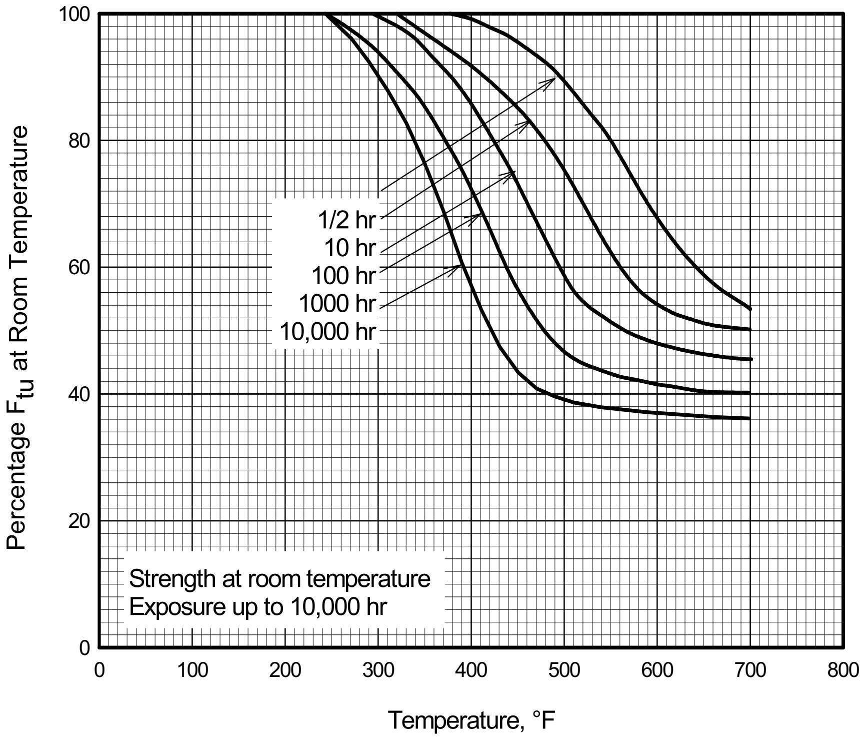


Figure 3.2.3.4.1(c). Effect of exposure at elevated temperatures on room-temperature tensile ultimate strength (F_{tu}) of 2024-T81 aluminum alloy sheet.

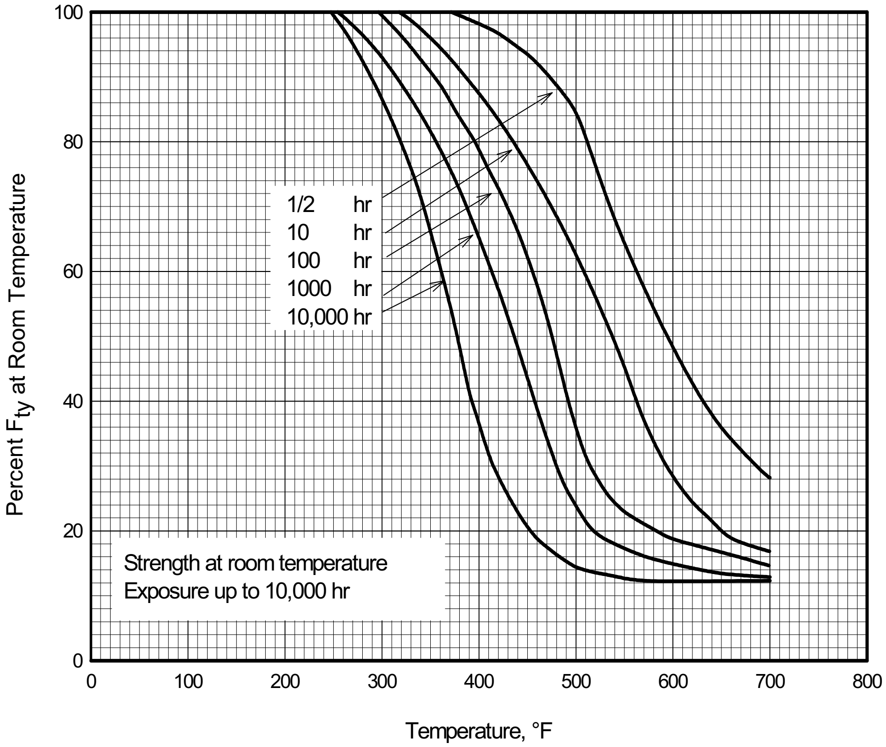


Figure 3.2.3.4.1(d). Effect of exposure at elevated temperatures on the room temperature tensile yield strength (F_{ty}) of 2024-T81 aluminum alloy sheet.

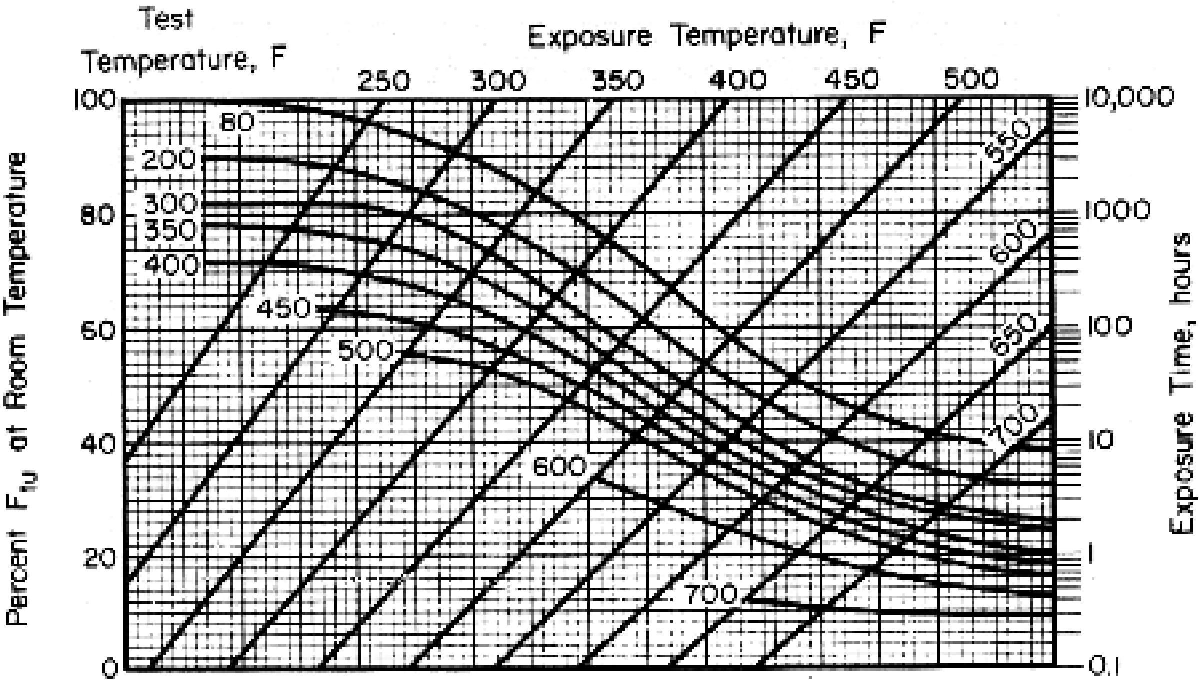


Figure 3.2.3.4.1(e). Effect of temperature on the tensile ultimate strength (F_{tu}) of 2024-T81 aluminum alloy clad sheet. Note: Instructions for use of these curves are presented in Section 3.7.4.1.

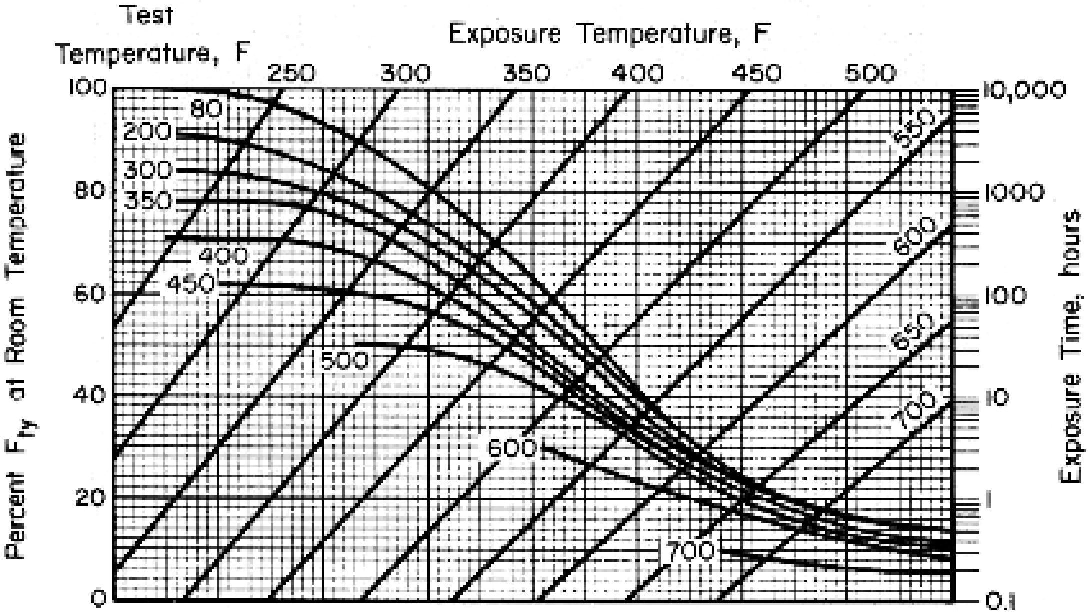


Figure 3.2.3.4.1(f). Effect of temperature on the tensile yield strength (F_{ty}) of 2024-T81 aluminum alloy clad sheet. Note: Instructions for use of these curves are presented in Section 3.7.4.1.

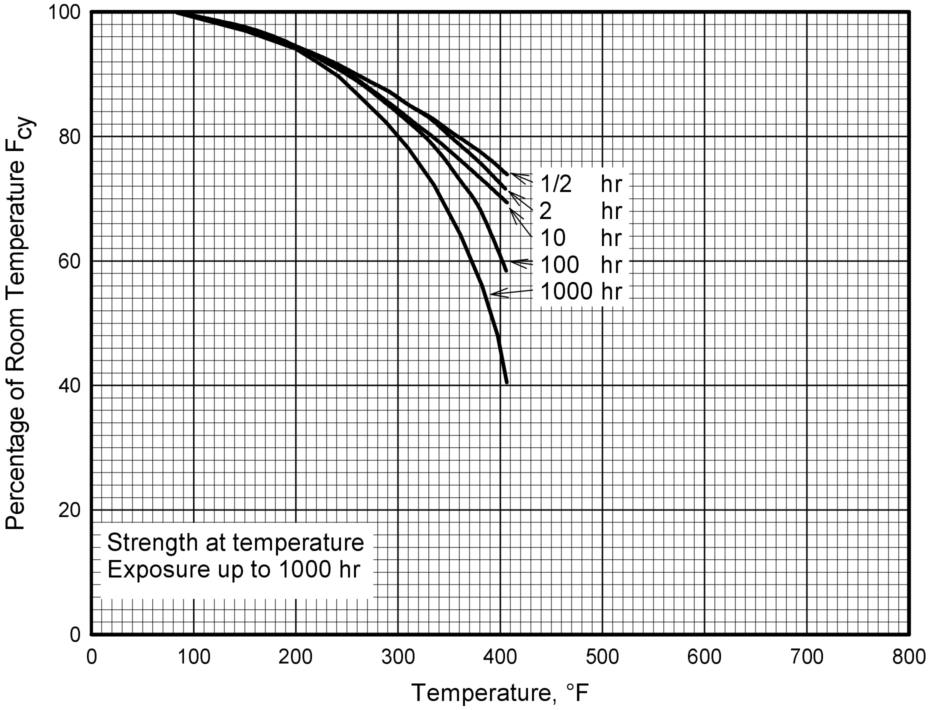


Figure 3.2.3.4.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of 2024-T81, T851, T8510, and T8511 aluminum alloy (all products).

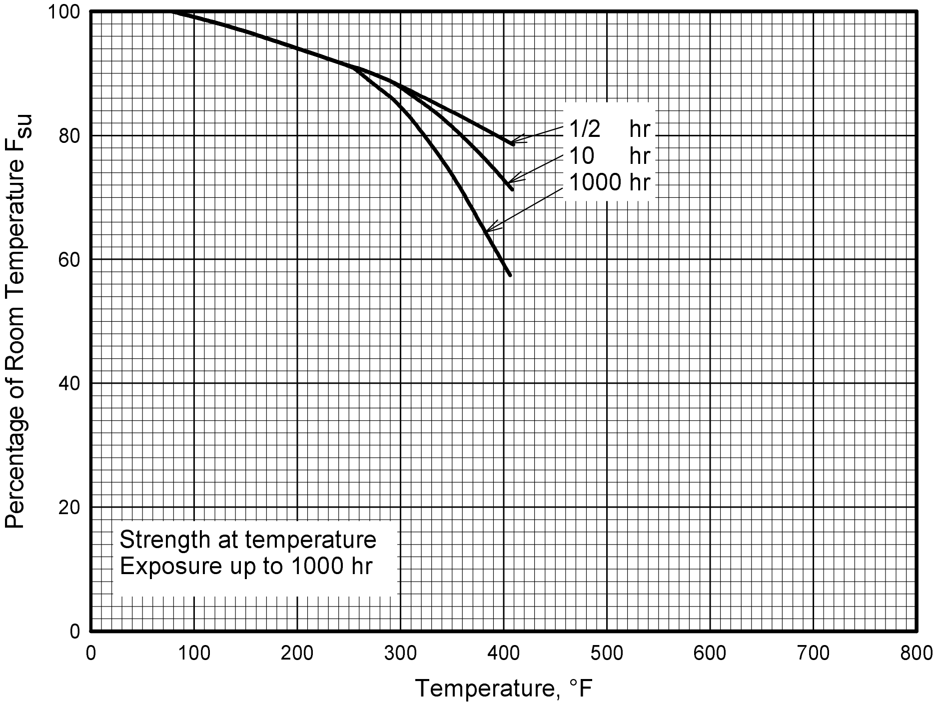


Figure 3.2.3.4.2(b). Effect of temperature on the shear ultimate strength (F_{su}) of 2024-T81, T851, T8510, and T8511 aluminum alloy (all products).

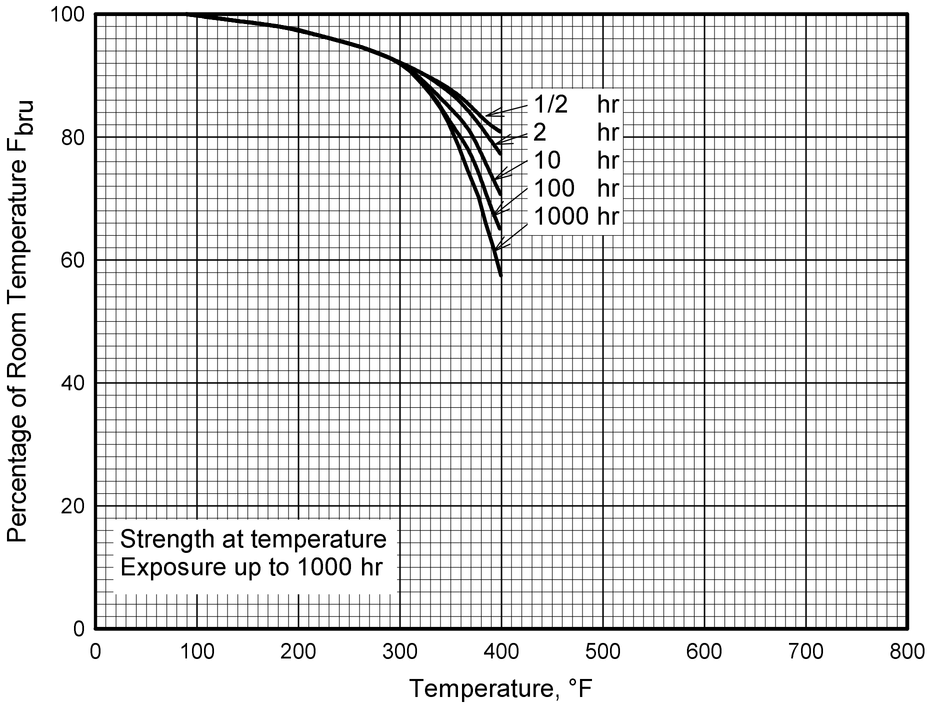


Figure 3.2.3.4.3(a). Effect of temperature on the bearing ultimate strength (F_{bru}) of 2024-T81, T851, T8510, and T8511 aluminum alloy (all products).

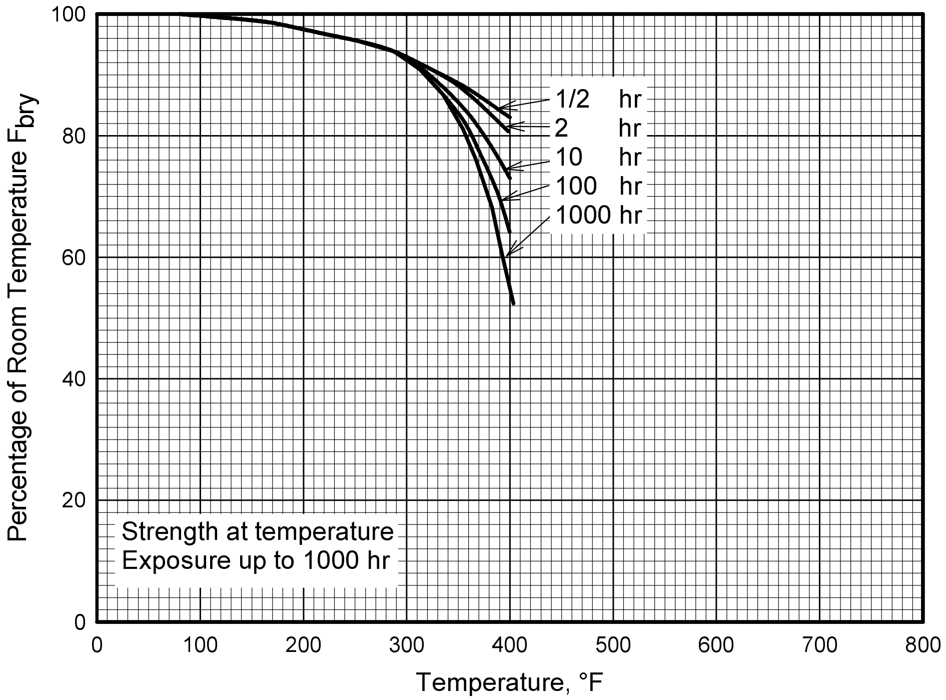


Figure 3.2.3.4.3(b). Effect of temperature on the bearing yield strength (F_{bry}) of 2024-T81, T851, T8510, and T8511 aluminum alloy (all products).

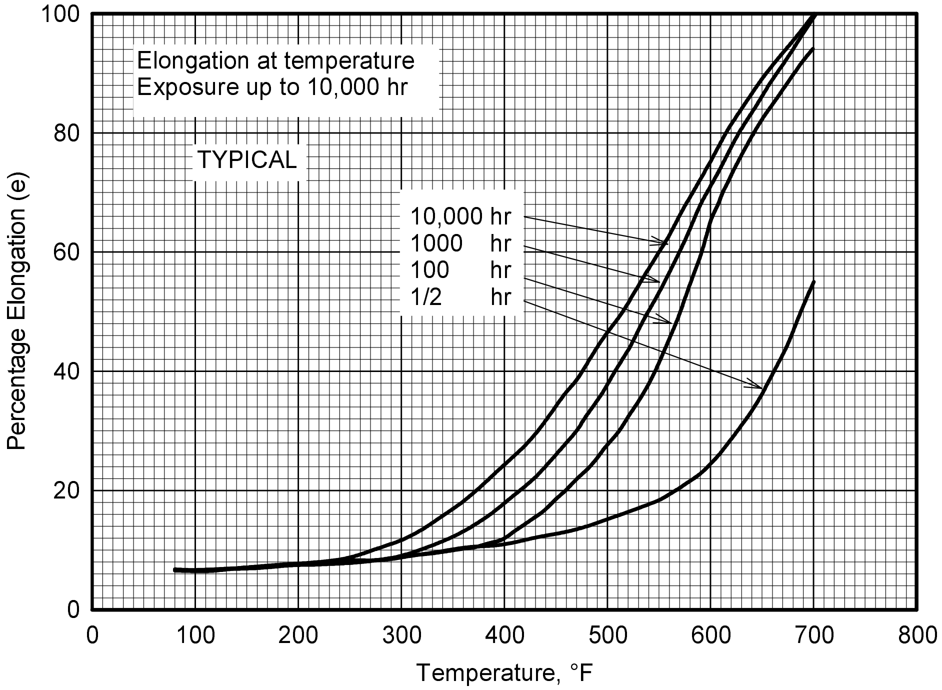


Figure 3.2.3.4.5(a). Effect of temperature on the elongation of 2024-T81, T851, T8510, and T8511 aluminum alloy (all products).

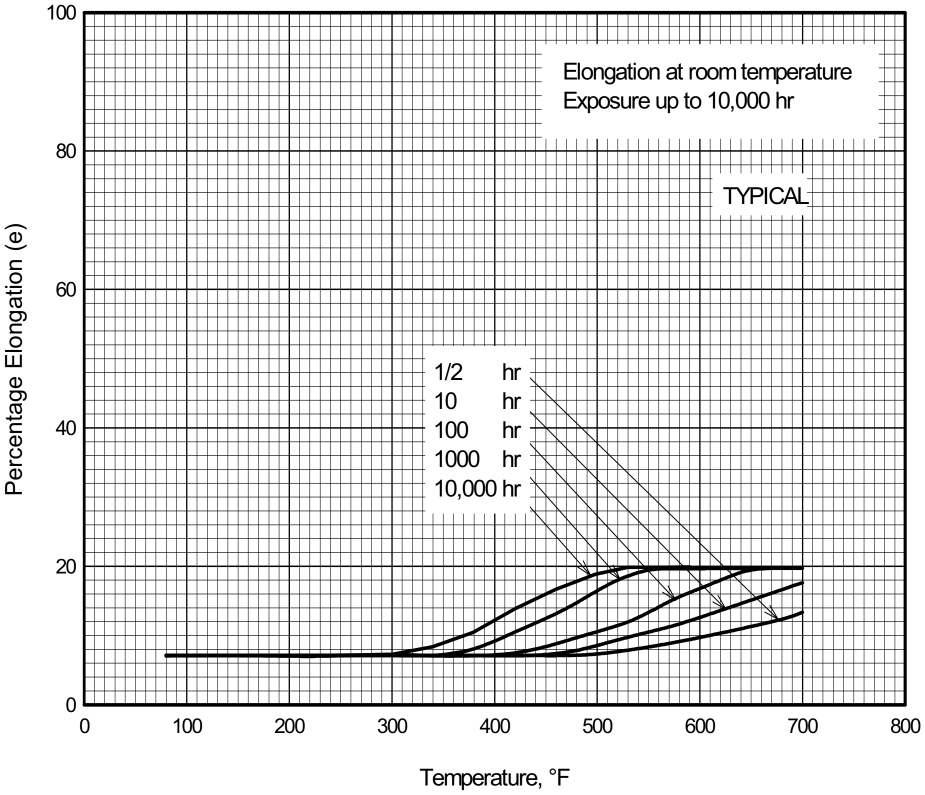


Figure 3.2.3.4.5(b). Effect of exposure at elevated temperatures on the room temperature elongation of 2024-T81, T851, T8510, and T8511 aluminum alloy (all products).

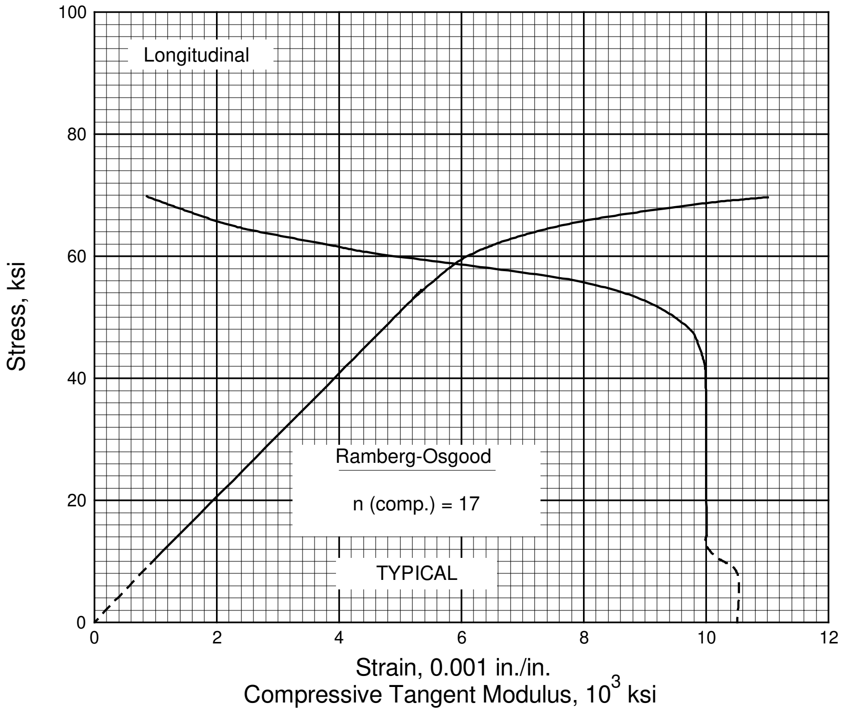


Figure 3.2.3.4.6(a). Typical compressive stress-strain and compressive tangent-modulus curves for clad 2024-T81 aluminum alloy sheet at room temperature.

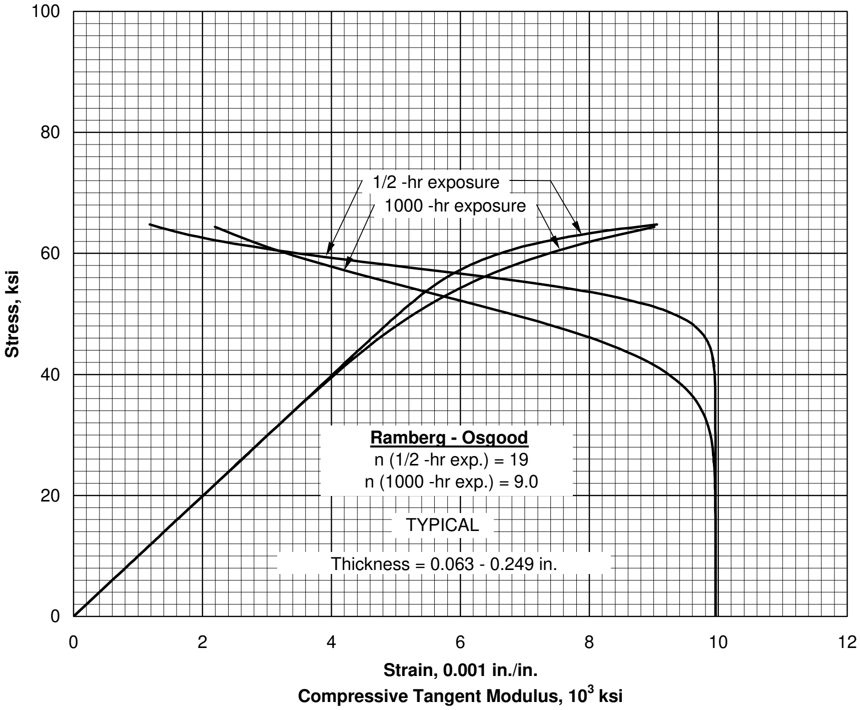


Figure 3.2.3.4.6(b). Typical compressive stress-strain and compressive tangent-modulus curves for clad 2024-T81 aluminum alloy sheet at 200°F.

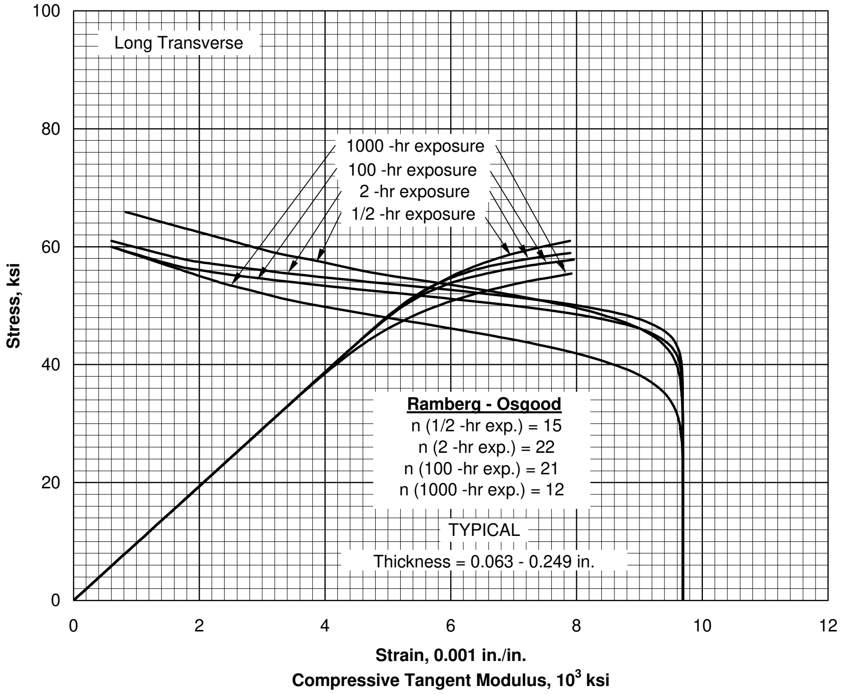


Figure 3.2.3.4.6(c). Typical compressive stress-strain and compressive tangent-modulus curves for clad 2024-T81 aluminum alloy sheet at 300°F.

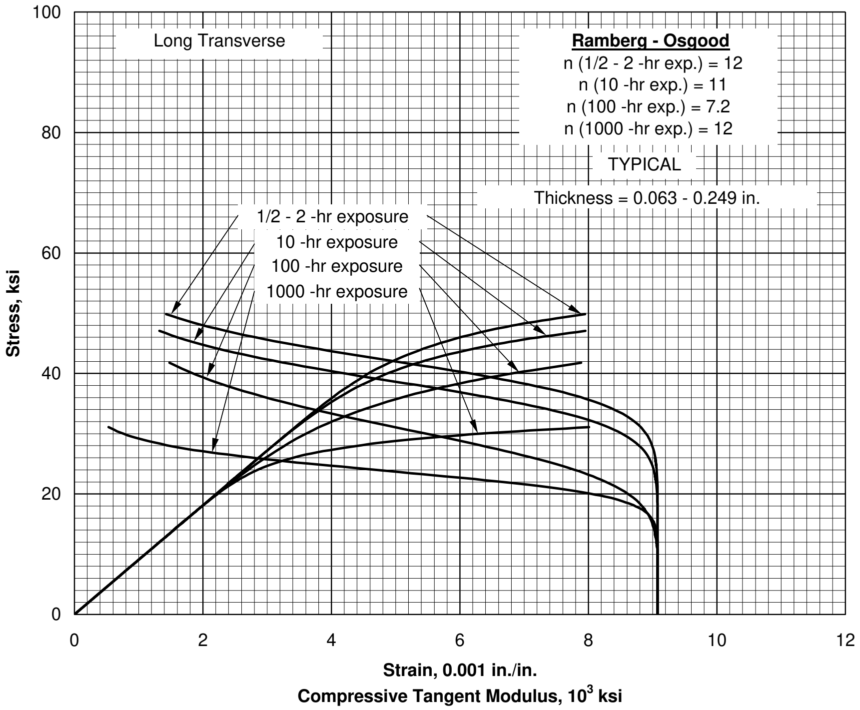


Figure 3.2.3.4.6(d). Typical compressive stress-strain and compressive tangent-modulus curves for clad 2024-T81 aluminum alloy sheet at 400°F.

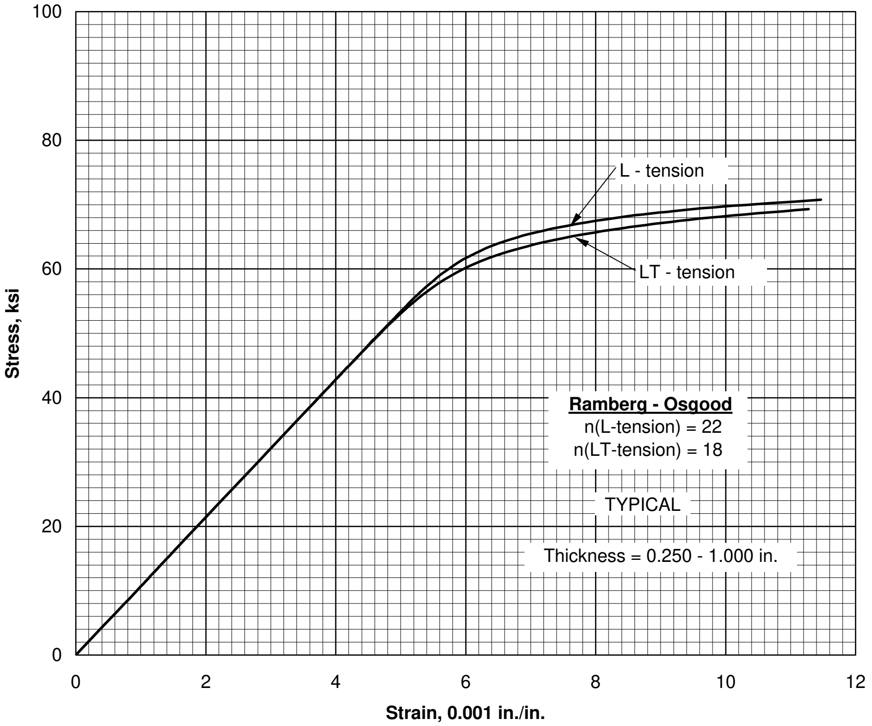


Figure 3.2.3.4.6(e). Typical tensile stress-strain curves for 2024-T851 aluminum alloy plate at room temperature.

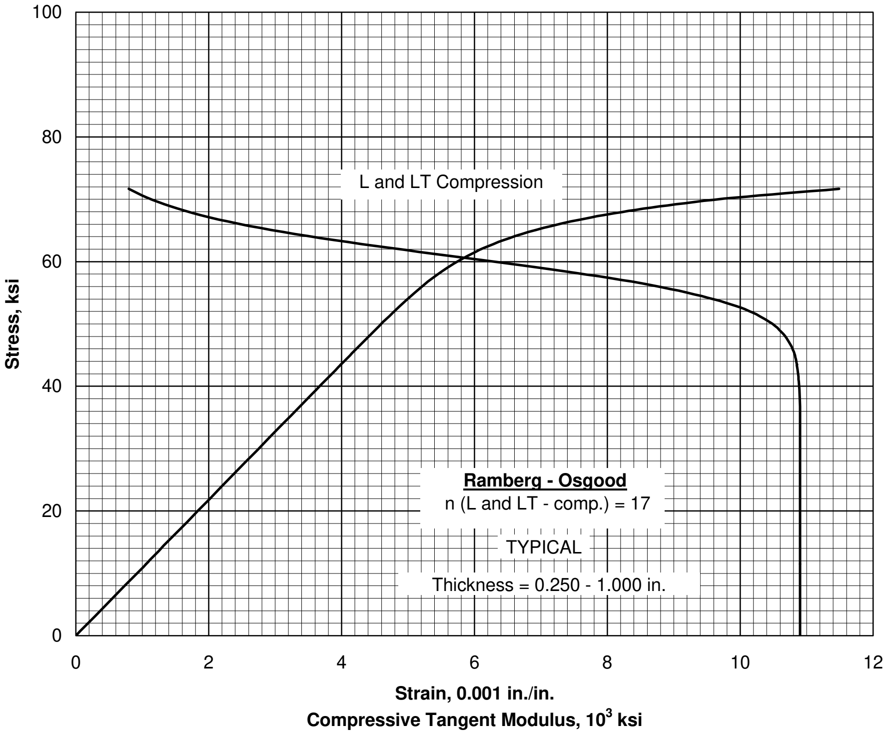


Figure 3.2.3.4.6(f). Typical compressive stress-strain and compressive tangent-modulus curves for 2024-T851 aluminum alloy plate at room temperature.

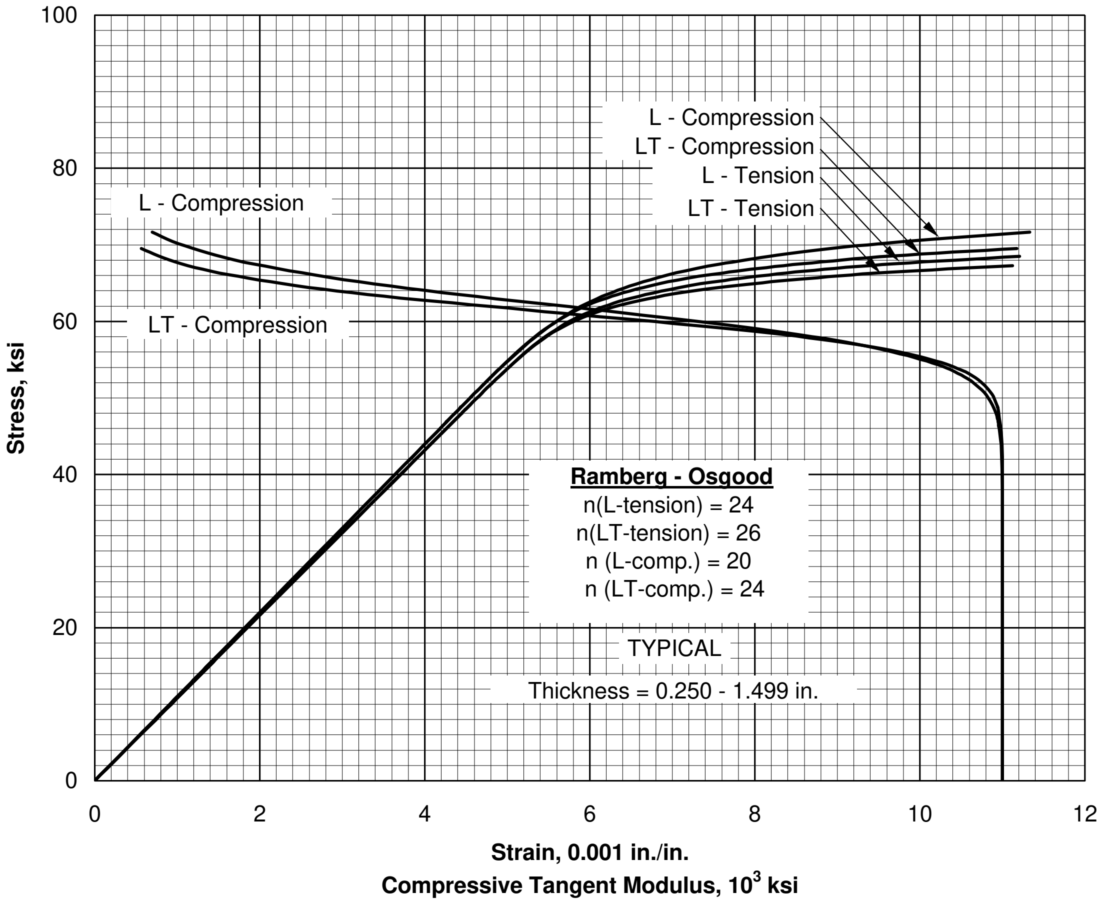


Figure 3.2.3.4.6(g). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 2024-T851X aluminum alloy extrusion at room temperature.

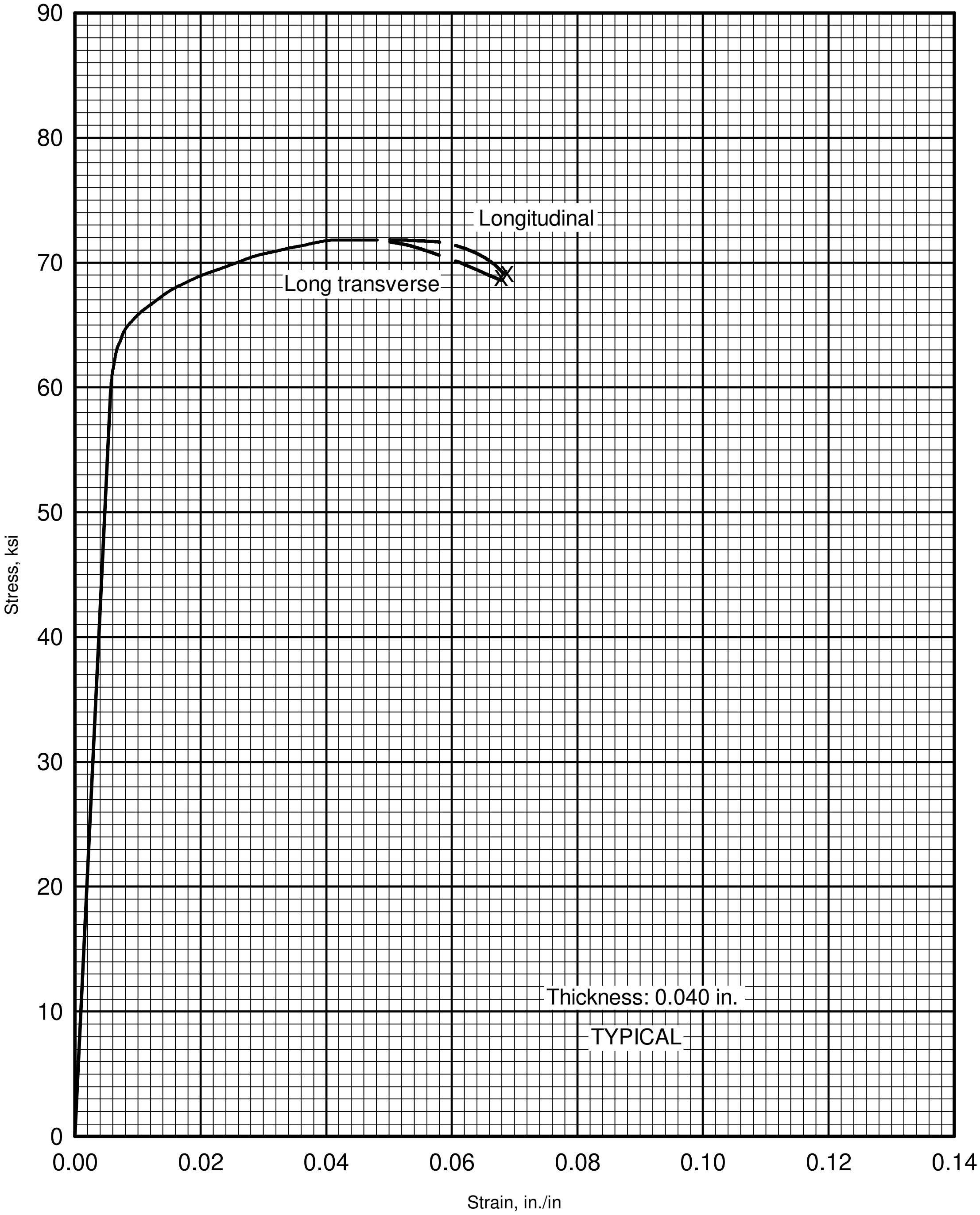


Figure 3.2.3.4.6(h). Typical tensile stress-strain curves (full range) for 2024-T81 aluminum alloy sheet at room temperature.

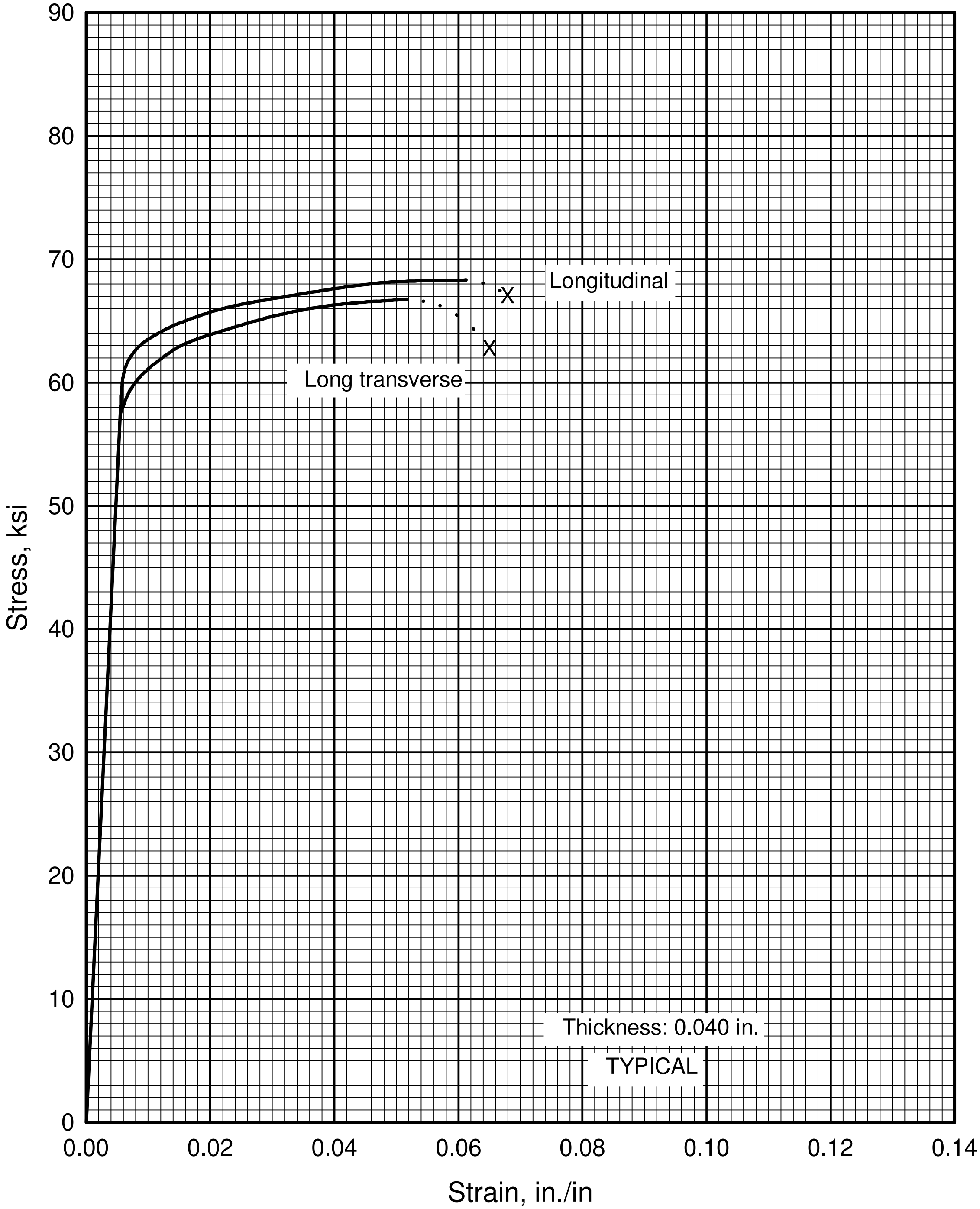


Figure 3.2.3.4.6(i). Typical tensile stress-strain curves (full range) for clad 2024-T81 aluminum alloy sheet at room temperature.

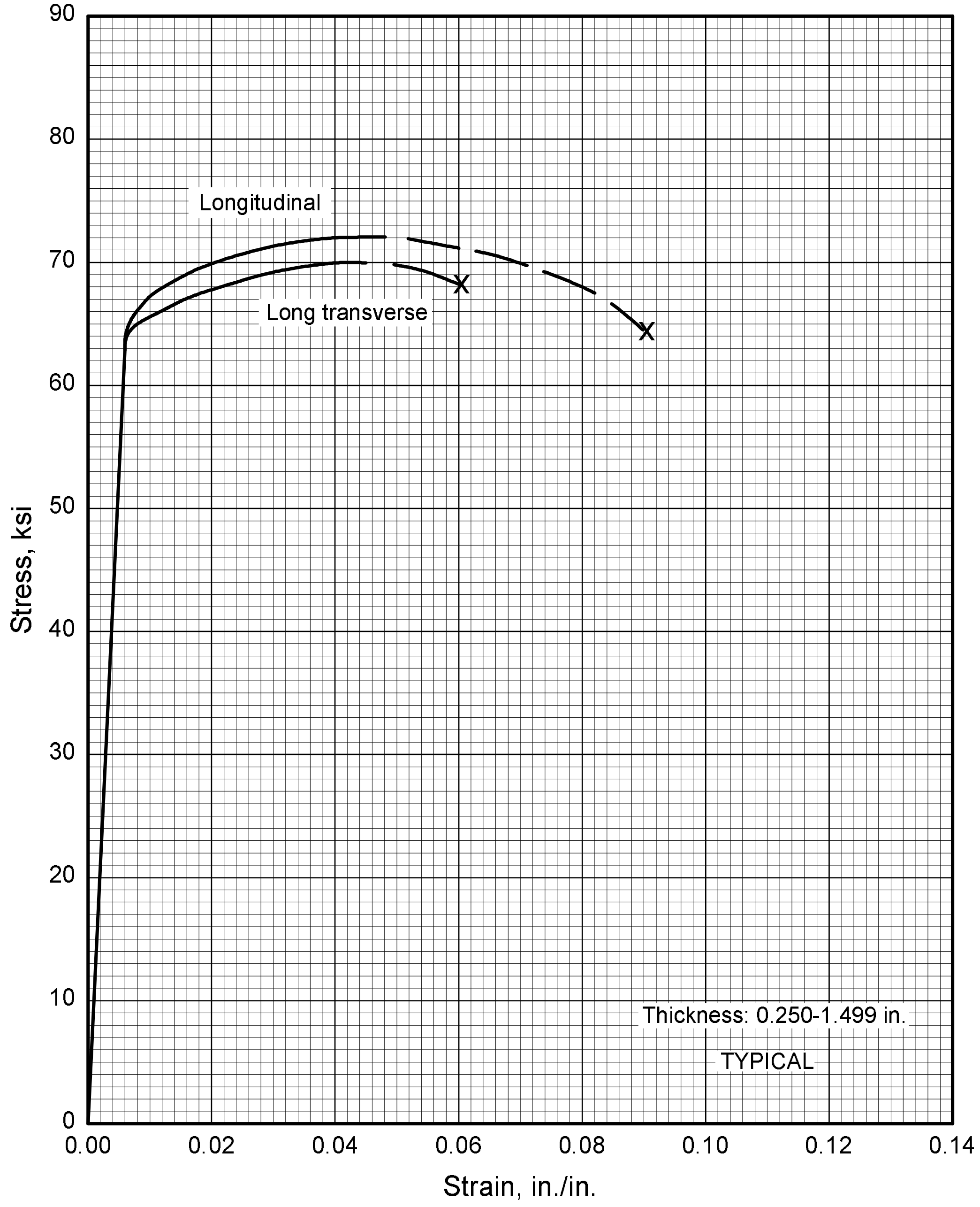


Figure 3.2.3.4.6(j). Typical tensile stress-strain curves (full range) for 2024-T851 aluminum alloy sheet at room temperature.

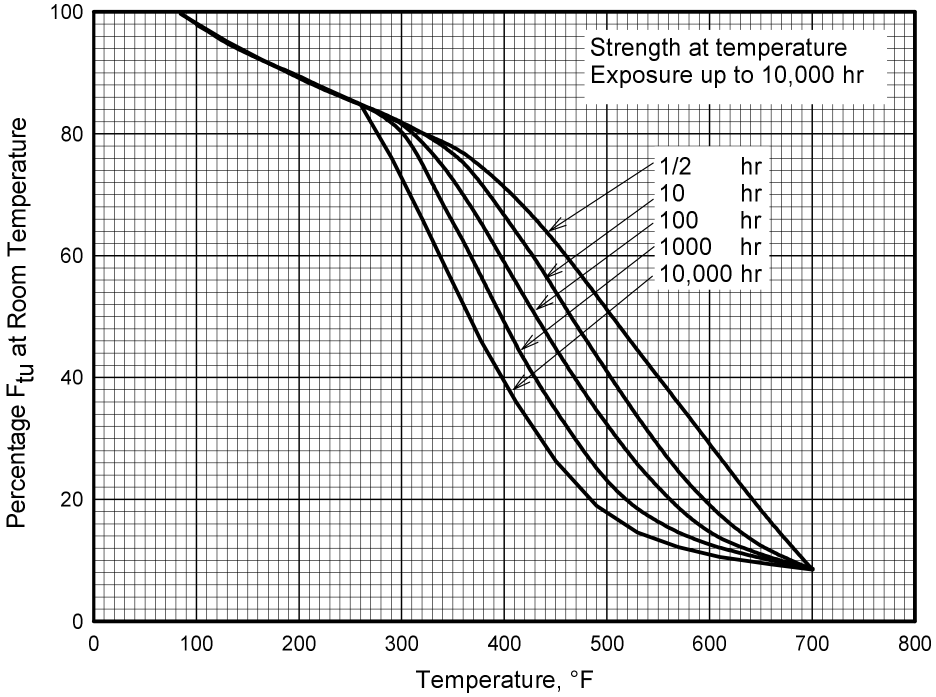


Figure 3.2.3.5.1(a). Effect of temperature on the tensile ultimate strength (F_{tu}) of 2024-T861 (T86) aluminum alloy sheet.

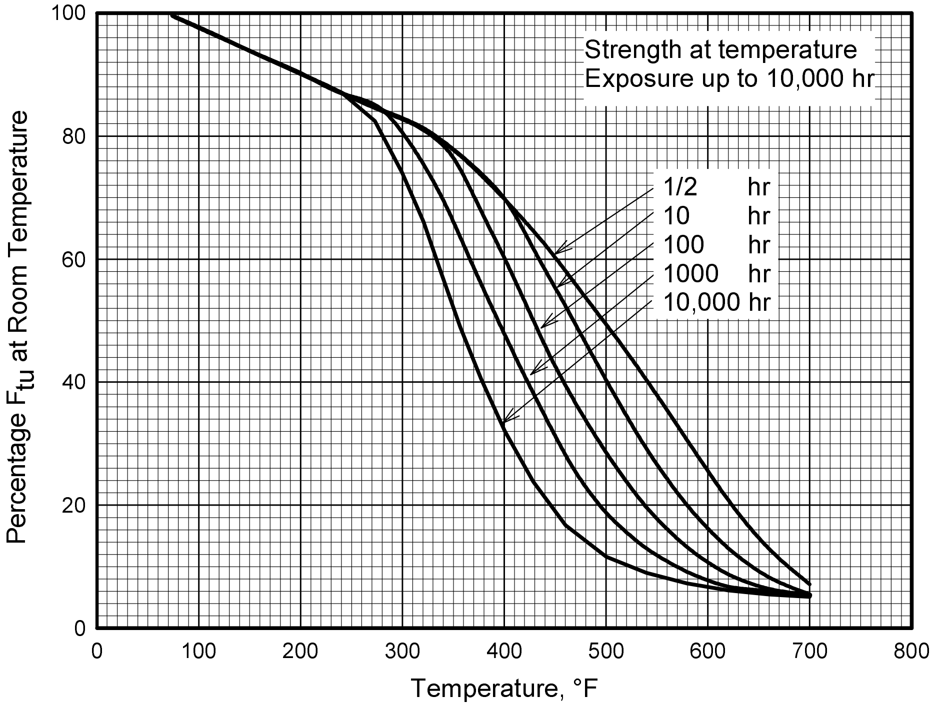


Figure 3.2.3.5.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of 2024-T861 (T86) aluminum alloy sheet.

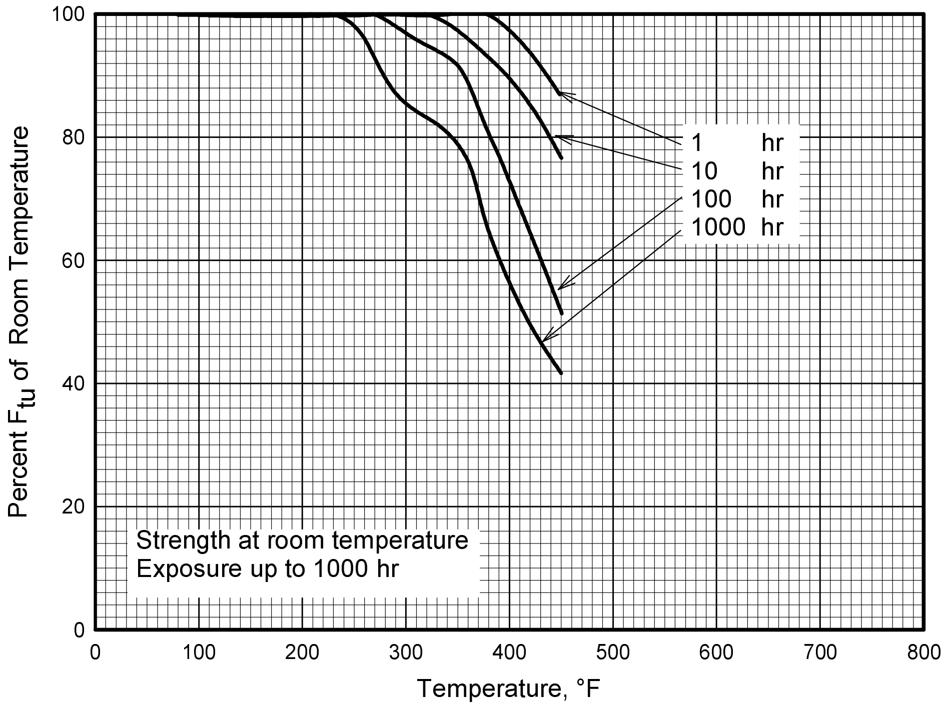


Figure 3.2.3.5.1(c). Effect of exposure at elevated temperatures on the room-temperature tensile ultimate strength (F_{tu}) of 2024-T861 (T86) aluminum alloy sheet.

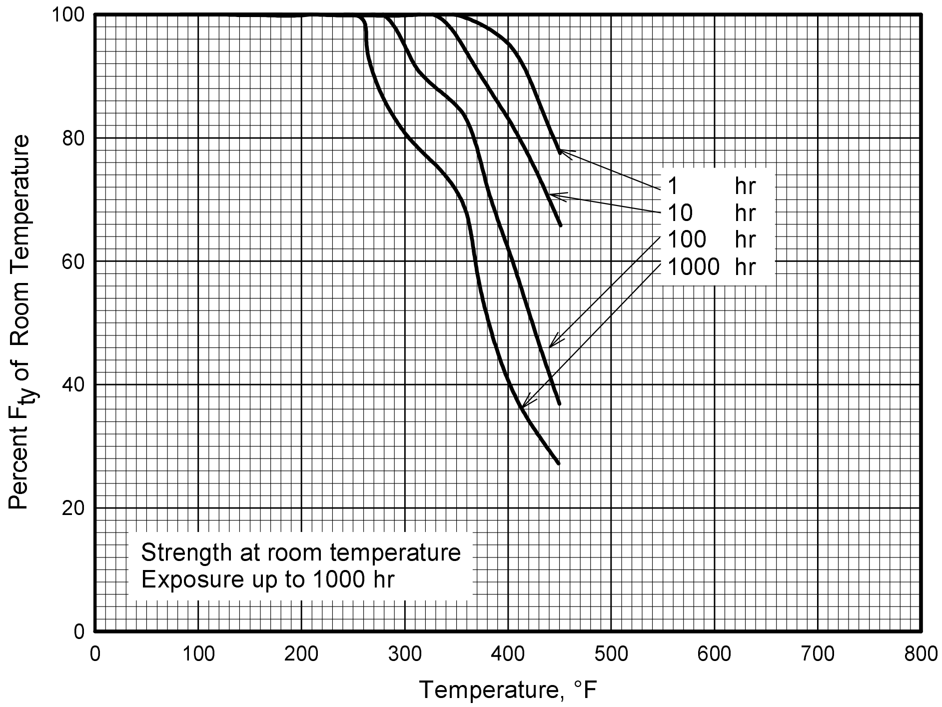


Figure 3.2.3.5.1(d). Effect of exposure at elevated temperatures on the room-temperature tensile yield strength (F_{ty}) of 2024-T861 (T86) aluminum alloy sheet.

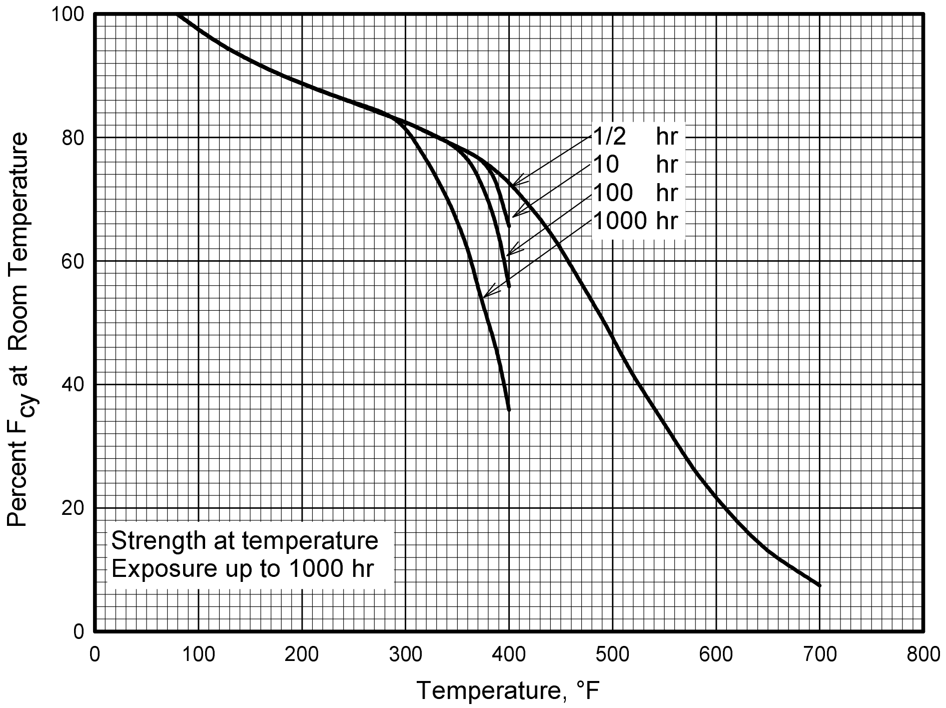


Figure 3.2.3.5.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of 2024-T861 (T86) aluminum alloy sheet.

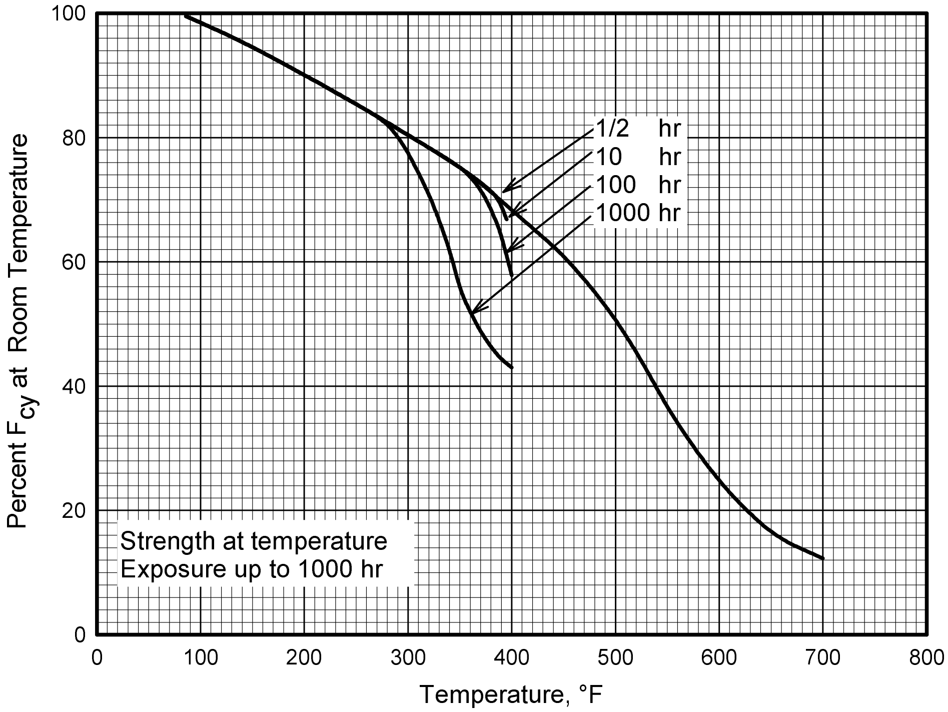


Figure 3.2.3.5.2(b). Effect of temperature on the shear ultimate strength (F_{su}) of 2024-T861 (T86) aluminum alloy sheet.

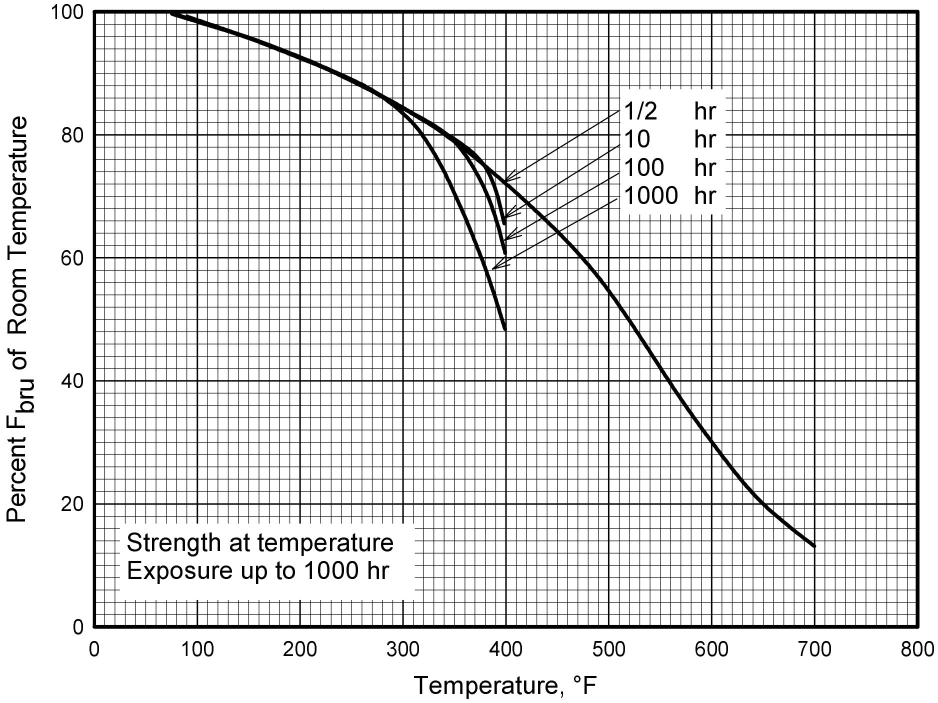


Figure 3.2.3.5.3(a). Effect of temperature on the bearing ultimate strength (F_{bru} , e/D = 1.5) of 2024-T861 (T86) aluminum alloy sheet.

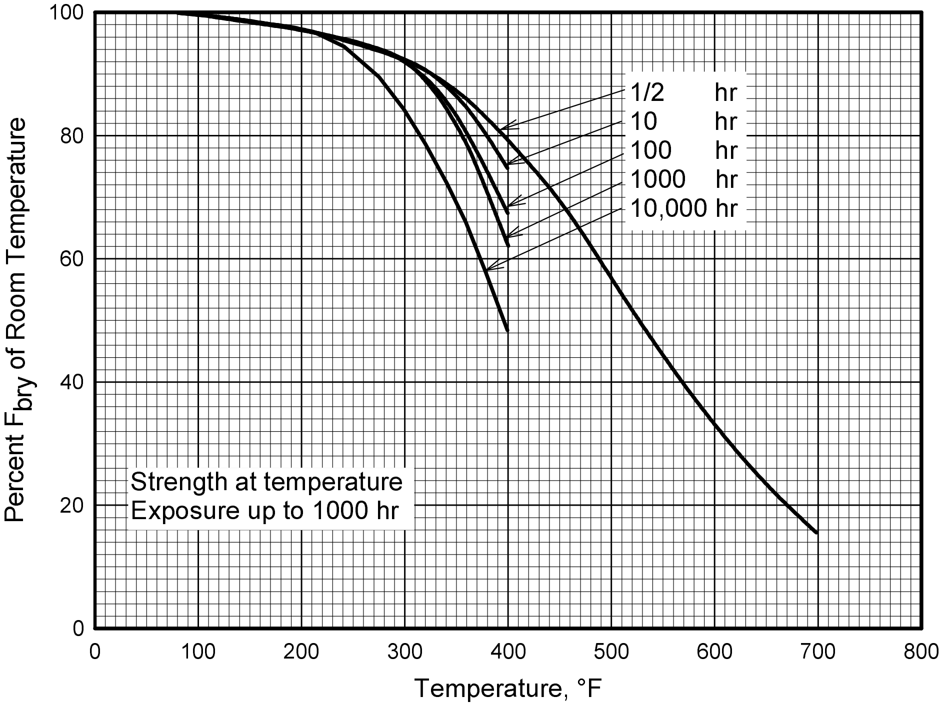


Figure 3.2.3.5.3(b). Effect of temperature on the bearing yield strength (F_{bry} , e/D = 1.5) of 2024-T861 (T86) aluminum alloy sheet.

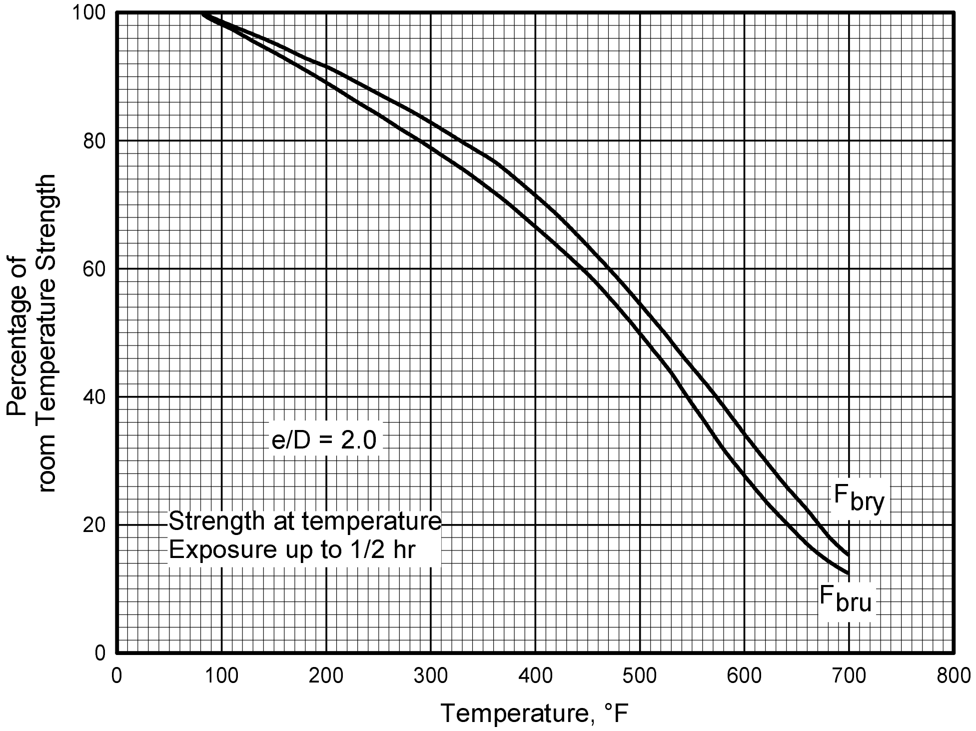


Figure 3.2.3.5.3(c). Effect of temperature on the bearing ultimate strength (F_{bru}, e/D = 2.0) and the bearing yield strength (F_{bry}, e/D = 2.0) of 2024-T861 (T86) aluminum alloy sheet.

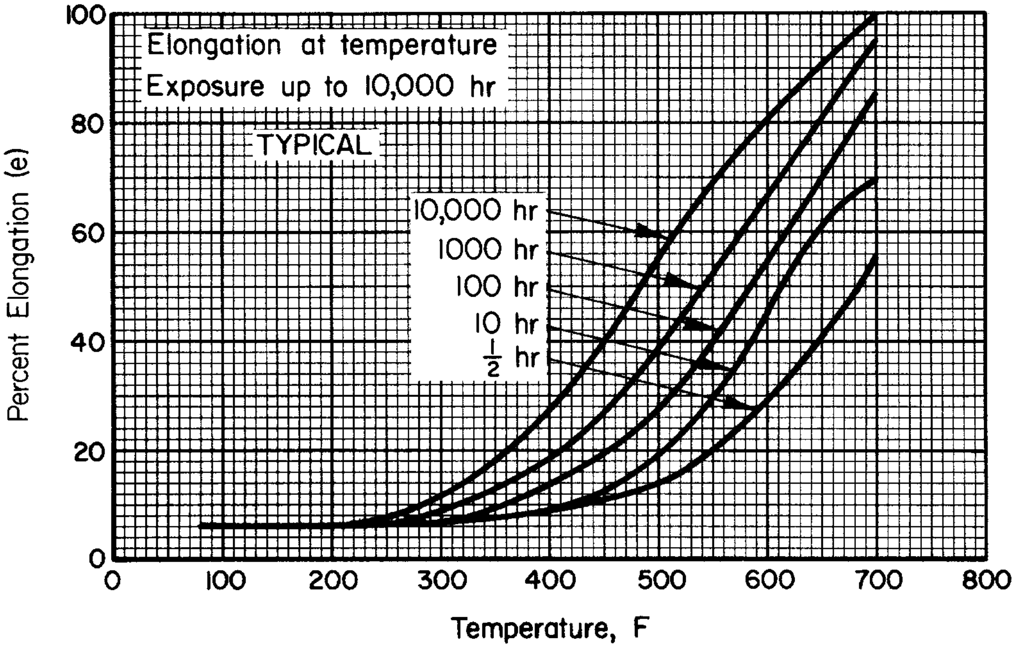


Figure 3.2.3.5.5(a). Effect of temperature on the elongation (e) of 2024-T861 (T86) aluminum alloy sheet.

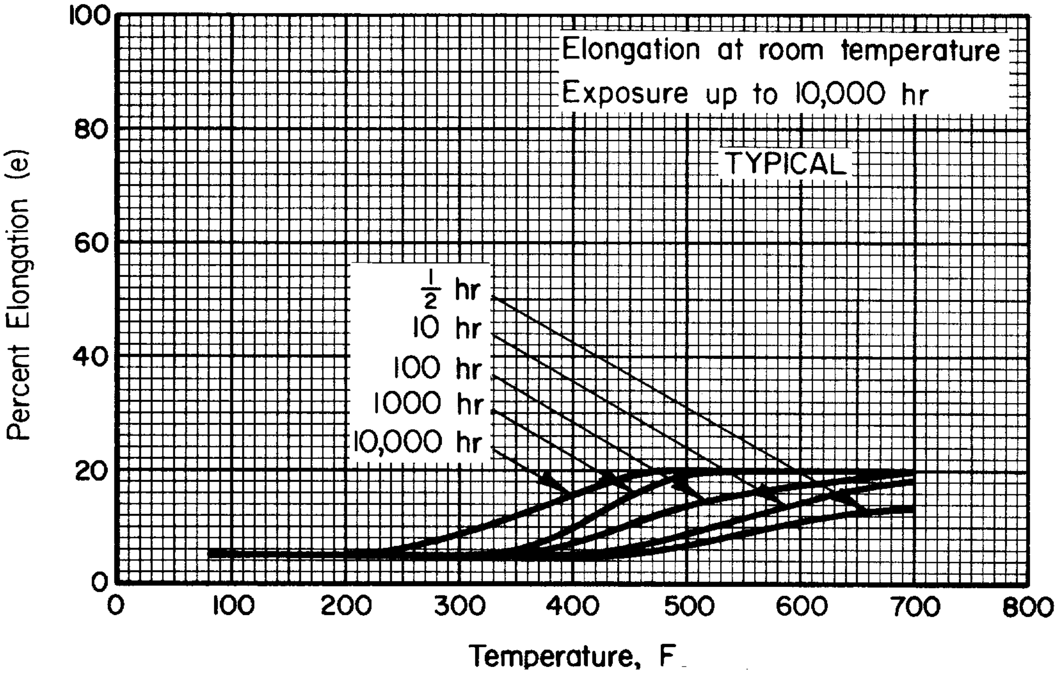


Figure 3.2.3.5.5(b). Effect of exposure at elevated temperatures on the room temperature elongation (e) of 2024-T861 (T86) aluminum alloy sheet.

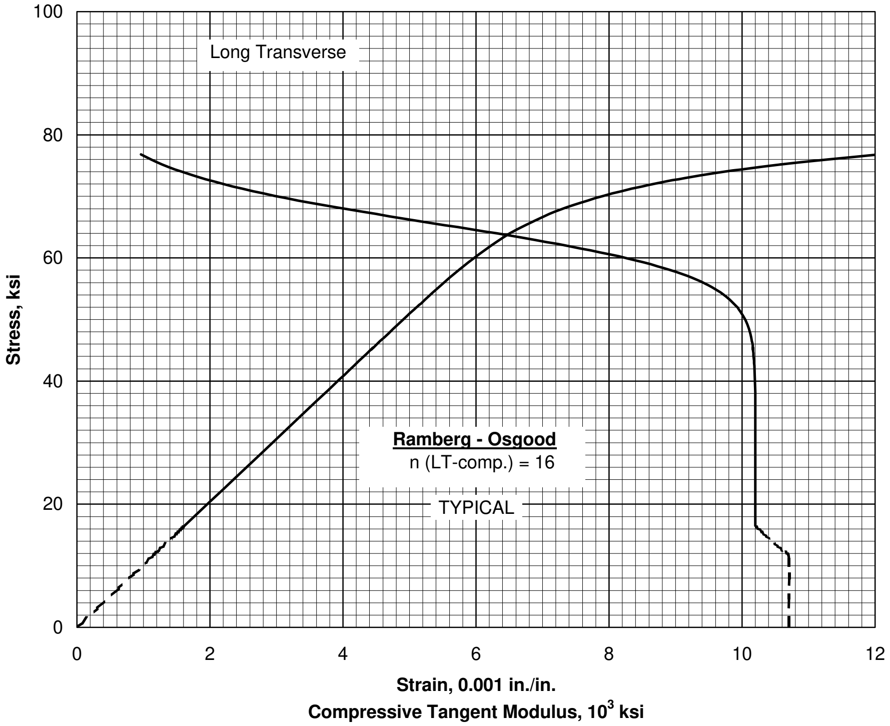


Figure 3.2.3.5.6(a). Typical compressive stress-strain and compressive tangent-modulus curves for clad 2024-T861 aluminum alloy sheet at room temperature.

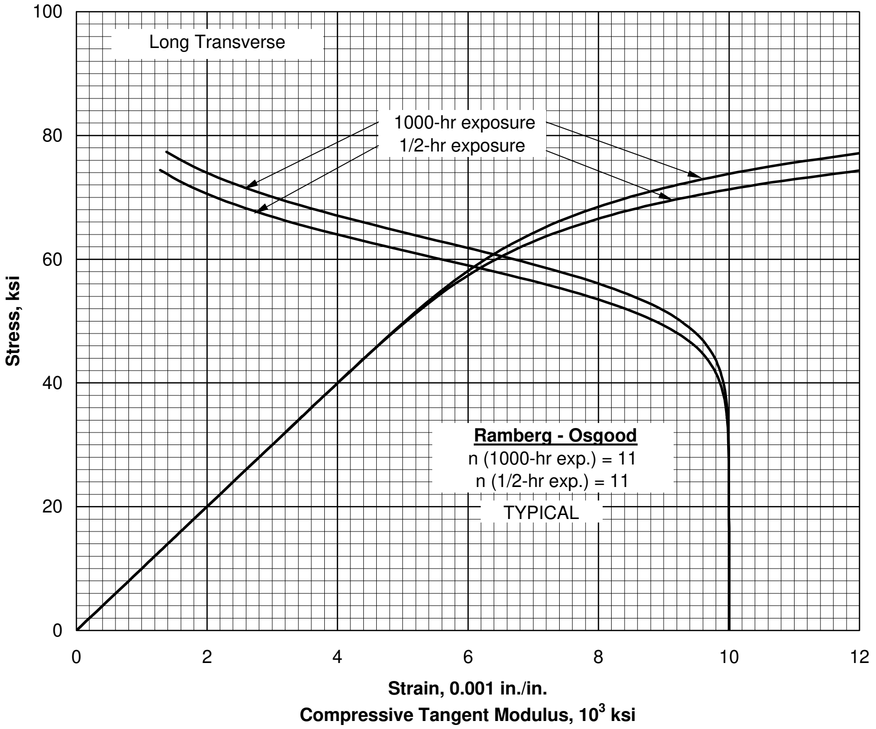


Figure 3.2.3.5.6(b). Typical compressive stress-strain and compressive tangent-modulus curves for clad 2024-T861 aluminum alloy sheet at 200°F.

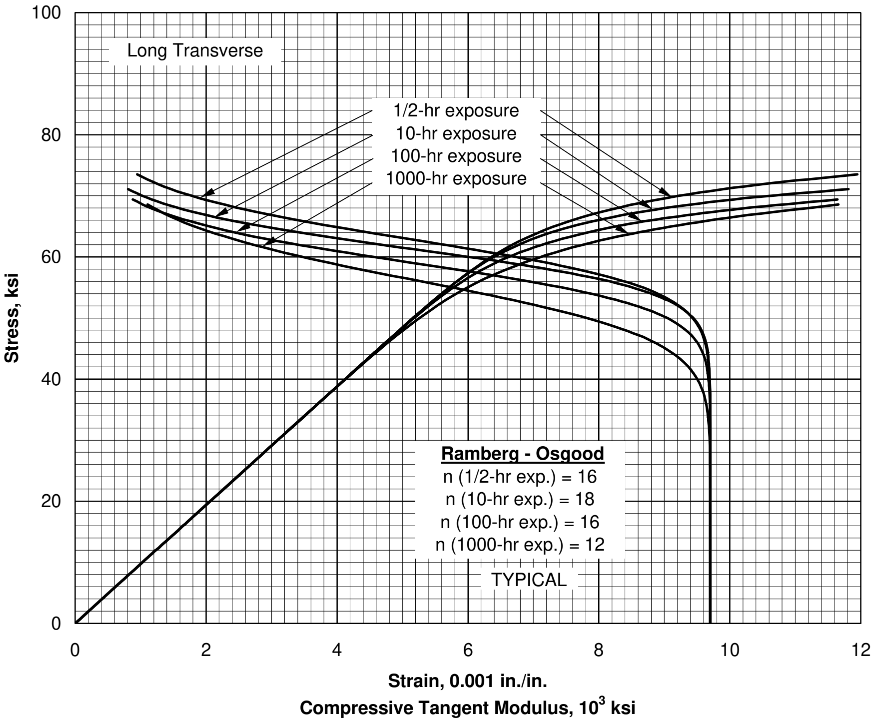


Figure 3.2.3.5.6(c). Typical compressive stress-strain and compressive tangent-modulus curves for clad 2024-T861 aluminum alloy sheet at 300°F.

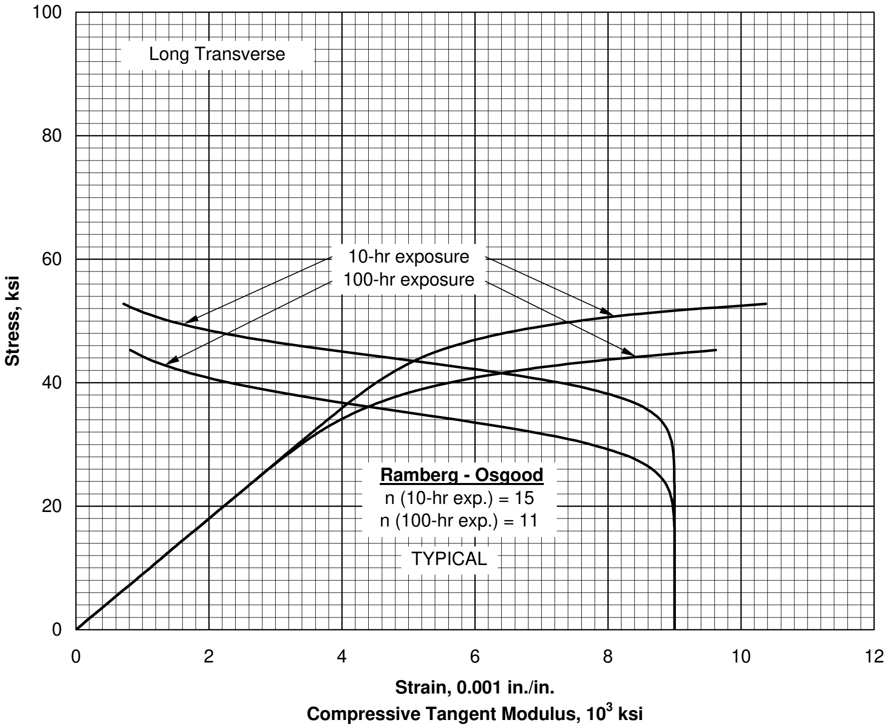


Figure 3.2.3.5.6(d). Typical compressive stress-strain and compressive tangent-modulus curves for clad 2024-T861 aluminum alloy sheet at 400°F.

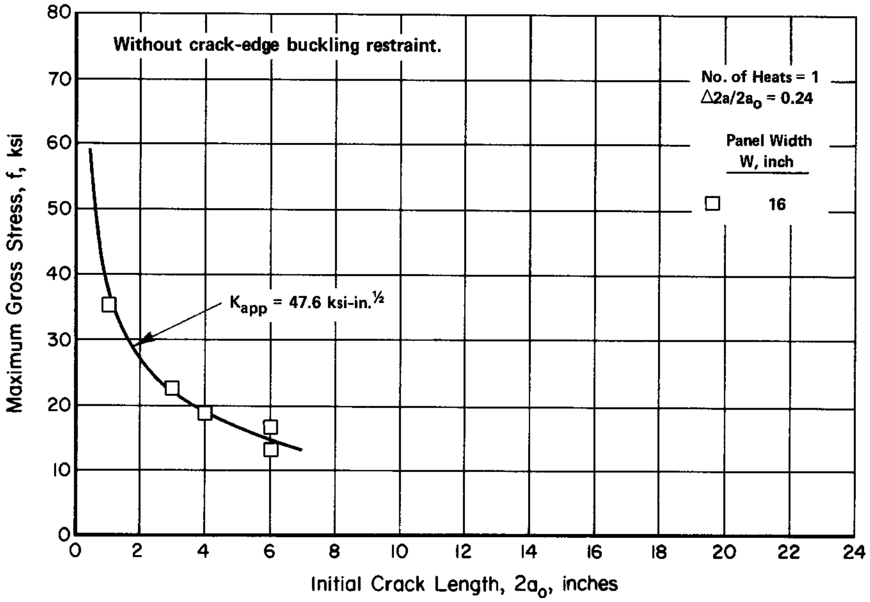


Figure 3.2.3.5.10(a). Residual strength behavior of 0.063-inch-thick 2024-T861 aluminum alloy sheet at room temperature. Crack orientation is T-L [Reference 3.1.2.1.6(d)].

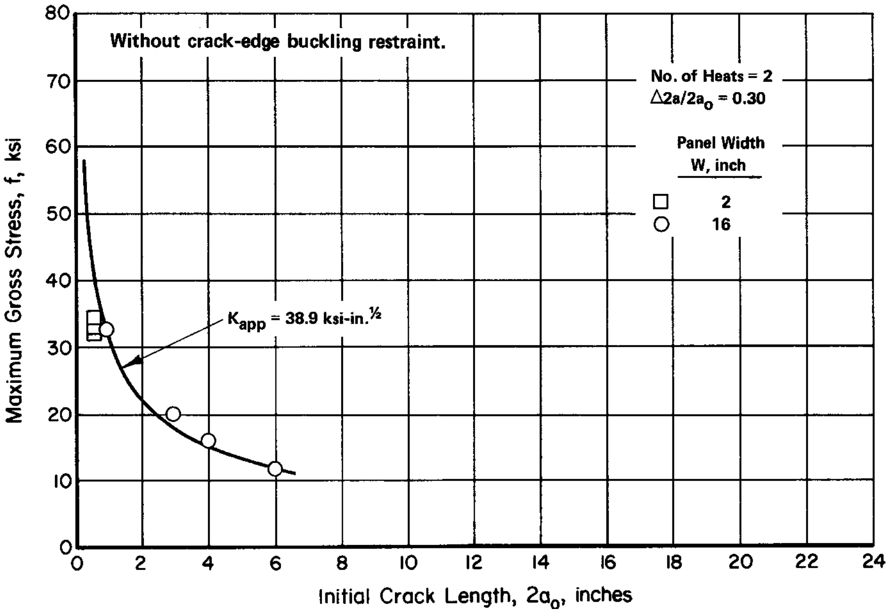


Figure 3.2.3.5.10(b). Residual strength behavior of 0.063-inch-thick 2024-T861 aluminum alloy sheet at room temperature. Crack orientation is L-T [Reference 3.1.2.1.6(d)].

3.2.4 2025 ALLOY

3.2.4.0 *Comments and Properties* — 2025 is a heat-treatable Al-Cu forging alloy for which applications have been limited primarily to propellers. Refer to Section 3.1.2.3 for comments regarding the resistance of the alloy to stress-corrosion cracking, and to Section 3.1.2.4 for comments regarding the weldability of the alloy.

A material specification for 2025 aluminum alloy is presented in Table 3.2.4.0(a). Room-temperature mechanical and physical properties are shown in Table 3.2.4.0(b). The effect of temperature on thermal expansion is shown in Figure 3.2.4.0.

Table 3.2.4.0(a). Material Specification for 2025 Aluminum Alloy

Specification	Form
AMS 4130	Die forging

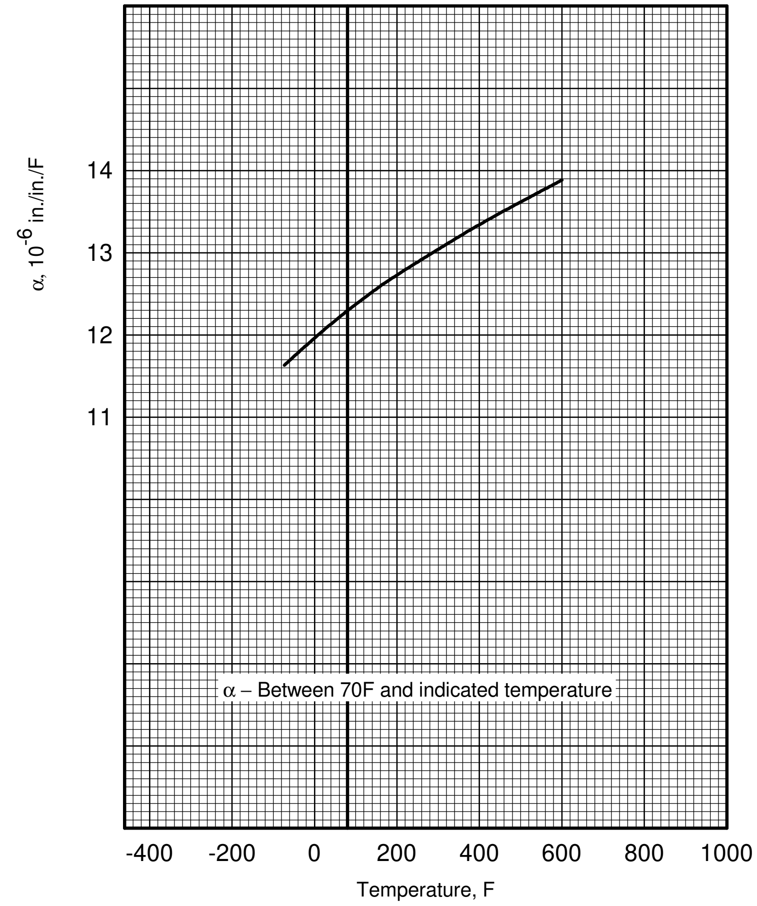


Figure 3.2.4.0. Effect of temperature on the thermal expansion of 2025 aluminum alloy.

Table 3.2.4.0(b). Design Mechanical and Physical Properties of 2025 Aluminum Alloy Die Forging

Specification	AMS 4130
Form	Die forging
Temper	T6
Thickness, in.	≤ 4.000
Basis	S
Mechanical Properties:	
F_{tu}, ksi:	
L	55
T[a]	52
F_{ty}, ksi:	
L	33
T[a]	32
F_{cy}, ksi:	
L	...
T[a]	...
F_{su}, ksi	...
F_{bru}, ksi:	
(e/D = 1.5)	...
(e/D = 2.0)	...
F_{bry}, ksi:	
(e/D = 1.5)	...
(e/D = 2.0)	...
e, percent:	
L	11
T[a]	8
E, 10^3 ksi	10.3
E_c, 10^3 ksi	10.5
G, 10^3 ksi	3.9
μ	0.33
Physical Properties:	
ω, lb/in.^{3}	0.101
C, Btu/(lb)(°F)	0.23 (at 212°F)
K, Btu/[(hr)(ft^2)(°F)/ft]	90 (at 77°F)
α, 10^{-6} in./in./°F	See Figure 3.2.4.0

[a] T indicates any grain direction within ±15° of being perpendicular to the forging flow lines.

3.2.5 2026 ALLOY

3.2.5.0 COMMENTS AND PROPERTIES —2026 is a 4.0Cu-1.3Mg-0.60Mn aluminum alloy used for extrusion of bars, rods, and profiles. These extrusions have been used typically for parts subject to cracking during forming operations and excessive warpage during machining processes, and for parts requiring high strength and damage tolerance, where fabrication does not normally involve welding.

Certain processing procedures may cause these extrusions to become susceptible to stress-corrosion cracking; ARP823 (Reference 3.2.1.0) recommends practices to minimize such conditions.

Extruded, solution heat treated and stress-relieved by stretching to produce a nominal permanent set of 1.5%, but not less than 1% nor more than 3%, to the T3511 temper. Solution heat treatment will be performed in accordance with AMS 2772.

Material specifications are shown in Table 3.2.5.0(a). Room temperature mechanical and physical properties are shown in Table 3.2.5.0 (b).

Table 3.2.5.0(a). Material Specifications for 2026-T3511

Specification	Form
AMS 4338	Extruded bars, rods, and profiles

Table 3.2.5.0(b). Design Mechanical and Physical Properties of 2026 Aluminum Alloy Bars, Rods, and Profiles

Specification	AMS 4338								
Form	Extrusions								
Temper	T3511								
Thickness, in.	≤0.249		0.250-0.499		0.500-1.499		1.500-2.249		2.250-3.250
Basis	A	B	A	B	A	B	A	B	S
Mechanical Properties:									
F_{tu}, ksi:									
L	66	69	70	72	72	75	73	76	73
LT	58	61	62	64	66	67	64	67	61
F_{ty}, ksi:									
L	48	51	52	53	53	56	54	57	54
LT	41	44	45	46	46	48	44	49	42
F_{cy}, ksi:									
L	43	45	46	47	47	47	49	52	50
LT	42	45	46	46	46	49	45	47	43
F_{su}, ksi	37	39	37	38	32	33	32	33	32
$F_{bru}{}^{a}$, ksi:									
(e/D = 1.5)	90	94	92	95	87	90	85	89	85
(e/D = 2.0)	112	117	113	117	109	114	108	112	105
$F_{bry}{}^{a}$, ksi:									
(e/D = 1.5)	62	66	66	67	61	64	61	64	61
(e/D = 2.0)	76	81	81	83	76	81	76	80	76
e, percent (S-basis):									
L	11	...	12	...	11	...	11	...	10
LT	...	...	...	...	8	...	8	...	8
E, 10^3 ksi	10.7								
E_c, 10^3 ksi	10.9								
G, 10^3 ksi	4.0								
μ	0.33								
Physical Properties:									
ω, lb/in.^{3}	0.100								
C, Btu/(lb)(°F)	...								
K, Btu/[(hr)(ft^2)(°F)/ft]	...								
α, 10^{-6} in./in./°F	...								

a See Table 3.1.2.1.1. Bearing values are "dry pin" values per Section 1.4.7.1.

3.2.6 2090 ALLOY

3.2.6.0 *Comments and Properties* — 2090 is an Al-Cu-Li alloy developed for applications requiring the high strength of 7075-T6 but with 8 percent lower density and 10 percent higher elastic modulus than 7075-T6. Sheet is available in the T83 temper. 2090 sheet has strength properties nearly equivalent to 7075-T6 sheet with improved exfoliation resistance. Refer to Section 3.1.3.4 for information on weldability of the alloy.

A material specification for 2090 aluminum alloy is shown in Table 3.2.6.0(a). Room-temperature mechanical and physical properties are shown in Table 3.2.6.0(b).

Table 3.2.6.0(a). Material Specification for 2090 Aluminum Alloy

Specification	Form
AMS 4251	Sheet

The temper index is as follows:

Section	Temper
3.2.6.1	T83

3.2.6.1 *T83 Temper* — Stress-strain and tangent-modulus curves are represented in Figures 3.2.6.1.6(a) and (b).

Table 3.2.6.0(b). Design Mechanical and Physical Properties of 2090-T83 Aluminum Alloy Sheet

Specification	AMS 4251	
Form	Sheet	
Temper	T83	
Thickness, in.	0.040-0.125	0.126-0.249
Basis	S	S
Mechanical Properties:		
F_{tu}, ksi:		
L	77	75
45°	64	65
LT	73	73
F_{ty}, ksi:		
L	70	70
45°	56	57
LT	66	66
F_{cy}, ksi:		
L	67	63
45°	58	60
LT	71	71
F_{su}, ksi	37	37
F_{bru}[a], ksi:		
(e/D = 1.5)	100	100
(e/D = 2.0)	126	126
F_{bry}[a], ksi:		
(e/D = 1.5)	84	88
(e/D = 2.0)	98	104
e, percent:		
L	3	4
LT	5	5
E, 10^3 ksi:		
L & LT	11.5	
45°	11.0	
E_c, 10^3 ksi:		
L & LT	11.8	
45°	11.4	
G, 10^3 ksi	4.3	
μ	0.34	
Physical Properties:		
ω, lb/in.^{3}	0.094	
C, K, and α	. . .	

a Bearing values are "dry pin" values per Section 1.4.7.1.

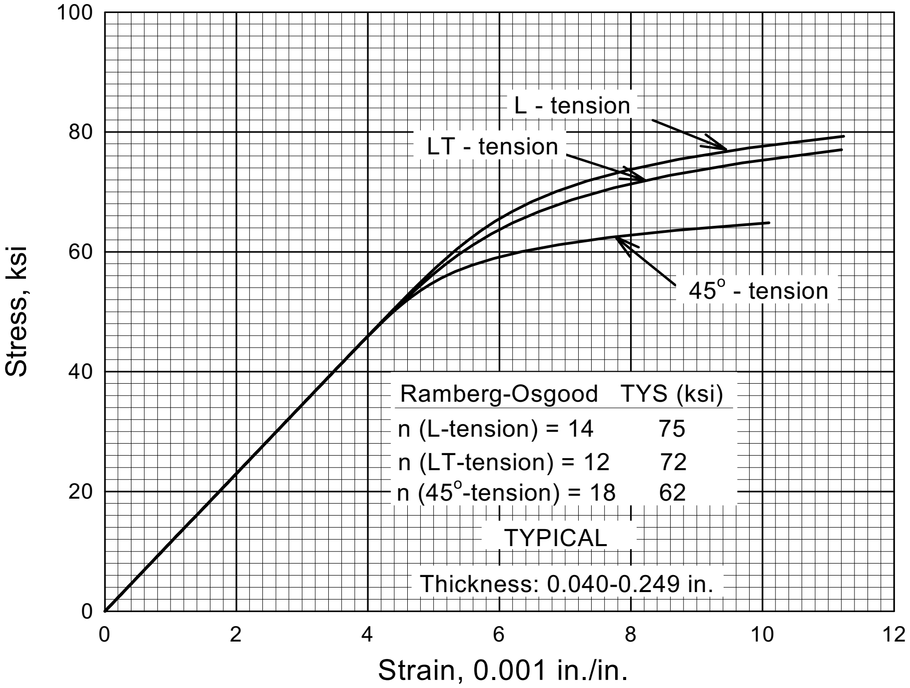


Figure 3.2.6.1.6(a). Typical tensile stress-strain curves for 2090-T83 aluminum alloy sheet at room temperature.

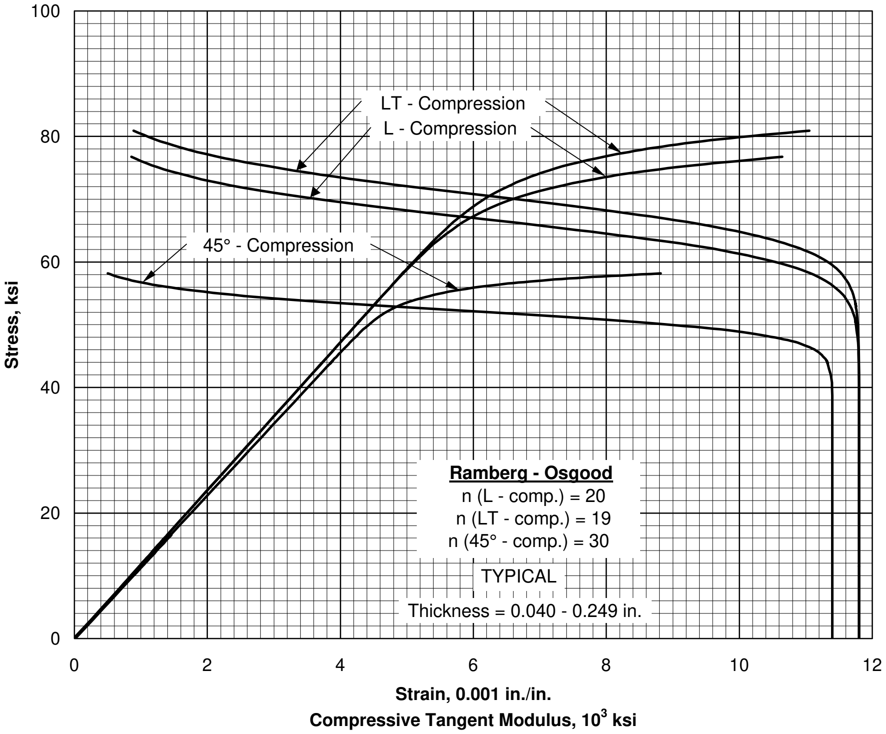


Figure 3.2.6.1.6(b). Typical compressive stress-strain and compressive tangent-modulus curves for 2090-T83 aluminum alloy sheet at room temperature.

3.2.7 2124 ALLOY

3.2.7.0 *Comments and Properties* — 2124 is an Al-Cu alloy available in the form of plate in thicknesses of 1 through 6 inches. This alloy is a high purity version of alloy 2024. The higher purity in conjunction with special production processing provides higher elongation in the short-transverse direction and improved fracture toughness over that exhibited by conventionally produced 2024 alloy. The alloy is currently only produced in the T851 temper. The alloy, like 2024 has excellent properties and creep resistance at elevated temperatures. The alloy in the T851 temper has good resistance to stress corrosion. Refer to Section 3.1.2.3.1 for information regarding resistance of the alloy to stress-corrosion cracking. Refer to Section 3.1.3.4 for comments regarding the weldability of the alloy. The physical properties are essentially the same as those for 2024-T851 plate.

Applicable material specification for 2124-T851 plate is presented in Table 3.2.7.0(a). Room-temperature mechanical properties are shown in Table 3.2.7.0(b).

Table 3.2.7.0(a). Material Specification for 2124 Aluminum Alloy

Specification	Form
AMS 4101	Plate
AMS-QQ-A-250/29	Plate

The temper index for 2124 is as follows:

Section	Temper
3.2.7.1	T851

3.2.7.1 *T851 Temper* — Elevated temperature data are presented in Figures 3.2.7.1.1(a) and (b). Typical tensile stress-strain, compressive stress-strain, and compressive tangent-modulus curves are presented in Figures 3.2.7.1.6(a) and (b). Fatigue crack-propagation data for plate are presented in Figures 3.2.7.1.9(a) through (e).

Table 3.2.7.0(b). Design Mechanical and Physical Properties of 2124 Aluminum Alloy Plate

Specification	AMS 4101 and AMS-QQ-A-250/29										
Form	Plate										
Temper	T851										
Thickness, in.	1.000-1.500	1.501-2.000		2.001-3.000		3.001-4.000		4.001-5.000		5.001-6.000	
Basis	S	A	B	A	B	A	B	A	B	A	B
Mechanical Properties:											
F_{tu}, ksi:											
L	66	66	68	65	68	65	67	64	66	63	65
LT	66	66	68	65	68	65	67	64	66	63	65
ST	64[a]	64	66	63	64	62	63	61	62	58	59
F_{ty}, ksi:											
L	57	57	61	57	61	56	60	55	58	54	56
LT	57	57	61	57	61	56	60	55	58	54	56
ST	55[a]	55	59	55	59	54	57	53	55	51	53
F_{cy}, ksi:											
L	57	57	61	56	60	55	59	53	56	52	54
LT	57	57	61	57	61	56	60	55	58	54	56
ST	...	57	61	58	62	57	61	57	60	56	58
F_{su}, ksi:											
L	...	38	39	38	39	38	39	37	38	37	38
LT	...	38	39	38	39	38	39	37	38	37	38
ST	...	36	37	36	37	36	37	35	36	35	36
F_{bru}[b], ksi:											
(e/D = 1.5)	...	97	100	96	100	96	99	94	97	93	96
(e/D = 2.0)	...	126	130	125	130	125	128	123	126	121	125
F_{bry}[b], ksi:											
(e/D = 1.5)	...	79	84	80	85	80	85	79	84	79	82
(e/D = 2.0)	...	91	98	92	99	92	99	92	97	91	95
e, percent (S-basis):											
L	6	6	...	6	...	5	...	5	...	5	...
LT	5	5	...	4	...	4	...	4	...	4	...
ST	1.5[a]	1.5	...	1.5	...	1.5	...	1.5	...	1.5	...
E, 10^3 ksi	10.4										
E_c, 10^3 ksi	10.9										
G, 10^3 ksi	4.0										
μ	0.33										
Physical Properties:											
ω, lb/in.^{3}	0.100										
C, Btu/(lb)(°F)	0.21 (at 212°F)										
K, Btu/[(hr)(ft^2)(°F)/ft]	87 (at 77°F)										
α, 10^{-6} in./in./°F	12.6 (68°F to 212°F)										

a Applicable to 1.500-inch thickness only.
b Bearing values are "dry pin" values per Section 1.4.7.1. See Table 3.1.2.1.1.

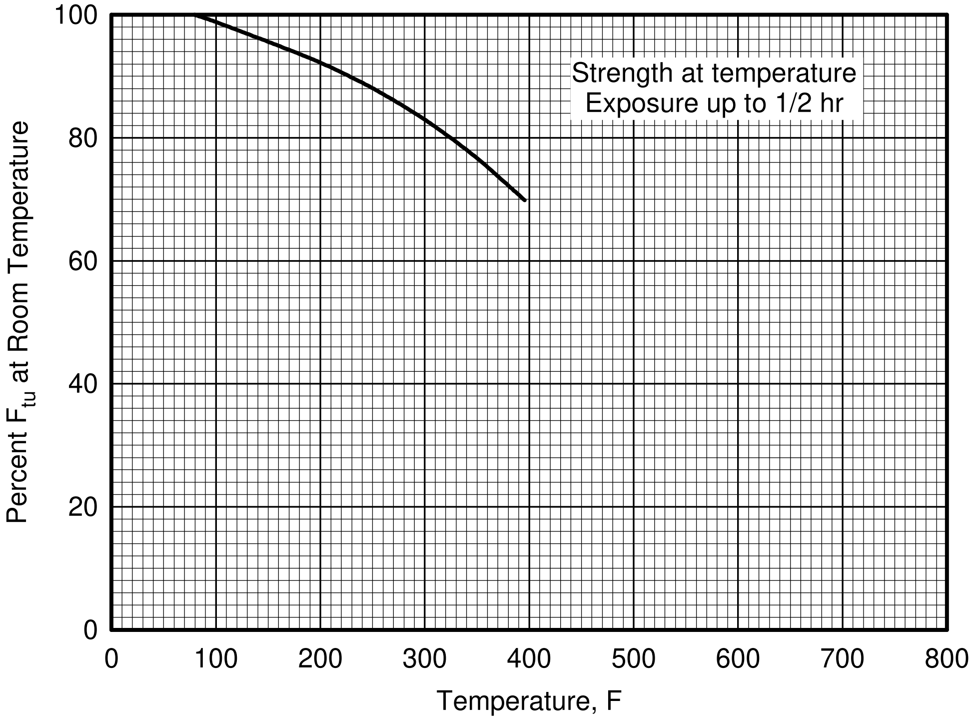


Figure 3.2.7.1.1(a). Effect of temperature on the tensile ultimate strength (F_{tu}) of 2124-T851 aluminum alloy plate.

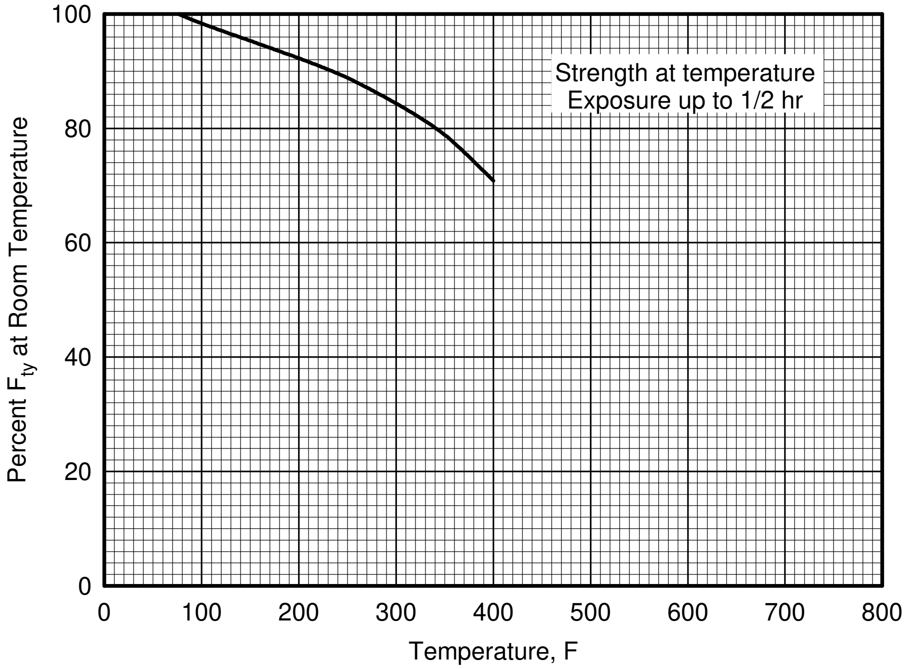


Figure 3.2.7.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of 2124-T851 aluminum alloy plate.

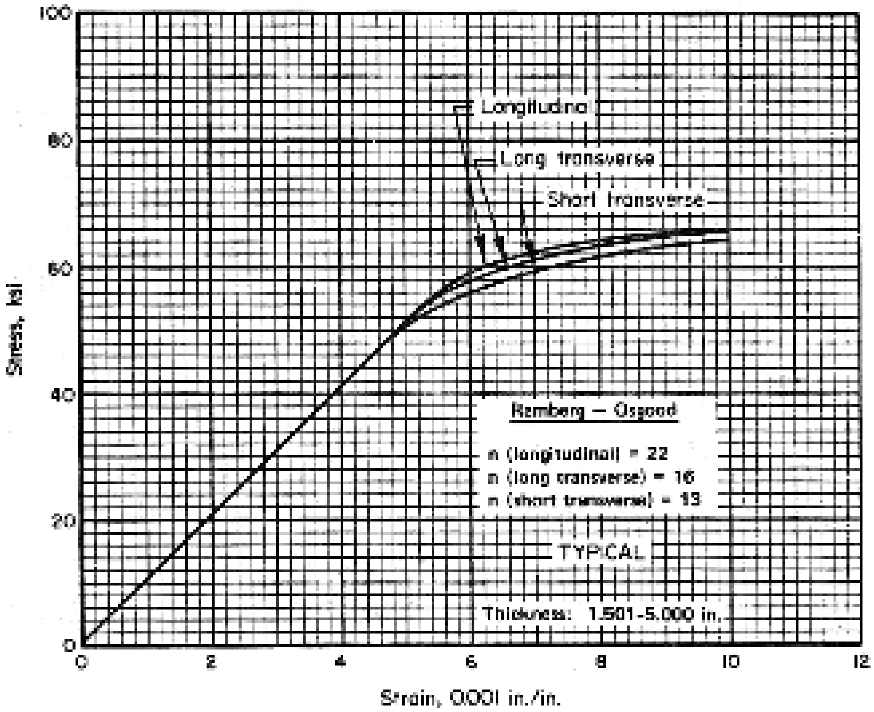


Figure 3.2.7.1.6(a). Typical tensile stress-strain curves for 2124-T851 aluminum alloy plate at room temperature.

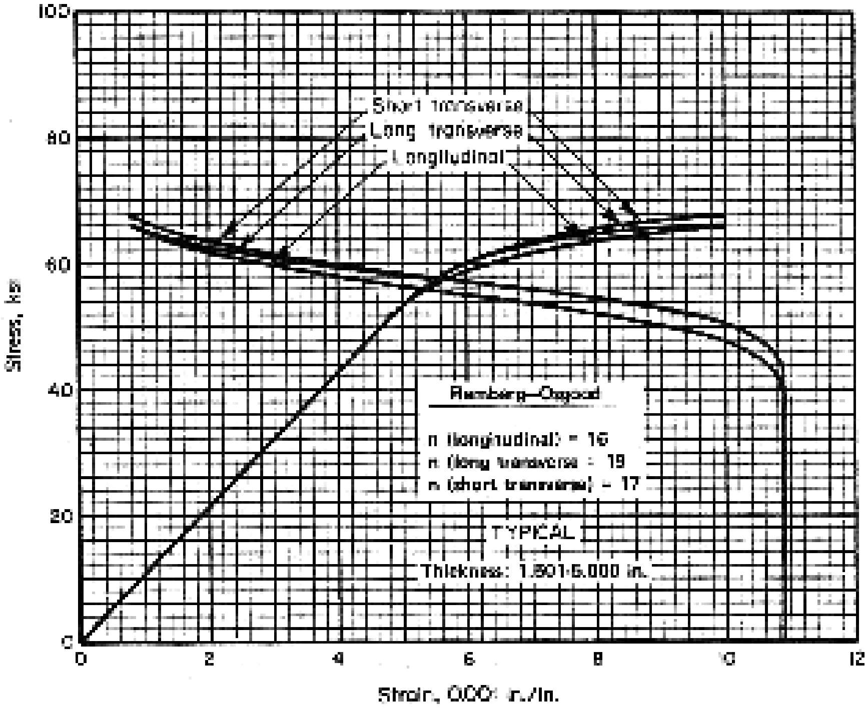


Figure 3.2.7.1.6(b). Typical compressive stress-strain and compressive tangent-modulus curves for 2124-T851 aluminum alloy plate at room temperature.

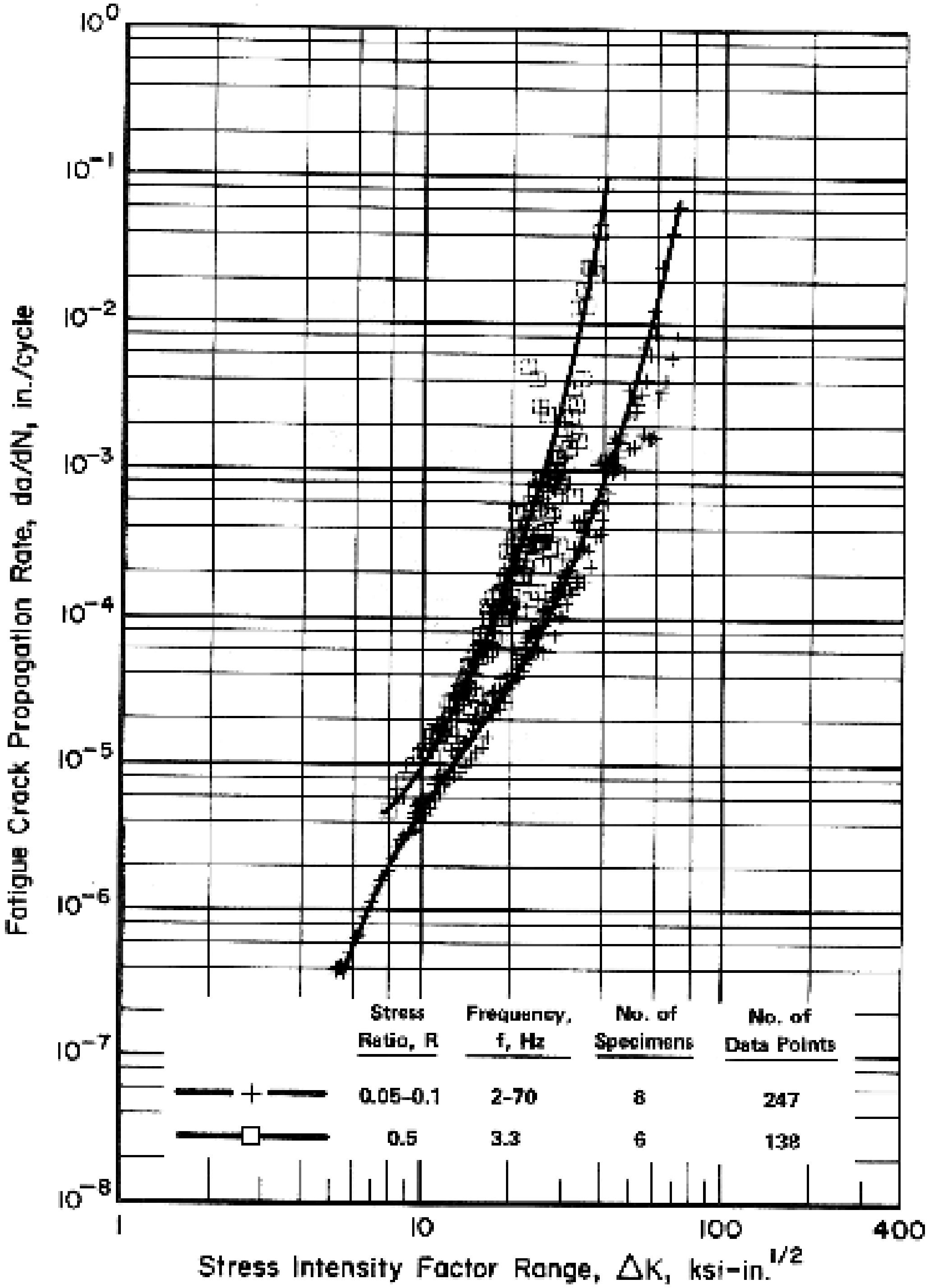


Figure 3.2.7.1.9(a). Fatigue-crack-propagation data for 2.0 to 5.5 inch thick, 2124-T851 aluminum alloy plate. [References 3.2.7.1.9(a), 3.2.7.1.9(c), and 3.2.7.1.9(d)].

Specimen Thickness:	*0.25-0.45 and 0.15 inch*	*Environment:*	*95% R.H.*
Specimen Width:	*11.75 and 3.0 inches*	*Temperature:*	*RT*
Specimen Type:	*M(T) and C(T)*	*Orientation:*	*L-T*

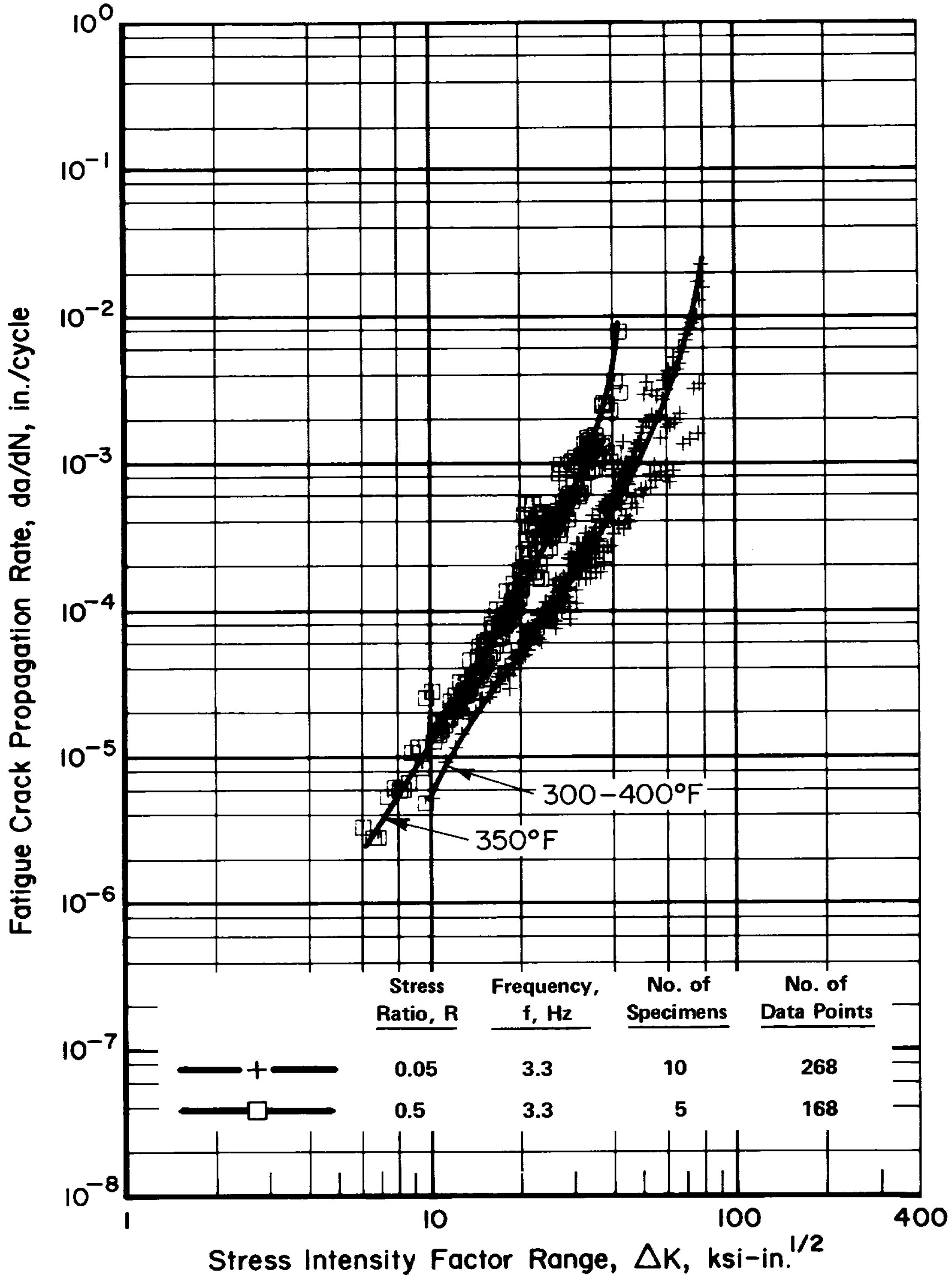


Figure 3.2.7.1.9(b). Fatigue-crack-propagation data for 2.0-inch thick, 2124-T851 aluminum alloy plate. [Reference 3.2.7.1.9(a)].

Specimen Thickness:	*0.25-0.45 inch*	*Environment:*	*Lab air*
Specimen Width:	*11.75 inches*	*Temperature:*	*300-400 °F*
Specimen Type:	*M(T)*	*Orientation:*	*L-T*

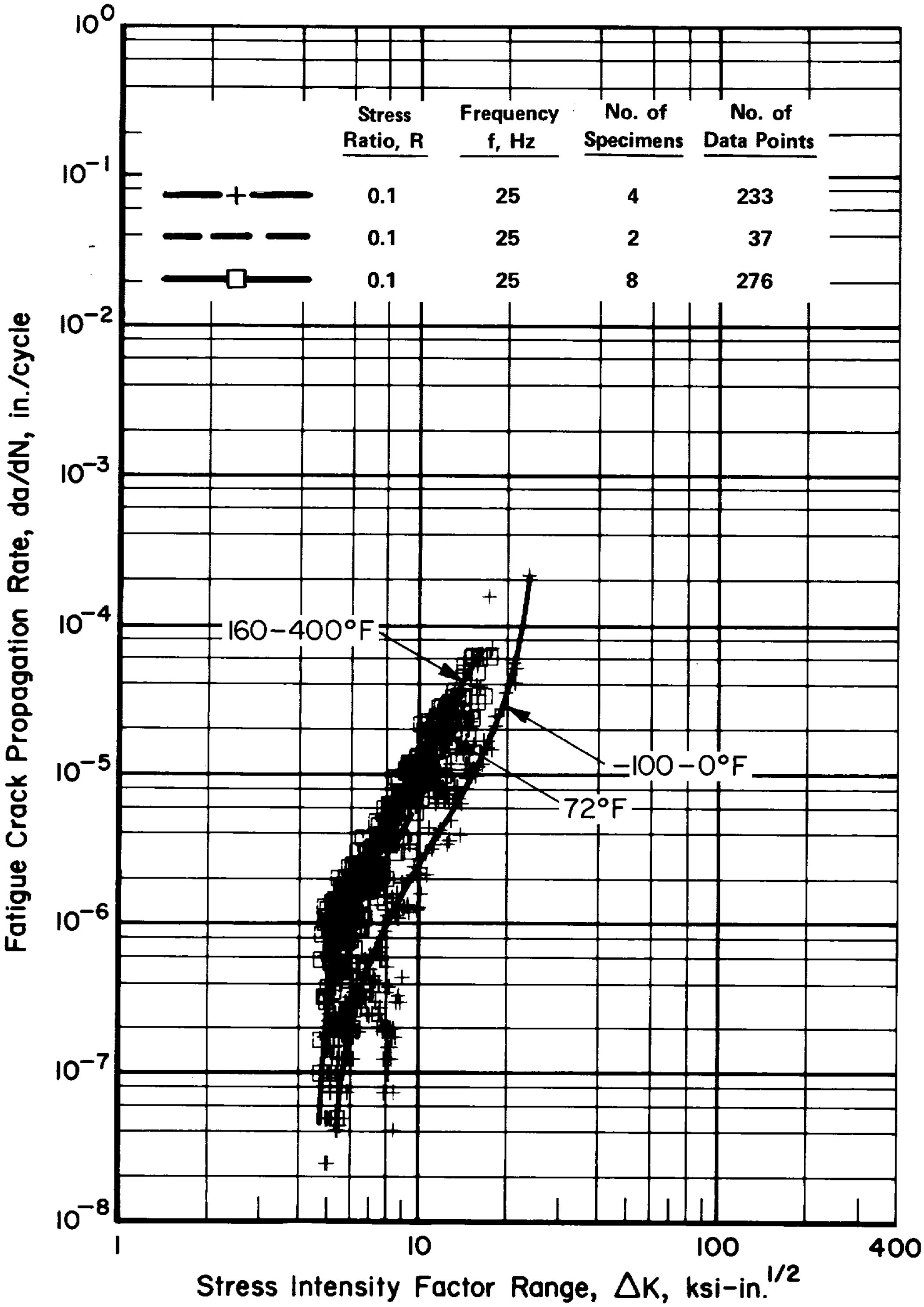


Figure 3.2.7.1.9(c). Fatigue-crack-propagation data for 2.5-inch thick, 2124-T851 aluminum alloy plate. [Reference 3.2.7.1.9(b)].

Specimen Thickness:	*0.75 inch*	*Environment:*	*Lab air*
Specimen Width:	*1.75 inches*	*Temperature:*	*-100 through 400 °F*
Specimen Type:	*C(T)*	*Orientation:*	*L-T*

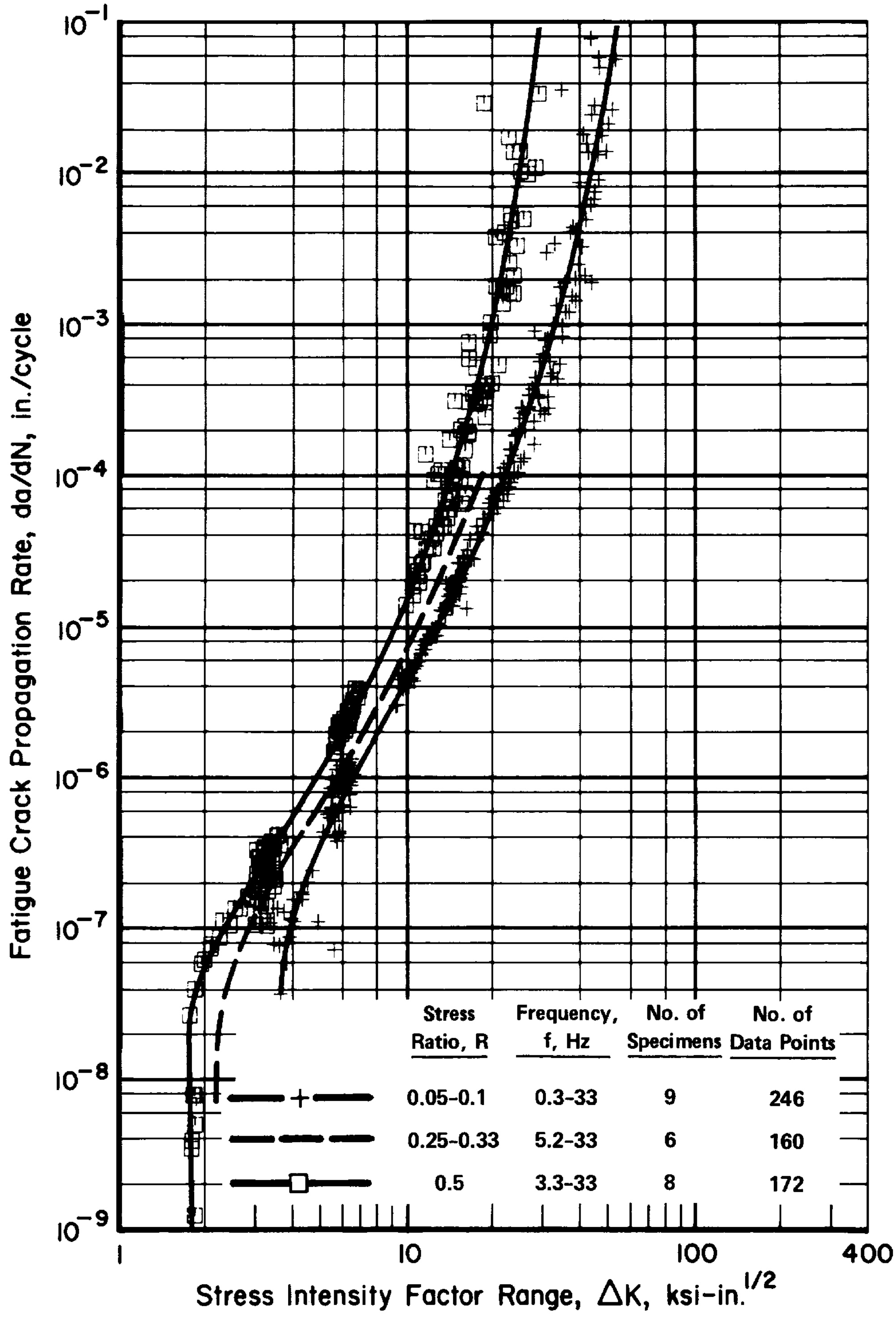


Figure 3.2.7.1.9(d). Fatigue-crack-propagation data for 2.0 to 5.5 inch thick, 2124-T851 aluminum alloy plate. [References 3.2.7.1.9(a), 3.2.7.1.9(d), and 3.7.4.2.9(c)].

Specimen Thickness:	*0.25-0.75 inch*	*Environment:*	*90-95% R.H.*
Specimen Width:	*4.0-11.75 inches*	*Temperature:*	*RT*
Specimen Type:	*M(T)*	*Orientation:*	*T-L*

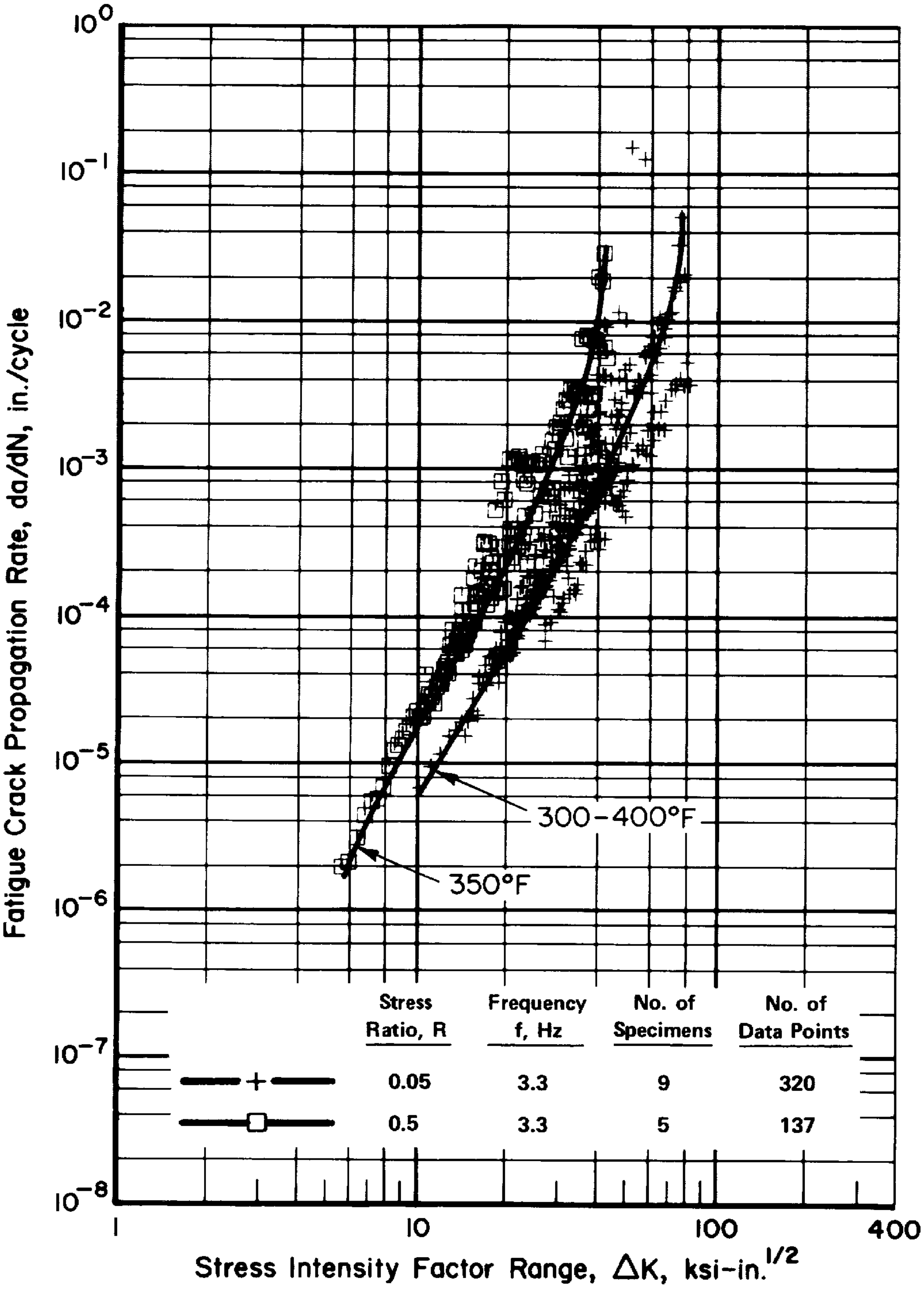


Figure 3.2.7.1.9(e). Fatigue-crack-propagation data for 2.0-inch thick, 2124-T851 aluminum alloy plate. [Reference 3.2.7.1.9(a)].

Specimen Thickness:	*0.25-0.45 inch*	*Environment:*	*Lab air*
Width:	*11.75 inches*	*Temperature:*	*300-400 °F*
Type:	*M(T)*	*Orientation:*	*T-L*

3.2.8 2219 ALLOY

3.2.8.0 *Comments and Properties* — 2219 is an Al-Cu alloy available in a wide variety of product forms. As shown in Table 3.1.2.3.1(a), 2219-T351X and -T37 rolled plate and extruded shapes have a 'D' SCC rating. This is the lowest rating and means that SCC failures have occurred in service or would be anticipated if there is any sustained stress. In-service failures are caused by stressed produced by any combination of sources including solution heat treatment, straightening, forming, fit-up, clamping, sustained service loads or high service compression stresses that produce residual tensile stresses. These stresses may be tension or compression as well as the stresses due to the Poisson effect, because the actual failures are caused by the resulting sustained shear stresses. Pin-hole flaws in corrosion protection are sufficient for SCC. Refer to Section 3.1.2.3 for comments regarding the resistance of the alloy to stress-corrosion cracking, and to Section 3.1.3.4 for comments regarding the weldability of the alloy. It has been used in critical cryogenic applications as well as those applications in which high strength and creep resistance at relatively high temperatures (400 to 600°F) are required.

The properties of extrusions should be based upon the thickness at the time of quenching prior to machining. Selection of the mechanical properties based upon its final machined thickness may be unconservative; therefore, the thickness at the time of quenching to achieve properties is an important factor in the selection of the proper thickness column. For extrusions having sections with various thicknesses, consideration should be given to the properties as a function of thickness.

Material specifications for 2219 are presented in Table 3.2.8.0(a). Room-temperature mechanical and physical properties are shown in Tables 3.2.8.0(b_1) through (d). The effect of temperature on the physical properties is shown in Figure 3.2.8.0.

Table 3.2.8.0(a). Material Specifications for 2219 Aluminum Alloy

Specification	Form
AMS 4031	Sheet and plate
AMS-QQ-A-250/30	Sheet and plate
AMS 4162	Extrusion
AMS 4163	Extrusion
AMS 4144	Hand forging

The temper index for 2219 is as follows:

Section	Temper
3.2.8.1	T62
3.2.8.2	T81, T851, T8510, and T8511
3.2.8.3	T852
3.2.8.4	T87

3.2.8.1 *T62 Temper* — Elevated temperature data for this temper are presented in Figures 3.2.8.1.1(a) and (b). Typical room-temperature tensile and compressive stress-strain, compressive tangent-modulus, and full-range tensile stress-strain curves for 2219 aluminum alloy sheet and plate for this temper are shown in Figures 3.2.8.1.6(a) and (b).

3.2.8.2 *T81 and T851X Tempers* — Elevated temperature data for these tempers are presented in Figures 3.2.8.2.1(a) and (b). Typical room-temperature tensile and compressive stress-strain, compressive tangent-modulus, and full-range tensile stress-strain curves for 2219 aluminum alloy for this condition are shown in Figures 3.2.8.2.6(a) and (b). Notched fatigue data for plate are presented in Figures 3.2.8.2.8(a) through (d).

3.2.8.3 *T852 Temper* — Typical room-temperature tensile and compressive stress-strain, compressive tangent-modulus, and full-range tensile stress-strain curves for 2219 aluminum alloy for this temper are shown in Figures 3.2.8.3.6(a) through (e).

3.2.8.4 *T87 Temper* — Elevated temperature data for this temper are presented in Figures 3.2.8.4.1(a) and (b). Typical room-temperature tensile and compressive stress-strain, compressive tangent-modulus, and full-range tensile stress-strain curves for 2219 aluminum alloy sheet and plate for this temper are shown in Figures 3.2.8.4.6(a) through (e).

Table 3.2.8.0(b_1). Design Mechanical and Physical Properties of 2219 Aluminum Alloy Sheet and Plate

Specification	AMS 4031 & AMS-QQ-A-250/30		AMS-QQ-A-250/30													
Form	Sheet and plate															
Temper	T62[a]		T81		T851											
Thickness, in.	0.020-2.000		0.020-0.249		0.250-1.000		1.001-2.000		2.001-3.000		3.001-4.000		4.001-5.000		5.001-6.000	
Basis	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
Mechanical Properties:																
F_{tu}, ksi:																
L	54	55	61	62	61	62	61	62	...	...	...	...	...	...	...	...
LT	54	55	62	63	62	63	62	63	62	63	60	61	59	60	57	58
F_{ty}, ksi:																
L	36	37	47	48	47	48	47	48	...	...	...	...	...	...	...	...
LT	36	37	46	47	46	47	46	47	45	46	44	45	43	44	42	43
F_{cy}, ksi:																
L	37	39	47	48	47	48	47	48	...	...	...	...	...	...	...	...
LT	37	38	48	49	48	49	48	49	...	...	...	...	...	...	...	...
F_{su}, ksi	31	32	35	35	36	36	36	36	...	...	...	...	...	...	...	...
F_{bru}[b], ksi:																
(e/D = 1.5)	84	85	95	96	95	96	95	96	...	...	...	...	...	...	...	...
(e/D = 2.0)	107	109	121	123	121	123	121	123	...	...	...	...	...	...	...	...
F_{bry}[b], ksi:																
(e/D = 1.5)	62	64	76	78	76	78	76	78	...	...	...	...	...	...	...	...
(e/D = 2.0)	79	81	92	94	94	94	92	94	...	...	...	...	...	...	...	...
e, percent (S-basis):																
LT	[c]	...	[c]	...	8	...	7	...	6	...	5	...	5	...	4	...
E, 10^3 ksi	10.5															
E_c, 10^3 ksi	10.8															
G, 10^3 ksi	4.0															
μ	0.33															
Physical Properties:																
ω, lb/in.^{3}	0.103															
C, K, and α	See Figure 3.2.8.0															

a Design allowables were based upon data obtained from testing samples of material, supplied in O and F temper, which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained by user may be lower than those listed if the material has been formed or otherwise cold or hot worked, particularly in the annealed temper, prior to solution heat treatment.

b Bearing values are "dry pin" values per Section 1.4.7.1. See Table 3.1.2.1.1.

c T62 and T81: 0.020-0.039 in., 6 percent, 0.040-0.249 in., 7 percent; T62: 0.250-1.000 in., 8 percent, 1.001-2.000 in., 7 percent.

Table 3.2.8.0(b_2). Design Mechanical and Physical Properties of 2219 Aluminum Alloy Sheet — Continued

Specification	AMS-QQ-A-250\30			
Form	Sheet			
Condition	T87			
Thickness, in.	0.020-0.039		0.040-0.249	
Basis	A	B	A	B
Mechanical Properties:				
F_{tu}, ksi:				
L	63	64	63	64
LT	64	65	64	65
F_{ty}, ksi:				
L	51	52	51	52
LT	52	53	52	53
F_{cy}, ksi:				
L	52	53	52	53
LT	55	56	55	56
F_{su}, ksi	36	37	36	37
F_{bru}[a], ksi:				
(e/D = 1.5)	99	100	99	100
(e/D = 2.0)	126	128	126	128
F_{bry}[a], ksi:				
(e/D = 1.5)	83	85	83	85
(e/D = 2.0)	96	98	96	98
e, percent (S-basis):				
LT	5	...	6	...
E, 10^3 ksi	10.5			
E_c, 10^3 ksi	10.8			
G, 10^3 ksi	4.0			
μ	0.33			
Physical Properties:				
ω, lb/in.^{3}	0.103			
C, K, and α	See Figure 3.2.8.0			

[a] See Table 3.1.2.1.1. Bearing values are “dry pin” values per Section 1.4.7.1.

Table 3.2.8.0(b$_3$). Design Mechanical and Physical Properties of 2219 Aluminum Alloy Plate — Continued

Specification	AMS-QQ-A-250\30											
Form	Plate											
Condition	T87											
Thickness, in.	0.250-1.000		1.001-1.500		1.501-2.000		2.001-3.000		3.001-4.000		4.001-5.000	
Basis	A	B	A	B	A	B	A	B	A	B	A	B
Mechanical Properties:												
F_{tu}, ksi:												
L	63	64	63	64	63	64	63	64	61	62	...	...
LT	64	65	64	65	64	65	64	65	62	63	61	62
ST	...	...	...	...	59	60	56	57	52	53	...	...
F_{ty}, ksi:												
L	50	51	50	51	50	51	50	51	49	50	...	...
LT	51	52	51	52	51	52	51	52	51	51	49	50
ST	...	...	...	...	51	52	50	51	48	49	...	...
F_{cy}, ksi:												
L	51	52	51	52	51	52	...	...	...	...	...	...
LT	53	54	52	53	52	53	...	...	...	...	...	...
F_{su}, ksi	37	38	37	38	37	38	...	...	...	...	...	...
F_{bru}[a], ksi:												
(e/D = 1.5)	99	100	99	100	99	100	...	...	...	...	...	...
(e/D = 2.0)	126	128	126	128	126	128	...	...	...	...	...	...
F_{bry}[a], ksi:												
(e/D = 1.5)	82	83	82	83	82	83	...	...	...	...	...	...
(e/D = 2.0)	94	96	94	96	94	96	...	...	...	...	...	...
e, percent (S-basis):												
LT	7	...	6	...	6	...	6	...	4	...	3	...
E, 10^3 ksi	10.5											
E_c, 10^3 ksi	10.8											
G, 10^3 ksi	4.0											
μ	0.33											
Physical Properties:												
ω, lb/in.^{3}	0.103											
C, K, and α	See Figure 3.2.8.0											

[a] See Table 3.1.2.1.1. Bearing values are "dry pin" values per Section 1.4.7.1.

Table 3.2.8.0(c). Design Mechanical and Physical Properties of 2219 Aluminum Alloy Hand Forging

Specification	AMS 4144							
Form	Hand Forging							
Temper	T852							
Thickness, in.	<2.000	2.000-4.000	4.001-6.000	6.001-8.000	8.001-10.000	10.001-12.000	12.001-14.000	14.001-17.000
Basis	S	S	S	S	S	S	S	S
Mechanical Properties:								
F_{tu}, ksi:								
L	62	62	58	57	56	54	53	51
LT	62	62	56	55	54	53	52	50
ST	...	60	56	55	54	53	52	50
F_{ty}, ksi:								
L	50	50	44	43	42	41	40	39
LT	49	49	42	41	41	40	40	39
ST	...	46	41	40	39	39	38	37
F_{cy}, ksi:								
L	...	46	40	39	...	...	...	...
LT	...	47	40	39	...	...	...	...
ST	...	47	41	40	...	...	...	...
F_{su}, ksi:								
L	...	37	35	35	...	...	...	...
LT	...	36	34	35	...	...	...	...
ST	...	32	32	33	...	...	...	...
F_{bru}[a], ksi:								
(e/D = 1.5)	...	...	...	80	...	...	...	...
(e/D = 2.0)	...	104	100	102	...	...	...	...
F_{bry}[a], ksi:								
(e/D = 1.5)	...	76	65	64	...	...	...	...
(e/D = 2.0)	...	89	76	75	...	...	...	...
e, percent:								
L	6	6	6	6	6	6	6	6
LT	4	4	4	4	3	3	3	3
ST	...	3	3	3	3	2	2	2
E, 10^3 ksi	10.2							
E_c, 10^3 ksi	10.4							
G, 10^3 ksi	3.9							
μ	0.33							
Physical Properties:								
ω, lb/in.^{3}	0.103							
C, *K*, and α	See Figure 3.2.8.0							

[a] Bearing values are "dry pin" values per Section 1.4.7.1.

Table 3.2.8.0(d). Design Mechanical and Physical Properties of 2219 Aluminum Alloy Extruded Shapes

Specification	AMS 4162 and AMS 4163[a]	
Form	Extruded shapes	
Temper	T8511	
Cross-Sectional Area, in.^{2}	≤25	
Thickness or Diameter,[b] in.	≤0.499	0.500-2.999
Basis	S	S
Mechanical Properties:		
F_{tu}, ksi:		
L	58	58
LT[c]	56	56
F_{ty}, ksi:		
L	42	42
LT[c]	39	39
F_{cy}, ksi:		
L	43	42
LT	43	41
F_{su}, ksi	33	33
F_{bru}[d], ksi:		
(e/D = 1.5)	87	81
(e/D = 2.0)	113	107
F_{bry}[d], ksi:		
(e/D = 1.5)	69	67
(e/D = 2.0)	84	82
e, percent:		
L	6	6
LT[c]	4	4
E, 10^3 ksi	10.5	
E_c, 10^3 ksi	10.8	
G, 10^3 ksi	4.0	
μ	0.33	
Physical Properties:		
ω, lb/in.^{3}	0.103	
C, K, and α	See Figure 3.2.8.0	

a Design allowables for extrusions procured to AMS 4163 were based upon data obtained from testing samples of material, supplied in T3511 temper, which were precipitation heat treated by suppliers to demonstrate response to aging treatment.

b The mechanical properties are to be based upon the thickness at the time of quench.

c Applicable providing LT dimension is ≥2.500 inches.

d Bearing values are "dry pin" values per Section 1.4.7.1.

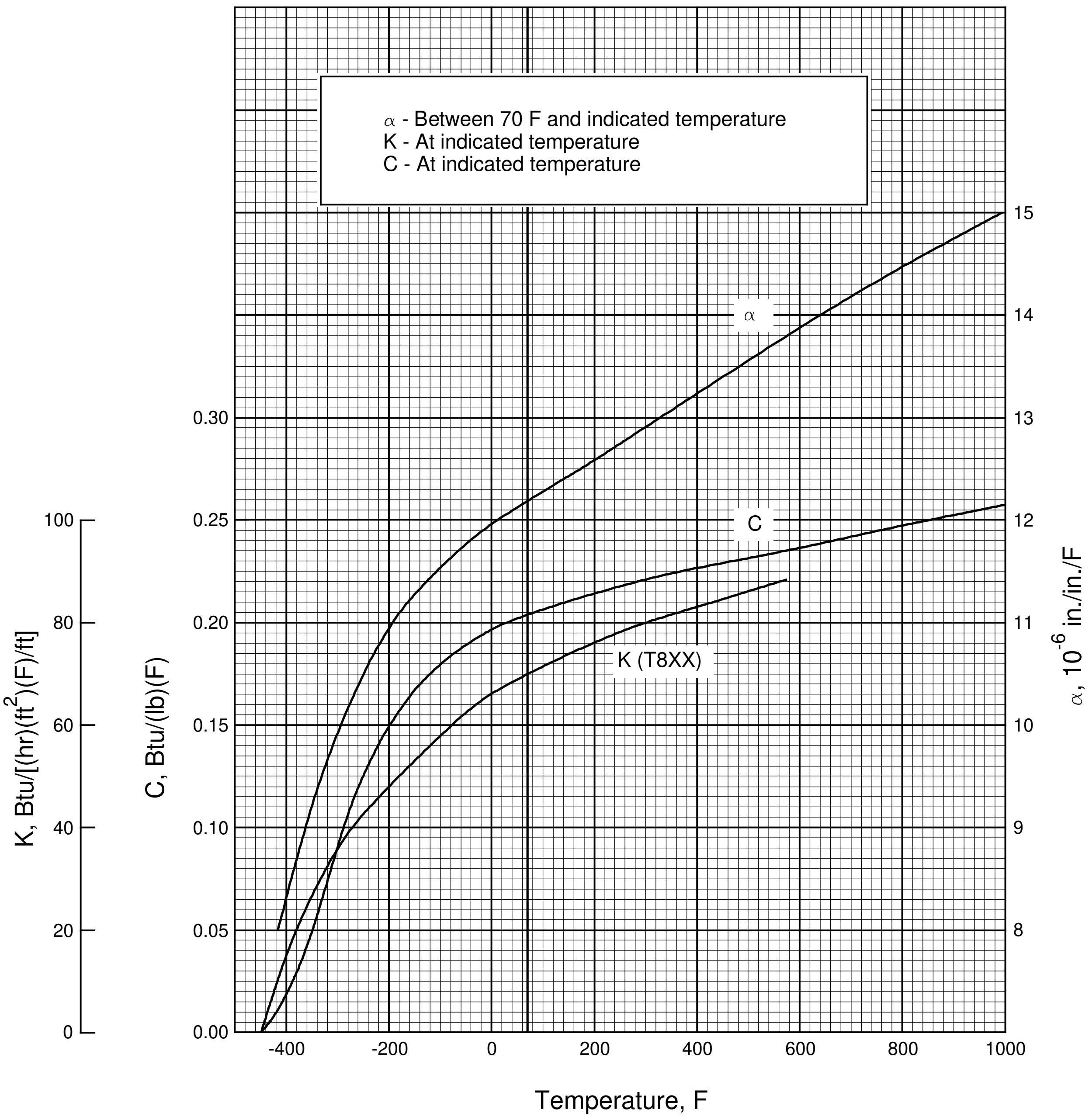


Figure 3.2.8.0. Effect of temperature on the physical properties of 2219 aluminum alloy.

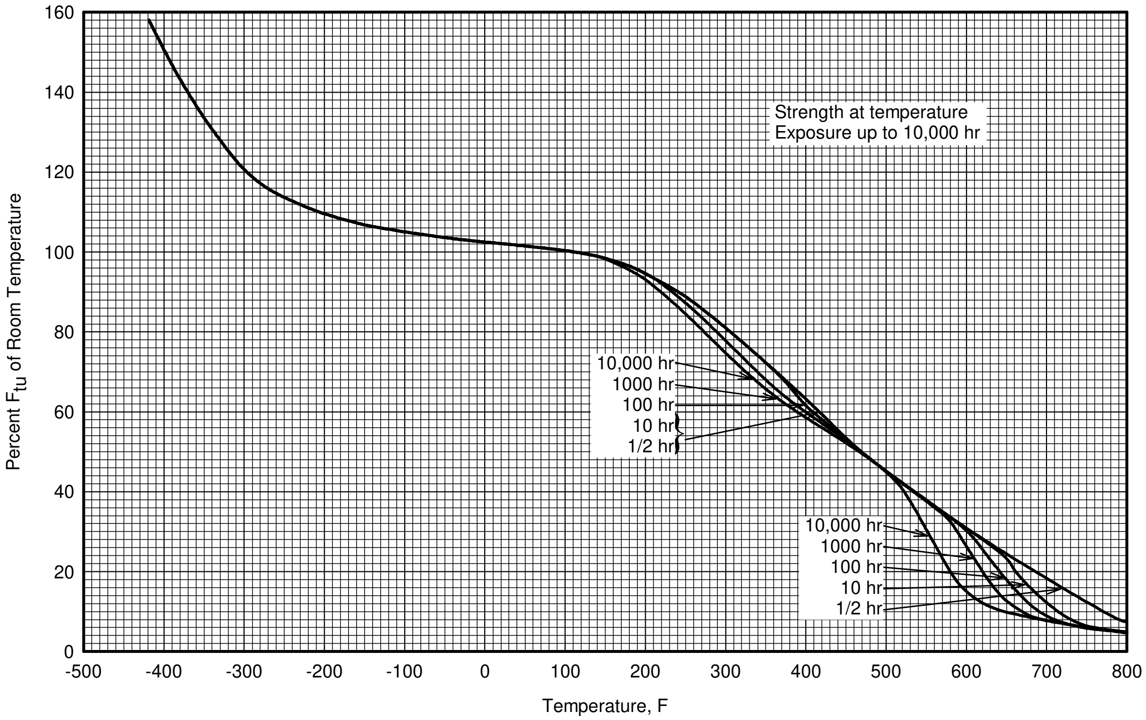


Figure 3.2.8.1.1(a). Effect of temperature on the tensile ultimate strength (F_{tu}) of 2219-T62 aluminum alloy sheet, 0.040-0.249, and plate, 0.250-1.000 in. thick.

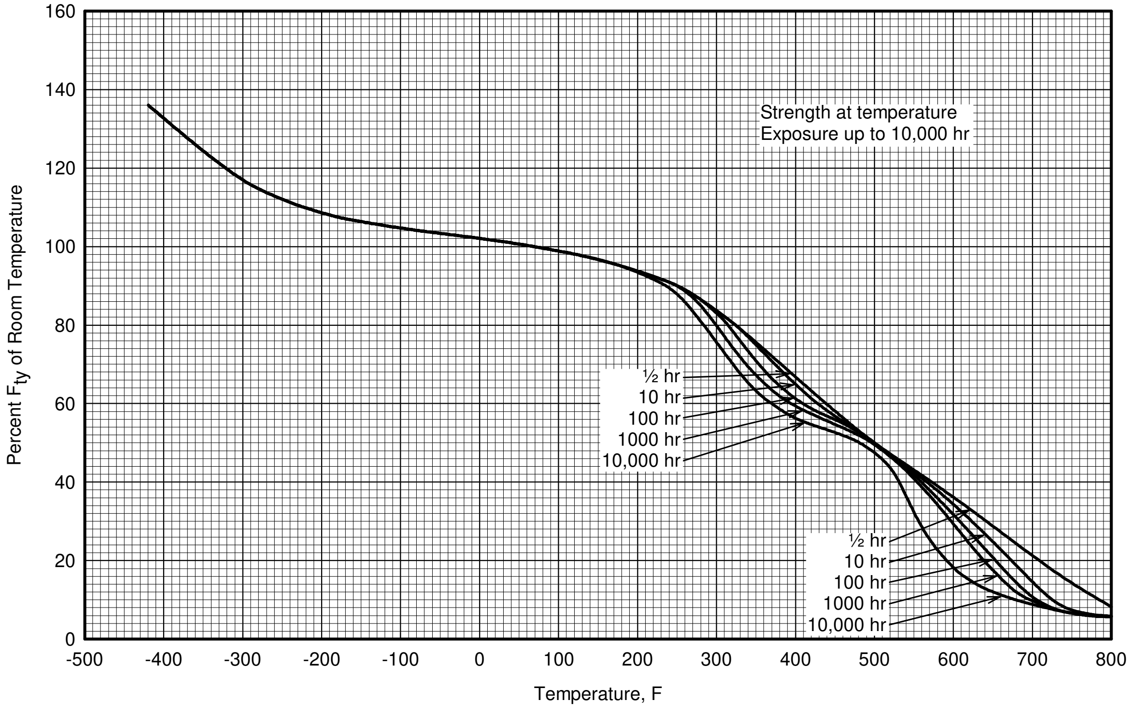


Figure 3.2.8.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of 2219-T62 aluminum alloy sheet, 0.040-0.249 and plate, 0.250-1.000 in. thick.

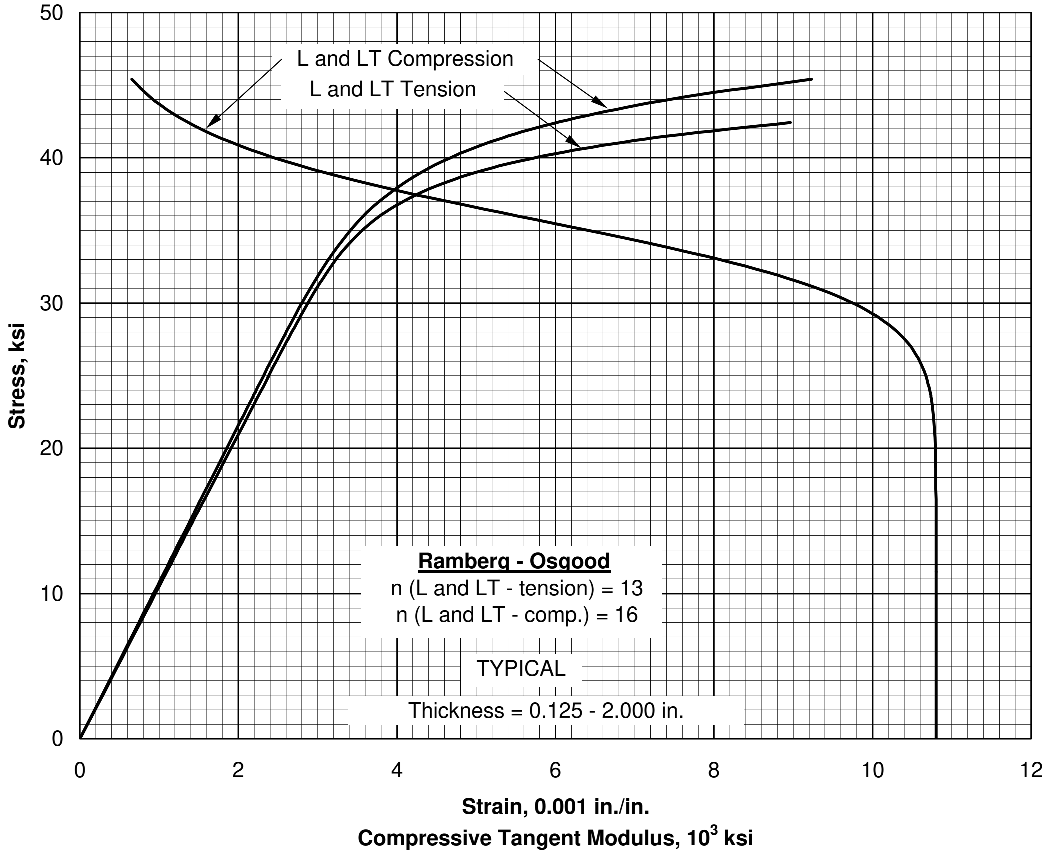


Figure 3.2.8.1.6(a). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 2219-T62 aluminum alloy sheet and plate at room temperature.

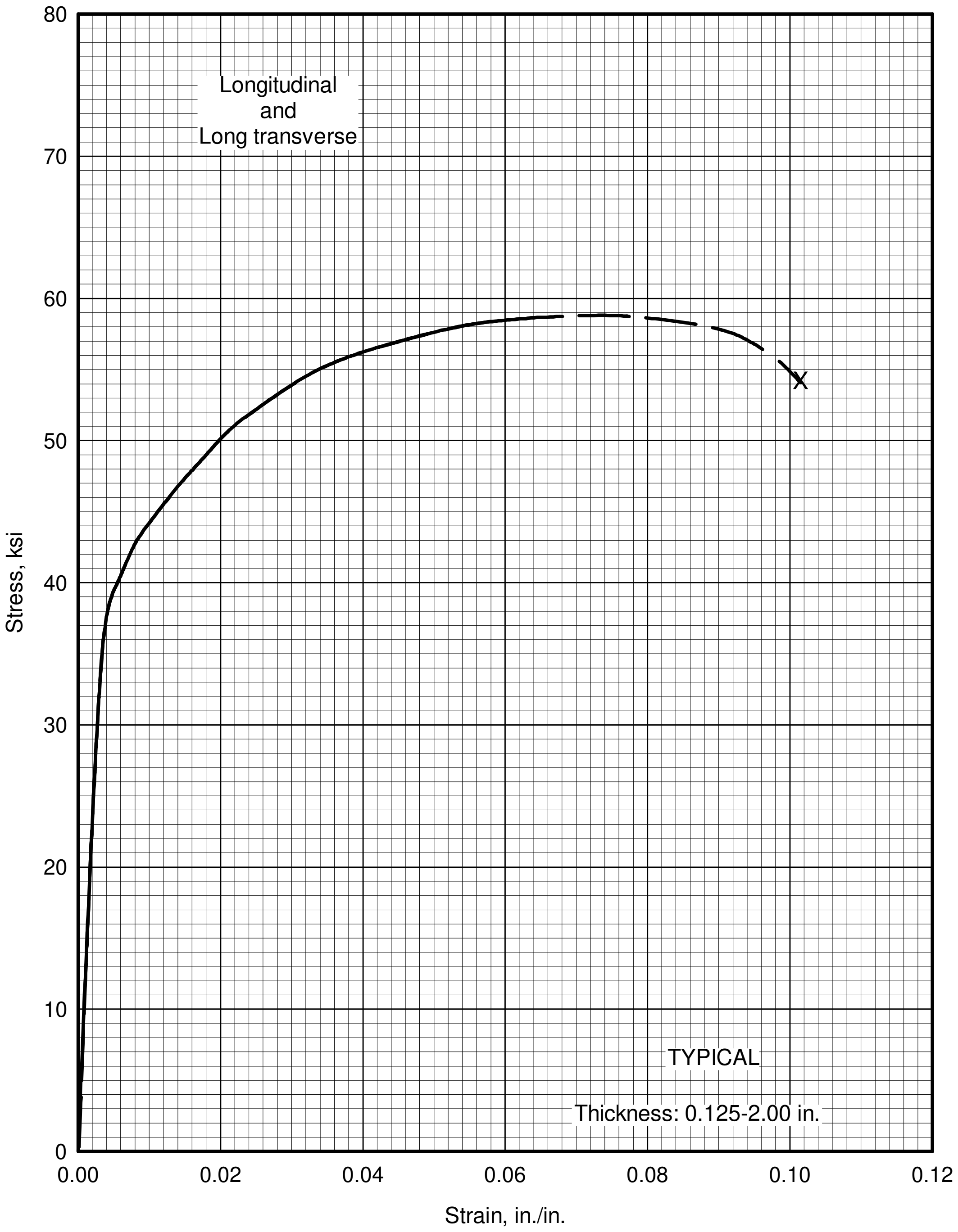


Figure 3.2.8.1.6(b). Typical tensile stress-strain (full range) curve for 2219-T62 aluminum alloy sheet and plate at room temperature.

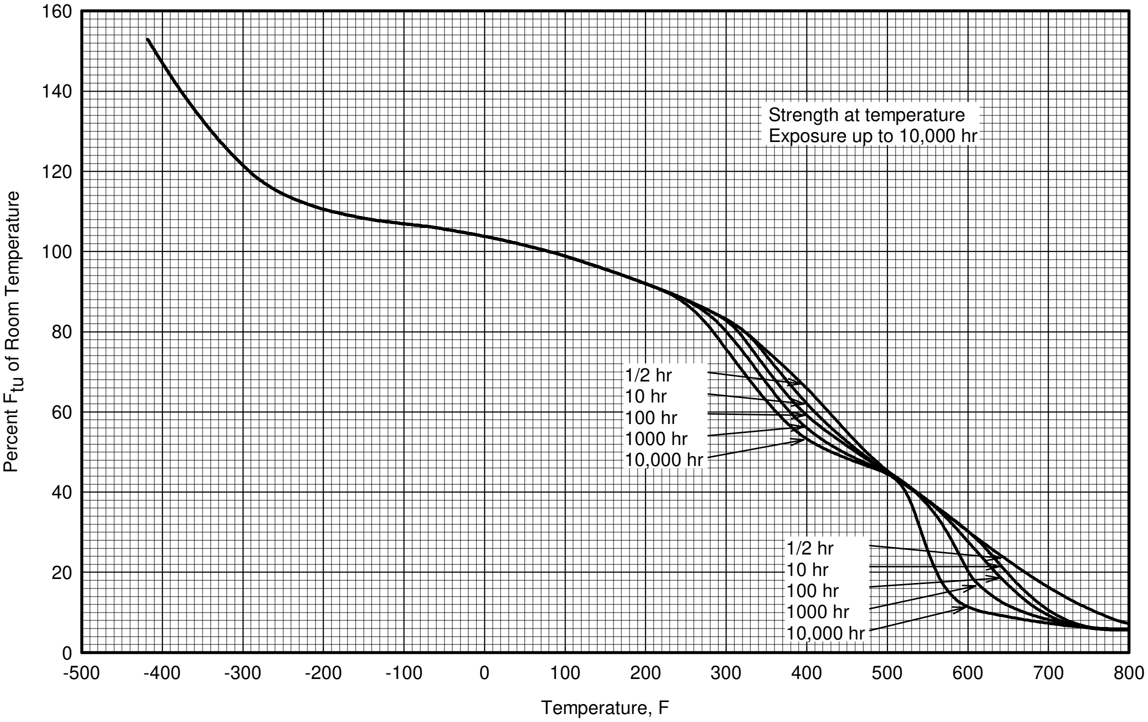


Figure 3.2.8.2.1(a). Effect of temperature on the tensile ultimate strength (F_{tu}) of 2219-T81 aluminum alloy sheet and 2219-T851 aluminum alloy plate.

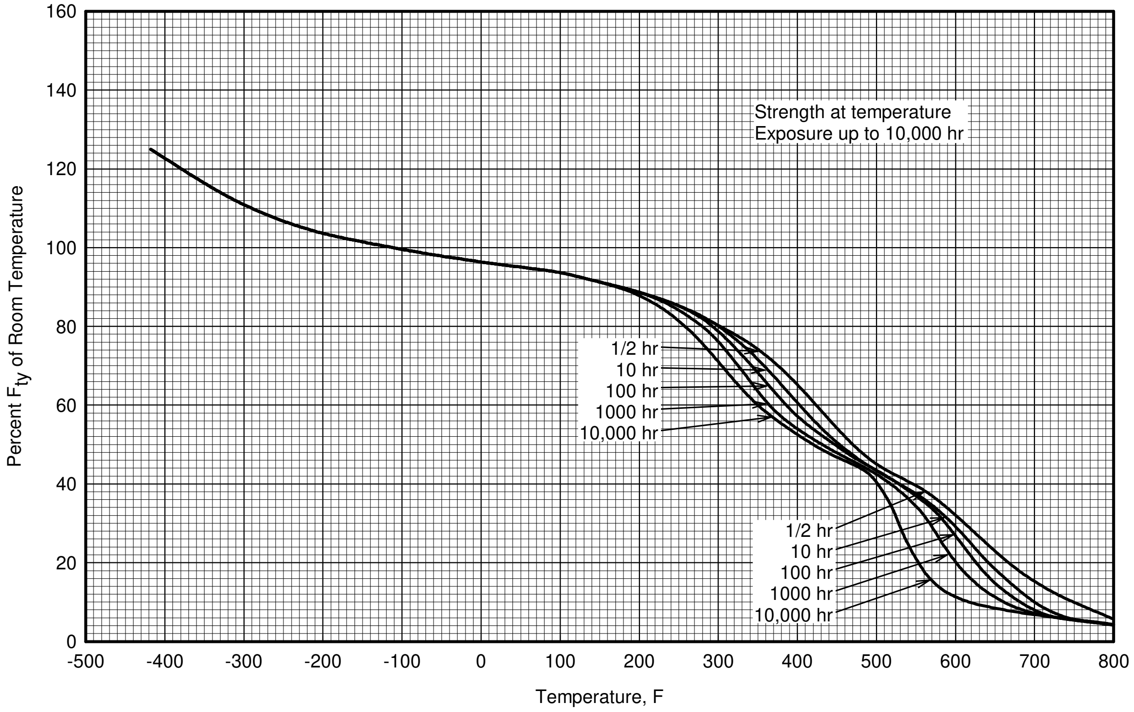


Figure 3.2.8.2.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of 2219-T81 aluminum alloy sheet and 2219-T851 aluminum alloy plate.

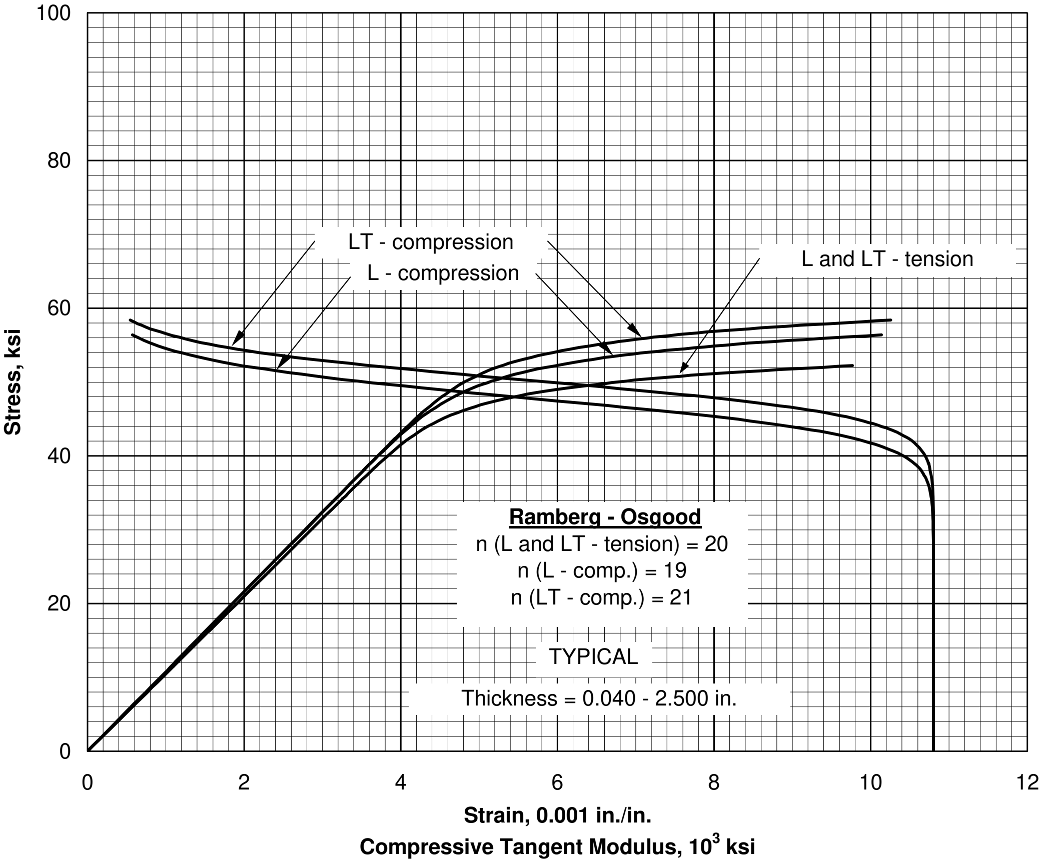


Figure 3.2.8.2.6(a). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 2219-T81 aluminum alloy sheet and 2219-T851 aluminum alloy plate at room temperature.

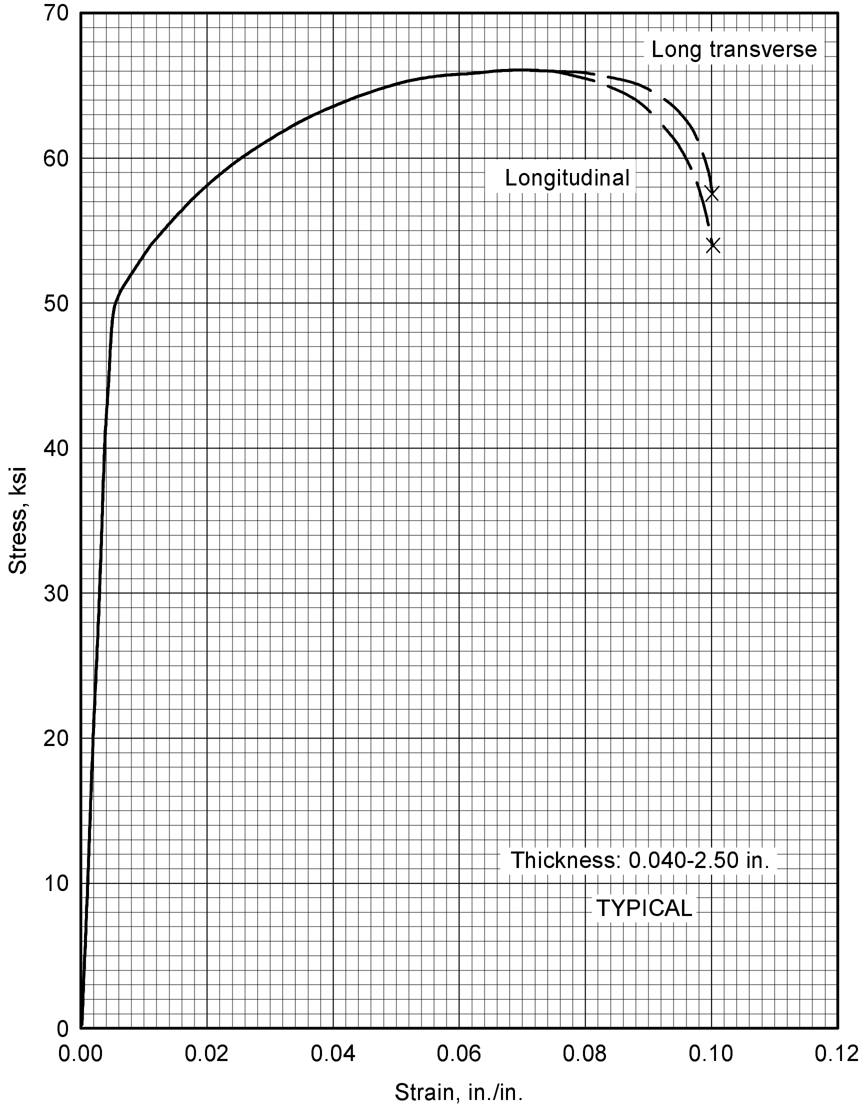


Figure 3.2.8.2.6(b). Typical tensile stress-strain curves (full range) for 2219-T81 aluminum alloy sheet and 2219-T851 aluminum alloy plate at room temperature.

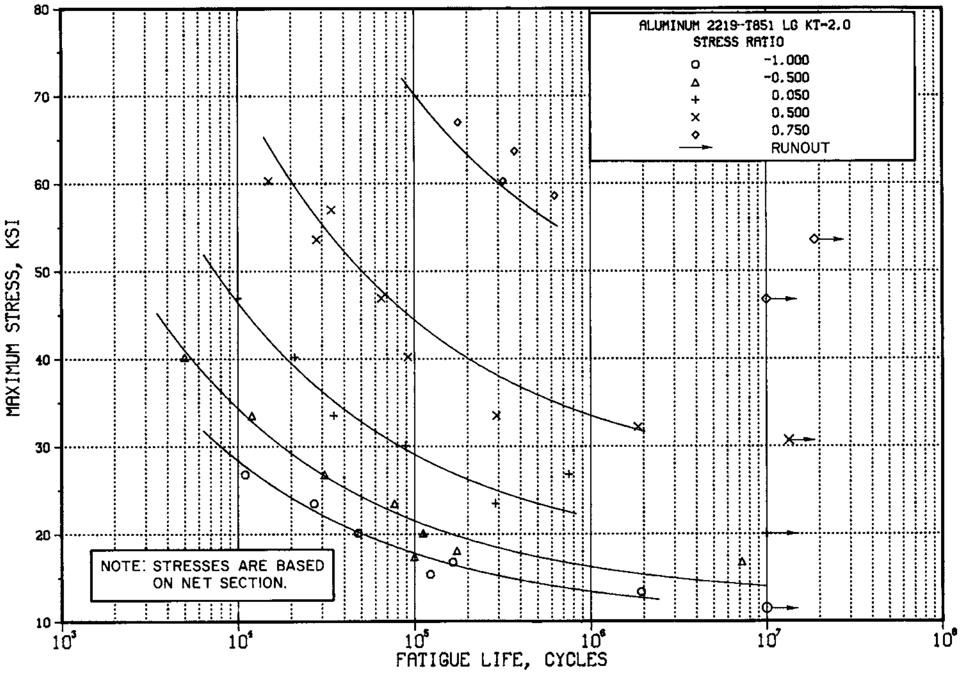


Figure 3.2.8.2.8(a). Best-fit S/N curves for notched, K_t = 2.0, 2219-T851 aluminum alloy plate, longitudinal direction.

Correlative Information for Figure 3.2.8.2.8(a)

Product Form: Plate, 2.00 inch thick

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	68	52	RT (unnotched)
	94	—	RT (notched)

Specimen Details: Notched, V-Groove, $K_t = 2.0$
0.195 inch gross diameter
0.136 inch net diameter
0.020 inch root radius, r
60° flank angle, ε

Surface Condition: As machined

Reference: 3.2.8.2.8

Test Parameters:
Loading - Axial
Frequency - 7000 to 8000 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 1

Equivalent Stress Equation:
$\text{Log } N_f = 7.92 - 2.69 \log (S_{eq} - 16.0)$
$S_{eq} = S_{max} (1-R)^{0.64}$ ksi
Std. Error of Estimate, Log (Life) = 0.313
Standard Deviation, Log (Life) = 0.739
$R^2 = 82\%$

Sample Size = 34

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

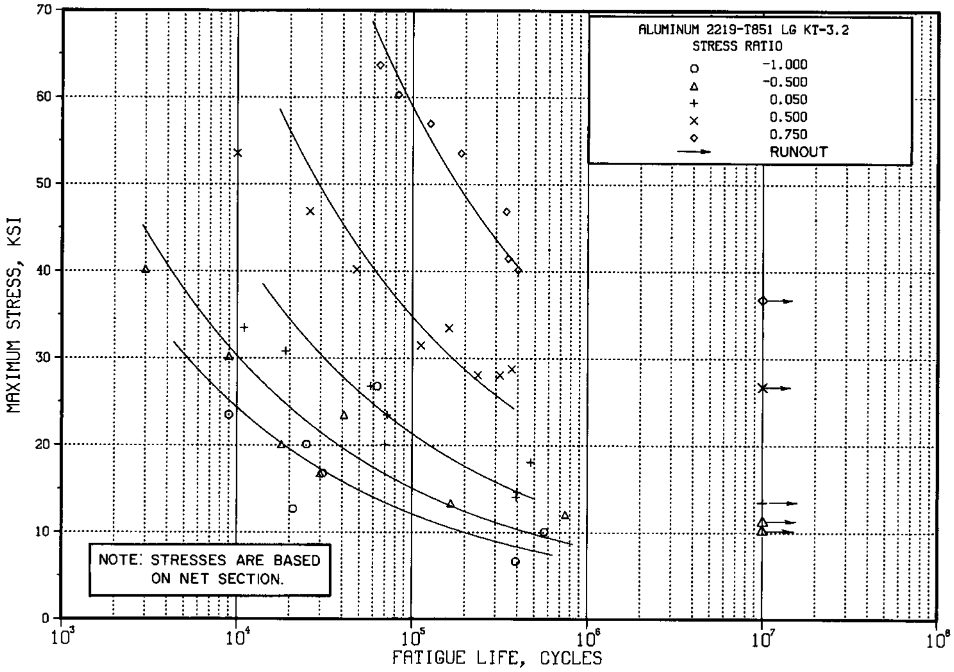


Figure 3.2.8.2.8(b). Best-fit S/N curves for notched, K_t = 3.2, 2219-T851 aluminum alloy plate, longitudinal direction.

Correlative Information for Figure 3.2.8.2.8(b)

Product Form: Plate, 2.00 inch thick

Properties:

TUS, ksi	TYS, ksi	Temp., °F
68	52	RT (unnotched)
92	—	RT (notched)

Specimen Details: Notched, V-Groove, K_t = 3.2
0.195 inch gross diameter
0.136 inch net diameter
0.006 inch root radius, r
60° flank angle, ω

Surface Condition: As machined

Reference: 3.2.8.2.8

Test Parameters:
Loading - Axial
Frequency - 7000 to 8000 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 1

Equivalent Stress Equation:
$\text{Log } N_f = 8.46 - 2.83 \log (S_{eq} - 3.93)$
$S_{eq} = S_{max} (1-R)^{0.76}$
Std. Error of Estimate, Log (Life) = 0.292
Standard Deviation, Log (Life) = 0.64
R^2 = 79%

Sample Size = 39

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

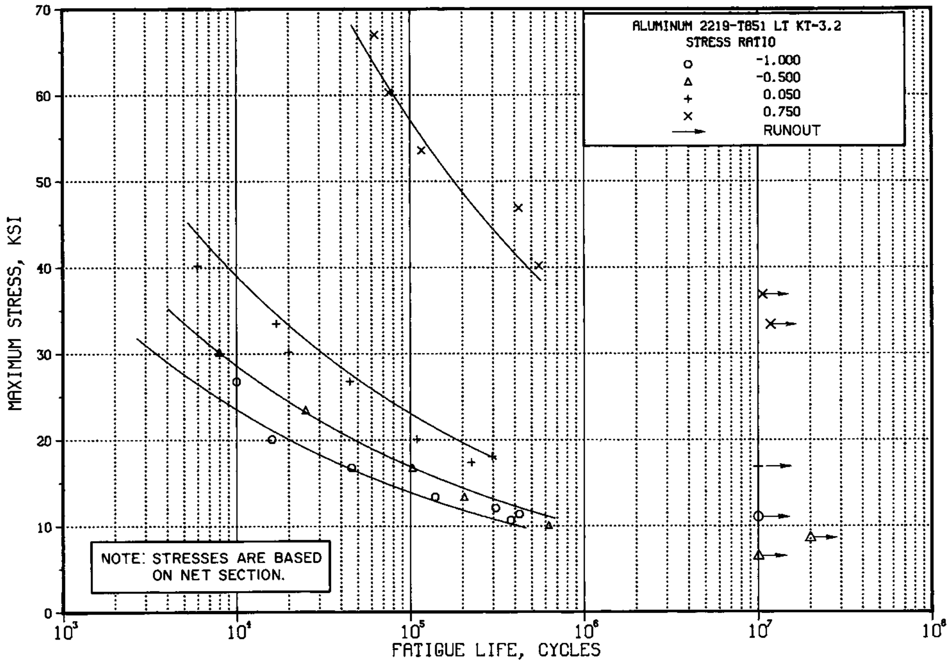


Figure 3.2.8.2.8(c). Best-fit S/N curves for notched, K_t = 3.2, 2219-T851 aluminum alloy plate, long transverse direction.

Correlative Information for Figure 3.2.8.2.8(c)

Product Form: Plate, 2.00 inch thick

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	68	51	RT (unnotched)
	89	—	RT (notched)

Specimen Details: Notched, V-Groove, K_t = 3.2
0.195 inch gross diameter
0.136 inch net diameter
0.006 inch root radius, r
60° flank angle, ω

Surface Condition: As machined

Reference: 3.2.8.2.8

Test Parameters:
Loading - Axial
Frequency - 7000 to 8000 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 1

Equivalent Stress Equation:
$\text{Log } N_f = 10.85 - 4.34 \log (S_{eq})$
$S_{eq} = S_{max} (1-R)^{0.686}$ ksi
Std. Error of Estimate, Log (Life) = 0.153
Standard Deviation, Log (Life) = 0.610
R^2 = 94%

Sample Size = 25

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

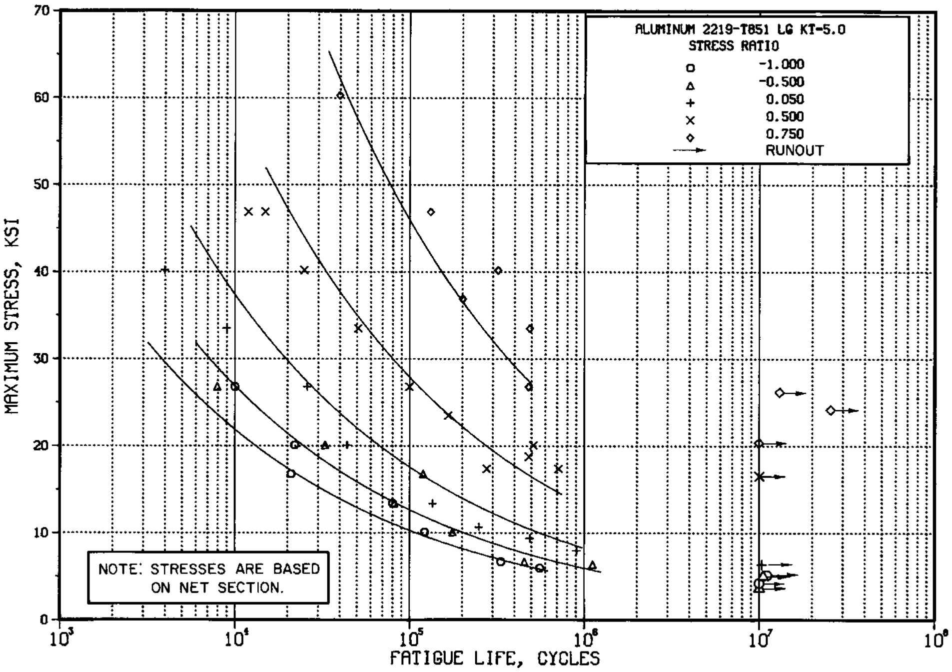


Figure 3.2.8.2.8(d). Best-fit S/N curves for notched, K_t = 5.0, 2219-T851 aluminum alloy plate, longitudinal direction.

Correlative Information for Figure 3.2.8.2.8(d)

Product Form: Plate, 2.00 inch thick

Properties:

TUS, ksi	TYS, ksi	Temp., °F
68 (L)	52 (L)	RT (unnotched)
91 (L)	—	RT (notched)

Specimen Details: Notched, V-Groove, K_t = 5.0
0.300 inch gross diameter
0.210 inch net diameter
0.0035 inch root radius, r
60° flank angle, ω

Surface Condition: As machined

Reference: 3.2.8.2.8

Test Parameters:
Loading - Axial
Frequency - 7000 to 8000 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 1

Equivalent Stress Equation:
$\text{Log } N_f = 8.76 - 3.05 \log (S_{eq})$
$S_{eq} = S_{max} (1-R)^{0.722}$ ksi
Std. Error of Estimate, Log (Life) = 0.194
Standard Deviation, Log (Life) = 0.660
$R^2 = 91\%$

Sample Size = 38

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

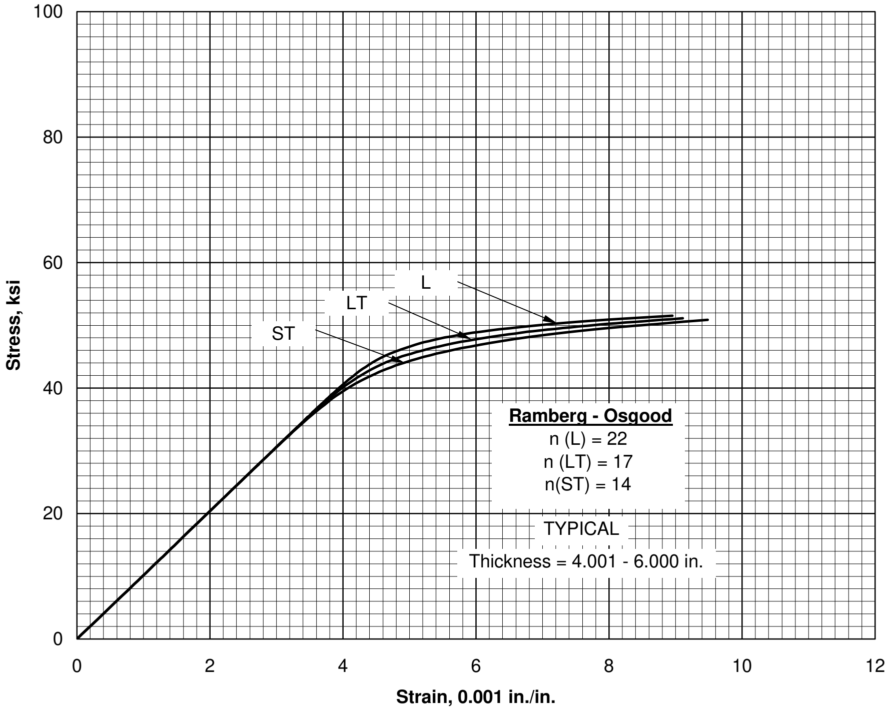


Figure 3.2.8.3.6(a). Typical tensile stress-strain curves for 2219-T852 aluminum alloy hand forging at room temperature.

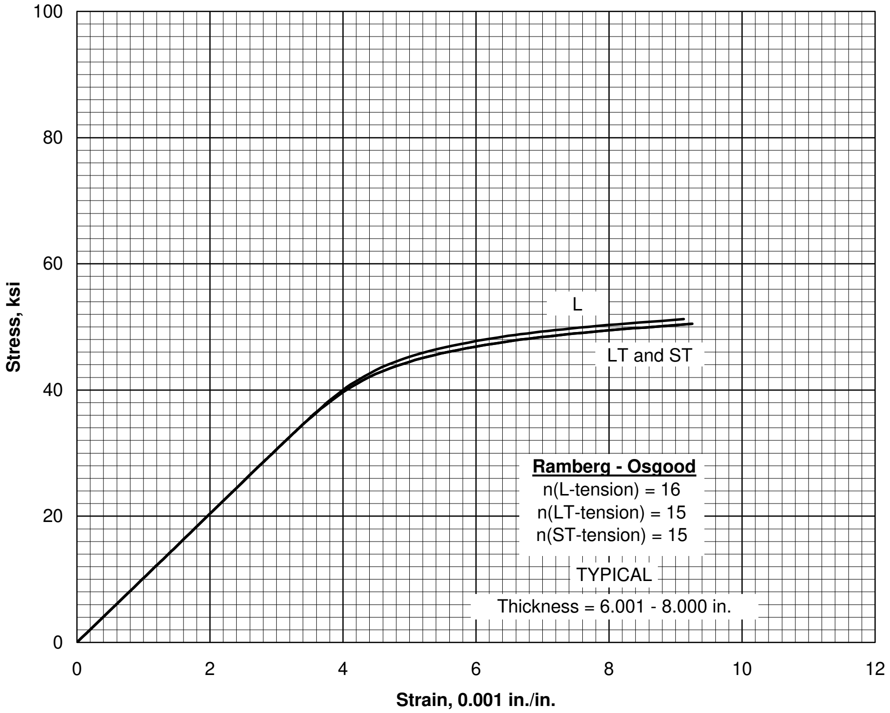


Figure 3.2.8.3.6(b). Typical tensile stress-strain curves for 2219-T852 aluminum alloy hand forging at room temperature.

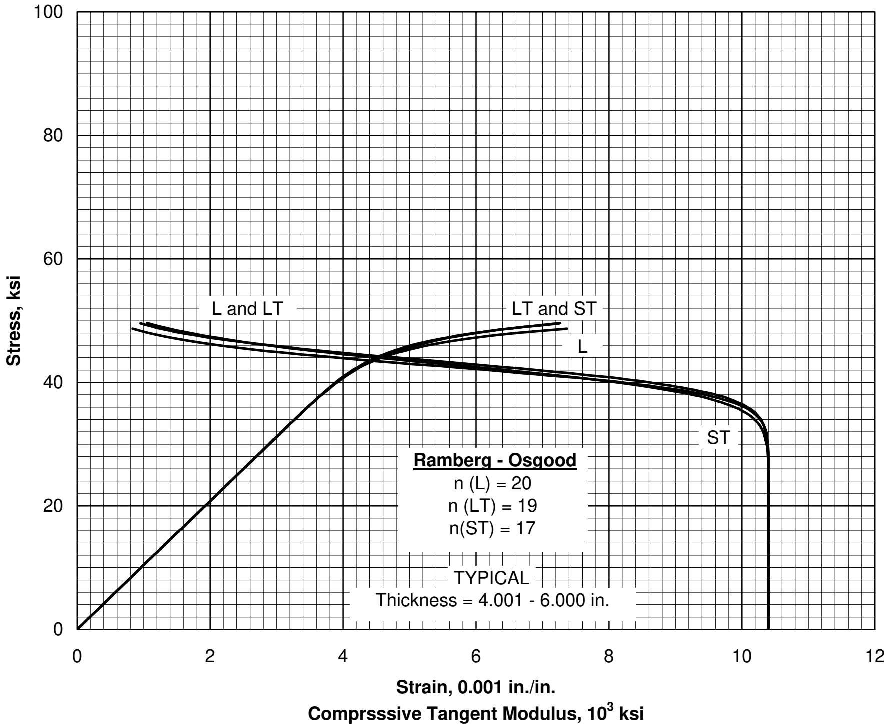


Figure 3.2.8.3.6(c). Typical compressive stress-strain and compressive tangent-modulus curves for 2219-T852 aluminum alloy hand forging at room temperature.

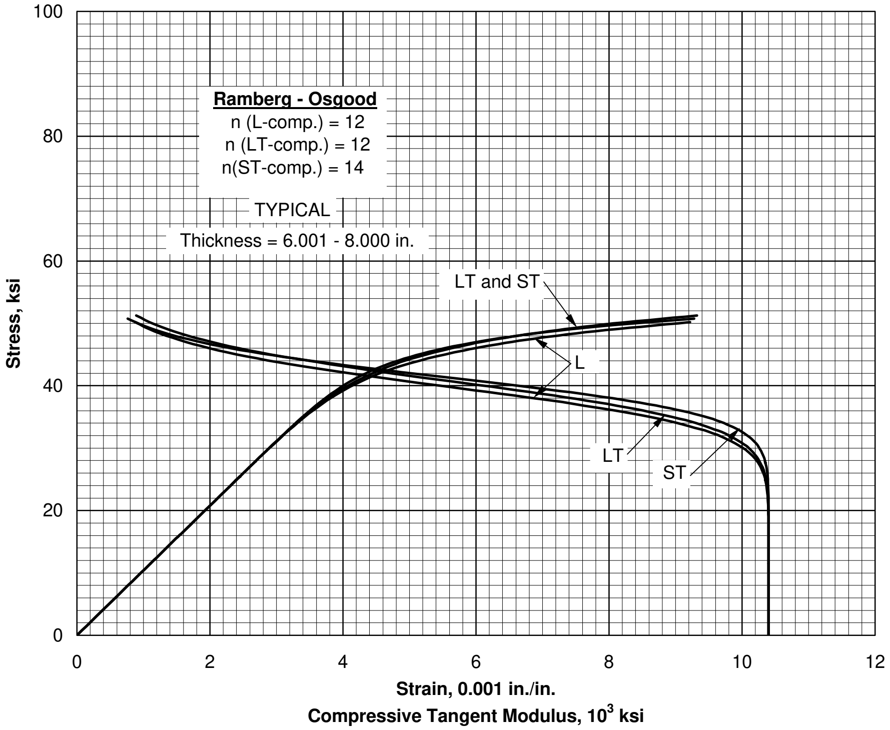


Figure 3.2.8.3.6(d). Typical compressive stress-strain and compressive tangent-modulus curves for 2219-T852 aluminum alloy hand forging at room temperature.

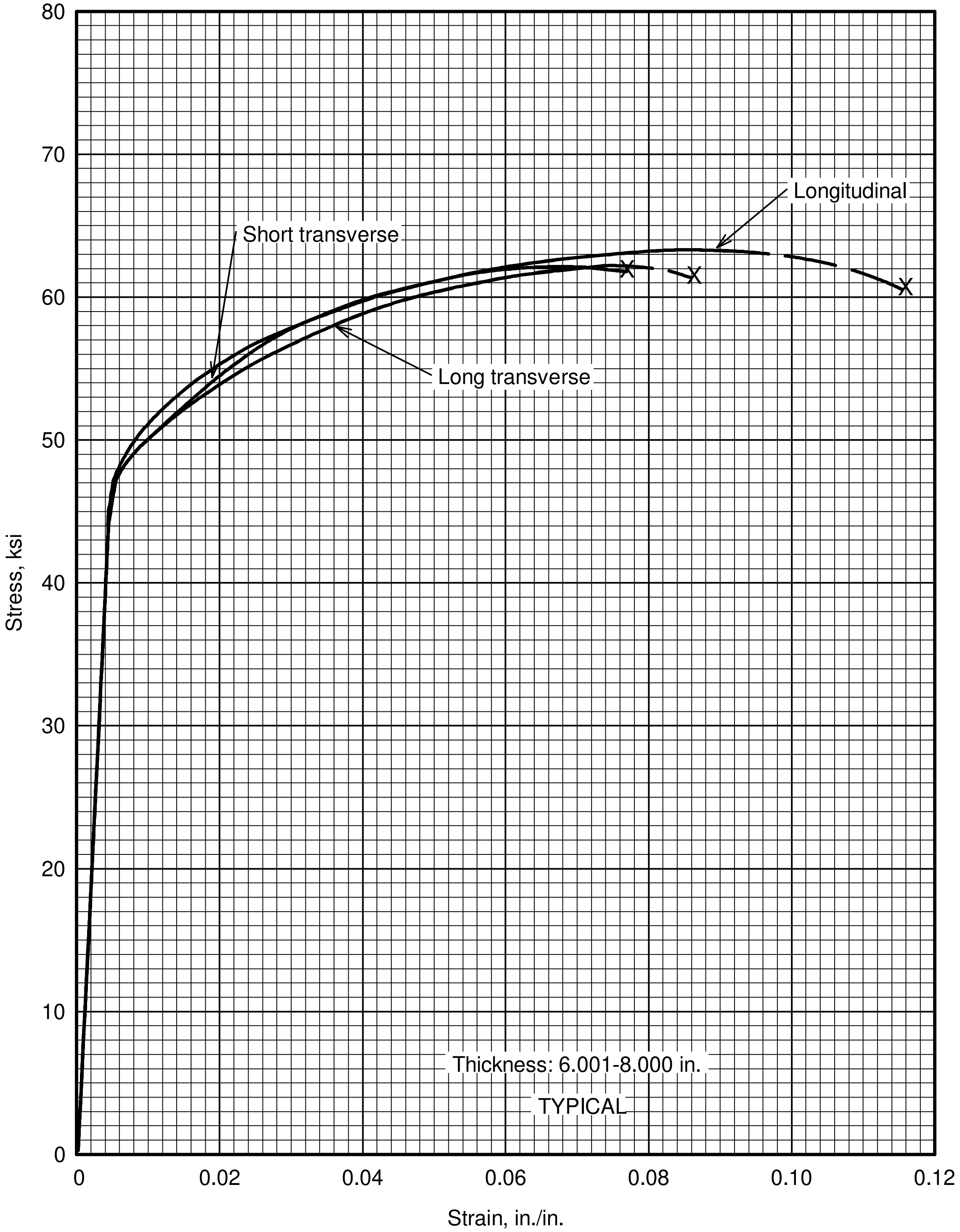


Figure 3.2.8.3.6(e). Typical tensile stress-strain curves (full range) for 2219-T852 aluminum alloy hand forging at room temperature.

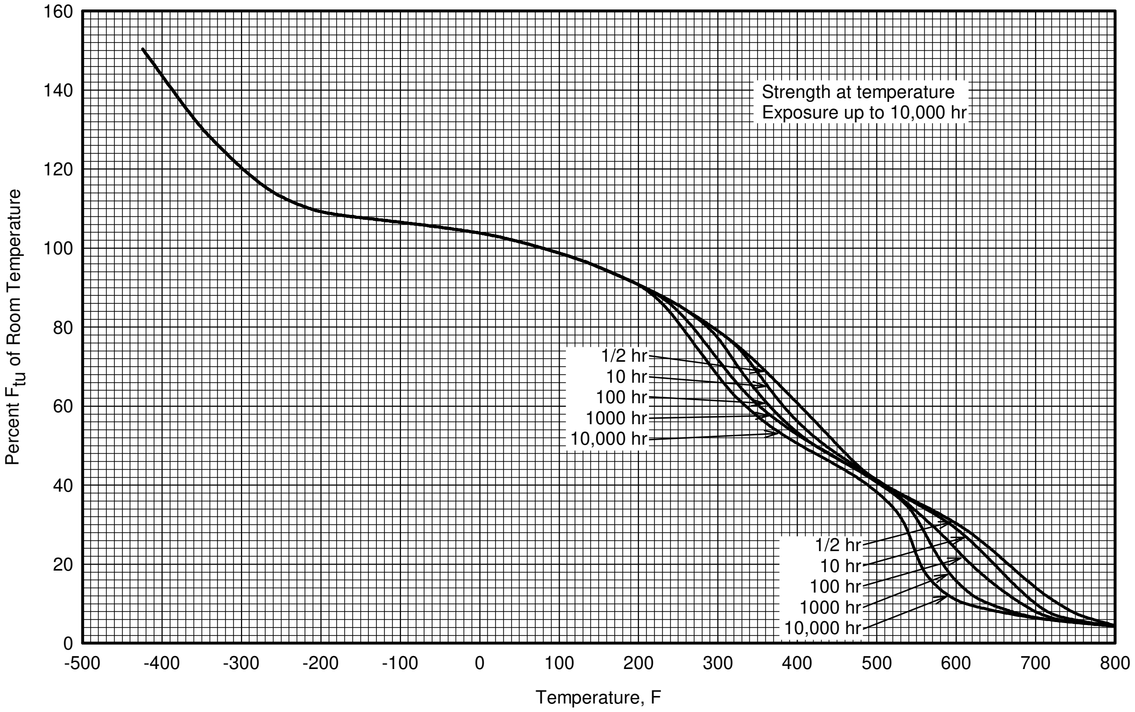


Figure 3.2.8.4.1(a). Effect of temperature on the tensile ultimate strength (F_{tu}) of 2219-T87 aluminum alloy sheet and plate.

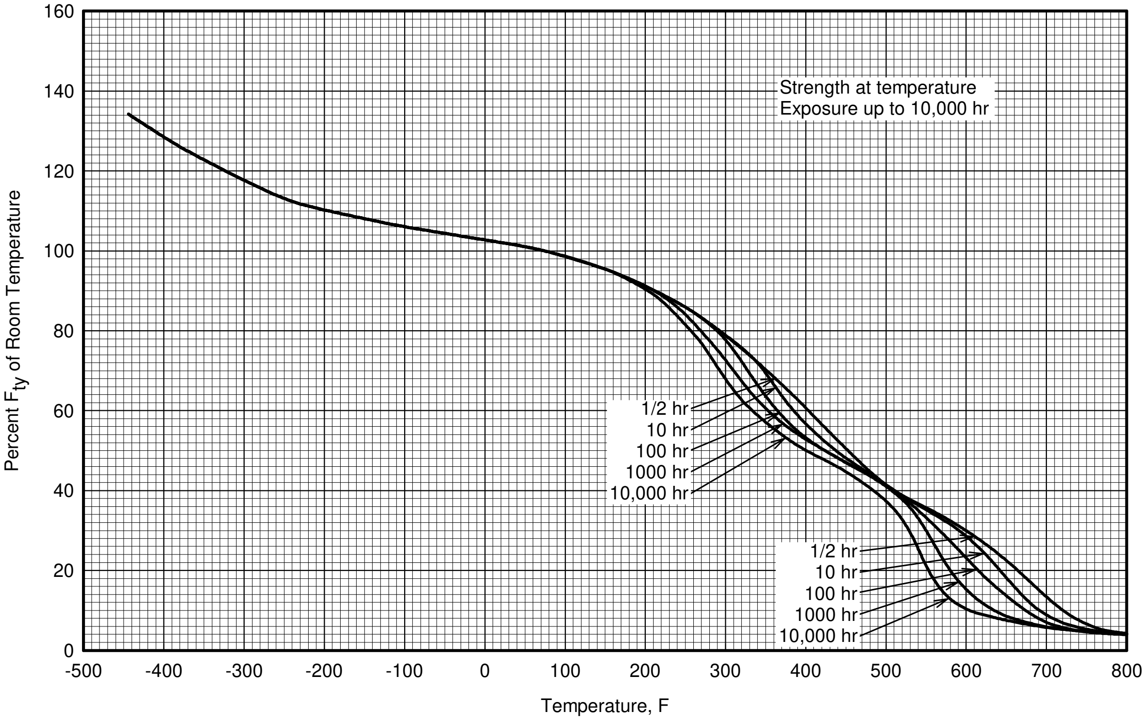


Figure 3.2.8.4.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of 2219-T87 aluminum alloy sheet and plate.

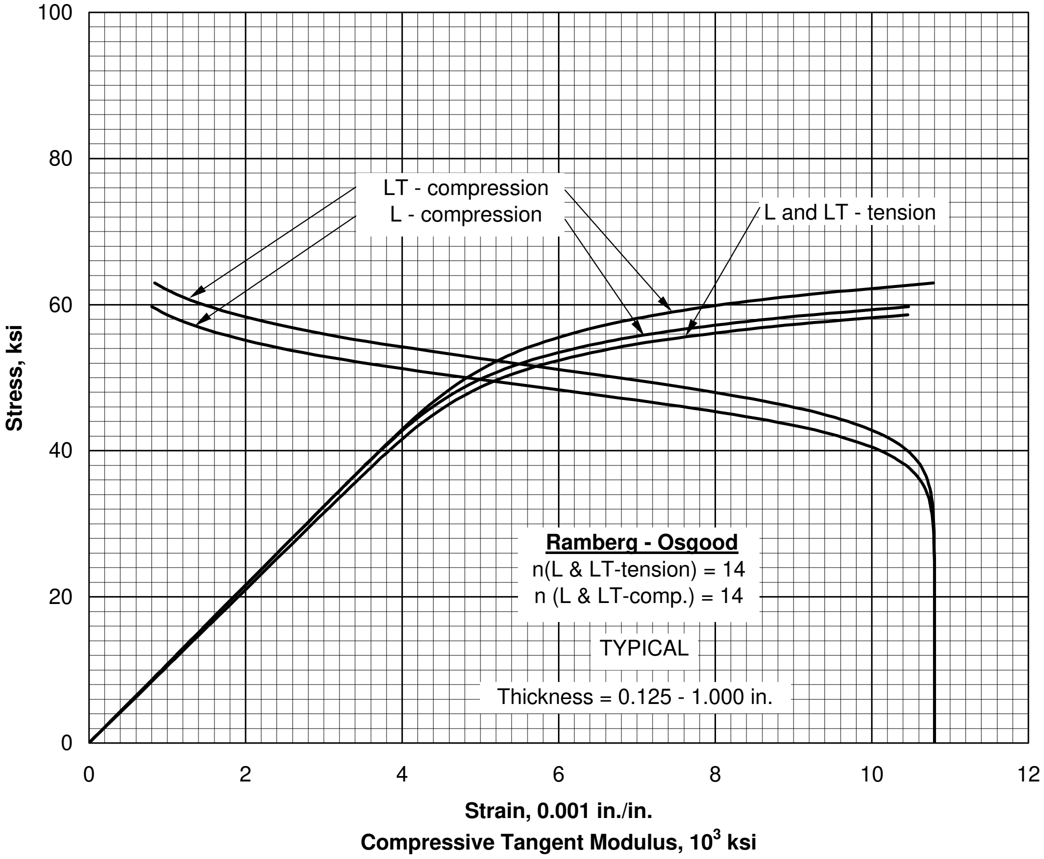


Figure 3.2.8.4.6(a). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 2219-T87 aluminum alloy sheet and plate at room temperature.

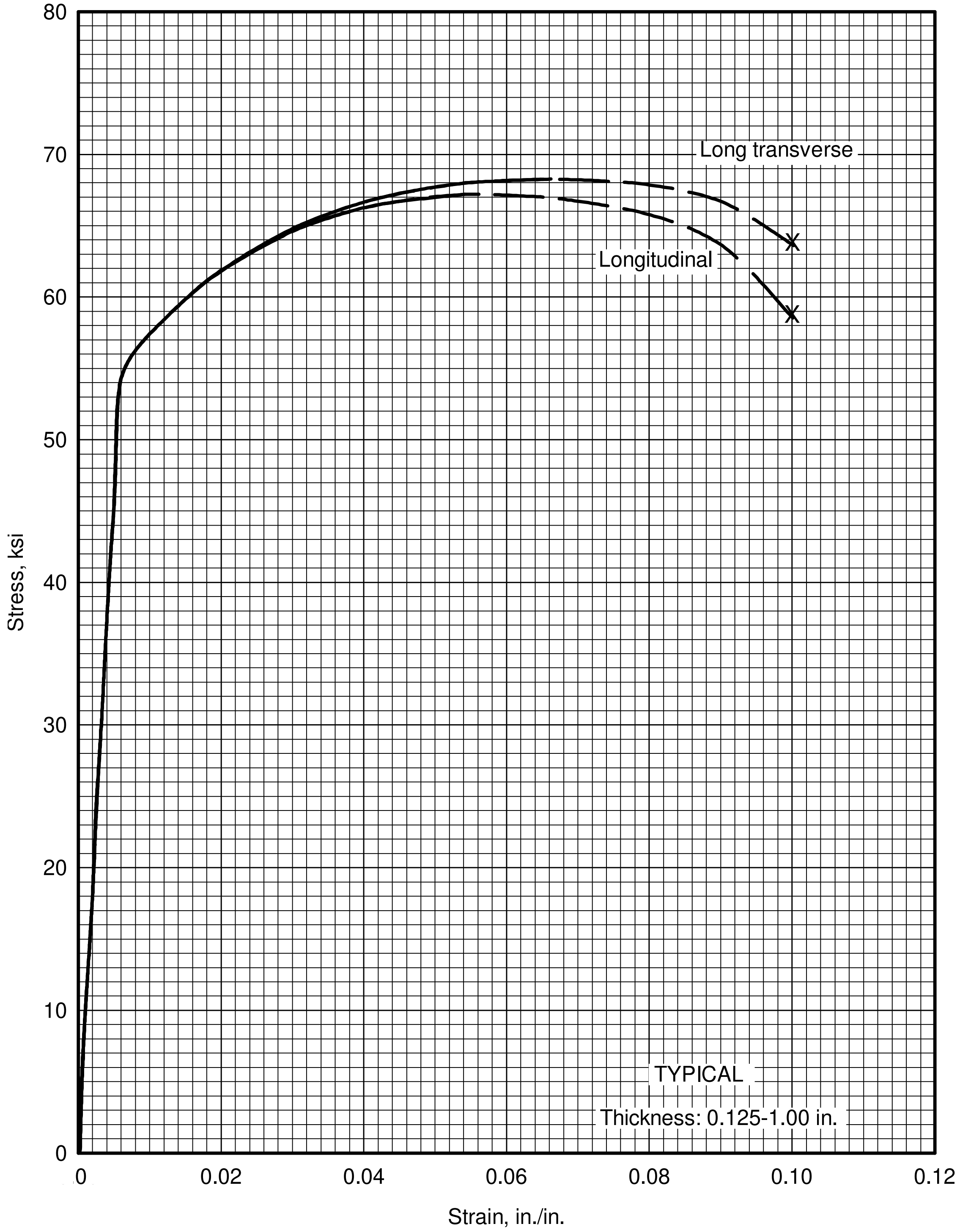


Figure 3.2.8.4.6(b). Typical tensile stress-strain curves (full range) for 2219-T87 aluminum alloy sheet and plate at room temperature.

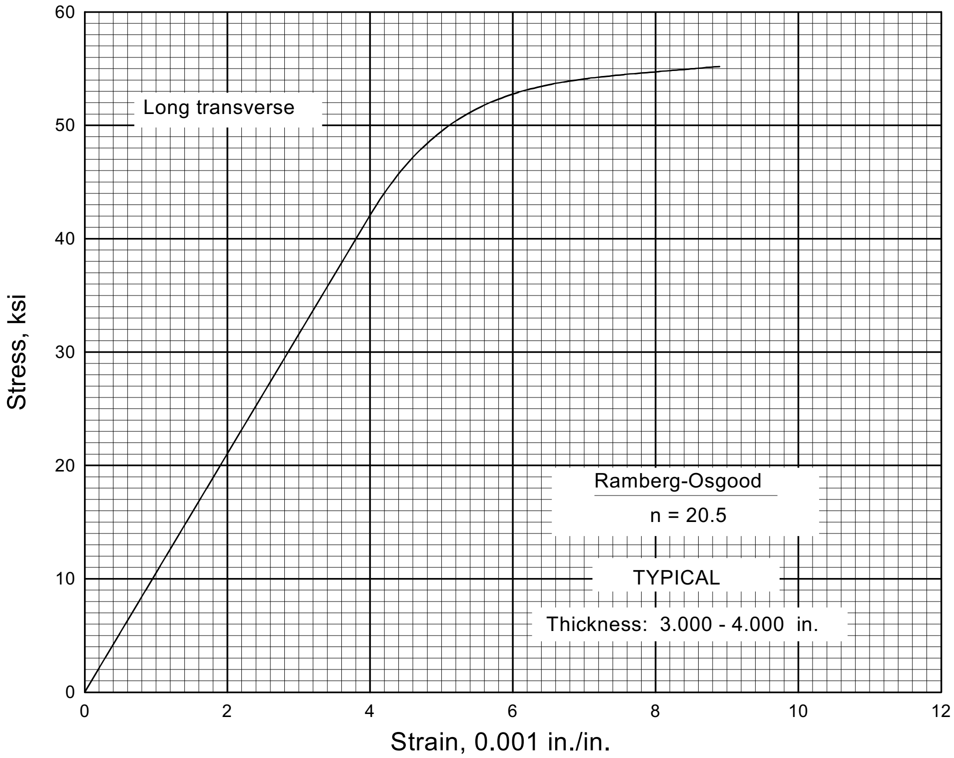


Figure 3.2.8.4.6(c). Typical tensile stress-strain curve for 2219-T87 aluminum alloy plate at room temperature.

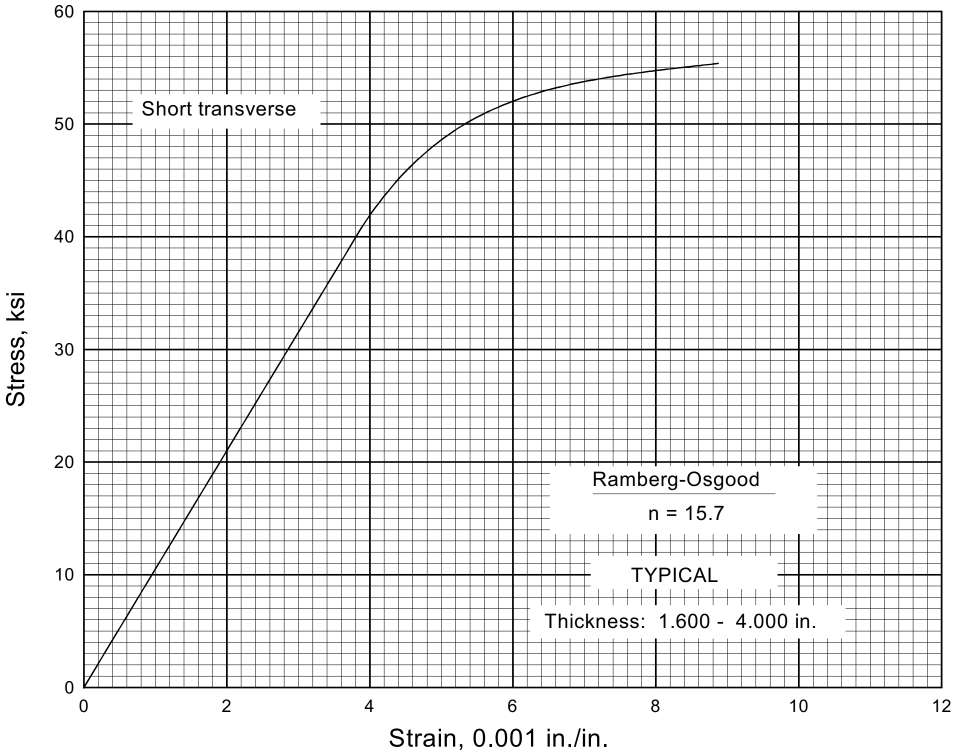


Figure 3.2.8.4.6(d). Typical tensile stress-strain curve for 2219-T87 aluminum alloy plate at room temperature.

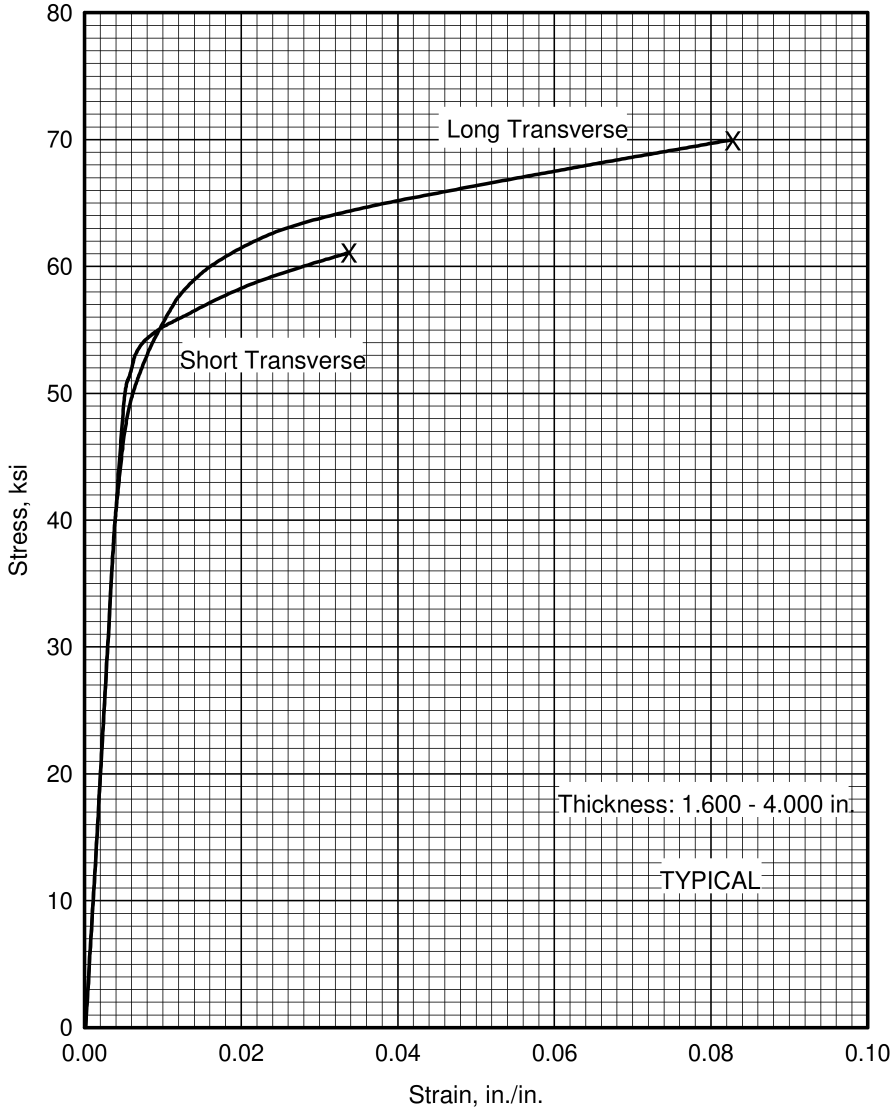


Figure 3.2.8.4.6(e). Typical tensile stress-strain curve (full range) for 2219-T87 aluminum alloy plate at room temperature.

3.2.9 2297 ALLOY

3.2.9.0 COMMENTS AND PROPERTIES — 2297 is an Al-Cu-Li-Mn-Zr plate alloy with moderately high strength and both high fatigue resistance and fracture toughness for durability and damage tolerant applications. The alloy shows excellent short-transverse mechanical properties and stress-corrosion cracking resistance in plate thicknesses to 6-inches. Tensile properties show good isotropy with only slightly lower strength in the in-plane 45° orientation, similar to the differences in in-plane properties usually found in Li-free high strength aluminum alloys.

The –T87 condition is obtained after solution heat treating, quenching, stress-relief by stretching, and artificial aging to peak strength. Little, or no, reduction in fracture toughness is found after elevated temperature exposure.

This alloy is not designed to be welded. Use of mechanical fasteners only is recommended.

This alloy has shown a sensitivity to cold-hole expansion for improved fatigue resistance when fastener holes, whose axes were perpendicular to the short transverse direction, were processed. Care should be taken to ensure that all of the processing parameters have been evaluated prior to the application of cold expansion to prevent cracking in the material.

Material specifications for 2297 are shown in Table 3.2.9.0(a). Room temperature mechanical and physical properties are shown in Table 3.2.9.0(b). Fracture toughness properties are shown in Table 3.1.2.1.6. Cyclic stress-strain and strain-life curves are shown in Figure 3.2.9.0.6. Fatigue crack propagation is shown in Figure 3.2.9.0.9.

Table 3.2.9.0(a). Material Specifications for 2297-T87 Aluminum Alloy

Specification	Form
AMS 4330	Plate

Table 3.2.9.0(b). Design Mechanical and Physical Properties of 2297-T87 Aluminum Alloy Plate

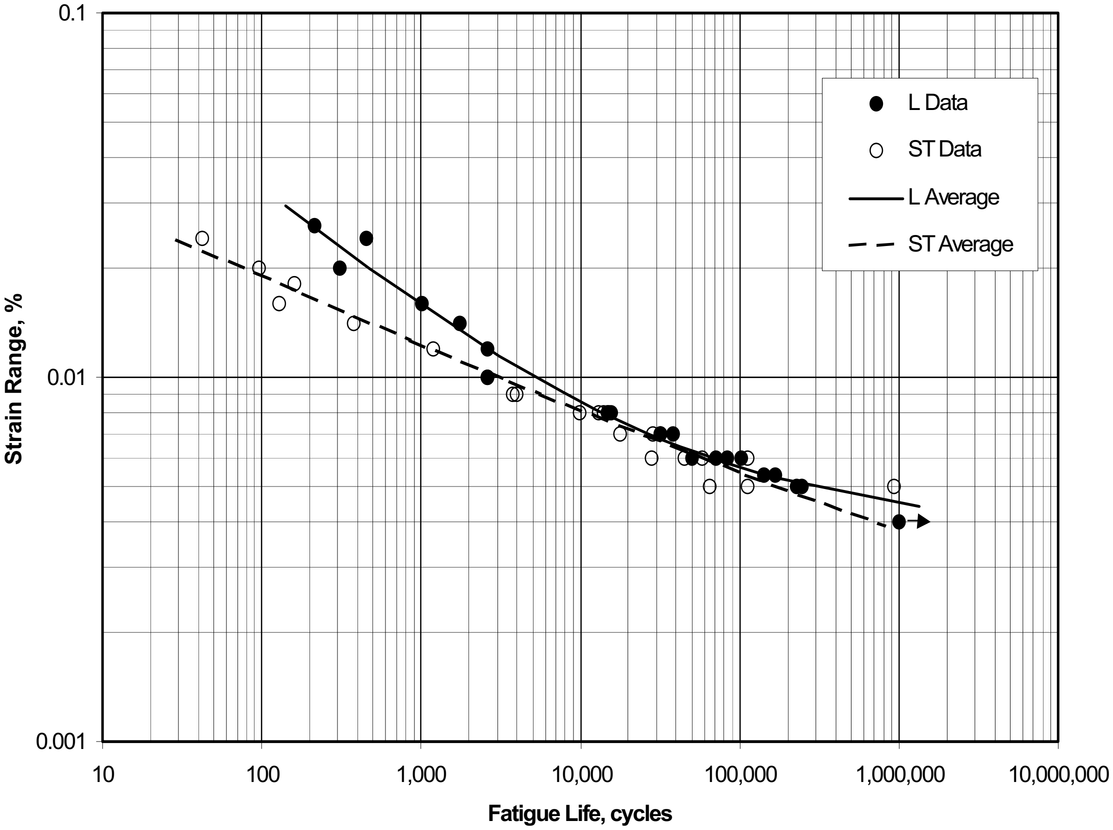
Specification	AMS 4330				
Form	Plate				
Temper	T87				
Thickness, in.	3.001-4.000	4.001-5.000		5.001-6.000	
Basis	S	A	B	A	B
Mechanical Properties:					
F_{tu}, ksi:					
L	62	61	62	60[a]	62
LT	62	61[b]	64	60[a]	64
ST	59	58[b]	61	57[a]	61
45°	60	59	63	59	63
F_{ty}, ksi:					
L	57	56[b]	58	55[a]	58
LT	57	56	57	55[a]	57
ST	54	52	54	52	54
45°	54	54	55	53	56
F_{cy}, ksi:					
L	...	...	...	...	...
LT	...	...	...	...	...
ST	...	...	...	...	...
F_{su}, ksi					
S-L[c]	30	31	33	32	34
T-S[c]	38	37	39	36	39
F_{bru}[d], ksi:					
(e/D = 1.5)	98	97	102	95	102
(e/D = 2.0)	128	126	132	123	132
F_{bry}[d], ksi:					
(e/D = 1.5)	85	84	85	82	85
(e/D = 2.0)	99	98	99	96	99
e, percent (S-basis):					
L	5	5	...	5	...
LT	4	4	...	4	...
ST	1.5	1.5	...	1.5	...
E, 10^3 ksi	11.3				
E_c, 10^3 ksi	...				
G, 10^3 ksi	...				
μ	...				
Physical Properties:					
ω, lb/in.^{3}	0.096				
C, Btu/(lb)(°F)	...				
K, Btu/[(hr)(ft^2)(°F)/ft]	...				
α, 10^{-6} in./in./°F	...				

a S-basis. The rounded T_{99} values are as follows; F_{tu}(L) = 61, F_{tu}(LT) = 62, F_{tu}(ST) = 59, F_{ty}(L) = 57, F_{ty}(LT) = 56.

b S-basis. The rounded T_{99} values are as follows; F_{tu}(LT) = 62 ksi, F_{tu}(ST) = 59 ksi, F_{ty}(L) = 57 ksi.

c Standard letter designations for shear properties per ASTM B769: 1st letter refers to grain direction, 2nd letter refers to loading direction.

d Bearing values are "dry pin" values per Section 1.4.7.1.



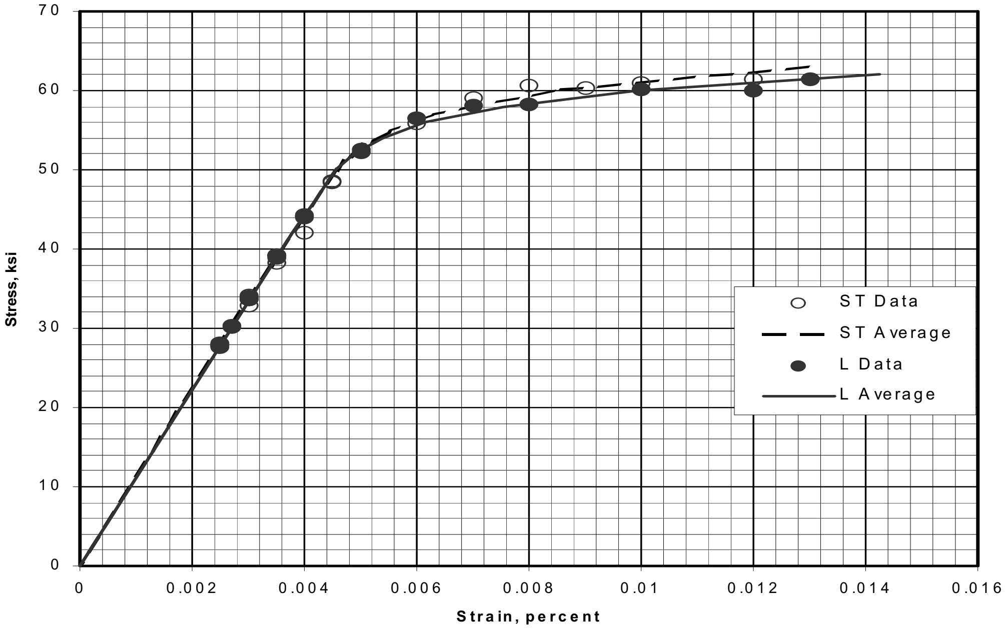


Figure 3.2.9.0.6. Strain-life and cyclic stress-strain curves for 2297-T87, 4 inch plate.

Correlative Information for Figure 3.2.9.0.6

Product Form: Plate, 4.00 inch thick

Properties:	TUS, ksi	TYS, ksi	Temp., °F
ST	63.5	56.0	RT
L	64.6	59.8	RT

Specimen Details:
Uniform gage test section
0.250-inch diameter

Surface Condition: Machined and polished along the length of the specimen using a commercial metal polishing paste called POL Metal Polish. The specimens had a mirror-like finish, estimated as an RMS of 4.

Reference: 3.2.9.0

Test Parameters:
Frequency - 0.5 - 5 Hz. (Higher frequencies typically used for the longer tests at the lower strains.)
Temperature - RT
Environment - Lab Air (approx. 50% relative humidity)

No. of Heats/Lots: 1

Strain Ratio = -1

Stress-Strain Equations:

ST Direction

$(\Delta\varepsilon)/2 = \sigma/E + \varepsilon_p$ where
$E = 11.3 \times 10^3$ ksi (reported),
$\varepsilon_p = 6.243 \times 10^{-10}\sigma^{3.187}$ for $\sigma < 50.86$ ksi, and
$\varepsilon_p = 1.606 \times 10^{-34}\,\sigma^{17.598}$ for $\sigma > 50.86$ ksi.

L Direction

$(\Delta\varepsilon)/2 = \sigma/E + \varepsilon_p$ where
$E = 11.3 \times 10^3$ ksi (reported),
$\varepsilon_p = 1.219 \times 10^{-10}\sigma^{3.566}$ for $\sigma < 50.03$ ksi, and
$\varepsilon_p = 1.074 \times 10^{-37}\,\sigma^{19.478}$ for $\sigma > 50.03$ ksi.

Equivalent Strain Equations:

ST Direction

$\text{Log } N_f = -6.66 - 4.96 \log(\varepsilon_t - 0.001)$
Standard Error of Estimate = 0.249
Standard Deviation in Life = 0.864
$R^2 = 96$ %
Sample Size = 21

L Direction

$\text{Log } N_f = -1.88 - 2.54 \log(\varepsilon_t - 0.0037)$
Standard Error of Estimate = 0.141
Standard Deviation in Life = 0.722
$R^2 = 98$ %
Sample Size = 21

3.2.10 2424 ALLOY

3.2.10.0 ***Comments and Properties*** — 2424 is a heat-treatable Al-Cu alloy which provides better ductility than 2024. 2424 is available in the form of bare and clad sheet.

Material specifications for 2424 are presented in Table 3.2.10.0(a). Room-temperature mechanical properties are presented in Tables 3.2.10.0(b_1) and 3.2.10.0(b_2).

Table 3.2.10.0(a). Material Specifications for 2424 Aluminum Alloy

Specification	Form
AMS 4270 (Clad)	Sheet
AMS 4273 (Bare)	Sheet

The temper index for 2424 is as follows:

Section	Temper
3.2.10.1	T3

Table 3.2.10.0(b_1). Design Mechanical and Physical Properties of Bare 2424-T3 Aluminum Alloy Sheet

Specification	AMS 4273	
Form	Sheet	
Temper	T3	
Thickness, in.	0.020 - 0.128	
Basis	A	B
Mechanical Properties:		
F_{tu}, ksi:		
L	65	66
LT	63	65
F_{ty}, ksi:		
L	49	51
LT	42[a]	45
F_{cy}, ksi:		
L	42	45
LT	46	49
F_{su},[b] ksi	41	43
F_{bru},[c] ksi:		
(e/D = 1.5)	97	100
(e/D = 2.0)	129	133
F_{bry},[c] ksi:		
(e/D = 1.5)	62	66
(e/D = 2.0)	78	83
e, percent (S-basis):		
L	...	...
LT	15	...
E, 10^3 ksi		
L	9.8	
LT	10.3	
E_c, 10^3 ksi		
L	10.0	
LT	10.5	
G, 10^3 ksi	...	
μ	0.34	
Physical Properties:		
ω, lb/in.^{3}	0.100	
C, Btu/(lb)(°F)	...	
K, Btu/[(hr)(ft^2)(°F)/ft]	...	
α, 10^{-6} in./in./°F	...	

[a] S-basis. The T_{99} value is 44 ksi.

[b] Determined in accordance with ASTM B769.

[c] Bearing values are "dry pin" values per Section 1.4.7.1.

Table 3.2.10.0(b_2). Design Mechanical and Physical Properties of Clad 2424-T3 Aluminum Alloy Sheet

Specification	AMS 4270	
Form	Sheet	
Temper	T3	
Thickness, in.	0.063 - 0.128	
Basis	A	B
Mechanical Properties:		
F_{tu}, ksi:		
L	64	65
LT	61	64
F_{ty}, ksi:		
L	46	49
LT	40[a]	44
F_{cy}, ksi:		
L	40	44
LT	43	47
F_{su},[b] ksi	41	43
F_{bru},[c] ksi:		
(e/D = 1.5)	94	98
(e/D = 2.0)	121	126
F_{bry},[c] ksi:		
(e/D = 1.5)	60	66
(e/D = 2.0)	70	77
e, percent (S-basis):		
L	...	...
LT	15	...
E, 10^3 ksi		
L	9.8	
LT	10.3	
E_c, 10^3 ksi		
L	10	
LT	10.5	
G, 10^3 ksi	...	
μ	0.34	
Physical Properties:		
ω, lb/in.^{3}	0.100	
C, Btu/(lb)(°F)	...	
K, Btu/[(hr)(ft^2)(°F)/ft]	...	
α, 10^{-6} in./in./°F	...	

[a] S-basis. The T_{99} value is 43 ksi.
[b] Determined in accordance with ASTM B769.
[c] Bearing values are “dry pin” values per Section 1.4.7.1.

3.2.11 2519 ALLOY

3.2.11.0 *Comments and Properties* — 2519 is an Al-Cu weldable alloy available in plate. This armor plate has equivalent ballistic protection characteristics compared to 7039 and superior stress-corrosion cracking resistance compared to 5083. See Section 3.1.2.3 for comments regarding resistance of the alloy to stress-corrosion cracking. The general corrosion characteristics of 2519 are similar to 2219. 2519 in the T87 temper has approximately 20 percent higher yield strength than 2219-T87 plate. 2519-T87 is easily welded with filler alloy 2319. Yield strengths of welded butt joints are higher than other commercially available alloys. 2519 can be post weld aged or post weld heat treated and aged to obtain improved mechanical properties compared to "as welded" condition. See Section 3.1.3.4 for further information regarding the weldability of the alloy.

A material specification of 2519 is presented in Table 3.2.11.0(a). Room-temperature mechanical and physical properties are shown in Table 3.2.11.0(b).

Table 3.2.11.0(a). Material Specification for 2519 Aluminum Alloy

Specification	Form
MIL-DTL-46192	Plate

The temper index for 2519 is as follows:

Section	Temper
3.2.11.1	T87

3.2.11.1 *T87 Temper* — Typical room-temperature tensile and compressive stress-strain and compressive tangent-modulus curves are presented in Figures 3.2.11.1.6(a) and (b).

Table 3.2.11.0(b). Design Mechanical and Physical Properties of 2519 Aluminum Alloy Plate

Specification	MIL-DTL-46192			
Form	Plate			
Temper	T87			
Thickness or Diameter, in	0.250-1.000	1.001-2.000	2.001-3.000	3.001-4.000
Basis	S	S	S	S
Mechanical Properties:				
F_{tu}, ksi:				
L	66	66	67	68
LT	68	68	68	68
ST	...	...	63	62
F_{ty}, ksi:				
L	59	59	60	61
LT	58	58	59	59
ST	...	...	55	55
F_{cy}, ksi:				
L	57	57	58	58
LT	60	60	61	61
ST	...	...	58	58
F_{su}, ksi	42	41	41	40
F_{bru}[a], ksi:				
(e/D = 1.5)	105	105	104	103
(e/D = 2.0)	135	134	133	131
F_{bry}[a], ksi:				
(e/D = 1.5)	85	85	87	87
(e/D = 2.0)	99	99	100	100
e, percent:				
L	10	9	8	7
LT	7	7	6	5
E, 10^3 ksi	10.5			
E_c, 10^3 ksi	10.8			
G, 10^3 ksi	4.0			
μ	0.33			
Physical Properties:				
ω, lb/in.^{3}	0.102			
C, K, and α	...			

[a] See Table 3.1.2.1.1. Bearing values are "dry pin" per Section 1.4.7.1.

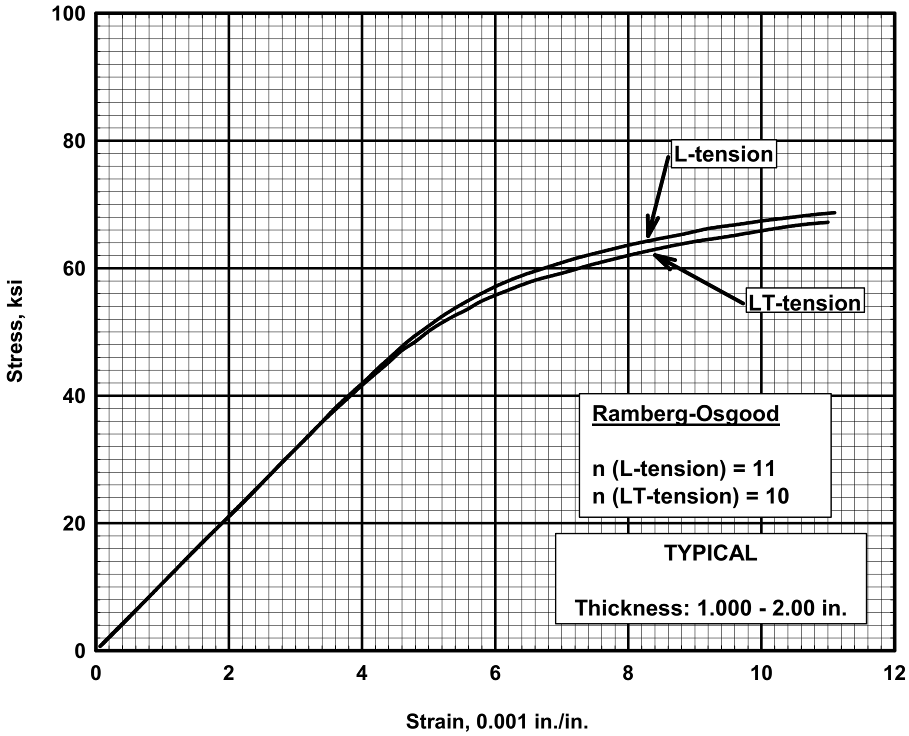


Figure 3.2.11.1.6(a). Typical tensile stress-strain curves for 2519-T87 aluminum alloy plate at room temperature.

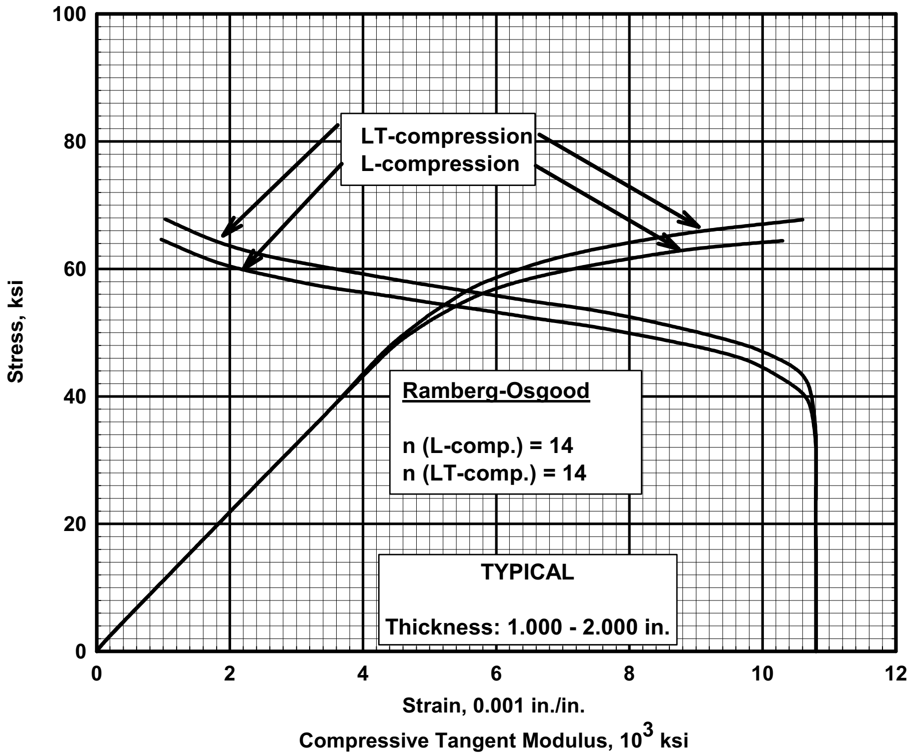


Figure 3.2.11.1.6(b). Typical compressive stress-strain and tangent-modulus curves for 2519-T87 plate at room temperature.

3.2.12 2524 ALLOY

3.2.12.0 *Comments and Properties* — 2524 is a heat-treatable Al-Cu alloy offering high toughness and improved resistance to fatigue crack growth relative to other available 2XXX sheet and plate materials. Sheet and plate is available in the T3 temper. Fatigue crack growth improvements are guaranteed through the material specification for Alclad 2524-T3 sheet and plate products. The static mechanical properties and general corrosion performance of Alclad 2524-T3 are similar to those of Alclad 2024-T3. This product has typically been used for formed structural aircraft parts requiring improved resistance to fatigue crack growth and high toughness with strength similar to Alclad 2024-T3, but usage is not limited to such applications.

A material specification for Alclad 2524-T3 sheet and plate is presented in Table 3.2.12.0(a). Room-temperature mechanical properties are shown in Table 3.2.12.0(b).

Table 3.2.12.0(a). Material Specifications for Alclad 2524-T3

Specification	Form
AMS 4296	Clad sheet and plate

The temper index for 2524 is as follows:

Section	Temper
3.2.12.1	T3

Table 3.2.12.0(b). Design Mechanical and Physical Properties of Alclad 2524-T3 Aluminum Alloy Sheet and Plate

Specification	AMS 4296						
Form	Sheet and Plate						
Condition	T3						
Thickness, in.	0.032-	0.063-0.128		0.129-0.249		0.250-0.310	
Basis	S	A	B	A	B	A	B
Mechanical Properties:							
F_{tu}, ksi:							
L	59	61	62	62	62	62	63
LT	59	61[a]	62	62	62	62	63
F_{ty}, ksi:							
L	44	45	47	45	46	45	46
LT	39	40[b]	42	40	41	40	41
F_{cy}, ksi:							
L	38	39	41	39	40	39	40
LT	42	43	45	43	44	43	44
F_{su},[c] ksi:	40	41	42	42	42	42	43
F_{bru},[d] ksi:							
(e/D = 1.5)	93	97	98	98	98	98	100
(e/D = 2.0)	117	121	123	123	123	123	125
F_{bry},[d] ksi:							
(e/D = 1.5)	65	67	70	67	69	67	69
(e/D = 2.0)	76	78	82	78	80	78	80
e, percent (S-basis):							
LT	15	15	...	15	...	15	...
E, 10^3 ksi:							
Primary	10.3						
Secondary	9.8						
E_c, 10^3 ksi:							
Primary	10.5						
Secondary	10.0						
G, 10^3 ksi	...						
μ	0.35						
Physical Properties:							
ω, lb/in.^{3}	0.100						
C, K, and α	not available						

a S-basis value. The T_{99} value is 62 ksi.
b S-basis value. The T_{99} value is 41 ksi.
c Determined in accordance with ASTM B 831-93.
d Bearing values are "dry pin" values per Section 1.4.7.1. See Table 3.1.2.1.1.

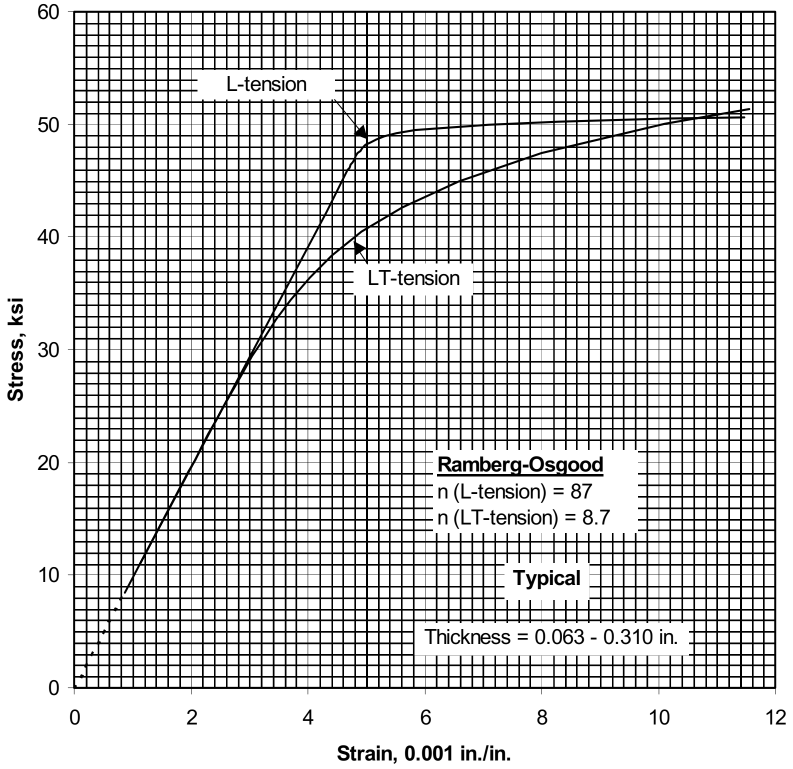


Figure 3.2.12.1.6(a). Typical tensile stress-strain curves for 2524-T3 clad aluminum alloy sheet and plate at room temperature.

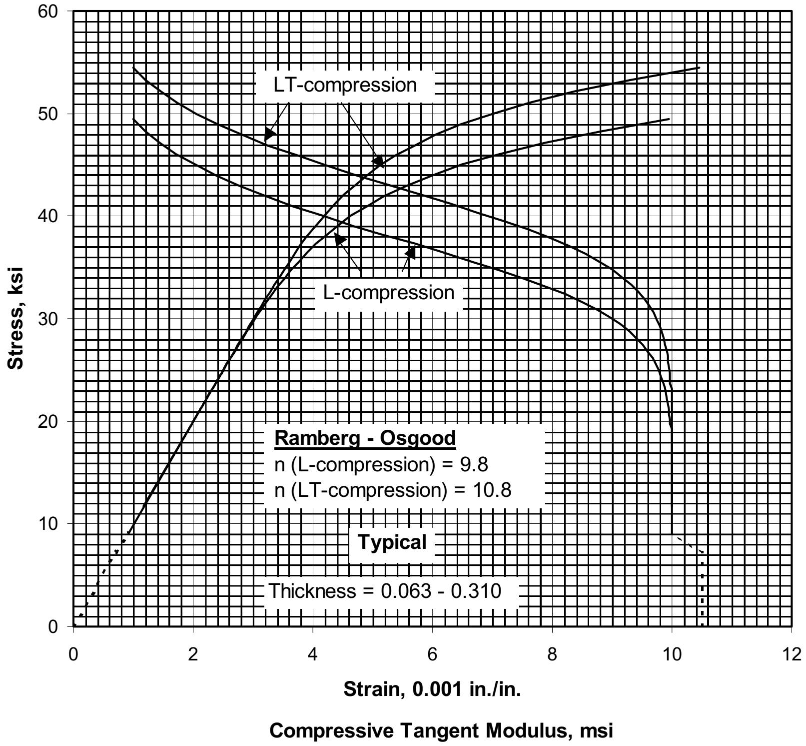


Figure 3.2.12.1.6(b). Typical compressive stress-strain and tangent modulus curves for 2524-T3 clad aluminum alloy sheet and plate at room temperature.

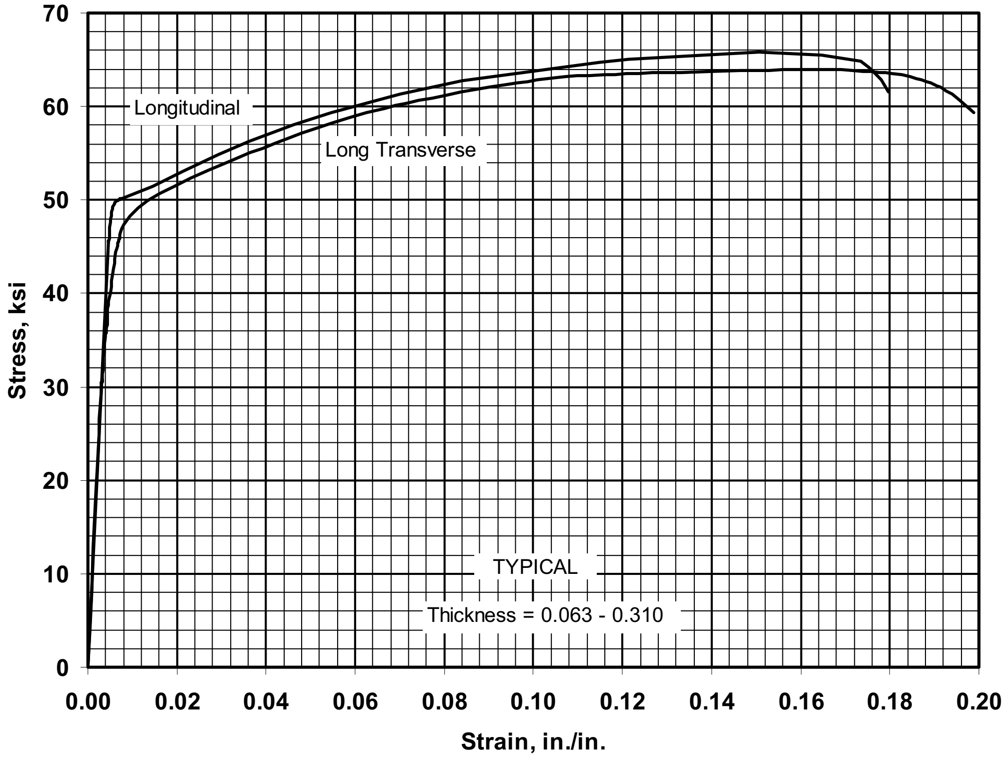


Figure 3.2.12.1.6(c). Typical tensile stress-strain curves (full range) for 2524-T3 clad aluminum alloy sheet and plate at room temperature.

3.2.13 2618 ALLOY

3.2.13.0 ***Comments and Properties*** — 2618 is an Al-Cu alloy which is available as hand and die forgings. It has excellent properties over a range of temperatures from -452 to 600°F and is usually used in applications where high strength and creep resistance are important considerations. Refer to Section 3.1.3.4 for comments regarding the weldability of the alloy. Refer to Section 3.1.2.3.1 for information regarding resistance of the alloy to stress-corrosion cracking.

Material specifications for 2618 aluminum alloy are presented in Table 3.2.13.0(a). Room-temperature mechanical and physical properties are shown in Table 3.2.13.0(b) and (c). The effect of temperature on the thermal expansion is shown in Figure 3.2.13.0.

Table 3.2.13.0(a). Material Specifications for 2618 Aluminum Alloy

Specification	Form
AMS 4132	Die and hand forgings
AMS-QQ-A-367	Forgings
AMS-A-22771	Die forging

The temper index for 2618 is as follows:

Section	Temper
3.2.13.1	T61

3.2.13.1 ***T61 Temper*** — Figures 3.2.13.1.1(a) through 3.2.13.1.5 present effect-of-temperature curves for various mechanical properties. Figure 3.2.13.1.6(a) presents tensile and compressive stress-strain and tangent-modulus curves at room temperature. Figure 3.2.13.1.6(b) is a full-range, tensile stress-strain curve at room temperature.

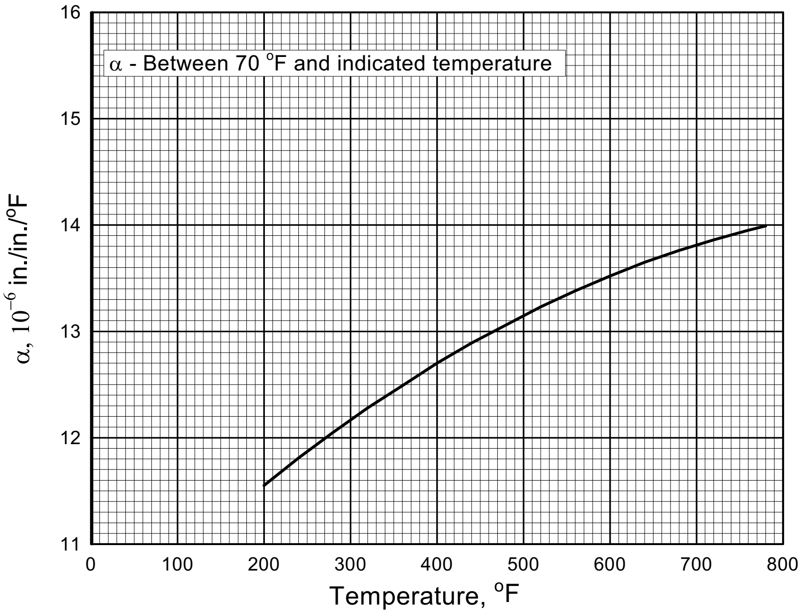


Figure 3.2.13.0. Effect of temperature on the thermal expansion of 2618 aluminum alloy.

Table 3.2.13.0(b). Design Mechanical and Physical Properties of 2618 Aluminum Alloy Die Forging

Specification	AMS-A-22771 and AMS-QQ-A-367
Form	Die forging
Temper	T61
Thickness, in.	≤ 4.000[a]
Basis	S
Mechanical Properties:	
F_{tu}, ksi:	
L	58
T[b]	55
F_{ty}, ksi:	
L	45
T[b]	42
F_{cy}, ksi:	
L	...
T[b]	...
F_{su},	...
F_{bru}, ksi:	
(e/D = 1.5)	...
(e/D = 2.0)	...
F_{bry}, ksi:	
(e/D = 1.5)	...
(e/D = 2.0)	...
e, percent:	
L	4
T[b]	4
E, 10^3 ksi	10.7
E_c, 10^3 ksi	10.9
G, 10^3 ksi	4.1
μ	0.33
Physical Properties:	
ω, lb/in.^{3}	0.100
C, Btu/(lb)(°F)	0.23 (at 212°F)
K, Btu/[(hr)(ft^2)(°F)/ft]	90 (at 77°F)
α, 10^{-6} in./in./°F	See Figure 3.2.13.0

a Thickness at the time of heat treatment. When die forgings are machined before heat treatment, the mechanical properties are applicable provided the as-forged thickness is not greater than twice the thickness at the time of heat treatment.

b T indicates any grain direction not within ±15° of being parallel to the forging flow lines.

Table 3.2.13.0(c). Design Mechanical and Physical Properties of 2618 Aluminum Alloy Hand Forging

Specification	AMS 4132, AMS-A-22771, and AMS-QQ-A-367		
Form	Hand forging		
Temper	T61		
Cross-Sectional Area, in.^{2}	$\leq$ 144		
Thickness,[a] in	< 2.000	2.000-3.000	3.001-4.000
Basis	S	S	S
Mechanical Properties:			
F_{tu}, ksi:			
L	58	57	56
LT	55	55	53
ST	...	52	51
F_{ty}, ksi:			
L	47	46	45
LT	42	42	40
ST	...	42	39
F_{cy}, ksi:			
L	...	...	44
LT	...	...	42
ST	...	...	40
F_{su}, ksi	...	...	33
F_{bru}, ksi:			
(e/D =1.5)	...	...	...
(e/D =2.0)	...	...	106
F_{bry}, ksi:			
(e/D = 1.5)	...	...	...
(e/D = 2.0)	...	...	71
e, percent:			
L	7	7	7
LT	5	5	5
ST	...	4	4
E, 10^3 ksi	10.7		
E_c, 10^3 ksi	10.9		
G, 10^3 ksi	4.1		
μ	0.33		
Physical Properties:			
ω, lb/in.^{3}	0.100		
C, Btu/(lb)(°F)	0.23 (at 212°F)		
K, Btu/[(hr)(ft^2)(°F)/ft]	90 (at 77°F)		
α, 10^{-6} in./in./°F	See Figure 3.2.13.0		

a When hand forgings are machined before heat treatment, the section thickness at time of heat treatment will determine the minimum mechanical properties as long as the original (as-forged) thickness does not exceed the maximum thickness for the alloy as shown in the table.

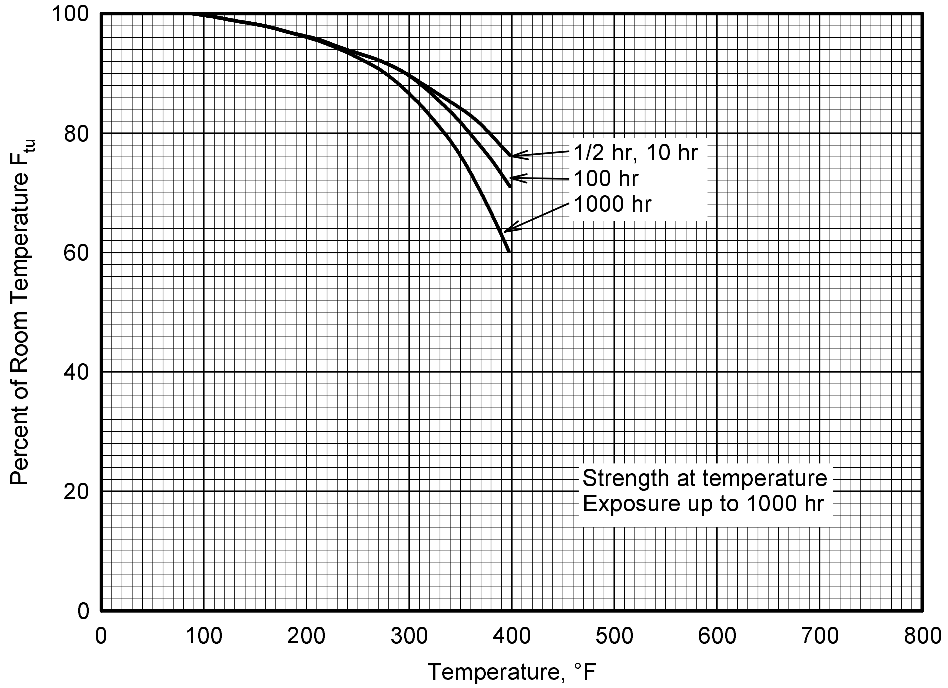


Figure 3.2.13.1.1(a). Effect of temperature on the tensile ultimate strength (F_{tu}) of 2618-T61 aluminum alloy hand forging.

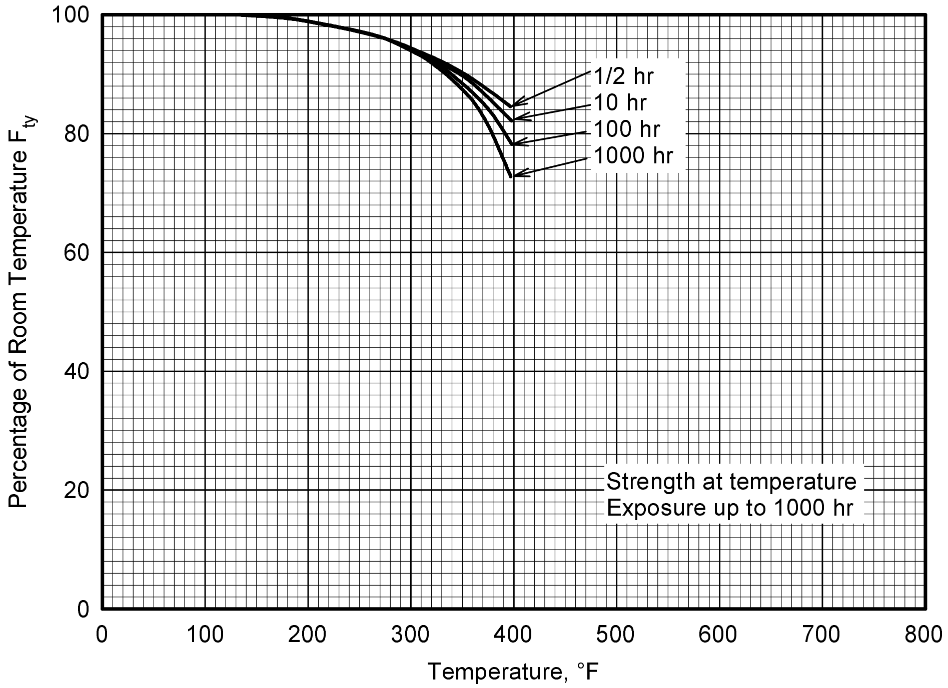


Figure 3.2.13.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of 2618-T61 aluminum alloy hand forging.

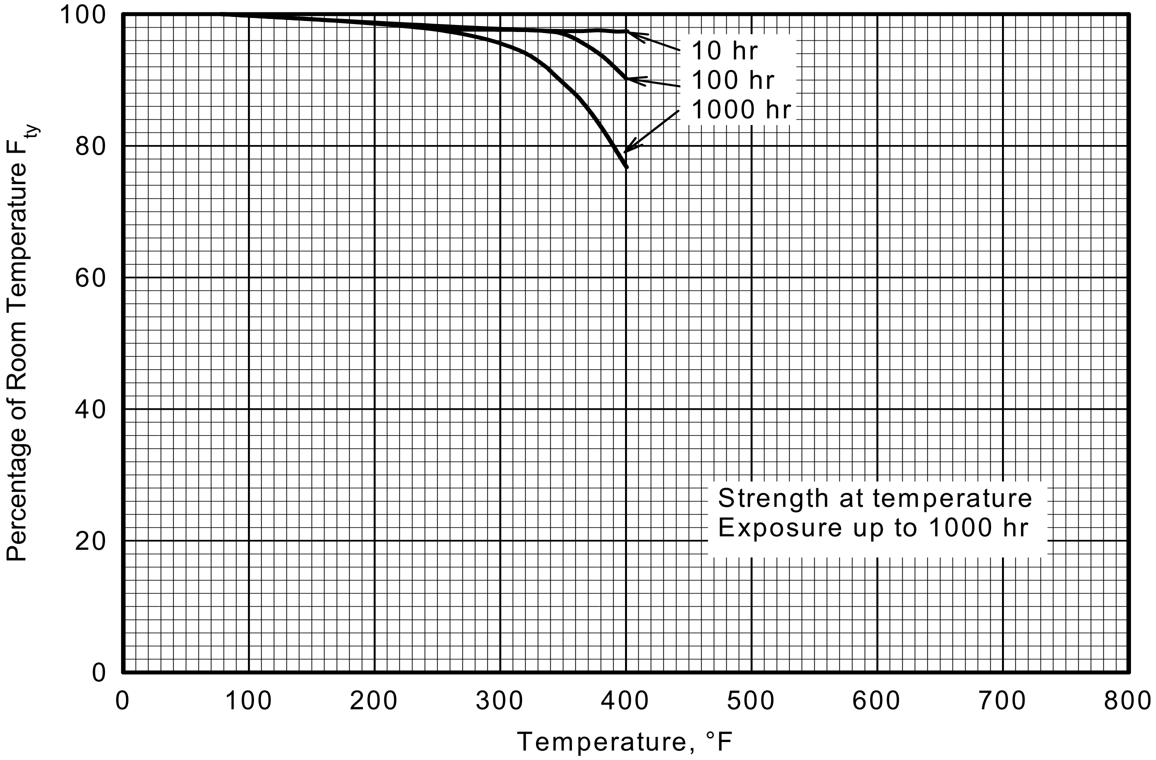


Figure 3.2.13.1.1(c). Effect of exposure at elevated temperatures on room-temperature tensile yield strength (F_{ty}) of 2618-T61 hand forging.

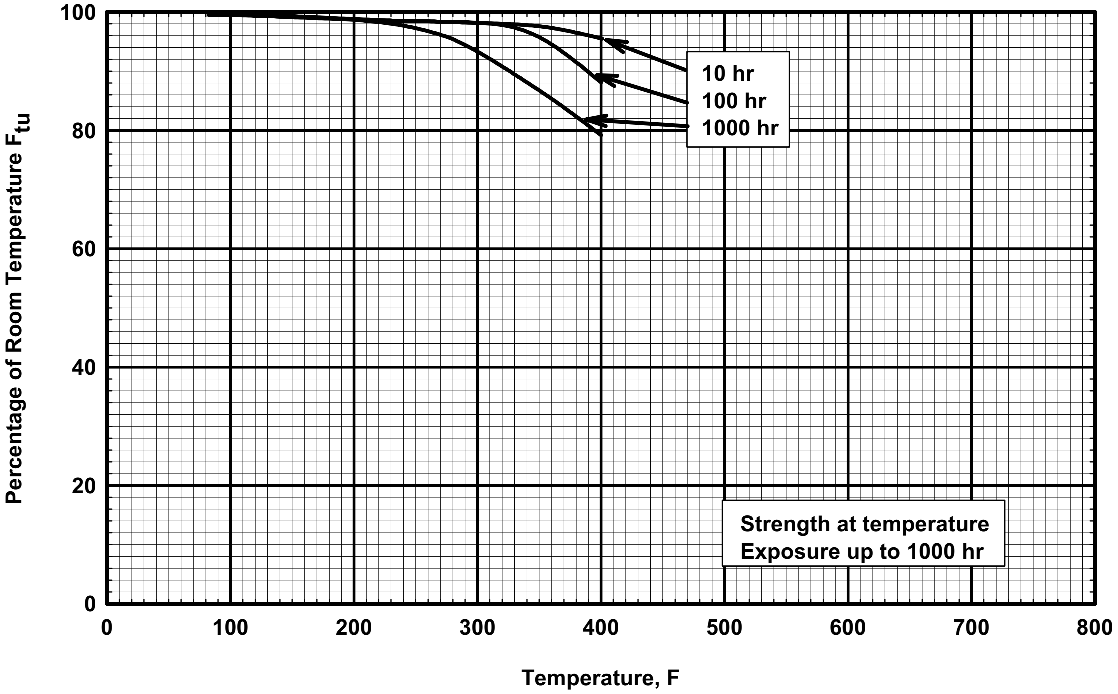


Figure 3.2.13.1.1(d). Effect of exposure at elevated temperatures on room-temperature tensile ultimate strength (F_{tu}) of 2618-T61 hand forging.

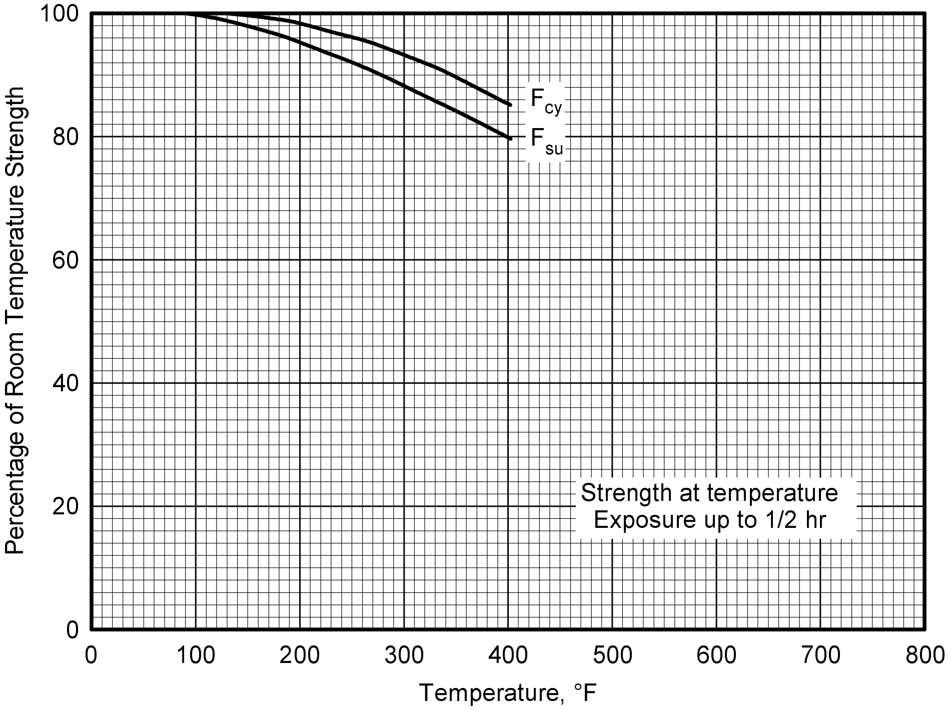


Figure 3.2.13.1.2. Effect of temperature on the compressive yield strength (F_{cy}) and ultimate shear strength (F_{su}) of 2618-T61 aluminum alloy hand forging.

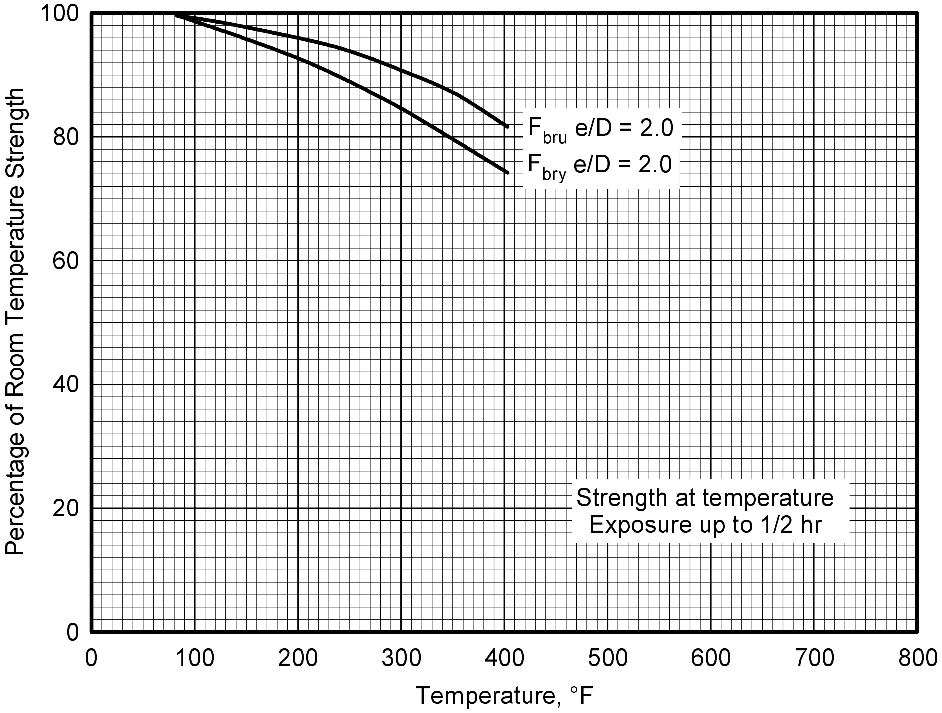


Figure 3.2.13.1.3. Effect of temperature on the bearing ultimate strength (F_{bru}) and bearing yield strength (F_{bry}) of 2618-T61 aluminum alloy hand forging.

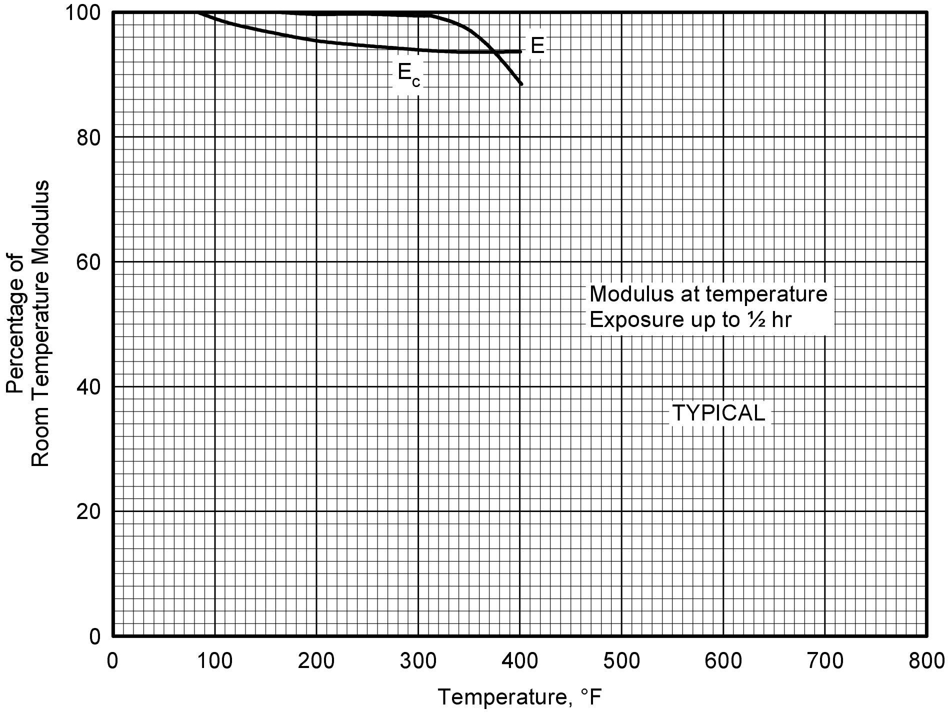


Figure 3.2.13.1.4. Effect of temperature on the tensile and compressive moduli (E and E$_c$) of 2618-T61 aluminum alloy hand forging.

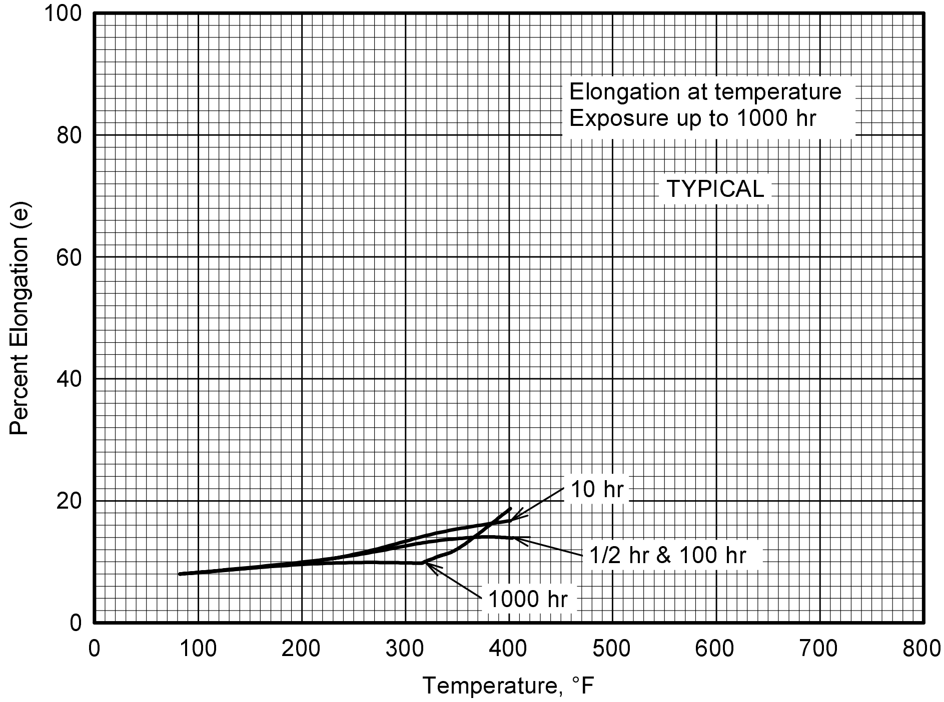


Figure 3.2.13.1.5. Effect of temperature on the elongation (e) of 2618-T61 aluminum alloy hand forging.

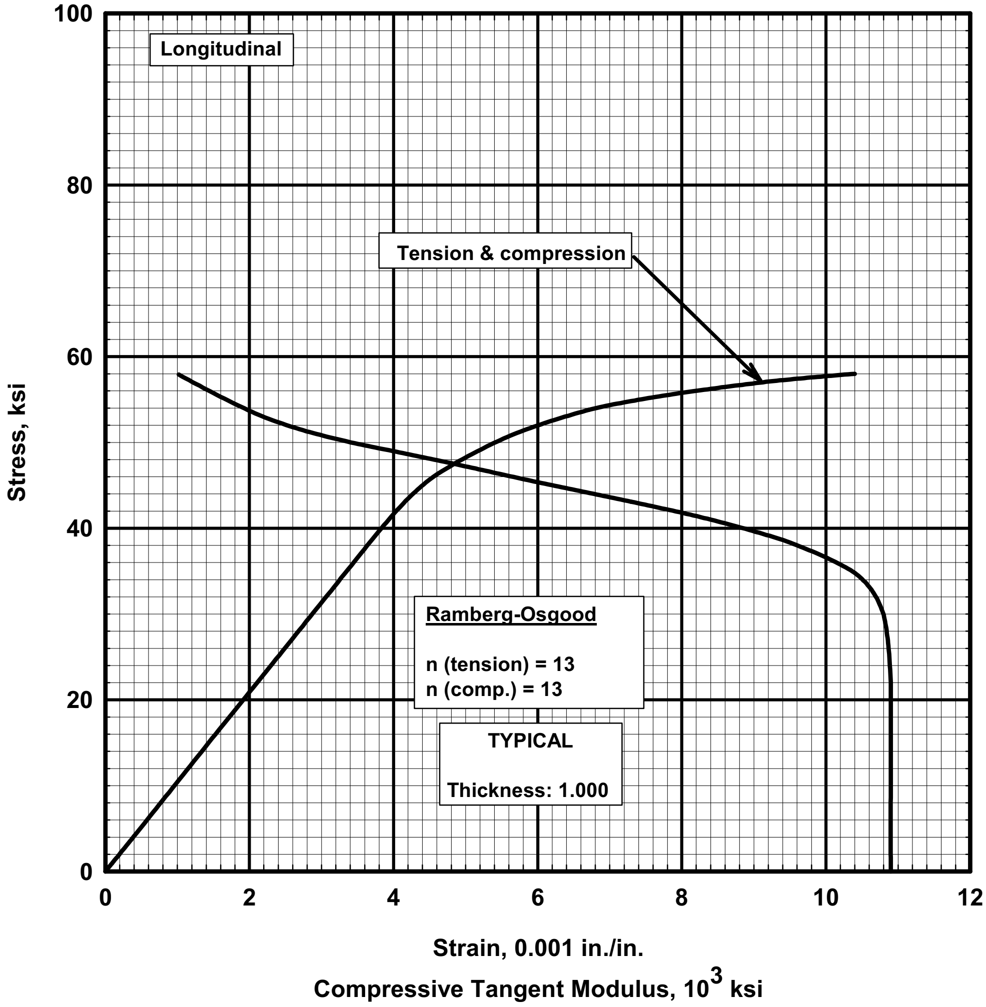


Figure 3.2.13.1.6(a). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 2618-T61 aluminum alloy forged bar at room temperature.

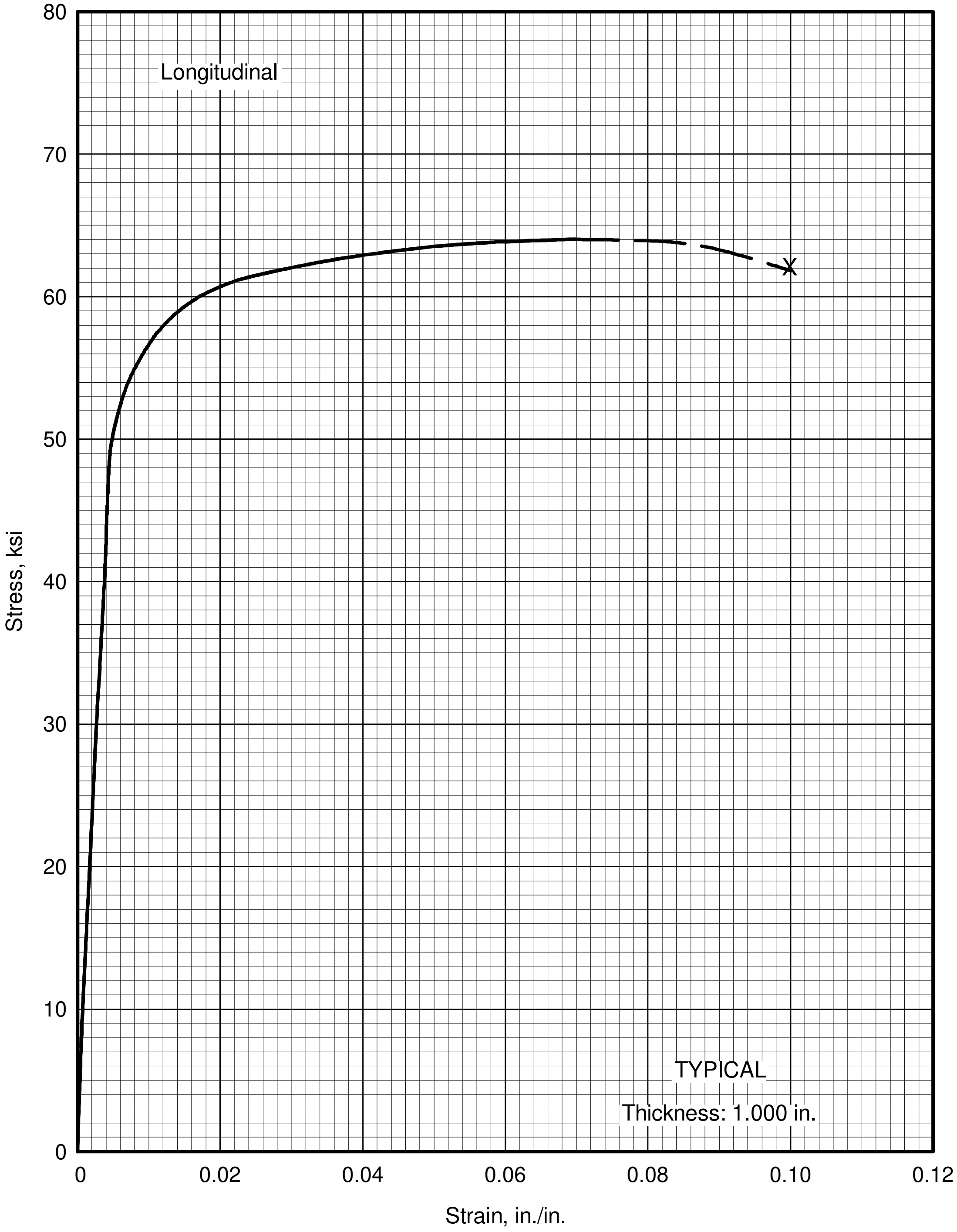


Figure 3.2.13.1.6(b). Typical tensile stress-strain curve (full range) at room temperature for 2618-T61 aluminum alloy forged bar.

3.3 3000 SERIES WROUGHT ALLOYS

3.4 4000 SERIES WROUGHT ALLOYS

3.5 5000 SERIES WROUGHT ALLOYS

Alloys of the 5000 series contain magnesium as the principal alloying element and are strengthened by cold work. Because of their high toughness at temperatures down to -452°F, they are widely used in cryogenic applications.

Magnesium in excess of that in solid solution forms a constituent that is anodic to the aluminum-magnesium matrix. This constituent may form a network of precipitates at grain boundaries or along slip planes. The formation of this continuous grain boundary precipitates, which is accelerated by prior cold work and by exposure to elevated temperatures, causes stress-corrosion cracking susceptibility. Therefore, it is recommended that the strain-hardened tempers of 5000 series alloys containing more than 3 percent magnesium not be used at temperatures above 150°F because susceptibility to SCC may result.

3.5.1 5052 ALLOY

3.5.1.0 *Comments and Properties* — 5052 is a low-strength Al-Mg alloy but extremely tough at low temperatures as well as at room temperature. It is highly resistant to corrosion; refer to Section 3.1.2.3 for comments regarding the resistance of the alloy to stress-corrosion cracking. Refer to Section 3.1.3.4 for comments regarding the weldability of the alloy.

Material specifications for 5052 aluminum alloy are presented in Table 3.5.1.0(a). Room-temperature mechanical and physical properties are shown in Tables 3.5.1.0(b_1) and (b_2). The effect of temperature on physical properties is shown in Figure 3.5.1.0.

Table 3.5.1.0(a). Material Specifications for 5052 Aluminum Alloy

Specification	Form
AMS 4015	Sheet and plate
AMS 4016	Sheet and plate
AMS 4017	Sheet and plate
AMS-QQ-A-250/8	Sheet and plate

The temper index for 5052 is as follows:

Section	Temper
3.5.1.1	O
3.5.1.2	H32
3.5.1.3	H34
3.5.1.4	H35
3.5.1.5	H38

3.5.1.1 *O-Temper* — Elevated temperature curves for this temper for various mechanical properties are presented in Figures 3.5.1.1.1, 3.5.1.1.4, and 3.5.1.1.5.

3.5.1.2 *H32 Temper* — Figure 3.5.1.1.4 may be used for the elevated temperature curve for modulus of elasticity.

3.5.1.3 *H34 Temper* — Elevated temperature curves for various mechanical properties are presented in Figures 3.5.1.3.1(a) through (d), and 3.5.1.3.5(a) and (b). Use Figure 3.5.1.1.4 for modulus values.

3.5.1.4 *H36 Temper* — Figure 3.5.1.1.4 may be used for the elevated temperature curve for modulus of elasticity.

3.5.1.5 *H38 Temper* — Elevated temperature curves for this temper for various mechanical properties are presented in Figures 3.5.1.5.1(a) through (d), and 3.5.1.5.5(a) and (b). Use Figure 3.5.1.1.4 for modulus values.

Table 3.5.1.0(b_1). Design Mechanical and Physical Properties of 5052 Aluminum Alloy Sheet and Plate

Specification	AMS 4015	AMS 4016	AMS 4017	AMS-QQ-A-250/8	
Form	Sheet and plate			Sheet	
Condition	O	H32	H34	H36	H38
Thickness, in.	0.006-3.000	0.017-2.000	0.009-1.000	0.006-0.162	0.006-0.128
Basis	S	S	S	S	S
Mechanical Properties:					
F_{tu}, ksi:					
L	25	31	34	37	39
LT	...	31	34	37	39
F_{ty}, ksi:					
L	9.5	23	26	29[a]	32[a]
LT	...	22	25	29	32
F_{cy}, ksi:					
L	...	22	25	...	...
LT	...	23	26	...	...
F_{su}, ksi	16	19	20	22	23
F_{bru}, ksi:					
(e/D = 1.5)	...	50	54	59	62
(e/D = 2.0)	...	65	71	78	82
F_{bry}, ksi:					
(e/D = 1.5)	...	32	37	41	44
(e/D = 2.0)	...	37	41	46	51
e, percent:					
L	[b]	[b]	[b]	[b]	[b]
E, 10^3 ksi	10.1				
E_c, 10^3 ksi	10.2				
G, 10^3 ksi	3.85				
μ	0.33				
Physical Properties:					
ω, lb/in.^{3}	0.097				
C, Btu/(lb)(°F)	0.23 (at 212°F)				
K and α	See Figure 3.5.1.0				

[a] From "Aluminum Standards and Data" dated 1982.

[b] See Table 3.5.1.0(b_2).

Table 3.5.1.0(b_2). Minimum Elongation Values for 5052 Aluminum Alloy Sheet and Plate

Temper	Thickness Range, inch	Elongation (L), percent
O	0.006-0.007	...
	0.008-0.012	14
	0.013-0.019	15
	0.020-0.031	16
	0.032-0.050	18
	0.051-0.113	19
	0.114-0.249	20
	0.250-3.000	18
H32	0.017-0.019	4
	0.020-0.050	5
	0.051-0.113	7
	0.114-0.249	9
	0.250-0.499	11
	0.500-2.000	12
H34	0.009-0.019	3
	0.020-0.050	4
	0.051-0.113	6
	0.114-0.249	7
	0.250-1.000	10
H36	0.006-0.007	2
	0.008-0.031	3
	0.032-0.162	4
H38	0.006-0.007	2
	0.008-0.031	3
	0.032-0.128	4

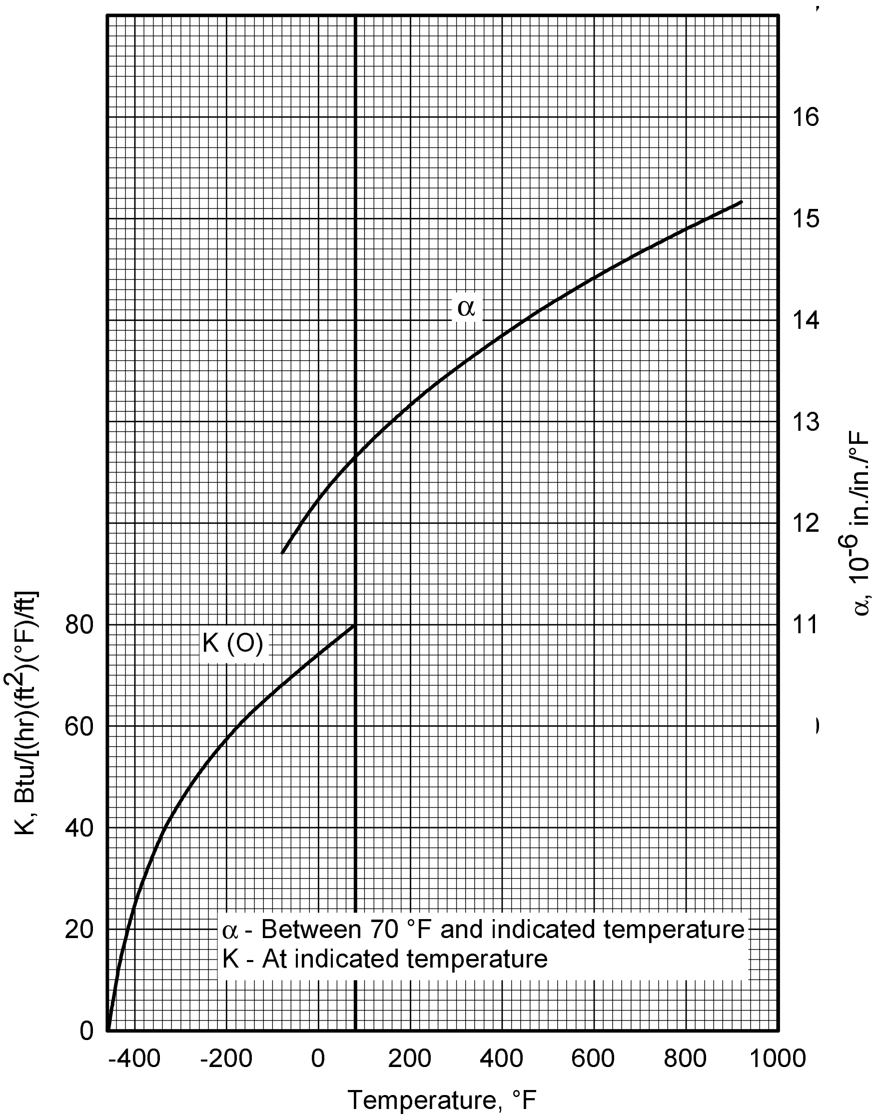


Figure 3.5.1.0. Effect of temperature on the physical properties of 5052 aluminum alloy.

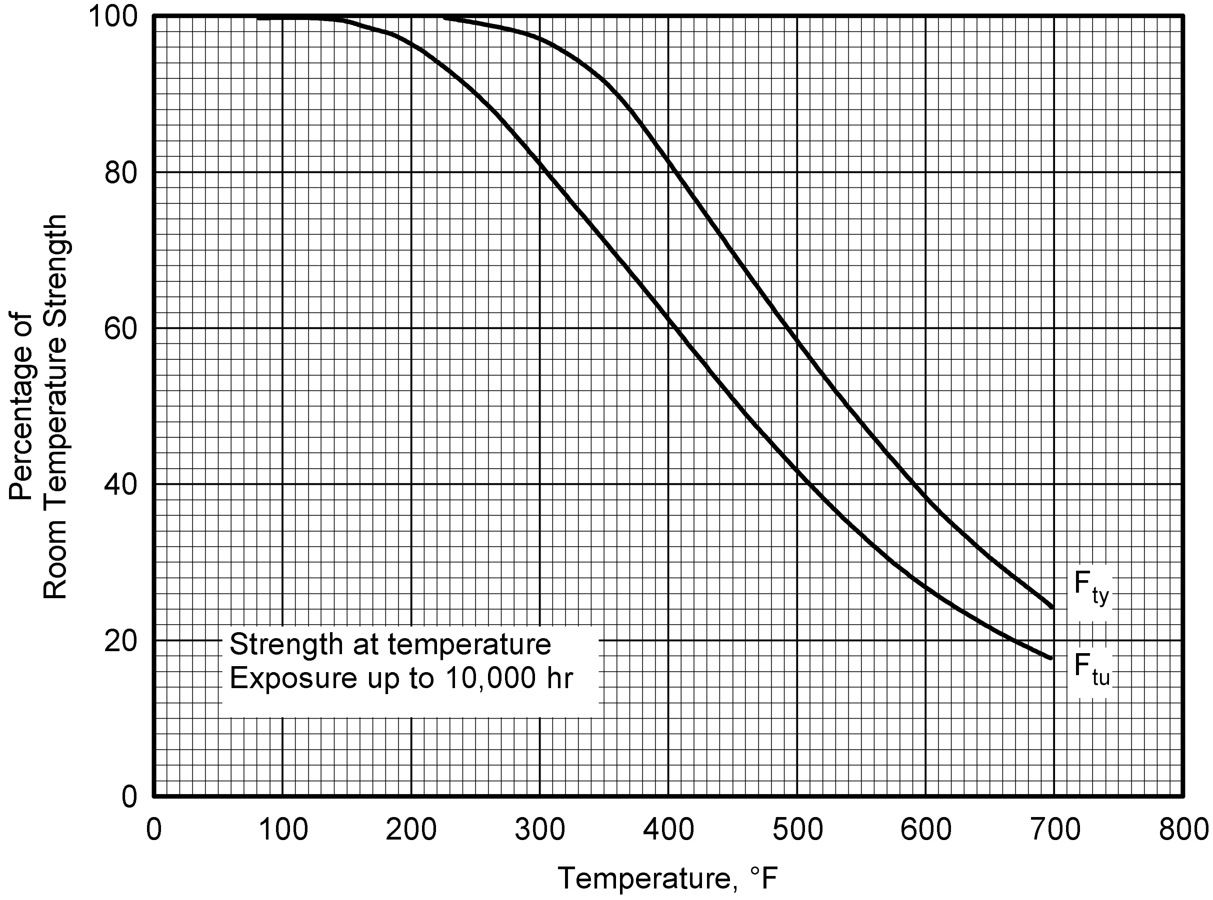


Figure 3.5.1.1.1. Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of 5052-0 aluminum alloy (all products).

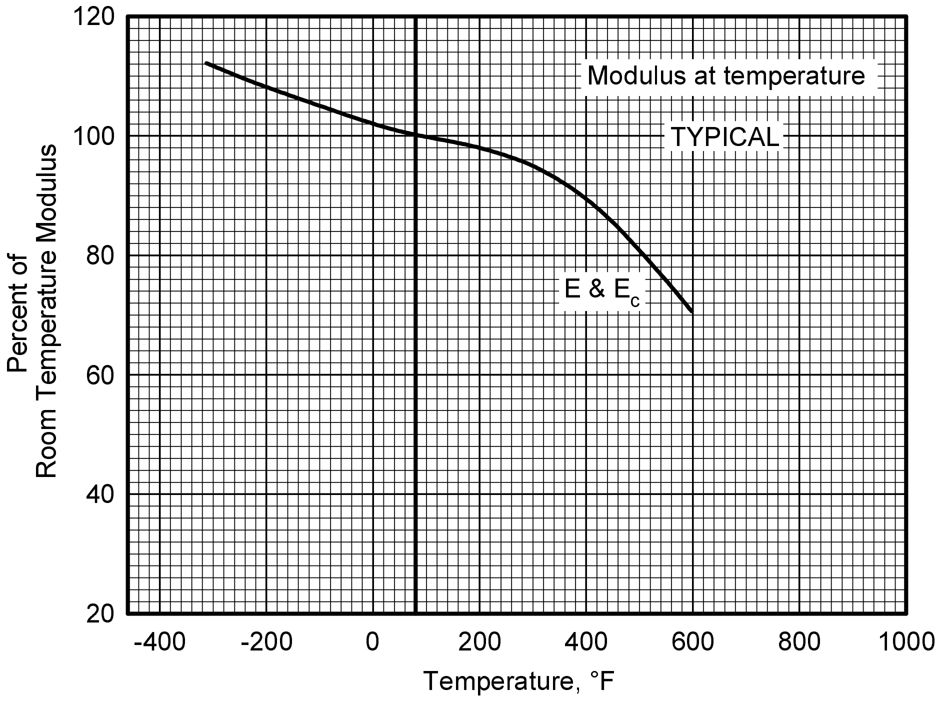


Figure 3.5.1.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of 5052-0 aluminum alloy (all products).

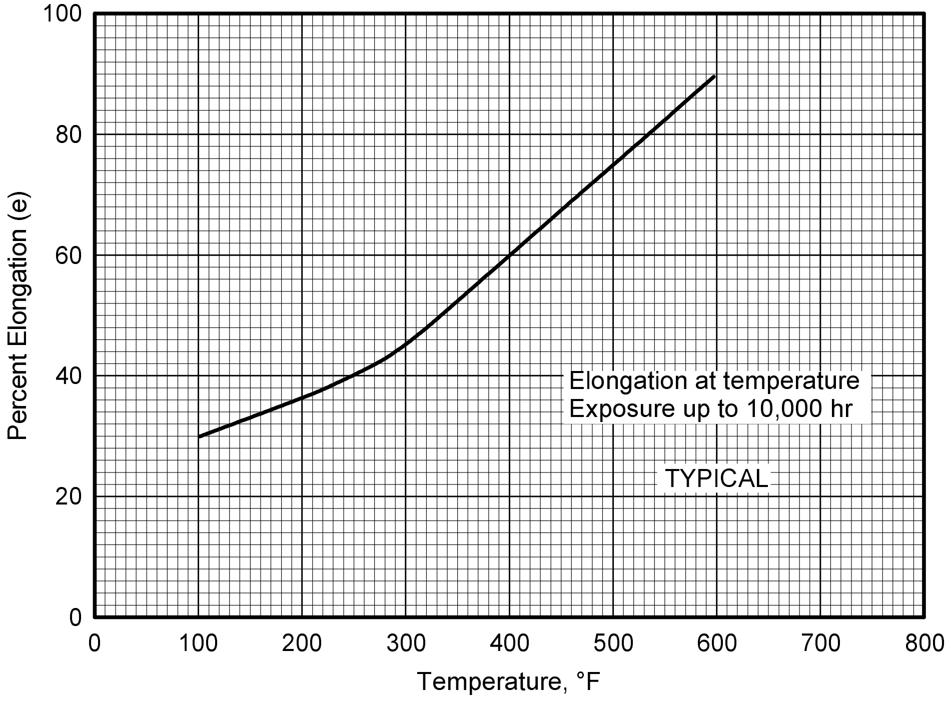


Figure 3.5.1.1.5. Effect of temperature on the elongation of 5052-0 aluminum alloy (all products).

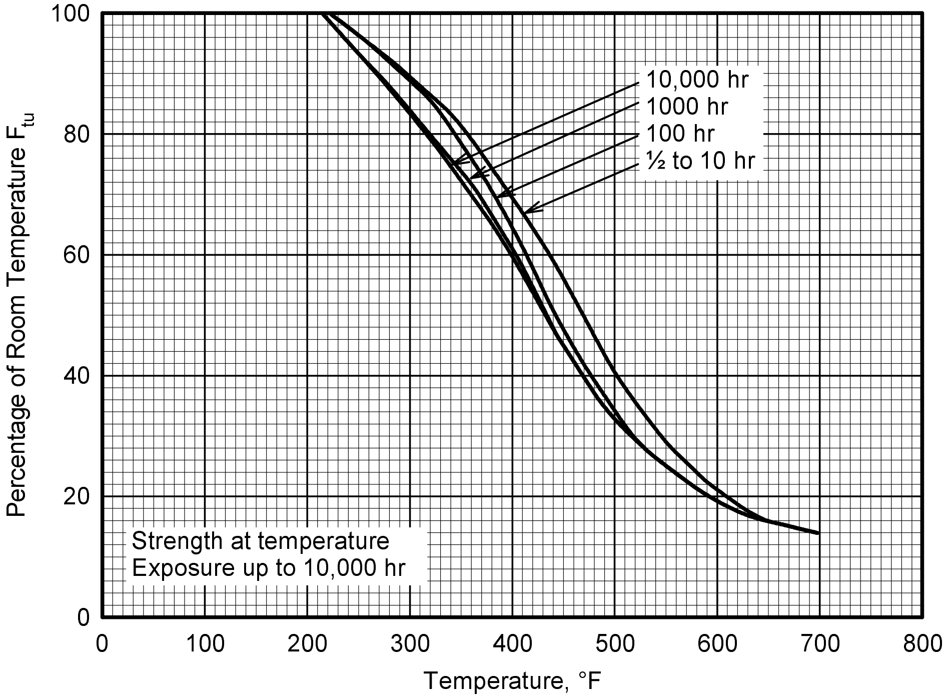


Figure 3.5.1.3.1(a). Effect of temperature on the tensile ultimate strength (F_{tu}) of 5052-H34 aluminum alloy sheet and plate.

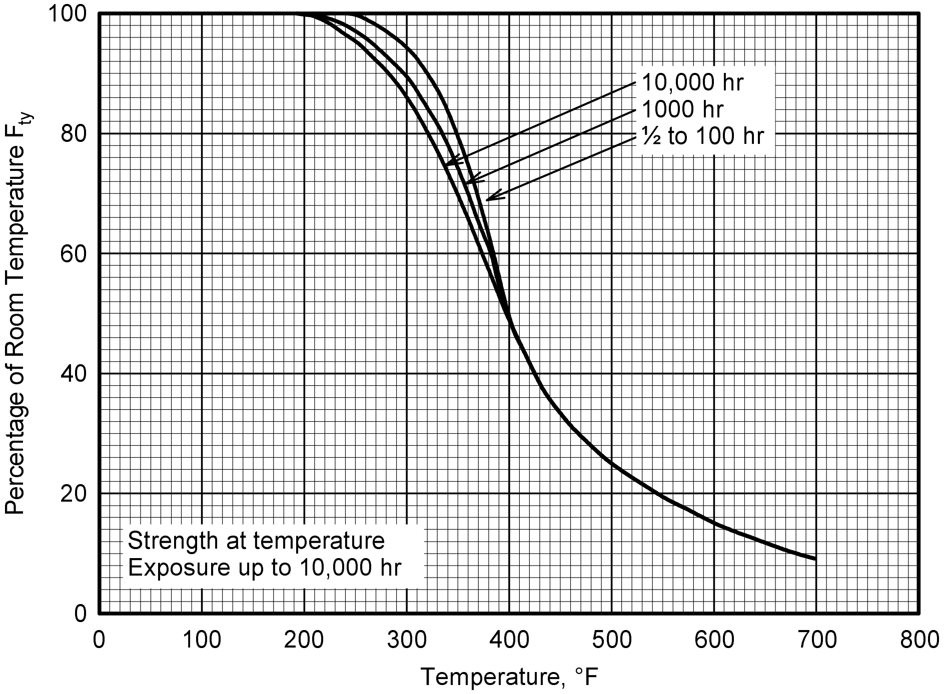


Figure 3.5.1.3.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of 5052-H34 aluminum alloy sheet and plate.

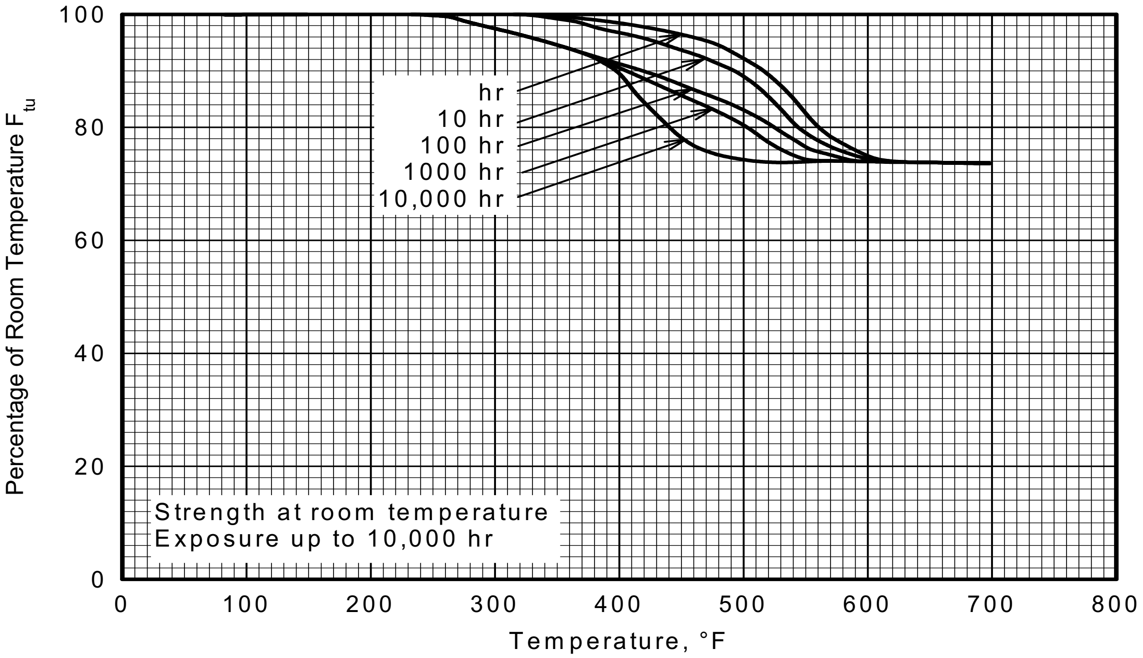


Figure 3.5.1.3.1(c). Effect of exposure at elevated temperatures on the room-temperature tensile ultimate strength (F_{tu}) of 5052-H34 aluminum alloy sheet and plate.

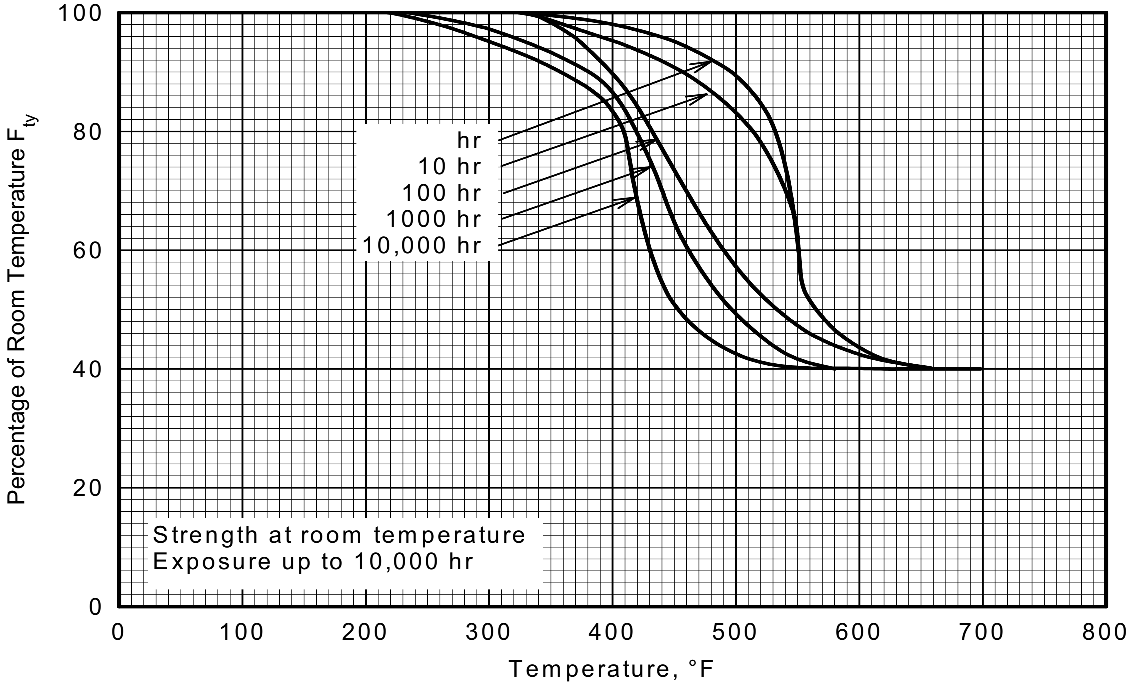


Figure 3.5.1.3.1(d). Effect of exposure at elevated temperatures on the room-temperature tensile yield strength (F_{ty}) of 5052-H34 aluminum alloy sheet and plate.

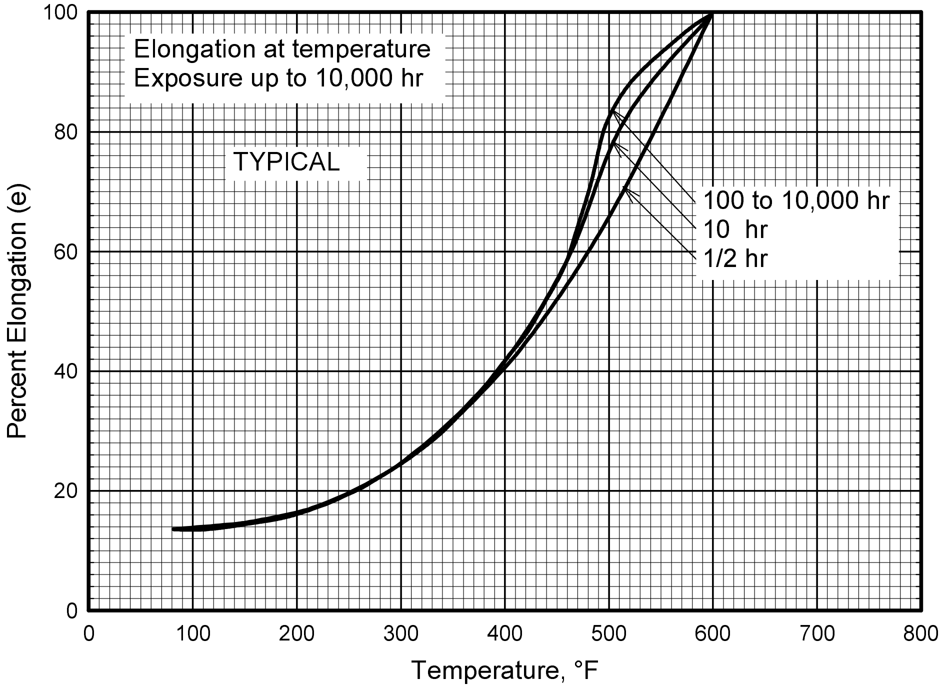


Figure 3.5.1.3.5(a). Effect of temperature on the elongation (e) of 5052-H34 aluminum alloy sheet and plate.

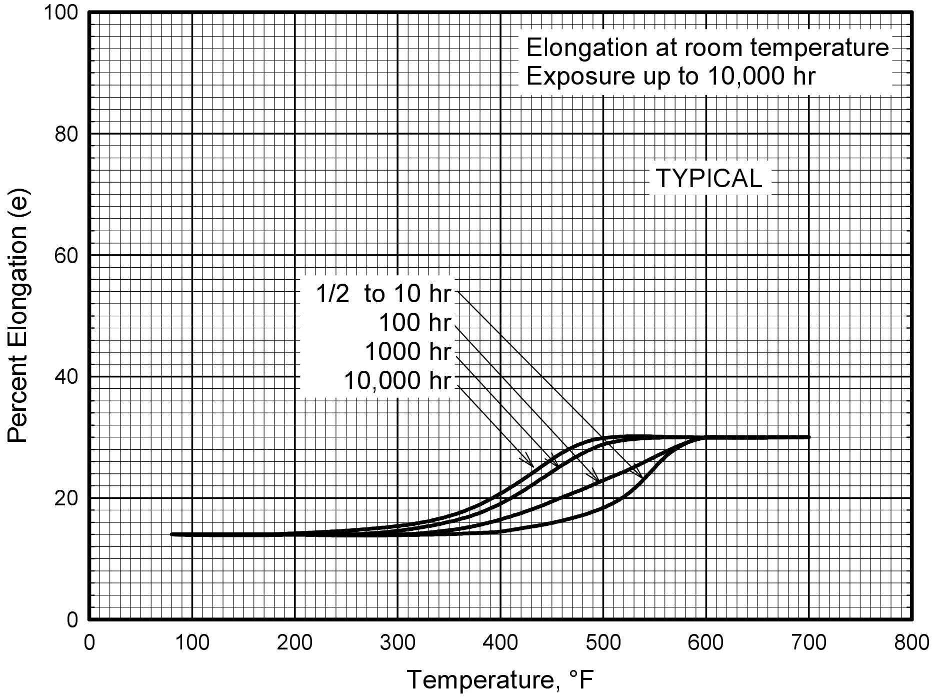


Figure 3.5.1.3.5(b). Effect of exposure at elevated temperatures on the room temperature elongation (e) of 5052-H34 aluminum alloy sheet and plate.

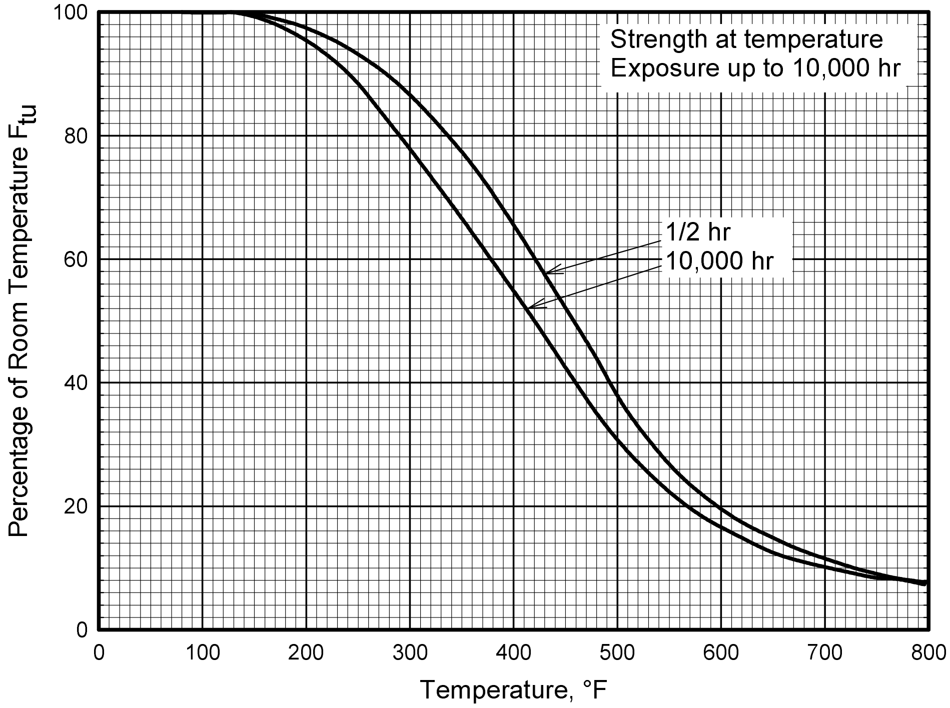


Figure 3.5.1.5.1(a). Effect of temperature on the tensile ultimate strength (F_{tu}) of 5052-H38 aluminum alloy (all products).

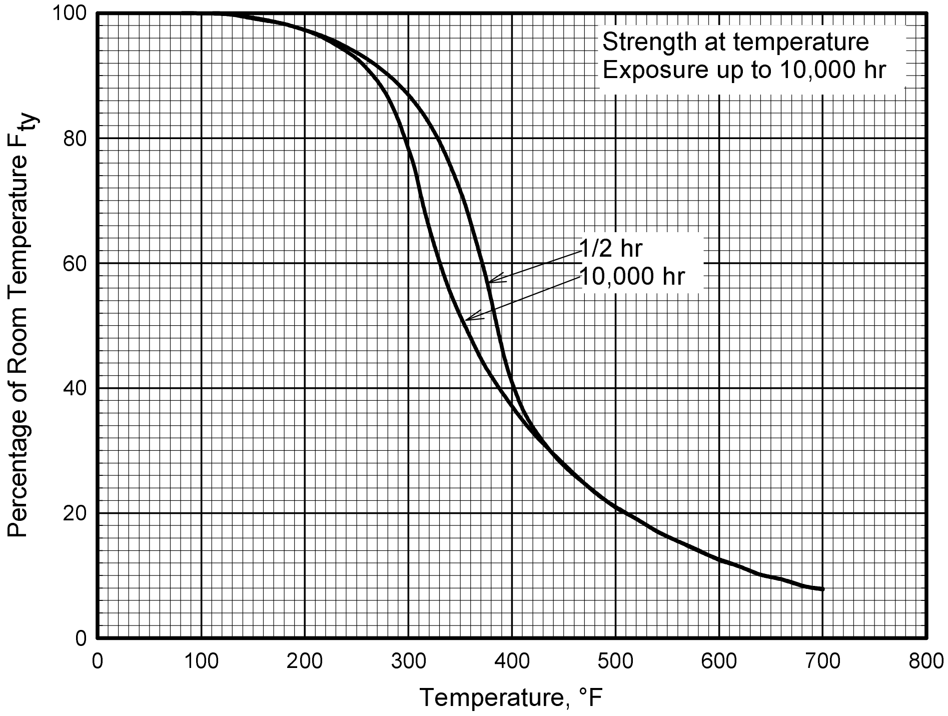


Figure 3.5.1.5.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of 5052-H38 aluminum alloy (all products).

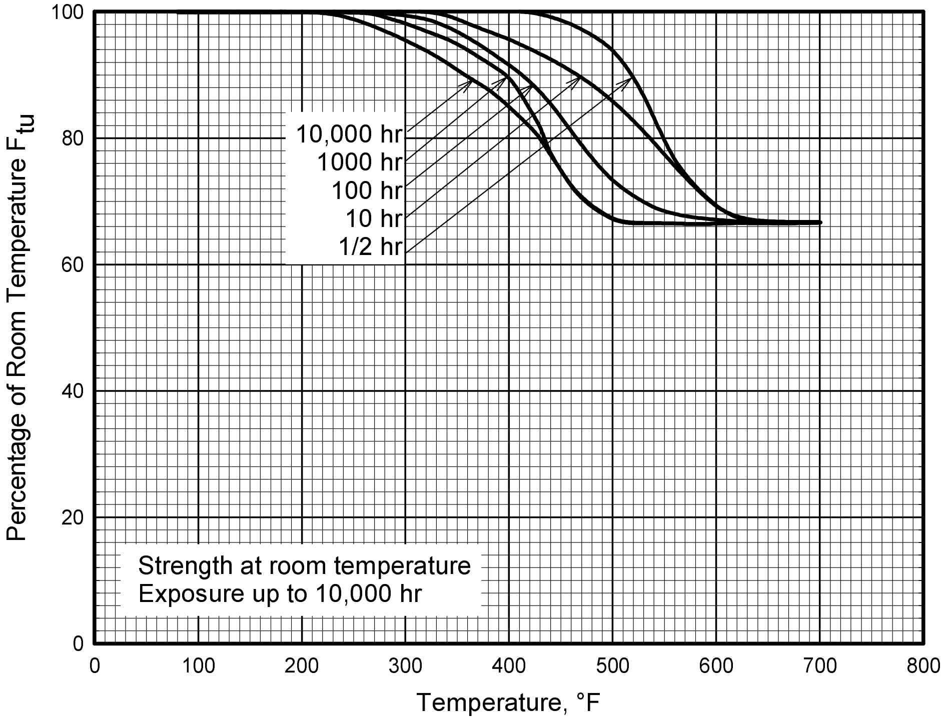


Figure 3.5.1.5.1(c). Effect of exposure at elevated temperatures on the room-temperature tensile ultimate strength (F_{tu}) of 5052-H38 aluminum alloy (all products).

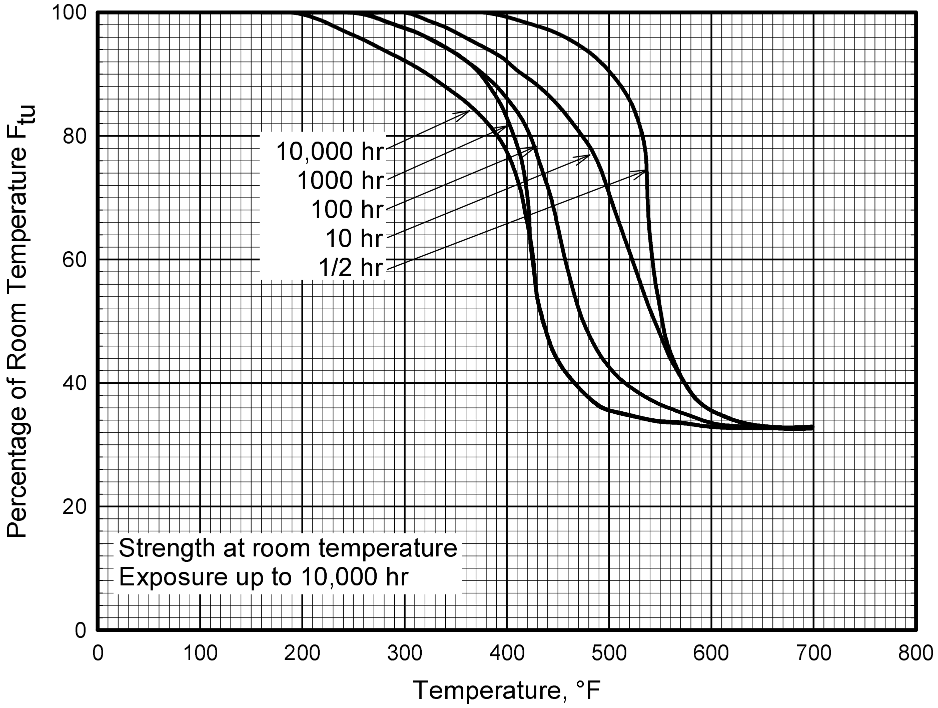


Figure 3.5.1.5.1(d). Effect of exposure at elevated temperatures on the room-temperature tensile yield strength (F_{ty}) of 5052-H38 aluminum alloy (all products).

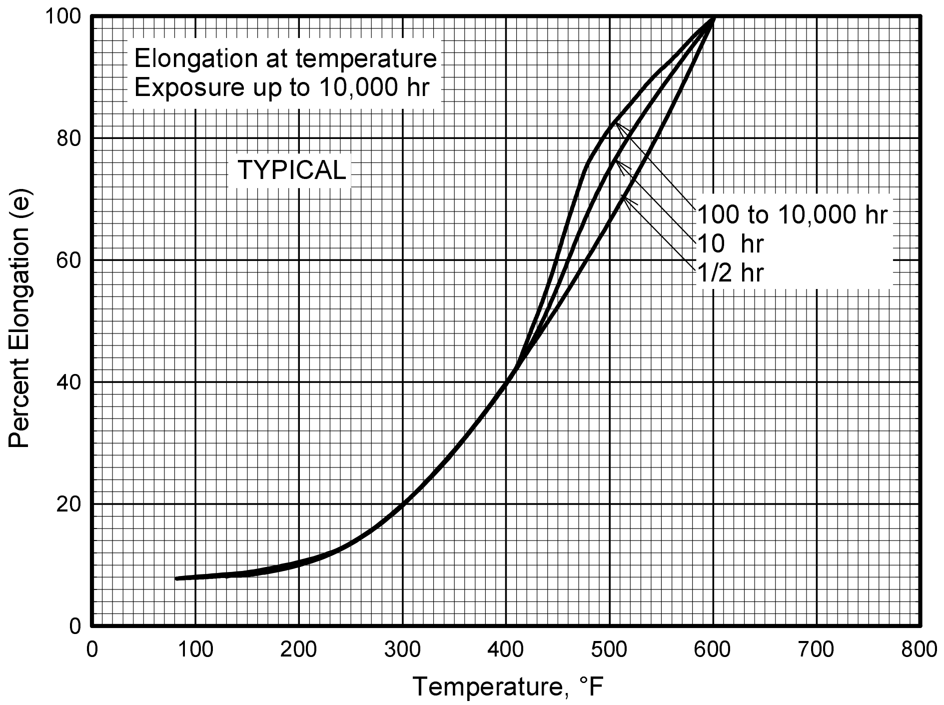


Figure 3.5.1.5.5(a). Effect of temperature on the elongation of 5052-H38 aluminum alloy (all products).

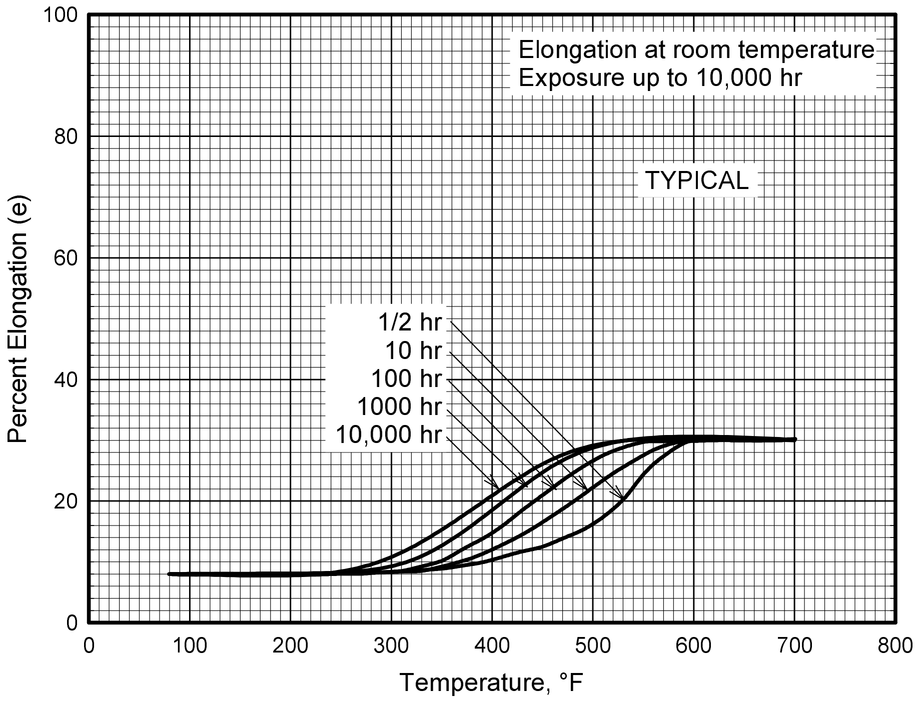


Figure 3.5.1.5.5(b). Effect of exposure at elevated temperatures on the room temperature elongation of 5052-H38 aluminum alloy (all products).

3.5.2 5083 ALLOY

3.5.2.0 *Comments and Properties* — 5083 is a high-strength Al-Mg alloy which has been widely used in cryogenic applications, because of its excellent combination of strength and toughness. It has high resistance to corrosion, but strain-hardened tempers should not be used at temperatures above 150°F because of possible sensitization to stress-corrosion cracking. Refer to Section 3.1.2.3 for comments regarding the resistance of the alloy to stress-corrosion cracking, and to Section 3.1.3.4 for comments regarding the weldability of the alloy.

Material specifications for 5083 aluminum alloy are presented in Table 3.5.2.0(a). Room-temperature mechanical and physical properties are shown in Tables 3.5.2.0(b) and (c). The effect of temperature on thermal expansion is shown in Figure 3.5.2.0.

Table 3.5.2.0(a). *Material Specifications for 5083 Aluminum Alloy*

Specification	Form
AMS 4056	Bare sheet and plate
AMS-QQ-A-250/6	Bare sheet and plate
AMS-QQ-A-200/4	Extruded bar, rod, and shapes

The temper index for 5083 is as follows:

Section	Temper
3.5.2.1	O
3.5.2.2	H111
3.5.2.3	H112
3.5.2.4	H321
3.5.2.5	H323
3.5.2.6	H343

3.5.2.1 *O Temper* — Tensile and compressive stress-strain and tangent-modulus curves at room temperature are presented in Figures 3.5.2.1.6(a) and (b). A full-range tensile stress-strain curve is shown in Figure 3.5.2.1.6(c) at room temperature.

Table 3.5.2.0(b). Design Mechanical and Physical Properties of 5083 Aluminum Alloy Sheet and Plate

Specification	AMS 4056 and AMS-QQ-A-250/6							AMS-QQ-A-250/6										
Form	Sheet and plate																	
Temper	O							H112		H321			H323			H343	
Thickness, in.	0.051-1.500		1.501-3.000	3.001-4.000	4.001-5.000	5.001-7.000	7.001-8.000	0.250-1.500	1.501-3.000	0.188-1.500		1.501-3.000	0.051-0.125		0.126-0.249	0.051-0.125	0.126-0.249
Basis	A	B	S	S	S	S	S	S	S	A	B	S	A	B	S	S	S
Mechanical Properties:																	
F_{tu}, ksi:																	
L	40	41	39	38	38	37	36	40	39	44	46	41	45	47	45	50	50
LT	40	41	...	...	...	...	...	...	...	44	46	...	...	...	...	...	...
F_{ty}, ksi:																	
L	18	19	17	16	16	15	14	18	17	31	32	29	34	36	34	39	39
LT	18	19	...	...	...	...	...	...	...	28	28	...	...	...	...	...	...
F_{cy}, ksi:																	
L	18	19	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
LT	18	19	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
F_{su}, ksi	25	26	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
F_{bru}, ksi:																	
(e/D = 1.5)	60	62	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
(e/D = 2.0)	76	78	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
F_{bry}, ksi:																	
(e/D = 1.5)	32	34	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
(e/D = 2.0)	38	40	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
e, percent (S basis):																	
L	16	...	16	16	14	14	12	12	12	12	...	12	8	...	10	6	8
E, 10^3 ksi	10.2																
E_c, 10^3 ksi	10.4																
G, 10^3 ksi	3.85																
μ	0.33																
Physical Properties:																	
ω, lb/in.^{3}	0.096																
C, Btu/(lb)(°F)	0.23 (at 212°F)																
K, Btu/[(hr)(ft^2)(°F)/ft]	68 (at 77°F)																
α, 10^{-6} in./in./°F	See Figure 3.5.2.0																

Table 3.5.2.0(c). Design Mechanical and Physical Properties of 5083 Aluminum Alloy Extrusion

Specification	AMS-QQ-A-200/4			
Form	Extrusion			
Temper	O	H111		H112
Thickness, in.	≤5.000[a]	<0.500[a]	0.501-5.000[a]	≤5.000[a]
Basis	S	S	S	S
Mechanical Properties:				
F_{tu}, ksi:				
L	39	40	40	39
LT	...	40	32	...
F_{ty}, ksi:				
L	16	24	24	16
LT	...	24	19	...
F_{cy}, ksi:				
L	...	...	...	...
LT	...	...	...	...
F_{su}, ksi	...	...	...	...
F_{bru}, ksi:				
(e/D = 1.5)	...	...	...	...
(e/D = 2.0)	...	...	...	...
F_{bry}, ksi:				
(e/D = 1.5)	...	...	...	...
(e/D = 2.0)	...	...	...	...
e, percent:				
L	14	12	12	12
E, 10^3 ksi	10.2			
E_c, 10^3 ksi	10.4			
G, 10^3 ksi	3.35			
μ	0.33			
Physical Properties:				
ω, lb/in.^{3}	0.096			
C, Btu/(lb)(°F)	0.23 (at 212°F)			
K, Btu/[(hr)(ft^2)(°F)/ft]	68 (at 77°F)			
α, 10^{-6} in./in./°F	See Figure 3.5.2.0			

a Cross-sectional area ≤32 in^2.

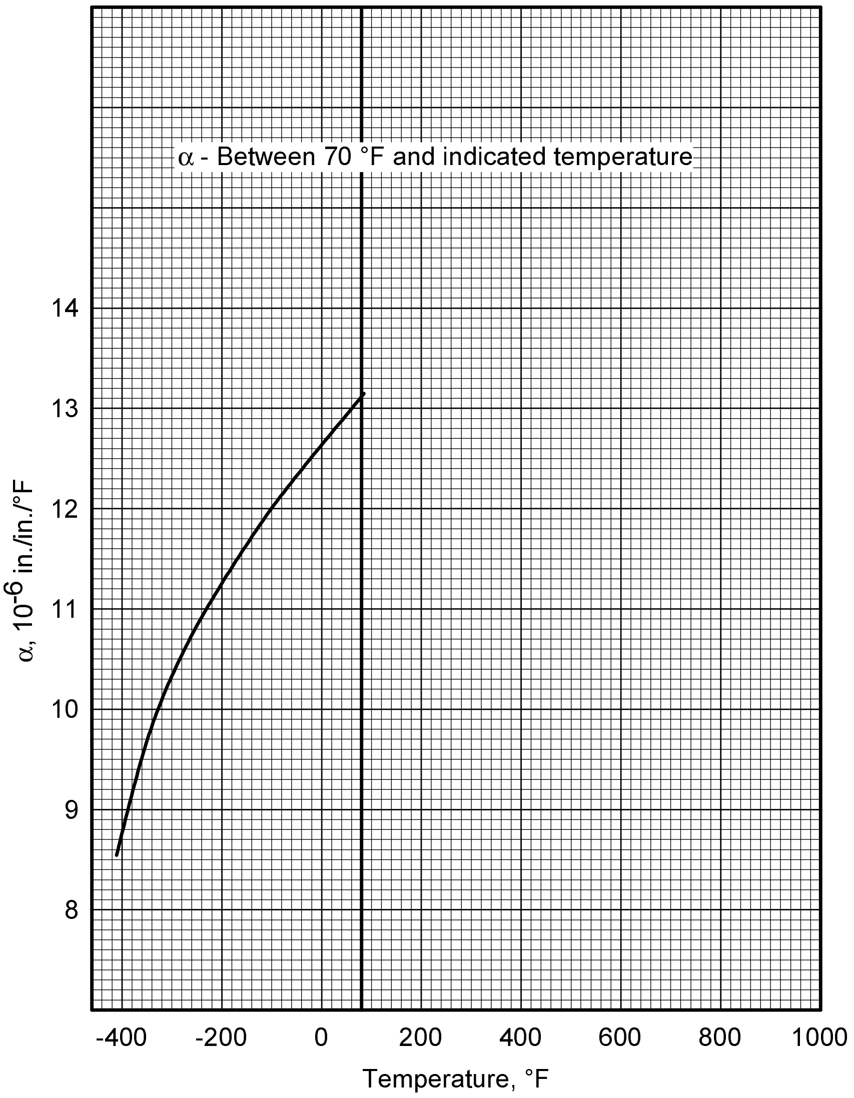


Figure 3.5.2.0. Effect of temperature on the thermal expansion of 5083 aluminum alloy.

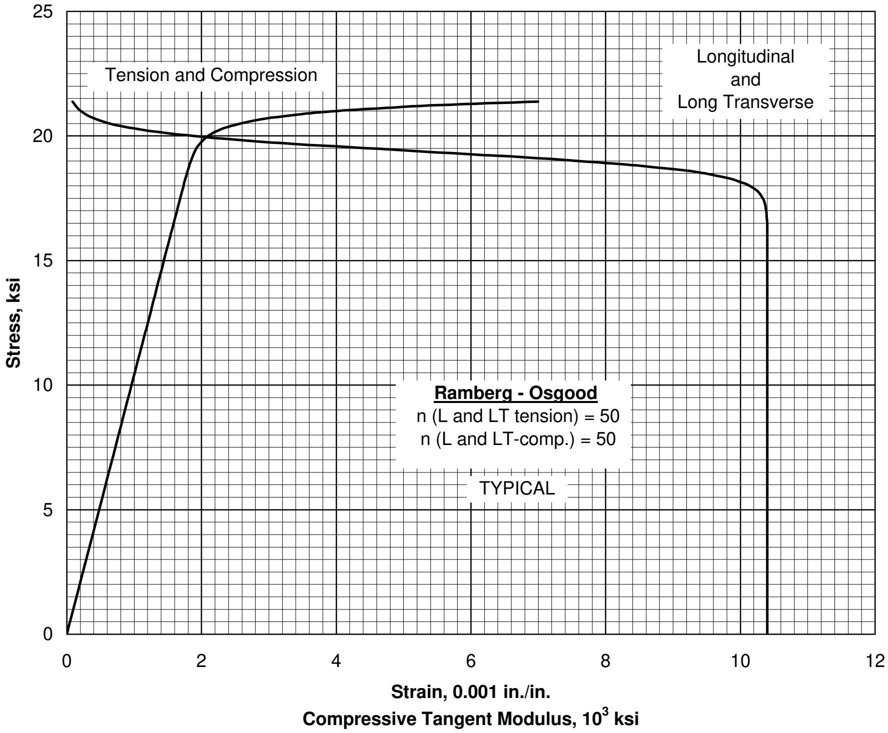


Figure 3.5.2.1.6(a). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 5083-0 aluminum alloy sheet at room temperature.

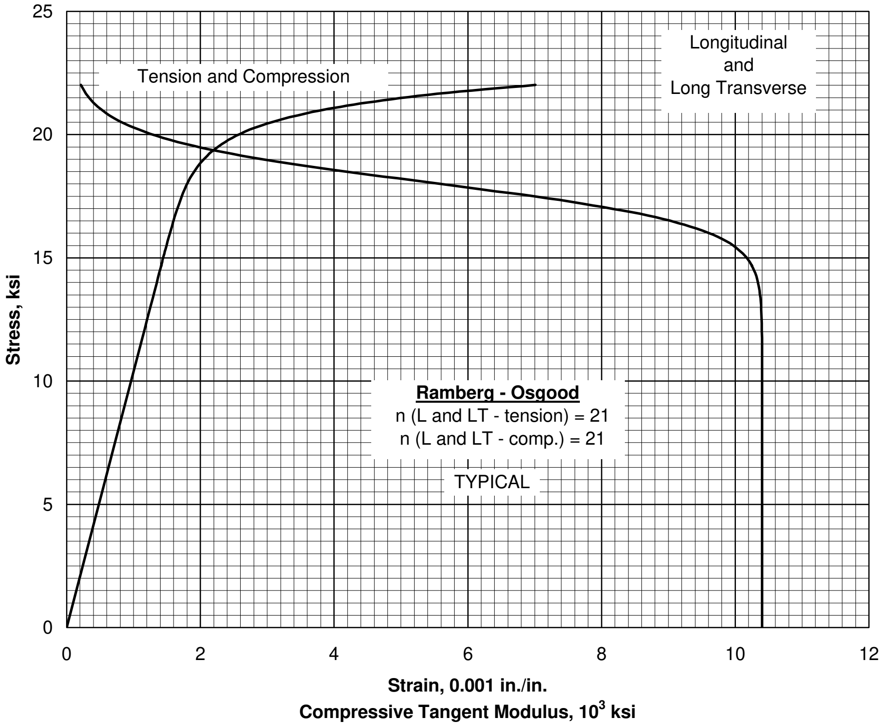


Figure 3.5.2.1.6(b). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 5083-0 aluminum alloy plate at room temperature.

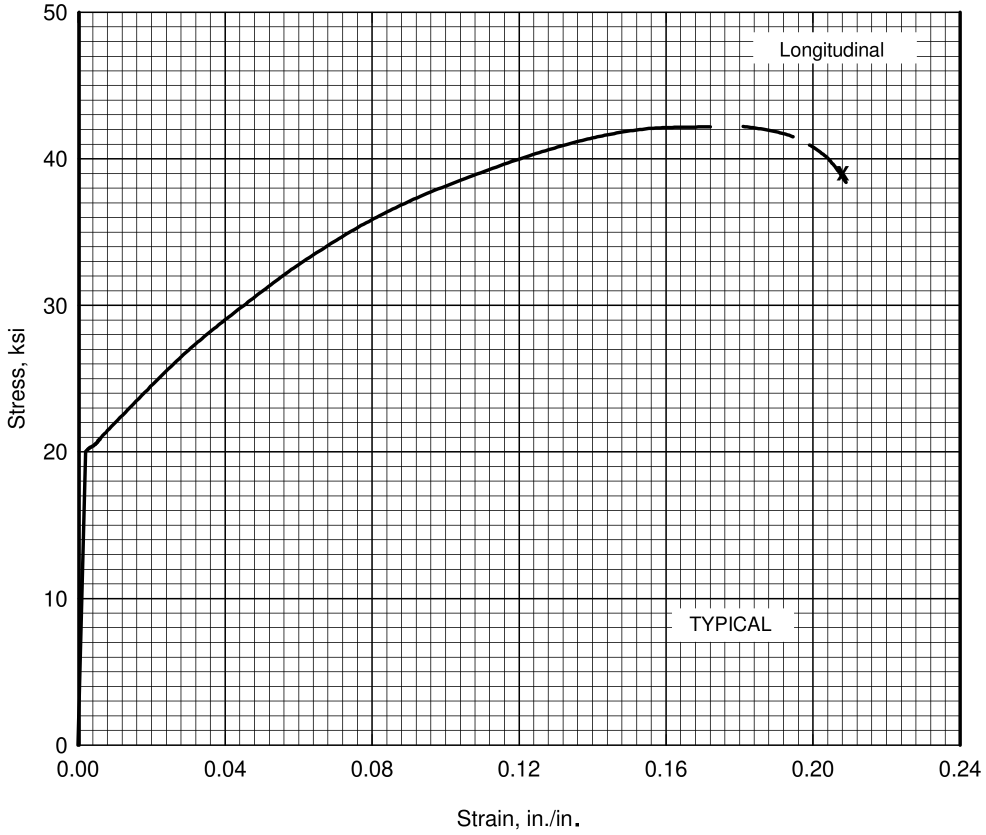


Figure 3.5.2.1.6(c). Typical tensile stress-strain curve (full range) for 5083-0 aluminum alloy plate at room temperature.

3.5.3 5086 ALLOY

3.5.3.0 *Comments and Properties* — 5086 is a tough, medium-strength Al-Mg alloy suitable for application over the range of temperatures from -452 to 150°F. Refer to Section 3.1.2.3 for comments regarding resistance of the alloy to stress-corrosion cracking, and to Section 3.1.3.4 for comments regarding the weldability of the alloy.

Material specifications for 5086 aluminum alloy are presented in Table 3.5.3.0(a). Room-temperature mechanical and physical properties are shown in Tables 3.5.3.0(b) and (c).

Table 3.5.3.0(a). Material Specifications for 5086 Aluminum Alloy

Specification	Form
AMS-QQ-A-250/7	Sheet and plate
AMS-QQ-A-200/5	Extruded bar, rod, and shapes

The temper index for 5086 is as follows:

Section	Temper
3.5.3.1	O
3.5.3.2	H32
3.5.3.3	H34
3.5.3.4	H36
3.5.3.5	H38
3.5.3.6	H111
3.5.3.7	H112

3.5.3.1 *O Temper* — Tensile, compressive stress-strain and tangent-modulus curves at room temperature are shown in Figures 3.5.3.1.6(a) and (b) for products with this temper. Figure 3.5.3.1.6(c) is a full-range tensile stress-strain curve.

3.5.3.2 *H32 Temper* — Figures 3.5.3.2.6(a) and (b) show tensile and compressive stress-strain and tangent-modulus curves at room temperature.

3.5.3.3 *H34 Temper* — Figures 3.5.3.3.6(a) and (b) show tensile, compressive stress-strain, and tangent-modulus curves for this temper. A full-range tensile stress-strain curve is shown in Figure 3.5.3.3.6(c).

3.5.3.4 *H36 Temper* — Figure 3.5.3.4.6 shows tensile, compressive stress-strain and tangent-modulus curves at room temperature.

3.5.3.5 *H38 Temper* —

3.5.3.6 *H111 Temper* —

3.5.3.7 *H112 Temper* — Figure 3.5.3.7.6 shows tensile, compressive stress-strain and tangent-modulus curves at room temperature.

Table 3.5.3.0(b). Design Mechanical and Physical Properties of 5086 Aluminum Alloy Sheet, Plate and Extrusion

Specification	AMS-QQ-A-250/7											AMS-QQ-A-200/5		
Form	Sheet and plate											Extrusion		
Condition	O		H32		H34	H36	H38	H112				O	H111	H112
Thickness, in	0.020-2.000		0.020-2.000		0.009-1.000	0.006-0.162	0.006-0.020	0.188-0.499	0.500-1.00	1.001-2.000	2.001-3.000	$\leq 5.000^a$	$\leq 5.000^a$	$\leq 5.000^a$
Basis	A	B	A	B	S	S	S	S	S	S	S	S	S	S
Mechanical Properties:														
F_{tu}, ksi:														
L	35	36	40	41	44	47	50	36	35	35	34	35	36	35
LT	35	36	40	41	44	47	...	36	35	35	34	...	...	...
F_{ty}, ksi:														
L	14	15	28	30	34	38	41	18	16	14	14	14	21	14
LT	14	15	26	28	33	37	...	17	16	14	14	...	...	...
F_{cy}, ksi:														
L	14	15	26	28	32	35	...	17	15	14	14	...	...	...
LT	14	15	28	30	34	38	...	18	16	14	14	...	...	...
F_{su}, ksi	21	22	24	25	26	27	...	22	21	21	20	...	...	...
F_{bru}, ksi:														
(e/D=1.5)	52	53	58	61	64	68	...	54	52	52	51	...	...	...
(e/D=2.0)	70	72	80	82	88	94	...	72	70	70	68	...	...	...
F_{bry}, ksi:														
(e/D=1.5)	24	26	39	42	48	53	...	25	24	24	24	...	...	...
(e/D=2.0)	28	30	48	51	58	65	...	31	28	28	28	...	...	...
e, percent (S basis):														
L	b	...	b	...	b	b	3	8	10	14	14	14	12	12
E, 10^3 ksi	10.2													
E_c, 10^3 ksi	10.4													
G, 10^3 ksi	3.85													
μ	0.33													
Physical Properties:														
ω, lb/in.^{3}	0.096													
C, Btu/(lb)(°F)	0.23 (at 212°F)													
K, Btu/[(hr)(ft^2)(°F)ft]	72 (at 77°F)													
α, 10^{-6}in/in/°F	13.2 (68 to 212°F)													

a Cross-sectional area ≤32.

b See Table 3.5.3.0(c).

Table 3.5.3.0(c). Minimum Elongation Values for 5086 Aluminum Alloy Sheet and Plate

Temper	Thickness Range, inch	Elongation (L), percent
O.............................	0.020-0.050	15
	0.051-0.249	18
	0.250-2.000	16
H32.........................	0.020-0.050	6
	0.051-0.249	8
	0.250-2.000	12
H34.........................	0.009-0.019	4
	0.020-0.050	5
	0.051-0.249	6
	0.250-1.000	10
H36.........................	0.006-0.019	3
	0.020-0.050	4
	0.051-0.162	6

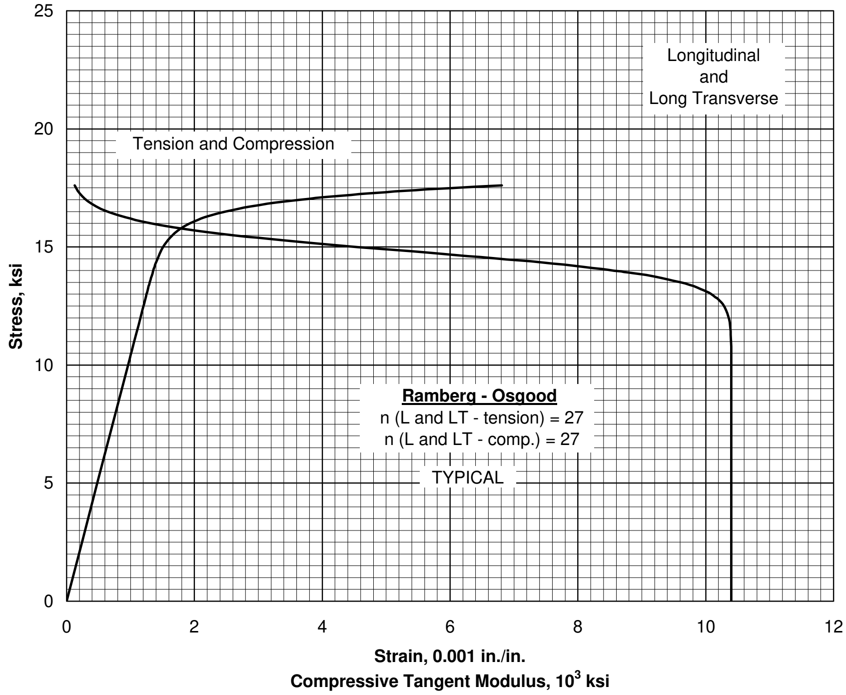


Figure 3.5.3.1.6(a). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 5086-0 aluminum alloy sheet at room temperature.

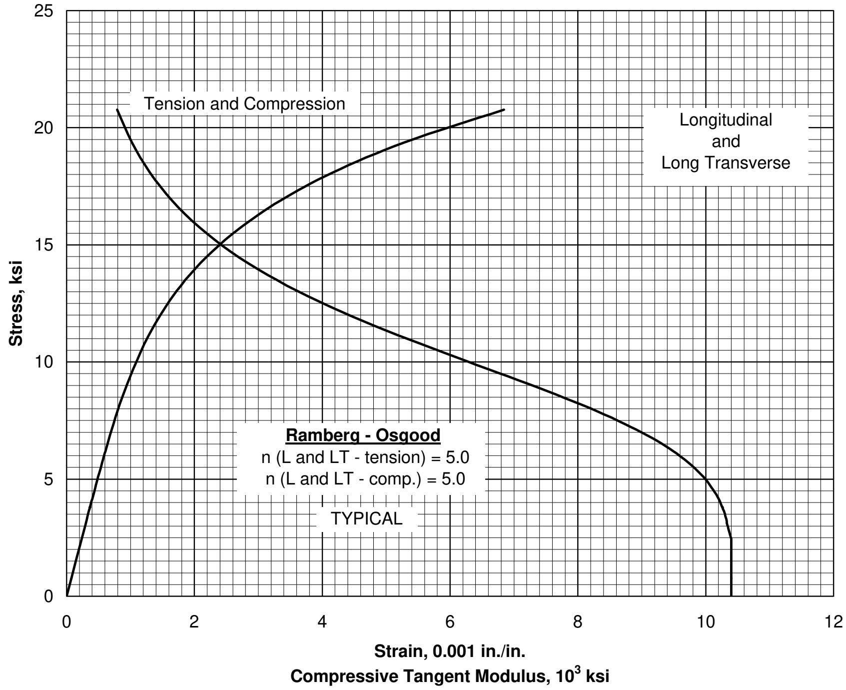


Figure 3.5.3.1.6(b). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 5086-0 aluminum alloy plate and extrusion at room temperature.

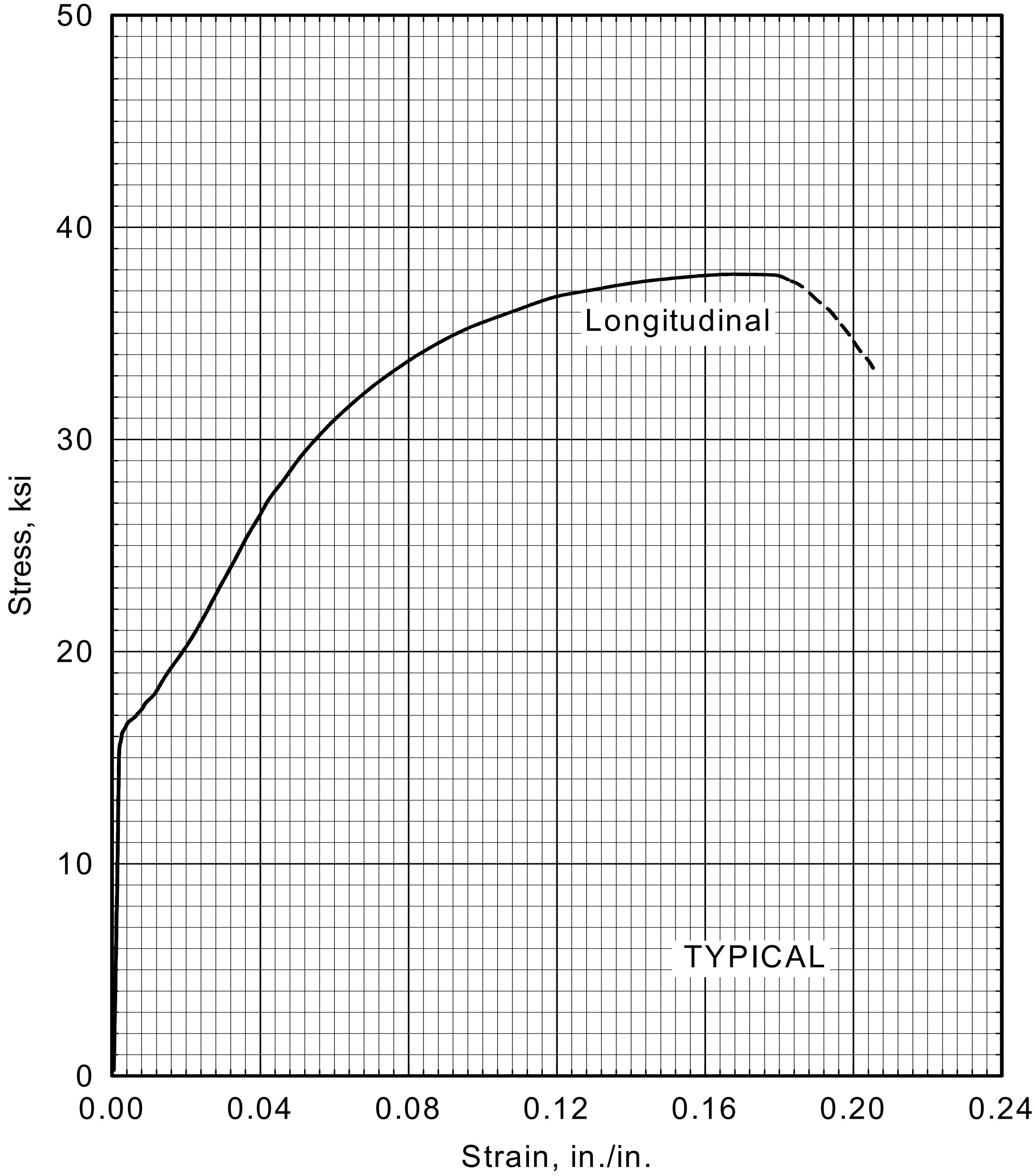


Figure 3.5.3.1.6(c). Typical tensile stress-strain curve (full range) for 5086-0 aluminum alloy sheet at room temperature.

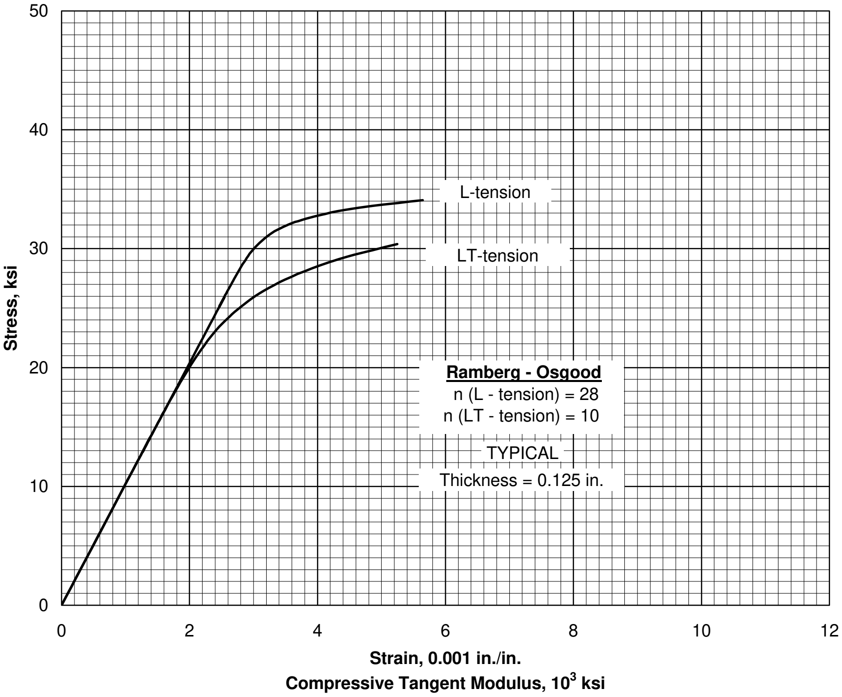


Figure 3.5.3.2.6(a). Typical tensile stress-strain curves for 5086-H32 aluminum alloy sheet at room temperature.

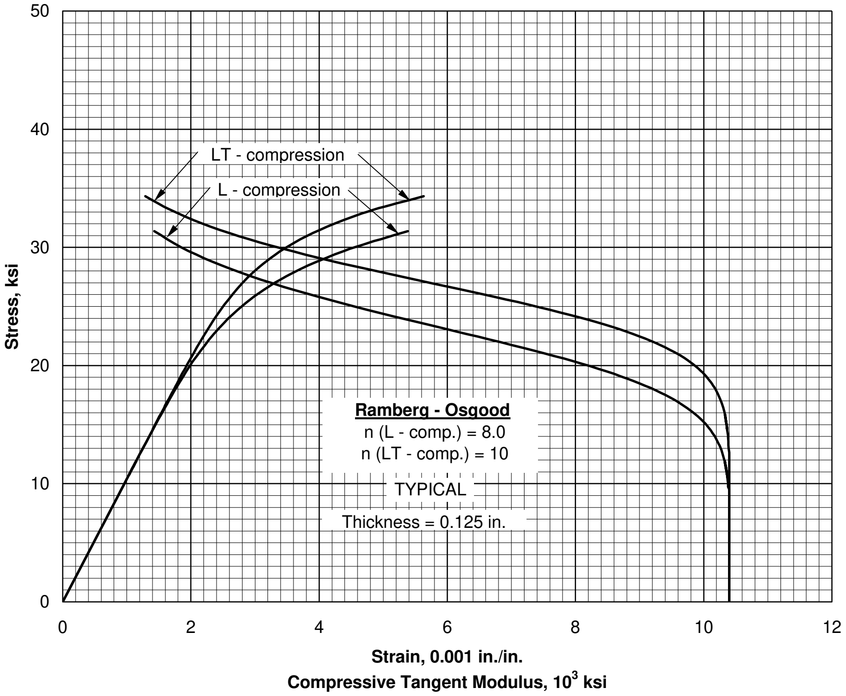


Figure 3.5.3.2.6(b). Typical compressive stress-strain and compressive tangent-modulus curves for 5086-H32 aluminum alloy sheet at room temperature.

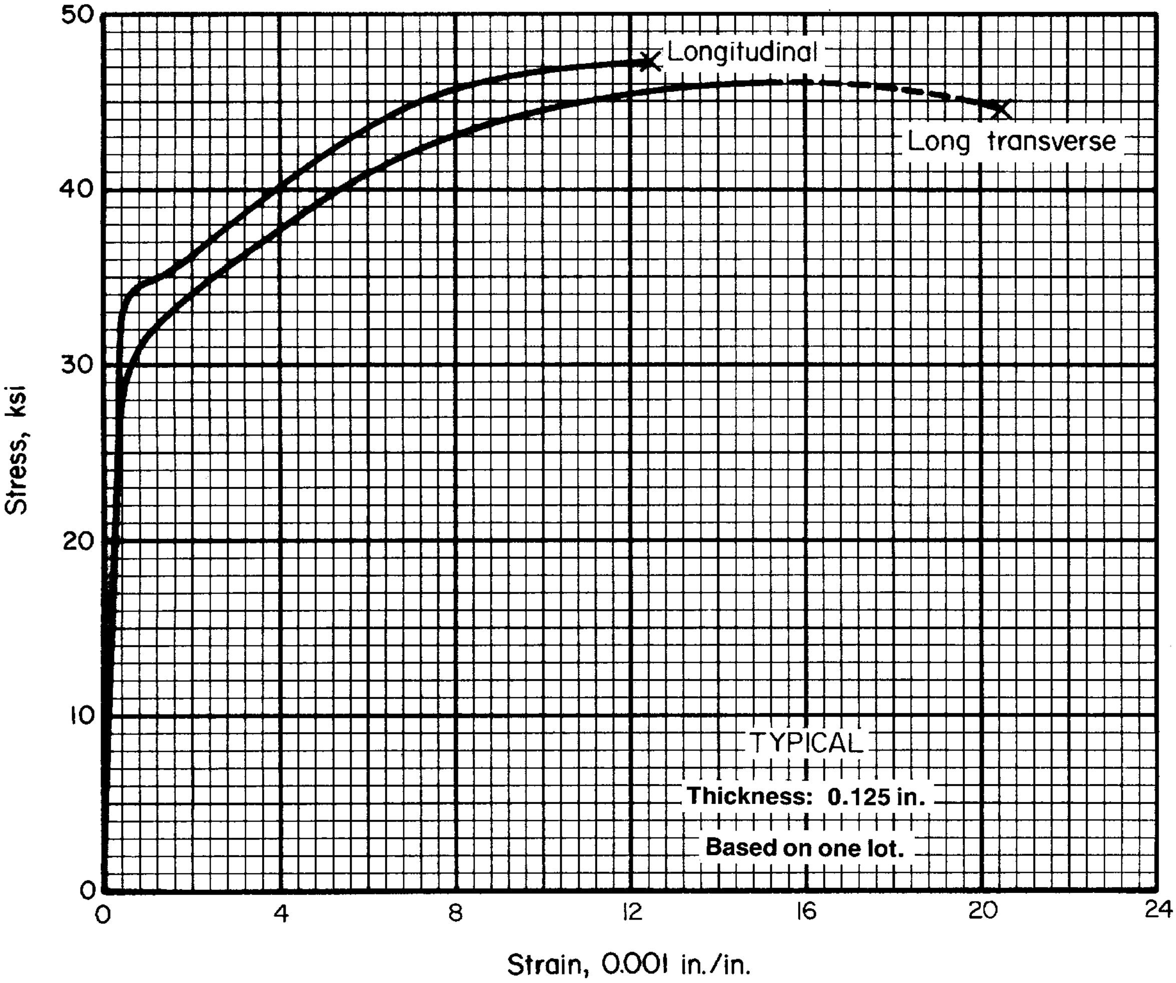


Figure 3.5.3.2.6(c). Typical tensile stress-strain curves (full range) for 5086-H32 aluminum alloy sheet at room temperature.

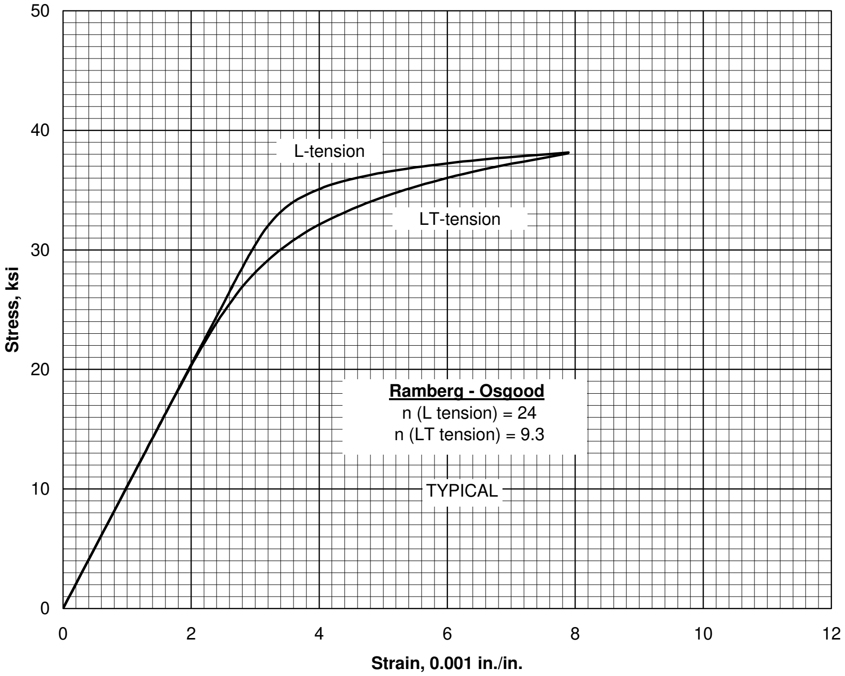


Figure 3.5.3.3.6(a). Typical tensile stress-strain curves for 5086-H34 aluminum alloy sheet at room temperature.

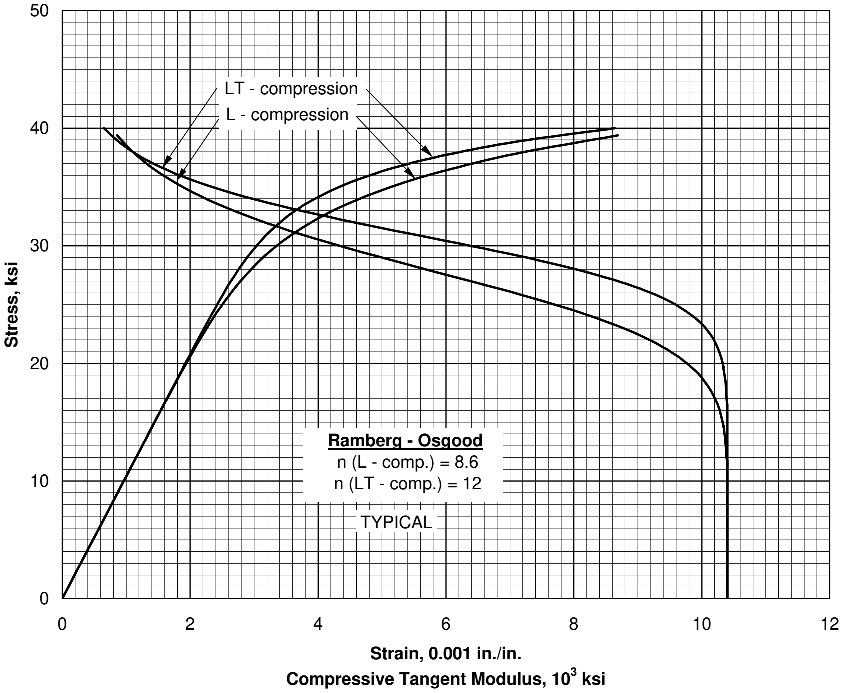


Figure 3.5.3.3.6(b). Typical compressive stress-strain and compressive tangent-modulus curves for 5086-H34 aluminum alloy sheet at room temperature.

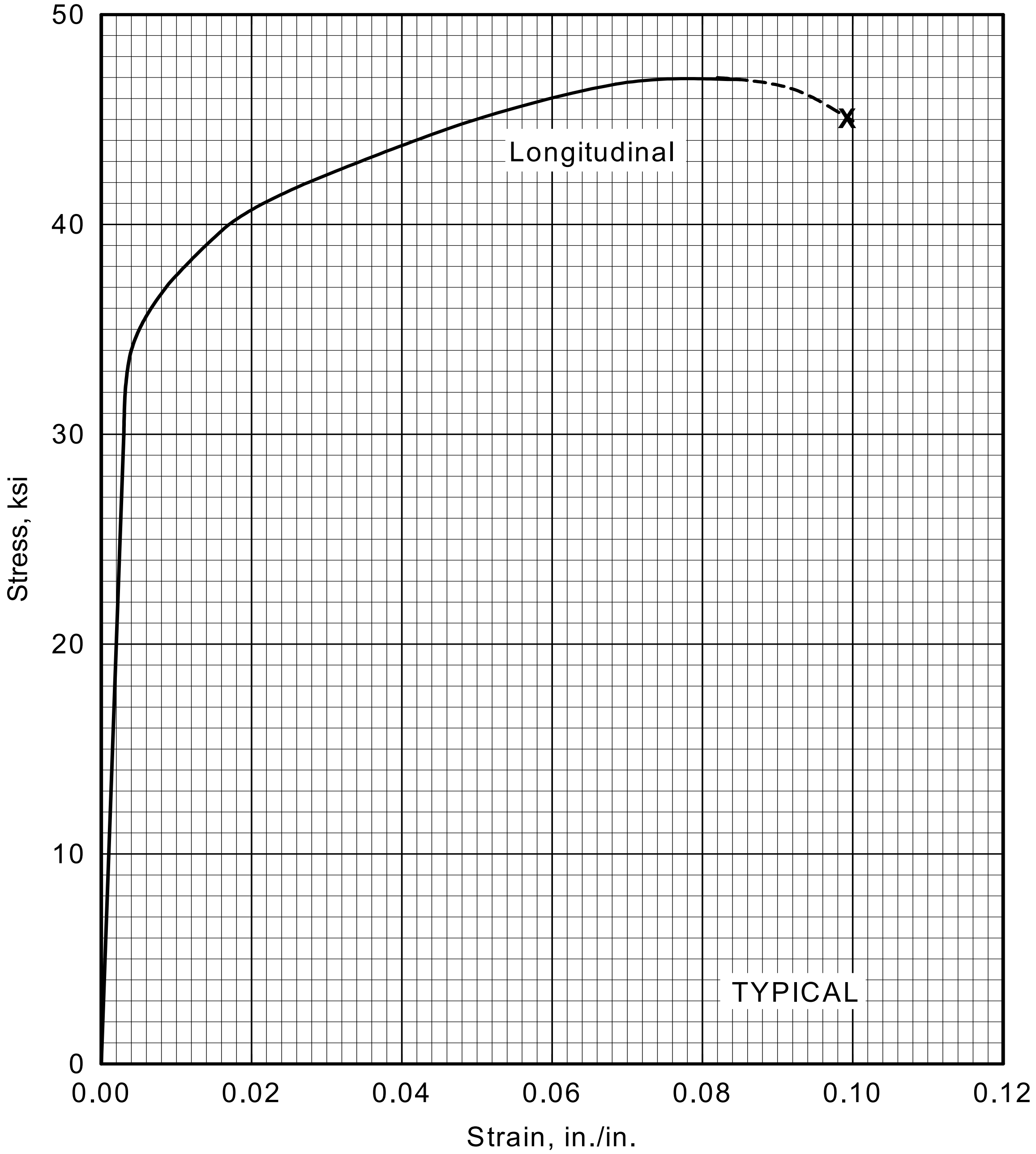


Figure 3.5.3.3.6(c). Typical tensile stress-strain curve (full range) for 5086-H34 aluminum alloy sheet at room temperature.

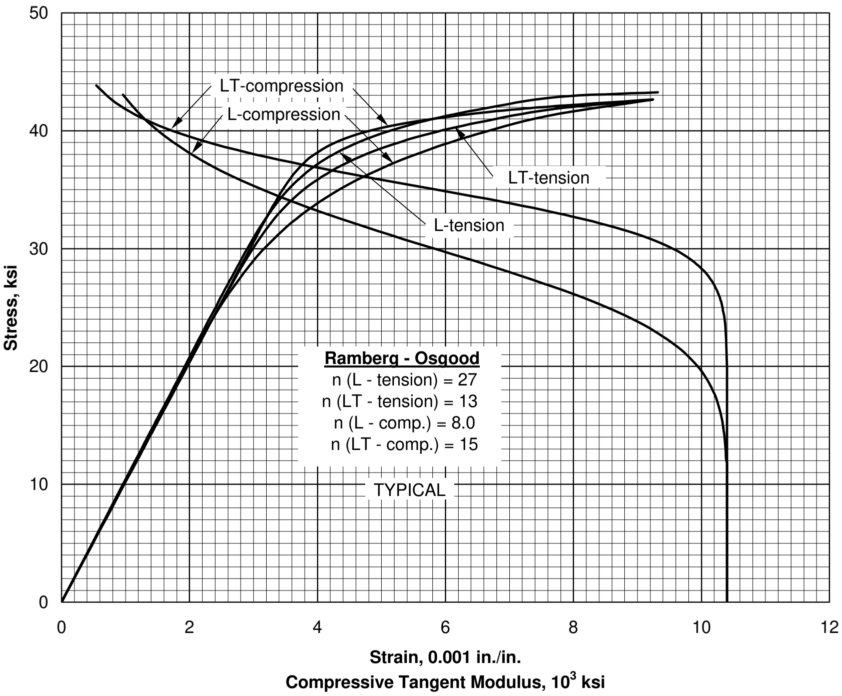


Figure 3.5.3.4.6. Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 5086-H36 aluminum alloy sheet at room temperature.

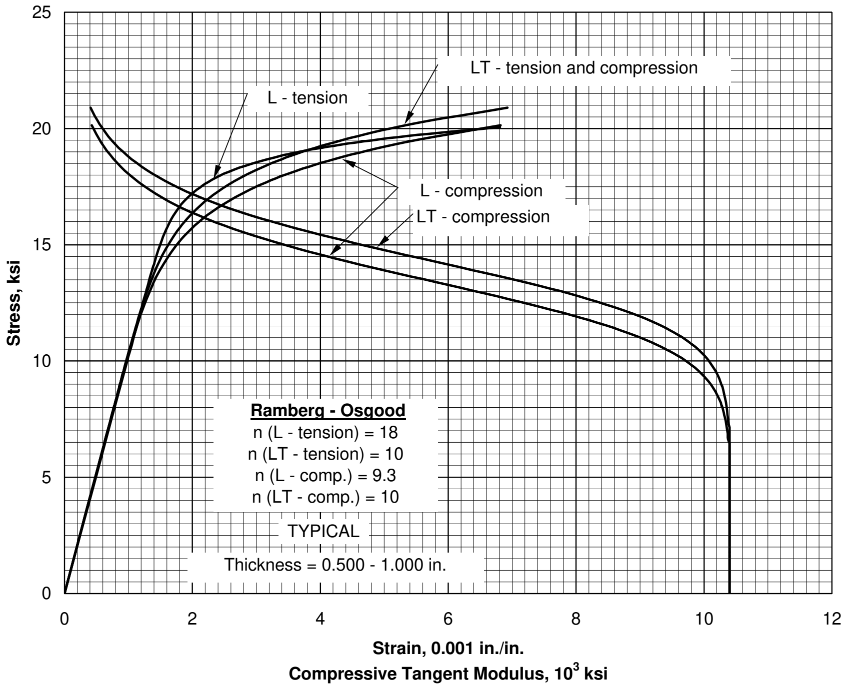


Figure 3.5.3.7.6. Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 5086-H112 aluminum alloy plate at room temperature.

3.5.4 5454 ALLOY

3.5.4.0 *Comments and Properties* — 5454 is a tough medium-strength Al-Mg alloy. It is the highest strength alloy of the 5000 series which may be used at elevated temperatures without concern about resensitization to stress-corrosion cracking. Refer to Section 3.1.2.3 for comments regarding the resistance of the alloy to stress-corrosion cracking, and to Section 3.1.3.4 for comments regarding the weldability of the alloy.

Materials specifications for 5454 aluminum alloy are presented in Table 3.5.4.0(a). Room-temperature physical properties are shown in Table 3.5.4.0(b) and (c).

Table 3.5.4.0(a). Material Specifications for 5454 Aluminum Alloy

Specification	Form
AMS-QQ-A-250/10	Sheet and plate
AMS-QQ-A-200/6	Extruded bar, rod, and shapes

The temper index for 5454 is as follows:

Section	Temper
3.5.4.1	O
3.5.4.2	H32
3.5.4.3	H34

3.5.4.1 *O Temper* — Figure 3.5.4.1.6 presents tensile and compressive stress-strain curves and this temper.

3.5.4.2 *H32 Temper* — Figure 3.5.4.2.6 presents room-temperature tensile stress-strain curves for this temper.

3.5.4.3 *H34 Temper* — Figures 3.5.4.3.6(a) and (b) present room-temperature tensile and compressive stress-strain and tangent-modulus curves for this temper.

Table 3.5.4.0(b). Design Mechanical and Physical Properties of 5454 Aluminum Alloy Sheet, Plate, and Extrusion

Specification	AMS-QQ-A-250/10							AMS-QQ-A-200/6		
Form	Sheet and plate							Extrusion		
Temper	O		H32		H34	H112		O	H111	H112
Thickness, in.	0.020-3.000		0.020-2.000		0.020-1.000	0.250-0.499	0.500-3.000	$\leq 5.000^a$	$\leq 5.000^a$	$\leq 5.000^a$
Basis	A	B	A	B	S	S	S	S	S	S
Mechanical Properties:										
F_{tu}, ksi:										
L	31	32	36	37	39	32	31	31	33	31
LT	31	32	36	37	39	32	31	...	...	31
F_{ty}, ksi:										
L	12	13	26	27	29	18	12	12	19	12
LT	12	13	24	25	28	18	12	...	...	12
F_{cy}, ksi:										
L	12	13	24	25	27	17	12	12	...	12
LT	12	13	26	27	29	18	12	...	...	12
F_{su}, ksi	19	20	21	22	23	20	19	...	...	19
F_{bru}, ksi:										
(e/D = 1.5)	46	48	52	54	57	48	46	...	...	43
(e/D = 2.0)	62	64	72	74	78	64	62	...	...	56
F_{bry}, ksi:										
(e/D = 1.5)	20	22	36	38	41	25	20	...	...	20
(e/D = 2.0)	24	26	44	46	49	31	24	...	...	24
e, percent (S-basis):										
L	[b]	...	[b]	...	[b]	8	[b]	14	12	12
E, 10^3 ksi	10.2									
E_c, 10^3 ksi	10.4									
G, 10^3 ksi	3.85									
μ	0.33									
Physical Properties:										
ω, lb/in.^{3}	0.097									
C, Btu/(lb)(°F)	0.23 (at 212°F)									
K, Btu/[(hr)(ft^2)(°F)/ft]	78 (at 77°F)									
α, 10^{-6} in./in./°F	13.1 (68 to 212°F)									

a Cross-sectional area ≤ 32 in^2.
b See Table 3.5.4.0(c).

Table 3.5.4.0(c). Minimum Elongation Values for 5454 Aluminum Alloy Sheet and Plate

Temper	Thickness Range, inch	Elongation (L), percent
O	0.020-0.031	12
	0.030-0.050	14
	0.051-0.113	16
	0.114-3.000	18
H32	0.020-0.050	5
	0.051-0.249	8
	0.250-2.000	12
H34	0.020-0.050	4
	0.051-0.161	6
	0.162-0.249	7
	0.250-1.000	10
H112	0.500-2.000	11
	2.001-3.000	15

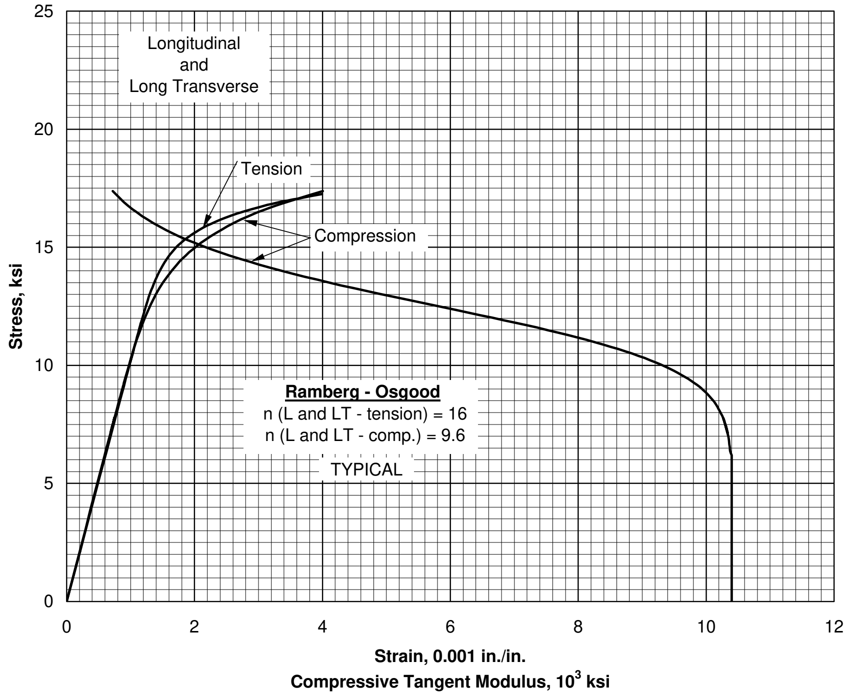


Figure 3.5.4.1.6. Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 5454-0 aluminum alloy sheet, plate, extrusion at room temperature.

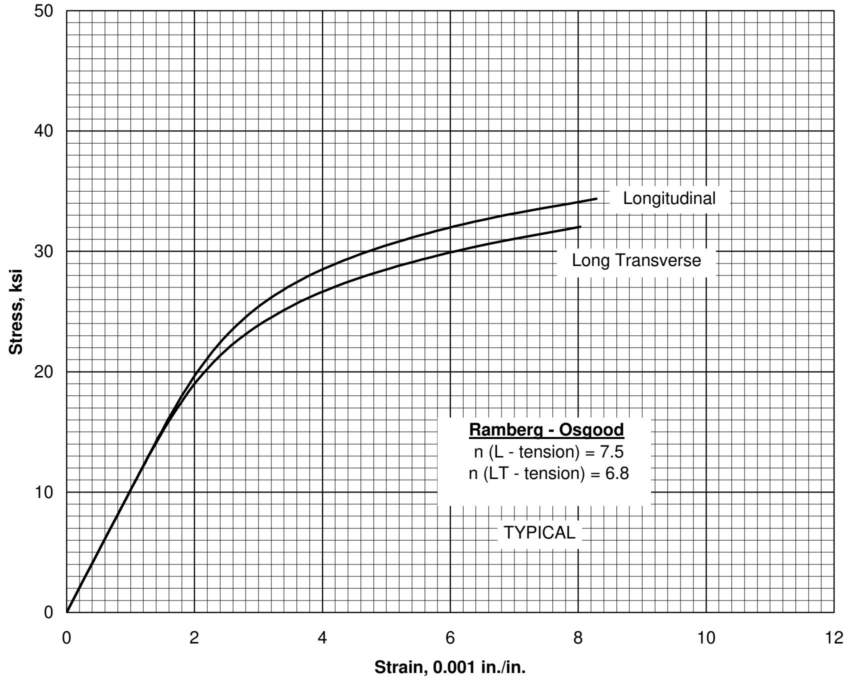


Figure 3.5.4.2.6. Typical tensile stress-strain curves for 5454-H32 aluminum alloy plate at room temperature.

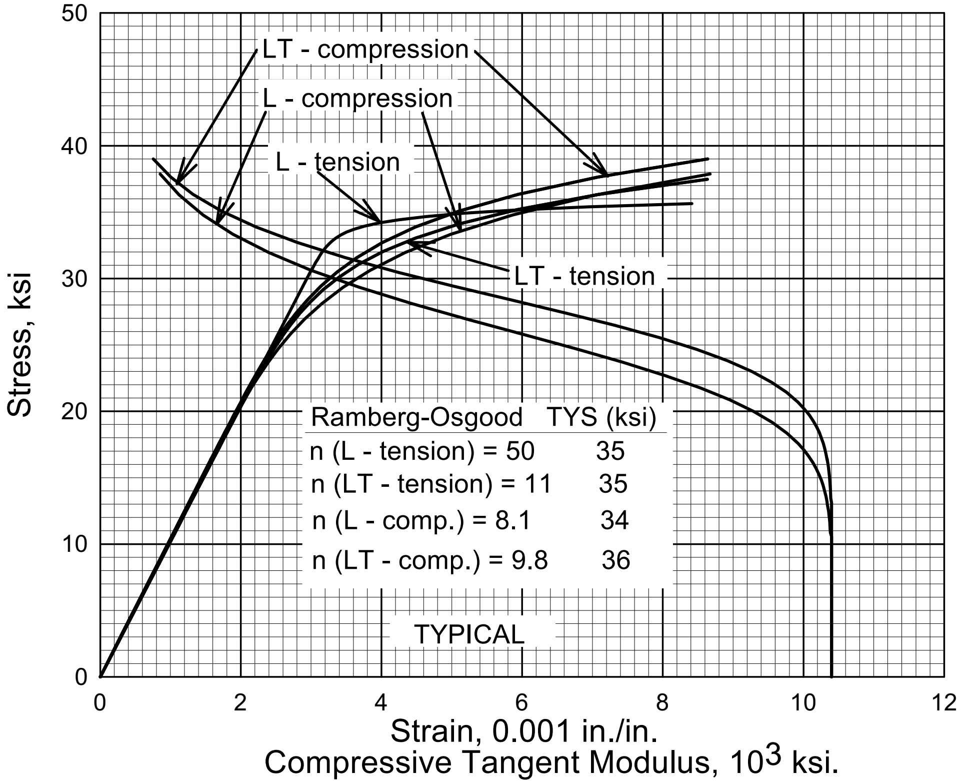


Figure 3.5.4.3.6(a). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 5454-H34 aluminum alloy sheet at room temperature.

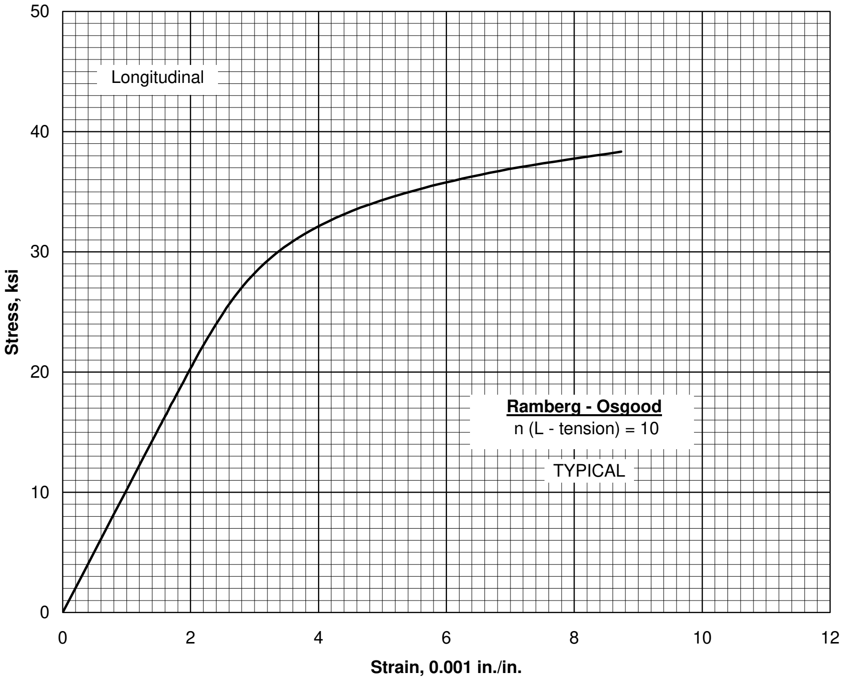


Figure 3.5.4.3.6(b). Typical tensile stress-strain curve for 5454-H34 aluminum alloy plate at room temperature.

3.5.5 5456 ALLOY

3.5.5.0 *Comments and Properties* — 5456 is the highest strength alloy of the Al-Mg group. It has high resistance to corrosion, but should not be used in strain-hardened tempers at temperatures above 150°F because of possible sensitization to stress-corrosion cracking. Refer to Section 3.1.2.3 for comments regarding the resistance of the alloy to stress-corrosion cracking, and to Section 3.1.3.4 for comments regarding the weldability of the alloy.

Some material specifications for 5456 aluminum alloy are presented in Table 3.5.5.0(a). Room-temperature mechanical and physical properties are shown in Tables 3.5.5.0(b) and (c). The effect of temperature on physical properties is shown in Figure 3.5.5.0.

Table 3.5.5.0(a). Material Specifications for 5456 Aluminum Alloy

Specification	Form
AMS-QQ-A-250/9	Sheet and plate
AMS-QQ-A-200/7	Extruded bar, rod, and shapes

The temper index for 5456 is as follows:

Section	Temper
3.5.5.1	O
3.5.5.2	H111
3.5.5.3	H112
3.5.5.4	H321

3.5.5.1 *O Temper* — Room-temperature tensile and compressive stress-strain and tangent-modulus curves for this temper are presented in Figures 3.5.5.1.6(a) and (b).

3.5.5.2 *H111 Temper* — Room-temperature tensile and compressive stress-strain and tangent-modulus curves for this temper are presented in Figure 3.5.5.2.6.

3.5.5.3 *H112 Temper* —

3.5.5.4 *H321 Temper* — Room-temperature tensile and compressive stress-strain and tangent-modulus curves for this temper are presented in Figure 3.5.5.4.6.

Table 3.5.5.0(b). Design Mechanical and Physical Properties of 5456 Aluminum Alloy Sheet and Plate

Specification	AMS-QQ-A-250/9										
Form	Sheet and plate										
Temper	O					H112		H321			
Thickness, in.	0.051-1.500	1.501-3.000	3.001-5.000	5.001-7.000	7.001-8.000	0.250-1.500	1.501-3.000	0.188-0.624	0.625-1.250	1.251-1.500	1.501-3.000
Basis	S	S	S	S	S	S	S	S	S	S	S
Mechanical Properties:											
F_{tu}, ksi:											
L	42	41	40	39	38	42	41	46	46	44	41
LT	42	...	...	...	...	...	...	46	45	43	...
F_{ty}, ksi:											
L	19	18	17	16	15	19	18	33	33	31	29
LT	19	...	...	...	...	...	...	30	29	28	...
F_{cy}, ksi:											
L	19	...	...	...	...	...	...	27	26	24	...
LT	19	...	...	...	...	...	...	33	31	29	...
F_{su}, ksi	26	...	...	...	...	...	...	27	27	25	...
F_{bru}, ksi:											
(e/D = 1.5)	63	...	...	...	...	...	...	67	67	64	...
(e/D = 2.0)	84	...	...	...	...	...	...	84	84	80	...
F_{bry}, ksi:											
(e/D = 1.5)	32	...	...	...	...	...	...	46	46	43	...
(e/D = 2.0)	38	...	...	...	...	...	...	53	53	50	...
e, percent:											
L	16	16	14	14	12	12	12	12	12	12	12
E, 10^3 ksi	10.2										
E_c, 10^3 ksi	10.4										
G, 10^3 ksi	3.85										
μ	0.33										
Physical Properties:											
ω, lb/in.^{3}	0.096										
C, Btu/(lb)(°F)	0.23 (at 212°F)										
K, Btu/[(hr)(ft^2)(°F)/ft] ..	...										
α, 10^{-6} in./in./°F	See Figure 3.5.5.0										

Table 3.5.5.0(c). Design Mechanical and Physical Properties of 5456 Aluminum Alloy Extrusion

Specification	AMS-QQ-A-200/7		
Form	Extruded bar, rod, and shapes		
Temper	O	H111	H112
Cross-Sectional Area, in.^{2}	≤32		
Thickness or Diameter, in.	≤5.000	≤5.000	≤5.000
Basis	S	S	S
Mechanical Properties:			
F_{tu}, ksi:			
L	41	42	41
LT	...	...	41
F_{ty}, ksi:			
L	19	26	19
LT	...	...	19
F_{cy}, ksi:			
L	19	...	19
LT	...	...	19
F_{su}, ksi	...	...	23
F_{bru}, ksi:			
(e/D = 1.5)	...	...	57
(e/D = 2.0)	...	...	74
F_{bry}, ksi:			
(e/D = 1.5)	...	...	34
(e/D = 2.0)	...	...	38
e, percent:			
L	14	12	12
E, 10^3 ksi	10.2		
E_c, 10^3 ksi	10.4		
G, 10^3 ksi	3.85		
μ	0.33		
Physical Properties:			
ω, lb/in.^{3}	0.096		
C, Btu/(lb)(°F)	0.23 (at 212°F)		
K, Btu/[(hr)(ft^2)(°F)/ft]	...		
α, 10^{-6} in./in./°F	See Figure 3.5.5.0		

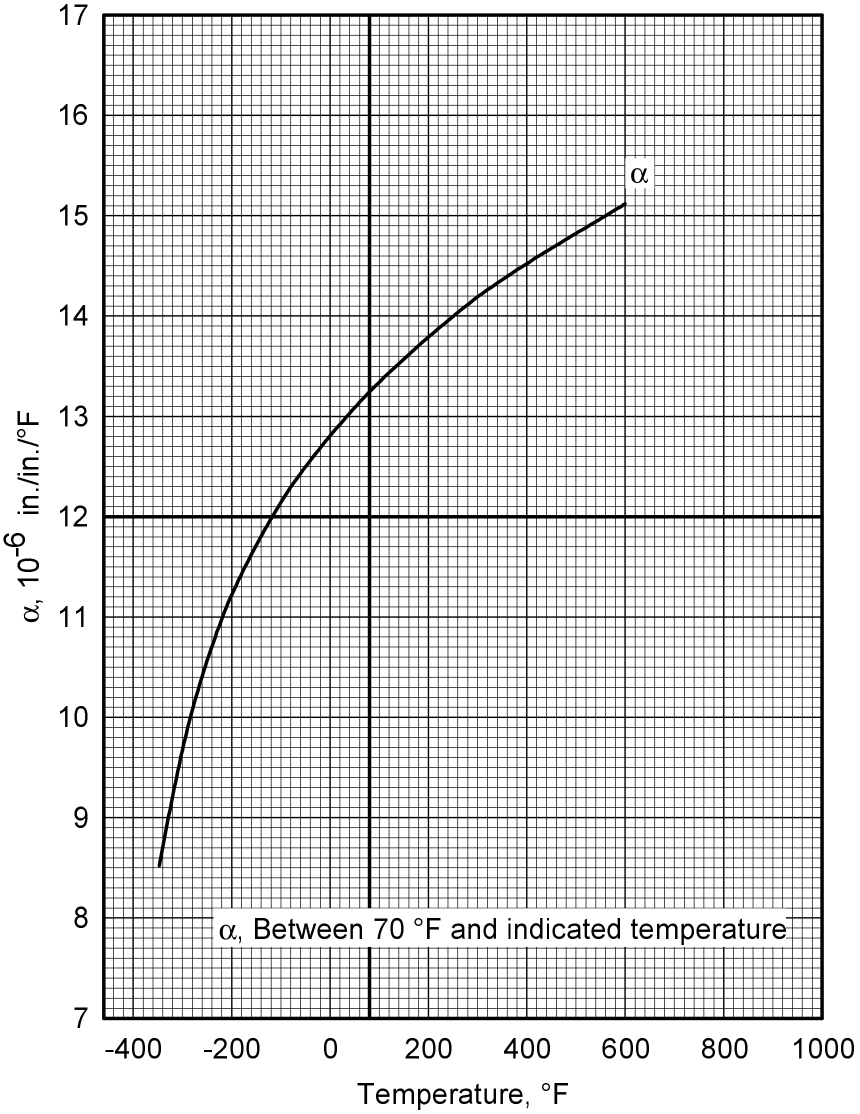


Figure 3.5.5.0. Effect of temperature on the physical properties of 5456 aluminum alloy.

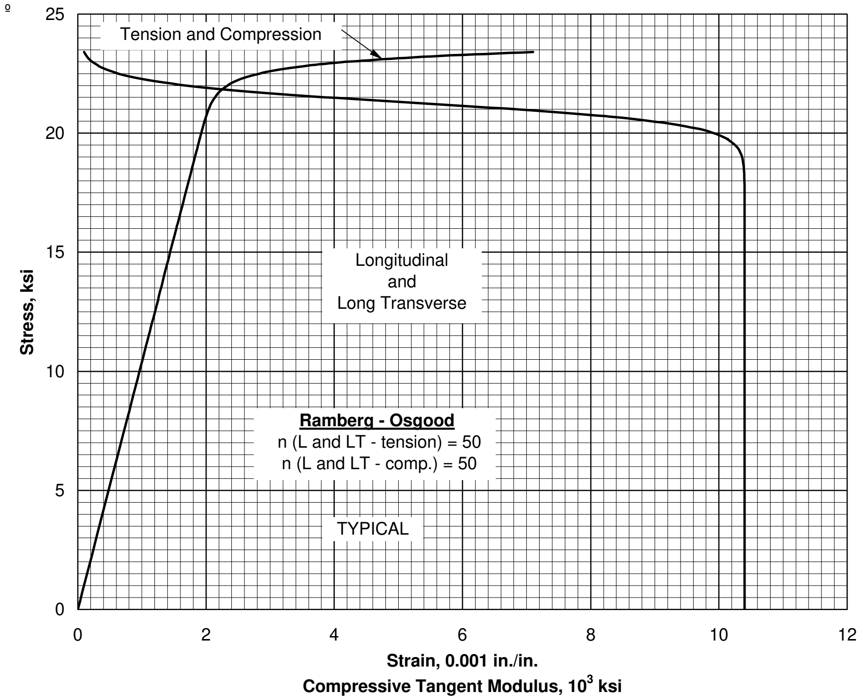


Figure 3.5.5.1.6(a). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 5456-0 aluminum alloy sheet and plate at room temperature.

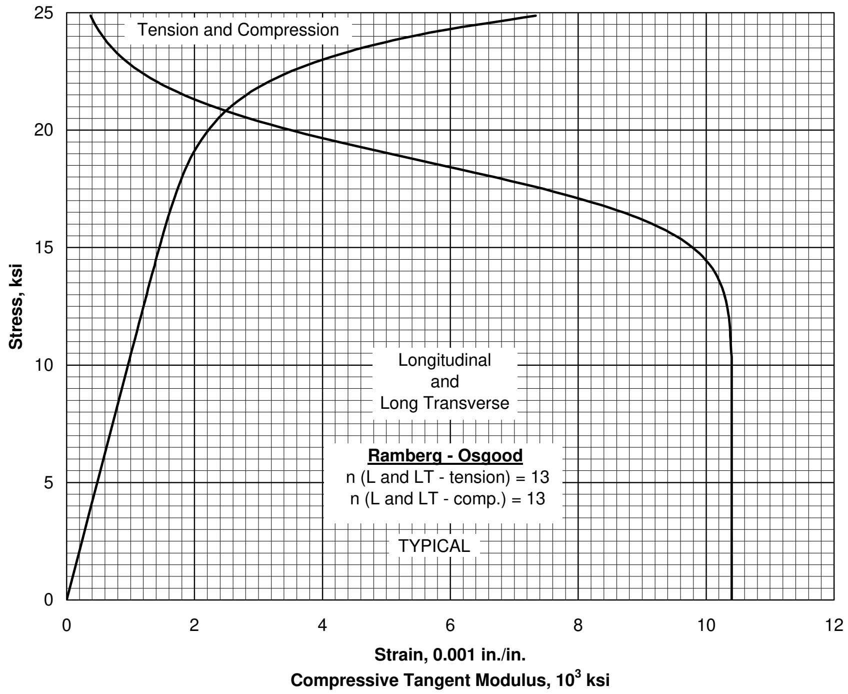


Figure 3.5.5.1.6(b). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 5456-0 aluminum alloy extrusion at room temperature.

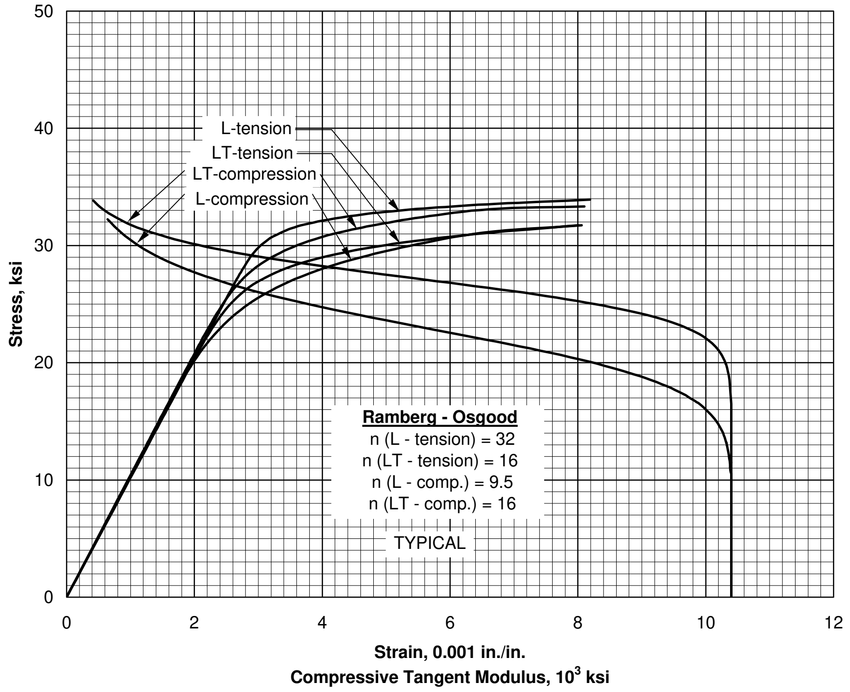


Figure 3.5.5.2.6. Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 5456-H111 aluminum alloy extrusion at room temperature.

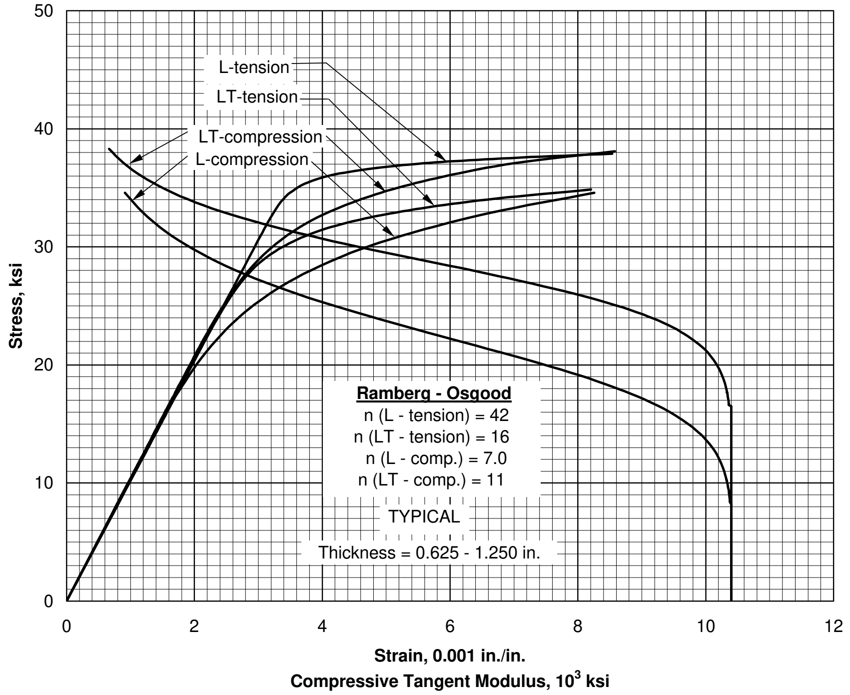


Figure 3.5.5.4.6. Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 5456-H321 aluminum alloy plate at room temperature.

3.6 6000 SERIES WROUGHT ALLOYS

Alloys of the 6000 series contain magnesium and silicon as their principal alloying elements.

3.6.1 6013 ALLOY

3.6.1.0 *Comments and Properties* — 6013 is a Mg-Si-Cu-Mn alloy which is weldable. This alloy has 25 percent higher strength in the T6 temper than 6061-T6. It has improved toughness, fatigue strength, and stretch forming characteristics compared to 6061 with equivalent stress corrosion characteristics. Refer to 3.1.3.4 for comments regarding weldability of the alloy. Material specifications for 6013 are shown in Table 3.6.1.0(a). Room-temperature mechanical and physical properties are presented in Table 3.6.1.0(b).

Table 3.6.1.0(a). Material Specifications for 6013 Aluminum Alloy

Specification	Form
AMS 4347	Sheet (T4)
AMS 4216	Sheet (T6)

The temper index is as follows:

Section	Temper
3.6.1.1	T6

3.6.1.1 *T6 Temper* — Stress-strain and tangent-modulus curves are presented in Figures 3.6.1.1.6(a) and (b).

Table 3.6.1.0(b). Design Mechanical and Physical Properties of 6013 Aluminum Alloy Sheet

Specification	AMS 4216 and AMS 4347		
Form	Sheet		
Temper	T6		
Thickness, in.	0.010-0.062	0.063-0.125	0.126-0.249
Basis	S	S	S
Mechanical Properties:			
F_{tu}, ksi:			
L	52	52	52
LT	52	52	52
F_{ty}, ksi:			
L	47	47	48
LT	46	46	46
F_{cy}, ksi:			
L	48	48	48
LT	48	48	49
F_{su}, ksi	32	32	32
F_{bru}[a], ksi:			
(e/D=1.5)	85	85	85
(e/D=2.0)	111	111	111
F_{bry}[a], ksi:			
(e/D=1.5)	66	69	71
(e/D=2.0)	76	80	82
e, percent:			
LT	8	8	8
E, 10^3 ksi	9.9		
E_c, 10^3 ksi	10.1		
G, 10^3 ksi	3.8		
μ	0.33		
Physical Properties:			
ω, lb/in^3	0.098		
C, K, and α	...		

[a] Bearing values are "dry pin" values per Section 1.4.7.1.

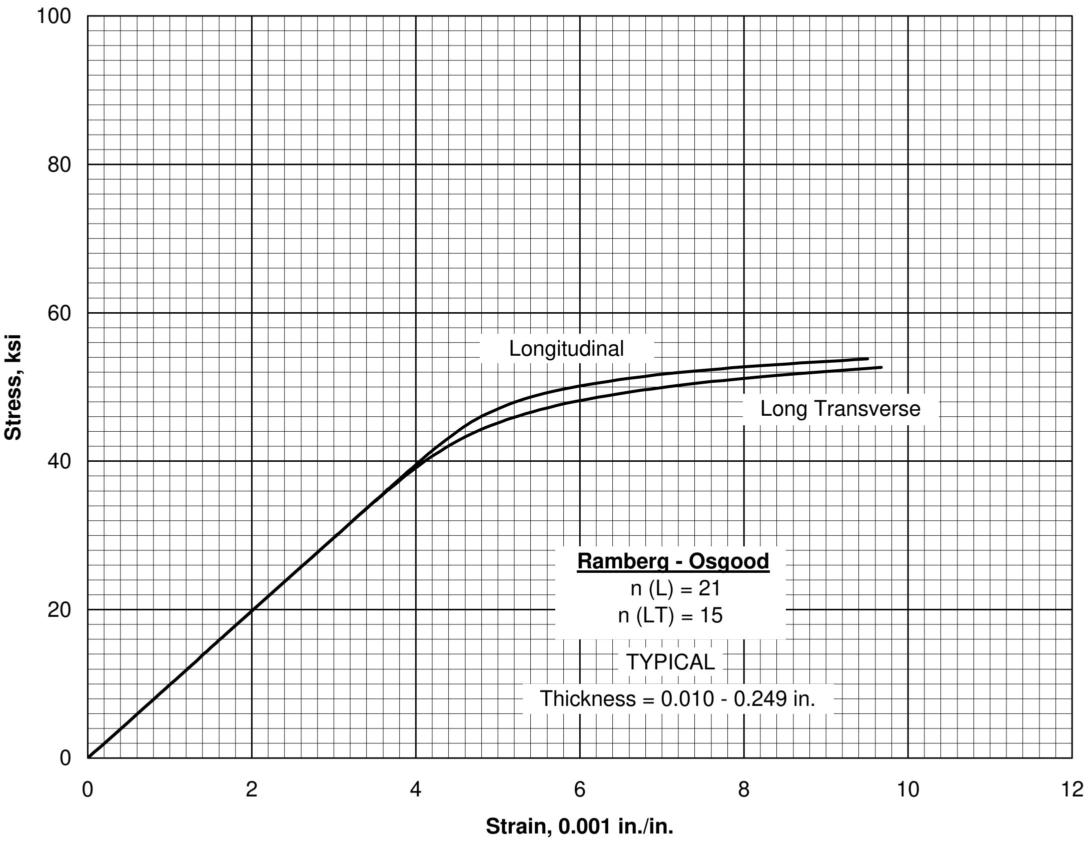


Figure 3.6.1.1.6(a). Typical tensile stress-strain curves for 6013-T6 aluminum alloy sheet at room temperature.

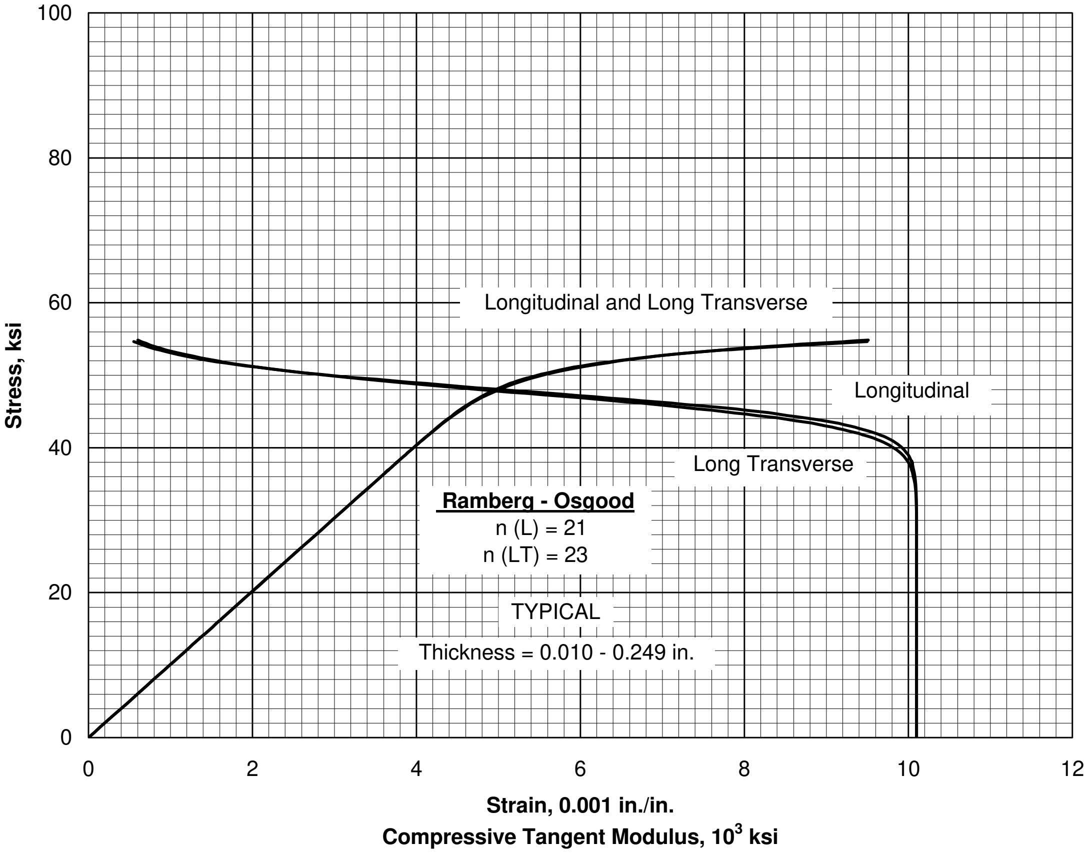


Figure 3.6.1.1.6(b). Typical compressive stress-strain and compressive tangent-modulus curves for 6013-T6 aluminum alloy sheet at room temperature.

3.6.2 6061 ALLOY

3.6.2.0 ***Comments and Properties*** — 6061 has been used in a wide range of applications, including cryogenic applications requiring high toughness. Refer to Section 3.1.3.4 for comments regarding the weldability of the alloy.

The properties of extrusions should be based upon the thickness at the time of quenching prior to machining. Selection of the mechanical properties based upon its final machined thickness may be unconservative; therefore, the thickness at the time of quenching to achieve properties is an important factor in the selection of the proper thickness column. For extrusions having sections with various thicknesses, consideration should be given to the properties as a function of thickness.

Material specifications for 6061 are presented in Table 3.6.2.0(a). Room-temperature mechanical and physical properties are shown in Tables 3.6.2.0(b) through (g). The effect of temperature on the physical properties is shown in Figure 3.6.2.0.

The temper index for 6061 is as follows:

Section	Temper
3.6.2.1	T4, T42, T451, T4510, and T4511
3.6.2.2	T6, T62, T651, T652, T6510, and T6511

3.6.2.1 ***T4, T42, T451, T4510, and T4511 Tempers*** — For effect of temperature on modulus values, use Figure 3.6.2.2.4.

3.6.2.2 ***T6, T62, T651, T652, T6510, and T6511 Tempers*** — Figures 3.6.2.2.1(a) through (d), 3.6.2.2.4, and 3.6.2.2.5(a) and (b) present elevated temperature curves for various mechanical properties. Figures 3.6.2.2.6(a) through (k) contain tensile and compression stress-strain curves at room temperature and elevated temperatures, and tangent-modulus curves at room temperature for various products and tempers. Figures 3.6.2.2.6(l) through (o) present full-range tensile stress-strain curves at room temperature for various products and tempers. Figure 3.6.2.2.8 contains unnotched fatigue data for various wrought products at room temperature.

Table 3.6.2.0(a). Material Specifications for 6061 Aluminum Alloy

Specification	Form
AMS 4025	Sheet and plate
AMS 4026	Sheet and plate
AMS 4027	Sheet and plate
AMS-QQ-A-250/11	Sheet and plate
AMS 4115	Bar and rod, rolled or cold-finished
AMS 4116	Bar and rod, cold-finished
AMS 4117	Bar and rod, rolled or cold-finished
AMS-QQ-A-225/8	Rolled bar, rod, and shapes
AMS 4150	Extruded rod, bar, and shapes
AMS 4160	Extrusion
AMS 4161	Extrusion
AMS 4172	Extrusion
AMS 4173	Extruded rod, bar, and shapes
AMS-QQ-A-200/8	Extruded rod, bar, shapes, and tubing
AMS-A-22771	Forging
AMS 4080	Tubing, seamless, drawn
AMS 4082	Tubing, seamless, drawn
AMS-WW-T-700/6	Seamless drawn tubing
AMS 4127	Forging
AMS 4248	Hand forging
AMS-QQ-A-367	Forging

Table 3.6.2.0(b$_1$). Design Mechanical and Physical Properties of 6061 Aluminum Alloy Sheet

Specification	AMS 4026 and AMS-QQ-A-250/11		AMS-QQ-A-250/11	AMS 4025, AMS 4027 and AMS-QQ-A-250/11	
Form	Sheet				
Temper	T4		T42[a]	T6 and T62[b]	
Thickness, in.	0.010-0.249		0.010-0.249	0.010-0.249	
Basis	A	B	S	A	B
Mechanical Properties:					
F_{tu}, ksi:					
L	...	...	...	42	43
LT	30	32	30	42	43
F_{ty}, ksi:					
L	...	...	...	36	38
LT	16	18	14	35	37
F_{cy}, ksi:					
L	...	...	...	35	37
LT	16	18	...	36	38
F_{su}, ksi	20	21	...	27	28
F_{bru}, ksi:					
(e/D = 1.5)	48	51	...	67	69
(e/D = 2.0)	63	67	...	88	90
F_{bry}, ksi:					
(e/D = 1.5)	22	25	...	50	53
(e/D = 2.0)	26	29	...	58	61
e, percent (S-basis):					
LT	[c]	...	[c]	[c]	...
E, 10^3 ksi	9.9				
E_c, 10^3 ksi	10.1				
G, 10^3 ksi	3.8				
μ	0.33				
Physical Properties:					
ω, lb/in.^{3}	0.098				
C, K, and α	See Figure 3.6.2.0				

[a] Design allowables were based upon data obtained from testing samples of material, supplied in the O or F temper, which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained by the user may be lower than those listed if the material has been formed or otherwise cold or hot worked, particularly in the annealed temper, prior to solution heat treatment.

[b] Design allowables were based upon data obtained from testing T6 sheet and from testing samples of sheet, supplied in the O or F temper, which were heat treated to T62 temper to demonstrate response to heat treatment by suppliers. Properties obtained may be lower than those listed if the material has been formed or otherwise cold worked, particularly in the annealed temper, prior to solution heat treatment.

[c] See Table 3.6.2.0(b$_3$).

Table 3.6.2.0(b_2). Design Mechanical and Physical Properties of 6061 Aluminum Alloy Plate

Specification	AMS 4026 and AMS-QQ-A-250/11				AMS-QQ-A-250/11		AMS 4025, AMS 4027 and AMS-QQ-A-250/11					
Form	Plate											
Temper	T451				T42[a]		T651 and T62[b]					
Thickness, in.	0.250-2.000		2.001-3.000		0.250-1.000	1.001-3.000	0.250-2.000		2.001-3.000		3.001-4.000	4.001-6.000[c]
Basis	A	B	A	B	S	S	A	B	A	B	S	S
Mechanical Properties:												
F_{tu}, ksi:												
L	...	...	...	...	...	...	42	43	...	...	...	...
LT	30	32	30	32	30	30	42	43	42	43	42	40
F_{ty}, ksi:												
L	...	...	...	...	...	...	36	38	...	...	...	...
LT	16	18	16	18	14	14	35	37	35	37	35	35
F_{cy}, ksi:												
L	...	...	...	...	...	...	35	37	...	...	...	...
LT	16	18	...	...	...	...	36	38	...	...	...	...
F_{su}, ksi	20	21	...	...	...	...	27	28	...	...	...	...
F_{bru}, ksi:												
(e/D = 1.5)	48	52	...	...	...	...	67	69	...	...	...	...
(e/D = 2.0)	63	67	...	...	...	...	88	90	...	...	...	...
F_{bry}, ksi:												
(e/D = 1.5)	22	25	...	...	...	...	50	53	...	...	...	...
(e/D = 2.0)	26	29	...	...	...	...	58	61	...	...	...	...
e, percent:												
L	[d]	...	16	...	18	16	[d]	...	6	...	6	6
E, 10^3 ksi	9.9											
E_c, 10^3 ksi	10.1											
G, 10^3 ksi	3.8											
μ	0.33											
Physical Properties:												
ω, lb/in.^{3}	0.098											
C, K, and α,	See Figure 3.6.2.0											

[a] Design allowables were based upon data obtained from testing samples of material, supplied in the O temper, which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained by the user may be lower than those listed if the material has been formed or otherwise cold or hot worked, particularly in the annealed temper, prior to solution heat treatment.

[b] Design allowables were based upon data obtained from testing T651 plate and from testing samples of plate, supplied in the O temper, which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained may be lower than those listed if the material has been formed or otherwise cold worked, particularly in the annealed temper, prior to solution heat treatment.

[c] Properties for this thickness apply only to T651 temper.

[d] See Table 3.6.2.0(b_3).

Table 3.6.2.0(b_3). Minimum Elongation Values for 6061 Aluminum Alloy Sheet and Plate

Temper and Product	Thickness, inch	Elongation (LT), percent
T4 or T42 sheet	0.010-0.020	14
	0.021-0.249	16
T451 plate	0.250-1.000	18
	1.001-2.000	16
T6 or T62 sheet	0.010-0.020	8
	0.021-0.249	10
T651 or T62 plate	0.250-0.499	10
	0.500-1.000	9
	1.001-2.000	8

Table 3.6.2.0(c_1). Design Mechanical and Physical Properties of 6061 Aluminum Alloy Tube and Pipe

Specification	AMS-WW-T-700/6		AMS 4080, AMS 4082, and AMS-WW-T-700/6
Form	Drawn tube		
Temper	T4	T42[a]	T6[b] and T62
Wall Thickness, in. ..	0.025-0.500	0.025-0.500	0.025-0.500
Outside Diameter, in.	...		
Basis	S	S	S
Mechanical Properties:			
F_{tu}, ksi:			
L	30	30	42
F_{ty}, ksi:			
L	16	14	35
F_{cy}, ksi:			
L	14	...	34
F_{su}, ksi	20	...	27
F_{bru}, ksi:			
(e/D = 1.5)	48	...	67
(e/D = 2.0)	63	...	88
F_{bry}, ksi:			
(e/D = 1.5)	22	...	49
(e/D = 2.0)	26	...	56
e, percent:			
L	[c]	[c]	[c]
E, 10^3 ksi	9.9		
E_c, 10^3 ksi	10.1		
G, 10^3 ksi	3.8		
μ	0.33		
Physical Properties:			
ω, lb/in.^{3}	0.098		
C, K, and α	See Figure 3.6.2.0		

a Design allowables were based upon data obtained from testing samples of material, supplied in the O temper, which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained by the user may be lower than those listed if the material has been formed or otherwise cold or hot worked, particularly in the annealed temper, prior to solution heat treatment.

b Design allowables were based upon data obtained from testing T6 temper tube and from testing samples of tube, supplied in the O temper, which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained by the user may be lower than those listed if the material has been formed or otherwise cold worked, particularly in the annealed temper, prior to solution heat treatment.

c See Table 3.6.2.0(c_2).

Table 3.6.2.0(c_2). Minimum Elongation Values for 6061 Aluminum Alloy Tubing

Temper	Wall Thickness, inch	Elongation (L), percent Full-Section Specimen	Elongation (L), percent Cut-Out Specimen
T4 or T42	0.025-0.049	16	14
	0.050-0.259	18	16
	0.260-0.500	20	18
T6 or T62	0.025-0.049	10	8
	0.050-0.259	12	10
	0.260-0.500	14	12

Table 3.6.2.0(d). Design Mechanical and Physical Properties of 6061 Aluminum Alloy Rolled, Drawn, or Cold-Finished Bar, Rod, and Shapes

Specification	AMS 4116 & AMS-QQ-A-225/8	AMS 4128 & AMS-QQ-A-225/8	AMS-QQ-A-225/8	AMS 4117 & AMS-QQ-A-225/8	AMS 4128 & AMS-QQ-A-225/8	AMS 4115, AMS 4116, & AMS-QQ-A-225/8
Form	Rolled, drawn, or cold-finished rod and special shapes					
Temper	T4	T451	T42[a]	T6	T651	T62[a]
Cross-Sectional Area, in^2	≤ 50					
Thickness, in.	≤ 8.000	0.500-8.000	≤ 8.000	≤ 8.000	0.500-8.000	≤ 8.000
Basis	S	S	S	S	S	S
Mechanical Properties:						
F_{tu}, ksi:						
L	30	30	30	42	42	42
F_{ty}, ksi:						
L	16	16	14	35	35	35
F_{cy}, ksi:						
L	14	14	...	34	34	...
F_{su}, ksi	20	20	...	27	27	...
F_{bru}, ksi:						
(e/D = 1.5)	48	48	...	67	67	...
(e/D = 2.0)	63	63	...	88	88	...
F_{bry}, ksi:						
(e/D = 1.5)	22	22	...	49	49	...
(e/D = 2.0)	26	26	...	56	56	...
e, percent:						
L	18	18	18	10	10	10
E, 10^3 ksi	9.9					
E_c, 10^3 ksi	10.1					
G, 10^3 ksi	3.8					
μ	0.33					
Physical Properties:						
ω, lb/in.^{3}	0.098					
C, K, and α,............	See Figure 3.6.2.0					

a Design allowables were based upon data obtained from testing samples of material, supplied in the O or F temper, which were heat treated to demonstrate response to heat treatment by suppliers.

Table 3.6.2.0(e). Design Mechanical and Physical Properties of 6061 Aluminum Alloy Die Forging

Specification	AMS 4127, MIL-A-22771, and QQ-A-367
Form	Die forging
Temper	T6 and T652
Thickness, in.	≤ 4.000[a]
Basis	S
Mechanical Properties:	
F_{tu}, ksi:	
L	38
T[b]	38
F_{ty}, ksi:	
L	35
T[b]	35
F_{cy}, ksi:	
L	36
T[b]	36
F_{su}, ksi	25
F_{bru}, ksi:	
(e/D = 1.5)	61
(e/D = 2.0)	76
F_{bry}, ksi:	
(e/D = 1.5)	54
(e/D = 2.0)	61
e, percent:	
L	7
T[b]	5
E, 10^3 ksi	9.9
E_c, 10^3 ksi	10.1
G, 10^3 ksi	3.8
μ	0.33
Physical Properties:	
ω, lb/in.^{3}	0.098
C, K, and α	See Figure 3.6.2.0

[a] Thickness at the time of heat treatment. When die forgings are machined before heat treatment, the mechanical properties are applicable provided the as-forged thickness is not greater than twice the thickness at the time of heat treatment.

[b] T indicates any grain direction not within ± 15° of being parallel to the forging flow lines. F_{cy}(T) values are based upon short transverse (ST) test data.

Table 3.6.2.0(f). Design Mechanical and Physical Properties of 6061 Aluminum Alloy Hand Forging

Specification	AMS 4127, AMS 4248, AMS-A-22771, and AMS-QQ-A-367		
Form	Hand forging		
Temper	T6[a] and T652		
Cross-Sectional Area, in.^{2}	≤256		
Thickness, in.	≤2.000	2.001-4.000	4.001-8.000
Basis	S	S	S
Mechanical Properties:			
F_{tu}, ksi:			
L	38	38	37
LT	38	38	37
ST	...	37	35
F_{ty}, ksi:			
L	35	35	34
LT	35	35	34
ST	...	33	32
F_{cy}, ksi:			
L	36	36	35
LT	36	36	35
ST	...	34	33
F_{su}, ksi	25	25	24
F_{bru}, ksi:			
(e/D = 1.5)	61	61	59
(e/D = 2.0)	76	76	74
F_{bry}, ksi:			
(e/D = 1.5)	54	54	53
(e/D = 2.0)	61	61	59
e, percent:			
L	10	10	8
LT	8	8	6
ST	...	5	4
E, 10^3 ksi	9.9		
E_c, 10^3 ksi	10.1		
G, 10^3 ksi	3.8		
μ	0.33		
Physical Properties:			
ω, lb/in.^{3}	0.098		
C, K, and α	See Figure 3.6.2.0		

a When hand forgings are machined before heat treatment, the section thickness at time of heat treatment will determine the minimum mechanical properties as long as the original (as-forged) thickness does not exceed the maximum thickness for the alloy as shown in the table.

Table 3.6.2.0(g). Design Mechanical and Physical Properties of 6061 Aluminum Alloy Extruded Rod, Bar, and Shapes

Specification	AMS 4161, AMS 4172, & AMS-QQ-A-200/8	AMS-QQ-A-200/8	AMS 4160 & AMS-QQ-A-200/8	AMS 4150, AMS 4173 & AMS-QQ-A-200/8			
Form	Extruded rod, bar, and shapes						
Temper	T4, T4510, and T4511	T42[a]	T62[a]	T6, T6510, and T6511			
Cross-sectional area, in.^{2}	...	...	...	≤32			
Thickness,[b] in.	≤3.000	All	All	≤1.000		1.001-6.500	
Basis	S	S	S	A	B	A	B
Mechanical Properties:							
F_{tu}, ksi:							
L	26	26	38	38	41	38	41
LT	...	...	...	37	40	33	35
F_{ty}, ksi:							
L	16	12	35	35	38	35	38
LT	...	...	...	33	36	28	31
F_{cy}, ksi:							
L	14	...	...	34	37	34	37
LT	...	...	...	35	38	30	33
F_{su}, ksi	16	...	...	26	28	19	21
F_{bru}[c], ksi:							
(e/D = 1.5)	42	...	...	64	69	52	57
(e/D = 2.0)	55	...	...	82	88	69	74
F_{bry}[c], ksi:							
(e/D = 1.5)	22	...	...	54	58	42	46
(e/D = 2.0)	26	...	...	60	65	50	55
e, percent (S-basis):							
L	16	16	10[d]	10[d]	...	10	...
E, 10^3 ksi	9.9						
E_c, 10^3 ksi	10.1						
G, 10^3 ksi	3.8						
μ	0.33						
Physical Properties:							
ω, lb/in.^{3}	0.098						
C, K, and α	See Figure 3.6.2.0						

a Design allowables were based upon data obtained from testing samples of material, supplied in the O to F temper which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained by the user, however, may be lower than those listed if the material has been formed or otherwise cold or hot worked, particularly in the annealed temper, prior to solution heat treatment.

b The mechanical properties are to be based upon the thickness at the time of quench.

c Bearing values are "dry pin" values per Section 1.4.7.1.

d For thicknesses ≤0.249 inch, e = 8%.

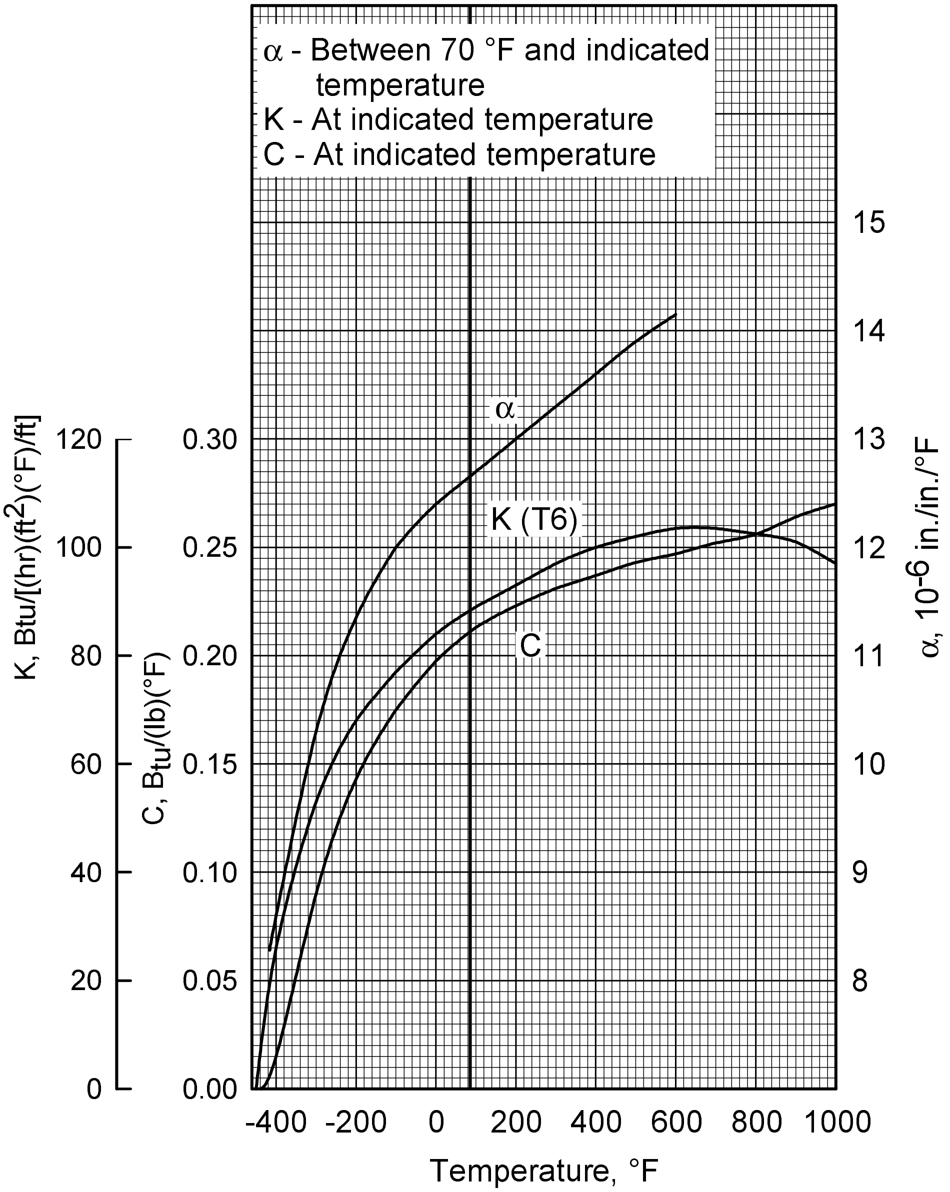


Figure 3.6.2.0. Effect of temperature on the physical properties of 6061 aluminum alloy.

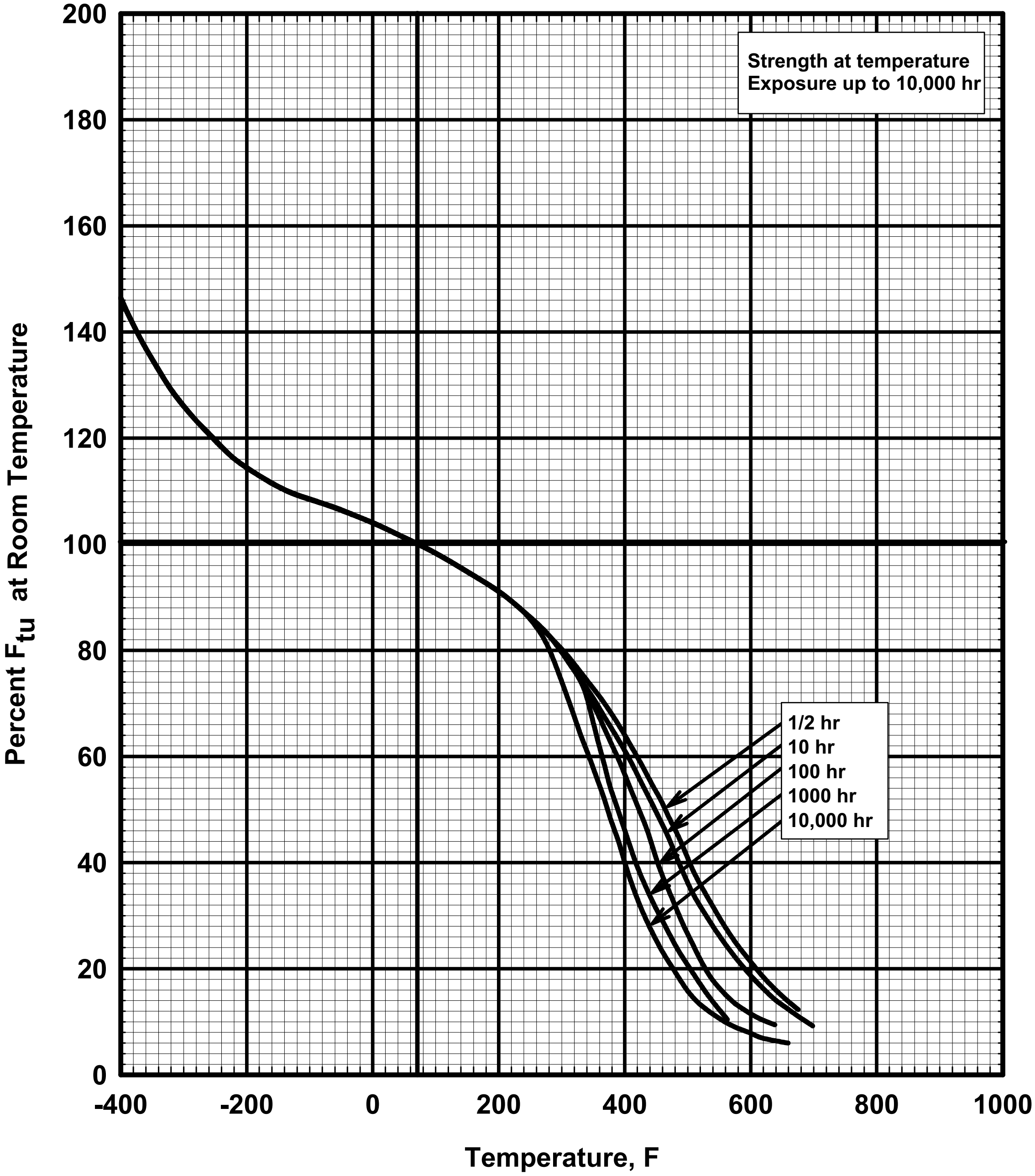


Figure 3.6.2.2.1(a). Effect of temperature on the tensile ultimate strength (F_{tu}) of 6061-T6 aluminum alloy (all products).

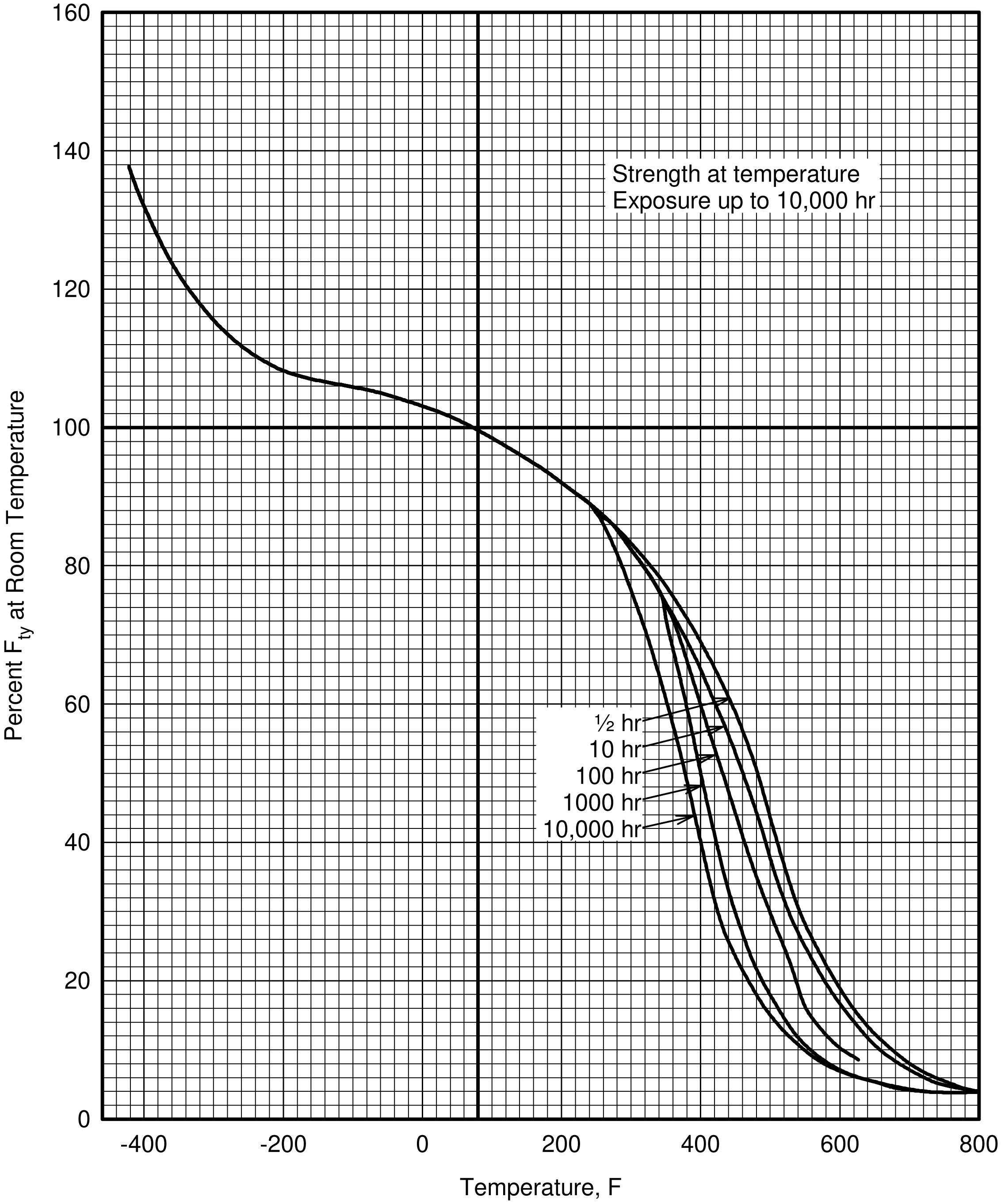


Figure 3.6.2.2.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of 6061-T6 aluminum alloy (all products).

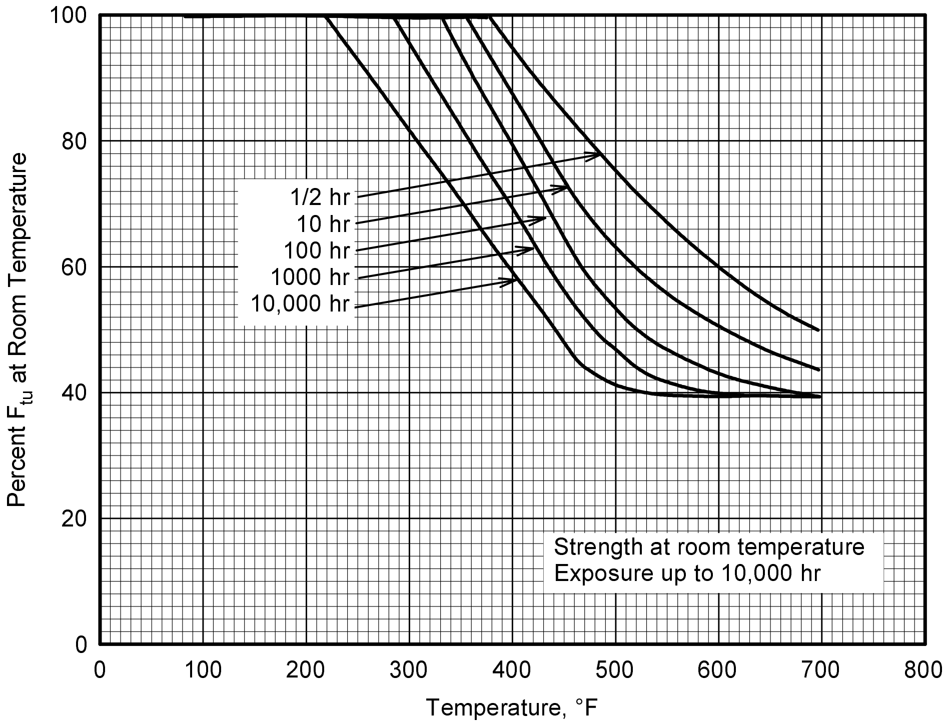


Figure 3.6.2.2.1(c). Effect of exposure at elevated temperatures on the room-temperature tensile ultimate strength (F_{tu}) of 6061-T6 aluminum alloy (all products).

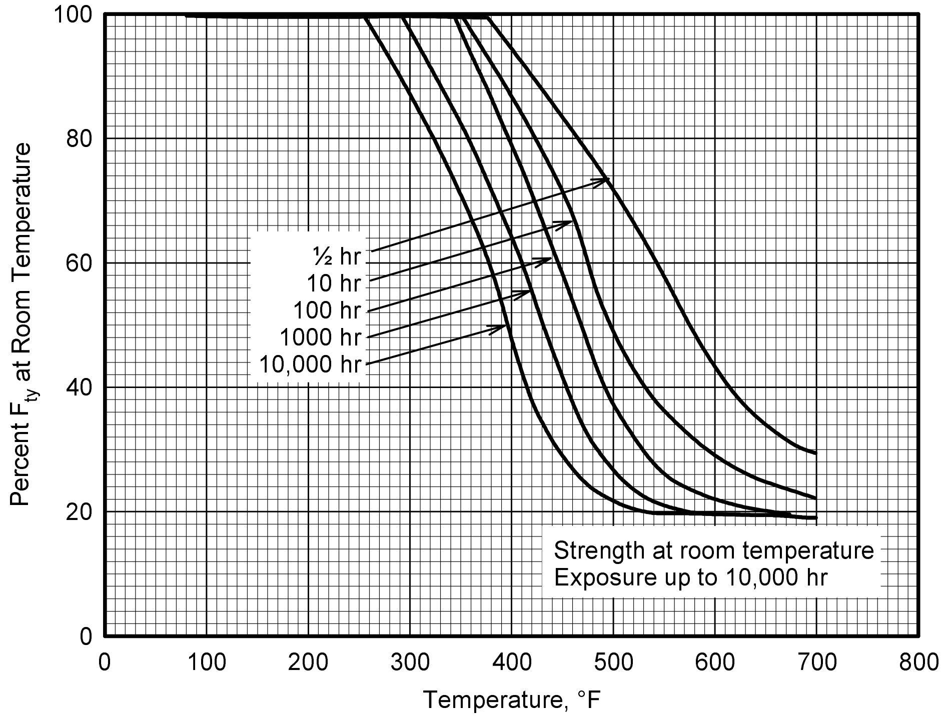


Figure 3.6.2.2.1(d). Effect of exposure at elevated temperatures on the room-temperature tensile yield strength (F_{ty}) of 6061-T6 aluminum alloy (all products).

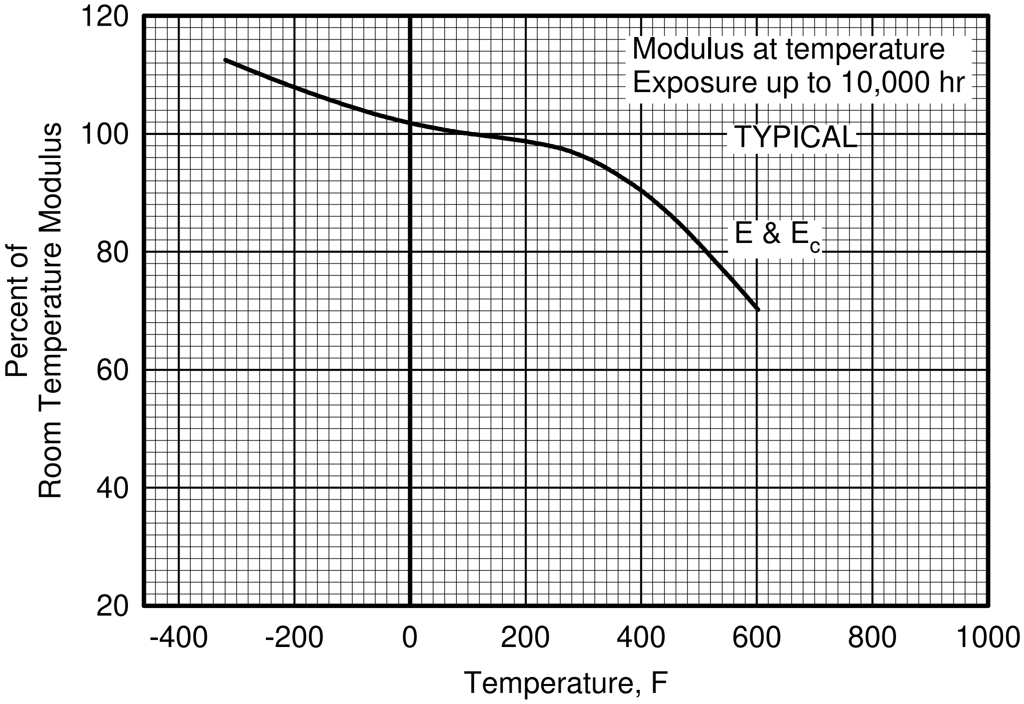


Figure 3.6.2.2.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of 6061 aluminum alloy.

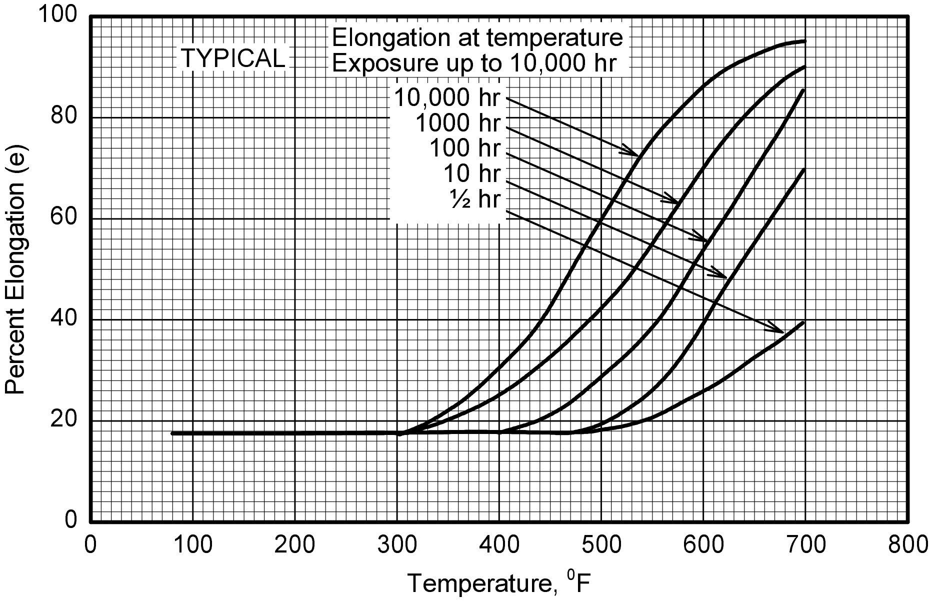


Figure 3.6.2.2.5(a). Effect of temperature on the elongation of 6061-T6 aluminum alloy (all products).

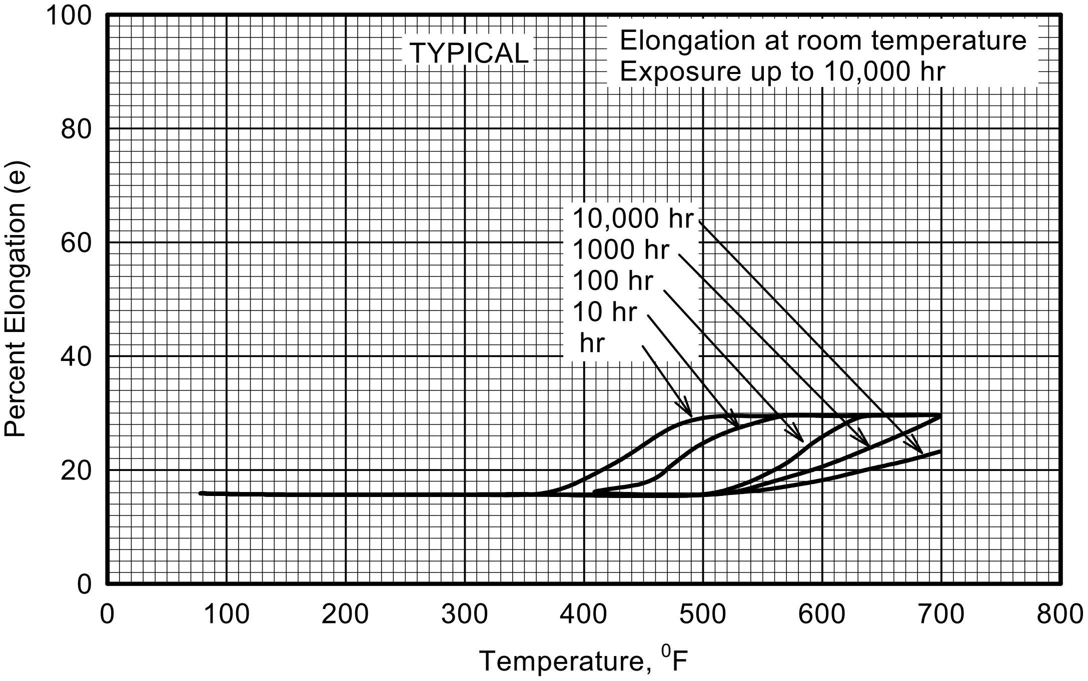


Figure 3.6.2.2.5(b). Effect of exposure at elevated temperatures on the room temperature elongation of 6061-T6 aluminum alloy (all products).

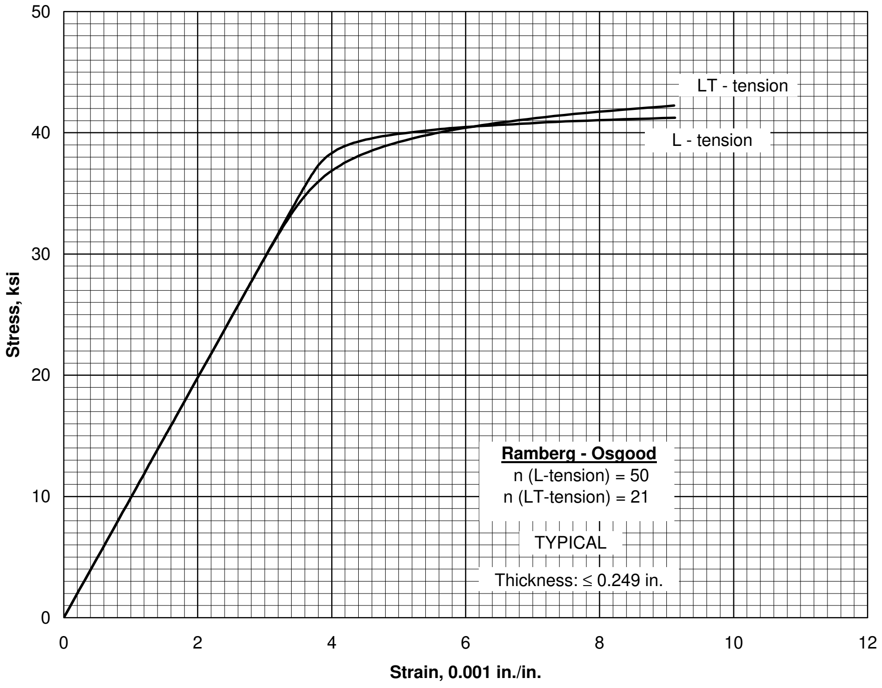


Figure 3.6.2.2.6(a). Typical tensile stress-strain curves for 6061-T6 aluminum alloy sheet at room temperature.

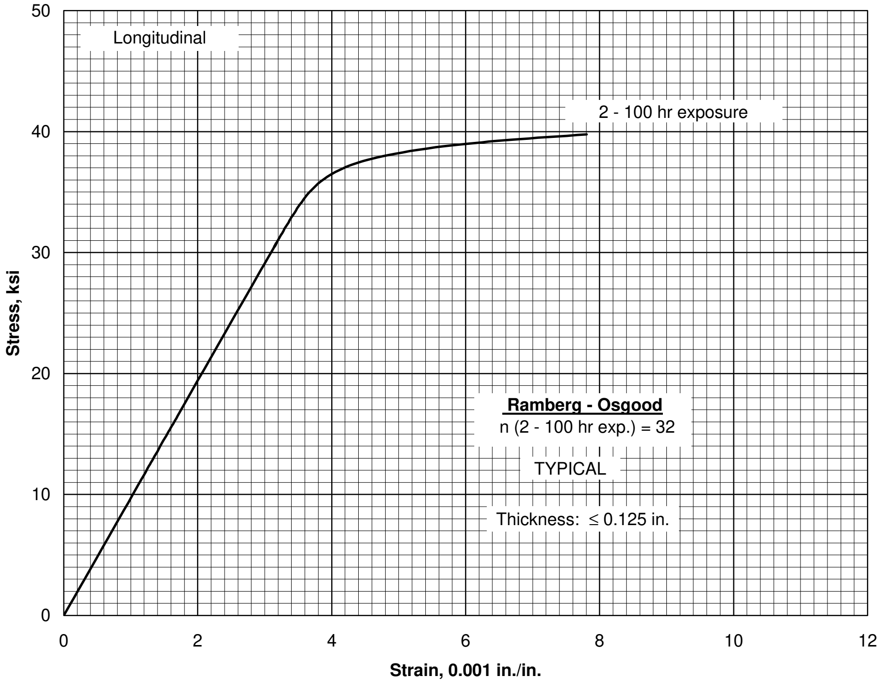


Figure 3.6.2.2.6(b). Typical tensile stress-strain curve for 6061-T6 aluminum alloy sheet at 200°F.

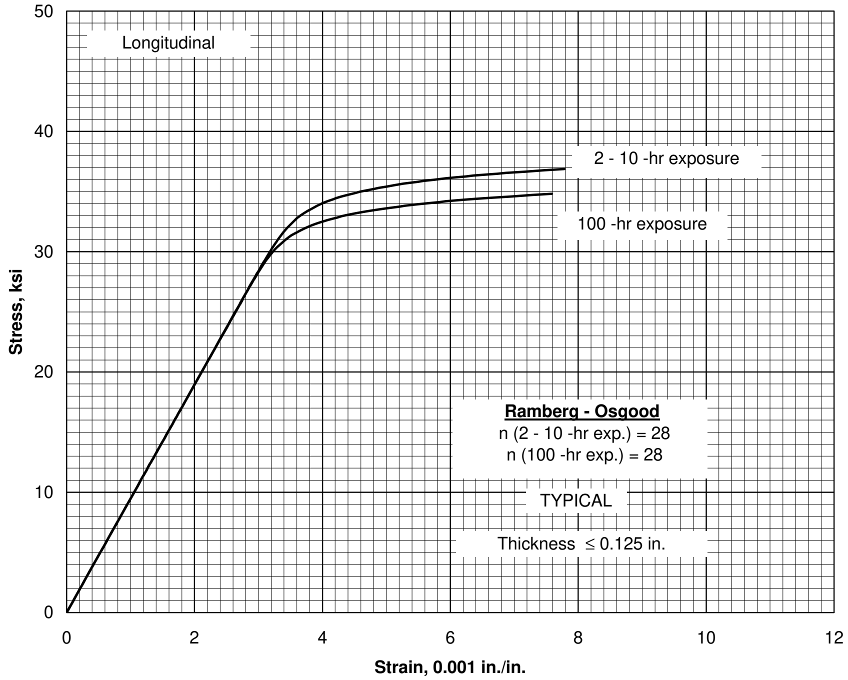


Figure 3.6.2.2.6(c). Typical tensile stress-strain curves for 6061-T6 aluminum alloy sheet at 300°F.

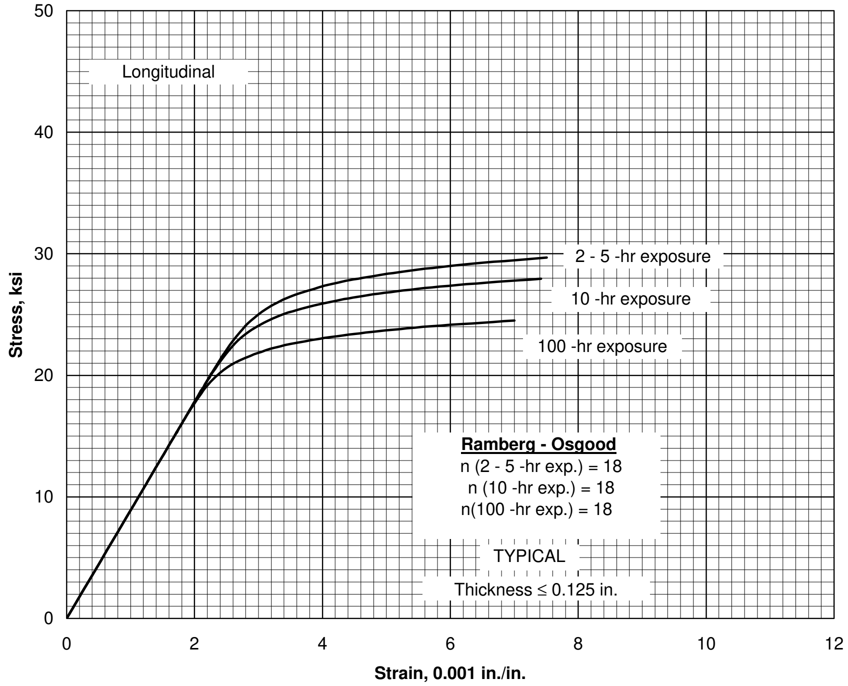


Figure 3.6.2.2.6(d). Typical tensile stress-strain curves for 6061-T6 aluminum alloy sheet at 400°F.

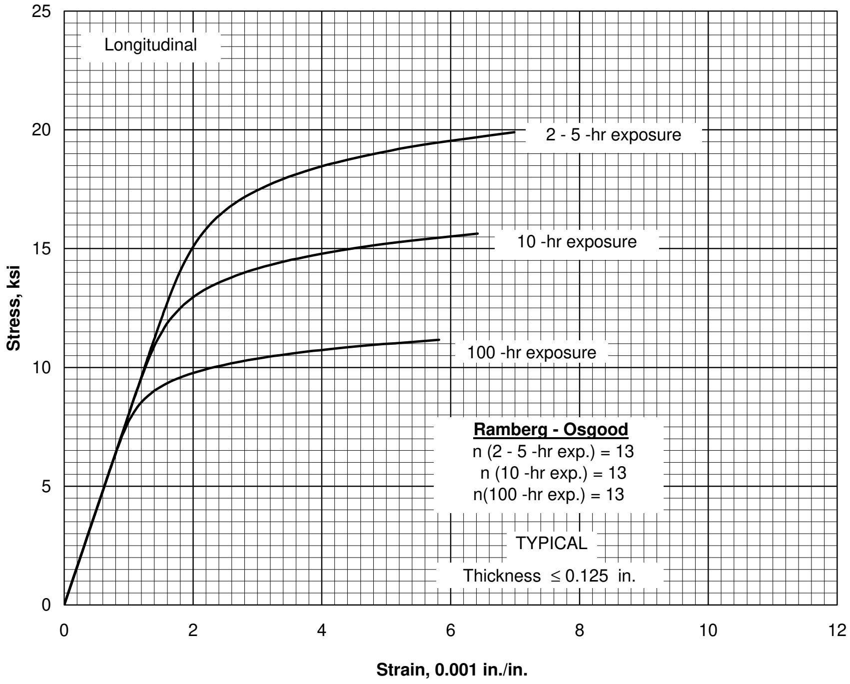


Figure 3.6.2.2.6(e). Typical tensile stress-strain curves for 6061-T6 aluminum alloy sheet at 500°F.

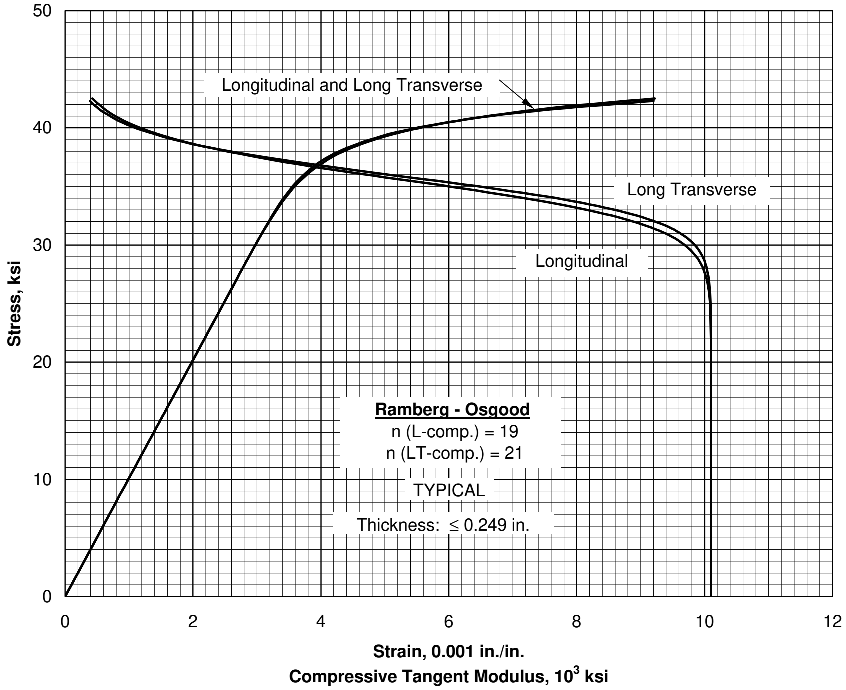


Figure 3.6.2.2.6(f). Typical compressive stress-strain and compressive tangent-modulus curves for 6061-T6 aluminum alloy sheet at room temperature.

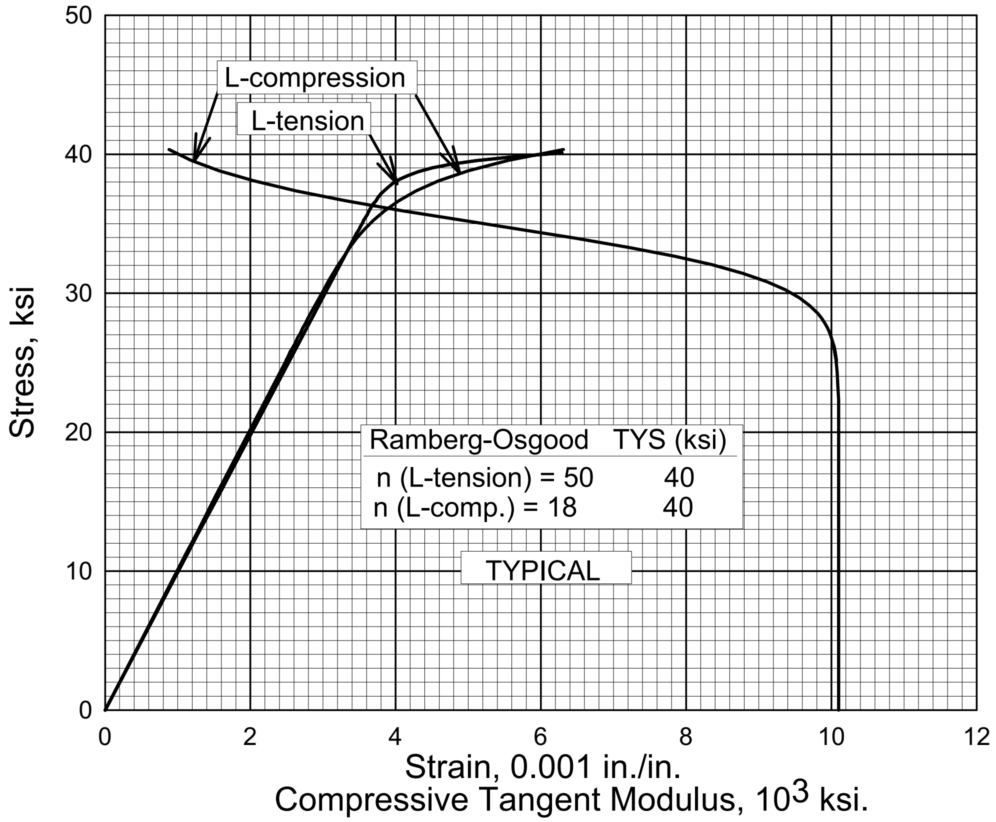


Figure 3.6.2.2.6(g). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 6061-T6 aluminum alloy sheet at room temperature.

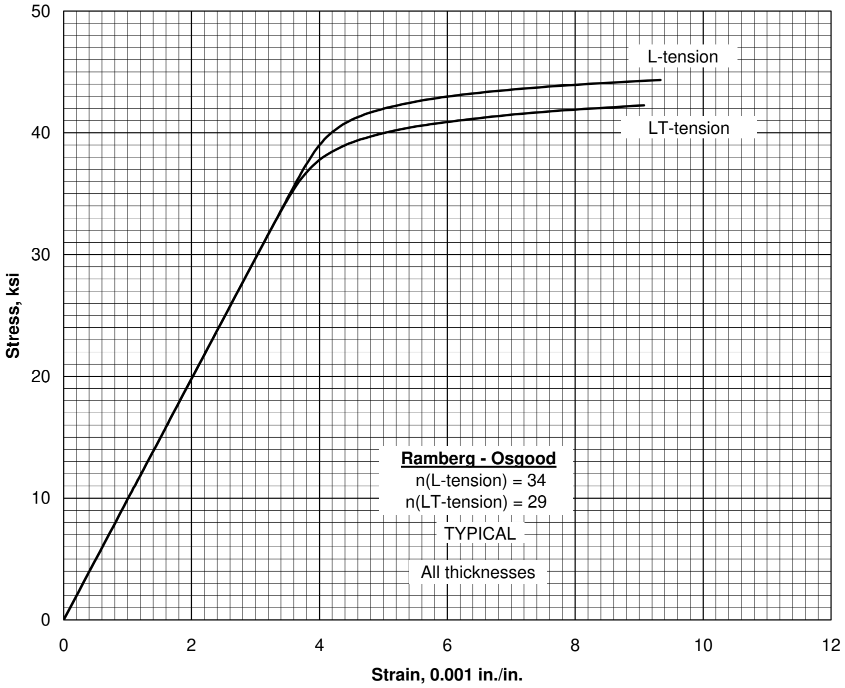


Figure 3.6.2.2.6(h). Typical tensile stress-strain curves for 6061-T6 aluminum alloy extrusion at room temperature.

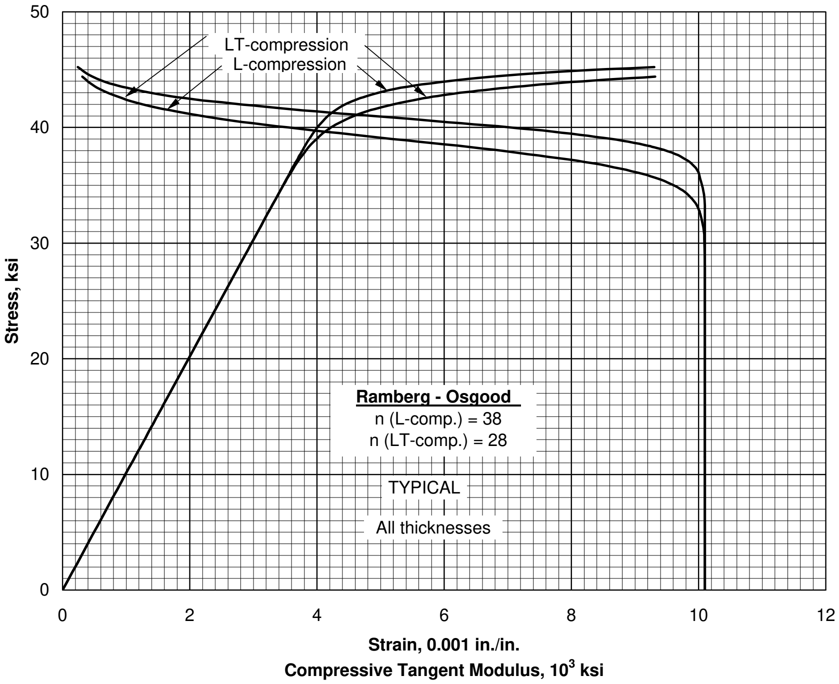


Figure 3.6.2.2.6(i). Typical compressive stress-strain and compressive tangent-modulus curves for 6061-T6 aluminum alloy extrusion at room temperature.

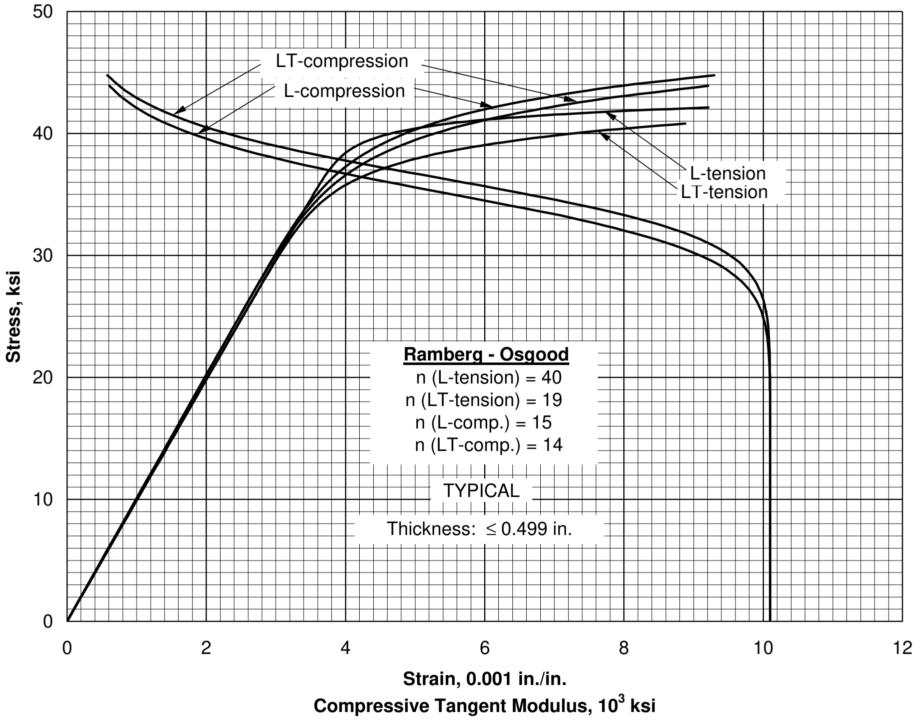


Figure 3.6.2.2.6(j). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 6061-T651X aluminum alloy extrusion at room temperature.

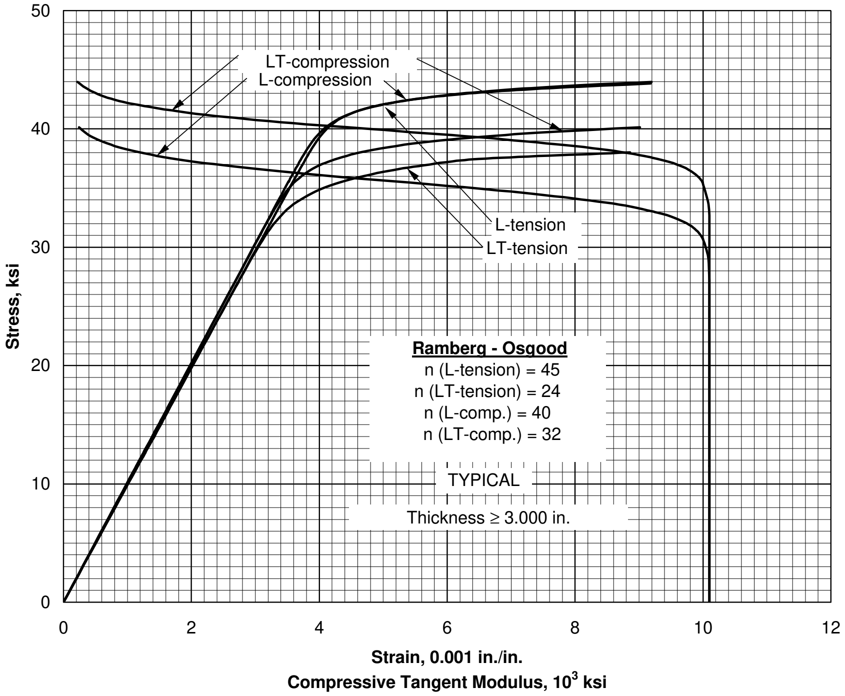


Figure 3.6.2.2.6(k). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 6061-T651X aluminum alloy extrusion at room temperature.

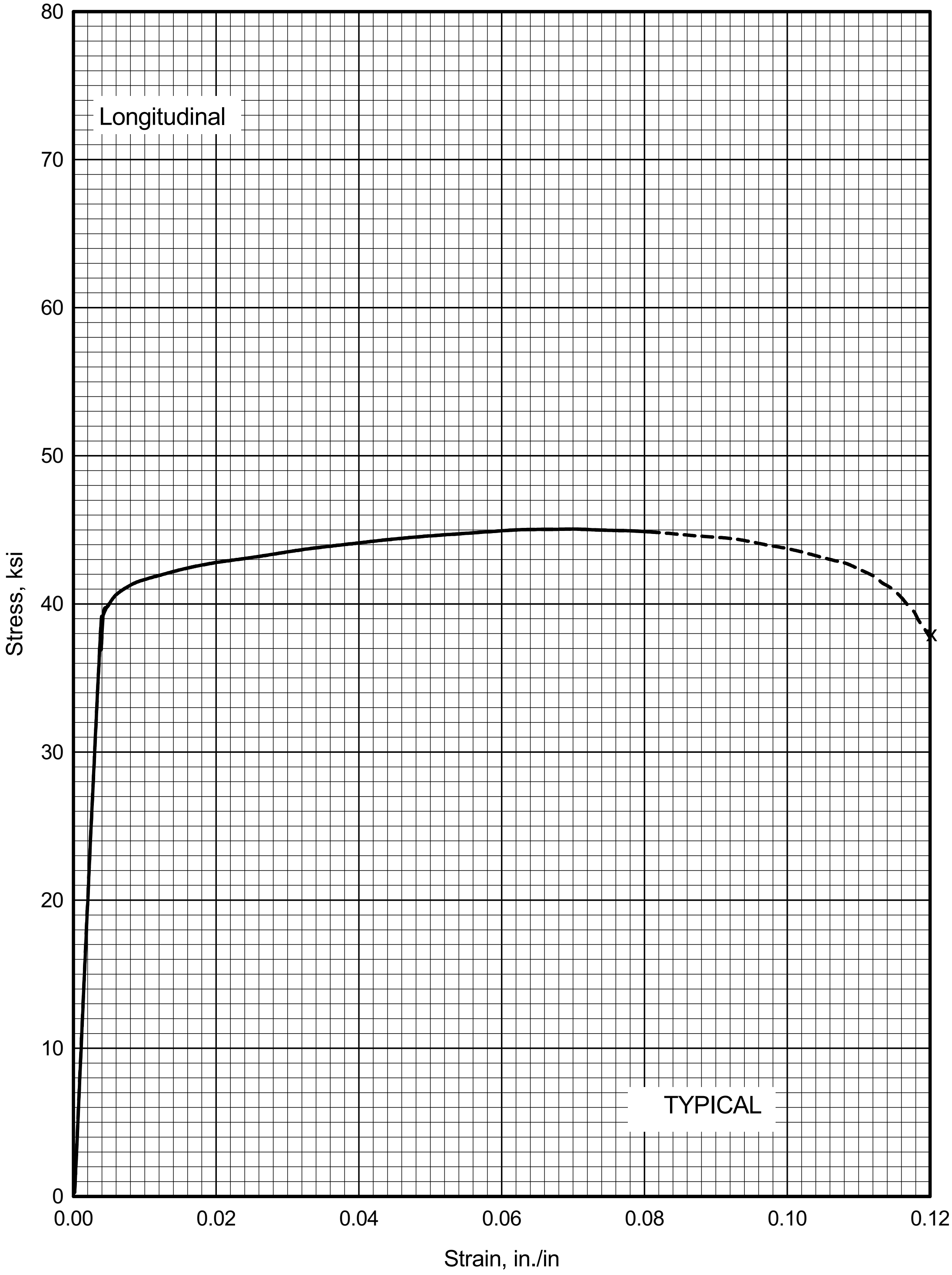


Figure 3.6.2.2.6(l). Typical tensile stress-strain (full range) for 6061-T6 aluminum alloy sheet at room temperature.

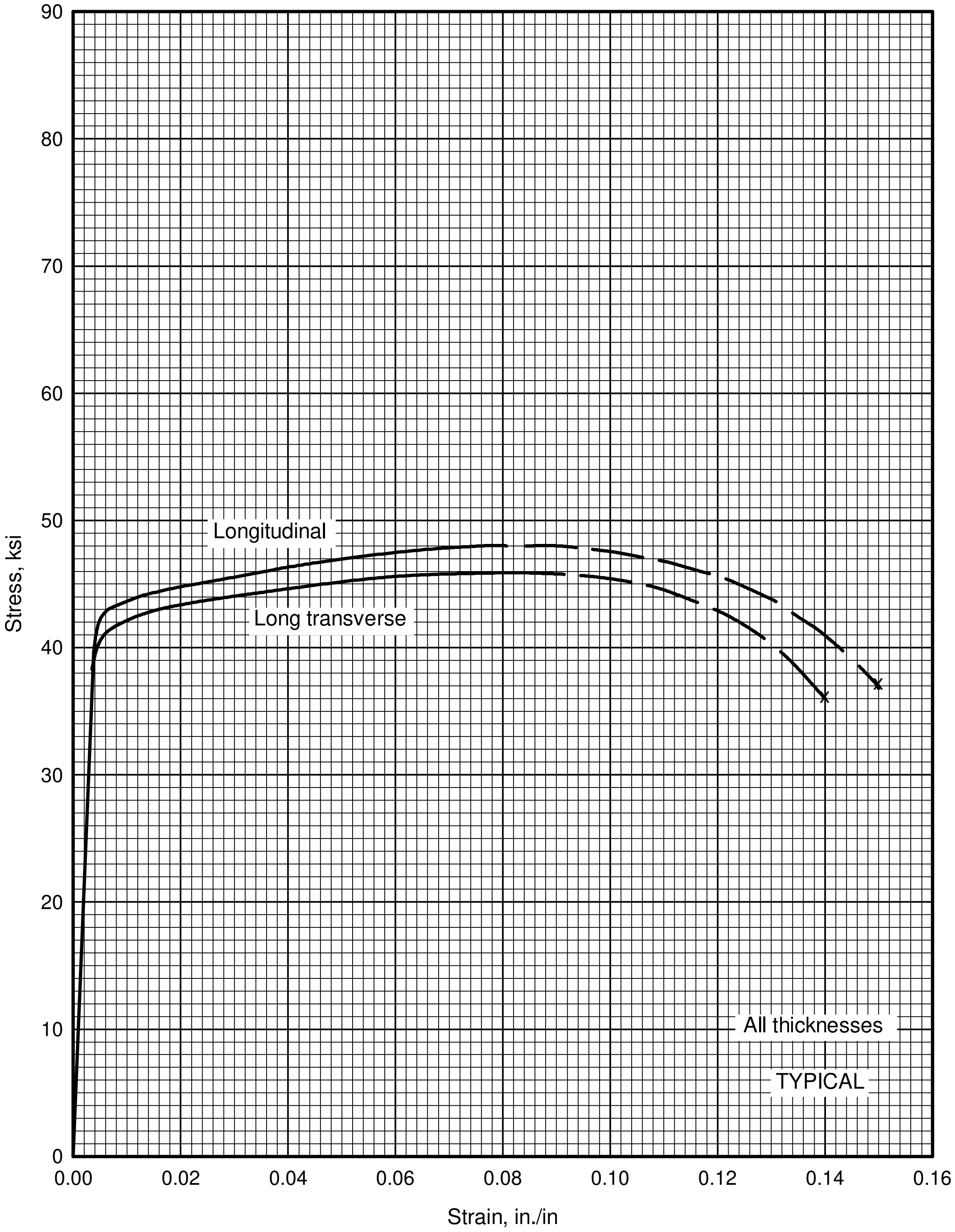


Figure 3.6.2.2.6(m). Typical tensile stress-strain curves (full range) for 6061-T62 aluminum alloy extrusion at room temperature.

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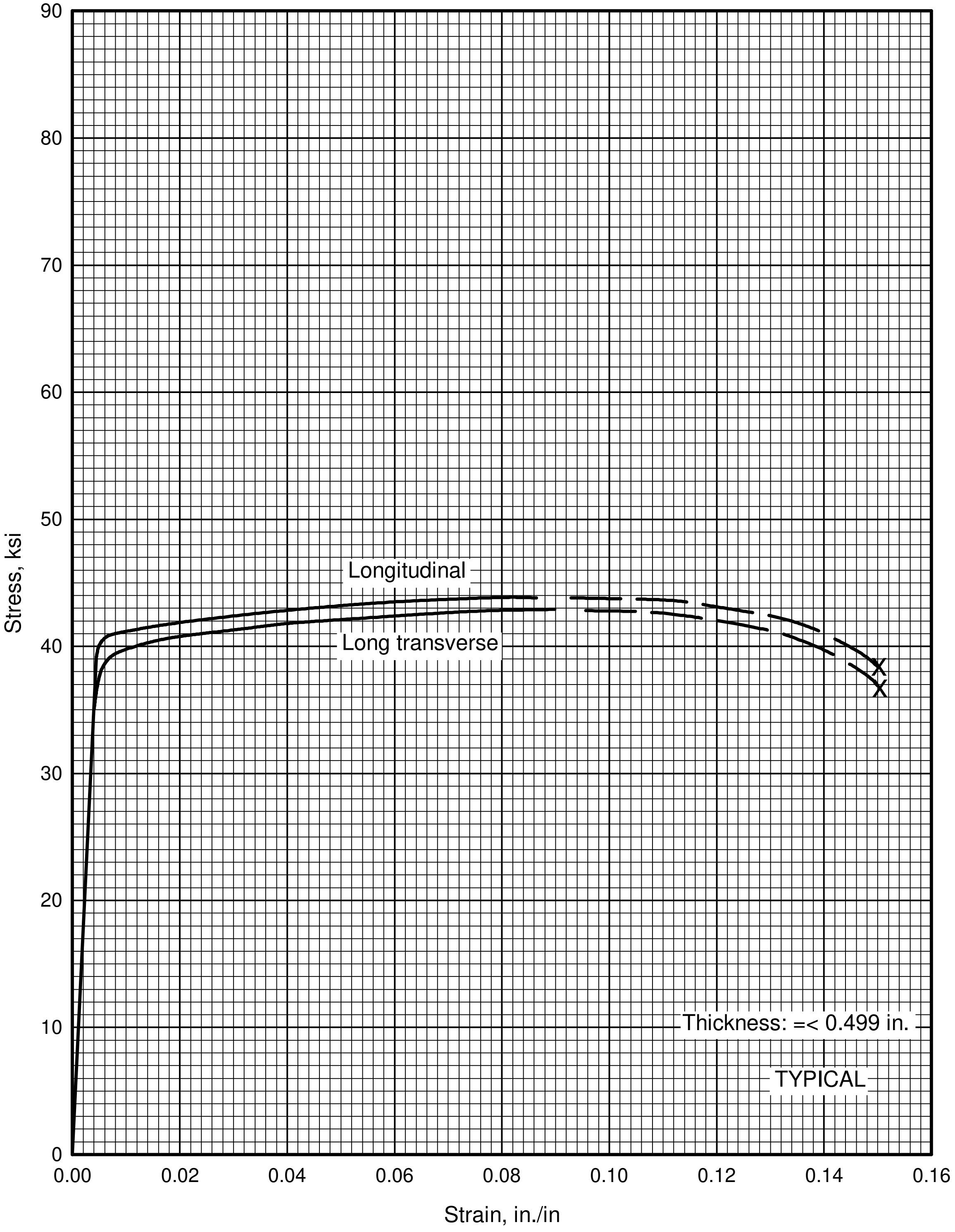


Figure 3.6.2.2.6(n). Typical tensile stress-strain curves (full range) for 6061-T651X aluminum alloy extrusion at room temperature.

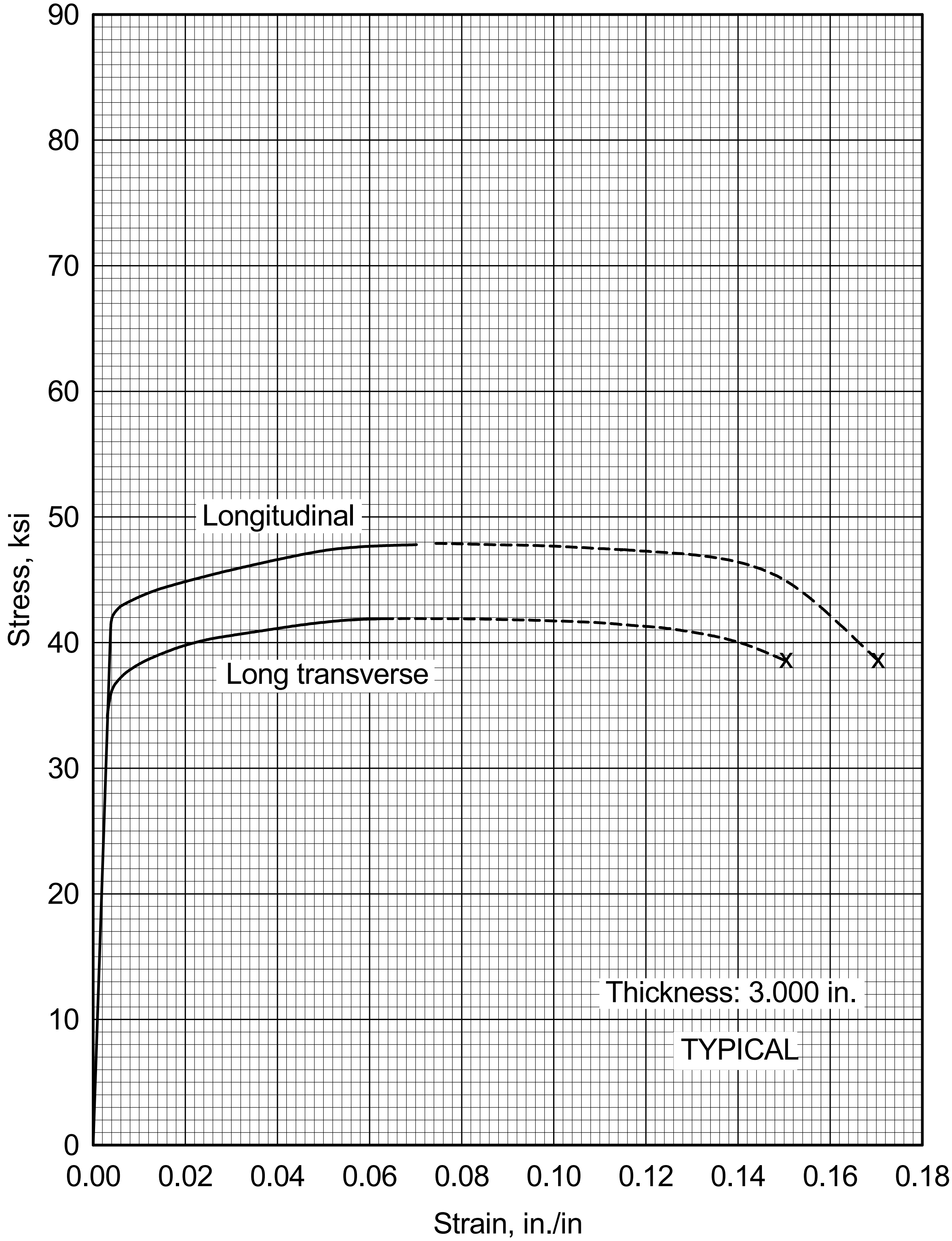


Figure 3.6.2.2.6(o). Typical tensile stress-strain curves (full range) for 6061-T651X aluminum alloy extrusion at room temperature.

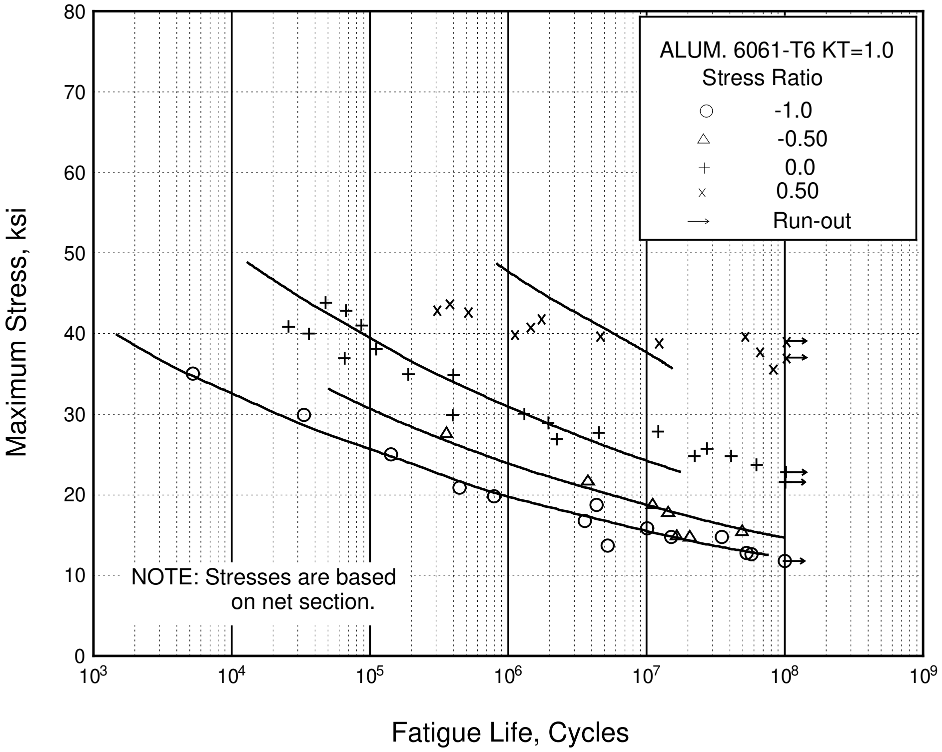


Figure 3.6.2.2.8. Best-fit S/N curves for unnotched 6061-T6 aluminum alloy, various wrought products, longitudinal direction.

Correlative Information for Figure 3.6.2.2.8

Product Form: Drawn rod, 0.75 inch diameter
Rolled bar, 1 x 7.5 inch

Properties:

TUS, ksi	TYS, ksi	Temp., °F
45	40	RT

Specimen Details: Unnotched
0.200 inch net diameter

Surface Condition: Not specified

Reference: 3.2.1.1.8(a)

Test Parameters:
Loading - Axial
Frequency - 2000 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
$\text{Log } N_f = 20.68 - 9.84 \log (S_{eq})$
$S_{eq} = S_{max} (1-R)^{0.63}$
Std. Error of Estimate, Log (Life) = 0.48
Standard Deviation, Log (Life) = 1.18
$R^2 = 83\%$

Sample Size = 55

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

3.6.3 6151 ALLOY

3.6.3.0 *Comments and Properties* — 6151 is an Al-Mg-Si alloy whose use has been restricted primarily to die forgings. It provides higher strengths than attainable with 6061, and has high resistance to corrosion. Refer to Section 3.1.3.4 for comments regarding the weldability of the alloy.

Material specifications for 6151 aluminum alloy are presented in Table 3.6.3.0(a). Room-temperature mechanical and physical properties are shown in Table 3.6.3.0(b). The effect of temperature on thermal expansion is shown in Figure 3.6.3.0.

Table 3.6.3.0(a). Material Specifications for 6151 Aluminum Alloy

Specification	Form
AMS 4125	Die forging
AMS-A-22771	Forging

The temper index for 6151 is as follows:

Section	Temper
3.6.3.1	T6

3.6.3.1 *T6 Temper* — Elevated temperature modulus data from Figure 3.6.2.2.4 may be used for this alloy.

Table 3.6.3.0(b). Design Mechanical and Physical Properties of 6151 Aluminum Alloy Die Forging

Specification	AMS 4125 and AMS-A-22771
Form	Die forging
Temper	T6
Thickness[a], in.	≤4.000
Basis	S
Mechanical Properties:	
F_{tu}, ksi:	
L	44
T[b]	44
F_{ty}, ksi:	
L	37
T[b]	37
F_{cy}, ksi:	
L	39
T[b]	35
F_{su}, ksi	28
F_{bru}, ksi:	
(e/D = 1.5)	...
(e/D = 2.0)	...
F_{bry}, ksi:	
(e/D = 1.5)	...
(e/D = 2.0)	...
e, percent:	
L	10
T[b]	6
E, 10^3 ksi	10.1
E_c, 10^3 ksi	10.3
G, 10^3 ksi	3.85
μ	0.33
Physical Properties:	
ω, lb/in.^{3}	0.098
C, Btu/(lb)(°F)	0.23 (at 212°F)
K, Btu/[(hr)(ft^2)(°F)/ft]	100 (at 77°F)
α, 10^{-6} in./in./°F	See Figure 3.6.3.0

[a] Thickness at the time of heat treatment. When die forgings are machined before heat treatment, the mechanical properties are applicable provided the as-forged thickness is not greater than twice the thickness at the time of heat treatment.

[b] T indicates any grain direction not within ±15° of being parallel to the forging flow lines.

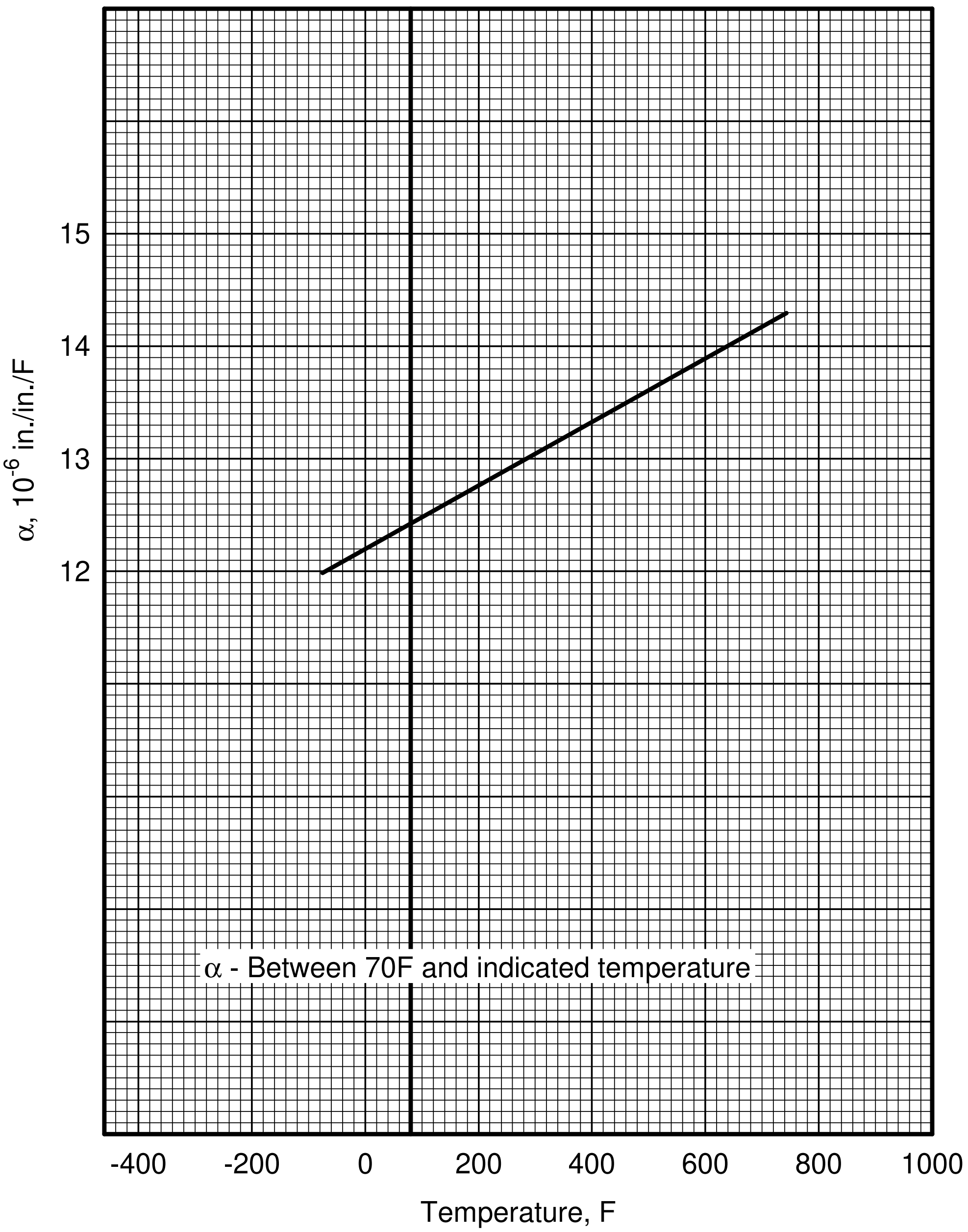


Figure 3.6.3.0. Effect of temperature on the thermal expansion of 6151 aluminum alloy.

3.7 7000 SERIES WROUGHT ALLOYS

The 7000 series of wrought alloys contain zinc as the principal alloying element and magnesium and copper as other major elements. They are available in a wide variety of product forms. They are strengthened principally by solution heat treatment and precipitation hardening and are among the highest- strength aluminum alloys.

The T6-type tempers of these alloys are susceptible to stress-corrosion cracking under certain conditions while the T7-type tempers are more resistant; these alloys should be considered in light of the corrosion resistance discussed in Sections 3.1.2.3 and 3.1.3.

3.7.1 7010 ALLOY

3.7.1.0 ***Comments and Properties*** — 7010 is an Al-Zn-Mg-Cu-Zr alloy developed to have a combination of high strength, high resistance to stress-corrosion cracking, and good fracture toughness, particularly in thick sections. The use of zirconium in lieu of chromium provides a low sensitivity to quench, which results in high strength in thick sections. The alloy is available only in plate. Plate, greater than 2 inches in thickness in the T7451 temper, has static strength equal to or greater than 7075-T651 plate with greater toughness.

Plate in the T7451 temper has a stress-corrosion resistance higher than 7075-T7651. The T73-type temper provides the highest resistance to stress-corrosion for this alloy. The T76-type temper provides for good exfoliation resistance and higher stress-corrosion resistance than T6-type tempers of 7075 and 7178. The T74-type temper provides stress-corrosion and strength characteristics intermediate to those of T76 and T73. Refer to Section 3.1.2.3 for information regarding the resistance of the alloy to stress-corrosion cracking.

Refer to Section 3.1.3.4 for comments regarding the weldability of the alloy.

Material specifications for 7010 are shown in Table 3.7.1.0(a). Room-temperature mechanical properties are shown in Tables 3.7.1.0(b_1) and (b_2).

Table 3.7.1.0(a). Material Specifications for 7010 Aluminum Alloy

Specification	Form
AMS 4205	Plate
AMS 4204	Plate

The temper index for 7010 is as follows:

Section	Temper
3.7.1.1	T7451
3.7.1.2	T7651

3.7.1.1 *T7451 Temper* — Elevated temperature curves for plate are presented in Figure 3.7.1.1.1. Figures 3.7.1.1.6(a) through (d) present stress-strain and tangent-modulus curves for plate.

3.7.1.2 *T7651 Temper* — Figures 3.7.1.2.6(a) through (d) present stress-strain and tangent-modulus curves for plate.

Table 3.7.1.0(b_1). Design Mechanical and Physical Properties of 7010 Aluminum Alloy Plate

Specification	AMS 4205									
Form	Plate									
Temper	T7451									
Thickness, in.	0.250-1.000	1.001-2.000	2.001-3.000		3.001-4.000		4.001-5.000		5.001-6.000	
Basis	S	S	A	B	A	B	A	B	A	B
Mechanical Properties:										
F_{tu}, ksi:										
L	71	71	70	72	70	71	68[a]	71	68	70
LT	72	72	71	72	70	72	69[a]	71	67[a]	71
ST	...	...	66	68	66	68	65[a]	67	63[a]	67
F_{ty}, ksi:										
L	62	62	60	62	60	62	59	61	57[a]	61
LT	62	62	60	62	59	61	58	60	57[a]	60
ST	...	...	55	57	54	56	53	55	52	54
F_{cy}, ksi:										
L	61	61	59	61	58	60	57	59	56	59
LT	63	63	62	64	61	63	60	62	59	63
ST	...	...	61	63	60	62	59	61	58	61
F_{su}, ksi	41	41	42	42	42	43	42	43	41	43
F_{bru}[b], ksi:										
(e/D = 1.5)	100	101	101	102	100	103	100	103	97	103
(e/D = 2.0)	127	129	130	132	130	134	129	133	126	133
F_{bry}[b], ksi:										
(e/D = 1.5)	81	82	81	84	81	84	81	84	80	84
(e/D = 2.0)	94	97	97	100	98	101	98	101	97	102
e, percent (S-basis):										
L	9	9	9	...	9	...	9	...	8	...
LT	6	6	6	...	6	...	5	...	5	...
ST	...	...	2.5	...	2	...	2	...	2	...
E, 10^3 ksi	10.2									
E_c, 10^3 ksi	10.6									
G, 10^3 ksi	3.9									
μ	0.33									
Physical Properties:										
ω, lb/in.^{3}	0.102									
C, Btu/(lb)(°F)	0.21 (at 214°F)									
K, Btu/[(hr)(ft^2)(°F)/ft]	95 (at 99°F)									
α, 10^{-6} in./in./°F	13.0 (68-212°F)									

[a] S-basis values. The rounded T_{99} values are as follows: for 4.001-5.000-inch thickness, F_{tu}(L) = 69, F_{tu}(LT) = 70, and F_{tu}(ST) = 66; for 5.001-6.000-inch thickness, F_{tu}(LT) = 69, F_{tu}(ST) = 65, F_{ty}(L) = 59, and F_{ty}(LT) = 58.

[b] See Table 3.1.2.1.1. Bearing values are "dry pin" values per Section 1.4.7.1.

Table 3.7.1.0(b_2). Design Mechanical Properties of 7010 Aluminum Alloy Plate—Continued

Specification	AMS 4204						
Form	Plate						
Temper	T7651						
Thickness, in.	0.250-1.000	1.001-2.000	2.001-2.500	2.501-3.000	3.001-4.000	4.001-5.000	5.001-5.500
Basis	S	S	S	S	S	S	S
Mechanical Properties:							
F_{tu}, ksi:							
L	76	76	75	73	72	72	71
LT	76	76	75	74	73	72	72
ST	...	...	71	70	69	68	66
F_{ty}, ksi:							
L	66	66	65	64	64	63	62
LT	66	66	65	64	63	62	61
ST	...	...	59	58	56	55	53
F_{cy}, ksi:							
L	65	65	64	63	62	61	60
LT	67	68	67	67	66	65	64
ST	...	...	68	67	65	64	62
F_{su}, ksi	42	44	44	44	44	45	46
F_{bru}[a], ksi:							
(e/D = 1.5)	105	106	106	105	105	105	105
(e/D = 2.0)	135	137	137	136	135	134	134
F_{bry}[a], ksi:							
(e/D = 1.5)	85	86	87	87	86	86	86
(e/D = 2.0)	103	104	103	102	101	100	99
e, percent:							
L	8	8	8	7	7	7	6
LT	6	6	6	5	5	5	4
ST	...	...	2.5	2.5	2	2	2
E, 10^3 ksi	10.2						
E_c, 10^3 ksi	10.6						
G, 10^3 ksi	3.9						
μ	0.33						
Physical Properties:							
ω, lb/in.^{3}	0.102						
C, Btu/(lb)(°F)	0.21 (at 214°F)						
K, Btu/[(hr)(ft^2)(°F)/ft]	95 (at 104°F)						
α, 10^{-6} in./in./°F	12.9 (68 to 212°F)						

[a] See Table 3.1.2.1.1. Bearing values are "dry pin" values per Section 1.4.7.1.

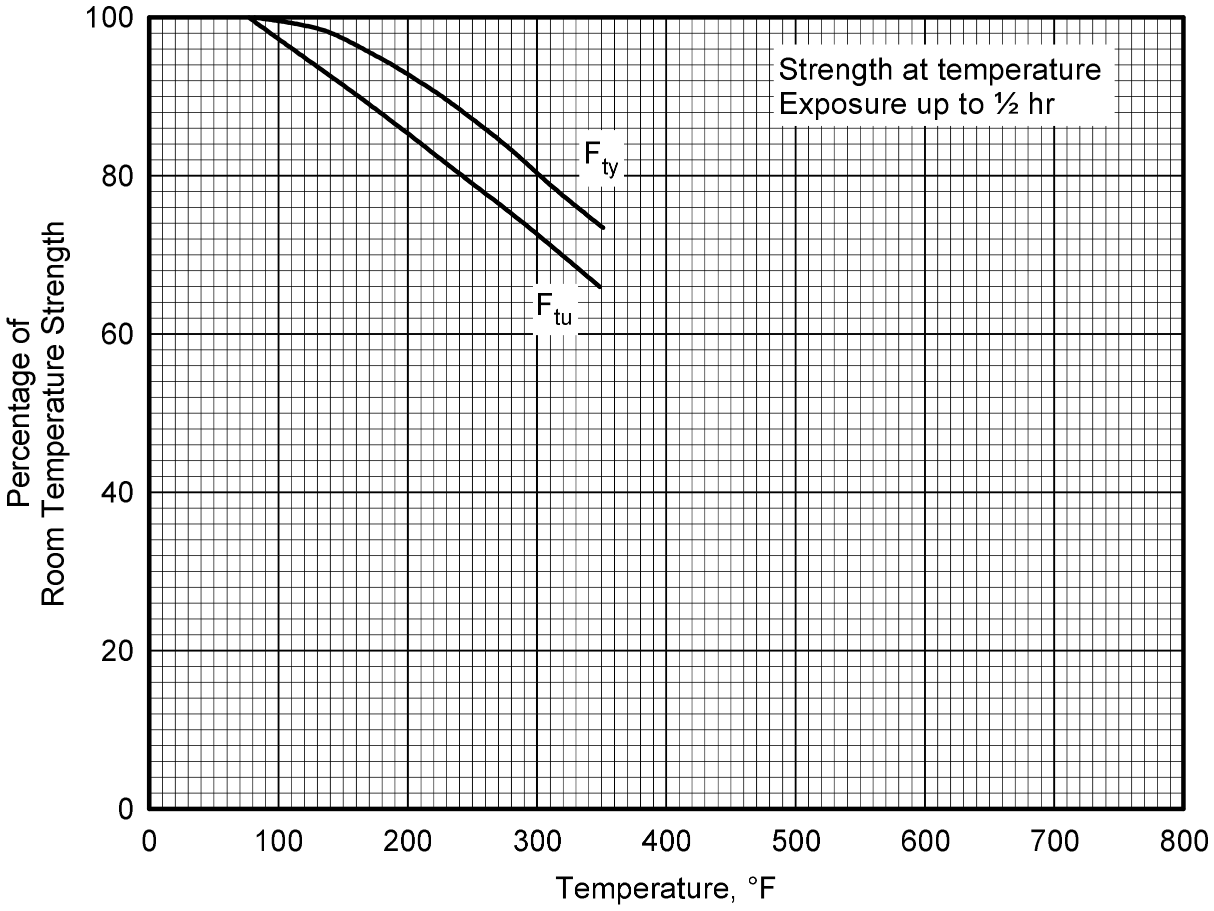


Figure 3.7.1.1.1. Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of 7010-T7451 aluminum alloy plate.

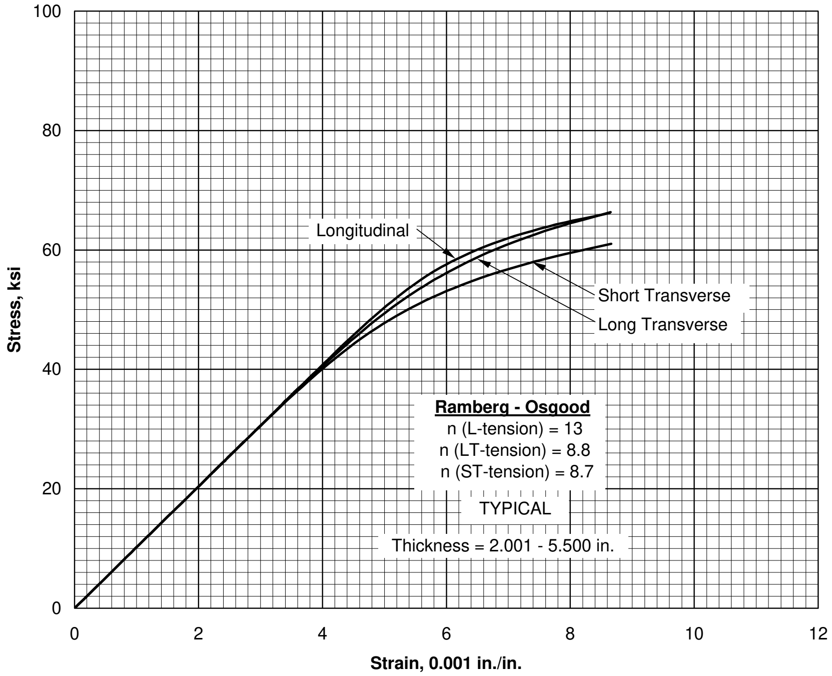


Figure 3.7.1.1.6(a). Typical tensile stress-strain curves for 7010-T7451 plate at room temperature.

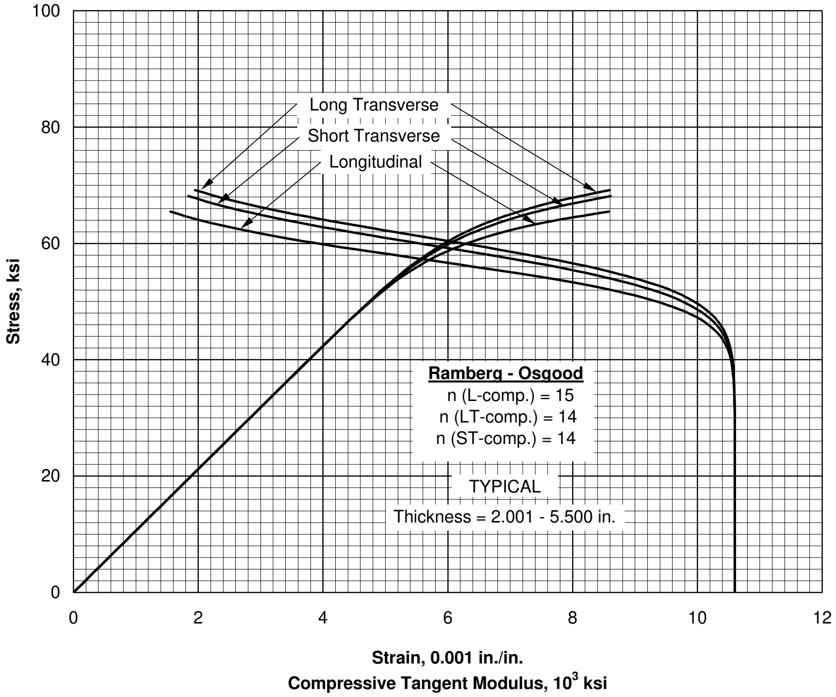


Figure 3.7.1.1.6(b). Typical compressive stress-strain and compressive tangent-modulus curves for 7010-T7451 plate at room temperature.

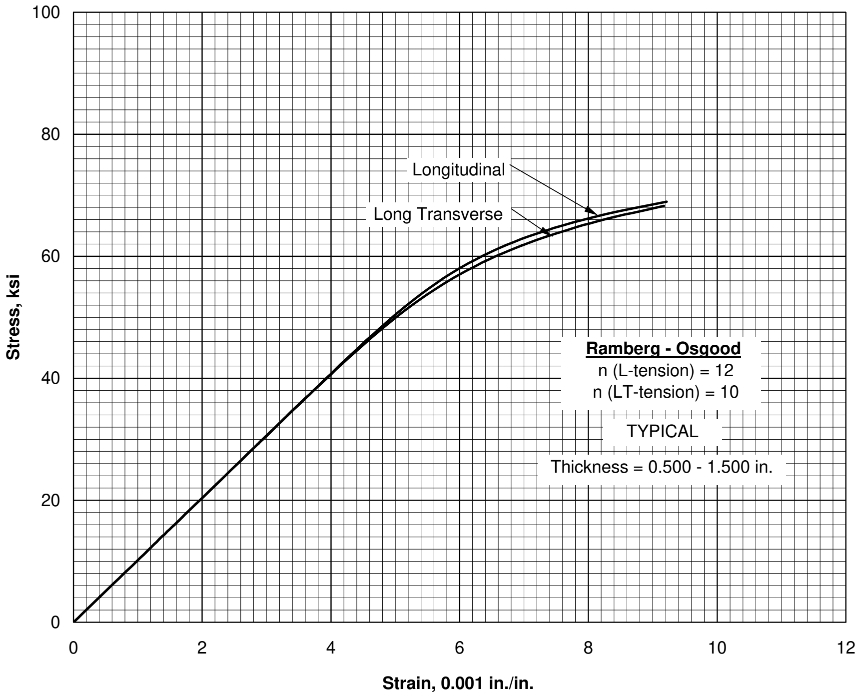


Figure 3.7.1.1.6(c). Typical tensile stress-strain curves for 7010-T7451 aluminum alloy plate at room temperature.

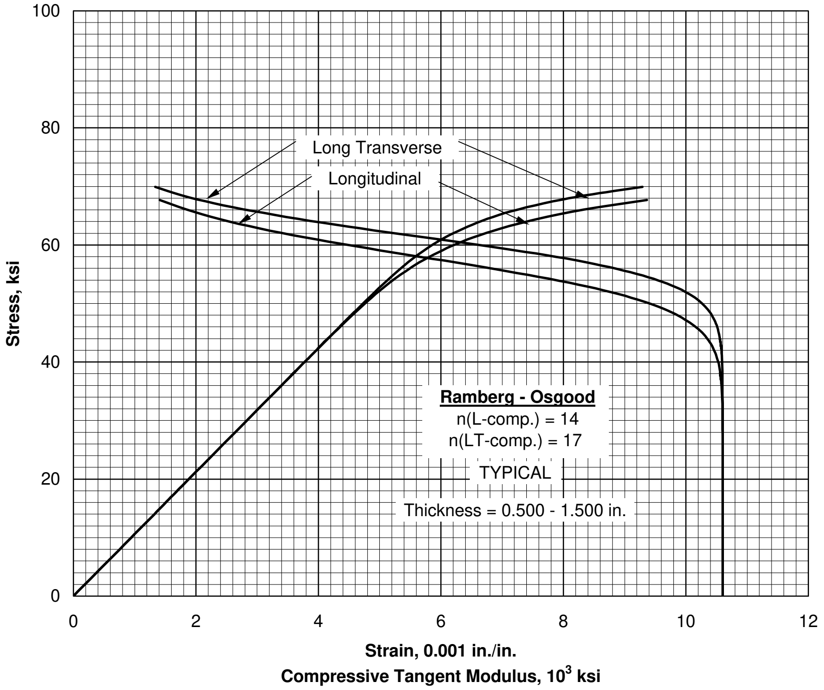


Figure 3.7.1.1.6(d). Typical compressive stress-strain and compressive tangent-modulus curves for 7010-T7451 aluminum alloy plate at room temperature.

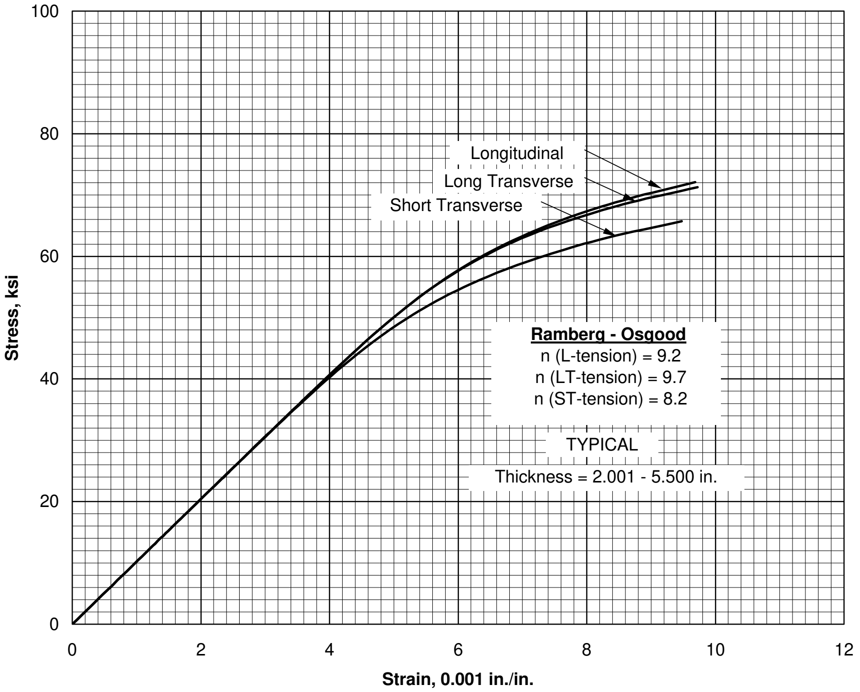


Figure 3.7.1.2.6(a). Typical tensile stress-strain curves for 7010-T7651 plate at room temperature.

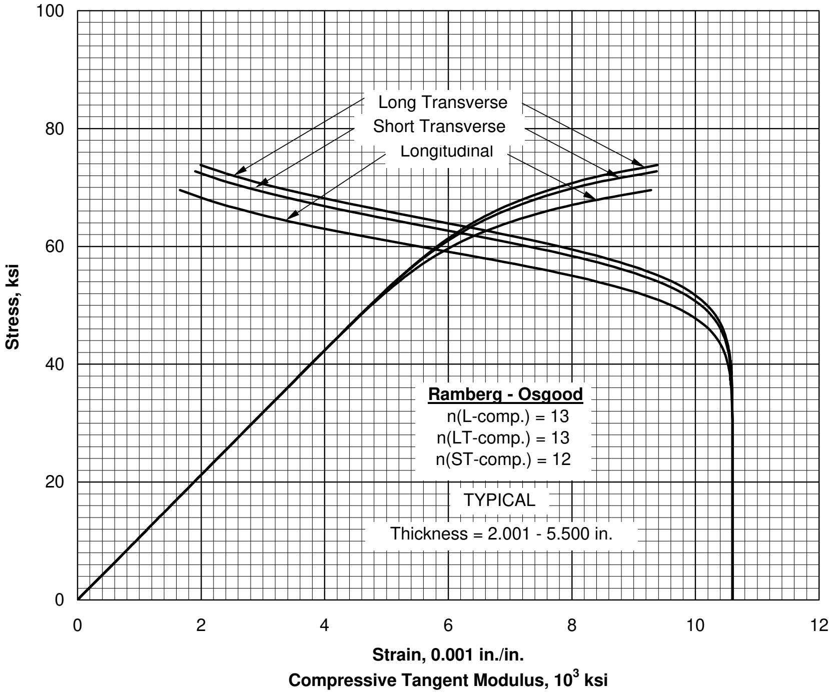


Figure 3.7.1.2.6(b). Typical compressive stress-strain and compressive tangent-modulus curves for 7010-T7651 plate at room temperature.

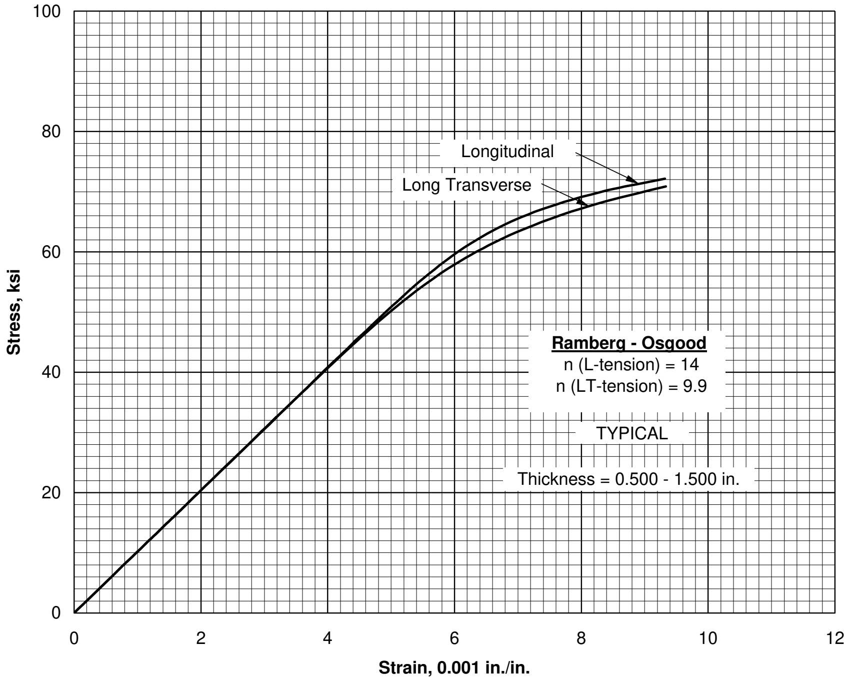


Figure 3.7.1.2.6(c). Typical tensile stress-strain curves for 7010-T7651 aluminum alloy plate at room temperature.

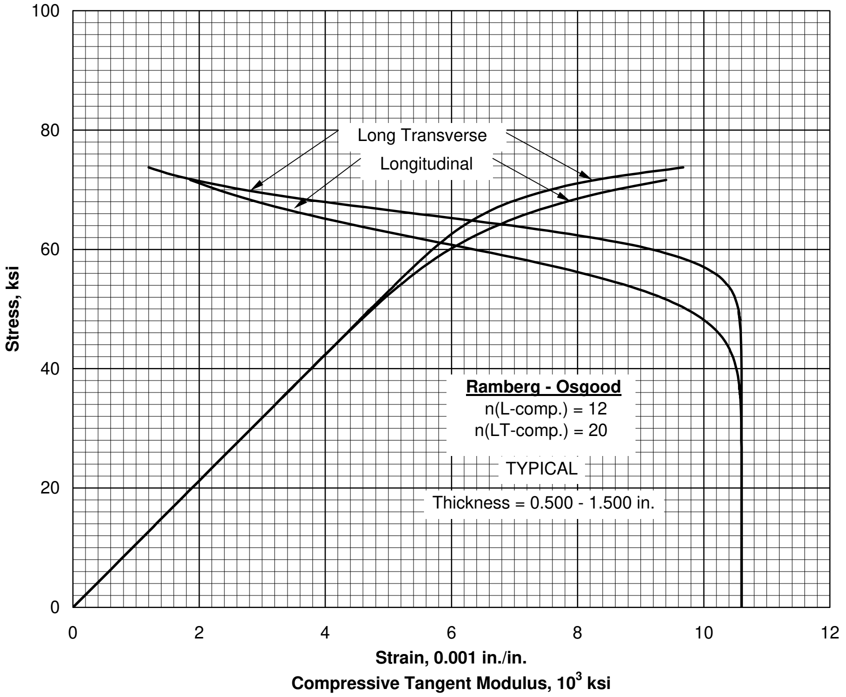


Figure 3.7.1.2.6(d). Typical compressive stress-strain and compressive tangent-modulus curves for 7010-T7651 aluminum alloy plate at room temperature.

3.7.2 7040 ALLOY

3.7.2.0 ***Comments and Properties*** — 7040 alloy is an Al-Mg-Zn-Cu-Zr alloy developed to provide a higher strength and toughness compromise than the currently available 7010 and 7050 alloys, particularly in heavy gauge plates up to 8.5 inch thickness. The use of a desaturated chemical composition in Mg and Cu together with a very close control of the Zr content and impurities, provide 7040 with a much lower quench sensitivity than that of 7050, resulting in high strength and toughness properties in very thick sections.

7040-T7451 plates are particularly suited for structures in which high strength, high toughness, and good corrosion resistance are the major requirements. Parts such as integrally machined spars, ribs, and main fuselage frames can benefit from this outstanding property combination.

7040 is available in the form of plates, range in thickness from 3.0 to 8.5 inches.

Manufacturing Considerations — Due to tight control of residual stress level, the 7040 plates exhibit a superior dimensional stability, thus offering a cost-efficient alternative to rolled or forged parts, which require distortion corrections after machining.

Refer to Section 3.1.3.4 for comments regarding the weldability of this alloy.

Specifications and Properties — Material specifications are shown in Table 3.7.2.0(a). Room-temperature properties are shown in Table 3.7.2.0(b_1). Figure 3.7.2.0 shows the effect of temperature on tensile properties.

Table 3.7.2.0(a). Material Specifications for 7040-T7451 Alloy Plate

Specification	Form
AMS 4211	Plate

Table 3.7.2.0(b_1). Design Mechanical and Physical Properties of 7040-T7451 Aluminum Alloy Plate

Specification	AMS 4211											
Form	Plate											
Temper	T7451											
Thickness, in.	3.001-4.000		4.001-5.000		5.001-6.000		6.001 - 7.000		7.001 - 8.000		8.001 - 8.500	
Basis	A	B	A	B	A	B	A	B	A	B	A	B
Mechanical Properties:												
F_{tu}, ksi:												
L	72	72	71	72	70^a	71	69	70	68^b	70	68^c	70
LT	72^d	74	71^e	73	70^a	72	69	70	68^b	69	68	69
ST	69	70	68^e	70	68	69	66	67	66	67	66	67
F_{ty}, ksi:												
L	62^d	65	62^e	64	62^a	64	62	62	61	62	61	63
LT	62^d	65	62^e	65	61^a	63	60	62	60	61	59	61
ST	59^d	61	58^e	61	58^a	61	57	58	57	58	56	58
F_{cy}, ksi:												
L	60	63	60	62	59	61	58	60	59	60	59	61
LT	64	67	64	67	63	66	62	64	62	64	61	63
ST	63	66	63	66	62	65	61	63	61	63	60	63
F_{su}, ksi	45	47	44	46	44	45	43	44	43	44	43	44
$F_{bru}{}^f$, ksi:												
(e/D = 1.5)	114	117	112	115	110	114	108	110	105	108	105	106
(e/D = 2.0)	145	150	143	147	140	145	137	140	134	136	133	134
$F_{bry}{}^f$, ksi:												
(e/D = 1.5)	93	97	93	97	92	96	90	93	90	92	88	91
(e/D = 2.0)	114	119	114	119	112	117	110	113	110	113	108	112
e, percent (S-basis):												
L	9	...	9	...	8	...	7	...	6	...	6	...
LT	6	...	5	...	4	...	4	...	4	...	4	...
ST	3	...	3	...	3	...	3	...	3	...	3	...
E, 10^3 ksi	10.4											
E_c, 10^3 ksi	10.6											
G, 10^3 ksi	3.9											
μ	0.33											
Physical Properties:												
ω, lb/in.^{3}	0.102											
C, Btu/(lb)(°F)	0.23											
K, Btu/[(hr)(ft^2)(°F)/ft]	91											
α, 10^{-6} in./in./°F	12.8											

a S-basis values. Rounded T_{99} values are as follows: F_{tu}(L) = 71 ksi; F_{tu}(LT) = 71 ksi; F_{ty}(L) = 63 ksi; F_{ty}(LT) = 62 ksi; and F_{ty}(ST) = 59 ksi.

b S-basis values. Rounded T_{99} values are as follows: F_{tu}(L) = 69 ksi; F_{tu}(LT) = 69 ksi.

c S-basis values. Rounded T_{99} values are as follows: F_{tu}(L) = 69 ksi.

d S-basis values. Rounded T_{99} values are as follows: F_{tu}(LT) = 73 ksi; F_{ty}(L) = 64 ksi; F_{ty}(LT) = 64 ksi; and F_{ty}(ST) = 60 ksi.

e S-basis values. Rounded T_{99} values are as follows: F_{tu}(LT) = 72 ksi; F_{tu}(ST) = 69 ksi; F_{ty}(L) = 63 ksi; and F_{ty}(LT) = 63 ksi, F_{ty}(ST) = 59 ksi.

f See Table 3.1.2.1.1. Bearing values are “dry pin” values per Section 1.4.7.1.

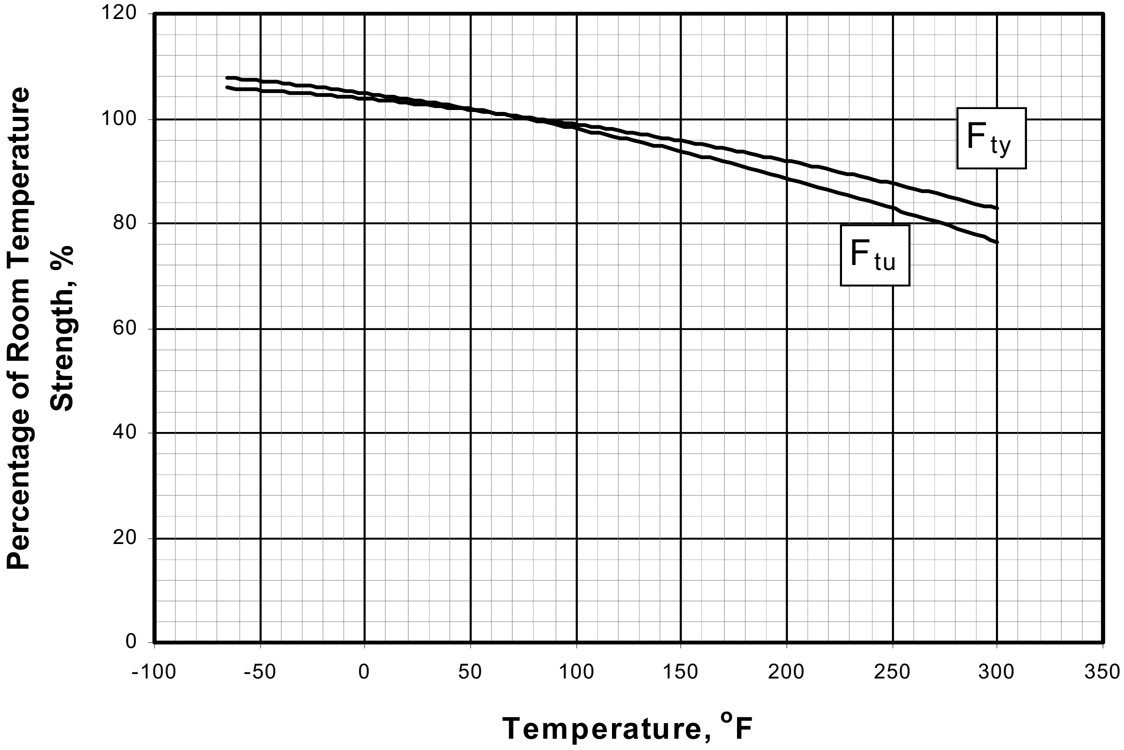


Figure 3.7.2.0 Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of 7040-T7451aluminum alloy plate, T/4 location.

3.7.3 7049/7149 ALLOY

3.7.3.0 *Comments and Properties* — Alloy 7049/7149 is available in the form of die forging, hand forging, plate, and extrusion. Alloy 7149 contains lower residual iron and silicon content than 7049. The T73XX temper provides good static strength with high resistance to stress-corrosion cracking. The fatigue strength of the T73XX temper is about equal to that of 7075-T6, while the toughness is somewhat higher. Refer to Section 3.1.2.3 for comments regarding the resistance of the alloys to stress-corrosion cracking and to Section 3.1.3.4 for comments regarding the weldability of the alloys.

The properties of extrusions should be based upon the thickness at the time of quenching prior to machining. Selection of the mechanical properties based upon its final machined thickness may be unconservative; therefore, the thickness at the time of quenching to achieve properties is an important factor in the selection of the proper thickness column. For extrusions having sections with various thicknesses, consideration should be given to the properties as a function of thickness.

Material specifications for 7049/7149 aluminum alloy are presented in Table 3.7.3.0(a). Room-temperature mechanical and physical properties are shown in Tables 3.7.3.0(b) through (e).

Table 3.7.3.0(a). Material Specifications for 7049/7149 Aluminum Alloy

Specification	Form
AMS-QQ-A-367 (7049)	Forging
AMS 4111 (7049)	Forging
AMS 4320 (7149)	Forging
AMS 4157 (7049)	Extrusion
AMS-A-22771	Forging
AMS 4200 (7049)	Plate
AMS 4343 (7149)	Extrusion

The temper index for 7049/7149 is as follows:

Section	Temper
3.7.3.1	T73 and T73511

3.7.3.1 *T73 and T73511 Tempers* — Figure 3.7.3.1.1 presents elevated temperature curves for various products. Figures 3.7.3.1.6(a) through (g) present tensile and compressive stress-strain and tangent-modulus curves. Fatigue data for 7049-T73 die and hand forgings are shown in Figures 3.7.3.1.8(a) through (g).

Table 3.7.3.0(b). Design Mechanical and Physical Properties of 7049 Aluminum Alloy Plate

Specification	AMS 4200							
Form	Plate							
Temper	T7351							
Thickness, in.	0.750-1.000	1.001-1.500	1.501-2.000	2.001-2.500	2.501-3.000	3.001-4.000	4.001-4.500	4.501-5.000
Basis	S	S	S	S	S	S	S	S
Mechanical Properties:								
F_{tu}, ksi:								
L	...	...	72	72	71	70	68	68
LT	74	73	73	73	72	70	68	68
ST	...	...	69	69	68	65	63	63
F_{ty}, ksi:								
L	...	...	64	63	62	60	58	58
LT	65	64	64	63	62	60	58	58
ST	...	...	59	58	57	56	54	54
F_{cy}, ksi:								
L	...	...	64	63	62	60	58	...
LT	...	...	69	68	67	64	62	...
ST	...	...	69	68	67	64	62	...
F_{su}, ksi	...	...	41	41	41	39	38	...
$F_{bru}{}^{a}$, ksi:								
(e/D = 1.5)	...	...	...	114	112	109	106	...
(e/D = 2.0)	...	...	...	146	144	140	136	...
$F_{bry}{}^{a}$, ksi:								
(e/D = 1.5)	...	...	...	91	89	86	83	...
(e/D = 2.0)	...	...	...	106	104	101	97	...
e, percent:								
L	...	...	...	...	...	6	6	5
LT	8	8	7	6	6	5	5	5
ST	...	...	...	...	...	2	2	2
E, 10^3 ksi	10.1							
E_c, 10^3 ksi	10.4							
G, 10^3 ksi	3.9							
μ	0.33							
Physical Properties:								
ω, lb/in.^{3}	0.103							
C, Btu/(lb)(°F)	0.23 (at 212°F)							
K, Btu/[(hr)(ft^2)(°F)/ft]	89 (at 77°F)							
α, 10^{-6} in./in./°F . . .	13.0 (RT to 212°F)							

a Bearing values are "dry pin" values per Section 1.4.7.1. See Table 3.1.2.1.1.

Table 3.7.3.0(c). Design Mechanical and Physical Properties of 7049/7149 Aluminum Alloy Die Forging

Specification	AMS-QQ-A-367, AMS 4111, AMS 4320, and AMS-A-22771									
Form	Die forging									
Temper	T73[a]									
Thickness[b], in.	≤1.000		1.001-2.000		2.001-3.000		3.001-4.000		4.001-5.000	
Basis	A	B	A	B	A	B	A	B	A	B
Mechanical Properties:										
F_{tu}, ksi:										
L	71	74	70	73	69	72	68	71	67	70
T[c] (S-basis)	71[d]	...	70[d]	...	70[d]	...	70[d]	...	68[d]	...
F_{ty}, ksi:										
L	60	64	59	63	58	61	57	60	55	59
T[c] (S-basis)	61[d]	...	60[d]	...	60[d]	...	60[d]	...	58[d]	...
F_{cy}, ksi:										
L	62	66	61	65	60	63	59	62	57	61
ST	56	60	55	59	54	57	53	56	51	55
F_{su}, ksi	40	41	39	41	39	40	38	40	37	39
F_{bru}[e], ksi:										
(e/D = 1.5)	100	105	99	103	98	102	96	100	95	99
(e/D = 2.0)	132	138	130	136	128	134	126	132	125	130
F_{bry}[e], ksi:										
(e/D = 1.5)	76	82	75	80	74	78	73	76	70	75
(e/D = 2.0)	93	99	91	97	90	94	88	93	85	91
e, percent (S-basis):										
L	7	...	7	...	7	...	7	...	7	...
T[c]	3	...	3	...	3	...	2	...	2	...
E, 10^3 ksi	10.2									
E_c, 10^3 ksi	10.7									
G, 10^3 ksi	3.9									
μ	0.33									
Physical Properties:										
ω, lb/in.^{3}	0.103									
C, Btu/(lb)(°F)	0.25 (at 212°F)									
K, Btu/[(hr)(ft^2)(°F)/ft]	89 (at 77°F)									
α, 10^{-6} in./in./°F	13.0 (RT to 212°F)									

a Design values were based upon data obtained from testing T73 die forgings, heat treated by suppliers and supplied in T73 temper.

b Thickness at the time of heat treatment. When die forgings are machined before heat treatment, the mechanical properties are applicable provided the as-forged thickness is not greater than twice the thickness at the time of heat treatment.

c T indicates any grain direction not within ±15° of being parallel to the forging flow lines. F_{cy}(T) values are based upon short transverse (ST) test data.

d Specification value. T tensile properties are presented on an S-basis only.

e Bearing values are "dry pin" values per Section 1.4.7.1.

Table 3.7.3.0(d). Design Mechanical and Physical Properties of 7049/7149 Aluminum Alloy Hand Forging

Specification	AMS-QQ-A-367, AMS 4111, AMS 4320, and AMS-A-22771		
Form	Hand forging		
Temper	T73		
Thickness[a], in.	2.001-3.000	3.001-4.000	4.001-5.000
Basis	S	S	S
Mechanical Properties:			
F_{tu}, ksi:			
L	71	69	67
LT	71	69	67
ST	69	67	66
F_{ty}, ksi:			
L	61	59	56
LT	59	57	56
ST	58	56	55
F_{cy}, ksi:			
L	60	58	57
LT	61	59	57
ST	61	59	58
F_{su}, ksi:			
L	42	41	39
LT	41	39	38
ST	41	40	39
F_{bru}[b], ksi:			
(e/D = 1.5)	102	100	97
(e/D = 2.0)	134	130	126
F_{bry}[b], ksi:			
(e/D = 1.5)	81	79	77
(e/D = 2.0)	96	92	91
e, percent:			
L	9	8	7
LT	4	3	3
ST	3	2	2
E, 10^3 ksi	10.2		
E_c, 10^3 ksi	10.6		
G, 10^3 ksi	3.9		
μ	0.33		
Physical Properties:			
ω, lb./in.^{3}	0.103		
C, Btu/(lb)(°F)	0.23 (at 212°F)		
K, Btu/[(hr)(ft^2)(°F)/ft]	89 (at 77°F)		
α, 10^{-6} in./in./°F	13.0 (RT to 212°F)		

a When hand forgings are machined before heat treatment, section thickness at time of heat treatment will determine minimum mechanical properties as long as original (as-forged) thickness does not exceed maximum thickness for the alloy as shown in the table. The maximum cross-section area of hand forgings is 256 sq. in.

b Bearing values are "dry pin" values per Section 1.4.7.1.

Table 3.7.3.0(e). Design Mechanical and Physical Properties of 7049/7149 Aluminum Alloy Extrusion

Specification	AMS 4157 and AMS 4343		
Form	Extrusion		
Temper	T73511		
Thickness,[a] in.	≤ 2.499	2.500-2.999	3.000-5.000
Basis	S	S	S
Mechanical Properties:			
F_{tu}, ksi:			
L	74	74	72
LT	70	70	68
ST	...	70	68
F_{ty}, ksi:			
L	64	64	62
LT	60	60	58
ST	...	60	58
F_{cy}, ksi:			
L	65	65	63
LT	...	...	...
ST	...	...	...
F_{su}, ksi	40	40	39
F_{bru}[b], ksi:			
(e/D = 1.5)	110	110	107
(e/D = 2.0)	144	144	140
F_{bry}[b], ksi:			
(e/D = 1.5)	85	85	83
(e/D = 2.0)	105	105	101
e, percent:			
L	7	7	7
LT	5	5	5
ST	...	5	5
E, 10^3 ksi	10.5		
E_c, 10^3 ksi	11.0		
G, 10^3 ksi	4.0		
μ	0.33		
Physical Properties:			
ω, lb/in.^{3}	0.103		
C, Btu/(lb)(°F)	0.23 (at 212°F)		
K, Btu/[(hr)(ft^2)(°F)/ft] ..	89 (at 77°F)		
α, 10^{-6} in./in./°F	13.0 (RT to 212°F)		

[a] The mechanical properties are to be based upon the thickness at the time of quench.
[b] Bearing values are "dry pin" values per Section 1.4.7.1.

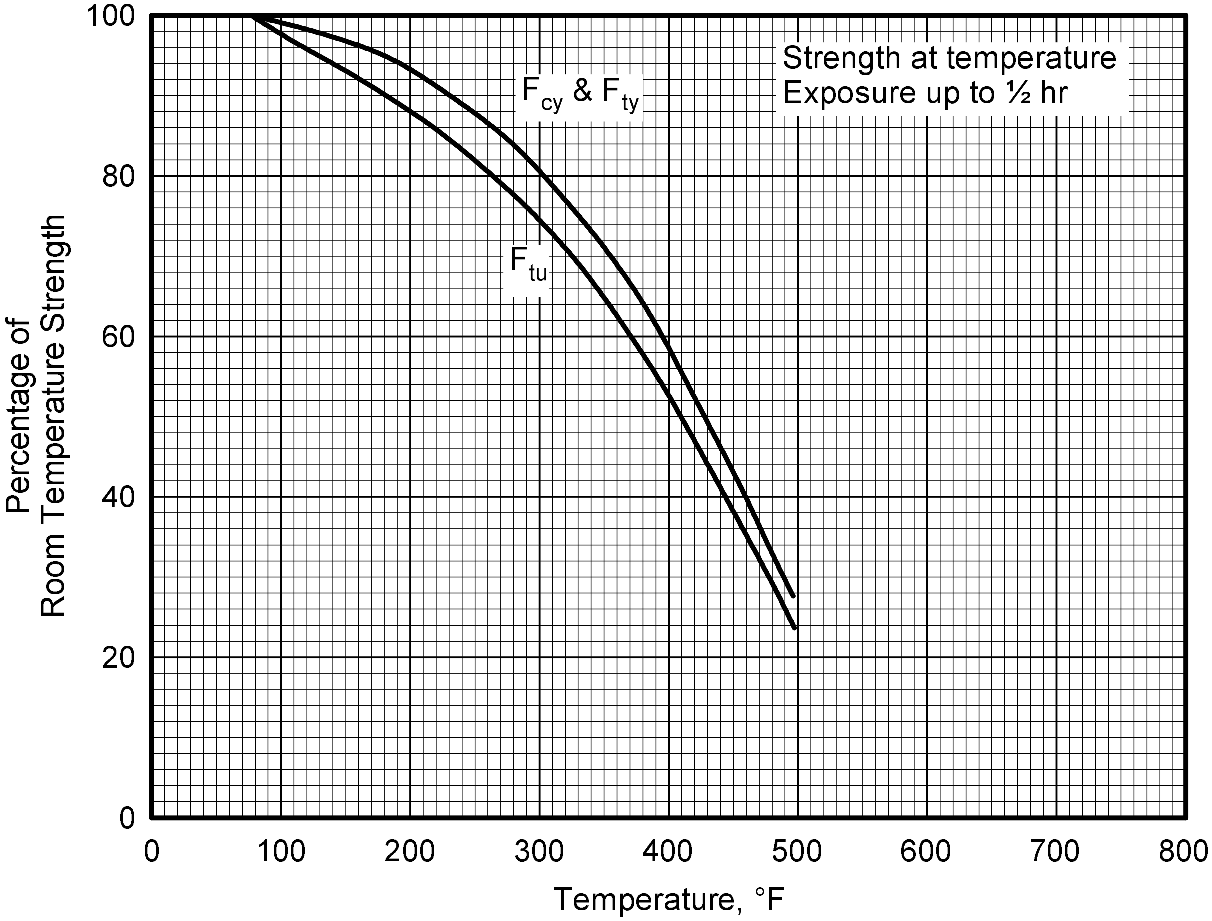


Figure 3.7.3.1.1. Effect of temperature on the tensile ultimate strength (F_{tu}), the tensile yield strength (F_{ty}), and the compressive yield strength (F_{cy}) of 7049-T7351 plate, 7049/7149-T73 hand forging, and 7049/7149-T7351 extrusion.

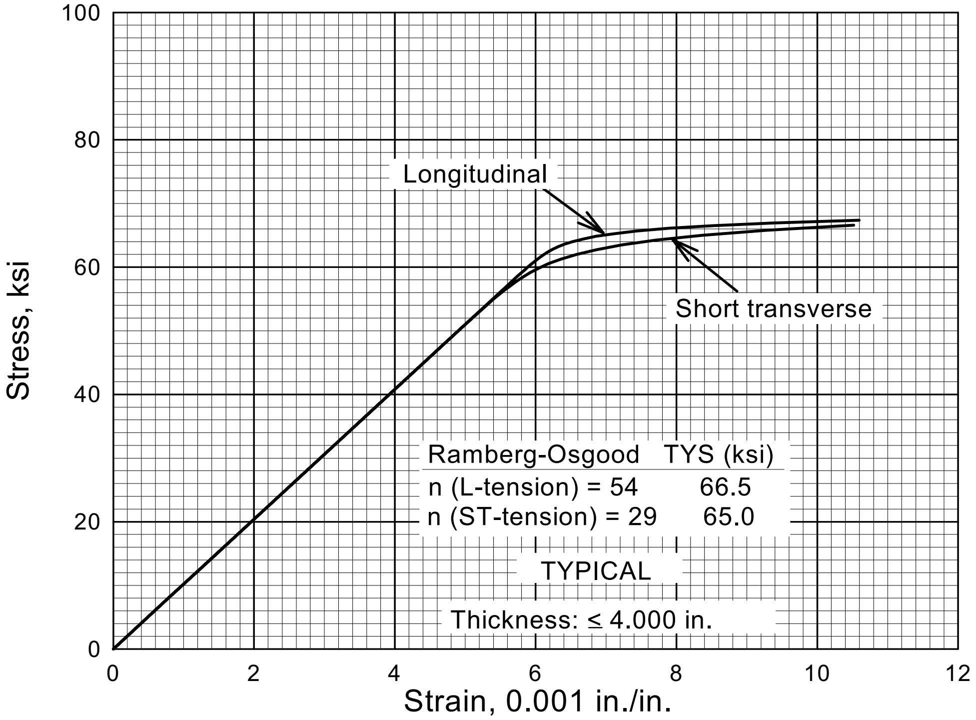


Figure 3.7.3.1.6(a). Typical tensile stress-strain curves for 7049/7149-T73 aluminum alloy die forging at room temperature.

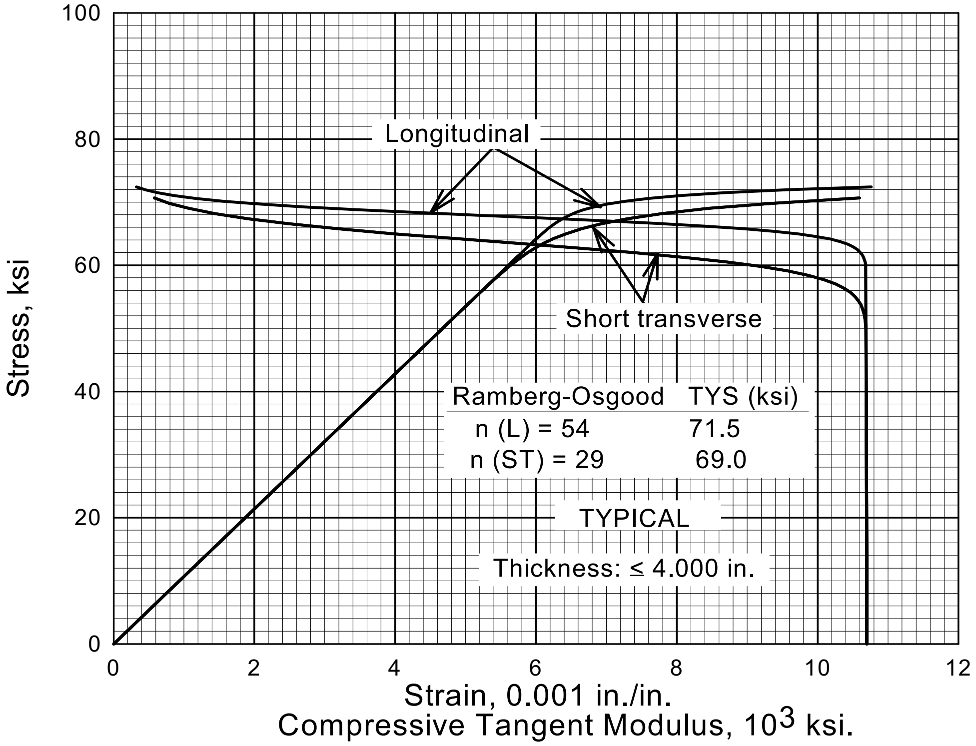


Figure 3.7.3.1.6(b). Typical compressive stress-strain and compressive tangent-modulus curves for 7049/7149-T73 aluminum alloy die forging at room temperature.

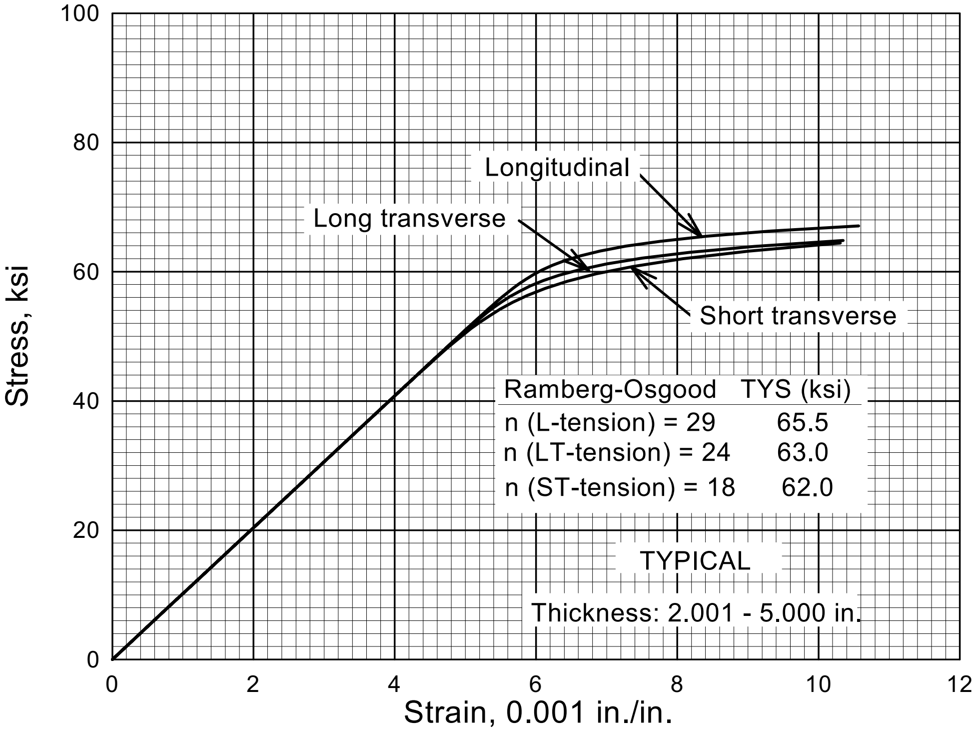


Figure 3.7.3.1.6(c). Typical tensile stress-strain curves for 7049/7149-T73 aluminum alloy hand forging at room temperature.

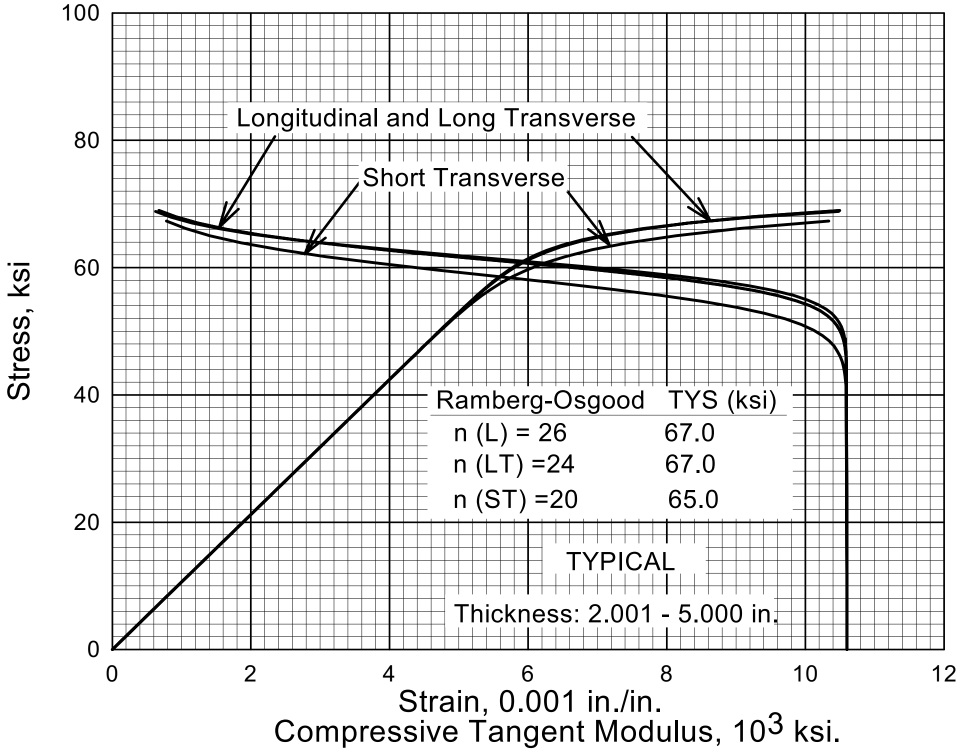


Figure 3.7.3.1.6(d). Typical compressive stress-strain and compressive tangent-modulus curves for 7049/7149-T73 aluminum alloy hand forging at room temperature.

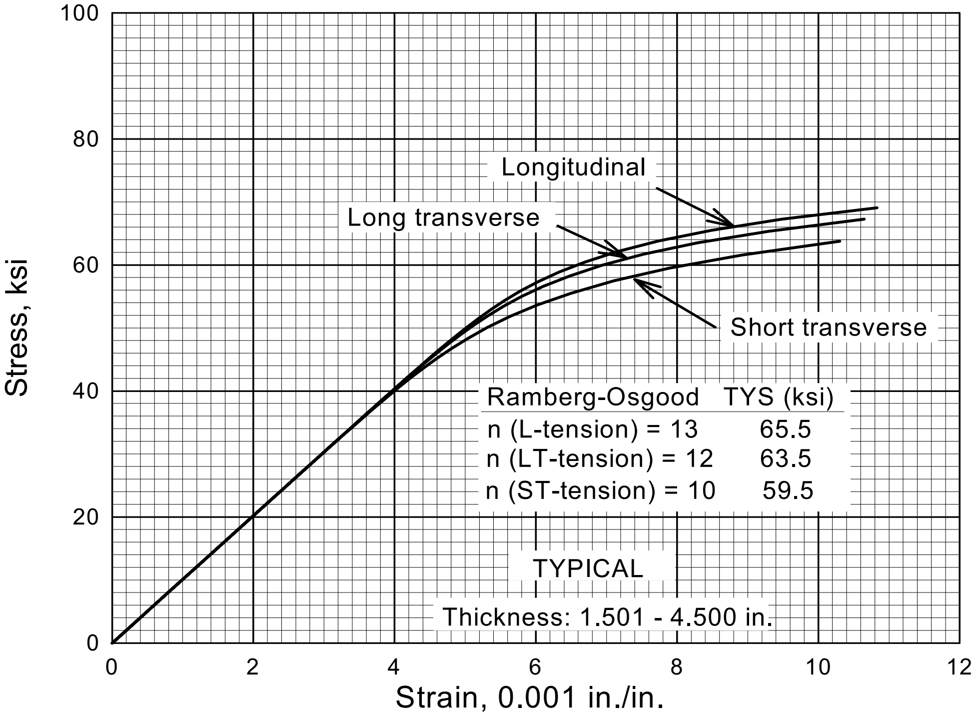


Figure 3.7.3.1.6(e). Typical tensile stress-strain curves for 7049-T7351 aluminum alloy plate at room temperature.

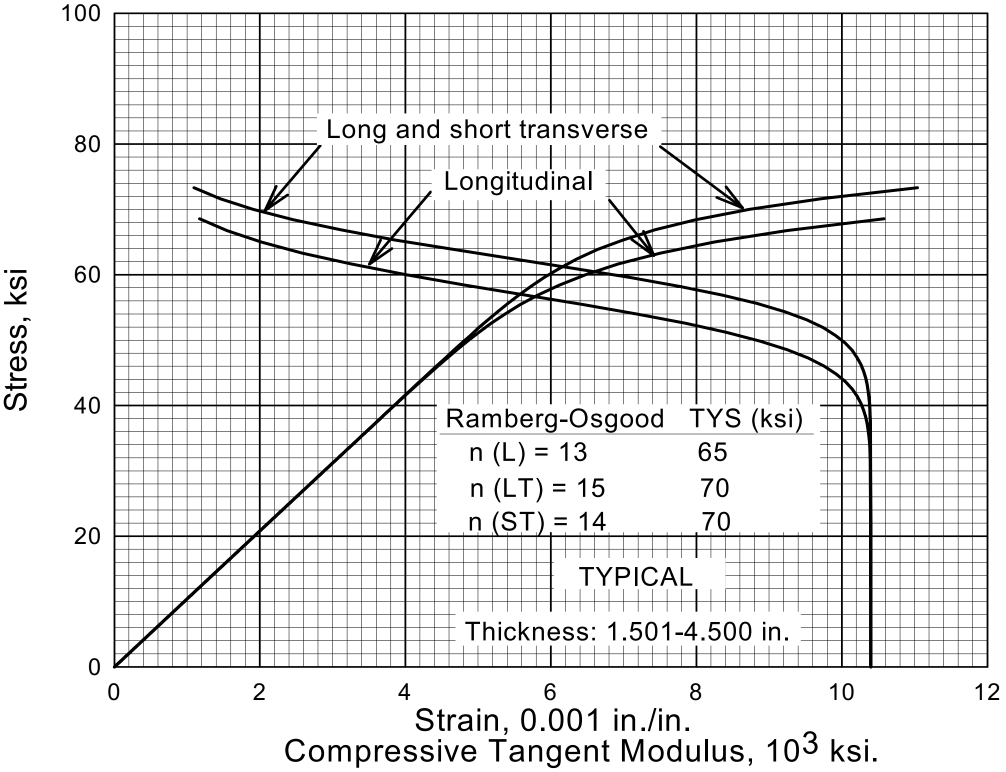


Figure 3.7.3.1.6(f). Typical compressive stress-strain and compressive tangent-modulus curves for 7049-T7351 aluminum alloy plate at room temperature.

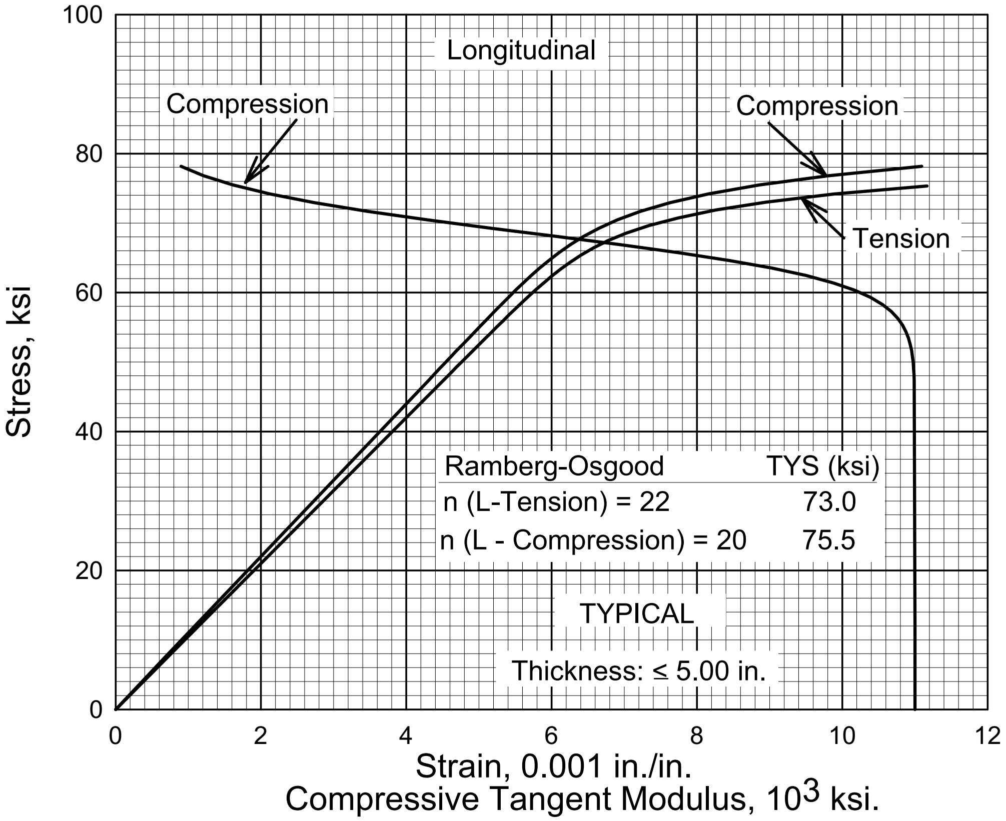


Figure 3.7.3.1.6(g). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 7049/7149-T73511 extrusion at room temperature.

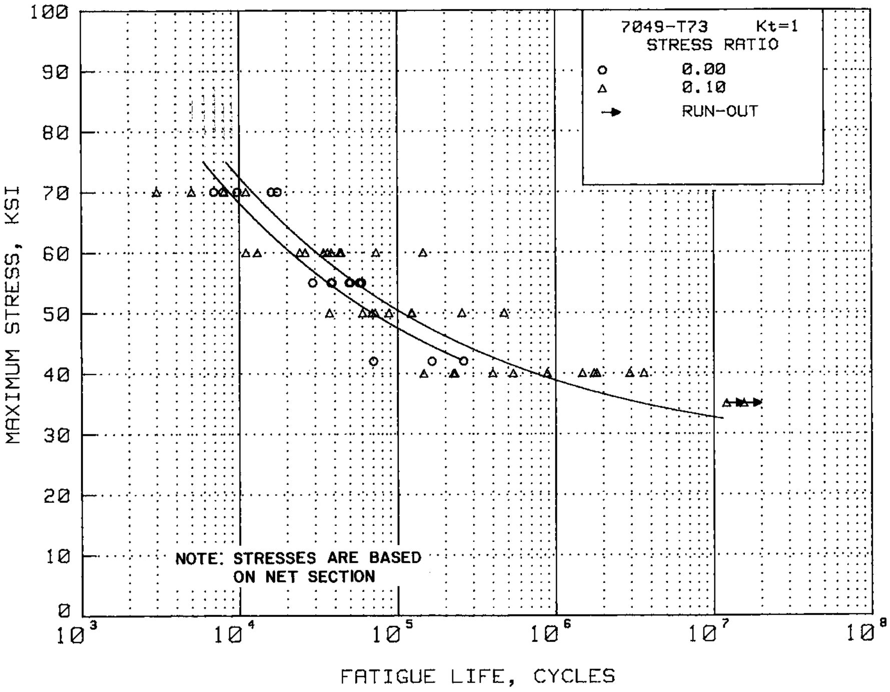


Figure 3.7.3.1.8(a). Best-fit S/N curves for unnotched 7049-T73 die and hand forgings, at room temperature, longitudinal and long-transverse directions.

Correlative Information for Figure 3.7.3.1.8(a)

Product Form: Die forging, 3 and 4.5 inches thick. Hand forging, 2, 3, 4, and 5 inches thick

Properties:	TUS, ksi	TYS, ksi	Temp., °F
(L)	78	70	RT
(LT)	74	65	RT

Specimen Details: Unnotched
Uniform Gage,
0.200 inch net diameter
Hourglass,
0.225 inch net diameter
3.00 inch test section radius
Hourglass,
0.300 inch net diameter
9.875 inch test section radius

Surface Condition: Longitudinally polished to 4 RMS finish or better
Unspecified

References: 3.7.3.1.8(a), (b), and 3.2.6.1.9(d)

Test Parameters:
Loading - Axial
Frequency - 1800 cpm
Temperature - RT
Environment - Lab air

No. of Heats/Lots: 6

Stress Life Equation:
Log $N_f = 9.95 - 3.62 \log (S_{eq} - 24.2)$
$S_{eq} = S_{max} (1-R)^{0.57}$
Std. Error of Estimate, Log (Life) = 0.346
Standard Deviation, Log (Life) = 0.736
$R^2 = 78\%$

Sample Size = 50

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

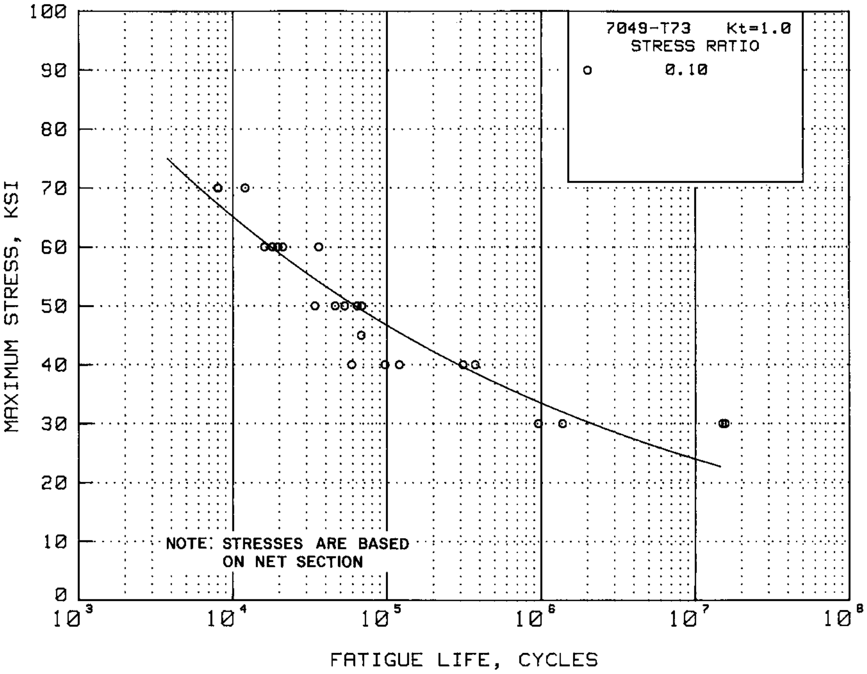


Figure 3.7.3.1.8(b). Best-fit curves for unnotched 7049-T73 die forging, at room temperature, short transverse direction.

Correlative Information for Figure 3.7.3.1.8(b)

Product Form: Die forging, 3 inches thick

Properties:

TUS, ksi	TYS, ksi	Temp., °F
73	64	RT

Specimen Details: Unnotched
0.200 inch net diameter

Surface Condition: Longitudinally polished to 4μ in. finish with no circumferential marks

Reference: 3.7.3.1.8(a)

Test Parameters:
Loading - Axial
Frequency - 1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 1

Maximum Stress Equation:
Log N_f = 16.55-6.92 log (S_{max})
Std. Error of Estimate, Log (Life) = 0.371
Standard Deviation, Log (Life) = 0.917
R^2 = 84%

Sample Size = 23

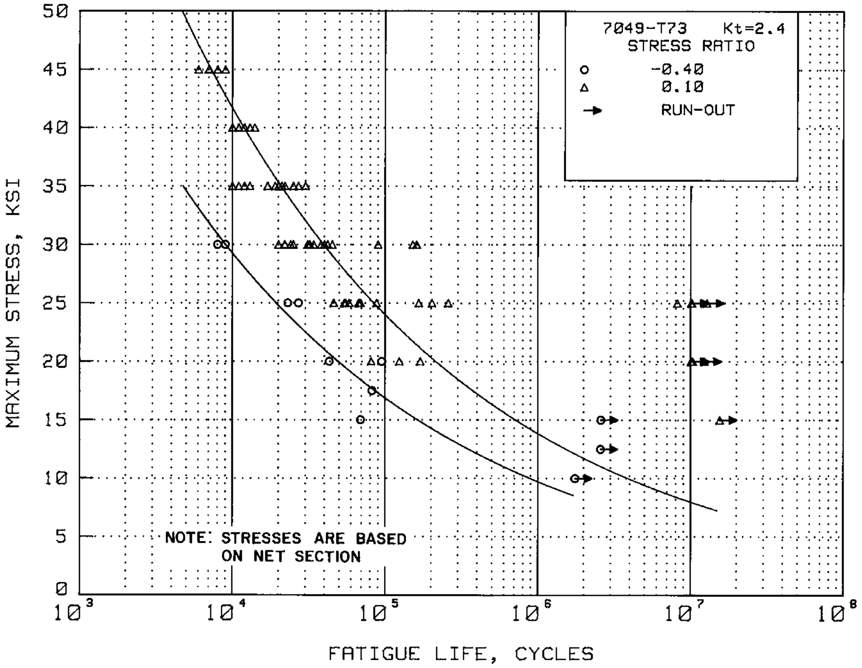


Figure 3.7.3.1.8(c). Best-fit S/N curves for notched, K_t = 2.4, 7049-T73 die forging, at room temperature, longitudinal, long-transverse and short-transverse directions.

Correlative Information for Figure 3.7.3.1.8(c)

Product Form: Die forging, 3 and 4.5 inches thick

Properties:	TUS, ksi	TYS, ksi	Temp., °F
(L)	77	68	RT Unnotched
	95	—	RT Notched
(LT)	73	64	RT Unnotched
	77	—	RT Notched
(ST)	75	66	RT Unnotched
	87	—	RT Notched

Specimen Details: Circumferentially notched,
$K_t = 2.4$
0.150 or 2.00 inch
net diameter
0.350 inch net diameter
0.500 inch gross diameter
0.032 inch notch
root radius, r
60° flank angle, ω

Surface Condition: Machined notch

References: 3.7.3.1.8(a) and (c)

Test Parameters:
Loading - Axial
Frequency - 1800 cpm
Temperature - RT
Environment - Lab air

No. of Heats/Lots: 2

Stress Life Equation:
$\text{Log } N_f = 10.6\text{-}4.18 \log (S_{eq})$
$S_{eq} = S_{max} (1\text{-}R)^{0.80}$
Std. Error of Estimate, Log (Life) = 0.320
Standard Deviation, Log (Life) = 0.500
$R^2 = 59\%$

Sample Size = 69

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

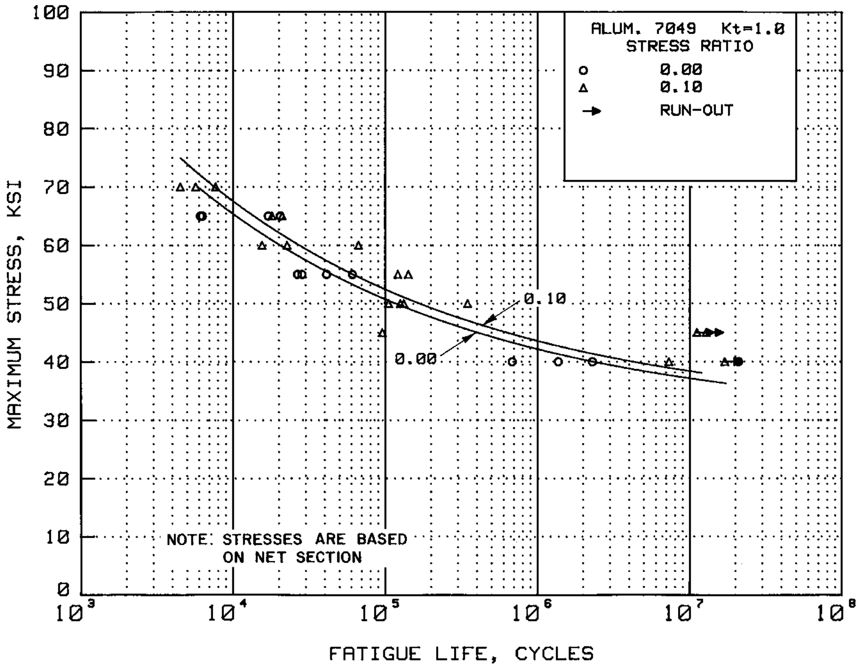


Figure 3.7.3.1.8(d). Best-fit S/N curves for unnotched 7049-T73 hand forging, longitudinal direction.

Correlative Information for Figure 3.7.3.1.8(d)

Product Form: Hand forging, 2.0 to 5.0 inches thick

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	70-80	60-73	RT

Specimen Details: Unnotched
0.125 and 0.300 inch diameter

Surface Condition: Polished with increasingly finer grits of emery paper to surface roughness of 10 rms with polishing marks longitudinal, or not specified.

References: 3.2.6.1.9(d) and 3.7.3.1.8(e)

Test Parameters:
Loading - Axial
Frequency - 800, 1500, or 1725 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 6

Equivalent Stress Equation:
Log N_f = 10.6-4.31 log (S_{eq}-30)
$S_{eq} = S_{max} (1-R)^{0.31}$
Std. Error of Estimate, Log (Life) = 0.348
Standard Deviation, Log (Life) = 0.944
R^2 = 86%

Sample Size = 28

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

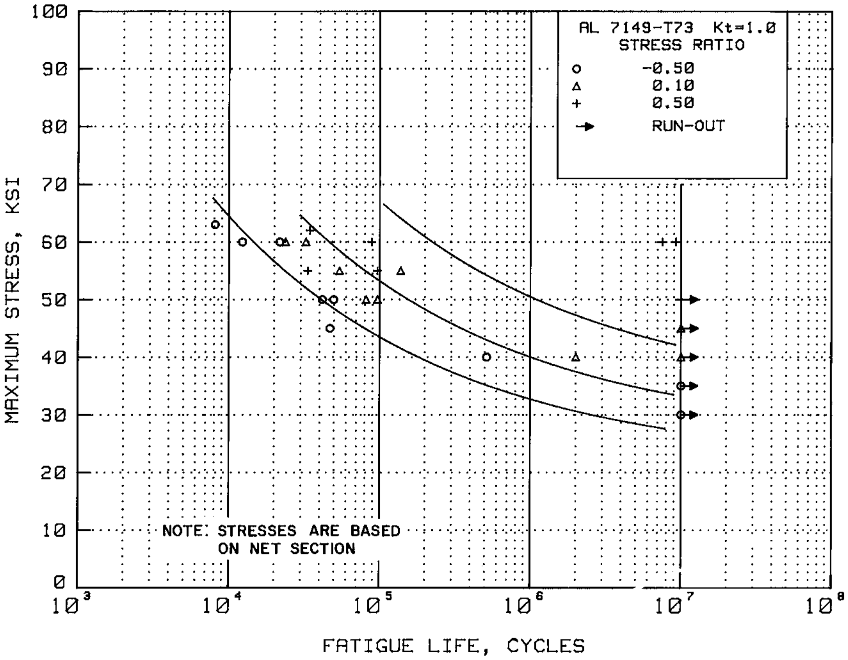


Figure 3.7.3.1.8(e). Best-fit S/N curves for unnotched 7149-T73 hand forging, long-transverse direction.

Correlative Information for Figure 3.7.3.1.8(e)

Product Form: Hand forging, 4.00 to 4.75 inches thick

Properties:

TUS, ksi	TYS, ksi	Temp., °F
73	64	RT

Specimen Details: Unnotched
0.250 inch diameter

Surface Condition: Not specified.

Reference: 3.7.3.1.8(e)

Test Parameters:
Loading - Axial
Frequency - Not specified
Temperature - RT
Environment - Air

No. of Heats/Lots: 3

Equivalent Stress Equation:
Log $N_f = 9.9 - 3.46 \log (S_{eq} - 25)$
$S_{eq} = S_{max} (1-R)^{0.39}$
Std. Error of Estimate, Log (Life) = 0.689
Standard Deviation, Log (Life) = 0.845
$R^2 = 34\%$

Sample Size = 20

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

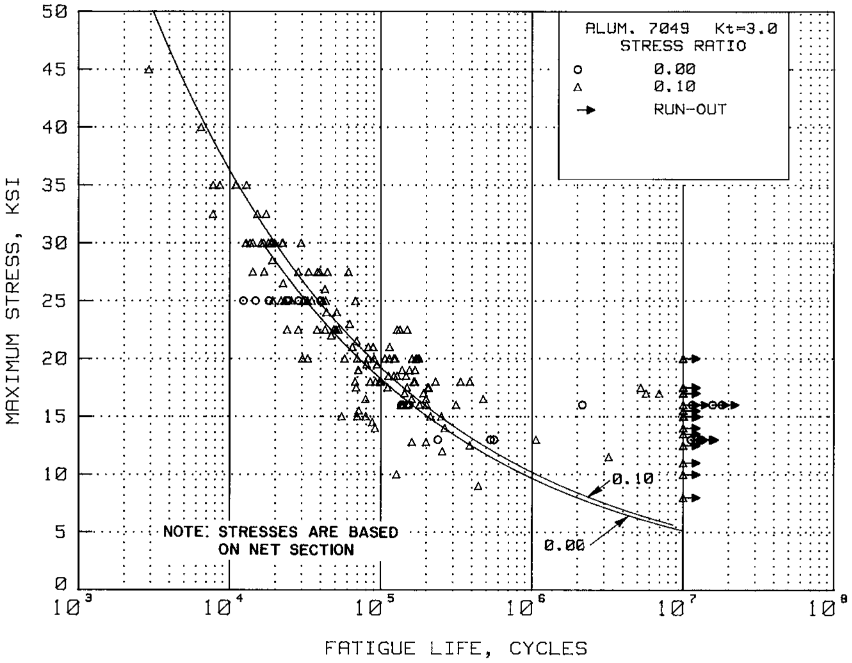


Figure 3.7.3.1.8(f). Best-fit S/N curves for notched, K_t = 3.0, 7049-T73 hand forging, longitudinal, long-transverse, and short-transverse directions.

<u>Correlative Information for Figure 3.7.3.1.8(f)</u>

<u>Product Form</u>: Hand forging, 2.0 to 5.0 inches thick

<u>Properties</u>:

	TUS, ksi	TYS, ksi	Temp., °F
	71-80	62-73	RT

<u>Specimen Details</u>: Circumferentially notched, K_t=3.0
0.200, 0.300, and 0.306 inch gross diameter
0.175, 0.200, and 0.253 inch net diameter
0.006, 0.010, and 0.013 inch root radius, r
60° flank angle, ω

<u>Surface Condition</u>: Polished with oil and alumdum grit applied to a rotating wire, or not specified.

<u>References</u>: 3.2.6.1.9(d), 3.7.3.1.8(d) and (e)

<u>Test Parameters:</u>
Loading - Axial
Frequency - 800, 1500, or 1725 cpm
Temperature - RT
Environment - Air

<u>No. of Heats/Lots</u>: 8

<u>Equivalent Stress Equation</u>:
Log N_f = 9.57-3.63 log (S_{eq})
$S_{eq} = S_{max} (1-R)^{0.49}$
Std. Error of Estimate, Log (Life) = 0.344
Standard Deviation, Log (Life) = 0.562
R^2 = 63%

<u>Sample Size</u> = 151

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

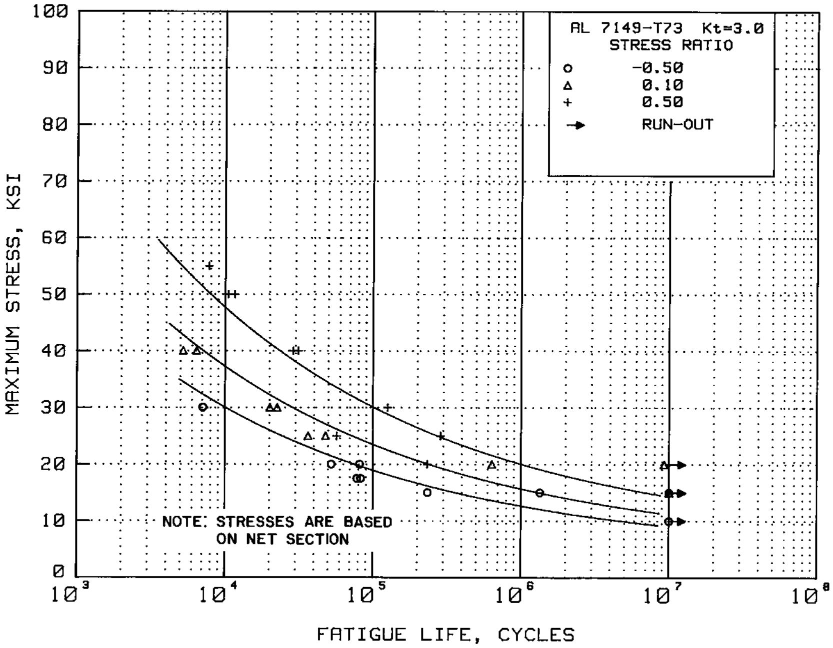


Figure 3.7.3.1.8(g). Best-fit S/N curves for notched, K_t = 3.0, 7149-T73 hand forging, long transverse direction.

Correlative Information for Figure 3.7.3.1.8(g)

Product Form: Hand forging, 4.00 to 4.75 inches thick

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	73	64	RT

Specimen Details: Circumferentially notched, $K_t = 3.0$
0.375 inch gross diameter
0.253 inch net diameter
0.013 inch root radius, r
60° flank angle, ω

Surface Condition: Not specified

Reference: 3.7.3.1.8(e)

Test Parameters:
Loading - Axial
Frequency - Not specified
Temperature - RT
Environment - Air

No. of Heats/Lots: 3

Equivalent Stress Equation:
$\text{Log } N_f = 10.1 - 4.10 \log (S_{eq} - 5)$
$S_{eq} = S_{max} (1-R)^{0.42}$
Std. Error of Estimate, Log (Life) = 0.450
Standard Deviation, Log (Life) = 0.797
$R^2 = 68\%$

Sample Size = 25

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

3.7.4 7050 ALLOY

3.7.4.0 *Comments and Properties* — 7050 is an Al-Zn-Mg-Cu-Zr alloy developed to have a combination of high strength, high resistance to stress-corrosion cracking, and good fracture toughness, particularly in thick sections. The use of zirconium in lieu of chromium provides a low sensitivity to quench, which results in high strengths in thick sections. Plate, hand, and die forgings in the T74 temper have static strengths about equivalent to those of corresponding products of 7079 in the T6 tempers and toughness levels equal to or higher than other conventional high-strength alloys.

The properties of extrusions should be based upon the thickness at the time of quenching prior to machining. Selection of the mechanical properties based upon its final machined thickness may be unconservative; therefore, the thickness at the time of quenching to achieve properties is an important factor in the selection of the proper thickness column. For extrusions having sections with various thicknesses, consideration should be given to the properties as a function of thickness.

Plate in the T7451 temper has stress-corrosion resistance higher than 7075-T7651, and hand and die forgings in the T7452 and T74 tempers, respectively, have stress-corrosion resistance similar to 7175-T74 forgings. The T73 temper provides the highest resistance to stress corrosion for this alloy. The T76 temper provides for good exfoliation resistance and higher stress-corrosion resistance than T6 tempers of 7075 and 7178. The T74 temper provides stress-corrosion and strength characteristics intermediate to those of T76 and T73. Refer to Section 3.1.2.3 for further comments regarding the resistance of the alloy to stress-corrosion cracking.

Refer to Section 3.1.3.4 for comments regarding the weldability of this alloy.

Material specifications for 7050 are shown in Table 3.7.4.0(a). Room-temperature properties are shown in Table 3.7.4.0(b_1) through (e_3).

Table 3.7.4.0(a). Material Specifications for 7050 Aluminum Alloy

Specification	Form
AMS 4050	Bare plate
AMS 4108	Hand forging
AMS 4107	Die forging
AMS 4333	Die forging
AMS 4340	Extruded shape
AMS 4341	Extruded shape
AMS 4342	Extruded shape
AMS 4201	Bare plate
AMS-A-22771	Forging

The temper index for 7050 is as follows:

Section	Temper
3.7.4.1	T73510 and T73511
3.7.4.2	T74, T7451, and T7452 (formerly T736, T73651, T73652)
3.7.4.3	T76510 and T76511

3.7.4.1 *T73510 and T73511 Tempers* — Figures 3.7.4.1.6(a) through (d) present stress-strain and tangent-modulus curves for extrusions. Fatigue data are presented in Figures 3.7.4.1.8(a) and (b).

3.7.4.2 *T74, T7451, and T7452 Tempers* — Elevated temperature curves for T7451 plate are presented in Figure 3.7.4.2.1. Figures 3.7.4.2.6(a) through (j) present stress-strain and tangent-modulus curves for various products and tempers. Fatigue data are presented in Figures 3.7.4.2.8(a) through (l). Fatigue-crack-propagation data for T7451 plate are presented in Figures 3.7.4.2.9(a) through (c).

3.7.4.3 *T76510 and T76511 Tempers* — Figures 3.7.4.3.6(a) through (f) present stress-strain and tangent-modulus curves for extruded shapes. Fatigue data are presented in Figure 3.7.4.3.8(a) and (b).

Table 3.7.4.0(b_1). Design Mechanical and Physical Properties of 7050 Aluminum Alloy Plate

Specification	AMS 4050															
Form	Plate															
Temper	T7451															
Thickness, in.	0.250-1.500		1.501-2.000		2.001-3.000		3.001-4.000		4.001-5.000		5.001-6.000		6.001 -7.000		7.001 - 8.000	
Basis	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
Mechanical Properties:																
F_{tu}, ksi:																
L	74[a]	76	74	76	73[a]	75	72	74	71[a]	73	70[a]	72	69	72	68	71
LT	74	76	74[a]	76	73[a]	75	72	75	71[a]	74	70	73	69	72	68	71
ST	...	...	...	...	68	72	68[a]	71	67	70	66	69	66	68	65	67
F_{ty}, ksi:																
L	64[b]	67	64[b]	66	63[b]	66	62[b]	65	61[b]	65	60	63	59	62	58[b]	63
LT	64	66	64	66	63[b]	66	62	65	61	64	60	62	59	62	58	61
ST	...	...	...	...	59	61	57	60	57[b]	60	57	59	56	58	55[b]	58
F_{cy}, ksi:																
L	63	64	62	64	61	64	60	63	58	61	57	59	56	59	55	57
LT	66	68	67	69	66	69	65	68	64	67	63	66	60	63	59	62
ST	...	...	...	...	63	66	63	66	63	66	62	64	60	63	59	62
F_{su}, ksi	42	43	43	44	43	44	43	45	43	45	43	45	44	46	44	46
F_{bru}[c], ksi:																
(e/D = 1.5)	107	110	109	112	108	111	107	111	107	111	105	110	107	112	103	108
(e/D = 2.0)	140	144	142	146	141	144	140	144	138	144	137	142	136	143	132	138
F_{bry}[c], ksi:																
(e/D = 1.5)	86	89	89	92	89	93	90	94	90	95	91	94	84	89	83	87
(e/D = 2.0)	101	104	104	107	104	109	104	109	105	110	105	108	99	105	98	102
e, percent (S-basis):																
L	10	...	10	...	9	...	9	...	9	...	8	...	7	...	6	...
LT	9	...	9	...	8	...	6	...	5	...	4	...	4	...	4	...
ST	...	...	...	...	3	...	3	...	3	...	3	...	3	...	3	...
E, 10^3 ksi	10.3															
E_c, 10^3 ksi	10.6															
G, 10^3 ksi	3.9															
μ	0.33															
Physical Properties:																
ω, lb/in.^{3}	0.102															
C, Btu/(lb)(°F)	0.23 (at 212°F)															
K, Btu/[(hr)(ft^2)(°F)/ft]	91 (at 77°F)															
α, 10^{-6} in./in./°F	12.8 (68 to 212°F)															

a S-basis values. Rounded T_{99} values for F_{tu} are as follows: for 0.250-1.500 (L) = 75 ksi, for 1.502-2.000 (LT) = 75 ksi, for 2.001-3.000 (L) and (LT) = 74 ksi, for 3.001-4.000 (ST) = 69 ksi, for 4.001-5.000 (L) and (LT) = 72 ksi, for 5.001-6.000 (L) = 71ksi.

b S-basis values. Rounded T_{99} values for F_{ty} are as follows: for 0.250-1.500 (L) = 65 ksi, for 1.502-2.000 (L) = 65 ksi, for 2.001-3.000 (L) = 65 ksi, (LT) = 64 ksi, for 3.001-4.000 (L) = 63 ksi, for 4.001-5.000 (L) = 62 ksi, (ST) = 58 ksi, for 7.001-8.000 (L) = 59 ksi, (ST) = 56 ksi.

c See Table 3.1.2.1.1. Bearing values are "dry pin" values per Section 1.4.7.1.

Table 3.7.4.0(b_2). Design Mechanical and Physical Properties of 7050 Aluminum Alloy Plate

Specification	AMS 4201							
Form	Plate							
Temper	T7651							
Thickness, in.	0.250-1.000	1.001-1.500		1.501-2.000		2.001-2.500		2.501-3.000
Basis	S	A	B	A	B	A	B	S
Mechanical Properties:								
F_{tu}, ksi:								
L	76	77	79	76	78	75	78	76
LT	76	76	79	75	78	75	78	76
ST	...	...	...	72	75	70	73	70
F_{ty}, ksi:								
L	66	66	71	66	70	66	70	66
LT	66	66	70	65	69	65	69	66
ST	...	...	...	59	63	60	62	60
F_{cy}, ksi:								
L	64	64	68	64	67	64	67	64
LT	68	68	73	68	72	68	72	69
ST	...	...	...	67	71	67	71	68
F_{su}, ksi	43	44	46	44	46	45	47	46
$F_{bru}{}^{a}$, ksi:								
(e/D = 1.5)	110	112	117	112	117	114	118	116
(e/D = 2.0)	142	144	150	144	150	146	151	149
$F_{bry}{}^{a}$, ksi:								
(e/D = 1.5)	87	90	96	91	96	93	98	96
(e/D = 2.0)	102	105	111	105	112	107	114	110
e, percent (S-basis):								
L	9	9	...	9	...	8	...	8
LT	8	8	...	8	...	7	...	7
ST	...	...	...	...	...	1.5	...	1.5
E, 10^3 ksi	10.3							
E_c, 10^3 ksi	10.8							
G, 10^3 ksi	4.0							
μ	0.33							
Physical Properties:								
ω, lb/in.^{3}	0.102							
C, Btu/(lb)(°F)	0.23 (at 212°F)							
K, Btu/[(hr)(ft^2)(°F)/ft]	89 (at 77°F)							
α, 10^{-6} in./in./°F	12.8 (68 to 212°F)							

[a] See Table 3.1.2.1.1. Bearing values are “dry pin” values per Section 1.4.7.1.

Table 3.7.4.0(c_1). Design Mechanical and Physical Properties of 7050 Aluminum Alloy Die Forging

Specification	AMS 4107 and AMS-A-22771			
Form	Die forging			
Temper	T74[a]			
Thickness[b], in.	≤2.000	2.001-4.000	4.001-5.000	5.001-6.000
Basis	S	S	S	S
Mechanical Properties:				
F_{tu}, ksi:				
L	72	71	70	70
T[c]	68	67	66	66
F_{ty}, ksi:				
L	62	61	60	59
T[c]	56	55	54	54
F_{cy}, ksi:				
L	63	63	63	62
ST	60	59	58	57
F_{su}, ksi	42	42	41	41
F_{bru}[d], ksi:				
(e/D = 1.5)	99	98	97	97
(e/D = 2.0)	131	129	127	127
F_{bry}[d], ksi:				
(e/D = 1.5)	82	81	78	78
(e/D = 2.0)	96	95	92	92
e, percent:				
L	7	7	7	7
T[c]	5	4	3	3
E, 10^3 ksi	10.2			
E_c, 10^3 ksi	10.7			
G, 10^3 ksi	3.9			
μ	0.33			
Physical Properties:				
ω, lb/in.^{3}	0.102			
C, Btu/(lb)(°F)	0.23 (at 212°F)			
K, Btu/[(hr)(ft^2)(°F)/ft]	91 (at 77°F)			
α, 10^{-6} in./in./°F	12.8 (68 to 212°F)			

a Design values were based upon data obtained from testing T74 die forgings, heat treated by suppliers and supplied in T74 temper.

b Thickness at the time of heat treatment. When die forgings are machined before heat treatment, the mechanical properties are applicable provided the as-forged thickness is not greater than twice the thickness at the time of heat treatment.

c T indicates any grain direction not within ±15° of being parallel to the forging flow lines. F_{cy}(T) values are based upon short transverse (ST) test data.

d Bearing values are “dry pin” values per Section 1.4.7.1.

Table 3.7.4.0(c_2). Design Mechanical and Physical Properties of 7050-T7452 Aluminum Alloy Die Forging

Specification	AMS 4333			
Form	Die forgings			
Temper	T7452			
Thickness[b], in.	≤2.000		2.001-4.000	
Basis	A	B	A	B
Mechanical Properties:				
F_{tu}, ksi:				
L	71	73	71	72
T[a]	68[b]	73	67[c]	71
F_{ty}, ksi:				
L	60	63	59	61
T[a]	55[b]	61	53[c]	61
F_{cy}, ksi:				
L	63	66	62	64
ST	63	66	62	64
F_{su}, ksi	43	44	43	43
F_{bru}[d], ksi:				
(e/D = 1.5)	101	104	101	103
(e/D = 2.0)	135	139	135	137
F_{bry}[d], ksi:				
(e/D = 1.5)	87	92	86	89
(e/D = 2.0)	105	110	103	106
e, percent (S-basis):				
L	9		8	
T[a]	5		4	
E, 10^3 ksi	10.2			
E_c, 10^3 ksi	10.5			
G, 10^3 ksi	3.9			
μ	0.33			
Physical Properties:				
ω, lb/in.^{3}	0.102			
C, Btu/(lb)(°F)	0.23 (at 212°F)			
K, Btu/[(hr)(ft^2)(°F)/ft]	91 (at 77°F)			
α, 10^{-6} in./in./°F	12.8 (68 to 212°F)			

[a] T indicates any grain direction not within ±15° of being perpendicular to the forging flow lines. F_{cy}(T) values are based on short transverse (ST) test data.

[b] S-basis. The T_{99} values are higher than the specification minimum values as follows: F_{tu}(T)=70.10 ksi, F_{ty}(t)=57.50 ksi.

[c] S-basis. The T_{99} values are higher than the specification minimum values as follows: F_{tu}(T)=69.36 ksi, F_{ty}(t)=57.38 ksi.

[d] Bearing values are “dry pin” values per Section 1.4.7.1.

Table 3.7.4.0(d). Design Mechanical and Physical Properties of 7050 Aluminum Alloy Hand Forging

Specification	AMS 4108 and AMS-A-22771							
Form	Hand Forging							
Temper	T7452							
Thickness, in.	≤2.000	2.001-3.000	3.001-4.000	4.001-5.000	5.001-6.000	6.001-7.000		7.001-8.000
Basis	S	S	S	S	S	A	B	S
Mechanical Properties:								
F_{tu}, ksi:								
L	72	72	71	70	69	68	71	67
LT	71	70	70	69	68	67	70	66
ST	...	67	67	66	66	65	69	64
F_{ty}, ksi:								
L	63	62	61	60	59	56	61	57
LT	61	60	59	58	56	54[a]	59	52
ST	...	55	55	54	53	51[a]	56	50
F_{cy}, ksi:								
L	63	62	61	60	58	56	61	54
LT	64	63	62	61	59	57	62	55
ST	...	63	61	60	58	56	61	54
F_{su}, ksi	42	41	41	41	40	40	41	39
F_{bru}[b], ksi:								
(e/D = 1.5)	98	97	97	96	94	93	97	91
(e/D = 2.0)	131	129	129	127	125	123	129	121
F_{bry}[b], ksi:								
(e/D = 1.5)	86	84	83	82	79	76	83	73
(e/D = 2.0)	101	100	98	96	93	90	98	86
e, percent (S-basis):								
L	9	9	9	9	9	9	...	9
LT	5	5	5	4	4	4	...	4
ST	...	4	4	3	3	3	...	3
E, 10^3 ksi	10.2							
E_c, 10^3 ksi	10.6							
G, 10^3 ksi	3.9							
μ	0.33							
Physical Properties:								
ω, lb/in.^{3}	0.102							
C, Btu/(lb)(°F)	0.23 (at 212°F)							
K, Btu/[(hr)(ft^2)(°F)/ft]	91 (at 77°F)							
α, 10^{-6} in./in./°F	12.8 (68 to 212°F)							

[a] S-basis values. The rounded T_{99} values for F_{ty}(LT) = 56 ksi and F_{ty}(ST) = 52 ksi.

[b] Bearing values are "dry pin" values per Section 1.4.7.1.

Table 3.7.4.0(e_1). Design Mechanical and Physical Properties of 7050 Aluminum Alloy Extrusion

Specification	AMS 4341				
Form	Extrusion				
Temper	T73511				
Cross-Sectional Area, in^2	≤32				
Thickness or Diameter,[a] in.	≤1.000	1.001-2.000	2.001-3.000	3.001-4.000	4.001-5.000
Basis	S	S	S	S	S
Mechanical Properties:					
F_{tu}, ksi:					
L	70	70	70	70	70
LT	68	66	65	63	62
F_{ty}, ksi:					
L	60	60	60	60	60
LT	57	56	55	53	52
F_{cy}, ksi:					
L	60	60	60	61	61
LT	60	59	58	56	55
F_{su}, ksi	39	39	38	37	36
F_{bru}[b], ksi:					
(e/D = 1.5)	103	100	96	91	87
(e/D = 2.0)	133	129	124	120	115
F_{bry}[b], ksi:					
(e/D = 1.5)	82	80	78	76	74
(e/D = 2.0)	97	95	93	91	88
e, percent:					
L	8	8	8	8	8
E, 10^3 ksi	10.3				
E_c, 10^3 ksi	10.7				
G, 10^3 ksi	3.9				
μ	0.33				
Physical Properties:					
ω, lb/in.^{3}	0.102				
C, Btu/(lb)(°F)	0.23 (at 212°F)				
K, Btu/[(hr)(ft^2)(°F)/ft]	93 (at 77°F)				
α, 10^{-6} in./in./°F	12.8 (68 to 212°F)				

a The mechanical properties are to be based upon the thickness at the time of quench.
b Bearing values are "dry pin" values per Section 1.4.7.1.

Table 3.7.4.0(e_2). Design Mechanical and Physical Properties of 7050 Aluminum Alloy Extrusion

Specification	AMS 4342				
Form	Extrusion[a]				
Temper	T74511				
Cross-Sectional Area, in^2	≤32				
Thickness or Diameter,[b] in.	≤1.000	1.001-2.000	2.001-3.000	3.001-4.000	4.001-5.000
Basis	S	S	S	S	S
Mechanical Properties:					
F_{tu}, ksi:					
L	73	73	73	73	73
LT	71	69	68	64	64
F_{ty}, ksi:					
L	63	63	63	63	63
LT	60	59	58	56	54
F_{cy}, ksi:					
L	63	63	63	64	64
LT	63	62	61	59	57
F_{su}, ksi	41	40	40	39	38
F_{bru}[c], ksi:					
(e/D = 1.5)	107	104	100	95	91
(e/D = 2.0)	139	135	130	125	121
F_{bry}[c], ksi:					
(e/D = 1.5)	86	84	82	80	78
(e/D = 2.0)	106	100	98	95	92
e, percent:					
L	7	7	7	7	7
E, 10^3 ksi	10.3				
E_c, 10^3 ksi	10.7				
G, 10^3 ksi	3.9				
μ	0.33				
Physical Properties:					
ω, lb/in.^{3}	0.102				
C, Btu/(lb)(°F)	0.23 (at 212°F)				
K, Btu/[(hr)(ft^2)(°F)/ft]	93 (at 77°F)				
α, 10^{-6} in./in./°F	12.8 (68 to 212°F)				

a Excluding tubing.
b The mechanical properties are to be based upon the thickness at the time of quench.
c Bearing values are "dry pin" values per Section 1.4.7.1.

Table 3.7.4.0(e_3). Design Mechanical and Physical Properties of 7050 Aluminum Alloy Extrusion

Specification	AMS 4340						
Form	Extrusion						
Temper	T76511						
Thickness,[a] in.	≤0.499		0.500-1.000	1.001-2.000	2.001-3.000	3.001-4.000	4.001-5.000
Basis	A	B	S	S	S	S	S
Mechanical Properties:							
F_{tu}, ksi:							
L	77	79	79	79	79	79	79
LT	76	78	77	75	73	71	68
F_{ty}, ksi:							
L	68	71	69	69	69	69	69
LT	67	69	67	65	63	61	59
F_{cy}, ksi:							
L	68	71	69	69	69	69	69
LT	70	73	70	69	67	66	64
F_{su}, ksi	42	44	43	43	42	41	40
F_{bru}[b], ksi:							
(e/D = 1.5)	113	116	115	114	110	107	103
(e/D = 2.0)	147	151	150	148	144	140	136
F_{bry}[b], ksi:							
(e/D = 1.5)	94	98	94	92	89	86	82
(e/D = 2.0)	109	114	110	108	104	98	93
e, percent (S-basis):							
L	7	...	7	7	7	7	7
E, 10^3 ksi	10.3						
E_c, 10^3 ksi	10.7						
G, 10^3 ksi	3.9						
μ	0.33						
Physical Properties:							
ω, lb/in.^{3}	0.102						
C, Btu/(lb)(°F)	0.23 (at 212°F)						
K, Btu/[(hr)(ft^2)(°F)/ft]	89 (at 77°F)						
α, 10^{-6} in./in./°F	12.8 (68 to 212°F)						

a The mechanical properties are to be based upon the thickness at the time of quench.
b Bearing values are "dry pin" values per Section 1.4.7.1.

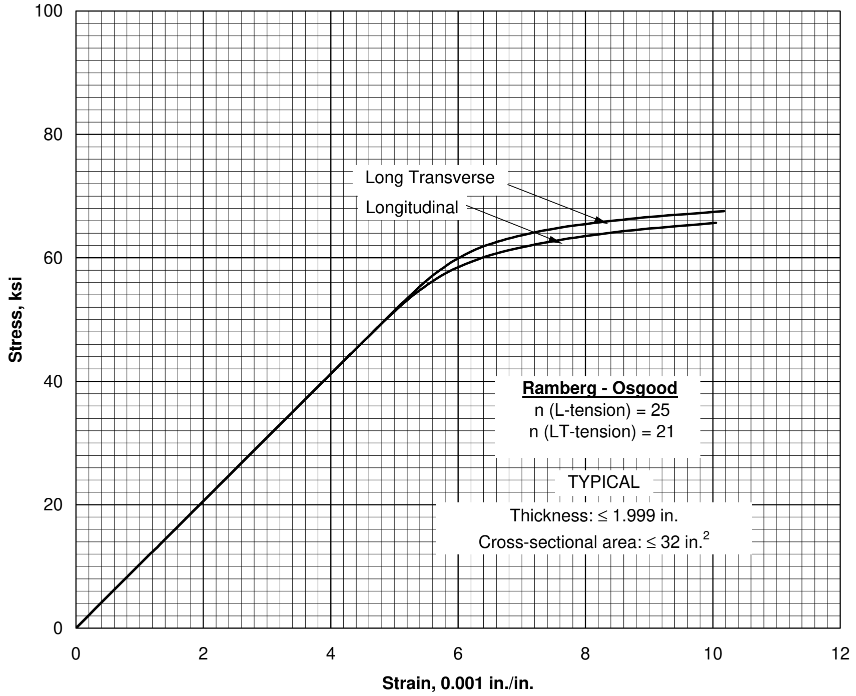


Figure 3.7.4.1.6(a). Typical tensile stress-strain curves for 7050-T7351X aluminum alloy extrusion at room temperature.

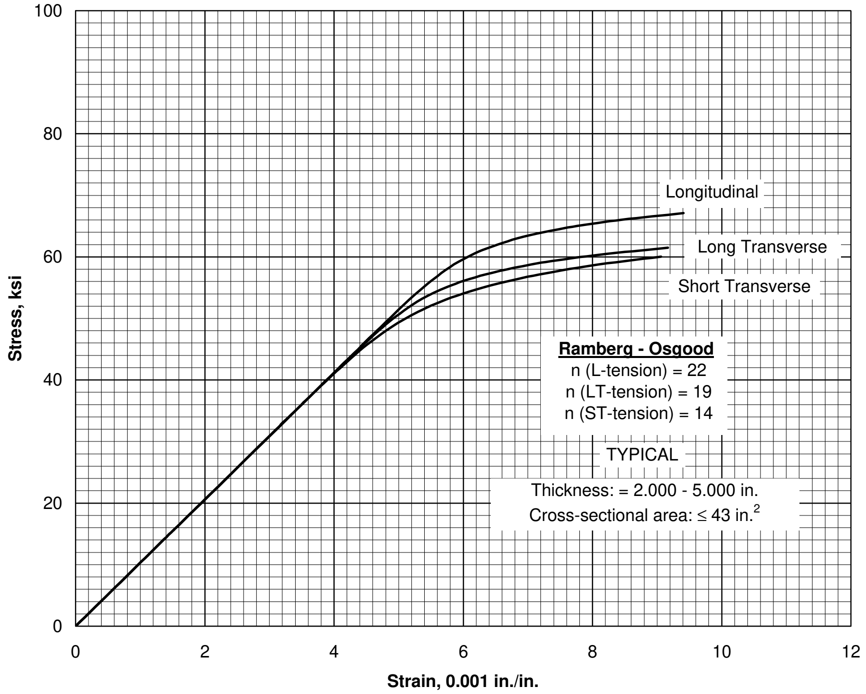


Figure 3.7.4.1.6(b). Typical tensile stress-strain curves for 7050-T7351X aluminum alloy extrusion at room temperature.

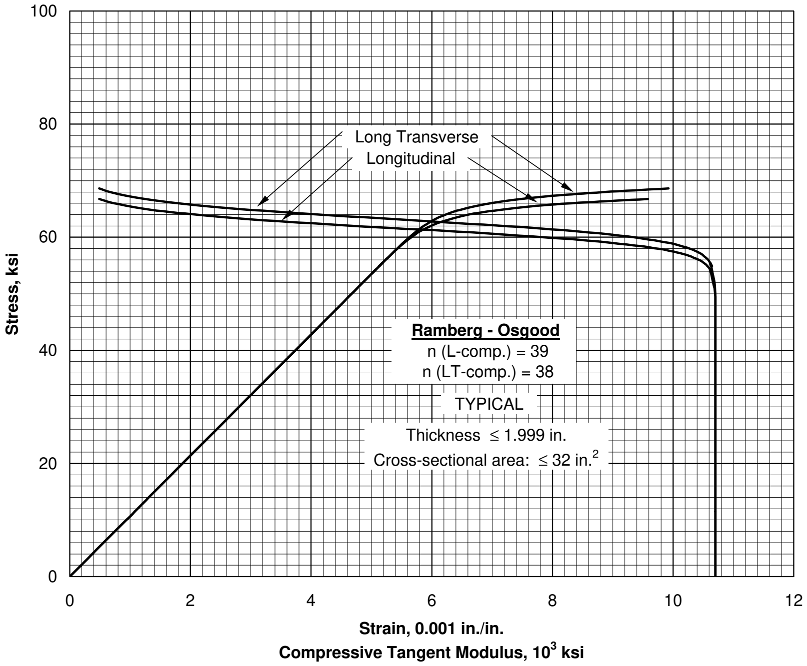


Figure 3.7.4.1.6(c). Typical compressive stress-strain and tangent-modulus curves for 7050-T7351X aluminum alloy extrusion at room temperature.

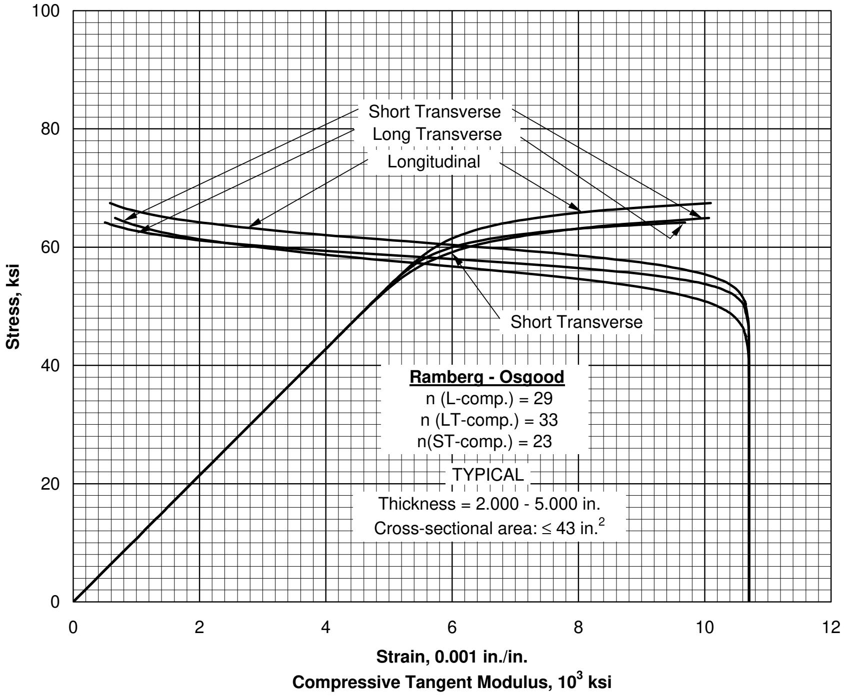


Figure 3.7.4.1.6(d). Typical compressive stress-strain and tangent-modulus curves for 7050-T7351X aluminum alloy extrusion at room temperature.

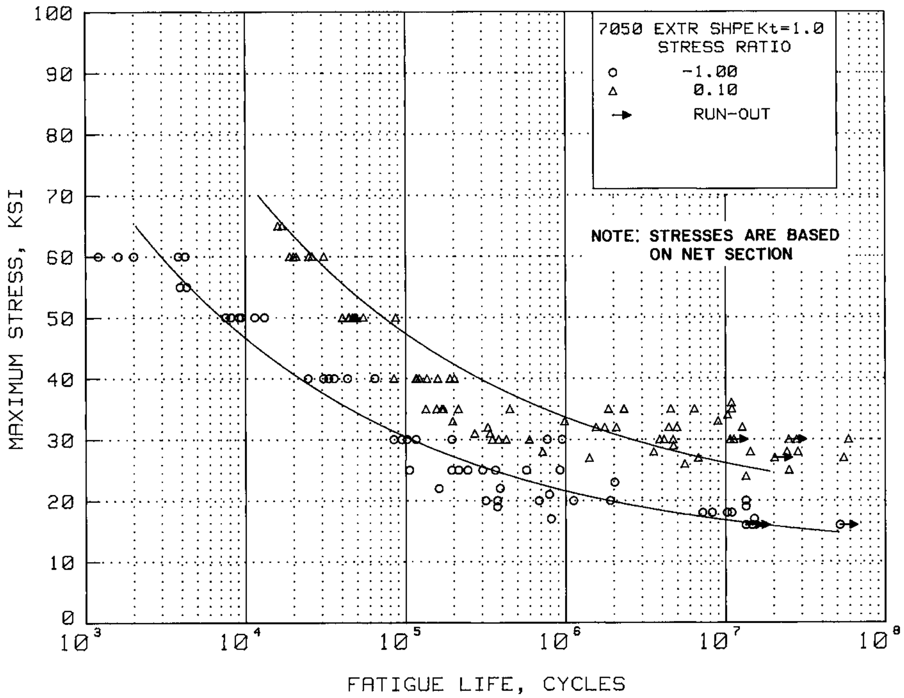


Figure 3.7.4.1.8(a). Best-fit S/N curves for unnotched 7050-T7351X extruded shape, longitudinal and long transverse directions.

Correlative Information for Figure 3.7.4.1.8(a)

Product Form: Extruded shape, 0.5 to 5.0 inch thick

Properties:	TUS, ksi	TYS, ksi	Temp.,°F
	72-79	62-69	RT

Specimen Details: Unnotched
0.300 inch diameter

Surface Condition: Not specified

References: 3.7.4.2.9(b) and 3.7.7.2.8(b)

Test Parameters:
Loading - Axial
Frequency - 800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
Log N_f = 10.5-3.79 log (S_{eq}-16)
$S_{eq} = S_{max} (1-R)^{0.55}$
Std. Error of Estimate, Log (Life) = 0.516
Standard Deviation, Log (Life) = 1.10
R^2 = 78%

Sample Size = 128

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

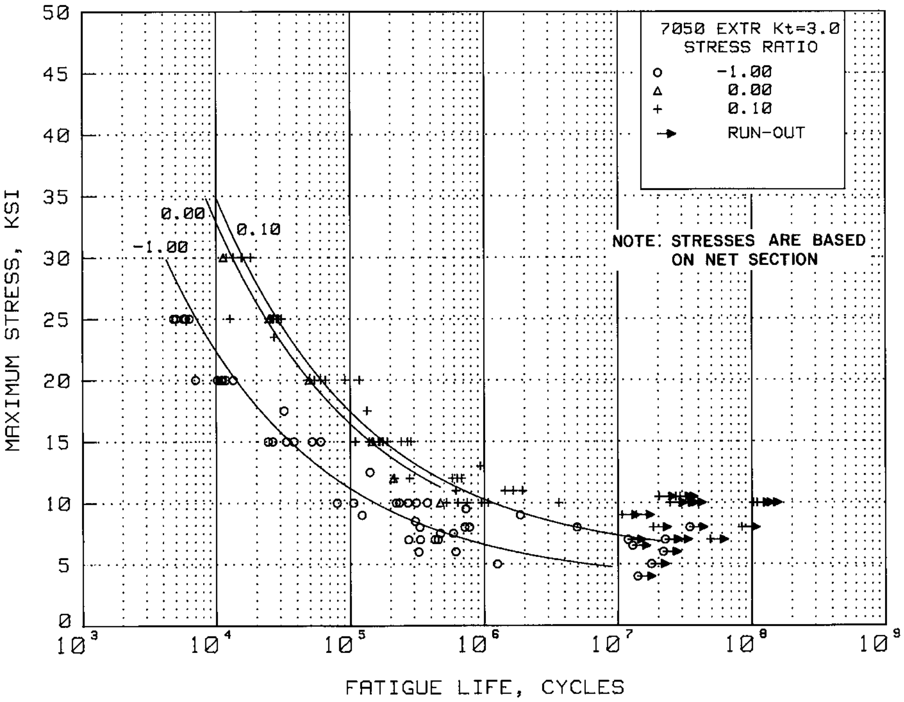


Figure 3.7.4.1.8(b). Best-fit S/N curves for notched, K_t = 3.0, 7050-T7351X extruded shape, longitudinal and long transverse directions.

Correlative Information for Figure 3.7.4.1.8(b)

Product Form: Extruded shape, 0.5 to 5.0 inch thick

Properties:

TUS, ksi	TYS, ksi	Temp.,°F
72-79	62-69	RT

Specimen Details: Circumferentially notched, K_t = 3.0
0.359 inch gross diameter
0.253 inch net diameter
0.013 inch root radius, r
60° flank angle, ω

Surface Condition: Not specified

References: 3.7.4.2.9(b) and 3.7.7.2.8(b)

Test Parameters:
Loading - Axial
Frequency - 800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
$\text{Log } N_f = 7.73 - 2.58 \log (S_{eq} - 5.0)$
$S_{eq} = S_{max} (1-R)^{0.56}$
Std. Error of Estimate, Log (Life) = 0.268
Standard Deviation, Log (Life) = 0.733
R^2 = 87%

Sample Size = 103

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

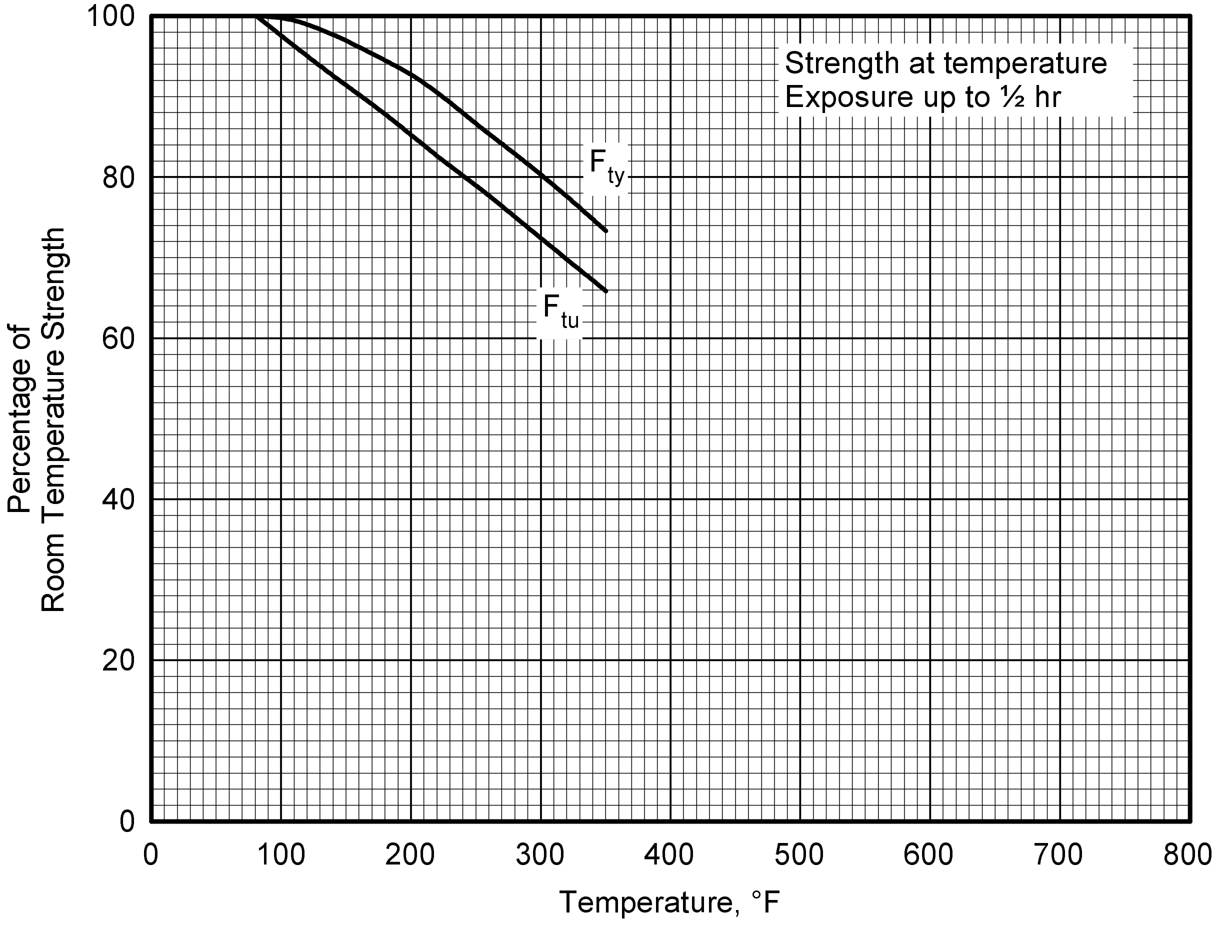


Figure 3.7.4.2.1. Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of 7050-T7451 aluminum alloy plate.

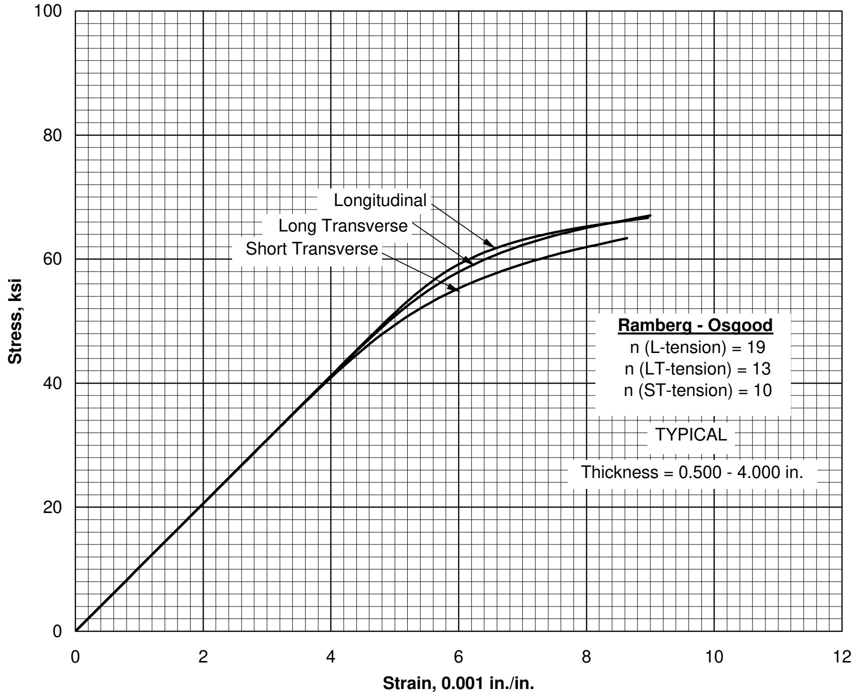


Figure 3.7.4.2.6(a). Typical tensile stress-strain curves for 7050-T7451 aluminum alloy plate at room temperature.

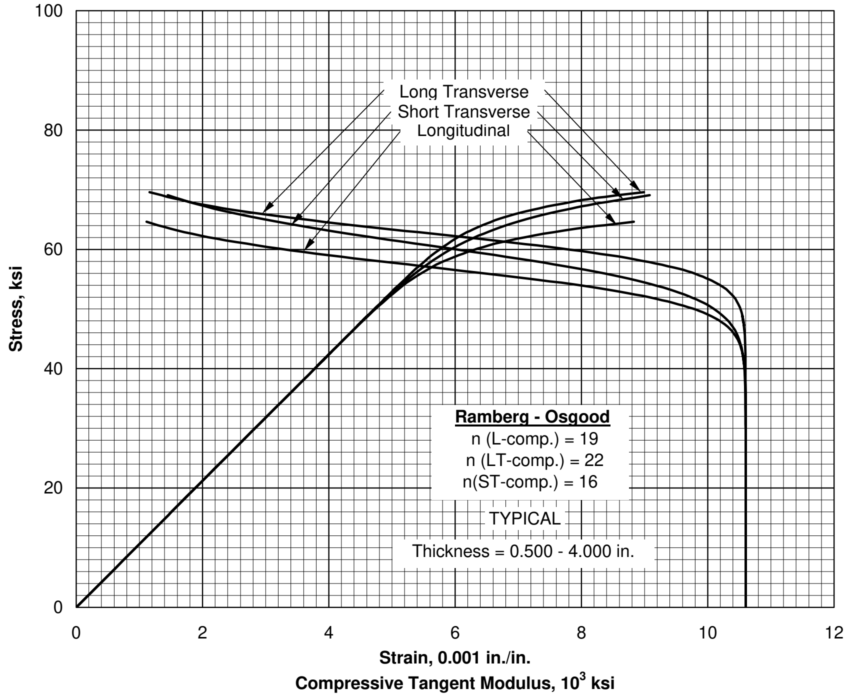


Figure 3.7.4.2.6(b). Typical compressive stress-strain and compressive tangent-modulus curves for 7050-T7451 aluminum alloy plate at room temperature.

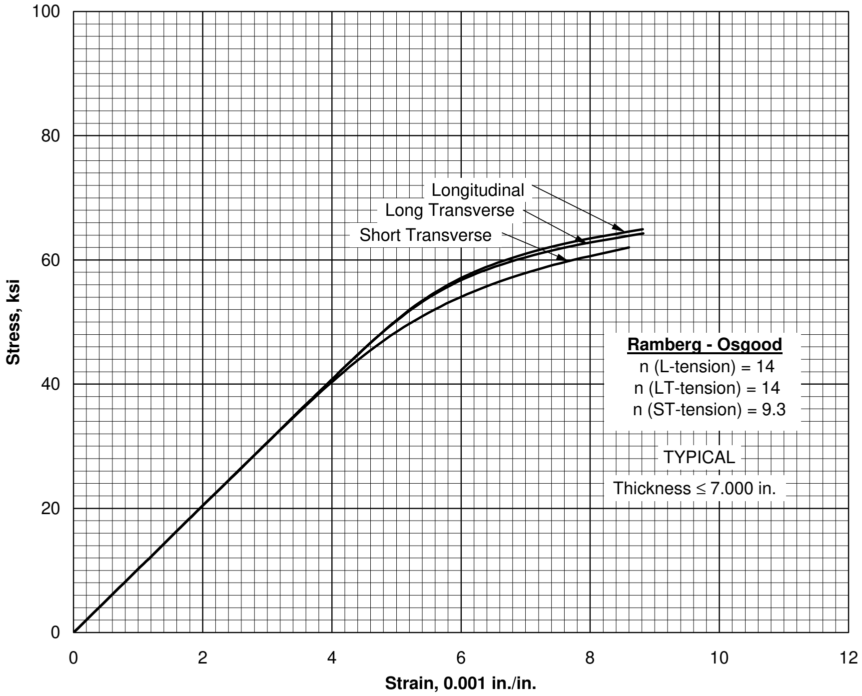


Figure 3.7.4.2.6(c). Typical tensile stress-strain curves for 7050-T7452 aluminum alloy hand forging at room temperature.

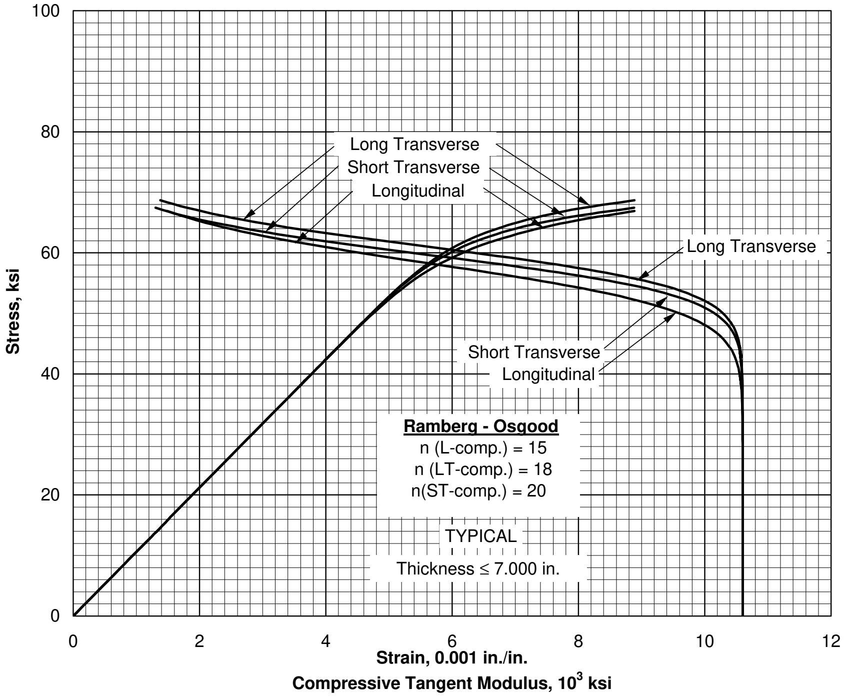


Figure 3.7.4.2.6(d). Typical compressive stress-strain and compressive tangent-modulus curves for 7050-T7452 aluminum alloy hand forging at room temperature.

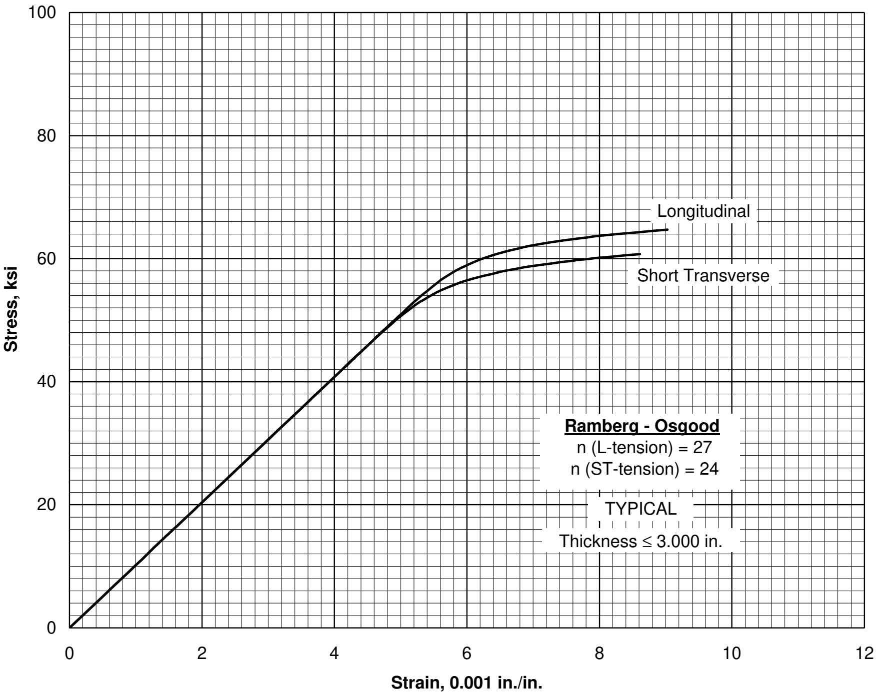


Figure 3.7.4.2.6(e). Typical tensile stress-strain curves for 7050-T74 aluminum alloy die forging at room temperature.

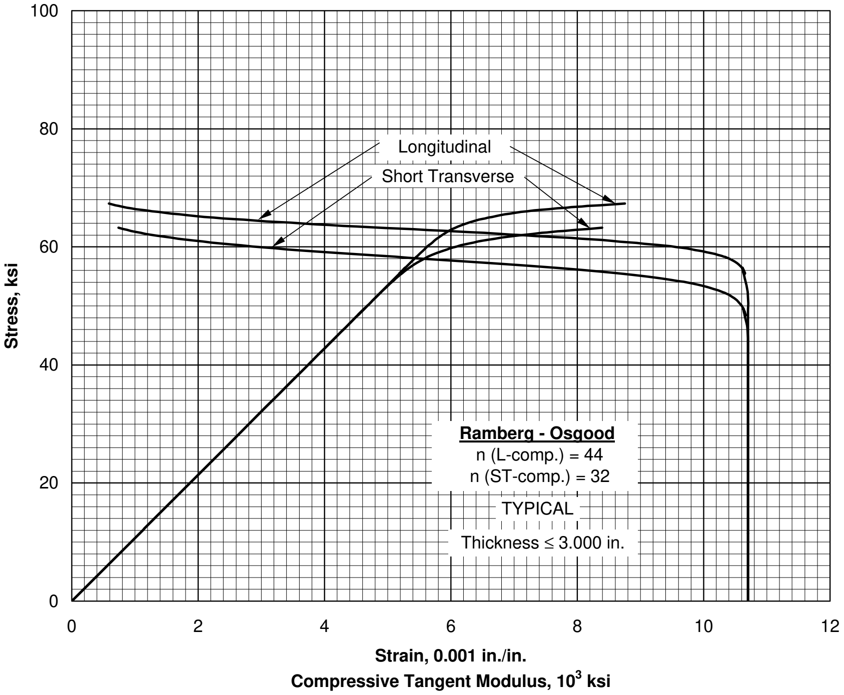


Figure 3.7.4.2.6(f). Typical compressive stress-strain and compressive tangent-modulus curves for 7050-T74 aluminum alloy die forging at room temperature.

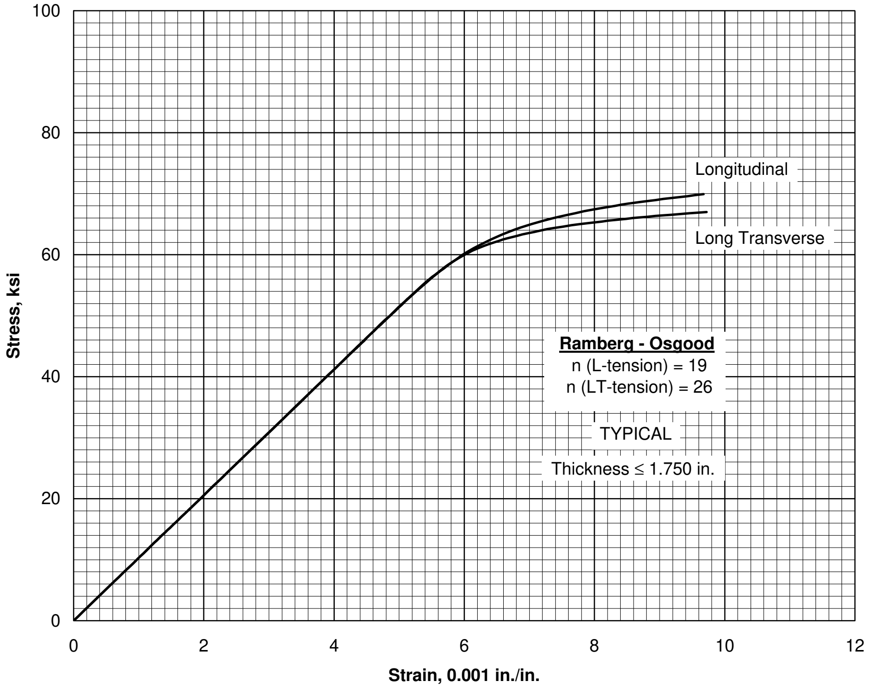


Figure 3.7.4.2.6(g). Typical tensile stress-strain curves for 7050-T74511 aluminum alloy extrusion at room temperature.

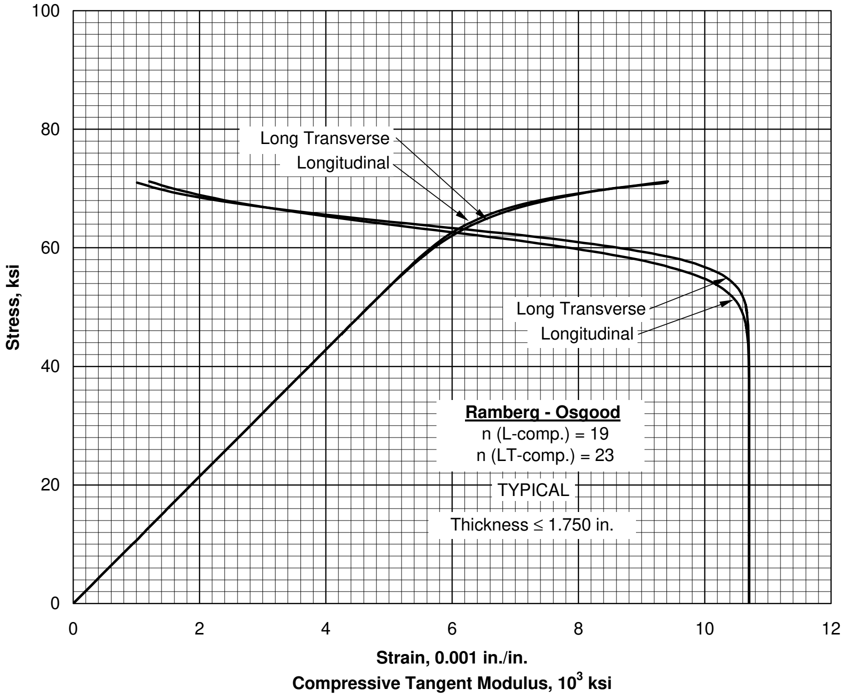


Figure 3.7.4.2.6(h). Typical compressive stress-strain and tangent-modulus curves for 7050-T74511 aluminum alloy extrusion at room temperature.

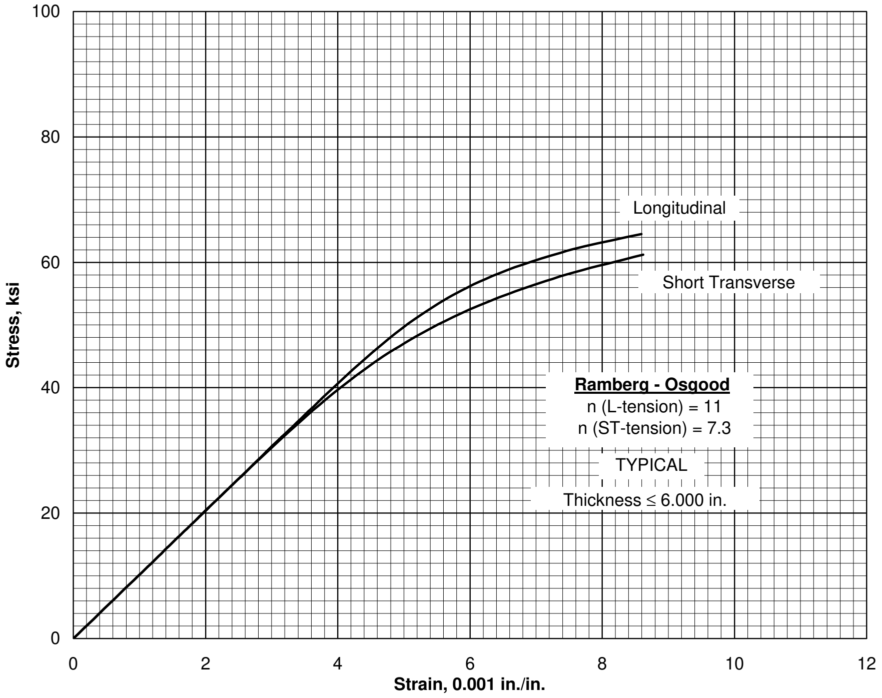


Figure 3.7.4.2.6(i). Typical tensile stress-strain curves for 7050-T7452 aluminum alloy die forging at room temperature.

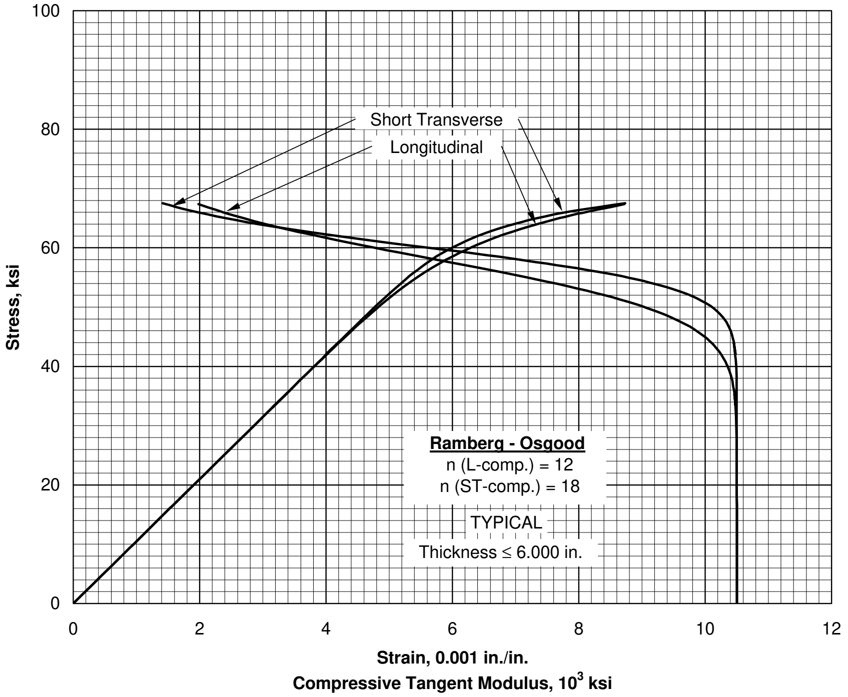


Figure 3.7.4.2.6(j). Typical compressive stress-strain and tangent-modulus curves for 7050-T7452 aluminum alloy die forging at room temperature.

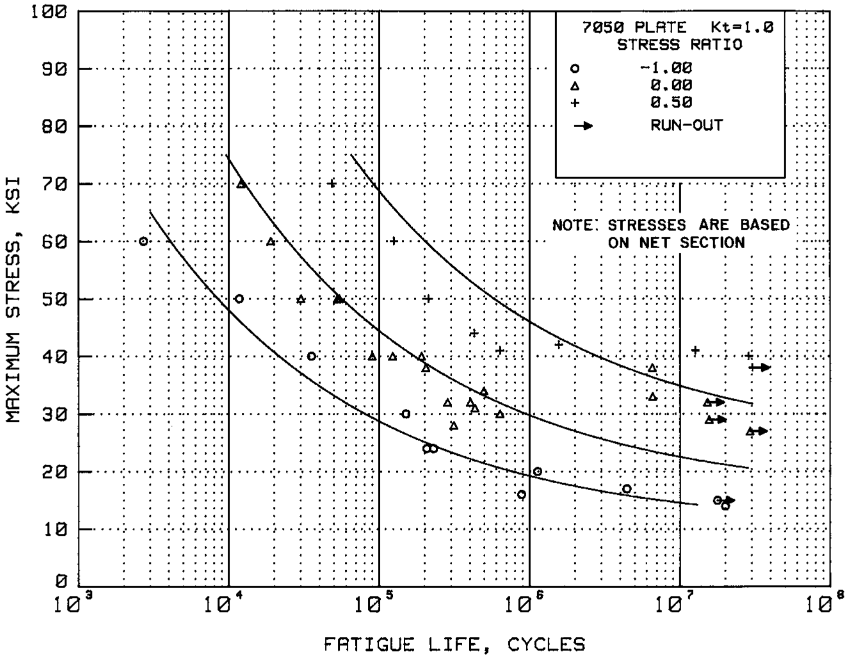


Figure 3.7.4.2.8(a). Best-fit S/N curves for unnotched 7050-T7451 plate, longitudinal direction and T/2 specimen location.

Correlative Information for Figure 3.7.4.2.8(a)

Product Form: Plate, 1.0 inch thick

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	79	72	RT

Specimen Details: Unnotched
0.30 inch diameter

Surface Condition: Not specified

References: 3.7.4.2.9(b) and 3.7.8.2.8(b)

Test Parameters:
Loading - Axial
Frequency - 800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 10

Equivalent Stress Equation:
Log N_f = 9.73-3.24 log (S_{eq}-15.5)
$S_{eq} = S_{max} (1-R)^{0.63}$
Std. Error of Estimate, Log (Life) = 0.490
Standard Deviation, Log (Life) = 0.942
R^2 = 73%

Sample Size = 35

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

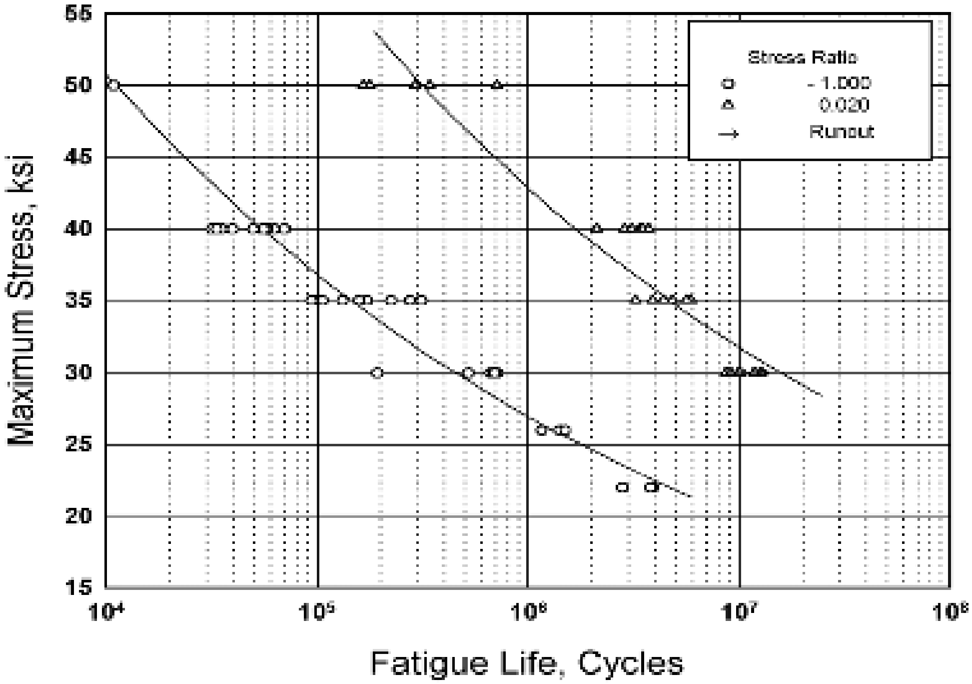


Figure 3.7.4.2.8(b). Best-fit S/N curves for unnotched 7050-T7451 plate, long transverse direction, t/4 specimen location.

Correlative Information for Figure 3.7.4.2.8(b)

Product Form: Plate, 4.25 to 8.50 inches thick

Properties:

TUS, ksi	TYS, ksi	Temp., F
N/A	62-67	RT

Specimen Details: Unnotched
0.250 inch diameter

Surface Condition: Polished, final surface finish unspecified

References: 3.7.4.2.8(d) and (e)

Test Parameters:
Loading – Axial
Frequency – 20 Hz
Temperature – RT
Environment – Air

Equivalent Stress Equation:
$\text{Log}(N_f) = 16.410 - 6.624 \log(S_{eq} - 5.0)$
$S_{eq} = S_{max}(1 - R)^{0.65}$
Std. Error of Estimate, Log (Life) = 0.183
Standard Deviation, Log (Life) = 0.814
$R^2 = 95.0\%$

Sample Size = 57

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

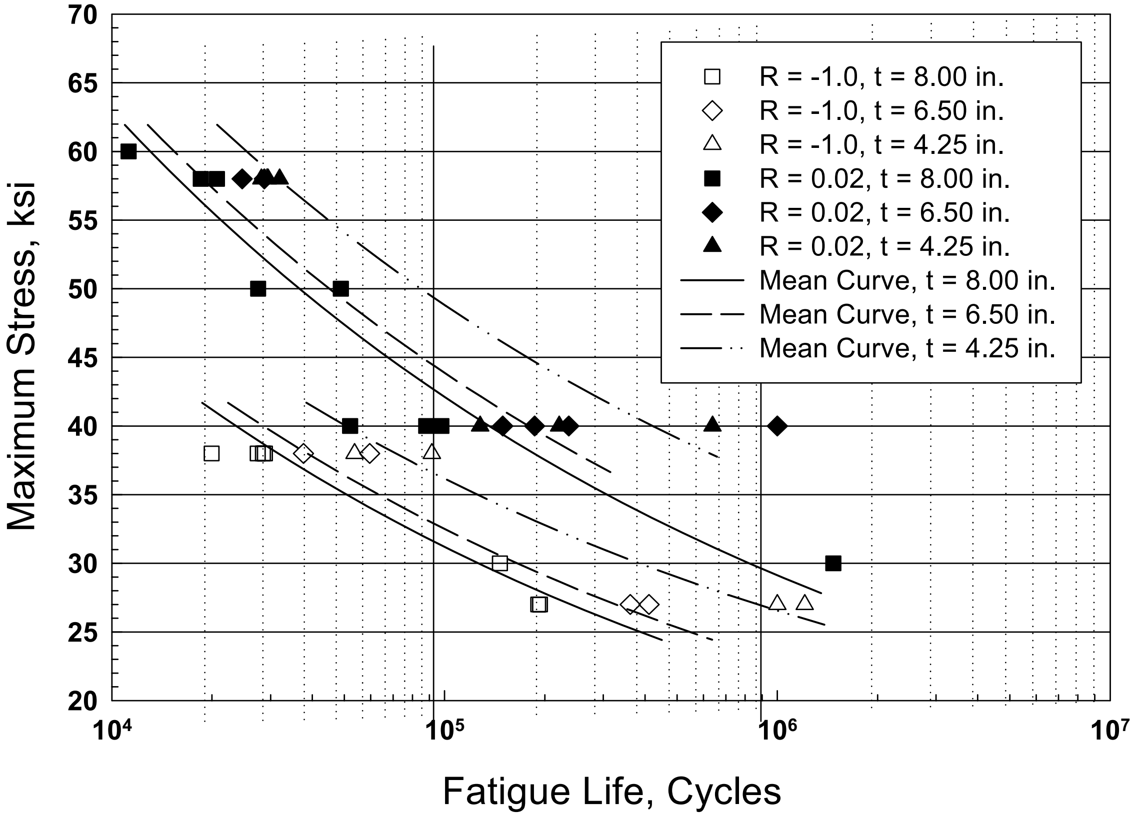


Figure 3.7.4.2.8(c). Best-fit S/N curves for unnotched 7050-T7451 plate, long transverse direction, t/2 specimen location.

<u>Correlative Information for Figure 3.7.4.2.8(c)</u>

Product Form: Plate, 4.25 to 8.50 inches thick

Properties:

TUS, ksi	TYS, ksi	Temp., F
N/A	62-67	RT

Specimen Details: Unnotched
0.250 inch diameter

Surface Condition: Polished, final surface finish unspecified

References: 3.7.3.2.8(d) and (e)

Test Parameters:
Loading – Axial
Frequency – 20 Hz
Temperature – RT
Environment – Air

Equivalent Stress Equation:
$\text{Log}(N_f) = 12.484 - 4.878 \log(S_{eq} - 60 / t)$
$S_{eq} = S_{max}(1 - R)^{0.42}$
t = plate thickness in inches.
Std. Error of Estimate, Log (Life) = 0.204
Standard Deviation, Log (Life) = 0.594
$R^2 = 88.2\%$

Sample Size = 36

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios and plate thicknesses beyond those represented above.]

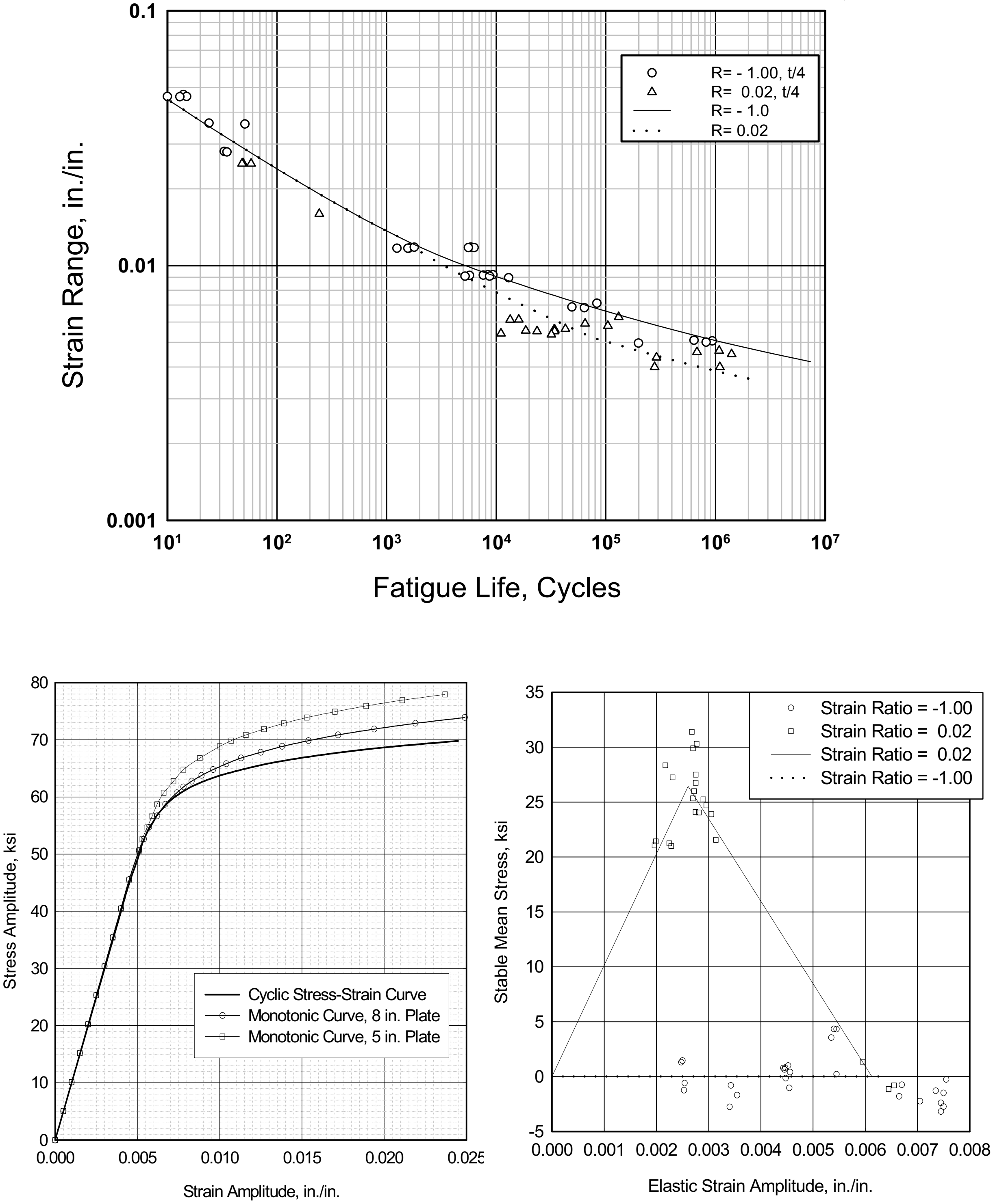


Figure 3.7.4.2.8(d). Best-fit strain-life curves, cyclic stress-strain curve, and mean stress relaxation curve for 7050-T7451 plate, long transverse direction, t/4 specimen location.

Correlative Information for Figure 3.7.4.2.8(d)

Product Form: Plate, 4.25 to 8.50 inches thick

Properties:	TUS, ksi	TYS, ksi	Temp., F
	N/A	62-67	RT

Stress-Strain Equations:
Cyclic Stress Strain Curve
$(\Delta\sigma/2) = 88.185\ (\Delta\epsilon_p/2)^{0.0578}$
Mean Stress Relaxation Curve
Minimal relaxation
for $(\Delta\epsilon/2) < 0.00261$
$\sigma_m = 46.0 - 7500\ (\Delta\epsilon/2)$
for $(\Delta\epsilon/2) < 0.00613$
Nearly complete relaxation
for $(\Delta\epsilon/2) \geq 0.00613$

Specimen Details: Unnotched
0.250 inch diameter

Surface Condition: Polished, final surface finish unspecified

References: 3.7.3.2.8(d) and (e)

Test Parameters:
Loading – Axial, Triangular Waveform
Frequency – 0.50 Hz
Temperature – RT
Environment – Air

Equivalent Strain Equation:
$\log (N_f) = -7.734 - 5.119 \log (\epsilon_{eq} - 0.0018)$
$\epsilon_{eq} = (\Delta\epsilon)^{0.61}\ (S_{max}/E)^{0.39}$
Std. Error of Estimate, Log (Life) = 0.301
Standard Deviation, Log (Life) = 1.573
$R^2 = 96.3\%$

Sample Size = 53

[Caution: The equivalent strain model may provide unrealistic life predictions for strain ratios beyond those represented above.]

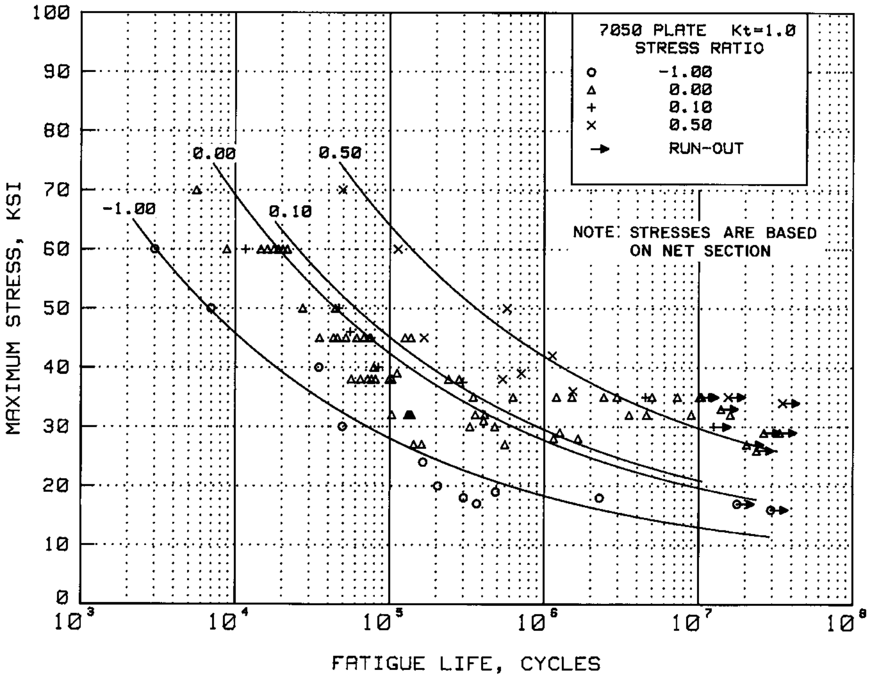


Figure 3.7.4.2.8(e). Best-fit S/N curves for unnotched 7050-T7451 plate, long transverse direction, t/4 specimen location.

Correlative Information for Figure 3.7.4.2.8(e)

Product Form: Plate, 1.0 to 6.0 inches thick

Properties:

TUS, ksi	TYS, ksi	Temp., °F
73-81	62-72	RT

Specimen Details: Unnotched
0.250 and 0.300 inch diameter

Surface Condition: Not specified

References: 3.7.4.2.9(b), 3.7.8.2.8(b) and (e)

Test Parameters:
Loading - Axial
Frequency - 800 cpm and unspecified
Temperature - RT
Environment - Air

No. of Heats/Lots: 15

Equivalent Stress Equation:
Log $N_f = 10.7-3.81 \log (S_{eq}-10)$
$S_{eq} = S_{max} (1-R)^{0.59}$
Std. Error of Estimate, Log (Life) = 0.507
Standard Deviation, Log (Life) = 0.794
$R^2 = 59\%$

Sample Size = 85

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

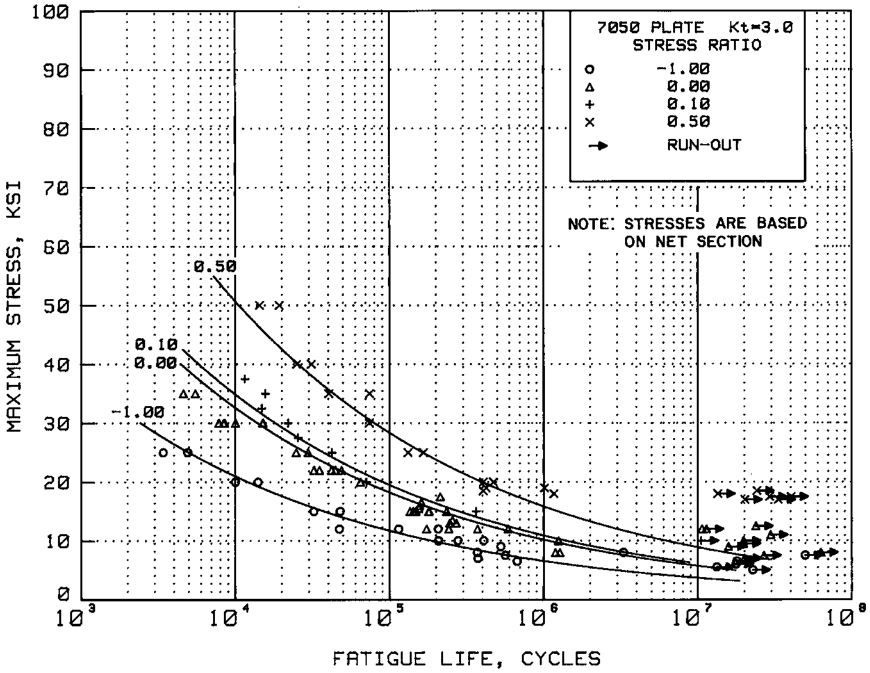


Figure 3.7.4.2.8(f). Best-fit S/N curves for notched, K_t = 3.0, 7050-T7451 plate, longitudinal and long transverse directions, t/4 specimen location.

Correlative Information for Figure 3.7.4.2.8(f)

Product Form: Plate, 1.0 to 6.0 inches thick

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	75-81	65-72	RT

Specimen Details: Circumferentially notched, K_t = 3.0
0.306 and 0.373 inch gross diameter
0.253 inch net diameter
0.013 inch notch-tip radius, r
60° flank angle, ω

Surface Condition: Not specified

References: 3.7.4.2.9(b) and 3.7.8.2.8(b) and (c)

Test Parameters:
Loading - Axial
Frequency - 800 cpm and unspecified
Temperature - RT
Environment - Air

No. of Heats/Lots: 11

Equivalent Stress Equation:
Log N_f = 10.0-3.96 log (S_{eq})
$S_{eq} = S_{max}(1-R)^{0.64}$
Std. Error of Estimate, Log (Life) = 0.248
Standard Deviation, Log (Life) = 0.728
R^2 = 88%

Sample Size = 79

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

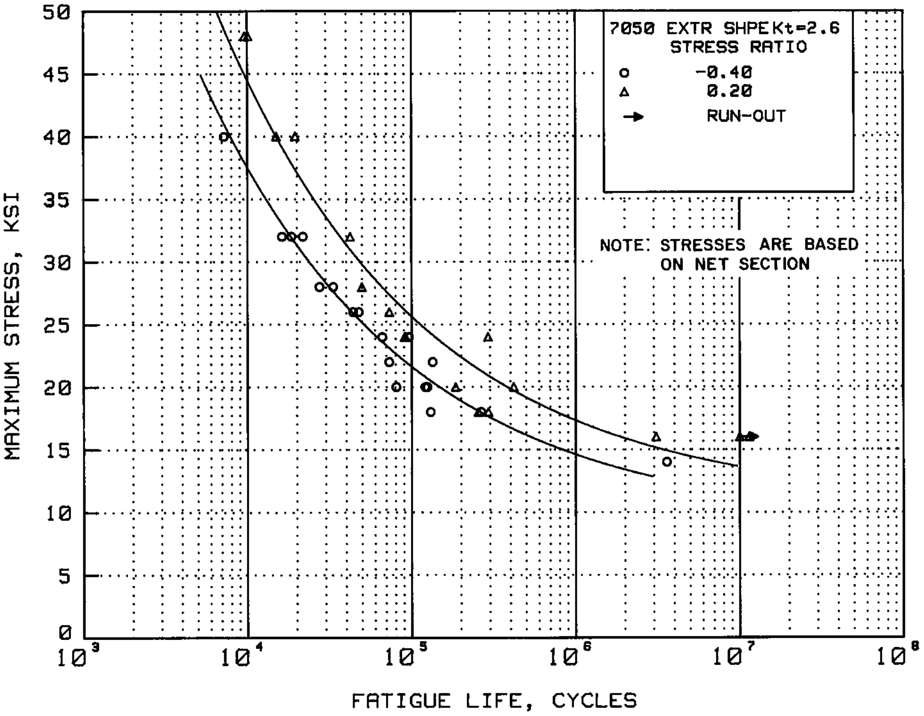


Figure 3.7.4.2.8(g). Best-fit S/N curves for notched, K_t = 2.6, 7050-T7451X extruded shape, longitudinal direction.

Correlative Information for Figure 3.7.4.2.8(g)

Product Form: Extruded shape, 0.5 to 5.0 inch thick

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	76-77	67-68	RT

Specimen Details: Notched, center hole,
$K_t = 2.6$
0.150 inch diameter
0.250 inch thick
1.00 inch wide

Surface Condition: Not specified

Reference: 3.7.4.2.8(a)

Test Parameters:
Loading - Axial
Frequency - Not specified
Temperature - RT
Environment - Air

No. of Heats/Lots: 6

Equivalent Stress Equation:
$\text{Log } N_f = 8.23 - 2.82 \log (S_{eq} - 10)$
$S_{eq} = S_{max} (1-R)^{0.30}$
Std. Error of Estimate, Log (Life) = 0.243
Standard Deviation, Log (Life) = 0.724
$R^2 = 89\%$

Sample Size = 34

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

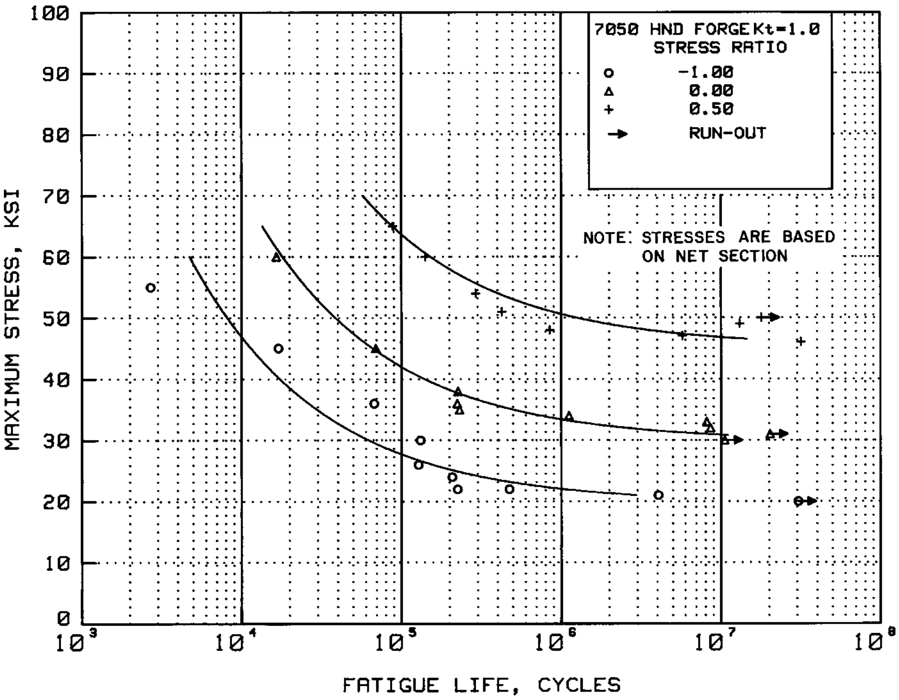


Figure 3.7.4.2.8(h). Best-fit S/N curves for unnotched 7050-T7452 hand forgings, longitudinal direction.

Correlative Information for Figure 3.7.4.2.8(h)

Product Form: Hand forgings, 2.0 to 8.0 inch thick

Properties:

TUS, ksi	TYS, ksi	Temp.,°F
76-81	66-72	RT

Specimen Details: Unnotched
0.300 inch diameter

Surface Condition: Not specified

References: 3.7.4.2.9(b) and 3.7.7.2.8(b)

Test Parameters:
Loading - Axial
Frequency - 800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 10

Equivalent Stress Equation:
$\text{Log } N_f = 7.06 - 1.89 \log (S_{eq} - 30)$
$S_{eq} = S_{max} (1-R)^{0.60}$
Std. Error of Estimate, Log (Life) = 0.400
Standard Deviation, Log (Life) = 0.982
$R^2 = 83\%$

Sample Size = 25

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

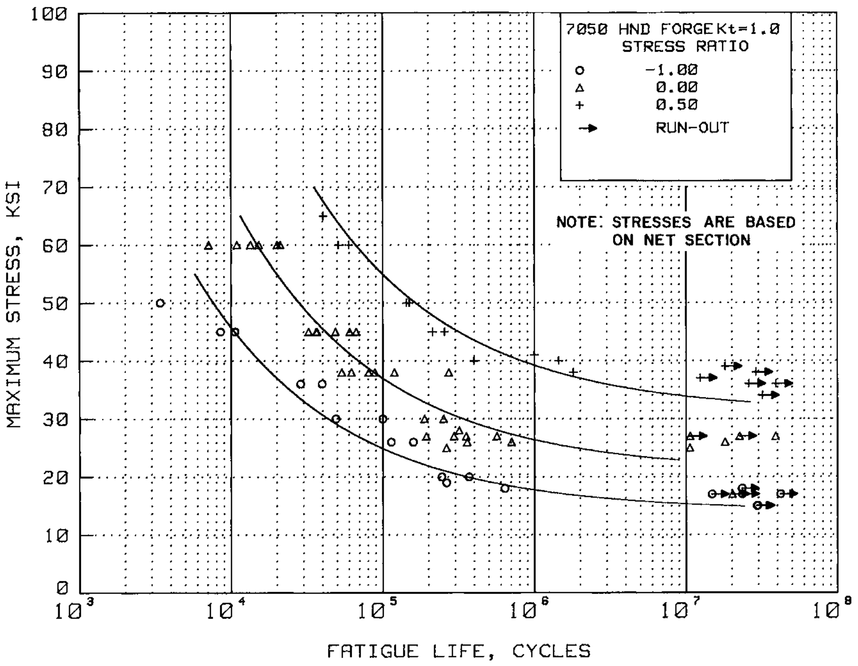


Figure 3.7.4.2.8(i). Best-fit S/N curves for unnotched 7050-T7452 hand forgings, long transverse and short transverse directions.

Correlative Information for Figure 3.7.4.2.8(i)

Product Form: Hand forgings, 2.0 to 8.0 inch thick

Properties:

TUS, ksi	TYS, ksi	Temp., °F
73-80	59-70	RT

Specimen Details: Unnotched
0.300 inch diameter

Surface Condition: Not specified

References: 3.7.4.2.9(b) and 3.7.8.2.8(b)

Test Parameters:
Loading - Axial
Frequency - 800 cpm and unspecified
Temperature - RT
Environment - Air

No. of Heats/Lots: 10

Equivalent Stress Equation:
Log $N_f = 7.58-2.14 \log (S_{eq}-21)$
$S_{eq} = S_{max} (1-R)^{0.57}$
Std. Error of Estimate, Log (Life) = 0.400
Standard Deviation, Log (Life) = 0.803
$R^2 = 75\%$

Sample Size = 55

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

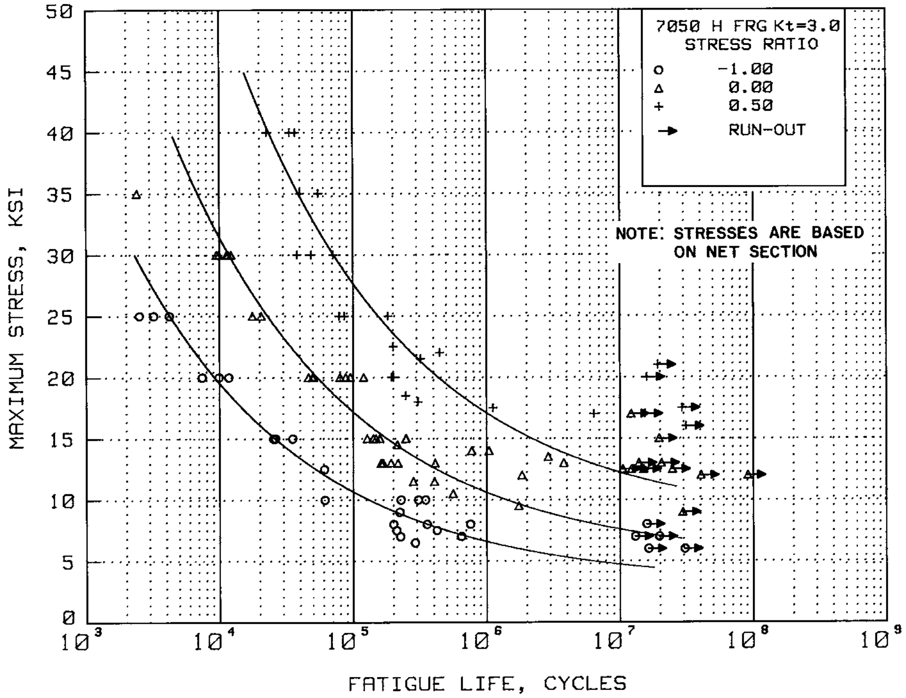


Figure 3.7.4.2.8(j). Best-fit S/N curves for notched, K_t = 3.0, 7050-T7452 hand forgings, longitudinal, long transverse, and short transverse directions.

Correlative Information for Figure 3.7.4.2.8(j)

Product Form: Hand forgings, 2.0 to 8.0 inch thick

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	73-81	59-72	RT

Specimen Details: Circumferentially notched, $K_t = 3.0$
0.306 inch gross diameter
0.253 inch net diameter
0.013 inch root radius, r
60° flank angle, ω

Surface Condition: Not specified

References: 3.7.4.2.9(b) and 3.7.8.2.8(b)

Test Parameters:
Loading - Axial
Frequency - 800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 10

Equivalent Stress Equation:
$\text{Log } N_f = 8.21 - 2.96 \log (S_{eq} - 5)$
$S_{eq} = S_{max} (1-R)^{0.68}$
Std. Error of Estimate, Log (Life) = 0.307
Standard Deviation, Log (Life) = 0.735
$R^2 = 83\%$

Sample Size = 80

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

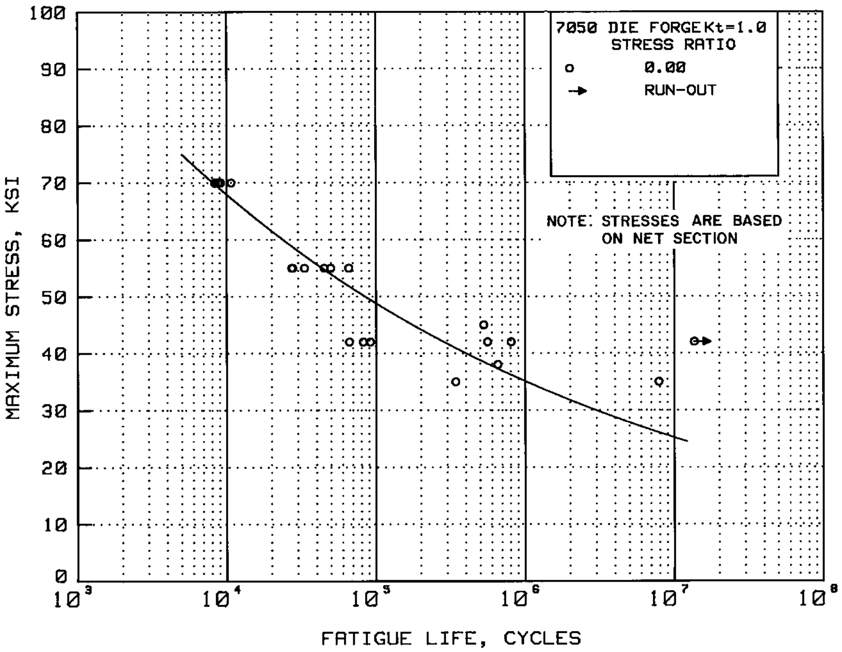


Figure 3.7.4.2.8(k). Best-fit S/N curves for unnotched 7050-T74 die forging, longitudinal directions.

Correlative Information for Figure 3.7.4.2.8(k)

Product Form: Die forging

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	74-81	68-71	RT

Specimen Details: Unnotched
0.300 inch diameter

Surface Condition: Not specified

References: 3.7.4.2.9(b) and 3.7.8.2.8(b)

Test Parameters:
Loading - Axial
Frequency - 800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 4

Equivalent Stress Equation:
Log N_f = 16.8-6.97 log (S_{max})
Std. Error of Estimate, Log (Life) = 0.381
Standard Deviation, Log (Life) = 0.820
R^2 = 78%

Sample Size = 20

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

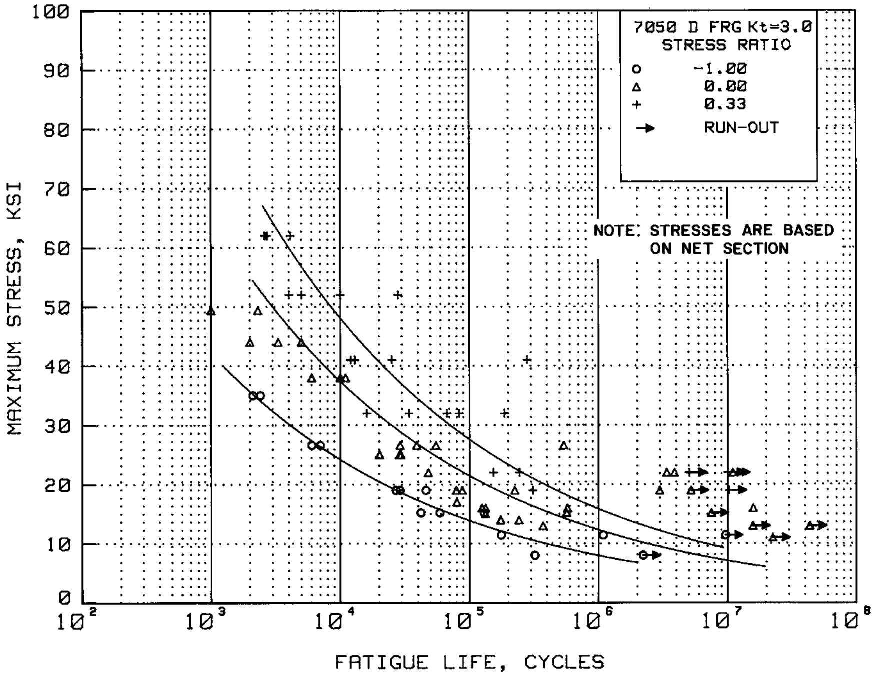


Figure 3.7.4.2.8(l). Best-fit S/N curves for notched, K_t = 3.0, 7050-T74 die forging, longitudinal direction.

Correlative Information for Figure 3.7.4.2.8(l)

Product Form: Die forging

Properties:

TUS, ksi	TYS, ksi	Temp., °F
77-81	68-71	RT

Specimen Details: Circumferentially notched, $K_t = 3.0$
0.306 and 0.305 inch gross diameter
0.253 or 0.222 inch net diameter
0.013 or 0.012 inch root radius, r
60° flank angle, ω

Surface Condition: Not specified

References: 3.7.4.2.8(b), 3.7.4.2.9(b), and 3.7.8.2.8(b)

Test Parameters:
Loading - Axial
Frequency - 800, 1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 6

Equivalent Stress Equation:
$\text{Log } N_f = 10.5\text{-}4.14 \log (S_{eq})$
$S_{eq} = S_{max} (1\text{-}R)^{0.629}$
Std. Error of Estimate, Log (Life) = 0.506
Standard Deviation, Log (Life) = 0.896
R^2 = 68%

Sample Size = 73

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

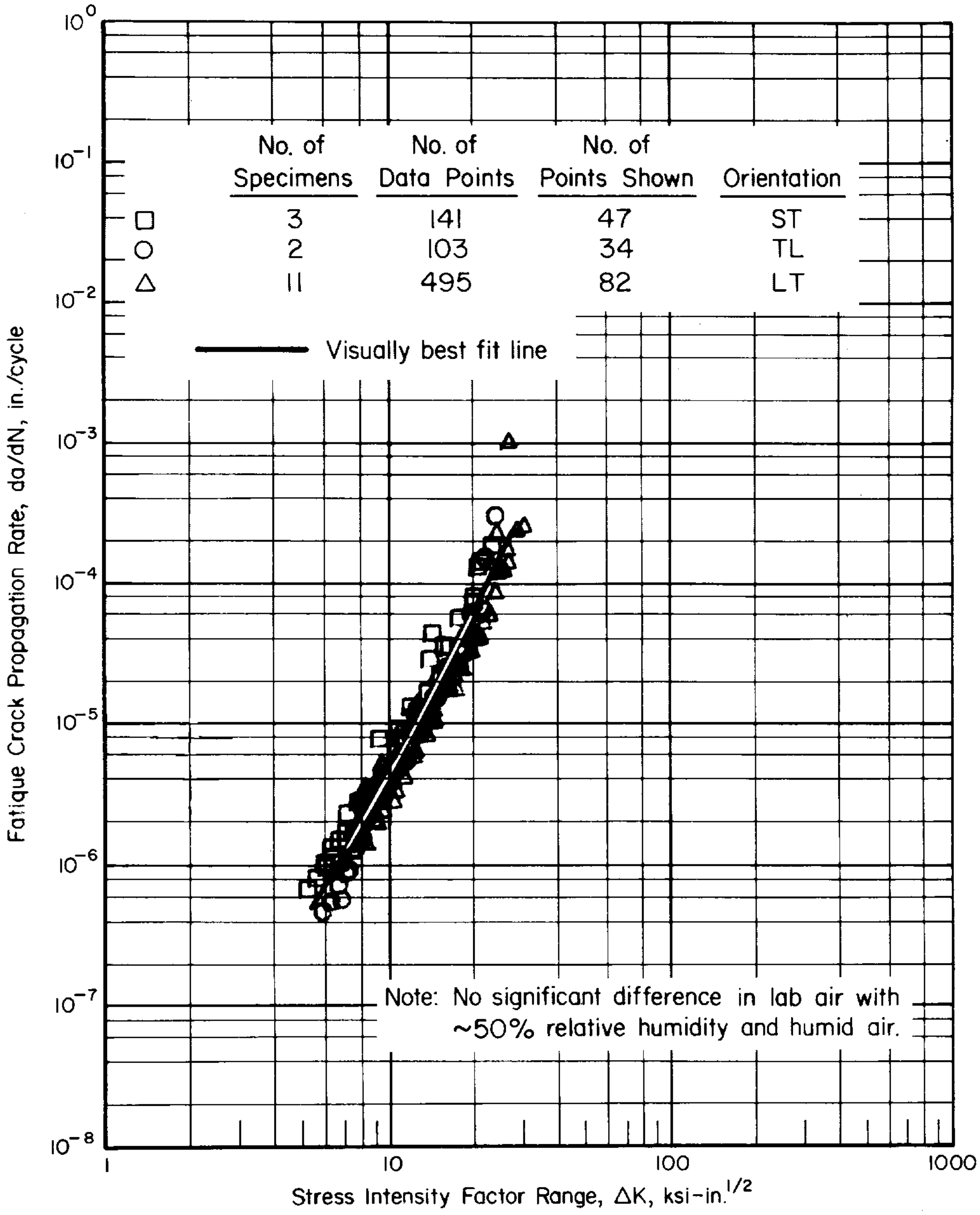


Figure 3.7.4.2.9(a). Fatigue-crack-propagation data for 3.15-inch-thick 7050-T7451 aluminum plate [Reference 3.7.4.2.9(a)].

Specimen Thickness:	*0.499-0.500 inch*	*Environment:*	*Lab air (~50% humidity) and humid air (100% humidity)*
Specimen Width:	*2.989-3.000 inches*		
Specimen Type:	*C(T)*	*Temperature:*	*RT*
Stress Ratio, R:	*0.1*	*Frequency, f:*	*10-20 Hz*

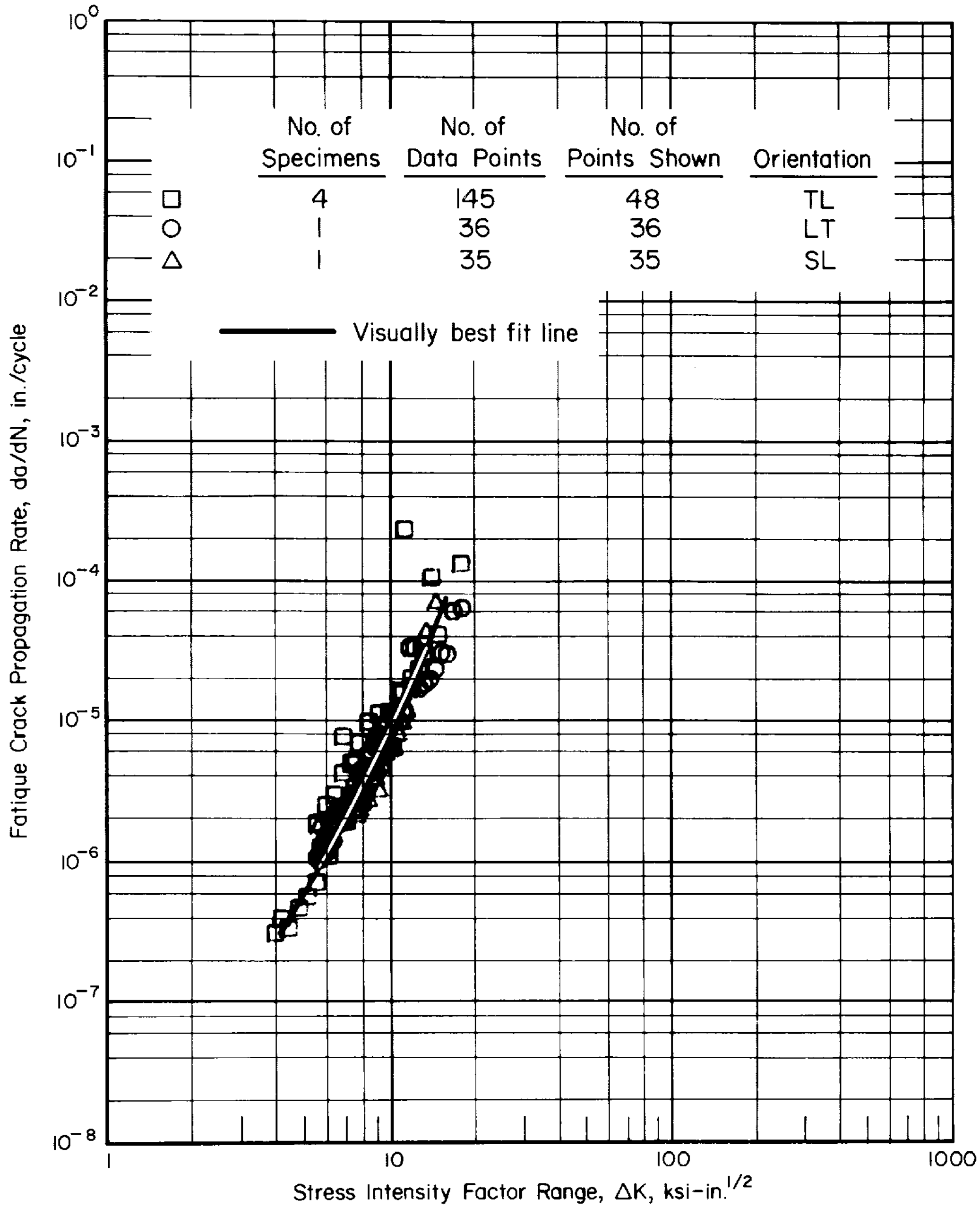


Figure 3.7.4.2.9(b). Fatigue-crack-propagation data for 1- and 6-inch-thick 7050-T7451 aluminum plate [Reference 3.7.4.2.9(b)].

Specimen Thickness:	*0.999-1.000 inch*	*Environment:*	*Dry air (< 10% humidity)*
Specimen Width:	*3.805 inches*	*Temperature:*	*RT*
Specimen Type:	*C(T)*	*Frequency, f:*	*18.3 Hz*
Stress Ratio, R:	*0.33*		

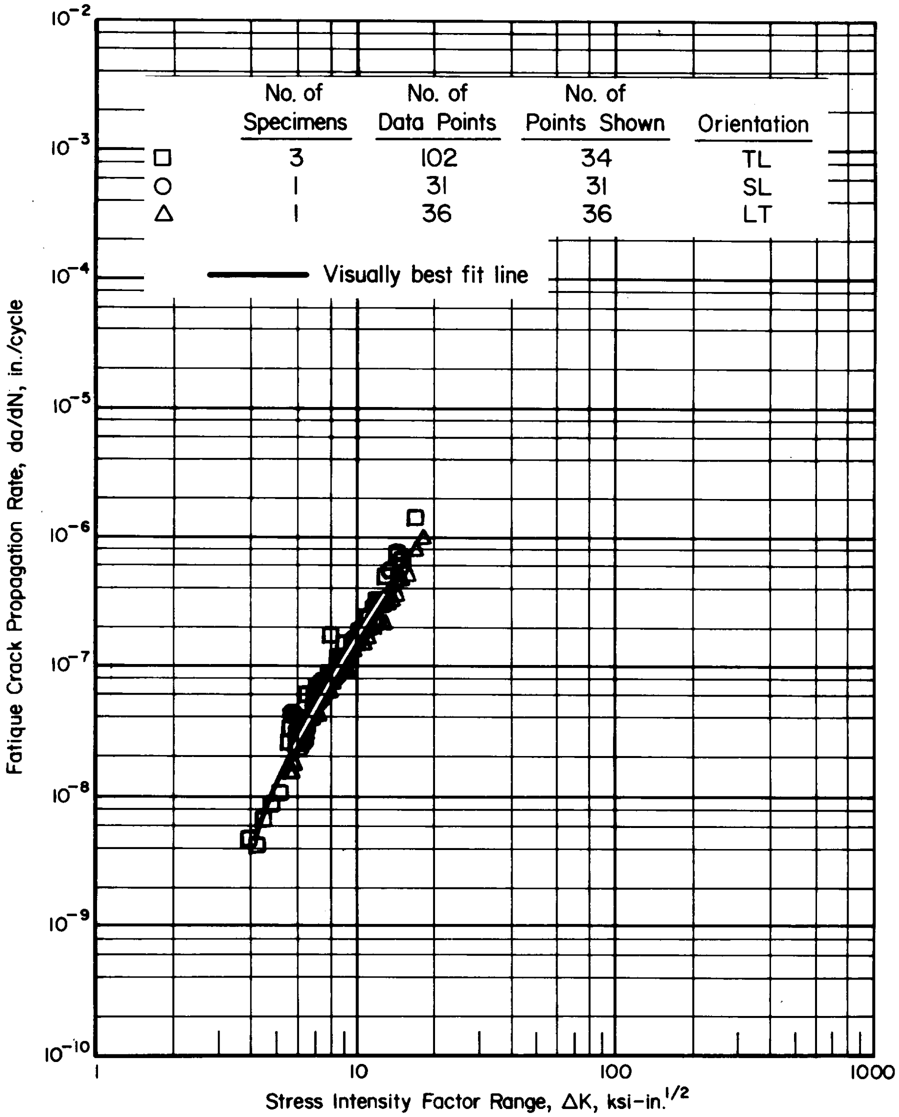


Figure 3.7.4.2.9(c). Fatigue-crack-propagation data for 1- and 6-inch-thick 7050-T7451 aluminum plate [Reference 3.7.4.2.9(b)].

Specimen Thickness:	*0.998-1.000 inch*	*Environment:*	*Humid air (>90% humidity)*
Specimen Width:	*3.805 inches*	*Temperature:*	*RT*
Specimen Type:	*C(T)*	*Frequency, f:*	*18.3 Hz*
Stress Ratio, R:	*0.33*		

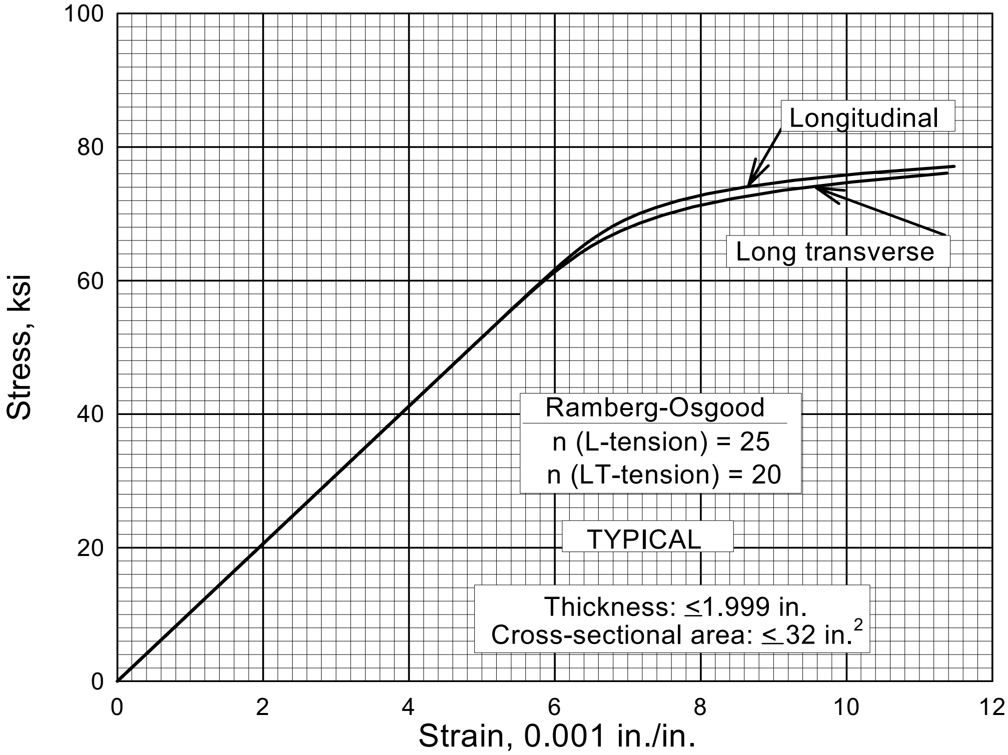


Figure 3.7.4.3.6(a). Typical tensile stress-strain curves for 7050-T7651X aluminum alloy extrusion at room temperature.

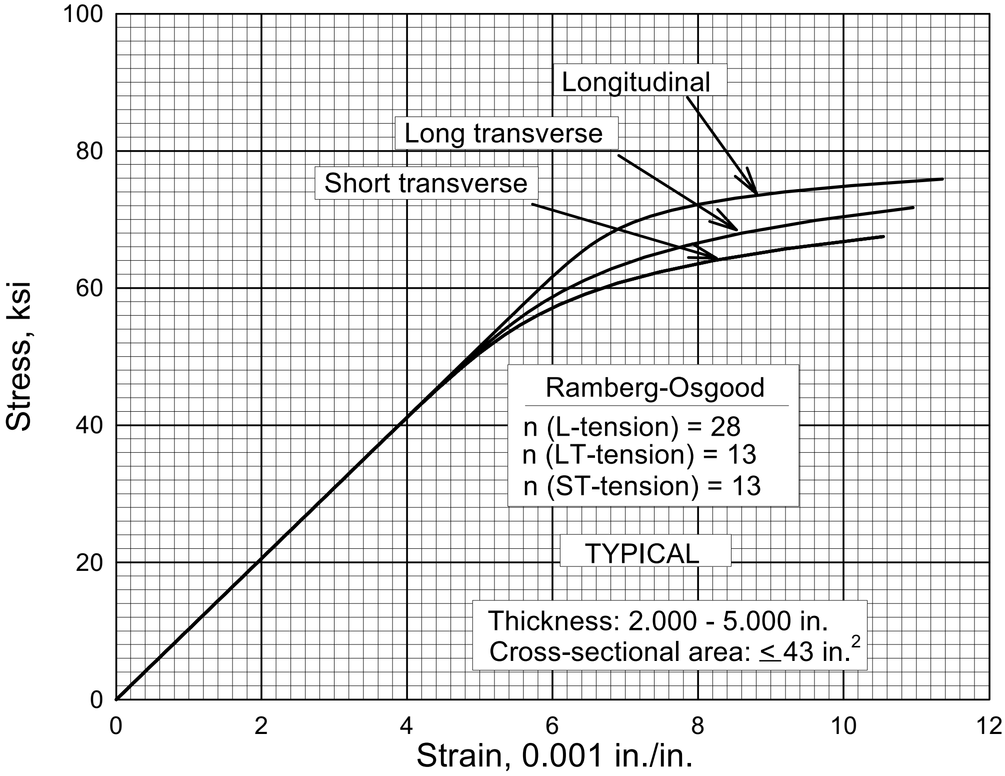


Figure 3.7.4.3.6(b). Typical tensile stress-strain curves for 7050-T7651X aluminum alloy extrusion at room temperature.

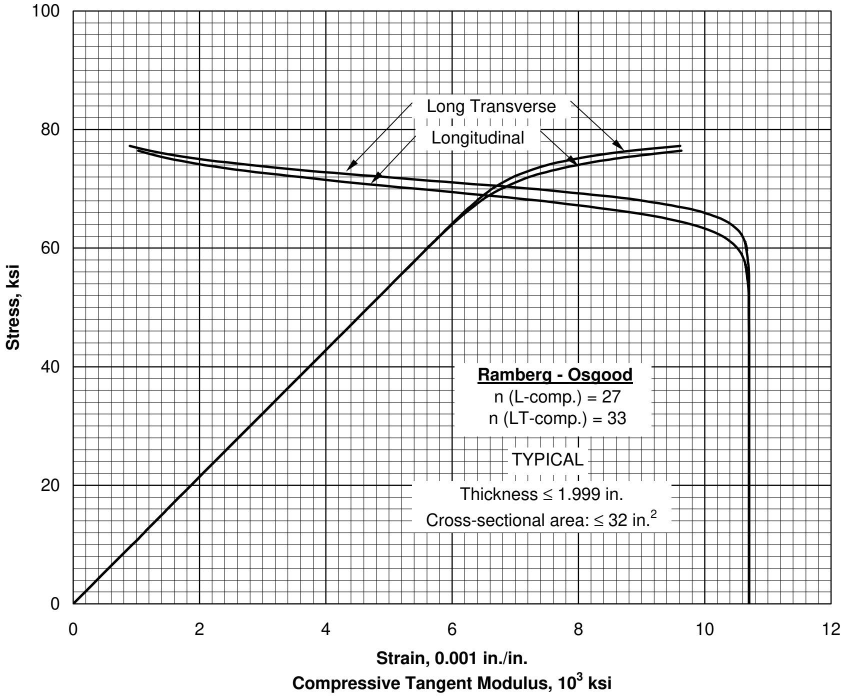


Figure 3.7.4.3.6(c). Typical compressive stress-strain and compressive tangent-modulus curves for 7050-T7651X aluminum alloy extrusion at room temperature.

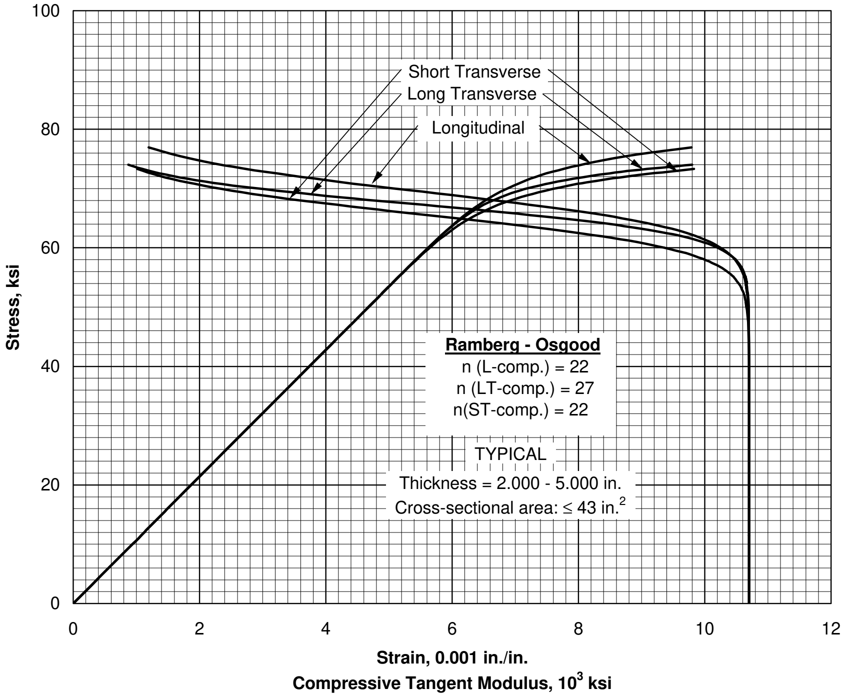


Figure 3.7.4.3.6(d). Typical compressive stress-strain and compressive tangent-modulus curves for 7050-T7651X aluminum alloy extrusion at room temperature.

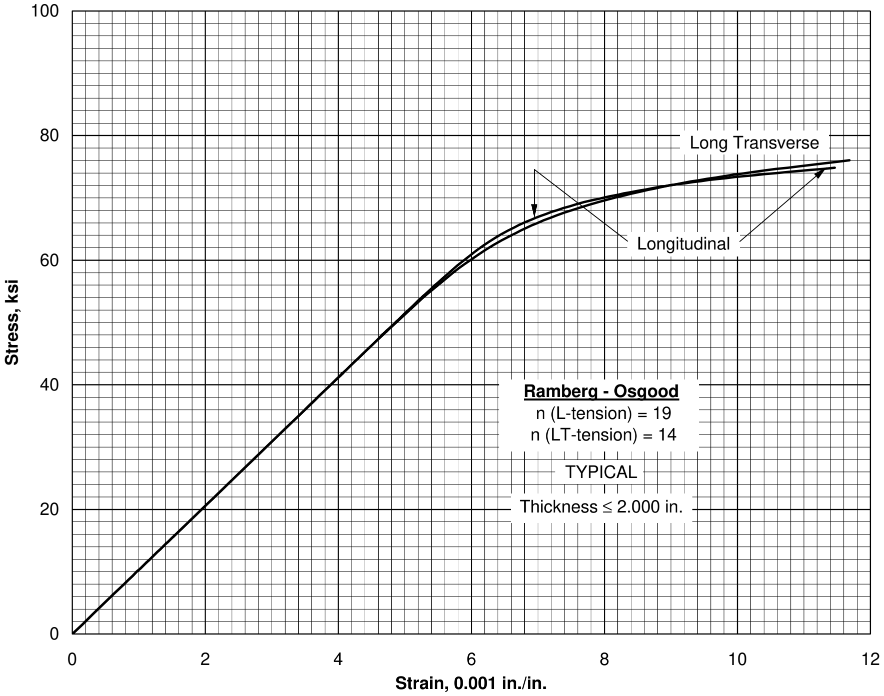


Figure 3.7.4.3.6(e). Typical tensile stress-strain curves for 7050-T7651 aluminum alloy plate at room temperature.

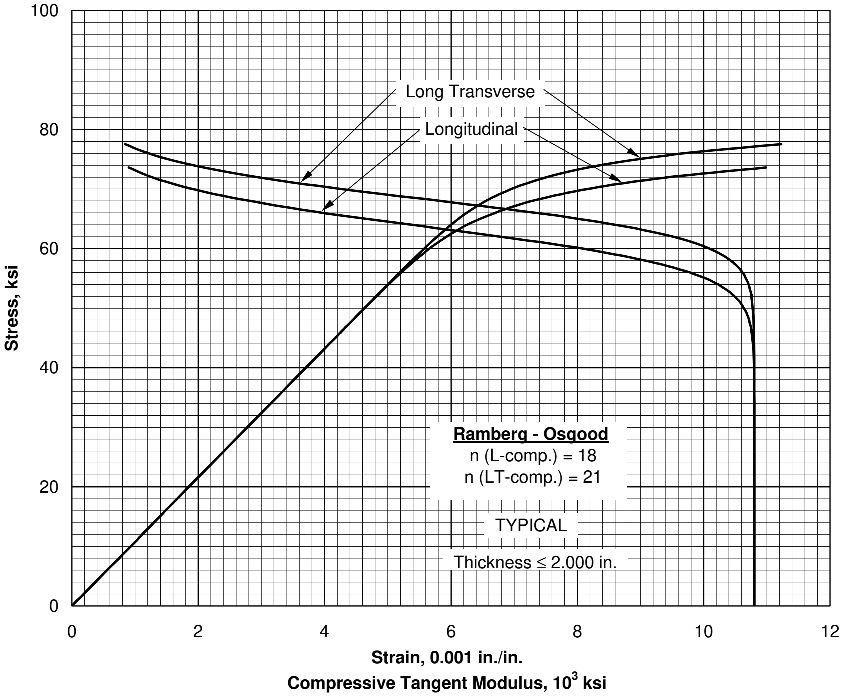


Figure 3.7.4.3.6(f). Typical compressive stress-strain and compressive tangent-modulus curves for 7050-T7651 aluminum alloy plate at room temperature.

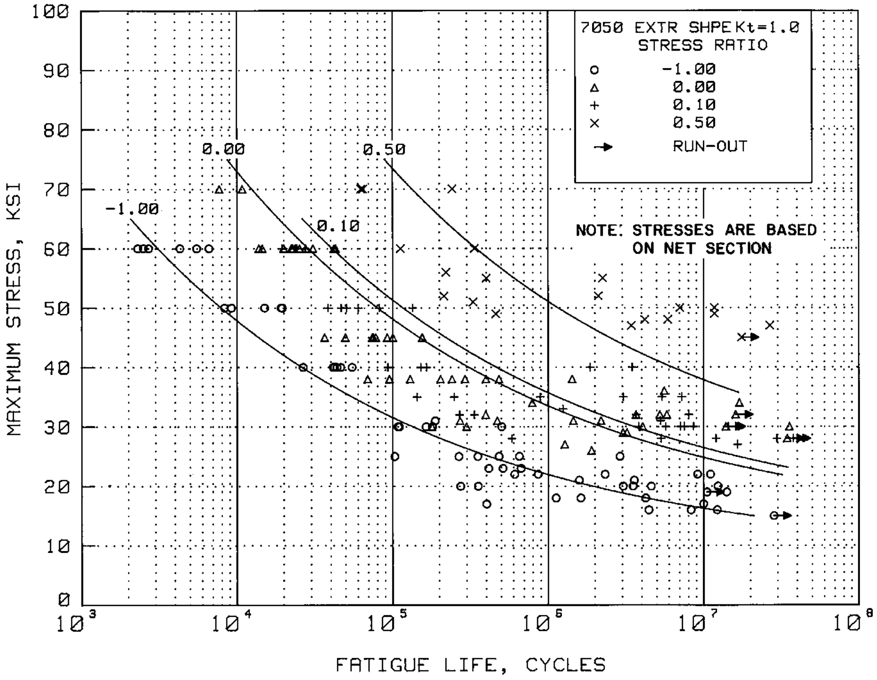


Figure 3.7.4.3.8(a). Best-fit S/N curves for unnotched 7050-T7651X extruded shape, longitudinal and long transverse directions.

Correlative Information for Figure 3.7.4.3.8(a)

Product Form: Extruded shape, 0.5 to 5.0 inch thick

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	84-90	75-81	RT

Specimen Details: Unnotched
0.300 inch diameter

Surface Condition: Not specified

References: 3.7.4.3.8(b), 3.7.4.2.9(b), and 3.7.7.2.8(b)

Test Parameters:
Loading - Axial
Frequency - 800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 10

Equivalent Stress Equation:
Log N_f = 11.8-4.38 log (S_{eq}-12)
$S_{eq} = S_{max} (1-R)^{0.61}$
Std. Error of Estimate, Log (Life) = 0.493
Standard Deviation, Log (Life) = 1.01
R^2 = 76%

Sample Size = 161

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

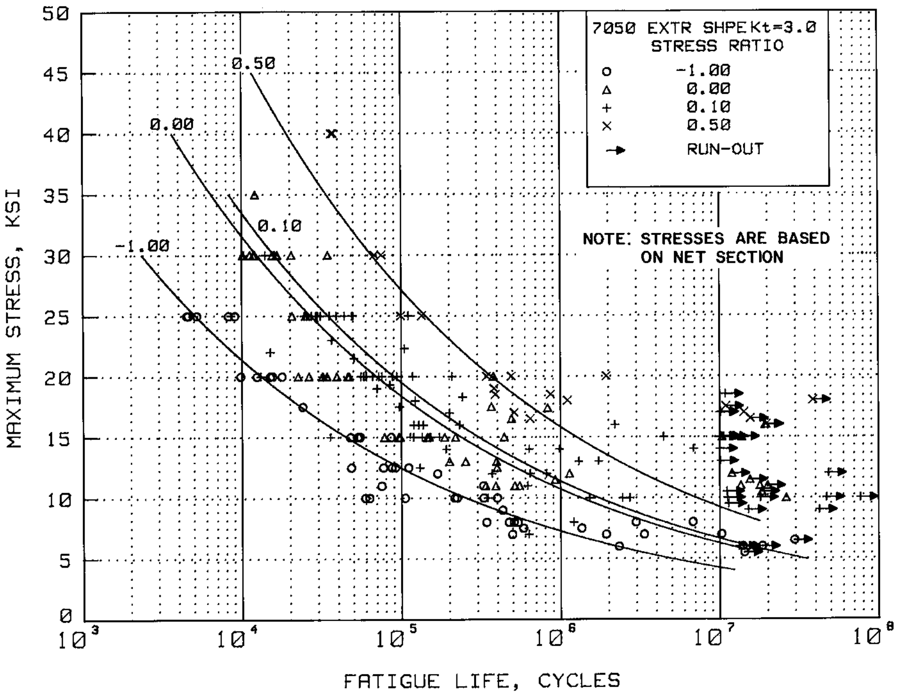


Figure 3.7.4.3.8(b). Best-fit S/N curves for notched, K_t = 3.0, 7050-T7651X extruded shape, longitudinal and long transverse directions.

Correlative Information for Figure 3.7.4.3.8(b)

Product Form: Extruded shape, 0.5 to 5.0 inch thick

Properties:

TUS, ksi	TYS, ksi	Temp.,°F
78-90	68-81	RT

Specimen Details:
Circumferentially notched, $K_t = 3.0$
0.359 inch gross diameter
0.253 inch net diameter
0.013 inch root radius, r
60° flank angle, ω

Surface Condition: Not specified

References: 3.7.4.2.9(b), 3.7.4.3.8(a), and 3.7.7.2.8(b)

Test Parameters:
Loading - Axial
Frequency - 800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 10

Equivalent Stress Equation:
$\text{Log } N_f = 10.38\text{-}4.26 \log (S_{eq})$
$S_{eq} = S_{max} (1\text{-}R)^{0.563}$
Std. Error of Estimate, Log (Life) = 0.398
Standard Deviation, Log (Life) = 0.778
$R^2 = 74\%$

Sample Size = 179

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

3.7.5 7055 ALLOY

3.7.5.0 *Comments and Properties* — 7055 is an Al-Zn-Mg-Cu-Zr alloy and provides higher strength properties than 7150. 7055 is available in the form of plate and extrusions. The T77-type temper provides high tensile and compressive strength with guaranteed toughness (plate only) and exfoliation corrosion resistance. The T77-type temper has exfoliation corrosion resistance comparable to the T76-type temper of other 7XXX series aluminum alloys.

The properties of extrusions should be based upon the thickness at the time of extrusion, solution heat treatment and quenching prior to machining. Selection of the mechanical properties based upon its final machined thickness may be overstated; therefore, the thickness at the time of extrusion, solution heat treatment and quenching to achieve properties is an important factor in the selection of the proper thickness column. For extrusions having sections with various thicknesses, consideration should be given to the properties as a function of thickness.

Materials specifications for 7055 are shown in Table 3.7.5.0(a). Room-temperature mechanical properties are presented in Tables 3.7.5.0(b) through (e).

Table 3.7.5.0(a). Material Specifications for 7055 Aluminum Alloy

Specification	Form
AMS 4206 (T7751)	Plate
AMS 4324 (T74511)	Extrusion
AMS 4336 (T76511)	Extrusion
AMS 4337 (T77511)	Extrusion

The temper index for 7055 is as follows:

Section	Temper
3.7.5.1	T74511
3.7.5.2	T76511
3.7.5.3	T7751 and T77511

Table 3.7.5.0(b) Design Mechanical and Physical Properties of 7055-T74511 Aluminum Alloy Extrusions

Specification	AMS 4324					
Form	Extrusion					
Temper	T74511					
Thickness, in.	≤ 0.249		0.250-0.499		0.500-3.000	
Basis	A	B	A	B	A	B
Mechanical Properties:						
F_{tu}, ksi:						
L	83	84	84	85	85[a]	87
LT	78	79	79	80	80	82
F_{ty}, ksi:						
L	76	78	77	79	78[a]	80
LT	72	74	73	75	74	76
F_{cy}, ksi:						
L	76	78	77	79	78	80
LT	77	79	78	80	79	81
F_{su},[b] ksi	43	44	46	45	45	46
F_{bru},[c] ksi:						
(e/D = 1.5)	115	116	116	117	117	120
(e/D = 2.0)	151	152	152	154	154	158
F_{bry},[c] ksi:						
(e/D = 1.5)	96	99	97	100	99	101
(e/D = 2.0)	114	117	116	119	117	120
e, percent (S-basis):						
L	8	...	8	...	8	...
LT	...	...	...	...	...	...
E, 10^3 ksi	10.3					
E_c, 10^3 ksi	10.7					
G, 10^3 ksi	3.9					
μ	0.33					
Physical Properties:						
ω, lb/in.^{3}	0.103					
C, Btu/(lb)(°F)	...					
K, Btu/[(hr)(ft^2)(°F)/ft]	...					
α, 10^{-6} in./in./°F	...					

a Rounded T_{99} values for F_{tu} =86 ksi, for F_{ty} = 79 ksi.

b Determined in accordance with ASTM B769.

c Bearing values are "dry pin" values per Section 1.4.7.1.

Table 3.7.5.0(c) Design Mechanical and Physical Properties of 7055-T76511 Aluminum Alloy Extrusions

Specification	AMS 4336			
Form	Extrusion			
Temper	T76511			
Thickness, in.	≤ 0.249		0.250-0.499	
Basis	A	B	A	B
Mechanical Properties:				
F_{tu}, ksi:				
L	89[a]	91	90	94
LT	83	85	84	87
F_{ty}, ksi:				
L	85	87	85	91
LT	79	81	79	85
F_{cy}, ksi:				
L	84	86	85	91
LT	86	88	86	92
F_{su},[b] ksi	46	47	47	49
F_{bru},[c] ksi:				
(e/D = 1.5)	122	125	124	129
(e/D = 2.0)	160	163	161	169
F_{bry},[c] ksi:				
(e/D = 1.5)	105	107	105	112
(e/D = 2.0)	124	127	124	132
e, percent (S-basis):				
L	7		9	
LT	...		...	
E, 10^3 ksi	10.4			
E_c, 10^3 ksi	10.8			
G, 10^3 ksi	3.9			
μ	0.33			
Physical Properties:				
ω, lb/in.^{3}	0.103			
C, Btu/(lb)(°F)	...			
K, Btu/[(hr)(ft^2)(°F)/ft]	...			
α, 10^{-6} in./in./°F	...			

[a] Rounded T_{99} values for F_{tu} =90 ksi

[b] Determined in accordance with ASTM B769.

[c] Bearing values are "dry pin" values per Section 1.4.7.1.

Table 3.7.5.0(d) Design Mechanical and Physical Properties of 7055-T7751 Aluminum Alloy Plate

Specification	AMS 4206	
Form	Plate	
Temper	T7751	
Thickness, in.	0.500 - 1.500	
Basis	A	B
Mechanical Properties:		
F_{tu}, ksi:		
L	89	91
LT	89	91
F_{ty}, ksi:		
L	86	88
LT	85	87
F_{cy}, ksi:		
L	86	88
LT	89	91
F_{su},[a] ksi	48	49
F_{bru},[b] ksi:		
(e/D = 1.5)	128	131
(e/D = 2.0)	167	170
F_{bry},[b] ksi:		
(e/D = 1.5)	112	115
(e/D = 2.0)	130	133
e, percent (S-basis):		
L	7	...
LT	8	...
E, 10^3 ksi	10.4	
E_c, 10^3 ksi	10.7	
G, 10^3 ksi	3.9	
μ	0.32	
Physical Properties:		
ω, lb/in.^{3}	0.103	
C, Btu/(lb)(°F)	...	
K, Btu/[(hr)(ft^2)(°F)/ft]	...	
α, 10^{-6} in./in./°F	...	

[a] Determined in accordance with ASTM B769.
[b] Bearing values are "dry pin" values per Section 1.4.7.1.

Table 3.7.5.0(e) Design Mechanical and Physical Properties of 7055-T77511 Aluminum Alloy Extrusion

Specification	AMS 4337	
Form	Extrusion	
Cross-sectional area, in^2		
Temper	T77511	
Thickness, in.	0.500 - 1.500	
Basis	A	B
Mechanical Properties:		
F_{tu}, ksi:		
L	94	95
LT	88	90
F_{ty}, ksi:		
L	90	93
LT	84[a]	88
F_{cy}, ksi:		
L	92	94
LT	89	92
F_{su},[b] ksi	48	49
F_{bru},[c] ksi:		
(e/D = 1.5)	128	131
(e/D = 2.0)	167	169
F_{bry},[c] ksi:		
(e/D = 1.5)	109	113
(e/D = 2.0)	131	135
e, percent (S-basis):		
L	9	
LT	5	
E, 10^3 ksi	10.4	
E_c, 10^3 ksi	11.0	
G, 10^3 ksi	...	
μ	0.33	
Physical Properties:		
ω, lb/in.^{3}	0.103	
C, Btu/(lb)(°F)	...	
K, Btu/[(hr)(ft^2)(°F)/ft]	...	
α, 10^{-6} in./in./°F	...	

a S-basis. The T_{99} value is 85.86 ksi.
b Determined in accordance with ASTM B769.
c Bearing values are “dry pin” values per Section 1.4.7.1.

3.7.6 7075 ALLOY

3.7.6.0 *Comments and Properties* — 7075 is a high-strength Al-Zn-Mg-Cu alloy and is available in a wide variety of product forms. It is also available in several types of tempers, the T6, T73, and T76 type. The T6 temper has the highest strength but lowest toughness and resistance to stress-corrosion cracking. Since toughness decreases with a decrease in temperature, the T6 temper is not generally recommended for cryogenic applications. As shown in Table 3.1.2.3.1(a), 7075-T6 rolled plate, rod and bar, extruded shapes, and forgings have a 'D' SCC rating. This is the lowest rating and means that SCC failures have occurred in service or would be anticipated if there is any sustained stress. In-service failures are caused by stressed produced by any combination of sources including solution heat treatment, straightening, forming, fit-up, clamping, sustained service loads or high service compression stresses that produce residual tensile stresses. These stresses may be tension or compression as well as the stresses due to the Poisson effect, because the actual failures are caused by the resulting sustained shear stresses. Pin-hole flaws in corrosion protection are sufficient for SCC. The T73 temper provides for much improved stress-corrosion resistance over T6 temper with a decrease in strength. The T76 temper provides for improved exfoliation resistance and limited stress-corrosion resistance over T6 temper with some decrease in strength. Refer to Section 3.1.2.3 for comments regarding the resistance of the alloy to stress-corrosion cracking and to Section 3.1.3.4 for comments regarding the weldability of this alloy.

The properties of extrusions should be based upon the thickness at the time of quenching prior to machining. Selection of the mechanical properties based upon its final machined thickness may be unconservative; therefore, the thickness at the time of quenching to achieve properties is an important factor in the selection of the proper thickness column. For extrusions having sections with various thicknesses, consideration should be given to the properties as a function of thickness.

Material specifications for 7075 aluminum alloy are presented in Table 3.7.6.0(a). Room-temperature mechanical and physical properties are shown in Tables 3.7.6.0(b_1) through (g_4). The effect of temperature on the physical properties of this alloy is presented in Figure 3.7.6.0.

Table 3.7.6.0(a). Material Specifications for 7075 Aluminum Alloy

Specification	Form
AMS 4044	Bare sheet and plate
AMS 4045	Bare sheet and plate
AMS 4078	Bare plate
AMS-QQ-A-250/12, 24	Bare sheet and plate
AMS-QQ-A-250/13, 25	Clad sheet and plate
AMS 4049	Clad sheet and plate
AMS 4122	Bar and rod, rolled or cold finished
AMS 4123	Bar and rod, rolled or cold finished
AMS 4124	Bar and rod, rolled or cold finished
AMS 4186	Bar and rod, rolled or cold finished
AMS 4187	Bar and rod, rolled or cold finished
AMS-QQ-A-225/9	Rolled or drawn bar and rod
AMS-QQ-A-200/11, 15	Extruded bar, rod, and shapes
AMS 4126	Forging

Table 3.7.6.0(a). Material Specifications for 7075 Aluminum Alloy Continued

Specification	Form
AMS 4141	Die forging
AMS 4147	Forging
AMS-A-22771	Forging
AMS-QQ-A-367	Forging

The temper index for 7075 is as follows:

Section	Temper
3.7.6.1	T6, T651, T652, T6510, T6511
3.7.6.2	T73, T7351, T7352, T73510, T73511

3.7.6.1 *T6, T651, T652, T6510, T6511 Temper* — Figures 3.7.6.1.1(a) and (b) permit calculation of residual tensile strengths for complex thermal exposure conditions. They are based upon the rate parameter T(C + log t), in which T is exposure temperature in degrees Rankine, t is exposure time in hours and C is a constant evaluated for each material. These curves have been verified for use only within the ranges of temperatures and exposure times covered in the figures. The following example illustrates their use.

Sample problem: Find F_{tu} at 250°F following a complex exposure of 300°F, 8 hours plus 350°F, 1 hour.

1. Reduce given complex exposure by converting 350°F exposure to equivalent exposure time at 300°F.*
    a. On the 350°F single exposure temperature line find 350°F, 1 hour.
    b. From this point move vertically to the 300°F exposure temperature line and then read right, 12 hours exposure.
    c. Total equivalent exposure time at 300°F is therefore 8 hours + 12 hours or 20 hours.
2. Find F_{tu} at 250°F following 300°F, 20 hours exposure:
    a. On the 300°F exposure temperature line find 300°F, 20 hours.
    b. From this point move vertically to the 250°F test temperature curve and then read left, 76 percent F_{tu}.

Solution: F_{tu} is 76 percent of the original room temperature F_{tu}. F_{ty} is determined in like manner. F_{cy} can be closely estimated by using the percent reduction factor determined for F_{ty}. For specific data, see Reference 3.7.6.1.

Stressed Thermal Exposure — Stress applied during sample and complex thermal exposure of 7075-T6 can have additional effect in reducing material strength. However, the effect becomes significant only when exposure strains exceed 0.2 percent. For specific data, see Reference 3.7.6.1.

---

* Choice of reference temperature is optional as long as it permits computation within the bounds of the figures.

Figures 3.7.6.1.1(c) through 3.7.6.1.5(b) present elevated temperature curves for various mechanical properties. Figures 3.7.6.1.6(a) through (m) present tensile and compressive stress-strain and tangent-modulus curves at several temperatures. Figures 3.7.6.1.6(n) through (q) are full-range stress-strain curves for various products. Figures 3.7.6.1.8(a) through (h) provide room-temperature fatigue curves for T6 temper products. Fatigue-crack propagation data for sheet are presented in Figure 3.7.6.1.9. Graphical displays of the residual strength behavior of middle tension panels are presented in Figure 3.7.6.1.10(a) through (h).

3.7.6.2 T73, T7351, T7352, T73510, T73511 Tempers — Figures 3.7.6.2.6(a) through (d) present stress-strain and tangent-modulus curves for various products and tempers. Figures 3.7.6.2.6(e) and (f) are full-range stress-strain curves at room temperature for extrusion. Fatigue-crack-propagation data for plate are presented in Figures 3.7.6.2.9(a) through (c). Graphical displays of the residual strength behavior of middle tension panels are presented in Figures 3.7.6.2.10(a) and (b).

Table 3.7.6.0(b$_1$). Design Mechanical and Physical Properties of 7075 Aluminum Alloy Sheet and Plate

Specification	AMS 4045 and AMS-QQ-A-250/12																				
Form	Sheet							Plate													
Temper	T6 and T62[a]							T651													
Thickness, in.	0.008-0.011	0.012-0.039		0.040-0.125		0.126-0.249		0.250-0.499		0.500-1.000		1.001-2.000		2.001-2.500		2.501-3.000		3.001-3.500		3.501-4.000	
Basis	S	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
Mechanical Properties:																					
F_{tu}, ksi:																					
L	...	76	78	78	80	78	80	77	79	77	79	76	78	75	77	71	73	70	72	66	68
LT	74	76	78	78	80	78	80	78	80	78	80	77	79	76	78	72	74	71	73	67	69
ST	...	...	...	...	...	...	...	...	...	...	...	...	...	70[b]	71[b]	66[b]	68[b]	65[b]	67[b]	61[b]	63[b]
F_{ty}, ksi:																					
L	...	69	72	70	72	71	73	69	71	70	72	69	71	66	68	63	65	60	62	56	58
LT	63	67	70	68	70	69	71	67	69	68	70	67	69	64	66	61	63	58	60	54	56
ST	...	...	...	...	...	...	...	...	...	...	...	...	...	59[b]	61[b]	56[b]	58[b]	54[b]	55[b]	50[b]	52[b]
F_{cy}, ksi:																					
L	...	68	71	69	71	70	72	67	69	68	70	66	68	62	64	58	60	55	57	51	52
LT	...	71	74	72	74	73	75	71	73	72	74	71	73	68	70	65	67	61	64	57	59
ST	...	...	...	...	...	...	...	...	...	...	...	...	...	67	70	64	66	61	63	57	59
F_{su}, ksi	...	46	47	47	48	47	48	43	44	44	45	44	45	44	45	42	43	42	43	39	41
F_{bru}[c], ksi:																					
(e/D = 1.5)	...	118	121	121	124	121	124	117	120	117	120	116	119	114	117	108	111	107	110	101	104
(e/D = 2.0)	...	152	156	156	160	156	160	145	148	145	148	143	147	141	145	134	137	132	135	124	128
F_{bry}[c], ksi:																					
(e/D = 1.5)	...	100	105	102	105	103	106	97	100	100	103	100	103	98	101	94	97	89	93	84	87
(e/D = 2.0)	...	117	122	119	122	121	124	114	118	117	120	117	120	113	117	109	112	104	108	98	103
e, percent (S-basis):																					
LT	5	7	...	8	...	8	...	9	...	7	...	6	...	5	...	5	...	5	...	3	...
E, 10^3 ksi	10.3							10.3													
E_c, 10^3 ksi	10.5							10.6													
G, 10^3 ksi	3.9							3.9													
μ	0.33							0.33													
Physical Properties:																					
ω, lb/in.^{3}	0.101																				
C, K, and α	See Figure 3.7.6.0																				

[a] Design allowables were based upon data obtained from testing T6 temper sheet and from testing samples of sheet, supplied in the O or F temper, which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained by the user may be lower than those listed if the material has been formed or otherwise cold worked, particularly in the annealed temper, prior to solution heat treatment.

[b] Caution: This specific alloy, temper, and product form exhibits poor stress-corrosion cracking resistance in this grain direction. It corresponds to an SCC resistance rating of D, as indicated in Table 3.1.2.3.1(a).

[c] Bearing values are “dry pin” values per Section 1.4.7.1. See Table 3.1.2.1.1.

Table 3.7.6.0(b$_2$). Design Mechanical and Physical Properties of 7075 Aluminum Alloy Plate—Continued

Specification	AMS 4044 and AMS-QQ-A-250/12						AMS-QQ-A-250/12							
Form	Plate													
Temper	T62[a]													
Thickness, in.	0.250-0.499		0.500-1.000		1.001-2.000		2.001-2.500		2.501-3.000		3.001-3.500		3.501-4.000	
Basis	A	B	A	B	A	B	A	B	A	B	A	B	A	B
Mechanical Properties:														
F_{tu}, ksi:														
L	74	76	74	76	73	75	72	74	69	71	68	70	64	66
LT	78	80	78	80	77	79	76	78	72	74	71	73	67	69
ST	...	...	...	...	...	...	70[b]	71[b]	66[b]	68[b]	65[b]	67[b]	61[b]	63[b]
F_{ty}, ksi:														
L	65	67	66	68	64	65	60	62	56	58	52	54	48	49
LT	67	69	68	70	67	69	64	66	61	63	58	60	54	56
ST	...	...	...	...	...	...	59[b]	61[b]	56[b]	58[b]	54[b]	55[b]	50[b]	52[b]
F_{cy}, ksi:														
L	70	72	70	72	68	70	63	65	59	61	55	57	50	52
LT	70	72	71	73	68	71	65	67	61	63	57	59	52	54
ST	...	...	...	...	...	...	63	65	60	62	57	59	53	55
F_{su}, ksi	43	44	44	45	44	45	44	45	42	43	42	43	39	41
F_{bru}[c], ksi:														
(e/D = 1.5)	117	120	117	120	116	119	114	117	108	111	107	110	101	104
(e/D = 2.0)	145	148	145	148	143	147	141	145	134	137	132	135	124	128
F_{bry}[c], ksi:														
(e/D = 1.5)	97	100	100	103	100	103	98	101	94	97	89	93	84	87
(e/D = 2.0)	114	118	117	120	117	120	113	117	109	112	104	108	98	103
e, percent (S-basis):														
LT	9	...	7	...	6	...	5	...	5	...	5	...	3	...
E, 10^3 ksi	10.3													
E_c, 10^3 ksi	10.6													
G, 10^3 ksi	3.9													
μ	0.33													
Physical Properties:														
ω, lb/in.^{3}	0.101													
C, K, and α	See Figure 3.7.6.0													

a Design allowables were based upon data obtained from testing samples of plate, supplied in O or F temper, which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained by the user may be lower than those listed if the material has been formed or otherwise cold worked, particularly in the annealed temper, prior to solution heat treatment.

b Caution: This specific alloy, temper, and product form exhibits poor stress-corrosion cracking resistance in this grain direction. It corresponds to an SCC resistance rating of D, as indicated in Table 3.1.2.3.1(a).

c Bearing values are “dry pin” values per Section 1.4.7.1. See Table 3.1.2.1.1.

Table 3.7.6.0(b_3). Design Mechanical and Physical Properties of 7075 Aluminum Alloy Sheet and Plate—Continued

Specification	AMS-QQ-A-250/12	AMS 4078 and AMS-QQ-A-250/12													
Form	Sheet	Plate													
Temper	T73	T7351													
Thickness, in.	0.040-0.249	0.250-0.499	0.500-1.000		1.001-1.500		1.501-2.000		2.001-2.500		2.501-3.000		3.001-3.500	3.501-4.000
Basis	S	S	A	B	A	B	A	B	A	B	A	B	S	S
Mechanical Properties:														
F_{tu}, ksi:														
L	67	68	68	70	67	69	66	68	65	67	63	65	62	60
LT	67	69	69	71	68	70	67	69	66	68	64[a]	66	63	61
ST	...	...	...	...	...	...	63	65	62	64	60	62	59	57
F_{ty}, ksi:														
L	56	57	57	59	57	59	55	57	52	55	49	53	49	48
LT	56	57	57	59	57	59	55	57	52[b]	55	49[a]	53	49	48
ST	...	...	...	...	...	...	52	54	49	52	47	50	47	46
F_{cy}, ksi:														
L	55	56	56	58	56	58	53	55	50	53	47	51	47	45
LT	58	59	59	61	59	61	57	59	54	57	51	55	51	50
ST	...	...	...	...	...	...	59	61	55	58	51	55	50	48
F_{su}, ksi	38	38	38	39	38	40	39	40	39	40	38	39	38	37
$F_{bru}{}^{c}$, ksi:														
(e/D = 1.5)	105	102	103	106	103	106	102	106	102	105	100	103	99	96
(e/D = 2.0)	134	131	132	136	132	136	132	136	131	135	128	132	127	124
$F_{bry}{}^{c}$, ksi:														
(e/D = 1.5)	84	79	81	83	83	86	82	85	79	83	76	81	76	76
(e/D = 2.0)	102	95	97	100	99	102	97	101	93	99	89	96	89	88
e, percent (S-basis):														
LT	8	7	7	...	6	...	6	...	6	...	6	...	6	6
E, 10^3 ksi	10.3	10.3												
E_c, 10^3 ksi	10.5	10.6												
G, 10^3 ksi	3.9	3.9												
μ	0.33	0.33												
Physical Properties:														
ω, lb/in.^{3}	0.101													
C, K, and α	See Figure 3.7.6.0													

[a] S-basis. The rounded T_{99} values are as follows: F_{tu}(LT) = 65 ksi and F_{ty}(LT) = 52 ksi.

[b] S-basis. The rounded T_{99} value is as follows: F_{ty}(LT) = 53 ksi.

[c] Bearing values are "dry pin" values per Section 1.4.7.1. See Table 3.1.2.1.1.

Table 3.7.6.0(b_4). Design Mechanical and Physical Properties of 7075 Aluminum Alloy Sheet and Plate—Concluded

Specification	AMS-QQ-A-250/24				
Form	Sheet and plate				
Temper	T76	T7651			
Thickness, in.	0.063-0.249	0.250-0.499	0.500-1.000	1.001-1.500	1.501-2.000
Basis	S	S	S	S	S
Mechanical Properties:					
F_{tu}, ksi:					
L	72	71	70	70	70
LT	73	72	71	71	71
ST	...	...	...	...	65
F_{ty}, ksi:					
L	62	60	59	59	59
LT	62	61	60	60	60
ST	...	...	...	...	56
F_{cy}, ksi:					
L	61	60	59	59	59
LT	65	64	63	63	63
ST	...	...	...	...	63
F_{su}, ksi	42	40	41	42	43
F_{bru}[a], ksi:					
(e/D = 1.5)	112	109	108	108	108
(e/D = 2.0)	145	141	140	140	140
F_{bry}[a], ksi:					
(e/D = 1.5)	88	86	86	86	87
(e/D = 2.0)	102	99	99	99	100
e, percent:					
LT	8	8	6	5	5
E, 10^3 ksi	10.3	10.3			
E_c, 10^3 ksi	10.5	10.6			
G, 10^3 ksi	3.9	3.9			
μ	0.33	0.33			
Physical Properties:					
ω, lb/in.^{3}	0.101				
C, K, and α	See Figure 3.7.6.0				

a Bearing values are "dry pin" values per Section 1.4.7.1. See Table 3.1.2.1.1.

Table 3.7.6.0(c_1). Design Mechanical and Physical Properties of Clad 7075 Aluminum Alloy Sheet

Specification	AMS 4049								
Form	Sheet								
Temper	T6								
Thickness, in.	0.008-0.011	0.012-0.039		0.040-0.062		0.063-0.187		0.188-0.249	
Basis	S	A	B	A	B	A	B	A	B
Mechanical Properties:									
F_{tu}, ksi:									
L	...	71	74	71	75	74	77	75	77
LT	68	71	74	71	75	74[a]	77	75	77
F_{ty}, ksi:									
L	...	62	65	63	66	66	69	66	68
LT	58	60	63	61	64	64	67	64	66
F_{cy}, ksi:									
L	...	61	64	62	65	65	68	65	67
LT	...	64	67	65	68	68	71	68	70
F_{su}, ksi	...	42	44	42	45	44	46	45	46
F_{bru}[b], ksi:									
(e/D = 1.5)	...	110	115	110	116	115	119	116	119
(e/D = 2.0)	...	142	148	142	150	148	154	150	154
F_{bry}[b], ksi:									
(e/D = 1.5)	...	90	94	91	96	96	100	96	99
(e/D = 2.0)	...	105	110	106	112	112	117	112	115
e, percent (S-basis):									
LT	5	8	...	9	...	9	...	9	...
E, 10^3 ksi:									
Primary	10.3					10.3		10.3	
Secondary	9.5					9.8		10.0	
E_c, 10^3 ksi:									
Primary	10.5					10.5		10.5	
Secondary	9.7					10.0		10.2	
G, 10^3 ksi	...					...		...	
μ	0.33					0.33		0.33	
Physical Properties:									
ω, lb/in.^{3}	0.101								
C, K, and α	...								

[a] S-Basis. The rounded T_{99} value is 75 ksi.

[b] Bearing values are "dry pin" values per Section 1.4.7.1.

Table 3.7.6.0(c$_2$). Design Mechanical and Physical Properties of Clad 7075 Aluminum Alloy Sheet—Continued

Specification	AMS-QQ-A-250/13								
Form	Sheet								
Temper	T6 and T62[a]								
Thickness, in.	0.008-0.011	0.012-0.039		0.040-0.062		0.063-0.187		0.188-0.249	
Basis	S	A	B	A	B	A	B	A	B
Mechanical Properties:									
F_{tu}, ksi:									
L	...	70	74	71	75	73	77	75	77
LT	68	70[b]	74	71	75	73[c]	77	75	77
F_{ty}, ksi:									
L	...	62	65	63	66	65	69	66	68
LT	58	60	63	61	64	63[d]	67	64	66
F_{cy}, ksi:									
L	...	61	64	62	65	64	68	65	67
LT	...	64	67	65	68	67	71	68	70
F_{su}, ksi	...	42	44	42	45	44	46	45	46
F_{bru}[e], ksi:									
(e/D = 1.5)	...	108	115	110	116	113	119	116	119
(e/D = 2.0)	...	140	148	142	150	146	154	150	154
F_{bry}[e], ksi:									
(e/D = 1.5)	...	90	94	91	96	94	100	96	99
(e/D = 2.0)	...	105	110	106	112	110	117	112	115
e, percent (S-basis):									
LT	5	7	...	8	...	8	...	8	...
E, 10^3 ksi:									
Primary	10.3					10.3		10.3	
Secondary	9.5					9.8		10.0	
E_c, 10^3 ksi:									
Primary	10.5					10.5		10.5	
Secondary	9.7					10.0		10.2	
G, 10^3 ksi	...					...		...	
μ	0.33					0.33		0.33	
Physical Properties:									
ω, lb/in.^{3}	0.101								
C, K, and α	...								

[a] Design allowables were based upon data obtained from testing T6 temper sheet and from testing samples of sheet, supplied in the O or F temper, which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained may be lower than those listed if the material has been formed or otherwise cold worked, particularly in the annealed temper, prior to solution heat treatment.

[b] S-Basis. The rounded T_{99} value is 71 ksi.

[c] S-Basis. The rounded T_{99} value is 75 ksi.

[d] S-Basis. The rounded T_{99} value is 64 ksi.

[e] Bearing values are “dry pin” values per Section 1.4.7.1.

Table 3.7.6.0(c_3). Design Mechanical and Physical Properties of Clad 7075 Aluminum Alloy Plate—Continued

Specification	AMS 4049 and AMS-QQ-A-250/13													
Form	Plate													
Temper	T651													
Thickness, in.	0.250-0.499		0.500-1.000^{a}		1.001-2.000^{a}		2.001-2.500^{a}		2.501-3.000^{a}		3.001-3.500^{a}		3.501-4.000^{a}	
Basis	A	B	A	B	A	B	A	B	A	B	A	B	A	B
Mechanical Properties:														
F_{tu}, ksi:														
L	74	76	75	77	74	76	73	75	69	71	68	70	64	66
LT	75	77	76	78	75	77	74	76	70	72	69	71	65	67
ST	...	...	...	...	...	...	70^{b}	71^{b}	66^{b}	68^{b}	65^{b}	67^{b}	61^{b}	63^{b}
F_{ty}, ksi:														
L	67	69	68	70	67	69	64	66	61	63	58	60	54	56
LT	65	67	66	68	65	67	62	64	59	61	56	58	52	54
ST	...	...	...	...	...	...	59^{b}	61^{b}	56^{b}	58^{b}	54^{b}	55^{b}	50^{b}	52^{b}
F_{cy}, ksi:														
L	65	67	66	68	64	66	60	62	57	58	53	55	49	51
LT	69	71	70	72	69	71	65	68	62	64	59	61	55	57
ST	...	...	...	...	...	...	67	70	64	66	61	63	57	59
F_{su}, ksi	42	43	42	44	42	44	43	44	41	42	40	42	38	39
$F_{bru}{}^{c}$, ksi:														
(e/D = 1.5)	113	116	114	117	113	116	111	114	105	108	104	107	98	101
(e/D = 2.0)	139	143	141	145	139	143	137	141	130	134	128	132	121	124
$F_{bry}{}^{c}$, ksi:														
(e/D = 1.5)	94	97	97	100	97	100	95	98	90	94	86	89	80	84
(e/D = 2.0)	111	114	113	116	113	117	110	113	105	109	100	104	93	97
e, percent (S-basis):														
LT	9	...	7	...	6	...	5	...	5	...	5	...	3	...
E, 10^3 ksi:														
Primary	10.3													
Secondary	10.0													
E_c, 10^3 ksi:														
Primary	10.6													
Secondary	10.3													
G, 10^3 ksi	...													
μ	0.33													
Physical Properties:														
ω, lb/in.^{3}	0.101													
C, K, and α	...													

a These values, except in the ST direction, have been adjusted to represent the average properties across the whole section, including the 1-1/2 percent per side nominal cladding thickness.

b Caution: This specific alloy, temper, and product form exhibits poor stress-corrosion cracking resistance in this grain direction. It corresponds to an SCC resistance rating of D, as indicated in Table 3.1.2.3.1(a).

c Bearing values are "dry pin" values per Section 1.4.7.1. See Table 3.1.2.1.1

Table 3.7.6.0(c_4). Design Mechanical and Physical Properties of Clad 7075 Aluminum Alloy Plate—Continued

Specification	AMS-QQ-A-250/13													
Form	Plate													
Temper	T62[a]													
Thickness, in.	0.250-0.499		0.500-1.000[b]		1.001-2.000[b]		2.001-2.500[b]		2.501-3.000[b]		3.001-3.500[b]		3.501-4.000[b]	
Basis	A	B	A	B	A	B	A	B	A	B	A	B	A	B
Mechanical Properties:														
F_{tu}, ksi:														
L	72	73	72	74	72	73	71	72	67	69	66	68	62	64
LT	75	77	76	78	75	77	74	76	70	72	69	71	65	67
ST	...	...	...	...	...	...	70[c]	71[c]	66[c]	68[c]	65[c]	67[c]	61[c]	63[c]
F_{ty}, ksi:														
L	63	65	64	66	62	64	58	60	54	56	50	52	46	48
LT	65	67	66	68	65	67	62	64	59	61	56	58	52	54
ST	...	...	...	...	...	...	59[c]	61[c]	56[c]	58[c]	54[c]	55[c]	50[c]	52[c]
F_{cy}, ksi:														
L	68	70	68	70	66	68	62	63	57	59	53	55	48	50
LT	68	70	69	71	66	68	62	65	59	61	55	57	50	52
ST	...	...	...	...	...	...	63	65	60	62	57	59	53	55
F_{su}, ksi	42	43	42	44	42	44	43	44	41	42	40	42	38	39
F_{bru}[d], ksi:														
(e/D = 1.5)	113	116	114	117	113	116	111	114	105	108	104	107	98	101
(e/D = 2.0)	139	143	141	145	139	143	137	141	130	134	128	132	121	124
F_{bry}[d], ksi:														
(e/D = 1.5)	94	97	97	100	97	100	95	98	90	94	86	89	80	84
(e/D = 2.0)	111	114	113	116	113	117	110	113	105	109	100	104	93	97
e, percent (S-basis):														
LT	9	...	7	...	6	...	5	...	5	...	5	...	3	...
E, 10^3 ksi:														
Primary	10.3													
Secondary	10.0													
E_c, 10^3 ksi:														
Primary	10.6													
Secondary	10.3													
G, 10^3 ksi	3.9													
μ	0.33													
Physical Properties:														
ω, lb/in.^{3}	0.101													
C, K, and α	...													

[a] Design allowables were based upon data obtained from testing samples of plate, supplied in the O or F temper, which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained may be lower than those listed if the material has been formed or otherwise cold worked, particularly in the annealed temper, prior to solution heat treatment.

[b] These values, except in the ST direction, have been adjusted to represent the average properties across the whole section.

[c] Caution: This specific alloy, temper, and product form exhibits poor stress-corrosion cracking resistance in this grain direction. It corresponds to an SCC resistance rating of D, as indicated in Table 3.1.2.3.1(a).

[d] Bearing values are "dry pin" values per Section 1.4.7.1. See Table 3.1.2.1.1.

Table 3.7.6.0(c_5). Design Mechanical and Physical Properties of Clad 7075 Aluminum Alloy Sheet and Plate—Continued

Specification	AMS-QQ-A-250/25				
Form	Sheet			Plate	
Temper	T76			T7651	
Thickness, in,.	0.040- 0.062	0.063- 0.187	0.188- 0.249	0.250- 0.499	0.500- 1.000[a]
Basis	S	S	S	S	S
Mechanical Properties:					
F_{tu}, ksi:					
L	66	67	69	68	68
LT	67	68	70	69	68
F_{ty}, ksi:					
L	56	57	59	58	57
LT	56	57	59	58	57
F_{cy}, ksi:					
L	55	56	58	57	56
LT	59	60	62	60	59
F_{su}, ksi	41	40	40	40	40
F_{bru}[b], ksi:					
(e/D = 1.5)	103	104	107	105	103
(e/D = 2.0)	133	135	139	133	131
F_{bry}[b], ksi:					
(e/D = 1.5)	80	81	84	87	87
(e/D = 2.0)	92	94	97	104	103
e, percent:					
LT	8	8	8	8	6
E, 10^3 ksi:					
Primary	10.3		10.3	10.3	
Secondary	9.8		10.0	10.0	
E_c, 10^3 ksi:					
Primary	10.5		10.5	10.6	
Secondary	10.0		10.2	10.3	
G, 10^3 ksi	...		...	...	
μ	0.33		0.33	0.33	
Physical Properties:					
ω, lb/in.^{3}	0.101				
C, K, and α	...				

---

a These values have been adjusted to represent the average properties across the whole section, including the 1-1/2 percent per side nominal cladding thickness.

b Bearing values are “dry pin” values per Section 1.4.7.1. See Table 3.1.2.1.1.

Table 3.7.6.0(d). Design Mechanical and Physical Properties of 7075 Aluminum Alloy Bar, Rod, and Shapes: Rolled, Drawn, or Cold-Finished

Specification	AMS 4122, AMS 4123, AMS 4186, AMS 4187, and AMS-QQ-A-225/9								AMS 4124 and AMS-QQ-A-225/9	
Form	Bar, rod, and shapes: rolled, drawn, or cold-finished									
Temper	T6, T651, and T62^a								T73^b or T7351	
Thickness^c, in.	≤1.000		1.001-2.000		2.001-3.000		3.001-4.000		0.375-2.000	2.001-3.000
Basis	A	B	A	B	A	B	A	B	S	S
Mechanical Properties:										
F_{tu}, ksi:										
L	77	79	77	79	77	79	77	79	68	68
LT	77^d	79^d	75^d	77^d	72^d	74^d	69^d	71^d	...	65^e
F_{ty}, ksi:										
L	66	68	66	68	66	68	66	68	56	56
LT	66^d	68^d	66^d	68^d	63^d	65^d	60^d	62^d	...	52^e
F_{cy}, ksi:										
L	64	66	64	66	64	66	64	66	54	54
LT	...	...	...	...	...	...	...	...	...	55^e
F_{su}, ksi	46	47	46	47	46	47	46	47	42	40
$F_{bru}{}^f$, ksi:										
(e/D = 1.5)	100	103	100	103	100	103	100	103	101	101
(e/D = 2.0)	123	126	123	126	123	126	123	126	131	131
$F_{bry}{}^f$, ksi:										
(e/D = 1.5)	86	88	86	88	86	88	86	88	81	81
(e/D = 2.0)	92	95	92	95	92	95	92	95	100	100
e, percent (S-basis):										
L	7	...	7	...	7	...	7	...	10	10
E, 10^3 ksi	10.3									
E_c, 10^3 ksi	10.5									
G, 10^3 ksi	3.9									
μ	0.33									
Physical Properties:										
ω, lb/in.^{3}	0.101									
C, K, and α	See Figure 3.7.6.0									

a Design allowables were based upon data obtained from testing of T6 and T651 material and from samples of material, supplied in the O or F temper, which were heat treated to T62 temper to demonstrate response to heat treatment by suppliers.

b Design allowables were based upon data obtained from testing T73 and T7351 temper material and from testing samples of material, supplied in the O or F temper, which were heat treated to T73 temper to demonstrate response to heat treatment by suppliers.

c For rounds (rod) maximum diameter is 4 inches; for square bar, maximum size is 3½ inches; for rectangular bar, maximum thickness is 3 inches with corresponding width of 6 inches; for rectangular bar less than 3 inches in thickness, maximum width is 10 inches.

d Caution: This specific alloy, temper, and product form exhibits poor stress-corrosion cracking resistance in this grain direction. It corresponds to an SCC resistance rating of D, as indicated in Table 3.1.2.3.1(a).
ST grain direction.

e ST grain direction.

f Bearing values are "dry pin" values per Section 1.4.7.1.

Table 3.7.6.0(e_1). Design Mechanical and Physical Properties of 7075 Aluminum Alloy Die Forging

Specification	AMS 4126, MIL-A-22771, and QQ-A-367							MIL-A-22771 and QQ-A-367						
Form	Die forging													
Temper	T6[a]							T652						
Thickness[b], in.	≤1.000		1.001-2.000		2.001-3.000		3.001-4.000	≤1.000		1.001-2.000		2.001-3.000		3.001-4.000
Basis	A	B	A	B	A	B	S	A	B	A	B	A	B	S
Mechanical Properties:														
F_{tu}, ksi:														
L	75	78	74	77	74	76	73	75	78	74	77	74	76	73
T[c]	71[d]	...	71[d]	...	70[d]	...	70	71[d]	...	71[d]	...	70[d]	...	70
F_{ty}, ksi:														
L	64	67	63	66	63	65	62	64	67	63	66	63	65	62
T[c]	61[d]	...	61[d]	...	60[d]	...	60	60[d]	...	60[d]	...	59[d]	...	59
F_{cy}, ksi:														
L	67	70	66	69	66	68	65	64	67	63	66	63	65	62
ST	64	68	64	67	63	66	63	65	69	65	68	64	67	64
F_{su}, ksi	43	45	43	44	42	43	42	43	45	43	44	42	43	42
F_{bru}[e], ksi:														
(e/D = 1.5)	105	109	104	108	104	106	102	105	109	104	108	104	106	102
(e/D = 2.0)	135	140	133	138	133	136	131	135	140	133	138	133	136	131
F_{bry}[e], ksi:														
(e/D = 1.5)	83	87	82	86	82	84	81	83	87	82	86	82	84	81
(e/D = 2.0)	96	100	94	99	94	97	93	96	100	94	99	94	97	93
e, percent (S-basis):														
L	7	...	7	...	7	...	7	7	...	7	...	7	...	7
T[c]	3	...	3	...	3	...	2	3	...	3	...	3	...	2
E, 10^3 ksi	10.0													
E_c, 10^3 ksi	10.4													
G, 10^3 ksi	3.8													
μ	0.33													
Physical Properties:														
ω, lb/in.^{3}	0.101													
C, K, and α	See Figure 3.7.6.0													

a When die forgings are machined before heat treatment, the mechanical properties are applicable provided the as-forged thickness is not greater than twice the thickness at time of heat treatment.
b Thickness at the time of heat treatment.
c T indicates any grain direction not within ±15° of being parallel to the forging flow lines. F_{cy}(T) values are based upon short transverse (ST) test data.
d Specification value. T tensile properties are presented on an S basis only.
e Bearing values are "dry pin" values per Section 1.4.7.1.

Table 3.7.6.0(e_2). Design Mechanical and Physical Properties of 7075 Aluminum Alloy Die Forging—Continued

Specification	AMS 4141, AMS-A-22771, and AMS-QQ-A-367								AMS 4141		AMS 4147, AMS-A-22771, and AMS-QQ-A-367		
Form	Die forging												
Temper	T73[a,b]										T7352		
Thickness[c], in.	≤1.000		1.001-2.000		2.001-3.000		3.001-4.000		4.001-5.000	5.001-6.000	≤3.000		3.001-4.000
Basis	A	B	A	B	A	B	A	B	S	S	A	B	S
Mechanical Properties[d]:													
F_{tu}, ksi:													
L	66[d]	71	66[d]	71	66	69	64[d]	69	62	61	66[e]	69	64
T[f]	62[g]	...	62[g]	...	62[g]	...	61[g]	...	59	58	62[g]	...	61
F_{ty}, ksi:													
L	56[d]	61	56	59	56	59	55[d]	59	53	51	56	59	53
T[f]	53[g]	...	53[g]	...	53[g]	...	52[g]	...	51	50	51[g]	...	49
F_{cy}, ksi:													
L	58	63	58	61	58	61	57	61	...	...	56	59	53
T[f]	55	60	55	59	55	59	54	58	...	...	55	60	53
F_{su}, ksi	39	42	39	42	39	41	38	41	...	...	39	41	38
F_{bru}[h], ksi:													
(e/D = 1.5)	96	103	96	103	96	100	93	100	...	...	96	100	93
(e/D = 2.0)	125	135	125	135	125	131	122	131	...	...	125	131	122
F_{bry}[h], ksi:													
(e/D = 1.5)	78	85	78	83	78	83	77	83	...	...	78	83	74
(e/D = 2.0)	90	98	90	94	90	94	88	94	...	...	90	94	85
e, percent (S-basis):													
L	7	...	7	...	7	...	7	...	7	6	7	...	7
T[f]	3	...	3	...	3	...	2	...	2	2	3	...	2
E, 10^3 ksi	10.0												
E_c, 10^3 ksi	10.4												
G, 10^3 ksi	3.8												
μ	0.33												
Physical Properties:													
ω, lb/in.^{3}	0.101												
C, K, and α	See Figure 3.7.6.0												

a When die forgings are machined before heat treatment, the mechanical properties are applicable, provided the as-forged thickness is not greater than twice the thickness at the time of heat treatment.

b Design allowables were based upon data obtained from testing die forgings, heat treated by suppliers, and supplied in T73 temper.

c Thickness at the time of heat treatment.

d Rounded T_{99} values for T73 temper ≤1.000 in., F_{tu} = 68 ksi, for F_{ty} = 57 ksi; 1.001-2.000 in., F_{tu} = 68 ksi; 3.001-4.000 in., F_{tu} = 66 ksi, for F_{ty} = 56 ksi.

e Rounded T_{99} values for T7352 temper, F_{tu} ≤1.000 inch = 67 ksi.

f When AMS-A-22771 or AMS-QQ-A-367 apply, T indicates any grain direction not within ±15° of being parallel to the forging flow lines. F_{cy} (T) values are based upon short transverse (ST) test data. When AMS 4141 applies, T indicates any grain direction within ±15° of being perpendicular to the forging flow lines.

g Specification value. T tensile properties are presented on an S basis only.

h Bearing values are "dry pin" values per Section 1.4.7.1.

Table 3.7.6.0(f_1). Design Mechanical and Physical Properties of 7075 Aluminum Alloy Hand Forging

Specification	AMS 4126, AMS-A-22771, and AMS-QQ-A-367					AMS-A-22771 and AMS-QQ-A-367				
Form	Hand forging									
Temper	T6[a]					T652				
Thickness, in.	≤2.000	2.001-3.000	3.001-4.000	4.001-5.000	5.001-6.000	≤2.000	2.001-3.000	3.001-4.000	4.001-5.000	5.001-6.000
Basis	S	S	S	S	S	S	S	S	S	S
Mechanical Properties:										
F_{tu}, ksi:										
L	74	73	71	69	68	74	73	71	69	68
LT	73	71	70	68	66	73	71	70	68	66
ST	...	69^{b}	68^{b}	66^{b}	65^{b}	...	69^{b}	68^{b}	66^{b}	65^{b}
F_{ty}, ksi:										
L	63	61	60	58	56	63	61	60	58	56
LT	61	59	58	56	55	61	59	58	56	55
ST	...	58^{b}	57^{b}	56^{b}	55^{b}	...	57^{b}	56^{b}	55^{b}	54^{b}
F_{cy}, ksi:										
L	63	61	...	...	...	63	61	...	...	...
LT	61	59	...	...	...	61	59	...	...	...
F_{su}, ksi	44	44	43	41	41	44	44	43	41	41
F_{bru}, ksi:										
(e/D = 1.5)	...	...	...	...	...	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...	...	...	...	...	...
F_{bry}, ksi:										
(e/D = 1.5)	...	...	...	...	...	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...	...	...	...	...	...
e, percent:										
L	9	9	8	7	6	9	9	8	7	6
LT	4	4	3	3	3	4	4	3	3	3
ST	...	3	2	2	2	...	2	1	1	1
E, 10^3 ksi	10.0									
E_c, 10^3 ksi	10.4									
G, 10^3 ksi	3.8									
μ	0.33									
Physical Properties:										
ω, lb/in.^{3}	0.101									
C, K, and α	See Figure 3.7.6.0									

a When hand forgings are machined before heat treatment, the section thickness at time of heat treatment will determine the minimum mechanical properties as long as the original (as-forged) thickness does not exceed the maximum thickness of the alloy as shown in the table. The maximum cross-sectional area of hand forgings is 256 sq in.

b Caution: This specific alloy, temper, and product form exhibits poor stress-corrosion cracking resistance in this grain direction. It corresponds to an SCC resistance rating of D, as indicated in Table 3.1.2.3.1(a).

Table 3.7.6.0(f_2). Design Mechanical and Physical Properties of 7075 Aluminum Alloy Hand Forging—Continued

Specification	AMS-A-22771 and AMS-QQ-A-367					AMS 4147, AMS-A-22771, and AMS-QQ-A-367					
Form	Hand forging										
Temper	T73[a]					T7352					
Thickness, in.	≤2.000	2.001-3.000	3.001-4.000	4.001-5.000	5.001-6.000	≤2.000	2.001-3.000	3.001-4.000		4.001-5.000	5.001-6.000
Basis	S	S	S	S	S	S	S	A	B	S	S
Mechanical Properties:											
F_{tu}, ksi:											
L	66	66	64	62	61	66	66	64	67	62	61
LT	64	64	63	61	59	64	64	63	66	61	59
ST	...	61	60	58	57	...	61	60	63	58	57
F_{ty}, ksi:											
L	56	56	55	53	51	54	54	53	55	51	49
LT	54	54	53	51	50	52	52	50	53	48	46
ST	...	52	51	50	49	...	50	48	51	46	44
F_{cy}, ksi:											
L	56	56	...	...	...	55	55	52	55	49	46
LT	52	52	...	...	...	55	55	52	55	49	46
ST	...	...	...	...	...	55	55	53	56	51	49
F_{su}, ksi:											
L	39	39	...	...	...	39	39	38	40	37	36
LT	...	...	...	...	...	36	36	37	38	36	35
ST	...	...	...	...	...	38	38	37	39	36	35
F_{bru}[b], ksi:											
(e/D = 1.5)	...	...	...	...	...	86	88	89	93	86	84
(e/D = 2.0)	...	...	...	...	...	120	120	118	123	114	110
F_{bry}[b], ksi:											
(e/D = 1.5)	...	...	...	...	...	71	73	73	77	71	68
(e/D = 2.0)	...	...	...	...	...	90	90	87	92	83	80
e, percent (S-basis):											
L	7	7	7	7	6	7	7	7	...	7	6
LT	4	4	3	3	3	4	4	3	...	3	3
ST	...	3	2	2	2	...	3	2	...	2	2
E, 10^3 ksi	10.2										
E_c, 10^3 ksi	10.4										
G, 10^3 ksi	3.8										
μ	0.33										
Physical Properties:											
ω, lb/in.^{3}	0.101										
C, K, and α	See Figure 3.7.6.0										

[a] When hand forgings are machined before heat treatment, the section thickness at time of heat treatment will determine the minimum mechanical properties as long as the original (as-forged) thickness does not exceed the maximum thickness for the alloy as shown in the table. The maximum cross-sectional area of hand forgings is 256 sq. in.

[b] Bearing values are “dry pin” values per Section 1.4.7.1.

Table 3.7.6.0(g_1). Design Mechanical and Physical Properties of 7075 Aluminum Alloy Extrusion

Specification	AMS-QQ-A-200/11														
Form	Extrusion (rod, bar, and shapes)														
Temper	T6, T6510, T6511, and T62[a]														
Cross-Sectional Area, in.^{2}	≤20												>20, ≤32	≤32	
Thickness, in.[b]	≤0.249		0.250-0.499		0.500-0.749		0.750-1.499		1.500-2.999		3.000-4.499			4.500-5.000	
Basis	A	B	A	B	A	B	A	B	A	B	A	B	S	A	B
Mechanical Properties:															
F_{tu}, ksi:															
L	78	82	81	85	81	85	81	85	81	85	81	84	78	78	81
LT	75	79	78	82	77	81	75	79	71	75	67	69	64	63	65
ST	...	...	...	...	...	...	...	...	67[c]	71[c]	67[c]	69[c]	64[c]	63[c]	65[c]
F_{ty}, ksi:															
L	70	74	73	77	72	76	72	76	72	76	71	74	70	68	71
LT	66	70	69	72	67	71	65	69	61	65	56	59	55	52	55
ST	...	...	...	...	...	...	...	...	56[c]	59[c]	55[c]	58[c]	55[c]	52[c]	55[c]
F_{cy}, ksi:															
L	70	74	73	77	72	76	72	76	72	76	71	74	70	68	71
LT	72	76	74	78	73	77	71	75	67	71	62	64	61	57	60
ST	...	...	...	...	...	...	...	...	62	66	62	64	61	57	60
F_{su}, ksi	41	44	43	45	43	45	43	45	42	44	40	42	39	38	40
F_{bru}[d], ksi:															
(e/D = 1.5)	111	117	115	121	115	120	113	119	110	115	106	110	102	101	105
(e/D = 2.0)	140	148	146	153	145	152	144	151	141	148	137	142	132	131	136
F_{bry}[d], ksi:															
(e/D = 1.5)	92	97	96	101	94	99	93	98	89	94	84	88	83	79	83
(e/D = 2.0)	108	114	113	119	111	117	110	116	106	112	101	105	100	95	100
e, percent (S-basis):															
L	7	...	7	...	7	...	7	...	7	...	7	...	6	6	...
E, 10^3 ksi	10.4														
E_c, 10^3 ksi	10.7														
G, 10^3 ksi	4.0														
μ	0.33														
Physical Properties:															
ω, lb/in.^{3}	0.101														
C, K, and α	See Figure 3.7.6.0														

a Design allowables were based upon data obtained from testing T6, T6510, and T6511 temper extrusions and from testing samples of extrusion supplied in the O or F temper, which were heat treated to T62 temper to demonstrate response to heat treatment by suppliers. Properties obtained by the user may be lower than those listed if the material has been formed or otherwise cold worked, particularly in the annealed temper, prior to solution heat treatment.

b The mechanical properties are to be based upon the thickness at the time of quench.

c Caution: This specific alloy, temper, and product form exhibits poor stress-corrosion cracking resistance in this grain direction. It corresponds to an SCC resistance rating of D, as indicated in Table 3.1.2.3.1(a).

d Bearing values are "dry pin" values per Section 1.4.7.1.

Table 3.7.6.0(g_2). Design Mechanical and Physical Properties of 7075 Aluminum Alloy Extrusion—Continued

Specification	AMS-QQ-A-200/11													
Form	Extrusion (rod, bars, and shapes)													
Temper	T73[a], T73510, T73511													
Cross-Sectional Area, in.^{2}	≤20		≤25								≤20		>20, ≤32	
Thickness, in.[b]	0.062-0.249		0.250-0.499		0.500-0.749		0.750-1.499		1.500-2.999		3.000-4.499		3.000-4.499	
Basis	A	B	A	B	A	B	A	B	A	B	A	B	A	B
Mechanical Properties:														
F_{tu}, ksi:														
L	68[c]	72	70[d]	74	70[d]	73	70[d]	73	69[d]	74	68[c]	71	65[e]	70
LT	66	70	68	72	67	70	66	69	62	67	58	61	56	60
F_{ty}, ksi:														
L	58	61	60	63	60	63	60	63	59[d]	65	57[c]	62	55[e]	60
LT	56	59	57	60	57	60	56	58	51	56	46	50	44	48
F_{cy}, ksi:														
L	58	61	60	63	60	63	60	63	59	65	57	62	55	60
LT	59	62	60	63	60	63	58	61	54	59	49	53	47	51
F_{su}, ksi	37	39	38	40	38	39	38	39	37	40	37	38	35	38
F_{bru}[f], ksi:														
(e/D = 1.5)	101	107	104	110	103	108	103	107	99	106	95	99	91	98
(e/D = 2.0)	129	137	133	141	133	139	132	138	128	138	124	130	119	128
F_{bry}[f], ksi:														
(e/D = 1.5)	82	86	84	89	84	88	83	87	79	87	72	79	70	76
(e/D = 2.0)	97	102	100	105	100	105	98	103	93	103	86	94	83	91
e, percent (S-basis):														
L	7	...	8	...	8	...	8	...	8	...	7	...	7	...
E, 10^3 ksi	10.4													
E_c, 10^3 ksi	10.7													
G, 10^3 ksi	4.0													
μ	0.33													
Physical Properties:														
ω, lb/in.^{3}	0.101													
C, K, and α	See Figure 3.7.6.0													

[a] Design allowables were based upon data obtained from testing T7351X temper extrusions and from testing samples of extrusions supplied in the O or F temper, which were heat treated to T73 temper to demonstrate response to treatment by suppliers. Properties obtained by the user may be lower than those listed if the material has been formed or otherwise cold worked, particularly in the annealed temper.

[b] The mechanical properties are to be based upon the thickness at the time of quench.

[c] S-basis. Rounded T_{99} values for cross sectional area ≤20 are as follows: for 0.062-0.249 F_{tu}(L) = 69 ksi, 3.000-4.499 F_{tu}(L) = 69 ksi, F_{ty}(L) = 59 ksi.

[d] S-basis. Rounded T_{99} values for cross sectional area ≤25 are as follows: 0.250-1.499 F_{tu}(L)= 71, 1.500-2.999 F_{tu}(L)= 72 ksi and F_{ty}(L) = 62 ksi.

[e] S-basis. Rounded T_{99} values for cross sectional area >20 and ≤32 are as follows: F_{tu}(L) = 68 ksi and F_{ty}(L) = 57 ksi.

[f] Bearing values are "dry pin" values per Section 1.4.7.1.

Table 3.7.6.0(g_3). Design Mechanical and Physical Properties of 7075 Aluminum Alloy Extrusion—Continued

Specification	AMS-QQ-A-200/15						
Form	Extrusion (rod, bar, and shapes)						
Temper	T76, T76510, T76511						
Cross-Sectional Area, in.^{2}	≤20						
Thickness, in.[a]	0.062-0.249		0.250-0.499	0.500-0.749		0.750-1.000	
Basis	A	B	S	A	B	A	B
Mechanical Properties:							
F_{tu}, ksi:							
L	71	74	75	75	76	75	76
LT	68	71	72	71	73	70	71
F_{ty}, ksi:							
L	61	65	65	65	67	65	67
LT	57	61	61	60	62	59	61
F_{cy}, ksi:							
L	61	65	65	65	67	65	67
LT	62	66	66	65	67	64	66
F_{su}, ksi	38	40	41	41	42	40	41
F_{bru}[b], ksi:							
(e/D = 1.5)	103	107	109	109	110	109	110
(e/D = 2.0)	131	137	139	139	141	139	141
F_{bry}[b], ksi:							
(e/D = 1.5)	82	88	88	88	90	88	90
(e/D = 2.0)	98	104	104	104	107	104	107
e, percent (S-basis):							
L	7	...	7	7	...	7	...
E, 10^3 ksi	10.4						
E_c, 10^3 ksi	10.7						
G, 10^3 ksi	4.0						
μ	0.33						
Physical Properties:							
ω, lb/in.^{3}	0.101						
C, K, and α	See Figure 3.7.6.0						

a The mechanical properties are to be based upon the thickness at the time of quench.
b Bearing values are "dry pin" values per Section 1.4.7.1.

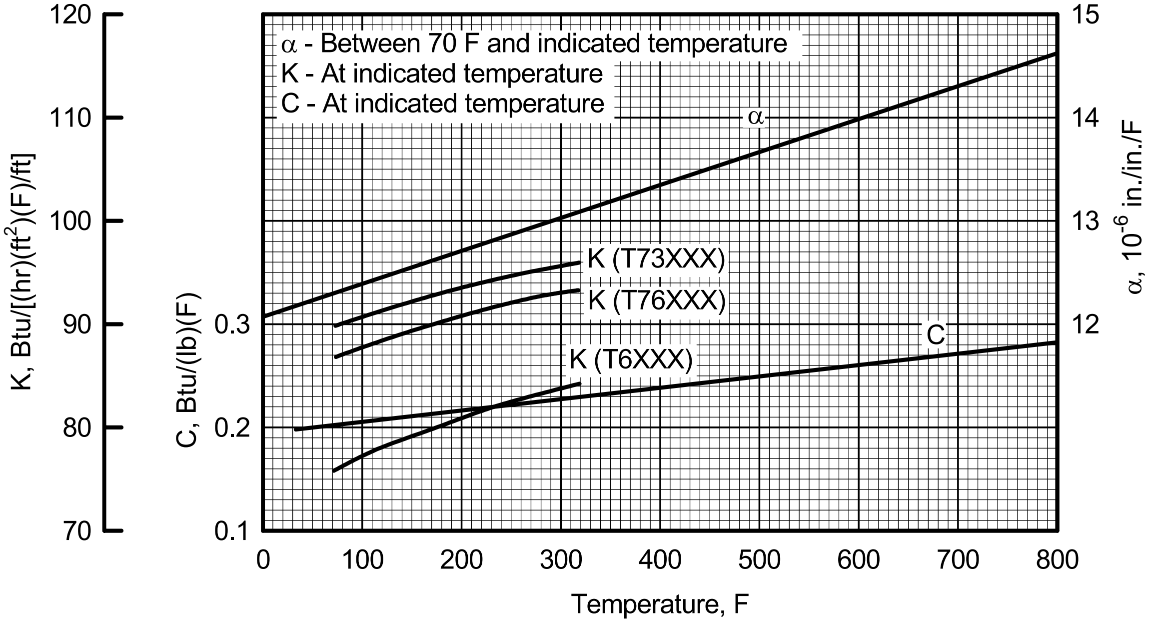


Figure 3.7.6.0. Effect of temperature on the physical properties of 7075 aluminum alloy.

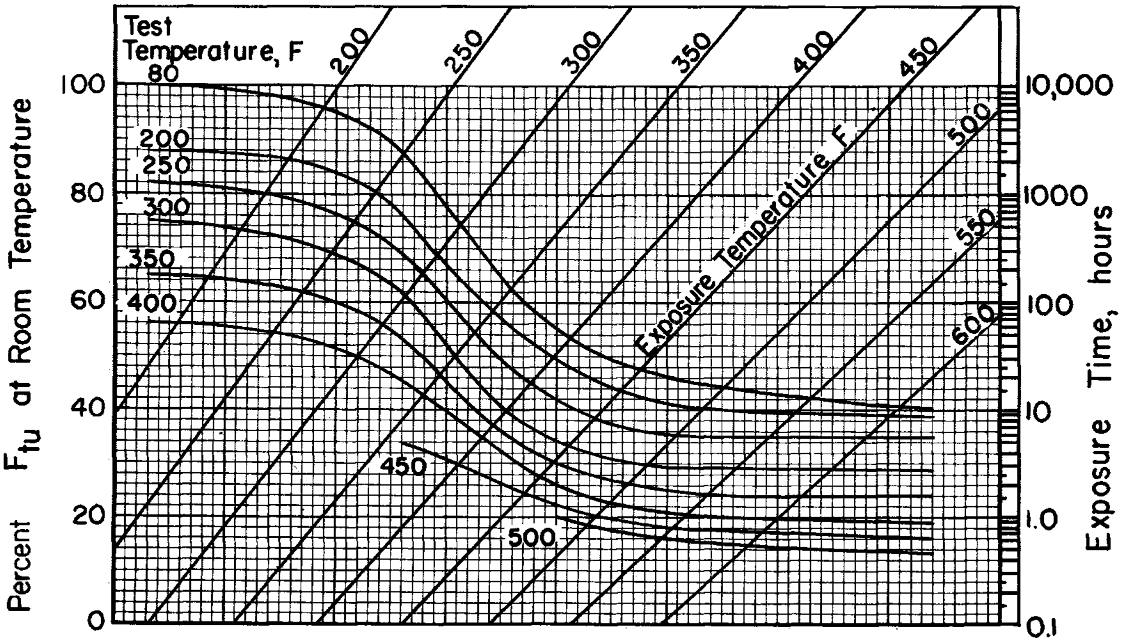


Figure 3.7.6.1.1(a). Effect of temperature on the tensile ultimate strength (F_{tu}) of 7075-T6, T651, T6510, and T6511 aluminum alloy (all products). Note: Instructions for use of these curves are presented in Section 3.7.6.1.

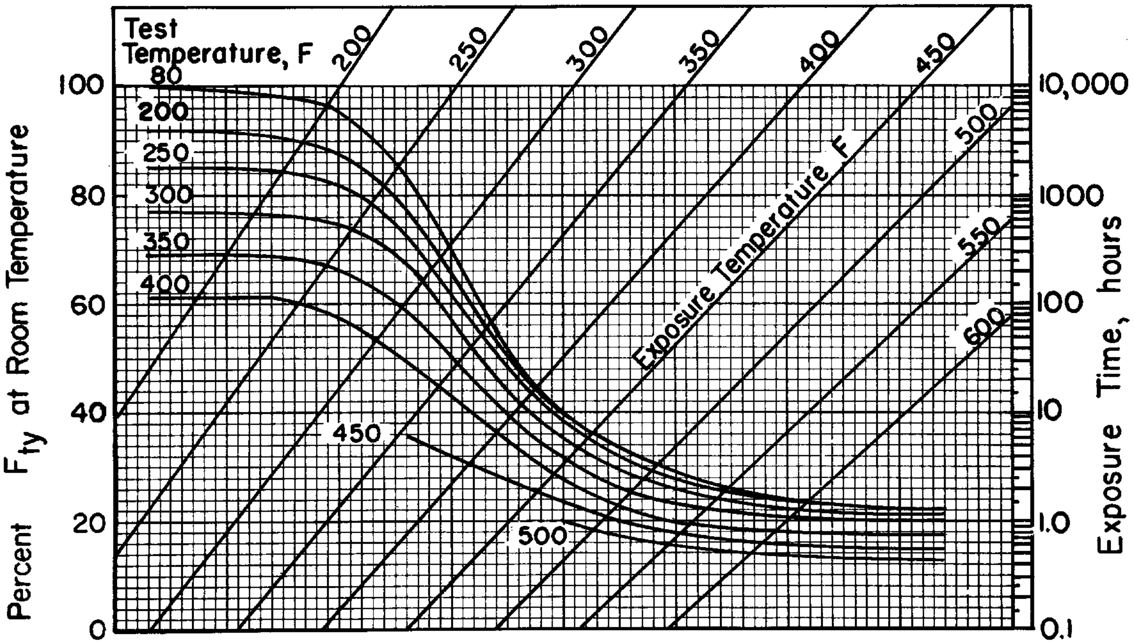


Figure 3.7.6.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of 7075-T6, T651, T6510, and T6511 aluminum alloy (all products). Note: Instructions for use of these curves are presented in Section 3.7.6.1.

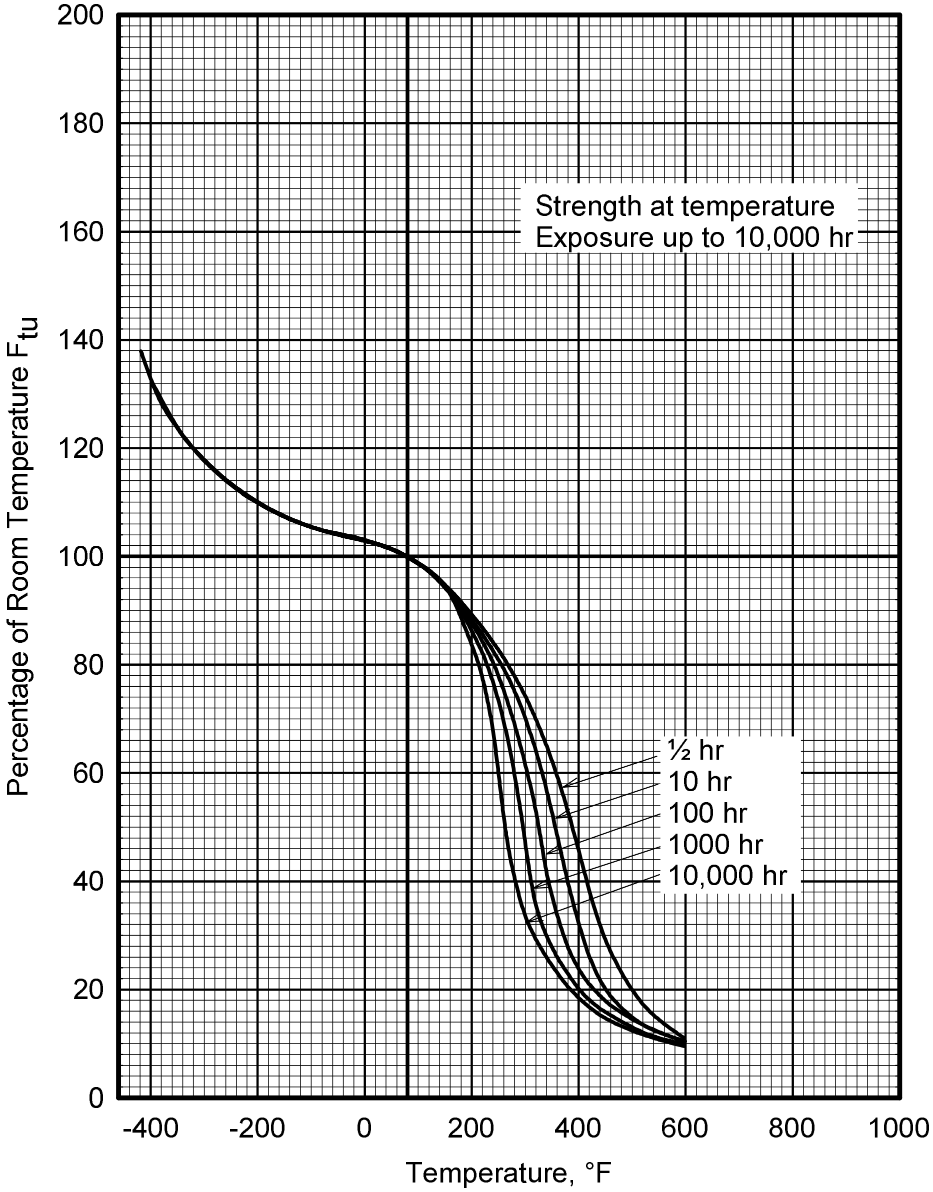


Figure 3.7.6.1.1(c). Effect of temperature on the tensile ultimate strength (F_{tu}) of 7075-T6, T651, T6510, and T6511 aluminum alloy (all products).

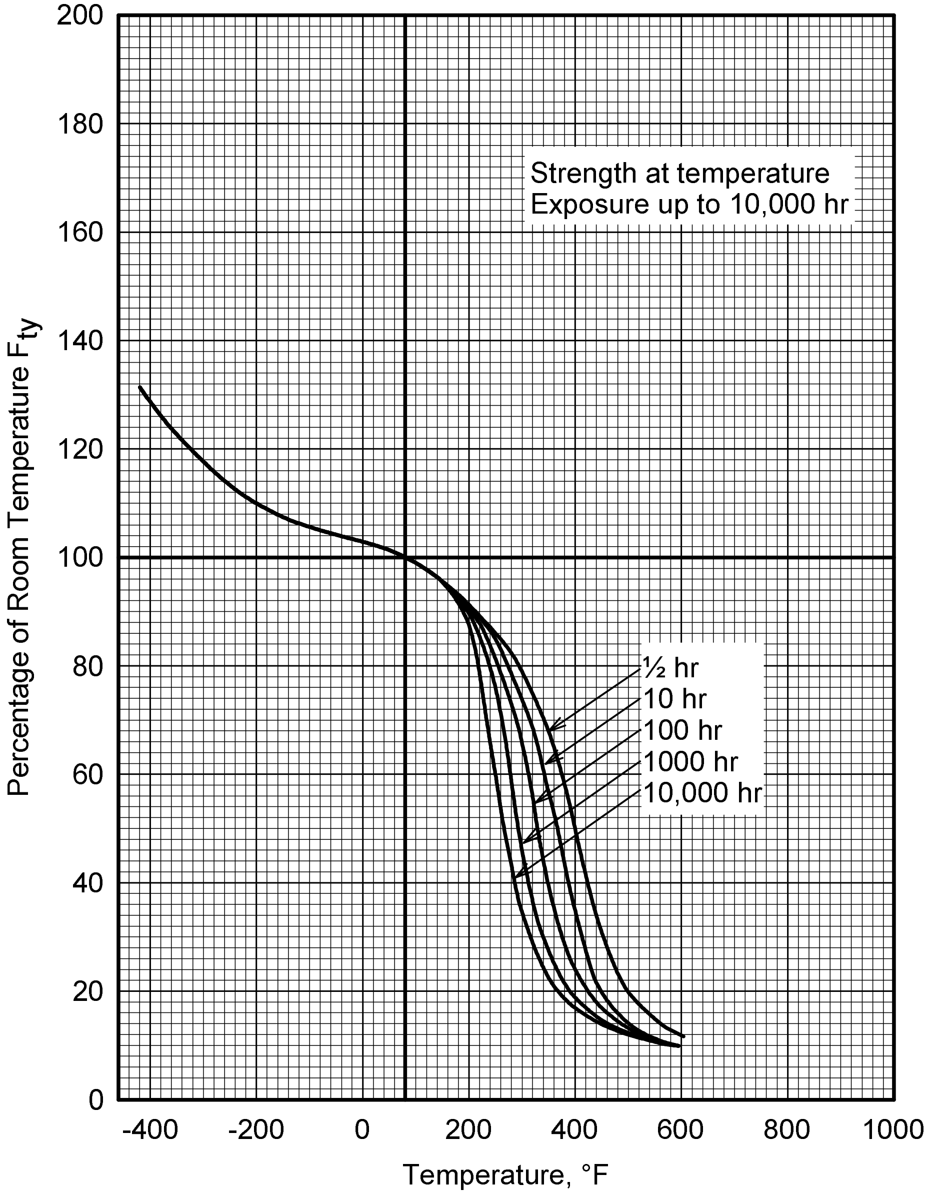


Figure 3.7.6.1.1(d). Effect of temperature on the tensile yield strength (F_{ty}) of 7075-T6, T651, T6510, and T6511 aluminum alloy (all products).

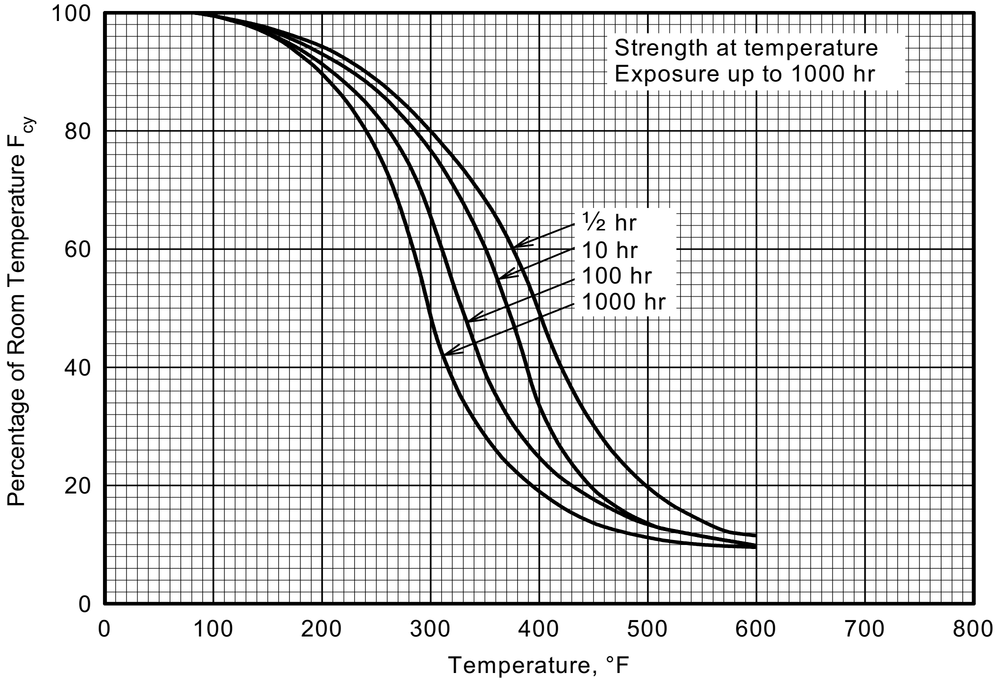


Figure 3.7.6.1.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of 7075-T6, T651, T6510, and T6511 aluminum alloy (all products).

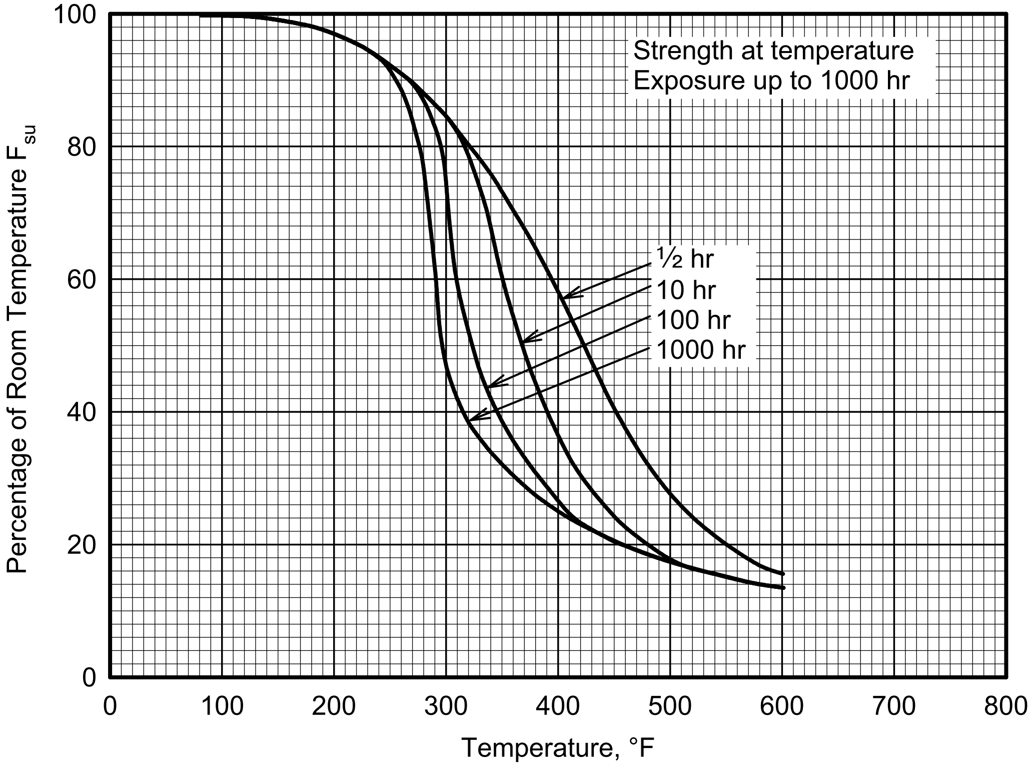


Figure 3.7.6.1.2(b). Effect of temperature on the shear ultimate strength (F_{su}) of 7075-T6, T651, T6510, and T6511 aluminum alloy (all products).

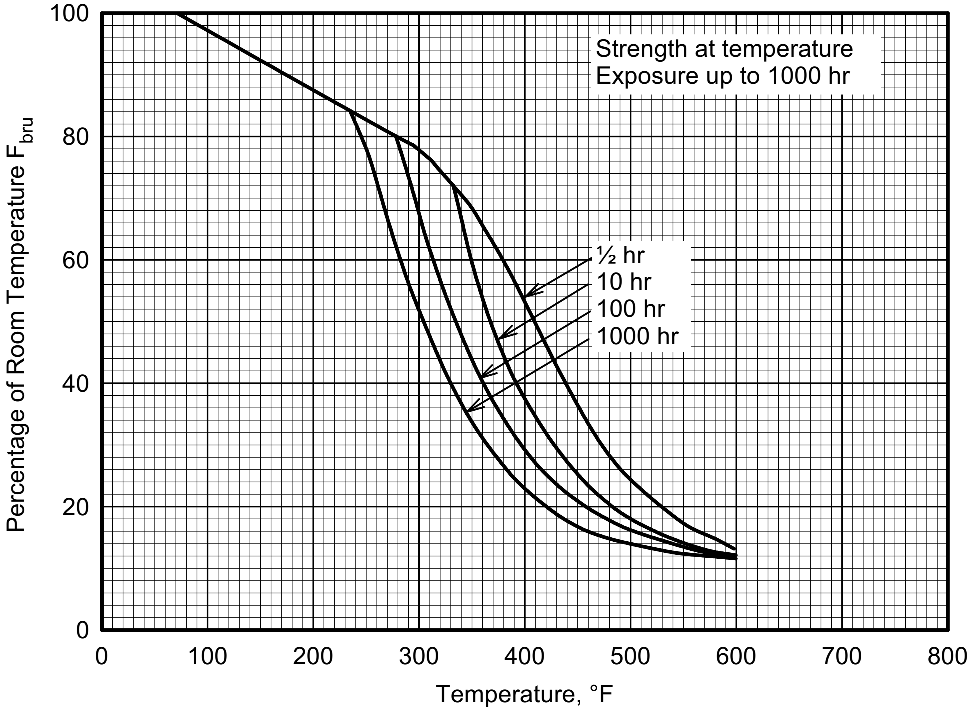


Figure 3.7.6.1.3(a). Effect of temperature on the bearing ultimate strength (F_{bru}) of 7075-T6, T651, T6510, and T6511 aluminum alloy (all products).

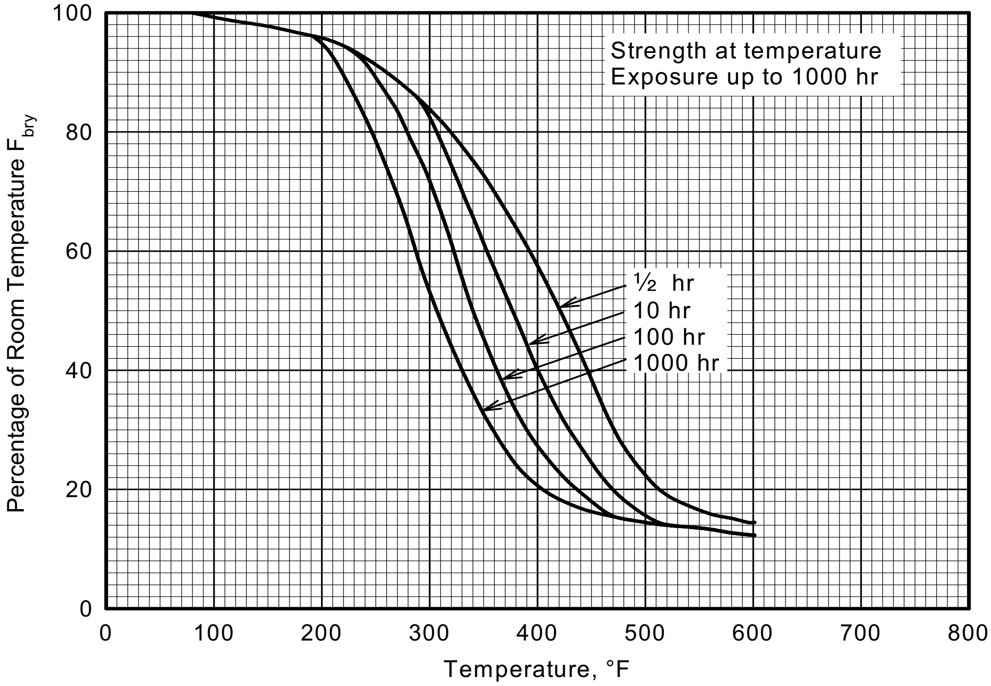


Figure 3.7.6.1.3(b). Effect of temperature on the bearing yield strength (F_{bry}) of 7075-T6, T651, T6510, and T6511 aluminum alloy (all products).

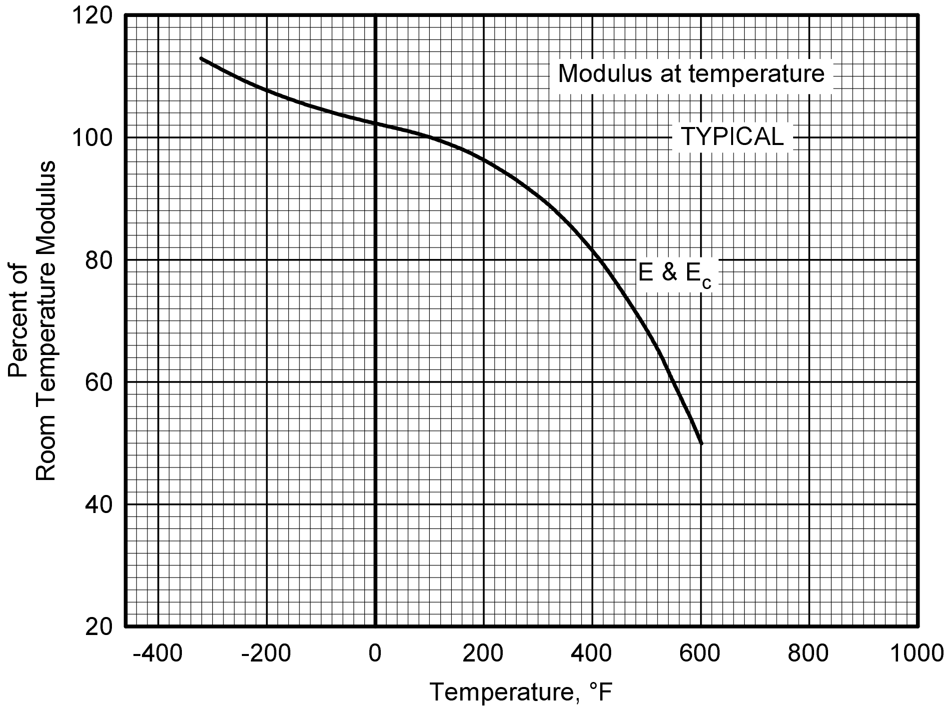


Figure 3.7.6.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of 7075 aluminum alloy.

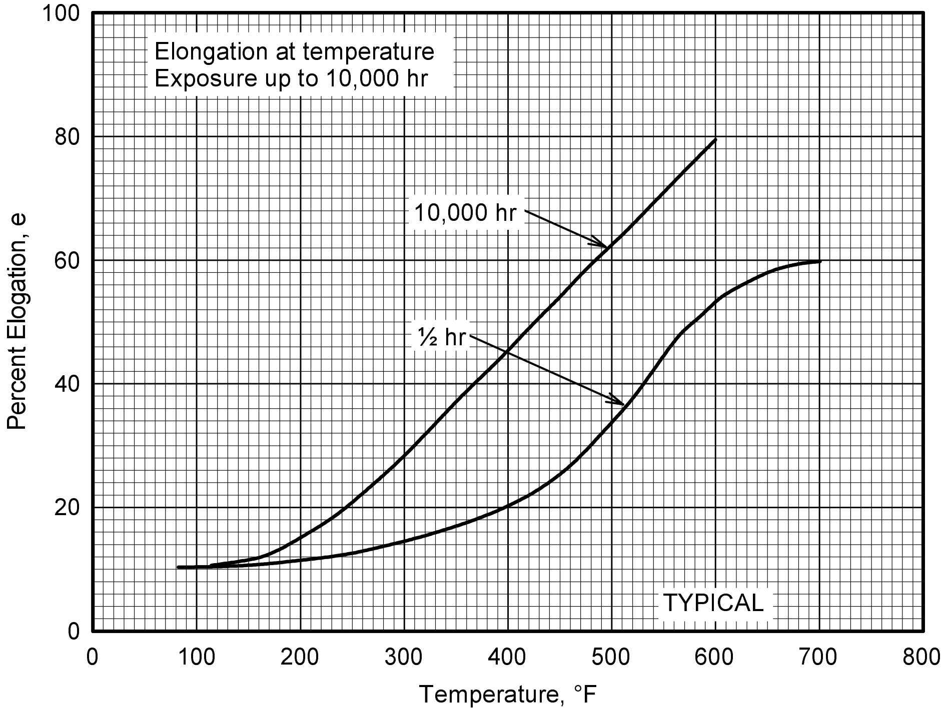


Figure 3.7.6.1.5(a). Effect of temperature on the elongation of 7075-T6, T651, T6510, and T6511 aluminum alloy (all products except thick extrusions).

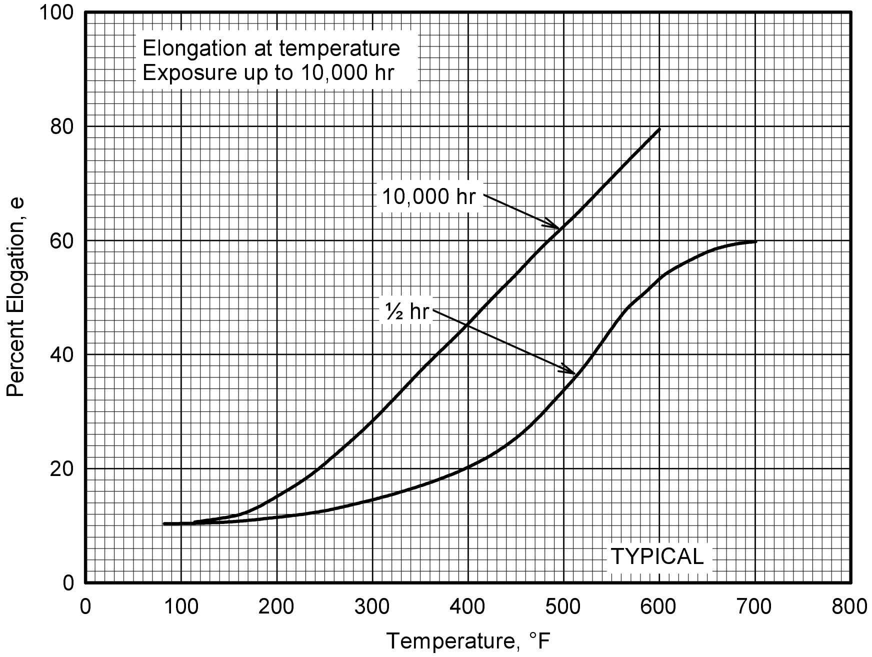


Figure 3.7.6.1.5(b). Effect of exposure at elevated temperatures on the elongation of 7075-T6, T651, T6510, and T6511 aluminum alloy (all products except thick extrusions).

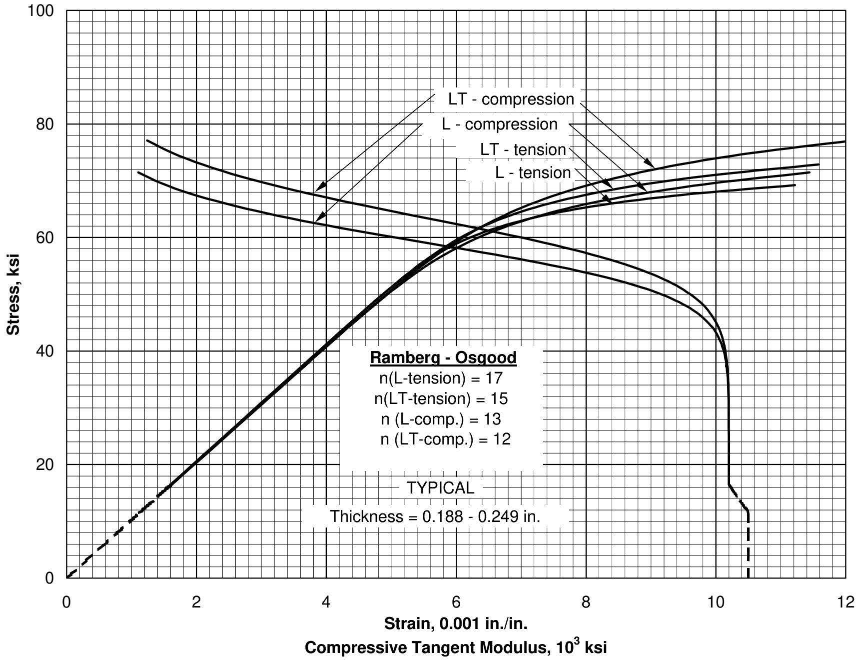


Figure 3.7.6.1.6(a). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for clad 7075-T6 aluminum alloy sheet at room temperature.

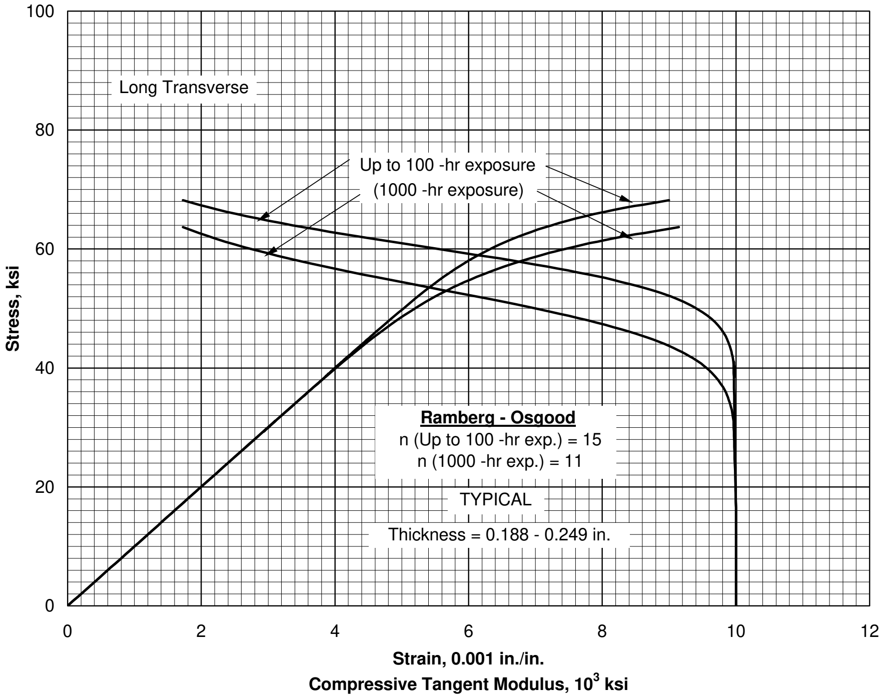


Figure 3.7.6.1.6(b). Typical compressive stress-strain and compressive tangent-modulus curves for clad 7075-T6 aluminum alloy sheet at 200°F.

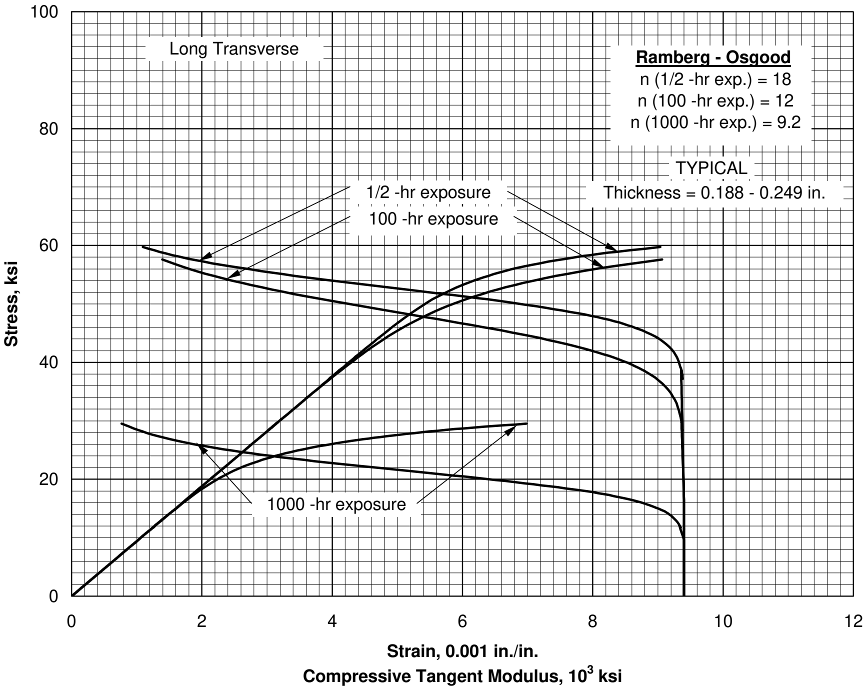


Figure 3.7.6.1.6(c). Typical compressive stress-strain and compressive tangent-modulus curves for clad 7075-T6 aluminum alloy sheet at 300°F.

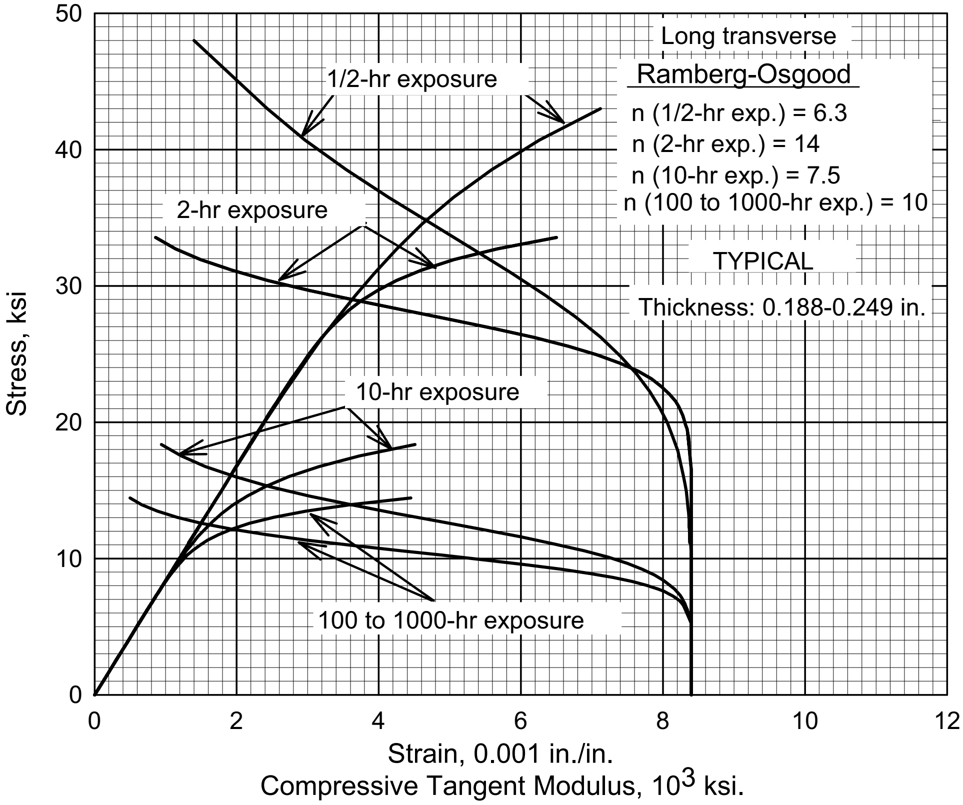


Figure 3.7.6.1.6(d). Typical compressive stress-strain and compressive tangent-modulus curves for clad 7075-T6 aluminum alloy sheet at 400°F.

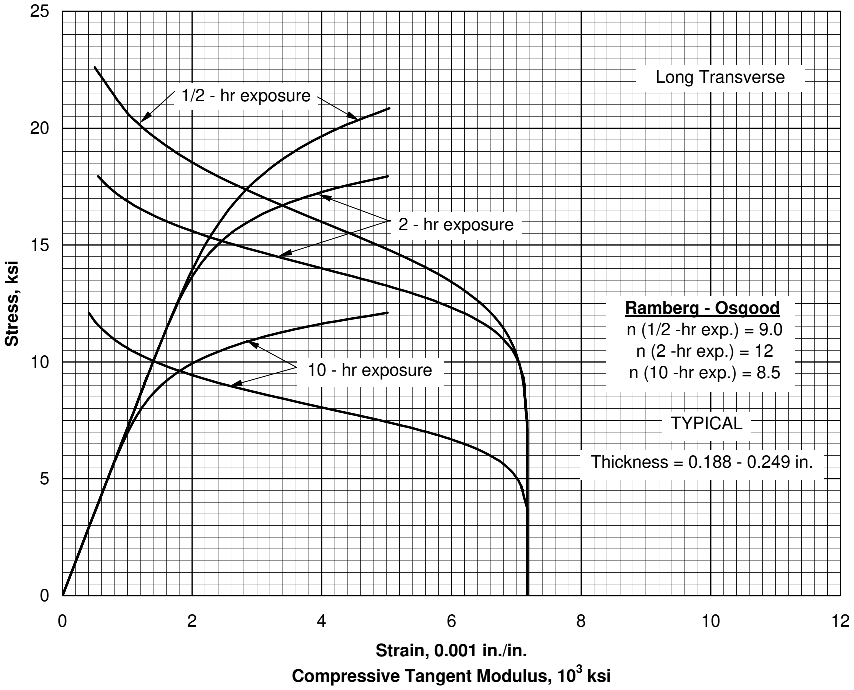


Figure 3.7.6.1.6(e). Typical compressive stress-strain and compressive tangent-modulus curves for clad 7075-T6 aluminum alloy sheet at 500°F.

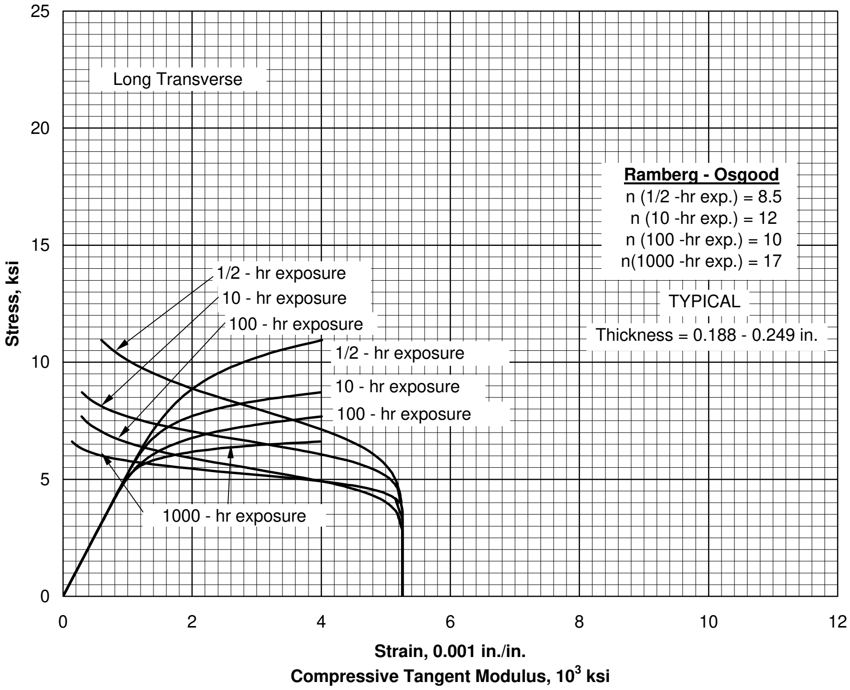


Figure 3.7.6.1.6(f). Typical compressive stress-strain and compressive tangent-modulus curves for clad 7075-T6 aluminum alloy sheet at 600°F.

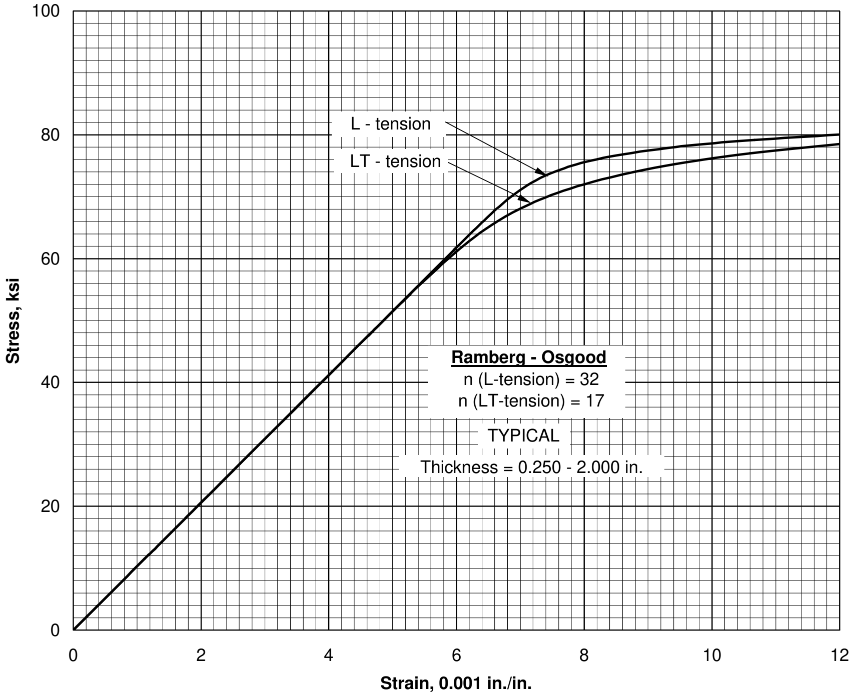


Figure 3.7.6.1.6(g). Typical tensile stress-strain curves for 7075-T651 aluminum alloy plate at room temperature.

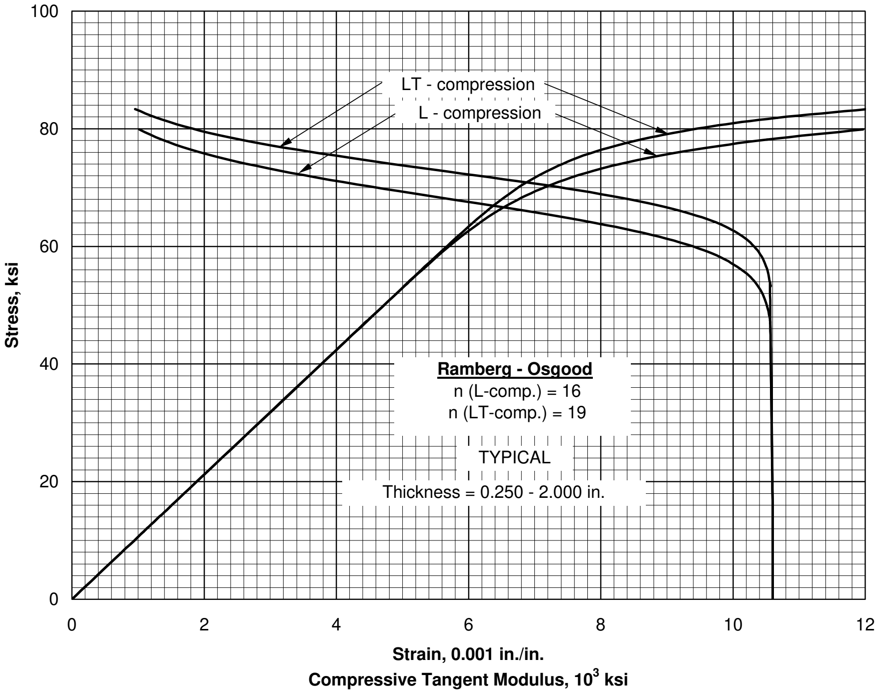


Figure 3.7.6.1.6(h). Typical compressive stress-strain and compressive tangent-modulus curves for 7075-T651 aluminum alloy plate at room temperature.

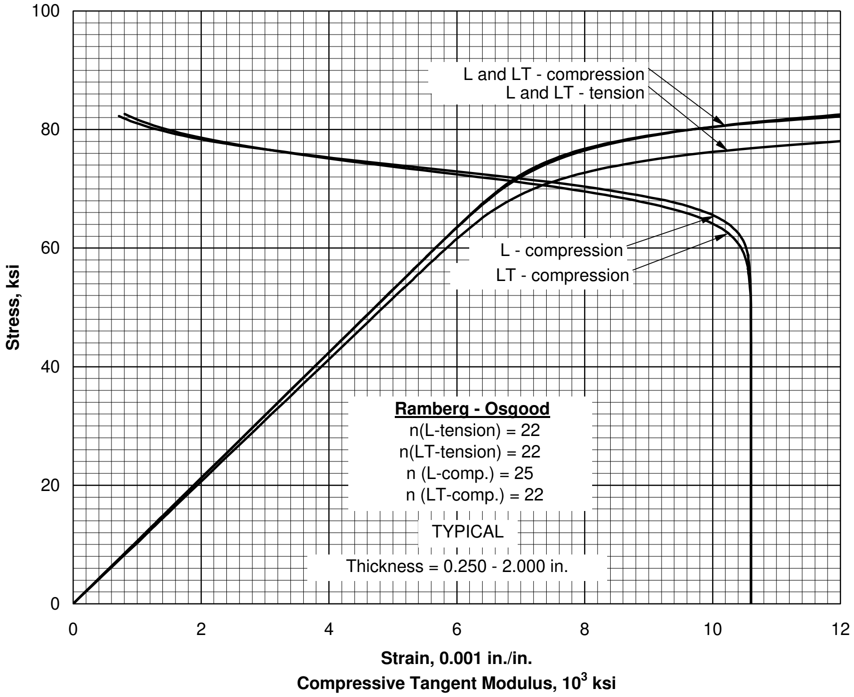


Figure 3.7.6.1.6(i). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 7075-T62 aluminum alloy plate at room temperature.

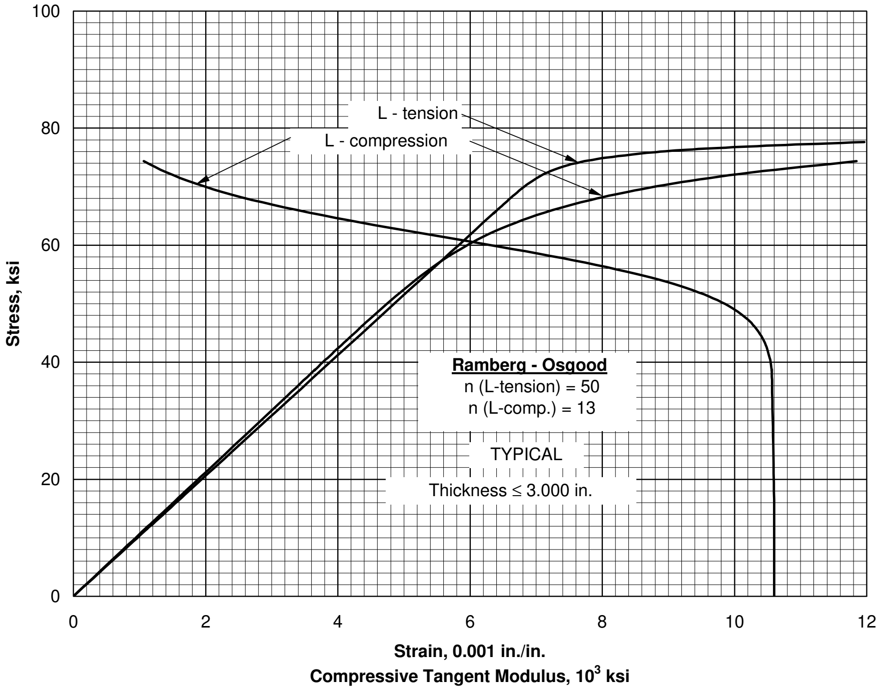


Figure 3.7.6.1.6(j). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 7075-T6 and T651 aluminum alloy rolled-bar, rod, and shape at room temperature.

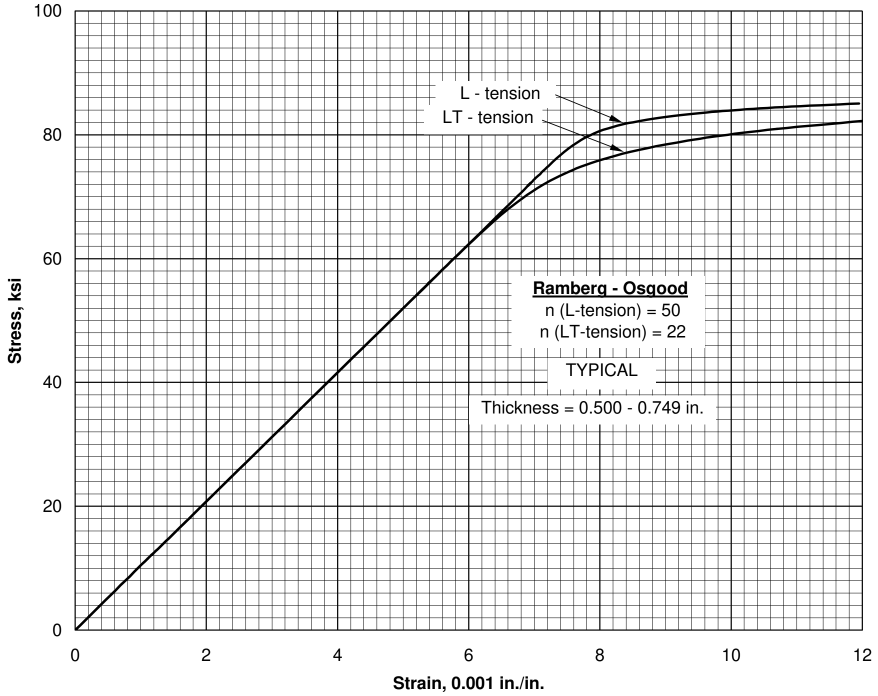


Figure 3.7.6.1.6(k). Typical tensile stress-strain curves for 7075-T651X aluminum alloy extrusion at room temperature.

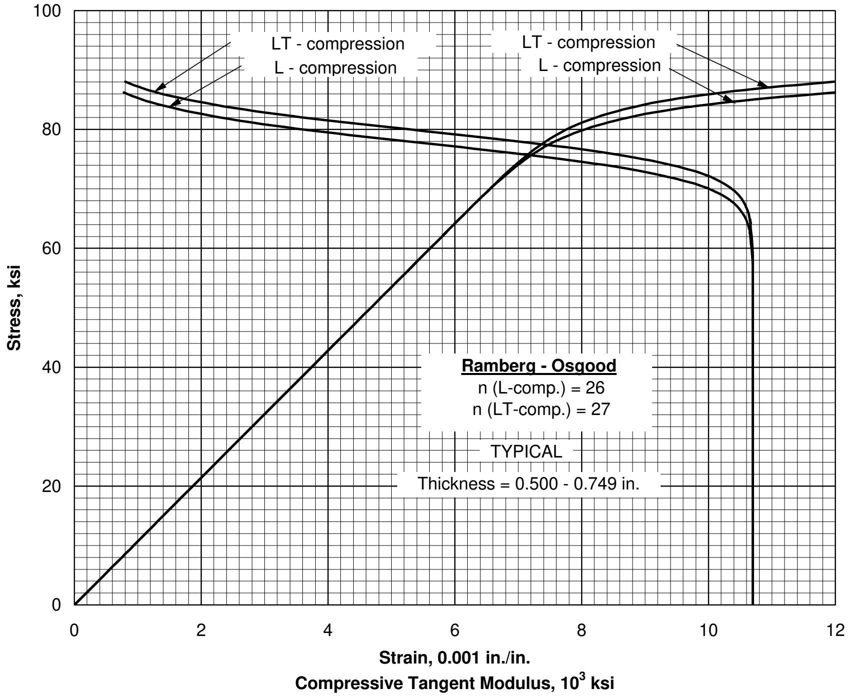


Figure 3.7.6.1.6(l). Typical compressive stress-strain and compressive tangent-modulus curve for 7075-T651X aluminum alloy extrusion at room temperature.

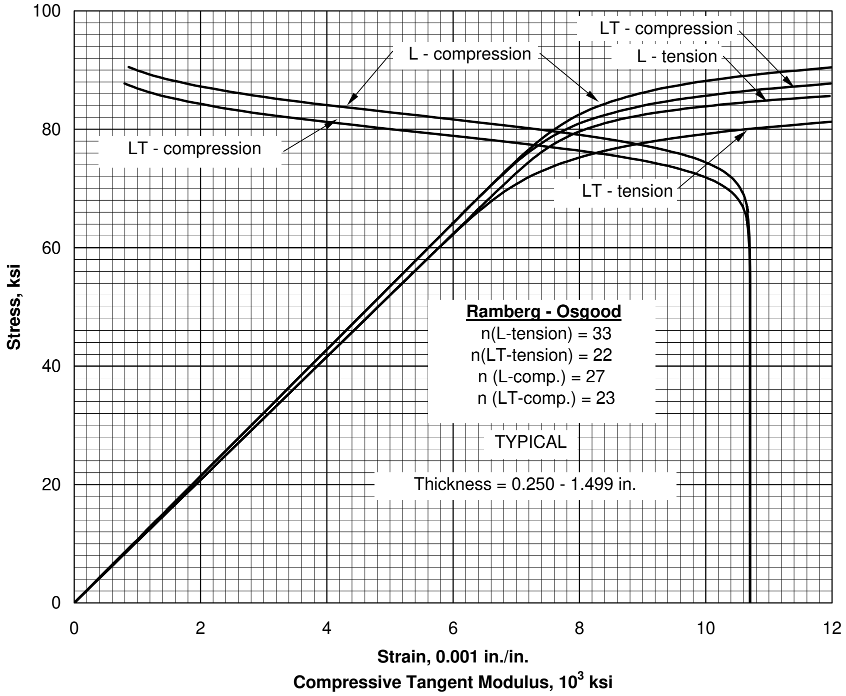


Figure 3.7.6.1.6(m). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 7075-T62 aluminum alloy extrusion at room temperature.

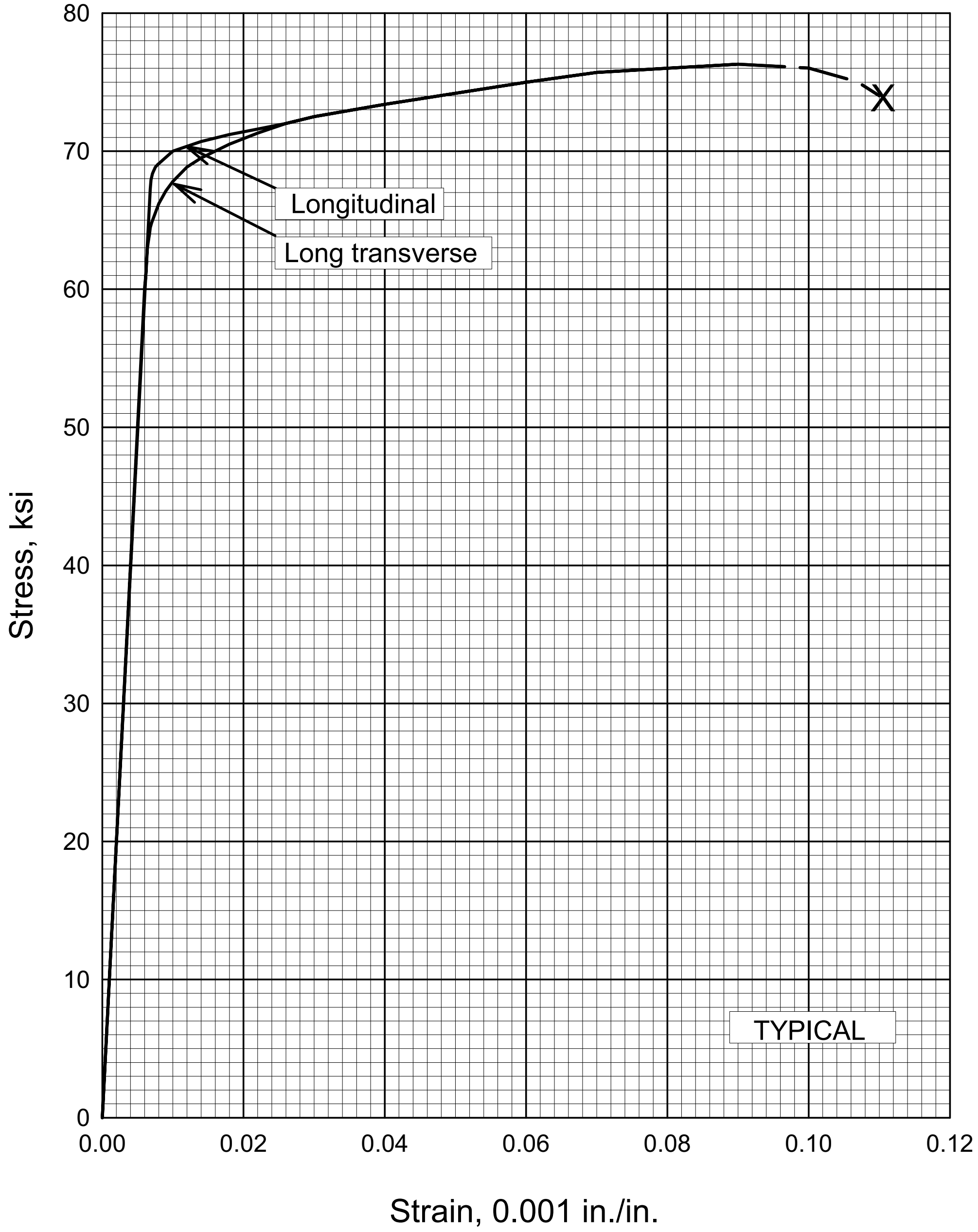


Figure 3.7.6.1.6(n). Typical tensile stress-strain curve (full range) for clad 7075-T6 aluminum alloy sheet at room temperature.

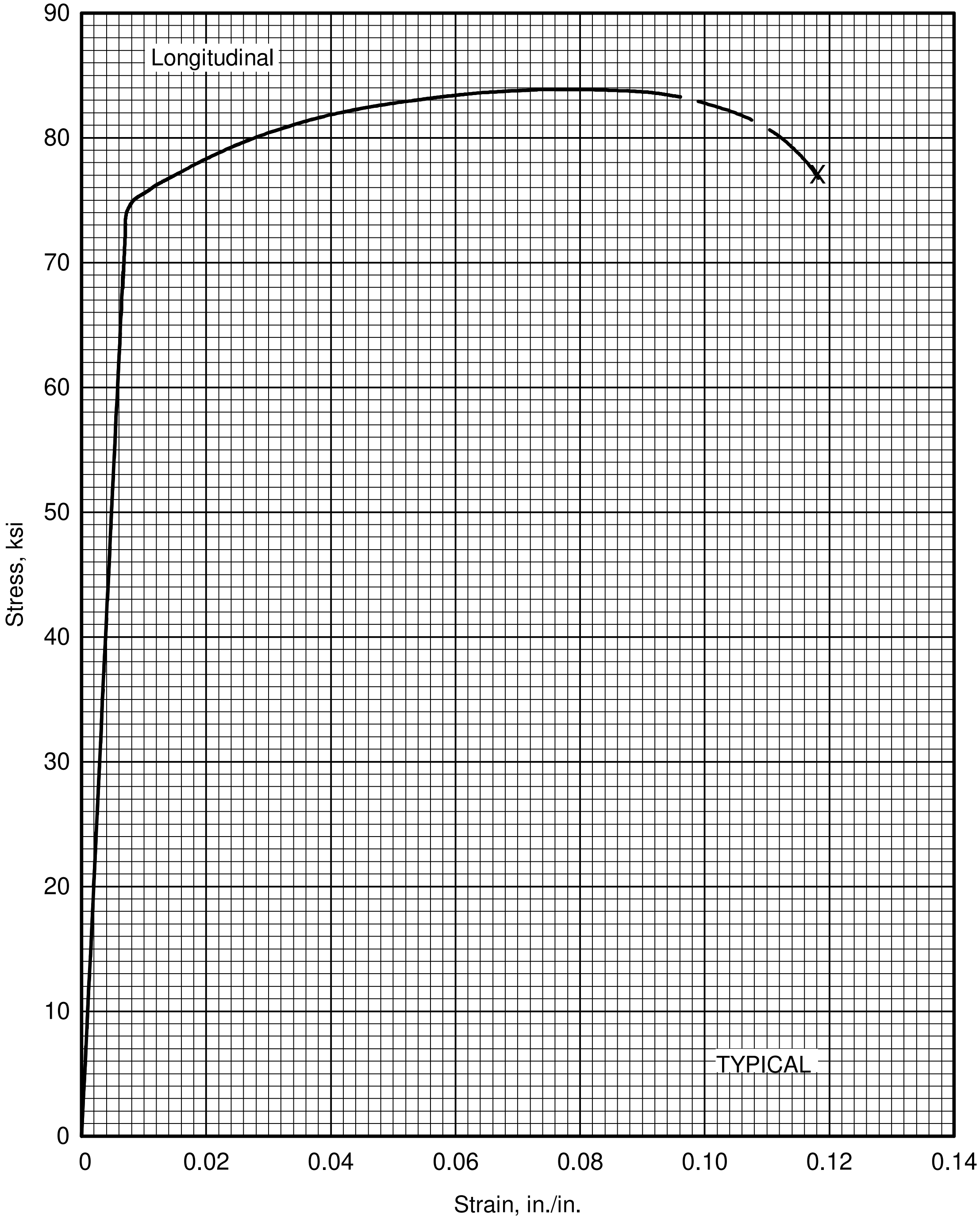


Figure 3.7.6.1.6(o). Typical tensile stress-strain curve (full range) for 7075-T6 and T651 aluminum alloy rolled or cold-finished bar at room temperature.

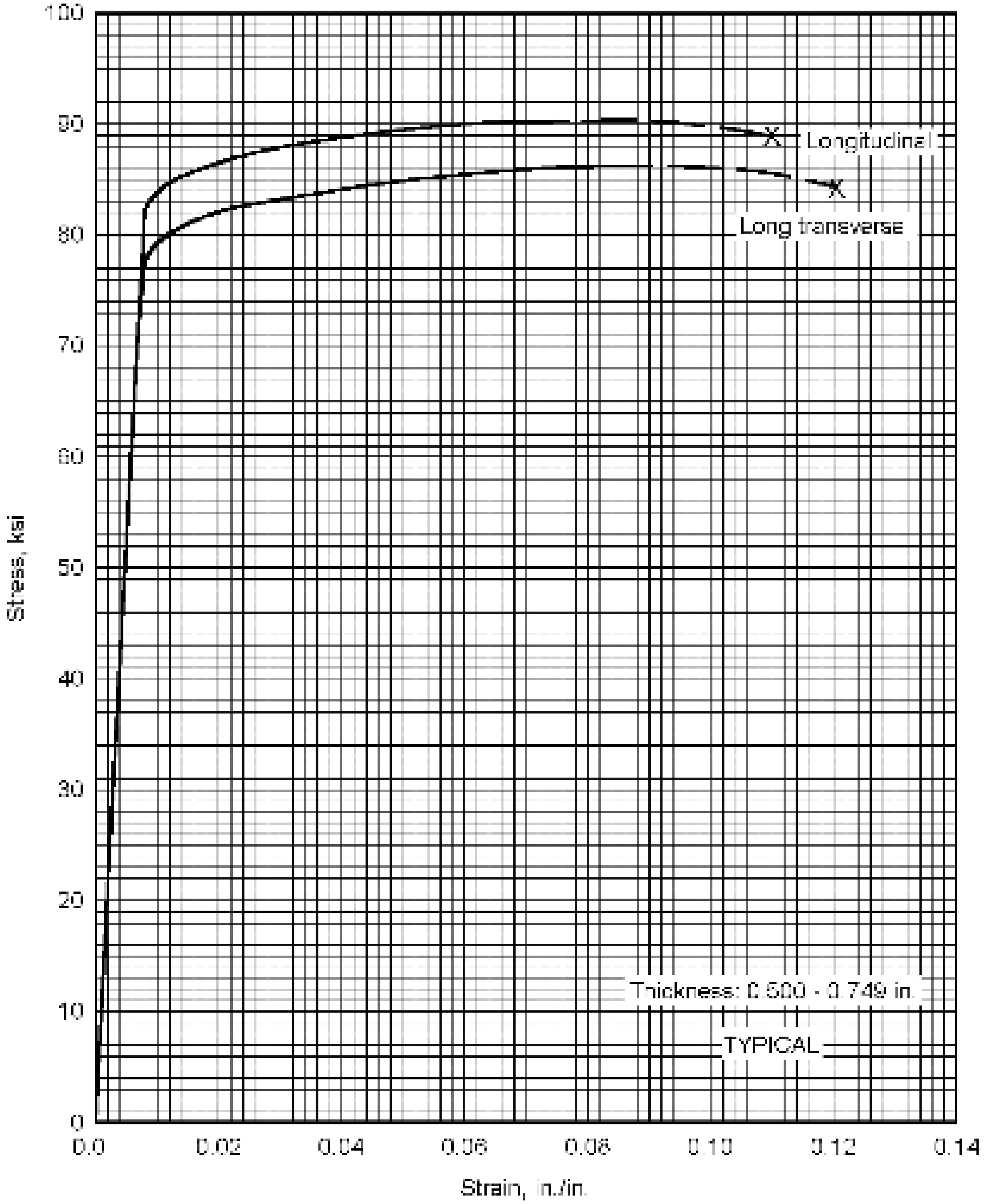


Figure 3.7.6.1.6(p). Typical tensile stress-strain curves (full range) for 7075-T651X aluminum alloy extrusion at room temperature.

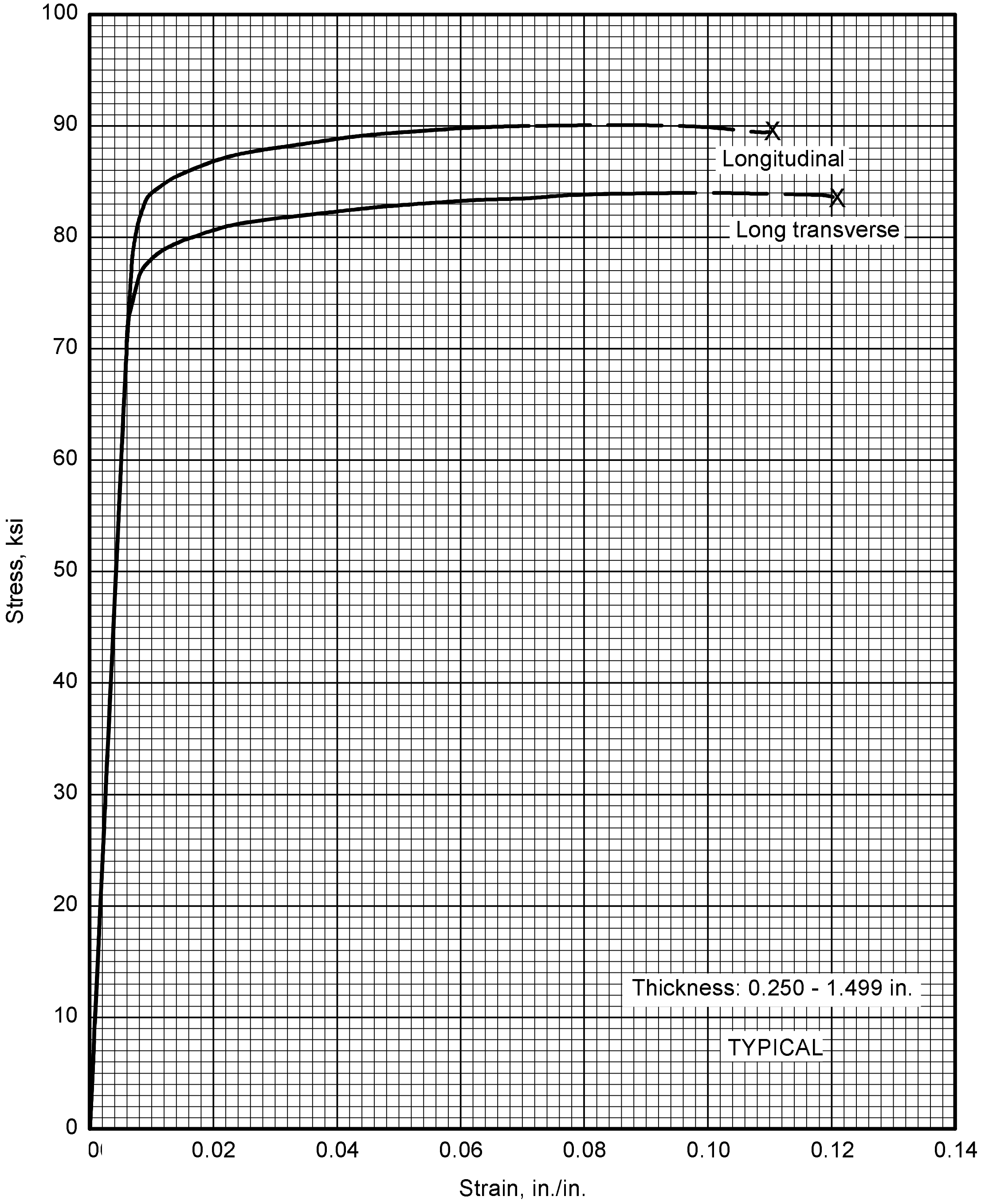


Figure 3.7.6.1.6(q). Typical tensile stress-strain curves (full range) for 7075-T62 aluminum alloy extrusion at room temperature.

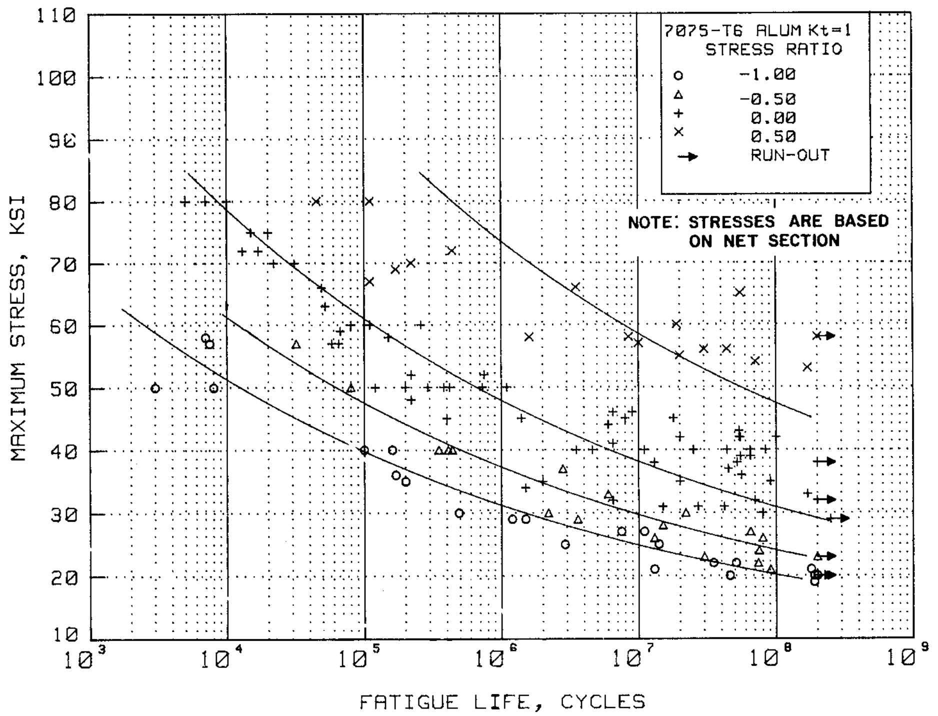


Figure 3.7.6.1.8(a). Best-fit S/N curves for unnotched 7075-T6 aluminum alloy, various product forms, longitudinal direction.

Correlative Information for Figure 3.7.6.1.8(a)

Product Form: 0.75 inch diam. drawn rod, 1.25 inch diam. rolled rod, and 1 x 7.5 inch bar, extruded 1.25 inch bar and 1.25 inch rod

Properties:

TUS, ksi	TYS, ksi	Temp., °F
82	72	RT

Specimen Details: Unnotched
Minimum diameter 0.200 inch

Surface Condition: Unspecified

Reference: 3.7.6.1.8

Test Parameters:
Loading - Axial
Frequency - 30 Hz
Temperature - RT
Environment - Air

No. of Heats/Lots: 8

Equivalent Stress Equation:
$\log N_f = 18.22 - 7.77 \log (S_{eq} - 10.15)$
$S_{eq} = S_{max} (1-R)^{0.62}$
Std. Error of Estimate, Log (Life) = 0.626
Standard Deviation, Log (Life) = 1.435
$R^2 = 81\%$

Sample Size = 130

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

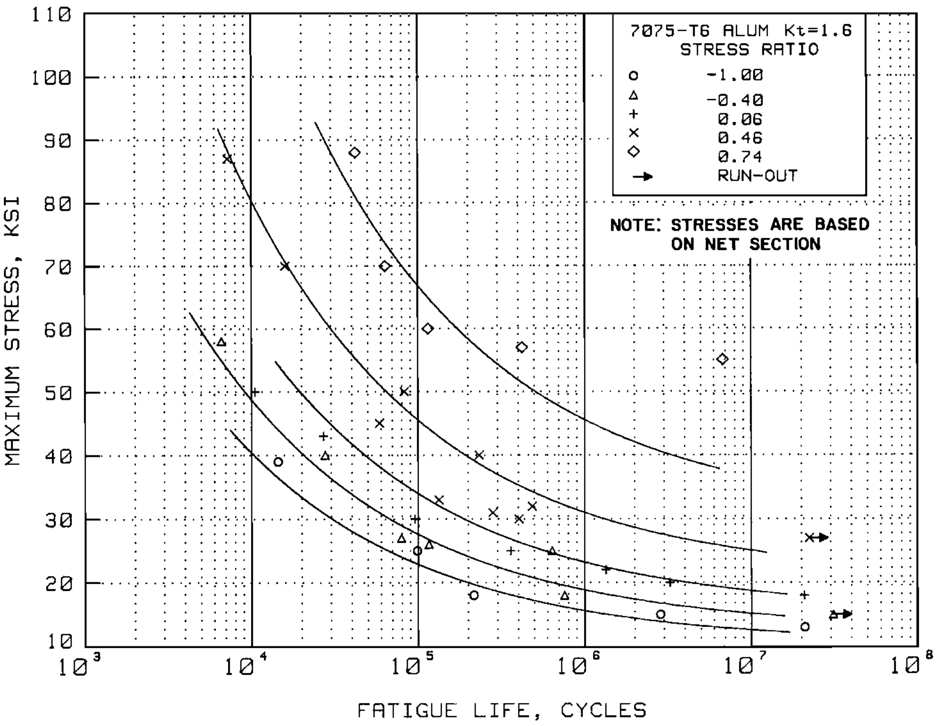


Figure 3.7.6.1.8(b). Best-fit S/N curve for notched, K_t = 1.6, 7075-T6 aluminum alloy rolled bar, longitudinal direction.

Correlative Information for Figure 3.7.6.1.8(b)

Product Form: 1.125 inch diam. rolled bar

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	99.2	—	RT

Specimen Details: Notched, K_t = 1.6
Notch-root-radius = 0.100
Test section diameter (Net) = 0.400 inches
Gross diameter = 0.450 inch
60° groove

Surface Condition: Polished to 10 micro-inches

Reference: 3.2.1.1.8(b)

Test Parameters:
Loading - Axial
Frequency - 60 Hz
Temperature - RT
Atmosphere - Air

No. of Heats/Lots: 1

Equivalent Stress Equation:
$\text{Log } N_f = 8.26 - 2.62 \log (S_{eq} - 15.3)$
$S_{eq} = S_{max} (1-R)^{0.525}$
Std. Error of Estimate, Log (Life) = 0.418
Standard Deviation, Log (Life) = 0.985
$R^2 = 82\%$

Sample Size = 34

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

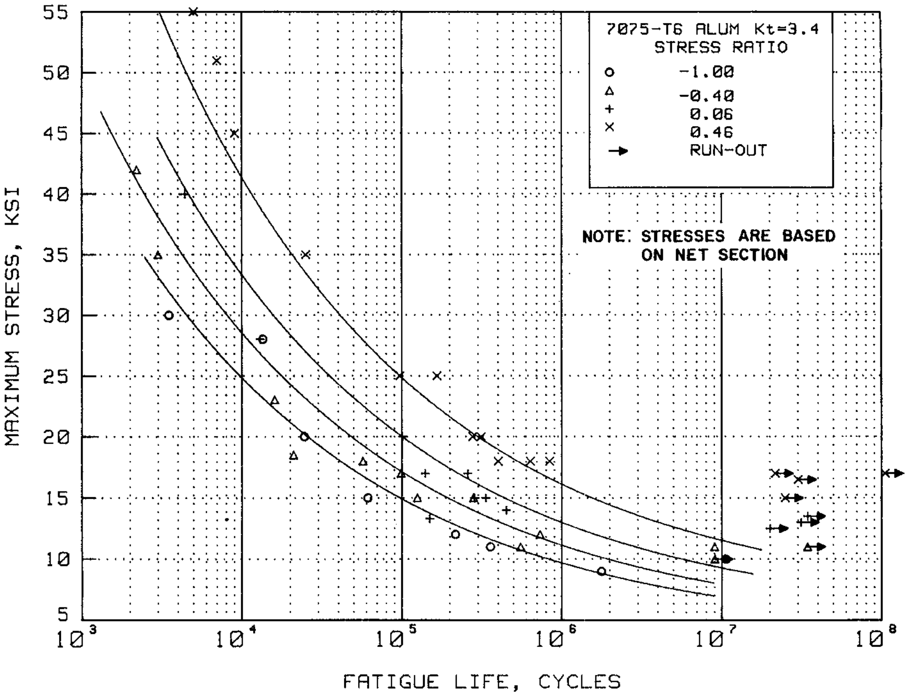


Figure 3.7.6.1.8(c). Best-fit S/N curves for notched, K_t = 3.4, 7075-T6 aluminum alloy rolled bar, longitudinal direction.

Correlative Information for Figure 3.7.6.1.8(c)

Product Form: 1.125 inch diam. rolled bar

Properties:

TUS, ksi	TYS, ksi	Temp., °F
96.5	—	RT

Specimen Details: Notched, K_t = 3.4
Notch-root-radius = 0.010
Test section diameter (Net) = 0.400 inch
Gross diameter = 0.450 inch
60° groove

Surface Condition: Polished to 10 micro-inches

Reference: 3.2.1.1.8(b)

Test Parameters:
Loading - Axial
Frequency - 60 Hz
Temperature - RT
Atmosphere - Air

No. of Heats/Lots: 1

Equivalent Stress Equation:
$\text{Log } N_f = 9.19 - 3.646 \log (S_{eq} - 5.36)$
$S_{eq} = S_{max} (1-R)^{0.386}$
Std. Error of Estimate, Log (Life) = 0.282
Standard Deviation, Log (Life) = 0.782
R^2 = 87%

Sample Size = 48

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

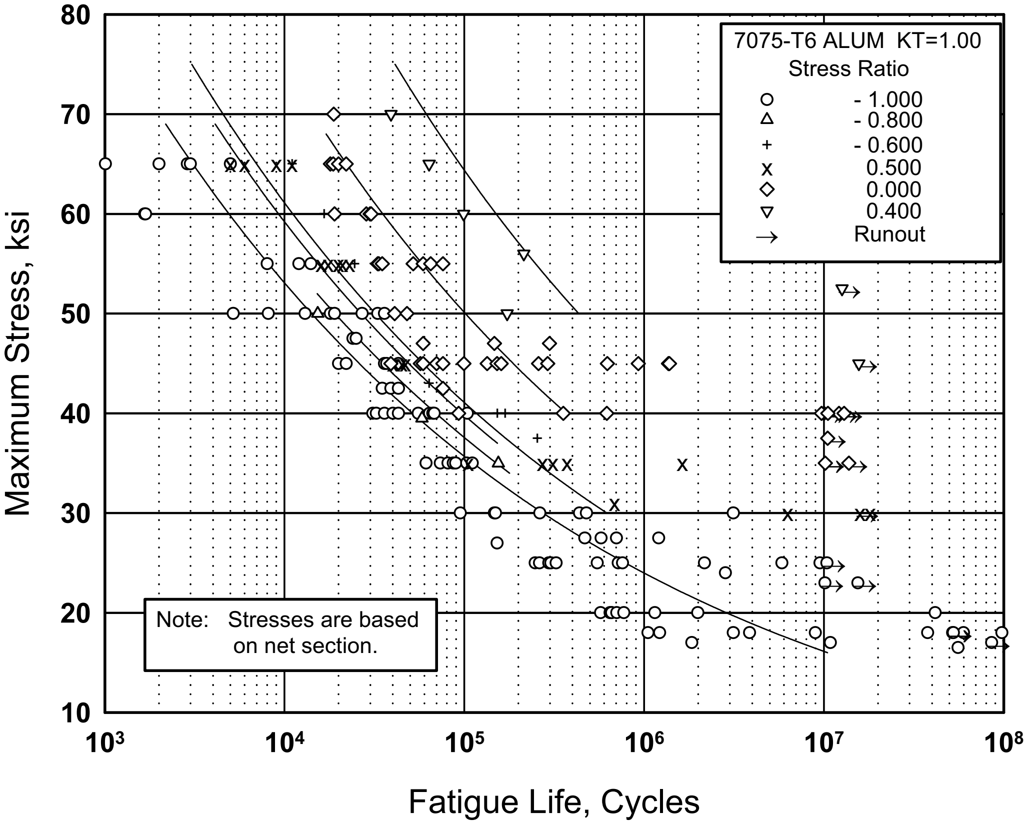


Figure 3.7.6.1.8(d). Best-fit S/N curves for unnotched 7075-T6 aluminum alloy sheet, longitudinal direction.

Correlative Information for Figure 3.7.6.1.8(d)

Product Form: Bare sheet, 0.090 inch

Properties:	TUS, ksi	TYS, ksi	Temp.,°F
	82	76	RT

Specimen Details: Unnotched
0.5 to 1.0 inch width

Surface Condition: Electropolished
150 grit emery paper

References: 3.2.3.1.8(a) and (f)

Test Parameters:
Loading - Axial
Frequency - 300 to 1800 cpm
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
$\text{Log } N_f = 14.86\text{-}5.80 \log (S_{eq})$
$S_{eq} = S_{max} (1\text{-}R)^{0.49}$
Std. Error of Estimate, Log (Life) = 0.41
Standard Deviation, Log (Life) = 0.92
$R^2 = 80\%$

Sample Size = 176

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

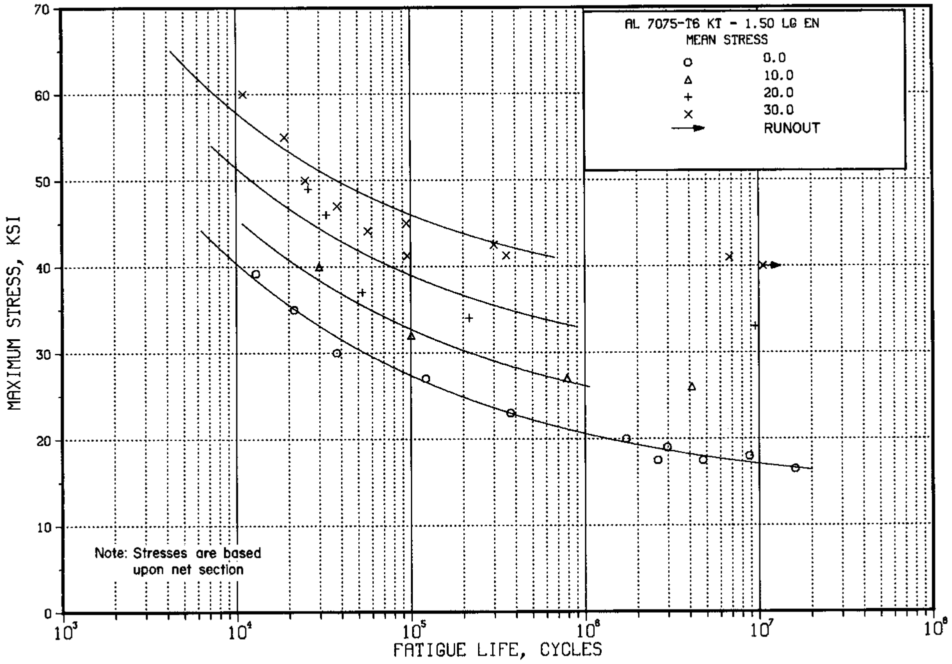


Figure 3.7.6.1.8(e). Best-fit S/N curves for notched, K_t = 1.5, 7075-T6 aluminum alloy sheet, longitudinal direction.

Correlative Information for Figure 3.7.6.1.8(e)

Product Form: Bare sheet, 0.090 inch

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	82	76	RT (unnotched)
	87	—	RT (notched)

Specimen Details: Edge Notched
3.000 inches gross width
1.500 inches net width
0.760 inch notch radius
60° flank angle

Surface Condition: Electropolished

Reference: 3.2.3.1.8(d)

Test Parameters:
Loading - Axial
Frequency - 1100 to 1500 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
$\text{Log } N_f = 9.54-3.52 \log (S_{eq}-18.7)$
$S_{eq} = S_{max} (1-R)^{0.49}$
Std. Error of Estimate, Log (Life) = 0.41
Standard Deviation, Log (Life) = 1.00
$R^2 = 83\%$

Sample Size = 30

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

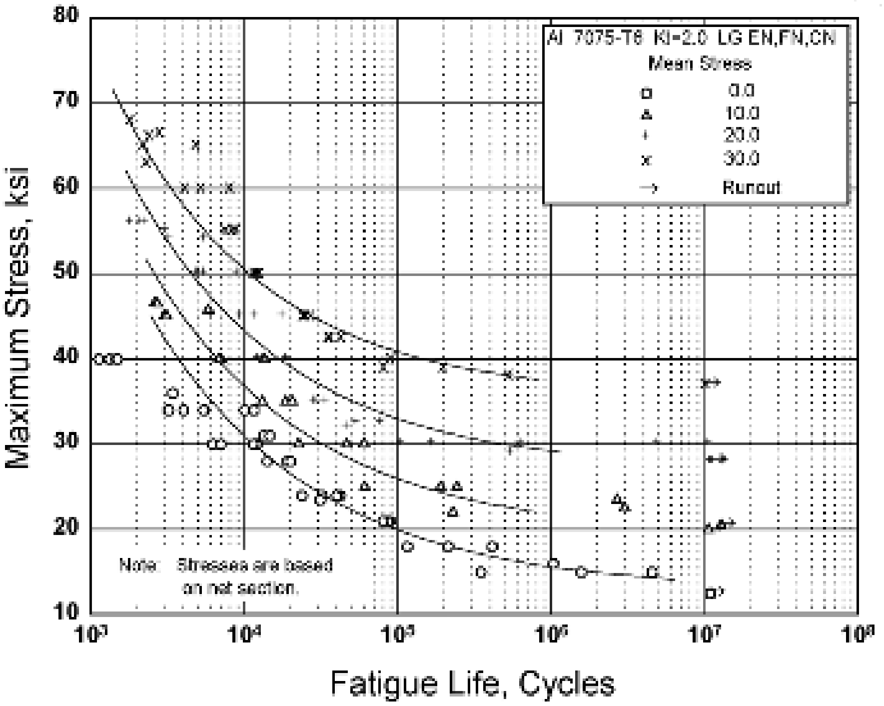


Figure 3.7.6.1.8(f). Best-fit S/N curves for notched, K_t = 2.0, 7075-T6 aluminum alloy sheet, longitudinal direction.

Correlative Information for Figure 3.7.6.1.8(f)

Product Form: Bare sheet, 0.090 inch

Properties:

TUS, ksi	TYS, ksi	Temp., °F
82	76	RT (unnotched)
88	—	RT (notched)

Specimen Details: Notched

Notch Type	Gross Width	Net Width	Notch Radius
Center	4.50	1.50	1.50
Edge	2.25	1.50	0.3175
Fillet	2.25	1.50	0.1736

Surface Condition: Electropolished

References: 3.2.3.1.8(b) and (f)

Test Parameters:
Loading - Axial
Frequency - 1100 to 1500 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
$\text{Log } N_f = 7.50 - 2.46 \log (S_{eq} - 18.6)$
$S_{eq} = S_{max} (1-R)^{0.54}$
Std. Error of Estimate, Log (Life) = 0.31
Standard Deviation, Log (Life) = 0.85
R^2 = 87%

Sample Size = 112

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

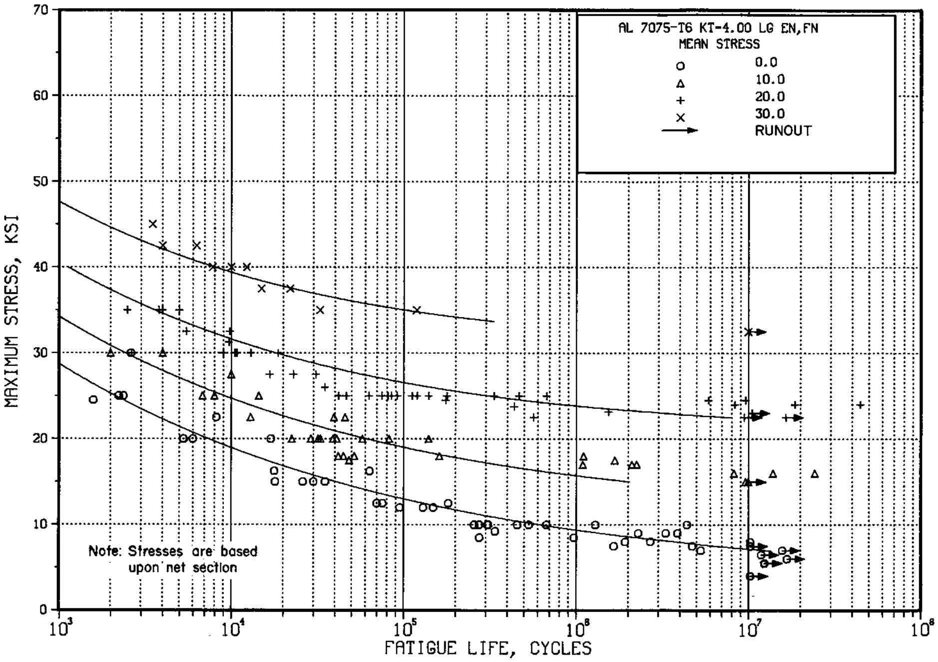


Figure 3.7.6.1.8(g). Best-fit S/N curves for notched, K_t = 4.0, 7075-T6 aluminum alloy sheet, longitudinal direction.

Correlative Information for Figure 3.7.6.1.8(g)

Product Form: Bare sheet, 0.090 inch

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	82	76	RT (unnotched)
	82	—	RT (notched)

Specimen Details: Notched

Notch Type	Gross Width	Net Width	Notch Radius
Edge	2.25	1.500	0.057
Edge	4.10	1.500	0.070
Fillet	2.25	1.500	0.0195

Surface Condition: Electropolished

References: 3.2.3.1.8(b), (f), (g), and (h)

Test Parameters:
Loading - Axial
Frequency - 1100 to 1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
$\text{Log } N_f = 10.2\text{-}4.63 \log (S_{eq}\text{-}5.3)$
$S_{eq} = S_{max} (1\text{-}R)^{0.51}$
Std. Error of Estimate, Log (Life) = 0.51
Standard Deviation, Log (Life) = 1.08
R^2 = 78%

Sample Size = 126

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

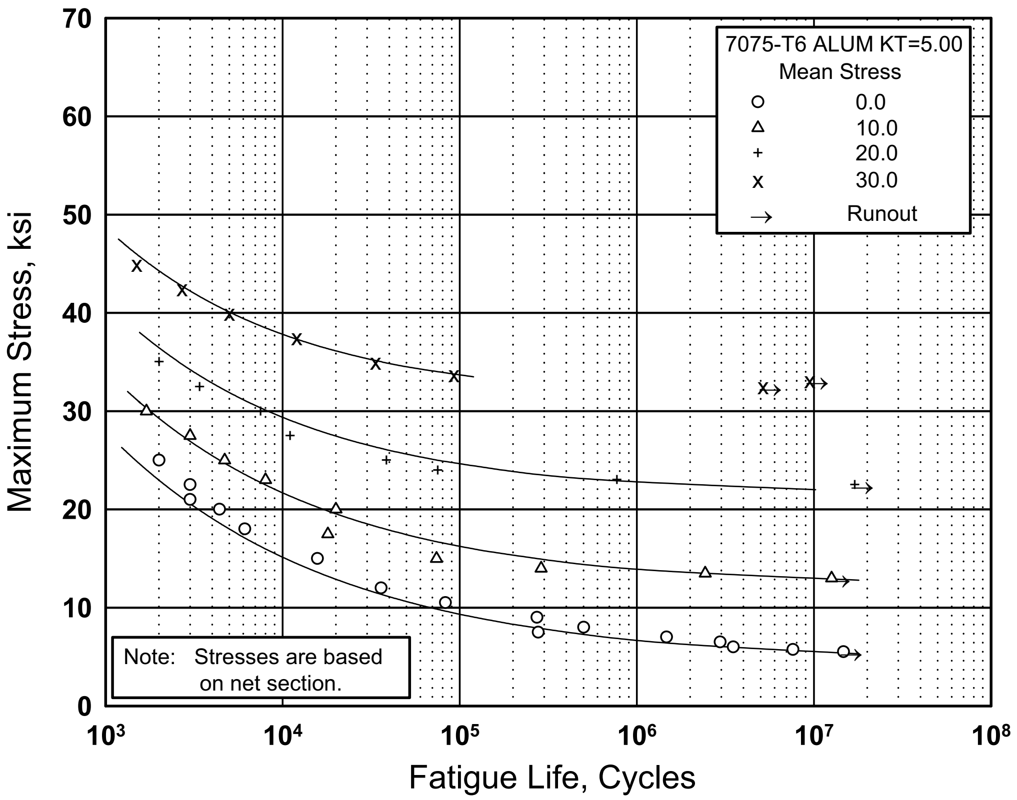


Figure 3.7.6.1.8(h). Best-fit S/N curves for notched, K_t = 5.0, 7075-T6 aluminum alloy sheet, longitudinal direction.

Correlative Information for Figure 3.7.6.1.8(h)

Product Form: Bare sheet, 0.090 inch

Properties:

TUS, ksi	TYS, ksi	Temp., °F
82	76	RT (unnotched)
77	—	RT (notched)

Specimen Details: Edge Notched
2.25 inch gross width
1.500 inch net width
0.03125 inch notch radius

Surface Condition: Electropolished

Reference: 3.2.3.1.8(c)

Test Parameters:
Loading - Axial
Frequency - 1100 to 1500 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
Log N_f = 7.51-2.92 log (S_{eq}-6.7)
$S_{eq} = S_{max} (1-R)^{0.58}$
Std. Error of Estimate, Log (Life) = 0.23
Standard Deviation, Log (Life) = 1.08
R^2 = 95%

Sample Size = 37

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

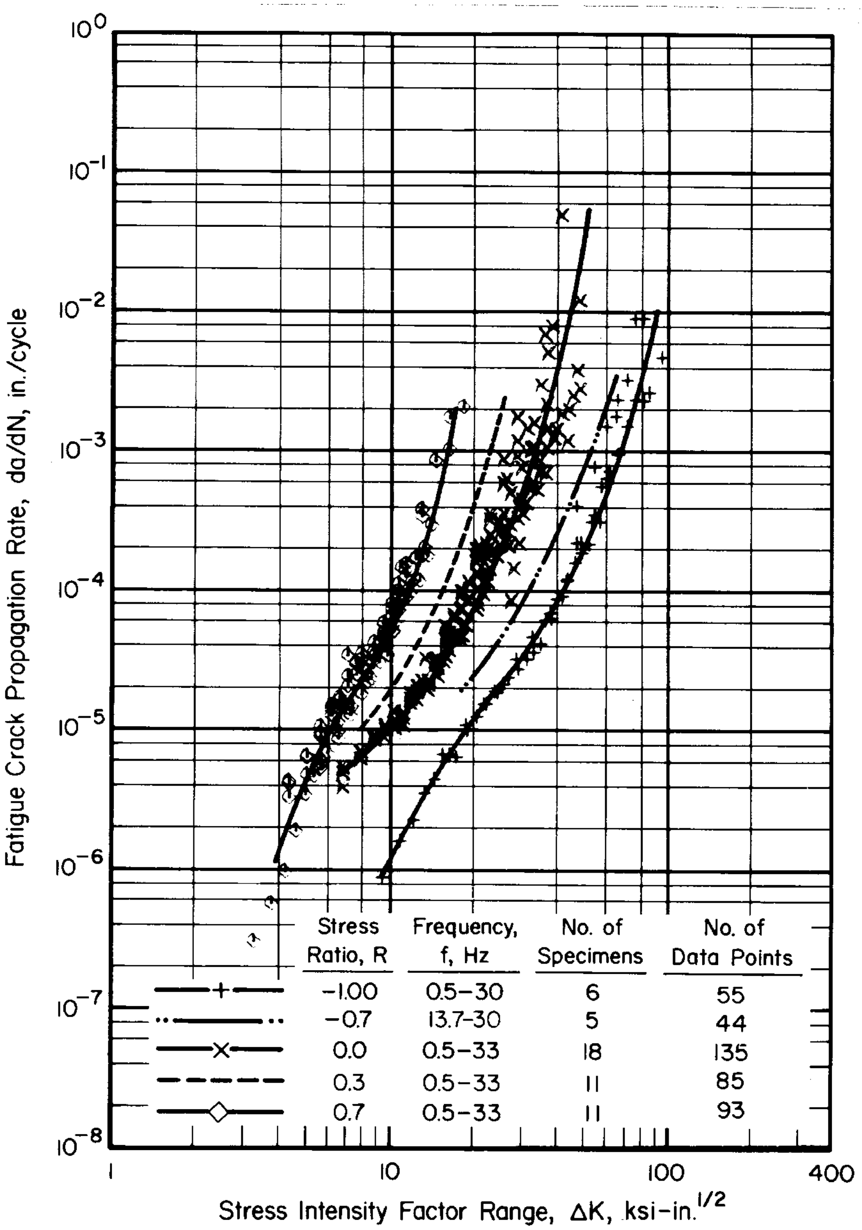


Figure 3.7.6.1.9. Fatigue-crack-propagation data for 0.090-inch-thick 7075-T6 aluminum alloy sheet with buckling restraint [References 3.7.6.1.9(a) through (e)].

Specimen Thickness:	*0.090 inch*	*Environment:*	*Lab air*
Specimen Width:	*1-1/2 - 12 inches*	*Temperature:*	*RT*
Specimen Type:	*M(T)*	*Orientation:*	*L-T*

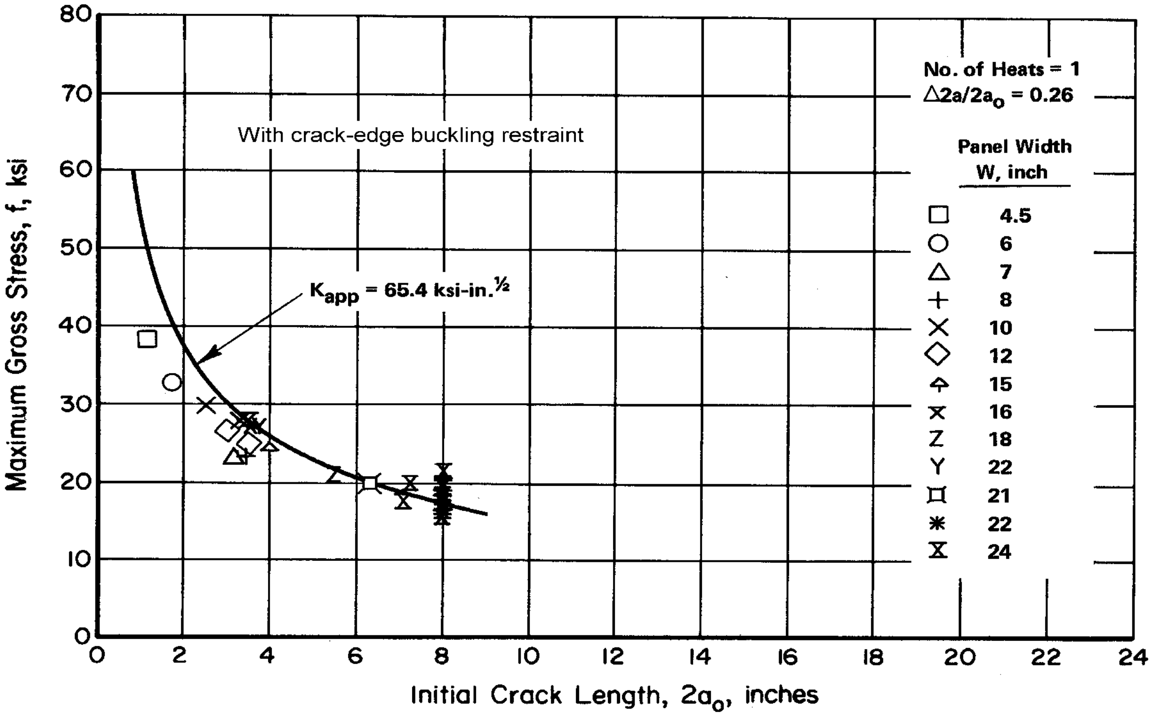


Figure 3.7.6.1.10(a). Residual strength behavior of 0.063-inch-thick 7075-T6 aluminum alloy sheet at room temperature. Crack orientation is T-L [Reference 3.1.2.1.6(f)].

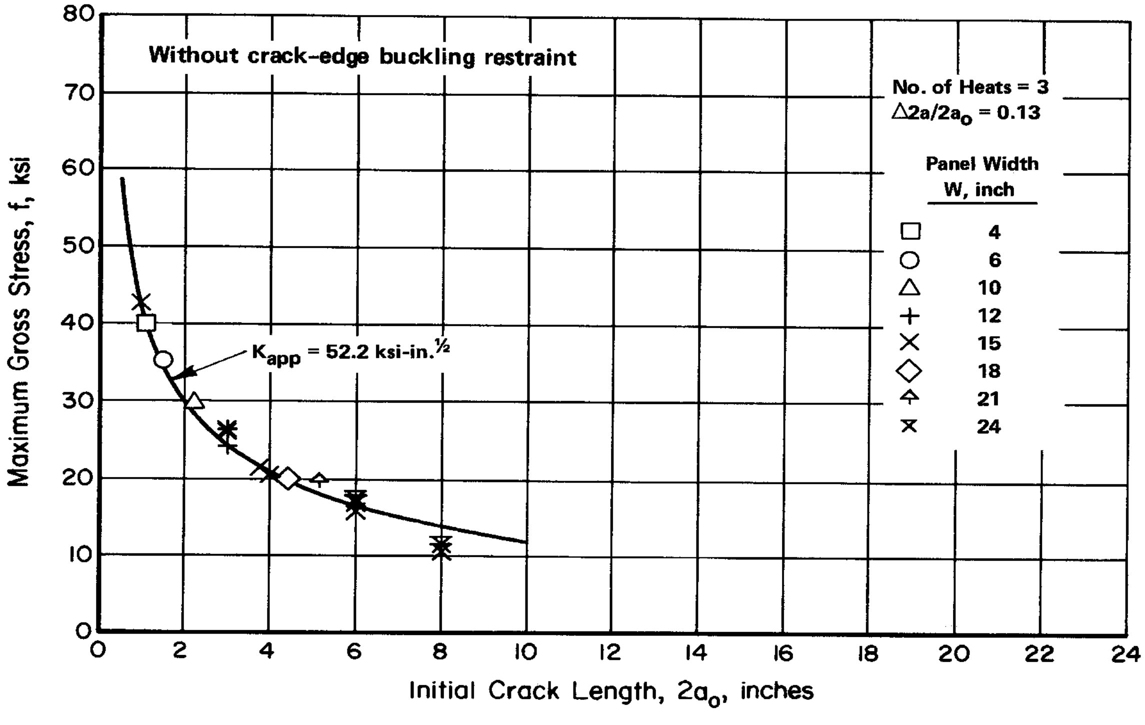


Figure 3.7.6.1.10(b). Residual strength behavior of 0.063-inch-thick 7075-T6 aluminum alloy sheet at room temperature. Crack orientation is T-L [References 3.1.2.1.6(d) and (f)].

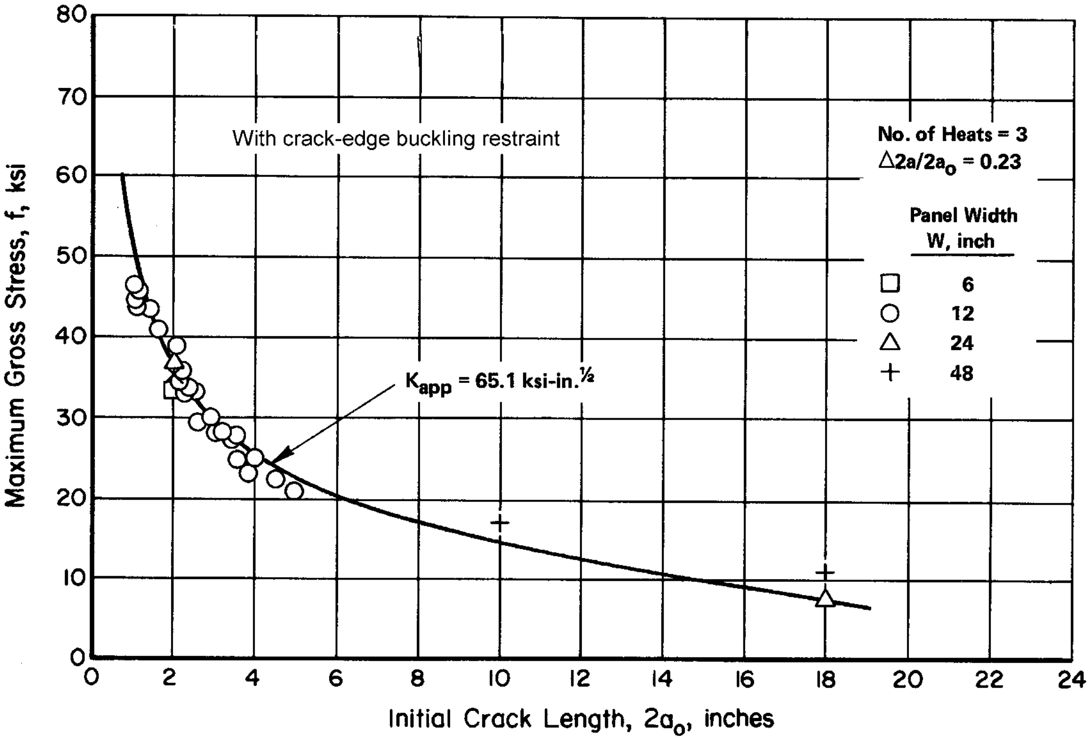


Figure 3.7.6.1.10(c). Residual strength behavior of 0.090- and 0.100-inch-thick 7075-T6 aluminum alloy sheet at room temperature. Crack orientation is L-T [References 3.1.2.1.6(e), (g), and 3.7.6.1.9(e)].

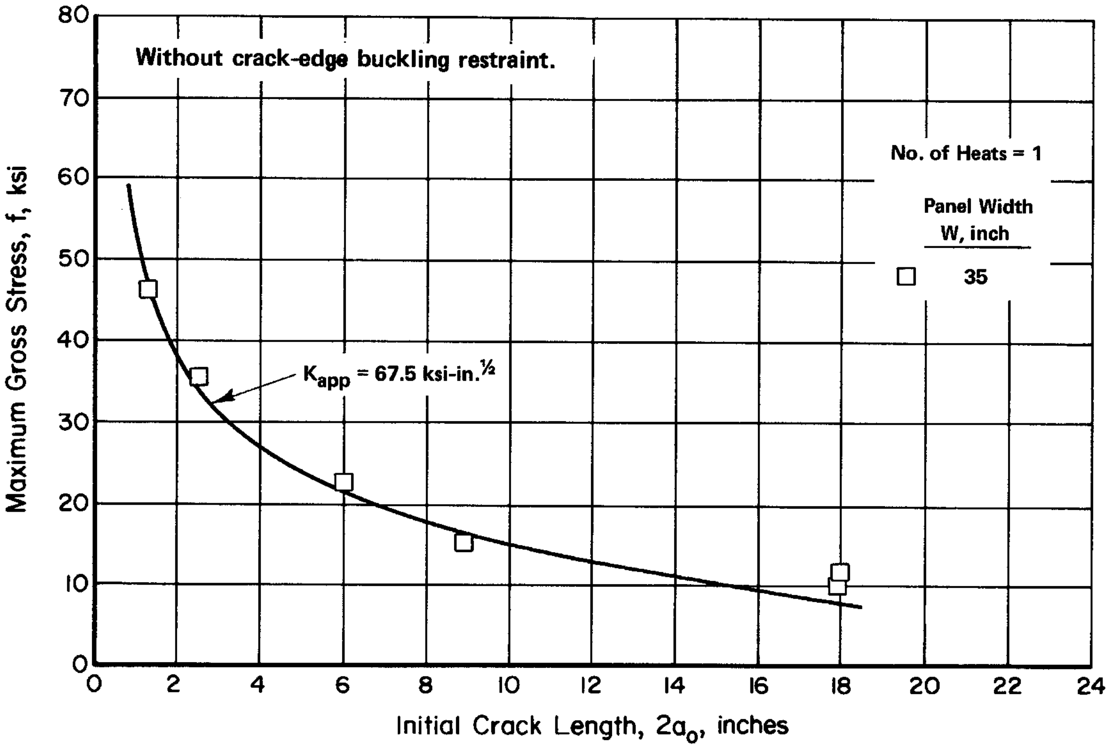


Figure 3.7.6.1.10(d). Residual strength behavior of 0.100-inch-thick 7075-T6 aluminum alloy sheet at room temperature. Crack orientation is L-T [Reference 3.1.2.1.6(g)].

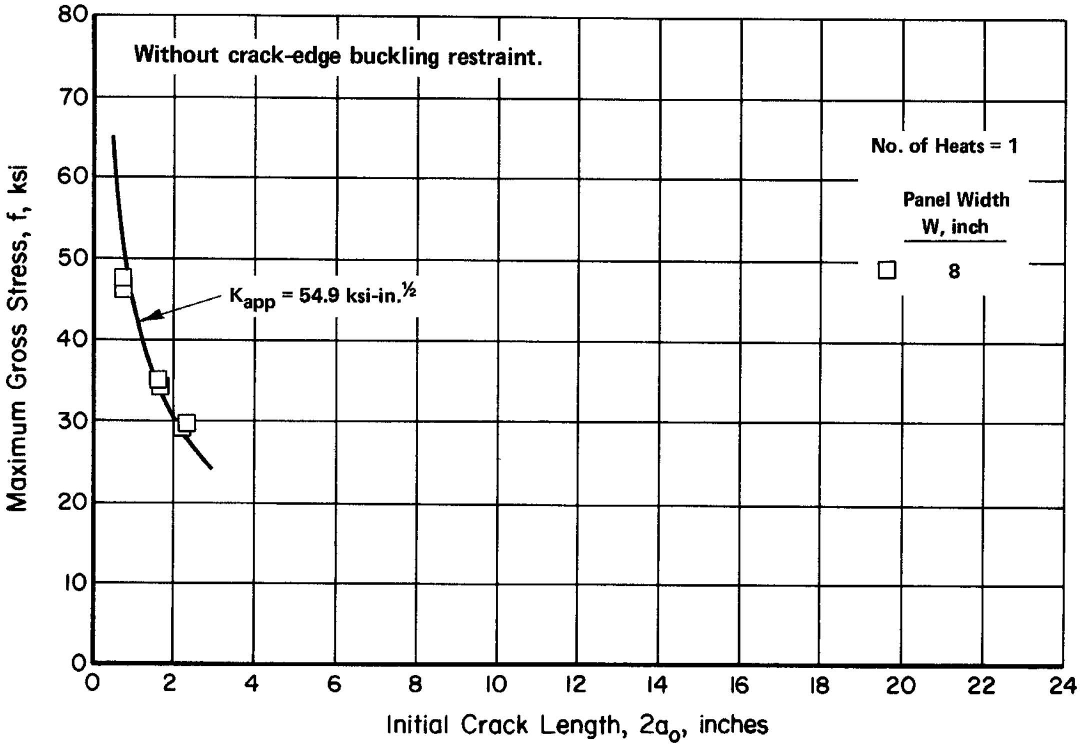


Figure 3.7.6.1.10(e). Residual strength behavior of 0.313-inch-thick 7075-T6 aluminum alloy plate at room temperature. Crack orientation is L-T [Reference 3.1.2.1.6(g)].

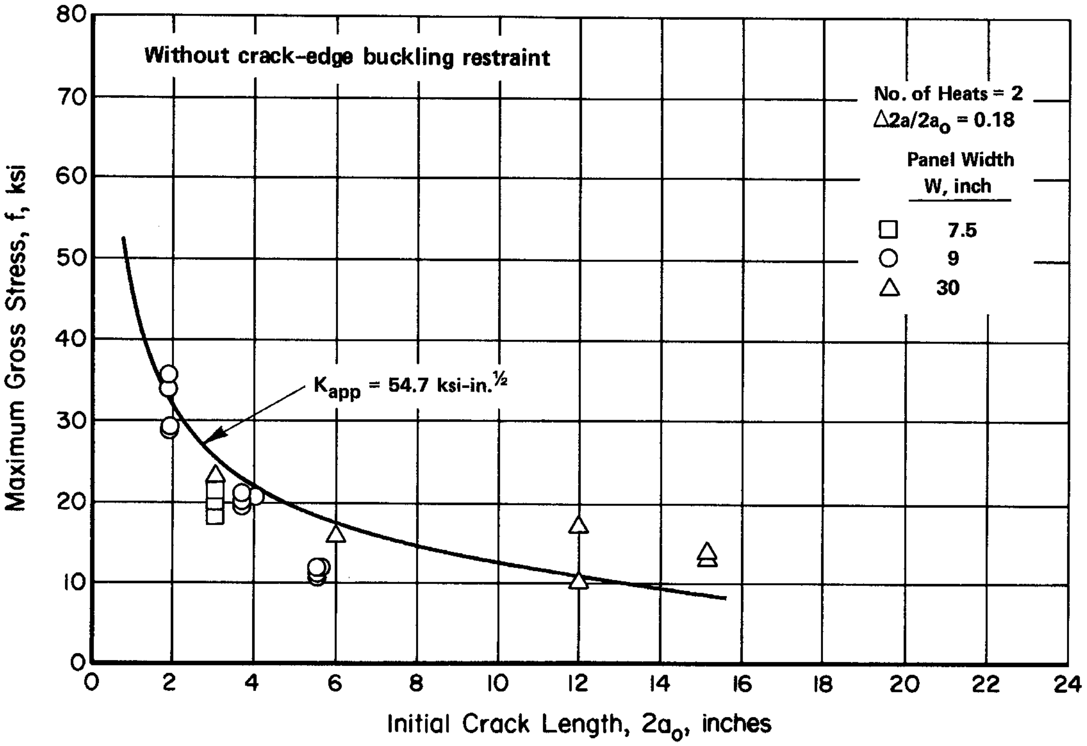


Figure 3.7.6.1.10(f). Residual strength behavior of 0.040-inch-thick 7075-T6 clad aluminum alloy sheet at room temperature. Crack orientation is L-T [References 3.1.2.1.6(f) and 3.7.6.1.10(f)].

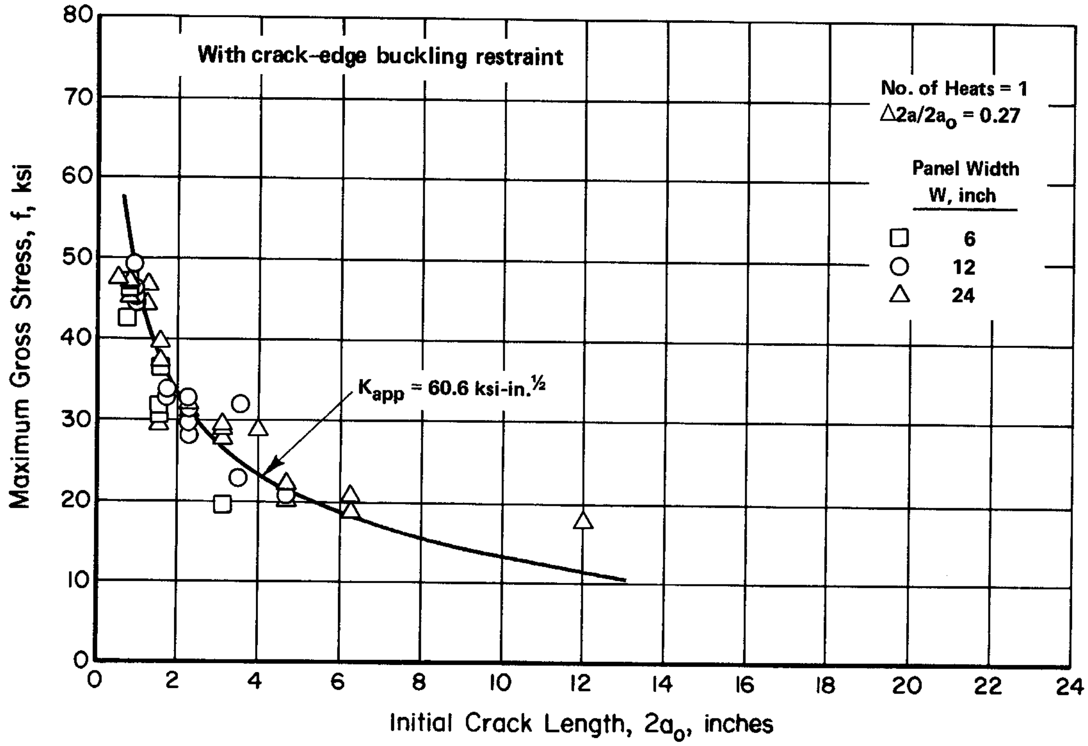


Figure 3.7.6.1.10(g). Residual strength behavior of 0.080-inch-thick 7075-T6 clad aluminum alloy sheet at room temperature. Crack orientation is L-T [References 3.1.2.1.6(h) and (i)].

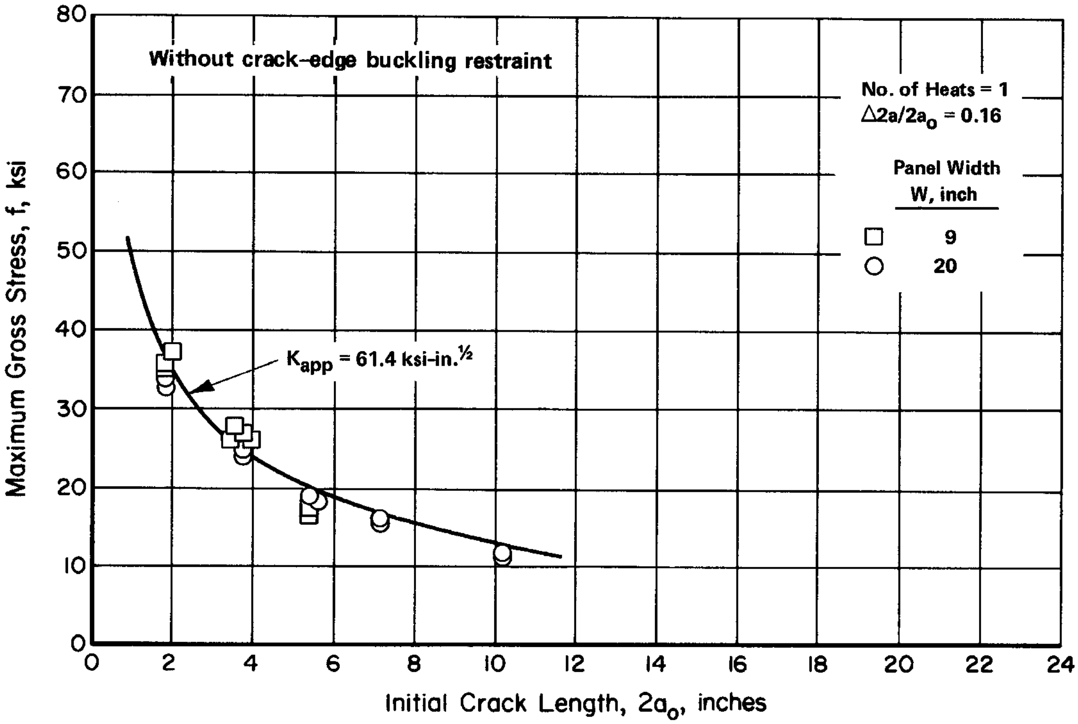


Figure 3.7.6.1.10(h). Residual strength behavior of 0.090-inch-thick 7075-T6 clad aluminum alloy sheet at room temperature. Crack orientation is L-T [Reference 3.7.6.1.10(f)].

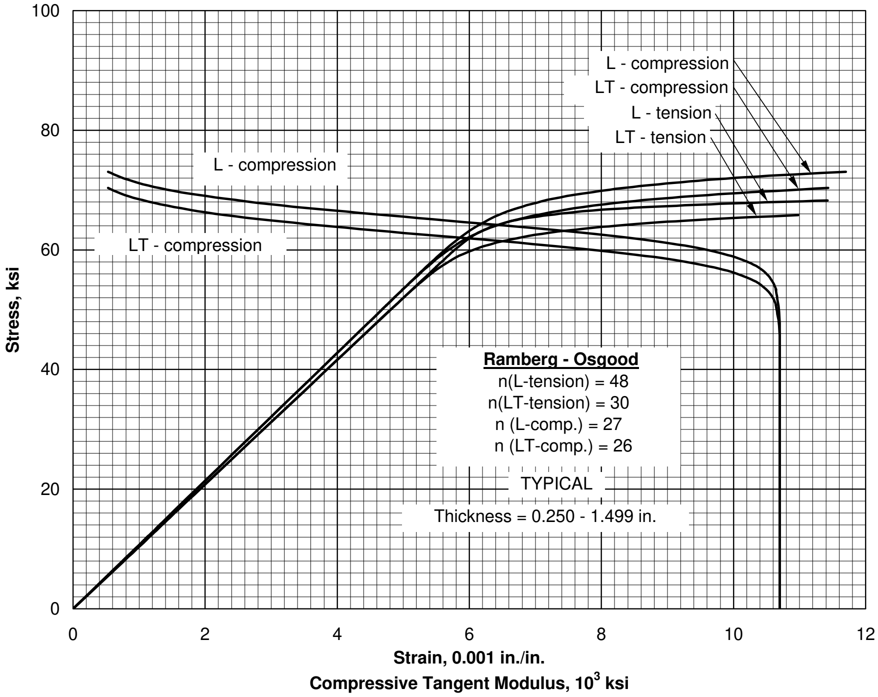


Figure 3.7.6.2.6(a). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 7075-T73 aluminum alloy extrusion at room temperature.

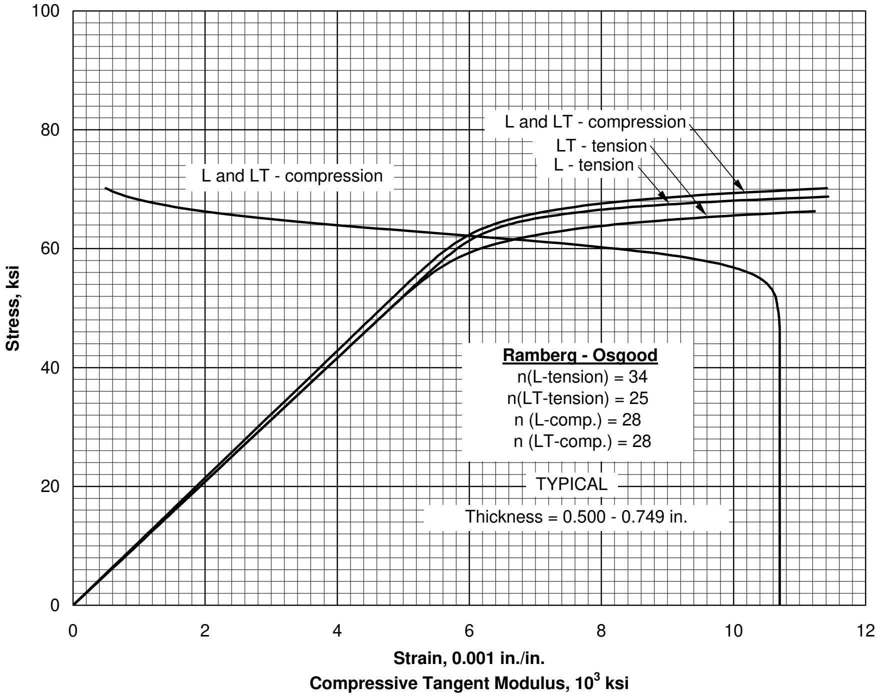


Figure 3.7.6.2.6(b). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 7075-T7351X aluminum alloy extrusion at room temperature.

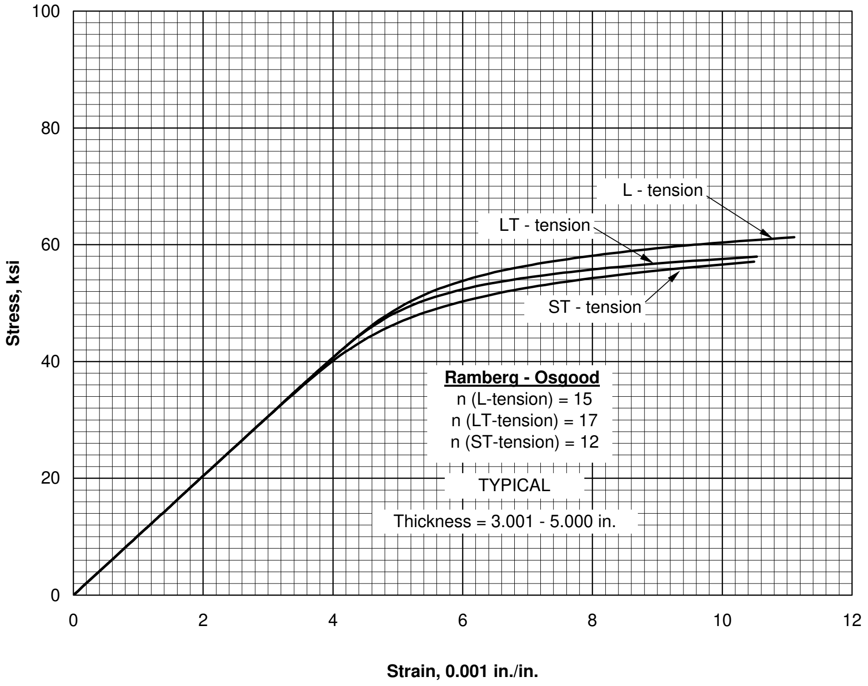


Figure 3.7.6.2.6(c). Typical tensile stress-strain curves for 7075-T7352 aluminum alloy hand forging at room temperature.

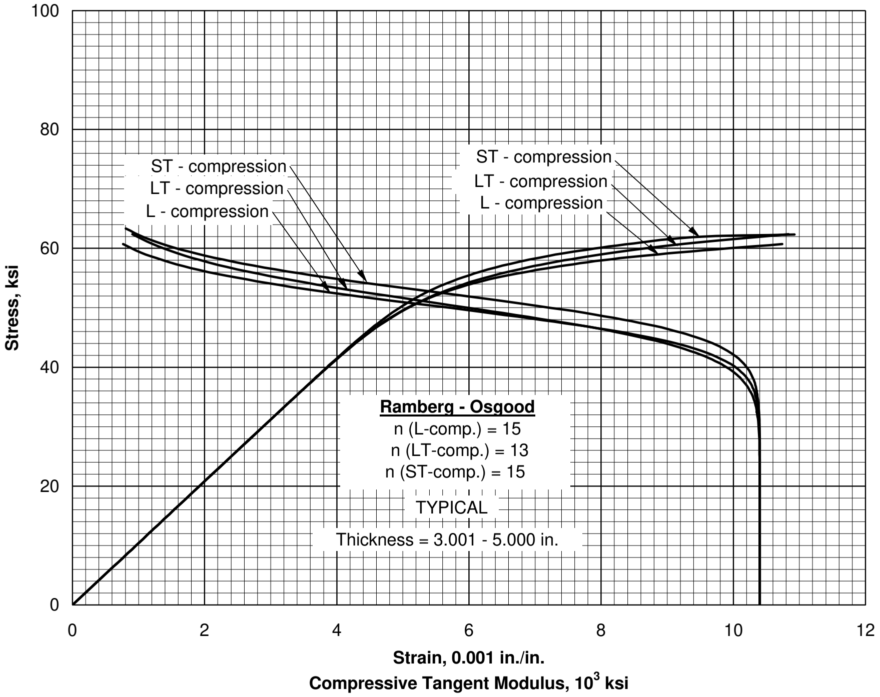


Figure 3.7.6.2.6(d). Typical compressive stress-strain and compressive tangent-modulus curves for 7075-T7352 aluminum alloy hand forging at room temperature.

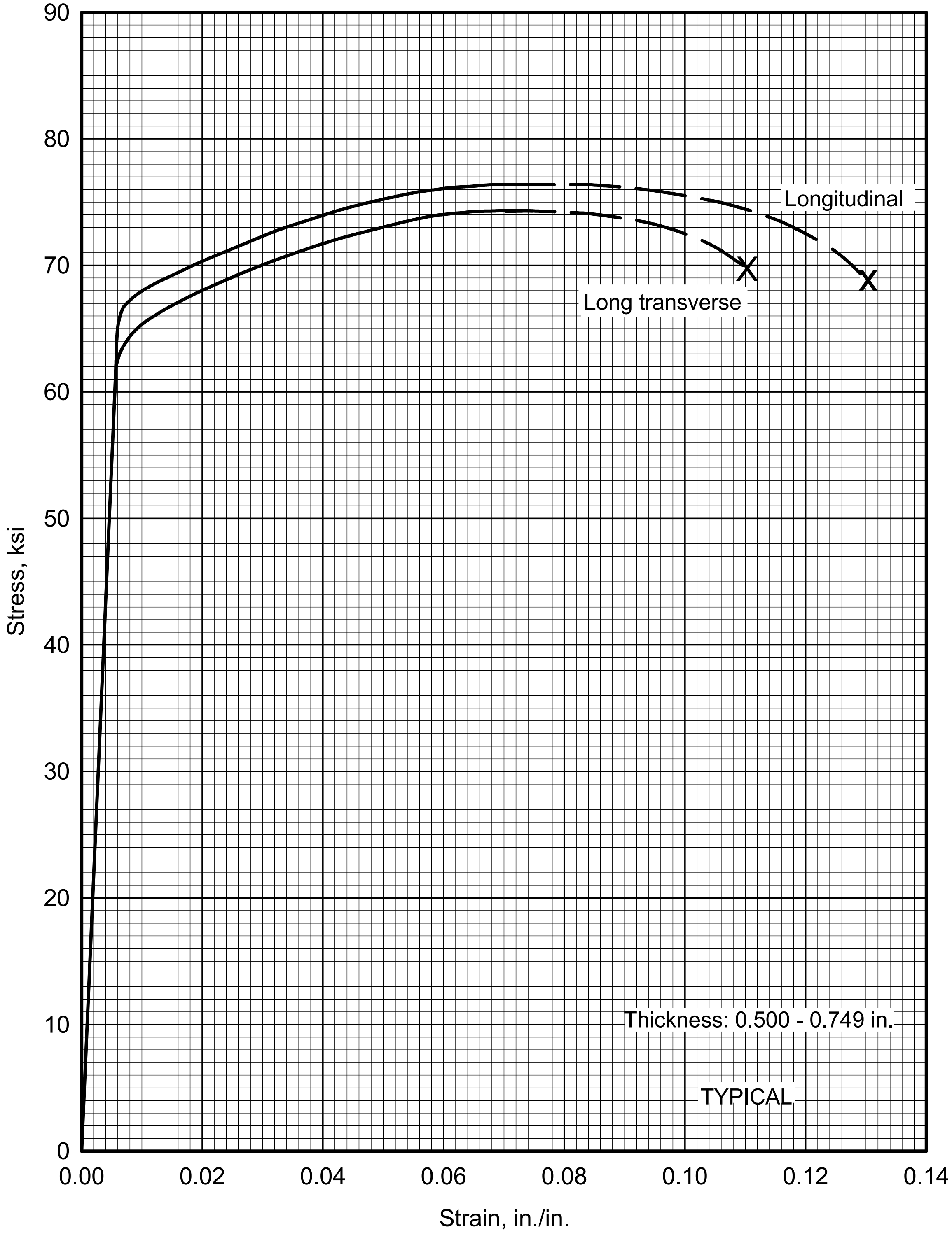


Figure 3.7.6.2.6(e). Typical tensile stress-strain curves (full range) for 7075-T7351X aluminum alloy extrusion at room temperature.

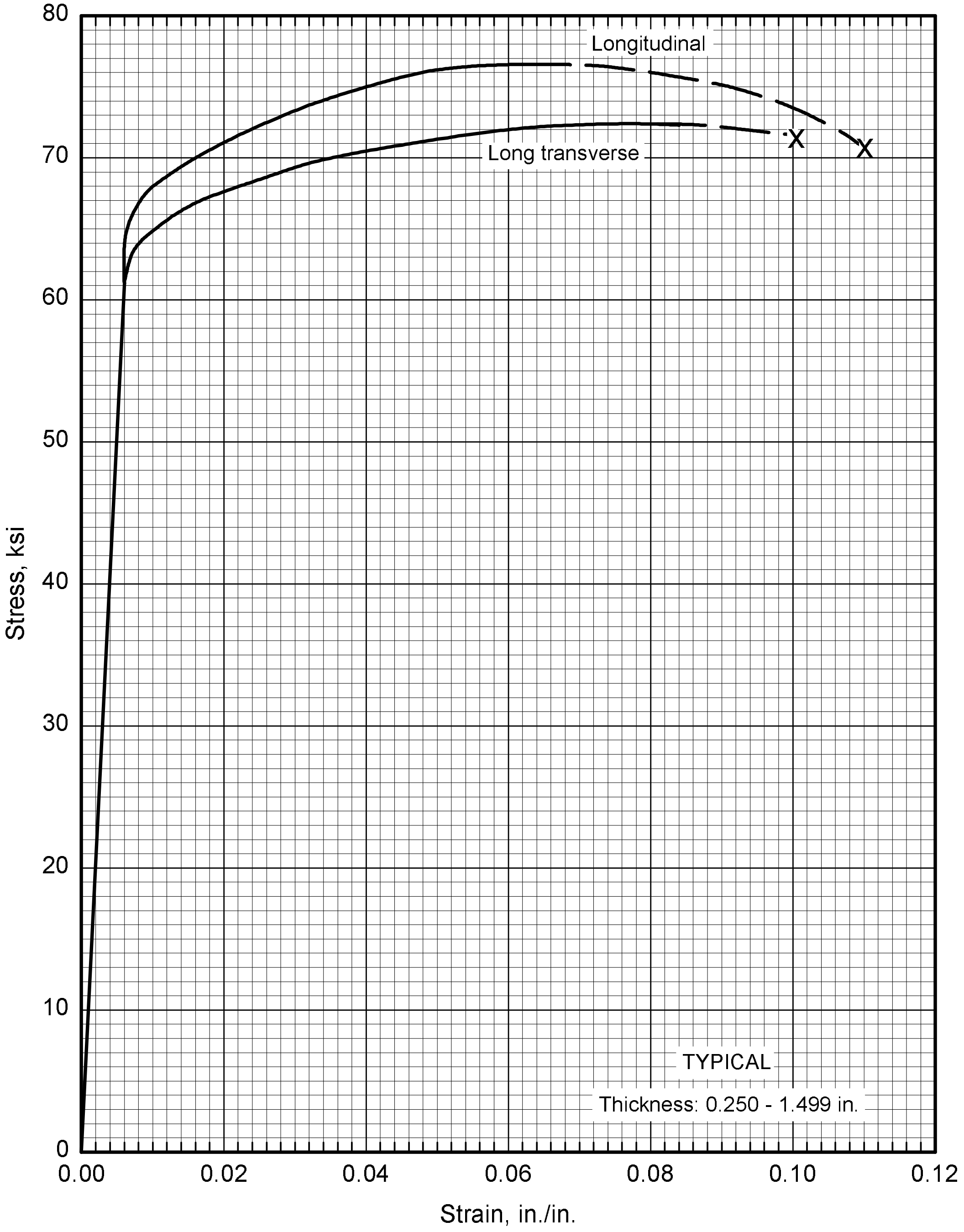


Figure 3.7.6.2.6(f). Typical tensile stress-strain curves (full range) for 7075-T73 aluminum alloy extrusion at room temperature.

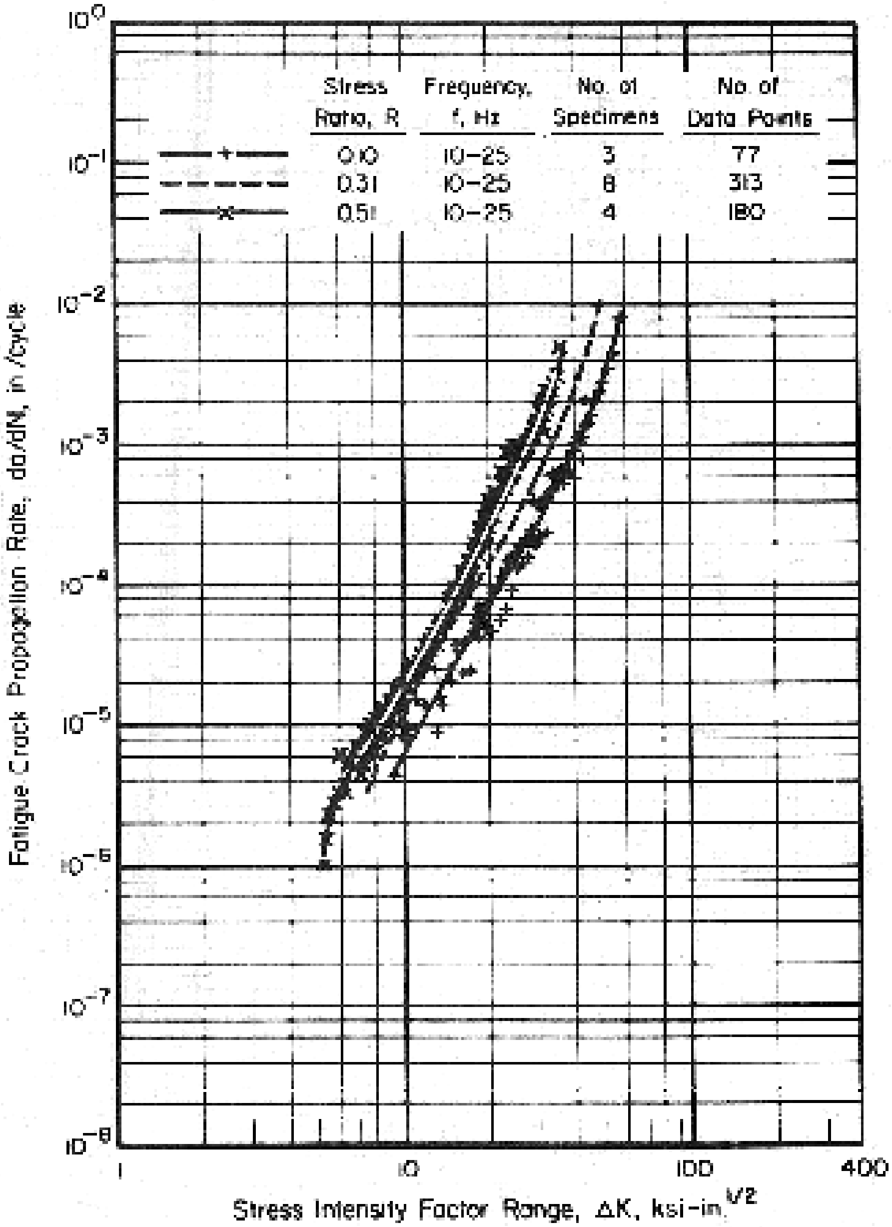


Figure 3.7.6.2.9(a). Fatigue-crack-propagation data for 0.250-inch-thick, 7075-T7351 aluminum alloy plate with buckling restraint [References 3.2.5.1.9(d) and 3.7.6.2.9(a)].

Specimen Thickness:	*0.250-inch*	*Environment:*	*50% R.H.*
Specimen Width:	*8, 16, 36-inches*	*Temperature:*	*RT*
Specimen Type:	*M(T)*	*Orientation:*	*L-T*

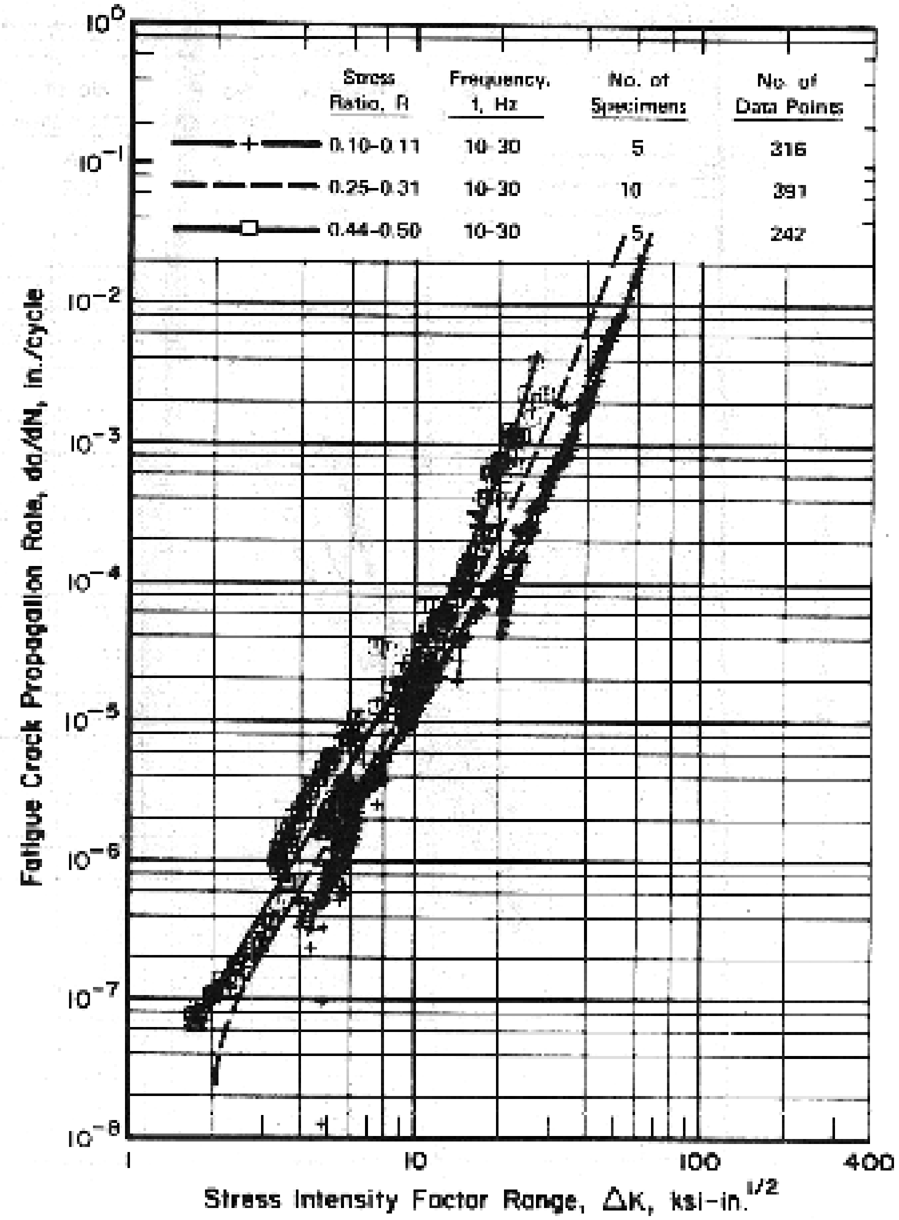


Figure 3.7.6.2.9(b). Fatigue-crack-propagation data for 0.500-inch-thick, 7075-T7351 aluminum alloy plate with buckling restraint [References 3.1.2.1.6(j) and 3.7.6.2.9(a) through (c)].

Specimen Thickness:	*0.475 to 0.500-inch*	*Environment:*	*50-95% R.H.*
Specimen Width:	*6, 8, 16, 36-inches*	*Temperature:*	*RT*
Specimen Type:	*M(T)*	*Orientation:*	*L-T*

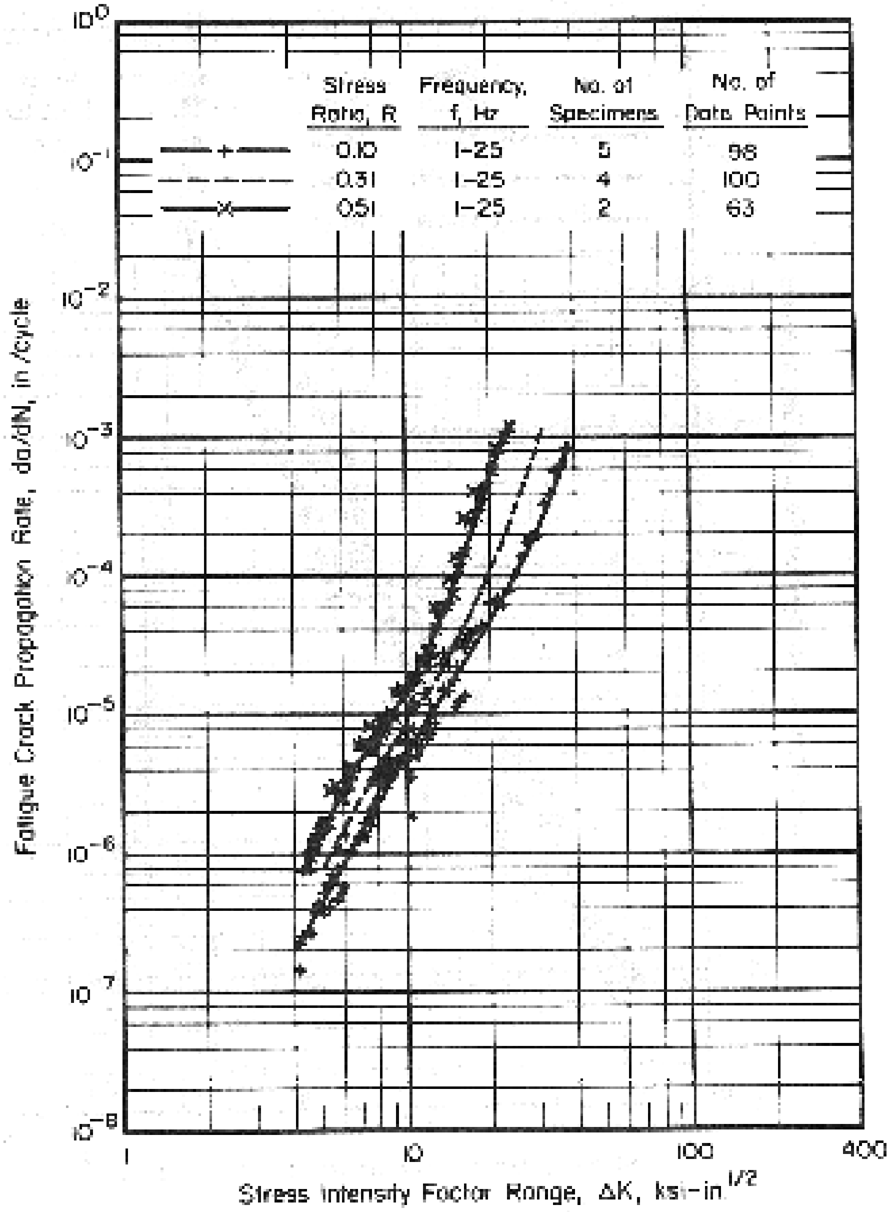


Figure 3.7.6.2.9(c). Fatigue-crack-propagation data for 1.00-inch-thick, 7075-T7351 aluminum alloy plate without buckling restraint [References 3.2.5.1.9(d) and 3.7.6.2.9(a) and (b)].

Specimen Thickness:	*1.00-inch*	*Environment:*	*50% R.H.*
Specimen Width:	*6, 8, 16, 36-inches*	*Temperature:*	*RT*
Specimen Type:	*M(T), C(T)*	*Orientation:*	*L-T*

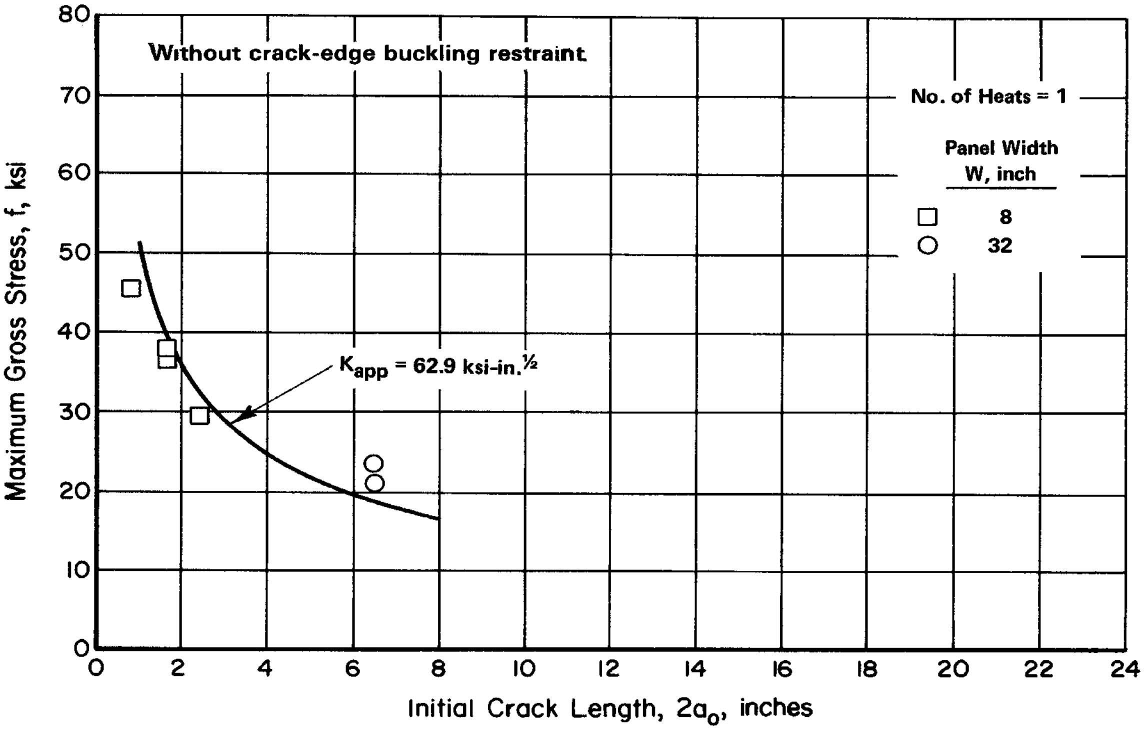


Figure 3.7.6.2.10(a). Residual strength behavior of 0.600-inch-thick 7075-T7351 aluminum alloy plate at room temperature. Crack orientation is L-T [Reference 3.1.2.1.6(g)].

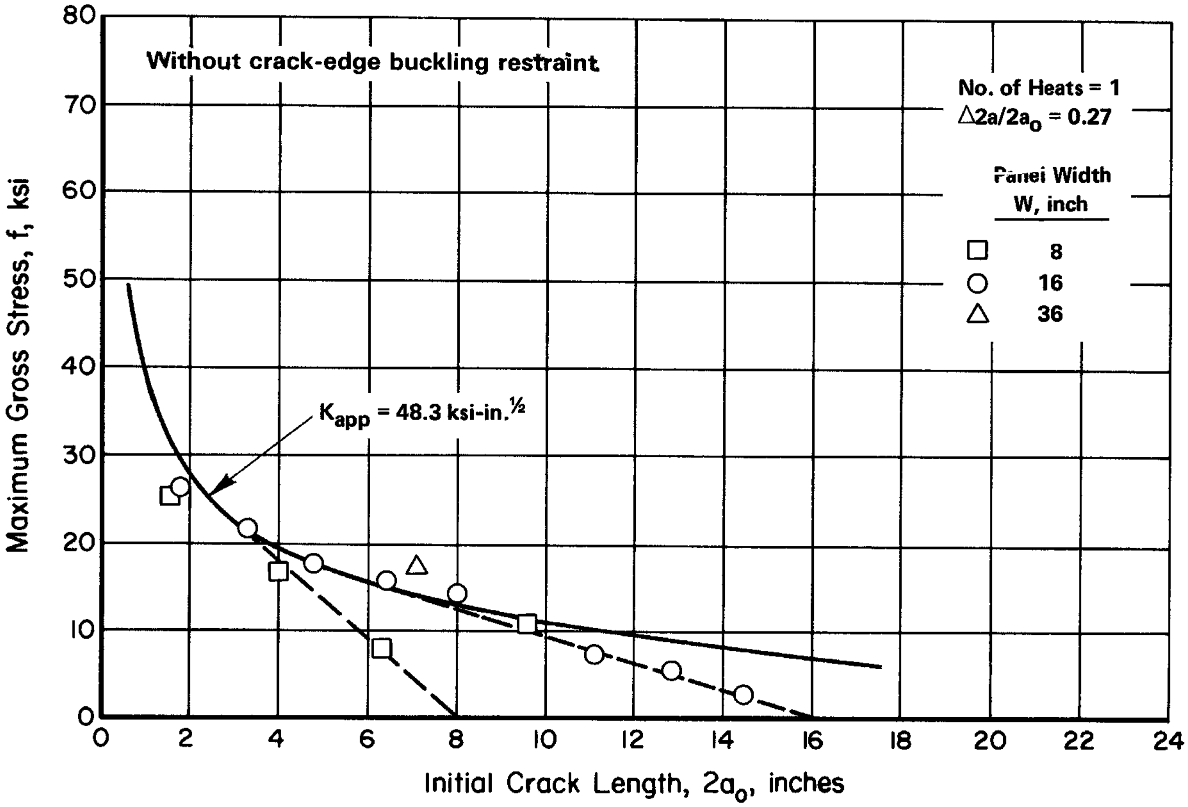


Figure 3.7.6.2.10(b). Residual strength behavior of 1.00-inch-thick 7075-T7351 aluminum alloy plate at room temperature. Crack orientation is L-T [Reference 3.1.2.1.6(j)].

3.7.7 7150 ALLOY

3.7.7.0 *Comments and Properties* — 7150, a second-generation version of 7050, is an Al-Zn-Mg-Cu-Zr alloy developed to provide higher strength properties than 7050 in thicknesses through 3 inches. 7150 is available in the form of plate and extrusion. The T61-type temper provides high strength with guaranteed levels of fracture toughness for plate. The T77-type temper provides high strength with guaranteed toughness and corrosion resistance. The T77-type temper has exfoliation and stress-corrosion resistance comparable to the T76-type temper of the other 7000 series aluminum alloys. Refer to Section 3.1.2.3 for further comments regarding resistance of the alloy to stress-corrosion cracking.

The properties of extrusions should be based upon the thickness at the time of quenching prior to machining. Selection of the mechanical properties based upon its final machined thickness may be unconservative; therefore, the thickness at the time of quenching to achieve properties is an important factor in the selection of the proper thickness column. For extrusions having sections with various thicknesses, consideration should be given to the properties as a function of thickness.

Refer to Section 3.1.3.4 for comments regarding the weldability of the alloy.

Material specifications for 7150 are shown in Table 3.7.7.0(a). Room-temperature mechanical properties are presented in Tables 3.7.7.0(b_1) through (c_2).

Table 3.7.7.0(a). Material Specifications for 7150 Aluminum Alloy

Specification	Form
AMS 4306	Bare plate
AMS 4252	Bare plate
AMS 4307	Extrusion
AMS 4345	Extrusion

The temper index for 7150 is as follows:

Section	Temper
3.7.7.1	T6151 and T61511
3.7.7.2	T7751 and T77511

3.7.7.1 *T6151 and T61511 Tempers* — Figures 3.7.7.1.6(a) and (b) present stress-strain and tangent-modulus curves for bare plate. Figures 3.7.7.1.6(c) and (d) depict stress-strain and tangent-modulus curves for extrusion.

3.7.7.2 *T7751 and T77511 Tempers* — Figures 3.7.7.2.6(a) and (b) present stress-strain and tangent-modulus curves for bare plate. Figures 3.7.7.2.6(c) and (d) depict stress-strain and tangent-modulus curves for extrusion.

Table 3.7.7.0(b_1). Design Mechanical and Physical Properties of 7150 Plate

Specification	AMS 4306			
Form	Plate			
Temper	T6151			
Thickness, in.	0.750-1.000		1.001-1.500	
Basis	A	B	A	B
Mechanical Properties:				
F_{tu}, ksi:				
L	85	87	86	87
LT	84	87	85	86
F_{ty}, ksi:				
L	79	81	80	81
LT	77	79	76	78
F_{cy}, ksi:				
L	77	80	75	77
LT	81	83	80	82
F_{su}, ksi	45	47	46	46
$F_{bru}{}^{a}$, ksi:				
(e/D = 1.5)	121	125	123	124
(e/D = 2.0)	155	160	156	158
$F_{bry}{}^{a}$, ksi:				
(e/D = 1.5)	102	105	101	104
(e/D = 2.0)	119	122	118	121
e, percent (S-basis):				
L	9	...	9	...
LT	9	...	9	...
E, 10^3 ksi	10.2			
E_c, 10^3 ksi	10.6			
G, 10^3 ksi	3.9			
μ	0.33			
Physical Properties:				
ω, lb/in.^{3}	0.102			
C, Btu/(lb)(°F)	...			

a Bearing values are "dry pin" values per Section 1.4.7.1. See Table 3.1.2.1.1.

Table 3.7.7.0(b_2). Design Mechanical and Physical Properties of 7150 Plate

Specification	AMS 4252				
Form	Plate				
Temper	T7751				
Thickness, in.	0.250-0.499	0.500-0.749	0.750-1.500	1.501-3.000	
Basis	S	S	S	A	B
Mechanical Properties:					
F_{tu}, ksi:					
L	80	83	84	82	84
LT	80	83	84	82[a]	84
ST	...	...	...	77[a]	81
F_{ty}, ksi:					
L	74	77	78	76	78
LT	74	76	77	75[a]	77
ST	...	...	...	67[a]	71
F_{cy}, ksi:					
L	74	76	77	75	77
LT	77	79	81	79	82
F_{su}, ksi	46	47	48	47	48
F_{bru}[b], ksi:					
(e/D = 1.5)	119	124	125	122	125
(e/D = 2.0)	154	160	162	158	162
F_{bry}[b], ksi:					
(e/D = 1.5)	102	105	106	104	108
(e/D = 2.0)	117	120	121	118	123
e, percent: (S-basis)					
L	8	8	8	7	
LT	8	8	8	6	
ST	...	...	...	1	
E, 10^3 ksi	10.3				
E_c, 10^3 ksi	10.7				
G, 10^3 ksi	3.9				
μ	0.33				
Physical Properties:					
ω, lb./in.^{3}	0.102				
C, K, and α	...				

a S-basis values. The rounded T_{99} values are as follows: F_{tu}(LT)=83 ksi, F_{tu}(ST)=78 ksi, F_{ty}(LT)=76 ksi, F_{ty}(ST)=68 ksi.
b Bearing values are "dry pin" values per Section 1.4.7.1. See Table 3.1.2.1.1.

Table 3.7.7.0(c_1). Design Mechanical and Physical Properties of 7150 Aluminum Alloy Extrusion

Specification	AMS 4307					
Form	Extrusion					
Temper	T61511					
Thickness or Diameter,[a] in	0.250-0.499	0.500-0.749	0.750-0.999	1.000-1.499		1.500-2.000
Basis	S	S	S	A	B	S
Mechanical Properties:						
F_{tu}, ksi:						
L	87	88	89	89	94	89
LT	80	79	79	85	86	74
F_{ty}, ksi:						
L	82	83	84	83	88	84
LT	73	73	73	77	78	68
F_{cy}, ksi:						
L	80	81	82	82	87	84
LT	80	80	80	77	81	75
F_{su}, ksi	44	45	45	44	46	42
F_{bru}[b], ksi:						
(e/D = 1.5)	119	120	120	118	125	116
(e/D = 2.0)	152	153	154	152	161	150
F_{bry}[b], ksi:						
(e/D = 1.5)	100	100	100	96	102	94
(e/D = 2.0)	118	120	120	117	124	117
e, percent (S-basis):						
L	8	9	8	8	...	8
E, 10^3 ksi	10.4					
E_c, 10^3 ksi	11.0					
G, 10^3 ksi	4.0					
μ	0.33					
Physical Properties:						
ω, lb/in.^{3}	0.102					
C, K, and α	...					

a The mechanical properties are to be based upon the thickness at the time of quench.
b Bearing values are "dry pin" values per Section 1.4.7.1.

Table 3.7.7.0(c_2). Design Mechanical and Physical Properties of 7150 Aluminum Alloy Extrusion

Specification	AMS 4345					
Form	Extrusion					
Temper	T77511					
Cross-Sectional Area, in^2	≤20					
Thickness or Diameter,[a] in.	≤0.249		0.250-0.499		0.500-0.749	0.750-2.000
Basis	A	B	A	B	S	S
Mechanical Properties:						
F_{tu}, ksi:						
L	85[b]	88	87[c]	89	88	89
LT	81	84	82[c]	86	83	83
F_{ty}, ksi:						
L	78[b]	83	82[c]	84	83	84
LT	74	79	76[c]	79	79	78
F_{cy}, ksi:						
L	78[b]	82	82[c]	85	83	84
LT	76	81	80	82	81	82
F_{su}, ksi	44	46	45	46	46	46
F_{bru}[d], ksi:						
(e/D = 1.5)	122	126	124	127	125	123
(e/D = 2.0)	158	163	161	165	162	159
F_{bry}[d], ksi:						
(e/D = 1.5)	100	106	105	108	106	108
(e/D = 2.0)	118	125	124	127	125	127
e, percent (S-Basis):						
L	7	...	8	...	9	8
E, 10^3 ksi	10.4					
E_c, 10^3 ksi	10.9					
G, 10^3 ksi	4.0					
μ	0.33					
Physical Properties:						
ω, lb/in.^{3}	0.102					
C, K, and α	...					

a The mechanical properties are to be based upon the thickness at the time of quench.

b S basis. The rounded T_{99} values for F_{tu},(L)= 87 ksi, for F_{ty}(L) = 81 ksi, and for F_{cy}(L) = 79ksi.

c S basis. The rounded T_{99} values for F_{tu}(L) = 88 ksi, for F_{tu}(LT) = 84 ksi, for F_{ty} (L) = 82 ksi, for F_{ty} (LT) = 77 ksi, and for F_{cy} (L) = 82 ksi.

d Bearing values are “dry pin” values per Section 1.4.7.1.

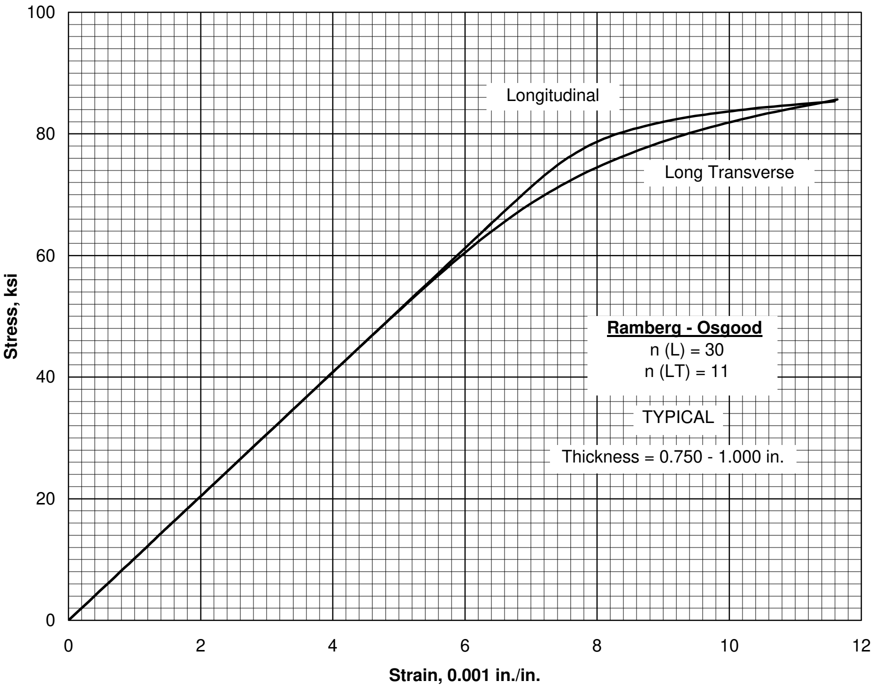


Figure 3.7.7.1.6(a). Typical tensile stress-strain curves for 7150-T6151 aluminum alloy plate at room temperature.

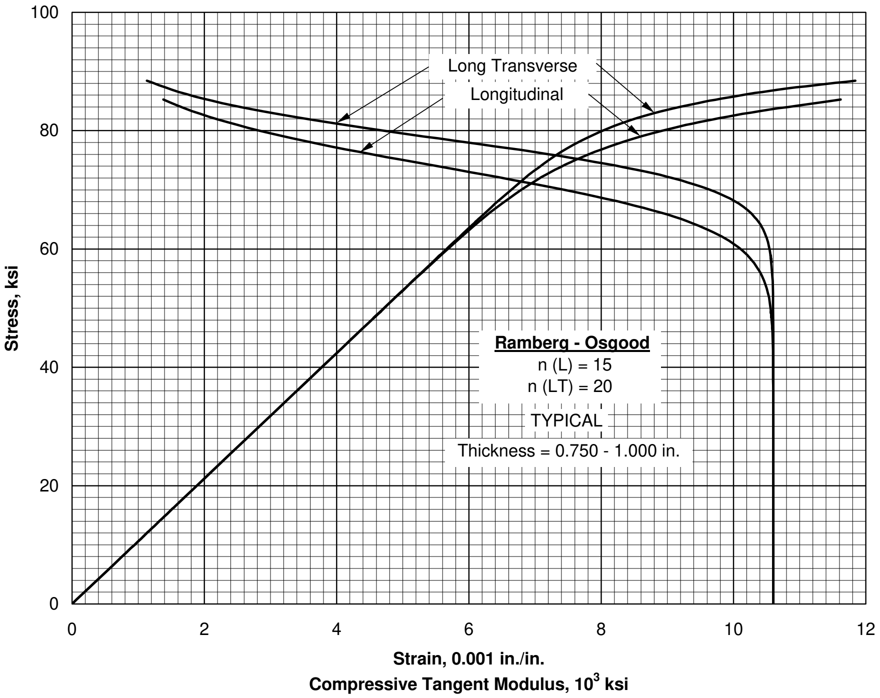


Figure 3.7.7.1.6(b). Typical compressive stress-strain and compressive tangent-modulus curves for 7150-T6151 aluminum alloy plate at room temperature.

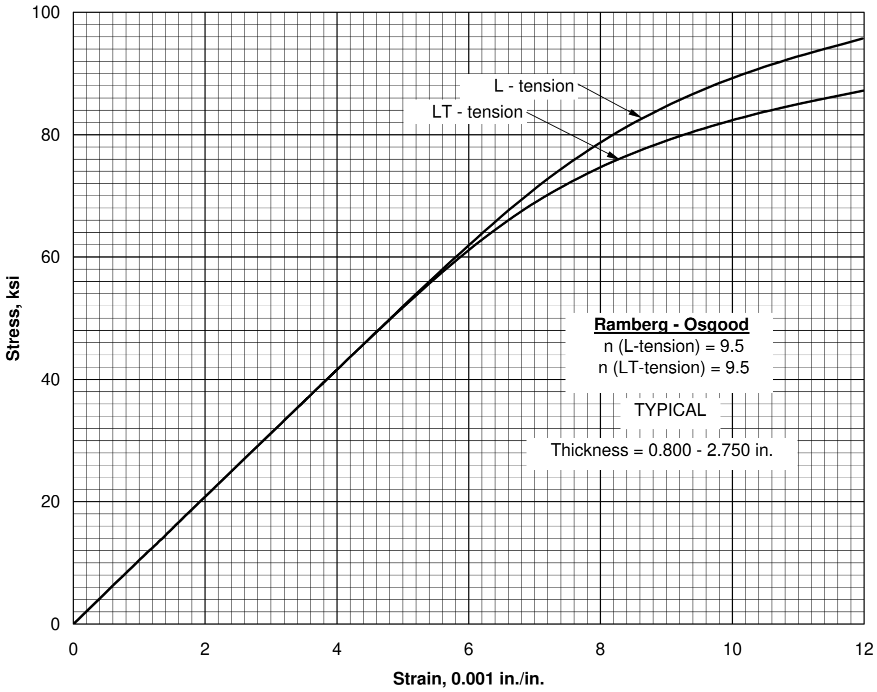


Figure 3.7.7.1.6(c). Typical tensile stress-strain curves for 7150-T61511 aluminum alloy extrusion at room temperature.

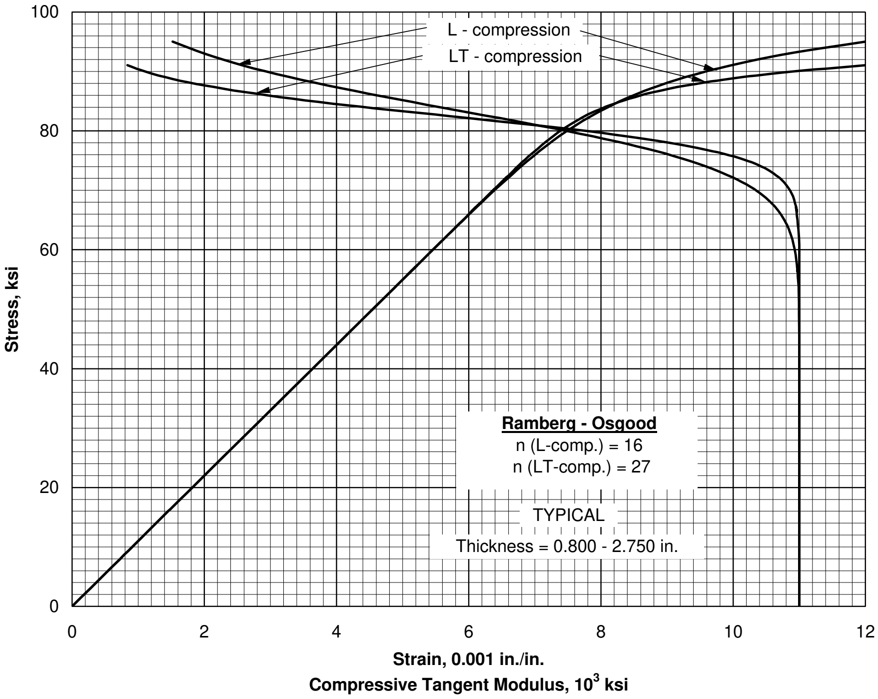


Figure 3.7.7.1.6(d). Typical compressive stress-strain and compressive tangent-modulus curves for 7150-T61511 aluminum alloy extrusion at room temperature.

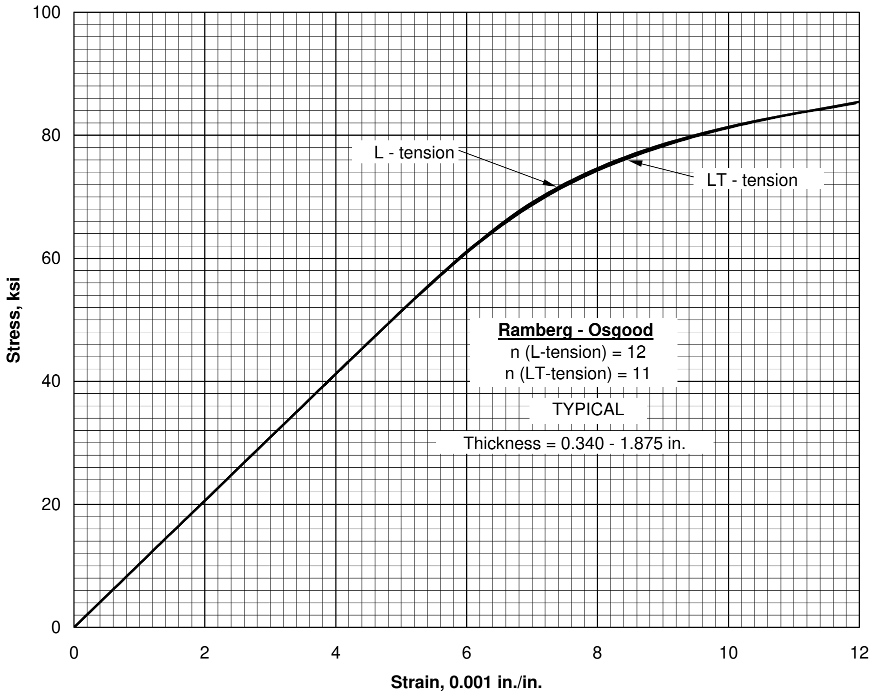


Figure 3.7.7.2.6(a). Typical tensile stress-strain curves for 7150-T7751 aluminum alloy plate at room temperature.

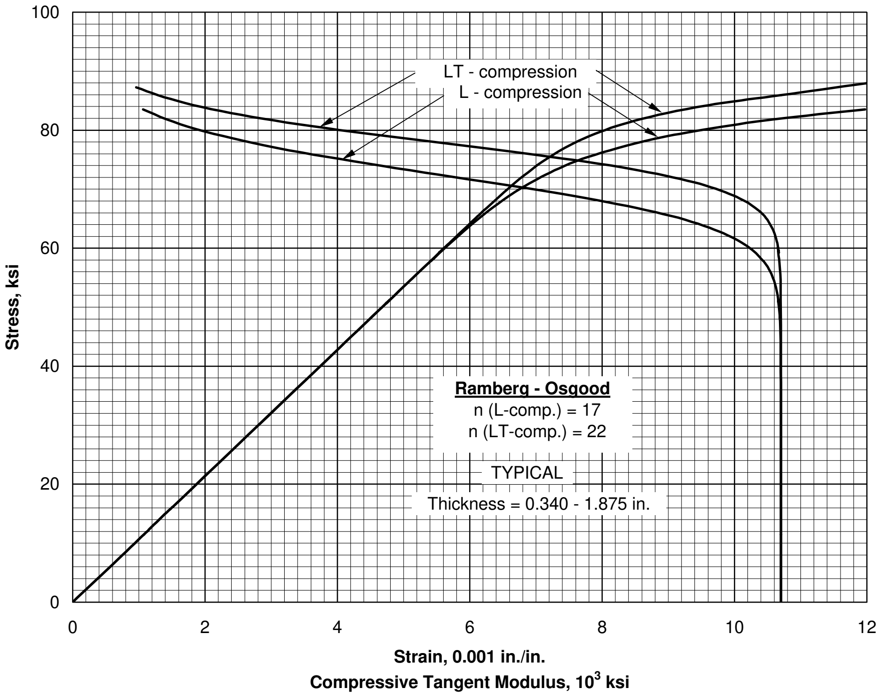


Figure 3.7.7.2.6(b). Typical compressive stress-strain and tangent-modulus curves for 7150-T7751 aluminum alloy plate at room temperature.

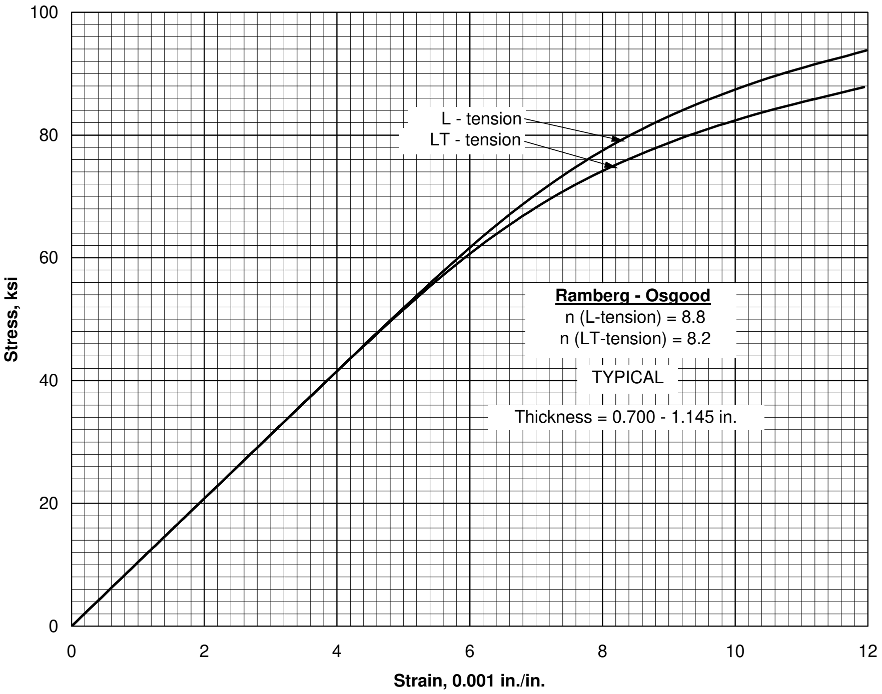


Figure 3.7.7.2.6(c). Typical tensile stress-strain curves for 7150-T77511 aluminum alloy extrusion at room temperature.

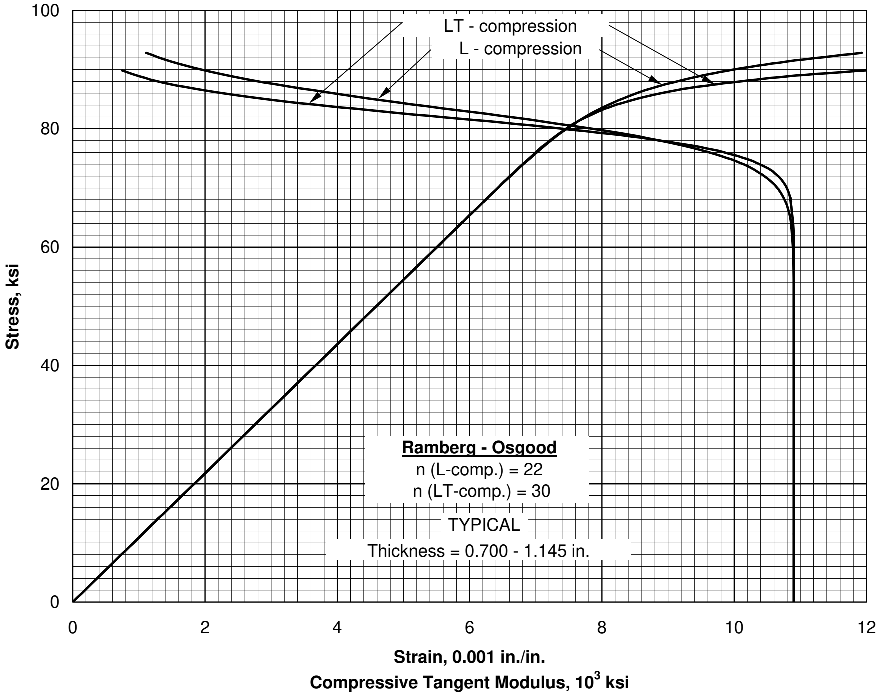


Figure 3.7.7.2.6(d). Typical compressive stress-strain and tangent-modulus curves for 7150-T77511 aluminum alloy extrusion.

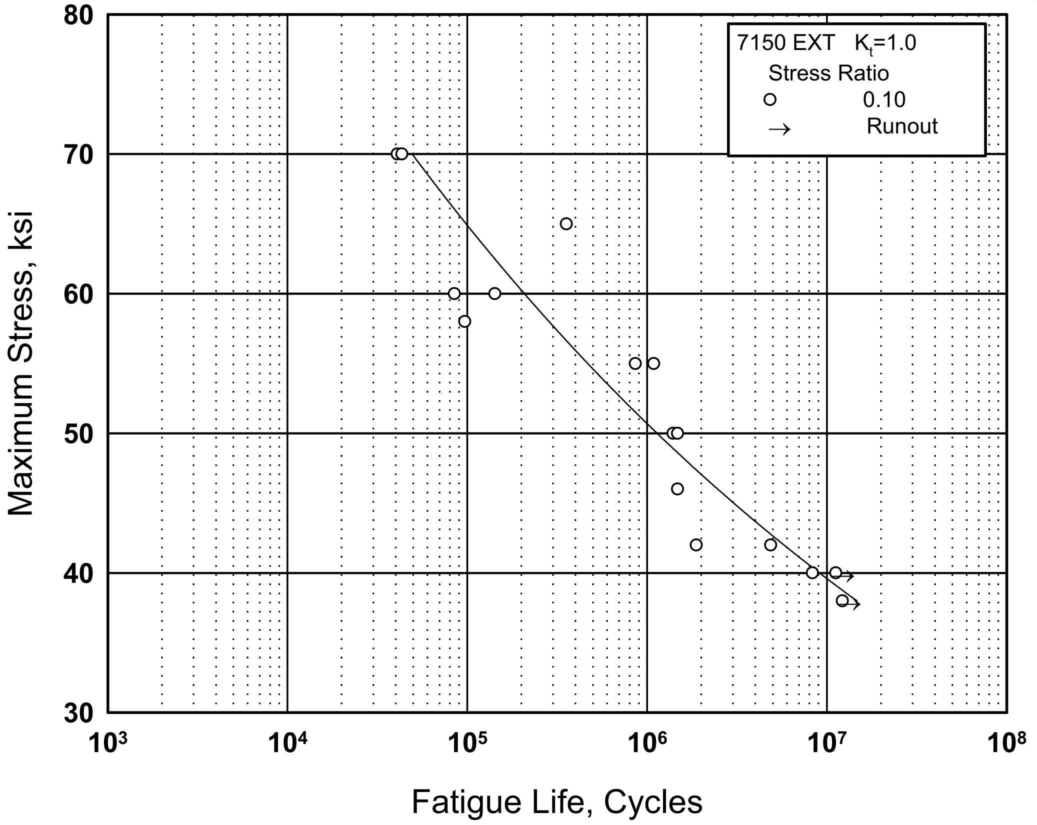


Figure 3.7.7.2.8(a). Best-fit S/N curves for unnotched 7150-T77511 aluminum alloy extrusion, longitudinal orientation.

Correlative Information for Figure 3.7.7.2.8(a).

Product Forms: Extruded shape, 1.125 inch, 1.45 inch

Properties:

TUS, ksi	TYS, ksi	Temp., °F
89	84	RT

Specimen Details: Unnotched
Round, 0.3 inch diameter, removed from center of section

Surface Condition: Polished to 10 micro-inch or better

Reference: 3.7.7.2.8

Test Parameters:
Loading - Axial
Frequency - 25 Hz
Temperature - RT
Environment - Air

No. of Heats/Lots: 2

Fatigue Life Equation:
Log N_f = 21.89 - 9.32 log (S_{max})
Std. Error of Estimate, Log (Life) = 0.321
Standard Deviation, Log (Life) = 0.753
R^2 = 81.8%

Sample Size: 16

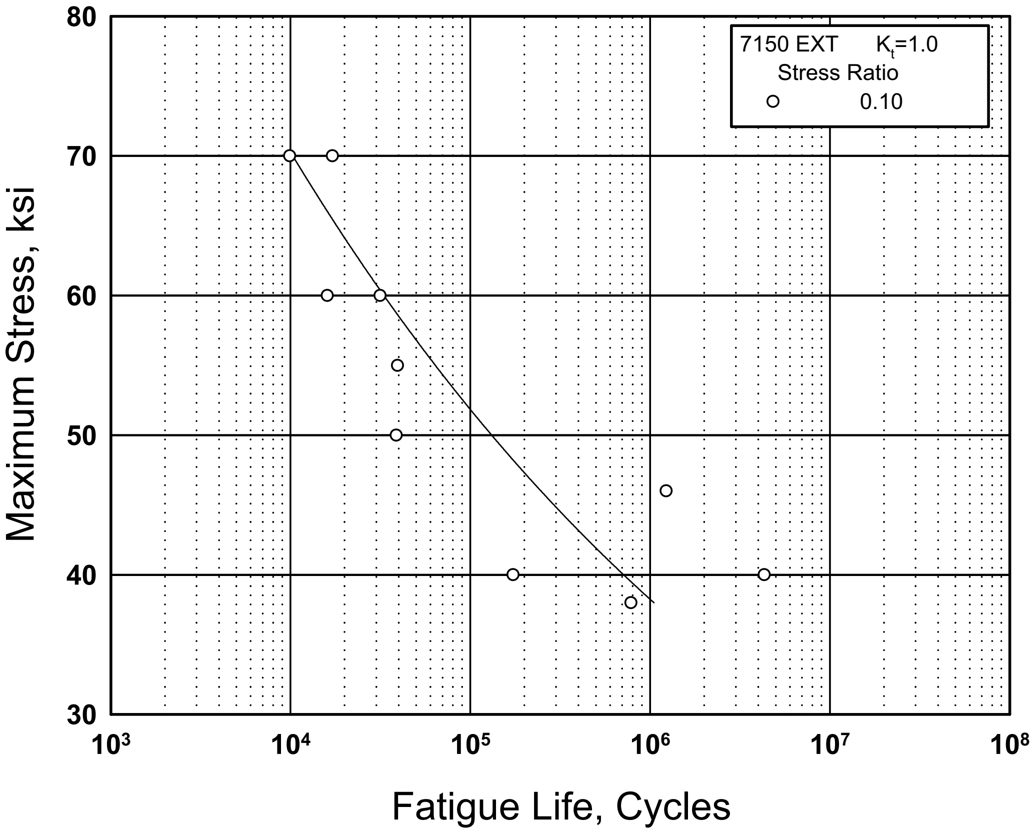


Figure 3.7.7.2.8(b). Best-fit S/N curves for unnotched 7150-T77511 aluminum alloy extrusion, long transverse orientation.

Correlative Information for Figure 3.7.7.2.8(b).

Product Forms: Extruded shape, 1.125 inch, 1.45 inch

Properties:	TUS, ksi	TYS, ksi	Temp.,°F
	83	78	RT

Specimen Details: Unnotched
Round, 0.3 inch diameter, removed from center of section

Surface Condition: Polished to 10 micro-inch or better

Reference: 3.7.7.2.8

Test Parameters:
Loading - Axial
Frequency - 25 Hz
Temperature - RT
Environment - Air

No. of Heats/Lots: 2

Fatigue Life Equation:
Log N_f = 17.98 - 7.57 log (S_{max})
Std. Error of Estimate, Log (Life) = 22.53(1/S_{max})
Standard Deviation, Log (Life) = 0.977
R^2 = 74.4 %

Sample Size: 10

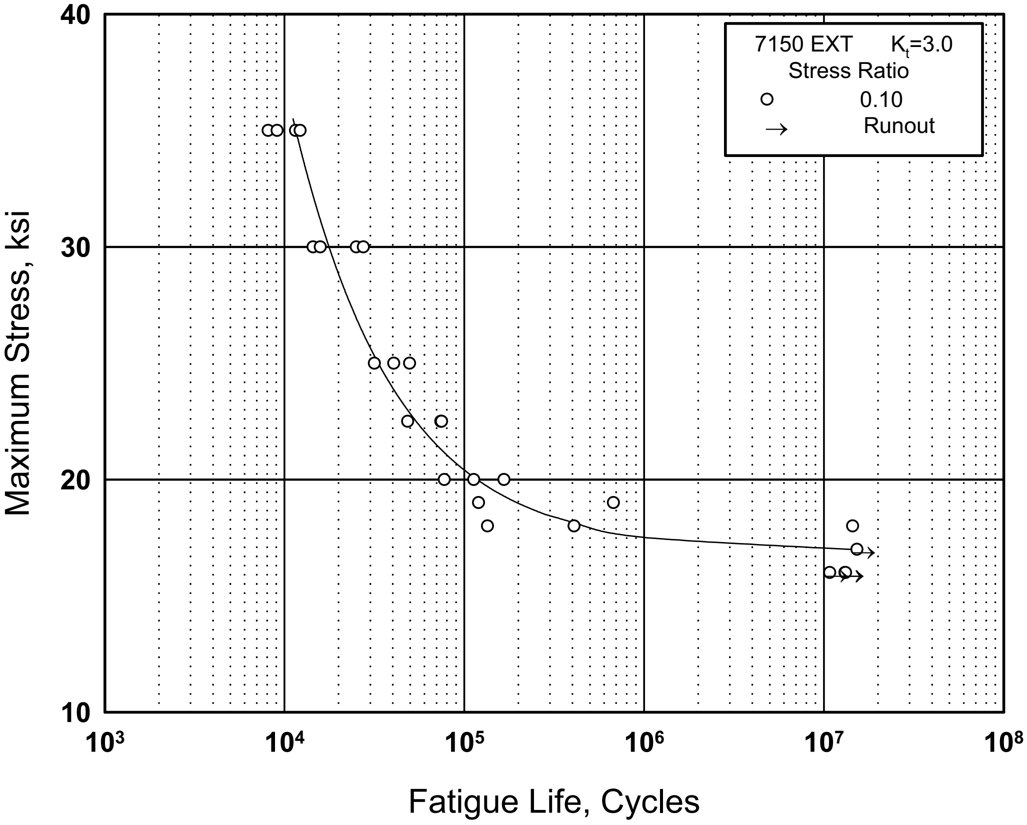


Figure 3.7.7.2.8(c). Best-fit S/N curves for notched, K_t = 3.0, 7150-T77511 aluminum alloy extrusion, longitudinal and long transverse orientations.

Correlative Information for Figure 3.7.7.2.8(c).

Product Forms: Extruded shape, 1.125 inch, 1.45 inch

Properties:	TUS, ksi	TYS, ksi	Temp.,°F
Longitudinal	89	84	RT
Long Transverse	83	78	RT

Specimen Details: Circumferentially notched, K_t = 3.0 round, 0.253 inch net diameter, 0.013 inch root radius, removed from center of section

Surface Condition: Notch

Reference: 3.7.7.2.8

Test Parameters:
Loading - Axial
Frequency - 25 Hz
Temperature - RT
Environment - Air

No. of Heats/Lots: 2

Fatigue Life Equation:
$\text{Log } N_f = 5.71 - 1.31 \log (S_{max} - 16.92)$
Std. Error of Estimate, Log (Life) = $4.51 (1/S_{max})$
Standard Deviation, Log (Life) = 0.750
R^2 = 92.4%

Sample Size: 25

3.7.8 7175 ALLOY

3.7.8.0 *Comments and Properties* — 7175 is a high-purity, high-strength Al-Zn-Mg-Cu alloy. In the form of die forgings the alloy is available in the T66, T74, and T7452 tempers. Die forgings of 7175-T66 develop higher static strength than 7075-T6 forgings with fatigue, fracture, and stress-corrosion properties about equivalent to those of 7075-T6 forgings. 7175-T74-type die and hand forgings develop static strengths about equivalent to those of 7075-T6 forgings, with toughness and fatigue properties equal or superior to those of 7075-T73 forgings. The T74-type temper provides stress-corrosion resistance and strength characteristics intermediate to those of T76 and T73 in 7075. Refer to Section 3.1.2.3 for comments regarding the resistance of the alloy to stress-corrosion cracking, and to Section 3.1.3.4 for comments regarding the weldability of the alloy.

The properties of extrusions should be based upon the thickness at the time of quenching prior to machining. Selection of the mechanical properties based upon its final machined thickness may be unconservative; therefore, the thickness at the time of quenching to achieve properties is an important factor in the selection of the proper thickness column. For extrusions having sections with various thicknesses, consideration should be given to the properties as a function of thickness.

Material specifications for 7175 are presented in Table 3.7.8.0(a). Room-temperature mechanical and physical properties are shown in Tables 3.7.8.0(b) through (d).

Table 3.7.8.0(a). Material Specifications for 7175 Aluminum Alloy

Specification	Form
AMS 4148	Die forging
AMS 4149	Die and hand forging
AMS 4179	Hand forging
AMS-A-22771	Forging
AMS 4344	Extrusion

The temper index for 7175 is as follows:

Section	Temper
3.7.8.1	T73511
3.7.8.2	T74 and T7452 (formerly T736 and T73652)

3.7.8.1 *T73511 Temper* — Figures 3.7.8.1.6(a) and (b) show tensile and compressive stress-strain and tangent-modulus curves for extrusion. Figures 3.7.8.1.8(a) through (d) present fatigue curves for extrusion.

3.7.8.2 *T74 and T7452 Tempers* — Figures 3.7.8.2.6(a) through (f) present tensile and compressive stress-strain and tangent-modulus curves for die and hand forging. Figures 3.7.8.2.8(a) and (b) present fatigue curves for die and hand forging.

Table 3.7.8.0(b). Design Mechanical and Physical Properties of 7175 Aluminum Alloy Die Forging

Specification	AMS 4148	AMS 4149						
Form	Die forging							
Temper	T66	T74[a,b]						
Thickness, in.	≤3.000	<1.000	1.001-2.000		2.001-3.000	3.001-4.000	4.001-5.000	5.001-6.000
Basis	S	S	A	B	S	S	S	S
Mechanical Properties:								
F_{tu}, ksi:								
L	86	76	74	77	76	73	70	68
T[c]	77	71	71[d]	...	71	70	68	65
F_{ty}, ksi:								
L	76	66	64	67	66	63	61	58
T[c]	66	62	62[d]	...	62	60	58	55
F_{cy}, ksi:								
L	...	67	65	68	67	...	...	...
ST	...	63	61	64	63	...	...	...
F_{su}, ksi	...	43	42	44	43	...	...	...
F_{bru}[e], ksi:								
(e/D = 1.5)	...	106	105	109	106	...	...	...
(e/D = 2.0)	...	140	137	142	140	...	...	...
F_{bry}[e], ksi:								
(e/D = 1.5)	...	86	84	88	86	...	...	...
(e/D = 2.0)	...	102	99	103	102	...	...	...
e, percent (S-basis):								
L	7	7	7	...	7	7	7	7
T[c]	4	4	4	...	4	4	4	4
E, 10^3 ksi	10.2							
E_c, 10^3 ksi	10.7							
G, 10^3 ksi	3.9							
μ	0.33							
Physical Properties:								
ω, lb/in.^{3}	0.101							
C, Btu/(lb)(°F)	0.23 (at 212°F)							
K, Btu/[(hr)(ft^2)(°F)/ft]	76 (at 77°F for T66); 90 (at 77°F for T736)							
α, 10^{-6} in./in./°F	12.9 (68 to 212°F)							

a When die forgings are machined before heat treatment, section thickness at time of heat treatment will determine minimum mechanical properties as long as original (as-forged) thickness does not exceed maximum thickness for the alloy as shown in the table.

b Design allowables were based upon data obtained from testing die forgings, heat treated by suppliers, and supplied in T74 temper.

c T indicates any grain direction not within ±15° of being parallel to the forging flow lines. F_{cy}(T) values are based upon short transverse (ST) test data.

d Specification value. T tensile properties are presented on an S basis only.

e Bearing values are "dry pin" values per Section 1.4.7.1.

Table 3.7.8.0(c_1). Design Mechanical and Physical Properties of 7175 Aluminum Alloy Hand Forging

Specification	AMS 4149 and AMS-A-22771				
Form	Hand forging				
Temper	T74				
Thickness or Diameter[a,b], in.	1.001-2.000	2.001-3.000	3.001-4.000	4.001-5.000	5.001-6.000
Basis	S	S	S	S	S
Mechanical Properties:					
F_{tu}, ksi:					
L	73	73	71	68	65
LT	71	71	70	67	64
ST	...	69	68	66	63
F_{ty}, ksi:					
L	63	63	61	57	54
LT	60	60	58	56	52
ST	...	60	57	55	52
F_{cy}, ksi:					
L	63	63	61	59	55
LT	62	63	61	60	56
ST	61	62	60	59	55
F_{su}, ksi:					
L	43	43	43	41	39
LT	42	42	41	39	38
ST	42	42	41	39	38
F_{bru}[c], ksi:					
(e/D = 1.5)	106	106	104	100	95
(e/D = 2.0)	138	138	136	131	125
F_{bry}[c], ksi:					
(e/D = 1.5)	73	78	80	81	76
(e/D = 2.0)	89	94	95	95	90
e, percent:					
L	9	9	9	8	8
LT	5	5	5	5	5
ST	...	4	4	4	4
E, 10^3 ksi	10.2				
E_c, 10^3 ksi	10.6				
G, 10^3 ksi	3.9				
μ	0.33				
Physical Properties:					
ω, lb/in.^{3}	0.101				
C, Btu/(lb)(°F)	0.23 (at 212°F)				
K, Btu/[(hr)(ft^2)(°F)/ft]	90 (at 77°F)				
α 10^{-6} in./in./°F	12.9 (68 to 212°F)				

[a] When hand forgings are machined before heat treatment, the section thickness at time of heat treatment will determine the minimum mechanical properties as long as the original (as-forged) thickness does not exceed the maximum thickness for the alloy as shown in the table.

[b] The maximum cross-sectional area of hand forgings in 256 sq. in.

[c] Bearing values are "dry pin" values per Section 1.4.7.1.

Table 3.7.8.0(c_2). Design Mechanical and Physical Properties of 7175 Aluminum Alloy Hand Forging

Specification	AMS 4149 and AMS-A-22771				
Form	Hand forging				
Temper	T7452				
Thickness or Diameter[a], in.	1.001- 2.000	2.001- 3.000	3.001- 4.000	4.001- 5.000	5.001- 6.000
Basis	S	S	S	S	S
Mechanical Properties:					
F_{tu}, ksi:					
L	71	71	68	65	63
LT	69	69	67	64	61
ST	...	67	65	63	60
F_{ty}, ksi:					
L	61	61	57	54	51
LT	58	58	55	52	49
ST	...	54	51	49	46
F_{cy}, ksi:					
L	58	58	55	52	49
LT	61	61	57	54	50
ST	60	60	57	54	51
F_{su}, ksi:					
L	38	39	39	38	37
LT	38	39	38	38	36
ST	40	41	40	39	38
F_{bru}[b], ksi:					
(e/D = 1.5)	102	102	99	95	90
(e/D = 2.0)	133	133	130	124	118
F_{bry}[b], ksi:					
(e/D = 1.5)	80	82	80	76	72
(e/D = 2.0)	95	98	95	92	87
e, percent:					
L	9	9	9	8	8
LT	5	5	5	5	5
ST	...	4	4	4	4
E, 10^3 ksi	10.2				
E_c, 10^3 ksi	10.5				
G, 10^3 ksi	3.9				
μ	0.33				
Physical Properties:					
ω, lb/in.^{3}	0.101				
C, Btu/(lb)(°F)	0.23 (at 212°F)				
K, Btu/[(hr)(ft^2)(°F)/ft]	90 (AT 77°F)				
α, 10^{-6} in./in./°F	12.9 (68 to 212°F)				

a The maximum cross-sectional area of hand forgings is 256 sq.in.
b Bearing values are "dry pin" values per Section 1.4.7.1.

Table 3.7.8.0(d). Design Mechanical and Physical Properties of 7175 Aluminum Alloy Extrusion

Specification	AMS 4344	
Form	Extrusion	
Condition	T73511	
Cross-Sectional Area, in^2	32-65	
Thickness or Diameter,[a] in.	0.250-0.999	1.000-2.000
Basis	S	S
Mechanical Properties:		
F_{tu}, ksi:		
L	69	69
LT	63	63
F_{ty}, ksi:		
L	59	59
LT	52	52
F_{cy}, ksi:		
L	...	59
LT	...	59
F_{su}, ksi	...	40
F_{bru}[b], ksi:		
(e/D = 1.5)	...	97
(e/D = 2.0)	...	125
F_{bry}[b], ksi:		
(e/D = 1.5)	...	79
(e/D = 2.0)	...	95
e, percent:		
L	...	8
LT	...	4
E, 10^3 ksi	10.1	
E_c, 10^3 ksi	10.5	
G, 10^3 ksi	3.9	
μ	0.33	
Physical Properties:		
ω, lb/in.^{3}	0.101	
C, Btu/(lb)(°F)	0.23 (at 212°F)	
K, Btu/[(hr)(ft^2)(°F)/ft]	...	
α, 10^{-6} in./in./°F	12.9 (68 to 212°F)	

[a] The mechanical properties are to be based upon the thickness at the time of quench.

[b] Bearing values are "dry pin" values per Section 1.4.7.1.

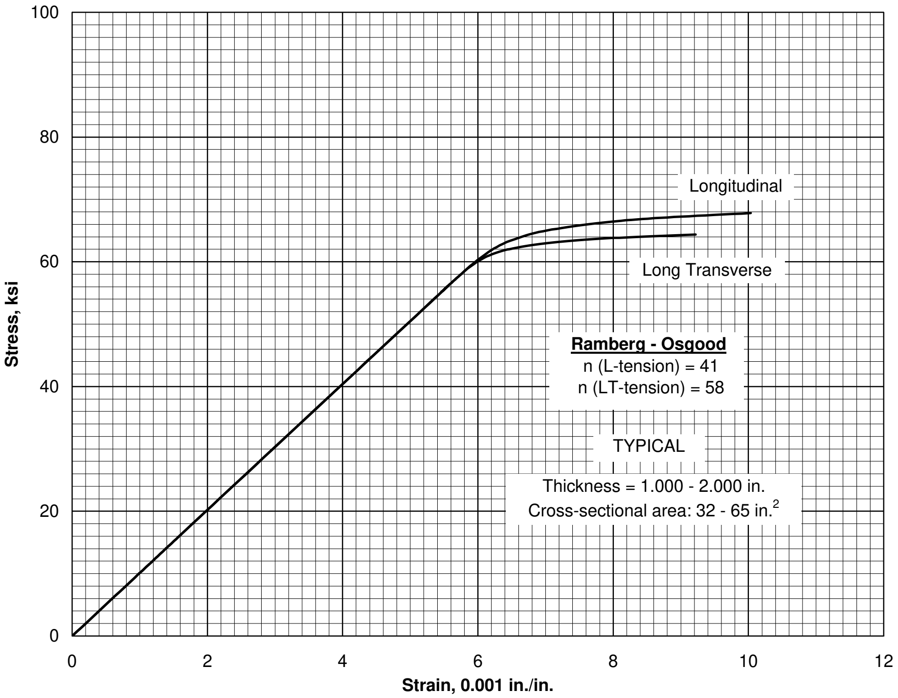


Figure 3.7.8.1.6(a). Typical tensile stress-strain curves for aluminum alloy 7175-T73511 extrusion at room temperature.

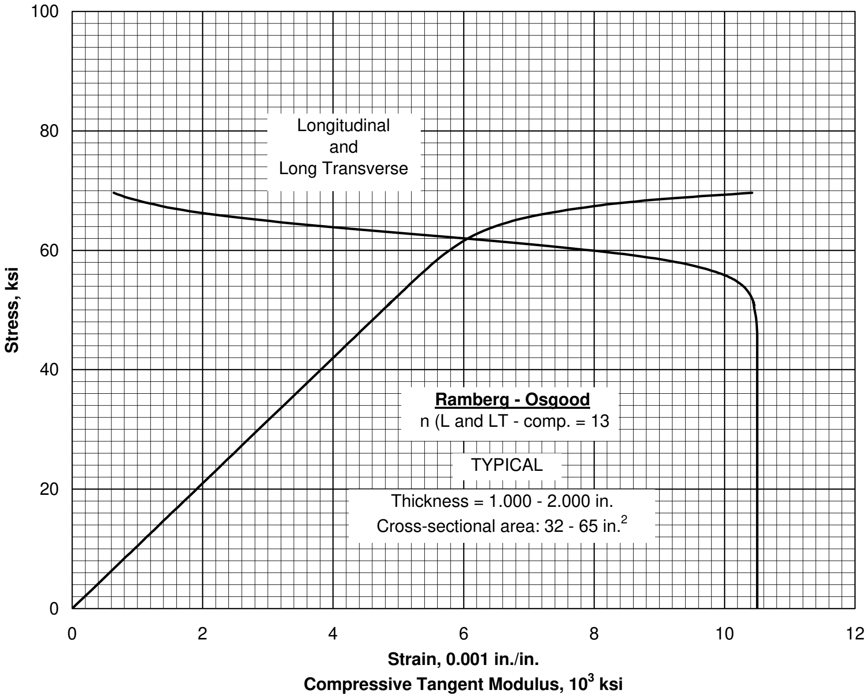


Figure 3.7.8.1.6(b). Typical compressive stress-strain and tangent-modulus curves for aluminum alloy 7175-T73511 extrusion at room temperature.

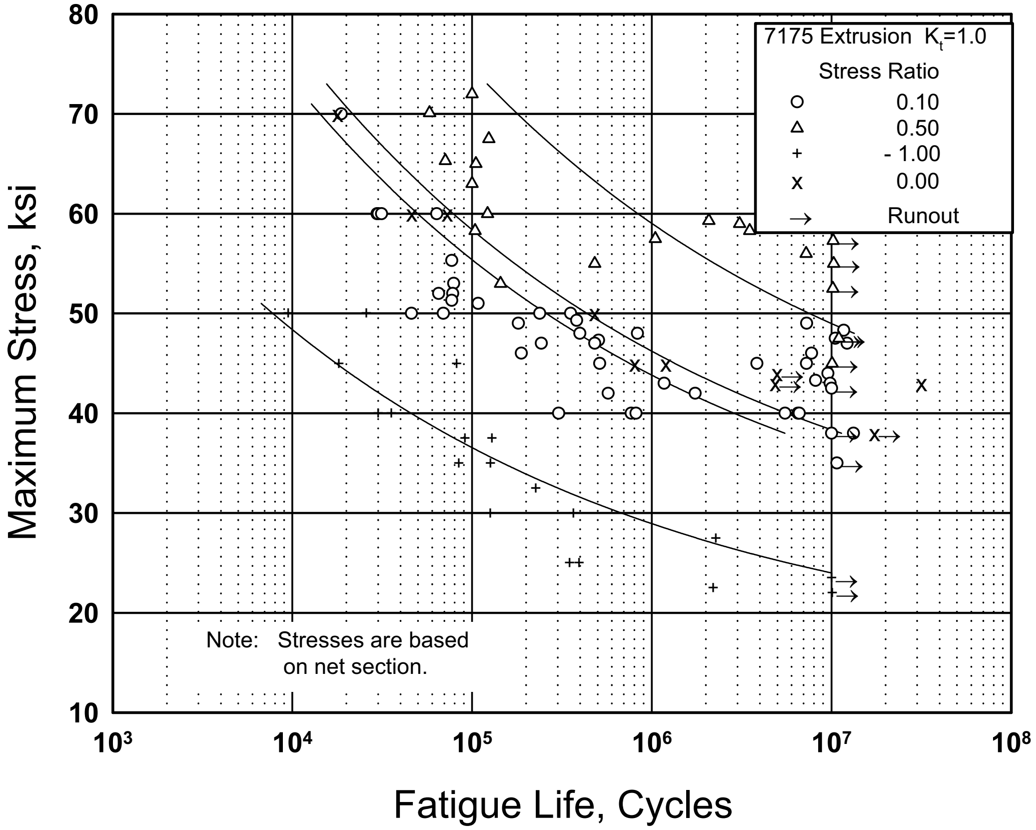


Figure 3.7.8.1.8(a). Best-fit S/N curves for unnotched 7175-T73511 alloy extrusion, longitudinal direction.

Correlative Information for Figure 3.7.8.1.8(a)

Product Form: Extrusion 1.8 inch thick, extruded round, 3.75 inch diameter, extruded rectangle, 2.5 x 5 inch thick, extrusion, unspecified size

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	76	67	70

Specimen Details: 0.25 inch minimum diameter hourglass gage section 30 inch diameter

Surface Condition: 32 RMS gage section specified

References: 3.7.8.1.8(a), (b), and (c)

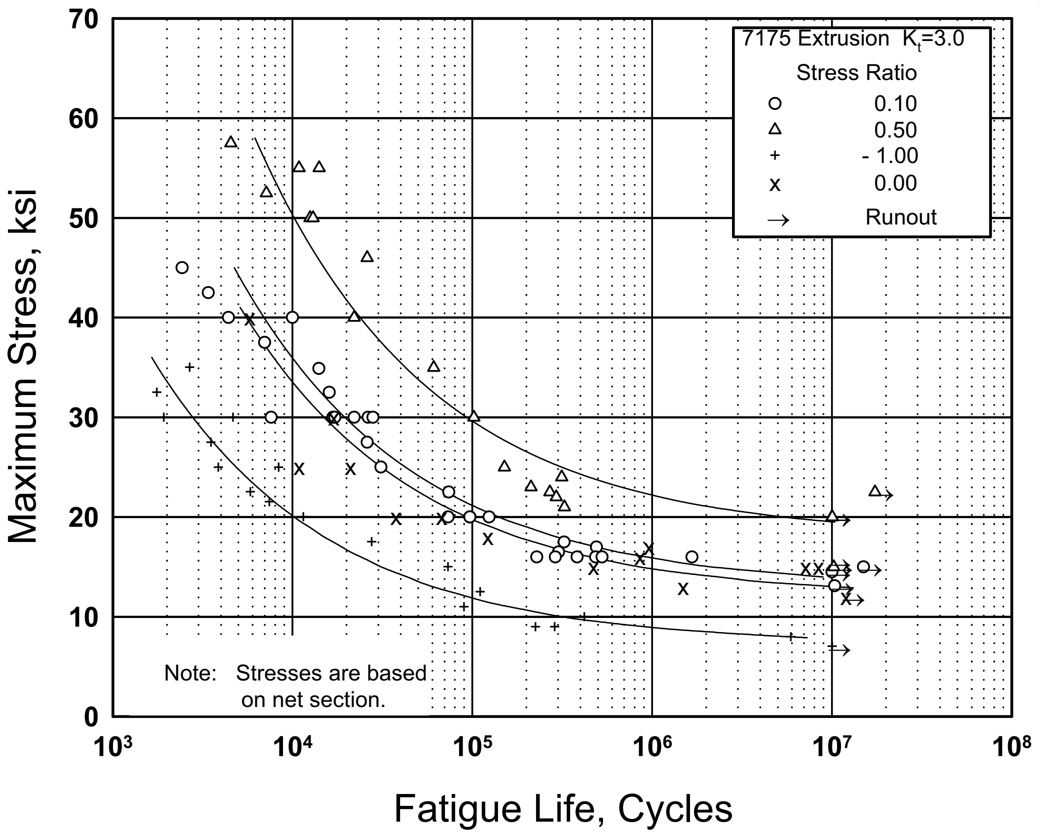
Test Parameters:
Loading - Axial
Frequency - Not specified
Temperature - 70°F
Environment - Air

No. of Heats/Lots: 11

Equivalent Stress Equation:
Log N_f = 12.01-5.26 log (S_{eq})
S_{eq} = S_a + 0.32S_m - 15.04
Std. Error of Estimate, Log (Life) = 18.44(1/S_{eq})
Standard Deviation, Log (Life) = 1.35
R^2 = 58%

Sample Size = 96

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]



Note: Stresses are based on net section.

Figure 3.7.8.1.8(b). Best-fit S/N curves for notched, K_t = 3.0, 7175-T73511 alloy extrusion, longitudinal direction.

<u>Correlative Information for Figure 3.7.8.1.8(b)</u>

<u>Product Form</u>: Extrusion 1.8 inch thick, extruded round, 3.75 inch diameter, extruded rectangle, 2.5 x 5 inch thick, extrusion, unspecified size

<u>Properties</u>:

TUS, ksi	TYS, ksi	Temp., °F
76	67	70

<u>Specimen Details</u>: Circumferential notch, K_t = 3
0.50 inch gross diameter
0.36 inch net diameter
0.0005 inch notch radius
Circumferential 60° V notch

<u>References</u>: 3.7.8.1.8(a), (b), and (c)

<u>Test Parameters:</u>
Loading - Axial
Frequency - Not specified
Temperature - 70°F
Environment - Air

<u>No. of Heats/Lots</u>: 11

<u>Equivalent Stress Equation</u>:
$\text{Log } N_f = 6.50 - 2.25 \log (S_{eq})$
$S_{eq} = S_a + 0.20 S_m - 7.21$
Std. Error of Estimate, Log (Life) = $3.92(1/S_{eq})$
Standard Deviation, Log (Life) = 1.51
R^2 = 91%

<u>Sample Size</u> = 86

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

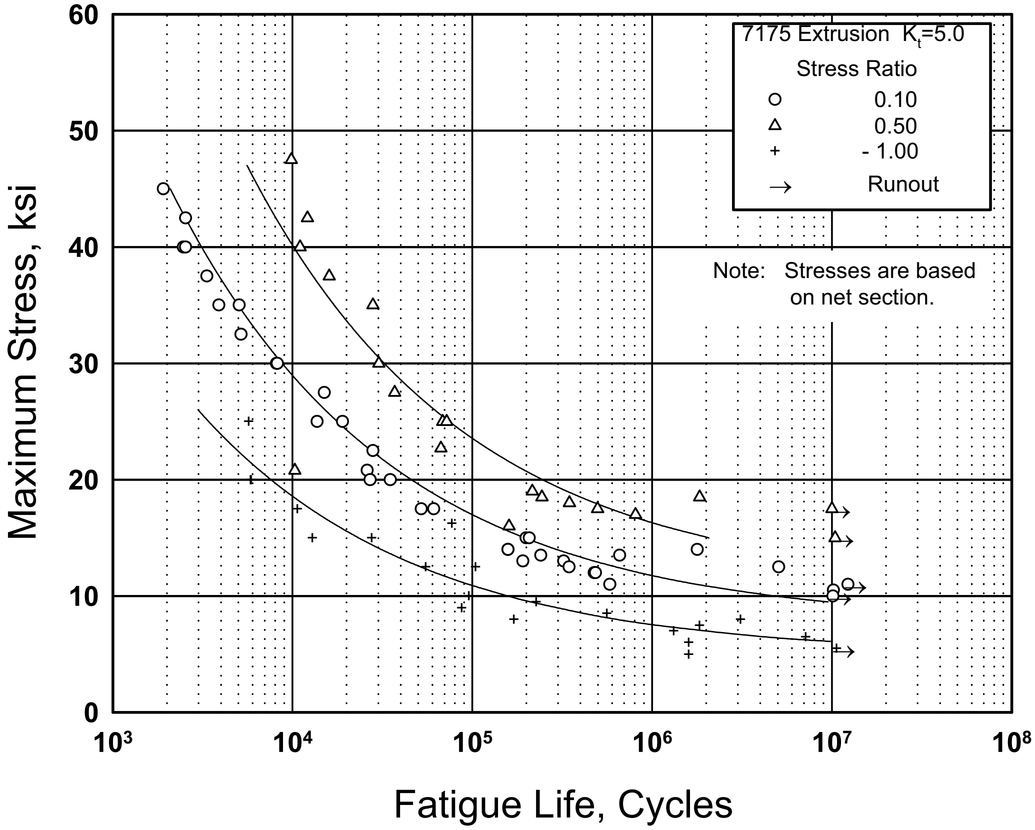


Figure 3.7.8.1.8(c). Best-fit S/N curves for notched, K_t = 5.0, 7175-T73511 alloy extrusion, longitudinal direction.

Correlative Information for Figure 3.7.8.1.8(c)

Product Form: Extrusion 1.8 inch thick

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	76	67	70

Specimen Details: Circumferential notch, K_t = 5
0.50 inch gross diameter
0.36 inch net diameter
0.0005 inch notch radius

References: 3.7.8.1.8(a) and (b)

Test Parameters:
Loading - Axial
Frequency - Not specified
Temperature - 70°F
Environment - Air

No. of Heats/Lots: 10

Equivalent Stress Equation:
Log N_f = 7.63-2.78 log (S_{eq}-7.3)
$S_{eq} = S_{max}(1-R)^{0.56}$
Std. Error of Estimate, Log (Life) = 3.71(1/S_{eq})
Standard Deviation, Log (Life) = 1.45
R^2 = 90%

Sample Size = 136

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

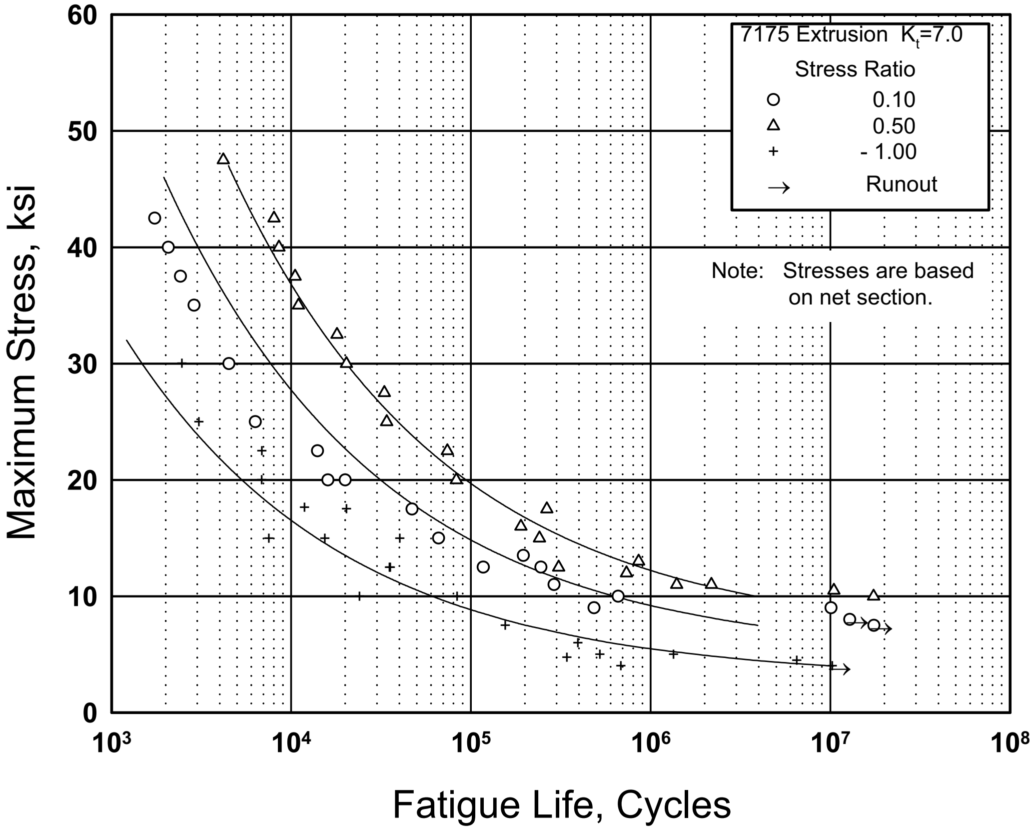


Figure 3.7.8.1.8(d). Best-fit S/N curves for notched, K_t = 7.0, 7175-T73511 alloy extrusion, longitudinal direction.

Correlative Information for Figure 3.7.8.1.8(d)

Product Form: Extrusion 1.8 inch thick

Properties:

TUS, ksi	TYS, ksi	Temp., °F
76	67	70

Specimen Details: Circumferential notch, K_t = 7
0.50 inch gross diameter
0.36 inch net diameter
0.0005 inch notch radius

References: 3.7.8.1.8(a) and (b)

Test Parameters:
Loading - Axial
Frequency - Not specified
Temperature - 70°F
Environment - Air

No. of Heats/Lots: 9

Equivalent Stress Equation:
$\text{Log } N_f = 7.15 - 2.78 \log (S_{eq})$
$S_{eq} = S_a + 0.27 S_m - 2.88$
Std. Error of Estimate, Log (Life) =
$0.11 + 1.60\,(1/S_{eq})$
Standard Deviation, Log (Life) = 1.55
R^2 = 92%

Sample Size = 63

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

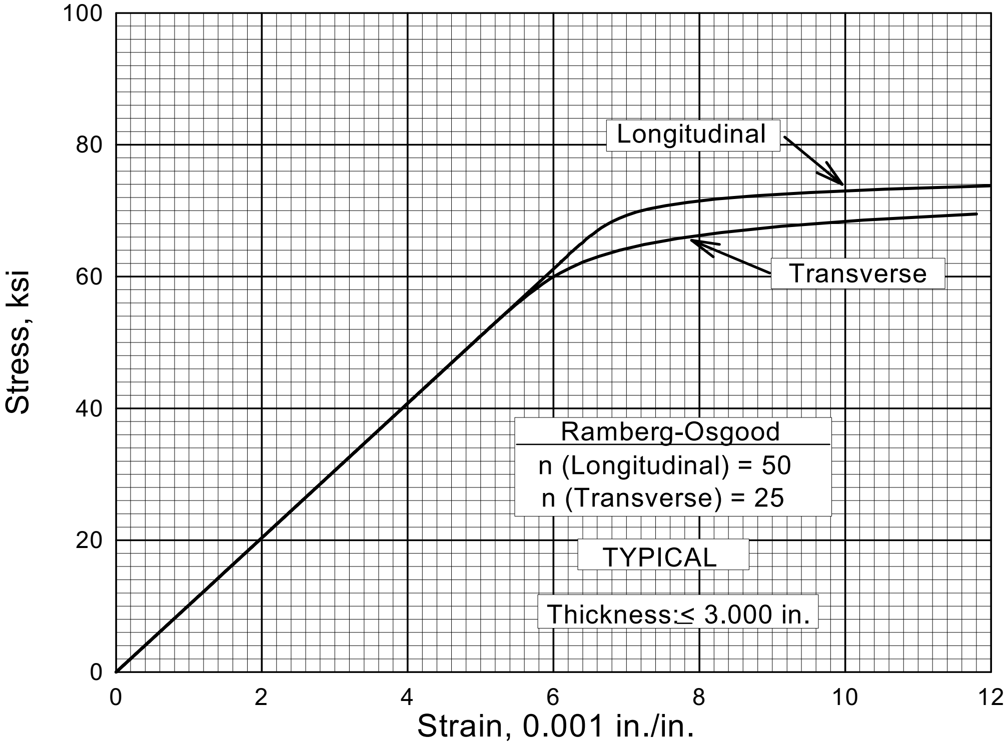


Figure 3.7.8.2.6(a). Typical tensile stress-strain curves for 7175-T74 aluminum alloy die forging at room temperature.

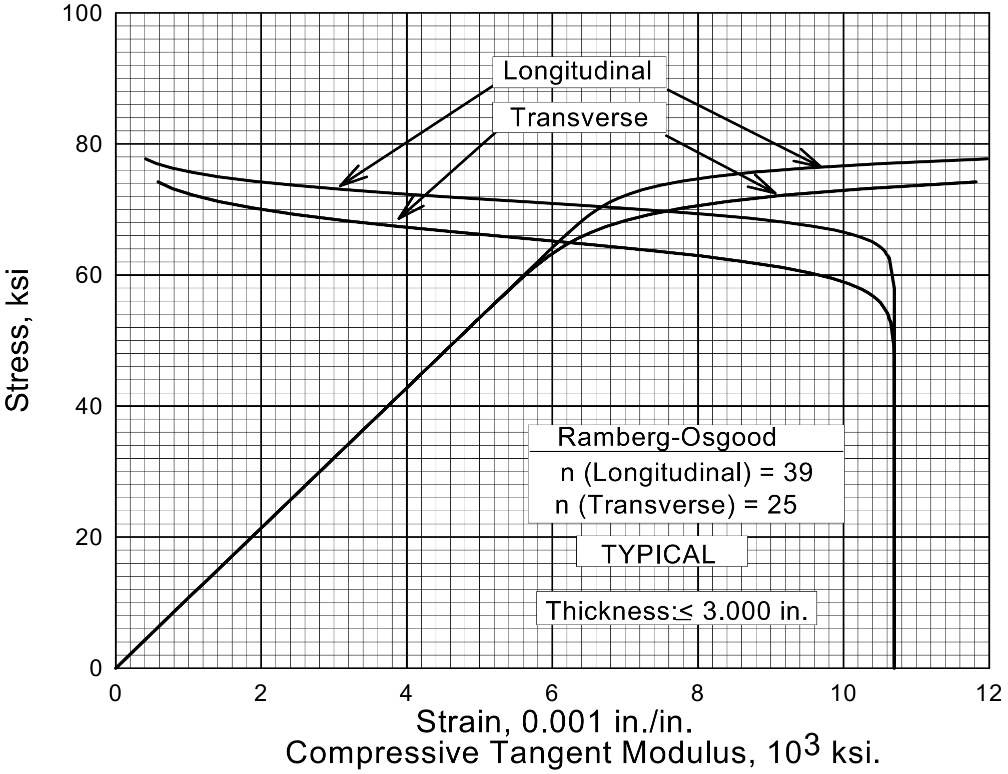


Figure 3.7.8.2.6(b). Typical compressive stress-strain and compressive tangent-modulus curves for 7175-T74 aluminum alloy die forging at room temperature.

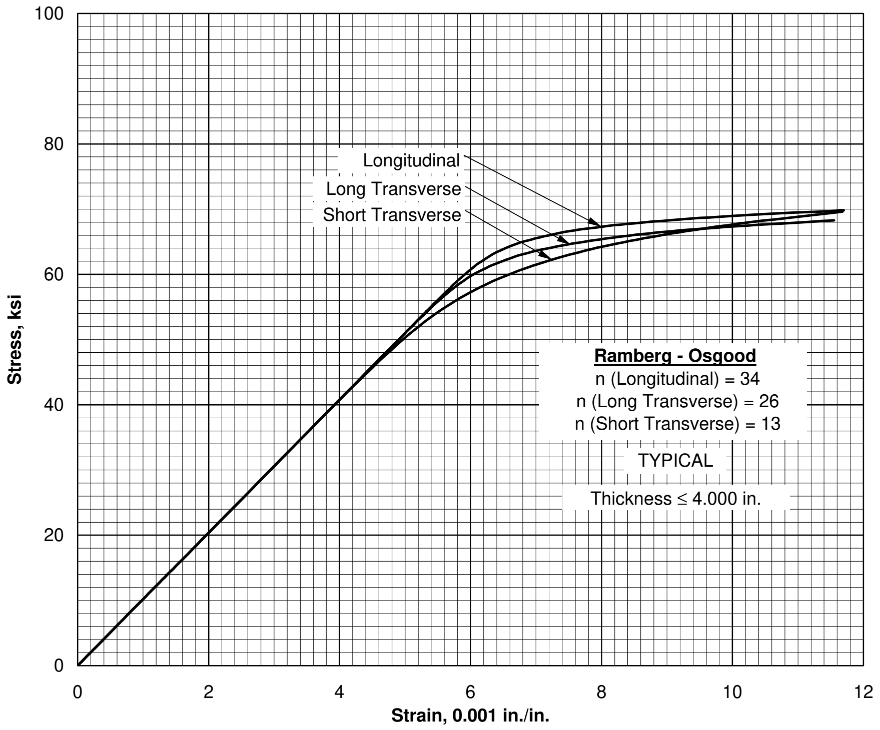


Figure 3.7.8.2.6(c). Typical tensile stress-strain curves for 7175-T74 aluminum alloy hand forging at room temperature.

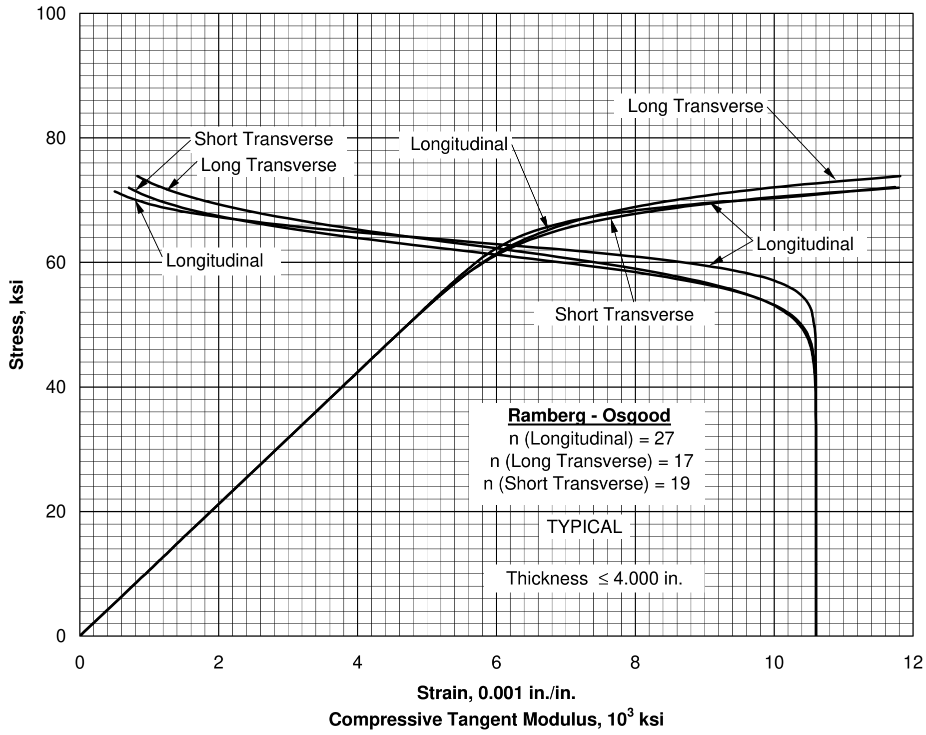


Figure 3.7.8.2.6(d). Typical compressive stress-strain and compressive tangent-modulus curves for 7175-T74 aluminum alloy hand forging at room temperature.

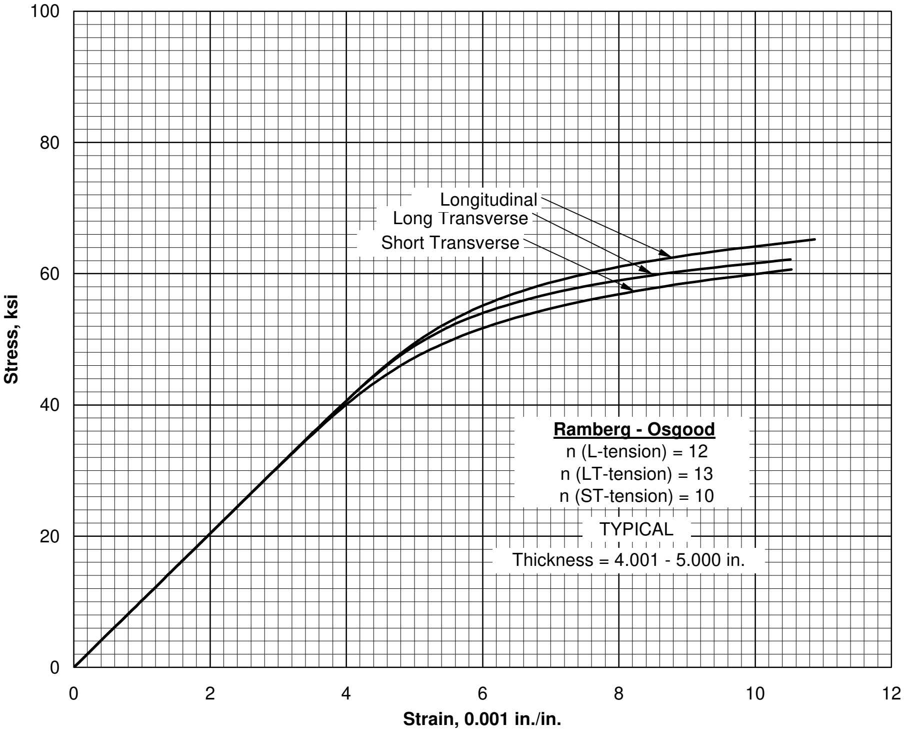


Figure 3.7.8.2.6(e). Typical tensile stress-strain curves for aluminum alloy 7175-T7452 hand forging at room temperature.

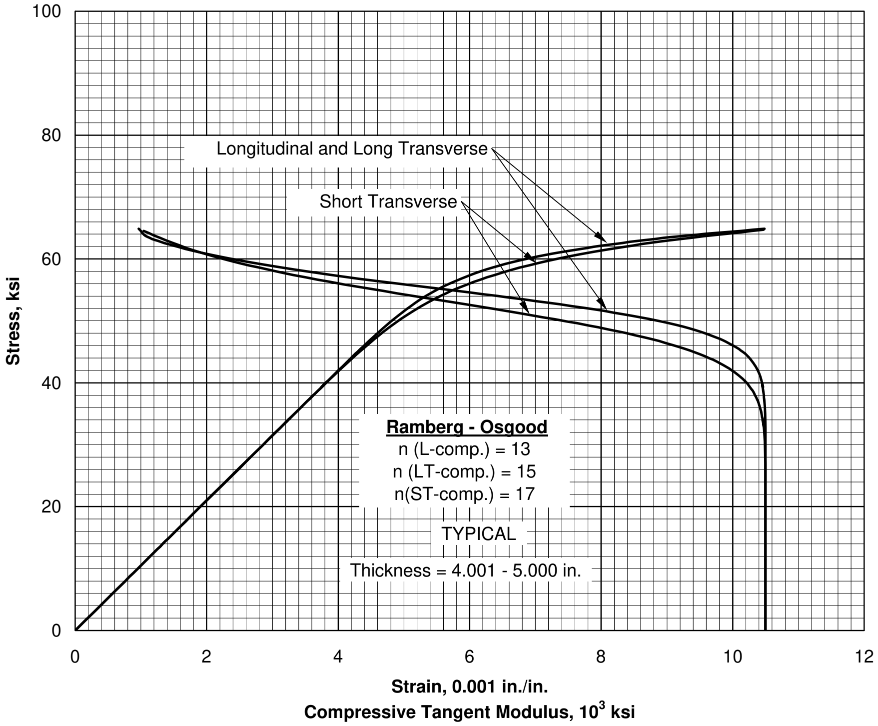


Figure 3.7.8.2.6(f). Typical compressive stress-strain and compressive tangent-modulus curves for aluminum alloy 7175-T7452 hand forging at room temperature.

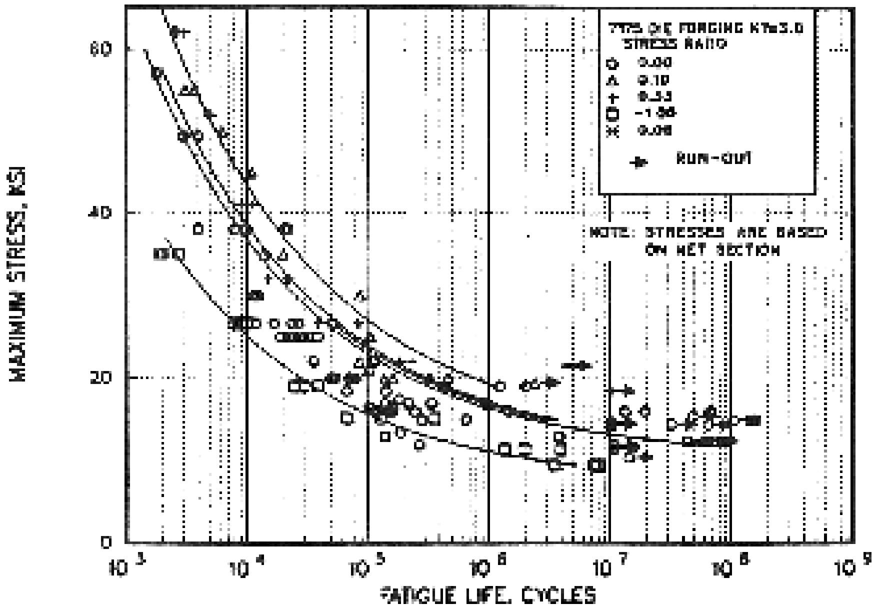


Figure 3.7.8.2.8(a). Best-fit S/N curves for notched, K_t=3.0, 7175-T74 alloy die forging, longitudinal direction.

Correlative Information for Figure 3.7.8.2.8(a)

Product Form: Die forging, 2.0 to 3.0 inch thick, unspecified thickness

Properties:

TUS, ksi	TYS, ksi
77-82	69-75

Specimen Details: Circumferential notch, K_t = 3
0.30 inch gross diameter
0.25 inch net diameter
Rectangular notched 0.10 x 0.20 inch

Surface Condition: Not specified

References: 3.2.5.1.9(d), 3.7.2.1.8(c), (d), 3.7.8.2.8(a), (b), and (c)

Test Parameters:
Loading - Axial
Frequency - 1200 cpm unspecified
Temperature - 70°F
Environment - Air

No. of Heats/Lots: 13

Equivalent Stress Equation:
Log N_f = 7.88-3.09 log (S_{eq}-7.15)
$S_{eq} = S_a + 0.37S_m$
Std. Error of Estimate, Log (Life) = 7.38 ($1/S_{eq}$)
Standard Deviation, Log (Life) = 1.95
R^2 = 83%

Sample Size = 137

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

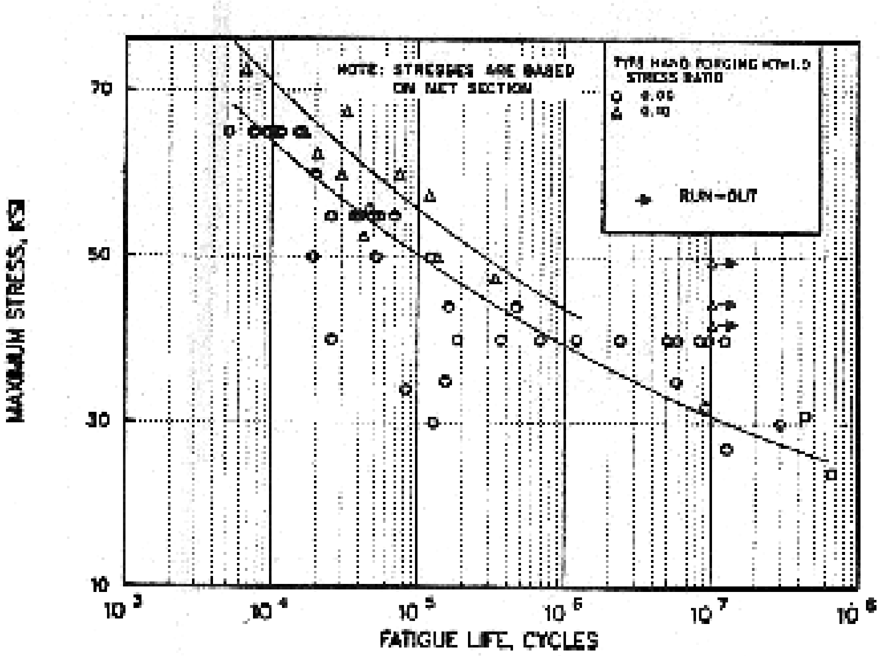


Figure 3.7.8.2.8(b). Best-fit S/N curves for unnotched 7175-T74 alloy hand forging, longitudinal and transverse directions.

Correlative Information for Figure 3.7.8.2.8(b)

Product Form: Hand forging, 2.0 to 6.25 inch thick

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	71-77	60-68	70

Specimen Details: Uniform gage length
3.0 inch diameter
Hourglass gage section
0.25 inch minimum diameter

References: 3.2.5.1.9(d) 3.7.2.1.8(c) and (d)

Test Parameters:
Loading - Axial
Frequency - 1200 cpm
Temperature - 20°F
Environment - Air

No. of Heats/Lots: Not Specified

Equivalent Stress Equation:
$\text{Log } N_f = 21.15\text{-}9.49 \log (S_{eq})$
$S_{eq} = S_{max} (1\text{-}R)$
Std. Error of Estimate, Log (Life) = $23.33(1/S_{eq})$
Standard Deviation, Log (Life) = 1.55
$R^2 = 76\%$

Sample Size: 50

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

3.7.9 7249 ALLOY

3.7.9.0 *Comments and Properties* — 7249 is an Al-Zn-Mg-Cu-Cr alloy developed as a derivative from alloy 7149. Alloy 7249 has tighter compositional tolerances on its major constituents and lowered maximums on the interstitials such as Si, Fe, Mn, and Ti than alloy 7149.

7249-T7452 was developed as a replacement material for 7075-T6 forgings, which are susceptible to stress-corrosion cracking and exfoliation. 7249 also has higher strength at the higher thickness ranges and higher ductility than 7075-T6.

Material specifications for 7249 are shown in Table 3.7.9.0(a). Room temperature mechanical properties are shown in Table 3.7.9.0(b).

Table 3.7.9.0(a). Material Specification for 7249 Alloy

Specification	Form
AMS 4334	Hand forging

The temper index for 7249 is as follows:

Section	Temper
3.7.9.1	T7452

3.7.9.1 *T7452 Temper* — Figures 3.7.9.1.6(a) and (b) presents the typical tensile and compressive stress-strain curves and compressive tangent-modulus curves at room temperature. Figure 3.7.9.1.6(c) presents the full range stress-strain curves for hand forged material at room temperature.

Table 3.7.9.0(b). Design Mechanical and Physical Properties of 7249 Aluminum Alloy Hand Forging

Specification	AMS 4334									
Form	Hand forging									
Temper	T7452									
Thickness, in.	≤1.500	1.501-2.000	2.001-2.500	2.501-3.000	3.001-3.500	3.501-3.900	3.901-4.500	4.501-5.000	5.001-5.500	5.501-6.000
Basis	S	S	S	S	S	S	S	S	S	S
Mechanical Properties:										
F_{tu}, ksi:										
L	76	75	74	73	72	71	69	68	67	66
LT	76	75	74	73	72	71	69	68	67	66
ST	...	...	...	...	72	71	69	68	67	66
F_{ty}, ksi:										
L	68	67	66	64	63	61	59	58	56	55
LT	68	67	66	64	63	61	59	58	56	55
ST	...	...	...	...	59	58	57	56	54	53
F_{cy}, ksi:										
L	66	65	64	62	61	59	57	56	54	53
LT	70	69	68	66	65	63	61	60	58	57
ST	73	72	71	68	67	65	63	62	60	59
F_{su}, ksi:										
L[a]	49	48	47	47	46	46	44	44	43	42
LT[a]	47	46	46	45	45	44	43	42	41	41
F_{bru}[b], ksi:										
(e/D = 1.5)	107	106	104	103	101	100	97	96	94	93
(e/D = 2.0)	137	135	134	132	130	128	125	123	121	119
F_{bry}[b], ksi:										
(e/D = 1.5)	94	93	91	88	87	84	82	80	77	76
(e/D = 2.0)	109	107	106	102	101	98	94	93	90	88
e, percent:										
L	12				12					
LT	10				10					
ST	...				5					
E, 10^3 ksi	10.1									
E_c, 10^3 ksi	10.4									
G, 10^3 ksi	3.8									
μ	0.33									
Physical Properties:										
ω, lb/in.^{3}	...									
C, K, and α	...									

a Determined in accordance with ASTM B769.
b Bearing values are "dry pin" values per Section 1.4.7.1.

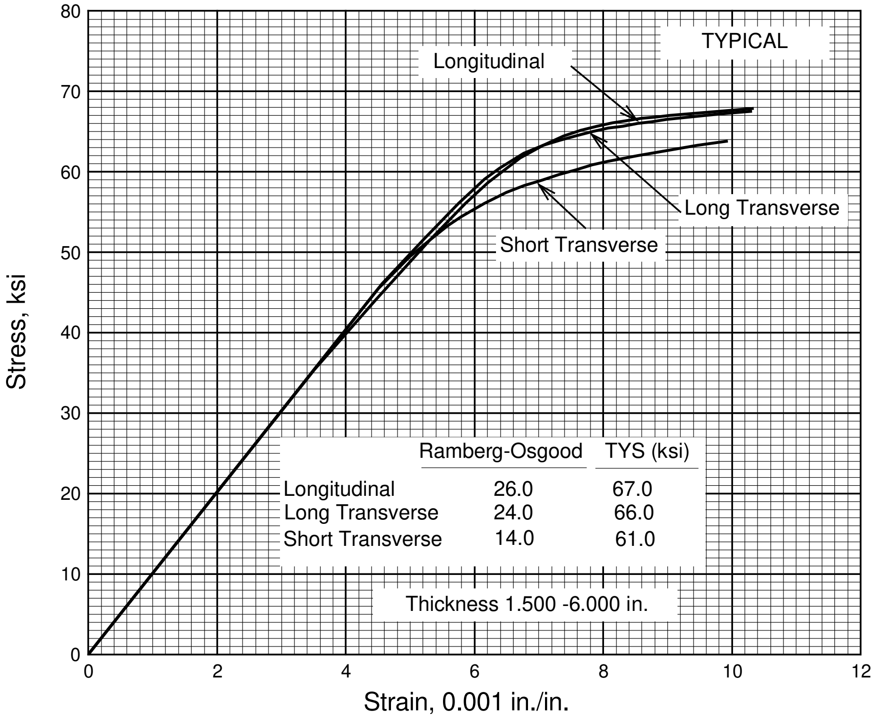


Figure 3.7.9.1.6(a). Typical tensile stress-strain curves for 7249-T7452 aluminum alloy hand forging at room temperature.

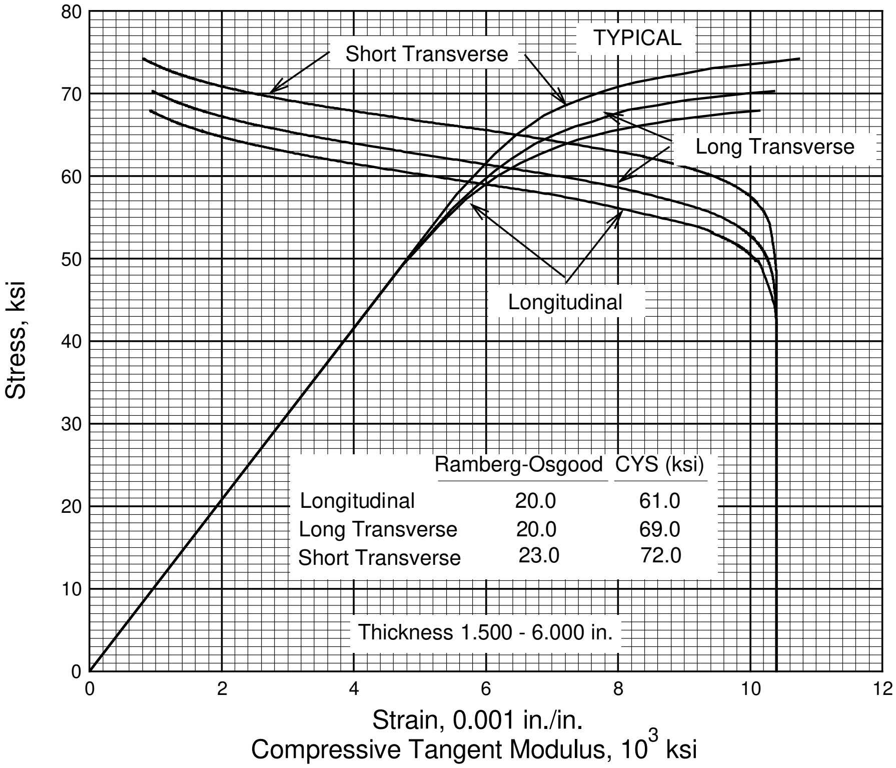
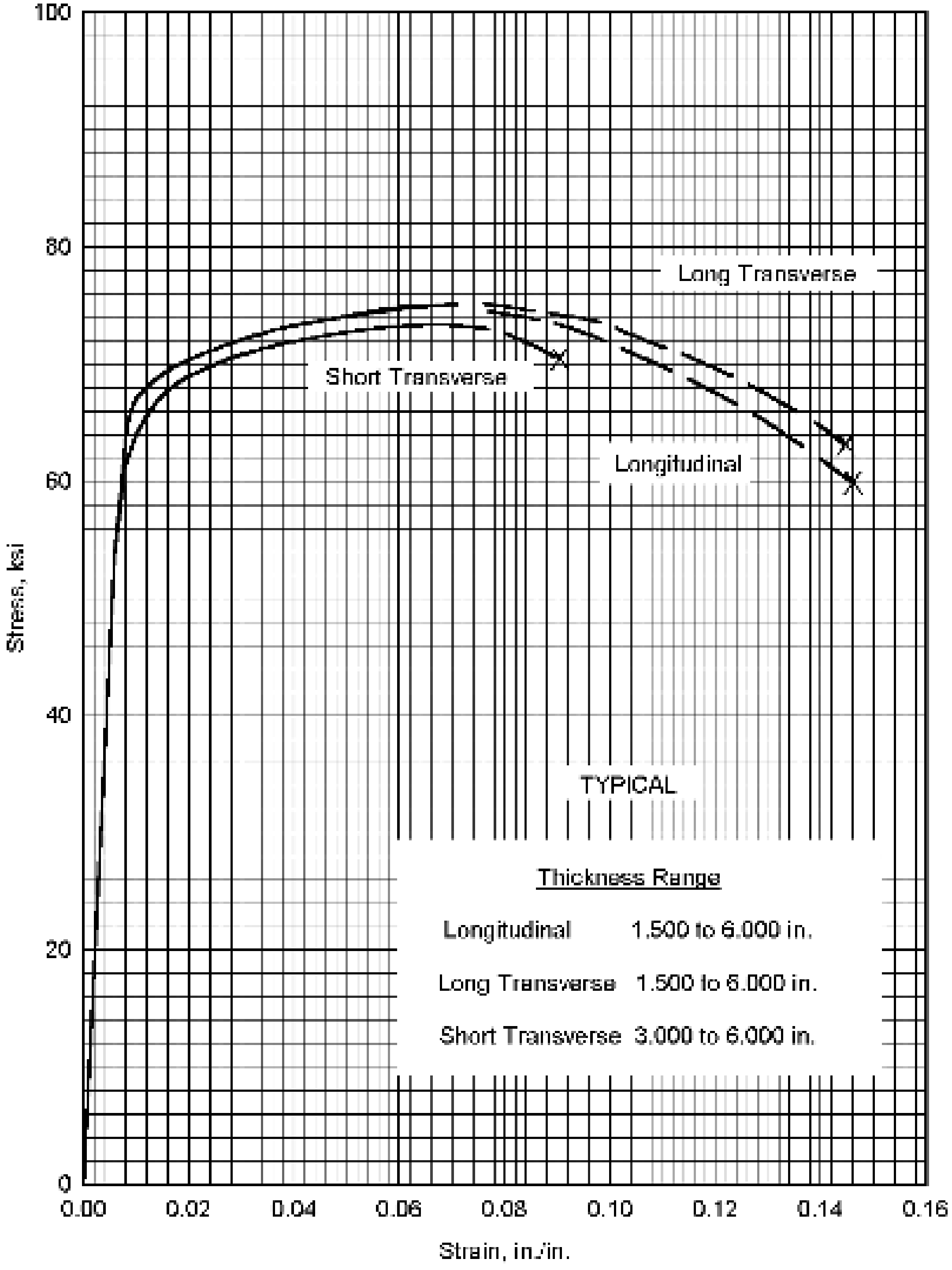


Figure 3.7.9.1.6(b). Typical compressive stress-strain and compressive tangent-modulus curves for 7249-T7452 aluminum alloy hand forging at room temperature.



Thickness Range

Longitudinal	1.500 to 6.000 in.
Long Transverse	1.500 to 6.000 in.
Short Transverse	3.000 to 6.000 in.

Figure 3.7.9.1.6(c). Typical tensile stress-strain curves (full range) for 7249-T7452 aluminum alloy hand forging at room temperature.

3.7.10 7475 ALLOY

3.7.10.0 *Comments and Properties* — 7475 is an Al-Zn-Mg-Cu alloy developed for applications requiring the high strength of 7075 but having fracture toughness superior to that of 7075. Sheet is available in the T61 and T761 tempers and plate in the T651 and T7651 tempers. Sheet has strength approximately the same as that of 7075 combined with toughness about the same as 2024-T3 at room temperature. Plate has strengths similar to those of corresponding tempers of 7075; the toughness of 7475-T651 equals or exceeds that of 7075-T7351.

Resistance to stress-corrosion cracking and exfoliation are comparable to that of 7075. The T73-type temper provides for much improved stress-corrosion resistance over T6-type temper with a decrease in strength. The T76-type temper provides for improved exfoliation resistance and stress-corrosion resistance over T6-type temper with some decrease in strength. Refer to Section 3.1.2.3.1 for information regarding resistance to stress-corrosion cracking.

Refer to Section 3.1.3.4 for comments regarding the weldability of the alloy.

Material specifications are shown in Table 3.7.10.0(a). Room-temperature mechanical and physical properties are shown in Tables 3.7.10.0(b) through (d).

Table 3.7.10.0(a). Material Specifications for 7475 Aluminum Alloy

Specification	Form
AMS 4084	Bare sheet
AMS 4085	Bare sheet
AMS 4090	Bare plate
AMS 4089	Bare plate
AMS 4202	Bare plate
AMS 4207	Clad sheet
AMS 4100	Clad sheet

The temper index for 7475 is as follows:

Section	Temper
3.7.10.1	T61 and T651
3.7.10.2	T7351
3.7.10.3	T761 and T7651

3.7.10.1 *T61 and T651 Tempers* — Figures 3.7.10.1.6(a) through (f) present tensile and compressive stress-strain and tangent-modulus curves for T61 sheet and T651 plate. Figure 3.7.10.1.6(g) contains full-range tensile curves for T61 sheet. Fatigue data for sheet are shown in Figures 3.7.10.1.8(a) through (c). Graphical displays of the residual behavior strength of middle-tension panels are presented in Figures 3.7.10.1.10(a) through (d).

3.7.10.2 *T7351 Temper* — Figures 3.7.10.2.6(a) and (b) present tensile and compressive stress-strain and tangent-modulus curves for T7351 plate. Fatigue data for 7475-T7351 plate are presented in

Figures 3.7.10.2.8(a) and (b). Figures 3.7.10.2.9(a) and (b) present fatigue-crack-propagation data for T7351 plate.

3.7.10.3 *T761 and T7651 Tempers* — Figures 3.7.10.3.6(a) through (j) present tensile and compressive stress-strain and tangent-modulus curves for T761 bare and clad sheet and T7651 plate. Figures 3.7.10.3.6(k) and (1) contain full-range tensile stress-strain curves for T761 bare and clad sheet, respectively. Fatigue data for 7475-T761 sheet are presented in Figures 3.7.10.1.8(a) through (c). Fatigue data for 7475-T7651 plate are shown in Figure 3.7.10.2.8(b). Graphical displays of the residual strength behavior of middle-tension panels are presented in Figures 3.7.10.3.10(a) and (b).

Table 3.7.10.0(b). Design Mechanical and Physical Properties of 7475 Aluminum Alloy Sheet and Plate

Specification	AMS 4084	AMS 4090			AMS 4085			AMS 4089		
Form	Sheet	Plate			Sheet			Plate		
Temper	T61	T651			T761			T7651		
Thickness, in.	0.040-0.249	0.250-0.499	0.500-1.000	1.001-1.500	0.040-0.062	0.063-0.187	0.188-0.249	0.250-0.499	0.500-1.000	1.001-1.500
Basis	S	S	S	S	S	S	S	S	S	S
Mechanical Properties:										
F_{tu}, ksi:										
L	75	77	77	77	71	71	71	70	69	69
LT	75	78	78	78	71	71	71	71	70	70
F_{ty}, ksi:										
L	66	69	70	70	61	61	61	60	59	59
LT	64	67	68	68	60	60	60	60	59	59
F_{cy}, ksi:										
L	64	67	68	67	60	59	58	60	59	59
LT	68	70	71	71	61	63	63	63	62	59
F_{su}, ksi	45	44	43	41	43	42	41	41	39	37
$F_{bru}{}^{a}$, ksi:										
(e/D = 1.5)	120	113	113	113	112	112	111	104	103	103
(e/D = 2.0)	154	144	144	144	143	143	142	136	134	134
$F_{bry}{}^{a}$, ksi:										
(e/D = 1.5)	97	91	93	93	90	90	90	82	81	81
(e/D = 2.0)	110	106	107	107	104	104	104	97	95	95
e, percent:										
L	9	10	9	9	9	9	9	9	8	6
LT	9	10	9	9	9	9	9	9	8	6
E, 10^3 ksi	10.0	10.2			10.0			10.2		
E_c, 10^3 ksi	10.5	10.6			10.5			10.6		
G, 10^3 ksi	3.8	3.9			3.8			3.9		
μ	0.33	0.33			0.33			0.33		
Physical Properties:										
ω, lb/in.^{3}	0.101									
C, K, and α	0.23 (at 212°F)									
K, Btu/[(hr)(ft^2)(°F)/ft]	80 (at 77°F) for T61 and T651; 90 (at 77°F) for T761 and T7651									
α, 10^{-6} in./in./°F	12.9 (68 to 212°F)									

a See Table 3.1.2.1.1. Bearing values are "dry pin" values per Section 1.4.7.1.

Table 3.7.10.0(c). Design Mechanical and Physical Properties of 7475 Aluminum Alloy Plate

Specification	AMS 4202											
Form	Plate											
Temper	T7351											
Thickness, in.	0.250-1.500		1.501-2.000		2.001-2.500		2.501-3.000		3.001-3.500		3.501-4.000	
Basis	A	B	A	B	A	B	A	B	A	B	A	B
Mechanical Properties:												
F_{tu}, ksi:												
L	70	72	70	71	68	70	68	69	64	67	64	66
LT	71	73	70	72	68	70	68	69	64	68	64	67
ST	66[a]	70[a]	65	69	65	69	65	68	63	67	63	66
F_{ty}, ksi:												
L	59	62	58	60	56	59	56	58	52	56	52	54
LT	60	62	58[b]	61	56	59	56	58	52	56	52	54
ST	54[a]	57[a]	53	56	53	56	53	55	50	53	50	52
F_{cy}, ksi:												
L	58	60	56	59	54	57	53	55	49	53	49	51
LT	61	63	60	63	58	61	58	60	54	58	54	56
ST	62[a]	64[a]	60	63	58	61	58	60	54	58	54	56
F_{su}, ksi	41	42	42	43	41	42	41	42	39	42	39	41
F_{bru}[c], ksi:												
(e/D = 1.5)	102	105	103	106	101	104	101	103	97	102	97	101
(e/D = 2.0)	132	136	134	138	131	135	131	134	125	133	125	131
F_{bry}[c], ksi:												
(e/D = 1.5)	81	84	82	86	81	84	81	84	77	82	77	80
(e/D = 2.0)	97	101	97	102	95	100	95	99	89	96	89	93
e, percent (S-basis):												
L	10	...	10	...	10	...	10	...	10	...	9	...
LT	9	...	8	...	8	...	8	...	8	...	7	...
ST	4[b]	...	4	...	4	...	3	...	3	...	3	...
E, 10^3 ksi	10.3											
E_c, 10^3 ksi	10.6											
G, 10^3 ksi	3.9											
μ	0.33											
Physical Properties:												
ω, lb/in.^{3}	0.101											
C, Btu/(lb)(°F)	0.21 (at 212°F)											
K, Btu/[(hr)(ft^2)(°F)/ft]	94 (at 77°F)											
α, 10^{-6} in./in./°F	13.0 (68 to 212°F)											

a Values applicable to 1.500-inch thickness only.

b S-basis. The rounded T_{99} value for F_{ty}(LT) = 59 ksi.

c See Table 3.1.2.1.1. Bearing values are "dry pin" values per Section 1.4.7.1.

Table 3.7.10.0(d). Design Mechanical and Physical Properties of Clad 7475 Aluminum Alloy Sheet

Specification	AMS 4207				AMS 4100				
Form	Sheet								
Temper	T61				T761				
Thickness, in.	0.040-0.062	0.063-0.187		0.188-0.249	0.040-0.062	0.063-0.187		0.188-0.249	
Basis	S	A	B	S	S	A	B	A	B
Mechanical Properties:									
F_{tu}, ksi:									
L	69	69	73	72	66	67	70	68	71
LT	69	70	73	72	66	68	70	70	72
F_{ty}, ksi:									
L	61	64	67	63	56	58	61	59	63
LT	59	60[a]	64	61	55	57	60	60	62
F_{cy}, ksi:									
L	60	61	65	62	55	56	59	58	60
LT	63	64	68	65	58	59	62	61	63
F_{su}, ksi	42	40	41	39	41	40	41	40	41
F_{bru}[b], ksi:									
(e/D = 1.5)	110	111	116	115	104	107	110	108	111
(e/D = 2.0)	140	142	148	146	133	136	140	138	142
F_{bry}[b], ksi:									
(e/D = 1.5)	89	90	96	92	83	86	90	90	93
(e/D = 2.0)	102	104	111	106	97	101	106	106	110
e, percent (S-basis):									
LT	9	9	...	9	9	9	...	9	...
E, 10^3 ksi:									
Primary	10.0	10.0		10.0	10.0	10.0		10.0	
Secondary	9.2	9.4		9.7	9.2	9.4		9.7	
E_c, 10^3 ksi:									
Primary	10.5	10.5		10.5	10.5	10.5		10.5	
Secondary	9.4	9.7		10.0	9.4	9.7		10.0	
G, 10^3 ksi	3.8	3.8		3.8	3.8	3.8		3.8	
μ	0.33	0.33		0.33	0.33	0.33		0.33	
Physical Properties:									
ω, lb/in.^{3}	0.101								
C, K, α	...								

[a] S-basis. The rounded T_{99} value is 61 ksi.

[b] Bearing values are "dry pin" values per Section 1.4.7.1.

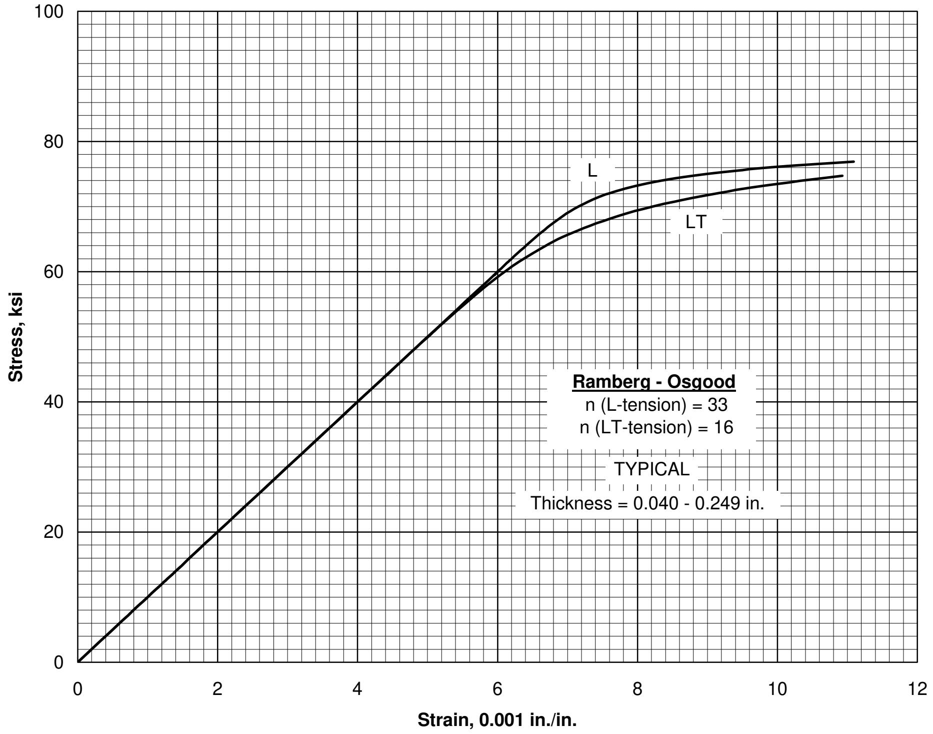


Figure 3.7.10.1.6(a). Typical tensile stress-strain curves for 7475-T61 aluminum alloy sheet at room temperature.

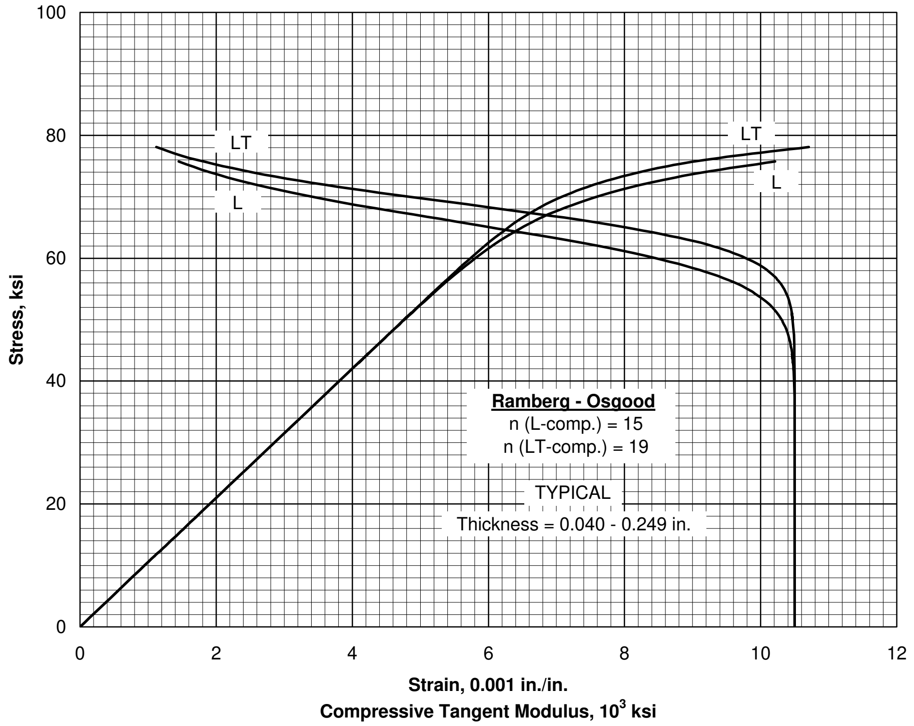


Figure 3.7.10.1.6(b). Typical compressive stress-strain and compressive tangent-modulus curves for 7475-T61 aluminum alloy sheet at room temperature.

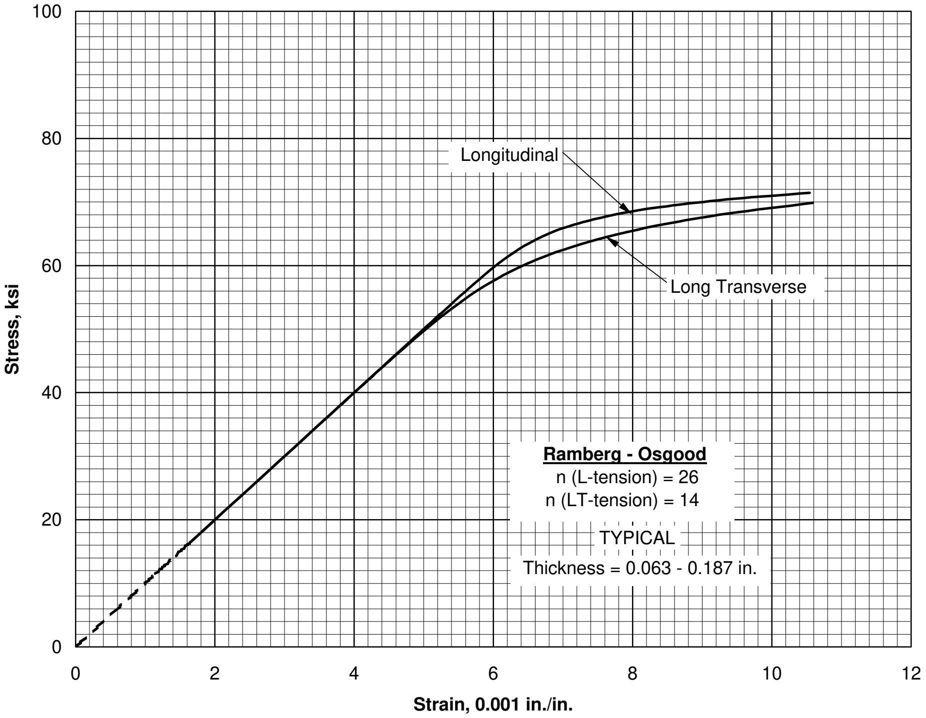


Figure 3.7.10.1.6(c). Typical tensile stress-strain curves for clad 7475-T61 aluminum alloy sheet at room temperature.

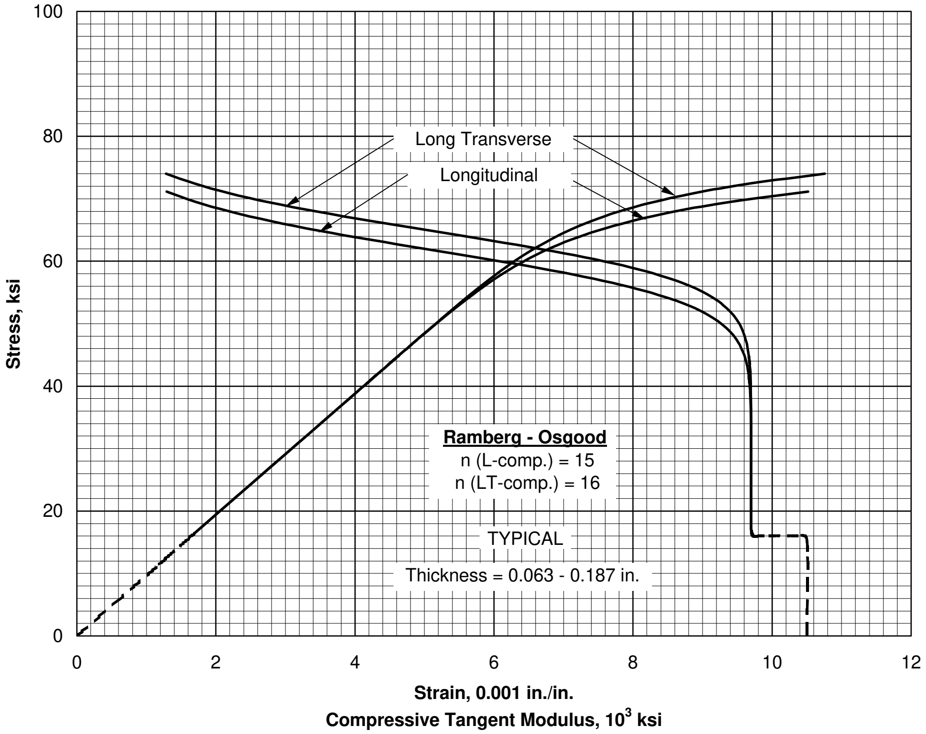


Figure 3.7.10.1.6(d). Typical compressive stress-strain and compressive tangent-modulus curves for clad 7475-T61 aluminum alloy sheet at room temperature.

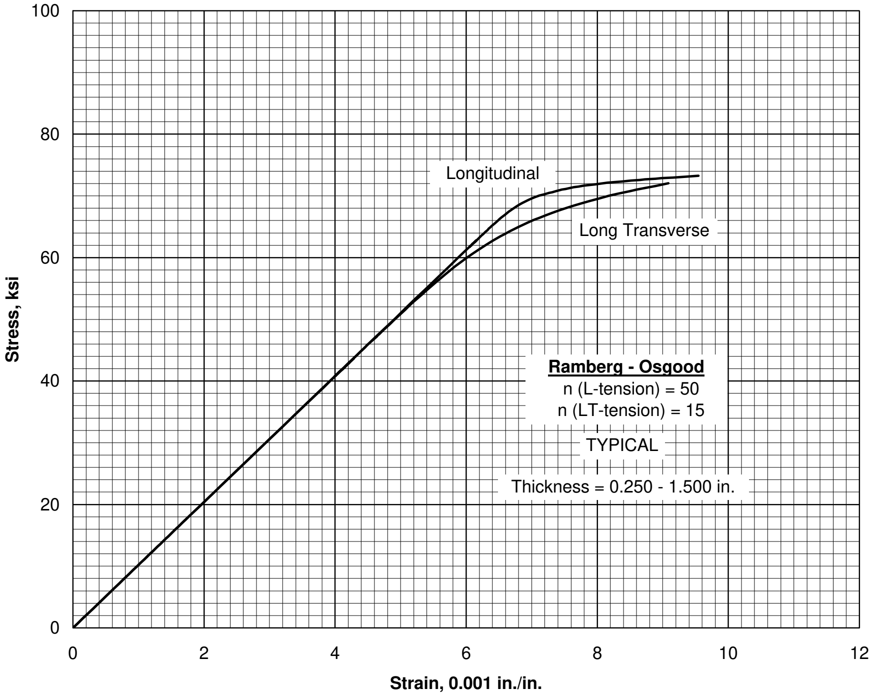


Figure 3.7.10.1.6(e). Typical tensile stress-strain curves for 7475-T651 aluminum alloy plate at room temperature.

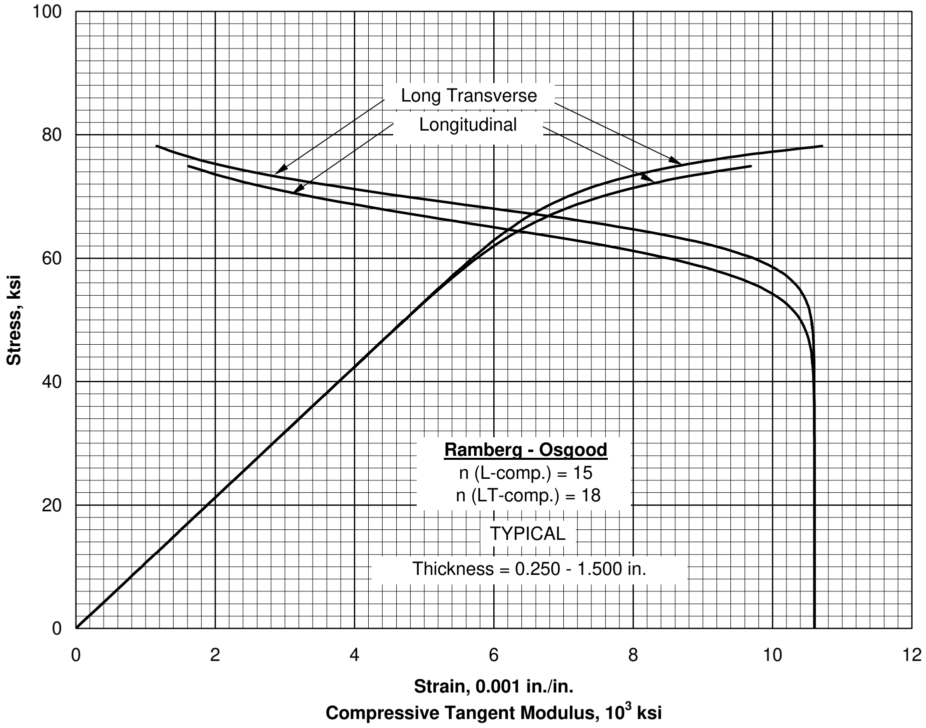


Figure 3.7.10.1.6(f). Typical compressive stress-strain and compressive tangent-modulus curves for 7475-T651 aluminum alloy plate at room temperature.

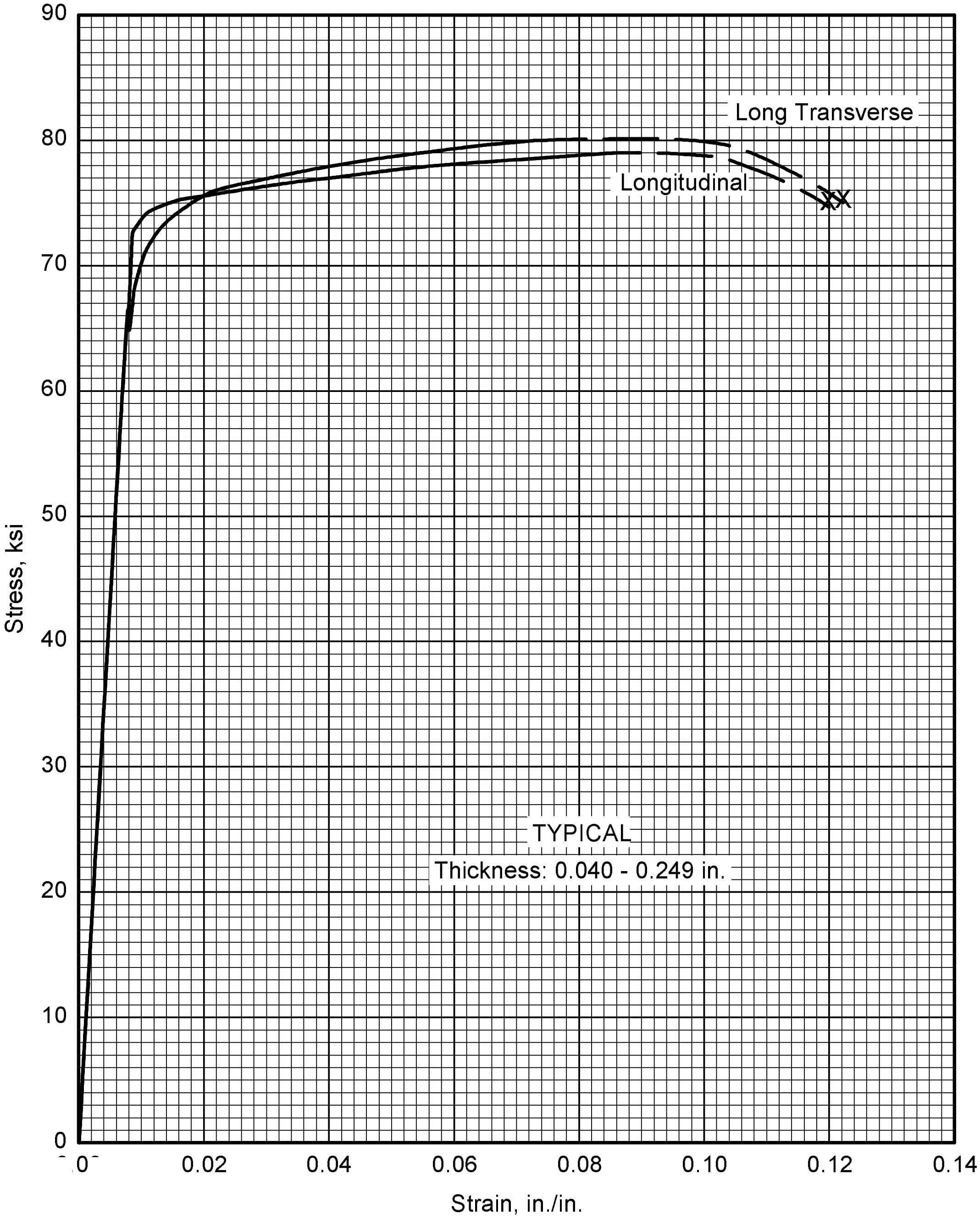


Figure 3.7.10.1.6(g). Typical tensile stress-strain curves (full range) for 7475-T61 aluminum alloy sheet at room temperature.

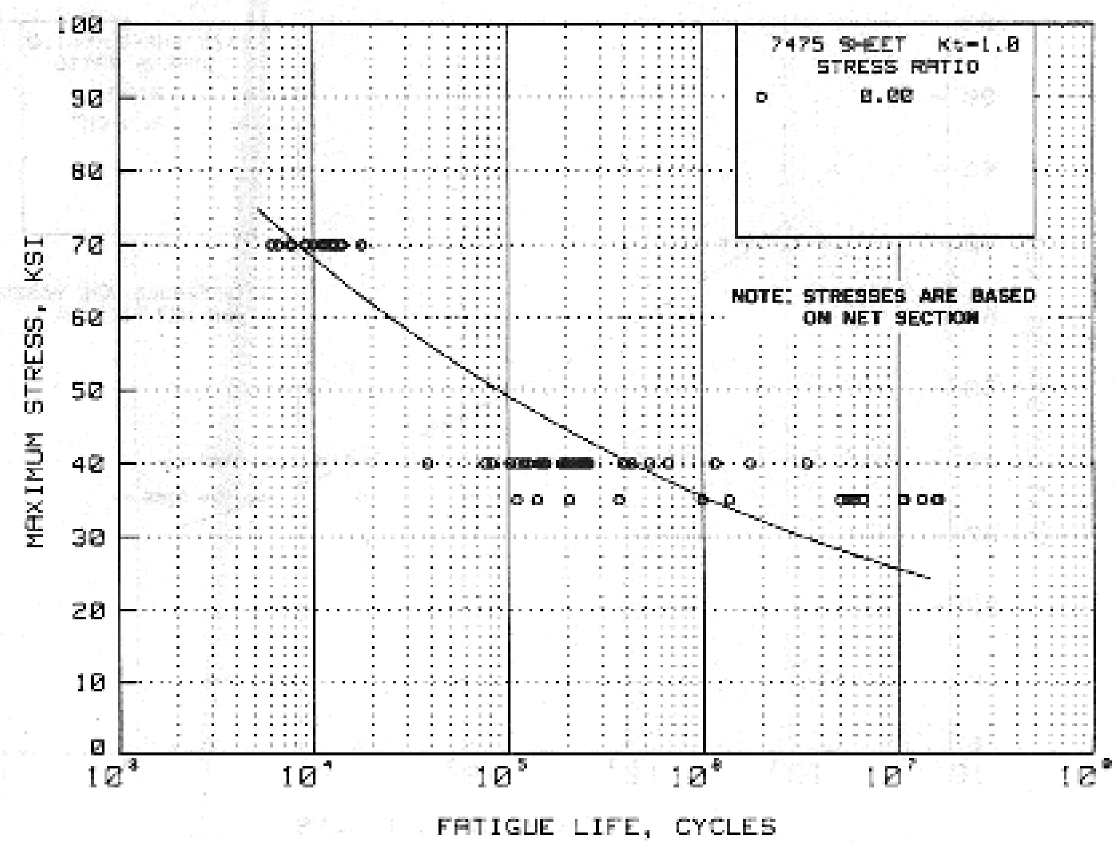


Figure 3.7.10.1.8(a). Best-fit S/N curve for unnotched 7475-T61 and T761 sheet, thickness ≤0.125 inch, longitudinal and long transverse directions.

Correlative Information for Figure 3.7.10.1.8(a)

Product Form: Sheet, 0.032 to 0.125 inch thick

Properties:	TUS, ksi	TYS, ksi	Temp., °F
T61	81	73-75	RT
T761	77	68-70	RT

Specimen Details: Unnotched, hourglass,
0.500 inch diameter
4.00 inch test section radius, r

Surface Condition: As machined

Reference: 3.2.6.1.9(d)

Test Parameters:
Loading - Axial
Frequency - 798, 1500, or 1728 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 2

Maximum Stress Equation:
$\text{Log } N_f = 16.9\text{-}7.03 \log (S_{max})$
Std. Error of Estimate, Log (Life) = 0.545
Standard Deviation, Log (Life) = 0.988
R^2=70%

Sample Size = 67

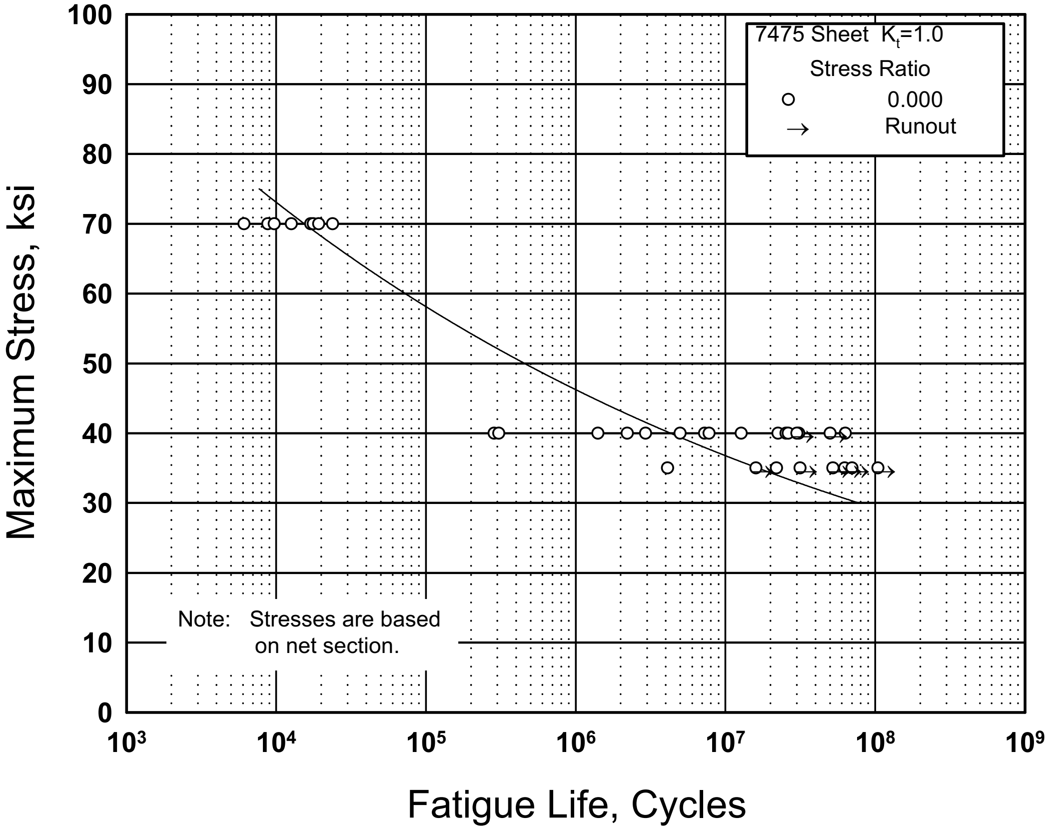


Figure 3.7.10.1.8(b). Best-fit S/N Curve for unnotched 7475-T61 and T761 sheet thickness > 0.125 inch, longitudinal and long transverse directions.

Correlative Information for Figure 3.7.10.1.8(b)

Product Form: Sheet, > 0.125 inch through 0.249 inch thick

Properties:	TUS, ksi	TYS, ksi	Temp.,°F
T61	80-81	73-76	RT
T761	75	66-67	RT

Specimen Details: Unnotched, hourglass,
0.500 inch diameter
4.000 inch test section
radius, R

Surface Condition: As machined

Reference: 3.2.6.1.9(d)

Test Parameters:
Loading - Axial
Frequency - 798, 1500, or 1728 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 2

Maximum Stress Equation:
Log N_f = 22.7-10.1 log (S_{max})
Std. Error of Estimate, Log (Life) = 0.657
Standard Deviation, Log (Life) = 1.380
R^2=77%

Sample Size = 24

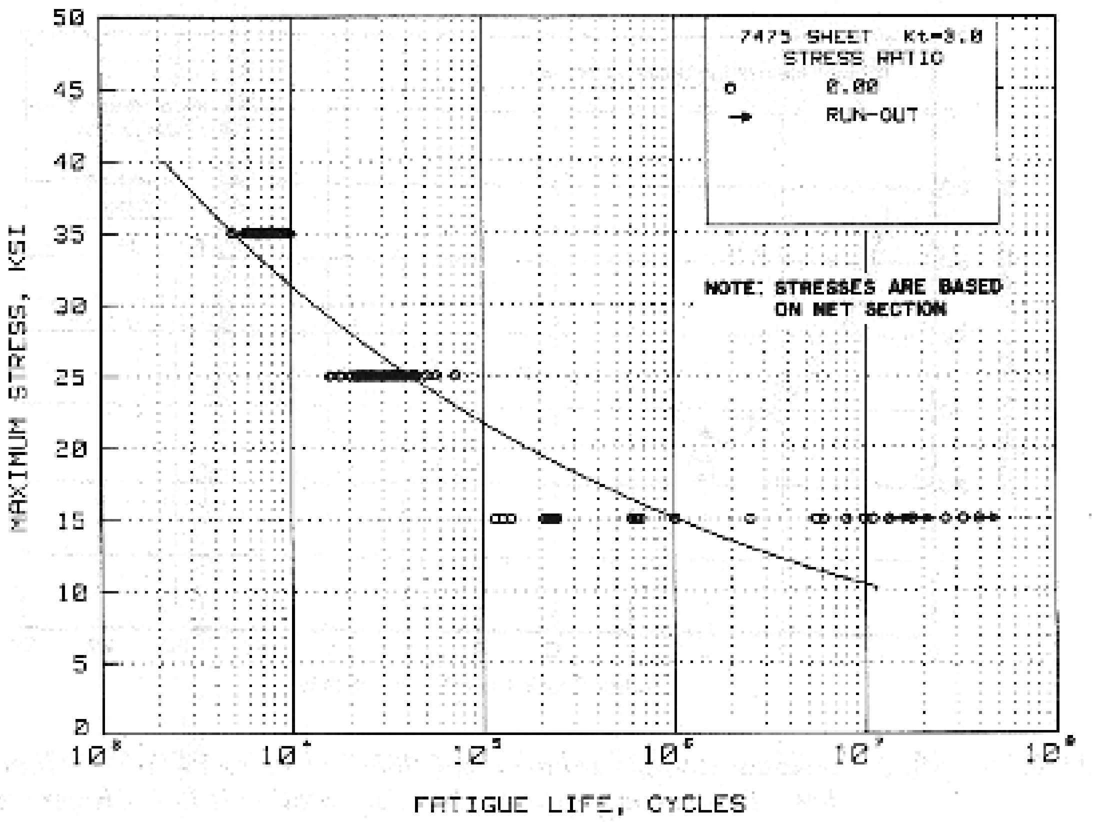


Figure 3.7.10.1.8(c). Best-fit S/N curve for notched, K_t = 3.0, 7475-T61 and T761 sheet, longitudinal and long transverse directions.

Correlative Information for Figure 3.7.10.1.8(c)

Product Form: Sheet, 0.032 to 0.249 inch thick

Properties:	TUS, ksi	TYS, ksi	Temp.,°F
T61	81-82	73-76	RT
T761	75-77	67-70	RT

Specimen Details: Notched, edge notched
K_t = 3.0
1.000 inch gross width
0.700 inch net width
0.050 inch root radius, r
60° flank angle, ω

Surface Condition: As machined

Reference: 3.2.6.1.9(d)

Test Parameters:
Loading - Axial
Frequency - 798, 1500, or 1728 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 2

Maximum Stress Equation:
Log N_f = 13.4-6.29 log (S_{max})
Std. Error of Estimate, Log (Life) = 0.441
Standard Deviation, Log (Life) = 0.931
R^2=78%

Sample Size = 99

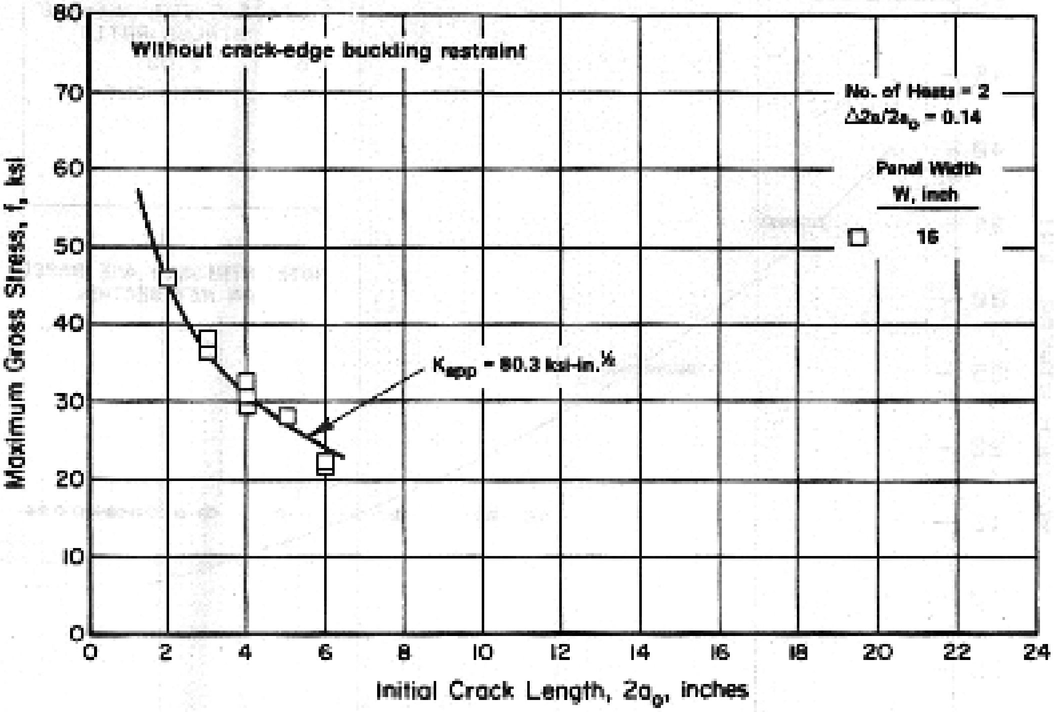


Figure 3.7.10.1.10(a). Residual strength behavior of 0.063-inch-thick 7475-T61 aluminum alloy sheet at room temperature. Crack orientation is L-T. [References 3.1.2.1.6(d) and 3.2.5.1.9(d).]

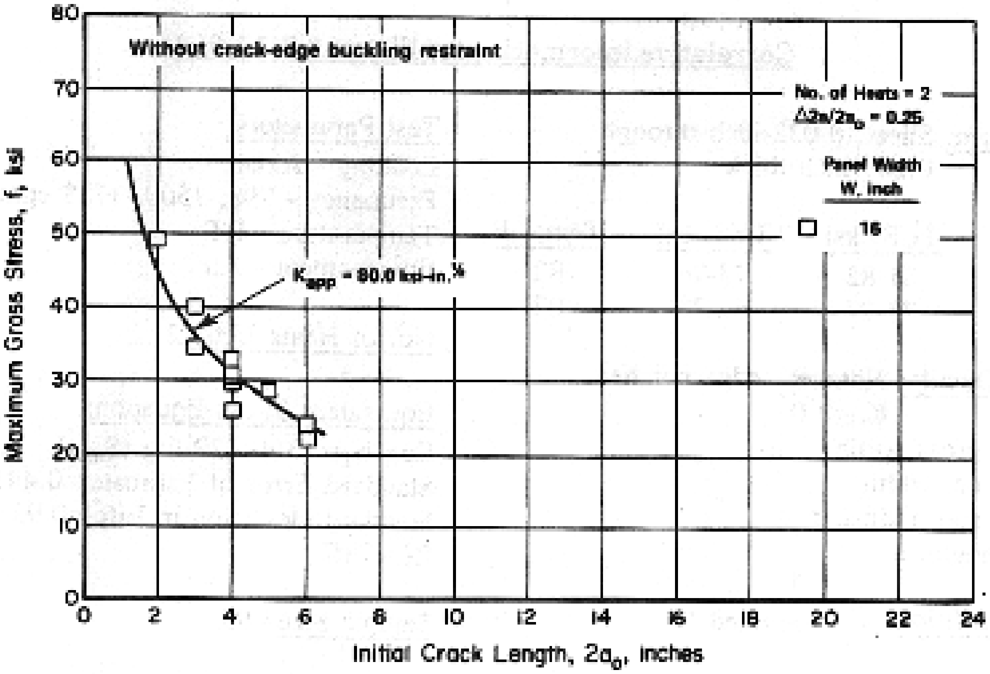


Figure 3.7.10.1.10(b). Residual strength behavior of 0.063-inch-thick 7475-T61 aluminum alloy sheet at room temperature. Crack orientation is T-L. [References 3.1.2.1.6(d) and 3.2.5.1.9(d).]

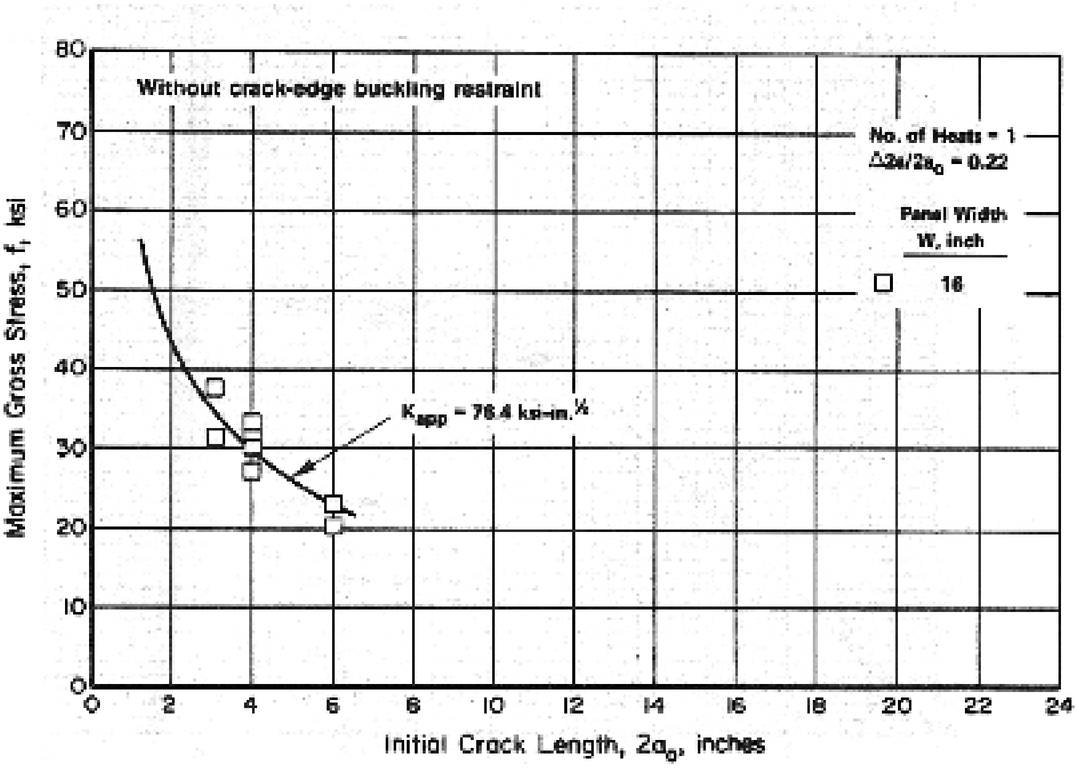


Figure 3.7.10.1.10(c). Residual strength behavior of 0.063-inch-thick 7475-T61 clad aluminum alloy sheet at room temperature. Crack orientation is L-T. [Reference 3.2.5.1.9(d).]

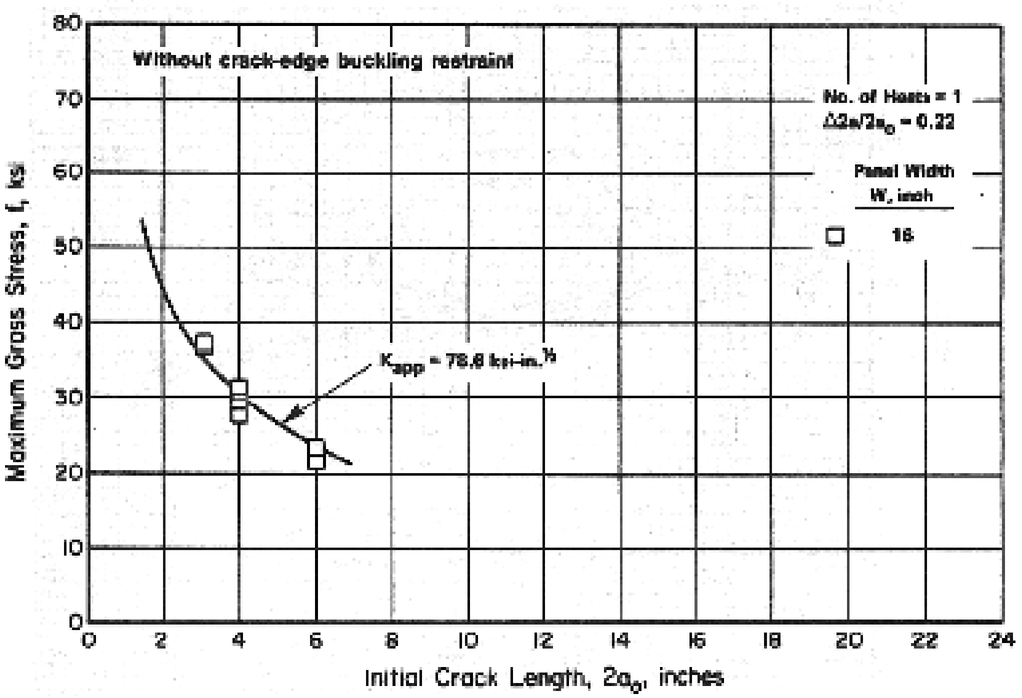


Figure 3.7.10.1.10(d). Residual strength behavior of 0.063-inch-thick 7475-T61 clad aluminum alloy sheet at room temperature. Crack orientation is T-L. [Reference 3.2.5.1.9(d).]

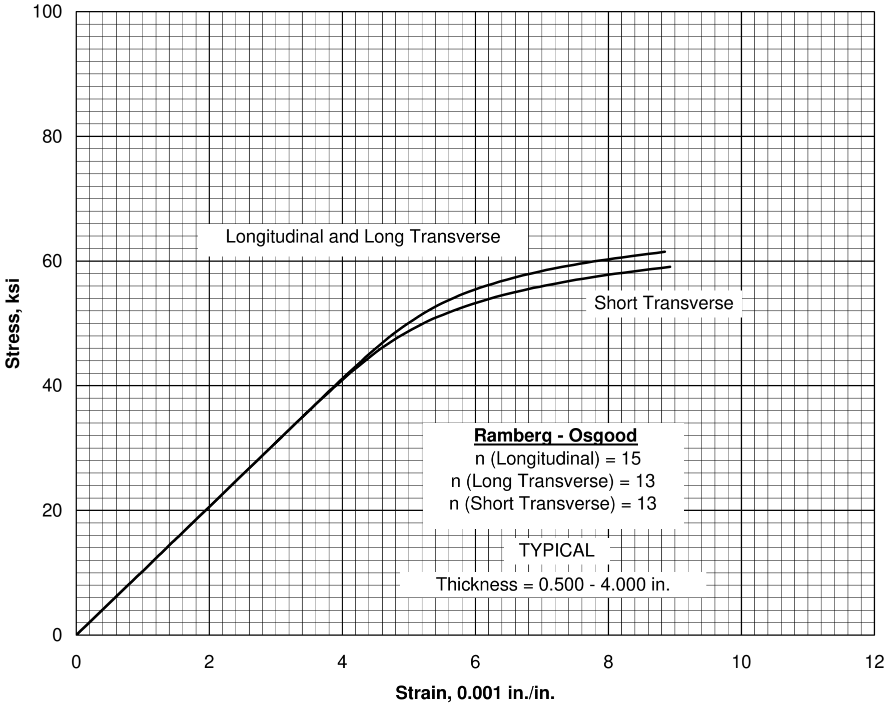


Figure 3.7.10.2.6(a). Typical tensile stress-strain curves for 7475-T7351 aluminum alloy plate at room temperature.

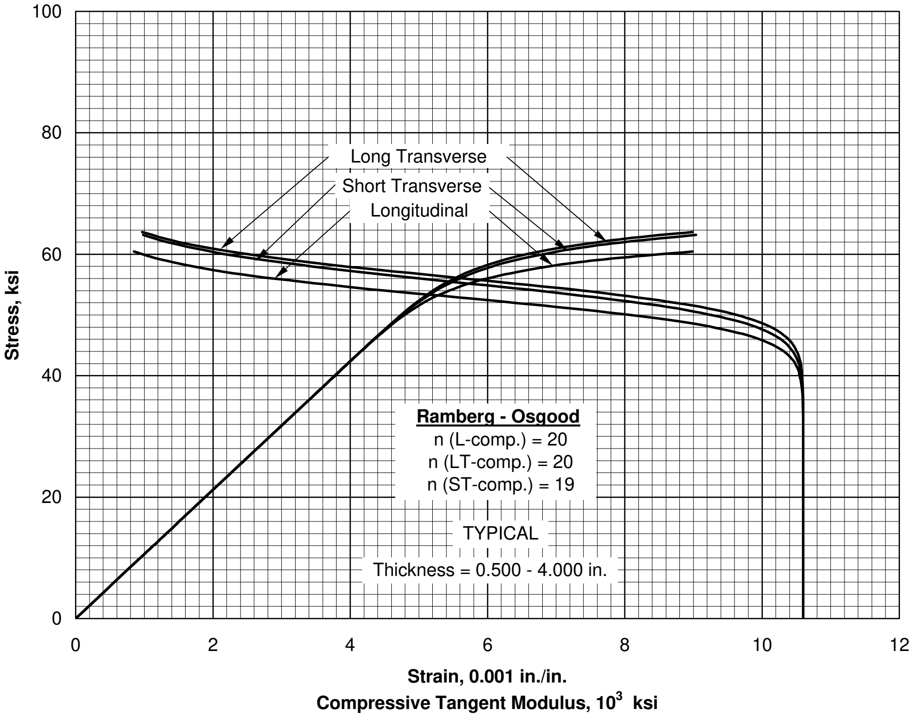


Figure 3.7.10.2.6(b). Typical compressive stress-strain and compressive tangent-modulus curves for 7475-T7351 aluminum alloy plate at room temperature.

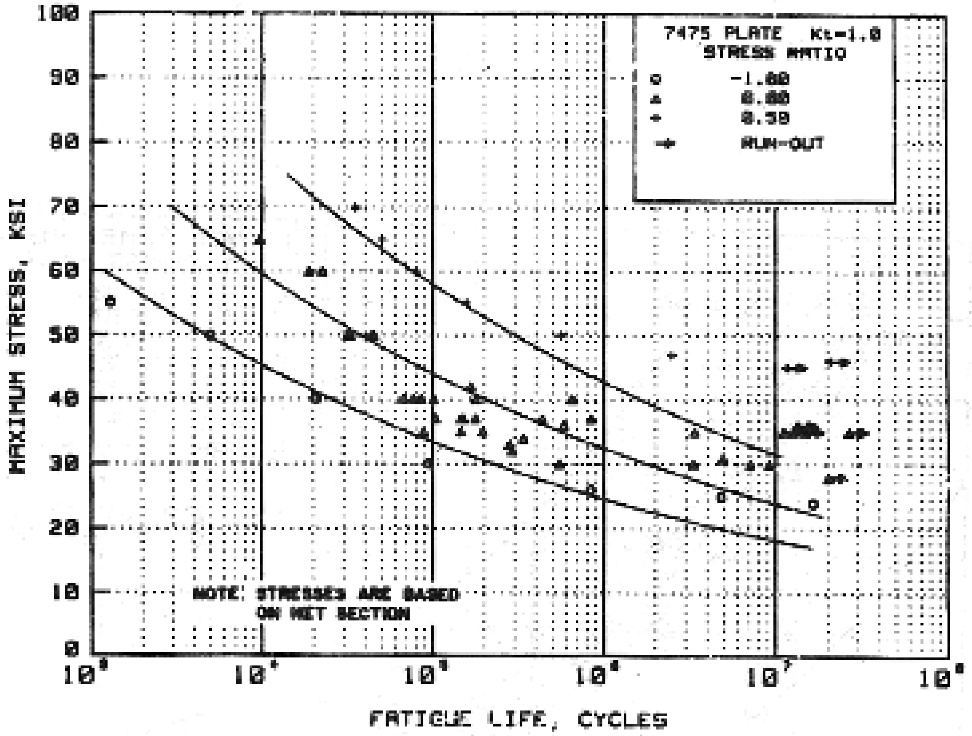


Figure 3.7.10.2.8(a). Best-fit S/N curves for unnotched 7475-T7351 plate, longitudinal and long transverse orientation.

Correlative Information for Figure 3.7.10.2.8(a)

Product Form: Plate, 0.5, 1.0, 2.0, 3.0, and 4.0-inches thick

Properties:	TUS, ksi	TYS, ksi	Temp..,°F
L	70	60	RT
LT	71	60	RT

Specimen Details: Unnotched
Hourglass,
0.300 inch net diameter
9.875 inch test section radius

Surface Condition: As machined

References: 3.7.10.2.8(a) and (b)

Test Parameters:
Loading — Axial
Frequency — Not specified
Temperature — RT
Environment — Air

No. of Heats/Lots: 5

Equivalent Stress Equation:
Log N_f = 17.42-7.56 log (S_{eq})
$S_{eq} = S_{max}(1-R)^{0.40}$
Std. Error of Estimate, Log (Life) = 0.433
Standard Deviation, Log (Life) = 0.857
R^2 = 74%

Sample Size = 52

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

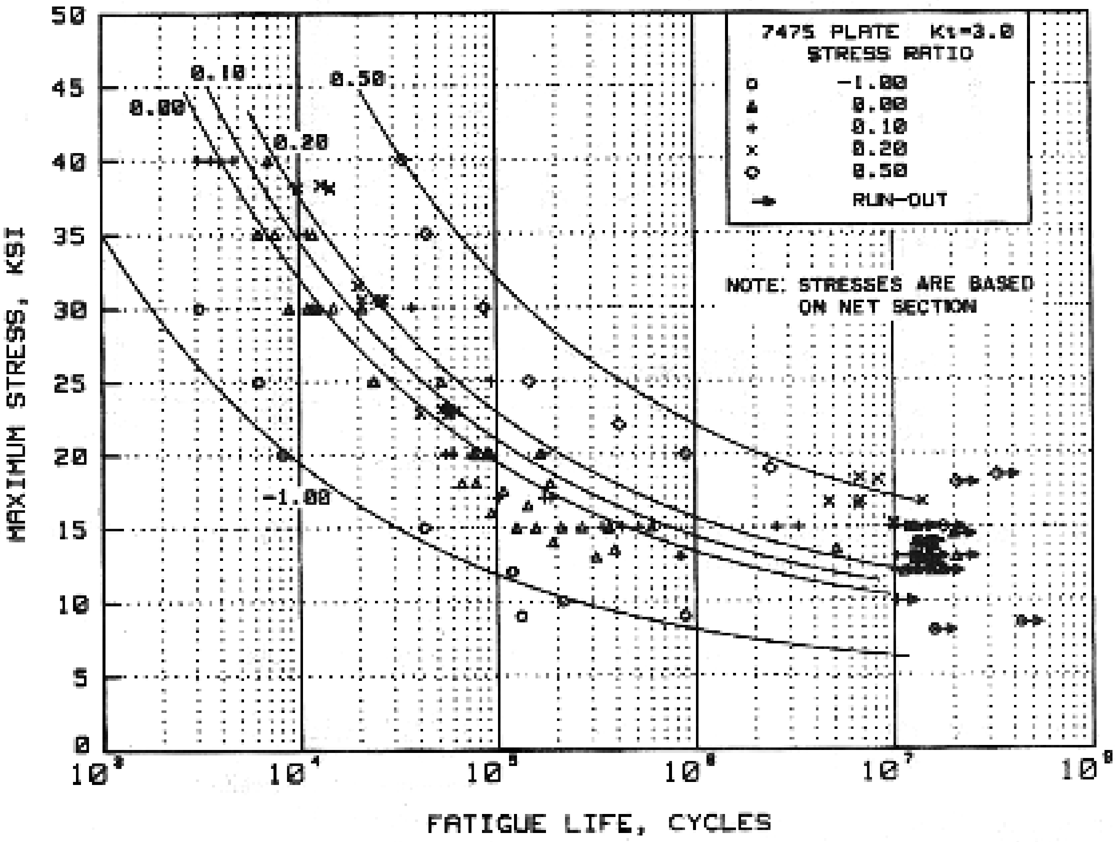


Figure 3.7.10.2.8(b). Best-fit S/N curves for notched, K_t = 3.0, 7475-T7351 and T7651 plate, longitudinal and long transverse direction.

(See following page for correlative information.)

Correlative Information for Figure 3.7.10.2.8(b)

Product Form: Plate, 0.5, 1.0, 1.5, 2.0, 3.0, and 4.0 inches thick

Properties:	TUS, ksi	TYS, ksi	Temp., °F
L (T7351)	70	60	RT
LT (T7351)	71	61	RT
L (T7351)	72	62	RT
(T7651)	Not specified		
L (T7351)	72	63	RT
LT (T7351)	73	62	RT

Specimen Details: Notched, $K_t = 3.0$
Circumferentially notched
    0.253 inch gross width
    0.147 inch net width
    0.013 inch root radius, r
    60° flank angle, ω
Edge notched
    1.00 inch gross width
    0.70 inch net width
    root radius not specified
    60° flank angle, ω
Edge notched
    2.25 inch gross width
    1.50 inch net width
    0.113 inch root radius, r
    60° flank angle, ω
Circumferentially notched
    1.375 inch gross width
    0.25 inch net width
    0.13 inch root radius, r
    60° flank angle, ω

References: 3.7.10.2.8 (a) through (e)

Surface Condition:
Not specified [Ref. (a) and (b)]
As machined and deburred [Ref. (c)]
32 RMS [Ref. (d)]
10 RMS [Ref. (e)]

Test Parameters:
Loading — Axial
Frequency
— Not specified [Ref. (a) and (b)]
— 1800 cpm [Ref. (c) and (d)]
— 1500 cpm [Ref. (e)]
Temperature — RT
Environment — Air

No. of Heats/Lots: 8

Equivalent Strain Equation:
$\text{Log } N_f = 8.46\text{-}3.21 \log (S_{eq}\text{-}7.5)$
$S_{eq} = S_{max}(1\text{-}R)^{0.72}$
Std. Error of Estimate, Log (Life) = 0.422
Standard Deviation, Log (Life) = 0.923
$R^2 = 79\%$

Sample Size = 97

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

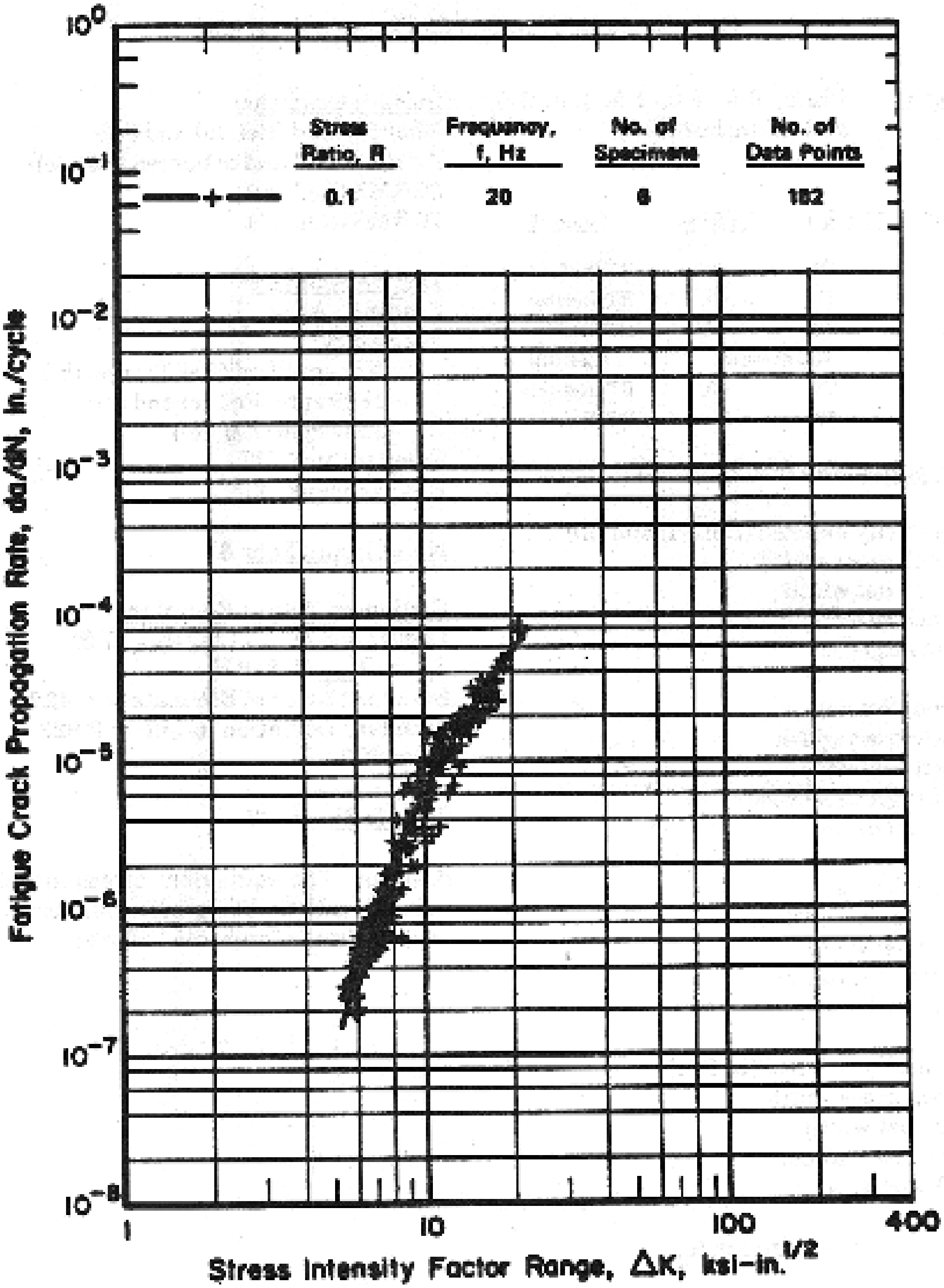


Figure 3.7.10.2.9(a). Fatigue-crack-propagation data for 1.5-inch-thick, 7475-T7351 aluminum alloy plate [References 3.7.10.2.9(a) and (b)].

Specimen Thickness:	*0.650-inch*	*Environment:*	*Lab air*
Specimen Width:	*1.500-inches*	*Temperature:*	*RT*
Specimen Type:	*C(T)*	*Orientation:*	*L-T*

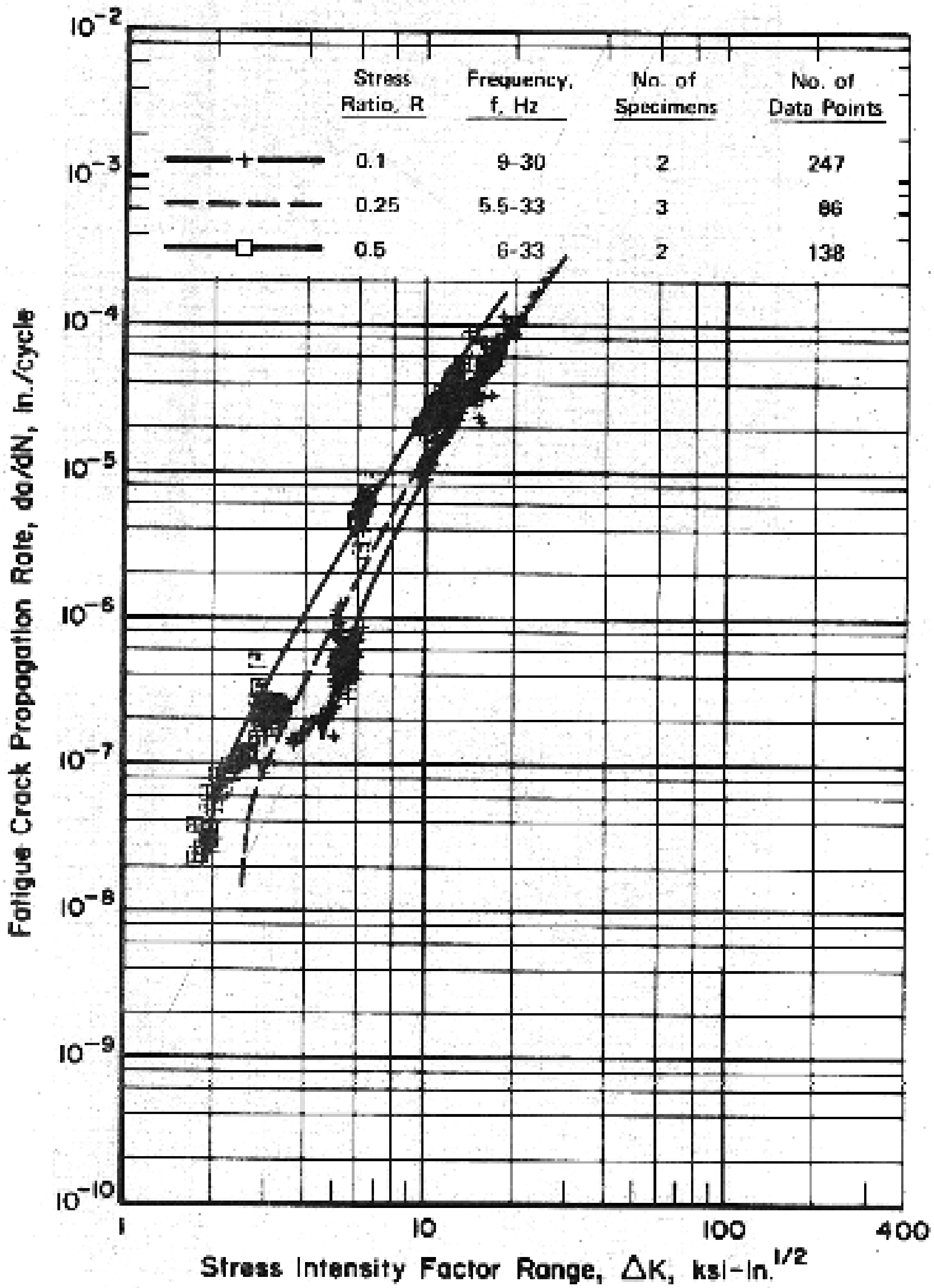


Figure 3.7.10.2.9(b). Fatigue-crack-propagation data for 0.500-inch-thick, 7475-T7351 aluminum alloy plate [Reference 3.7.10.2.9(c)].

Specimen Thickness:	*0.528 to 0.530-inch*	*Environment:*	*95% R.H.*
Specimen Width:	*4.6-inches*	*Temperature:*	*RT*
Specimen Type:	*M(T)*	*Orientation:*	*L-T*

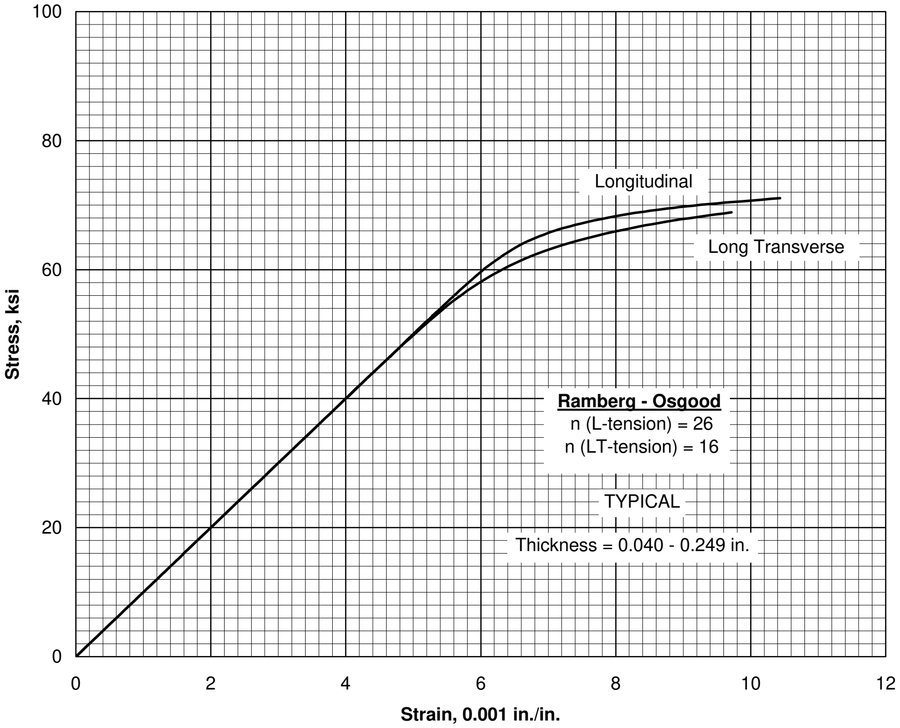


Figure 3.7.10.3.6(a). Typical tensile stress-strain curves for 7475-T761 aluminum alloy sheet at room temperature.

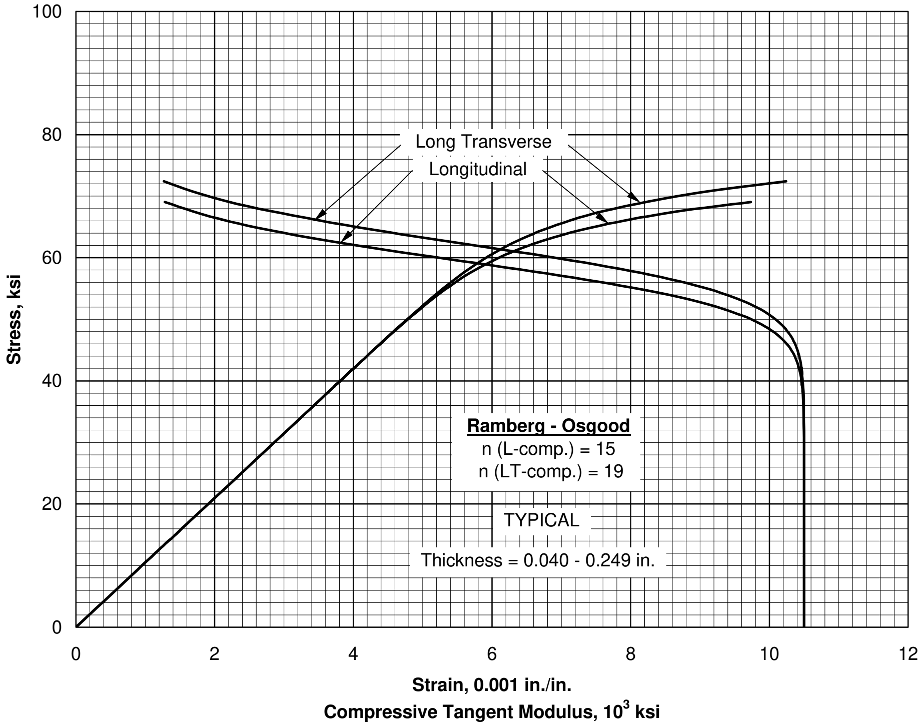


Figure 3.7.10.3.6(b). Typical compressive stress-strain and compressive tangent-modulus curves for 7475-T761 aluminum alloy sheet at room temperature.

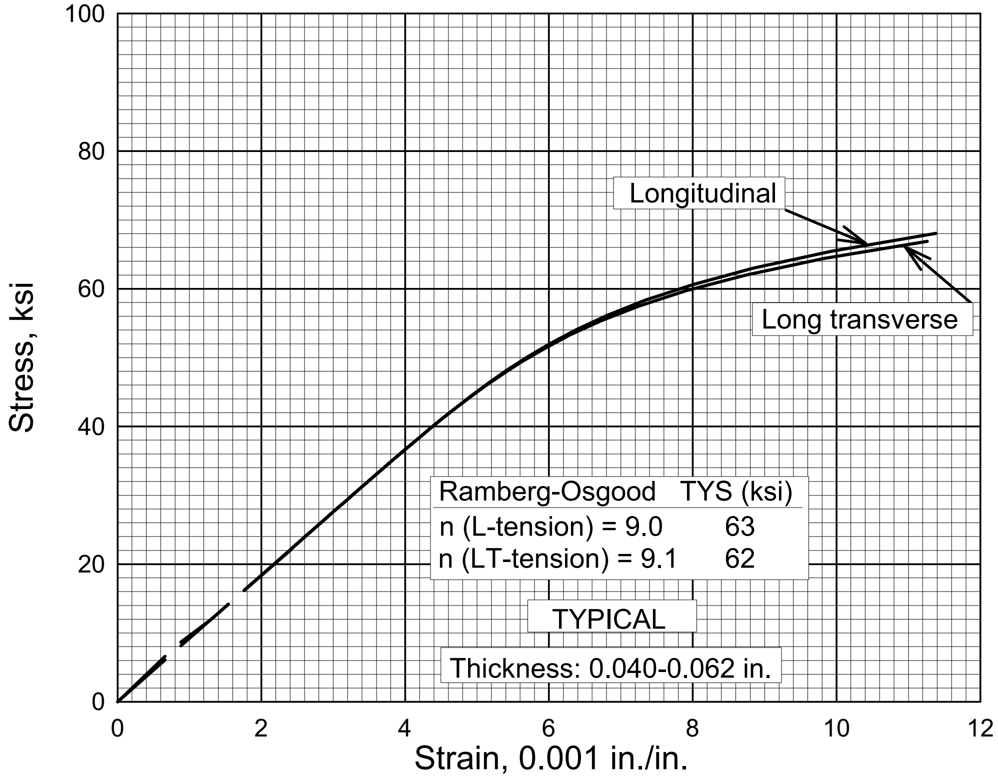


Figure 3.7.10.3.6(c). Typical tensile stress-strain curves for clad 7475-T761 aluminum alloy sheet at room temperature.

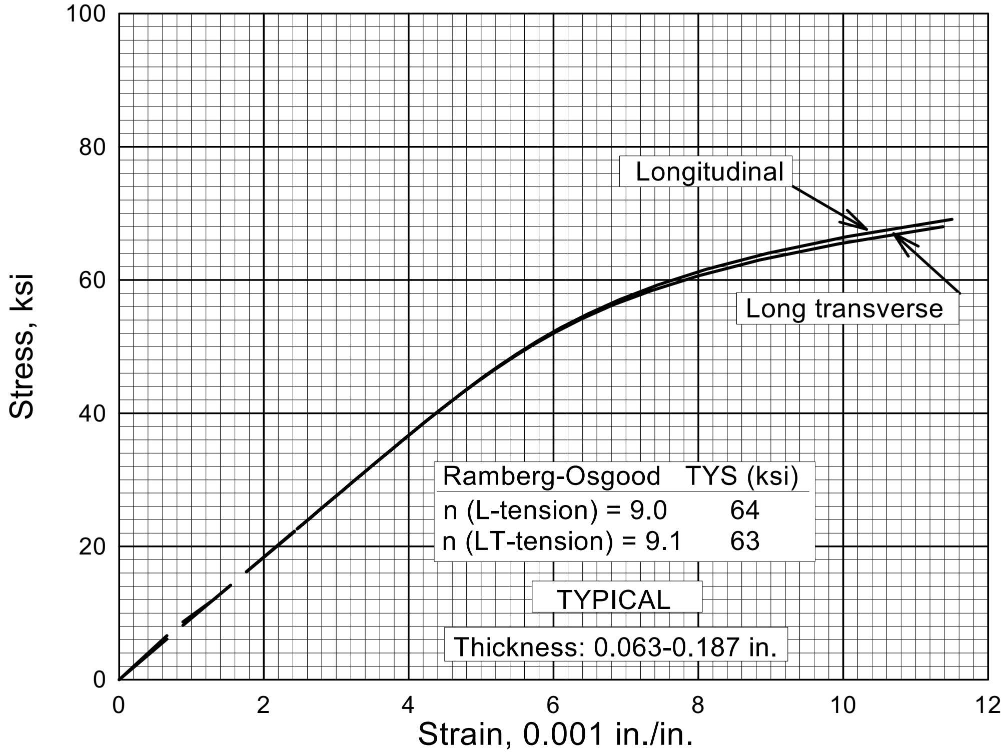


Figure 3.7.10.3.6(d). Typical tensile stress-strain curves for clad 7475-T761 aluminum alloy sheet at room temperature.

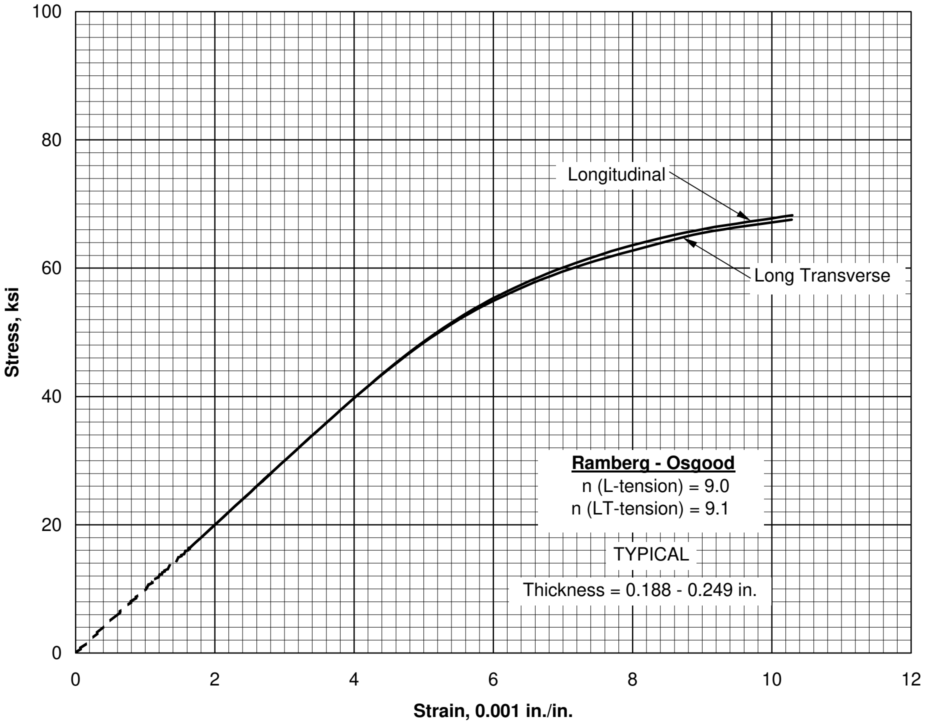


Figure 3.7.10.3.6(e). Typical tensile stress-strain curves for clad 7475-T761 aluminum alloy sheet at room temperature.

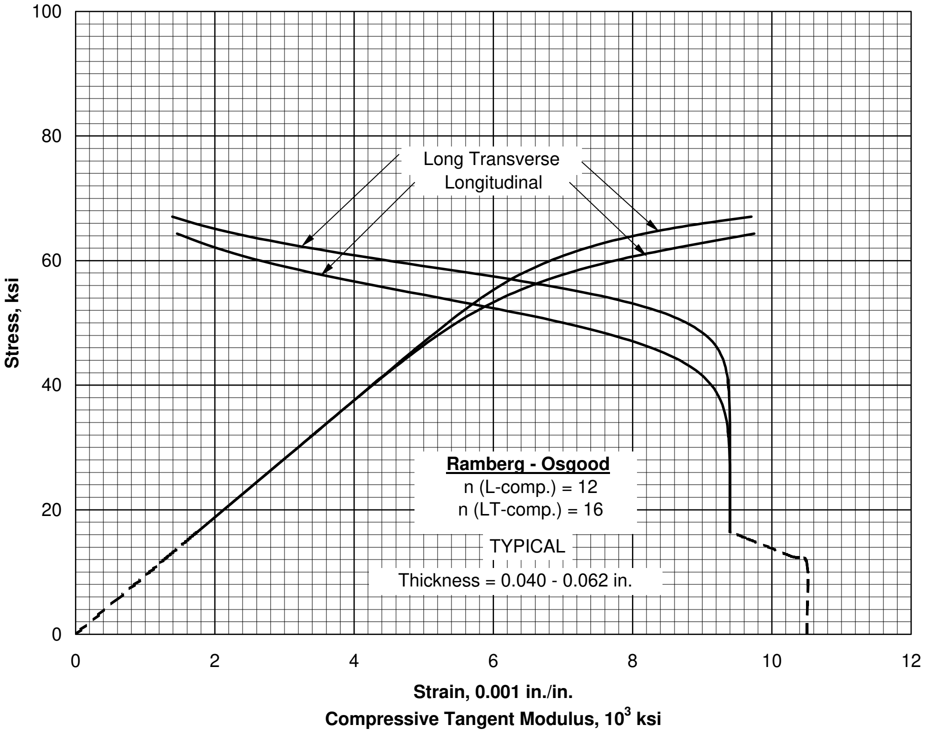


Figure 3.7.10.3.6(f). Typical compressive stress-strain and compressive tangent-modulus curves for clad 7475-T761 aluminum alloy sheet at room temperature.

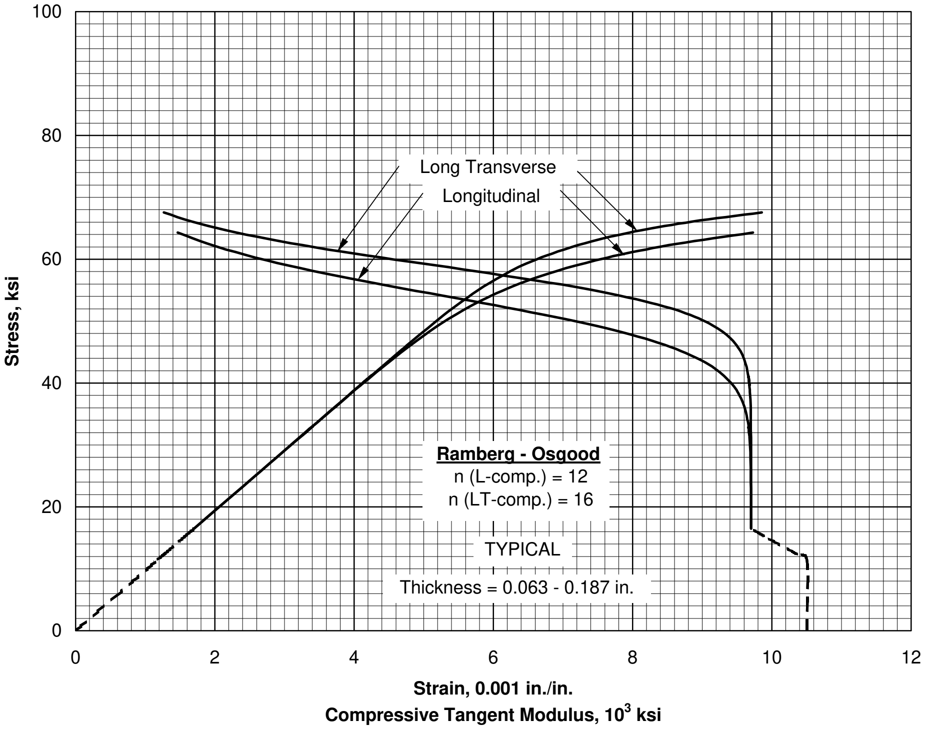


Figure 3.7.10.3.6(g). Typical compressive stress-strain and compressive tangent-modulus curves for clad 7475-T761 aluminum alloy sheet at room temperature.

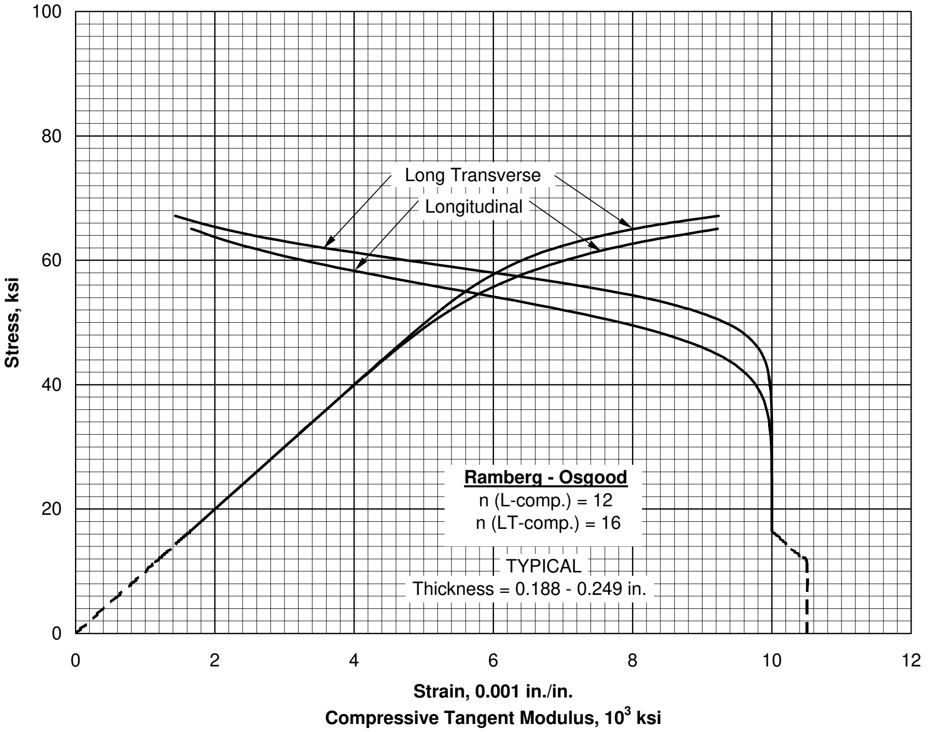


Figure 3.7.10.3.6(h). Typical compressive stress-strain and compressive tangent-modulus curves for clad 7475-T761 aluminum alloy sheet at room temperature.

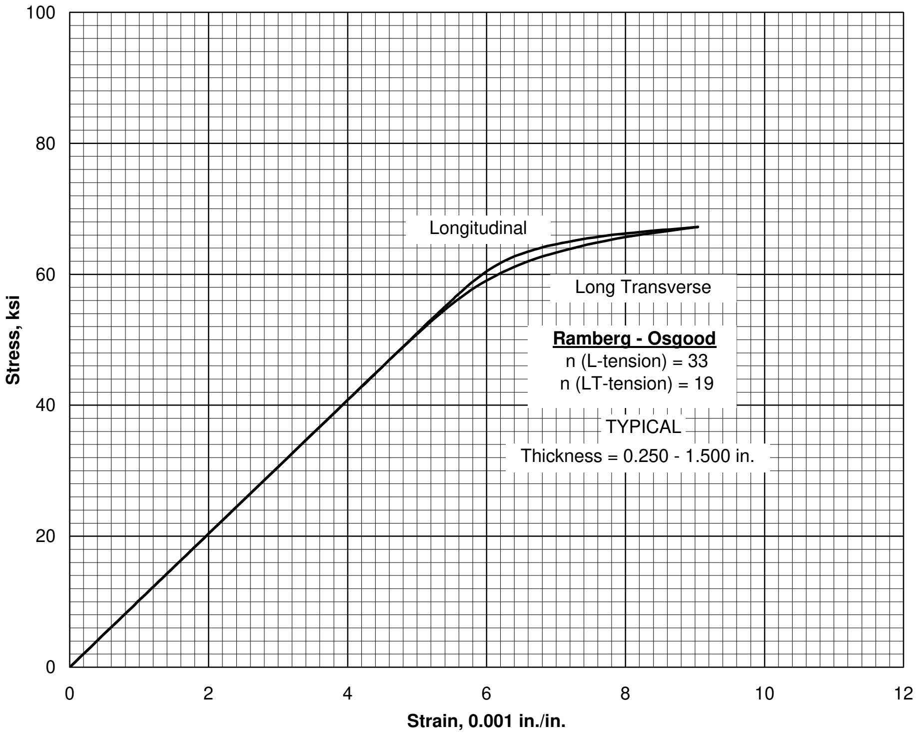


Figure 3.7.10.3.6(i). Typical tensile stress-strain curves for 7475-T7651 aluminum alloy plate at room temperature.

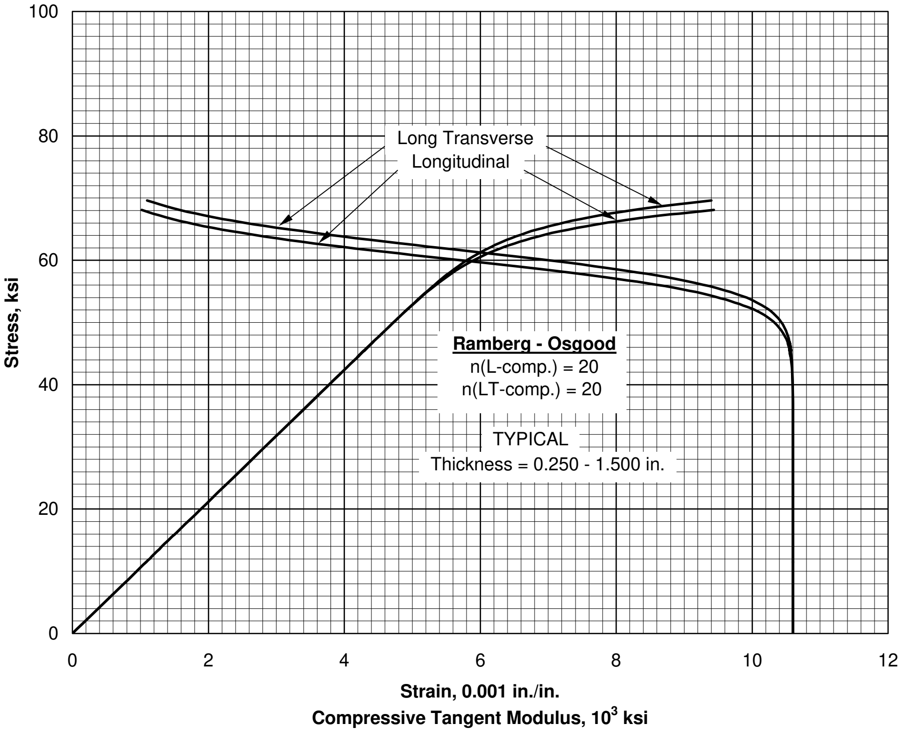


Figure 3.7.10.3.6(j). Typical compressive stress-strain and compressive tangent-modulus curves for 7475-T7651 aluminum alloy plate at room temperature.

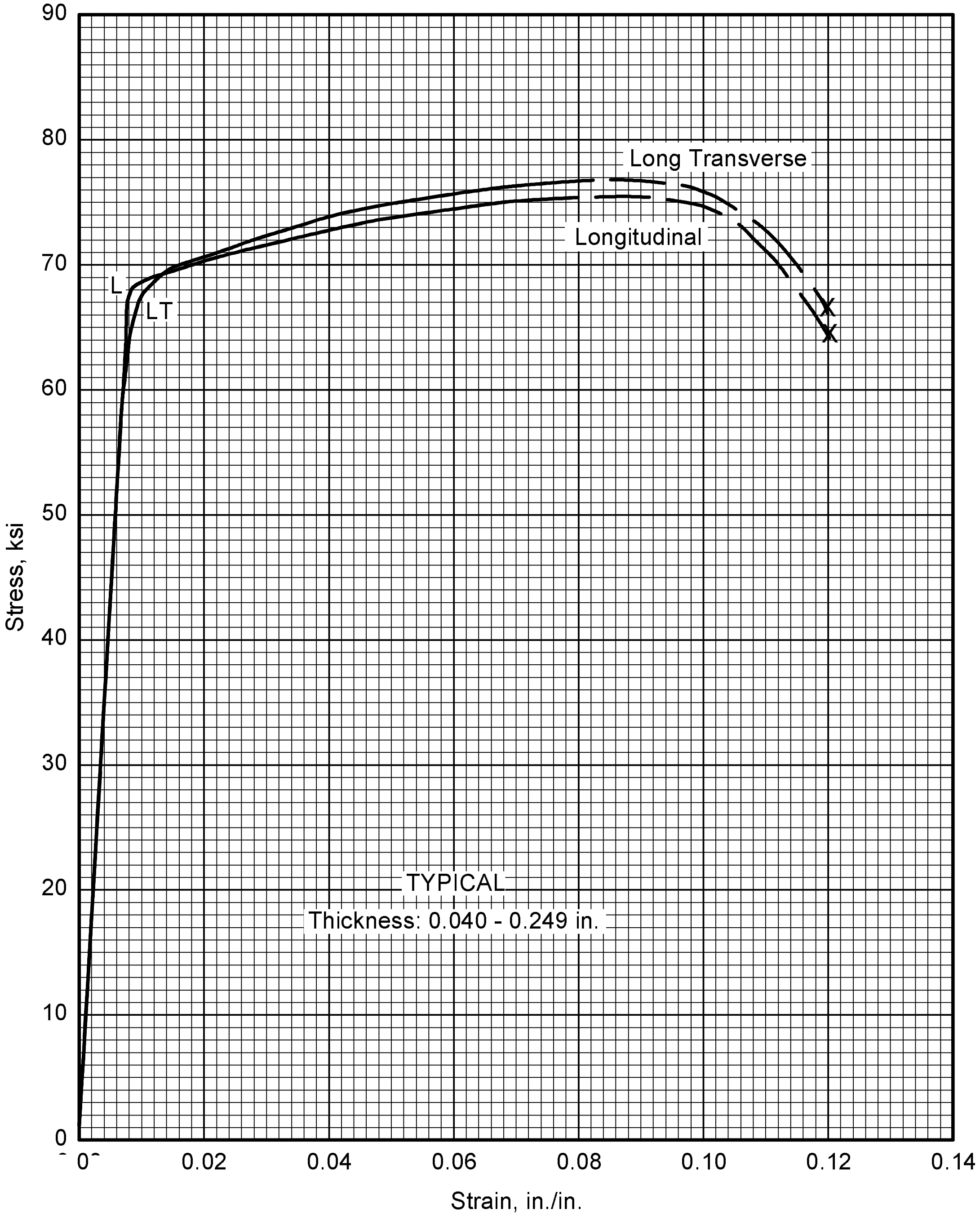


Figure 3.7.10.3.6(k). Typical tensile stress-strain (full range) curves for 7475-T761 aluminum alloy sheet at room temperature.

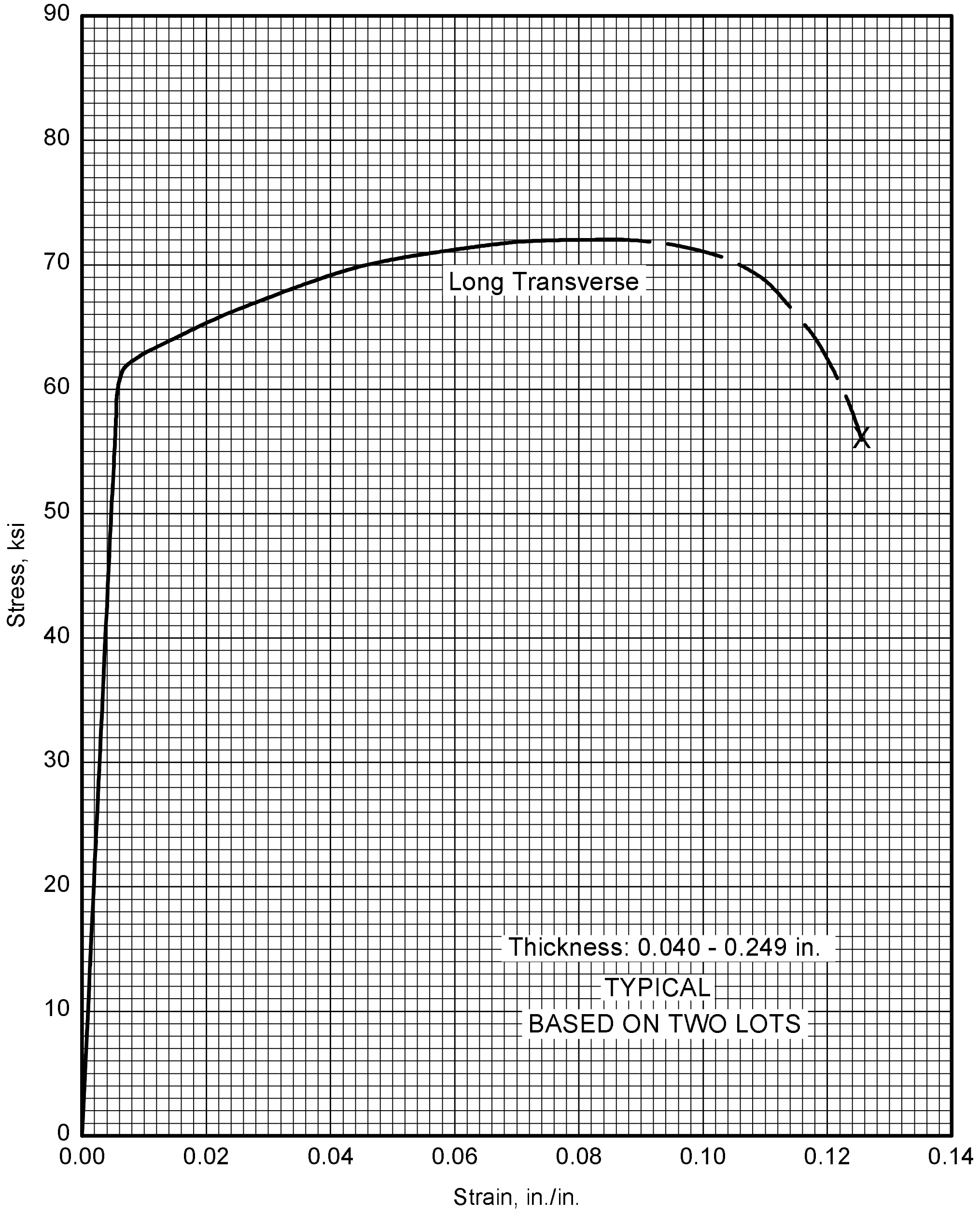


Figure 3.7.10.3.6(l). Typical tensile stress-strain (full range) curves for clad 7475-T761 aluminum alloy sheet at room temperature.

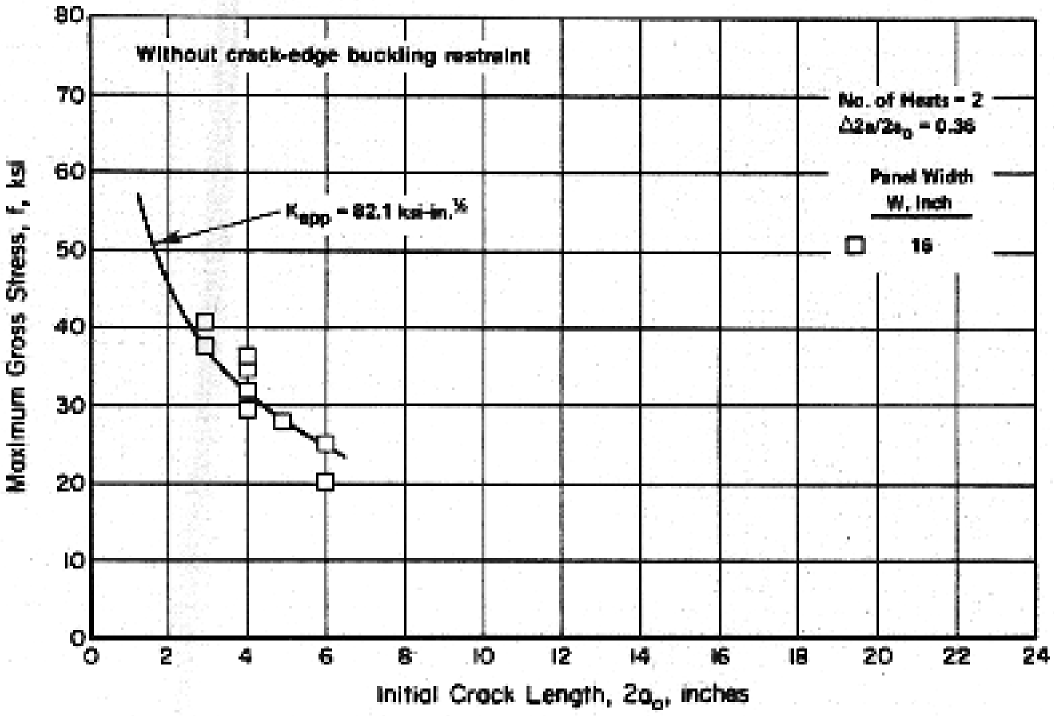


Figure 3.7.10.3.10(a). Residual strength behavior of 0.063-inch-thick 7475-T761 aluminum alloy sheet at room temperature. Crack orientation is L-T. [References 3.1.2.1.6(d) and 3.2.5.1.9(d).]

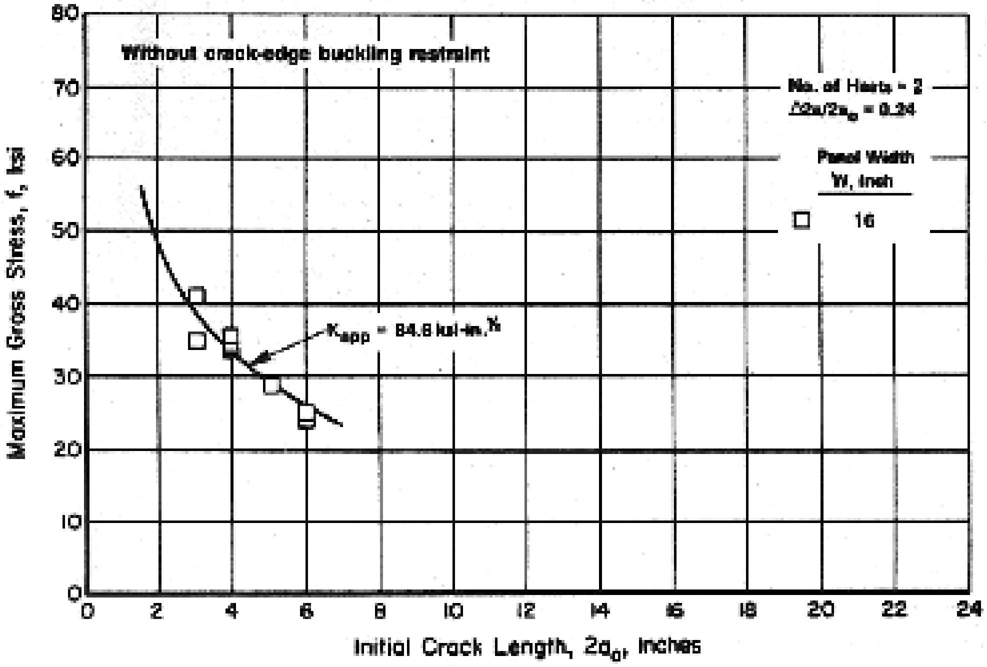


Figure 3.7.10.3.10(b). Residual strength behavior of 0.063-inch-thick 7475-T761 aluminum alloy sheet at room temperature. Crack orientation is T-L. [References 3.1.2.1.6(d) and 3.2.5.1.9(d).]

3.8 200.0 SERIES CAST ALLOYS

Alloys of the 200 series contain copper as the principal alloying element, and are particularly useful for elevated temperature applications.

3.8.1 A201.0 ALLOY

3.8.1.0 *Comments and Properties* — A201.0 is a high-strength, heat-treatable Al-Cu-Ag casting alloy. In the T7 (overaged) temper, it possesses high strength, moderate ductility and optimum resistance to stress-corrosion cracking. Refer to Section 3.1.3.4 for comments regarding the weldability of the alloy.

A material specification covering this alloy is presented in Table 3.8.1.0(a). Room-temperature mechanical and physical properties are presented in Table 3.8.1.0(b). The effect of temperature on thermal expansion is shown in Figure 3.8.1.0.

Table 3.8.1.0(a). Material Specification for A201.0 Aluminum Alloy

Specification	Form
AMS-A-21180	Casting (T7 temper)

The temper index for A201.0 is as follows:

Section	Temper
3.8.1.1	T7

3.8.1.1 *T7 Temper* — Figure 3.8.1.1.6 presents a typical tensile stress-strain curve. Strain control fatigue data are shown in Figures 3.8.1.1.8(a) through (c).

Table 3.8.1.0(b). Design Mechanical and Physical Properties of A201.0 Aluminum Alloy Casting

Specification	AMS-A-21180			
Form	Casting			
Temper	T7			
Location Within Casting	Designated area		Nondesignated area	
Strength Class Number[a]	1	2	10	11
Basis	S	S	S	S
Mechanical Properties[b,c]:				
F_{tu}, ksi:	60	60	60	56
F_{ty}, ksi:	50	50	50	48
F_{cy}, ksi:	51	51	51	49
F_{su}, ksi	36	36	36	34
F_{bru}[d], ksi:				
(e/D = 1.5)	95	95	95	88
(e/D = 2.0)	122	122	122	114
F_{bry}[d], ksi:				
(e/D = 1.5)	74	74	74	71
(e/D = 2.0)	87	87	87	83
e, percent	3	5	3	1.5
E, 10^3 ksi	10.3			
E_c, 10^3 ksi	10.7			
G, 10^3 ksi	4.0			
μ	0.33			
Physical Properties:				
ω, lb/in.^{3}	0.101			
C, Btu/(lb)(°F)	0.22 (at 212°F)			
K, Btu/[(hr)(ft^2)(°F)/ft]	70 (at 77°F)			
α, 10^{-6} in./in./°F	See Figure 3.8.1.0			

a The attainable strength class number is dependent on the casting configuration, complexity, and size (both weight and wall thickness). Favorable experience with a particular configuration may allow some foundries to produce a higher strength class number than others. In case of doubt regarding the strength class number, the designer should consult or negotiate with the foundry to determine the proper strength class number to assign for a specific casting.

b For any casting process; i.e., special mold, permanent mold, or sand mold (including chilling).

c The mechanical properties shown are reliably obtainable in castings of this alloy and heat-treat condition when produced under the quality assurance provisions of AMS-A-21180. These provisions require preproduction approval, documentation of foundry procedures, and specific destructive and nondestructive testing procedures for the acceptance of each production lot of castings. Strict adherence to these requirements is mandatory if these properties are to be reliably assured in each casting.

d Bearing values are “dry pin” values per Section 1.4.7.1.

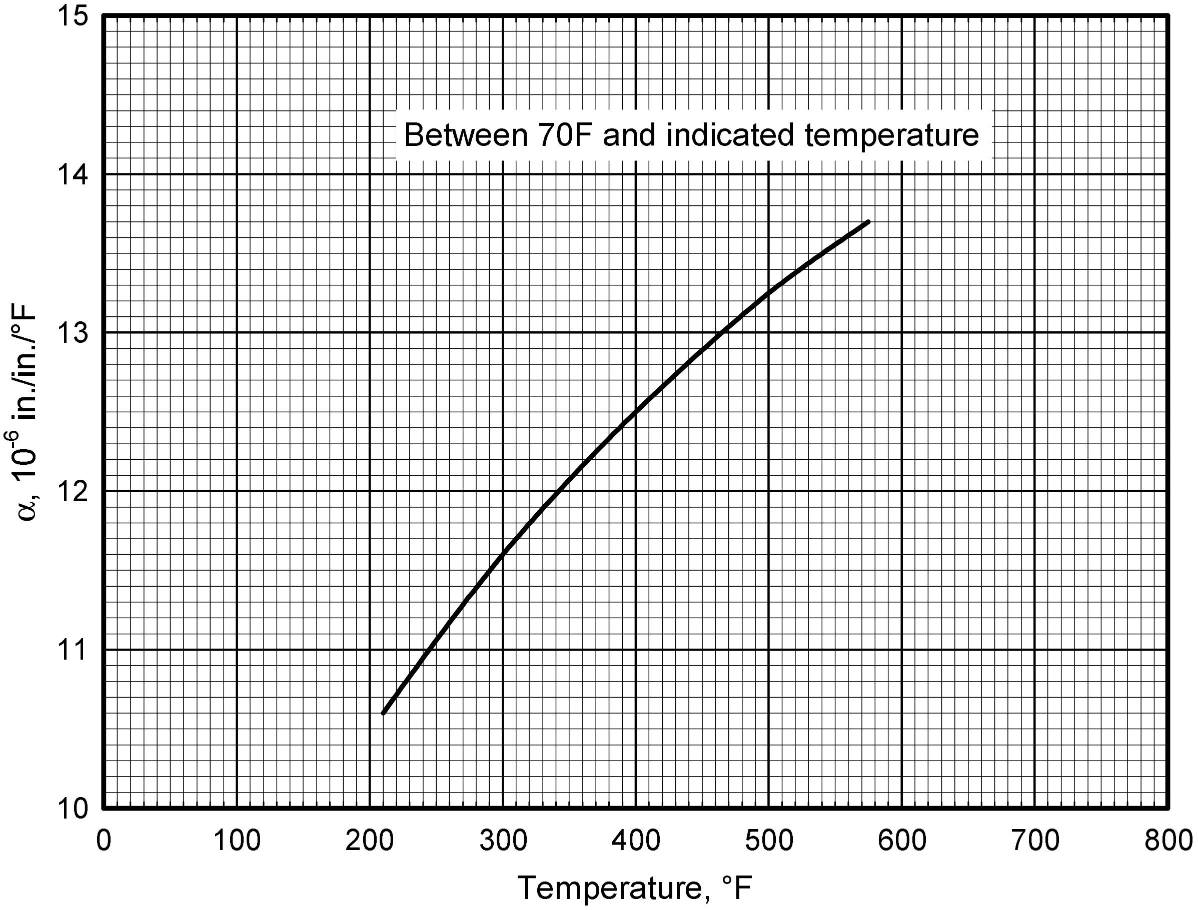


Figure 3.8.1.0. Effect of temperature on the thermal expansion of A201.0 aluminum alloy casting.

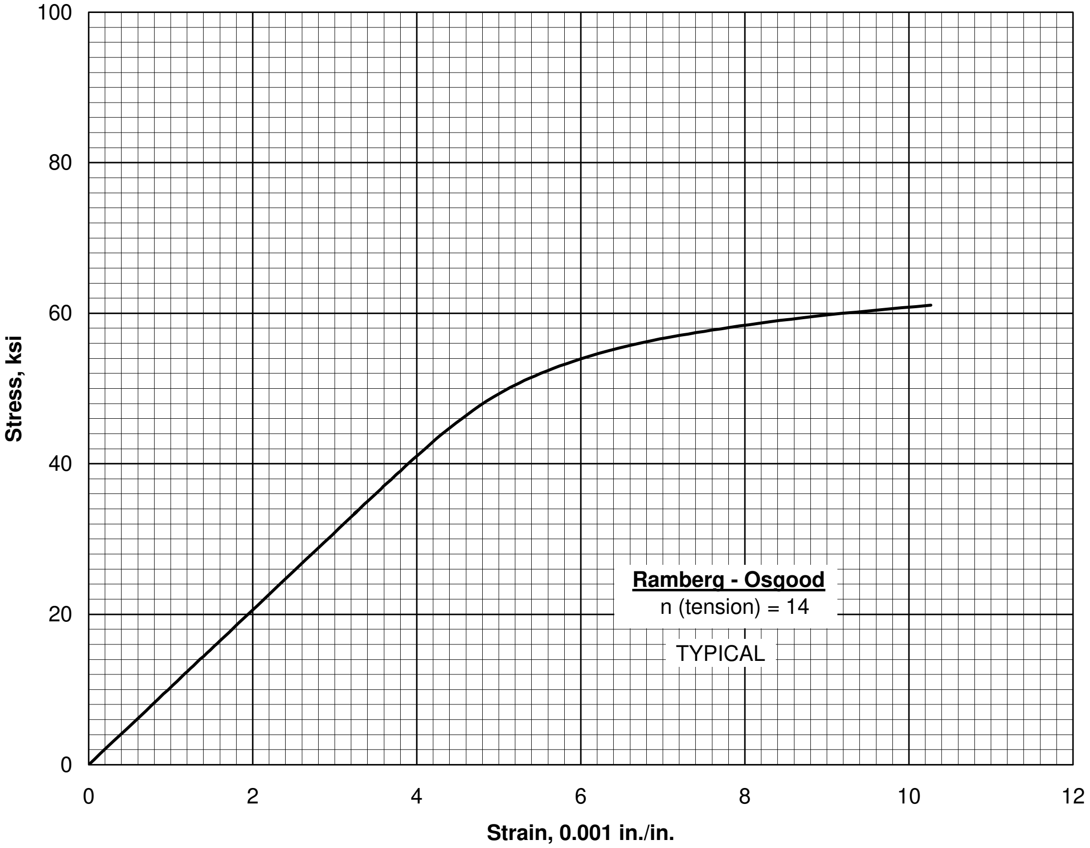


Figure 3.8.1.1.6. Typical tensile stress-strain curve for A201.0-T7 aluminum alloy casting, designated area, at room temperature.

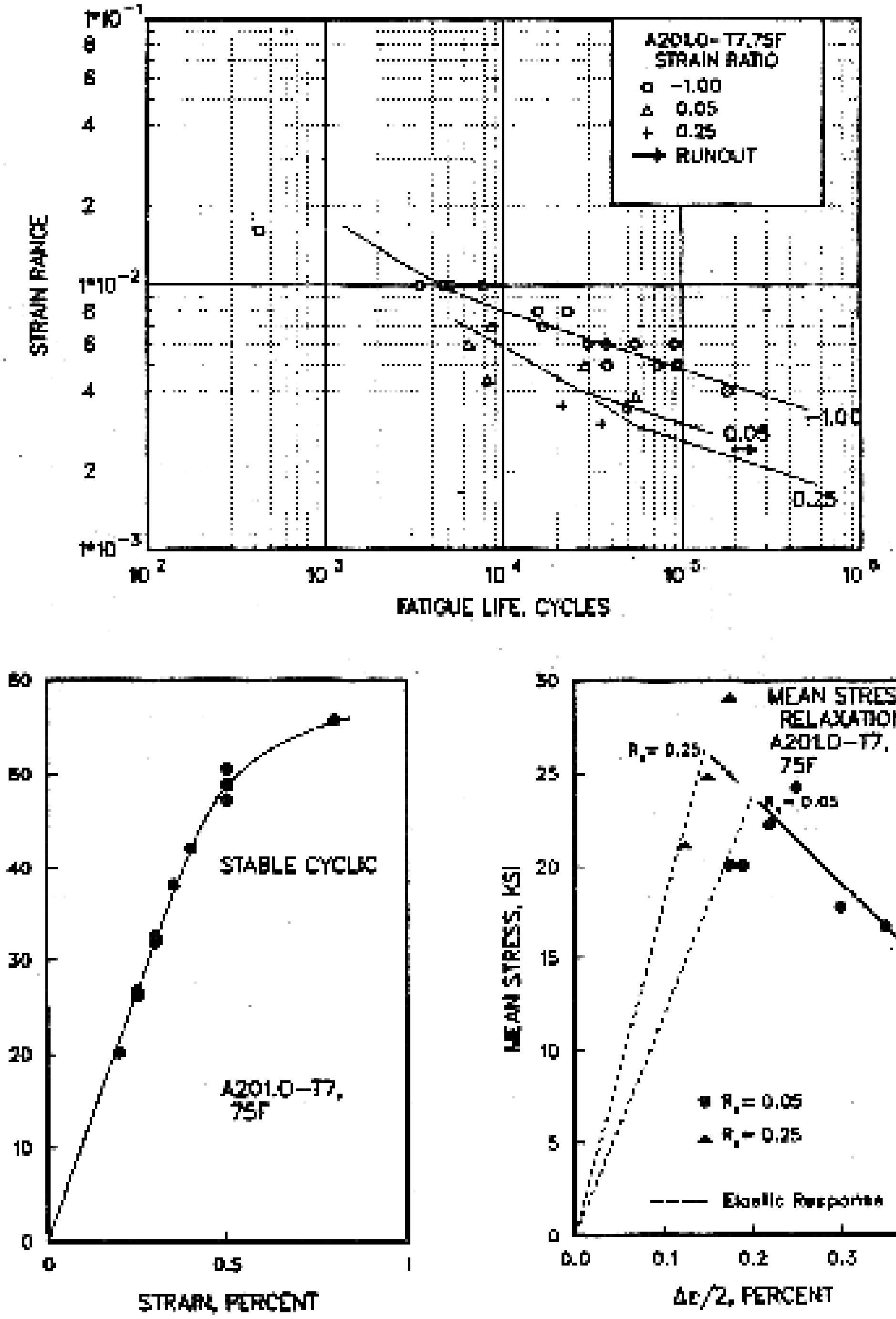


Figure 3.8.1.1.8(a). Best-fit ε/N curves, cyclic stress-strain curve, and mean stress relaxation curve for A201.0-T7 casting at 75°F.

Correlative Information for Figure 3.8.1.1.8(a)

Product Form/Thickness: Casting

Thermal Mechanical Processing History: T7, HIP

Properties:

TUS, ksi	TYS, ksi	E, ksi	Temp., °F
57-66	45-57	10,800	75

Stress-Strain Equations:
Cyclic (Companion Specimen)
Proportional Limit = 42 ksi
$(\Delta\sigma/2) = 72(\Delta\varepsilon_p/2)^{0.058}$
Mean Stress Relaxation, ksi
$\sigma_m = 33.3 - 4755(\Delta\varepsilon/2)$

Specimen Details: Uniform gage test section
0.250 inch diameter

References: 3.8.1.1.8(a) and (b)

Test Parameters:
Strain Rate/Frequency - 20 cpm
Wave Form - Triangular
Temperature - 75°F
Atmosphere - Air

No. of Heats/Lots: 3

Equivalent Strain Equation:
$\text{Log } N_f = -6.54\text{-}4.60 \log(\varepsilon_{eq})$
$\varepsilon_{eq} = (\Delta\varepsilon)^{0.37} (S_{max}/E)^{0.63}$
Std. Error of Estimate, Log (Life) = 0.242
Standard Deviation, Log (Life) = 0.587
Adjusted R^2 Statistic: 83%

Sample Size: 26

[Caution: The equivalent strain model may provide unrealistic life predictions for strain ratios and ranges beyond those represented above.]

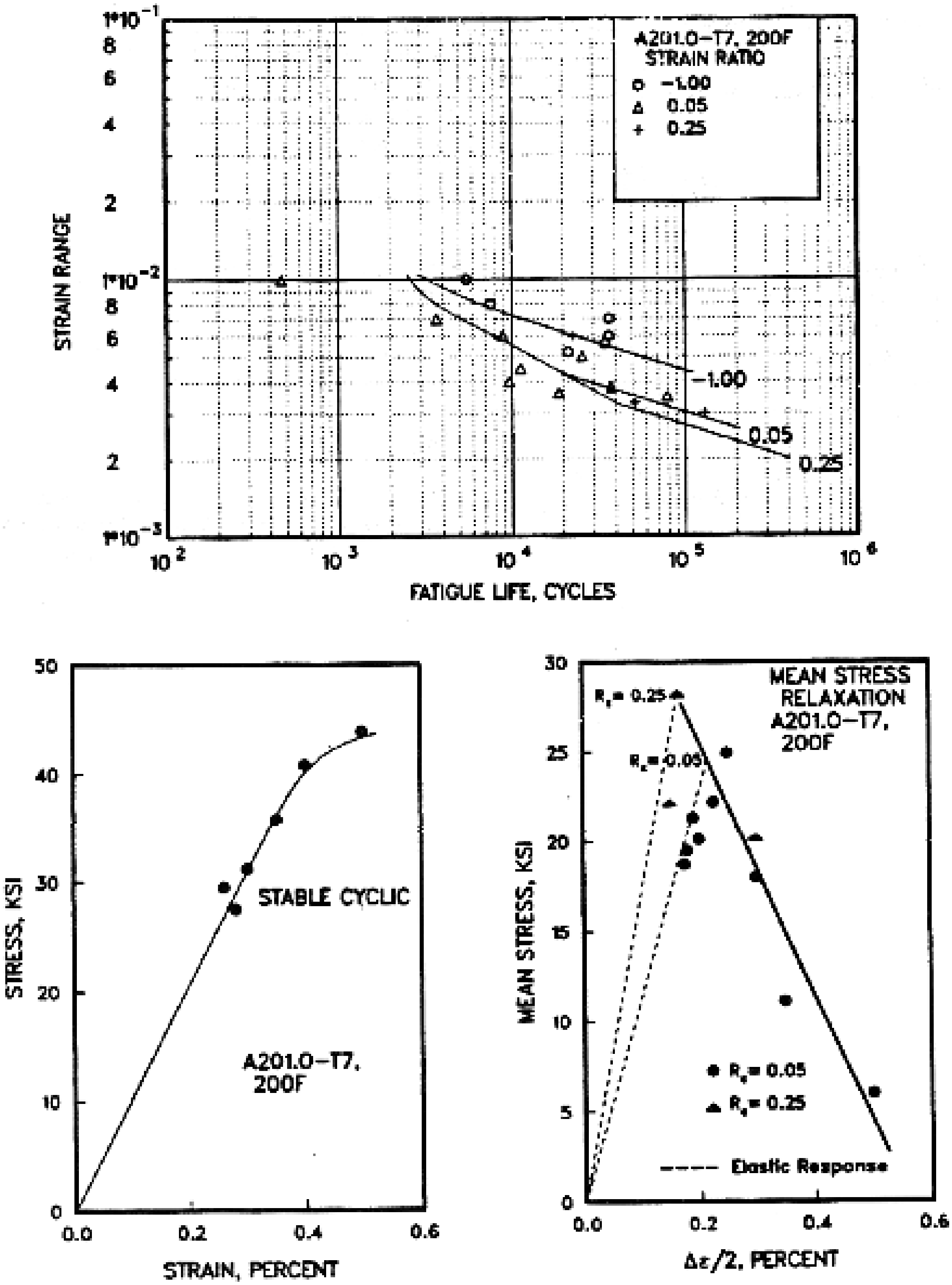


Figure 3.8.1.1.8(b). Best-fit ε/N curves, cyclic stress-strain curve, and mean stress reduction curve for A201.0-T7 casting at 200°F.

Correlative Information for Figure 3.8.1.1.8(b)

Product Form/Thickness: Casting

Thermal Mechanical Processing History: T7, HIP

Properties:

TUS, ksi	TYS, ksi	E, ksi	Temp., °F
53-59	47-55	10,339	200

Stress-Strain Equations:
Cyclic (Companion Specimen)
Proportional Limit = 39 ksi
$(\Delta\sigma/2) = 58(\Delta\varepsilon_p/2)^{0.041}$
Mean Stress Relaxation, ksi
$\sigma_m = 39.7 - 7049(\Delta\varepsilon/2)$

Specimen Details: Uniform gage test section
0.250 inch diameter

Reference: 3.8.1.1.8(a)

Test Parameters:
Strain Rate/Frequency - 20 cpm
Wave Form - Triangular
Temperature - 200°F
Atmosphere - Air

No. of Heats/Lots: 3

Equivalent Strain Equation:
$\text{Log } N_f = -6.68-4.66 \log (\varepsilon_{eq})$
$\varepsilon_{eq} = (\Delta\varepsilon)^{0.50} (S_{max}/E)^{0.50}$
Std. Error of Estimate, Log (Life) = 0.359
Standard Deviation in Log (Life) = 0.561
Adjusted R^2 Statistic: 59%

Sample Size: 18

[Caution: The equivalent strain model may provide unrealistic life predictions for strain ratios and ranges beyond those represented above.]

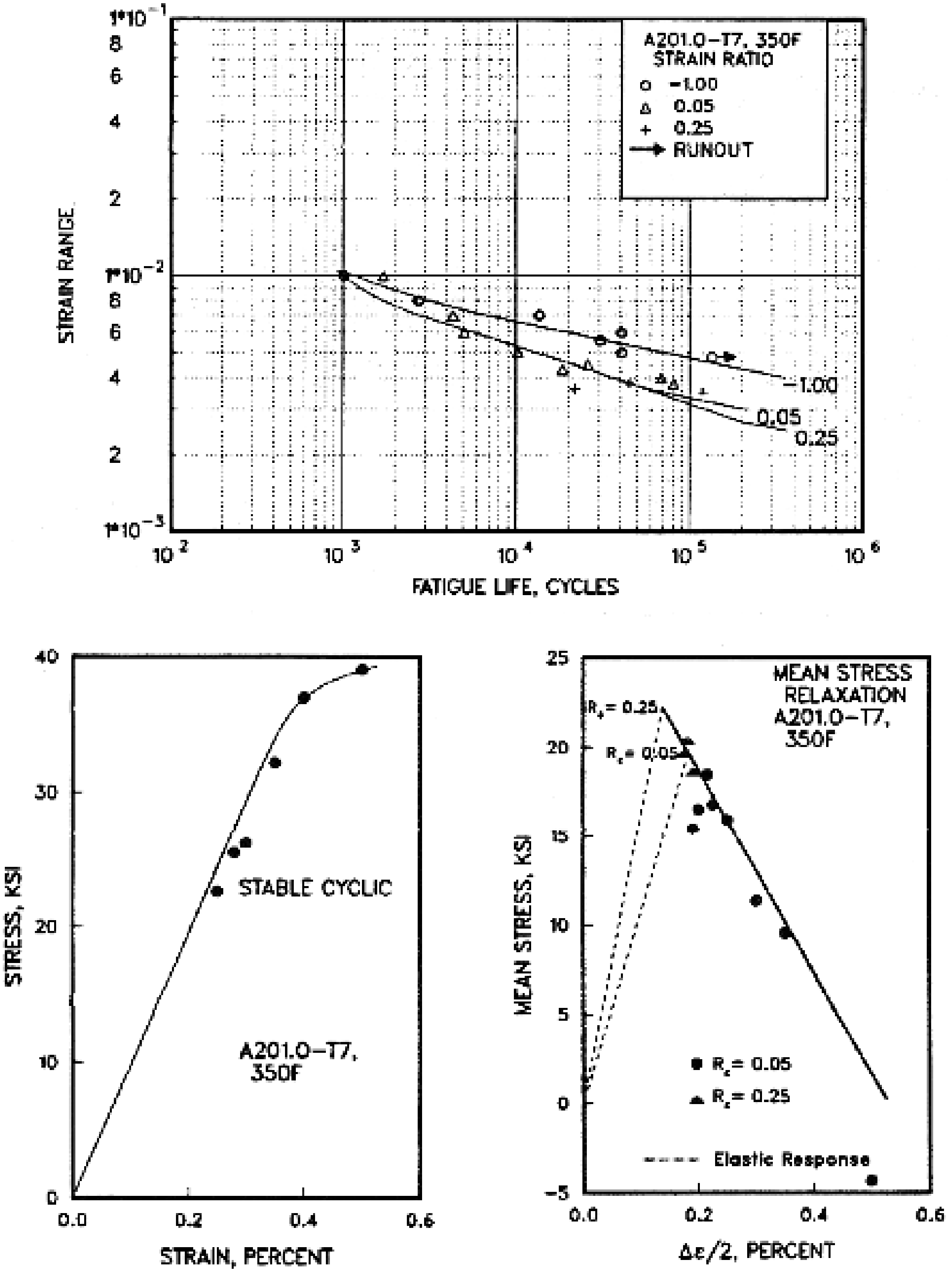


Figure 3.8.1.1.8(c). Best-fit ∈/N curves, cyclic stress-strain curve, and mean stress relaxation curve for A201.0-T7 casting at 350°F.

Correlative Information for Figure 3.8.1.1.8(c)

Product Form/Thickness: Casting

Thermal Mechanical Processing History: T7, HIP

Properties:

TUS, ksi	TYS, ksi	E, ksi	Temp., °F
48-53	40-48	9,783	350

Stress-Strain Equations:
Cyclic (Companion Specimen)
Proportional Limit = 36 ksi
$(\Delta\sigma/2) = 50(\Delta\varepsilon_p/2)^{0.036}$
Mean Stress Relaxation, ksi
$\sigma_m = 30.0 - 5664(\Delta\varepsilon/2)$

Specimen Details: Uniform gage test section
0.250 inch diameter

Reference: 3.8.1.1.8(a)

Test Parameters:
Strain Rate/Frequency - 20 cpm
Wave Form - Triangular
Temperature - 350°F
Atmosphere - Air

No. of Heats/Lots: 3

Equivalent Strain Equation:
$\text{Log } N_f = -12.44-7.07 \log (\varepsilon_{eq})$
$\varepsilon_{eq} = (\Delta\varepsilon)^{0.52} (S_{max}/E)^{0.48}$
Std. Error of Estimate, Log (Life) = $0.000817 (1/\varepsilon_{eq})$
Standard Deviation, Log (Life) = 0.545

Adjusted R^2 Statistic: 93%

Sample Size: 18

[Caution: The equivalent strain model may provide unrealistic life predictions for strain ratios and ranges beyond those represented above.]

3.9 300.0 SERIES CAST ALLOYS

Casting alloys of the 300.0 series contain silicon with added copper and/or magnesium as the principal alloying elements. They are heat treatable. Because of the high silicon content, they are among the easiest to cast by a variety of techniques. They have high resistance to corrosion.

3.9.1 354.0 ALLOY

3.9.1.0 ***Comments and Properties*** — 354.0 is a heat-treatable Al-Si-Mg alloy being among the highest strength of commercial casting alloys. It has good casting characteristics; however, its use is generally restricted to permanent mold castings. Refer to Section 3.1.3.4 for comments regarding the weldability.

A material specification for 354.0 aluminum alloy is presented in Table 3.9.1.0(a). Room-temperature mechanical and physical properties are shown in Table 3.9.1.0(b).

Table 3.9.1.0(a). *Material Specifications for 354.0 Aluminum Alloy*

Specification	Form
AMS-A-21180	Casting

Table 3.9.1.0(b). Design Mechanical and Physical Properties of 354.0 Aluminum Alloy Casting

Specification	AMS-A-21180			
Form	Casting			
Temper	T6			
Location Within Casting	Designated area		Nondesignated area	
Strength Class Number[a]	1	2	10	11
Basis	S	S	S	S
Mechanical Properties[b,c]:				
F_{tu}, ksi	47	50	47	43
F_{ty}, ksi	36	42	36	33
F_{cy}, ksi	36	42	36	33
F_{su}, ksi	29	31	29	27
F_{bru}[d], ksi:				
(e/D = 1.5)	81	86	81	74
(e/D = 2.0)	101	107	101	92
F_{bry}[d], ksi:				
(e/D = 1.5)	57	66	57	52
(e/D = 2.0)	67	78	67	62
e, percent	3	2	3	2
E, 10^3 ksi	10.6			
E_c, 10^3 ksi	10.8			
G, 10^3 ksi	4.0			
μ	0.33			
Physical Properties:				
ω, lb/in.^{3}	0.098			
C, Btu/(lb)(°F)	0.23 (at 212°F)			
K, Btu/[(hr)(ft^2)(°F)/ft]	...			
α, 10^{-6} in./in./°F	1.6 (68 to 212°F)			

a The attainable strength class number is dependent on the casting configuration, complexity, and size (both weight and wall thickness). Favorable experience with a particular configuration may allow some foundries to produce a higher strength class number than others. In case of doubt regarding the strength class number, the designer should consult or negotiate with the foundry to determine the proper strength class number to assign for a specific casting.

b For any casting process; i.e., special mold, permanent mold, or sand mold (including chilling).

c The mechanical properties shown are reliably obtainable in castings of this alloy and heat-treat condition when produced under the quality assurance provisions of AMS-A-21180. These provisions require preproduction approval, documentation of foundry procedures, and specific destructive and nondestructive testing procedures for the acceptance of each production lot of castings. Strict adherence to these requirements is mandatory if these properties are to be reliably assured in each casting.

d Bearing values are "dry pin" values per Section 1.4.7.1.

3.9.2 355.0 ALLOY

3.9.2.0 ***Comments and Properties*** — 355.0 is a heat-treatable Al-Si-Mg alloy that is readily cast and has good pressure tightness. Refer to Section 3.1.3.4 for comments regarding the weldability of the alloy.

A material specification for 355.0 aluminum alloy is presented in Table 3.9.2.0(a). Room-temperature mechanical and physical properties are shown in Table 3.9.2.0(b). The effect of temperature on thermal expansion is shown in Figure 3.9.2.0.

Table 3.9.2.0(a). Material Specification for 355.0 Aluminum Alloy

Specification	Form
AMS 4281	Permanent mold casting

Table 3.9.2.0(b). Design Mechanical and Physical Properties of 355.0 Aluminum Alloy

Specification	AMS 4281
Form	Permanent mold casting
Temper	T6
Location Within Casting	As specified
Basis	S
Mechanical Properties:	
F_{tu}, ksi	27[a]
F_{ty}, ksi	17[a]
F_{cy}, ksi	17
F_{su}, ksi	17
F_{bru}[b], ksi:	
(e/D = 1.5)	46
(e/D = 2.0)	58
F_{bry}[b], ksi:	
(e/D = 1.5)	27
(e/D = 2.0)	32
e, percent	0.4[a]
E, 10^3 ksi	10.3
E_c, 10^3 ksi	10.3
G, 10^3 ksi	3.8
μ	0.33
Physical Properties:	
ω, lb/in.^{3}	0.098
C, Btu/(lb)(°F)	0.23 (at 212°F)
K, Btu/[(hr)(ft^2)(°F)/ft]	88 (at 77°F)
α, 10^{-6} in./in./°F	See Figure 3.9.2.0

[a] Conformance to tensile property requirements is determined by testing specimens cut from casting only when specified on drawing.

[b] Bearing values are "dry pin" values per Section 1.4.7.1.

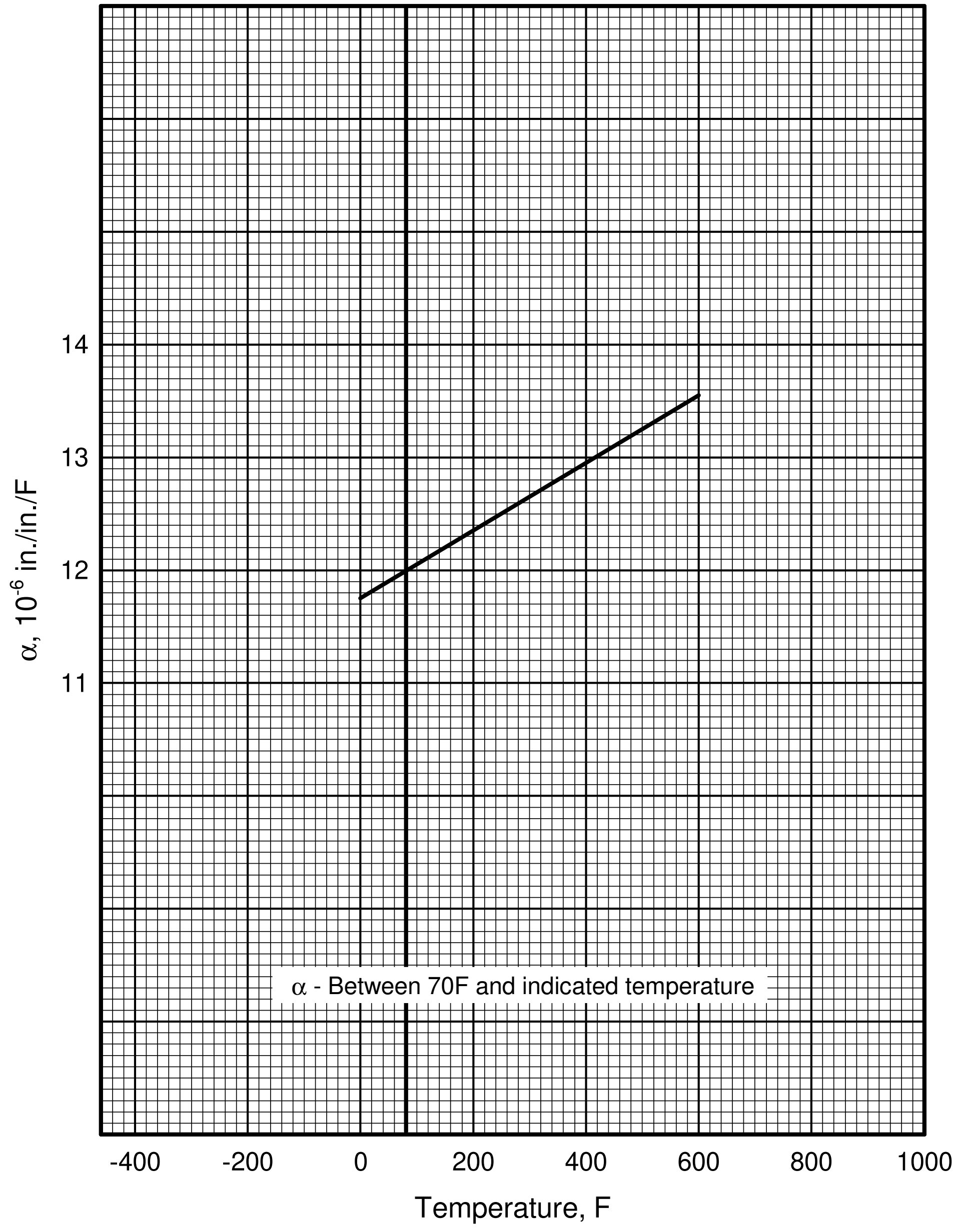


Figure 3.9.2.0. Effect of temperature on the thermal expansion of 355.0 aluminum alloy casting.

3.9.3 C355.0 ALLOY

3.9.3.0 *Comments and Properties* — C355.0 is an Al-Si-Mg alloy similar to 355.0 but has impurities controlled to lower limits resulting in higher strengths. It has good casting characteristics. Refer to Section 3.1.3.4 for comments regarding the weldability of the alloy.

A material specification for C355.0 aluminum alloy is presented in Table 3.9.3.0(a). Room-temperature mechanical and physical properties are shown in Table 3.9.3.0(b).

Table 3.9.3.0(a). Material Specification for C355.0 Aluminum Alloy

Specification	Form
AMS-A-21180	Casting

Table 3.9.3.0(b). Design Mechanical and Physical Properties of C355.0 Aluminum Alloy Casting

Specification	AMS-A-21180					
Form	Casting					
Location Within Casting	T6					
Strength Class Number[a]	1	2	3	10	11	12
Basis	S	S	S	S	S	S
Mechanical Properties[b,c]:						
F_{tu}, ksi	41	44	50	41	37	35
F_{ty}, ksi	31	33	40	31	30	28
F_{cy}, ksi	31	33	40	31	30	28
F_{su}, ksi	26	28	31	26	23	22
F_{bru}[d], ksi:						
(e/D = 1.5)	70	75	86	70	63	60
(e/D = 2.0)	88	94	107	88	79	75
F_{bry}[d], ksi:						
(e/D = 1.5)	49	52	63	49	47	44
(e/D = 2.0)	58	62	75	58	59	52
e, percent	3	3	2	3	1	1
E, 10^3 ksi	10.1					
E_c, 10^3 ksi	10.3					
G, 10^3 ksi	3.85					
μ	0.33					
Physical Properties:						
ω, lb/in.^{3}	0.098					
C, Btu/(lb)(°F)	0.23 (at 212°F)					
K, Btu/[(hr)(ft^2)(°F)/ft]	88 (at 77°F)					
α, 10^{-6} in./in./°F	12.4 (68 to 212°F)					

a The attainable strength class number is dependent on the casting configuration, complexity, and size (both weight and wall thickness). Favorable experience with a particular configuration may allow some foundries to produce a higher strength class number than others. In case of doubt regarding the strength class number, the designer should consult or negotiate with the foundry to determine the proper strength class number to assign for a specific casting.

b For any casting process; i.e., special mold, permanent mold, or sand mold (including chilling).

c The mechanical properties shown are reliably obtainable in castings of this alloy and heat-treat condition when produced under the quality assurance provisions of AMS-A-21180. These provisions require preproduction approval, documentation of foundry procedures, and specific destructive and nondestructive testing procedures for the acceptance of each production lot of castings. Strict adherence to these requirements is mandatory if these properties are to be reliably assured in each casting.

d Bearing values are “dry pin” values per Section 1.4.7.1.

3.9.4 356.0 ALLOY

3.9.4.0 *Comments and Properties* — 356.0 is among the easiest of alloys to cast by a variety of techniques. It is heat treatable, has intermediate strengths, and has high resistance to corrosion. Refer to Section 3.1.3.4 for comments regarding the weldability of the alloy.

Material specifications for 356.0 aluminum alloy are presented in Table 3.9.4.0(a). Room-temperature mechanical and physical properties are shown in Table 3.9.4.0(b). The effect of temperature on thermal expansion is given in Figure 3.9.4.0.

Table 3.9.4.0(a). Material Specifications for 356.0 Aluminum Alloy

Specification	Form
AMS 4284	Permanent mold casting
AMS 4217	Sand casting
AMS 4260	Investment casting

Table 3.9.4.0(b). Design Mechanical and Physical Properties of 356.0 Aluminum Alloy

Specification	AMS 4217	AMS 4260	AMS 4284
Form	Sand casting	Investment casting	Permanent mold casting
Temper	T6	T6	T6
Location Within Casting	Thick and thin areas	As specified	As specified
Basis	S	S	S
Mechanical Properties:			
F_{tu}, ksi	22[a,b]	25[a]	25[a]
F_{ty}, ksi	15[a,b]	16[a]	16[a]
F_{cy}, ksi	15	16	16
F_{su}, ksi	14	16	16
F_{bru}[c], ksi:			
(e/D = 1.5)	38	43	43
(e/D = 2.0)	47	53	53
F_{bry}[c], ksi:			
(e/D = 1.5)	24	25	25
(e/D = 2.0)	28	30	30
e, percent	0.7[a,b]	1[a]	0.7[a]
E, 10^3 ksi	10.3		
E_c, 10^3 ksi	10.3		
G, 10^3 ksi	3.85		
μ	0.33		
Physical Properties:			
ω, lb/in.^{3}	0.097		
C, Btu/(lb)(°F)	0.23 (at 212°F)		
K, Btu/[(hr)(ft^2)(°F)/ft]	88 (at 77°F)		
α, 10^{-6} in./in./°F	See Figure 3.9.4.0		

a Conformance to tensile property requirements is determined by testing specimens cut from casting only when specified on drawing.

b Not minimum values, but based upon average of not less than four specimens.

c Bearing values are “dry pin” values per Section 1.4.7.1.

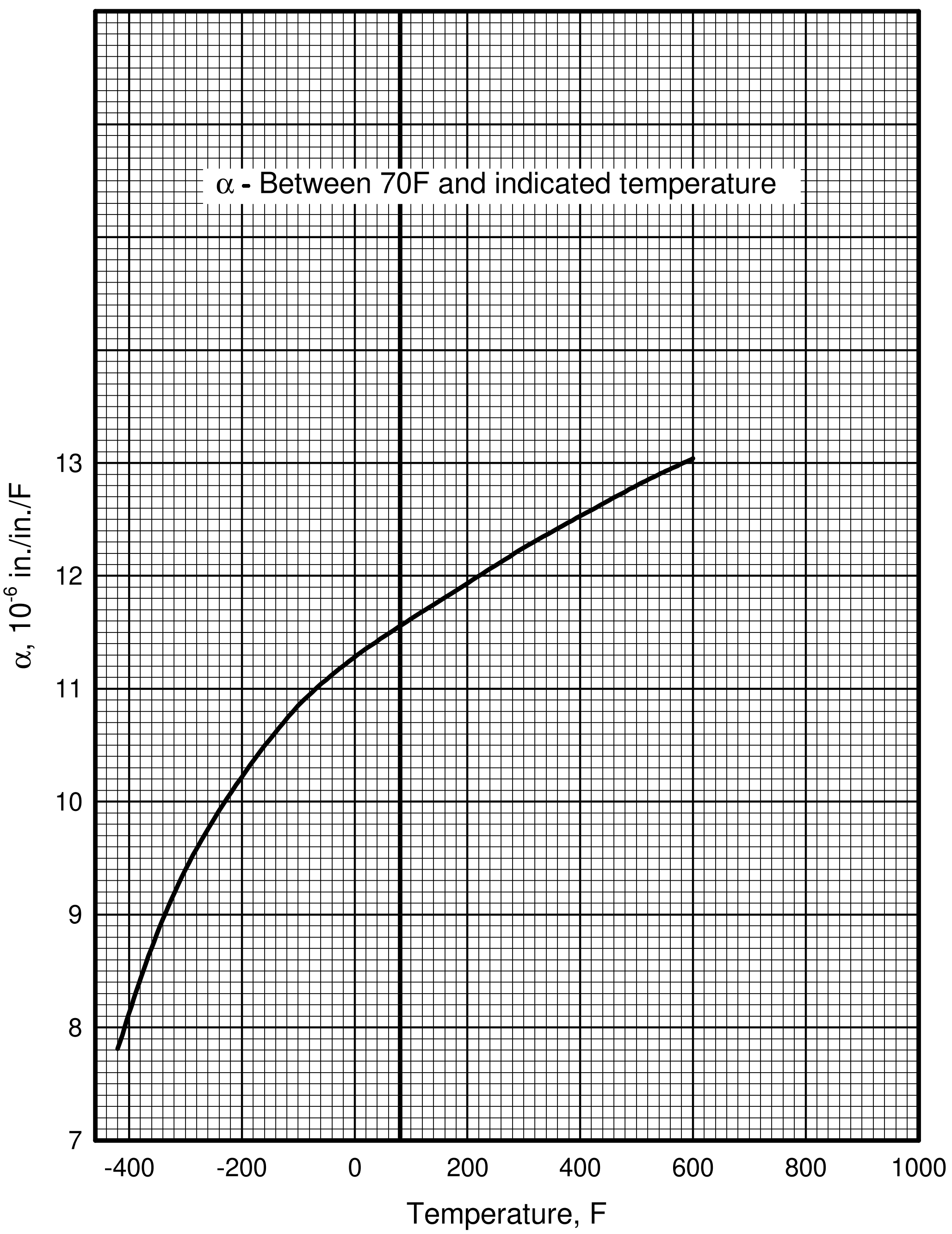


Figure 3.9.4.0. Effect of temperature on the thermal expansion of 356.0 aluminum alloy casting.

3.9.5 A356.0 ALLOY

3.9.5.0 *Comments and Properties* — A356.0 is an Al-Si-Mg alloy similar to 356.0, but with impurities controlled to lower limits resulting in higher strengths and ductility. It has good casting characteristics and high resistance to corrosion. Refer to 3.1.3.4 for comments regarding the weldability of the alloy.

Material specifications for A356.0 aluminum alloy are presented in Table 3.9.5.0(a). Room-temperature mechanical and physical properties are shown in Tables 3.9.5.0(b) and (c).

Table 3.9.5.0(a). Material Specifications for A356.0 Aluminum Alloy

Specification	Form
AMS-A-21180	Casting
AMS 4218	Casting

The temper index for A356.0 is as follows:

Section	Temper
3.9.5.1	T6P
3.9.5.2	T6

3.9.5.1 *T6P Temper* — Tensile stress-strain and full-range stress-strain curves at room temperature are presented in Figures 3.9.5.1.6(a) and (b), respectively.

Table 3.9.5.0(b). Design Mechanical and Physical Properties of A356.0 Aluminum Alloy Casting

Specification	AMS-A-21180					
Form	Casting					
Temper	T6					
Location Within Casting	Designated area			Nondesignated area		
Strength Class Number[a]	1	2	3	10	11	12
Basis	S	S	S	S	S	S
Mechanical Properties[b,c]:						
F_{tu}, ksi	38	40	45	38	33	32
F_{ty}, ksi	28	30	34	28	27	22
F_{cy}, ksi	28	30	34	28	27	22
F_{su}, ksi	24	25	28	24	21	20
F_{bru}[d], ksi:						
(e/D = 1.5)	65	69	77	65	57	55
(e/D = 2.0)	81	86	96	81	71	68
F_{bry}[d], ksi:						
(e/D = 1.5)	44	47	54	44	43	35
(e/D = 2.0)	52	56	63	52	50	41
e, percent	5	3	3	5	3	2
E, 10^3 ksi	10.4					
E_c, 10^3 ksi	10.5					
G, 10^3 ksi	3.9					
μ	0.33					
Physical Properties:						
ω, lb/in.^{3}	0.097					
C, Btu/(lb)(°F)	0.23 (at 212°F)					
K, Btu/[(hr)(ft^2)(°F)/ft]	88 (at 77°F)					
α, 10^{-6} in./in./°F	See Figure 3.9.4.0					

[a] The attainable strength class number is dependent on the casting configuration, complexity, and size (both weight and wall thickness). Favorable experience with a particular configuration may allow some foundries to produce a higher strength class number than others. In case of doubt regarding the strength class number, the designer should consult or negotiate with the foundry to determine the proper strength class number to assign for a specific casting.

[b] For any casting process; i.e., special mold, permanent mold, or sand mold (including chilling).

[c] The mechanical properties shown are reliably obtainable in castings of this alloy and heat-treat condition when produced under the quality assurance provisions of AMS-A-21180. These provisions require preproduction approval, documentation of foundry procedures, and specific destructive and nondestructive testing procedures for the acceptance of each production lot of castings. Strict adherence to these requirements is mandatory if these properties are to be reliably assured in each casting.

[d] Bearing values are “dry pin” values per Section 1.4.7.1.

Table 3.9.5.0(c). Design and Physical Properties of A356.0 Aluminum Alloy Casting

Specification	AMS 4218
Form	Sand, investment, permanent mold, and composite castings
Temper	T6P[a]
Location Within Casting	Any
Basis	S
Mechanical Properties:[b]	
F_{tu}, ksi	32
F_{ty}, ksi	22
F_{cy}, ksi	22
F_{su}, ksi	20
F_{bru}, ksi:	
(e/D = 1.5)	55
(e/D = 2.0)	68
F_{bry}, ksi:	
(e/D = 1.5)	35
(e/D = 2.0)	41
e, percent	2
E, 10^3 ksi	10.4
E_c, 10^3 ksi	10.5
G, 10^3 ksi	3.9
μ	0.33
Physical Properties:	
ω, lb/in.^{3}	0.097
C, Btu/(lb)(°F)	0.23 (at 212°F)
K Btu/[(hr)(ft^2)(°F)/ft]	88 (at 77°F)
α, 10^{-6} in./in./°F	See Figure 3.9.4.0

[a] The letter, P, indicates a variation compared to the standard heat treatment procedure of this temper and/or a difference in the minimum tensile property requirements compared to the Aluminum Association's registered limits.

[b] The mechanical properties shown are reliably obtainable when produced under the quality assurance provisions of AMS 4218. These procedures require radiographic control and specific destructive testing for acceptance of each production lot. Strict adherence to these requirements is mandatory if these properties are to be reliably assured in each casting.

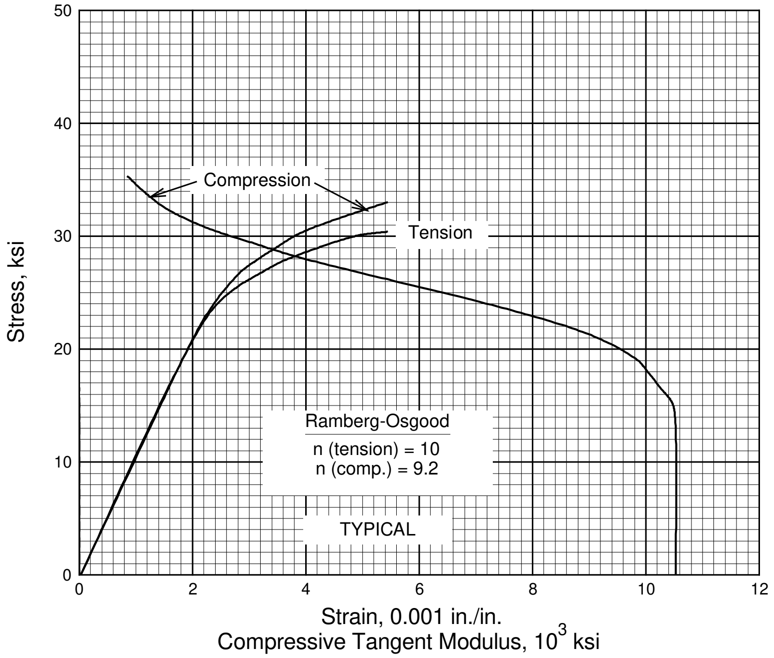


Figure 3.9.5.1.6(a). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for A356.0-T6P aluminum alloy casting at room temperature.

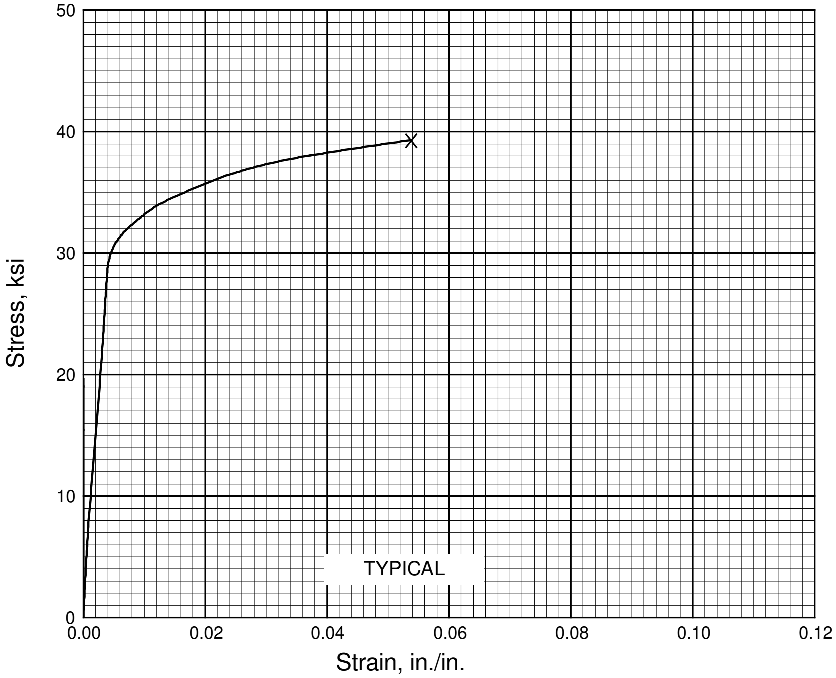


Figure 3.9.5.1.6(b). Typical tensile stress-strain (full-range) curve for A356.0-T6P aluminum alloy casting at room temperature.

3.9.6 A357.0 ALLOY

3.9.6.0 *Comments and Properties* — A357.0 is a heat-treatable Al-Si-Mg alloy generally used for permanent mold and premium quality castings in which special properties are developed by careful control of casting and chilling techniques. It has excellent casting characteristics, is heat treatable, and provides high strength, together with good toughness. The alloy also has excellent corrosion resistance. Refer to Section 3.1.3.4 for comments regarding the weldability of the alloy.

A material specification for A357.0 aluminum alloy is presented in Table 3.9.6.0(a). Room-temperature mechanical and physical properties are shown in Table 3.9.6.0(b).

Table 3.9.6.0(a). Material Specification for A357.0 Aluminum Alloy

Specification	Form
AMS-A-21180	Casting

The temper index for A357.0 is as follows:

Section	Temper
3.9.6.1	T6

3.9.6.1 *T6 Temper* — Figure 3.9.6.1.6 presents a typical tensile stress-strain curve.

Table 3.9.6.0(b). Design Mechanical and Physical Properties of A357.0 Aluminum Alloy Casting

Specification	AMS-A-21180				
Form	Casting[a]				
Temper	T6				
Location Within Casting	Designated area		Nondesignated area		
Strength Class Number[b]	1	2	10	11	12
Basis	S	S	S	S	S
Mechanical Properties:[c]					
F_{tu}, ksi	45	50	38	41	45
F_{ty}, ksi	35	40	28	31	35
F_{cy}, ksi	35	40	28	31	35
F_{su}, ksi	28	31	24	26	28
F_{bru}[d], ksi:					
(e/D = 1.5)	77	86	65	70	77
(e/D = 2.0)	96	107	81	88	96
F_{bry}[d], ksi:					
(e/D = 1.5)	55	63	44	49	55
(e/D = 2.0)	65	75	52	58	65
e, percent	3	5	5	3	3
E, 10^3 ksi	10.4				
E_c, 10^3 ksi	10.5				
G, 10^3 ksi	3.9				
μ	0.33				
Physical Properties:					
ω, lb/in.^{3}	0.097				
C, Btu/(lb)(°F)	0.23 (at 212°F)				
K, Btu/[(hr)(ft^2)(°F)/ft]	88 (at 77°F)				
α, 10^{-6} in./in./°F	12.0 (68 to 212°F)				

a For any casting process; i.e., special mold, permanent mold, or sand mold (including chilling).

b The attainable strength class number is dependent on the casting configuration, complexity, and size (both weight and wall thickness). Favorable experience with a particular configuration may allow some foundries to produce a higher strength class number than others. In case of doubt regarding the strength class number, the designer should consult or negotiate with the foundry to determine the proper strength class number to assign for a specific casting.

c The mechanical properties shown are reliably obtainable in castings of this alloy and heat-treat condition when produced under the quality assurance provisions of AMS-A-21180. These provisions require preproduction approval, documentation of foundry procedures, and specific destructive and nondestructive testing procedures for the acceptance of each production lot of castings. Strict adherence to these requirements is mandatory if these properties are to be reliably assured in each casting.

d Bearing values are “dry pin” values per Section 1.4.7.1.

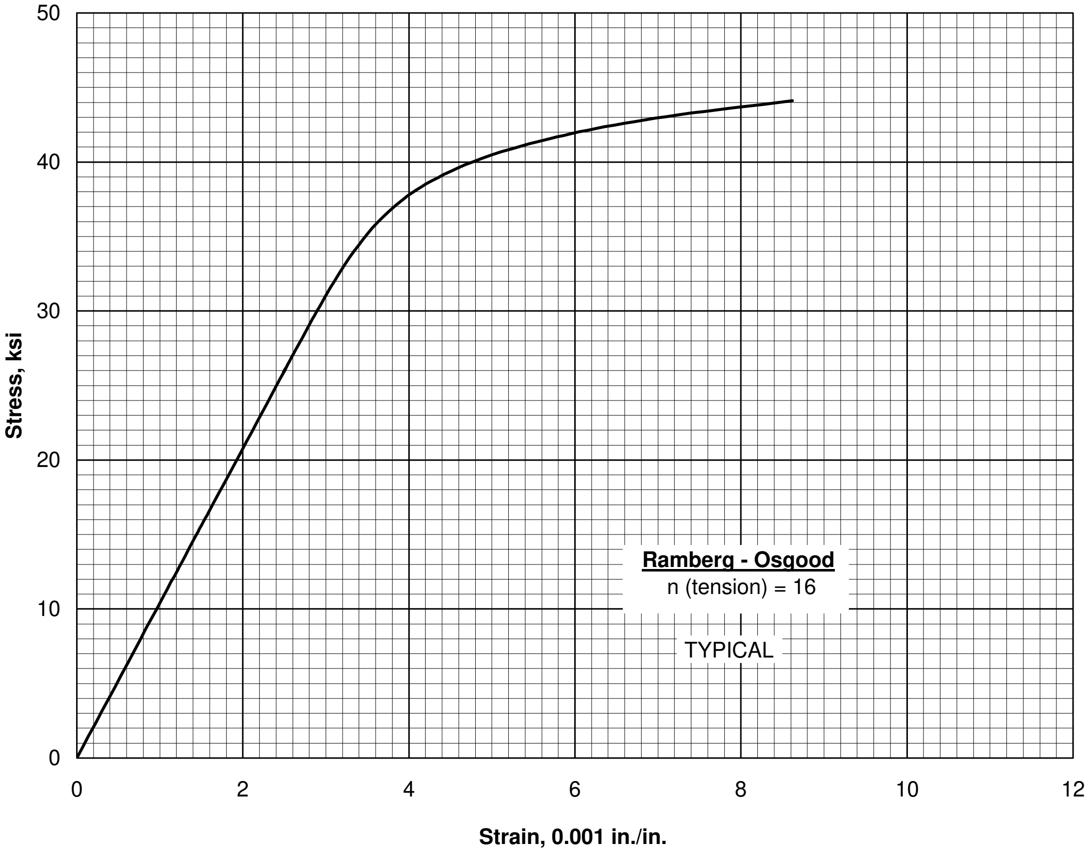


Figure 3.9.6.1.6. Typical tensile stress-strain curve for A357.0-T6 aluminum alloy casting, Class 2, designated area, at room temperature.

3.9.7 D357.0 ALLOY

3.9.7.0 *Comments and Properties* — D357.0 is a modification of A357.0 with narrower compositional limits and more stringent inspection requirements. These modifications were necessary to reduce variability in mechanical properties to a degree compatible with the determination of A- and B-basis values. D357.0 is a heat-treatable Al-Si-Mg alloy generally used for premium quality castings in which special properties are developed by careful control of casting and chilling techniques. It has excellent casting characteristics and provides high strength together with good toughness. The alloy also has excellent corrosion resistance. Refer to Section 3.1.3.4 for comments regarding the weldability of the alloy.

A material specification for D357.0 aluminum is presented in Table 3.9.7.0(a). Room temperature mechanical and physical properties are shown in Table 3.9.7.0(b).

Table 3.9.7.0(a). Material Specification for D357.0 Aluminum Alloy

Specification	Form
AMS 4241	Casting

The temper index for D357.0 is as follows:

Section	Temper
3.9.7.1	T6

3.9.7.1 *T6 Temper* — Figure 3.9.7.1.6 presents a typical tensile stress-strain curve.

Table 3.9.7.0(b). Design Mechanical and Physical Properties of D357.0 Aluminum Alloy Casting

Specification	AMS 4241		
Form	Casting		
Temper	T6		
Thickness, in.	≤2.500		...
Location Within Casting	Designated area		Nondesignated area
Basis	A	B	S
Mechanical Properties[a]:			
F_{tu}, ksi	46	49	45
F_{ty}, ksi	39	41	36
F_{cy}, ksi	39	41	36
F_{su}, ksi	29	31	28
F_{bru}[b], ksi:			
(e/D = 1.5)	79	84	77
(e/D = 2.0)	99	105	96
F_{bry}[b], ksi:			
(e/D = 1.5)	62	65	57
(e/D = 2.0)	73	77	67
e, percent (S-basis)	3	...	2
E, 10^3 ksi	10.4		
E_c, 10^3 ksi	10.5		
G, 10^3 ksi	3.9		
μ	0.33		
Physical Properties:			
ω, lb/in.^{3}	0.097		
C, Btu/(lb)(°F)	0.23 (at 212°F)		
K, Btu/[(hr)(ft^2)(°F)/ft]	88 (at 77°F)		
α, 10^{-6} in./in./°F	12.0 (68 to 212°F)		

a The mechanical properties shown are reliably obtainable when castings are produced under the quality assurance provisions of AMS 4241. These provisions require preproduction approval, documentation of foundry procedures, and specific destructive and nondestructive testing procedures for the acceptance of each production lot of castings. Strict adherence to these requirements is mandatory if these properties are to be reliably assured in each casting.

b Bearing values are "dry pin" values per Section 1.4.7.1.

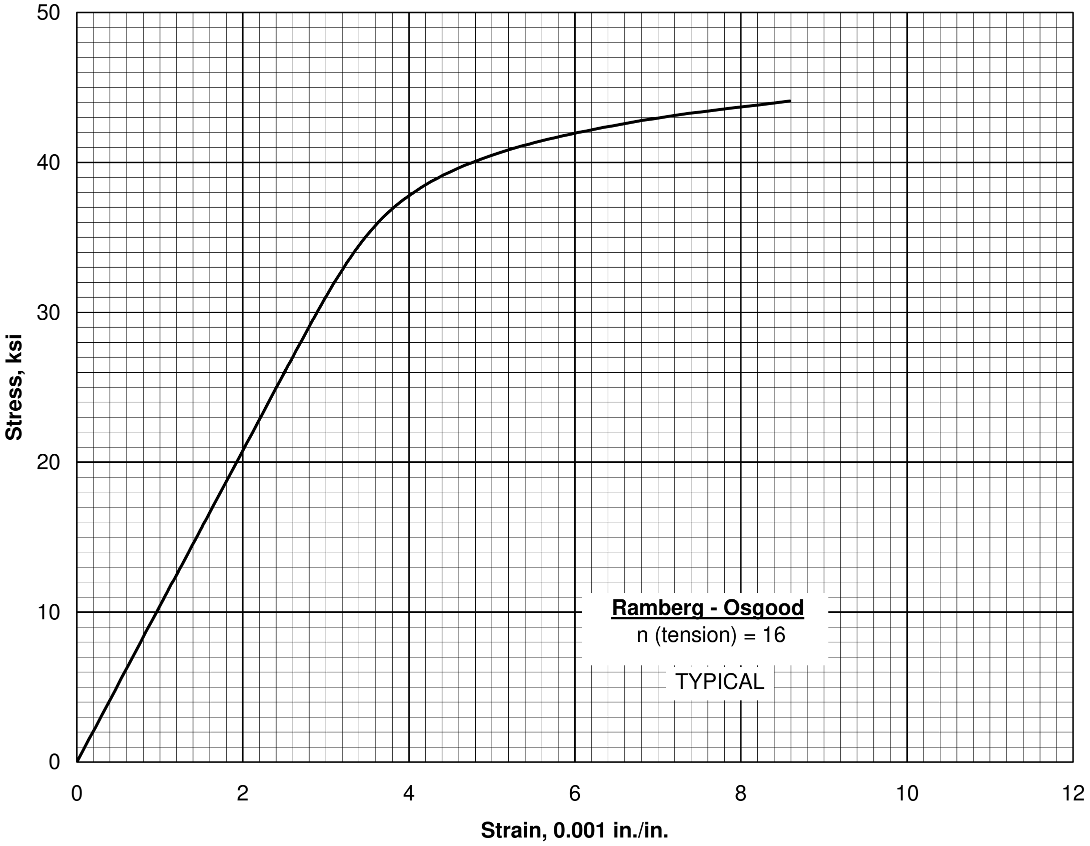


Figure 3.9.7.1.6. Typical tensile stress-strain curve for D357.0-T6 aluminum alloy casting, designated area, at room temperature.

3.9.8 359.0 ALLOY

3.9.8.0 ***Comments and Properties*** — 359.0 is a relatively high-strength permanent-mold casting alloy. It is heat treatable, and has good corrosion resistance. Refer to Section 3.1.3.4 for comments regarding the weldability of the alloy.

A material specification for 359.0 aluminum alloy is presented in Table 3.9.8.0(a). Room-temperature mechanical and physical properties are shown in Table 3.9.8.0(b).

Table 3.9.8.0(a). Material Specification for 359.0 Aluminum Alloy

Specification	Form
AMS-A-21180	Casting

Table 3.9.8.0(b). Design Mechanical and Physical Properties of 359.0 Aluminum Alloy Casting

Specification	AMS-A-21180			
Form	Casting			
Temper	T6			
Location Within Casting	Designated area		Nondesignated area	
Strength Class Number[a]	1	2	10	11
Basis	S	S	S	S
Mechanical Properties[b,c]:				
F_{tu}, ksi:	45	47	45	40
F_{ty}, ksi:	35	38	34	30
F_{cy}, ksi:	35	38	34	30
F_{su}, ksi	28	29	28	25
F_{bru}[d], ksi:				
(e/D = 1.5)	77	81	77	69
(e/D = 2.0)	96	101	96	86
F_{bry}[d], ksi:				
(e/D = 1.5)	55	60	54	47
(e/D = 2.0)	65	71	63	56
e, percent	4	3	4	3
E, 10^3 ksi	10.5			
E_c, 10^3 ksi	10.7			
G, 10^3 ksi	4.0			
μ	0.33			
Physical Properties:				
ω, lb/in.^{3}	0.097			
C, Btu/(lb)(°F)	0.23 (at 212°F)			
K, Btu/[(hr)(ft^2)(°F)/ft]	88 (at 77°F)			
α, 10^{-6} in./in./°F	11.0 (68 to 212°F)			

[a] The attainable strength class number is dependent on the casting configuration, complexity, and size (both weight and wall thickness). Favorable experience with a particular configuration may allow some foundries to produce a higher strength class number than others. In case of doubt regarding the strength class number, the designer should consult or negotiate with the foundry to determine the proper strength class number to assign for a specific casting.

[b] For any casting process; i.e., special mold, permanent mold, or sand mold (including chilling).

[c] The mechanical properties shown are reliably obtainable in castings of this alloy and heat-treat condition when produced under the quality assurance provisions of AMS-A-21180. These provisions require preproduction approval, documentation of foundry procedures, and specific destructive and nondestructive testing procedures for the acceptance of each production lot of castings. Strict adherence to these requirements is mandatory if these properties are to be reliably assured in each casting.

[d] Bearing values are “dry pin” values per Section 1.4.7.1.

3.10 ELEMENT PROPERTIES

3.10.1 BEAMS — See Chapter 1 and Reference 1.7.1 for general information on stress analysis of beams.

3.10.1.1 *Simple Beams* — Beams of solid, tubular, or similar cross sections can be assumed to fail through exceeding an allowable modulus of rupture in bending (F_b). In the absence of specific data, the ratio F_b/F_{tu} can be assumed to be 1.25 for solid sections.

3.10.1.1.1 *Round Tubes* — For round tubes, the value of F_b will depend on the D/t ratio as well as the ultimate tensile stress. The bending moduli of rupture of round tubes of various aluminum alloys are given in Figure 3.10.1.1.1. It should be noted that these values apply only when the tubes are restrained against local buckling at the loading points.

3.10.1.1.2 *Unconventional Cross Section* — Sections other than solid or tubular should be tested to determine the allowable bending stress.

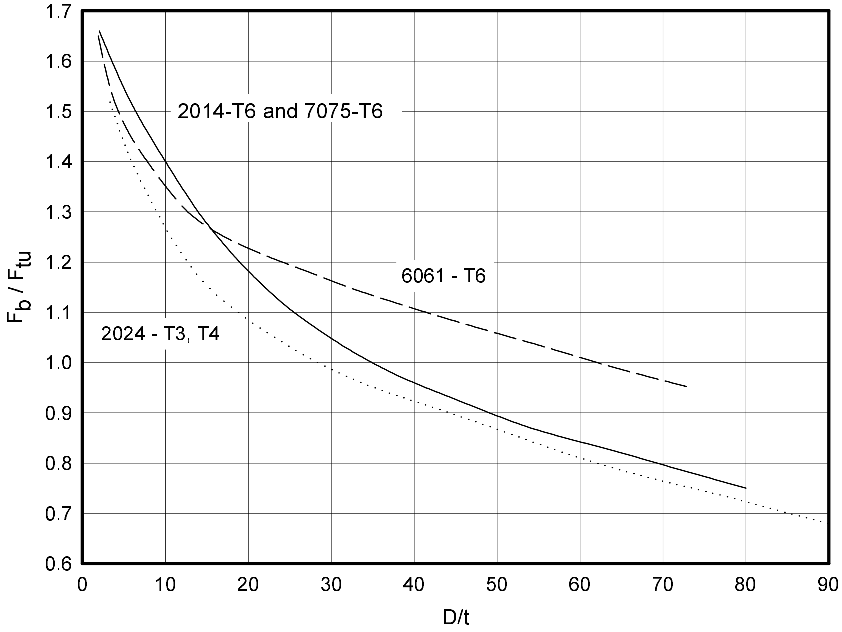


Figure 3.10.1.1.1. Bending modulus of rupture for aluminum alloy round tubing.

3.10.1.2 *Built-Up Beams* — Built-up beams will usually fail because of local failures of the component parts. In aluminum-alloy construction, the strength of fittings and joints is an important feature (see Reference 3.10.1.2).

3.10.1.3 *Thin-Web Beams* — The allowable stress for thin-web beams will depend on the nature of the failure and is determined from the allowable stresses of the web in tension and of the flanges or stiffeners in compression.

3.10.2 COLUMNS

3.10.2.1 *Primary Failure* — The general formula for primary instability is given in Section 1.3.8.

3.10.2.2 *Local Failure* — The local stability of aluminum alloy column sections may be determined using the methods outlined in References 3.10.2.2(a) through (e).

3.10.2.3 *Column Properties* — Curves of the allowable column stresses for round and streamline tubing are given in Figure 3.10.2.3. The allowable stress is plotted against the effective slenderness ratio, defined by the formula:

$$\frac{L'}{\rho} = \frac{L}{\rho\sqrt{c}} \qquad (3.10.2.3)$$

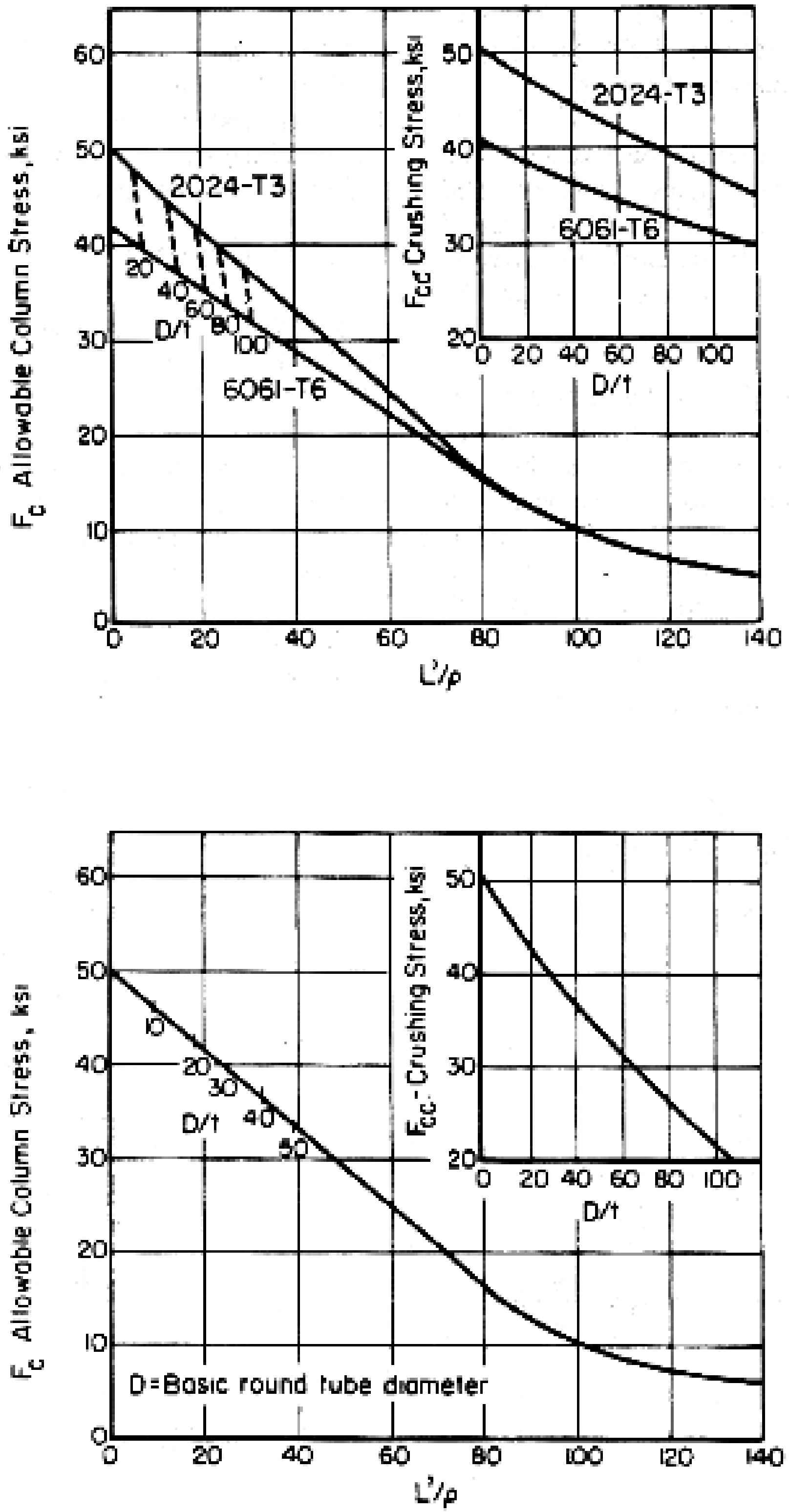


Figure 3.10.2.3. Allowable column and crushing stresses for 2024 and 6061 aluminum alloy tubing.

3.10.3 TORSION

3.10.3.1 *General* — The torsional failure of aluminum-alloy tubes may be due to plastic failure of metal, elastic instability of the walls, or an intermediate condition. Pure shear failure will not usually occur within the range of wall thicknesses commonly used for aircraft tubing.

3.10.3.2 *Torsion Properties* — The curves of Figures 3.10.3.2(a) through (g) are derived from the method outlined in Reference 2.8.1.1 and take into account the parameter L/D. The theoretical results set forth in Reference 2.8.3.2 have been found to be in good agreement with the experimental results.

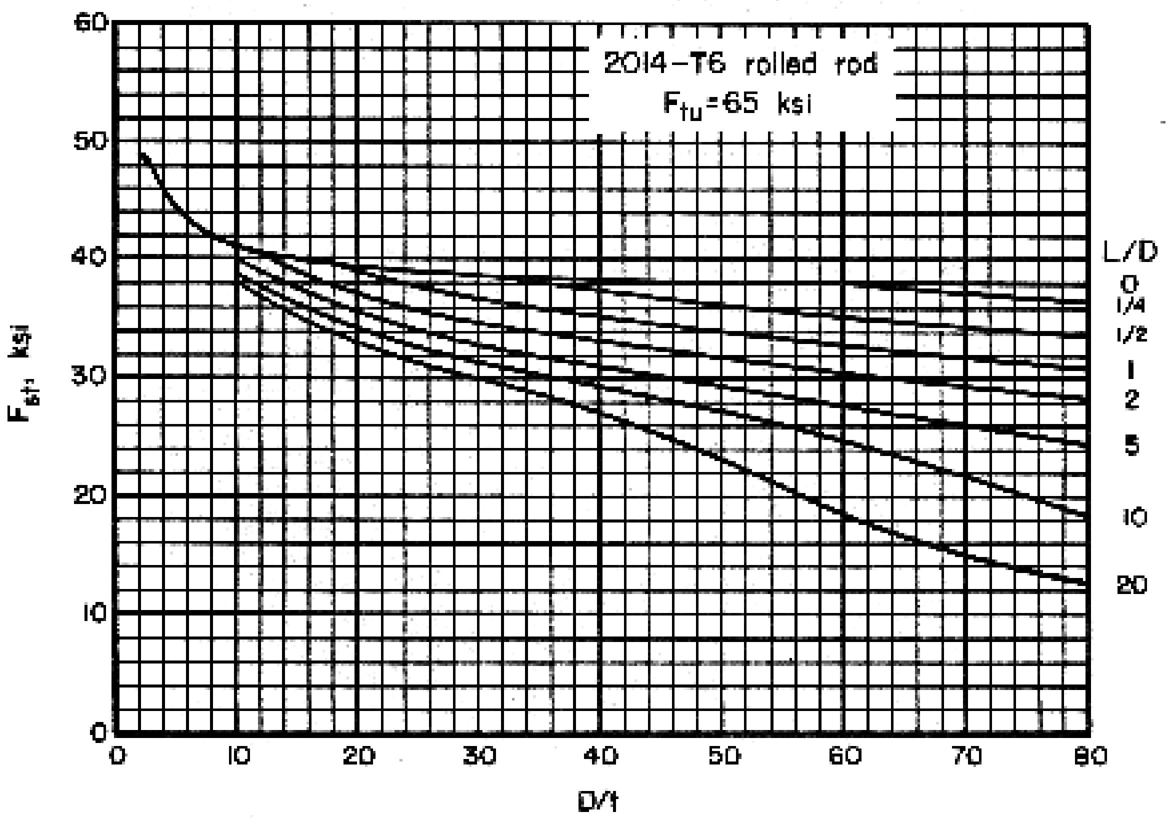
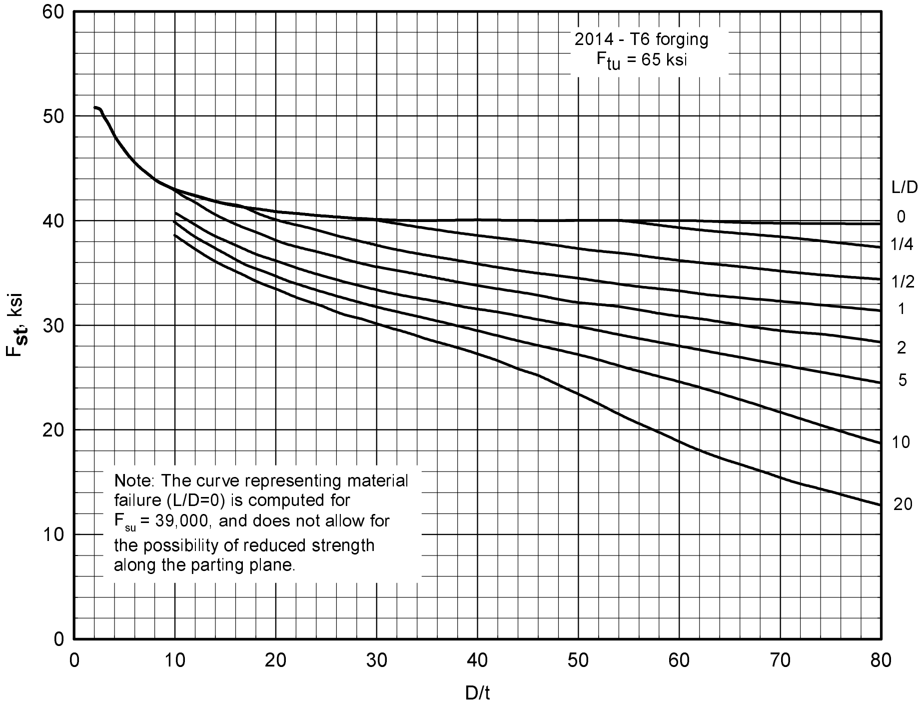


Figure 3.10.3.2(a). Torsional modulus of rupture—2014-T6 aluminum alloy rolled rod.



Note: The curve representing material failure (L/D=0) is computed for F_{su} = 39,000, and does not allow for the possibility of reduced strength along the parting plane.

Figure 3.10.3.2(b). Torsional modulus of rupture—2014-T6 aluminum alloy forging.

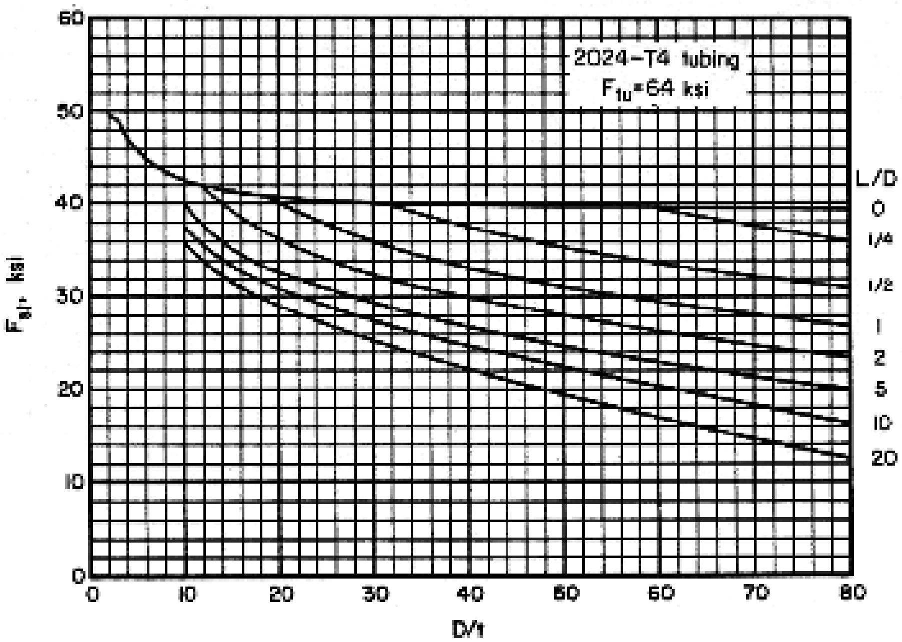


Figure 3.10.3.2(c). Torsional modulus of rupture—2024-T3 aluminum alloy tubing.

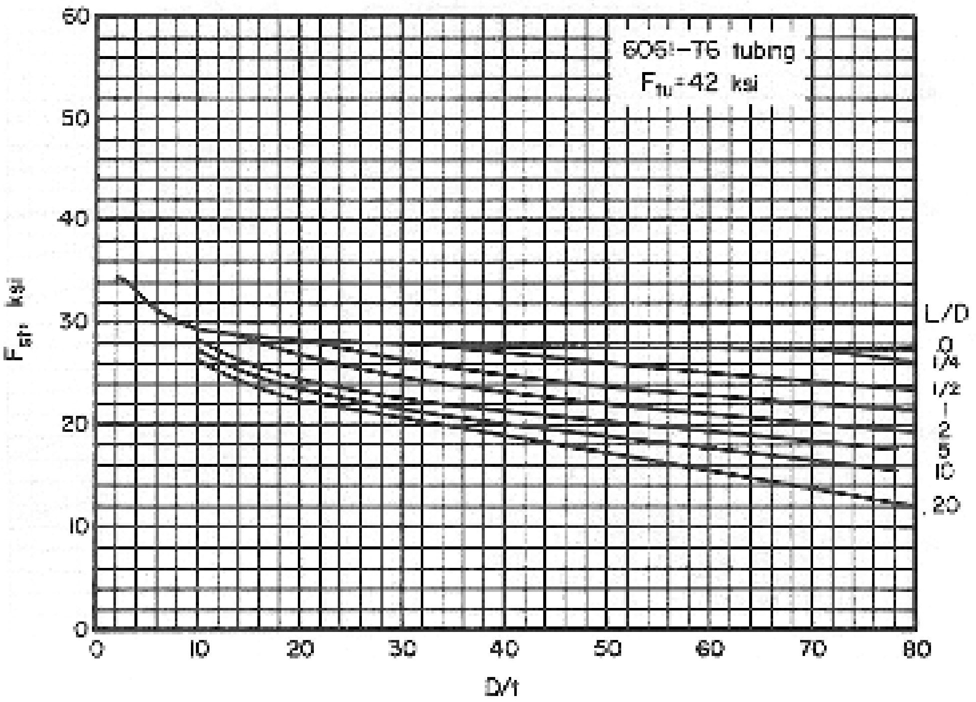


Figure 3.10.3.2(d). Torsional modulus of rupture—2024-T4 aluminum alloy tubing.

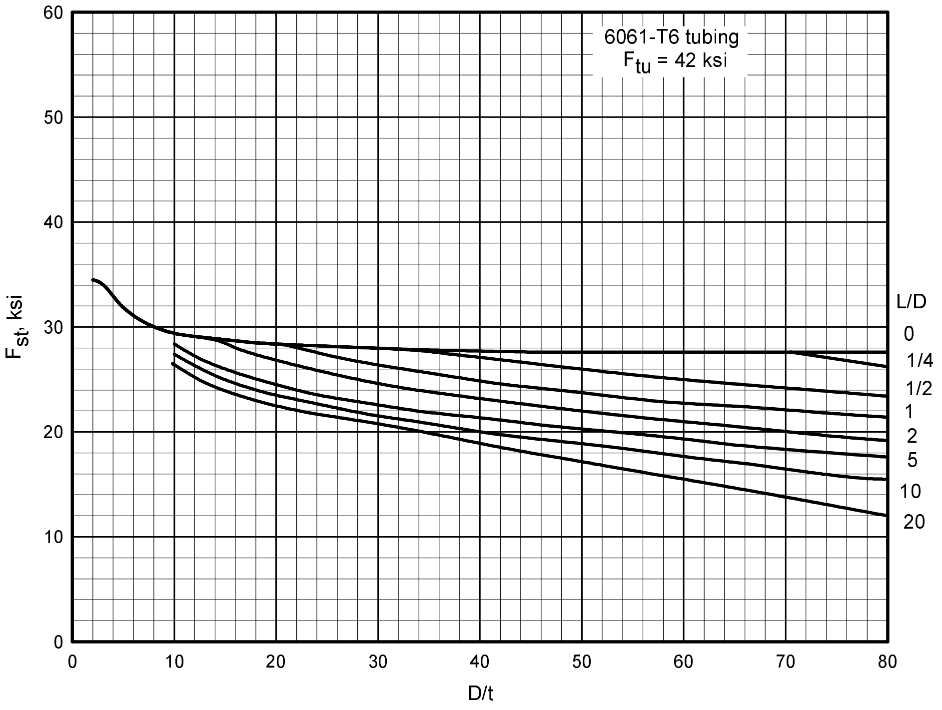


Figure 3.10.3.2(e). Torsional modulus of rupture—6061-T6 aluminum alloy tubing.

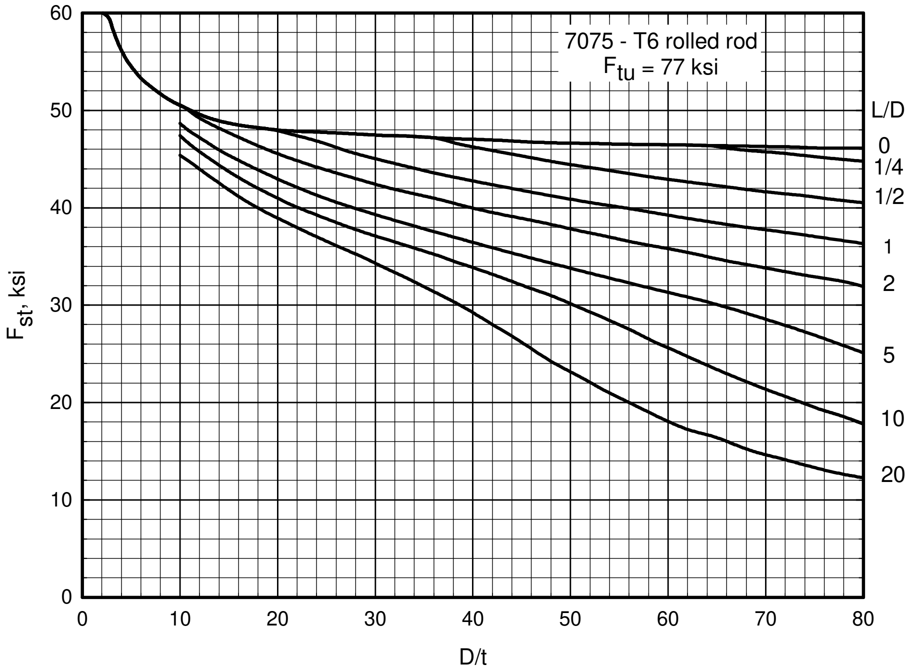


Figure 3.10.3.2(f). Torsional modulus of rupture—7075-T6 aluminum alloy rolled rod.

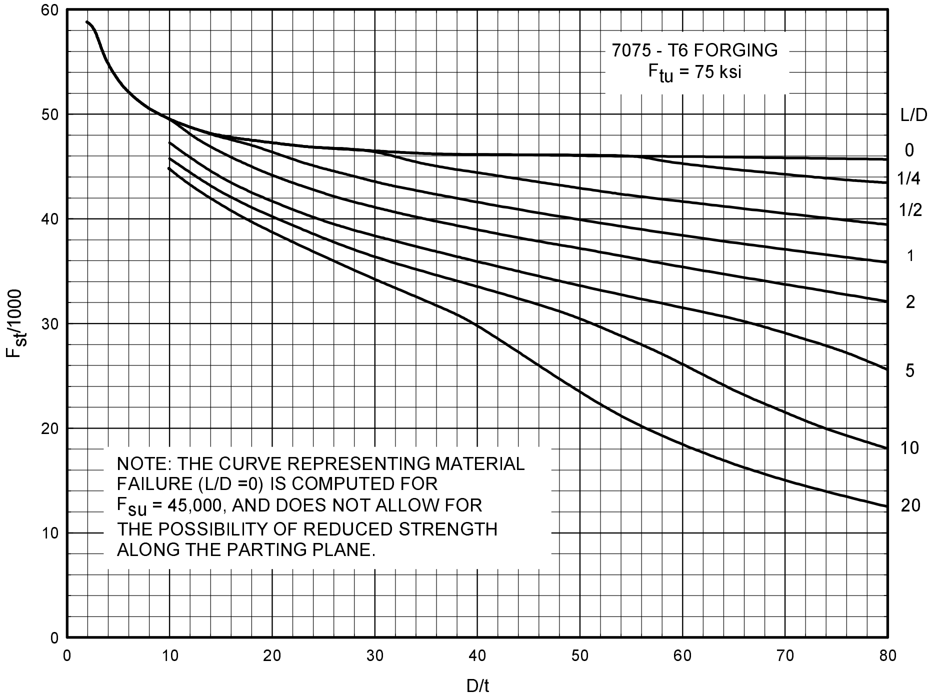


Figure 3.10.3.2(g). Torsional modulus of rupture—7075-T6 aluminum alloy forging.

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3.8.1.1.8(b) Unpublished data from Northrop Corporation, 1988 (MIL-HDBK-5 Source M-701).

3.10.1.2 Eato, I. D., and Holt, M., “Flexural Fatigue Strengths of Riveted Box Beams—Alclad 14S-T6, Alclad 75S-T6, and Various Tempers of Alcald 24S,” National Advisory Committee for Aeronautics, Technical Note 2452, 25 pp. (November 1951).

3.10.2.2(a) Gerard, G., and Becker, H., Handbook of Structural Stability, “Part I—Buckling of Flat Plates,” National Advisory Committee for Aeronautics, Technical Note 3781 (July 1957).

3.10.2.2(b) Becker, H., Handbook of Structural Stability, “Part II—Buckling of Composite Elements,” National Advisory Committee for Aeronautics, Technical Note 3782 (July 1957).

3.10.2.2(c) Gerard, G., and Becker, H., Handbook of Structural Stability, “Part III—Buckling of Curved Plates and Shells,” National Advisory Committee for Aeronautics, Technical Note 3783 (1957).

3.10.2.2(d) Gerard, G., Handbook of Structural Stability, “Part IV—Failure of Plates and Composite Elements,” National Advisory Committee for Aeronautics, Technical Note 3784 (1957).

3.10.2.2(e) Gerard, G., Handbook of Structural Stability, “Part V—Compressive Strengths of Flat Stiffened Panels,” National Advisory Committee for Aeronautics, Technical Note 3785 (August 1957).

CHAPTER 4

MAGNESIUM ALLOYS

4.1 GENERAL

This chapter contains the engineering properties and characteristics of wrought and cast magnesium alloys used in aircraft and missile applications. Magnesium is a lightweight structural metal that can be strengthened greatly by alloying, and in some cases by heat treatment or cold work or by both.

4.1.1 ALLOY INDEX — The magnesium alloys in this chapter are listed in alphanumeric sequence in each of two parts, the first one being wrought forms of magnesium and the second cast forms. These sections and the alloys covered under each are shown in Table 4.1.

Table 4.1. Magnesium Alloys Index

Section	Designation
4.2	**Magnesium-Wrought Alloys**
4.2.1	AZ31B
4.2.2	AZ61A
4.2.3	ZK60A
4.3	**Magnesium-Cast Alloys**
4.3.1	AM100A
4.3.2	AZ91C/AZ91E
4.3.3	AZ92A
4.3.4	EZ33A
4.3.5	QE22A
4.3.6	ZE41A

4.1.2 MATERIAL PROPERTIES

4.1.2.1 *Mechanical Properties* — The mechanical properties are given either as design values or for information purposes. The tensile strength (F_{tu}), tensile yield strength (F_{ty}), elongation (e), and sometimes the compressive yield strength (F_{cy}) are guaranteed by procurement specifications. The properties obtained reflect the location of sample, type of test specimen and method of testing required by the product specification. The remaining design values are "derived" values; that is, sufficient tests have been made to ascertain that if a given material meets the requirements of the product specification, the material will have the compression (F_{cy}), shear (F_{su}) and bearing (F_{bru} and F_{bry}) strengths listed.

4.1.2.1.1 *Tension Testing* — Room-temperature tension tests are made according to ASTM E 8. The yield strength (F_{ty}) is obtained by the "offset method" using an offset of 0.2 percent. The speed of testing for room-temperature tests has a small effect on the strength and elongation values obtained on most magnesium alloys. The rate of stressing generally specified to the yield strength is less than 100,000 psi per minute and the rate of straining from the yield strength to fracture is less than 0.5 in./in./min. It can be expected that the speed of testing used for room-temperature tension tests will approach the maximum permitted.

Elevated-temperature tension tests are made according to ASTM E 21. The speed of testing has a considerable effect on the results obtained and no one standard rate of straining is given in ASTM E 21. The strain rates most commonly used on magnesium are 0.005 in./in./min. to the yield and 0.10 in./in./min. from yield to fracture [see References 4.1.2.1.1(a) to (d)].

4.1.2.1.2 *Compression Testing* — Compression test methods used for magnesium are specified in ASTM E 9. The values given for the compressive yield strength (F_{cy}), are taken at an offset of 0.2 percent. References 4.1.2.1.2(a) and (b) provide information on test techniques.

4.1.2.1.3 *Bearing Testing* — Bearing tests of magnesium alloys are made according to ASTM E 238. The size of pin used has a significant effect on the values obtained, especially the bearing ultimate strength (F_{bru}). On tests made to obtain the data on magnesium alloys shown in this document, pin diameters of 0.187 and 0.250 inch were used. For pin diameters significantly larger than 0.250 inch lower values may be obtained. Additional information on bearing testing is given in References 4.1.2.1.3(a) and (b). Bearing values in the property tables are considered to be "dry pin" values in accordance with the discussion in Section 1.4.7.1.

4.1.2.1.4 *Shear Testing* — The shear strength values used in this document were obtained by the "double shear" method using a pin-type specimen, the "punch shear" method and the "tension shear" method as applicable. Just as tensile ultimate strength (F_{tu}) values vary with location and direction of sample in relation to the method of fabrication, the shear strength (F_{su}) may be expected to reflect the effect of orientation, either as a function of the sampling or the maximum stresses imposed by the method of test. Information on shear testing is given in Reference 4.1.2.1.4.

4.1.2.1.5 *Stress Raisers* — The effect of notches, holes, and stress raisers on the static properties of magnesium alloys is described in References 4.1.2.1.5(a) through (c). Additional data on the strength properties of magnesium alloys are presented in References 4.1.2.1.5(d) through (h).

4.1.2.1.6 *Creep* — Some creep data on magnesium alloys are summarized in Reference 4.1.2.1.6.

4.1.2.1.7 *Fatigue* — Room-temperature axial load fatigue data for several magnesium alloys are presented in appropriate alloy sections. References 4.1.2.1.7(a) and (b) provide additional data on fatigue of magnesium alloys.

4.1.3 PHYSICAL PROPERTIES — Selected experimental data from the literature were used in determining values for physical properties. In other cases, enough information was available to calculate the constants. Estimated values of some of the remaining constants were also included. Estimated values are noted.

4.1.4 ENVIRONMENTAL CONSIDERATIONS — Corrosion protection must be considered for all magnesium applications. Protection can be provided by anodic films, chemical conversion coatings, paint systems, platings, or a combination of these methods. Proper drainage must be provided to prevent entrapment of water or other fluids. Dissimilar metal joints must be properly and completely insulated, including barrier strips and sealants.

Strain-hardened or age-hardened alloys may be annealed or overaged by prolonged exposure to elevated temperatures, with a resulting decrease in strength. Maximum recommended temperatures for prolonged service are reported, where available, for specific alloys.

4.1.5 ALLOY AND TEMPER DESIGNATIONS — Standard ASTM nomenclature is used for the alloys listed. Temper designations are given in ASTM B 296. A summary of the temper designations is given in Table 4.1.5.

Table 4.1.5. Temper Designation System for Magnesium Alloys[a]

Basis of Codification

The designations for temper are used for all forms of magnesium and magnesium alloy products except ingots and are based on the sequence of basic treatments used to produce the various tempers. The temper designation follows the alloy designation, the two being separated by a dash. Basic temper designations consist of letters. Subdivisions of the basic tempers, where required, are indicated by a digit or digits following the letter. These designate specific sequences of basic treatments, but only operations recognized as significantly influencing the characteristics of the product are indicated. Should some other variation of the same sequence of basic operations be applied to the same alloy, resulting in different characteristics, then additional digits are added to the designation.

NOTE—In material specifications containing reference to two or more tempers of the same alloy which result in identical mechanical properties, the distinction between the tempers should be covered in suitable explanatory notes.

Basic Temper Designations

F *As Fabricated.* Applies to the products that acquire some temper from shaping processes not having special control over the amount of strain-hardening or thermal treatment.

O *Annealed Recrystallized* **(wrought products only).** Applies to the softest temper of wrought products.

H *Strain-Hardened* **(wrought products only).** Applies to products that have their strength increased by strain-hardening with or without supplementary thermal treatments to produce partial softening. The H is always followed by two or more digits.

H1 *Strain-Hardened Only.* Applies to products that are strain-hardened to obtain the desired mechanical properties without supplementary thermal treatment. The number following this designation indicates the degree of strain-hardening.

H2 *Strain-Hardened and Then Partially Annealed.* Applies to products which are strain-hardened more than the desired final amount and then reduced in strength to the desired final amount by partial annealing. The number following this designation indicates the degree of strain-hardening remaining after the product has been partially annealed.

H3 *Strain-Hardened and Stabilized.* Applies to products that are strain-hardened and then stabilized by a low temperature heating to slightly lower their strength and increase ductility. This designation applies only to alloys which, unless stabilized, gradually age soften at room temperature. The number following this designation indicates the degree of strain-hardening remaining after the product has been strain-hardened a specific amount and then stabilized.

Subdivisions of the “H1", “H2" and “H3" Tempers: The digit following the designations “H1", “H2", and “H3" indicates the final degree of strain hardening. Tempers between 0 (annealed) and 8 (full hard) are designated by numerals 1 through 7. Material having a strength about midway between that of the 0 temper and that of the 8 temper is designated by the numeral 4 (half hard); between 0 and 4 by the numeral 2 (quarter hard); between 4 and 8 by the numeral 6 (three-quarter

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[a] From ASTM B 296-96.

Table 4.1.5. Temper Designation System for Magnesium Alloys (Continued)[a]

hard), etc. The third digit, when used, indicates a variation of a two-digit H temper. It is used when the degree of control of temper or the mechanical properties are different from but close to those for the two-digit H temper to which it is added. Numerals 1 through 9 may be arbitrarily assigned as the third digit for an alloy and product to indicate a specific degree of control of temper or special mechanical property limits.

W ***Solution Heat-Treated.*** An unstable temper applicable only to alloys which spontaneously age at room temperature after solution heat-treatment. This designation is specific only when the period of natural aging is indicated: for example, W ½ hr.

T ***Thermally Treated to Product Stable Tempers Other Than F, O, or H.*** Applies to products which are thermally treated, with or without supplementary strain-hardening, to product stable tempers. The T is always followed by one or more digits. Numerals 1 through 10 have been assigned to indicate specific sequences of basic treatments, as follows.

T1 ***Cooled from an Elevated Temperature Shaping Process and Naturally Aged to a Substantially Stable Condition.*** Applies to products for which the rate of cooling from an elevated temperature shaping process, such as casting or extrusion, is such that their strength is increased by room temperature aging.

T3 ***Solution Heat-treated and Then Cold Worked.*** Applies to products that are cold worked to improve strength, or in which the effect of cold work in flattening and straightening is recognized in applicable mechanical properties.

T4 ***Solution Heat-treated and Naturally Aged to a Substantially Stable Condition.*** Applies to products that are not cold worked after solution heat-treatment, or in which the effect of cold work in flattening or straightening may not be recognized in applicable mechanical properties.

T5 ***Cooled from an Elevated-Temperature Shaping Process and Then Artificially Aged.*** Applies to products which are cooled from an elevated-temperature shaping process, such as casting or extrusion, and then artificially aged to improve mechanical properties or dimensional stability or both.

T6 ***Solution Heat-treated and Then Artificially Aged.*** Applies to products that are not cold worked after solution heat-treatment, or in which the effect of cold work is flattening or straightening may not be recognized in applicable mechanical properties.

T7 ***Solution Heat-treated and Then Stabilized.*** Applies to products that are stabilized to carry them beyond the point of maximum strength to provide control of some special characteristics.

T8 ***Solution Heat-treated, Cold Worked, and Then Artificially Aged.*** Applies to products which are cold worked to improve strength, or in which the effect of cold work in flattening or straightening is recognized in applicable mechanical properties.

T9 ***Solution Heat-treated, Artificially Aged, and Then Cold Worked.*** Applies to products that are cold worked to improve strength.

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[a] From ASTM B 296-96.

Table 4.1.5. Temper Designation System for Magnesium Alloys (Continued)[a]

T10 ***Cooled from an Elevated Temperature Shaping Process, Artificially Aged, and Then Cold Worked.*** Applies to products which are artificially aged after cooling from an elevated temperature shaping process, such as extrusion, and then cold worked to further improve strength.

A period of natural aging at room temperature may occur between or after the operations listed for tempers T3 through T10. Control of this period is exercised when it is metallurgically important.

Additional digits, may be added to designations T1 through T10 to indicate a variation in treatment that significantly alters the characteristics of the product.

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[a] From ASTM B 296-96.

4.1.6 JOINING METHODS — Most magnesium alloys may be welded; refer to "Comments and Properties" in individual alloy sections. Adhesive bonding and brazing may be used to join magnesium to itself or other alloys. All types of mechanical fasteners may be used to join magnesium. Refer to Section 4.1.4 when using mechanical fasteners or joining of dissimilar materials with magnesium alloys.

4.2 MAGNESIUM-WROUGHT ALLOYS

4.2.1 AZ31B

4.2.1.0 *Comments and Properties* — AZ31B is a wrought magnesium-base alloy containing aluminum and zinc. It is available in the form of sheet, plate, extruded sections, forgings, and tubes. AZ31B has good room-temperature strength and ductility and is used primarily for applications where the temperature does not exceed 300°F. Increased strength is obtained in the sheet and plate form by strain hardening with a subsequent partial anneal (H24 and H26 temper). No treatments are available for increasing the strength of this alloy after fabrication.

Forming of AZ31B must be done at elevated temperatures if small radii or deep draws are required. If the temperatures used are too high or the times too great, H24 and H26 temper material will be softened. This alloy is readily welded but must be stress relieved after welding to prevent stress corrosion cracking.

Material specifications covering AZ31B wrought products are given in Table 4.2.1.0(a). Room-temperature mechanical and physical properties are shown in Tables 4.2.1.0(b) through (d). The effect of temperature on physical properties is shown in Figure 4.2.1.0.

Table 4.2.1.0(a). Material Specifications for AZ31B Magnesium Alloy

Specification	Form
AMS 4375	Sheet and plate
AMS 4376	Plate
AMS 4377	Sheet and plate
ASTM B 107	Extrusion
ASTM B 91	Forging

The temper index for AZ31B is as follows:

Section	Temper
4.2.1.1	O
4.2.1.2	H24
4.2.1.3	H26
4.2.1.4	F

4.2.1.1 *AZ31B-O Temper* — Effect of temperature on the tensile modulus of sheet and plate is presented in Figure 4.2.1.1.4. Typical room-temperature stress-strain and tangent-modulus curves are presented in Figure 4.2.1.1.6.

4.2.1.2 *AZ31B-H24 Temper* — Effect of temperature on the mechanical properties of sheet and plate is shown in Figures 4.2.1.2.1 through 4.2.1.2.4, and 4.2.1.2.6. Typical room-temperature tension and compression stress-strain and tangent-modulus curves for sheet are shown in Figure 4.2.1.2.6.

4.2.1.3 *AZ31B-H26 Temper*

4.2.1.4 *AZ31B-F Temper* — Figures 4.2.1.4.8 (a) and (b) contain fatigue data for forged disk at room temperature.

Table 4.2.1.0(b). Design Mechanical and Physical Properties of AZ31B Magnesium Alloy Sheet and Plate

Specification	AMS 4375					AMS 4377						
Form	Sheet		Plate			Sheet		Plate				
Temper	0					H24						
Thickness, in.	0.016-0.060	0.061-0.249	0.250-0.500	0.501-2.000	2.001-3.000	0.016-0.062	0.063-0.249	0.250-0.374	0.375-0.500	0.501-1.000	1.001-2.000	2.001-3.000
Basis	S	S	S	S	S	S	S	S	S	S	S	S
Mechanical Properties:												
F_{tu}, ksi:												
L	32	32	32	32	32	39	39	38	37	36	34	34
LT	...	...	...	...	...	40	40	39	38	37	35	...
F_{ty}, ksi:												
L	18	15	15	15	15	29	29	26	24	22	20	18
LT	...	...	...	...	...	32	32	29	27	25	23	...
F_{cy}, ksi:												
L	...	12	10	10	8	...	24	20	16	13	10	9
LT[a]	...	...	...	...	...	...	...	...	...	...	...	...
F_{su}, ksi	17	17	17	...	...	18	18	18	18	...	...	...
F_{bru}[b], ksi:												
(e/D = 1.5)	50	50	50	...	...	58	58	56	54	...	...	...
(e/D = 2.0)	60	60	60	...	...	68	68	65	63	...	...	...
F_{bry}[b], ksi:												
(e/D = 1.5)	29	29	27	...	...	43	43	38	34	...	...	...
(e/D = 2.0)	29	29	27	...	...	43	43	38	34	...	...	...
e, percent												
L	12	12	12	10	9	6	6	8	8	8	8	8
E, 10^3 ksi	6.5											
E_c, 10^3 ksi	6.5											
G, 10^3 ksi	2.4											
μ	0.35											
Physical Properties:												
ω, lb/in.^{3}	0.0639											
C, K, and α	See Figure 4.2.1.0											

a F_{cy}(LT) allowables are equal to or greater than F_{cy}(L) allowables.
b Bearing values are "dry pin" values per Section 1.4.7.1.

Table 4.2.1.0(c). Design Mechanical and Physical Properties of AZ31B Magnesium Alloy Plate

Specification	AMS 4376						
Form	Plate						
Temper	H26						
Thickness, in.	0.250-0.375	0.376-0.438	0.439-0.500	0.501-0.750	0.751-1.000	1.001-1.500	1.501-2.000
Basis	S	S	S	S	S	S	S
Mechanical Properties:							
F_{tu}, ksi:							
L	39	38	38	37	37	35	35
LT	40	39	39	38	38	36	36
F_{ty}, ksi:							
L	27	26	26	25	23	22	21
LT	30	29	29	28	26	25	24
F_{cy}, ksi:							
L	22	21	18	17	16	15	14
LT[a]	...	...	....	...	...	...	...
F_{su}, ksi	18	18	18	...	...	...	...
F_{bru}[b], ksi:							
(e/D = 1.5)	58	56	56	...	...	...	...
(e/D = 2.0)	68	65	65	...	...	...	...
F_{bry}[b], ksi:							
(e/D = 1.5)	40	39	36	...	...	...	...
(e/D = 2.0)	40	39	36	...	...	...	...
e, percent:							
L	6	6	6	6	6	6	6
E, 10^3 ksi	6.5						
E_c, 10^3 ksi	6.5						
G, 10^3 ksi	2.4						
μ	0.35						
Physical Properties:							
ω, lb/in.^{3}	0.0639						
C, K, and α	See Figure 4.2.1.0						

[a] F_{cy}(LT) allowables are equal to or greater than F_{cy}(L) values.
[b] Bearing values are "dry pin" values per Section 1.4.7.1.

Table 4.2.1.0(d). Design Mechanical and Physical Properties of AZ31B Magnesium Alloy Extrusion and Forging

Specification	ASTM B 107							ASTM B 91
Form	Extruded bar, rod, and solid shapes				Extruded hollow shapes	Extruded tube		Forging
Temper	F							
Thickness, in.	≤0.249	0.250-1.499	1.500-2.499	2.500-4.999	All	0.028-0.250^b	0.251-0.750^b	...
Basis	S	S	S	S	S	S	S	S
Mechanical Properties:								
F_{tu}, ksi:								
L	35	35	34	32	32	32	32	34
LT	...	...	...	...	...	...	...	...
F_{ty}, ksi:								
L	21	22	22	20	16	16	16	19
LT	...	...	...	...	...	...	...	...
F_{cy}, ksi:								
L	...	12	12	10	10	10	10	...
LT	...	...	...	...	...	...	...	...
F_{su}, ksi	17	17	17	...	...	...	...	...
$F_{bru}{}^b$, ksi:								
(e/D = 1.5)	36	36	36	...	...	...	...	...
(e/D = 2.0)	45	45	45	...	...	...	...	...
$F_{bry}{}^b$, ksi:								
(e/D = 1.5)	23	23	23	...	...	...	...	...
(e/D = 2.0)	23	23	23	...	...	...	...	...
e, percent:								
L	7	7	7	7	8	8	4	6
E, 10^3 ksi	6.5							
E_c, 10^3 ksi	6.5							
G, 10^3 ksi	2.4							
μ	0.35							
Physical Properties:								
ω, lb/in.^{3}	0.0639							
C, K, and α	See Figure 4.2.1.0							

a Wall thickness for tube; for outside diameter ≤ 6.000 inches.

b Bearing values are "dry pin" values per Section 1.4.7.1.

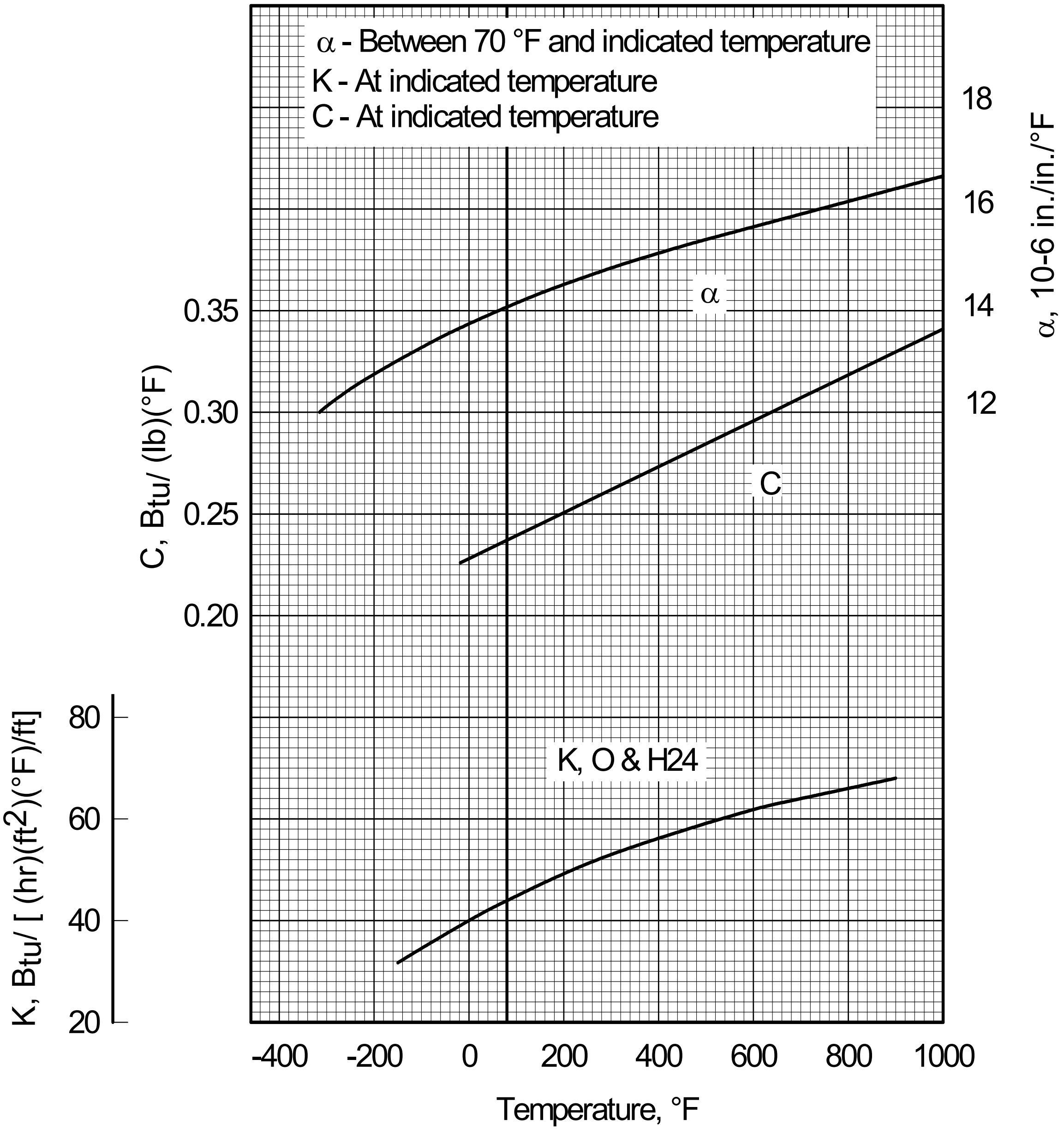

Figure 4.2.1.0. Effect of temperature on the physical properties of AZ31B.

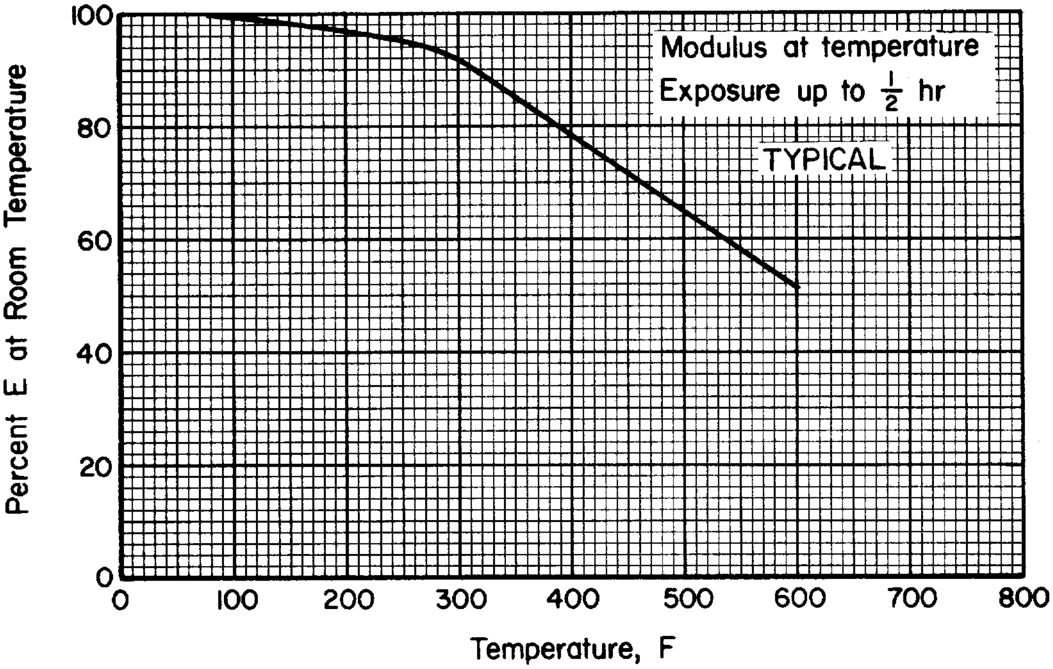

Figure 4.2.1.1.4. Effect of temperature on the tensile modulus (E) of AZ31B-O sheet and plate.

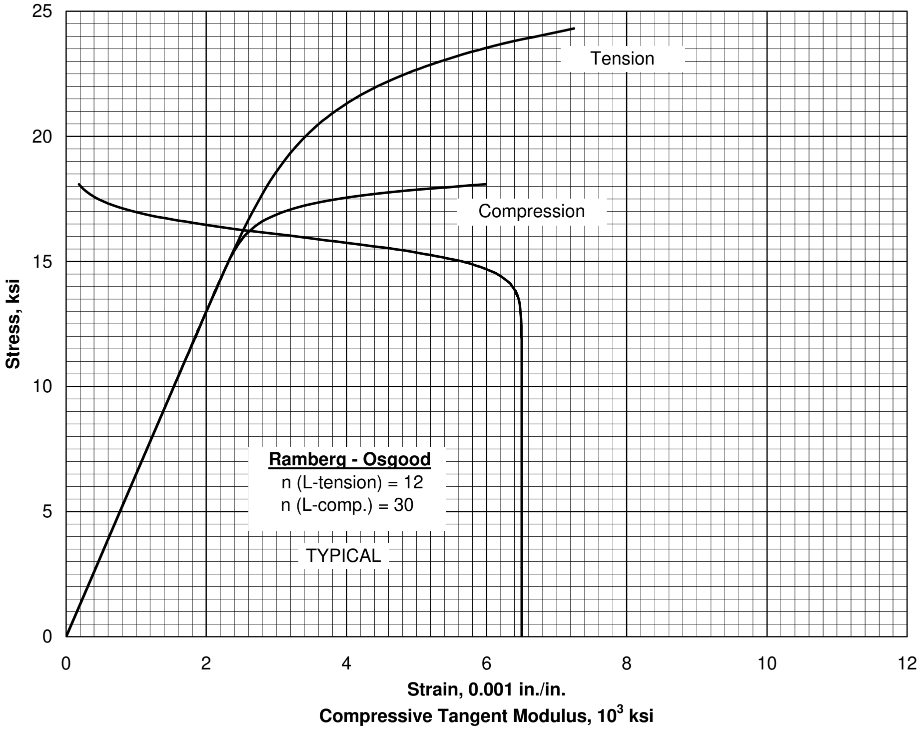

Figure 4.2.1.1.6. Typical tensile and compressive stress-strain and compressive tangent-modulus curves for AZ31B-O sheet and plate at room temperature.

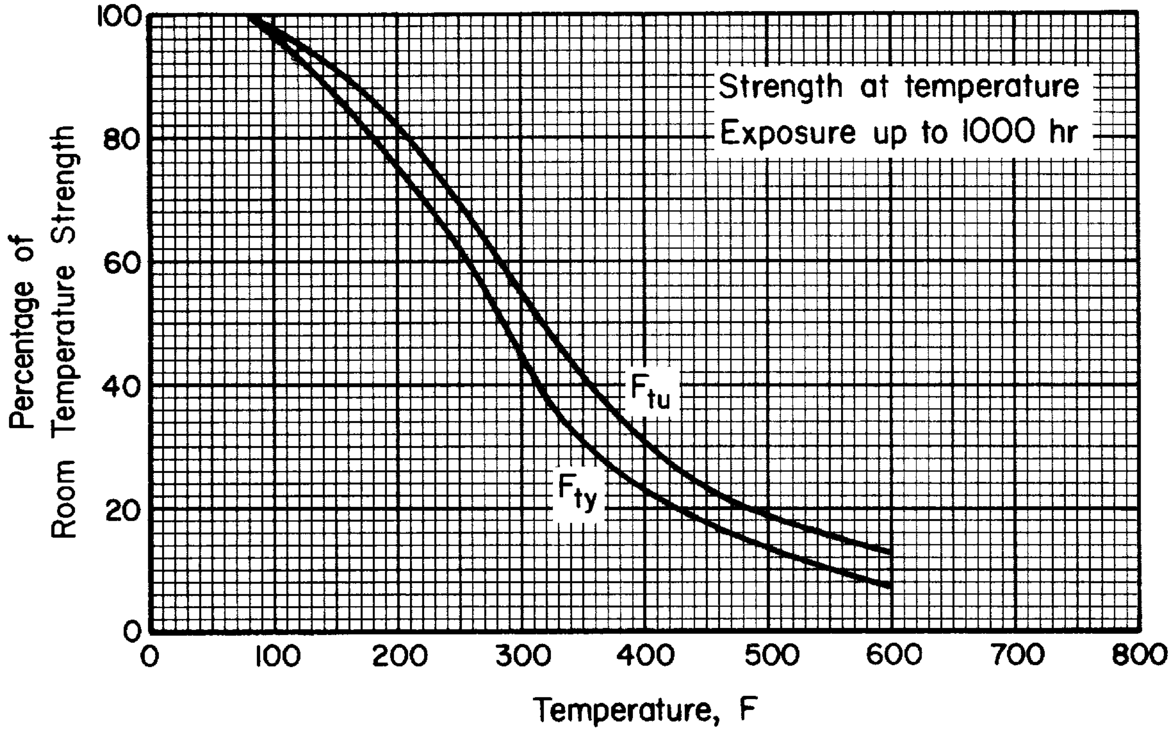

Figure 4.2.1.2.1. Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of AZ31B-H24 sheet and plate.

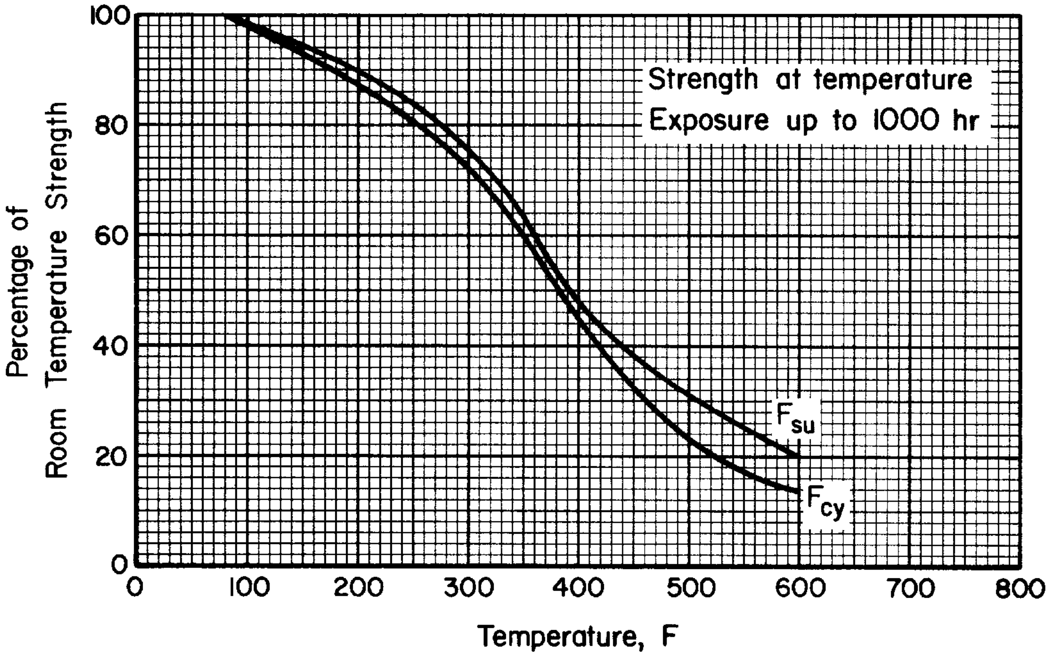

Figure 4.2.1.2.2. Effect of temperature on the compressive yield strength (F_{cy}) and the shear ultimate strength (F_{su}) of AZ31B-H24 sheet and plate.

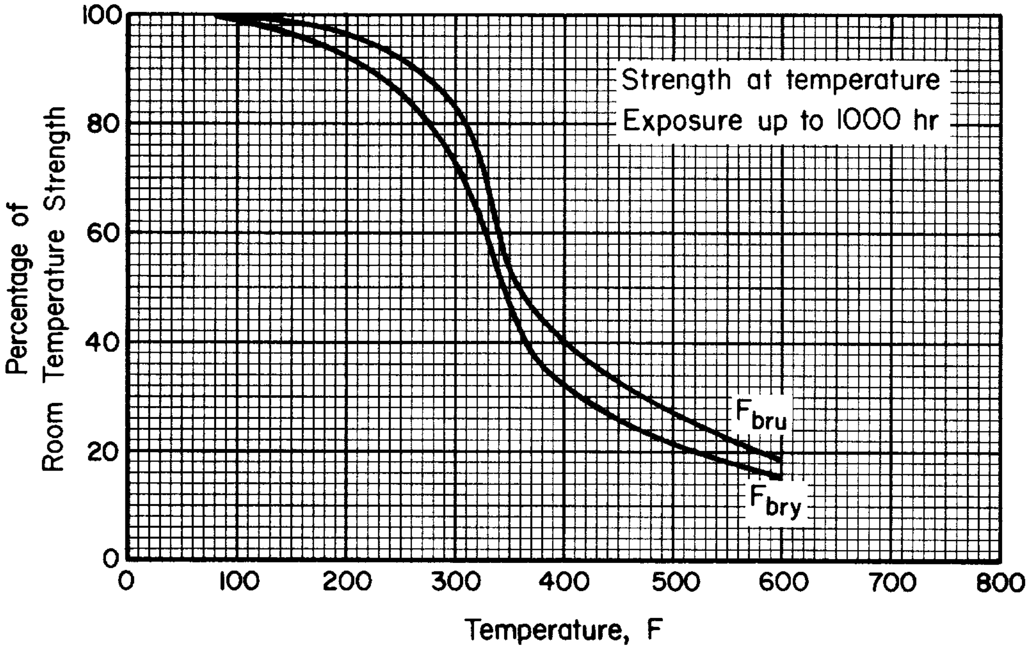

Figure 4.2.1.2.3. Effect of temperature on the bearing ultimate strength (F_{bru}) and the bearing yield strength (F_{bry}) of AZ31B-H24 sheet and plate.

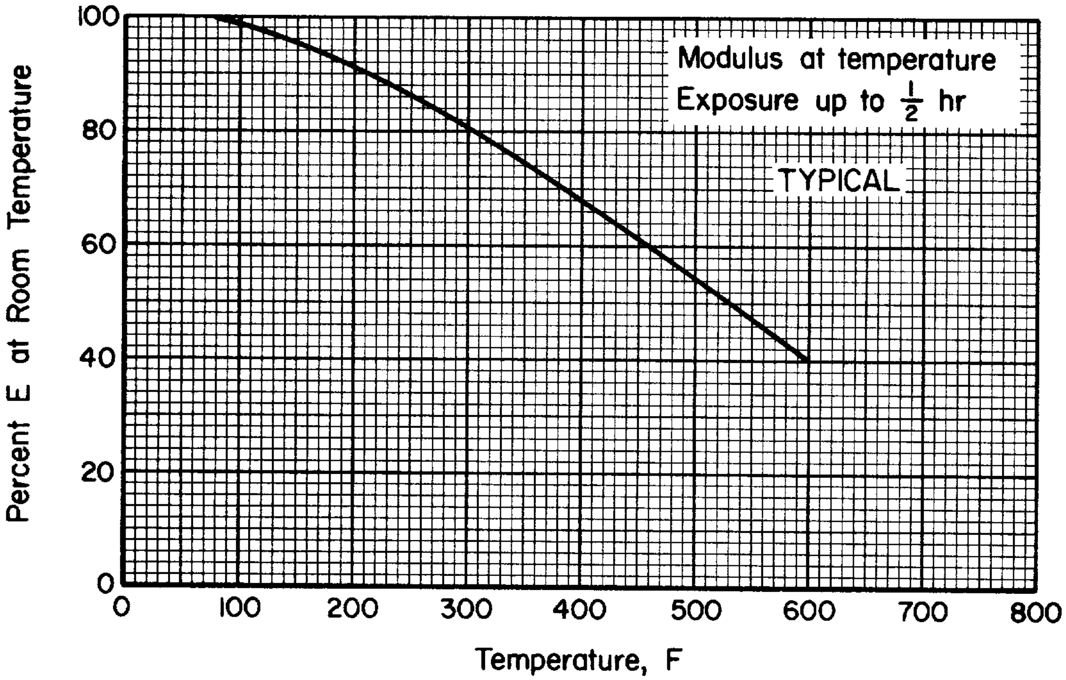

Figure 4.2.1.2.4. Effect of temperature on the tensile modulus (E) of AZ31B-H24 sheet and plate.

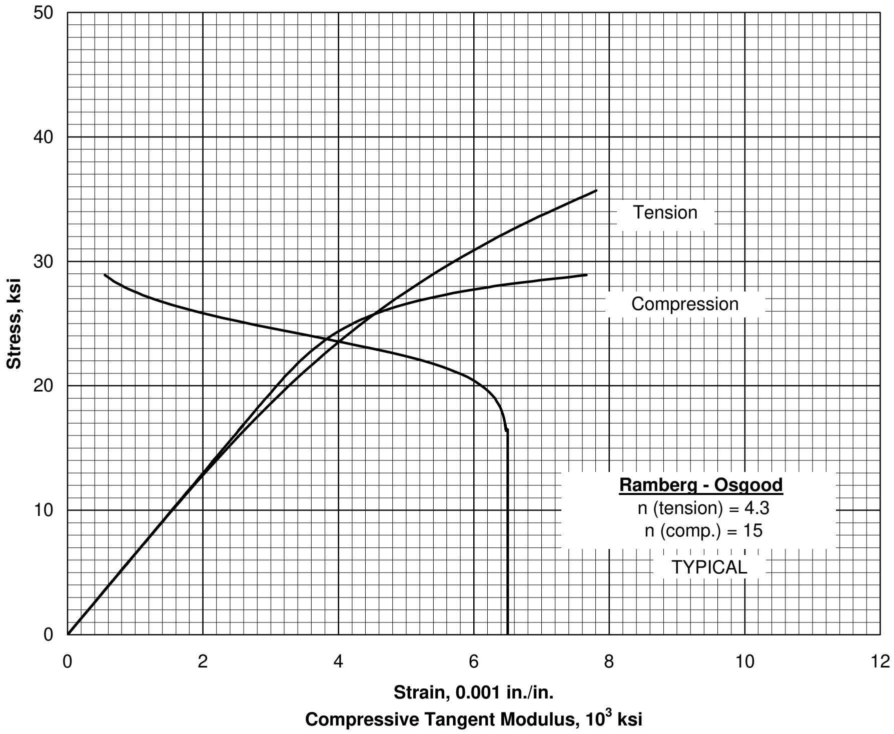

Figure 4.2.1.2.6. Typical tensile and compressive stress-strain and compressive tangent-modulus curves for AZ31B-H24 sheet at room temperature.

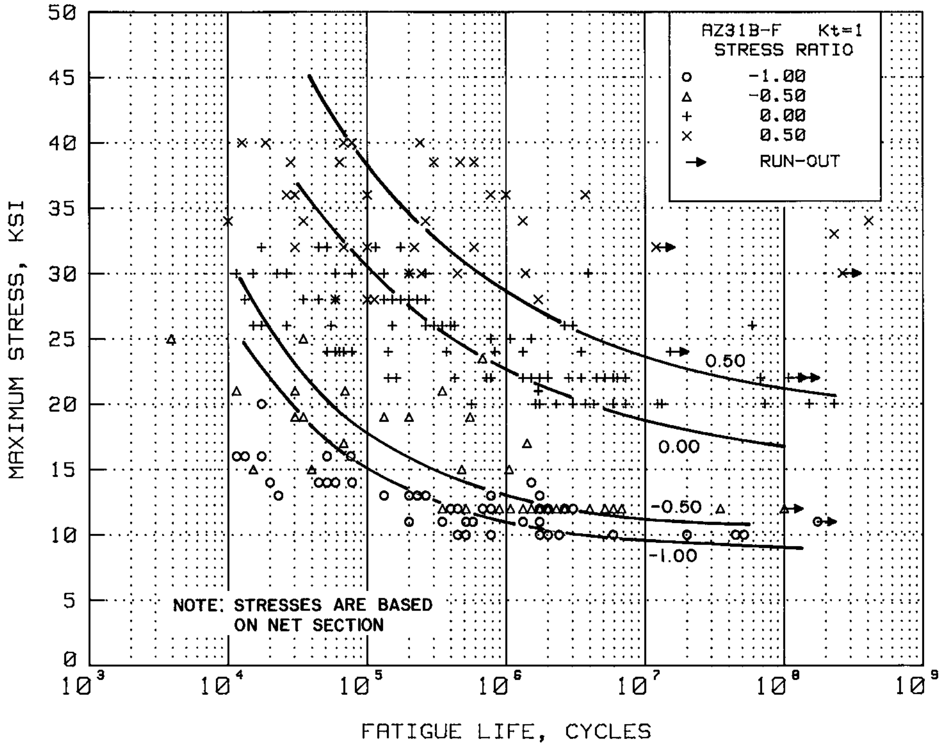

Figure 4.2.1.4.8(a). Best-fit S/N curves for unnotched AZ31B-F magnesium alloy forged disk, transverse direction.

Correlative Information for Figure 4.2.1.4.8(a)

Product Form: Forged disk, 1 inch thick

Properties:

TUS, ksi	TYS, ksi	Temp., °F
38	26	RT

Specimen Details: Unnotched
0.75 inch gross diameter
0.30 inch net diameter

Surface Condition: Polished sequentially with No. 320 aluminum oxide cloth, No. 0, 00, and 000 emery paper and finally No. 600 aluminum oxide powder in water

References: 4.2.1.1.8

Test Parameters:
Loading - Axial
Frequency - 1500 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 1

Equivalent Stress Equation:

For R values between -1.0 and -0.50
Log N_f = 7.13-2.20 log (S_{eq}-12.9)
$S_{eq} = S_{max}(1-R)^{0.56}$
Std. Error of Estimate, Log (Life) = 0.613
Standard Deviation, Log (Life) = 0.916
R^2 = 55.2%

For R values between 0.0 and 0.50
Log N_f = 8.87-3.26 log (S_{eq}-15.0)
$S_{eq} = S_{max}(1-R)^{0.33}$
Std. Error of Estimate, Log (Life) = 0.829
Standard Deviation, Log (Life)= 1.014
R^2 = 33.2%

Sample Size = 194

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

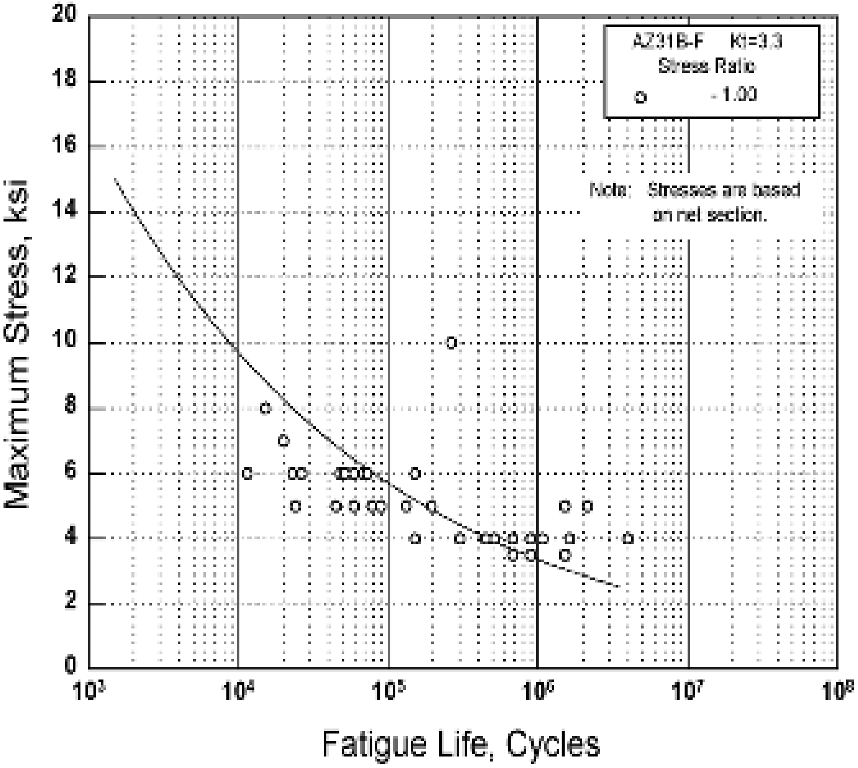

Figure 4.2.1.4.8(b). Best-fit S/N curves for notched, K_t = 3.3, AZ31B-F magnesium alloy forged disk, transverse direction.

Correlative Information for Figure 4.2.1.4.8(b)

Product Form: Forged disk, 1 inch thick

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	38	26	RT

Specimen Details: Notched, K_t = 3.3
0.350 inch gross diameter
0.280 inch net diameter
0.010 inch root radius, r
60° flank angle, ω

Reference: 4.2.1.1.8

Test Parameters:
Loading - Axial
Frequency - 1500 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 1

Maximum Stress Equation:
$\text{Log } N_f = 8.28 - 4.34 \log (S_{max})$
Std. Error of Estimate, Log (Life) = 0.534
Standard Deviation, Log (Life) = 0.707
$R^2 = 43\%$

Sample Size = 34

4.2.2 AZ61A

4.2.2.0 *Comments and Properties* — AZ61A is a wrought magnesium-base alloy containing aluminum and zinc. It is available in the form of extruded sections, tubes, and forgings in the as-fabricated (F) temper. AZ61A is much like AZ31B in general characteristics. The increased aluminum content increases the strength and decreases the ductility slightly.

Severe forming must be done at elevated temperatures. This alloy is readily welded but must be stress relieved after welding to prevent stress corrosion cracking.

Material specifications covering AZ61A are given in Table 4.2.2.0(a). Room-temperature mechanical and physical properties are shown in Table 4.2.2.0(b).

Table 4.2.2.0(a). Material Specifications for AZ61A Magnesium Alloy

Specification	Form
AMS 4350	Extrusion
ASTM B 91	Forging

Table 4.2.2.0(b). Design Mechanical and Physical Properties of AZ61A Magnesium Alloy Extrusion and Forging

Specification	AMS 4350					ASTM B 91
Form	Extruded bar, rod, and solid shapes			Extruded hollow shapes	Extruded tube	Forging
Temper	F					
Thickness, in.	≤0.249	0.250-2.499	2.500-4.499[a]	All	0.028-0.750[b]	...
Basis	S	S	S	S	S	S
Mechanical Properties:						
F_{tu}, ksi:						
L	38	40	40	36	36	38
LT	...	...	...	...	...	...
F_{ty}, ksi:						
L	21	24	22	16	16	22
LT	...	...	...	...	...	...
F_{cy}, ksi:						
L	14	14	14	11	11	14
LT	...	...	...	...	...	...
F_{su}, ksi	19	19	...	...	...	19
F_{bru}[c], ksi:						
(e/D = 1.5)	45	45	...	...	...	50
(e/D = 2.0)	55	55	...	...	...	60
F_{bry}[c], ksi:						
(e/D = 1.5)	28	28	...	...	...	28
(e/D = 2.0)	32	32	...	...	...	32
e, percent:						
L	8	9	7	7	7	6
E, 10^3 ksi	6.3					
E_c, 10^3 ksi	6.3					
G, 10^3 ksi	2.4					
μ	0.31					
Physical Properties:						
ω, lb/in.^{3}	0.0647					
C, Btu/(lb)(°F)	0.25 (at 78°F)[d]					
K, Btu/[(hr)(ft^2)(°F)/ft]	46 (212 to 572°F)					
α, 10^{-6} in./in./°F	14 (65 to 212°F)					

a For cross-sectional area ≤25 square inches.
b Wall thickness for outside diameters ≤6.000 inches.
c Bearing values are "dry pin" values per Section 1.4.7.1.
d Estimated.

4.2.3 ZK60A

4.2.3.0 *Comments and Properties* — ZK60A is a wrought magnesium-base alloy containing zinc and zirconium. It is available as extruded sections, tubes, and forgings. Increased strength is obtained by artificial aging (T5) from the as-fabricated (F) temper. ZK60A has the best combination of high room-temperature strength and ductility of the wrought magnesium-base alloys. It is used primarily at temperatures below 300°F.

ZK60A has good ductility as compared with other high-strength magnesium alloys and can be formed or bent cold into shapes not possible with those alloys having less ductility. It is not considered a weldable alloy.

Material specifications for ZK60A are given in Table 4.2.3.0(a). Room-temperature mechanical and physical properties are shown in Tables 4.2.3.0(b) and (c). Elevated temperature curves for physical properties are shown in Figures 4.2.3.0.

Table 4.2.3.0(a). Material Specifications for ZK60A Magnesium Alloy

Specification	Form
ASTM B 107	Extrusion
AMS 4352	Extrusion
AMS 4362	Die and hand forgings

The temper index for ZK60A is as follows:

Section	Temper
4.2.3.1	F
4.2.3.2	T5

4.2.3.1 *ZK60A-F Temper*

4.2.3.2 *ZK60A-T5 Temper* — Typical room-temperature tension and compression stress-strain curves for extrusions are shown in Figures 4.2.3.2.6(a) and (b). Fatigue curves are presented in Figure 4.2.3.2.8(a) through (c).

Table 4.2.3.0(b). Design Mechanical and Physical Properties of ZK60A Magnesium Alloy Extrusion

Specification	ASTM B 107					
Form	Extruded rod, bar, and solid shapes				Extruded hollow shapes	Extruded tube
Temper	F					
Cross-sectional area, in.^{2}	<2.000	2.000-2.999	3.000-4.999	5.000-39.999	All	$\leq$3.000 in. O.D.
Thickness, in.	All	All	All	All	All	0.028-0.750 wall
Basis	S	S	S	S	S	S
Mechanical Properties:						
F_{tu}, ksi:						
L	43	43	43	43	40	40
LT	...	...	...	...	...	...
F_{ty}, ksi:						
L	31	31	31	31	28	28
LT	...	...	...	...	...	...
F_{cy}, ksi:						
L	27	26	25	20	20	20
LT	...	...	...	...	...	...
F_{su}, ksi	22	22	22	...	...	...
F_{bru}[a], ksi:						
(e/D = 1.5)	...	...	...	...	...	...
(e/D = 2.0)	70	70	70	...	...	...
F_{bry}[a], ksi:						
(e/D = 1.5)	...	...	...	...	...	...
(e/D = 2.0)	45	45	45	...	...	...
e, percent:						
L	5	5	5	4	5	5
E, 10^3 ksi	6.5					
E_c, 10^3 ksi	6.5					
G, 10^3 ksi	2.4					
μ	0.35					
Physical Properties:						
ω, lb/in.^{3}	0.0659					
C, K, and α	See Figure 4.2.3.0					

[a] Bearing values are "dry pin" values per Section 1.4.7.1.

Table 4.2.3.0(c). Design Mechanical and Physical Properties of ZK60A Magnesium Alloy Extrusion and Forging

Specification	AMS 4352									AMS 4362	
Form	Extruded rod, bar, and solid shapes						Extruded hollow shapes	Extruded tube		Die forging	Hand forging
Temper	T5										
Cross-sectional area, in.^{2}	<2.000	2.000-2.999	3.000-4.999	5.000-9.999	10.000-24.999	25.000-39.999	All	≤3.000 in. O.D.	3.000-8.500 in. O.D.	...	...
Thickness, in.	All	All	All	All	All	All	All	0.028-0.250 wall	0.094-1.188 wall	≤3.000	≤6.000
Basis	S	S	S	S	S	S	S	S	S	S	S
Mechanical Properties:											
F_{tu}, ksi:											
L	45	45	45	45	45	43	46	46	44	42	38
LT	...	...	...	...	...	...	...	...	...	...	...
F_{ty}, ksi:											
L	36	36	36	34	34	31	38	38	33	26	20
LT	...	...	...	...	...	...	...	...	...	...	...
F_{cy}, ksi:											
L	30	28	25	23	22	20	26	26	21	...	...
LT	...	...	...	...	...	...	...	...	...	...	...
F_{su}, ksi	22	22	22	...	...	...	...	...	...	...	...
F_{bru}[a], ksi:											
(e/D = 1.5)	...	...	...	...	...	...	...	...	...	...	...
(e/D = 2.0)	71	71	71	...	...	...	...	...	...	...	...
F_{bry}[a], ksi:											
(e/D = 1.5)	...	...	...	...	...	...	...	...	...	...	...
(e/D = 2.0)	47	47	47	...	...	...	...	...	...	...	...
e, percent:											
L	4	4	4	6	6	6	4	4	4	7	7
E, 10^3 ksi	6.5										
E_c, 10^3 ksi	6.5										
G, 10^3 ksi	2.4										
μ	0.35										
Physical Properties:											
ω, lb/in.^{3}	0.0659										
C, K, and α	See Figure 4.2.3.0										

[a] Bearing values are “dry pin” values per Section 1.4.7.1.

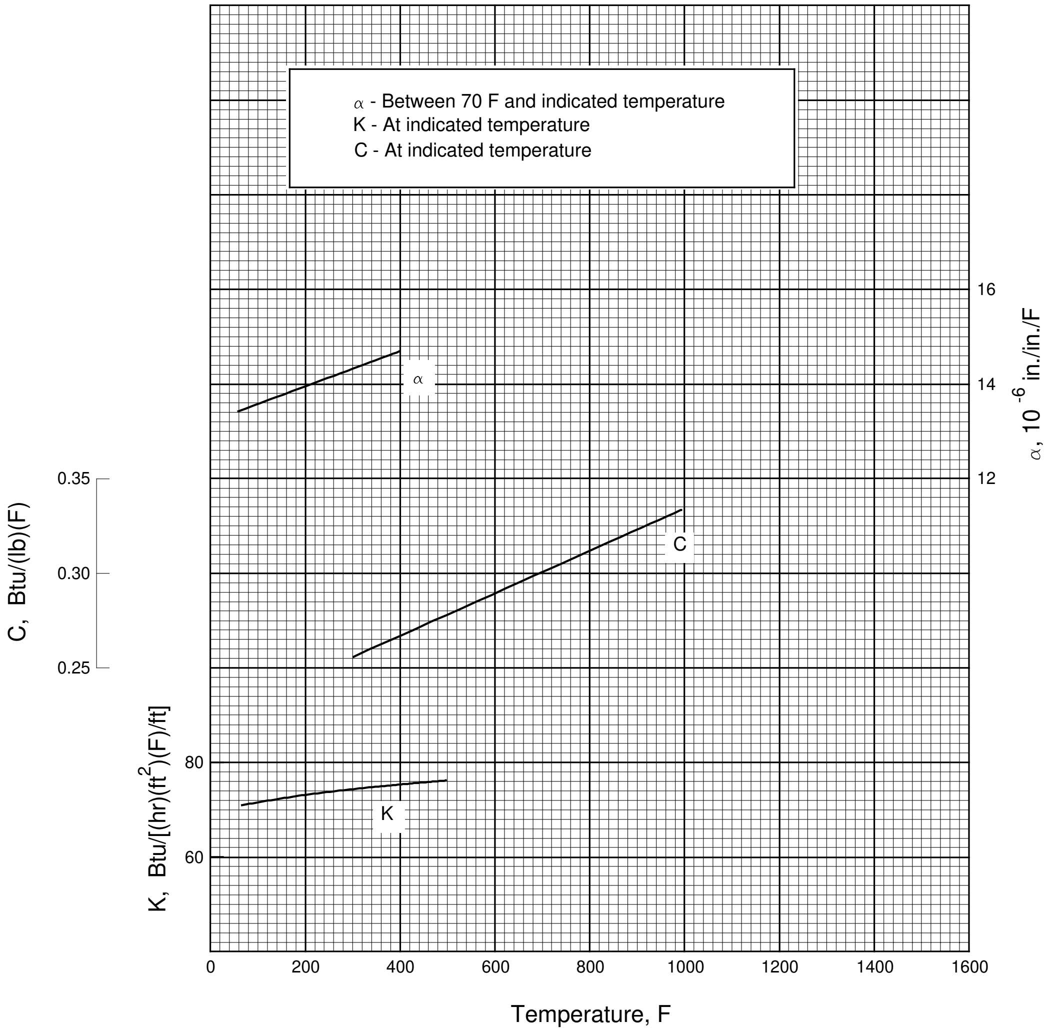

Figure 4.2.3.0. Effect of temperature on the physical properties of ZK60A magnesium alloy.

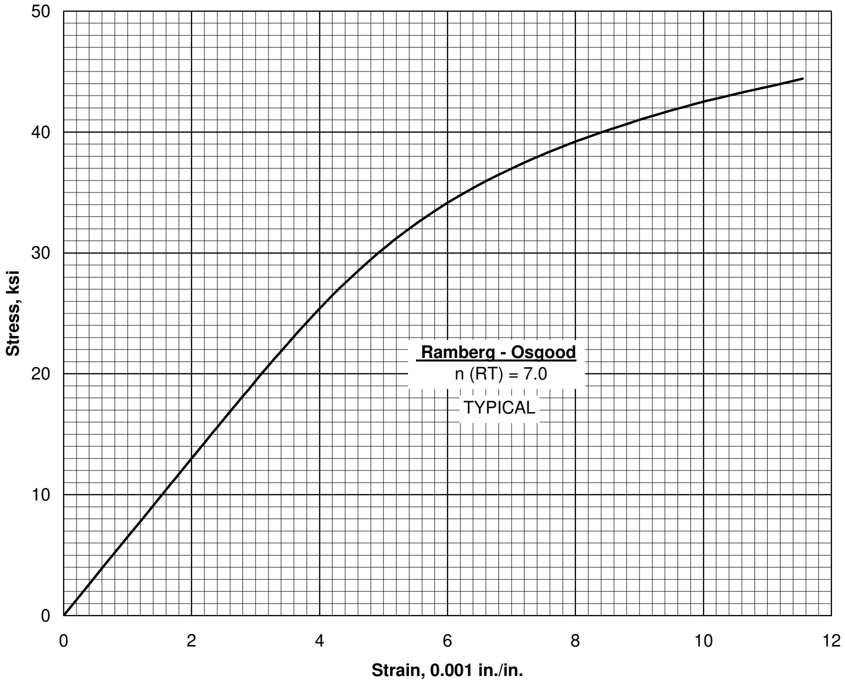

Figure 4.2.3.2.6(a). Typical tensile stress-strain curve for ZK60A-T5 extrusion at room temperature.

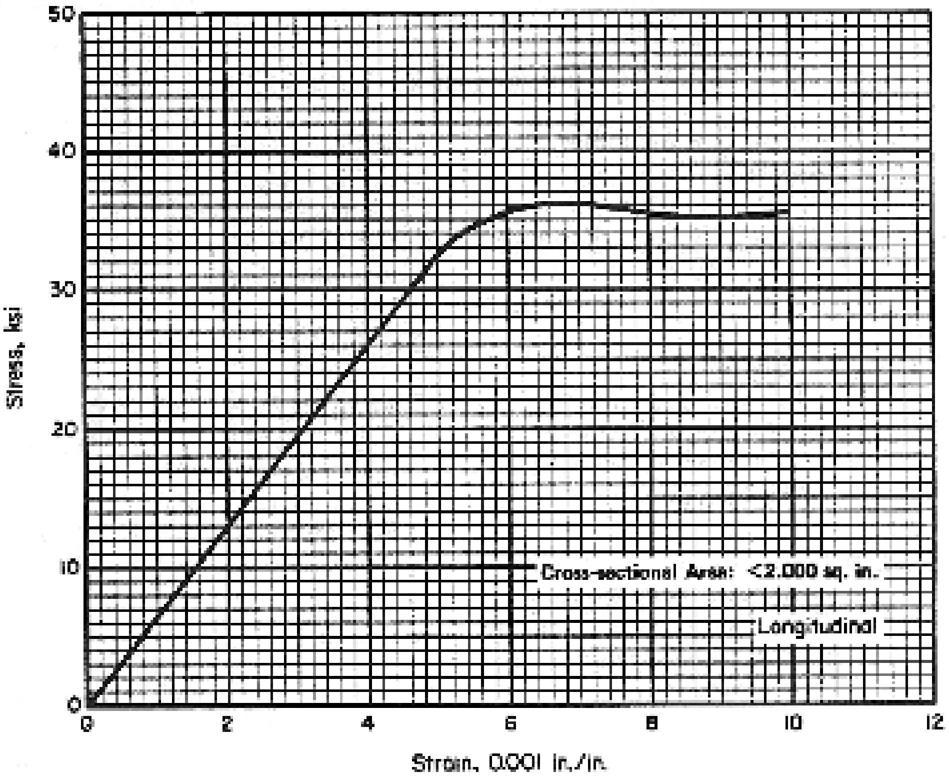

Figure 4.2.3.2.6(b). Typical compressive stress-strain curve for ZK60A-T5 extrusion at room temperature.

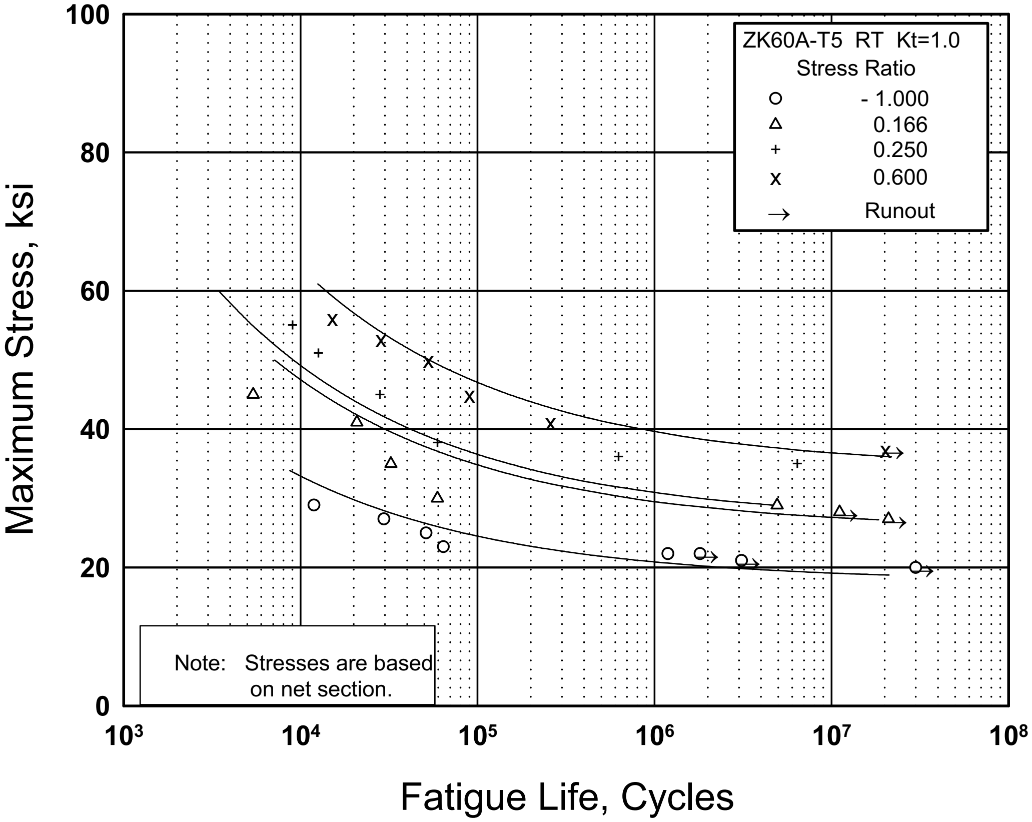

Figure 4.2.3.2.8(a). Best-fit S/N curves for unnotched ZK60A-T5 extruded bar, longitudinal direction.

Correlative Information for Figure 4.2.3.2.8(a)

Product Form: Extruded bar, 0.50 inch diameter

Properties:

TUS, ksi	TYS, ksi	Temp., °F
47.5	40.9	RT (unnotched)

Specimen Details: Unnotched
0.500 inch gross diameter
0.400 inch net diameter
0.750 inch root diameter
7.500 inch long

Surface Condition: Polished with No. 240 grit aluminum oxide belt and then a No. 400 grit; polished with kerosene to better than 10 micro-inches

Reference: 4.2.3.2.8

Test Parameters:
Loading - Axial
Frequency - 3600 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
Log N_f = 7.56-2.73 log (S_{eq}-23.7)
$S_{eq} = S_{max}(1-R)^{0.40}$
Std. Error of Estimate, Log (Life) = 0.60
Standard Deviation, Log (Life) = 0.85
R^2 = 51%

Sample Size = 21

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

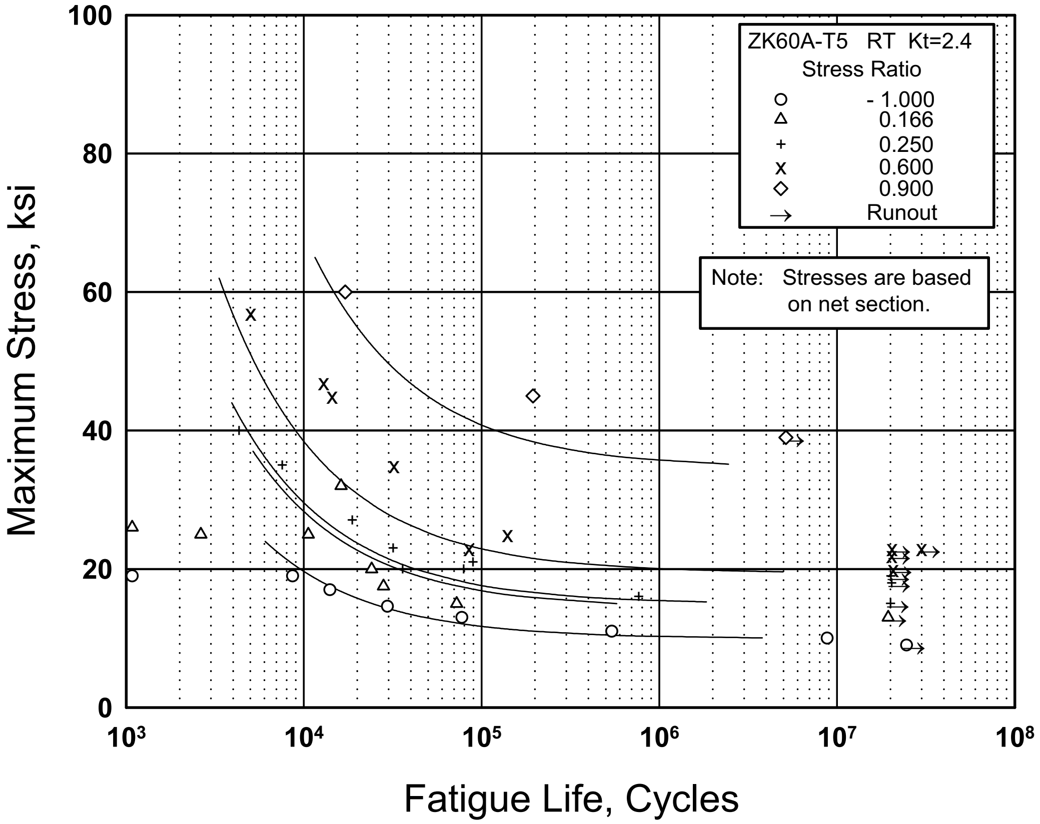

Figure 4.2.3.2.8(b). Best-fit S/N curves for notched, K_t = 2.4, ZK60A-T5 extruded bar, longitudinal direction.

Correlative Information for Figure 4.2.3.2.8(b)

Product Form: Extruded bar, 0.50 inch diameter

Properties:

TUS, ksi	TYS, ksi	Temp., °F
63.7	40.9	RT (notched)

Specimen Details: Circumferential notched,
K_t = 2.4
0.500 inch gross diameter
0.400 inch net diameter
0.032 inch notch radius
60° flank angle, ω

Surface Condition: Ground with aluminum oxide wheel lubricated with sulfur cutting oil; lapped with a copper rod and No. 600 grit alundum lapping compound

Reference: 4.2.3.2.8

Test Parameters:
Loading - Axial
Frequency - 3600 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
$\text{Log } N_f = 5.51 - 1.36 \log (S_{eq} - 13.2)$
$S_{eq} = S_{max}(1-R)^{0.42}$
Std. Error of Estimate, Log (Life) = 0.46
Standard Deviation, Log (Life) = 0.82
R^2 = 69%

Sample Size = 30

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

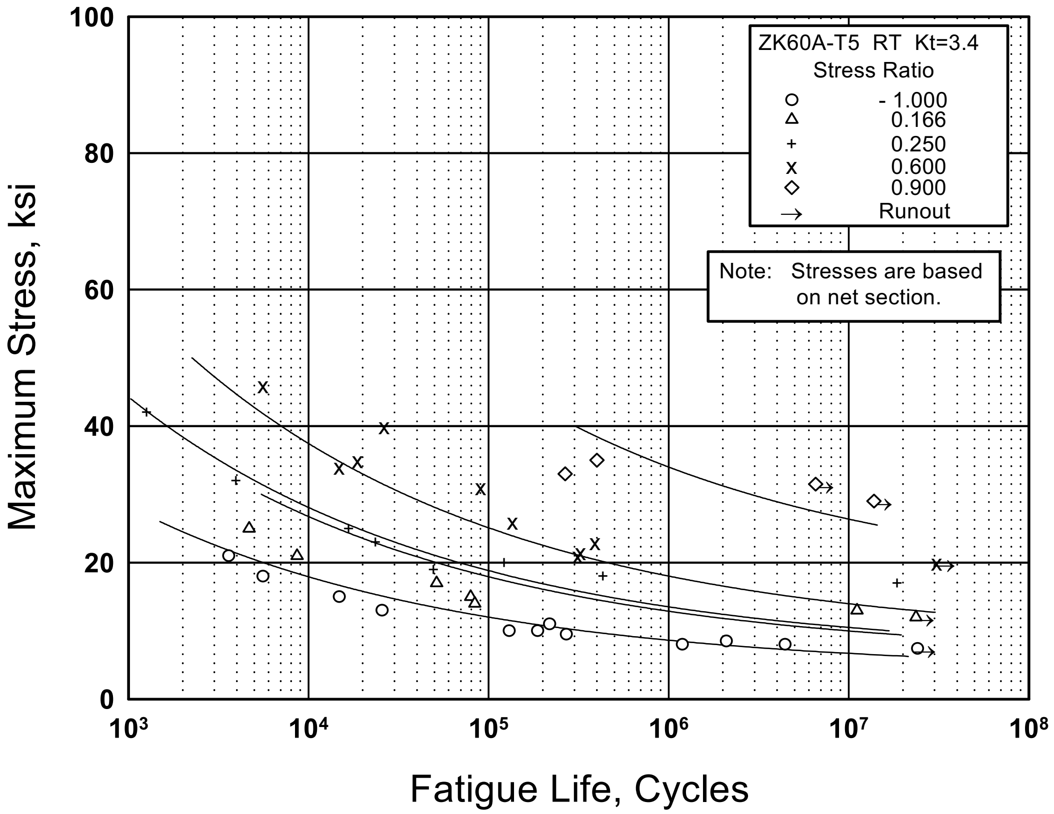

Figure 4.2.3.2.8(c). Best-fit S/N curves for notched, K_t = 3.4, ZK60A-T5 extruded bar, longitudinal direction.

Correlative Information for Figure 4.2.3.2.8(c)

Product Form: Extruded bar, 0.50 inch diameter

Properties:

TUS, ksi	TYS, ksi	Temp., °F
58.2	40.9	RT (notched)

Specimen Details: Circumferential notched,
K_t = 4
0.500 inch gross diameter
0.400 inch net diameter
0.010 inch notch radius
60° flank angle, ω

Surface Condition: Ground with aluminum oxide wheel lubricated with sulfur cutting oil; lapped with a copper rod and No. 600 grit alundum lapping compound

Reference: 4.2.3.2.8

Test Parameters:
Loading - Axial
Frequency - 3600 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
$\text{Log } N_f = 9.27 - 4.13 \log (S_{eq} - 5.63)$
$S_{eq} = S_{max}(1-R)^{0.46}$
Std. Error of Estimate, Log (Life) = 0.55
Standard Deviation, Log (Life) = 0.99
R^2 = 70%

Sample Size = 36

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

4.3 MAGNESIUM CAST ALLOYS

4.3.1 AM100A

4.3.1.0 *Comments and Properties* — AM100A is a magnesium-base casting alloy containing aluminum and a small amount of manganese. It is primarily used as permanent mold castings. AM100A has about the same characteristics as AZ92A. AM100A has less tendency to microshrinkage and hot shortness than the Mg-Al-Zn alloys. It has good weldability and fair pressure tightness.

Material specifications for AM100A are given in Table 4.3.1.0(a). Room-temperature mechanical and physical properties are shown in Table 4.3.1.0(b).

Table 4.3.1.0(a). Material Specifications for AM100A Magnesium Alloy

Specification	Form
AMS 4455	Investment casting
AMS 4483[a]	Permanent mold casting

a Noncurrent specification.

Table 4.3.1.0(b). Design Mechanical and Physical Properties of AM100A Magnesium Alloy Casting

Specification	AMS 4455	AMS 4483[a]
Form	Investment casting	Permanent mold casting
Temper	T6	T6
Location within casting	Any area	
Basis	S	S
Mechanical Properties[c]:		
F_{tu}, ksi	17[c]	17[c]
F_{ty}, ksi	9.5[c]	10[c]
F_{cy}, ksi	9.5	10
F_{su}, ksi	...	...
F_{bru}, ksi:		
(e/D = 1.5)	...	...
(e/D = 2.0)	...	...
F_{bry}, ksi:		
(e/D = 1.5)	...	...
(e/D = 2.0)	...	...
e, percent	1[b]	...
E, 10^3 ksi	6.5	
E_c, 10^3 ksi	6.5	
G, 10^3 ksi	2.4	
μ	0.35	
Physical Properties:		
ω, lb./in.^{3}	0.0651	
C, K, and α	...	

a Noncurrent specification.
b Reference should be made to the specific requirements of the procuring or certificating agency with regard to the use of the above values in the design of castings.
c When specified on drawing, conformance to tensile property requirements is determined by testing specimens cut from castings.

4.3.2 AZ91C/AZ91E

4.3.2.0 *Comments and Properties* — AZ91C is a magnesium-base casting alloy containing aluminum and zinc. AZ91E is a version which contains a significantly lower level of impurities resulting in improved corrosion resistance. These alloys have good castability with a good combination of ductility and strength. AZ91C and AZ91E are the most commonly used sand castings for temperatures under 300°F. AZ91C is available as sand and investment castings, while AZ91E is available as a sand casting. AZ91C and AZ91E have fair weldability and pressure tightness.

Some material specifications covering AZ91C/AZ91E are presented in Table 4.3.2.0(a). Room-temperature mechanical and physical properties are shown in Tables 4.3.2.0(b) and (c).

Table 4.3.2.0(a). Material Specifications for AZ91C/AZ91E Magnesium Alloy

Specification	Form
AMS 4437	Sand casting
AMS 4452	Investment casting
AMS 4446	Sand casting

The temper index for AZ91C/AZ91E is as follows:

Section	Temper
4.3.2.1	T6

4.3.2.1 *T6 Temper* — Figure 4.3.2.1.4 contains an elevated temperature curve for tension and compression moduli. Typical tensile stress-strain curves at room temperature and several elevated temperatures are presented in Figure 4.3.2.1.6.

Table 4.3.2.0(b). Design Mechanical and Physical Properties of AZ91C Magnesium Alloy Casting

Specification	AMS 4437	AMS 4452
Form	Sand casting	Investment casting
Temper	T6	T6
Location within casting	Any area	
Basis	S	S
Mechanical Properties[a]:		
F_{tu}, ksi	17[b]	17[b]
F_{ty}, ksi	12[b]	12[b]
F_{cy}, ksi	12	12
F_{su}, ksi	...	...
F_{bru}, ksi:		
(e/D = 1.5)	...	...
(e/D = 2.0)	...	...
F_{bry}, ksi:		
(e/D = 1.5)	...	...
(e/D = 2.0)	...	...
e, percent	0.75[b]	1[b]
E, 10^3 ksi	6.5	
E_c, 10^3 ksi	6.5	
G, 10^3 ksi	2.4	
μ	0.35	
Physical Properties:		
ω, lb./in.^{3}	0.0652	
C,Btu/(lb)(°F)	0.25[c]	
K, Btu/[(hr)(ft^2)(°F)/ft]	41 (212°F to 572°F)	
α, 10^{-6} in./in./°F	14 (65°F to 212°F)	

a Reference should be made to the specific requirements of the procuring or certificating agency with regard to the use of the above values in the design of castings.

b When specified on drawing, conformance to tensile property requirements is determined by testing specimens cut from castings.

c Estimated.

Table 4.3.2.0(c). Design Mechanical and Physical Properties of AZ91E Magnesium Alloy Casting

Specification	AMS 4446
Form	Sand casting
Condition	T6
Location within casting	Any area
Basis	S
Mechanical Properties[a]:	
F_{tu}, ksi	17[b]
F_{ty}, ksi	12[b]
F_{cy}, ksi	12
F_{su}, ksi	...
F_{bru}, ksi:	
(e/D = 1.5)	...
(e/D = 2.0)	...
F_{bry}, ksi:	
(e/D = 1.5)	...
(e/D = 2.0)	...
e, percent	...
E, 10^3 ksi	6.5
E_c, 10^3 ksi	6.5
G, 10^3 ksi	2.4
μ	0.35
Physical Properties:	
ω, lb/in.^{3}	0.0652
C, Btu/(lb)(°F)	0.25[c]
K, Btu/[(hr)(ft^2)(°F)/ft]	41 (212°F to 572°F)
α, 10^{-6} in./in./F	14 (65°F to 212°F)

a Reference should be made to the specific requirements of the procuring or certificating agency with regard to the use of the above values in the design of castings.
b When specified on drawing, conformance to tensile property requirements is determined by testing specimens cut from castings.
c Estimated.

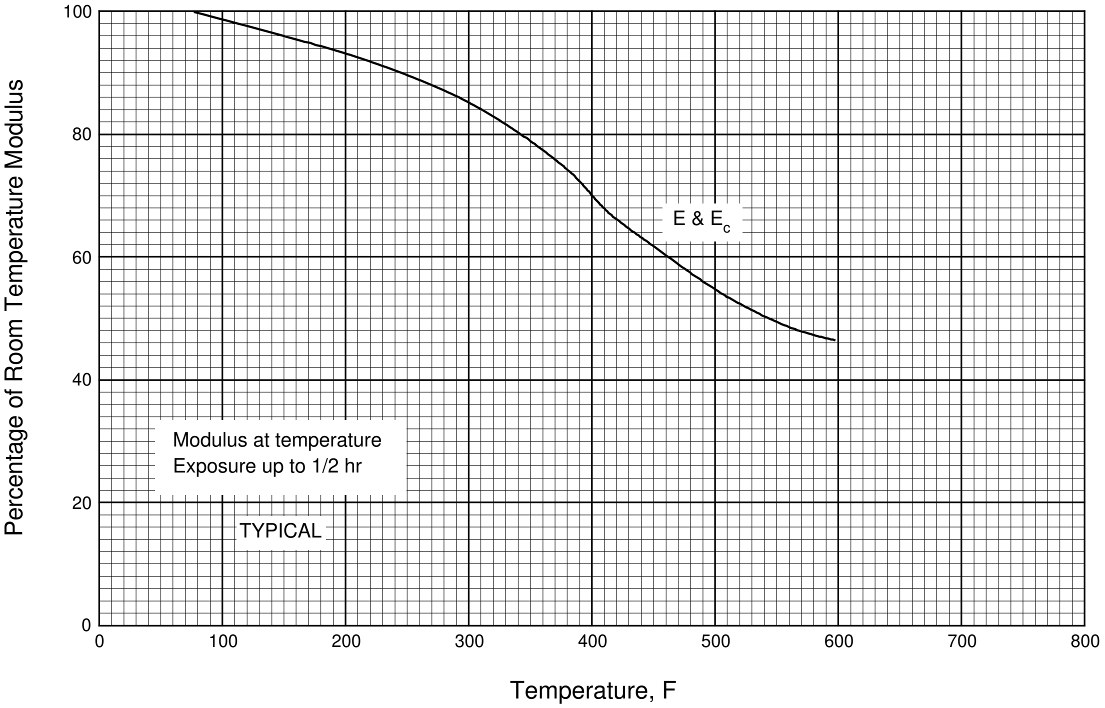

Figure 4.3.2.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of cast AZ91C-T6/AZ91E-T6.

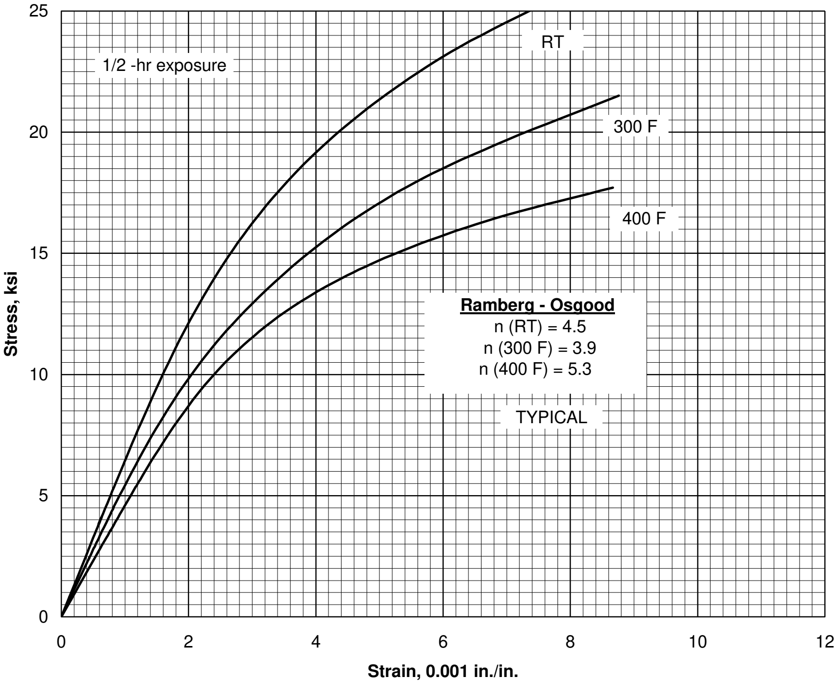

Figure 4.3.2.1.6. Typical tensile stress-strain curves for cast AZ91C-T6/AZ91E-T6 at room and elevated temperatures.

4.3.3 AZ92A

4.3.3.0 *Comments and Properties* — AZ92A is a magnesium-base casting alloy containing aluminum and zinc. It is slightly stronger and less ductile than AZ91C but is much like it in other characteristics. It is available as sand and permanent-mold casting. AZ92A has fair weldability and pressure tightness.

Material specifications for AZ92A are presented in Table 4.3.3.0(a). Room-temperature mechanical and physical properties are shown in Table 4.3.3.0(b). Elevated temperature curves for physical properties are shown in Figure 4.3.3.0.

Table 4.3.3.0(a). Material Specifications for AZ92A Magnesium Alloy

Specification	Form
AMS 4434	Sand casting
AMS 4484[a]	Permanent-mold casting
AMS 4453	Investment casting

[a] Noncurrent specification.

The temper index for AZ92A is as follows:

Section	Temper
4.3.3.1	T6

4.3.3.1 *AZ92A-T6 Temper* — Elevated temperature curves for various mechanical properties are presented in Figures 4.3.3.1.1(a) through (c), and 4.3.3.1.4. Typical stress-strain and tangent-modulus curves at room temperature and several elevated temperatures are shown in Figures 4.3.3.1.6(a) and (b).

Table 4.3.3.0(b). Design Mechanical and Physical Properties of AZ92A Magnesium Alloy Casting

Specification	AMS 4484[a]	AMS 4434	AMS 4453
Form	Permanent mold casting	Sand casting	Investment Casting
Temper	T6	T6	T6
Location within casting	Any area		
Basis	S	S	S
Mechanical Properties[b]:			
F_{tu}, ksi	17[c]	17[c]	19
F_{ty}, ksi	13.5[c]	13.5[c]	15
F_{cy}, ksi	13.5	13.5	...
F_{su}, ksi	...	...	...
F_{bru}, ksi:			
(e/D = 1.5)	...	...	...
(e/D = 2.0)	...	...	...
F_{bry}, ksi:			
(e/D = 1.5)	...	...	...
(e/D = 2.0)	...	...	...
e, percent	...	...	0.7
E, 10^3 ksi	6.5		
E_c, 10^3 ksi	6.5		
G, 10^3 ksi	2.4		
μ	0.35		
Physical Properties:			
ω, lb./in.^{3}	0.0659		
C, Btu/(lb)(°F)	0.25[d]		
K and α	See Figure 4.3.3.0		

a Noncurrent specification.

b Reference should be made to the specific requirements of the procuring or certificating agency with regard to the use of the above values in the design of castings.

c When specified on drawing, conformance to tensile property requirements is determined by testing specimens cut from castings.

d Estimated.

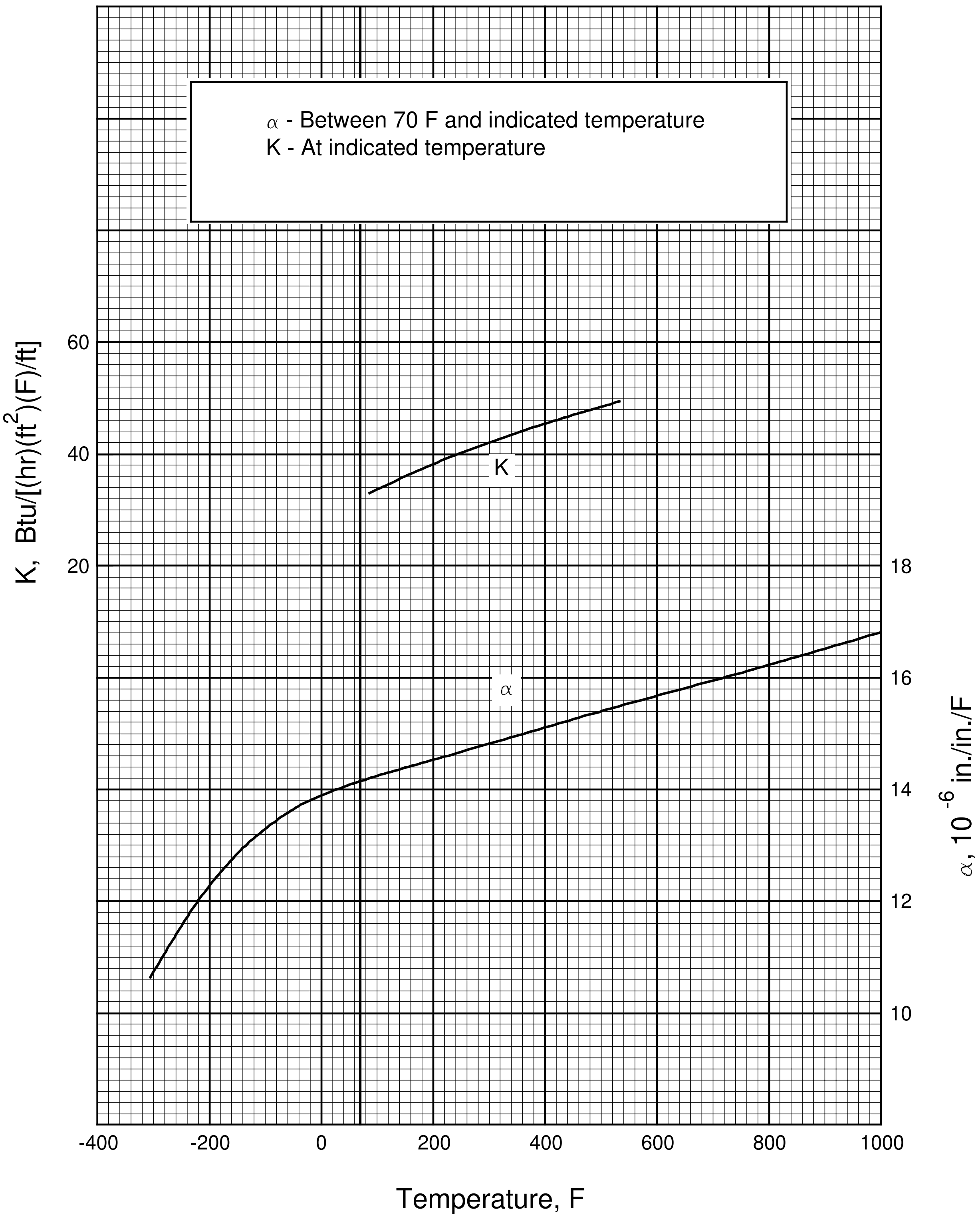

Figure 4.3.3.0. Effects of temperature on the physical properties of cast AZ92A-T6.

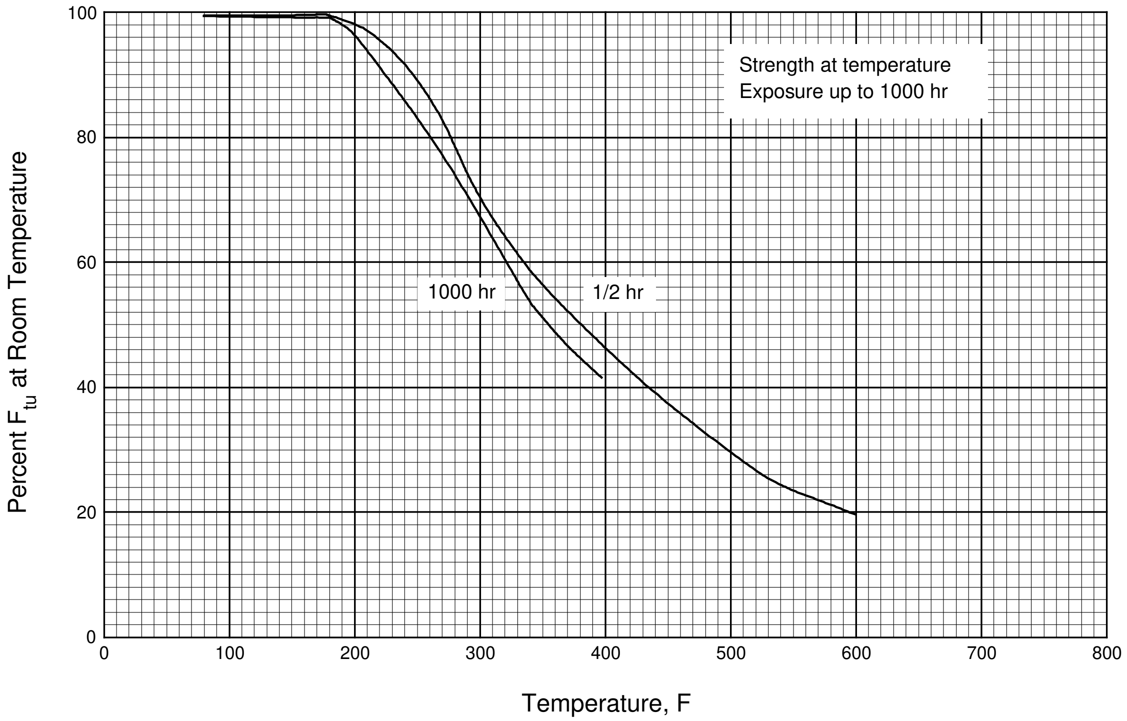

Figure 4.3.3.1.1(a). Effect of temperature on the tensile ultimate strength (F_{tu}) of cast AZ92A-T6.

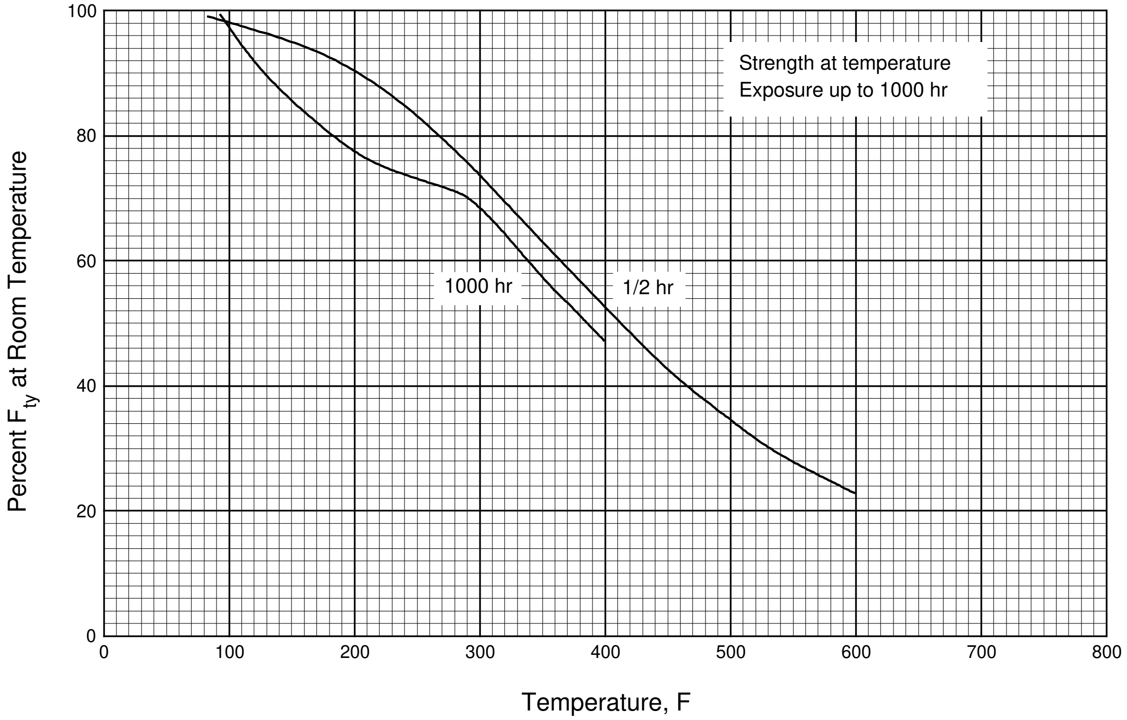

Figure 4.3.3.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of cast AZ92A-T6.

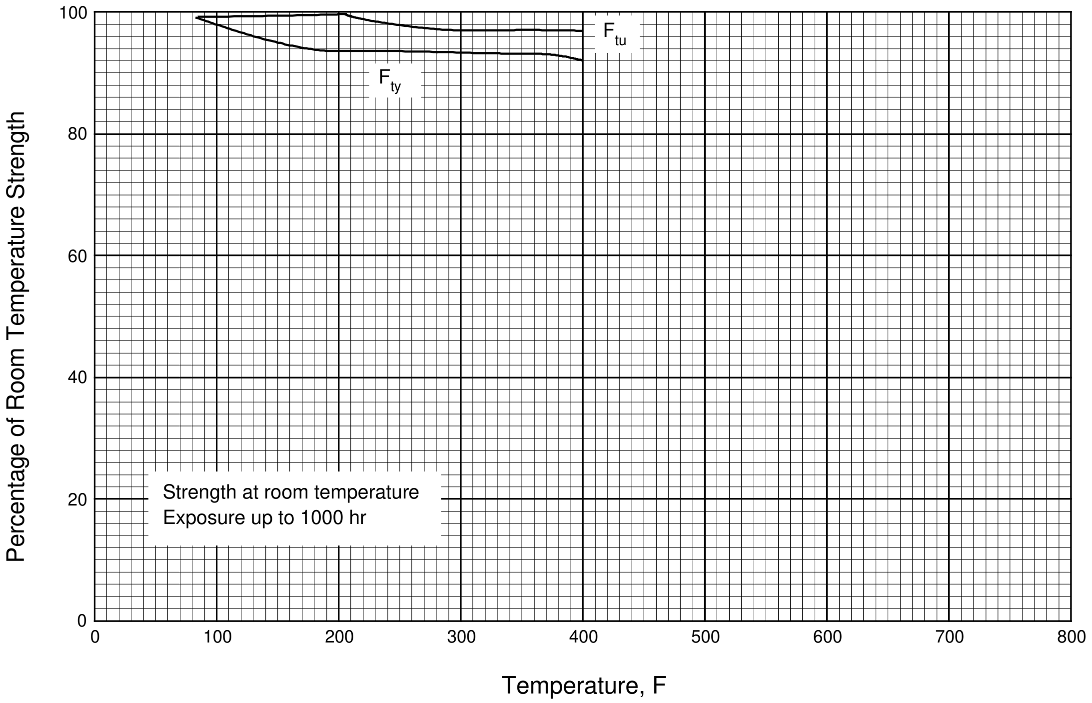

Figure 4.3.3.1.1(c). Effect of exposure at elevated temperature on the room-temperature tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of cast AZ92A-T6.

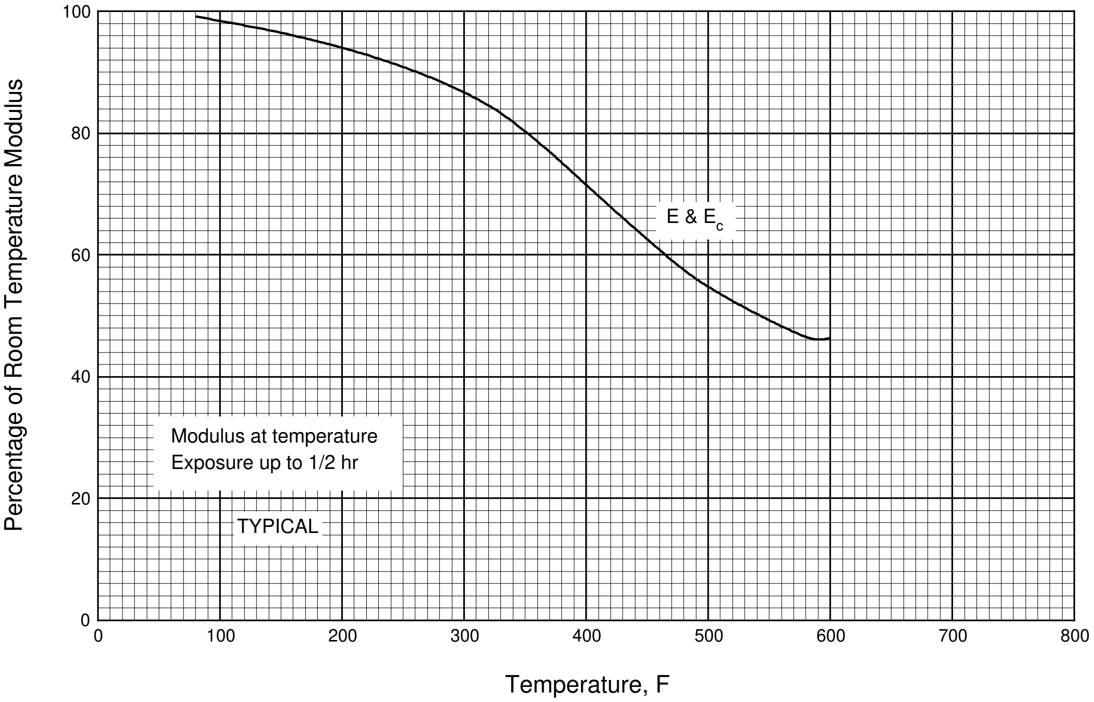

Figure 4.3.3.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of cast AZ92A-T6.

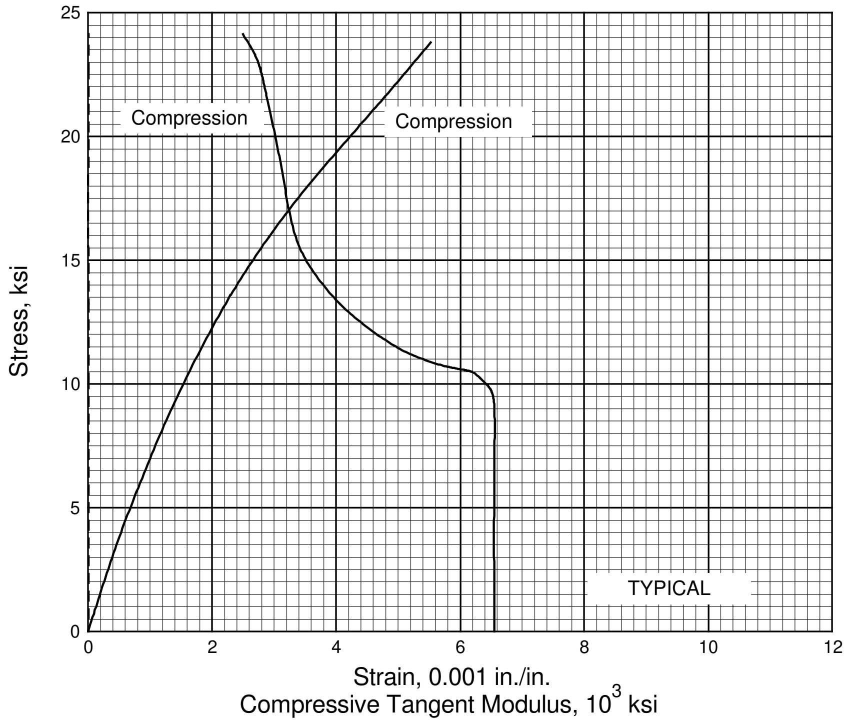

Figure 4.3.3.1.6(a). Typical compressive stress-strain and compressive tangent-modulus curves for cast AZ92A-T6 at room temperature.

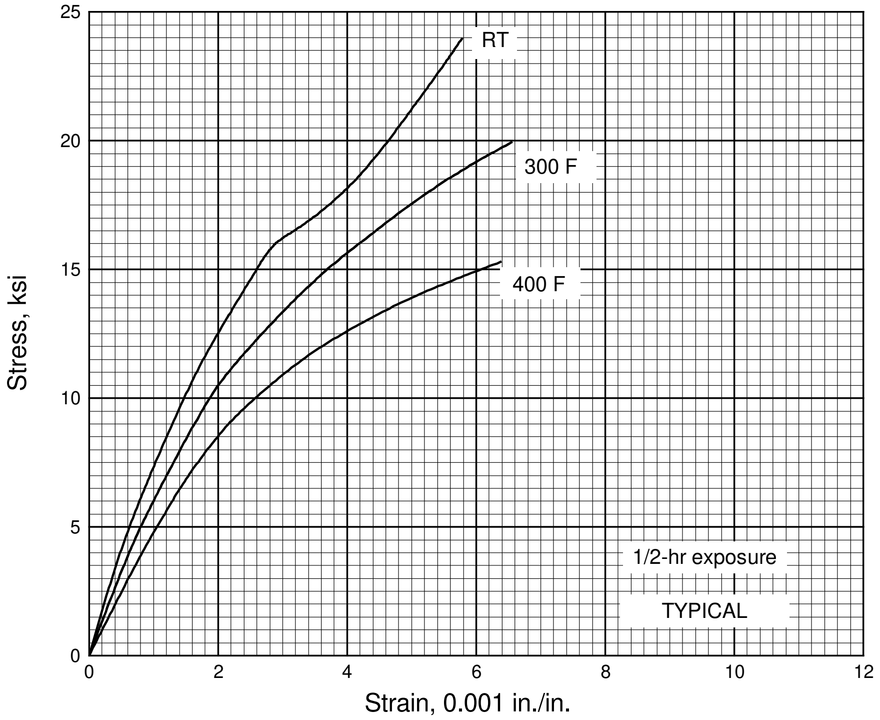

Figure 4.3.3.1.6(b). Typical tensile stress-strain curves for cast AZ92A-T6 at room and elevated temperatures.

4.3.4 EZ33A

4.3.4.0 *Comments and Properties* — EZ33A is a magnesium-base casting alloy containing rare earths, zinc, and zirconium. It is available as sand castings in the artificially aged (T5) temper. EZ33A has lower strength than the Mg-Al-Zn alloys at room temperature but is less affected by increasing temperature. It is generally used for applications at temperatures of 300 to 500°F. EZ33A castings are very sound and are sometimes used for pressure tightness. It has good stability in the T5 temper and excellent weldability. It is sometimes used for applications requiring good damping ability.

A material specification for EZ33A is presented in Table 4.3.4.0(a). Room-temperature mechanical and physical properties are shown in Table 4.3.4.0(b). The effect of temperature on physical properties is shown in Figure 4.3.4.0.

Table 4.3.4.0(a). Material Specification for EZ33A Magnesium Alloy

Specification	Form
AMS 4442	Sand casting

The temper index for EZ33A is as follows:

Section	Temper
4.3.4.1	T5

4.3.4.1 *EZ33A-T5 Temper* — Elevated temperature curves for tensile properties are presented in Figures 4.3.4.1.1(a) through (c). A typical tensile stress-strain curve at room temperature is presented in Figure 4.3.4.1.6.

Table 4.3.4.0(b). Design Mechanical and Physical Properties of EZ33A Magnesium Alloy Casting

Specification	AMS 4442
Form	Sand casting
Temper	T5
Location within casting	Any area
Basis	S
Mechanical Properties[a]:	
F_{tu}, ksi	13[b]
F_{ty}, ksi	11[b]
F_{cy}, ksi	11
F_{su}, ksi	...
F_{bru}, ksi:	
(e/D = 1.5)	...
(e/D = 2.0)	...
F_{bry}, ksi:	
(e/D = 1.5)	...
(e/D = 2.0)	...
e, percent	1.5
E, 10^3 ksi	6.5
E_c, 10^3 ksi	6.5
G, 10^3 ksi	2.4
μ	0.35
Physical Properties:	
ω, lb/in.^{3}	0.0659
C, Btu/(lb)(°F)	0.25
K and α	See Figure 4.3.4.0

a Reference should be made to the specific requirements of the procuring or certificating agency with regard to the use of the above values in the design of castings.

b When specified on drawing, conformance to tensile property requirements is determined by testing specimens cut from castings.

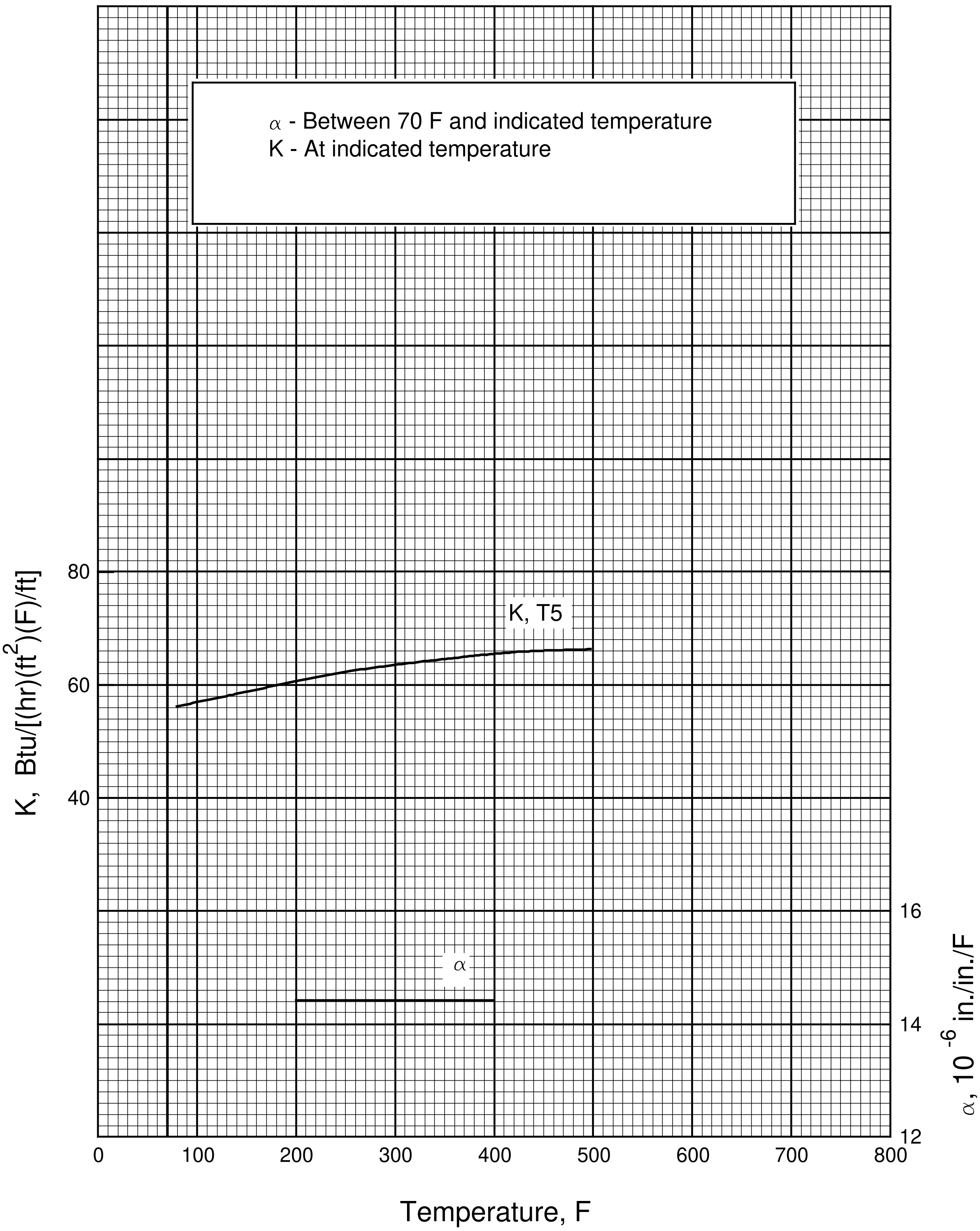

Figure 4.3.4.0. Effect of temperature on the physical properties of cast EZ33A.

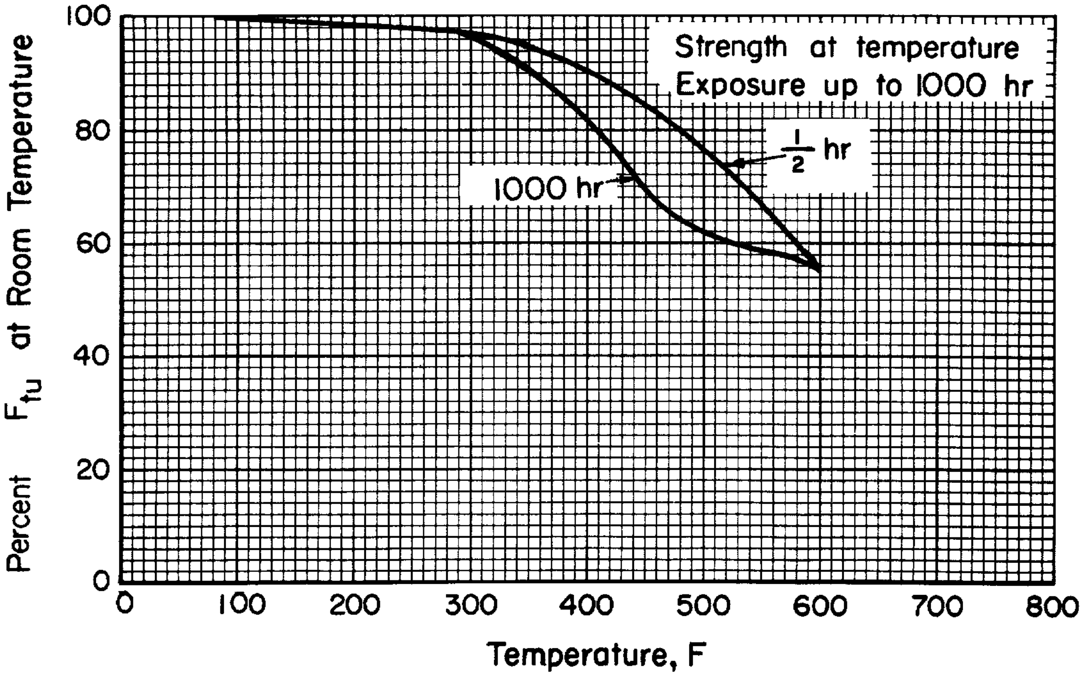

Figure 4.3.4.1.1(a). **Effect of temperature on the tensile ultimate strength (F_{tu}) of cast EZ33A-T5.**

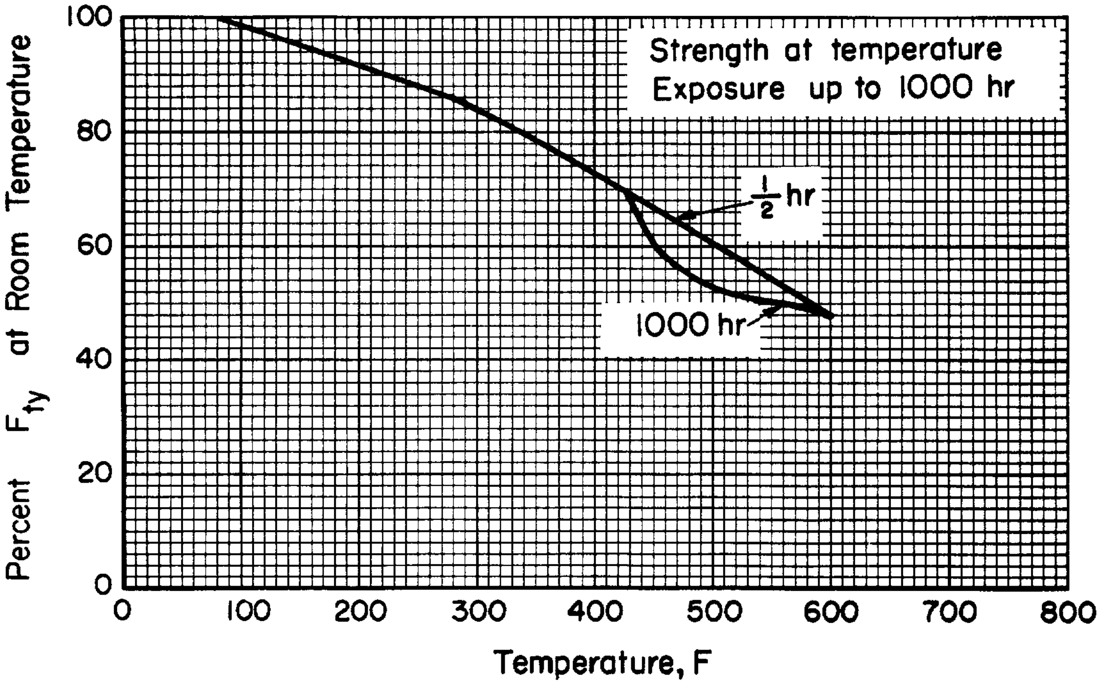

Figure 4.3.4.1.1(b). **Effect of temperature on the tensile yield strength (F_{ty}) of cast EZ33A-T5.**

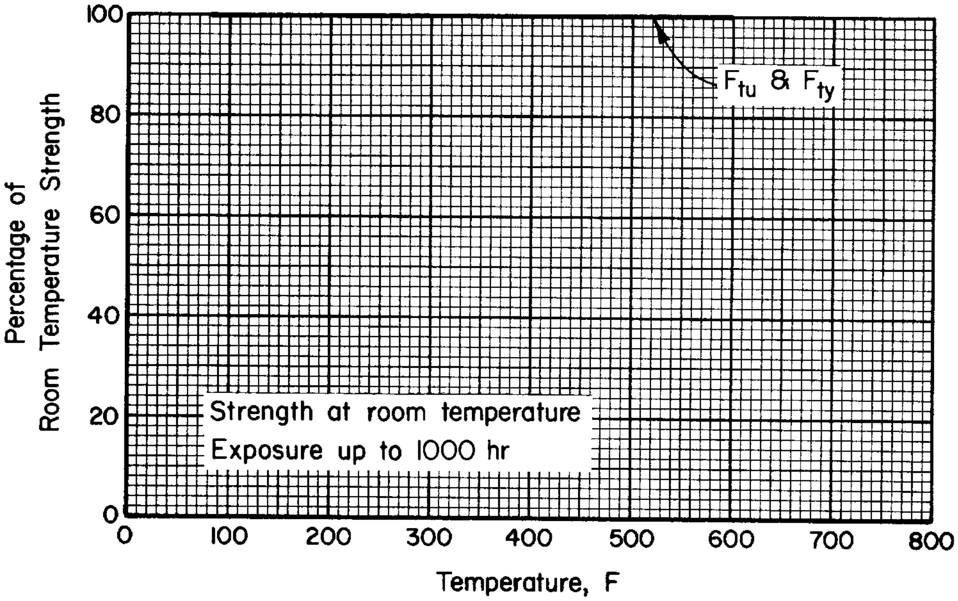

Figure 4.3.4.1.1(c). Effect of exposure at elevated temperatures on the room temperature tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of cast EZ33A-T5.

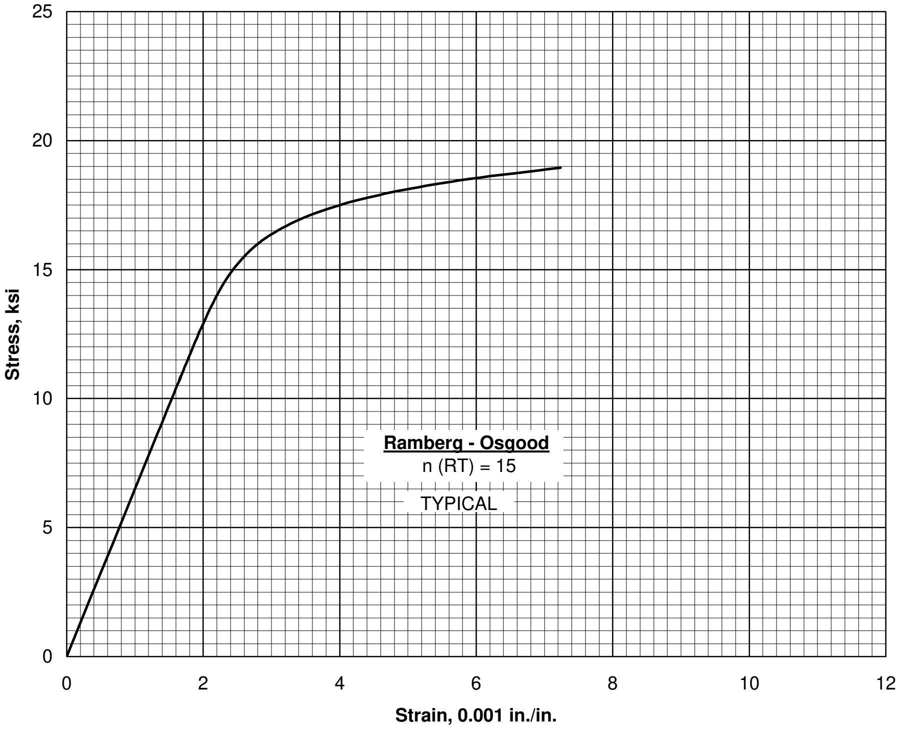

Figure 4.3.4.1.6. Typical tensile stress-strain curve for cast EZ33A-T5 at room temperature.

4.3.5 QE22A

4.3.5.0 *Comments and Properties* — QE22A is a magnesium-base alloy containing silver, rare earths in the form of didymium, and zirconium. It is available as sand and permanent-mold castings. It is used in the solution heat-treated and artificially aged (T6) condition where a high yield strength is needed at temperatures up to 600°F. QE22A has good weldability and fair pressure tightness.

Material specifications for QE22A are presented in Table 4.3.5.0(a). Room-temperature mechanical and physical properties are shown in Table 4.3.5.0(b).

Table 4.3.5.0(a). Material Specifications for QE22A Magnesium Alloy

Specification	Form
AMS 4418	Sand casting

The temper index for QE22A is as follows:

Section	Temper
4.3.5.1	T6

4.3.5.1 *QE22A-T6 Temper* — Elevated temperature curves for various tensile properties and modulus of elasticity are presented in Figures 4.3.5.1.1 and 4.3.5.1.4. Typical tensile stress-strain curves at various temperatures from room temperature through 700°F are shown in Figure 4.3.5.1.6.

Table 4.3.5.0(b). Design Mechanical and Physical Properties of QE22A Magnesium Alloy Casting

Specification	AMS 4418
Form	Sand casting
Temper	T6
Location within casting	Any area
Basis	S
Mechanical Properties[a]:	
F_{tu}, ksi	32[b]
F_{ty}, ksi	23[b]
F_{cy}, ksi	23
F_{su}, ksi	...
F_{bru}, ksi:	
(e/D = 1.5)	...
(e/D = 2.0)	...
F_{bry}, ksi:	
(e/D = 1.5)	...
(e/D = 2.0)	...
e, percent	2[b]
E, 10^3 ksi	6.5
E_c, 10^3 ksi	6.5
G, 10^3 ksi	2.4
μ	0.35
Physical Properties:	
ω, lb/in.^{3}	0.0653
C, Btu/(lb)(°F)	0.25[c]
K, Btu/[(hr)(ft^2)(°F)/ft]	59
α, 10^{-6} in./in./°F	14 (68°F to 392°F)

a Reference should be made to the specific requirements of the procuring or certificating agency with regard to the use of the above values in the design of castings.

b When specified on drawing, conformance to tensile property requirements is determined by testing specimens cut from castings.

c Estimated.

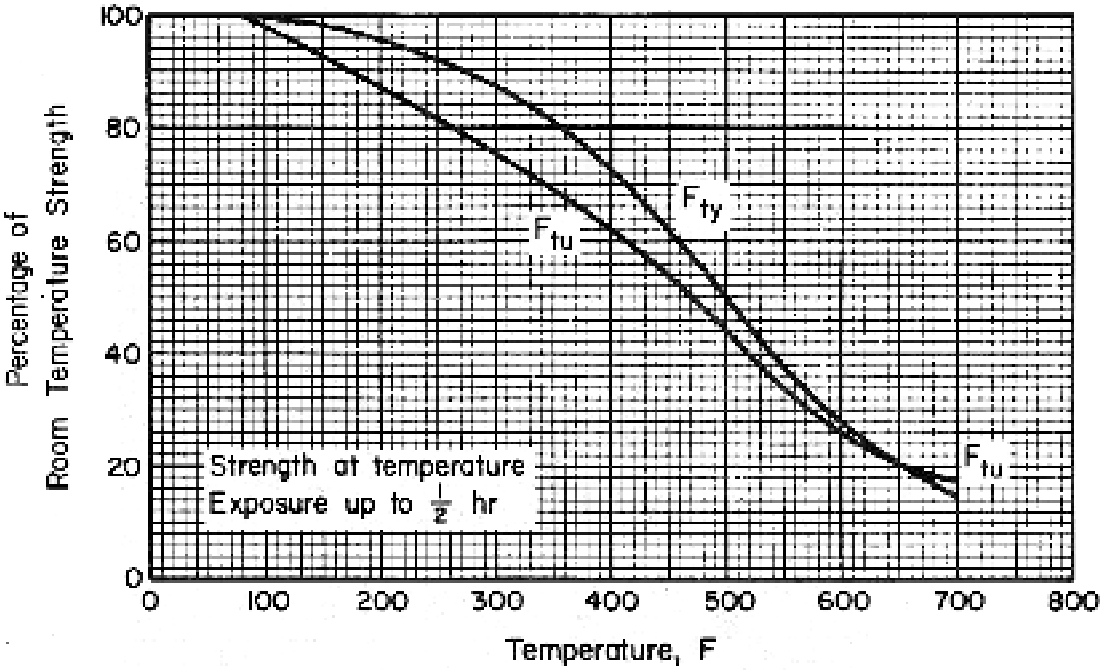

Figure 4.3.5.1.1. Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of cast QE22A-T6.

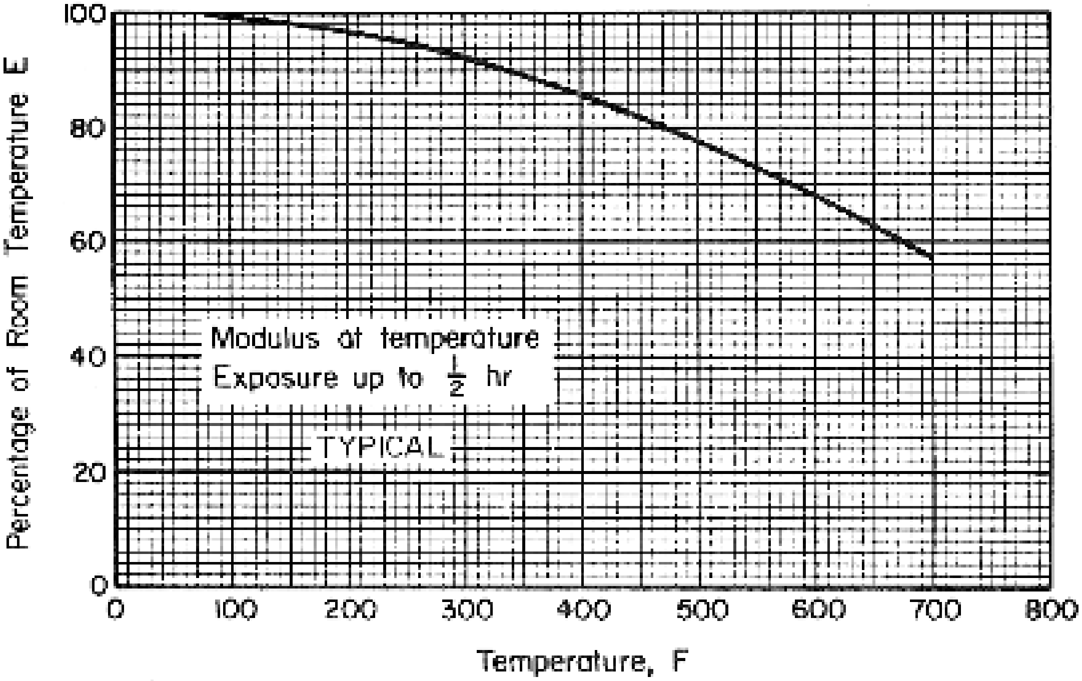

Figure 4.3.5.1.4. Effect of temperature on the tensile modulus (E) of cast QE22A-T6.

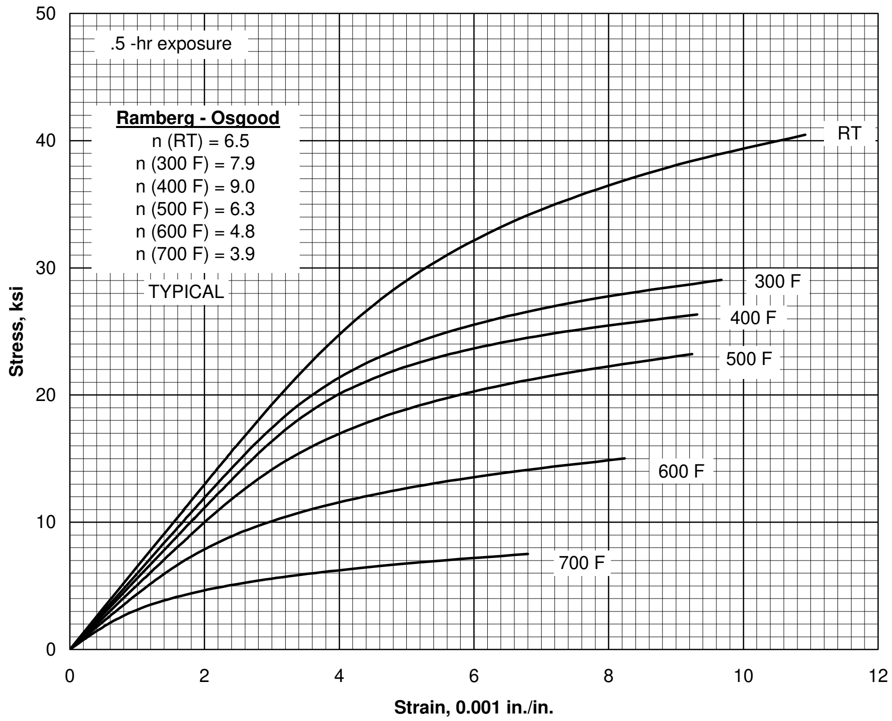

Figure 4.3.5.1.6. Typical tensile stress-strain curves for cast QE22A-T6 at room and elevated temperatures.

4.3.6 ZE41A

4.3.6.0 *Comments and Properties* — ZE41A is a magnesium-base casting alloy containing zinc, zirconium, and rare earth elements. It is available as sand or permanent-mold castings in the artificially aged temper (T5). ZE41A has a higher yield strength than the Mg-Al-Zn alloys at room temperature and is more stable at elevated temperatures. It is useful for applications at temperatures up to 320°F. ZE41A castings possess good weldability and are pressure tight.

A material specification for ZE41A is presented in Table 4.3.6.0(a). Room temperature mechanical and physical properties are shown in Table 4.3.6.0(b). The effect of temperature on thermal conductivity is shown in Figure 4.3.6.0.

Table 4.3.6.0(a). Material Specification for ZE41A Magnesium Alloy

Specification	Form
AMS 4439	Sand casting

The temper index for ZE41A is as follows:

Section	Temper
4.3.6.1	T5

4.3.6.1 *T5 Temper* — Elevated temperature curves for tensile yield and ultimate strengths are presented in Figure 4.3.6.1.1. The effect of temperature on the tensile modulus of elasticity is shown in Figure 4.3.6.1.4. Figures 4.3.6.1.6(a) and (b) contain tensile and compressive stress-strain curves as well as a compressive tangent-modulus curve.

Table 4.3.6.0(b). Design Mechanical and Physical Properties of ZE41A Magnesium Alloy Casting

Specification	AMS 4439
Form	Sand casting
Temper	T5
Thickness, in.	Any area
Basis	S
Mechanical Properties[a]:	
F_{tu}, ksi	26[b]
F_{ty}, ksi	17.5[b]
F_{cy}, ksi	15
F_{su}, ksi	17
F_{bru}[c], ksi:	
(e/D = 1.5)	38
(e/D = 2.0)	49
F_{bry}[c], ksi:	
(e/D = 1.5)	31
(e/D = 2.0)	35
e, percent	2[b]
E, 10^3 ksi	6.5
E_c, 10^3 ksi	6.5
G, 10^3 ksi	2.4
μ	0.35
Physical Properties:	
ω, lb/in.^{3}	0.0656
C, Btu/(lb)(°F)	0.234 (at 68°F)
K, Btu/[(hr)(ft^2)(°F)/ft]	See Figure 4.3.6.0
α, 10^{-6} in./in./°F	15.5 (68 to 212°F)

[a] The mechanical properties shown are reliably obtainable when castings are produced under the quality assurance provisions of AMS 4439. These provisions require preproduction approval, documentation of foundry procedures, and specific testing procedures for the acceptance of each production lot of castings. Strict adherence to these requirements is mandatory if these properties are to be reliably assured in each casting.

[b] Conformance to tensile property requirements is determined by testing specimens cut from casting only when specified on drawing.

[c] Bearing values are "dry pin" values per Section 1.4.7.1.

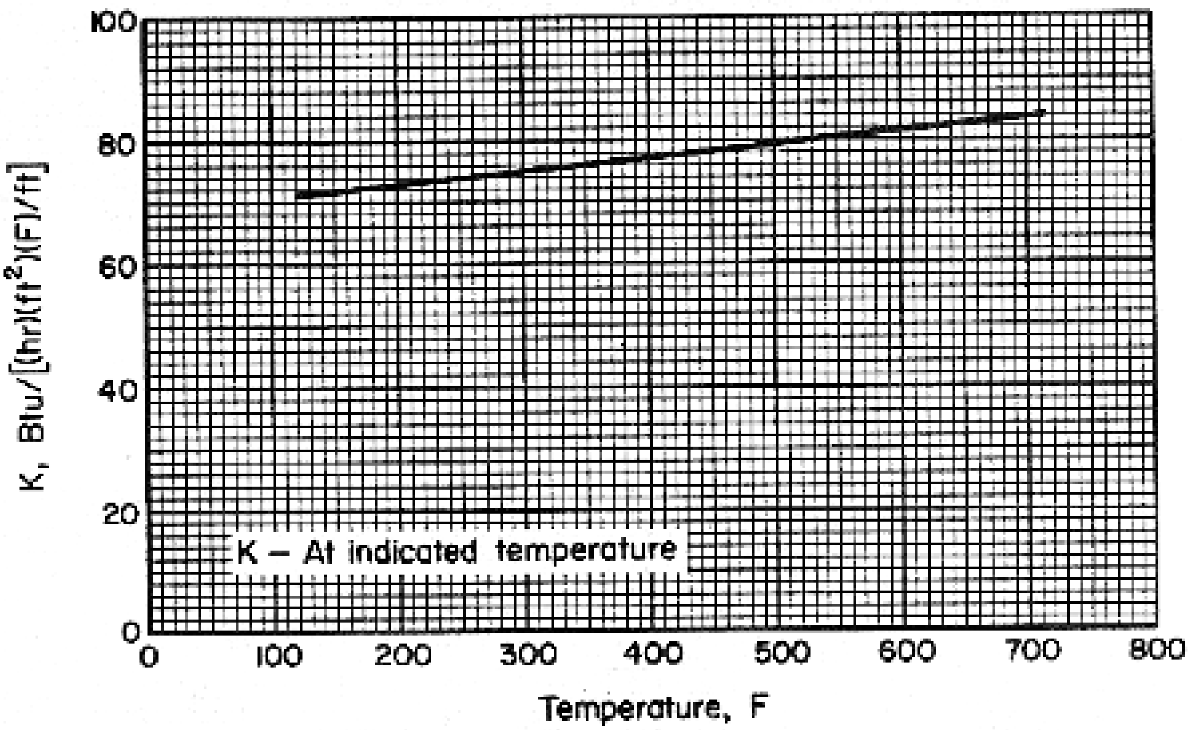

Figure 4.3.6.0. Effect of temperature on the thermal conductivity (K) of ZE41A-T5 sand casting.

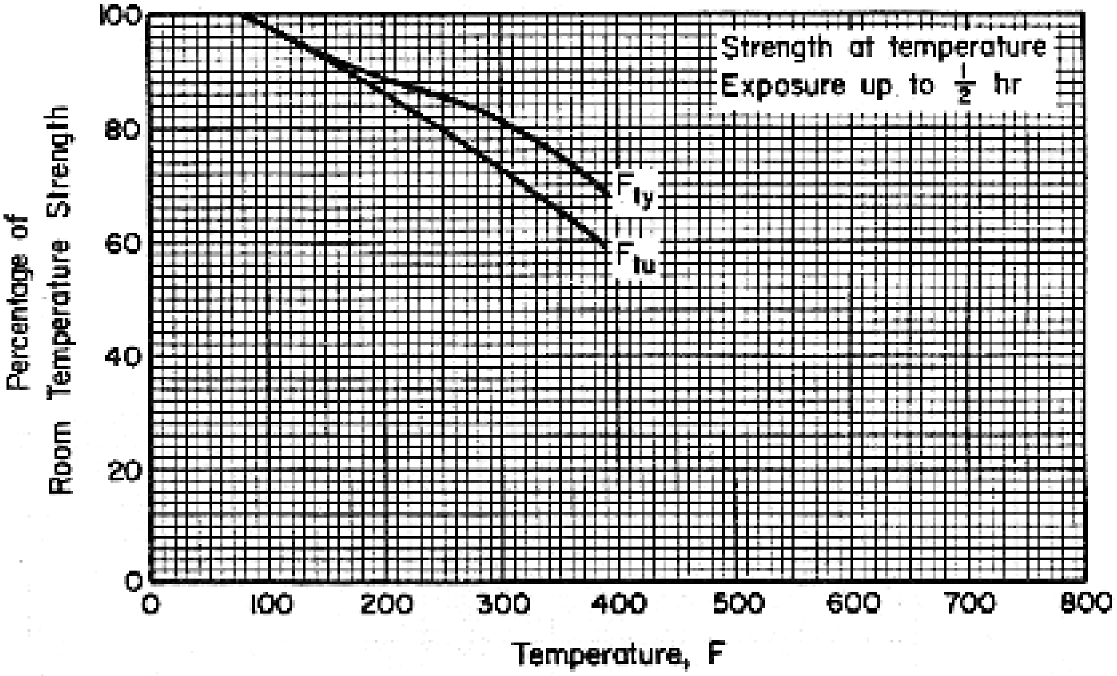

Figure 4.3.6.1.1. Effect of temperature on the tensile ultimate strength (F_{tu}) and tensile yield strength (F_{ty}) of ZE41A-T5 sand casting.

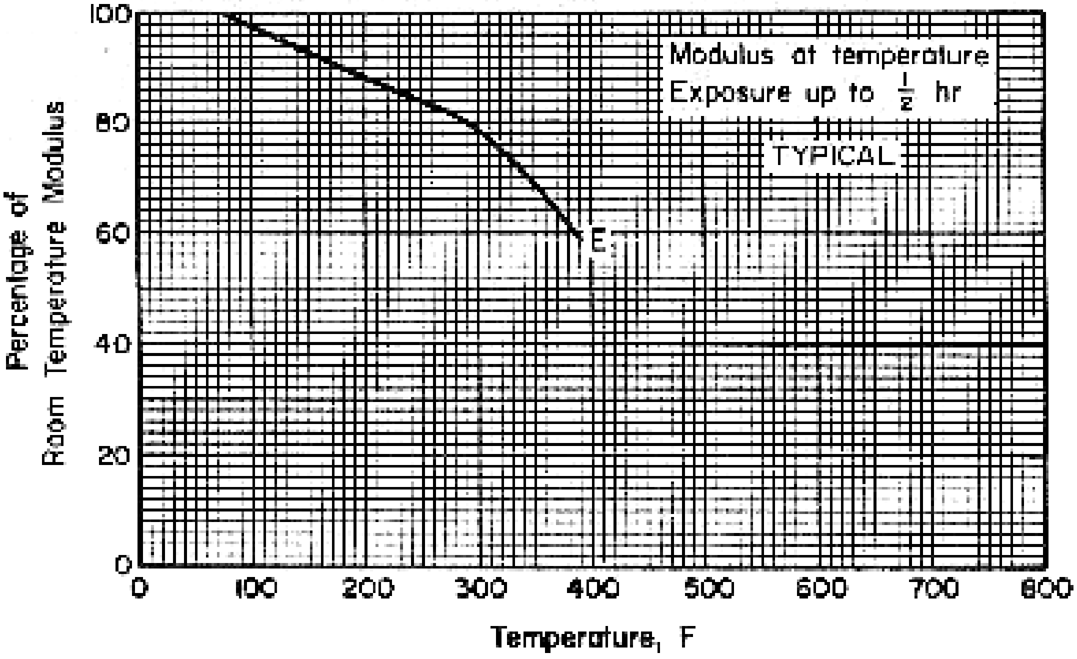

Figure 4.3.6.1.4. Effect of temperature on the tensile modulus (E) of ZE41A-T5 sand casting.

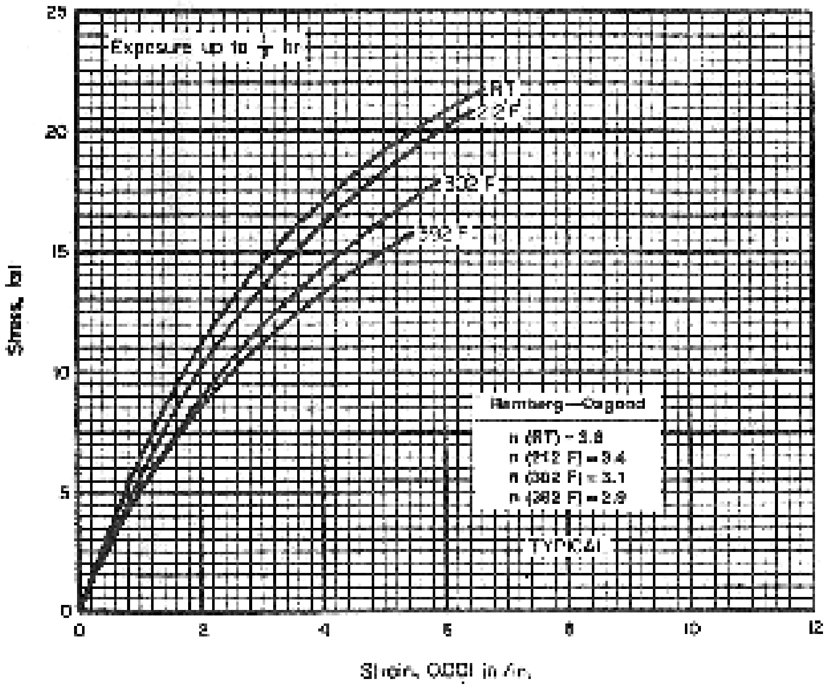

Figure 4.3.6.1.6(a). Typical tensile stress-strain curves for ZE41A-T5 sand casting at room and elevated temperatures.

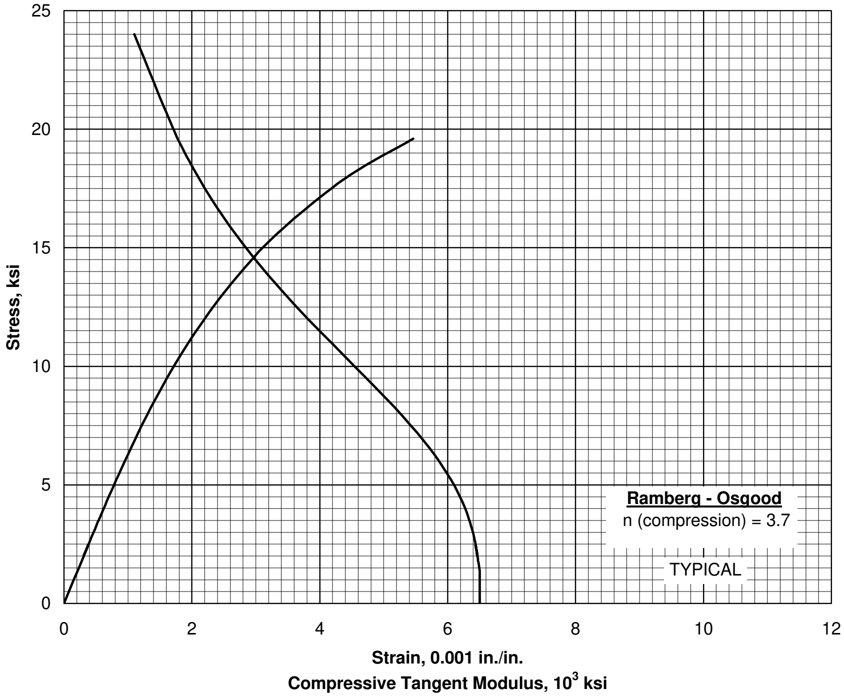

Figure 4.3.6.1.6(b). Typical compressive stress-strain and tangent-modulus curves for ZE41A-T5 sand casting at room temperature.

4.4 ELEMENT PROPERTIES

4.4.1 BEAMS — Refer to Chapter 1 and References 1.7.1(a) and (b) for general information on stress analysis of beams.

4.4.1.1 *Simple Beams* — Beams of solid tubular, or similar cross sections can be assumed to fail through exceeding an allowable modulus of rupture in bending (F_b). In the absence of specific data, the ratio F_b/F_{tu} can be assumed to be 1.25 for solid sections.

4.4.1.1.1 *Round Tubes* — For round tubes, the value of F_b will depend on the D/t ratio as well as the compressive yield stress.

4.4.1.1.2 *Unconventional Cross Sections* — Sections other than solid or tubular should be tested to determine allowable bending stress.

4.4.1.2 *Built-Up Beams* — Built-up beams will usually fail because of local failure of component parts.

4.4.1.3 *Thin-Web Beams* — The allowable stress for thin-web beams will depend on the nature of the failure and are determined from the allowable stress of the web in tension and of the flanges or stiffeners in compression.

4.4.2 COLUMNS

4.4.2.1 *Primary Failure* — The general formula for primary instability is given in Section 1.3.8. Formulas applicable to magnesium-alloy columns are given in Tables 4.4.2.1(a) and (b). See References 4.4.2(a) and (b).

Table 4.4.2.1(a). Column Formula for Magnesium-Alloy Extruded Open Shapes

General Formula[a]

$$\frac{P}{A} = \frac{K(F_{cy})^n}{(L'/\rho)^m}$$

(Stress values are in ksi)

Alloy	K	n	m	Max. P/A
AZ31B, AZ61A	2,900	¼	1.5	F_{cy}
ZK60A-T5	3,300	¼	1.5	$0.96\ F_{cy}$

aFormula is for members that do not fail by local buckling. See Figure 4.4.2.3(a).

Table 4.4.2.1(b). Column Formula for AZ31B-H24 Magnesium-Alloy Sheet

$$\frac{P}{A} = 1.05\ F_{cy} - \frac{(1.05\ F_{cy})^2\ (L'/\rho)^2}{4\ \pi^2\ E}$$

$$\text{MAX}\ \frac{P}{A} = F_{cy}$$

See Figure 4.4.2.3(b).

4.4.2.2 *Local Failure*

4.4.2.3 *Column Properties* — Curves of the allowable column stresses for various magnesium alloy columns are given in Figures 4.4.2.3(a) and (b). The allowable stress is plotted against the effective slenderness ratio defined by Equation 3.10.2.3.

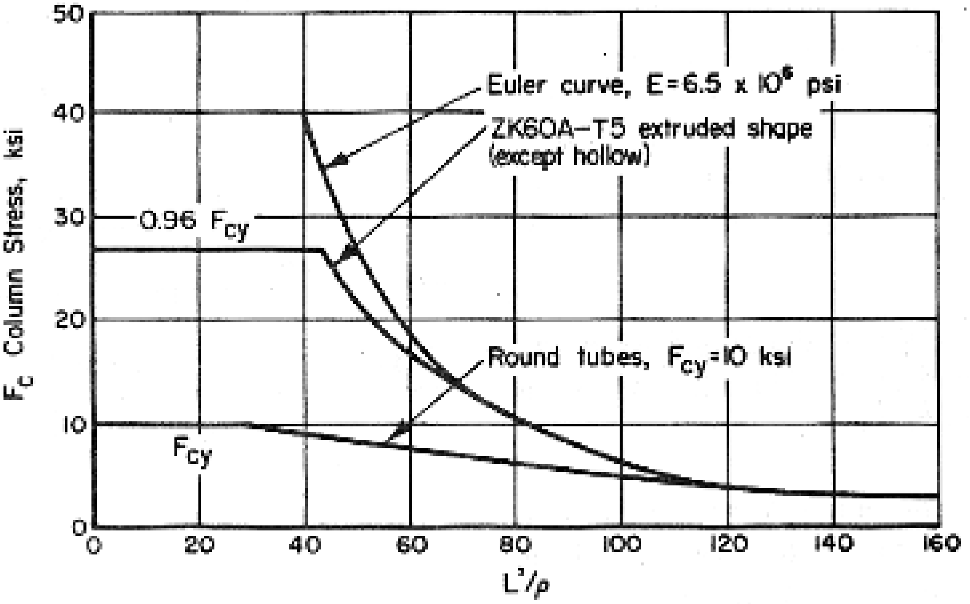

Figure 4.4.2.3(a). Allowable column stresses for magnesium-alloy columns.

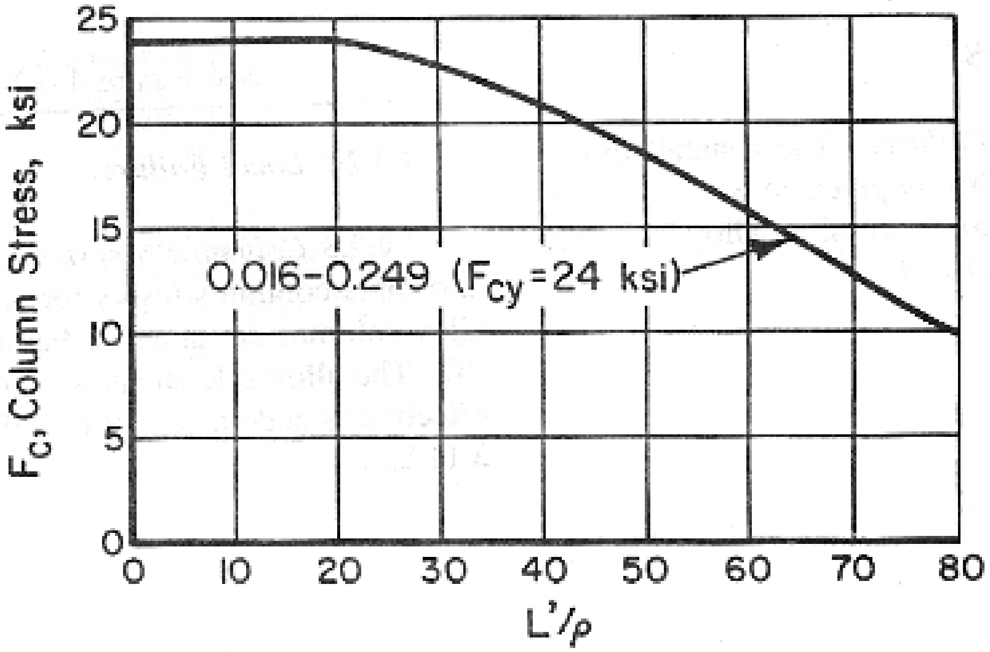

Figure 4.4.2.3(b). Allowable column stresses for AZ31B-H24 magnesium-alloy sheet.

4.4.3 TORSION

4.4.3.1 *General* — The general statements relating to aluminum-alloy tubing in 3.10.3 are applicable to magnesium tubing.

4.4.3.2 *Torsion Properties* — An empirical curve of the allowable torsional modulus of rupture for AZ62A-F magnesium-alloy round tubing (specification WW-T-825) is given in Figure 4.4.3.2.

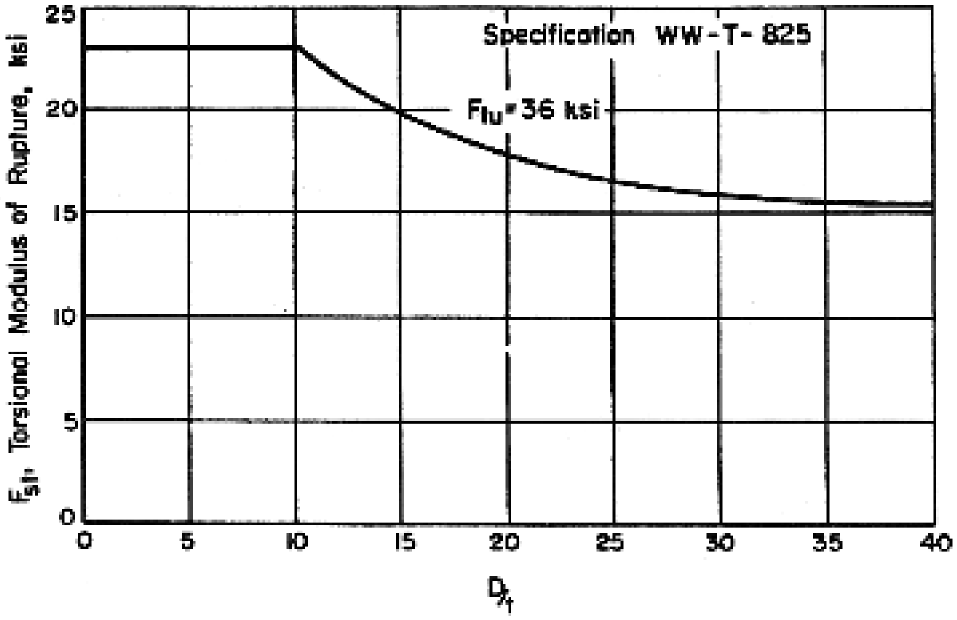

Figure 4.4.3.2. Torsional modulus of rupture for AZ61A-F magnesium-alloy round tubing.

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CHAPTER 5

TITANIUM

5.1 GENERAL

This chapter contains the engineering properties and related characteristics of titanium and titanium alloys used in aircraft and missile structural applications.

General comments on engineering properties and the considerations relating to alloy selection are presented in Section 5.1. Mechanical- and physical-property data and characteristics pertinent to specific alloy groups or individual alloys are reported in Sections 5.2 through 5.5.

Titanium is a relatively lightweight, corrosion-resistant structural material that can be strengthened greatly through alloying and, in some of its alloys, by heat treatment. Among its advantages for specific applications are: good strength-to-weight ratio, low density, low coefficient of thermal expansion, good corrosion resistance, good oxidation resistance at intermediate temperatures, good toughness, and low heat-treating temperature during hardening, and others.

5.1.1 TITANIUM INDEX — The coverage of titanium and its alloys in this chapter has been divided into four sections for systematic presentation. The system takes into account unalloyed titanium and three groups of alloys based on metallurgical differences which in turn result in differences in fabrication and property characteristics. The sections and the individual alloys covered under each are shown in Table 5.1.

Table 5.1. Titanium Alloys Index

Section	Alloy Designation
5.2	**Unalloyed Titanium**
5.2.1	Commercially Pure Titanium
5.3	**Alpha and Near-Alpha Titanium Alloys**
5.3.1	Ti-5A1-2.5Sn (Alpha)
5.3.2	Ti-8A1-1Mo-1V (Near-Alpha)
5.3.3	Ti-6A1-2Sn-4Zr-2Mo (Near-Alpha)
5.4	**Alpha-Beta Titanium Alloys**
5.4.1	Ti-6A1-4V
5.4.2	Ti-6A1-6V-2Sn
5.4.3	Ti - 4.5Al-3V-2Fe-2Mo
5.5	**Beta, Near-Beta, and Metastable Titanium Alloys**
5.5.1	Ti-13V-11Cr-3A1
5.5.2	Ti-15V-3Cr-3Sn-3A1
5.5.3	Ti-10V-2Fe-3A1

5.1.2 MATERIAL PROPERTIES — The material properties of titanium and its alloys are determined mainly by their alloy content and heat treatment, both of which are influential in determining the allotropic forms in which this material will be bound. Under equilibrium conditions, pure titanium has an "alpha" structure up to 1620°F, above which it transforms to a "beta" structure. The inherent properties of these two structures are quite different. Through alloying and heat treatment, one or the other or a combination of these two structures can be made to exist at service temperatures, and the properties of the material vary accordingly. References 5.1.2(a) and (b) provide general discussion of titanium microstructures and associated metallography.

Titanium and titanium alloys of the alpha and alpha-beta type exhibit crystallographic textures in sheet form in which certain crystallographic planes or directions are closely aligned with the direction of prior working. The presence of textures in these materials lead to anisotropy with respect to many mechanical and physical properties. Poisson's ratio and Young's modulus are among those properties strongly affected by texture. Wide variations experienced in these properties both within and between sheets of titanium alloys have been qualitatively related to variations of texture. In general, the degree of texturing, and hence the variation of Young's modulus and Poisson's ratio, that is developed for alpha-beta alloys tends to be less than that developed in all alpha titanium alloys. Rolling temperature has a pronounced effect on the texturing of titanium alloys which may not in general be affected by subsequent thermal treatments. The degree of applicability of the effect of textural variations discussed above on the mechanical properties of products other than sheet is unknown at present. The values of Young's modulus and Poisson's ratio listed in this document represent the usual values obtained on products resulting from standard mill practices. References 5.1.2(c) and (d) provide further information on texturing in titanium alloys.

5.1.2.1 *Mechanical Properties*

5.1.2.1.1 *Fracture Toughness* — The fracture toughness of titanium alloys is greatly influenced by such factors as chemistry variations, heat treatment, microstructure, and product thickness, as well as yield strength. For fracture critical applications, these factors should be closely controlled. Typical values of plane-strain fracture toughness for titanium alloys are presented in Table 5.1.2.1.1. Minimum, average, and maximum values, as well as coefficient of variation, are presented for various products for which valid data are available, but these values do not have the statistical reliability of the room-temperature mechanical properties.

5.1.3 MANUFACTURING CONSIDERATIONS — Comments relating to formability, weldability, and final heat treatment are presented under individual alloys. These comments are necessarily brief and are intended only to aid the designer in the selection of an alloy for a specific application. In practice, departures from recommended practices are very common and are based largely on in-plant experience. Springback is nearly always a factor in hot or cold forming.

Final heat treatments that are indicated as "specified" heat treatments do not necessarily coincide with the producers' recommended heat treatments. Rather, these treatments, along with the specified room-temperature minimum tensile properties, are contained in the heat treating-capability requirements of applicable specifications, for example, MIL-H-81200. Departures from the specified aging cycles are often necessary to account for aging that may take place during hot working or hot sizing or to obtain more desirable mechanical properties, for example, improved fracture toughness. More detailed recommendations for specific applications are generally available from the material producers.

5.1.4 ENVIRONMENTAL CONSIDERATIONS — Comments relating to temperature limitations in the application of titanium and titanium alloys are presented under the individual alloys.

Below about 300°F, as well as above about 700°F, creep deformation of titanium alloys can be expected at stresses below the yield strength. Available data indicate that room-temperature creep of unalloyed titanium may be significant (exceed 0.2 percent creep-strain in 1,000 hours) at stresses that exceed approximately 50 percent F_{ty}, room-temperature creep of Ti-5A1-1.5Sn ELI may be significant at stresses above approximately 60 percent F_{ty}, and room-temperature creep of the standard grades of titanium alloys may be significant at stresses above approximately 75 percent F_{ty}. References 5.1.4(a) through (c) provide some limited data regarding room-temperature creep of titanium alloys.

The use of titanium and its alloys in contact with either liquid oxygen or gaseous oxygen at cryogenic temperatures should be avoided, since either the presentation of a fresh surface (such as produced by tensile rupture) or impact may initiate a violent reaction [Reference 5.1.4(d)]. Impact of the surface in contact with liquid oxygen will result in a reaction at energy levels as low as 10 ft-lb. In gaseous oxygen, a partial pressure of about 50 psi is sufficient to ignite a fresh titanium surface over the temperature range from -250°F to room temperature or higher.

Titanium is susceptible to stress-corrosion cracking in certain anhydrous chemicals including methyl alcohol and nitrogen tetroxide. Traces of water tend to inhibit the reaction in either environment. However, in N_2O_4, NO is preferred and inhibited N_2O_4 contains 0.4 to 0.8 percent NO. Red fuming nitric acid with less than 1.5 percent water and 10 to 20 percent NO_2 can crack the metal and result in a pyrophoric reaction.

Titanium alloys are also susceptible to stress corrosion by dry sodium chloride at elevated temperatures. This problem has been observed largely in laboratory tests at 450 to 500°F and higher and occasionally in fabrication shops. However, there have been no reported failures of titanium components in service by hot salt stress corrosion. Cleaning with a nonchlorinated solvent (to remove salt deposits, including fingerprints) of parts used above 450°F is recommended.

In laboratory tests, with a fatigue crack present in the specimen, certain titanium alloys show an increased crack propagation rate in the presence of water or salt water as compared with the rate in air. These alloys also may show reduced sustained load-carrying ability in aqueous environments in the presence of fatigue cracks. Crack growth rates in salt water are a function of sheet or section thickness. These alloys are not susceptible in the form of thin-gauge sheet, but become susceptible as thickness increases. The thickness at which susceptibility occurs varies over a visual range with the alloy and processing. Alloys of titanium found susceptible to this effect include some from alpha, alpha-beta, and beta-type microstructures. In some cases, special processing techniques and heat treatments have been developed that minimize this effect. References 5.1.4(e) through (g) present detailed summaries of corrosion and stress corrosion of titanium alloys.

Under certain conditions, titanium, when in contact with cadmium, silver, mercury, or certain of their compounds, may become embrittled. Refer to MIL-HDBK-1568 for restrictions concerning applications with titanium in contact with these metals or their compounds.

Table 5.1.2.1.1. Values of Room Temperature Plane-Strain Fracture Toughness of Titanium Alloys[a]

									K_{Ic}, ksi $\sqrt{in.}$			
Alloy	Heat Treat Condition	Product Form	Orientation[b]	Yield Strength Range, ksi	Product Thickness Range, inches	Number of Sources	Sample Size	Specimen Thickness Range, inches	Max.	Avg.	Min.	Coefficient of Variation
Ti-6Al-4V	Mill Annealed	Forged Bar	L-T	121-143	<3.5	2	43	0.6-1.1	77	60	38	10.5
Ti-6Al-4V	Mill Annealed	Forged Bar	T-L	124-145	<3.5	2	64	0.5-1.3	81	57	33	11.7

[a] These values are for information only.

[b] Refer to Figure 1.4.12.3 for definition of symbols.

5.2 UNALLOYED TITANIUM

Several grades of unalloyed titanium are offered and are classified on the basis of manufacturing method, degree of purity, or strength, there being a close relationship among these. The unalloyed titanium grades most commonly used are produced by the Kroll process, are intermediate in purity, and are commonly referred to as being of commercial purity.

5.2.1 COMMERCIALLY PURE TITANIUM

5.2.1.0 *Comments and Properties* — Unalloyed titanium is available in all familiar product forms and is noted for its excellent formability. Unalloyed titanium is readily welded or brazed. It has been used primarily where strength is not the main requirement.

Manufacturing Considerations — Unalloyed titanium is supplied in the annealed condition permitting extensive forming at room temperature. Severe forming operations also can be accomplished at elevated temperatures (300 to 900°F). Property degradation can be experienced after severe forming if as-received material properties are not restored by re-annealing.

Commercially pure titanium can be welded readily by the several methods employed for titanium joining. Atmospheric shielding is preferable although spot or seam welding may be accomplished without shielding. Brazing requires protection from the atmosphere which may be obtained by fluxing as well as by inert gas or vacuum shielding.

Environmental Considerations — Titanium has an unusually high affinity for oxygen, nitrogen, and hydrogen at temperatures above 1050°F. This results in embrittlement of the material, thus usage should be limited to temperatures below that indicated. Additional chemical reactivity between titanium and selected environments such as methyl alcohol, chloride salt solutions, hydrogen, and liquid metal, can take place at lower temperatures, as discussed in Section 5.1.4 and its references.

Under certain conditions, titanium, when in contact with cadmium, silver, mercury, or certain of their compounds, may become embrittled. Refer to MIL-HDBK-1568 for restrictions concerning applications with titanium in contact with these metals or their compounds.

Heat Treatment — Commercially pure titanium is fully annealed by heating to 1000 to 1300°F for 10 to 30 minutes. It is stress relieved by heating to 900 to 1000°F for 30 minutes. Commercially pure titanium cannot be hardened by heat treatment.

Specifications and Properties — Some material specifications for commercially pure titanium are presented in Table 5.2.1.0(a). Room-temperature mechanical properties for commercially pure titanium are shown in Tables 5.1.2.0(b) and (c). The effect of temperature on physical properties is shown in Figure 5.2.1.0.

5.2.1.1 *Annealed Condition* — Elevated-temperature data for annealed commercially pure titanium are presented in Figures 5.2.1.1.1(a) through 5.2.1.1.3(b). Typical full-range stress-strain curves for the 40 and 70 ksi yield strength commercially pure titanium are shown in Figures 5.2.1.1.6(a) and (b).

Table 5.2.1.0(a). Material Specifications for Commercially Pure Titanium

Specification	Form
AMS 4900	Sheet, strip, and plate
AMS 4901	Sheet, strip, and plate
AMS 4902	Sheet, strip, and plate
AMS-T-9046	Sheet, strip, and plate
MIL-T-9047[a]	Bar
AMS 4921	Bar
AMS-T-81556	Extruded bars and shapes

[a] Inactive for new design

Table 5.2.1.0(b). Design Mechanical and Physical Properties of Commercially Pure Titanium

Specification	AMS-T-9046	AMS 4902 and AMS-T-9046	AMS 4900 and AMS-T-9046	AMS 4901 and AMS-T-9046	AMS 4921 and MIL-T-9047	MIL-T-9047[a]
Designation	CP-4	CP-3	CP-2	CP-1	CP-70	
Form	Sheet, strip, and plate				Bar	
Condition	Annealed				Annealed	
Thickness or diameter, in.	≤ 1.000				$\leq 2.999^b$	$3.000\text{-}4.000^b$
Basis	S	S	S	S	S	S
Mechanical Properties:						
F_{tu}, ksi:						
L	35	50	65	80	80	80
LT	35	50	65	80	80^c	80
ST	...	...	...	...	...	80
F_{ty}, ksi:						
L	25	40	55	70	70	70
LT	25	40	55	70	70^c	70
ST	...	...	...	...	...	70
F_{cy}, ksi:						
L	...	...	...	70	...	...
LT	...	...	...	70	...	...
F_{su}, ksi	...	...	...	42	...	...
F_{bru}, ksi:						
(e/D = 1.5)	...	...	...	120	...	...
(e/D = 2.0)	...	...	...	...	...	...
F_{bry}, ksi:						
(e/D = 1.5)	...	...	...	101	...	...
(e/D = 2.0)	...	...	...	...	...	...
e, percent:						
L	24^d	20^d	18^d	15^d	15	15
LT	24^d	20^d	18^d	15^d	15^c	15
ST	...	...	...	...	...	15
RA, percent:						
L	...	...	...	...	30	30
LT	...	...	...	...	30^c	30
ST	...	...	...	...	...	30
E, 10^3 ksi	15.5					
E_c, 10^3 ksi	16.0					
G, 10^3 ksi	6.5					
μ	...					
Physical Properties:						
ω, lb/in.^{3}	0.163					
C, K, and α	See Figure 5.2.1.0					

a Inactive for new design.
b Maximum of 16-square-inch cross-sectional area.
c Long transverse properties apply to rectangular bar only for thickness >0.500 inches and widths >3.000 inches. For AMS 4921, (e) (LT) = 12% and RA (LT) = 25%.
d Thickness of 0.025 inch and above.

Table 5.2.1.0(c). Design Mechanical and Physical Properties of Commercially Pure Titanium Extruded Bars and Shapes

Specification	AMS-T-81556			
	Comp. CP-4	Comp. CP-3	Comp. CP-2	Comp. CP-1
Form	Extruded bars and shapes			
Condition	Annealed			
Thickness or diameter, in.	0.188-3.000			
Basis	S	S	S	S
Mechanical Properties:				
F_{tu}, ksi:				
L	40	50	65	80
LT	...	...	...	...
F_{ty}, ksi:				
L	30	40	55	70
LT	...	...	...	...
F_{cy}, ksi:				
L	...	...	...	...
LT	...	...	...	...
F_{su}, ksi	...	...	...	...
F_{bru}, ksi:				
(e/D = 1.5)	...	...	...	...
(e/D = 2.0)	...	...	...	...
F_{bry}, ksi:				
(e/D = 1.5)	...	...	...	...
(e/D = 2.0)	...	...	...	...
e, percent:				
L	a	a	a	a
E, 10^3 ksi	15.5			
E_c, 10^3 ksi	16.0			
G, 10^3 ksi	6.5			
μ	...			
Physical Properties:				
ω, lb/in.^{3}	0.163			
C, K, and α	See Figure 5.2.1.0			

a Elongation in percent as follows:

Thickness, inches	Comp. CP-4	Comp. CP-3	Comp. CP-2	Comp. CP-1
0.188-1.000	25	20	18	15
1.001-2.000	20	18	15	12
2.001-3.000	18	15	12	10

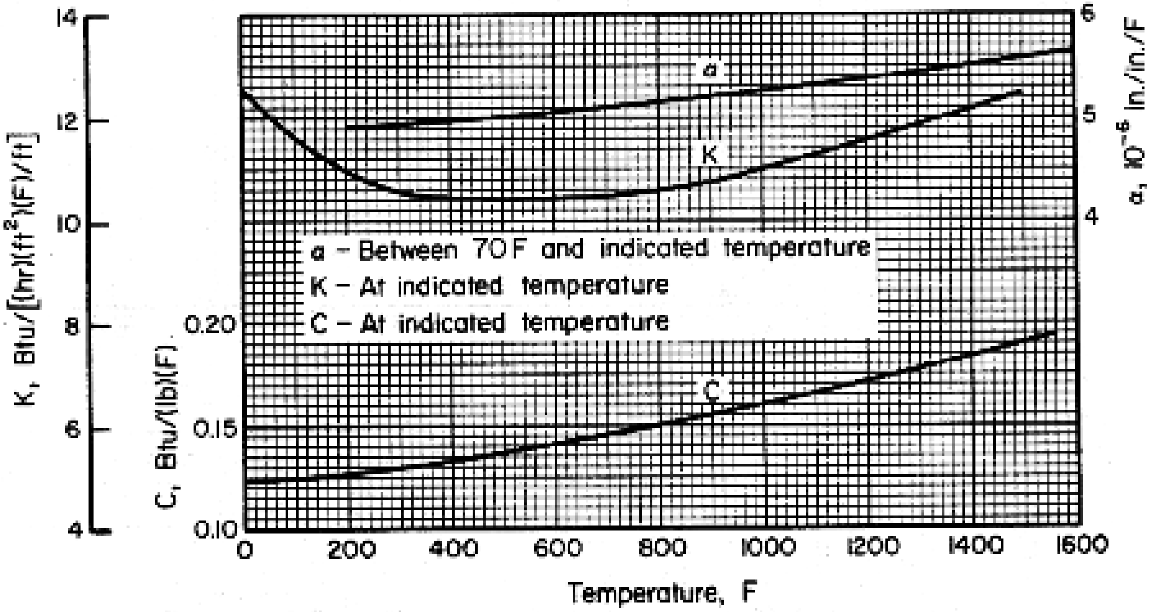


Figure 5.2.1.0. Effect of temperature on the physical properties of commercially pure titanium.

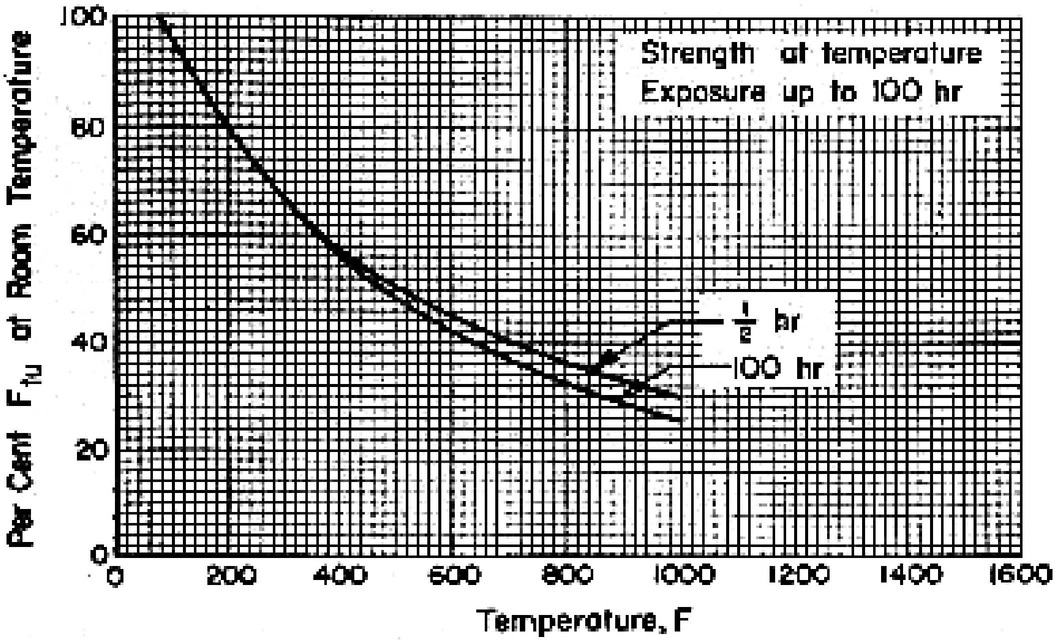


Figure 5.2.1.1.1(a). Effect of temperature on the tensile ultimate strength (F_{tu}) of annealed commercially pure titanium.

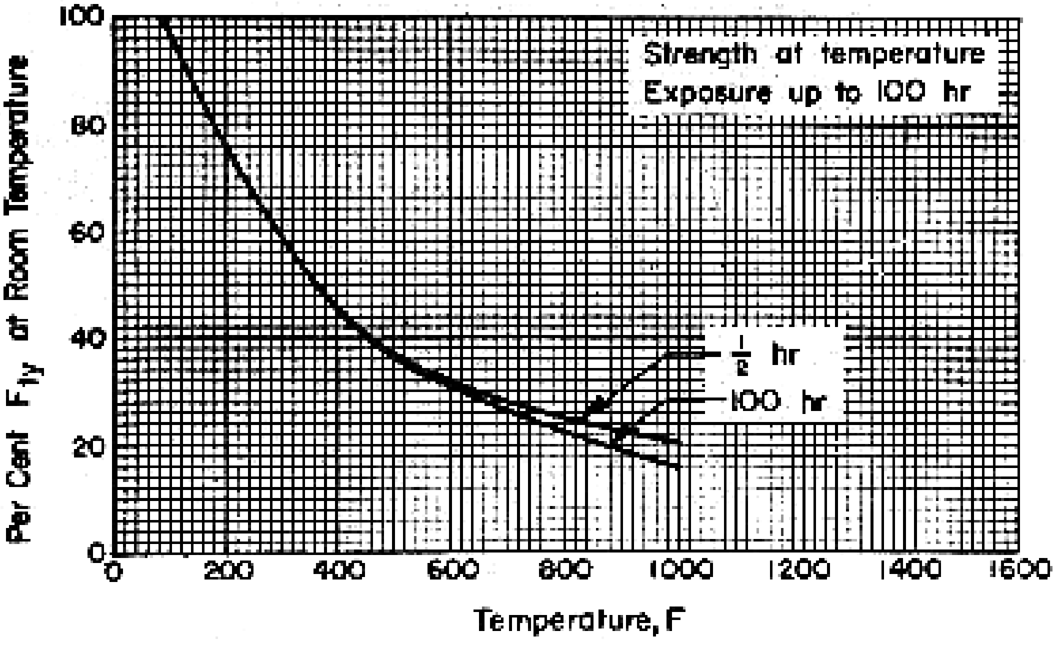


Figure 5.2.1.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of annealed commercially pure titanium.

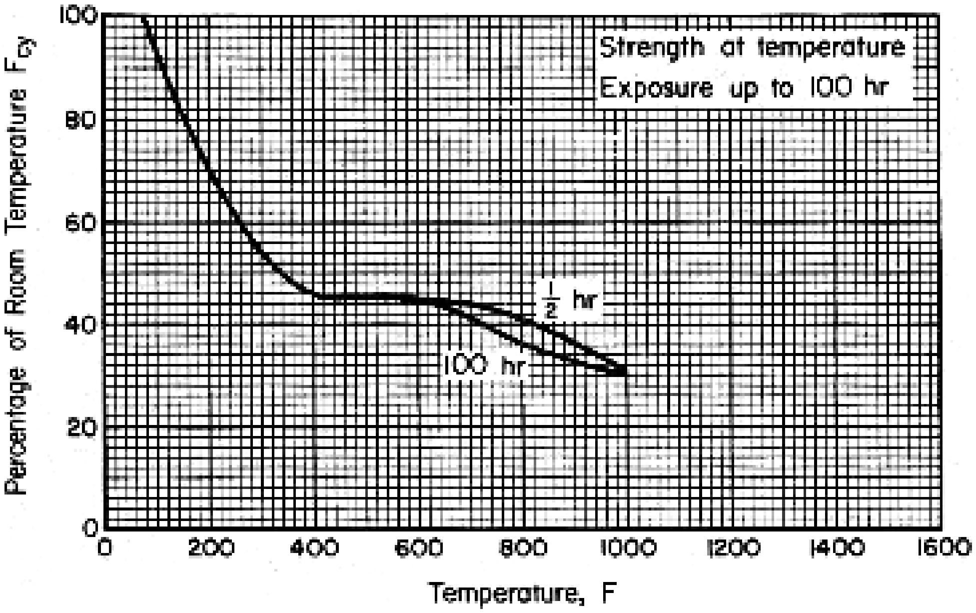


Figure 5.2.1.1.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of annealed commercially pure titanium.

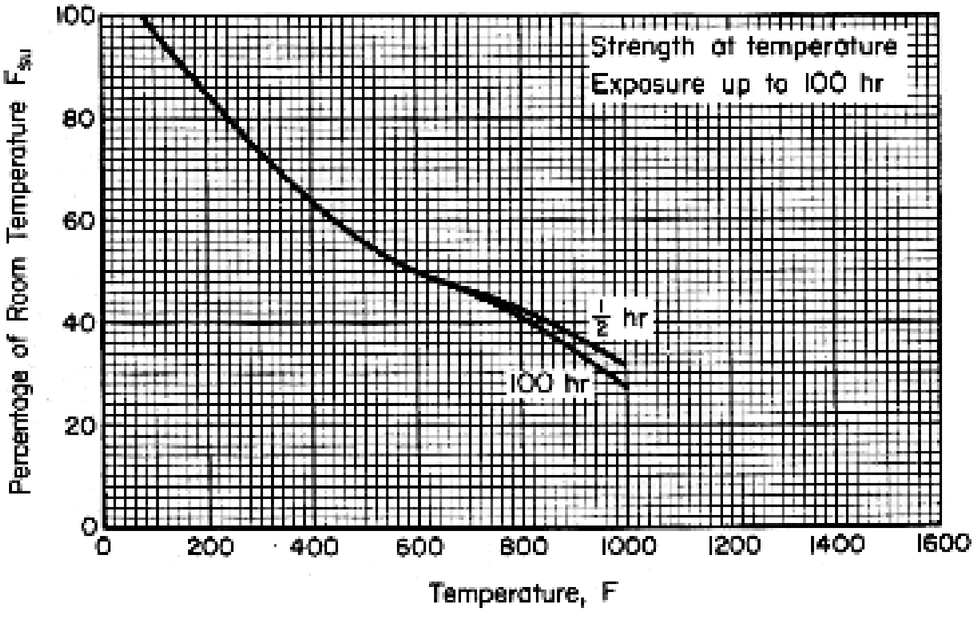


Figure 5.2.1.1.2(b). Effect of temperature on the shear ultimate strength (F_{su}) of annealed commercially pure titanium.

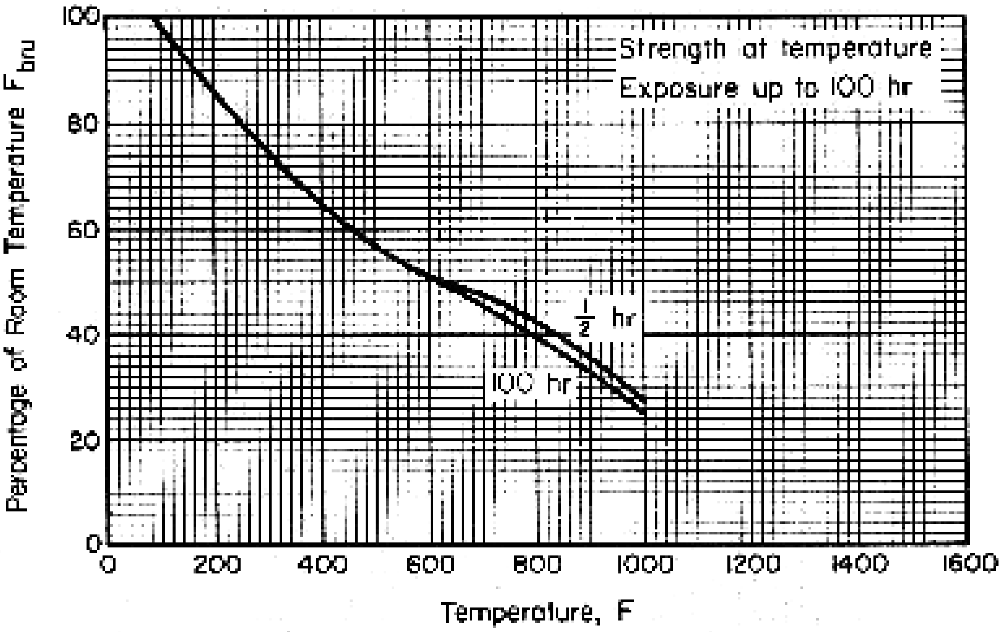


Figure 5.2.1.1.3(a). Effect of temperature on the bearing ultimate strength (F_{bru}) of annealed commercially pure titanium.

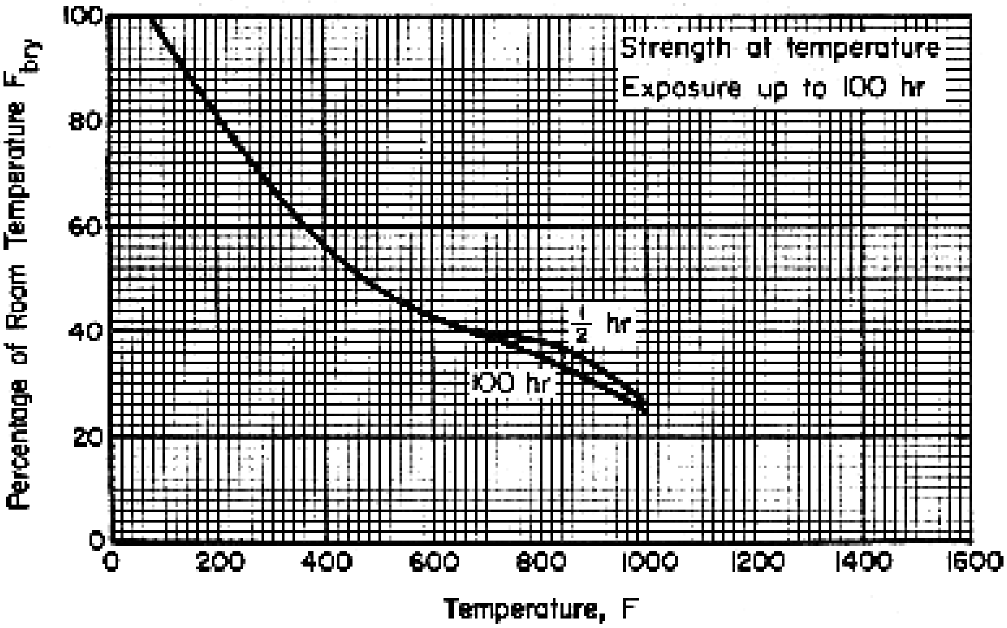


Figure 5.2.1.1.3(b). Effect of temperature on the bearing yield strength (F_{bry}) of annealed commercially pure titanium.

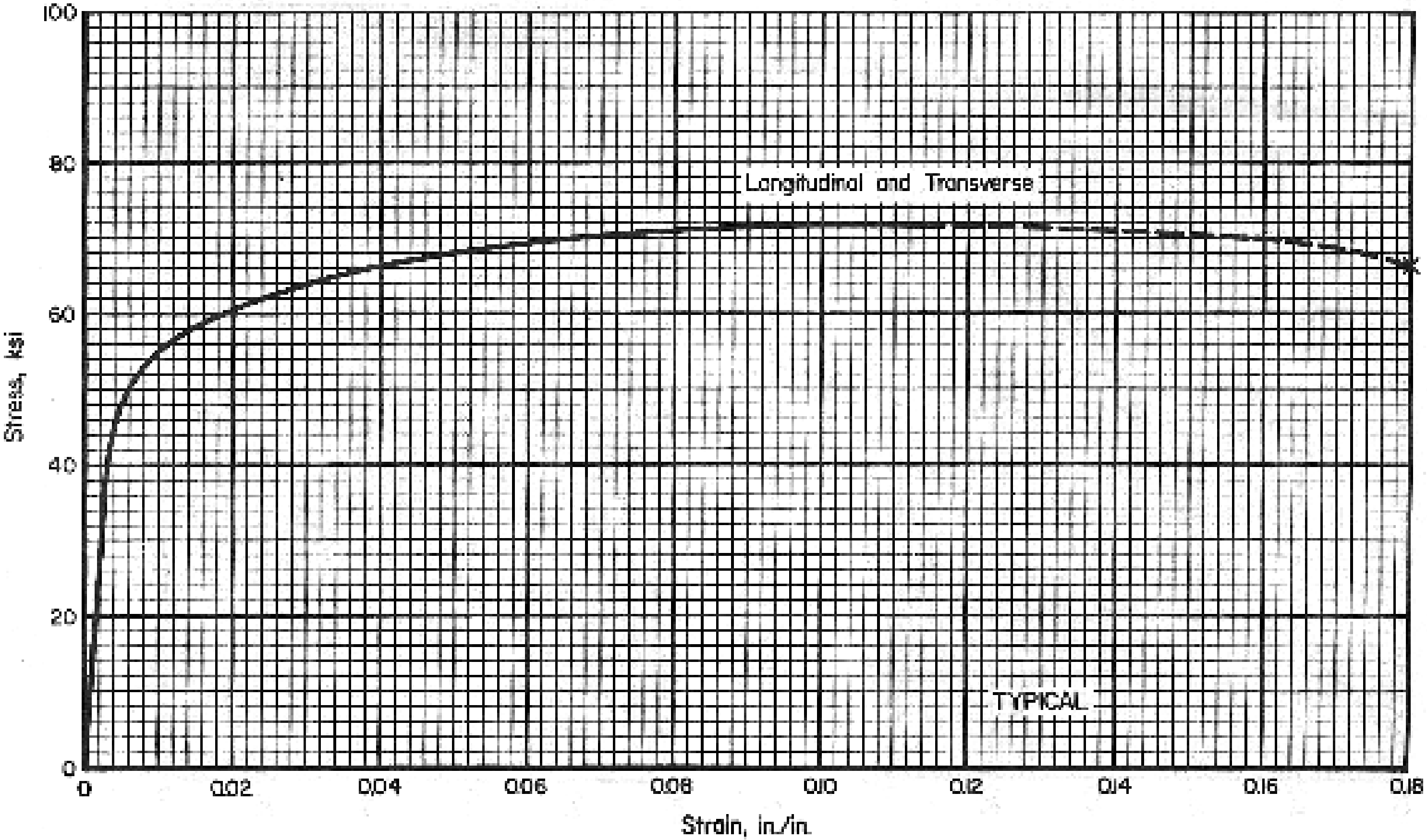


Figure 5.2.1.1.6(a). Typical full-range tensile stress-strain curve for commercially pure titanium sheet (40 ksi yield at room temperature).

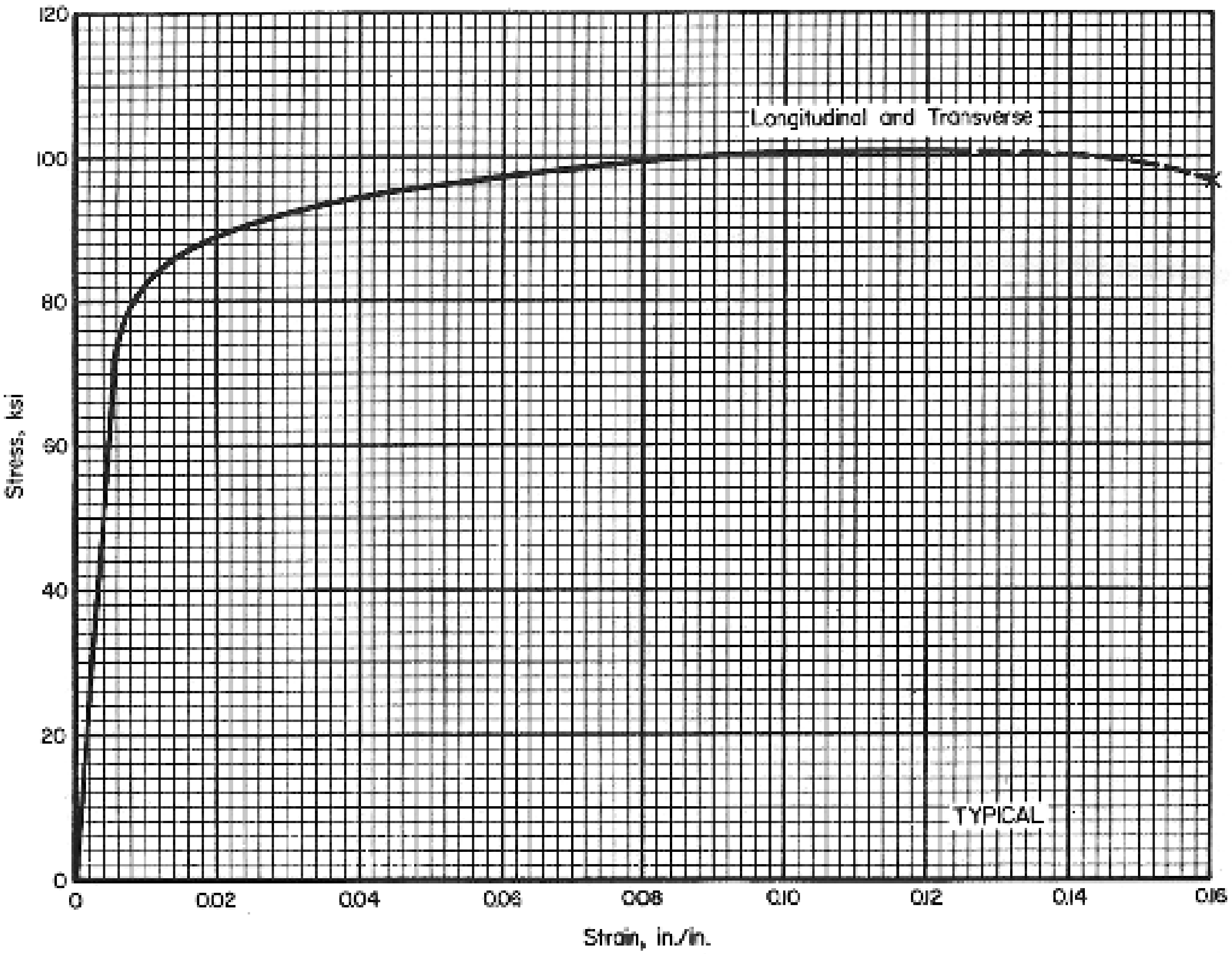


Figure 5.2.1.1.6(b). Typical full-range tensile stress-strain curve for commercially pure titanium sheet (70 ksi yield at room temperature).

5.3 ALPHA AND NEAR-ALPHA TITANIUM ALLOYS

The alpha titanium alloys contain essentially a single phase at room temperature, similar to that of unalloyed titanium. Alloys identified as near-alpha titanium have principally an all-alpha structure but contain small quantities of a beta phase because the composition contains some beta stabilizing elements. In both alloy types, alpha phase is stabilized by aluminum, tin, and zirconium. These elements, especially aluminum, contribute greatly to strength. The beta stabilizing additions (e.g., molybdenum and vanadium) improve fabricability and metallurgical stability of highly alpha-alloyed materials.

All alpha alloys have excellent weldability, toughness at low temperatures, and long-term elevated-temperature strength. They are well suited to cryogenic applications and to uses requiring good elevated-temperature creep strength. The characteristics of near-alpha alloys are predictably between those of all alpha and alpha-beta alloys in regard to fabricability, weldability, and elevated-temperature strength. The hot workability of both alpha and near-alpha alloys is inferior to that of the alpha-beta or beta alloys and the cold workability is very limited at the high-strength level of these grades. However, considerable forming is possible if correct forming temperatures and procedures are used.

5.3.1 TI-5AL-2.5SN

5.3.1.0 *Comments and Properties* — Ti-5Al-2.5Sn is an all-alpha alloy available in many product forms and at two purity levels. The high purity grade of this composition is used principally for cryogenic applications and may be characterized as having lower strength but higher ductility and toughness than the standard grade. The normal purity grade also may be used at low temperatures but it is primarily suitable for room to elevated temperature applications (up to 900°F or to 1100°F for short times) where weldability is an important consideration.

Manufacturing Considerations — Ti-5Al-2.5Sn is not so readily formed into complex shapes as other alloys with similar room-temperature properties, but far surpasses them in weldability. Except for some forging operations, fabrication of Ti-5Al-2.5Sn is conducted at temperatures where the structure remains all alpha. Severe forming operations may be accomplished at temperatures up to 1200°F. Moderately severe forming can be done at 300 to 600°F and simple forming may be done at room temperature. Most forming and welding operations are followed by an annealing treatment to relieve residual stresses imposed by the prior operation.

Ti-5Al-2.5Sn can be welded readily by inert-gas or vacuum-shielded arc methods or by spot or seam welding without atmospheric shielding. Brazing requires protection from the atmosphere; however, this is accomplished by fluxing as well as by inert gas or vacuum shielding.

Environmental Considerations — Ti-5Al-2.5Sn is metallurgically stable at moderate elevated temperatures. The material is susceptible to hot-salt stress corrosion as well as aqueous chloride solution stress corrosion. Care should be exercised in applications involving such environments. The alloy has good oxidation resistance up to 1050°F. Standard grade material has been used at moderately low cryogenic temperatures; however, the ELI grade has higher toughness and has been used in cryogenic applications down to -423°F. Under certain conditions, titanium, when in contact with cadmium, silver, mercury, or certain of their compounds, may become embrittled. Refer to MIL-HDBK-1568 for restrictions concerning applications with titanium in contact with these metals or their compounds.

Heat Treatment — This alloy is annealed by heating 1400°F for 60 minutes and 1600°F for 10 minutes and cooling in air. Stress relieving requires 1 or 2 hours at 1000 to 1200°F. Ti-5Al-2.5Sn cannot be hardened by heat treatment.

Specifications and Properties — Some material specifications for Ti-5Al-2.5Sn are shown in Table 5.3.1.0(a). Room-temperature mechanical properties for Ti-5Al-2.5Sn are shown in Tables 5.3.1.0(b) through (d). The effect of temperature on physical properties is shown in Figure 5.3.1.0.

Table 5.3.1.0(a). Material Specifications for Ti-5Al-2.5Sn

Specification	Form
AMS-T-9046	Sheet, strip, and plate
AMS 4926	Bar
MIL-T-9047[a]	Bar
AMS-T-81556	Extruded bar and shapes
AMS 4910	Sheet, strip, and plate
AMS 4966	Forging

[a] Inactive for new design

5.3.1.1 ***Annealed Condition*** — Elevated temperature curves for annealed Ti-5Al-2.5Sn are shown in Figures 5.3.1.1.1 through 5.3.1.1.5. Tensile properties cover the range -423°F to 1000°F; whereas other properties are for the range room temperature to 1000°F. Fatigue-crack-propagation data for sheet are shown in Figures 5.3.1.1.9(a) through (c).

Table 5.3.1.0(b). Design Mechanical and Physical Properties of Ti-5Al-2.5Sn Sheet, Strip, and Plate

Specification	AMS 4910 and AMS-T-9046, Comp. A-1								
Form	Strip	Sheet				Plate			
Condition	Annealed								
Thickness, in.	<0.187	0.015-0.079		0.080-0.187		0.188-0.250		0.251-1.500	1.501-4.000
Basis	S	A	B	A	B	A	B	S	S
Mechanical Properties:									
F_{tu}, ksi:									
L	120	120[a]	128	120[a]	131	120[a]	135	120	115
LT	120	120[a]	129	120[a]	132	120[a]	137	120	115
F_{ty}, ksi:									
L	113	110	115	113	118	113[a]	123	113	110
LT	113	113	118	113[a]	121	113[a]	125	113	110
F_{cy}, ksi:									
L	115	115	120	118	123	118	128	118	...
LT	118	118	123	118	126	118	130	118	...
F_{su}, ksi	75	75	80	75	82	75	85	75	...
F_{bru}, ksi:									
(e/D = 1.5) . . .	167	167	179	167	183	167	190	167	...
(e/D = 2.0) . . .	250	250	268	250	275	250	285	250	...
F_{bry}, ksi:									
(e/D = 1.5) . . .	133	133	139	133	142	133	147	133	...
(e/D = 2.0) . . .	190	190	198	190	203	190	210	190	...
e, percent (S-basis):									
L	10	10[b]	...	10	...	10	...	10	10
LT	10	10[b]	...	10	...	10	...	10	10
E, 10^3 ksi	15.5								
E_c, 10^3 ksi	15.5								
G, 10^3 ksi	...								
μ	...								
Physical Properties:									
ω, lb/in.^{3}	0.162								
C, K, and α	See Figure 5.3.1.0								

[a] S-basis. The rounded T_{99} values are higher than specification values as follows:

		0.015-0.079	0.080-0.187	0.188-0.250
F_{tu}	L......	123	126	130
	LT......	123	126	131
F_{ty}	L.......	....	...	118
	LT......	....	115	120

[b] Thickness 0.025 inch and above.

Table 5.3.1.0(c). Design Mechanical and Physical Properties of Ti-5Al-2.5Sn Bar and Forging

Specification	AMS 4926[a] and MIL-T-9047[b]			AMS 4966
Form	Bar			Forging
Condition	Annealed			Annealed
Thickness or diameter, in.	≤2.999[c]		3.000-4.000[c]	...
Basis	A	B	S	
Mechanical Properties:				
F_{tu}, ksi:				
L	115[d]	126	115	115
LT	115[e]	...	115	115[f]
ST	...	...	115	115[f]
F_{ty}, ksi:				
L	110[d]	120	110	110
LT	110[e]	...	110	110[f]
ST	...	...	110	110[f]
F_{cy}, ksi:				
L	...	...	...	...
LT	...	...	...	...
F_{su}, ksi	...	...	...	...
F_{bru}, ksi:				
(e/D = 1.5)	...	...	...	...
(e/D = 2.0)	...	...	...	...
F_{bry}, ksi:				
(e/D = 1.5)	...	...	...	...
(e/D = 2.0)	...	...	...	...
e, percent (S-basis):				
L	10	...	10	10
LT	10[e]	...	10	10[f]
ST	...	...	8	10[f]
RA, percent (S-basis):				
L	25	...	25	25
LT	25[e]	...	25	25[f]
ST	...	...	20	25[f]
E, 10^3 ksi	15.5			
E_c, 10^3 ksi	15.5			
G, 10^3 ksi	...			
μ	...			
Physical Properties:				
ω, lb/in.^{3}	0.162			
C, K, and α	See Figure 5.3.1.0			

a For AMS 4926, LT and ST values for *e* and *RA* may be different than those shown.
b Inactive for new design.
c Maximum of 16-square-inch cross-sectional area.
d The rounded T_{99} values are higher than S values as follows: F_{tu} = 117 ksi, F_{ty} = 113 ksi.
e S-basis. Applicable providing LT dimension is >3.000 inches.
f Applicable, providing LT or ST dimension is ≥2.500 inches.

Table 5.3.1.0(d). Design Mechanical and Physical Properties of Ti-5Al-2.5Sn Extrusion

Specification	AMS-T-81556, Comp. A-1			
Form	Extruded bars and shapes			
Condition	Annealed			
Thickness or diameter, in.	0.188-1.000	1.001-2.000	2.001-3.000	3.001-4.000
Basis	S	S	S	S
Mechanical Properties:				
F_{tu}, ksi:				
L	120	115	115	115
LT	...	...	...	...
F_{ty}, ksi:				
L	115	110	110	110
LT	...	...	...	...
F_{cy}, ksi:				
L	...	...	...	...
LT	...	...	...	...
F_{su}, ksi	...	...	...	...
F_{bru}, ksi:				
(e/D = 1.5)	...	...	...	...
(e/D = 2.0)	...	...	...	...
F_{bry}, ksi:				
(e/D = 1.5)				
(e/D = 2.0)				
e, percent:				
L	10	10	8	6
LT	...	...	...	...
E, 10^3 ksi	15.5			
E_c, 10^3 ksi	15.5			
G, 10^3 ksi	...			
μ	...			
Physical Properties:				
ω, lb/in.^{3}	0.162			
C, K, and α	See Figure 5.3.1.0			

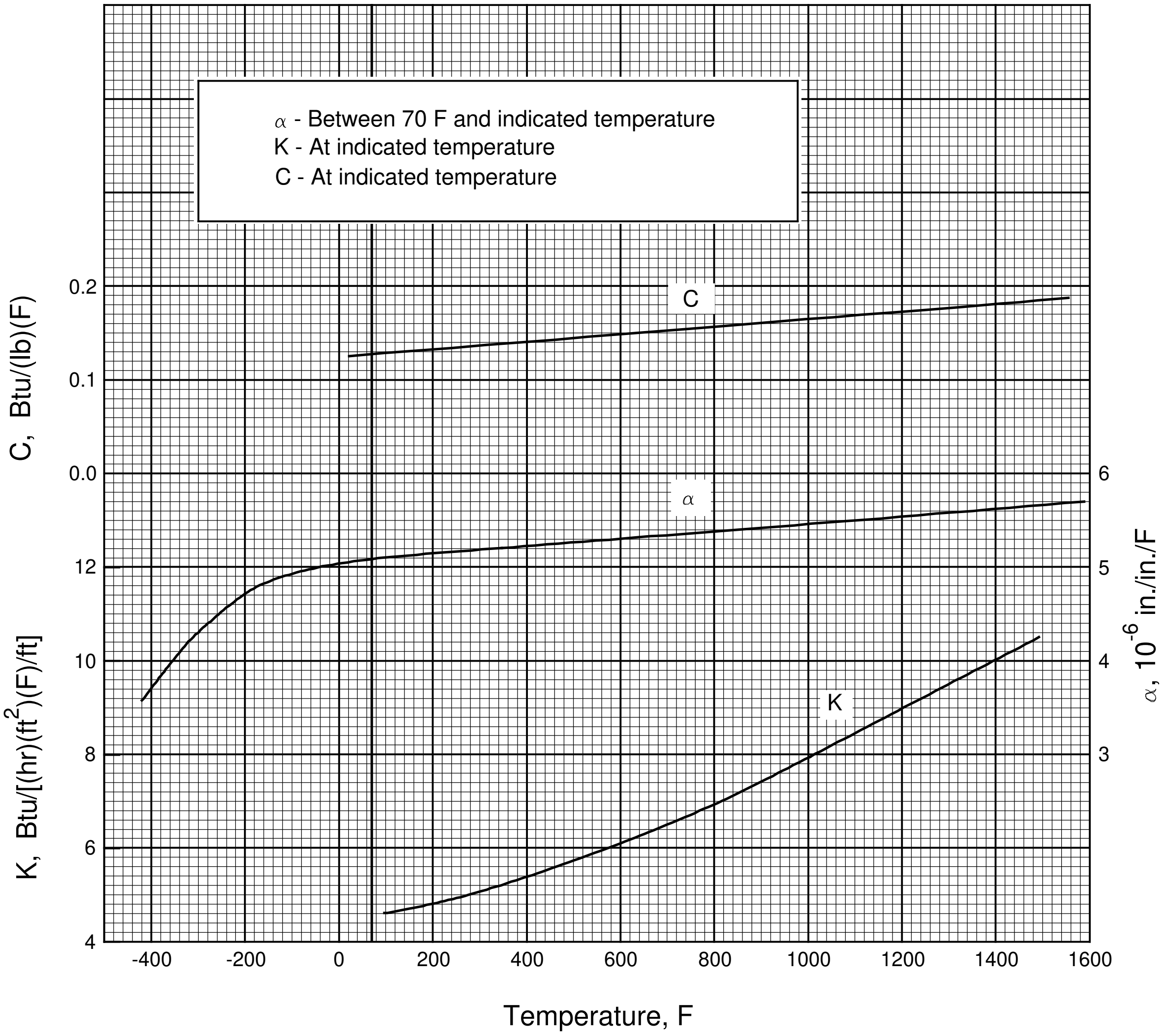


Figure 5.3.1.0. Effect of temperature on the physical properties of Ti-5Al-2.5Sn alloy.

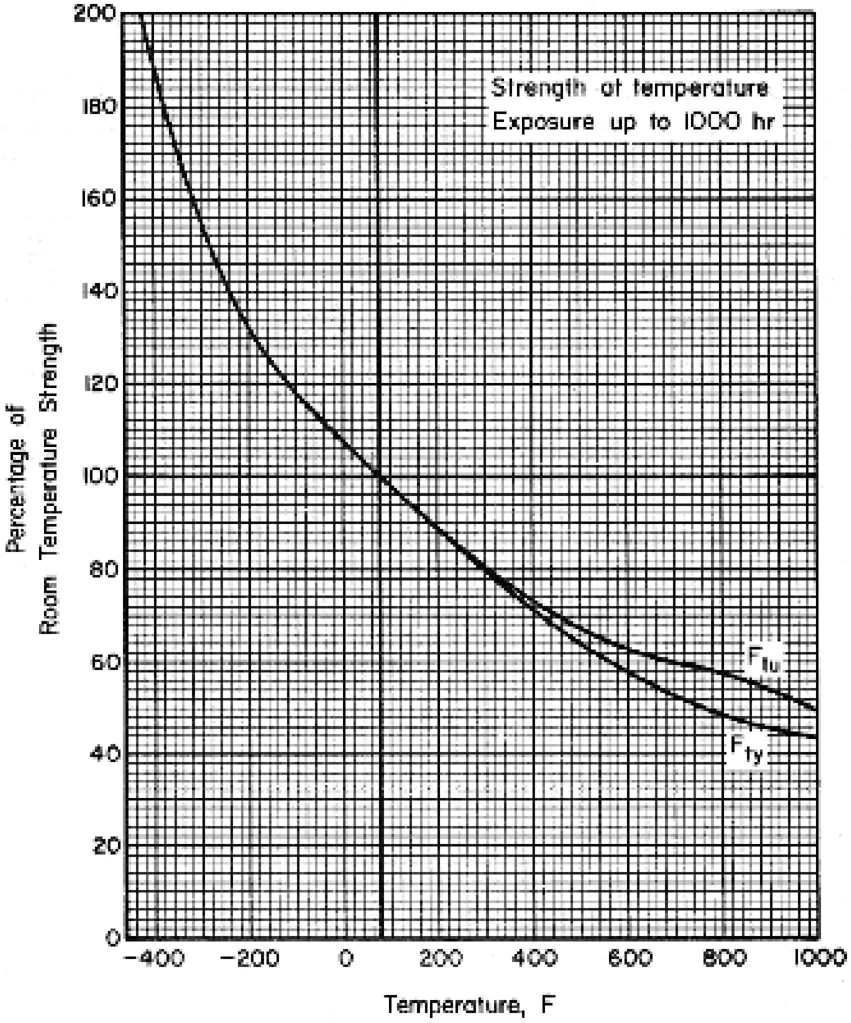


Figure 5.3.1.1.1. Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of annealed Ti-5Al-2.5Sn alloy sheet.

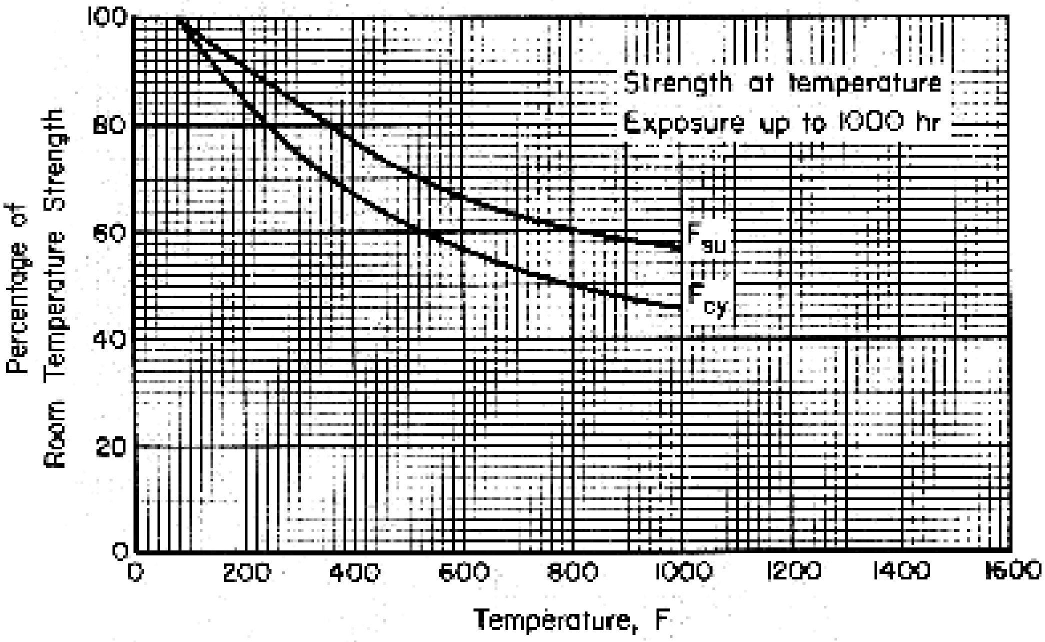


Figure 5.3.1.1.2. Effect of temperature on the compressive yield strength (F_{cy}) and the shear ultimate strength (F_{su}) of annealed Ti-5Al-2.5Sn alloy sheet.

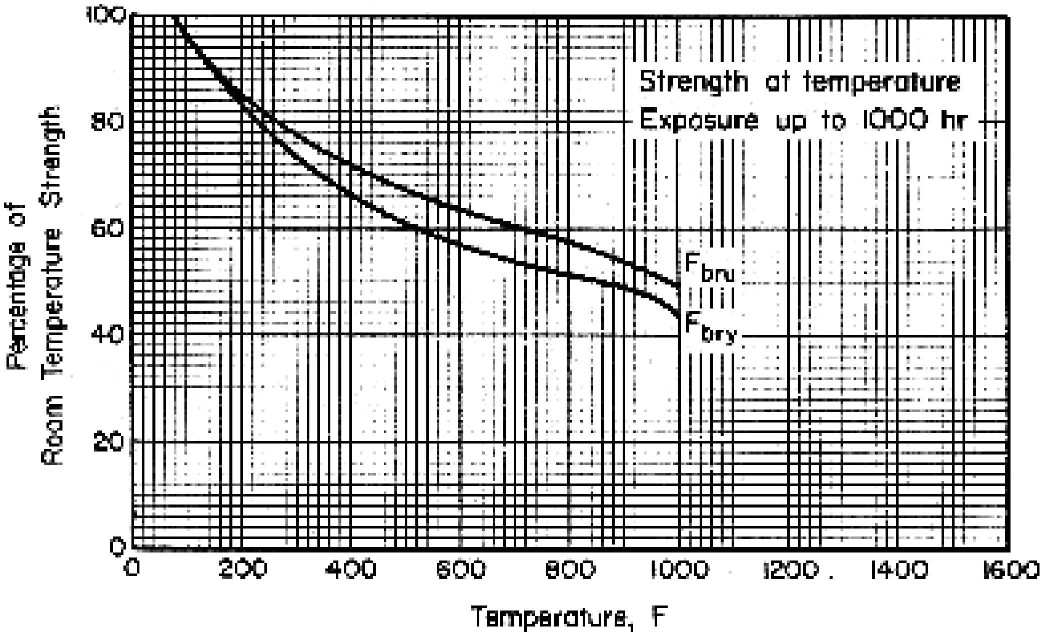


Figure 5.3.1.1.3. Effect of temperature on the bearing ultimate strength (F_{bru}) and the bearing yield strength (F_{bry}) of annealed Ti-5Al-2.5Sn alloy sheet.

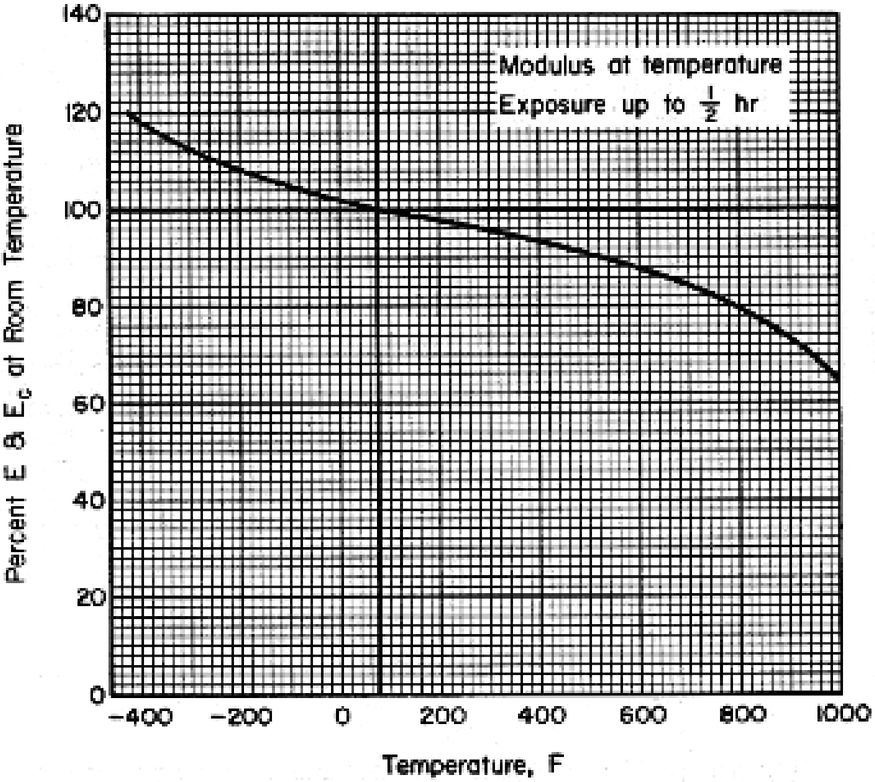


Figure 5.3.1.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of annealed Ti-5Al-2.5Sn alloy sheet.

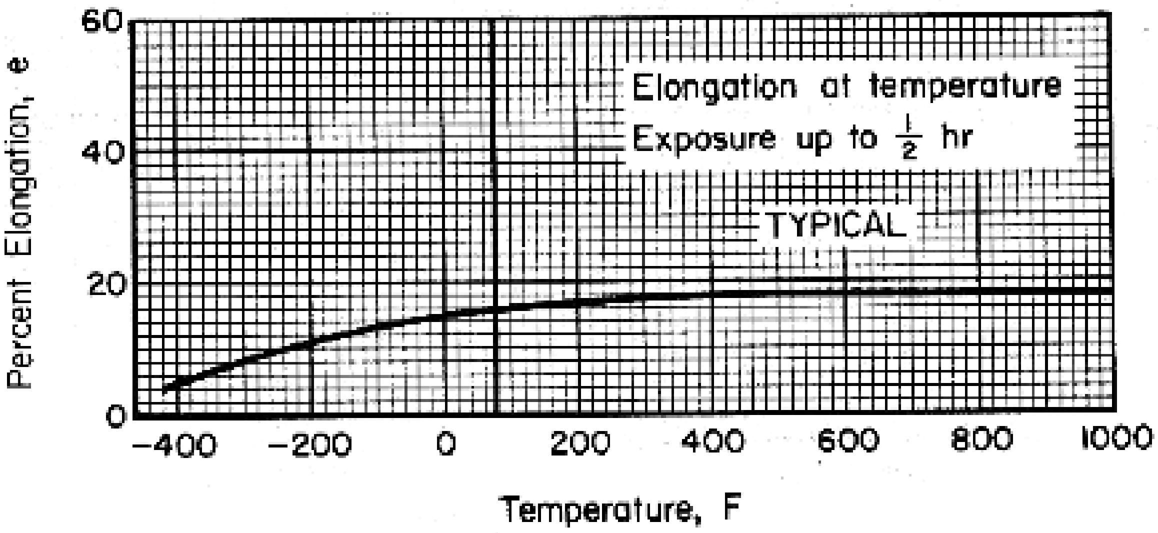


Figure 5.3.1.1.5. Effect of temperature on the elongation (e) of annealed Ti-5Al-2.5Sn alloy sheet.

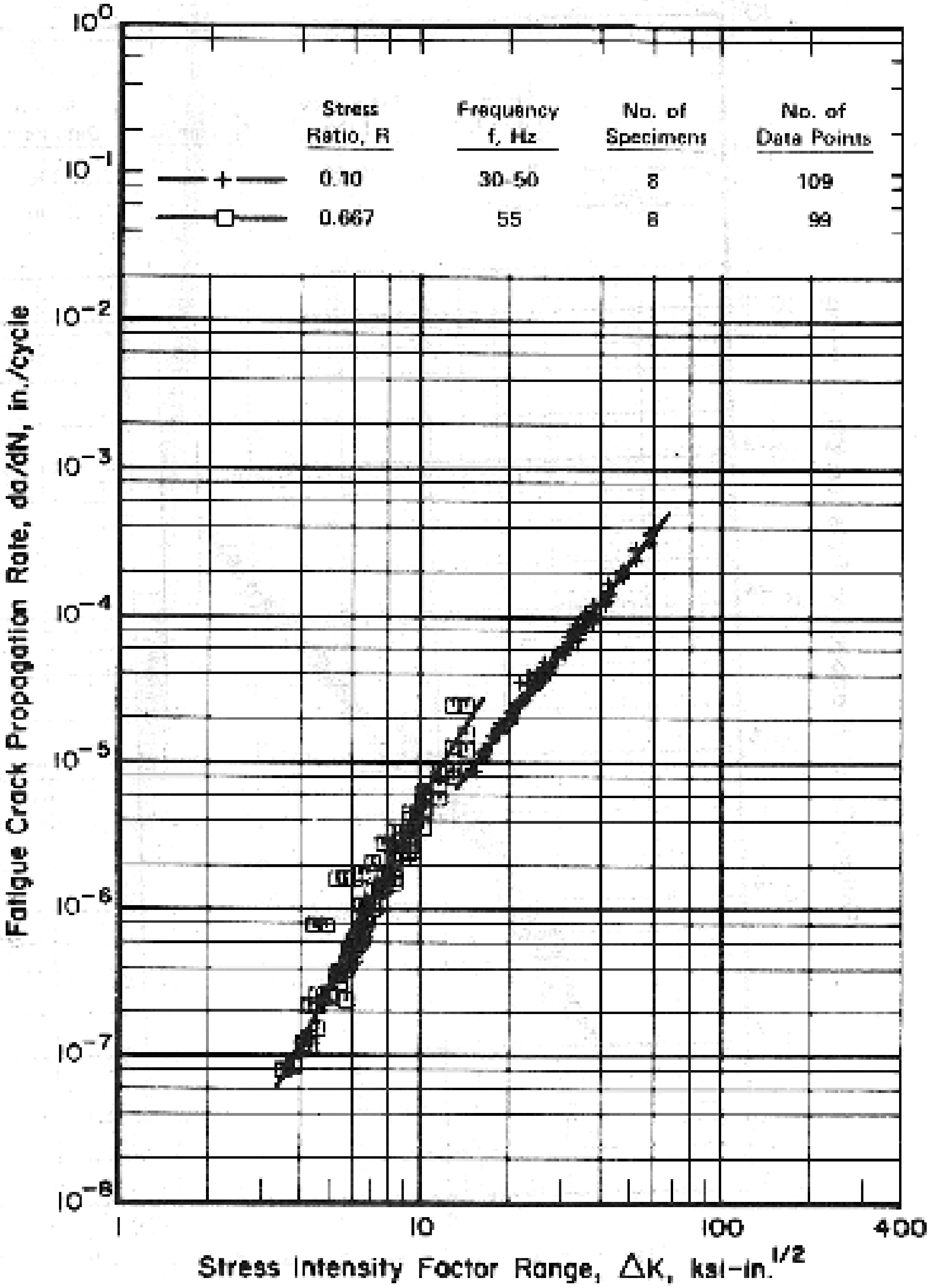


Figure 5.3.1.1.9(a). Fatigue-crack-propagation data for 0.084-inch-thick Ti-5Al-2.5Sn titanium alloy mill-annealed sheet. [Reference 5.3.1.1.9].

Specimen Thickness: 0.08 inch	*Environment: Lab air*
Specimen Width: 2.76 inches	*Temperature: RT*
Specimen Type: M(T)	*Orientation: L-T and T-L*

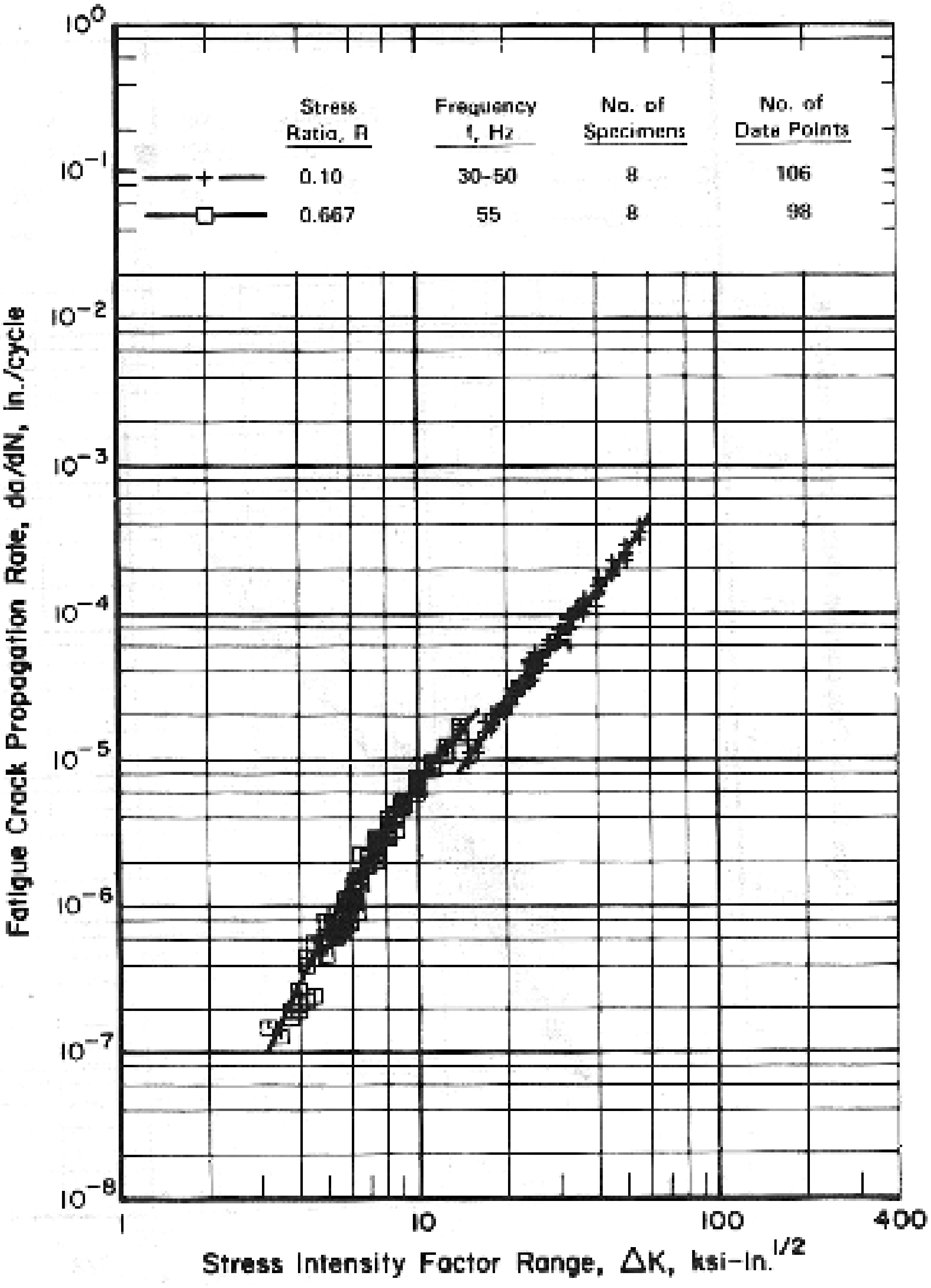


Figure 5.3.1.1.9(b). Fatigue-crack-propagation data for 0.084-inch-thick Ti-5Al-2.5Sn titanium alloy mill-annealed sheet. [Reference 5.3.1.1.9].

Specimen Thickness: 0.08 inch	*Environment: Distilled water*
Specimen Width: 2.76 inches	*Temperature: RT*
Specimen Type: M(T)	*Orientation: L-T and T-L*

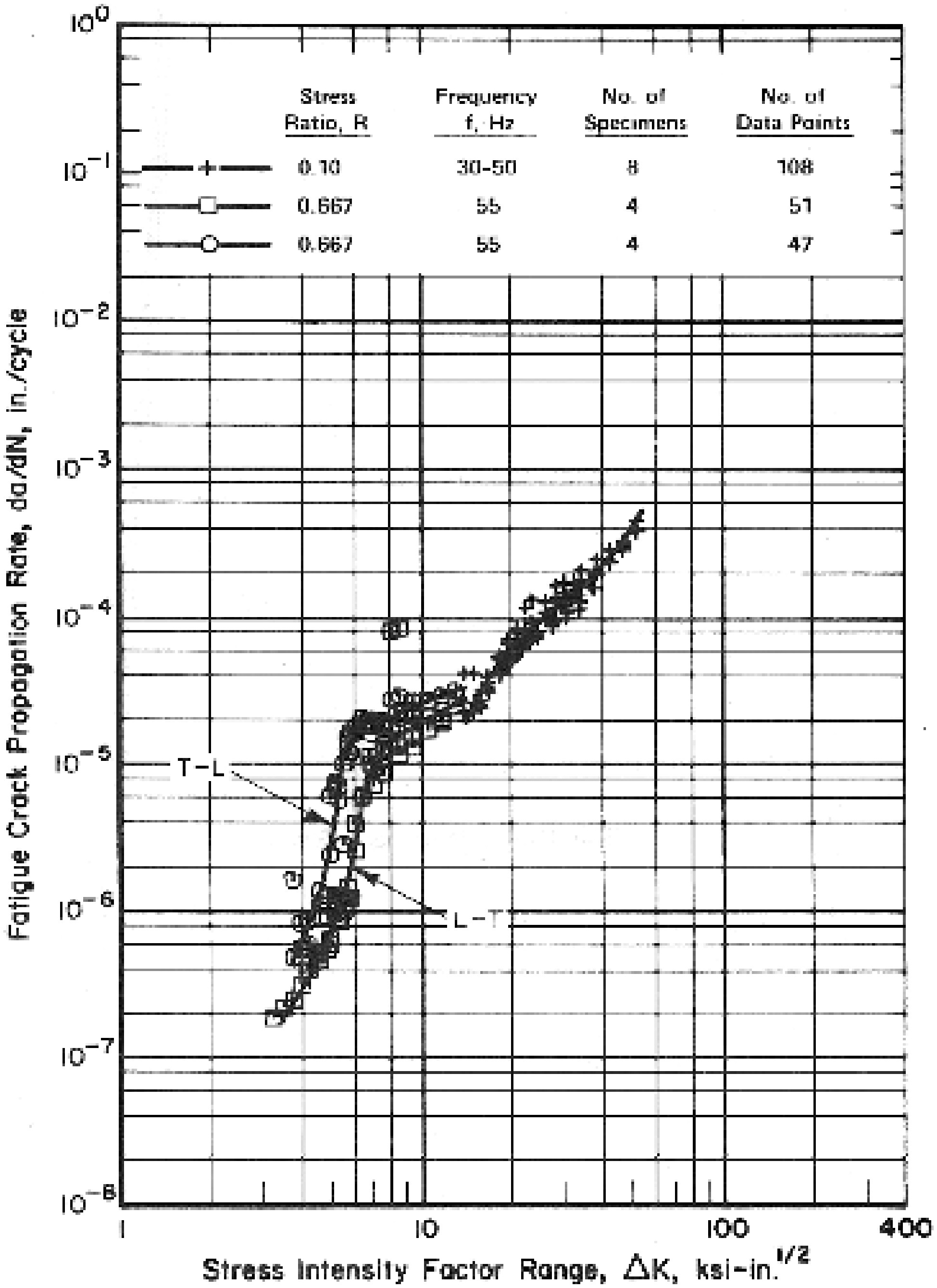


Figure 5.3.1.1.9(c). Fatigue-crack-propagation data for 0.084-inch-thick Ti-5Al-2.5Sn titanium alloy mill-annealed sheet. [Reference 5.3.1.1.9].

Specimen Thickness: 0.08 inch	*Environment: 3.5% NaCl*
Specimen Width: 2.76 inches	*Temperature: RT*
Specimen Type: M(T)	*Orientation: L-T and T-L*

5.3.2 TI-8AL-1MO-1V

5.3.2.0 ***Comments and Properties*** — Ti-8Al-1Mo-1V alloy is a near-alpha composition developed for improved creep resistance and thermal stability up to about 850°F. The alloy is available as billet, bar, plate, sheet, strip, extrusions, and forgings.

Manufacturing Considerations — Room temperature forming of Ti-8Al-1Mo-1V sheet is somewhat more difficult than in Ti-6Al-4V, and for severe operations hot forming is required. Ti-8Al-1Mo-1V can be fusion welded readily with inert-gas protection or spot welding without atmospheric protection. Weld strengths are comparable to those of the parent metal although ductility is somewhat lower in the weldment.

Environmental Considerations — Ti-8Al-1Mo-1V exhibits good oxidation resistance and thermal stability up to 850°F. A decrease in tensile elongation has been reported for single-annealed sheet following 150 hours stressed exposure at 1000°F. Extended exposure to temperatures exceeding 600°F adversely affects room-temperature spot-weld tension strength. This alloy is not recommended for structural applications at liquid-hydrogen temperatures (-423°F). The Ti-8Al-1Mo-1V alloy also is susceptible to chloride stress-corrosion attack in either elevated-temperature (hot-salt stress-corrosion) or ambient-temperature (aqueous stress-corrosion) chloride environments. Thus, care should be exercised in applying the material in chloride containing environments. Under certain conditions, titanium, when in contact with cadmium, silver, mercury, or certain of their compounds, may become embrittled. Refer to MIL-S-5002 and MIL-STD-1568 for restrictions concerning applications with titanium in contact with these metals or their compounds.

Heat Treatment — Three treatments are used with Ti-8Al-1Mo-1V. These are:

Single Anneal: 1450°F for 8 hours, furnace cool.

Duplex Anneal: 1450°F for 8 hours, furnace cool, followed by 1450°F for 15 to 20 minutes, air cool.

Solution Treated and Stabilized: 1825°F for 1 hour, air cool, 1075°F for 8 hours, air cool.

As a general guide, the single anneal is used to obtain highest room-temperature mechanical properties and the duplex anneal to obtain highest fracture toughness. Both the single anneal and the duplex anneal are compatible with hot-forming operations. The solution treated and stabilized condition is used for forgings.

Specifications and Properties — Material specifications for Ti-8Al-1Mo-1V are presented in Table 5.3.2.0(a). Room-temperature mechanical and physical properties for Ti-8Al-1Mo-1V are shown in Tables 5.3.2.0(b) and (c). The effect of temperature on physical properties is shown in Figure 5.3.2.0.

Table 5.3.2.0(a). Material Specifications for Ti-8Al-1Mo-1V

Specification	Form
AMS-T-9046	Sheet, strip, and plate
MIL-T-9047	Bar
AMS 4973	Forging
AMS 4915	Sheet, strip, and plate
AMS 4916	Sheet, strip, and plate

5.3.2.1 ***Single-Annealed Condition*** — Cryogenic, room-temperature, and elevated temperature property curves for this condition are shown in Figures 5.3.2.1.1 and 5.3.2.1.4. Typical tensile and compressive stress-strain and tangent-modulus curves are shown in Figures 5.3.2.1.6(a) and (b) for room temperature and several elevated temperatures.

5.3.2.2 ***Duplex-Annealed Condition*** — Cryogenic, room temperature, and elevated temperature curves for this condition are shown in Figure 5.3.2.2.1. Typical tensile and compressive stress-strain and tangent-modulus curves are shown in Figures 5.3.2.2.6(a) and (b) for room temperature and several elevated temperatures. Fatigue S/N curves for unnotched and notched specimens at room temperature and several elevated temperatures are shown in Figures 5.3.2.2.8(a) through (f).

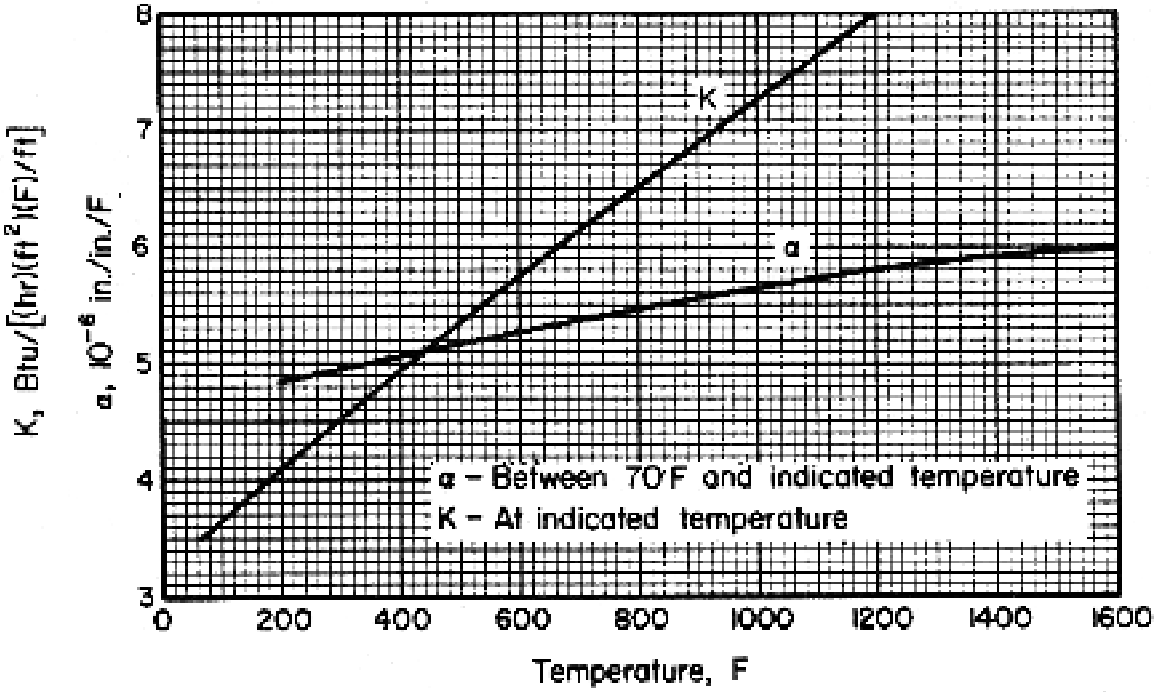


Figure 5.3.2.0. Effect of temperature on the physical properties of Ti-8Al-1Mo-1V alloy.

Table 5.3.2.0(b_1). Design Mechanical and Physical Properties of Ti-8Al-1Mo-1V Sheet and Plate

Specification	AMS 4915, AMS-T-9046, and Comp A-4				
Form	Sheet	Plate			
Condition	Single Annealed				
Thickness, in.	≤ 0.1875	0.1875-0.500	0.501-1.000	1.001-2.500	2.501-4.000
Basis	S	S	S	S	S
Mechanical Properties:					
F_{tu}, ksi:					
L	145	145	140	130	120
LT	145	145	140	130	120
ST	...	...	...	...	120[b]
F_{ty}, ksi:					
L	135	135	130	120	110
LT	135	135	130	120	110
ST	...	...	...	...	110[b]
F_{cy}, ksi:					
L	144	...	...	...	...
LT	149	...	...	...	...
ST	...	...	...	...	...
F_{su}, ksi	93	...	...	...	...
F_{bru}, ksi:					
(e/D = 1.5)	239	...	...	...	...
(e/D = 2.0)	294	...	...	...	...
F_{bry}, ksi:					
(e/D = 1.5)	196	...	...	...	...
(e/D = 2.0)	214	...	...	...	...
e, percent:					
L	[a]	10	10	10	8
LT	[a]	10	10	10	8
ST	...	...	...	...	8[b]
E, 10^3 ksi	17.5[c]				
E_c, 10^3 ksi	18.0[c]				
G, 10^3 ksi	6.7				
μ	0.32				
Physical Properties:					
ω, lb/in.^{3}	0.158				
C, Btu/(lb)(°F)	0.12				
K and α	See Figure 5.3.2.0				

a 0.008-0.014 in. thickness, 6 percent; 0.015-0.024 in. thickness, 8 percent; > 0.025 in. thickness, 10 percent.
b Applicable, providing ST dimension is > 3.000 inches.
c Average, values may vary with test direction.

Table 5.3.2.0(b_2). Design Mechanical and Physical Properties of Ti-8Al-1Mo-1V Sheet and Plate

Specification	AMS 4916, AMS-T-9046, and Comp. A-4					
Form	Sheet		Plate			
Condition	Duplex Annealed					
Thickness, in.	0.015-0.024	0.025-0.1875	0.1875-0.500	0.501-1.000	1.001-2.000	2.001-4.000
Basis	S	S	S	S	S	S
Mechanical Properties:						
F_{tu}, ksi:						
L	135	135	130	130	125	120
LT	135	135	130	130	125	120
F_{ty}, ksi:						
L	120	120	120	120	115	110
LT	120	120	120	120	115	110
F_{cy}, ksi:						
L	126	126	...	...	...	...
LT	126	126	...	...	...	...
F_{su}, ksi	84	84	...	...	...	...
F_{bru}, ksi:						
(e/D = 1.5)	223	223	...	...	...	...
(e/D = 2.0)	269	269	...	...	...	...
F_{bry}, ksi:						
(e/D = 1.5)	174	174	...	...	...	...
(e/D = 2.0)	191	191	...	...	...	...
e, percent:						
L	8	10	10	10	10	8
LT	8	10	10	10	10	8
E, 10^3 ksi	17.5[a]					
E_c, 10^3 ksi	18.0[a]					
G, 10^3 ksi	6.7					
μ	0.32					
Physical Properties:						
ω, lb/in.^{3}	0.158					
C, Btu/(lb)(°F)	0.12					
K and α	See Figure 5.3.2.0					

[a] Average, L and LT; values may vary with test direction.

Table 5.3.2.0(c). Design Mechanical and Physical Properties of Ti-8Al-1Mo-1V Bar and Forging

Specification	MIL-T-9047		AMS 4973	
Form	Bar		Forging	
Condition	Duplex annealed		Solution treated and stabilized	
Thickness or diameter, in.	≤ 2.500[a]	2.501-4.000[a]	≤ 2.499	2.500-4.000
Basis	S	S	S	S
Mechanical Properties:				
F_{tu}, ksi:				
L	130	120	130	120
LT	130[b]	120[b]	130[c]	120
ST	...	120[b]	...	120
F_{ty}, ksi:				
L	120	110	120	110
LT	120[b]	110[b]	120[c]	110
ST	...	110[b]	...	110
F_{cy}, ksi:				
L	...	...	...	...
LT	...	...	...	...
ST	...	...	...	...
F_{su}, ksi	...	...	...	...
F_{bru}, ksi:				
(e/D = 1.5)	...	...	...	...
(e/D = 2.0)	...	...	...	...
F_{bry}, ksi:				
(e/D = 1.5)	...	...	...	...
(e/D = 2.0)	...	...	...	...
e, percent:				
L	10	10	10	10
LT	10[b]	10[b]	10[c]	10
ST	...	8[b]	...	10
E, 10^3, ksi	17.5[d]			
E_c, 10^3 ksi	18.0[d]			
G, 10^3 ksi	6.7			
μ	0.32			
Physical Properties:				
ω, lb/in.^{3}	0.158			
C, Btu/(lb)(°F)	0.12			
K and α	See Figure 5.3.2.0			

[a] Maximum of 16 square-inch cross-sectional area.
[b] Applicable, providing LT or ST dimension is > 3.000 inches.
[c] Applicable, providing LT dimension is ≥ 2.500 inches.
[d] Average, values may vary with test direction.

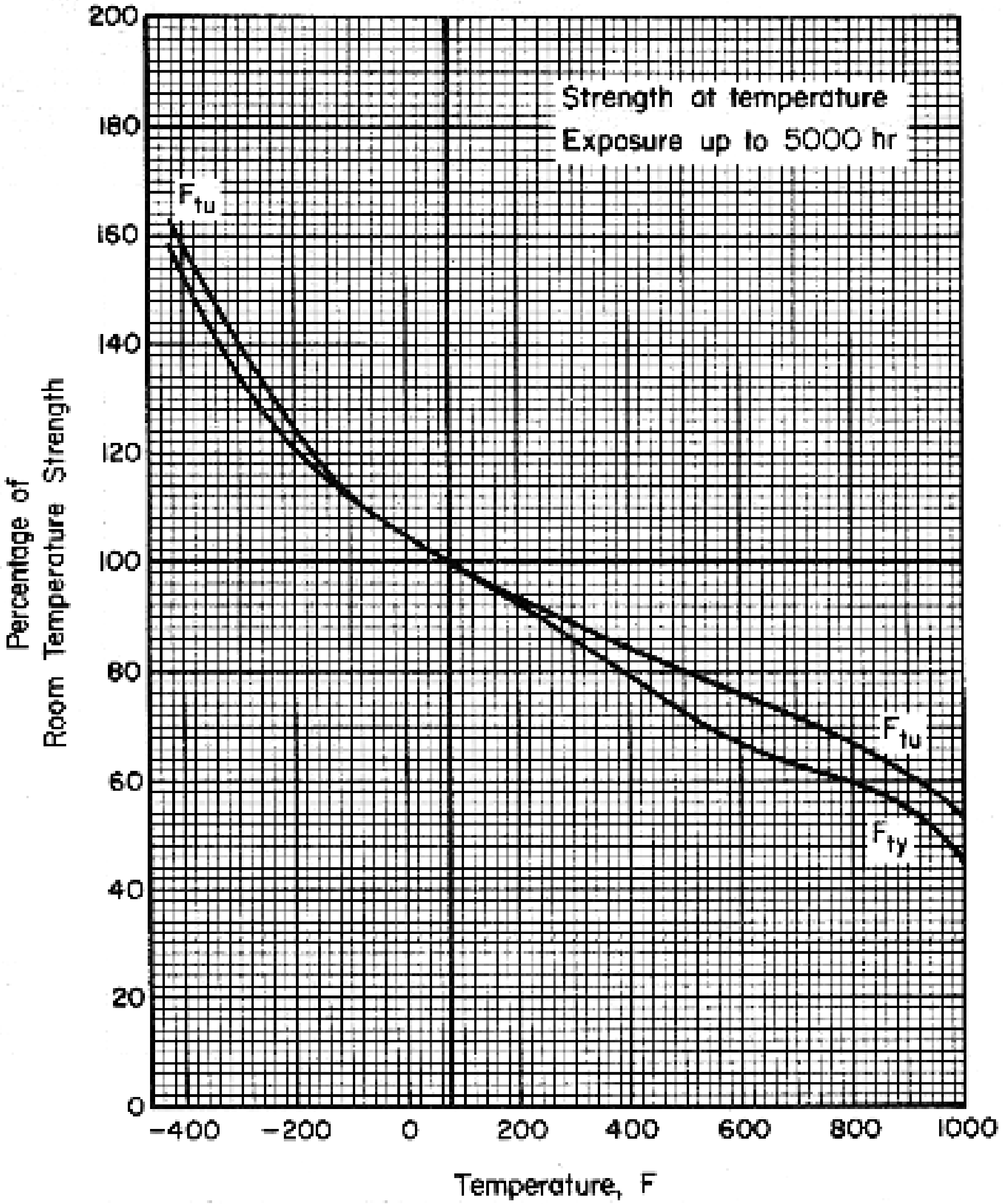


Figure 5.3.2.1.1. Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of single-annealed Ti-8Al-1Mo-1V alloy sheet.

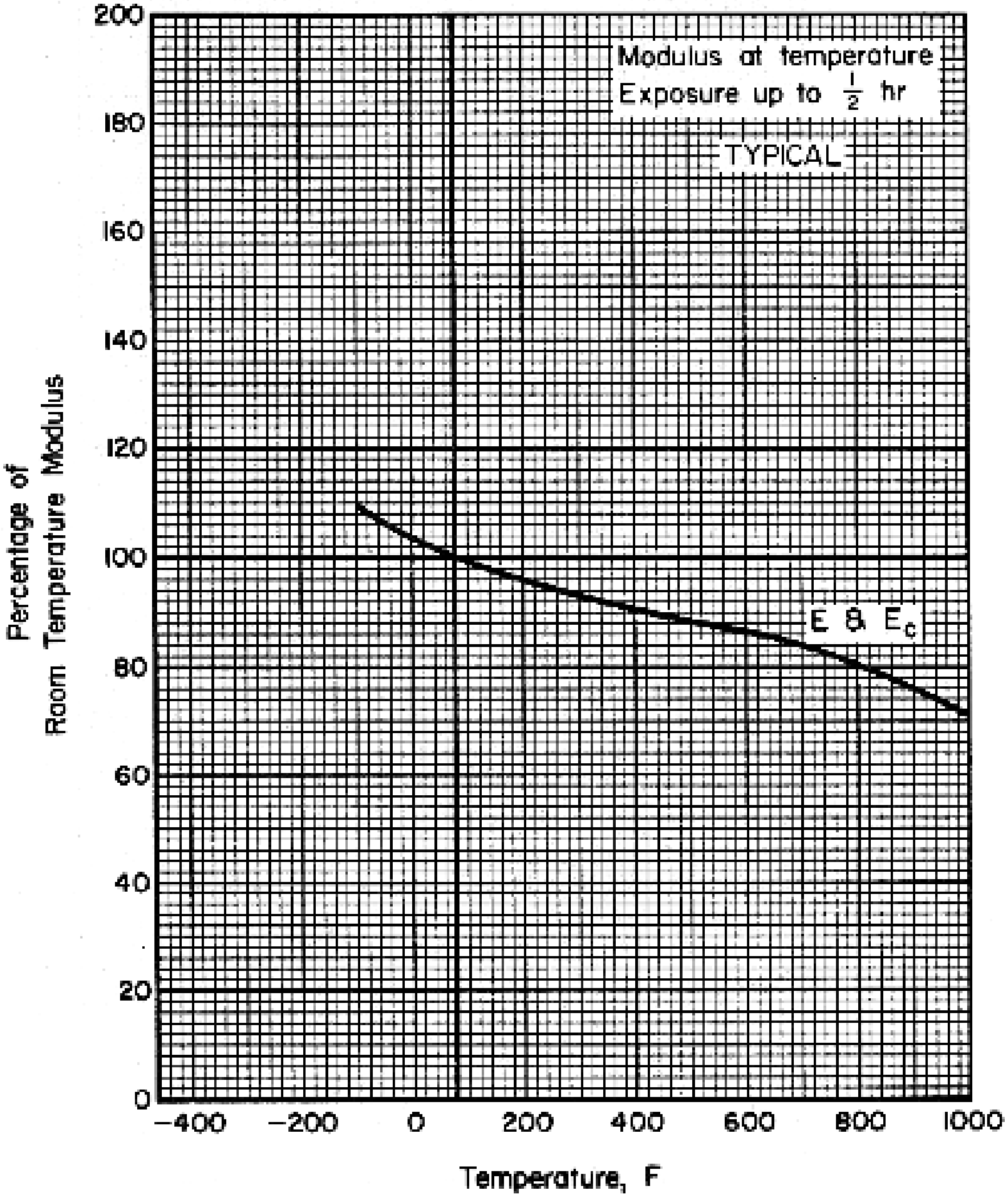


Figure 5.3.2.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of Ti-8Al-1Mo-1V alloy sheet.

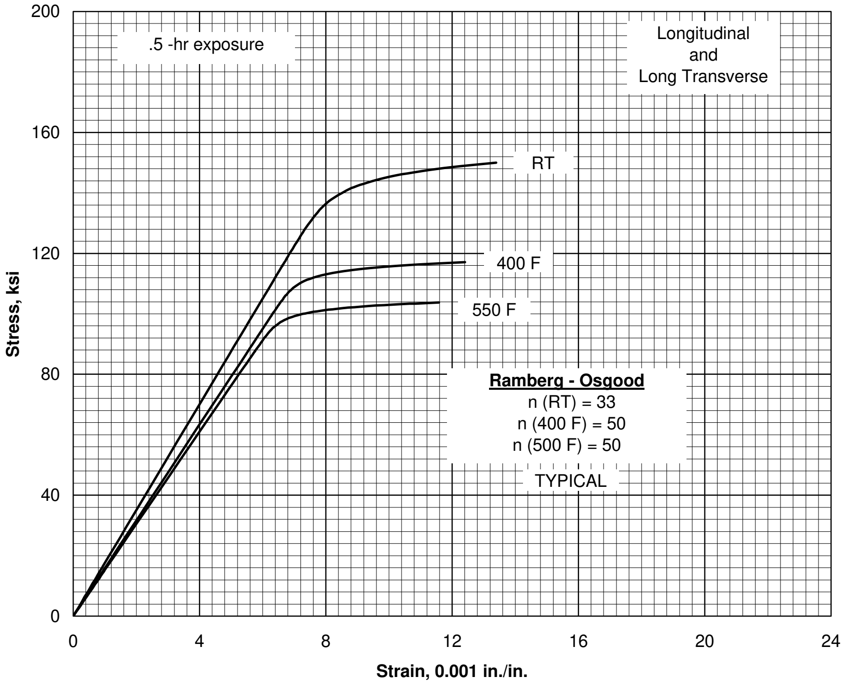


Figure 5.3.2.1.6(a). Typical tensile stress-strain curves for single-annealed Ti-8Al-1Mo-1V alloy sheet at room and elevated temperatures.

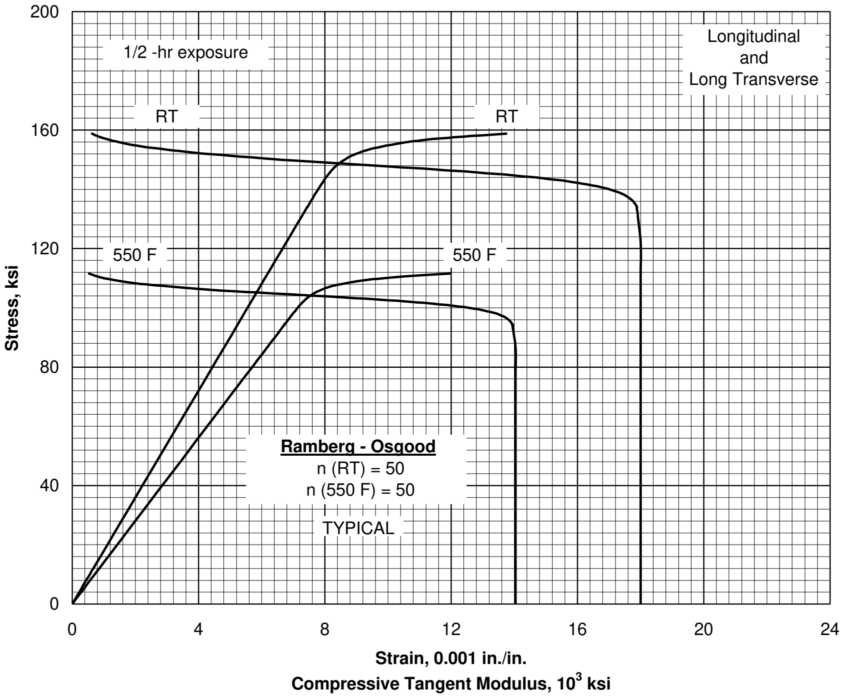


Figure 5.3.2.1.6(b). Typical compressive stress-strain and compressive tangent-modulus curves for single-annealed Ti-8Al-1Mo-1V alloy sheet at room and elevated temperatures.

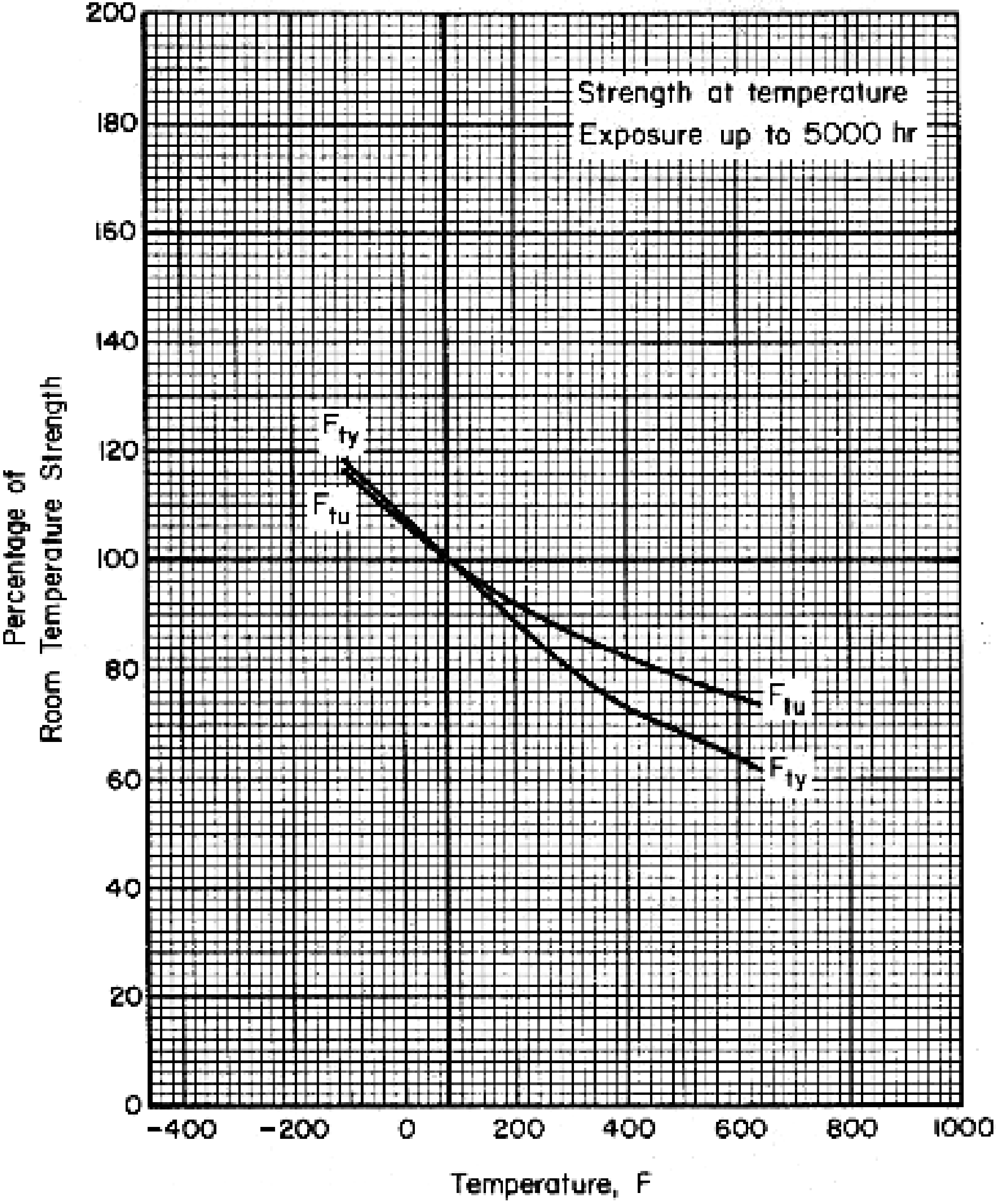


Figure 5.3.2.2.1. Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of duplex-annealed Ti-8Al-1Mo-1V alloy sheet.

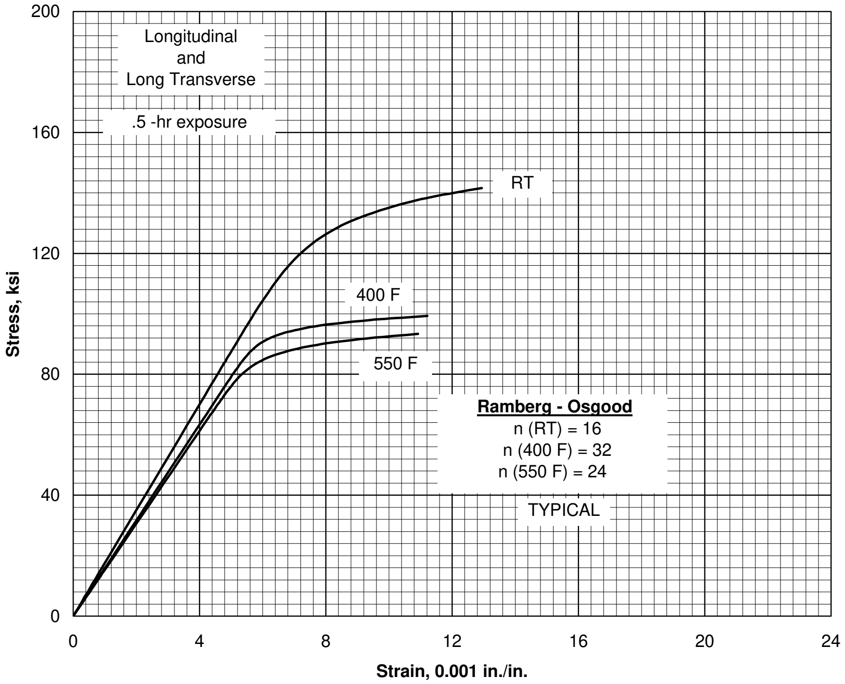


Figure 5.3.2.2.6(a). Typical tensile stress-strain curves for duplex-annealed Ti-8Al-1Mo-1V alloy sheet at room and elevated temperatures.

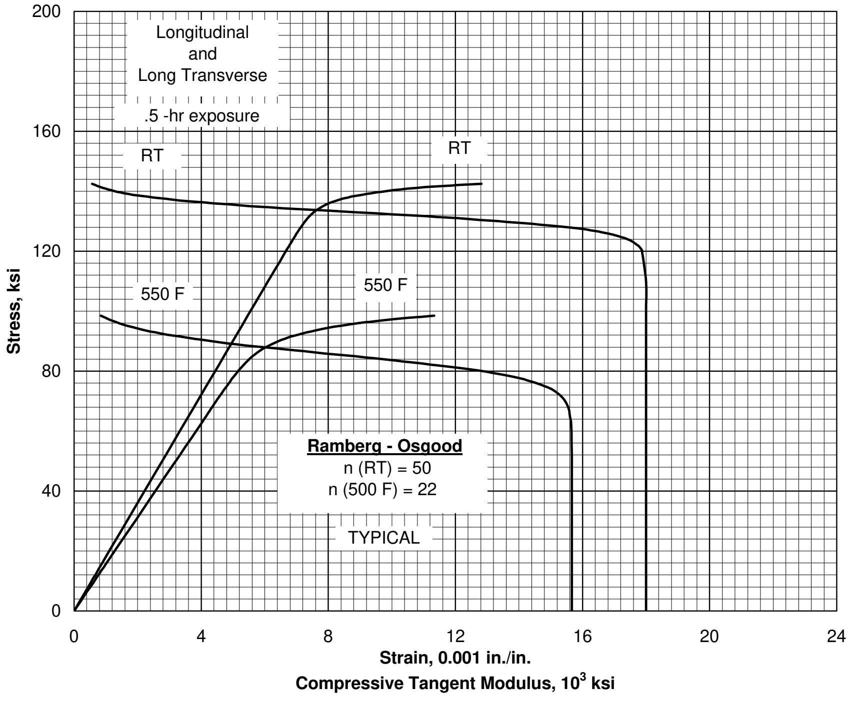


Figure 5.3.2.2.6(b). Typical compressive stress-strain and compressive tangent-modulus curves for duplex-annealed Ti-8Al-1Mo-1V alloy sheet at room and elevated temperatures.

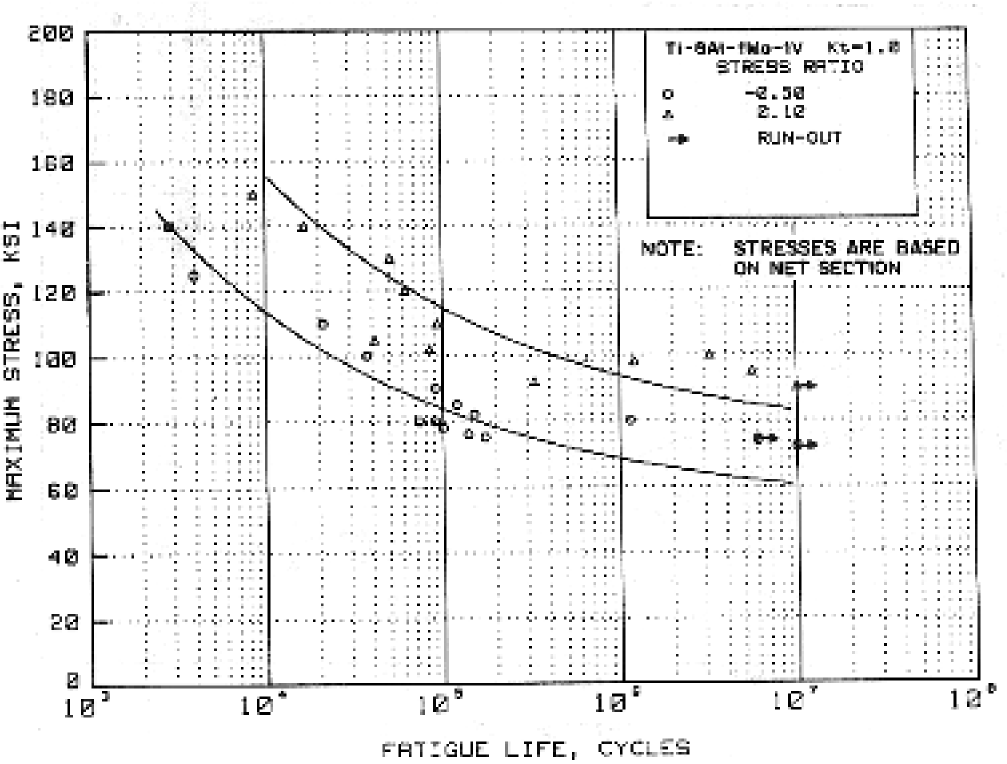


Figure 5.3.2.2.8(a). Best-fit S/N curves for unnotched, duplex annealed Ti-8Al-1Mo-1V sheet at room temperature, long transverse direction.

Correlative Information for Figure 5.3.2.2.8(a)

Product Form: Sheet, 0.050 inch thick

Properties:

TUS, ksi	TYS, ksi	Temp., °F
147.2	135.6	RT

Specimen Details: Unnotched
0.750 inch net width

Surface Condition: HNO_3/HF pickled

References: 5.3.2.2.8(a) and (b)

Test Parameters:
Loading - Axial
Frequency - 1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 1

Equivalent Stress Equation:
$\text{Log } N_f = 10.57 - 3.46 \log (S_{eq} - 66.7)$
$S_{eq} = S_{max} (1-R)^{0.61}$
Std. Error of Estimate, Log (Life) = 0.47
Standard Deviation, Log (Life) = 0.81
$R^2 = 66.7\%$

Sample Size = 24

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

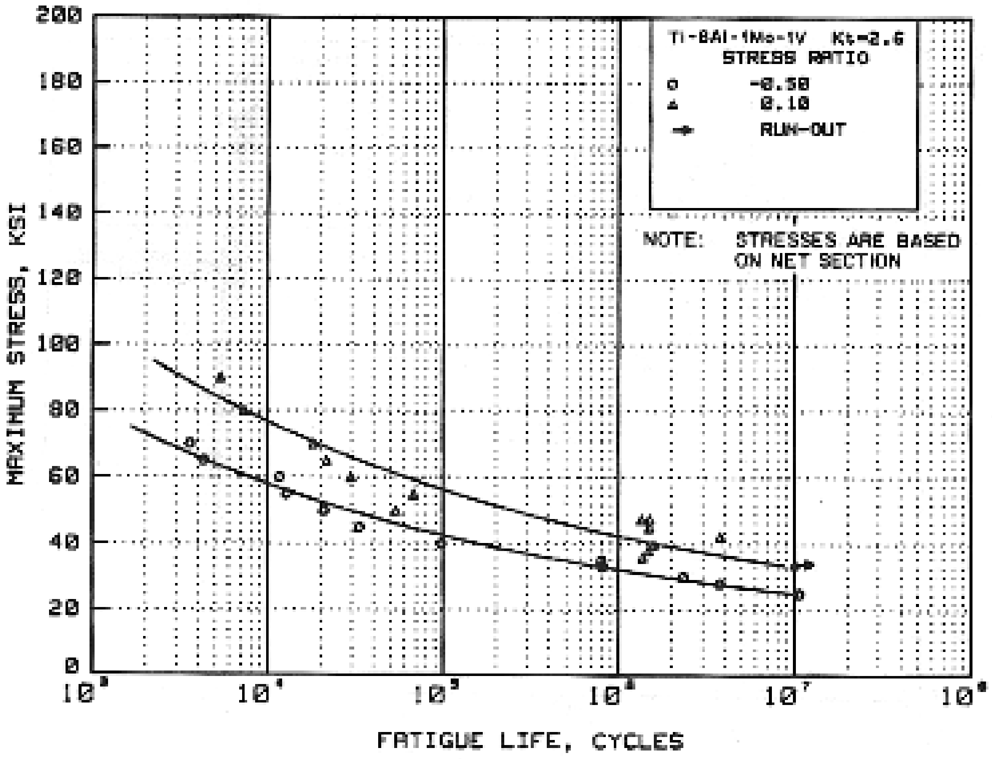


Figure 5.3.2.2.8(b). Best-fit S/N curves for notched, K_t = 2.6, duplex annealed Ti-8Al-1Mo-1V sheet at room temperature, long transverse direction.

Correlative Information for Figure 5.3.2.2.8(b)

Product Form: Sheet, 0.050 inch thick

Properties:	TUS, ksi	TYS, ksi	Temp.,°F
	147.2	135.6	RT
			Unnotched

Specimen Details: Notched, hole type, K_t = 2.6
1.500 inch, gross width
1.250 inch, net width
0.250 inch, diameter hole

Surface Condition: HNO_3/HF pickled

References: 5.3.2.2.8(a) and (b)

Test Parameters:
Loading - Axial
Frequency - 1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 1

Equivalent Stress Equation:
$\log N_f = 14.49-5.90 \log (S_{eq}-12.7)$
$S_{eq} = S_{max} (1-R)^{0.55}$
Std. Error of Estimate, Log (Life) = 0.33
Standard Deviation, Log (Life) = 1.10
R^2 = 90.9%

Sample Size = 26

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

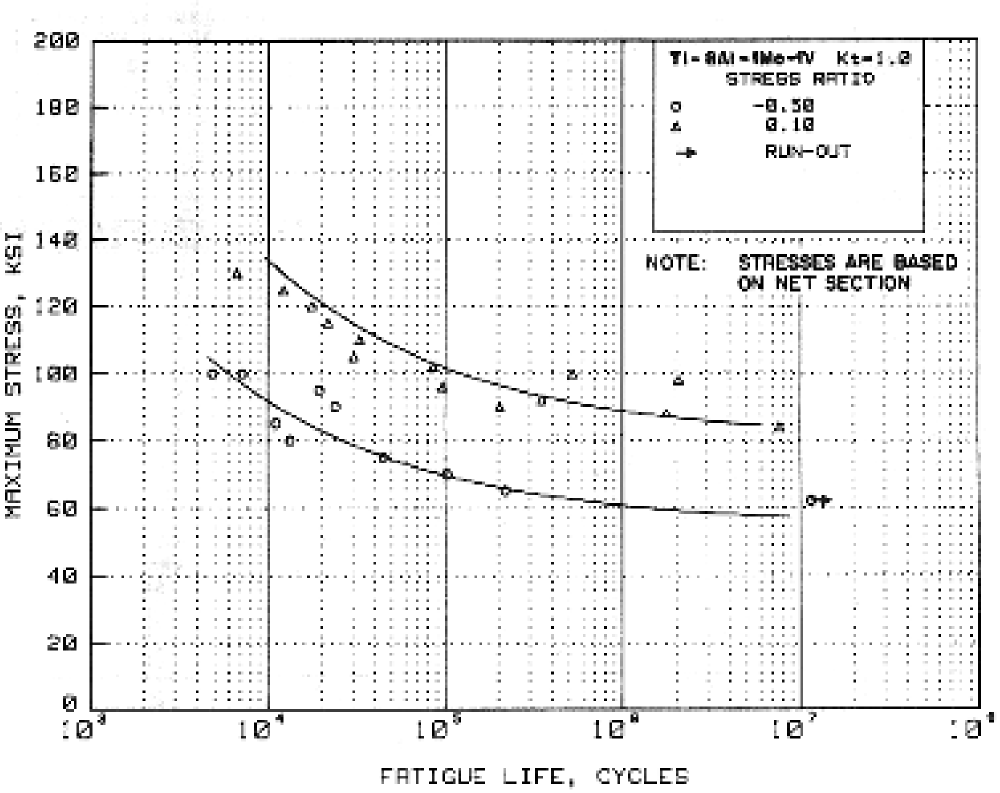


Figure 5.3.2.2.8(c). Best-fit S/N curves for unnotched duplex annealed Ti-8Al-1Mo-1V sheet at 400°F, long transverse direction.

Correlative Information for Figure 5.3.2.2.8(c)

Product Form: Sheet, 0.050 inch thick

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	119.5	100.8	400

Specimen Details: Unnotched
0.750 inch net width

Surface Condition: HNO_3/HF pickled

References: 5.3.2.2.8(a) and (b)

Test Parameters:
Loading - Axial
Frequency - 1800 cpm
Temperature - 400°F
Environment - Air

No. of Heats/Lots: 1

Equivalent Stress Equation:
$\text{Log } N_f = 8.30-2.53 \log (S_{eq}-73.9)$
$S_{eq} = S_{max} (1-R)^{0.74}$
Std. Error of Estimate, Log (Life) = 0.38
Standard Deviation, Log (Life) = 0.87
$R^2 = 80.9\%$

Sample Size = 23

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

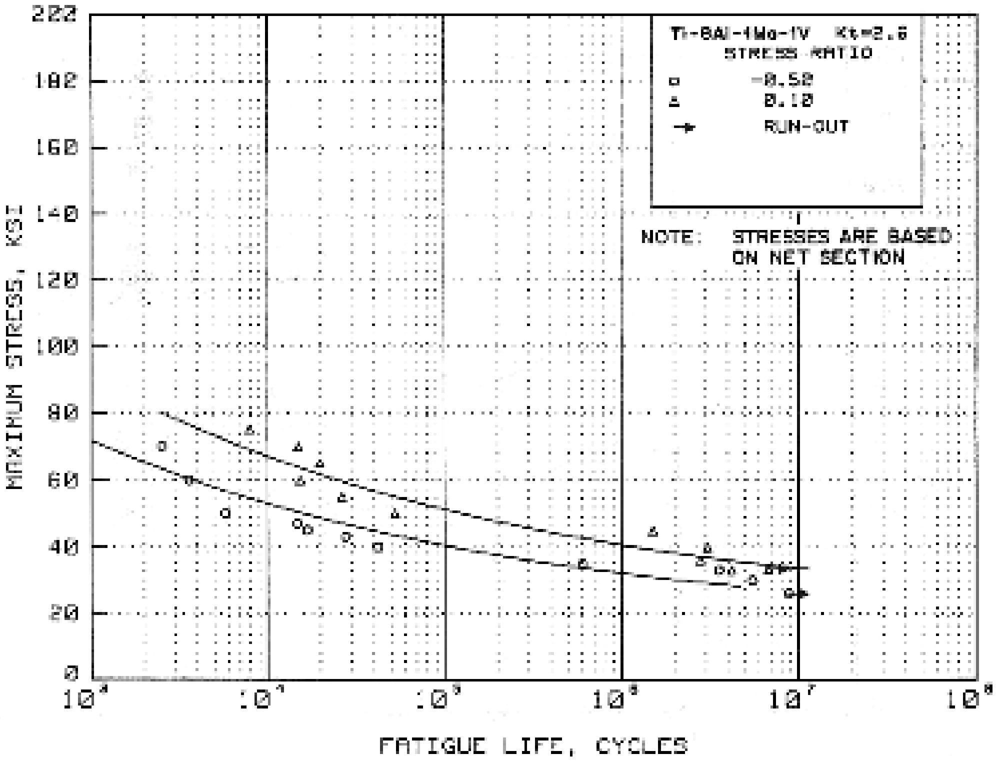


Figure 5.3.2.2.8(d). Best-fit S/N curves for notched, K_t = 2.6, duplex annealed Ti-8Al-1Mo-1V sheet at 400°F, long transverse direction.

Correlative Information for Figure 5.3.2.2.8(d)

Product Form: Sheet, 0.050 inch thick

Properties:

TUS, ksi	TYS, ksi	Temp.,°F
119.5	100.8	400
		Unnotched

Specimen Details: Notched, hole type, K_t = 2.6
1.500 inch, gross width
1.250 inch, net width
0.250 inch, diameter hole

Surface Condition: HNO_3/HF pickled

References: 5.3.2.2.8(a) and (b)

Test Parameters:
Loading - Axial
Frequency - 1800 cpm
Temperature - 400°F
Environment - Air

No. of Heats/Lots: 1

Equivalent Stress Equation:
$\text{Log } N_f = 13.39\text{-}5.68 \log (S_{eq}\text{-}18.7)$
$S_{eq} = S_{max} (1\text{-}R)^{0.46}$
Std. Error of Estimate, Log (Life) = 0.41
Standard Deviation, Log (Life) = 1.16
R^2 = 87.2%

Sample Size = 20

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

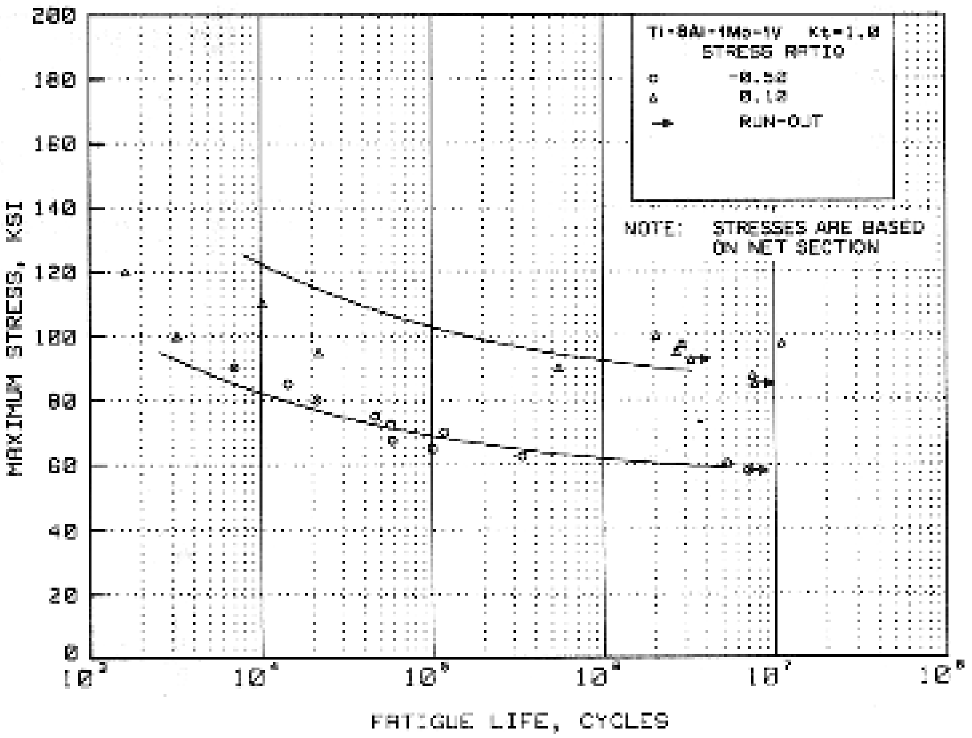


Figure 5.3.2.2.8(e). Best-fit S/N curves for unnotched duplex annealed Ti-8Al-1Mo-1V sheet at 650°F, long transverse direction.

Correlative Information for Figure 5.3.2.2.8(e)

Product Form: Sheet, 0.050 inch thick

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	110.2	86.8	650

Specimen Details: Unnotched
0.750 inch, net width

Surface Condition: HNO_3/HF pickled

References: 5.3.2.2.8(a) and (b)

Test Parameters:
Loading - Axial
Frequency - 1800 cpm
Temperature - 650°F
Environment - Air

No. of Heats/Lots: 1

Equivalent Stress Equation:
Log $N_f = 9.83-3.66 \log (S_{eq}-73)$
$S_{eq} = S_{max} (1-R)^{0.78}$
Std. Error of Estimate, Log (Life) = 0.88
Standard Deviation, Log (Life) = 1.18
$R^2 = 44.3\%$

Sample Size = 20

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

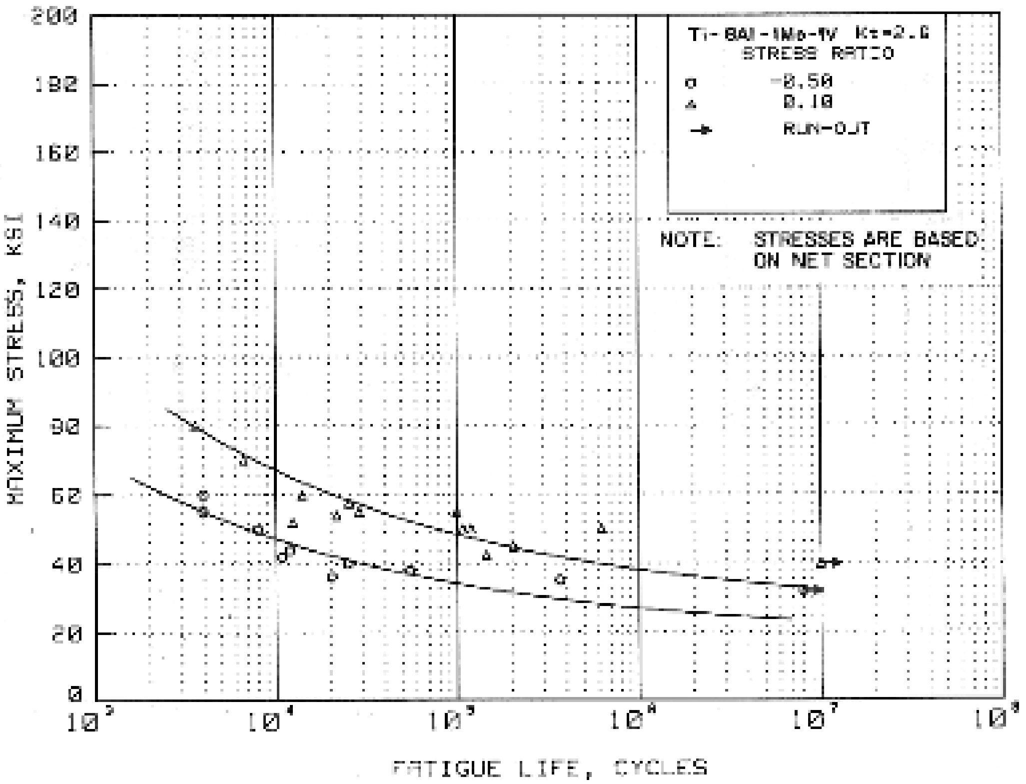


Figure 5.3.2.2.8(f). Best-fit S/N curves for notched, K_t = 2.6, duplex annealed Ti-8Al-1Mo-1V sheet at 650°F, long transverse direction.

Correlative Information for Figure 5.3.2.2.8(f)

Product Form: Sheet, 0.050 inch thick

Properties:

TUS, ksi	TYS, ksi	Temp.,°F
110.2	86.8	650
		Unnotched

Specimen Details: Notched, hole type, K_t = 2.6
1.500 inch, gross width
1.250 inch, net width
0.250 inch, diameter hole

Surface Condition: HNO_3/HF pickled

References: 5.3.2.2.8(a) and (b)

Test Parameters:
Loading - Axial
Frequency - 1800 cpm
Temperature - 650°F
Environment - Air

No. of Heats/Lots: 1

Equivalent Stress Equation:
$\text{Log } N_f = 10.16-3.88 \log (S_{eq}-23)$
$S_{eq} = S_{max} (1-R)^{0.69}$
Std. Error of Estimate, Log (Life) = 0.38
Standard Deviation, Log (Life) = 0.65
R^2 = 66.0%

Sample Size = 22

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

5.3.3 Ti-6Al-2Sn-4Zr-2Mo

5.3.3.0 *Comments and Properties* — Ti-6Al-2Sn-4Zr-2Mo is a near-alpha titanium composition developed for improved elevated-temperature performance. The alloy has a titanium-aluminum base that is solid solution strengthened by additions of tin and zirconium. Molybdenum improves both room and elevated temperature strength, creep and thermal stability. Introduction of this alloy initially met the requirements for certain advanced performance gas turbine engine applications. Some of the more recent applications, however, require better creep strength than the alloy initially provided. Development work showed that a small addition of silicon, approximately 0.08 percent, substantially improved the creep strength of the alloy without significantly affecting the thermal stability. The alloy is creep resistant and relatively stable to about 1050°F. Creep and thermal stability of the alloy are further enhanced by solution treating high in the alpha-beta phase field. The alloy is available in bar, billet, plate, sheet, strip, and extrusions.

Manufacturing Conditions — Forging of Ti-6Al-2Sn-4Zr-2Mo at temperatures below the beta transus temperature is recommended. For optimum creep properties beta forging or a modification of it is recommended with some loss in ductility to be expected. Elevated temperatures may be used for severe sheet forming operations while room-temperature forming may be used for mild contouring. Stress relief annealing may be combined with a final hot-sizing operation. The material can be welded using TIG or MIG fusion processes to achieve 100 percent joint efficiencies but with limited weld zone ductility. As in welding any titanium alloy, shielding from atmospheric contamination is required except for spot or seam welding.

Environmental Considerations — Ti-6Al-2Sn-4Zr-2Mo is somewhat more resistant to hot-salt cracking than either Ti-8Al-1Mo-1V or Ti-6Al-4V alloys. The material is marginally susceptible to aqueous chloride solution stress-corrosion cracking. Surface oxides formed during exposure to service temperature (~950°F) do not adversely affect properties. Under certain conditions, titanium, when in contact with cadmium, silver, mercury, or certain of their compounds, may become embrittled. Refer to MIL-S-5002 and MIL-STD-1568 for restrictions concerning applications with titanium in contact with these metals or their compounds.

Heat Treatment — Several different annealing treatments, which are described below, are available for Ti-6Al-2Sn-4Zr-2Mo.

For sheet and strip:

Duplex Anneal: 1650°F for ½ hour, air cool, followed by 1450°F for ¼ hour, and air cool.

Triplex Anneal: 1650°F for ½ hour, air cool, followed by 1450°F for ¼ hour, air cool, followed by 1100°F for 2 hours and air cool.

For plate:

Duplex Anneal: 1650°F for 1 hour, air cool, followed by 1100°F for 8 hours and air cool.

Triplex Anneal: 1650°F for ½ hour, air cool, followed by 1450°F for ¼ hour, air cool, followed by 1100°F for 2 hours and air cool.

For bars and forgings:

Duplex Anneal: Solution anneal 25 to 50°F below beta transus temperature for 1 hour, air cool or faster, followed by 1100°F for 8 hours and air cool.

Table 5.3.3.0(a). Material Specifications for Ti-6Al-2Sn-4Zr-2Mo

Specification	Form
AMS-T-9046	Sheet and strip
AMS 4975	Bar
AMS 4976	Forging
AMS 4919	Sheet, strip, and plate

Specifications and Properties — Material specifications for Ti-6Al-2Sn-4Zr-2Mo are given in Table 5.3.3.0(a). Room-temperature mechanical and physical properties for Ti-6Al-2Sn-4Zr-2Mo are presented in Table 5.3.3.0(b) and (c). The effect of temperature on physical properties is shown in Figure 5.3.3.0.

5.3.3.1 ***Single, Duplex, and Triplex Annealed*** — Room and elevated temperature property curves are shown in Figures 5.3.3.1.1, 5.3.3.1.2, and 5.3.3.1.4. Typical stress-strain curves at room and elevated temperatures are shown in Figures 5.3.3.1.6(a) and (b). Full range stress-strain curves at room and elevated temperatures are shown in Figure 5.3.3.1.6(c).

Table 5.3.3.0(b). Design Mechanical and Physical Properties of Ti-6Al-2Sn-4Zr-2Mo

Specification	AMS 4919								AMS-T-9046, Comp. AB-4
Form	Sheet								
Condition	Duplex annealed								Triplex annealed
Thickness or diameter, in.	≤0.046		0.047-0.093		0.094-0.140		0.141-0.187		≤0.187
Basis	A	B	A	B	A	B	A	B	S[a]
Mechanical Properties:									
F_{tu}, ksi:									
L	135[b]	143	135[b]	143	135[b]	143	135[b]	143	145
LT	135[b]	143	135[b]	143	135[b]	143	135[b]	143	145
F_{ty}, ksi:									
L	125[c]	136	125[c]	136	125[c]	136	125[c]	136	135
LT	125[c]	134	125[c]	134	125[c]	134	125[c]	134	135
F_{cy}, ksi:									
L	132	142	132	142	132	142	132	142	...
LT	132	142	132	142	132	142	132	142	...
F_{su}, ksi	...	...	...	...	...	...	...	...	...
F_{bru}[d], ksi:									
(e/D=1.5)	195	206	205	217	214	227	219	232	...
(e/D=2.0)	217	230	243	258	266	282	279	295	...
F_{bry}[d], ksi:									
(e/D=1.5)	171	183	171	183	171	183	171	183	...
(e/D=2.0)	202	217	202	217	202	217	202	217	...
e, percent (S-basis):									
L	8[e]	...	e	...	10	...	10	...	e
LT	8[e]	...	e	...	10	...	10	...	e
E, 10^3 ksi	16.5								
E_c, 10^3 ksi	18.0								
G, 10^3 ksi	6.2								
μ	0.32								
Physical Properties:									
ω, lb/in.^{3}	0.164								
C, *K* and α	See Figure 5.3.3.0								

a S-basis values are representative of test specimens excised from duplex annealed material and thermally treated to triplex annealed condition in a laboratory furnace.
b S-basis. The rounded T_{99} values are as follows: F_{tu}(L&LT) = 139 ksi.
c S-basis. The rounded T_{99} values are as follows: F_{ty}(L) = 131 ksi and F_{ty}(LT) = 129 ksi.
d Bearing values are "dry pin" values per Section 1.4.7.1.
e 8% for 0.025 through 0.062 inch and 10% for >0.062 inch.

Table 5.3.3.0(c). Design Mechanical and Physical Properties of Ti-6Al-2Sn-4Zr-2Mo

Specification	AMS 4975		AMS 4976
Form	Bar		Forging
Condition	STA (Duplex annealed)		STA (Duplex annealed)
Cross-Sectional area, in.^{2}	≤ 16		≤ 9
Thickness, or diameter, in.	≤ 3.000		≤ 3.000
Basis	A	B	S
Mechanical Properties:			
F_{tu}, ksi:			
L	130[a]	144	130
LT	130[b]	...	130[b]
ST	130[b]	...	130[b]
F_{ty}, ksi:			
L	120[a]	131	120
LT	120[b]	...	120[b]
ST	120[b]	...	120[b]
F_{cy}, ksi:			
L	...	...	...
LT	...	...	...
ST	...	...	...
F_{su}, ksi	...	...	...
F_{bru}, ksi:			
(e/D=1.5)	...	...	...
(e/D=2.0)	...	...	...
F_{bry}, ksi:			
(e/D=1.5)	...	...	...
(e/D=2.0)	...	...	...
e, percent(S basis):			
L	10	...	10
LT	10[b]	...	10[b]
ST	10[b]	...	10[b]
RA, percent (S basis):			
L	25	...	25
LT	25[b]	...	25[b]
ST	25[b]	...	25[b]
E, 10^3 ksi	16.5		
E_c, 10^3 ksi	18.0		
G, 10^3 ksi	6.2		
μ	0.32		
Physical Properties:			
ω, lb/in.^{3}	0.164		
C, K, and α	See Figure 5.3.3.0		

[a] S basis. The rounded T_{99} values are as follows: F_{tu}(L) = 138 ksi and F_{ty}(L) = 125 ksi.
[b] S basis. Applicable providing transverse dimension is ≥2.500 in.

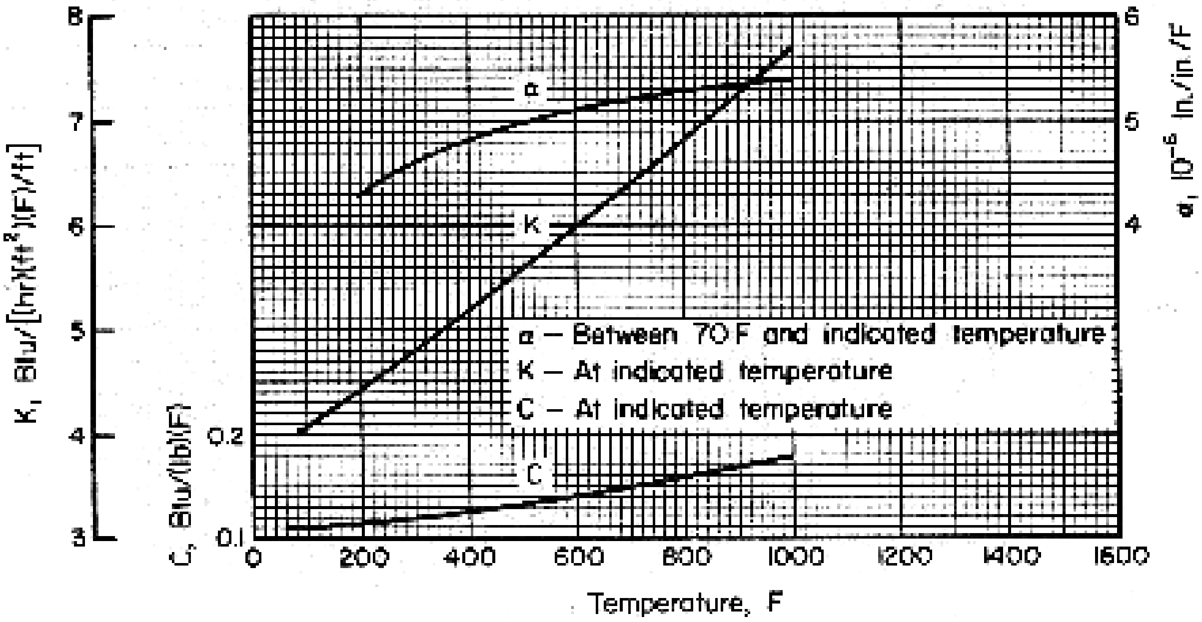


Figure 5.3.3.0. Effect of temperature on the physical properties of Ti-6Al-2Sn-4Zr-2Mo alloy.

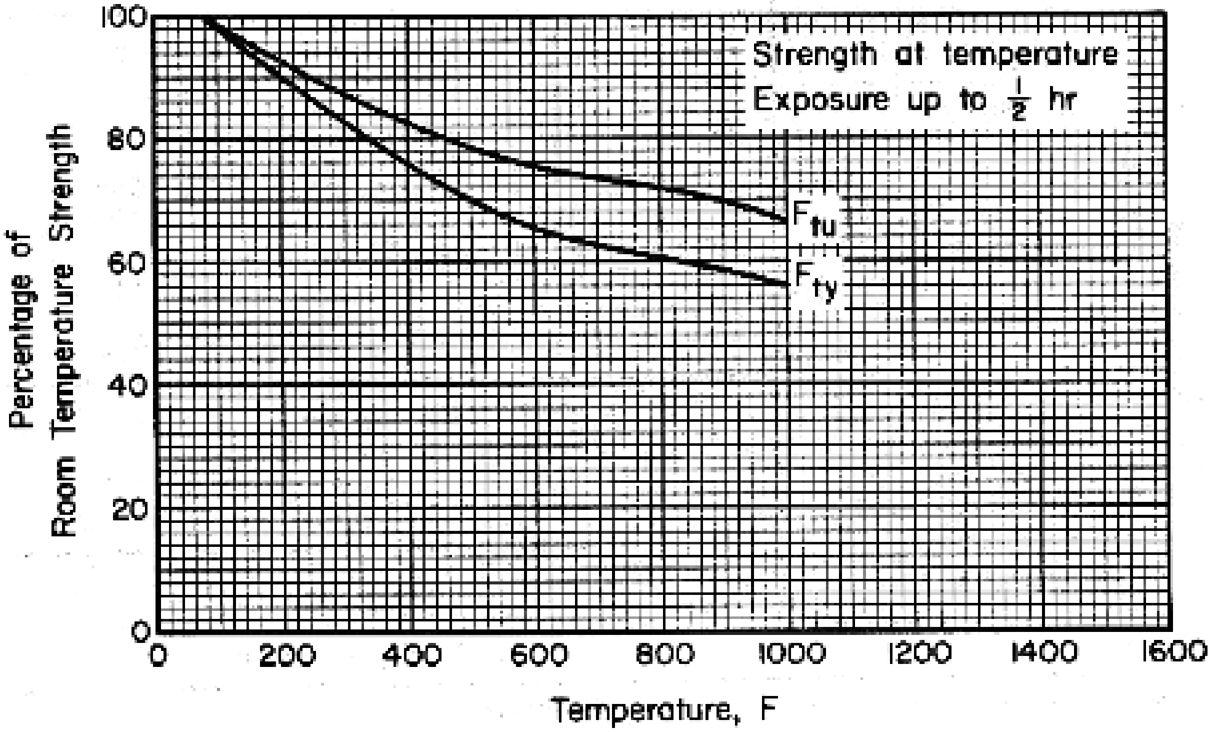


Figure 5.3.3.1.1. Effect of temperature in the tensile ultimate strength (F_{tu}) and tensile yield strength (F_{ty}) of duplex- and triplex-annealed Ti-6Al-2Sn-4Zr-2Mo (all products).

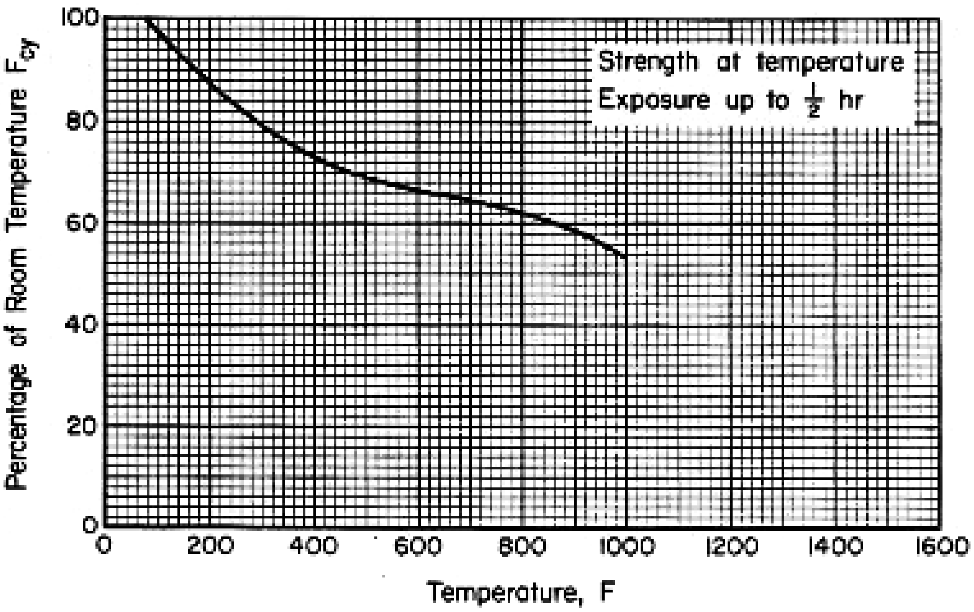


Figure 5.3.3.1.2. Effect of temperature on the compressive yield strength (F_{cy}) of duplex annealed Ti-6Al-2Sn-4Zr-2Mo alloy sheet.

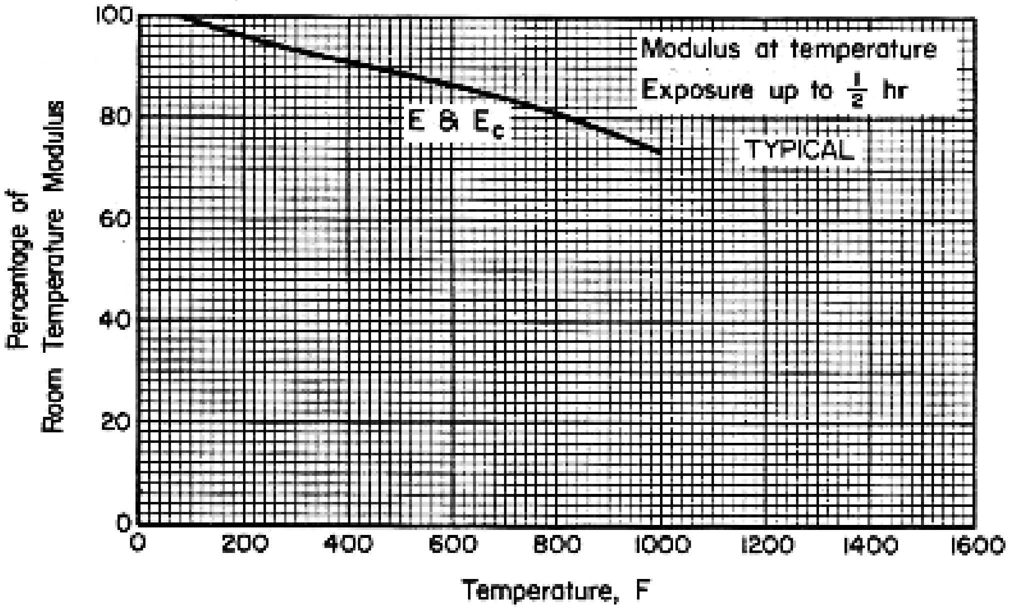


Figure 5.3.3.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of duplex- and triplex-annealed Ti-6Al-2Sn-4Zr-2Mo alloy.

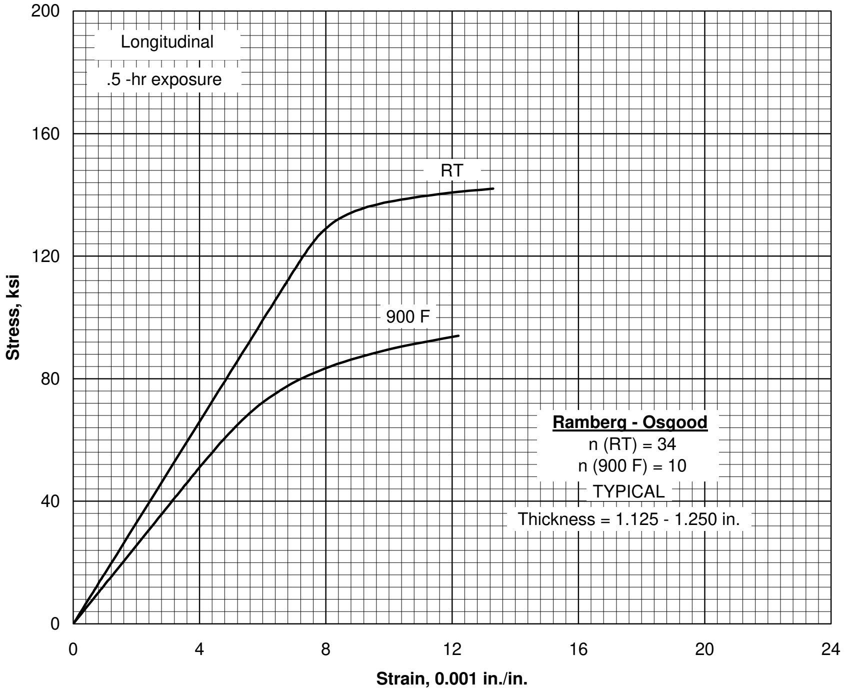


Figure 5.3.3.1.6(a). Typical tensile stress-strain curves for duplex annealed Ti-6Al-2Sn-4Zr-2Mo alloy bar at various temperatures.

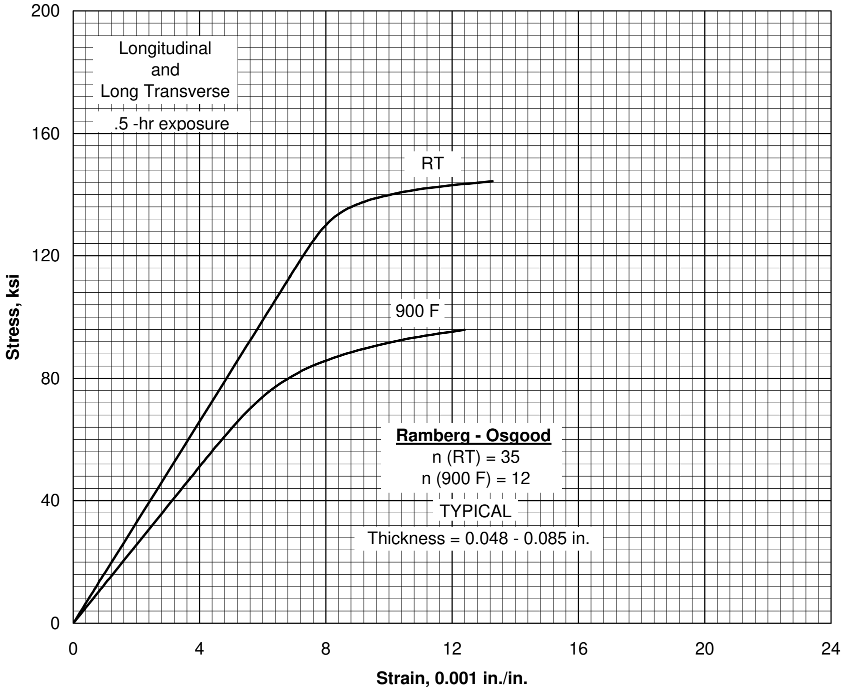


Figure 5.3.3.1.6(b). Typical tensile stress-strain curves for duplex- and triplex-annealed Ti-6Al-2Sn-4Zr-2Mo alloy sheet at various temperatures.

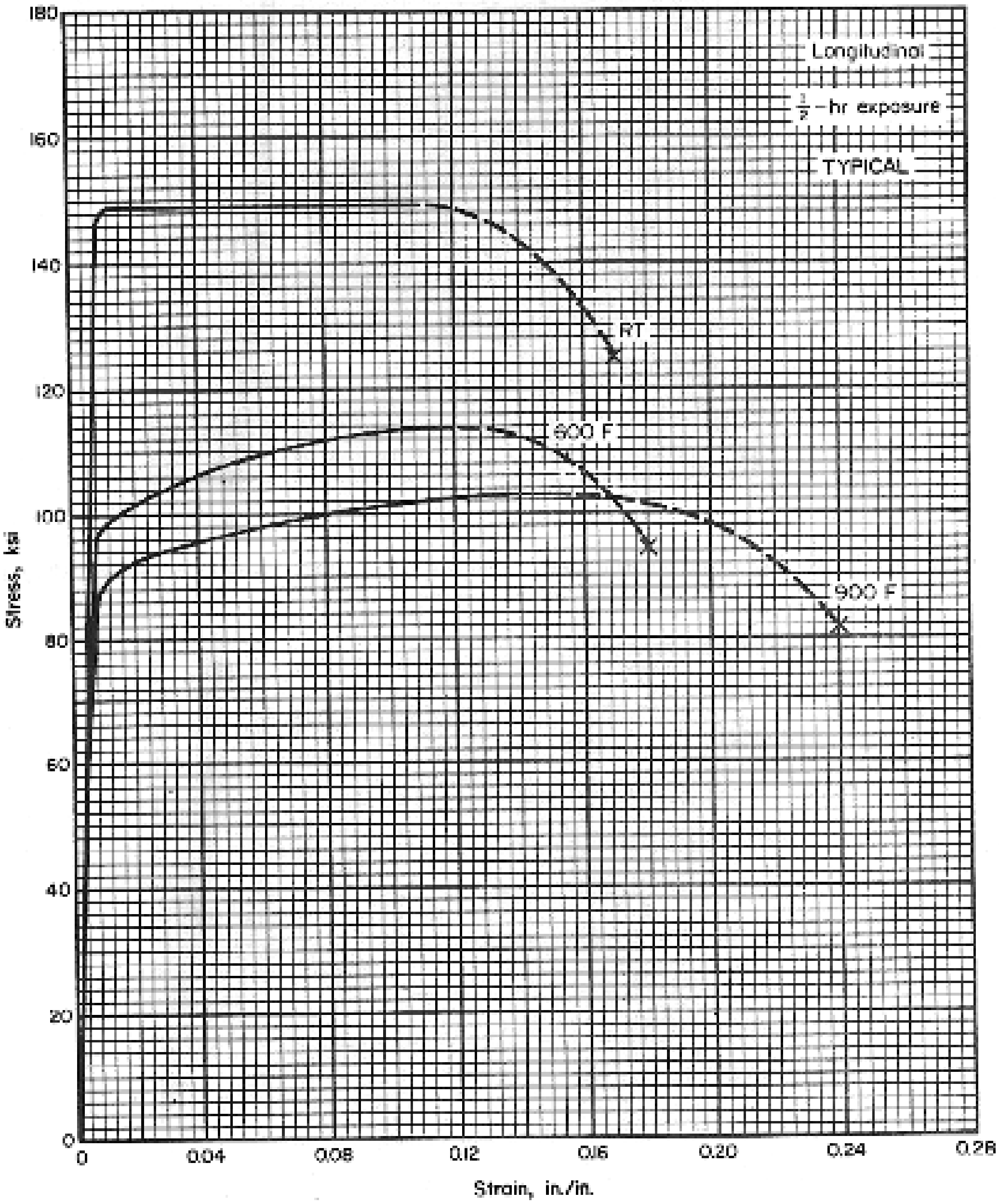


Figure 5.3.3.1.6(c). Typical tensile stress-strain curves (full range) for duplex-annealed Ti-6Al-2Sn-4Zr-2Mo alloy sheet at room and elevated temperatures.

5.4 ALPHA-BETA TITANIUM ALLOYS

The alpha-beta titanium alloys contain both alpha and beta phases at room temperature. The alpha phase is similar to that of unalloyed titanium but is strengthened by alpha stabilizing additions (e.g., aluminum). The beta phase is the high-temperature phase of titanium but is stabilized to room temperature by sufficient quantities of beta stabilizing elements such as vanadium, molybdenum, iron, or chromium. In addition to strengthening of titanium by the alloying additions, alpha-beta alloys may be further strengthened by heat treatment. The alpha-beta alloys have good strength at room temperature and for short times at elevated temperature. They are not noted for long-time creep strength. With the exception of annealed Ti-6Al-4V, these alloys are not recommended for cryogenic applications. The weldability of many of these alloys is poor because of the two-phase microstructure. However, some of them can be welded successfully with special precautions.

5.4.1 TI-6AL-4V

5.4.1.0 *Comments and Properties* — Ti-6Al-4V is available in all mill product forms as well as castings and powder metallurgy forms. It can be used in either the annealed or solution treated plus aged (STA) conditions and is weldable. Useful temperature range is from -320 to 750°F. For maximum toughness, Ti-6Al-4V should be used in the annealed or duplex-annealed conditions whereas for maximum strength, the STA condition is used. The full strength potential for this alloy is not available in sections greater than 1 inch.

Manufacturing Considerations — Ti-6Al-4V alloy may be forged above the beta transus temperature using procedures to promote a high toughness material. The material is routinely finished below beta transus temperature for good combinations of fabricability, strength, ductility, and toughness. Elevated temperatures are usually used for form flat-rolled products although extensive forming may be accomplished at room temperature. Flat-rolled products are usually formed and used in the annealed condition although some forming in the STA condition is possible.

This alloy can be spot welded and is being fusion welded extensively in certain applications. Established titanium-welding techniques must be employed and special design considerations may be involved in fusion weldments. Stress-relief annealing after welding is recommended.

Environmental Considerations — Ti-6Al-4V can withstand prolonged exposure to temperatures up to 750°F without loss of ductility. Its toughness in the annealed condition is adequate at temperatures down to -320°F. (A special low interstitial grade may be used down to -423°F.) Ti-6Al-4V is resistant to hot-salt stress corrosion to about its maximum use temperature depending on exposure time and exposure stress. The material is marginally susceptible to aqueous chloride solution stress corrosion, but is considered to have good resistance to this reaction compared with other commonly used alloys. Under certain conditions, titanium, when in contact with cadmium, silver, mercury, or certain of their compounds, may become embrittled. Refer to MIL-S-5002 and MIL-STD-1568 for restrictions concerning applications with titanium in contact with these metals or their compounds.

Heat Treatment — This alloy is commonly specified in either the annealed condition or in the fully heat-treated condition. Annealing requires 1 hour at 1300°F followed by furnace cooling if maximum ductility is required.

The specified fully heat-treated, or solution-treated and aged condition for sheet is as follows:

Solution treat at 1700°F for 5 to 25 minutes, quench in water.

Age at 975°F for 4 to 6 hours, air cool.

For bars and forgings:

Solution treat at 1700°F for 1 hour, quench in water.

Age at 1000°F for 3 hours, air cool.

Specifications and Properties — Some material specifications for Ti-6Al-4V are shown in Table 5.4.1.0(a). Room-temperature mechanical properties for Ti-6Al-4V are shown in Tables 5.4.1.0(b) through (g). The effect of temperature on physical properties is shown in Figure 5.4.1.0.

Table 5.4.1.0(a). Material Specifications for Ti-6Al-4V

Specification	Form
AMS-T-9046	Sheet, strip, and plate
MIL-T-9047[a]	Bar
AMS 4934	Extrusion
AMS 4935	Extrusion
AMS 4965	Bar
AMS 4928	Bar and die forging
AMS 4911	Sheet, strip, and plate
AMS 4920	Die forging
AMS 4962	Investment casting

a Inactive for new design

5.4.1.1 ***Annealed Condition*** — Elevated temperature curves for annealed Ti-6Al-4V are shown in Figures 5.4.1.1.1 through 5.4.1.1.5. Typical stress-strain curves at several temperatures are shown in Figures 5.4.1.1.6(a) through (c). Typical full-range stress-strain curves at room temperature are shown in Figure 5.4.1.1.6(d). Unnotched and notched fatigue data are shown in Figures 5.4.1.1.8(a) through (g). Fatigue crack-propagation data for plate are shown in Figure 5.4.1.1.9.

5.4.1.2 ***Solution-Treated and Aged Condition*** — Elevated temperature curves for solution-treated and aged alloy are shown in Figures 5.4.1.2.1 through 5.4.1.2.4. Typical tensile and compressive stress-strain and tangent-modulus curves are shown in Figures 5.4.1.2.6(a) through (g). Typical full-range stress-strain curves at several temperatures up to 1000°F are shown in Figure 5.4.1.2.6(h). A nomograph of typical creep properties of solution-treated and aged sheet for the temperature range 600°F through 800°F is shown in Figure 5.4.1.2.7. Fatigue data at room and elevated temperatures are shown in Figures 5.4.1.2.8(a) through (i).

Table 5.4.1.0(b). Design Mechanical and Physical Properties of Ti-6Al-4V Sheet, Strip, and Plate

Specification	AMS 4911 and AMS-T-9046[a], Comp. AB-1						AMS-T-9046[a], Comp. AB-1			
Form	Sheet		Plate				Sheet, strip, and plate			
Condition	Annealed						Solution treated and aged			
Thickness, in.	≤ 0.1875		0.1875-2.000		2.001-4.000		≤ 0.1875	0.1875-0.750	0.751-1.000	1.001-2.000
Basis	A	B	A	B	A	B	S	S	S	S
Mechanical Properties:										
F_{tu}, ksi:										
L	134	139	130[b]	135	130[c]	137	160	160	150	145
LT	134	139	130[b]	138	130[c]	137	160	160	150	145
F_{ty}, ksi:										
L	126	131	120	125	118	123	145	145	140	135
LT	126	131	120[b]	131	118	129	145	145	140	135
F_{cy}, ksi:										
L	133	138	124	129	122	127	154	150	145	...
LT	135	141	130	142	128	140	162	...	...	...
F_{su}, ksi	87	90	79	84	79	84	100	93	87	...
F_{bru}, ksi:										
(e/D = 1.5)	213[d]	221[d]	206[d]	214[d]	206[d]	217[d]	236	248	233	...
(e/D = 2.0)	272[d]	283[d]	260[d]	276[d]	260[d]	274[d]	286	308	289	...
F_{bry}, ksi:										
(e/D = 1.5)	171[c]	178[d]	164[d]	179[d]	161[d]	176[d]	210	210	203	...
(e/D = 2.0)	208[d]	217[d]	194[d]	212[d]	191[d]	209[d]	232	243	235	...
e, percent (S-basis):										
L	8[e]	...	10	...	10	...	5[f]	8	6	6
LT	8[e]	...	10	...	10	...	5[f]	8	6	6
E, 10^3 ksi	16.0									
E_c, 10^3 ksi	16.4									
G, 10^3 ksi	6.2									
μ	0.31									
Physical Properties:										
ω, lb/in.^{3}	0.160									
C, K, and α	See Figure 4.5.1.0									

a MIL-T-9046 was canceled and superceded by AMS-T-9046

b The rounded T_{99} values are higher than specification values as follows: F_{tu}(L) = 131 ksi, F_{tu}(LT) = 132 ksi, and F_{ty}(LT) = 123 ksi.

c The rounded T_{99} values are higher than specification values as follows: F_{tu}(L) = 133 ksi and F_{tu}(LT) = 133 ksi.

d Bearing values are “dry pin” values per Section 1.4.7.1.

e 8%—0.025 to 0.062 in. and 10%—0.063 in. and above.

f 5%—0.050 in. and above; 4%—0.033 to 0.049 in. and 3%—0.032 in. and below.

Table 5.4.1.0(c_1). Design Mechanical and Physical Properties of Ti-6Al-4V Bar

Specification	AMS 4928												
Form	Bar												
Condition	Annealed												
Thickness or diameter, in.	<0.500	0.500-1.000		1.001-2.000		2.001-3.000		3.001-4.000		4.001-5.000		5.001-6.000	
Basis	S	A	B	A	B	A	B	A	B	A	B	A	B
Mechanical Properties:													
F_{tu}, ksi:													
L	135	135^{a}	142	134	140	130^{a}	138	130	135	128	133	125	131
LT	135^{b}	135^{a}	144	135^{a}	143	130^{a}	142	130^{a}	141	130^{a}	139	130^{a}	138
F_{ty}, ksi:													
L	125	125^{c}	134	125^{c}	131	120^{c}	128	120	125	117	122	114	119
LT	125^{b}	125^{c}	134	125^{c}	132	120^{c}	131	120^{c}	129	120^{c}	127	119	125
F_{cy}, ksi:													
L	129	129	138	129	135	...	...	...	...	...	...	...	...
LT	...	...	...	...	...	...	...	...	...	...	...	...	...
F_{su}, ksi	83	83	87	82	86	...	...	...	...	...	...	...	...
F_{bru}, ksi:													
(e/D = 1.5)	201	201	212	200	209	...	...	...	...	...	...	...	...
(e/D = 2.0)	253	253	266	251	262	...	...	...	...	...	...	...	...
F_{bry}, ksi:													
(e/D = 1.5)	177	177	190	177	186	...	...	...	...	...	...	...	...
(e/D = 2.0)	205	205	220	205	215	...	...	...	...	...	...	...	...
e, percent (S-basis):													
L	10	10	...	10	...	10	...	10	...	10	...	10	...
LT	10^{b}	10^{b}	...	10^{b}	...	10^{b}	...	10	...	10	...	10	...
ST	...	...	...	...	...	10^{b}	...	10	...	8	...	8	...
RA, percent (S-basis):													
L	25	25	...	25	...	25	...	25	...	20	...	20	...
LT	20^{b}	20^{b}	...	20^{b}	...	20^{b}	...	20	...	20	...	20	...
ST	...	...	...	...	...	15^{b}	...	15	...	15	...	15	...
E, 10^3 ksi	16.9												
E_c, 10^3 ksi	17.2												
G, 10^3 ksi	6.2												
μ	0.31												
Physical Properties:													
ω, lb/in.^{3}	0.160												
C, K, and α	See Figure 5.4.1.0												

a S-basis. The rounded T_{99} values for F_{tu} are as follows: 0.500-1.000 (L) = 137 ksi and (LT) = 140 ksi, 1.001-2.000 (LT) = 139 ksi, 2.001-3.000 (L) = 132 ksi and (LT) = 138 ksi, 3.001-4.000 (LT) = 136 ksi, 4.001-5.000 (LT) = 135 ksi, and 5.001-6.000 (LT) = 134 ksi.

b Applicable, providing LT or ST dimension is ≥ 2.500 inches.

c S-basis. The rounded T_{99} values for F_{ty} are as follows: 0.500-1.000 (L)and (LT) = 129 ksi, 1.001-2.000 (L) = 126 ksi and (LT) = 127 ksi, 2.001-3.000 (L) = 123 ksi and (LT) = 127 ksi, 3.001-4.000 (LT) = 123 ksi, and 4.001-5.000 (LT) = 121 ksi.

Table 5.4.1.0(c_2). Design Mechanical and Physical Properties of Ti-6Al-4V Bar

Specification	MIL-T-9047[a]												
Form	Bar												
Condition	Annealed												
Cross-sectional area, in.^{2}	≤48												
Thickness or diameter, in.	<0.500	0.500-1.000		1.001-2.000		2.001-3.000		3.001-4.000		4.001-5.000		5.001-6.000	
Basis	S	A	B	A	B	A	B	A	B	A	B	A	B
Mechanical Properties:													
F_{tu}, ksi:													
L	130	130[b]	142	130[b]	140	130[b]	138	130	135	128	133	125	131
LT	130[c]	130[b]	144	130[b]	143	130[b]	142	130[b]	141	130[b]	139	130[b]	138
F_{ty}, ksi:													
L	120	120[d]	134	120[d]	131	120[d]	128	120	125	117	122	114	119
LT	120[c]	120[d]	134	120[d]	132	120[d]	131	120[d]	129	120	127	119	125
F_{cy}, ksi:													
L	124	124	138	124	135	...	...	...	...	...	...	...	...
LT	...	...	...	...	...	...	...	...	...	...	...	...	...
F_{su}, ksi	80	80	87	80	86	...	...	...	...	...	...	...	...
F_{bru}, ksi:													
(e/D = 1.5)	194	194	212	194	209	...	...	...	...	...	...	...	...
(e/D = 2.0)	244	244	266	244	262	...	...	...	...	...	...	...	...
F_{bry}, ksi:													
(e/D = 1.5)	170	170	190	170	186	...	...	...	...	...	...	...	...
(e/D = 2.0)	197	197	220	197	215	...	...	...	...	...	...	...	...
e, percent (S basis):													
L	10	10	...	10	...	10	...	10	...	10	...	10	...
LT	10[c]	10[c]	...	10[c]	...	10[c]	...	10	...	10	...	10	...
ST	...	...	...	...	...	...	...	8	...	8	...	8	...
RA, percent (S-basis):													
L	25	25	...	25	...	25	...	25	...	20	...	20	...
LT	25[c]	25[c]	...	25[c]	...	25[c]	...	25	...	20	...	20	...
ST	...	...	...	...	...	...	...	15	...	15	...	15	...
E, 10^3 ksi	16.9												
E_c, 10^3 ksi	17.2												
G, 10^3 ksi	6.5												
μ	0.31												
Physical Properties:													
ω, lb/in.^{3}	0.160												
C, K, and α	See Figure 5.4.1.0												

a Inactive for new design.

b S-basis. The rounded T_{99} values for F_{tu} are as follows: 0.500-1.000 (L) = 137 ksi and (LT) = 140 ksi, 1.001-2.000 (L) = 134 ksi and (LT) = 139 ksi, 2.001-3.000 (L) = 132 ksi and (LT) = 138 ksi, 3.001-4.000 (LT) = 136 ksi, 4.001-5.000 (LT) = 135 ksi, and 5.001-6.000 (LT) = 134 ksi.

c Applicable, providing LT dimension is ≥ 3.000 inches.

d S-basis. The rounded T_{99} values for F_{ty} are as follows: 0.500-1.000 (L)and (LT) = 129 ksi, 1.001-2.000 (L) = 126 ksi and (LT) = 127 ksi, 2.001-3.000 (L) = 123 ksi and (LT) = 125 ksi, 3.001-4.000 (LT) = 123 ksi, and 4.001-5.000 (LT) = 121 ksi.

Table 5.4.1.0(d). Design Mechanical and Physical Properties of Ti-6Al-4V Bar

Specification	AMS 4965[a] and MIL-T-9047[b]									MIL-T-9047[b]				
Form	Rectangular bar									Round, square, and hexagon bar				
Condition	Solution treated and aged													
Width, in.	0.501-8.000	1.001-4.000	4.001-8.000	1.501-4.000	4.001-8.000	2.001-4.000	4.001-8.000	3.001-8.000	4.001-8.000	...	...	...	...	...
Thickness, in.	≤0.500	0.501-1.000		1.001-1.500		1.501-2.000		2.001-3.000	3.001-4.000	≤0.500	0.501-1.000	1.001-1.500	1.501-2.000	2.001-3.000
Basis	S	S	S	S	S	S	S	S	S	S	S	S	S	S
Mechanical Properties:														
F_{tu}, ksi:														
L	160	155	150	150	145	145	140	135	130	165	160	155	150	140
LT	160	155	150	150	145	145	140	135	130	165	160	155	150	140
F_{ty}, ksi:														
L	150	145	140	140	135	135	130	125	120	155	150	145	140	130
LT	150	145	140	140	135	135	130	125	120	155	150	145	140	130
F_{cy}, ksi:														
L	...	...	...	...	...	...	...	...	...	...	...	...	...	...
LT	...	...	...	...	...	...	...	...	...	...	...	...	...	...
F_{su}, ksi	92	...	...	...	...	...	...	...	...	...	...	...	...	...
F_{bru}, ksi:														
(e/D = 1.5)	...	...	...	...	...	...	...	...	...	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...	...	...	...	...	...	...	...	...	...
F_{bry}, ksi:														
(e/D = 1.5)	...	...	...	...	...	...	...	...	...	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...	...	...	...	...	...	...	...	...	...
e, percent:														
L	10	10	10	10	10	10	10	10	8	10	10	10	10	10
LT	10	10	10	10	10	10	10	10	8	10	10	10	10	10
RA, percent:														
L	25	20	20	20	20	20	20	20	15	20	20	20	20	20
LT	25	20	20	20	20	20	20	20	15	20	20	20	20	20
E, 10^3 ksi	16.9													
E_c, 10^3 ksi	17.2													
G, 10^3 ksi	6.2													
μ	0.31													
Physical Properties:														
ω, lb/in.^{3}	0.160													
C, K, and α	See Figure 5.4.1.0													

a For AMS 4965, *e* and *RA* values may be different than those shown.
b Inactive for new design.

Table 5.4.1.0(e). Design Mechanical and Physical Properties of Ti-6Al-4V Extrusion

Specification	AMS 4935				AMS 4934							
Form	Extrusion											
Condition	Annealed				Solution treated and aged							
Thickness or diameter, in.	≤2.000		2.001-3.000		<0.500		0.501-0.750		0.751-1.000		1.001-2.000	2.001-3.000
Basis	A	B	A	B	A	B	A	B	A	B	S	S
Mechanical Properties:												
F_{tu}, ksi:												
L	130[a]	137	130[b]	135	155	163	151	157	147	153	140	130
LT[c]	130[a]	139	130[b]	139	155	163	151	157	147	155	140	130
F_{ty}, ksi:												
L	120	124	118	122	138	147	138	143	133	140	130	120
LT[c]	120[a]	128	120	125	138	147	138	145	133	142	130	120
F_{cy}, ksi:												
L	128	133	124	128	147	157	147	153	142	150	139	128
LT[c]	129	138	...	...	147	157	147	155	139	152	139	128
F_{su}, ksi	83	89	...	...	94	99	92	96	89	93	85	79
F_{bru}[d], ksi:												
(e/D = 1.5)	214	226	...	...	243	256	237	246	231	240	220	204
(e/D = 2.0)	264	278	...	...	311	327	303	315	295	307	281	261
F_{bry}[d], ksi:												
(e/D = 1.5)	180	186	...	...	208	222	208	216	201	212	196	182
(e/D = 2.0)	210	217	...	...	242	257	242	250	233	245	228	210
e, percent (S-basis):												
L	10	...	10	...	6	...	6	...	6	...	6	6
LT[c]	8	...	8	...	6	...	6	...	6	...	6	6
RA, percent (S-basis):												
L	20	...	20	...	12	...	12	...	12	...	12	12
LT[c]	15	...	15	...	12	...	12	...	12	...	12	12
E, 10^3 ksi	16.9											
E_c, 10^3 ksi	17.2											
G, 10^3 ksi	6.5											
μ	0.31											
Physical Properties:												
ω, lb/in.^{3}	0.160											
C, K, and α	See Figure 5.4.1.0											

a S-basis. The rounded T_{99} values are higher than specification values as follows: F_{tu} (L) and (LT) = 132 ksi and F_{ty} (LT) = 121 ksi.

b S-basis. The rounded T_{99} values are higher than specification values as follows: F_{tu} (L) = 132 ksi and F_{tu} (LT) = 136 ksi.

c Applicable, providing LT dimension is ≥2.500 inches.

d Bearing values are "dry pin" values per Section 1.4.7.1.

Table 5.4.1.0(f). Design Mechanical and Physical Properties of Ti-6Al-4V Die Forging

Specification	AMS 4928			AMS 4920	
Form	Die forging				
Condition	Alpha-beta processed, annealed			Alpha-beta or beta processed, annealed	
Thickness, in.	≤2.000	2.001-4.000	4.001-6.000	≤2.000	2.001-6.000
Basis	S	S	S	S	S
Mechanical Properties:					
F_{tu}, ksi:					
L	135	130	130	130	130
LT	135[a]	130[a]	130	130[a]	130[a]
ST	...	130[a]	130	...	130[a]
F_{ty}, ksi:					
L	125	120	120	120	120
LT	125[a]	120[a]	120	120[a]	120[a]
ST	...	120[a]	120	...	120[a]
F_{cy}, ksi:					
L	...	123	123	...	123
LT	...	128	128	...	128
ST	...	...	...	...	...
F_{su}, ksi	...	79	79	...	79
F_{bru}, ksi:					
(e/D = 1.5)	...	203	203	...	203
(e/D = 2.0)	...	257	257	...	257
F_{bry}, ksi:					
(e/D = 1.5)	...	171	171	...	171
(e/D = 2.0)	...	201	201	...	201
e, percent:					
L	10	10	10	8	8
LT	10[a]	10[a]	10	8[a]	8[a]
ST	...	10[a]	8	...	8[a]
RA, percent:					
L	25	25	20	15	15
LT	20[a]	20[a]	20	15[a]	15[a]
ST	...	15[a]	15	...	15[a]
E, 10^3 ksi	16.9				
E_c, 10^3 ksi	17.2				
G, 10^3 ksi	6.5				
μ	0.31				
Physical Properties:					
ω, lb/in.^{3}	0.160				
C, K, and α	See Figure 5.4.1.0				

a Applicable providing LT or ST dimension is ≥2.500 inches.

Table 5.4.1.0(g). Design Mechanical and Physical Properties of Ti-6Al-4V Titanium Alloy Casting

Specification	AMS 4962	
Form	HIP Casting	
Temper	Annealed	
Thickness, in.	≤1.000	
Location within casting	Designated area	
Basis	A	B
Mechanical Properties:		
F_{tu}, ksi	125[a]	128
F_{ty}, ksi	119	122
F_{cy}, ksi	...	...
F_{su}, ksi	...	...
F_{bru}, ksi:		
(e/D = 1.5)	...	...
(e/D = 2.0)	...	...
F_{bry}, ksi:		
(e/D = 1.5)	...	...
(e/D = 2.0)	...	...
e, percent (S-basis)	5	...
E, 10^3 ksi	16.9	
E_c, 10^3 ksi	16.9	
G, 10^3 ksi	...	
μ	...	
Physical Properties:		
ω, lb/in.^{3}	...	
C, Btu/(lb)(°F)	...	
K, Btu/[(hr)(ft^2)(°F)/ft]	...	
α, 10^{-6} in./in./°F	...	

[a] S-basis. The rounded T_{99} value is 126 ksi.

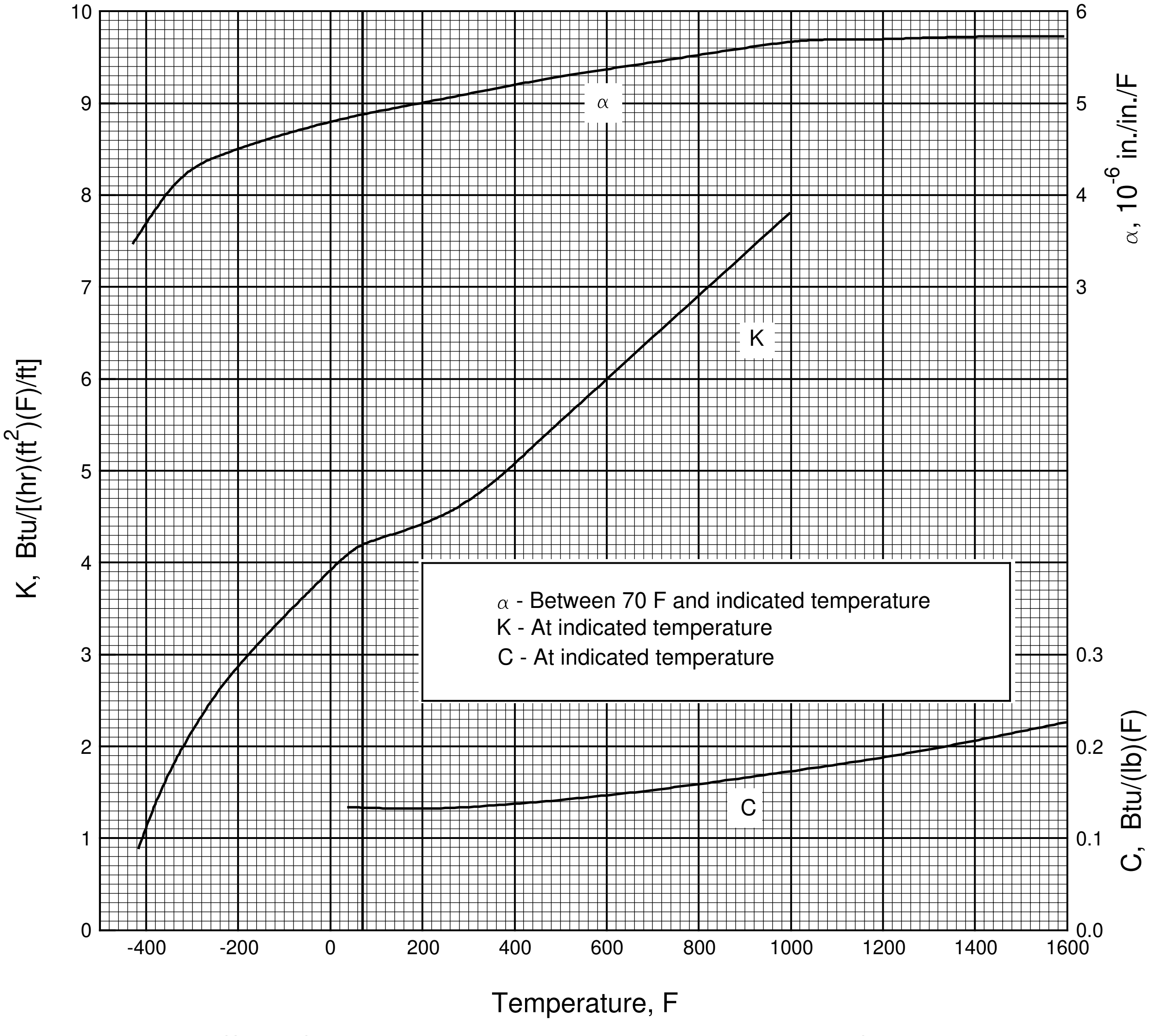


Figure 5.4.1.0. Effect of temperature on the physical properties of Ti-6Al-4V alloy (wrought products).

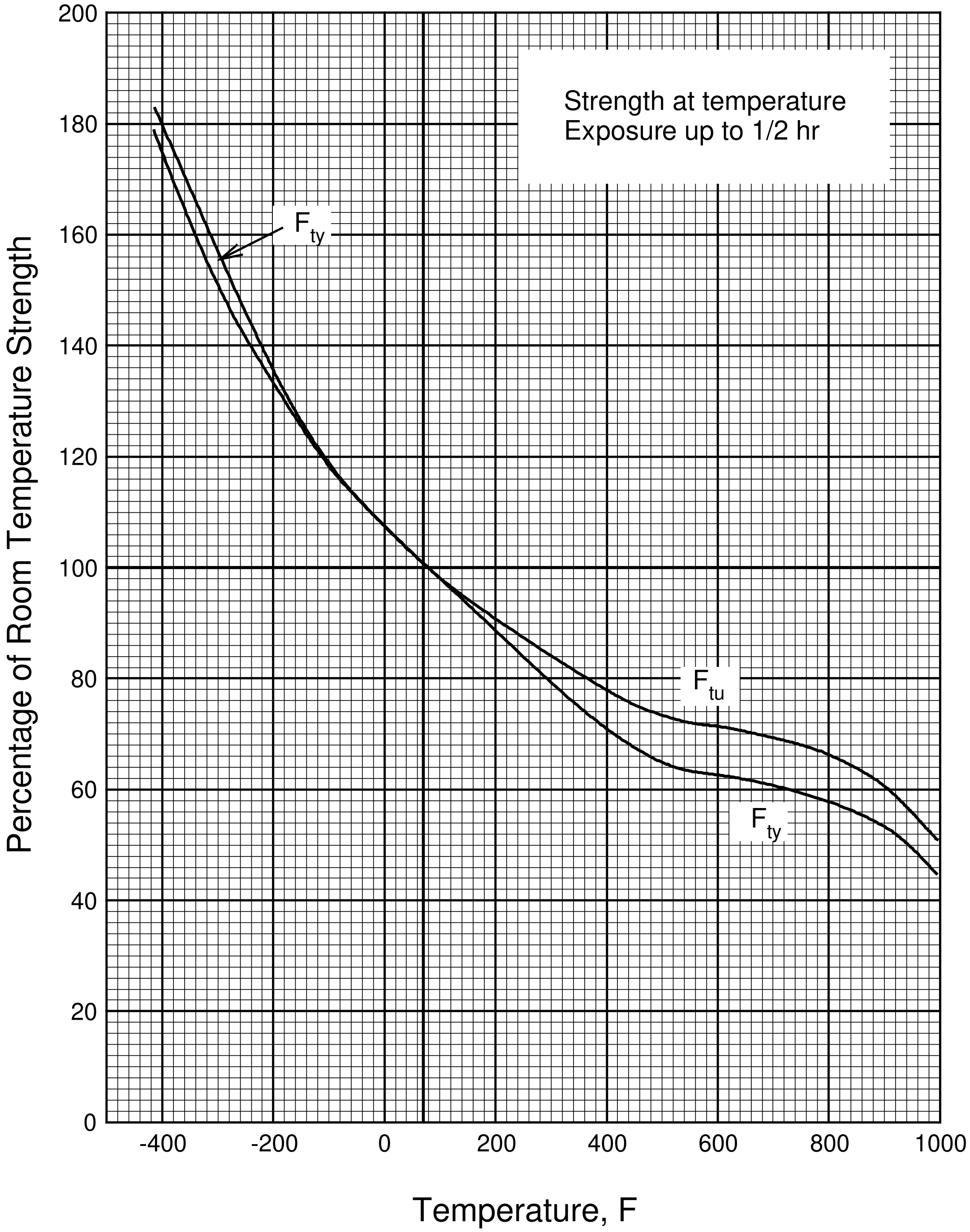


Figure 5.4.1.1.1. Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of annealed Ti-6Al-4V alloy (all wrought products).

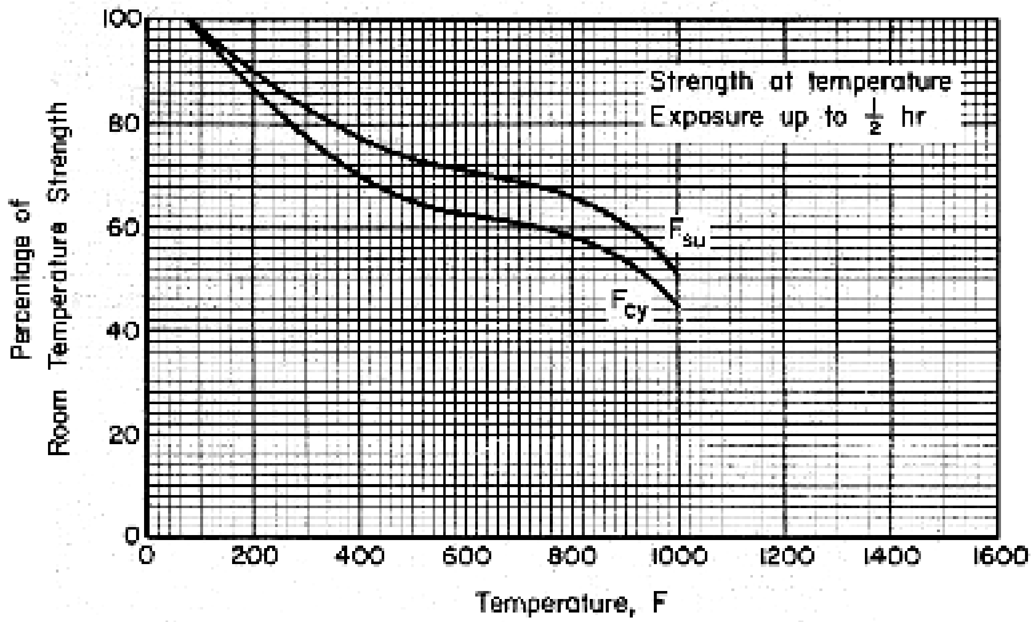


Figure 5.4.1.1.2. Effect of temperature on the compressive yield strength (F_{cy}) and the shear ultimate strength (F_{su}) of annealed Ti-6Al-4V alloy (all wrought products).

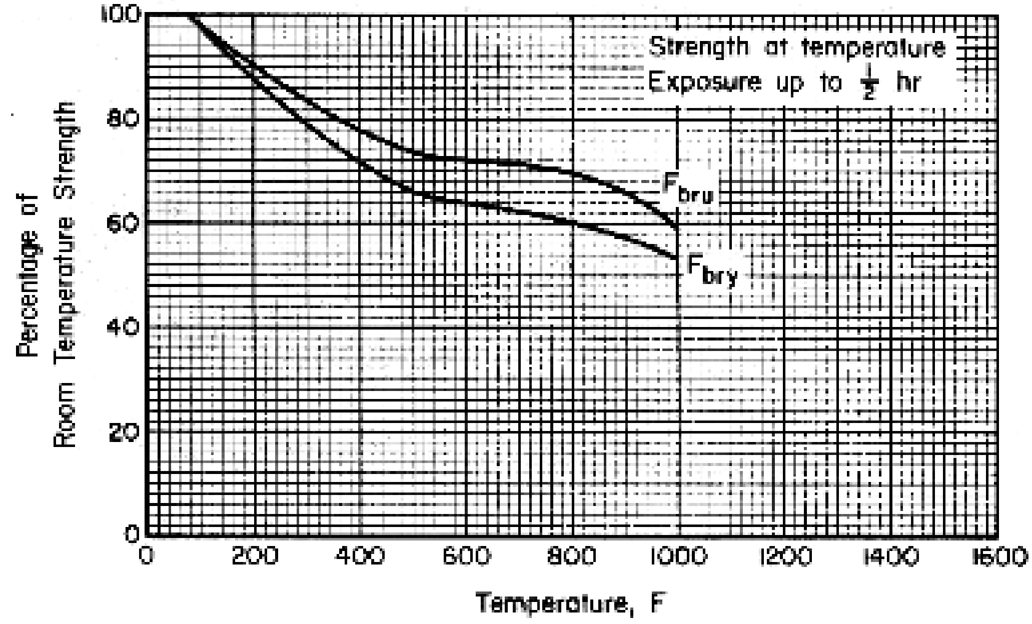


Figure 5.4.1.1.3. Effect of temperature on the bearing ultimate strength (F_{bru}) and the bearing yield strength (F_{bry}) of annealed Ti-6Al-4V alloy (all wrought products).

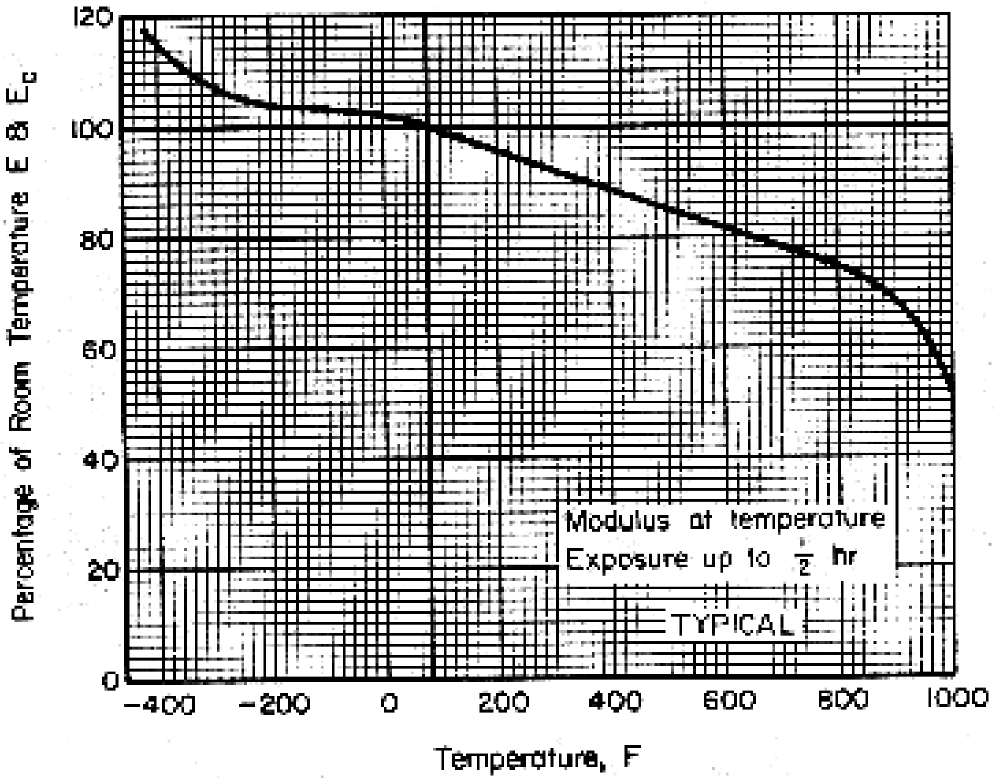


Figure 5.4.1.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of annealed Ti-6Al-4V alloy sheet and bar.

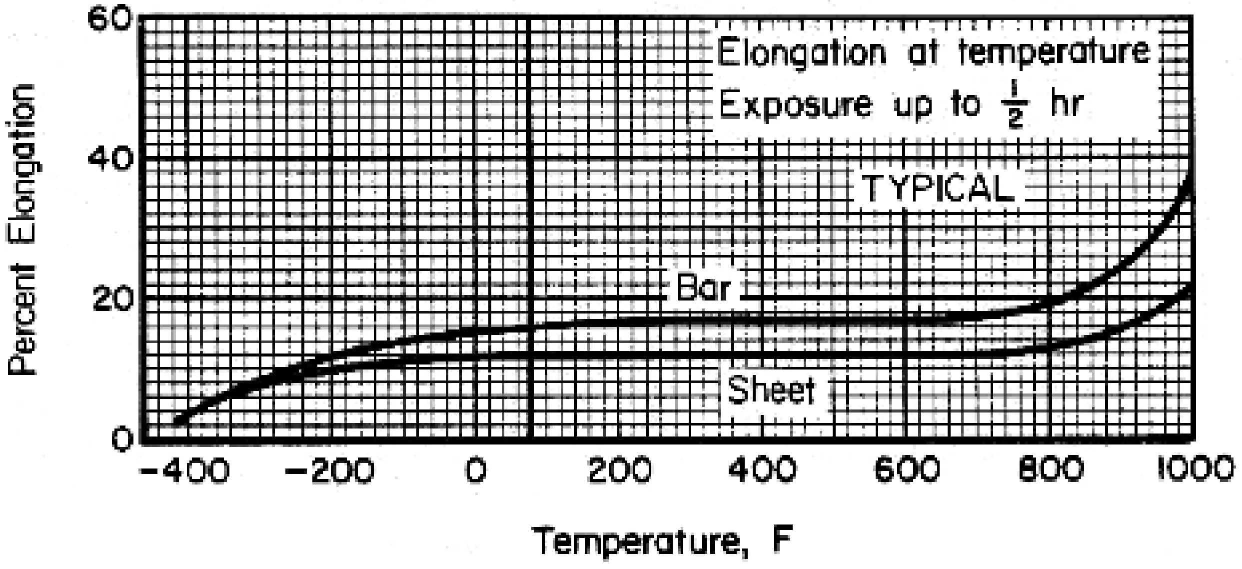


Figure 5.4.1.1.5. Effect of temperature on the elongation of annealed Ti-6Al-4V alloy sheet and bar.

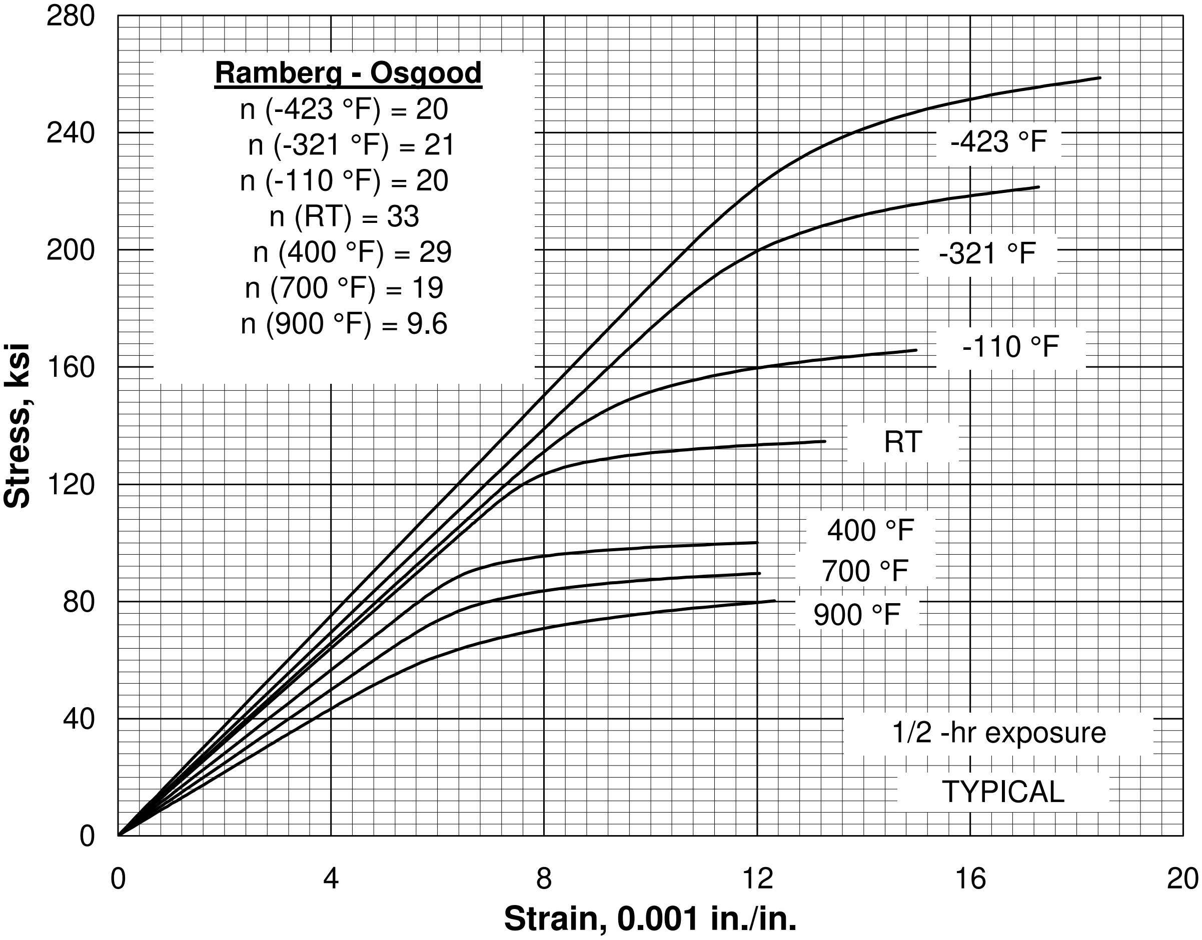


Figure 5.4.1.1.6(a). Typical tensile stress-strain curves at cryogenic, room, and elevated temperatures for annealed Ti-6Al-4V alloy extrusion.

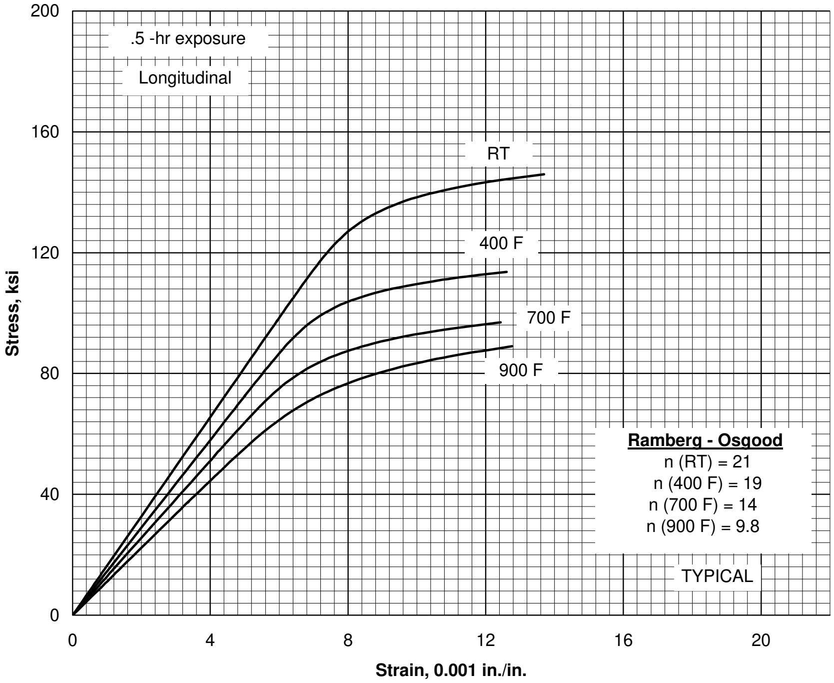


Figure 5.4.1.1.6(b). Typical compressive stress-strain curves at room and elevated temperatures for annealed Ti-6Al-4V alloy extrusion.

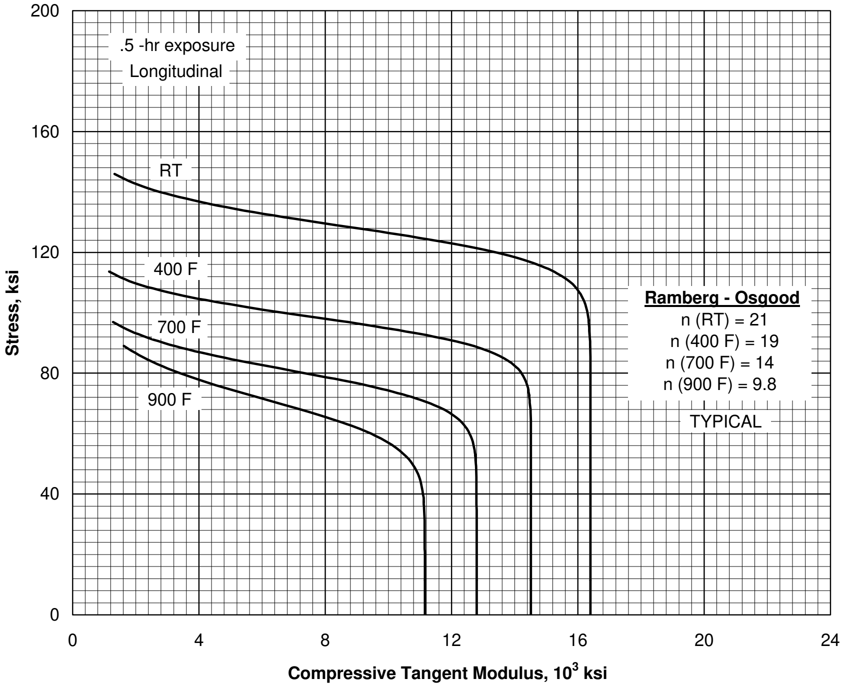


Figure 5.4.1.1.6(c). Typical compressive tangent-modulus curves at room and elevated temperatures for annealed Ti-6Al-4V alloy extrusion.

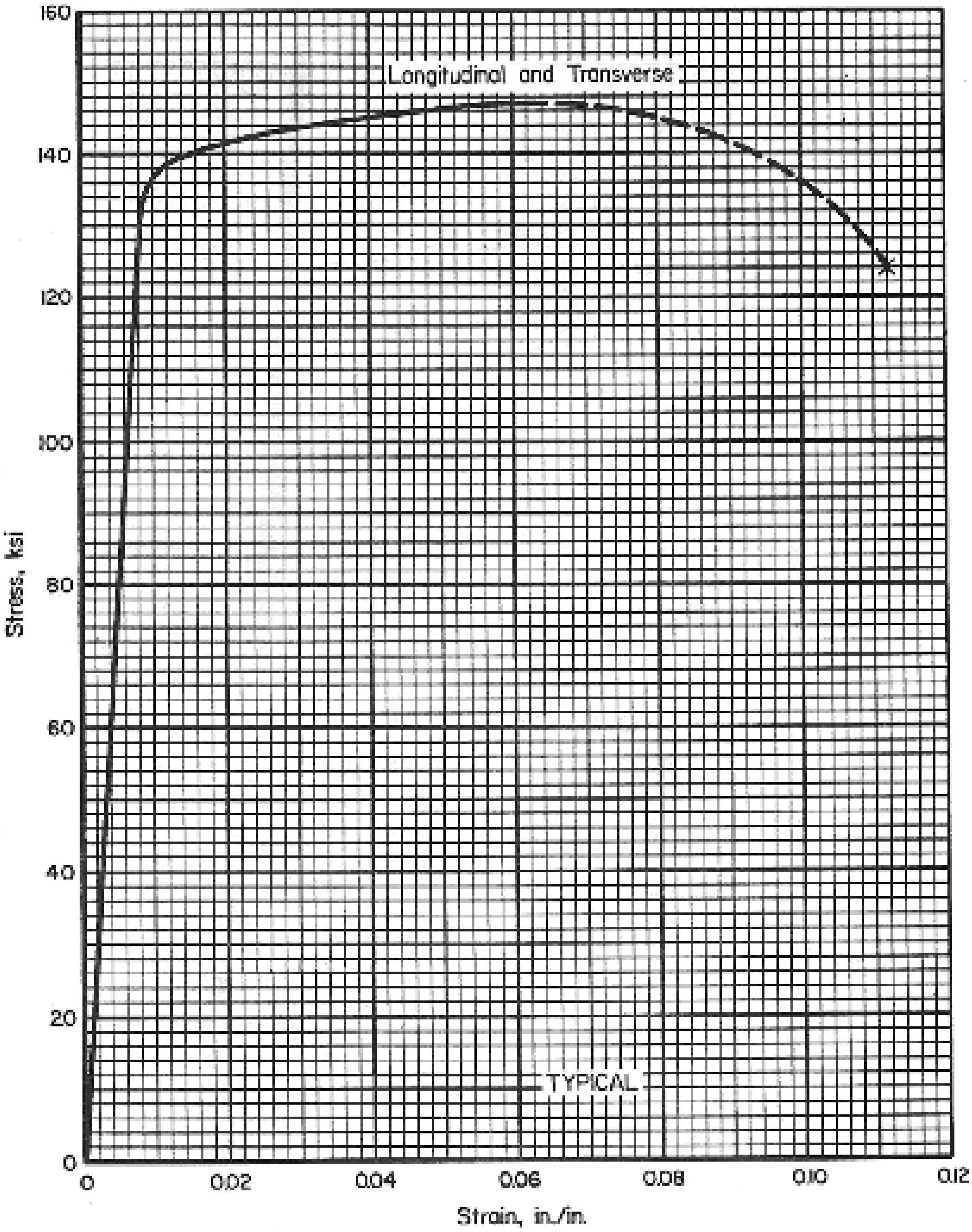


Figure 5.4.1.1.6(d). Typical tensile stress-strain curves (full range) for annealed Ti-6Al-4V sheet at room temperature.

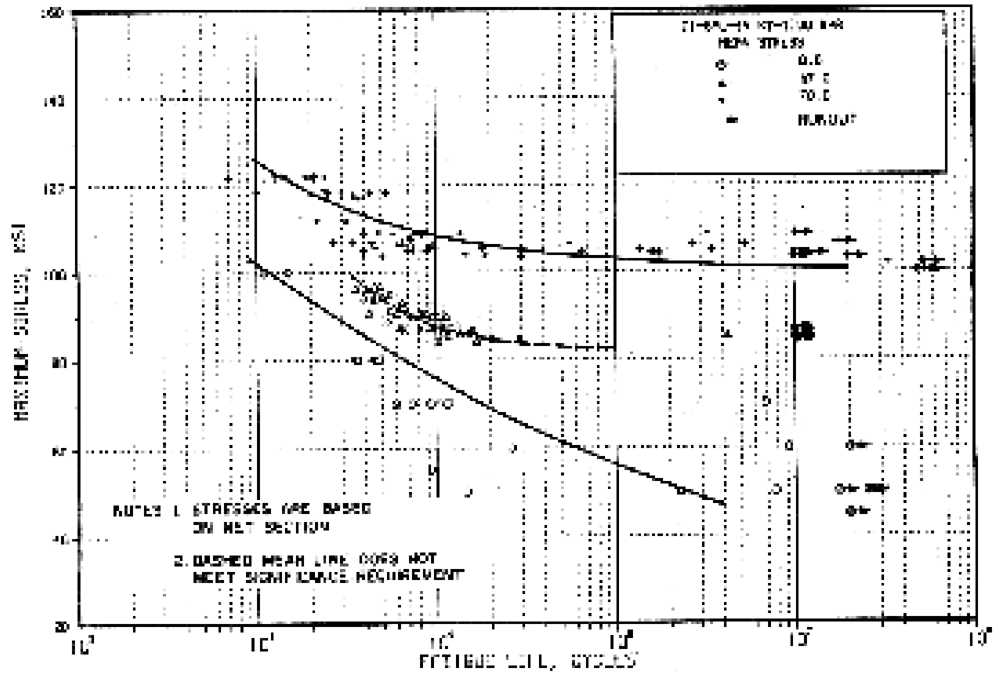


Figure 5.4.1.1.8(a). Best-fit S/N curves for unnotched Ti-6Al-4V annealed bar, longitudinal direction.

Correlative Information for Figure 5.4.1.1.8(a)

Product Form: Bar, 1.25 inch diameter

Properties:	TUS, ksi	TYS, ksi	Temp.,°F
	137	129	RT

Specimen Details: Unnotched
0.280 inch diameter

Surface Conditions:
0 ksi mean stress—32 RMS ground
47 ksi mean stress—100 RMS machined
70 ksi mean stress—32 RMS ground and 100 RMS machined

Reference: 5.4.1.1.8(a)

Test Parameters:
Loading — Axial
Frequency — 1800 cpm
Temperature — RT
Environment — Air

No. of Heats/Lots: Not specified

Equivalent Strain Equation:
Log N_f = 19.18-7.55 log S_{max} $S_m = 0$
= 5.70-0.94 Log (S_{max}-82.3), $S_m = 47$
= 7.08-2.18 Log (S_{max}-99.6), $S_m = 70$

Sample Size = 134

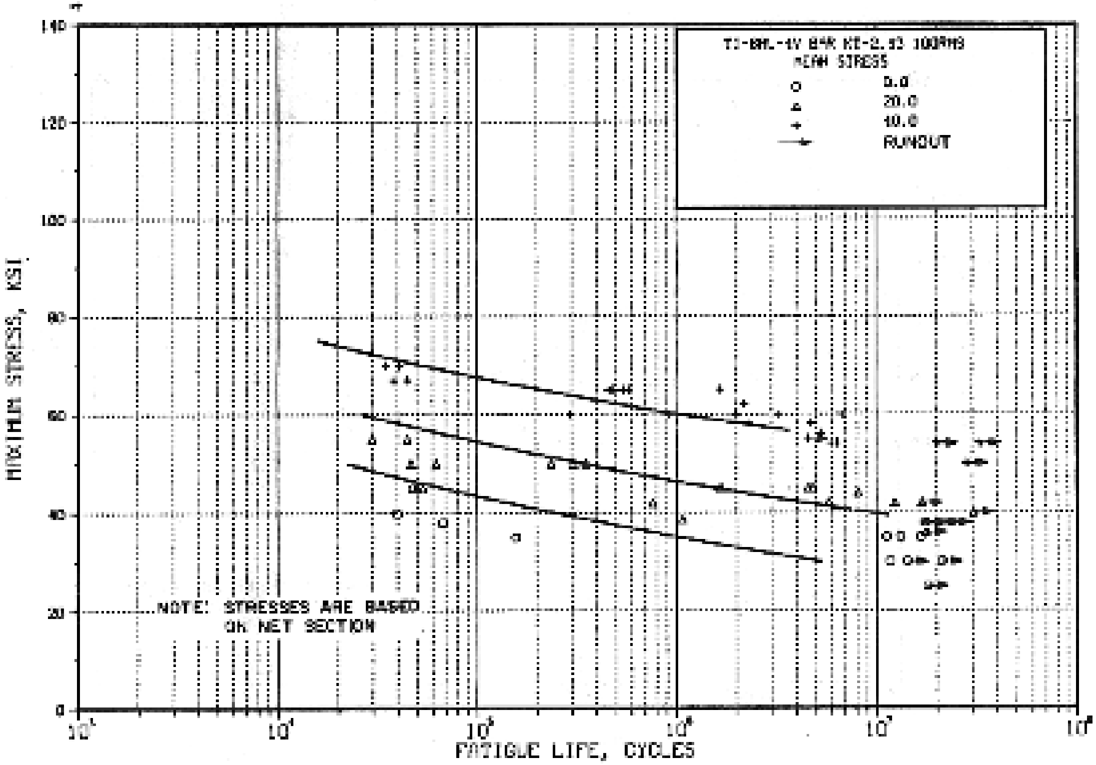


Figure 5.4.1.1.8(b). Best-fit S/N curves for notched, K_t = 2.43, Ti-6Al-4V annealed bar, longitudinal direction.

Correlative Information for Figure 5.4.1.1.8(b)

Product Form: Bar, 1 inch diameter

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	150	143	RT

Specimen Details: 60° V-notch
0.025 inch notch radius
0.260 inch test section diameter at notch

Surface Condition: RMS 100 machined

Reference: 5.4.1.1.8(a)

Test Parameters:
Loading — Axial
Frequency — 1800 cpm
Temperature — RT
Environment — Air

No. of Heats/Lots: Not specified

Equivalent Strain Equation:
Log N_f = 24.1-10.7 log S_{eq}
$S_{eq} = S_{max}(1-R)^{0.49}$
Std. Error of Estimate, Log (Life) = 0.677
Standard Deviation, Log (Life) = 0.920
R^2 = 46%

Sample Size = 46

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

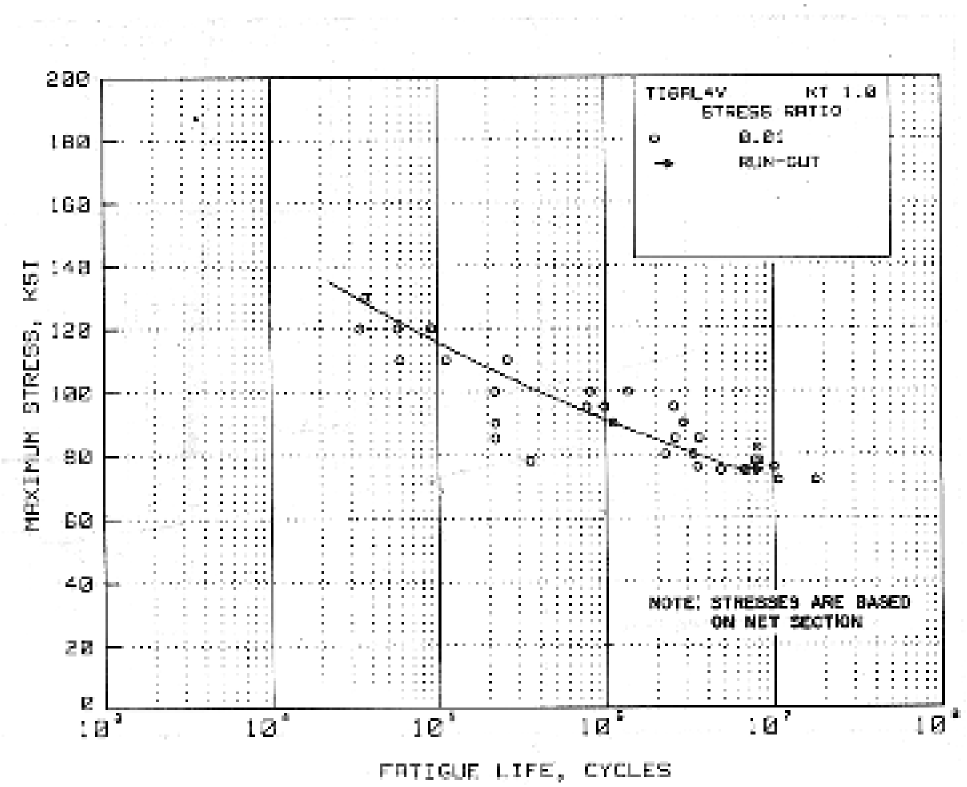


Figure 5.4.1.1.8(c). Best-fit S/N curves for unnotched annealed Ti-6Al-4V extrusion at room temperature, longitudinal direction.

Correlative Information for Figure 5.4.1.1.8(c)

Product Form: Extrusion, 0.300 and 0.560 inch thick

Properties:

TUS, ksi	TYS, ksi	Temp., °F
143	127	RT

Specimen Details: Unnotched
1.50 inch gross width
0.75 inch net width
4.00 inch net section radius

Surface Conditions: RMS 63

Reference: 5.4.1.1.8(b)

Test Parameters:
Loading — Axial
Frequency — 1800 cpm
Temperature — RT
Environment — Air

No. of Heats/Lots: Not specified

Equivalent Strain Equation:
Log N_f = 24.8-9.6 log (S_{max})
Std. Error of Estimate, Log (Life) = 0.41
Standard Deviation, Log (Life) = 0.81
R^2 = 75%

Sample Size = 30

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

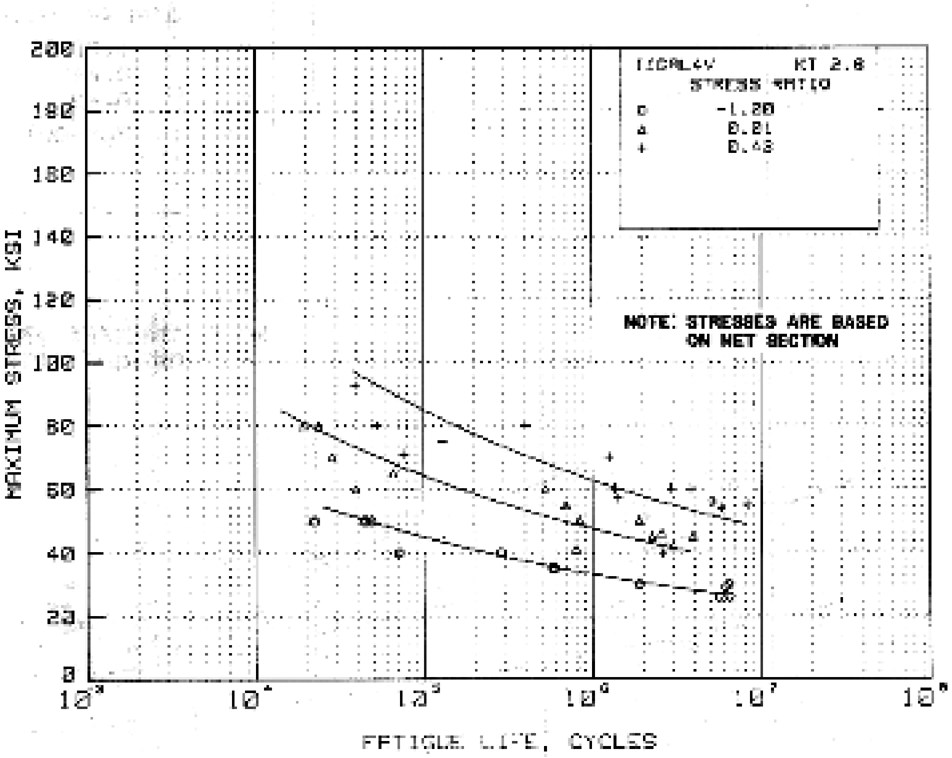


Figure 5.4.1.1.8(d). Best-fit S/N curves for notched, K_t = 2.8, annealed Ti-6Al-4V extrusion at room temperature, longitudinal direction.

Correlative Information for Figure 5.4.1.1.8(d)

Product Form: Extrusion, 0.300 and 0.560 inch thick

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	143	127	RT

Specimen Details: Notched, hole type, K_t = 2.8
0.250 inch hole diameter
1.50 inch gross width
1.25 inch net width

Surface Conditions: RMS 63

Reference: 5.4.1.1.8(b)

Test Parameters:
Loading — Axial
Frequency — 1800 cpm
Temperature — RT
Environment — Air

No. of Heats/Lots: Not specified

Equivalent Strain Equation:
$\text{Log } N_f = 14.8\text{-}5.8 \log (S_{eq}\text{-}14)$
$S_{eq} = S_{max}(1\text{-}R)^{0.50}$
Std. Error of Estimate, Log (Life) = 0.41
Standard Deviation, Log (Life) = 0.86
R^2 = 78%

Sample Size = 40

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

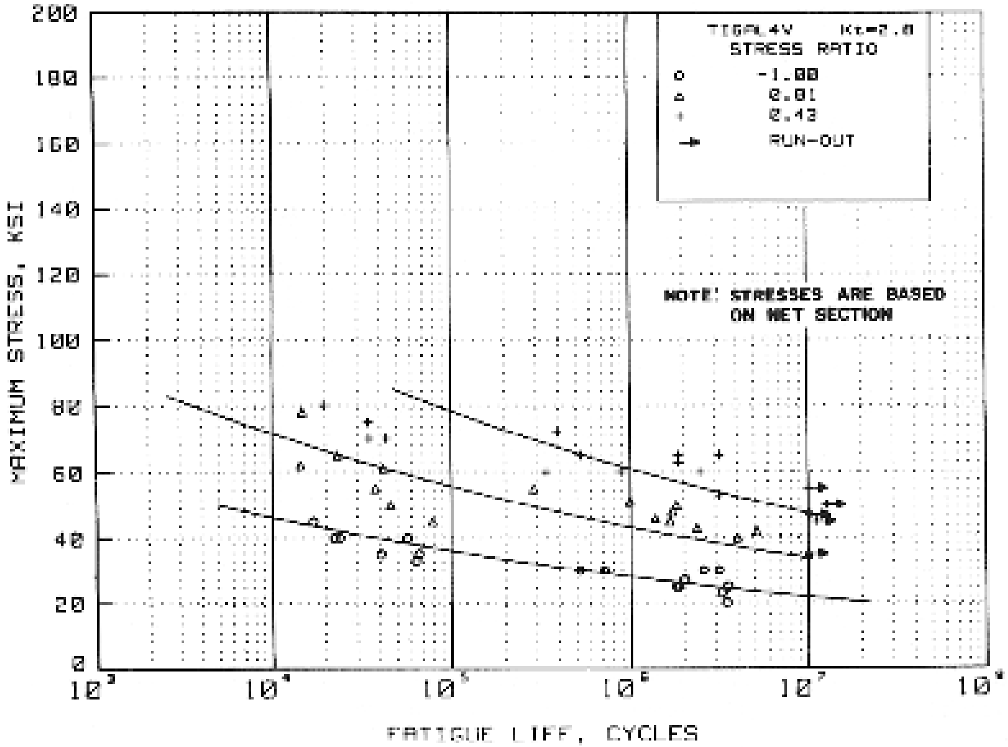


Figure 5.4.1.1.8(e). Best-fit S/N curves for notched, K_t = 2.8, annealed Ti-6Al-4V extrusion at 400 and 600°F, longitudinal direction.

Correlative Information for Figure 5.4.1.1.8(e)

Product Form: Extrusion, 0.300 and 0.560 inch thick

Properties:

TUS, ksi	TYS, ksi	Temp., °F
112	92	400
101	77	600

Specimen Details: Notched, hole type, K_t = 2.8
0.250 inch hole diameter
1.250 inch net width
1.500 inch gross width

Surface Conditions: RMS 63

Reference: 5.4.1.1.8(b)

Test Parameters:
Loading — Axial
Frequency — 1800 cpm
Temperature — 400°F and 600°F
Environment — Air

No. of Heats/Lots: Not specified

Equivalent Strain Equation:
$\text{Log } N_f = 21.0\text{-}9.18 \log (S_{eq})$
$S_{eq} = S_{max}(1\text{-}R)^{0.62}$
Std. Error of Estimate, Log (Life) = 0.50
Standard Deviation, Log (Life) = 0.89
R^2 = 68%

Sample Size = 47

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

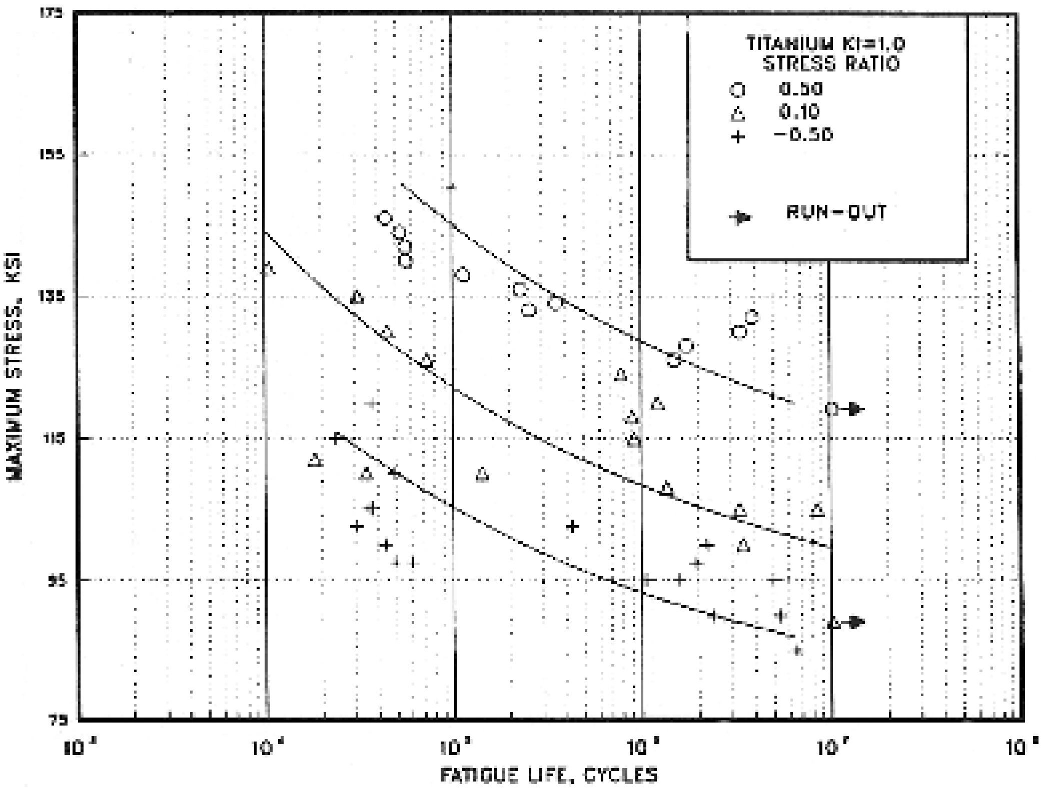


Figure 5.4.1.1.8(f). Best-fit S/N curves for unnotched Ti-6Al-4V annealed sheet, long transverse direction.

Correlative Information for Figure 5.4.1.1.8(f)

Product Form: Sheet, 0.063, 0.070, 0.078 inch thick

Properties:

TUS, ksi	TYS, ksi	Temp., °F
147-152	136-143	RT

Specimen Details: Unnotched, 0.375 inch width

Surface Conditions: Machined to 32 RMS, lightly polished with 400 grit emery paper

Reference: 5.4.1.1.8(c)

Test Parameters:
Loading — Axial
Frequency — 10-95 Hz
Temperature — RT
Environment — Air

No. of Heats/Lots: 3

Equivalent Strain Equation:
Log N_f = 12.59-4.89 log (S_{eq}-82.8)
$S_{eq} = S_{max}(1-R)^{0.29}$
Std. Error of Estimate, Log (Life) = 0.62
Standard Deviation, Log (Life) = 0.88
R^2 = 50.6%

Sample Size = 47

[Caution: The equivalent strain model may provide unrealistic life predictions for strain ratios and ranges beyond those represented above.]

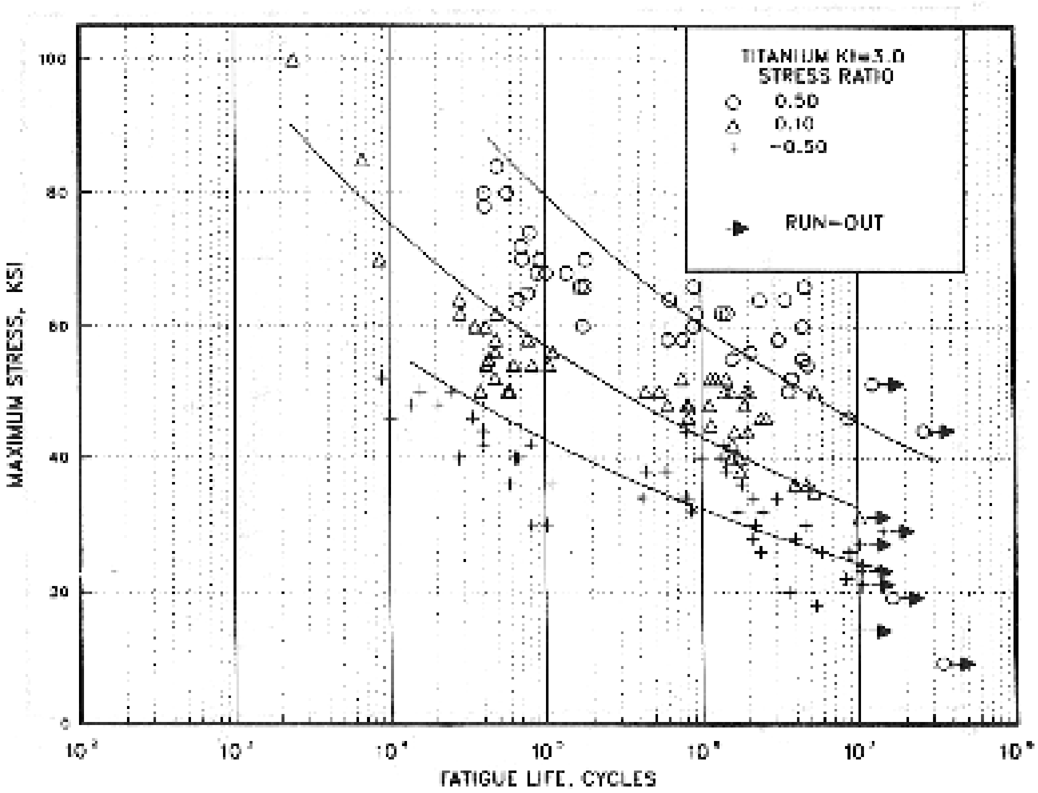


Figure 5.4.1.1.8(g). Best-fit S/N curves for notched, K_t = 3.0, Ti-6Al-4V annealed sheet, longitudinal and long transverse direction.

Correlative Information for Figure 5.4.1.1.8(g)

Product Form: Sheet, 0.063, 0.070, 0.078 inch thick

Properties:

TUS, ksi	TYS, ksi	Temp., °F
145-152	136-146	RT

Specimen Details: Notched, K_t = 3.0
0.487 inch net section

Surface Conditions: Machined to 32 RMS, lightly polished with 400 grit emery paper

Reference: 5.4.1.1.8(c)

Test Parameters:
Loading — Axial
Frequency — 10-95 Hz
Temperature — RT
Environment — Air

No. of Heats/Lots: 3

Equivalent Strain Equation:
$\text{Log } N_f = 19.28\text{-}8.25 \log (S_{eq})$
$S_{eq} = S_{max}(1\text{-}R)^{0.57}$
Std. Error of Estimate, Log (Life) = 0.53
Standard Deviation, Log (Life) = 0.87
R^2 = 62.5%

Sample Size = 141

[Caution: The equivalent strain model may provide unrealistic life predictions for strain ratios and ranges beyond those represented above.]

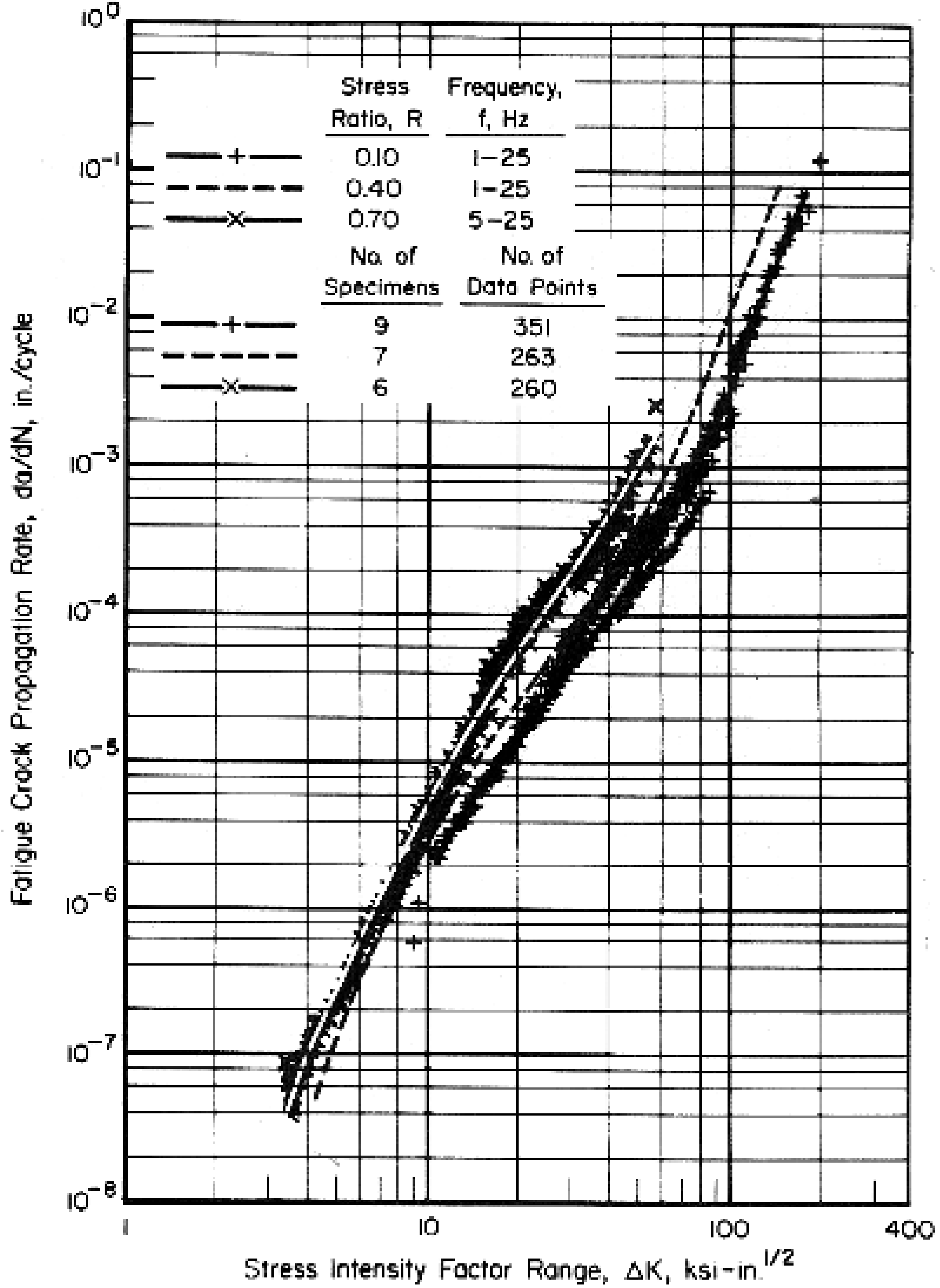


Figure 5.4.1.1.9. Fatigue-crack-propagation data for 0.250-inch-thick Ti-6Al-4V mill-annealed titanium alloy plate with buckling restraint. [Reference 5.4.1.1.9.]

Specimen Thickness:	*0.250 inch*	*Environment:*	*50% R.H.*
Specimen Width:	*9.6, 16, 32 inches*	*Temperature:*	*RT*
Specimen Type:	*M(T)*	*Orientation:*	*L-T*

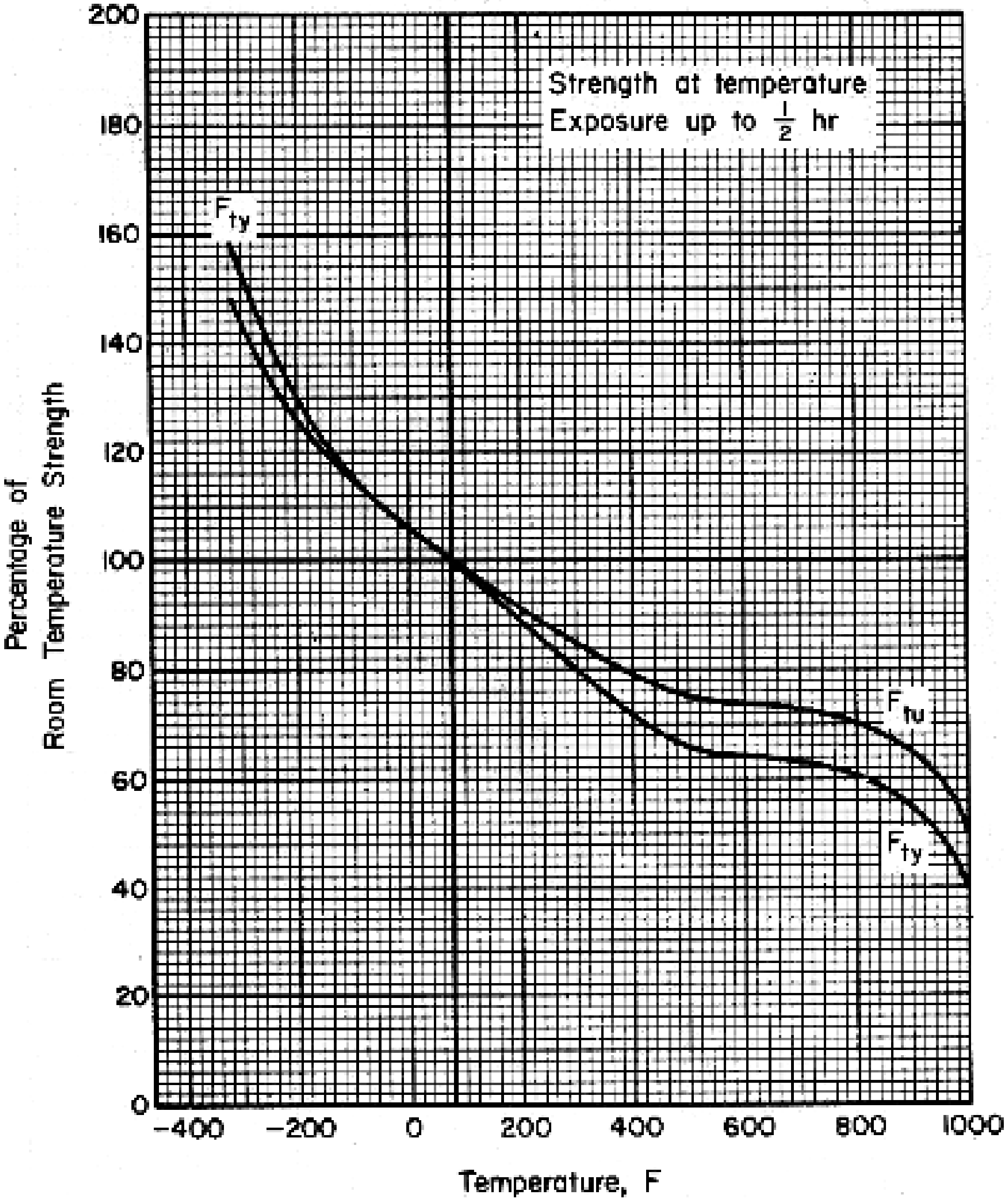


Figure 5.4.1.2.1. Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of solution-treated and aged Ti-6Al-4V alloy (all products).

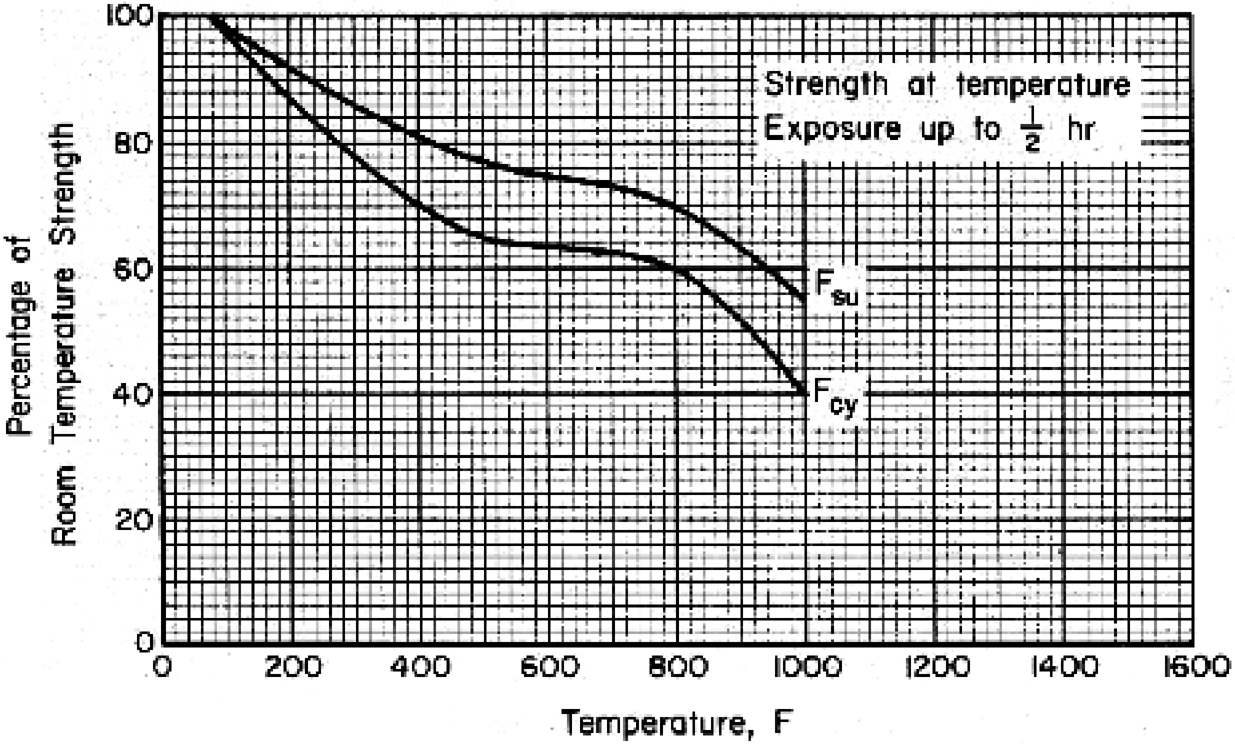


Figure 5.4.1.2.2. Effect of temperature on the compressive yield strength (F_{cy}) and the shear ultimate strength (F_{su}) of solution-treated and aged Ti-6Al-4V alloy (all products).

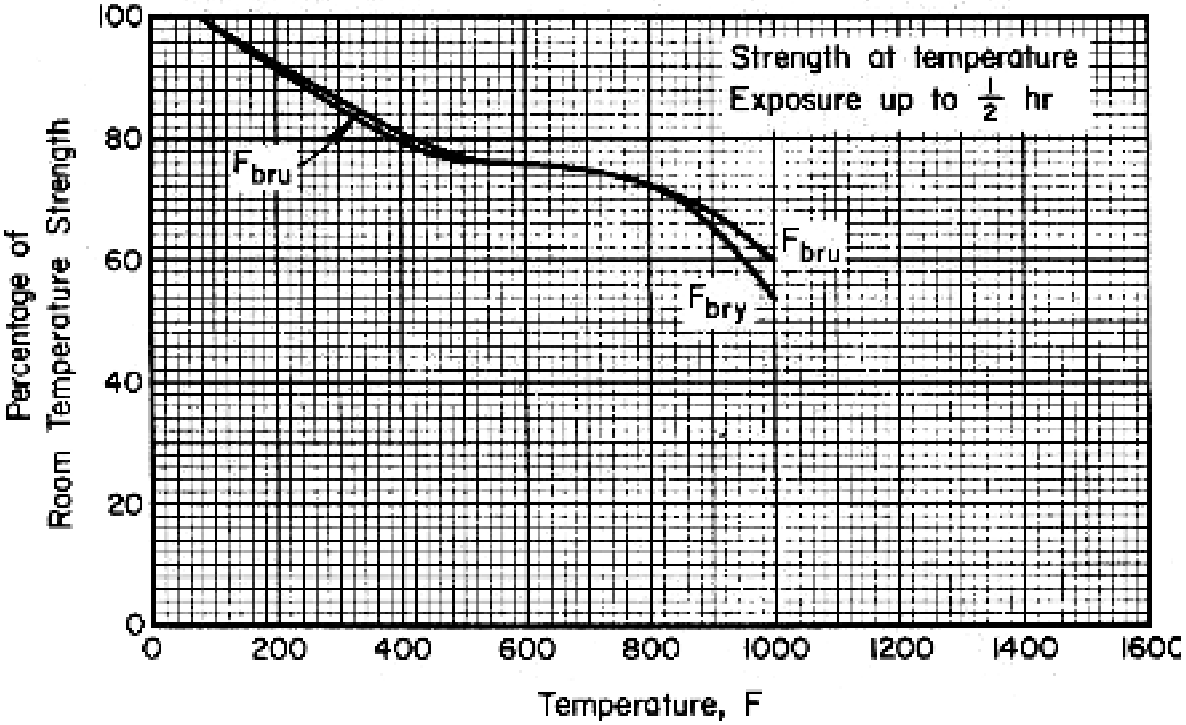


Figure 5.4.1.2.3. Effect of temperature on the bearing ultimate strength (F_{bru}) and the bearing yield strength (F_{bry}) of solution-treated and aged Ti-6Al-4V alloy (all products).

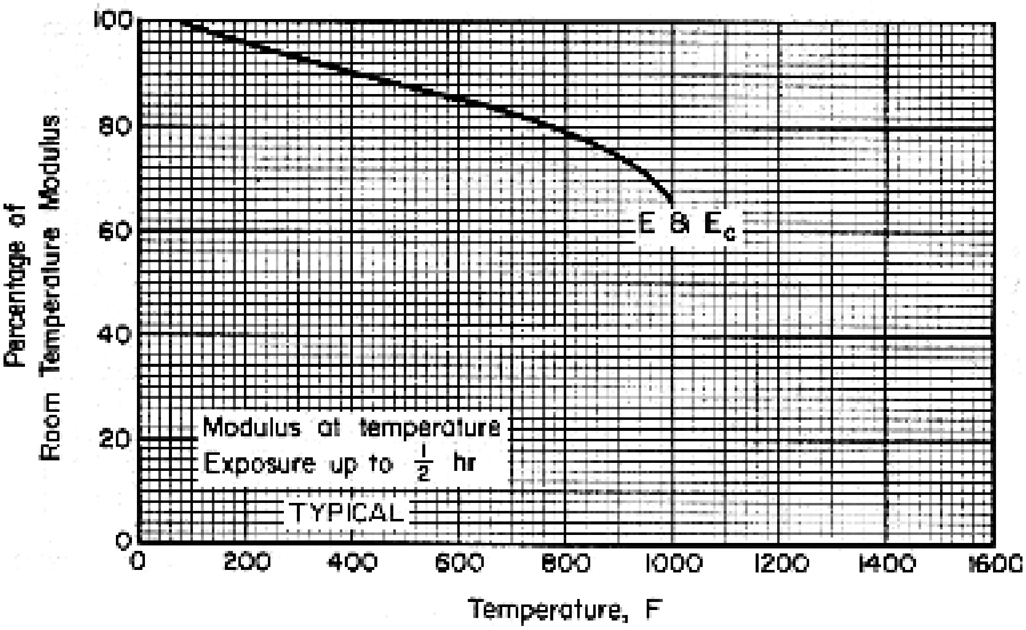


Figure 5.4.1.2.4. Effect of temperature on the tensile and compressive moduli (E and E$_c$) of solution-treated and aged Ti-6Al-4V alloy.

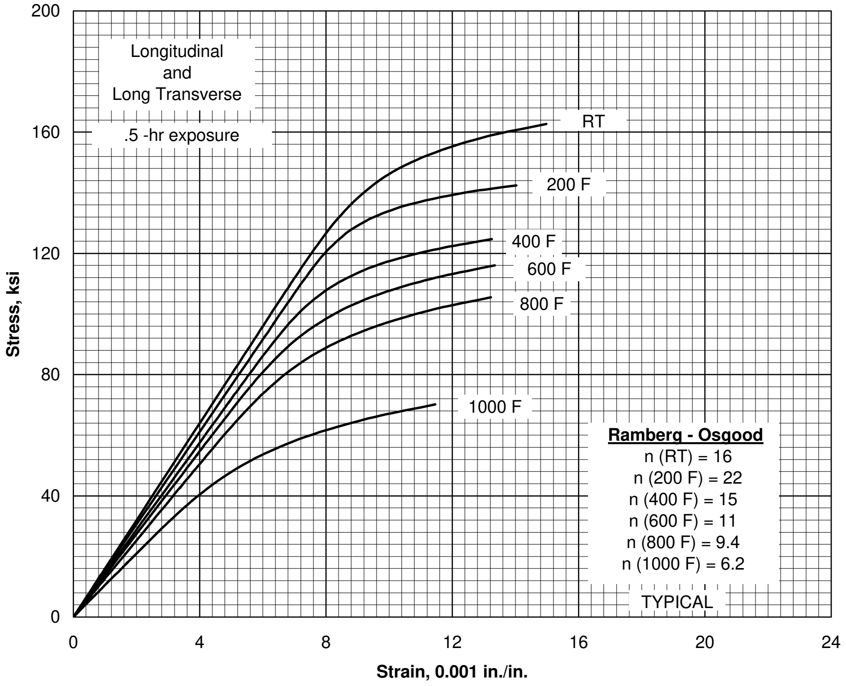


Figure 5.4.1.2.6(a). Typical tensile stress-strain curves for solution-treated and aged Ti-6Al-4V alloy sheet at room and elevated temperatures.

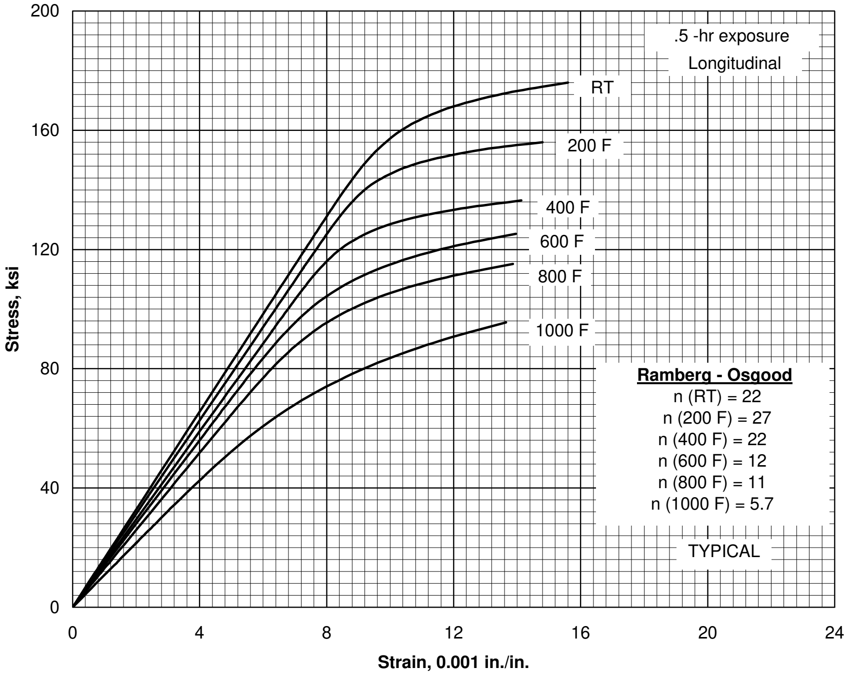


Figure 5.4.1.2.6(b). Typical compressive stress-strain curves for solution-treated and aged Ti-6Al-4V alloy sheet at room and elevated temperatures.

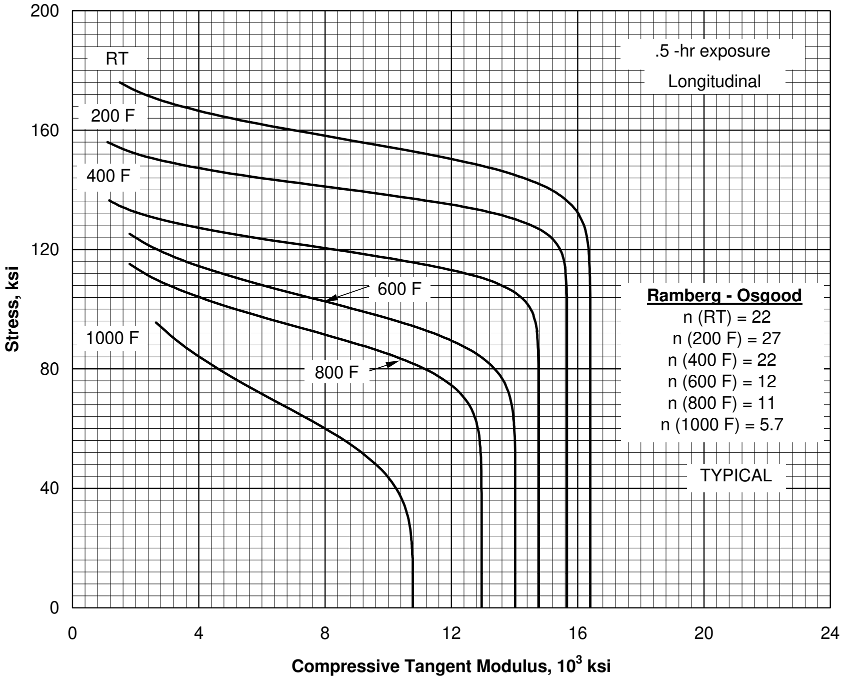


Figure 5.4.1.2.6(c). Typical compressive tangent-modulus curves for solution-treated and aged Ti-6Al-4V alloy sheet at room and elevated temperatures.

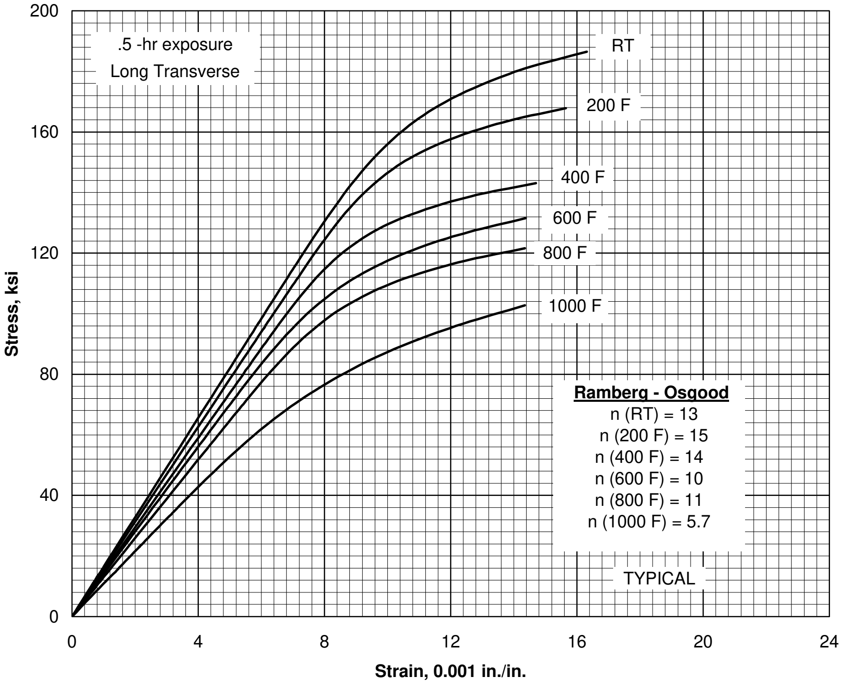


Figure 5.4.1.2.6(d). Typical compressive stress-strain curves for solution-treated and aged Ti-6Al-4V alloy sheet at room and elevated temperatures.

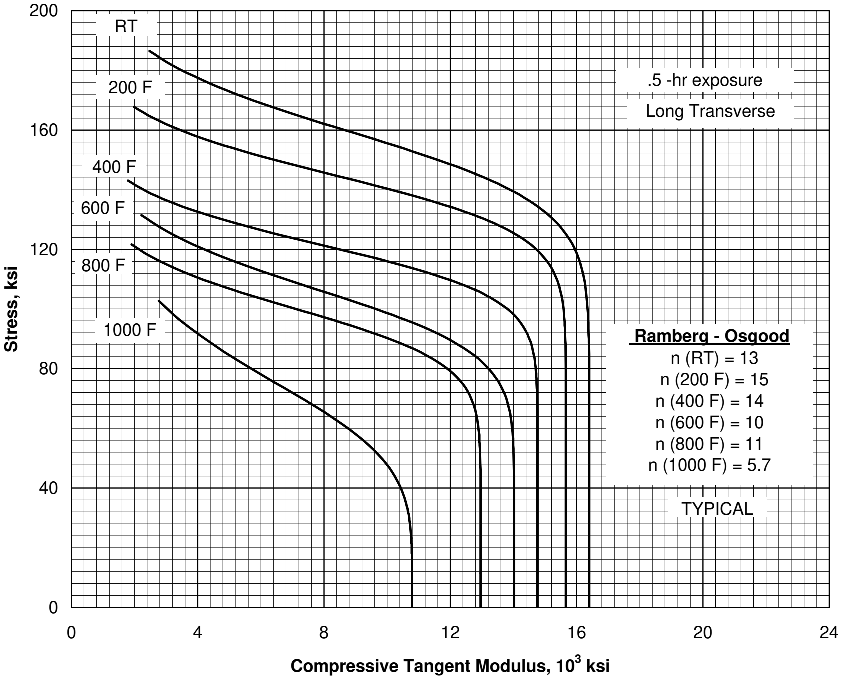


Figure 5.4.1.2.6(e). Typical compressive tangent-modulus curves for solution-treated and aged Ti-6Al-4V alloy sheet at room and elevated temperatures.

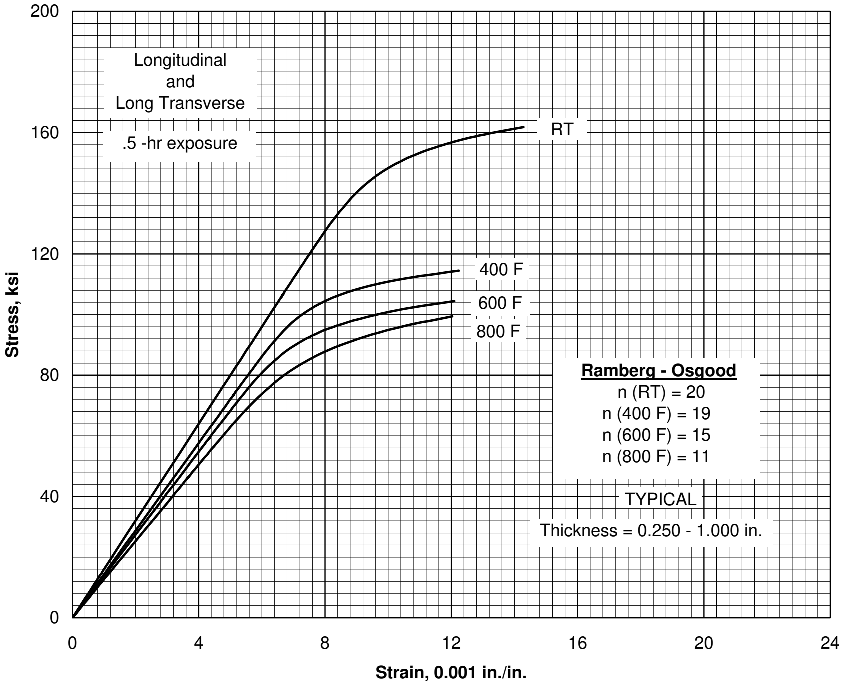


Figure 5.4.1.2.6(f). Typical tensile stress-strain curves for solution-treated and aged Ti-6Al-4V alloy plate at room and elevated temperatures.

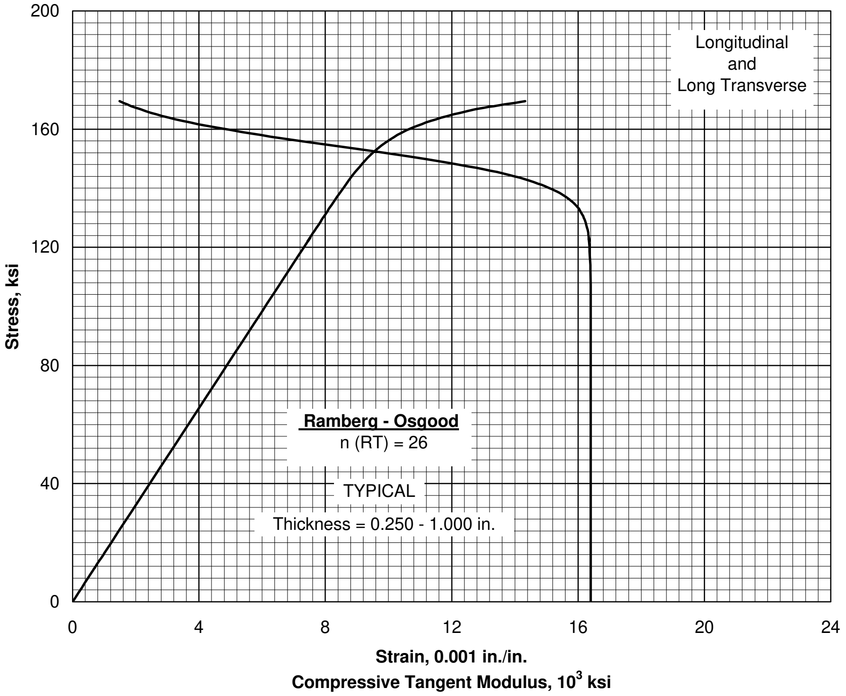


Figure 5.4.1.2.6(g). Typical compressive stress-strain and tangent-modulus curves for solution-treated and aged Ti-6Al-4V alloy plate at room temperature.

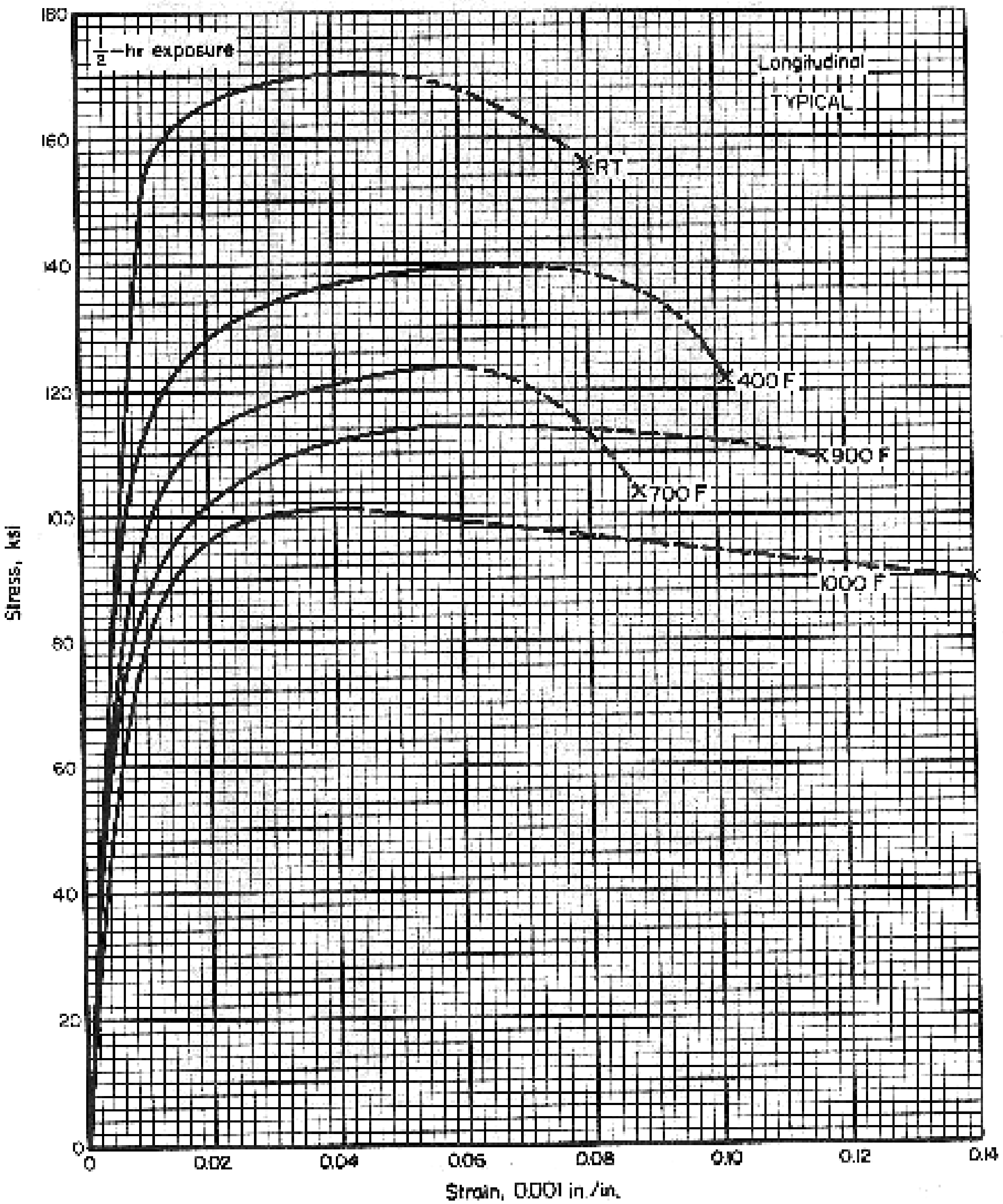
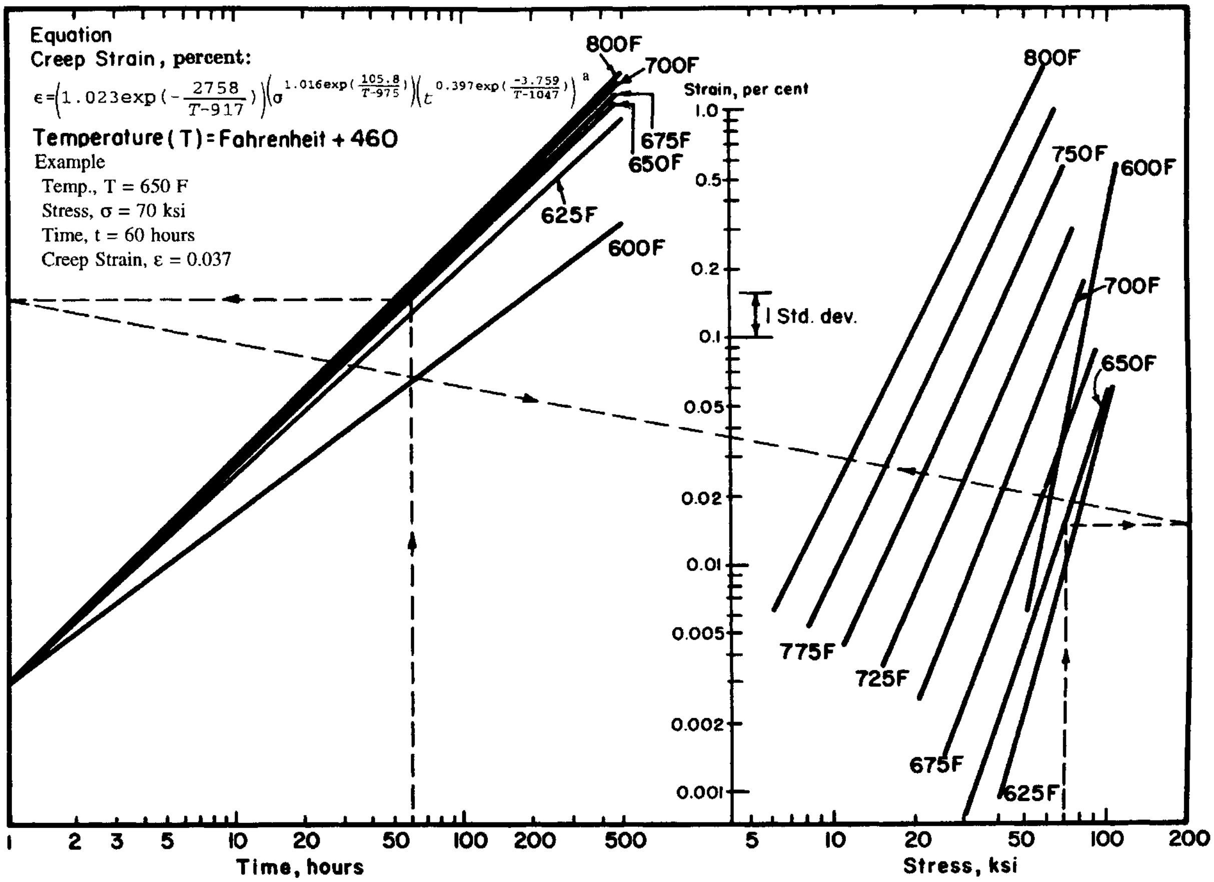


Figure 5.4.1.2.6(h). Typical tensile stress-strain curves (full range) for solution-treated and aged Ti-6Al-4V alloy at room and elevated temperatures.



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a This equation should only be used in the same temperature ranges indicated in the nomograph. Creep strains computed outside these temperature ranges may yield unreasonable values.

Figure 5.4.1.2.7. Typical creep properties of solution-treated and aged Ti-6Al-4V alloy sheet for temperature range 600°F through 800°F.

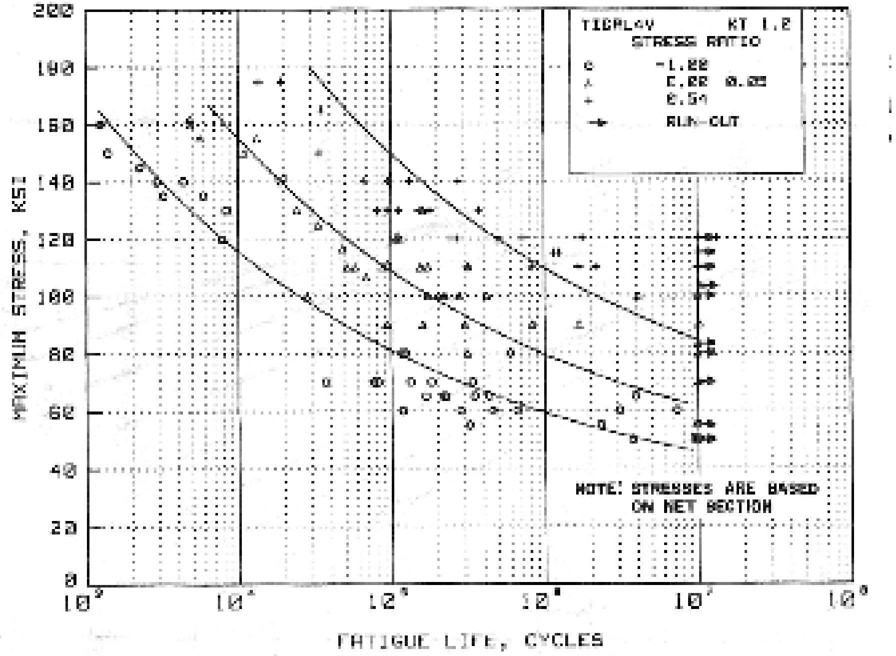

Figure 5.4.1.2.8(a). Best-fit S/N curves for unnotched solution-treated and aged Ti-6Al-4V sheet at room temperature, longitudinal direction.

Correlative Information for Figure 5.4.1.2.8(a)

Product Forms: Sheet, 0.063 inch and 0.125 inch thick

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	166-177	153-167	RT

Specimen Details: Unnotched
Ref. 5.4.3.2.8(a)
Specimen details not available
Ref. 5.4.3.2.8(b)
1.000 inch net width
8.000 inch test section radius
3.00 inch gross width

Surface Conditions:
Ref. 5.4.3.2.8(a). Edges finished with a crocus cloth.
Ref. 5.4.3.2.8(b). Machined specimens were cleaned with methyl ethyl ketone. Edges polished with number 1 and 00 grit emery paper, recleaned with methyl ethyl ketone.

References: 5.4.1.2.8(a) and (b)

Test Parameters:
Loading — Axial
Frequency —
Ref. 5.4.3.2.8(a), not specified
Ref. 5.4.3.2.8(b), 1500-2200 cpm
Temperature — RT
Environment — Air

No. of Heats/Lots: 4

Equivalent Strain Equation:
Log N_f = 14.29-4.91 log (S_{eq}-30.6)
$S_{eq} = S_{max}(1-R)^{0.42}$
Std. Error of Estimate, Log (Life) = 0.48
Standard Deviation, Log (Life) = 0.90
R^2 = 72%

Sample Size = 99

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

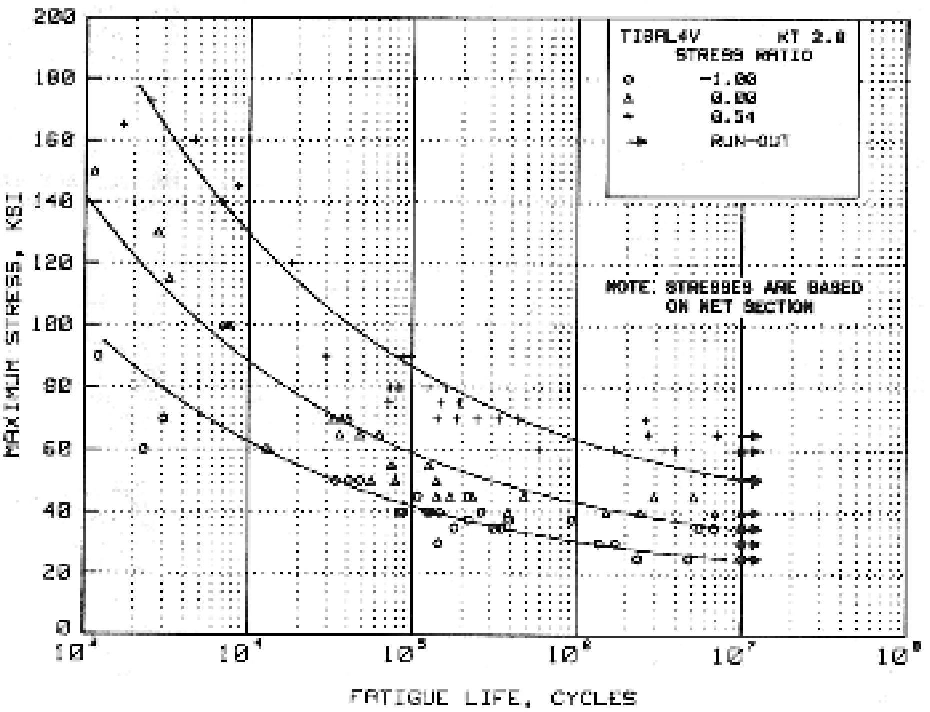

Figure 5.4.1.2.8(b). Best-fit S/N curves for notched, K_t = 2.8, solution-treated and aged Ti-6Al-4V sheet at room temperature, longitudinal direction.

Correlative Information for Figure 5.4.1.2.8(b)

Product Forms: Sheet, 0.063 inch and 0.125 inch thick

Properties:	TUS, ksi	TYS, ksi	Temp.,°F
	166-177	153-167	RT

Specimen Details: Notched, hole type, K_t = 2.8
0.9375 inch net width
1.000 inch gross width
8.000 inch test section radius
0.0625 inch-diameter hole

Surface Conditions: Machined specimens were cleaned with methyl ethyl ketone. Edges polished with number 1 and 00 grit emery paper and recleaned with methyl ethyl ketone.

Reference: 5.4.1.2.8(b)

Test Parameters:
Loading — Axial
Frequency — 1500-2200 cpm
Temperature — RT
Environment — Air

No. of Heats/Lots: 3

Equivalent Strain Equation:
$\text{Log } N_f = 10.87\text{-}3.80 \log (S_{eq}\text{-}24.0)$
$S_{eq} = S_{max}(1\text{-}R)^{0.50}$
Std. Error of Estimate, Log (Life) = 0.43
Standard Deviation, Log (Life) = 0.98
R^2 = 81%

Sample Size = 87

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

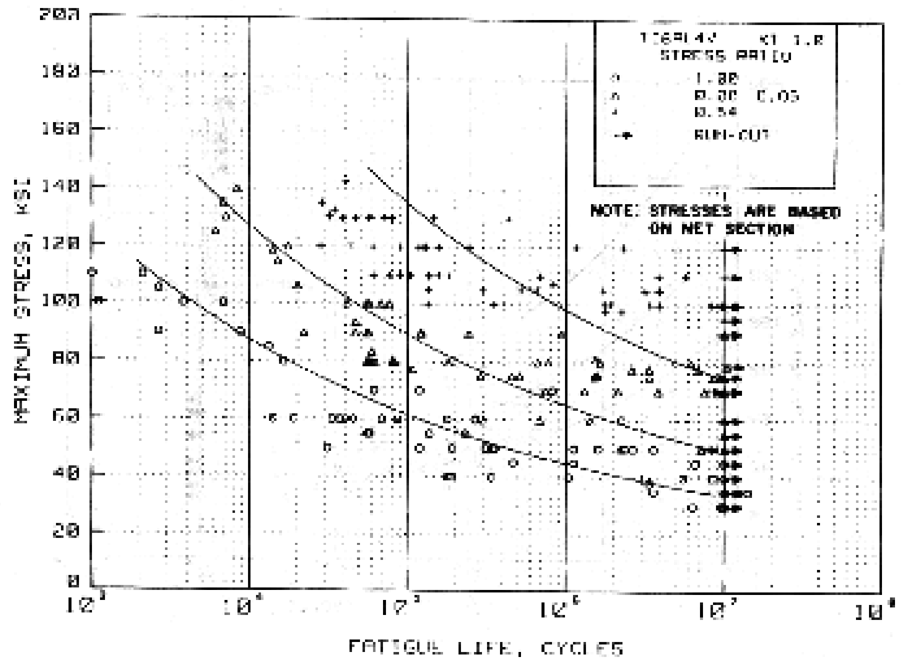

Figure 5.4.1.2.8(c). Best-fit S/N curves for unnotched solution-treated and aged Ti-6Al-4V sheet at 400°F and 600°F, longitudinal direction.

Correlative Information for Figure 5.4.1.2.8(c)

Product Forms: Sheet, 0.063 inch and 0.125 inch thick

Properties:

TUS, ksi	TYS, ksi	Temp., °F
142-143	117-121	400°F
125-134	102-113	600°F

Specimen Details: Unnotched
Ref. 5.4.3.2.8(a)
Specimen details not available
Ref. 5.4.3.2.8(b)
1.000 inch gross width
8.000 inch test section radius
3.00 inch gross width
0.9375 inch net width

Surface Conditions:
Ref. 5.4.3.2.8(a). Edges finished with a crocus cloth
Ref. 5.4.3.2.8(b). Machined specimens were cleaned with methyl ethyl ketone. Edges polished with number 1 and 00 grit emery paper, recleaned with methyl ethyl ketone.

References: 5.4.1.2.8(a) and (b)

Test Parameters:
Loading — Axial
Frequency —
Ref. 5.4.3.2.8(a), not specified
Ref. 5.4.3.2.8(b), 1500-2200 cpm
Temperature — 400°F and 600°F
Environment — Air

No. of Heats/Lots: 4

Equivalent Strain Equation:
$\text{Log } N_f = 14.7 - 5.31 \log (S_{eq} - 21.8)$
$S_{eq} = S_{max}(1-R)^{0.54}$
Std. Error of Estimate, Log (Life) = 0.58
Standard Deviation, Log (Life) = 0.93
$R^2 = 61\%$

Sample Size = 163

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

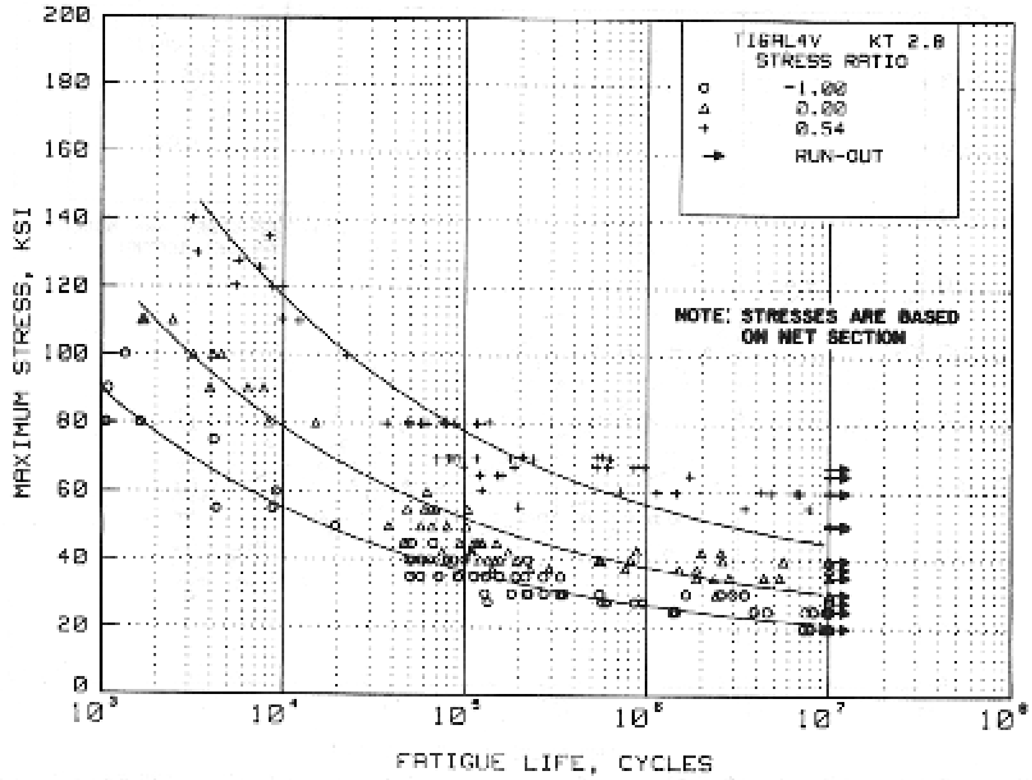

Figure 5.4.1.2.8(d). Best-fit S/N curves for notched, K_t = 2.8, solution-treated and aged Ti-6Al-4V sheet at 400 F and 600 F, longitudinal direction.

Correlative Information for Figure 5.4.1.2.8(d)

Product Forms: Sheet, 0.063 inch and 0.125 inch thick

Properties:

TUS, ksi	TYS, ksi	Temp., °F
142-143	117-121	400°F
129-133	103-105	600°F

Specimen Details: Notched, hole type, K_t = 2.8
1.000 inch gross width
8.000 inch test section radius
0.0625 inch-diameter hole
0.9375 inch net width

Surface Conditions: Machined specimens were cleaned with methyl ethyl ketone. Edges polished with number 1 and 00 grit emery paper and recleaned with methyl ethyl ketone.

Reference: 5.4.1.2.8(b)

Test Parameters:
Loading — Axial
Frequency — 1500-2200 cpm
Temperature — 400°F and 600°F
Environment — Air

No. of Heats/Lots: 3

Equivalent Stress Equation:
$\text{Log } N_f = 10.64\text{-}3.77 \log (S_{eq}\text{-}20.9)$
$S_{eq} = S_{max}(1\text{-}R)^{0.51}$
Std. Error of Estimate, Log (Life) = 0.42
Standard Deviation, Log (Life) = 0.93
R^2 = 80%

Sample Size =175

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

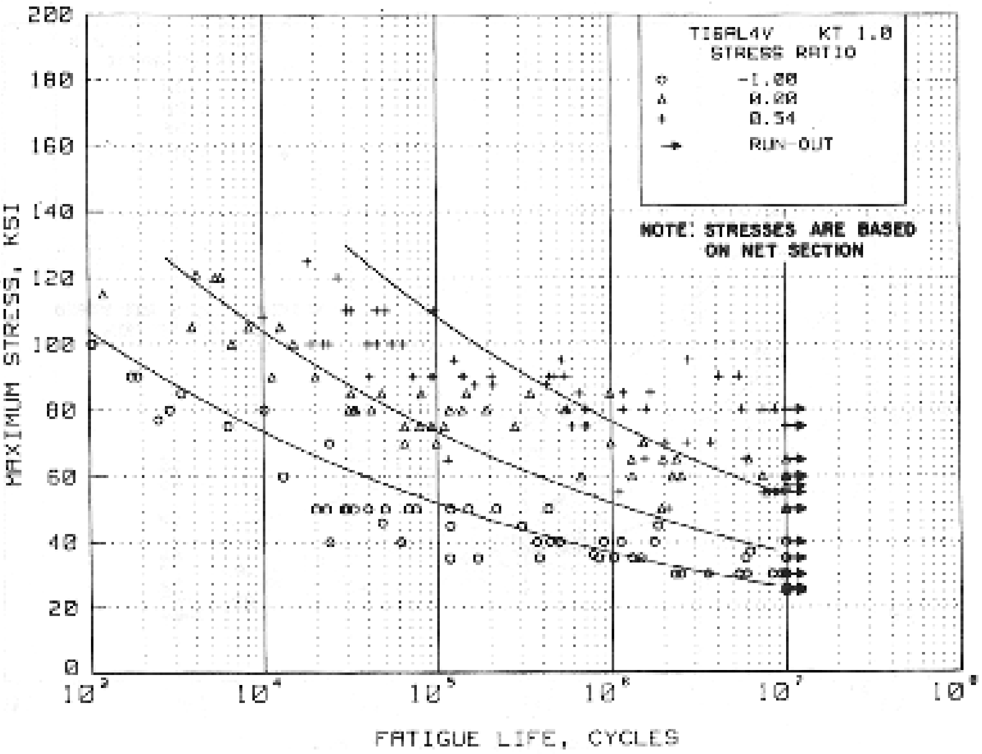

Figure 5.4.1.2.8(e). Best-fit S/N curves for unnotched solution-treated and aged Ti-6Al-4V sheet at 800°F and 900°F, longitudinal direction.

Correlative Information for Figure 5.4.1.2.8(e)

Product Forms: Sheet, 0.063 inch and 0.125 inch thick

Properties:

TUS, ksi	TYS, ksi	Temp., °F
120-125	93-96	800°F
110-111	84-86	900°F

Specimen Details: Unnotched
1.000 inch gross width
8.000 inch test section radius
3.00 inch gross width
0.9375 inch net width

Surface Conditions: Machined specimens were cleaned with methyl ethyl ketone. Edges polished with number 1 and 00 grit emery paper and recleaned with methyl ethyl ketone.

References: 5.4.1.2.8(b)

Test Parameters:
Loading — Axial
Frequency — 1500-2200 cpm
Temperature — 800°F and 900°F
Environment — Air

No. of Heats/Lots: 3

Equivalent Stress Equation:
Log $N_f = 17.34-6.61 \log (S_{eq})$
$S_{eq} = S_{max}(1-R)^{0.50}$
Std. Error of Estimate, Log (Life) = 0.51
Standard Deviation, Log (Life) = 0.99
$R^2 = 73\%$

Sample Size = 154

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

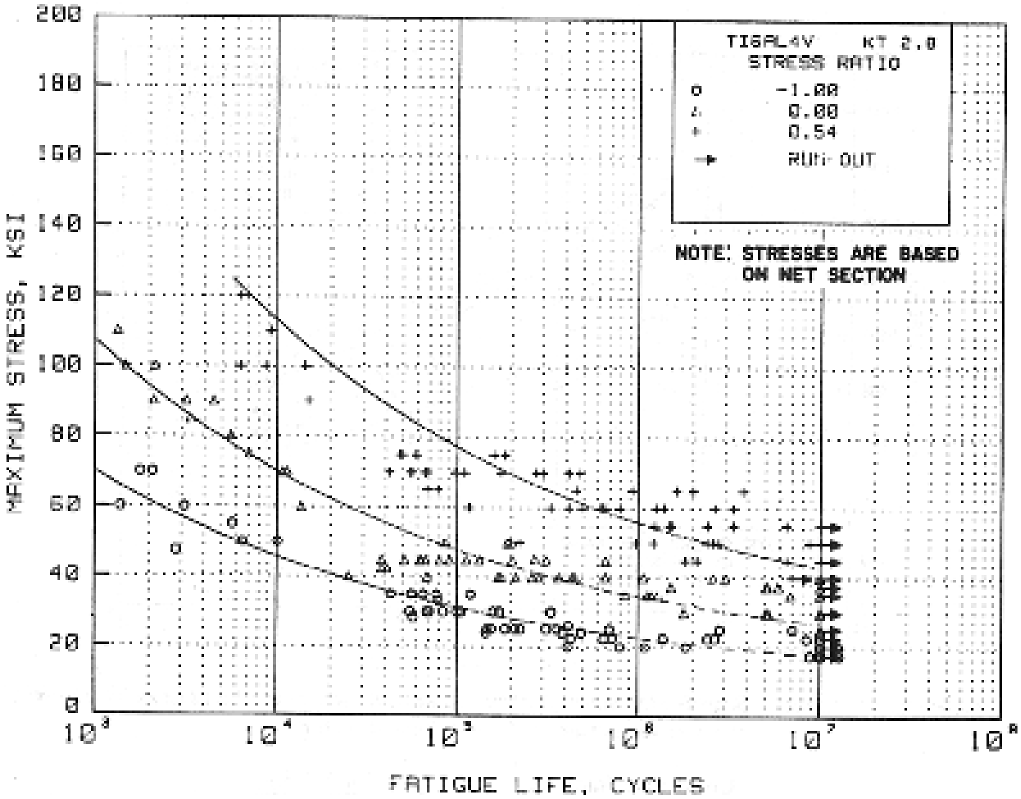

Figure 5.4.1.2.8(f). Best-fit S/N curves for notched, K_t = 2.8, solution-treated and aged Ti-6Al-4V sheet at 800°F and 900°F, longitudinal direction.

Correlative Information for Figure 5.4.1.2.8(f)

Product Forms: Sheet, 0.063 inch and 0.125 inch thick

Properties:

TUS, ksi	TYS, ksi	Temp., °F
120-124	93-96	800°F
110-111	84-88	900°F

Specimen Details: Notched, hole type, K_t = 2.8
1.000 inch gross width
8.000 inch test section radius
0.0625 inch-diameter hole
0.9375 inch net width

Surface Conditions: Machined specimens were cleaned with methyl ethyl ketone. Edges polished with number 1 and 00 grit emery paper and recleaned with methyl ethyl ketone.

Reference: 5.4.1.2.8(b)

Test Parameters:
Loading — Axial
Frequency — 1500-2200 cpm
Temperature — 800°F and 900°F
Environment — Air

No. of Heats/Lots: 3

Equivalent Stress Equation:
$\text{Log } N_f = 11.75 - 4.45 \log (S_{eq} - 15.0)$
$S_{eq} = S_{max}(1-R)^{0.62}$
Std. Error of Estimate, Log (Life) = 0.43
Standard Deviation, Log (Life) = 0.96
R^2 = 79%

Sample Size = 173

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

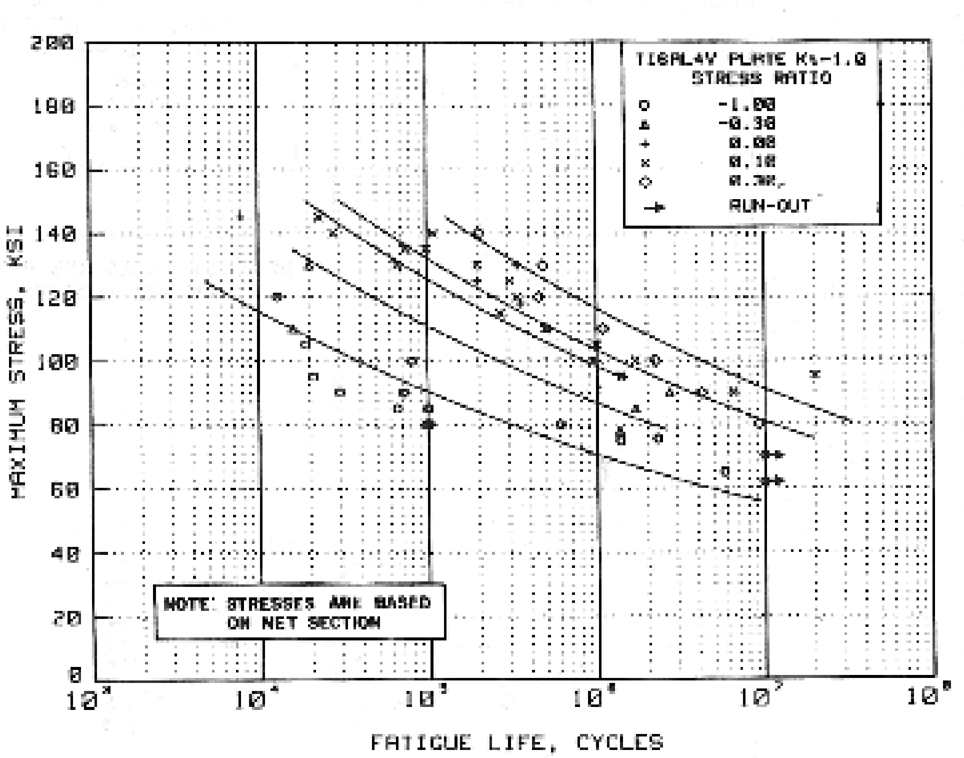

Figure 5.4.1.2.8(g). Best-fit S/N curves for unnotched solution-treated and aged Ti-6Al-4V plate at room temperature, longitudinal direction.

Correlative Information for Figure 5.4.1.2.8(g)

Product Form: Plate, 1.00 inch

Properties:

TUS, ksi	TYS, ksi	Temp., °F
158	149	RT
155	145	RT

Specimen Details: Unnotched, rounded

Uniform Gage	Hourglass	
---	3.25	Reduced section radius of curvature, inch
0.195	0.250	Diameter, inch

Surface Condition: Longitudinally polished with No. 000 emery paper removing all circumferential marks.

References: 5.4.1.2.8(c) and (d)

Test Parameters:
Loading — Axial
Frequency — 1,800-18,000 cpm
Temperature — RT
Environment — Air

No. of Heats/Lots: 2

Equivalent Stress Equation:
Log N_f = 24.6-9.35 log (S_{max})
$S_{eq} = S_{max}(1\text{-}R)^{0.48}$
Std. Error of Estimate, Log (Life) = 0.39
Standard Deviation, Log (Life) = 0.83
R^2 = 79%

Sample Size = 49

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

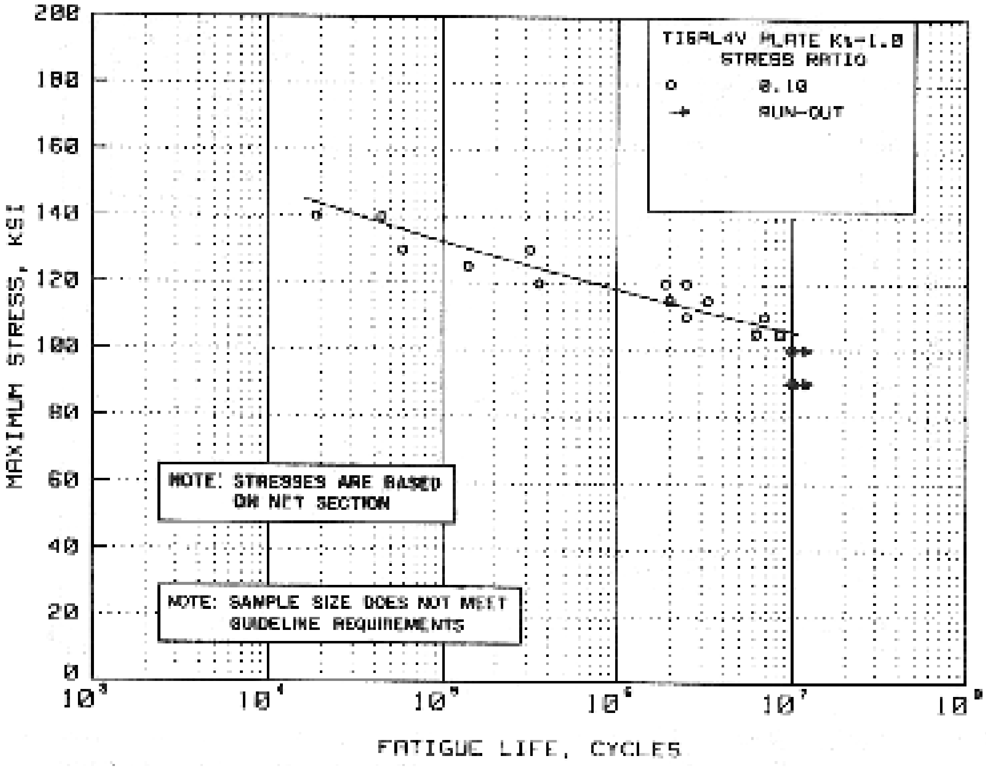

Figure 5.4.1.2.8(h). Best-fit S/N curves for unnotched solution-treated and aged Ti-6Al-4V plate at room temperature, long transverse direction.

Correlative Information for Figure 5.4.1.2.8(h)

Product Form: Plate, 0.50 inch thick

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	173	164	RT

Specimen Details: Unnotched, flat hourglass
10 inch reduced section radius of curvature
1 inch net section width
0.156 inch net section thickness

Surface Conditions: Machined to 63 RMS

Reference: 5.4.1.2.8(d)

Test Parameters:
Loading — Axial
Frequency — Unspecified
Temperature — RT
Environment — Air

No. of Heats/Lots: 1

Maximum Stress Equation:
Log N_f = 47.9-20.2 log (S_{max})
Std. Error of Estimate, Log (Life) = 0.33
Standard Deviation, Log (Life) = 0.89
R^2 = 87%

Sample Size = 14

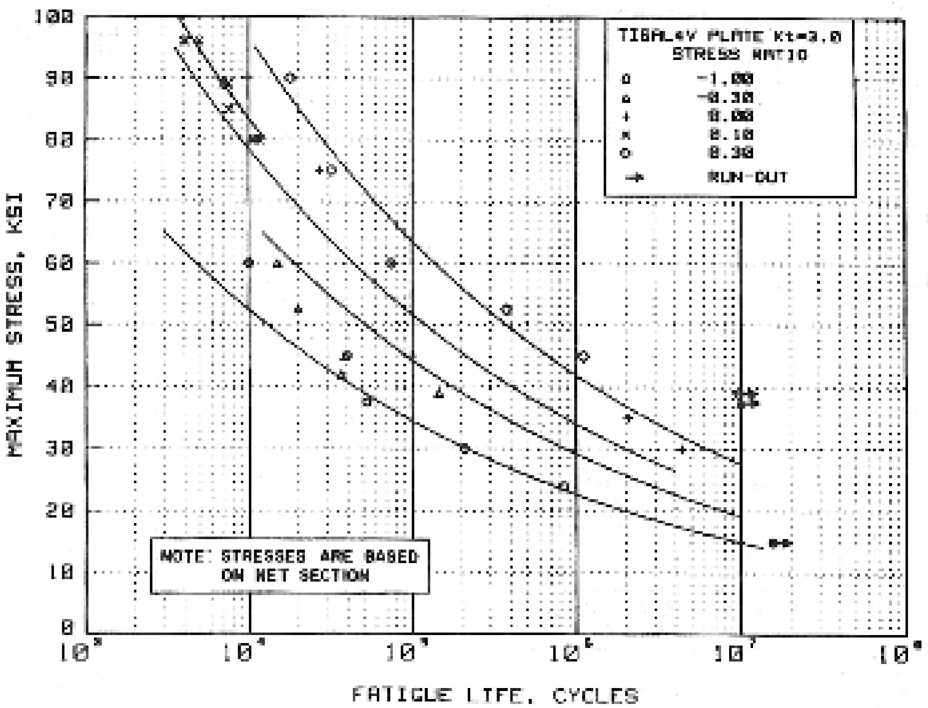

Figure 5.4.1.2.8(i). Best-fit S/N curves for notched, K_t = 3.0, solution-treated and aged Ti-6Al-4V plate at room temperature, longitudinal direction.

Correlative Information for Figure 5.4.1.2.8(i)

Product Form: Plate, 1.025 and 0.750 inch thick

Properties:

TUS, ksi	TYS, ksi	Temp., °F
155	145	RT (unnotched)
187	—	RT (notched)

Specimen Details: Circumferentially notched, $K_t = 3.0$

Ref. (c)	Ref. (e)	
0.195	0.430	Gross diameter, inch
0.136	0.300	Net section, inch
0.005	0.016	Notch radius, r, inch
60°	60°	Flank angle, ω

Surface Condition:
Ref. (c) notch made with light finishing cuts
Ref. (e) notch polished in lathe

References: 5.4.1.2.8(c) and (e)

Test Parameters:
Loading — Axial
Frequency — 1,800-18,000 cpm
Temperature — RT
Environment — Air

No. of Heats/Lots: 2

Equivalent Stress Equation:
$\text{Log } N_f = 14.4\text{-}5.51 \log (S_{eq})$
$S_{eq} = S_{max}(1\text{-}R)^{0.58}$
Std. Error of Estimate, Log (Life) = 0.24
Standard Deviation, Log (Life) = 0.81
$R^2 = 92\%$

Sample Size = 31

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

5.4.2 TI-6AL-6V-2SN

5.4.2.0 *Comments and Properties* — Ti-6Al-6V-2Sn alloy is similar to Ti-6Al-4V alloy in many respects but has higher strength and deeper hardenability (i.e., use of thicker sections possible). A variety of mill product forms are available including billet, bar, plate, sheet, strip, and extrusions and these may be used in either the annealed or the solution-treated and aged (STA) conditions. The maximum strength is developed in the STA condition in sections up to about 2 inches in thickness.

Manufacturing Considerations — To ensure optimum mechanical properties in Ti-6Al-6V-2Sn forgings, at least 50 percent reduction should be done at temperatures below the beta transus temperature (i.e., <1735°F). The Ti-6Al-6V-2Sn is readily formable in the annealed condition. In the sheet or plate forms the alloy is generally used in the annealed condition, although the alloy is capable of heat treatment to higher strength levels with some loss of toughness. When the Ti-6Al-6V-2Sn sheet and plate are hot formed at any temperature over 1000°F and air cooled, the material should be stabilized by reheating to 1000°F followed by air cooling. Welding is not usually recommended although limited weld joining operations are possible if the assembly is amenable to post-weld thermal treatments for the restoration of ductility to the weld and heat-affected zones.

Environmental Considerations — While the short-time elevated-temperature properties and stability of Ti-6Al-6V-2Sn alloy are good, creep strength above 650°F and long-term stability at temperatures above 800°F are not. The material ages during prolonged exposures around 800°F and above, particularly when under stress. Oxidation resistance of Ti-6Al-6V-2Sn is satisfactory in short-term exposures to 1000°F. The material is nearly equivalent to the Ti-6Al-4V alloy in terms of hot-salt and aqueous chloride solution stress-corrosion resistance. Under certain conditions, titanium, when in contact with cadmium, silver, mercury, or certain of their compounds, may become embrittled. Refer to MIL-S-5002 and MIL-STD-1568 for restrictions concerning applications with titanium in contact with these metals or their compounds.

Heat Treatment — This alloy is commonly specified in either the annealed condition or the solution-treated and aged condition. The solution-treated and aged condition is as follows:

Solution treat at 1625°F for ½ to 1 hour, quench in water.

Age at 1000 ± 25°F for 4 to 8 hours, air cool.

Specifications and Properties — Material specifications for Ti-6Al-6V-2Sn are shown in Table 5.4.2.0(a). Room-temperature mechanical properties are shown in Tables 5.4.2.0(b) through (e). The effect of temperature on physical properties is shown in Figure 5.4.2.0.

5.4.2.1 *Annealed Condition* — Elevated temperature curves for annealed condition are shown in Figures 5.4.2.1.1(a) through 5.4.2.1.3(b). Typical stress-strain and tangent-modulus curves for this condition are shown in Figures 5.4.2.1.6(a) and (b). A typical full range tensile stress-strain curve is shown in Figure 5.4.2.1.6(c). Unnotched and notched fatigue data are presented in Figures 5.4.2.1.8(a) and (b).

5.4.2.2 *Solution-Treated and Aged Condition* — Elevated temperature curves are shown in Figures 5.4.2.2.1 and 5.4.2.2.2.

Table 5.4.2.0(a). Material Specifications for Ti-6Al-6V-2Sn

Specification	Form
AMS-T-9046	Sheet, strip, and plate
AMS 4979	Bar and forging
MIL-T-81556, AMS-T-81556	Extruded bar and shapes
AMS 4971	Bar and forging
AMS 4978	Bar and forging
AMS 4918	Sheet, strip, and plate

Table 5.4.2.0(b). Design Mechanical and Physical Properties of Ti-6Al-6V-2Sn Sheet, Strip, and Plate

Specification	AMS-T-9046, Comp. AB-3, and AMS 4918							AMS-T-9046, Comp. AB-3			
Form	Sheet, strip, and plate										
Condition	Annealed							Solution treated and aged			
Thickness, in.	<0.1875		0.1875-0.500	0.501-1.000	1.001-1.500	1.501-2.000	2.001-4.000	≤0.1875	0.1875-1.500	1.501-2.500	2.501-4.000
Basis	A	B	S	S	S	S	S	S	S	S	S
Mechanical Properties:											
F_{tu}, ksi:											
L	155	160	150	150	150	150	145	170	170	160	150
LT	155	150	150	150	150	150	145	170	170	160	150
F_{ty}, ksi:											
L	145[a]	152	140	140	140	140	135	160	160	150	140
LT	145[a]	154	140	140	140	140	135	160	160	150	140
F_{cy}, ksi:											
L	...	...	139	142	146	148	...	...	170	...	...
LT	...	...	151	147	141	136	...	...	170	...	...
F_{su}, ksi	...	...	91	93	95	95	...	...	101	...	...
F_{bru}, ksi:											
(e/D = 1.5)	...	...	236	241	247	250	...	...	264	...	...
(e/D = 2.0)	...	...	294	303	312	317	...	...	324	...	...
F_{bry}, ksi:											
(e/D = 1.5)	...	...	193	196	199	202	...	...	237	...	...
(e/D = 2.0)	...	...	215	223	234	240	...	...	266	...	...
e, percent (S-basis):											
L	10[b]	...	10	10	10	10	8	8	8	6	6
LT	8[b]	...	8	8	8	8	6	6	8	6	6
E, 10^3 ksi	16.0										
E_c, 10^3 ksi	16.4										
G, 10^3 ksi	6.2										
μ	0.31										
Physical Properties:											
ω, lb/in.^{3}	0.164										
C, K, and α	See Figure 5.4.2.0										

a The rounded T_{99} values are higher than specification values as follows: F_{ty} (L) = 147 ksi, F_{ty} (LT) = 149 ksi.

b Longitudinal <0.025 in. = 8 percent. Long transverse < 0.025 in. = 6 percent.

Table 5.4.2.0(c). Design Mechanical and Physical Properties of Ti-6Al-6V-2Sn Bar

Specification	AMS 4978						AMS 4971 and AMS 4979			
Form	Bar						Bar and forging			
Condition	Air-cool annealed[a]						Solution treated and aged			
Thickness or diameter, in.	≤1.500		1.501-3.000		3.001-4.000		≤1.000	1.001-2.000	2.001-3.000	3.001-4.000
Basis	A	B	A	B	A	B	S	S	S	S
Mechanical Properties:										
F_{tu}, ksi:										
L	144	150	139	145	136	142	175	170	155	150
LT[b]	147	152	143	148	140	145	175	170	155	150
ST[b]	...	...	...	...	...	...	...	...	155	150
F_{ty}, ksi:										
L	131	138	126	132	123	129	160	155	145	140
LT[b]	136	141	131	136	127	132	160	155	145	140
ST[b]	...	...	...	...	...	...	...	...	145	140
F_{cy}, ksi:										
L	...	...	...	...	...	...	...	...	...	...
LT[b]	...	...	...	...	...	...	...	...	...	...
ST[b]	...	...	...	...	...	...	...	...	...	...
F_{su}, ksi	...	...	...	...	...	...	...	...	...	...
F_{bru}, ksi:										
(e/D = 1.5)	...	...	...	...	...	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...	...	...	...	...	...
F_{bry}, ksi:										
(e/D = 1.5)	...	...	...	...	...	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...	...	...	...	...	...
e, percent (S-basis):										
L	10	...	10	...	10	...	8	8	8	8
LT[b]	8	...	8	...	8	...	6	6	6	6
ST[b]	...	...	8	...	8	...	...	...	6	6
RA, percent (S-basis):										
L	20	...	20	...	15	...	20	20	20	20
LT[b]	15	...	15	...	15	...	15	15	15	15
ST[b]	...	...	15	...	15	...	...	...	15	15
E, 10^3 ksi	16.0									
E_c, 10^3 ksi	16.4									
G, 10^3 ksi	6.2									
μ	0.31									
Physical Properties:										
ω, lb/in.^{3}	0.164									
C, K, and α	See Figure 5.4.2.0									

[a] 1300 to 1350°F for 1-3 hours, air cool to room temperature.
[b] Applicable, providing LT or ST dimension is ≥2.500 inches.

Table 5.4.2.0(d). Design Mechanical and Physical Properties of Ti-6Al-6V-2Sn Forging

Specification	AMS 4978	
Form	Forging	
Condition	Annealed	
Thickness, or diameter, in.	≤2.000	2.001-4.000
Basis	S	S
Mechanical Properties:		
F_{tu}, ksi:		
L	150	145
LT[a]	150	145
ST[a]	...	145
F_{ty}, ksi:		
L	140	135
LT[a]	140	135
ST[a]	...	135
F_{cy}, ksi:		
L	...	...
LT[a]	...	...
ST[a]	...	...
F_{su}, ksi	...	...
F_{bru}, ksi:		
(e/D=1.5)	...	...
(e/D=2.0)	...	...
F_{bry}, ksi:		
(e/D=1.5)	...	...
(e/D=2.0)	...	...
e, percent:		
L	10	10
LT[a]	8	8
ST[a]	...	7
RA, percent:		
L	20	20
LT[a]	15	15
ST[a]	15	15
E, 10^3 ksi	16.0	
E_c, 10^3 ksi	16.4	
G, 10^3 ksi	6.2	
μ	0.31	
Physical Properties:		
ω, lb/in.^{3}	0.164	
C, K, and α	See Figure 5.4.2.0	

[a] Applicable, providing LT or ST dimension is ≥2.500 inches.

Table 5.4.2.0(e). Design Mechanical and Physical Properties of Ti-6Al-6V-2Sn Extruded Bar and Shapes

Specification	MIL-T-81556 & AMS-T-81556, Comp. AB-3							
Form	Extruded bar and shapes							
Condition	Annealed				Solution treated and aged			
Thickness or diameter, in.	≤2.000		2.001-3.000	3.001-4.000	0.188-0.500	0.501-1.500	1.501-2.500	2.501-4.000
Basis	A	B	S	S	S	S	S	S
Mechanical Properties:								
F_{tu}, ksi:								
L	142	148	145	140	170	165	160	150
LT	141	148	145	140	170	165	160	150
F_{ty}, ksi:								
L	129	135	135	130	160	155	150	140
LT	128	135	135	130	160	155	150	140
F_{cy}, ksi:								
L	137	144	140	135	165	160	155	145
LT	136	142	140	135	165	160	155	145
F_{su}, ksi	93	97	...	...	...	...	...	...
F_{bru}[a], ksi:								
(e/D=1.5)	218	229	...	...	...	...	...	...
(e/D=2.0)	268	281	...	...	...	...	...	...
F_{bry}[a], ksi:								
(e/D=1.5)	196	203	...	...	...	...	...	...
(e/D=2.0)	227	235	...	...	...	...	...	...
e, percent (S-basis):								
L	10	...	10	10	8	8	8	8
LT	8	...	8	8	6	6	6	6
RA, percent (S-basis):								
L	20	...	20	20	15	15	15	15
LT	15	...	15	15	12	12	12	12
E, 10^3 ksi	16.0							
E_c, 10^3 ksi	16.4							
G, 10^3 ksi	6.2							
μ	0.31							
Physical Properties:								
ω, lb/in.^{3}	0.164							
C, K, and α	See Figure 5.4.2.0							

a Bearing values are "dry pin" values per Section 1.4.7.1.

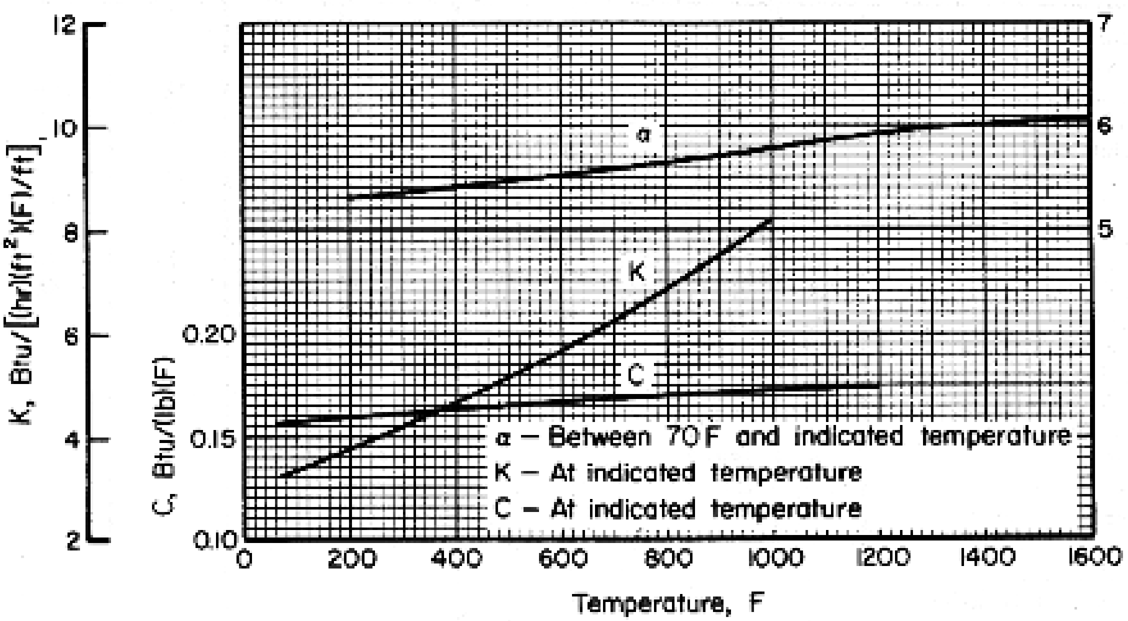

Figure 5.4.2.0. Effect of temperature on the physical properties of Ti-6Al-6V-2Sn alloy.

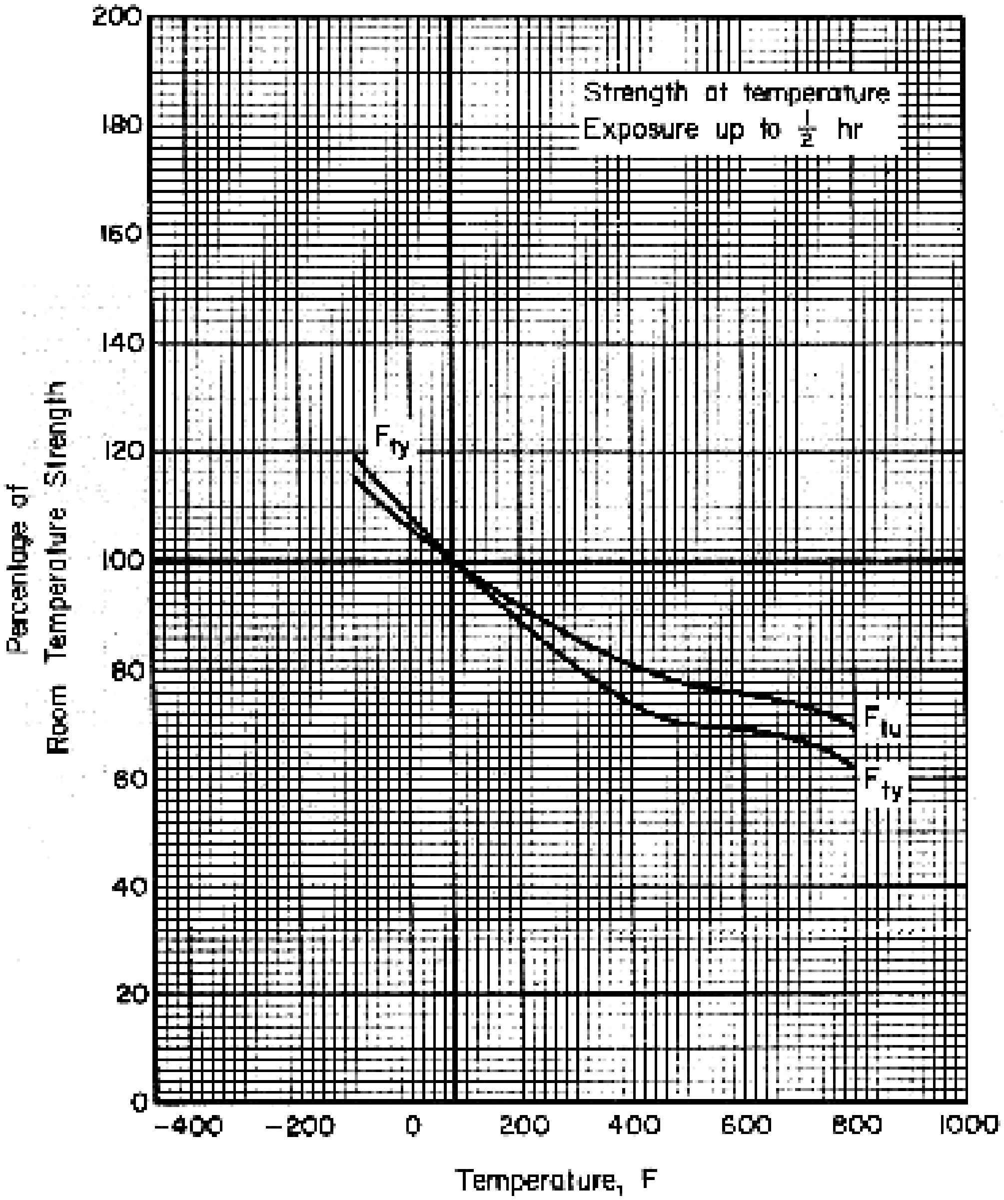

Figure 5.4.2.1.1(a). Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of annealed Ti-6Al-6V-2Sn extrusion.

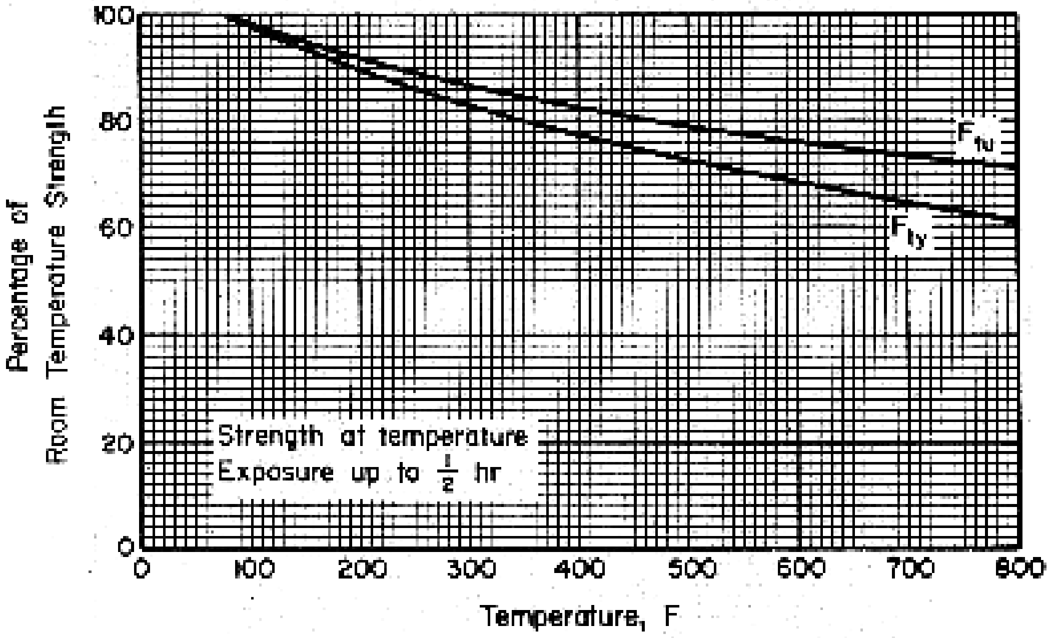

Figure 5.4.2.1.1(b). Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of annealed Ti-6Al-6V-2Sn plate.

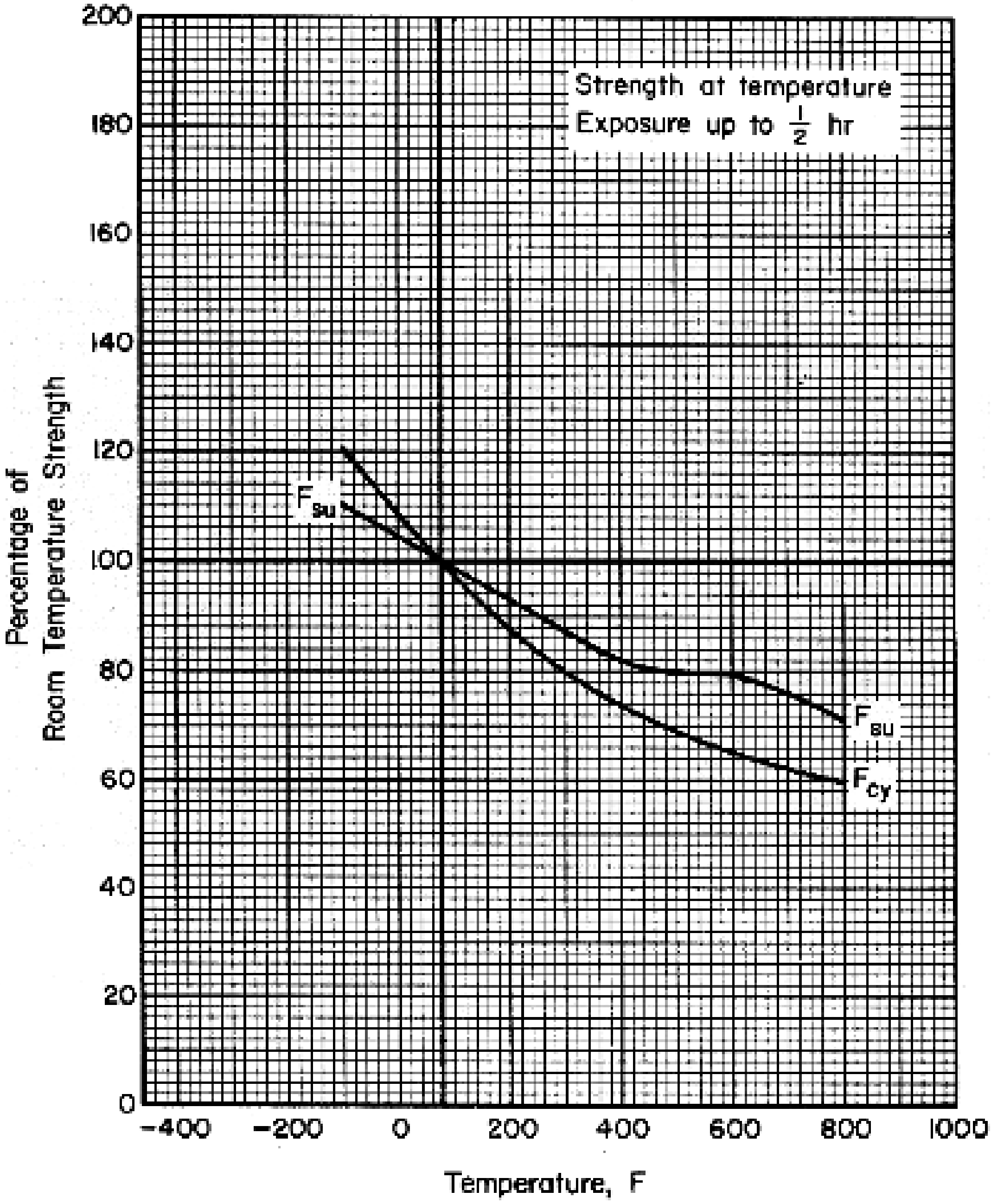

Figure 5.4.2.1.2(a). Effect of temperature on the compressive yield strength (F_{cy}) and the shear ultimate strength (F_{su}) of annealed Ti-6Al-6V-2Sn extrusion.

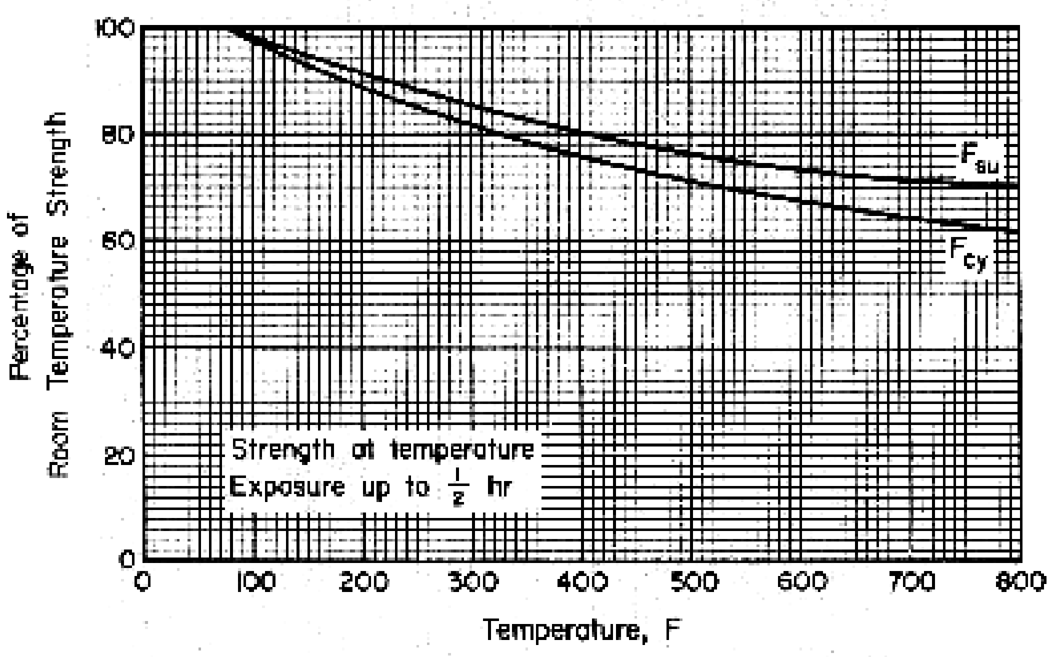

Figure 5.4.2.1.2(b). Effect of temperature on the compressive yield strength (F_{cy}) and the shear ultimate strength (F_{su}) of annealed Ti-6Al-6V-2Sn plate.

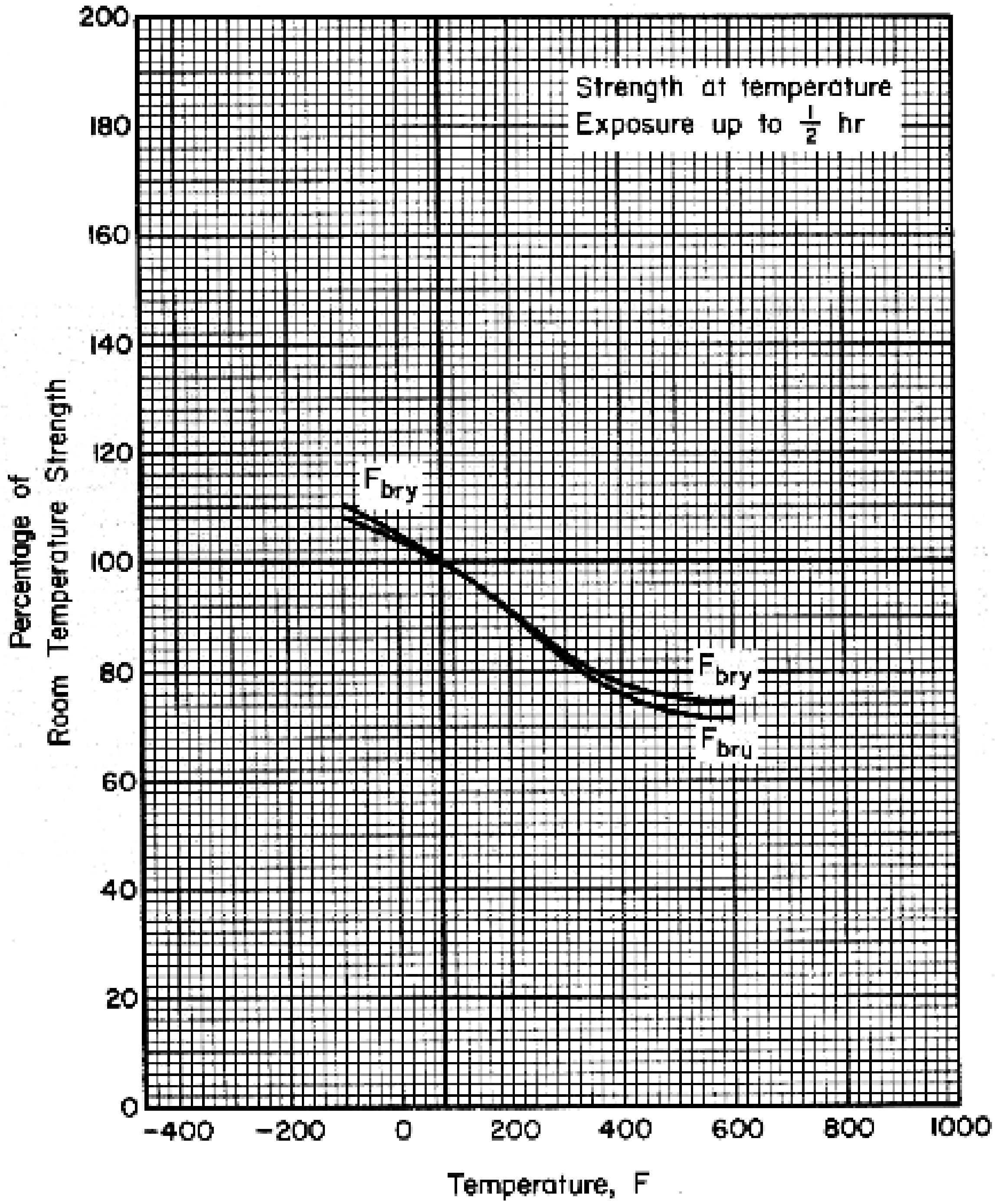

Figure 5.4.2.1.3(a). Effect of temperature on the bearing ultimate strength (F_{bru}) and the bearing yield strength (F_{bry}) of annealed Ti-6Al-6V-2Sn extrusion.

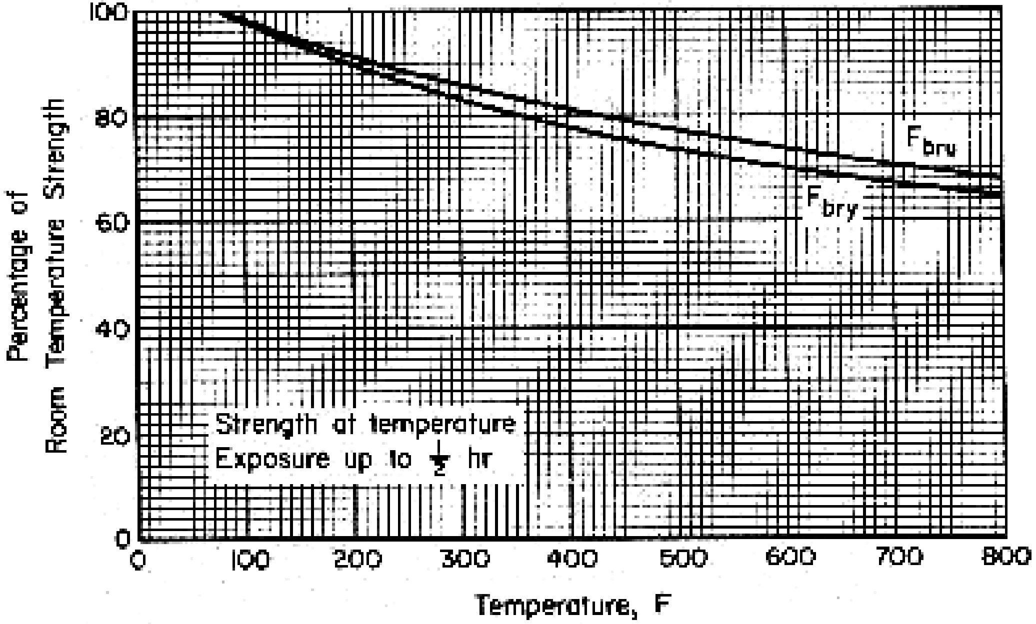

Figure 5.4.2.1.3(b). Effect of temperature on the bearing ultimate strength (F_{bru}) and the bearing yield strength (F_{bry}) of annealed Ti-6Al-6V-2Sn plate.

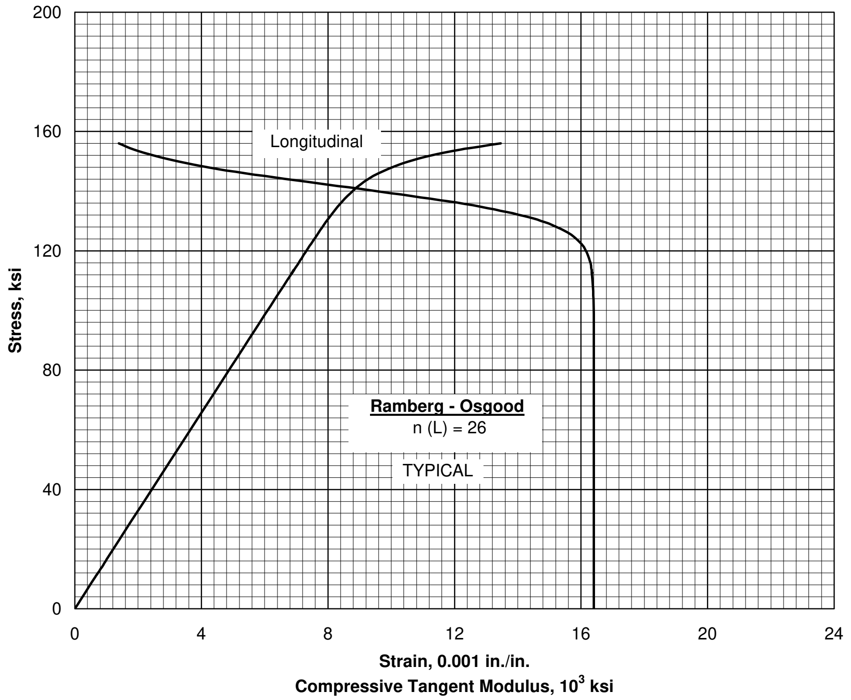

Figure 5.4.2.1.6(a). Typical compressive stress-strain and tangent-modulus curves at room temperature for annealed Ti-6Al-6V-2Sn extrusion.

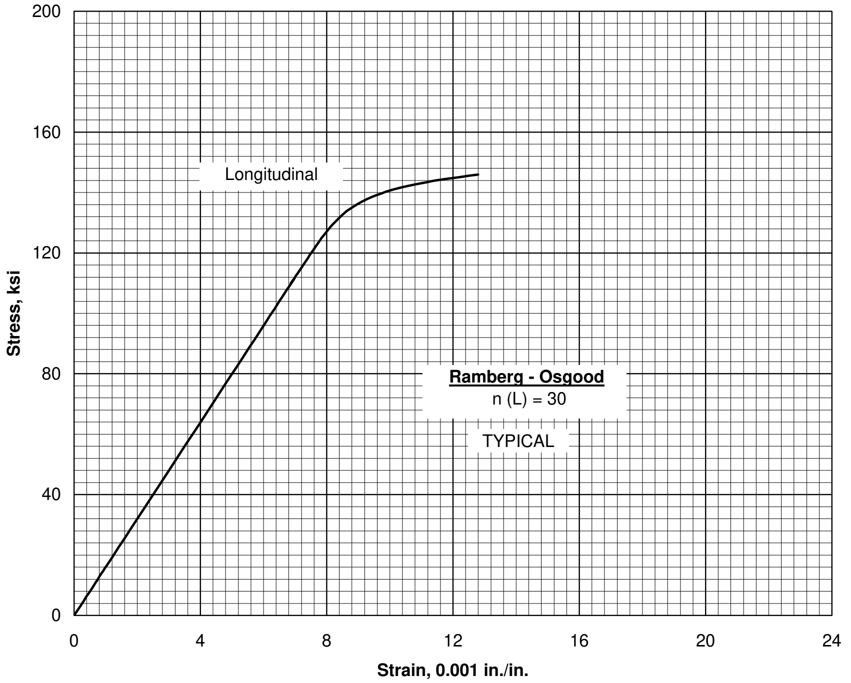

Figure 5.4.2.1.6(b). Typical tensile stress-strain curve at room temperature for annealed Ti-6Al-6V-2Sn extrusion.

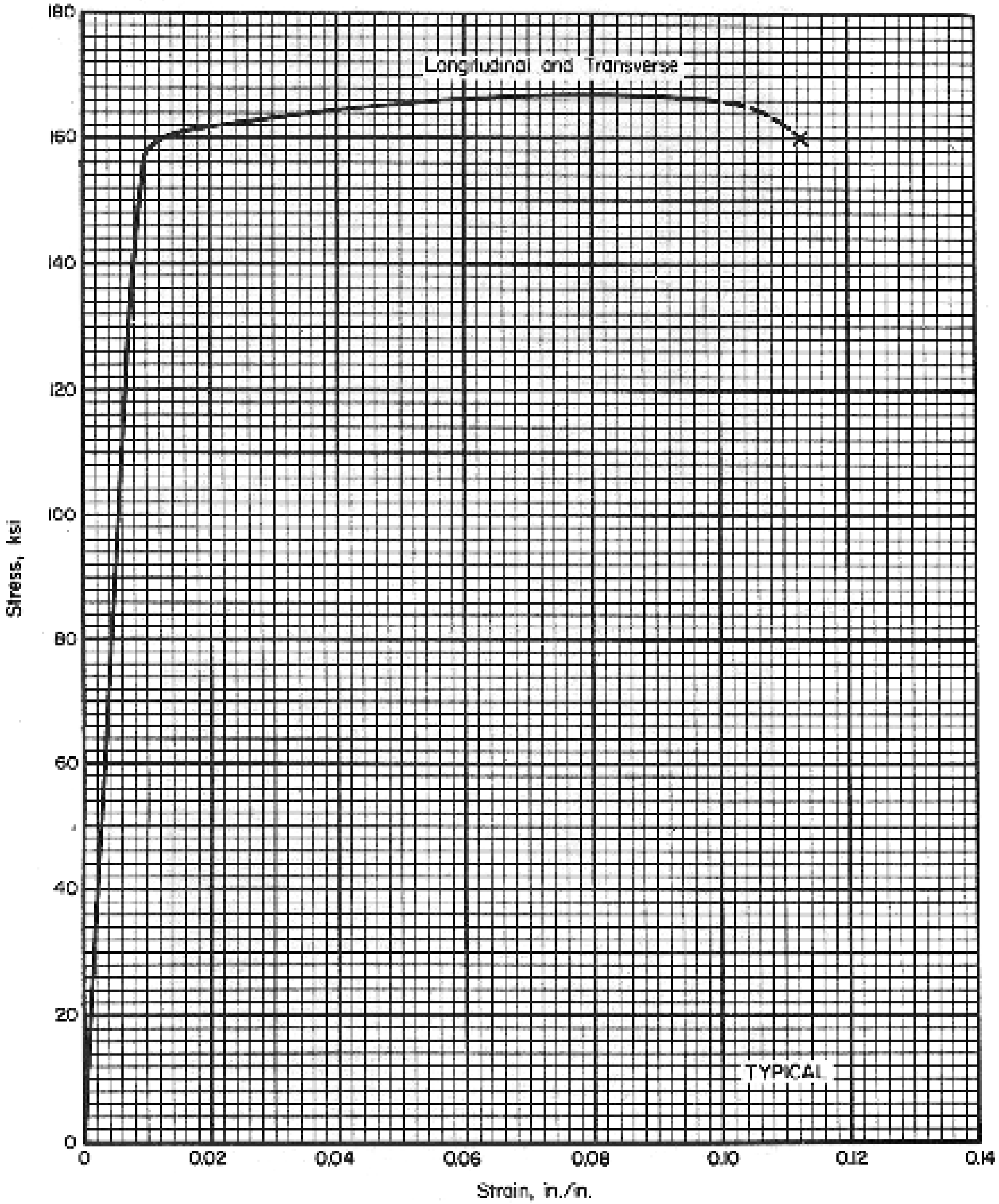

Figure 5.4.2.1.6(c). Typical tensile stress-strain curve (full range) for annealed Ti-6Al-6V-2Sn sheet at room temperature.

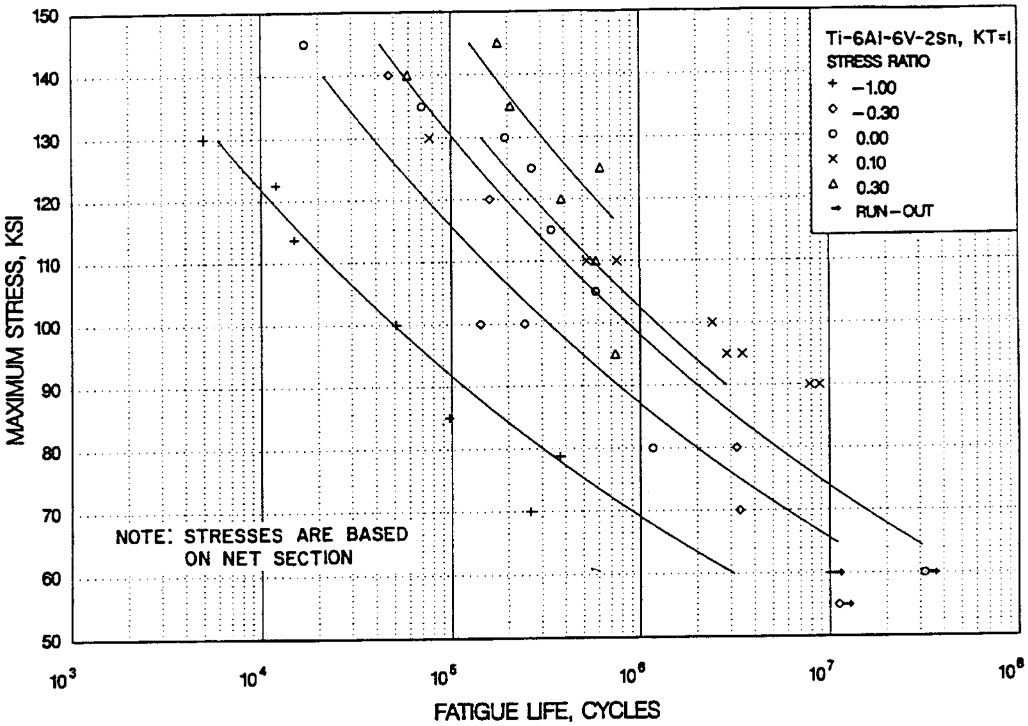

Figure 5.4.2.1.8(a). Best-fit S/N curves for annealed Ti-6Al-6V-2Sn plate and die forging, K_t = 1.0, longitudinal direction.

Correlative Information for Figure 5.4.2.1.8(a)

Product Form: Plate, 1.57 inch thick; die forging, thickness not specified

Properties:

TUS, ksi	TYS, ksi	Temp., °F
154.5	148.5	RT
159.9	151.5	RT

Specimen Details: Unnotched
0.195 inch diameter
Unspecified diameter from forging

Surface Condition: RMS 32
Unspecified from forging

References: 5.4.1.2.8(c) and 5.4.2.1.8

Test Parameters:
Loading—Axial
Frequency—Unspecified
Temperature—RT
Atmosphere—Air

No. of Heats/Lot: 3

Equivalent Stress Equation:
Log N_f = 20.90 - 8.10 log (S_{eq})
$S_{eq} = S_a + 0.41\ S_m$
Std. Error of Estimate, Log (Life) = 23.5 (1/S_{eq})
Standard deviation, Log (Life) = 0.884
R^2 = 89%

Sample Size = 38

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

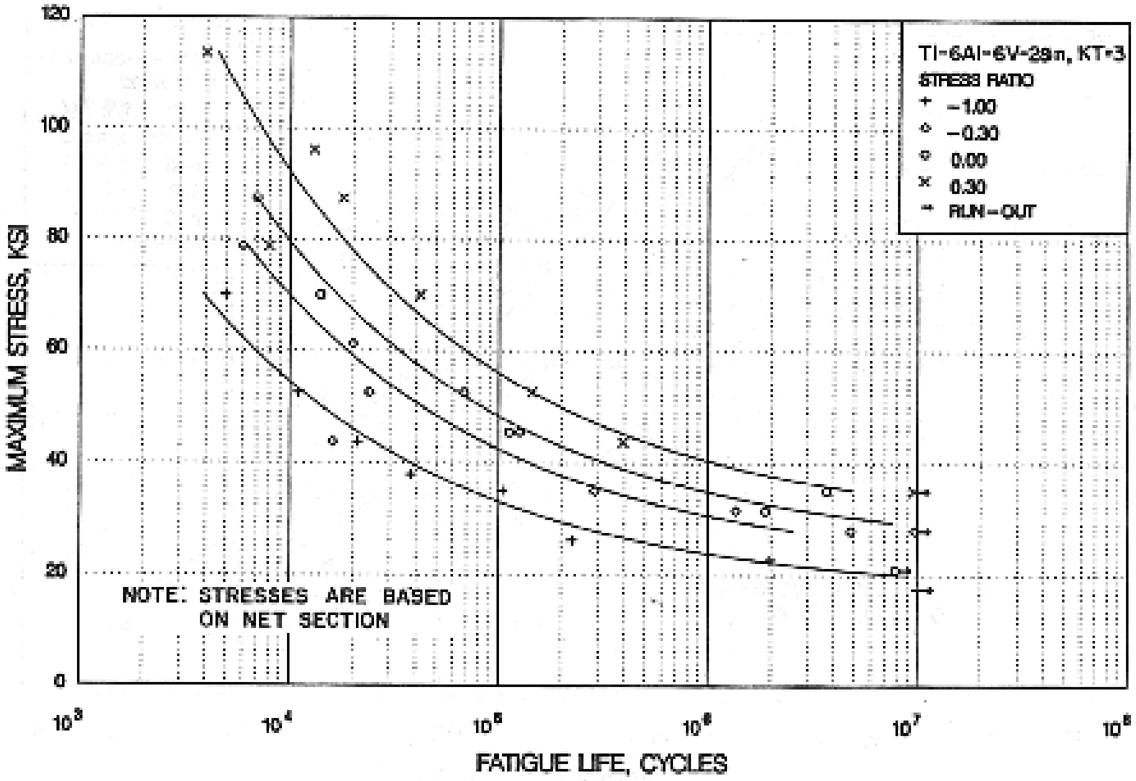

Figure 5.4.2.1.8(b). Best-fit S/N curves for annealed Ti-6Al-6V-2Sn plate, K_t = 3.0, longitudinal direction.

Correlative Information for Figure 5.4.2.1.8(b)

Product Form: Plate, 1.57 inch thick

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	154.6	148.5	RT

Specimen Details: V-Groove, K_t = 3.0
0.195 inch gross diameter
0.136 inch net diameter
0.005 inch root radius
60° flank angle

Surface Condition: RMS 32

References: 5.4.1.2.8(c)

Test Parameters:
Loading—Axial
Frequency—Unspecified
Temperature—RT
Atmosphere—Air

No. of Heats/Lot: 1

Equivalent Stress Equation:
Log N_f = 8.31 - 2.73 log (S_{eq} - 16.9)
$S_{eq} = S_a + 0.37\ S_m$
Std. Error of Estimate, Log (Life) = 8.87 (1/S_{eq})
Standard Deviation, Log (Life) = 0.947
R^2 = 92%

Sample Size = 32

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

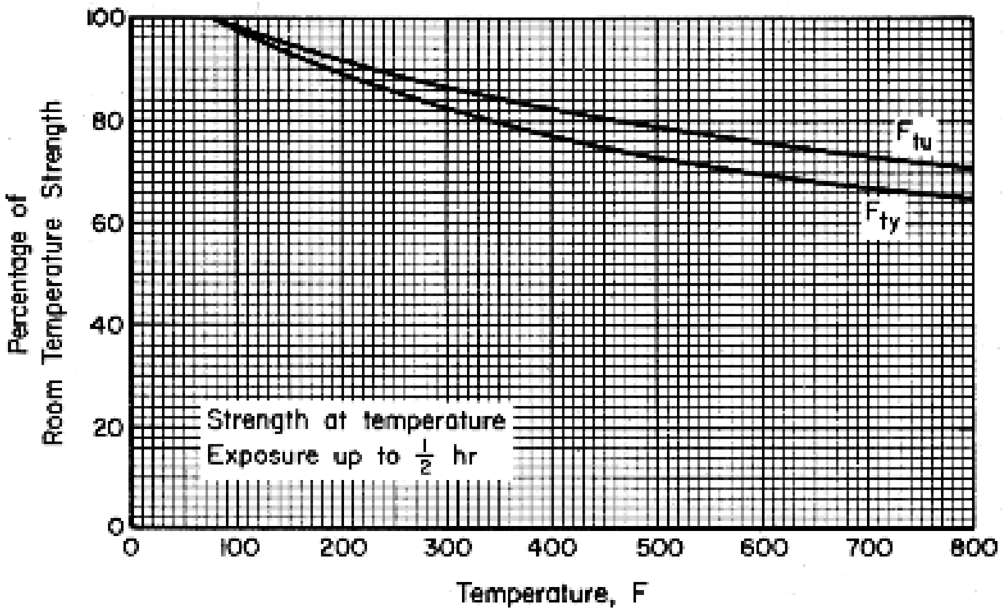

Figure 5.4.2.2.1. Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of solution-treated and aged Ti-6Al-6V-2Sn plate.

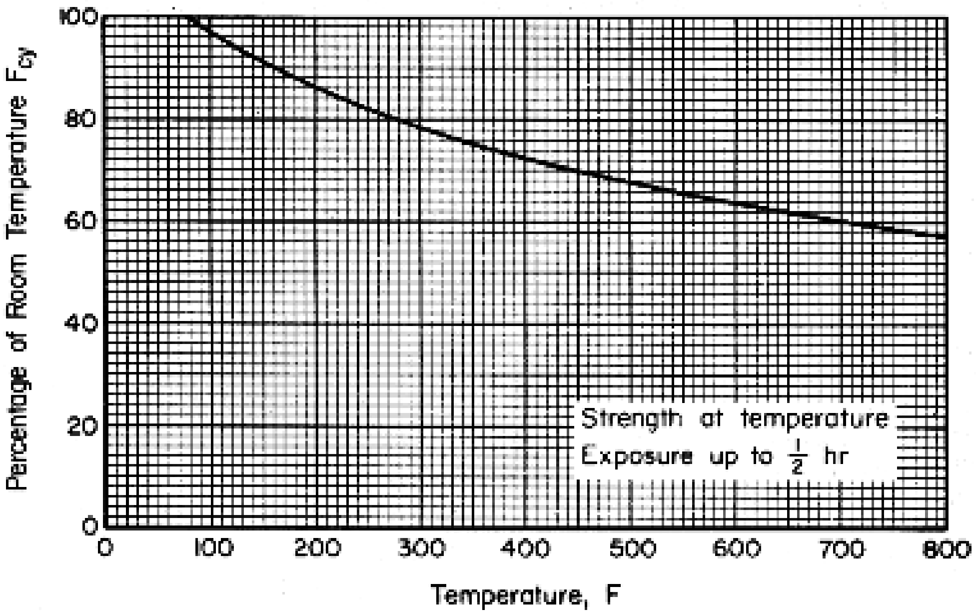

Figure 5.4.2.2.2. Effect of temperature on compressive yield strength (F_{cy}) of solution-treated and aged Ti-6Al-6V-2Sn plate.

5.4.3 TI-4.5AL-3V-2FE-2MO

5.4.3.0 Comments and Properties —Ti-4.5Al-3V-2Fe-2Mo alloy is a beta rich alpha-beta titanium composition developed for improved hot formability and fatigue resistance. The alloy consists of fine microstructure and has excellent superplastic formability at temperatures below 1475°F. This alloy also shows significantly improved cold formability over Ti-6Al-4V. Although this alloy was originally developed for flat product applications in the annealed condition, it has expanded into other areas such as billets, bars, and forgings. This alloy has been reported to possess significantly better hardenability than Ti-6Al-4V.

Manufacturing Considerations – Superplastic forming of Ti-4.5Al-3V-2Fe-2Mo at temperatures between 1380F-1425°F is recommended. At these forming temperatures the formation of alpha case is not observed and the thickness of oxygen enriched layer is generally less than 0.001”. Diffusion bonding at 1425°F is possible but slightly higher temperatures than the superplastic forming temperature e.g., 1470°F are recommended to ensure perfect bonding. Ti-4.5Al-3V-2Fe-2Mo is weldable by standard titanium welding techniques. This alloy shows an increase in hardness in the welded zone but with limited ductility loss. Stress relief annealing after welding is recommended.

Environmental Considerations – Ti-4.5Al-3V-2Fe-2Mo exhibits significantly improved resistance to aqueous chloride solution stress-corrosion cracking over Ti-6Al-4V. The alloy is nearly equivalent to Ti-6Al-4V hot - salt stress corrosion cracking.

Heat Treatment – This alloy is commonly specified in the annealed condition, but is also used in the solution-treated and aged condition.

Annealing : 1325°F for a time commensurate with product thickness.

Annealing requires 1 hour at 1475°F followed by furnace cooling if maximum ductility is required.
The solution treated and aged conditions commonly employed are as follows :
Solution treat at 1500-1580°F for 1/2 –1hour followed by air cooling.
Age at 900-1060°F followed by air cooling.

Specifications and Properties – Some material specifications for Ti-4.5Al-3V-2Fe-2Mo are shown in Table 5.4.3.0(a). Room temperature mechanical properties and physical properties are shown in Table 5.4.3.0(b) through (d).

Table 5.4.3.0(a). Material Specification for Ti-4.5Al-3V-2Fe-2Mo Titanium Alloy

Specification	Form
AMS 4899	Sheet, Strip, and Plate
AMS 4964	Bars, Wire, Forgings, and Rings

5.4.3.1 Anneal Condition – Typical tensile stress-strain and full-range stress-strain curves are shown in Figures 5.4.3.1.6(a) and (b). Compressive stress-strain and tangent modulus curves are shown in Figure 5.4.3.1.6(c). Unnotched and notched fatigue data as well as fatigue crack propagation data are presented in Figures 5.4.3.1.8(a), (b) and 5.4.3.1.9.

Table 5.4.3.0 (b). Design Mechanical and Physical Properties of Ti-4.5Al-3V-2Fe-2Mo Titanium Alloy Sheet

Specification	AMS 4899			
Form	Sheet			
Condition	Annealed			
Thickness, in.	0.025 to 0.063, exclusive		0.063 to 0.187, exclusive	
Basis	A	B	A	B
Mechanical Properties:				
F_{tu}, ksi:				
L	134[a]	145	134[b]	144
LT	134[a]	147	134[b]	144
F_{ty}, ksi:				
L	126[a]	134	126[b]	132
LT	126[a]	137	126[b]	134
F_{cy}, ksi:				
L	128	136	130	139
LT	131	143	132	141
F_{su},[c] ksi:				
LT	90	99	91	98
F_{bru},[d] ksi: LT				
(e/D = 1.5)	196	215	207	223
(e/D = 2.0)	258	283	276	296
F_{bry},[d] ksi: LT				
(e/D = 1.5)	157	171	165	176
(e/D = 2.0)	190	207	198	210
e, percent (S-basis):				
L	8	...	10	...
LT	8	...	10	...
E, 10^3 ksi	16.0			
E_c, 10^3 ksi	16.2			
G, 10^3 ksi	...			
μ	...			
Physical Properties:				
ω, lb/in.^{3}	0.164			
C, Btu/(lb)(°F)	0.12			
K, Btu/[(hr)(ft^2)(°F)/ft]	4.00			
α, 10^{-6} in./in./°F	5.17 (60-932°F)			

---

a S-basis. Rounded T_{99} values for thickness range 0.025 - 0.063 in. are as follows; F_{tu} (L) and (LT) = 140 ksi, F_{ty} (L) = 129 ksi and F_{ty} (LT) = 131 ksi.

b S-basis. Rounded T_{99} values for thickness range 0.063 - 0.187 in. are as follows; F_{tu} (L) = 141 ksi, F_{tu} (LT) = 140 ksi, F_{ty} (L) = 128 ksi and F_{ty} (LT) = 127 ksi.

c Determined in accordance with ASTM B769.

d Bearing values are “dry pin” values per Section 1.4.7.1.

Table 5.4.3.0 (c). Design Mechanical and Physical Properties of Ti-4.5Al-3V-2Fe-2Mo Titanium Alloy Bar

Specification	AMS 4964					
Form	Bar					
Condition	Annealed					
Thickness, in.	≤ 2.000		2.001-4.000		4.001-6.000	
Basis	A	B	A	B	A	B
Mechanical Properties:						
F_{tu}, ksi:						
L	135	139	130[a]	135	130	133
LT (S-basis)	135	...	130	...	130	...
F_{ty}, ksi:						
L	124	128	119	123	119	123
LT (S-basis)	125	...	120	...	120	...
F_{cy}, ksi:						
L	124	128	...	...	...	...
LT (S-basis)	...	...	...	...	...	...
F_{su}[b], ksi						
L -R	81	84	...	...	...	...
F_{bru}[c] ksi:						
(e/D = 1.5)	...	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...	...
F_{bry},[c] ksi:						
(e/D = 1.5)	...	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...	...
e, percent (S-basis):						
L	10	...	10	...	10	...
LT	10[d]	...	10[d]	...	10	...
Red. in Area, percent (S-basis):						
L	25	...	20	...	20	...
LT	20[d]	...	20[d]	...	20	...
E, 10^3 ksi	16.0					
E_c, 10^3 ksi	16.2					
G, 10^3 ksi	...					
μ	...					
Physical Properties:						
ω, lb/in.^{3}	0.164					
C, Btu/(lb)(°F)	0.12					
K, Btu/[(hr)(ft^2)(°F)/ft]	4.00					
α, 10^{-6} in./in./°F	5.17 (60-932°F)					

a Rounded T_{99} for F_{tu} = 131 ksi.
b Determined in accordance with ASTM B769.
c Bearing values are “dry pin” values per Section 1.4.7.1.
d Applicable, providing LT dimension is no less than 2.500 inches.

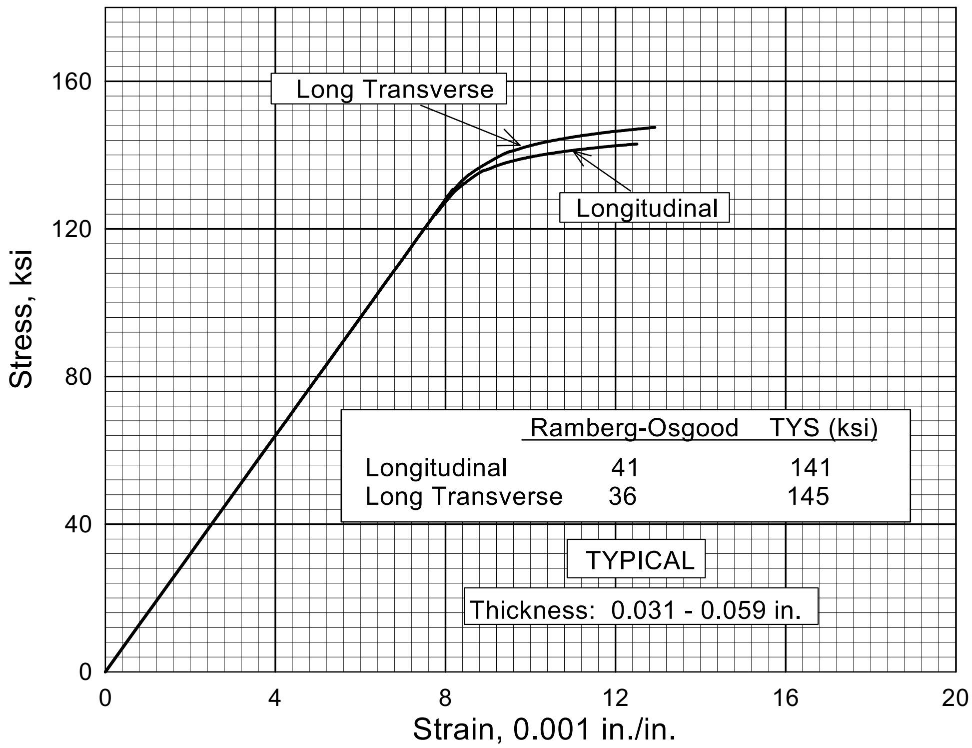

Figure 5.4.3.1.6(a). Typical tensile stress-strain curves at room temperature for annealed Ti-4.5Al-3V-2Fe-2Mo alloy sheet.

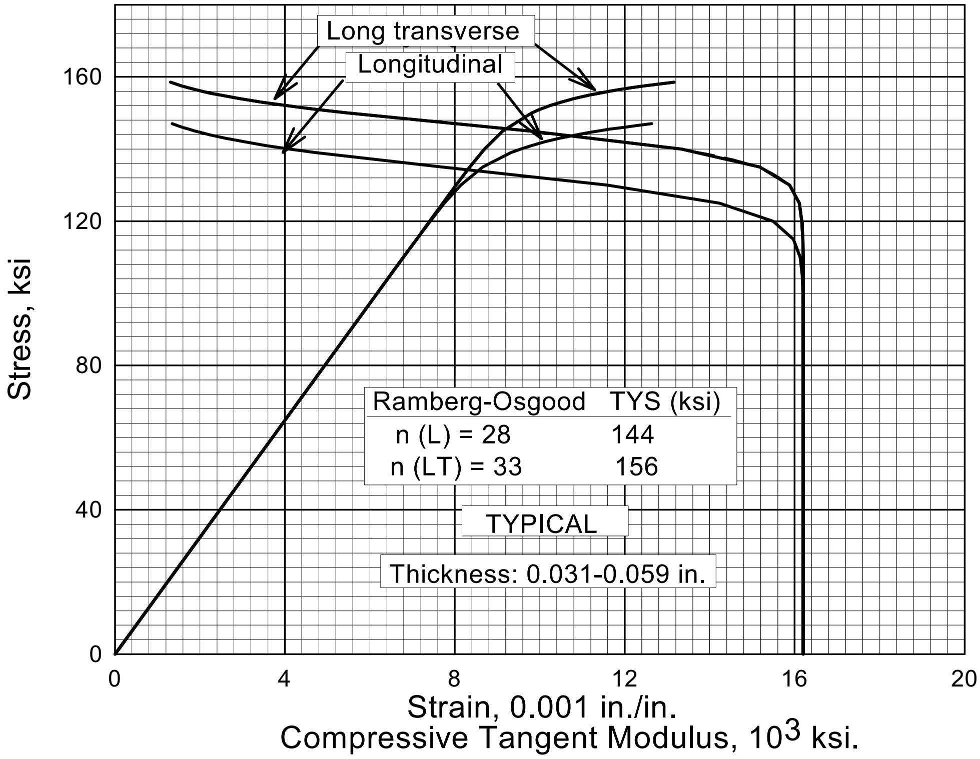

Figure 5.4.3.1.6(b). Typical compressive stress-strain and tangent-modulus curves at room temperature for annealed Ti-4.5Al-3V-2Fe-2Mo alloy sheet.

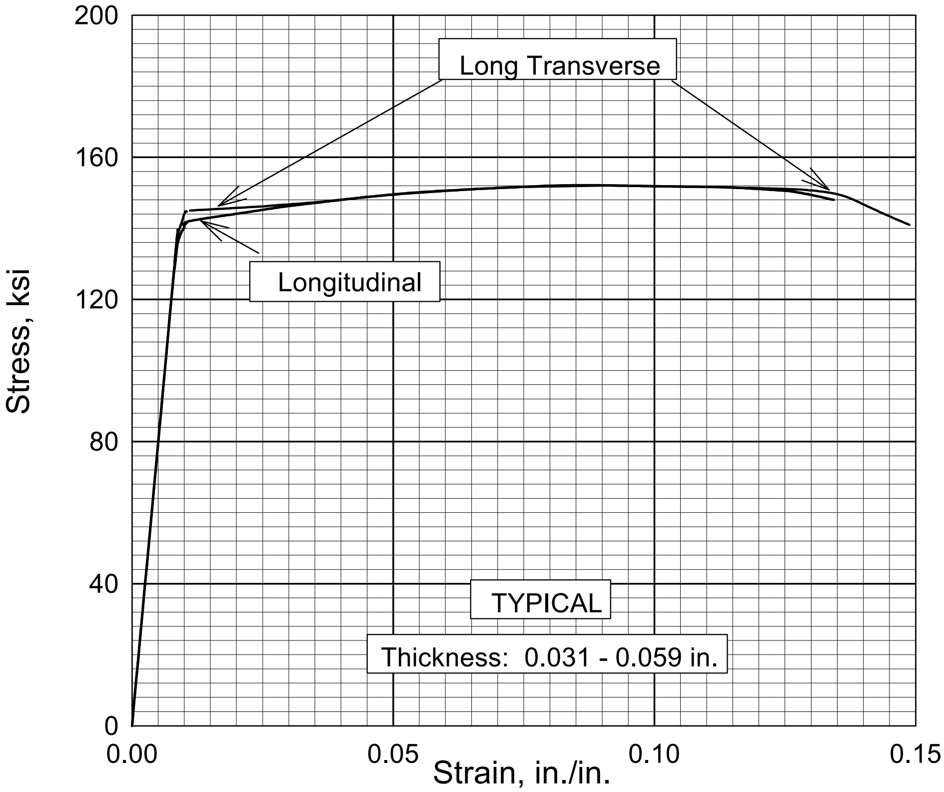

Figure 5.4.3.1.6(c). Typical tensile stress-strain curves (full-range) for annealed Ti-4.5Al-3V-2Fe-2Mo alloy sheet.

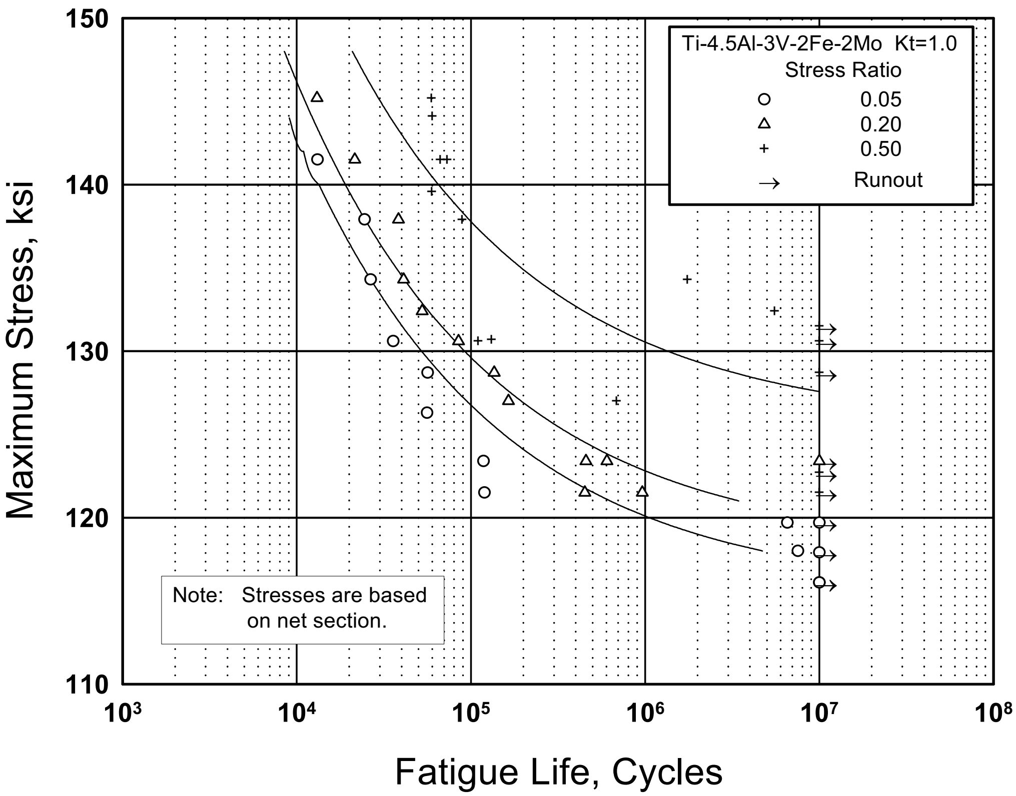

Figure 5.4.3.1.8 (a) Best-fit S/N curves for unnotched Ti-4.5Al-3V-2Fe-2Mo annealed sheet.

Correlative Information for Figure 5.4.3.1.8 (a)

Product Form: 0.059, 0.118, 0.157 inch thick

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	148 - 149	135 - 138	RT

Specimen Details: Unnotched, 0.252 inch width

Surface Conditions: Lightly polished with 400 grit emery paper

References: 5.4.3.1.8

Test Parameter:
Loading - Axial
Frequency - 10Hz
Temperature - RT
Environment - Air

No. of Heats : 3

Equivalent Stress Equation:
Log N_f = 7.72 - 2.59 log (S_{eq} - 114.68)
$S_{eq} = S_{max} (1 - R)^{0.13}$
Std. Error of Estimate, Log (Life) = 0.40
Standard Deviation, Log (Life) = 0.60
Adjusted R^2 = 56.5%

Sample Size = 43

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

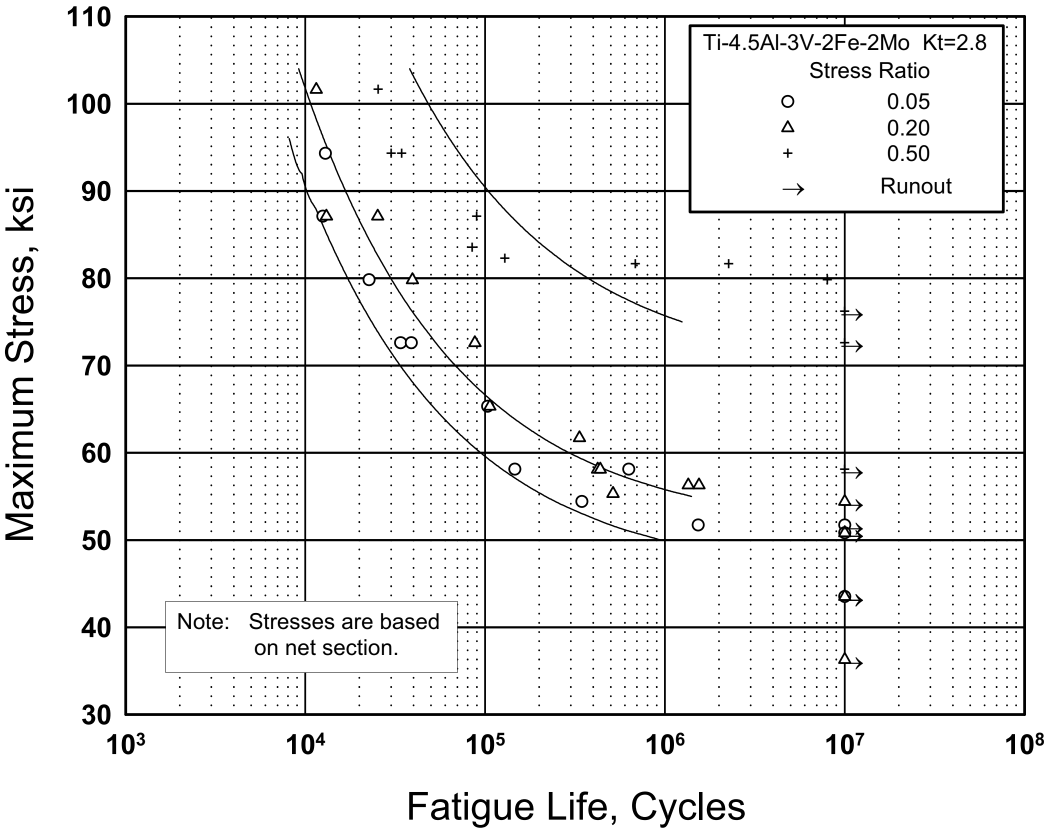

Figure 5.4.3.1.8 (b) Best-fit S/N curves for notched, Kt = 2.8, Ti-4.5Al-3V-2Fe-2Mo annealed sheet.

Correlative Information for Figure 5.4.3.1.8 (b)

Product Form: 0.059, 0.118, 0.157 inch thick

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	148 - 149	135 - 138	RT

Specimen Details: Notched, Kt = 2.8
0.466 inch net width

Surface Conditions: HF/HNO_3 pickled

References: 5.4.3.1.8

Test Parameter:
Loading - Axial
Frequency - 10Hz
Temperature - RT
Environment - Air

No. of Heats: 3

Equivalent Stress Equation:
$\text{Log } N_f = 7.22 - 1.96 \log (S_{eq} - 44.05)$
$S_{eq} = S_{max} (1 - R)^{0.65}$
Std. Error of Estimate, Log (Life) = 0.24
Standard Deviation, Log (Life) = 0.47
Adjusted R^2 = 72.9%

Sample Size = 41

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

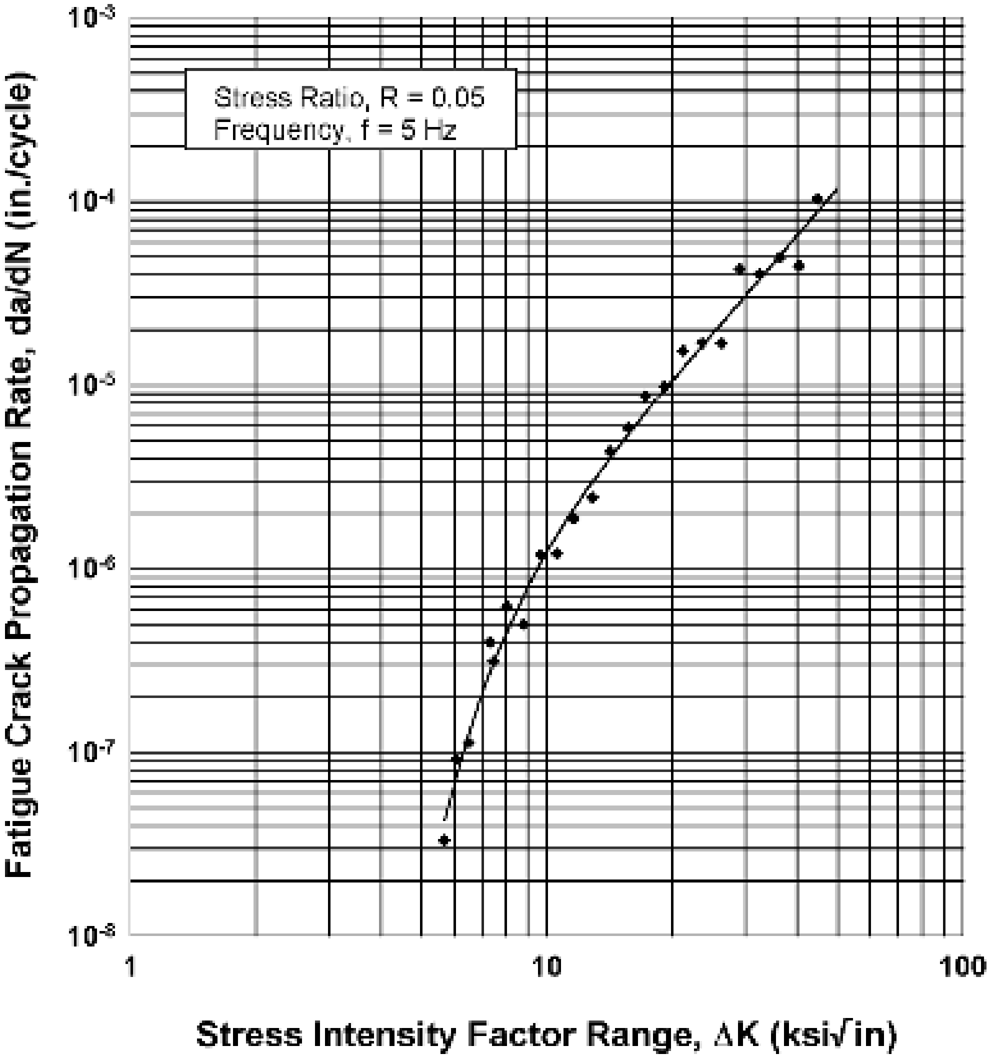

Figure 5.4.3.1.9 Fatigue-crack-propagation data for 1 inch thick Ti-4.5Al-3V-2Fe-2Mo mill annealed titanium alloy plate.

Specimen Thickness:	*0.25 inch*	*Environment:*	*50% RH*
Specimen Width:	*2.0 inches*	*Temperature:*	*RT*
Specimen Type:	*C(T)*	*Orientation:*	*L-T*

5.5 BETA, NEAR-BETA, AND METASTABLE-BETA TITANIUM ALLOYS

There is no clear-cut definition for beta titanium alloys. Conventional terminology usually refers to near-beta alloys and metastable-beta alloys as classes of beta titanium alloys. A near-beta alloy is generally one which has appreciably higher beta stabilizer content than a conventional alpha-beta alloy such as Ti-6Al-4V, but is not quite sufficiently stabilized to readily retain an all-beta structure with an air cool of thin sections. For such alloys, a water quench even of thin sections is required. Due to the marginal stability of the beta phase in these alloys, they are primarily solution treated below the beta transus to produce primary alpha phase which in turn results in an enriched, more stable beta phase. This enriched beta phase is more suitable for aging. The Ti-10V-2Fe-3Al alloy is an example of a near-beta alloy.

On the other hand, the metastable-beta alloys are even more heavily alloyed with beta stabilizers than near-beta alloys and, as such, readily retain an all-beta structure upon air cooling of thin sections. Due to the added stability of these alloys, it is not necessary to heat treat below the beta transus to enrich the beta phase. Therefore, these alloys do not normally contain primary alpha since they are usually solution treated above the beta transus. These alloys are termed “metastable” because the resultant beta phase is not truly stable—it can be aged to precipitate alpha for strengthening purposes. Alloys such as Ti-15-3, B120VCA, Beta C, and Beta III are considered metastable-beta alloys.

Unfortunately, the classification of an alloy as either near-beta or metastable beta is not always obvious. In fact, the “metastable” terminology is not precise since a near-beta alloy is also metastable—i.e., it also decomposes to alpha plus beta upon aging.

There is one obvious additional category of beta alloys—the stable beta alloys. These alloys are so heavily alloyed with beta stabilizers that the beta phase will not decompose to alpha plus beta upon subsequent aging. There are no such alloys currently being produced commercially. An example of such an alloy is Ti-30Mo.

The interest in beta alloys stems from the fact that they contain a high volume fraction of beta phase which can be subsequently hardened by alpha precipitation. Thus, these alloys can generate quite high-strength levels (in excess of 200 ksi) with good ductilities. Also, such alloys are much more deep hardenable than alpha-beta alloys such as Ti-6Al-4V. Finally, many of the more heavily alloyed beta alloys exhibit excellent cold formability and as such offer attractive sheet metal forming characteristics.

5.5.1 TI-13V-11CR-3AL

5.5.1.0 *Comments and Properties* — Ti-13V-11Cr-3Al is a heat-treatable alloy possessing good workability and toughness in the annealed condition and high strength in the heat-treated condition. It is noted for its exceptional ability to harden in heavy sections (up to 6-inch diameter or greater) to tensile strength of 170 ksi F_{tu}.

Manufacturing Considerations — This alloy possesses very good formability at room temperature; stretch forming is usually conducted at 500°F. Ti-13V-11Cr-3Al is readily fusion or spot welded. Arc-welded joints are very ductile in the as-welded condition, but have low strengths.

Environmental Considerations — Ti-13V-11Cr-3Al is stable for times up to 1000 hours in the annealed condition at 550°F and in the solution treated and aged condition up to 600°F. Prolonged exposure above these temperatures may result in ductility losses. If welding is employed, the stability of the weld should be investigated under the particular exposure conditions to be encountered. While the material is not noted for good creep performance, Ti-13V-11Cr-3Al has exceptional short-time strength at temperatures to 1200°F and above. Oxidation resistance is satisfactory at such temperatures for short-time exposure and for long-time exposure at the lower elevated temperatures. Hot-salt stress corrosion has been shown to be possible in this alloy at temperatures as low as 500°F in highly stressed applications (e.g., rivet heads). It is generally thought that the material is moderately susceptible to aqueous chloride solution stress corrosion. Ti-13V-11Cr-3Al is not noted for good fracture toughness in the aged or high-strength condition and is not recommended in any condition for cryogenic temperature applications. Under certain conditions, titanium, when in contact with cadmium, silver, mercury, or certain of their compounds, may become embrittled. Refer to MIL-S-5002 and MIL-STD-1568 for restrictions concerning applications with titanium in contact with these metals or their compounds.

Heat Treatment — This alloy is commonly specified in either the annealed condition or in the fully heat-treated condition. The specified fully heat-treated, or solution-treated and aged, condition is as follows:

> Solution treat at 1450°F for 15 to 60 minutes, air cool (water quench if material is over 2 inches thick).
>
> Age at 900°F for 2 to 60 hours, dependent on strength level. (Note: typical aging time to achieve F_{tu} = 170 ksi is 24 to 36 hours.)

Specifications and Properties — Material specifications for Ti-13V-11Cr-3Al are shown in Table 5.5.1.0(a). Room-temperature mechanical and physical properties for Ti-13V-11Cr-3Al are shown in Table 5.5.1.0(b). The effect of temperature on physical properties is shown in Figure 5.5.1.0.

Table 5.5.1.0(a). Material Specifications for Ti-13V-11Cr-3Al

Specification	Form
AMS-T-9046	Sheet, strip, and plate
MIL-T-9047[a]	Bar

a Inactive for new design

5.5.1.1 *Annealed Condition*

5.5.1.1 *Annealed Condition* — Elevated temperature curves for annealed Ti-13V-11Cr-3Al are shown in Figures 5.5.1.1.1 through 5.5.1.1.4. Typical tensile stress-strain curves for annealed material at temperatures ranging from room temperature to 1000°F are shown in Figure 5.5.1.1.6. Unnotched and notched fatigue data at room and elevated temperatures for annealed sheet are shown in Figures 5.5.1.1.8(a) through (d).

5.5.1.2 *Solution-Treated and Aged Condition* — Elevated temperature curves for solution-treated and aged Ti-13V-11Cr-3Al are shown in Figures 5.5.1.2.1 through 5.5.2.1.4. Typical tensile stress-strain curves at various temperatures are shown in Figure 5.5.1.2.6. Unnotched fatigue data at room and elevated temperatures for solution-treated and aged sheet are shown in Figures 5.5.1.2.8(a) through (c).

Table 5.5.1.0(b). Design Mechanical and Physical Properties of Ti-13V-11Cr-3Al

Specification	AMS-T-9046, Comp. B-1			MIL-T-9047[a]	
Form	Sheet, strip, and plate			Bar	
Condition	Annealed		Solution treated and aged	Annealed	Solution treated and aged
Thickness or diameter, in.	0.012-0.049	0.050-4.000	≤4.000	≤7.000[b]	≤4.000[b]
Basis	S	S	S	S	S
Mechanical Properties:					
F_{tu}, ksi:					
L	132	125	170	125	170
LT	132	125	170	125[c]	170[c]
ST	...	125	170	125[c]	170[c]
F_{ty}, ksi:					
L	126	120	160	120	160
LT	126	120	160	120[c]	160[c]
ST	...	120	160	120[c]	160[c]
F_{cy}, ksi:					
L	...	120	162	...	...
LT	...	120	162	...	...
ST	...	120	162	...	...
F_{su}, ksi	...	92	105	...	...
F_{bru}, ksi:					
(e/D = 1.5)	...	207	248	...	...
(e/D = 2.0)	...	270	313	...	...
F_{bry}, ksi:					
(e/D = 1.5)	...	169	217	...	...
(e/D = 2.0)	...	200	247	...	...
e, percent:					
L	8	10	4[d]	10	6
LT	8	10	4[d]	10[c]	2[c]
ST	...	10	4[d]	10[c]	2[c]
RA, percent:					
L	...	...	...	25	10
LT	...	...	...	25[c]	5[c]
ST	...	...	...	25[c]	5[c]
E, 10^3 ksi	14.5		15.5	14.5	15.5
E_c, 10^3 ksi	...		...	...	...
G, 10^3 ksi	...		...	...	...
μ	...		...	...	...
Physical Properties:					
ω, lb/in.^{3}	0.174				
C, K, and α	See Figure 5.5.1.0				

[a] Inactive for new design

[b] Maximum of 16 square-inch cross-sectional area.

[c] Applicable, providing LT or ST dimension is ≥3.000 inches

[d] Thickness 0.025 inch and above: 3 percent below 0.025 inch.

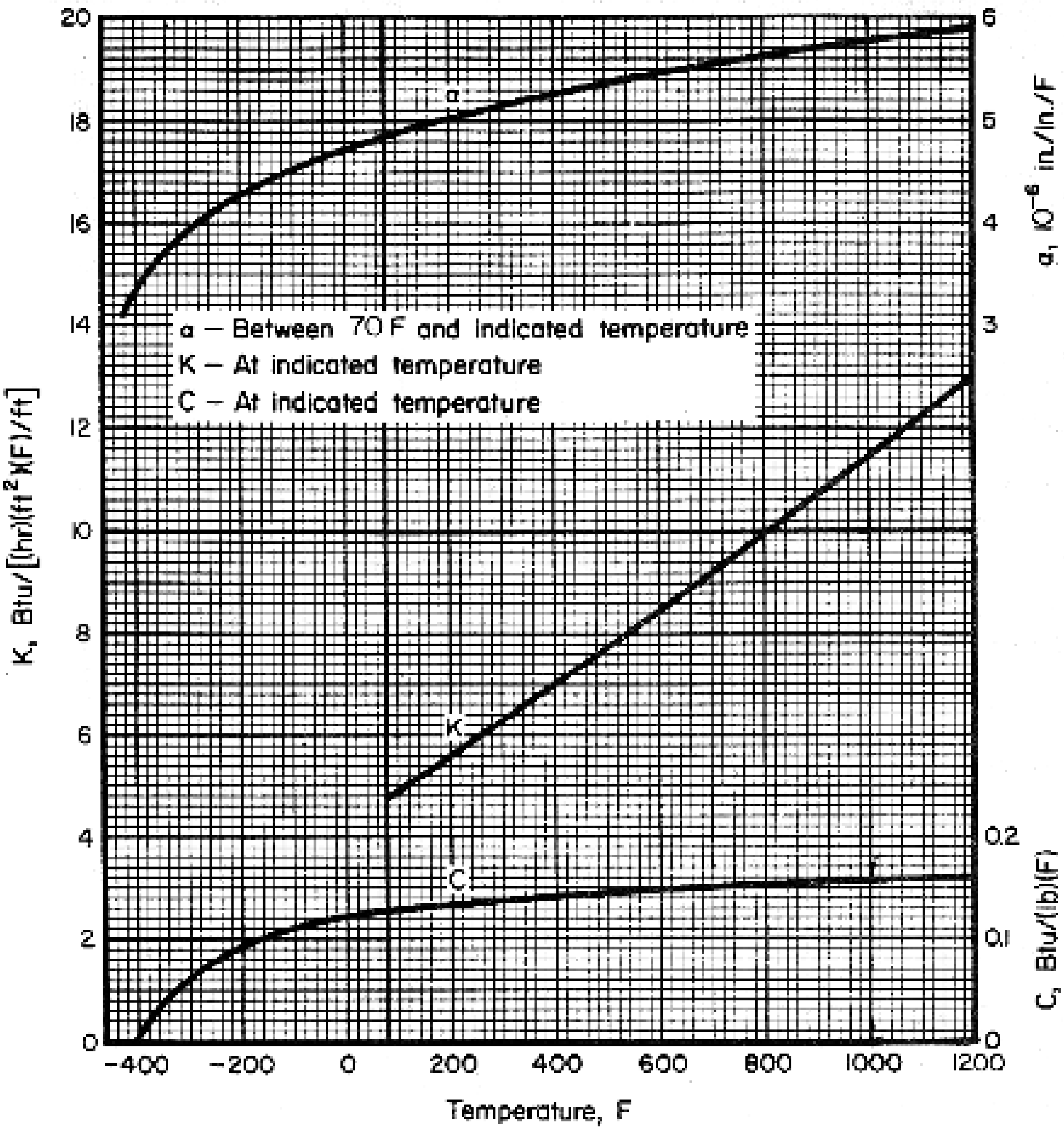

Figure 5.5.1.0. Effect of temperature on the physical properties of Ti-13V-11Cr-3Al alloy.

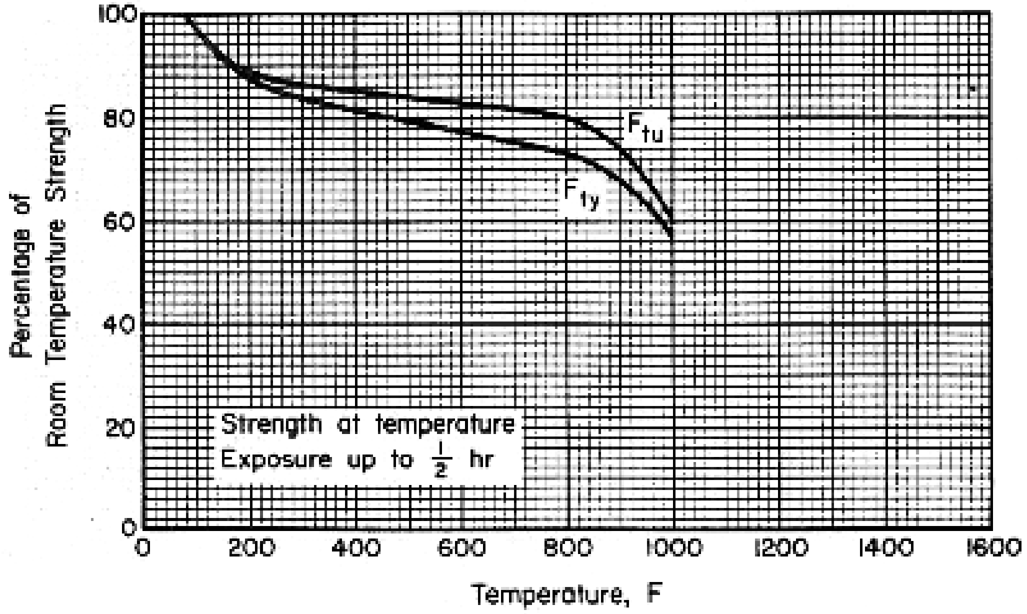

Figure 5.5.1.1.1. Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of annealed Ti-13V-11Cr-3Al alloy sheet.

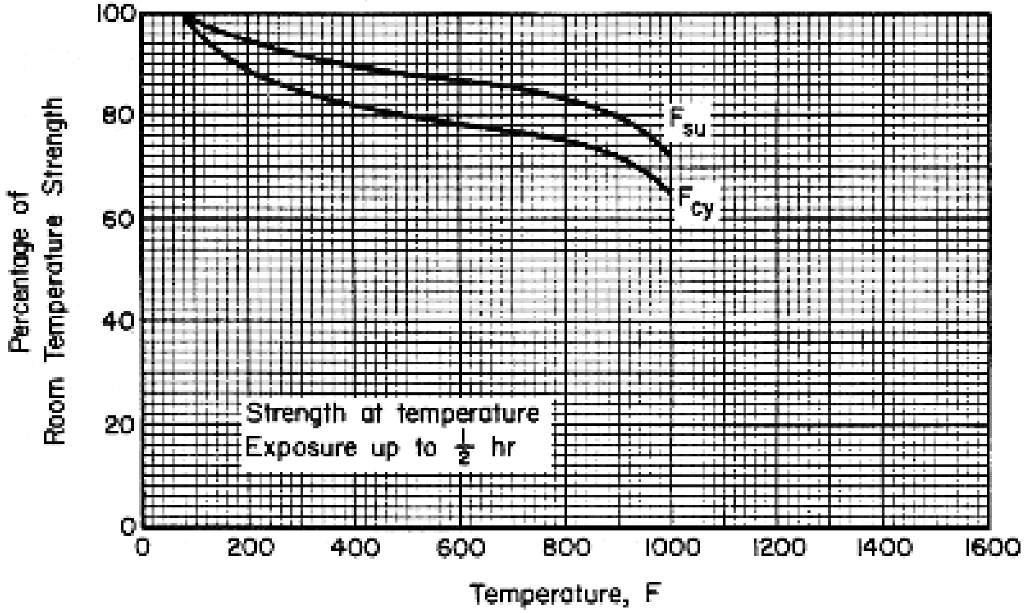

Figure 5.5.1.1.2. Effect of temperature on the compressive yield strength (F_{cy}) and the shear ultimate strength (F_{su}) of annealed Ti-13V-11Cr-3Al alloy sheet.

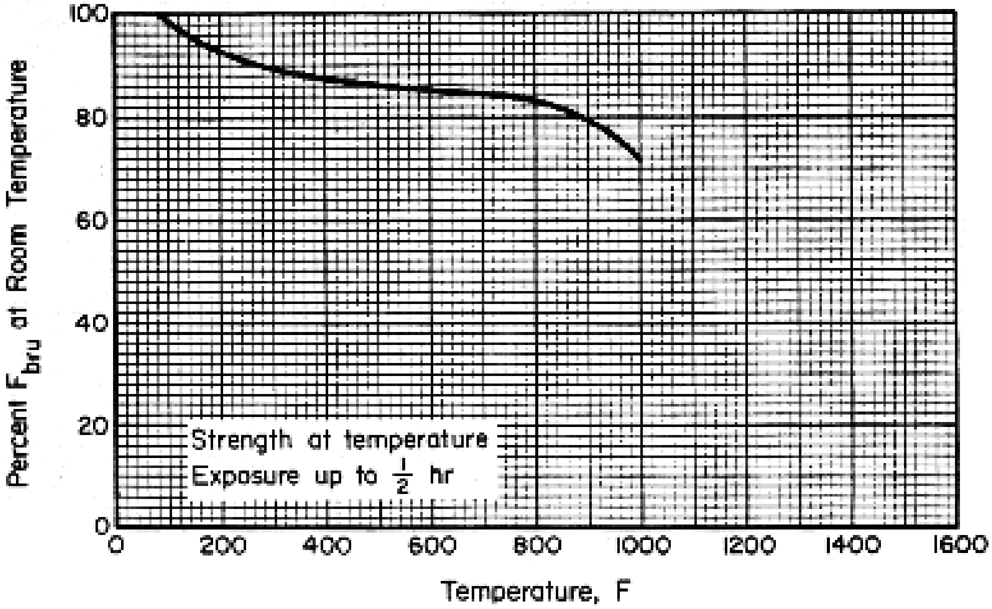

Figure 5.5.1.1.3(a). Effect of temperature on the bearing ultimate strength (F_{bru}) of annealed Ti-13V-11Cr-3Al alloy sheet.

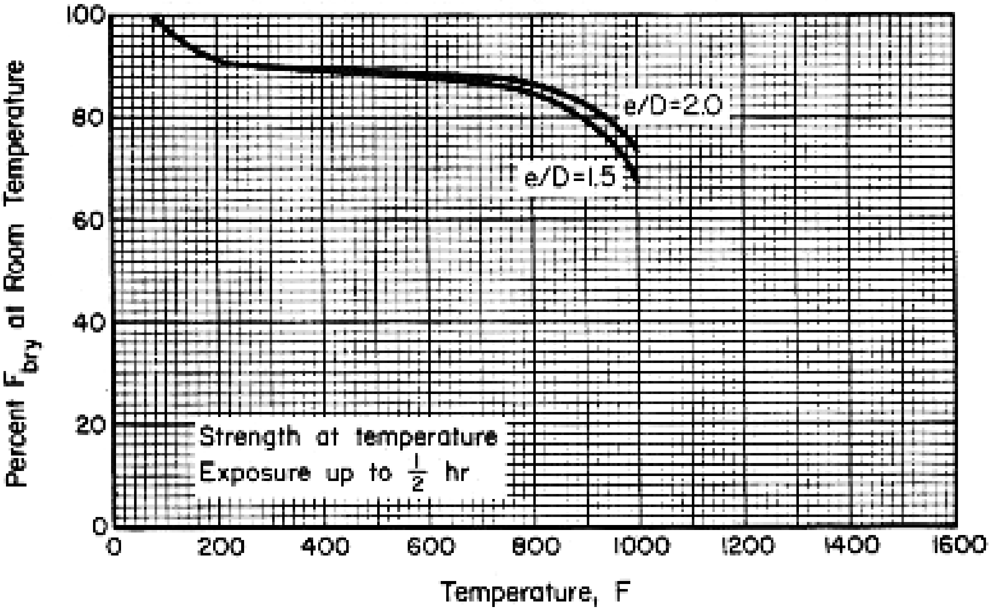

Figure 5.5.1.1.3(b). Effect of temperature on the bearing yield strength (F_{bry}) of annealed Ti-13V-11Cr-3Al alloy sheet.

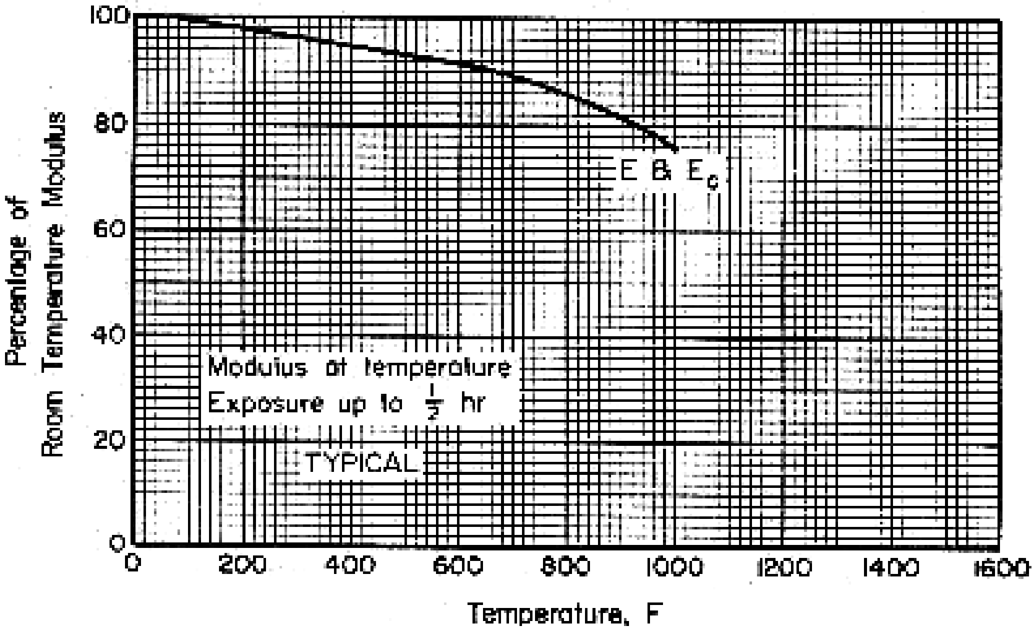

Figure 5.5.1.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of annealed Ti-13V-11Cr-3Al alloy sheet.

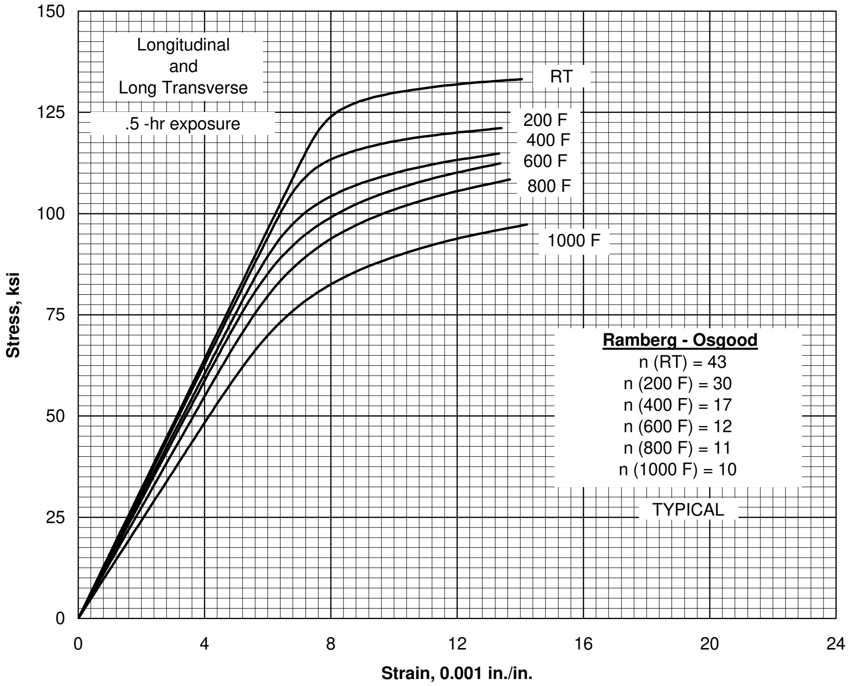

Figure 5.5.1.1.6. Typical tensile stress-strain curves for annealed Ti-13V-11Cr-3Al alloy sheet at room and elevated temperatures.

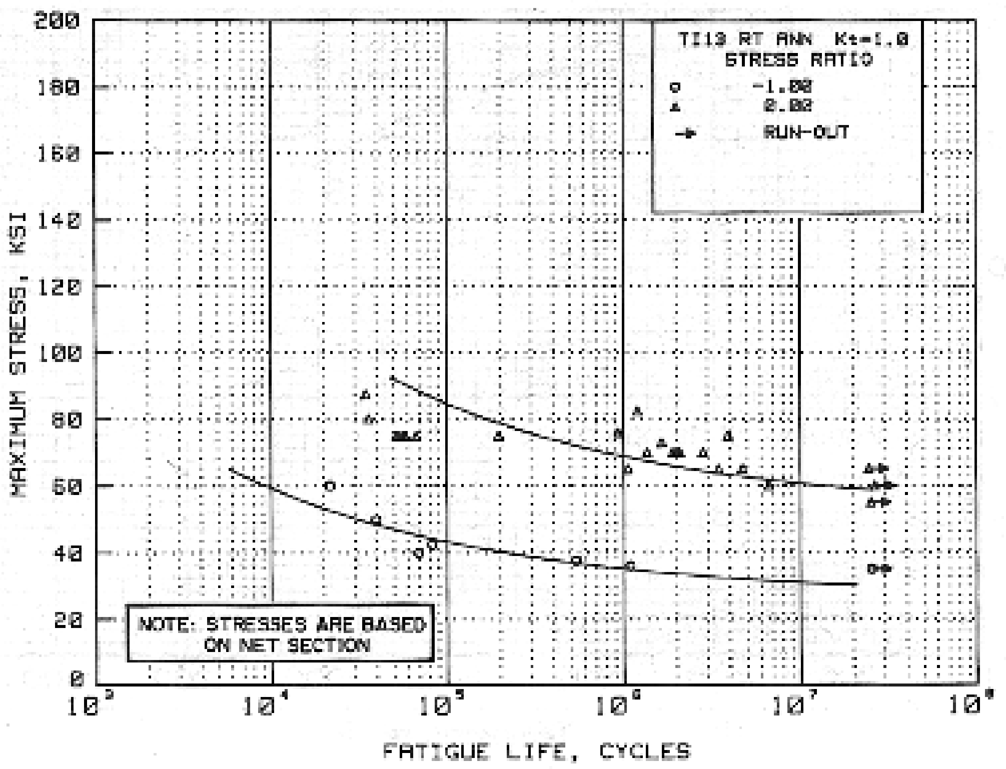

Figure 5.5.1.1.8(a). Best-fit S/N curves for unnotched, annealed Ti-13V-11Cr-3Al alloy sheet, longitudinal direction.

Correlative Information for Figure 5.5.1.1.8(a)

Product Form: Sheet, 0.043 inch thick

Properties:

TUS, ksi	TYS, ksi	Temp., °F
138.50	132.80	RT

Specimen Details: Unnotched, 0.30 inch wide

Surface Condition: As machined, edges polished with emery paper.

Reference: 5.5.1.1.8

Test Parameters:
Loading—Axial
Frequency—3600 cpm
Temperature—RT
Atmosphere—Air

No. of Heats/Lot: Not specified

Equivalent Stress Equation:
Log N_f = 10.15-3.41 log (S_{eq}-52.2)
$S_{eq} = S_{max} (1-R)^{0.97}$
Std. Error of Estimate, Log (Life) = 0.58
Standard Deviation, Log (Life) = 0.82
R^2 = 50%

Sample Size = 27

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

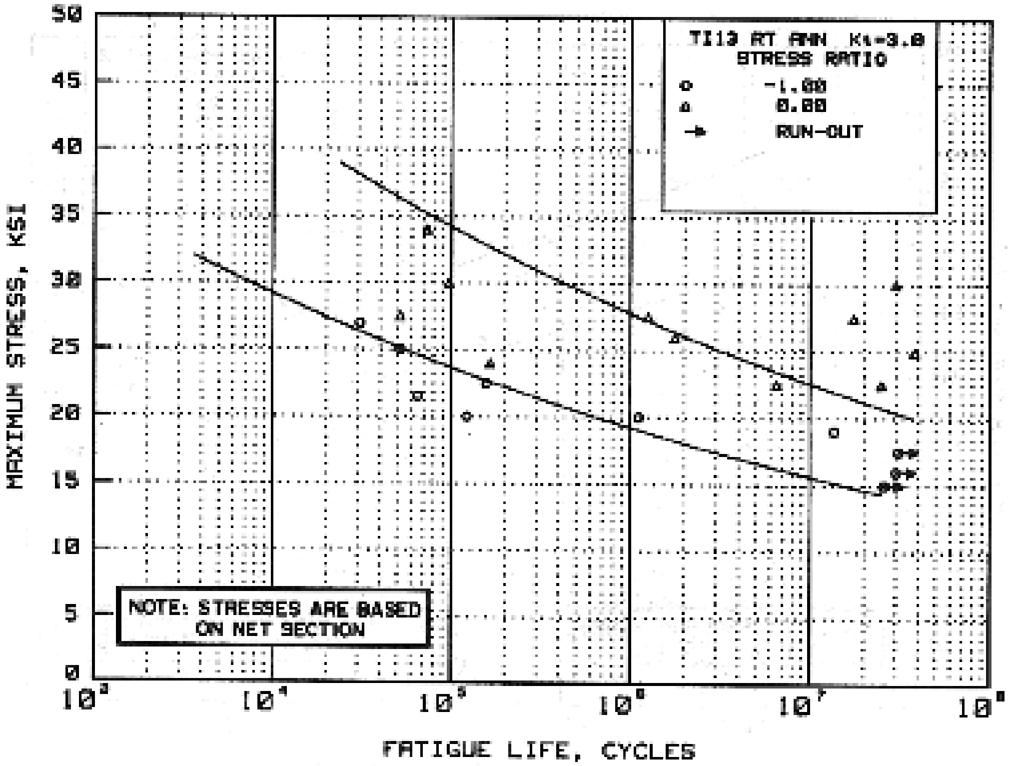

Figure 5.5.1.1.8(b). Best-fit S/N curves for notched, K_t = 3.0, annealed Ti-13V-11Cr-3Al alloy sheet, longitudinal direction.

Correlative Information for Figure 5.5.1.1.8(b)

Product Form: Sheet, 0.043 inch thick

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	138.50	132.80	RT

Specimen Details: Notched, edge, K = 3.0
0.448 inch gross width
0.300 inch net width
0.022 inch root radius, r
60° flank angle, ω

Surface Condition: As machined, edges polished with emery paper.

Reference: 5.5.1.1.8

Test Parameters:
Loading—Axial
Frequency—3600 cpm
Temperature—RT
Atmosphere—Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
Log N_f = 21.93-11.03 log (S_{eq})
$S_{eq} = S_{max} (1-R)^{0.53}$
Std. Error of Estimate, Log (Life) = 0.91
Standard Deviation, Log (Life) = 1.11
R^2 = 33%

Sample Size = 19

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

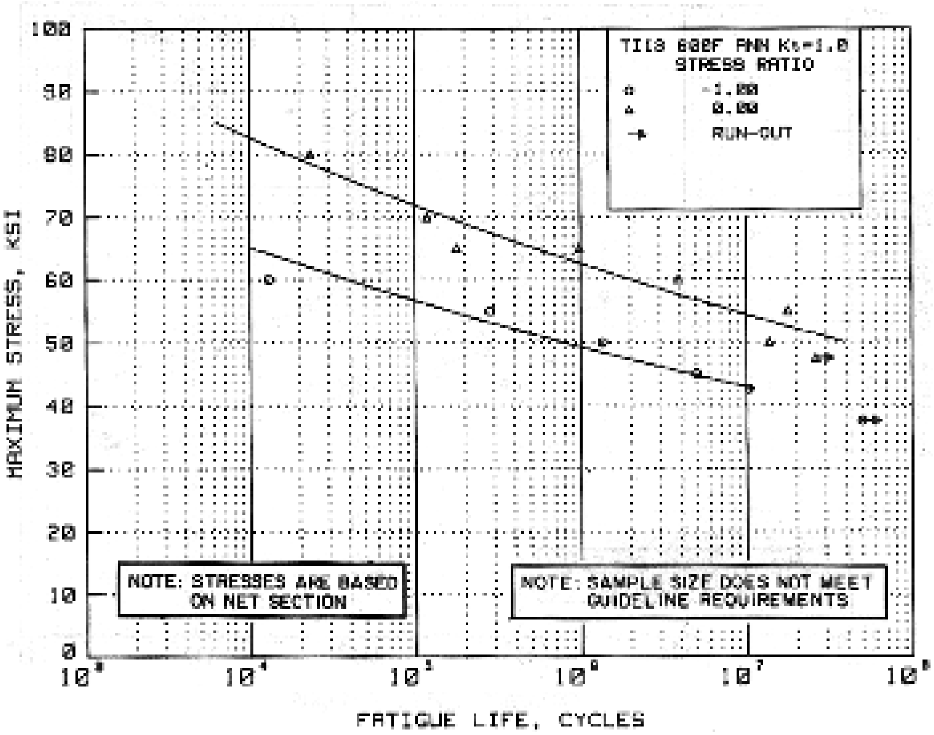

Figure 5.5.1.1.8(c). Best-fit S/N curves for unnotched, annealed Ti-13V-11Cr-3Al alloy sheet at 600°F, longitudinal direction.

Correlative Information for Figure 5.5.1.1.8(c)

Product Form: Sheet, 0.043 inch thick

Properties:

TUS, ksi	TYS, ksi	Temp., °F
116.00	102.61	600°F

Specimen Details: Unnotched, 0.300 inch wide

Surface Condition: As machined, edges polished with emery paper.

Reference: 5.5.1.1.8

Test Parameters:
Loading—Axial
Frequency—3600 cpm
Temperature—600°F
Atmosphere—Air

No. of Heats/Lot: Not specified

Equivalent Stress Equation:
Log N_f = 35.63-16.50 log (S_{eq})
$S_{eq} = S_{max} (1-R)^{0.34}$
Std. Error of Estimate, Log (Life) = 0.35
Standard Deviation, Log (Life) = 1.07
R^2 = 90%

Sample Size = 12

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

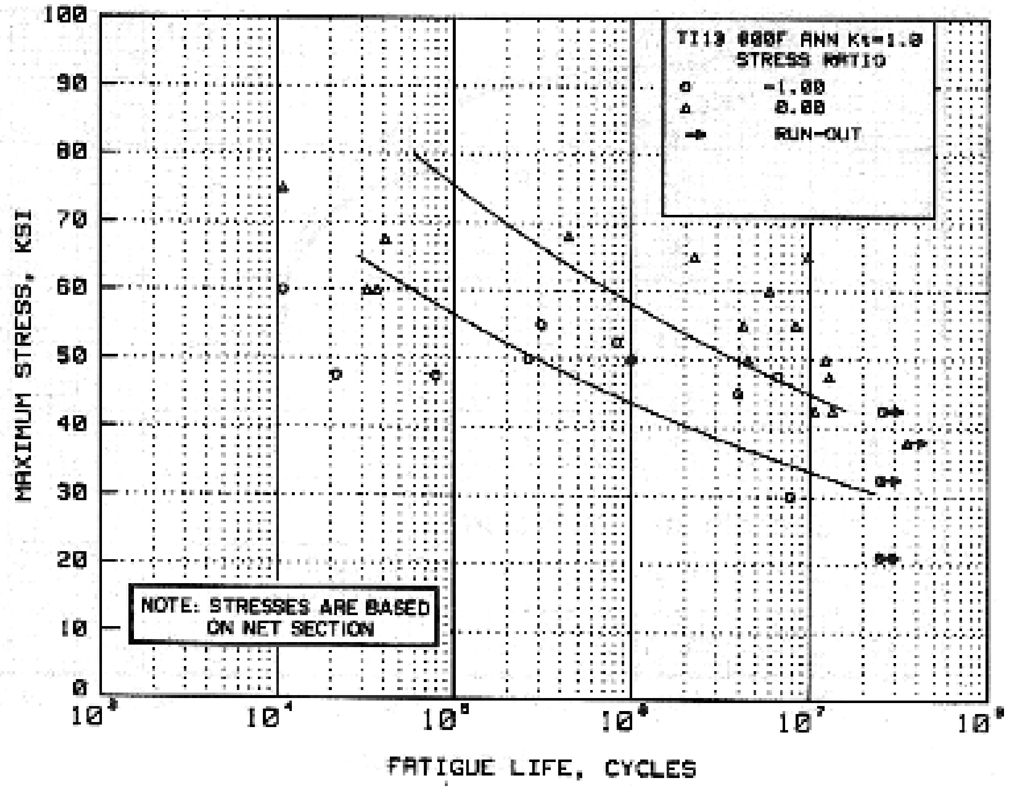

Figure 5.5.1.1.8(d). Best-fit S/N curves for unnotched annealed Ti-13V-11Cr-3Al alloy sheet at 800°F, longitudinal direction.

Correlative Information for Figure 5.5.1.1.8(d)

Product Form: Sheet, 0.043-inch thick

Properties:

TUS, ksi	TYS, ksi	Temp., °F
115.80	98.61	800°F

Specimen Details: Unnotched, 0.300-inch wide

Surface Condition: As machined, edges polished with emery paper.

Reference: 5.5.1.1.8

Test Parameters:
Loading—Axial
Frequency—3600 cpm
Temperature—800°F
Atmosphere—Air

No. of Heats/Lot: Not specified

Equivalent Stress Equation:
Log N_f = 21.67-8.88 log (S_{eq})
$S_{eq} = S_{max}(1-R)^{0.42}$
Std. Error of Estimate, Log (Life) = 0.84
Standard Deviation, Log (Life) = 1.07
R^2 = 39%

Sample Size = 26

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

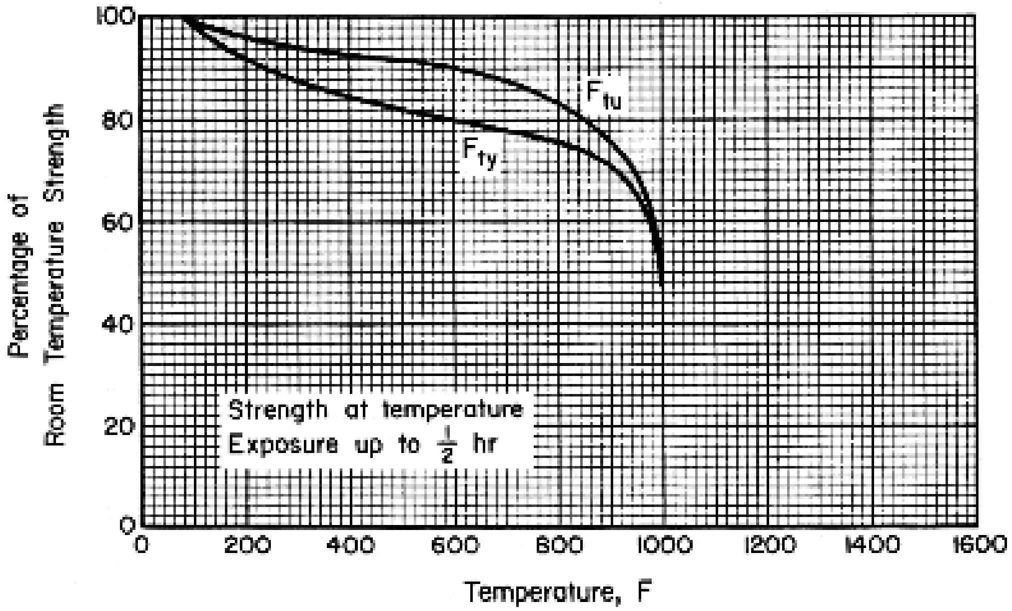

Figure 5.5.1.2.1. Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of solution-treated and aged Ti-13V-11Cr-3Al alloy sheet.

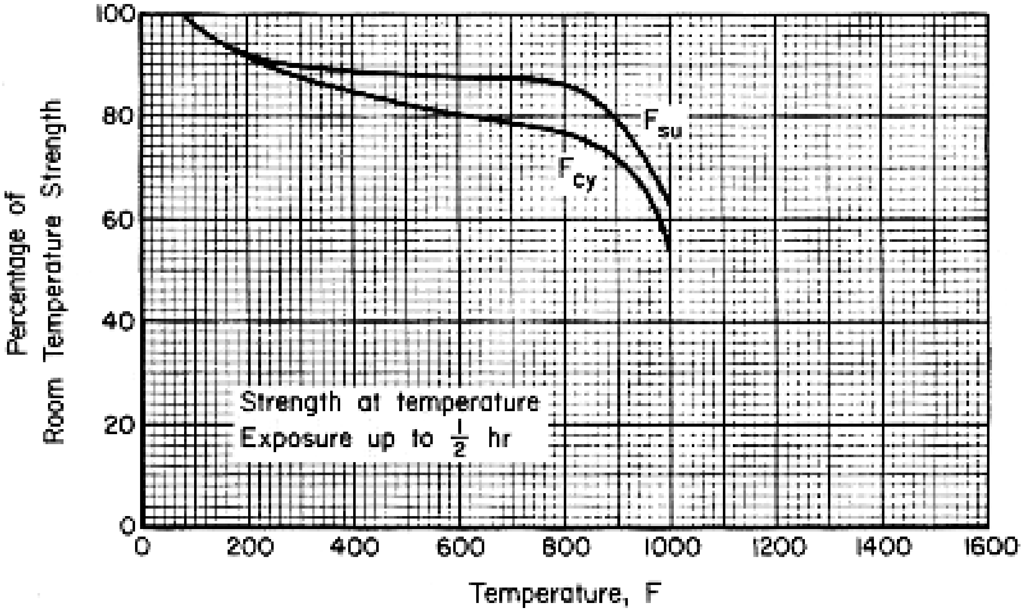

Figure 5.5.1.2.2. Effect of temperature on the compressive yield strength (F_{cy}) and the shear ultimate strength (F_{su}) of solution-treated and aged Ti-13V-11Cr-3Al alloy sheet.

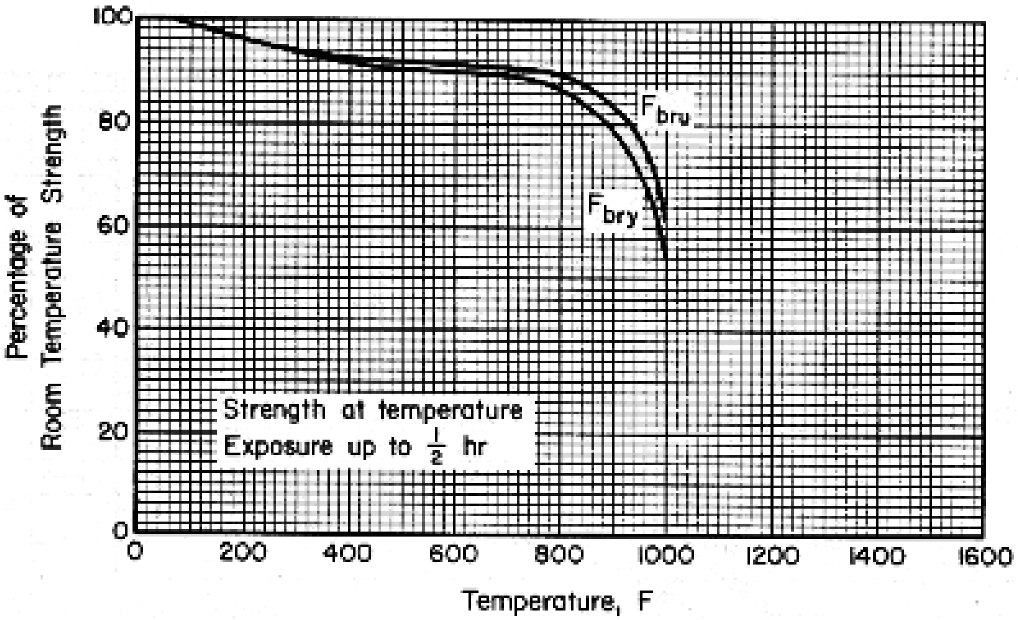

Figure 5.5.1.2.3. Effect of temperature on the bearing ultimate strength (F_{bru}) and the bearing yield strength (F_{bry}) of solution-treated and aged Ti-13V-11Cr-3Al alloy sheet.

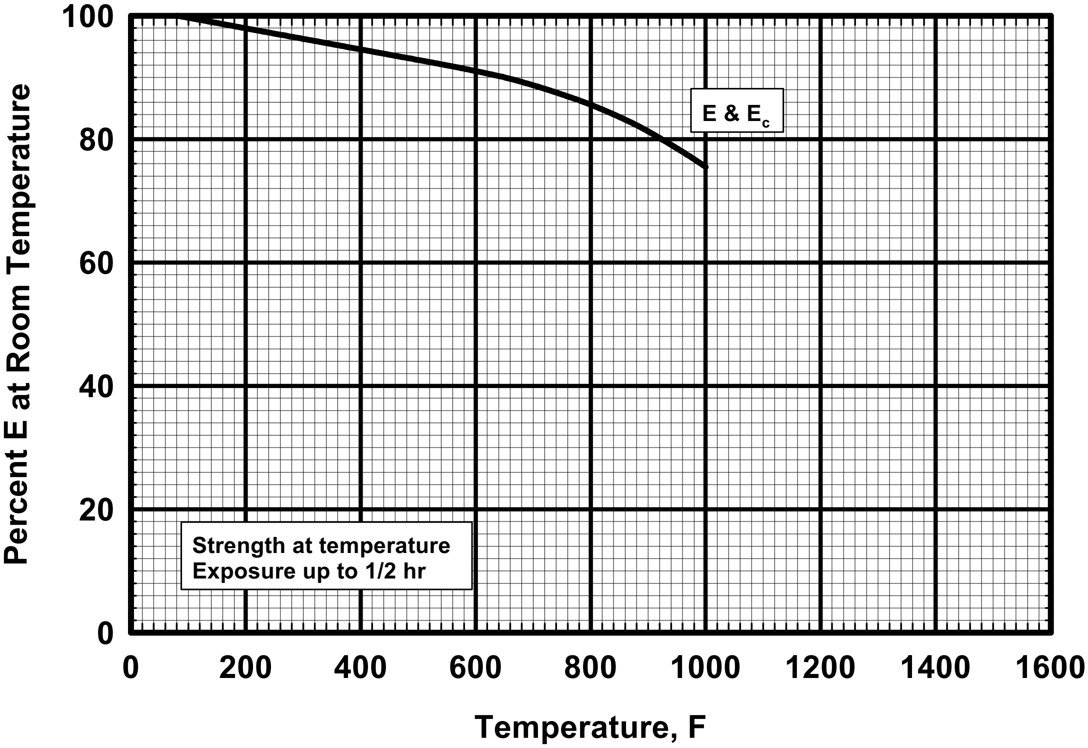

Figure 5.5.1.2.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of solution-treated and aged Ti-13V-11Cr-3Al alloy sheet.

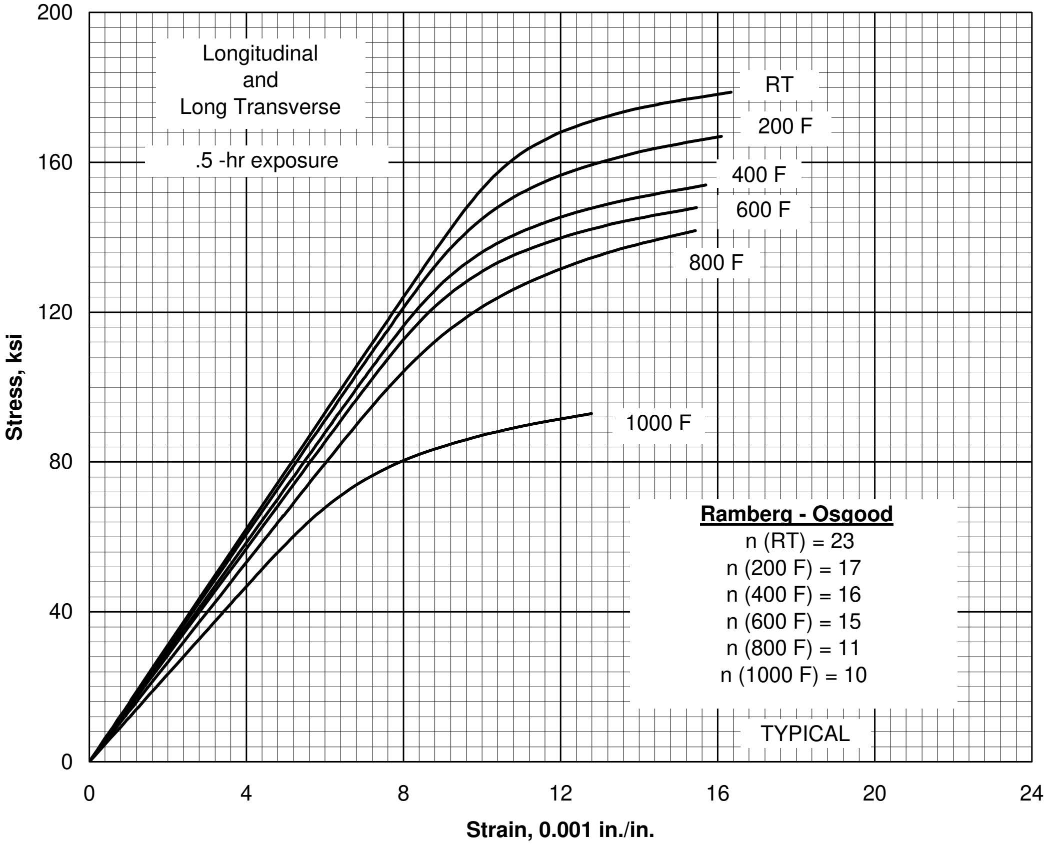

Figure 5.5.1.2.6. Typical tensile stress-strain curves for solution-treated and aged Ti-13V-11Cr-3Al alloy sheet at room and elevated temperatures.

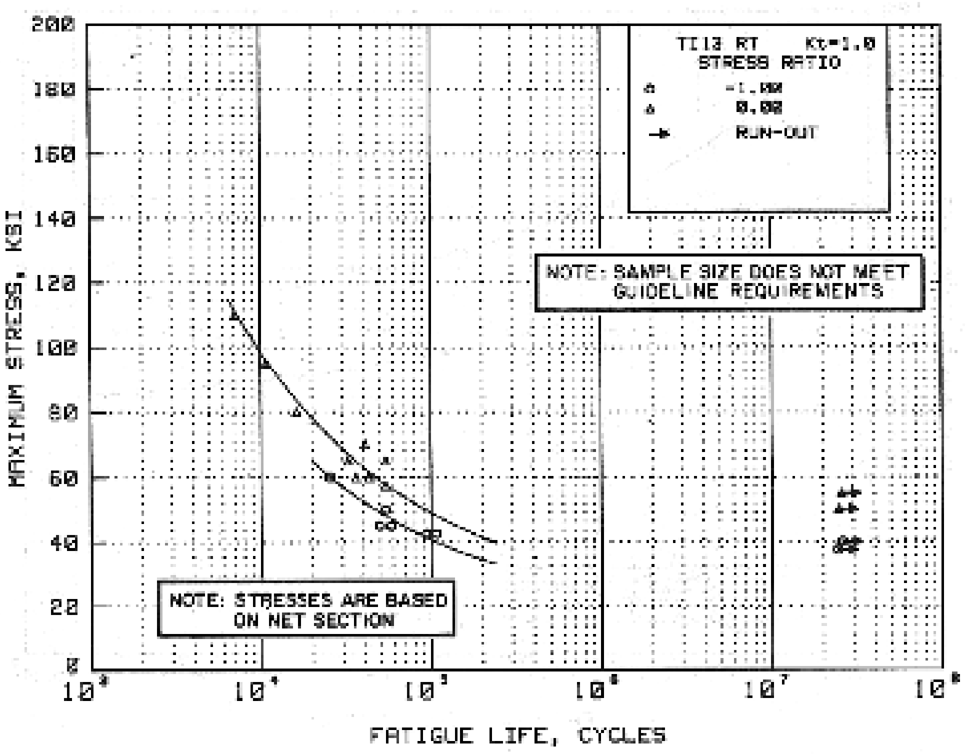

Figure 5.5.1.2.8(a). Best-fit S/N curves for unnotched, solution treated and aged Ti-13V-11Cr-3Al alloy sheet and plate, longitudinal direction.

Correlative Information for Figure 5.5.1.2.8(a)

Product Form: Sheet, 0.043 inch thick and plate, 1.00 inch thick

Properties:

TUS, ksi	TYS, ksi	Temp., °F
174.5	156.7	RT

Specimen Details: Unnotched, 0.30 inch wide
Unnotched, 0.20 inch wide

Surface Condition: As machined, edges polished with emery paper.
As machined, edges were hand-polished.

References: 5.5.1.1.8 and 5.5.1.2.8

Test Parameters:
Loading—Axial
Frequency—3600 cpm, 10,000 cpm
Temperature—RT
Atmosphere—Air

No. of Heats/Lot: Not specified

Equivalent Stress Equation:
Log N_f = 8.37-2.30 log (S_{eq}-20)
$S_{eq} = S_{max} (1-R)^{0.27}$
Std. Error of Estimate, Log (Life) = 0.093
Standard Deviation, Log (Life) = 0.31
R^2 = 91%

Sample Size = 17

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

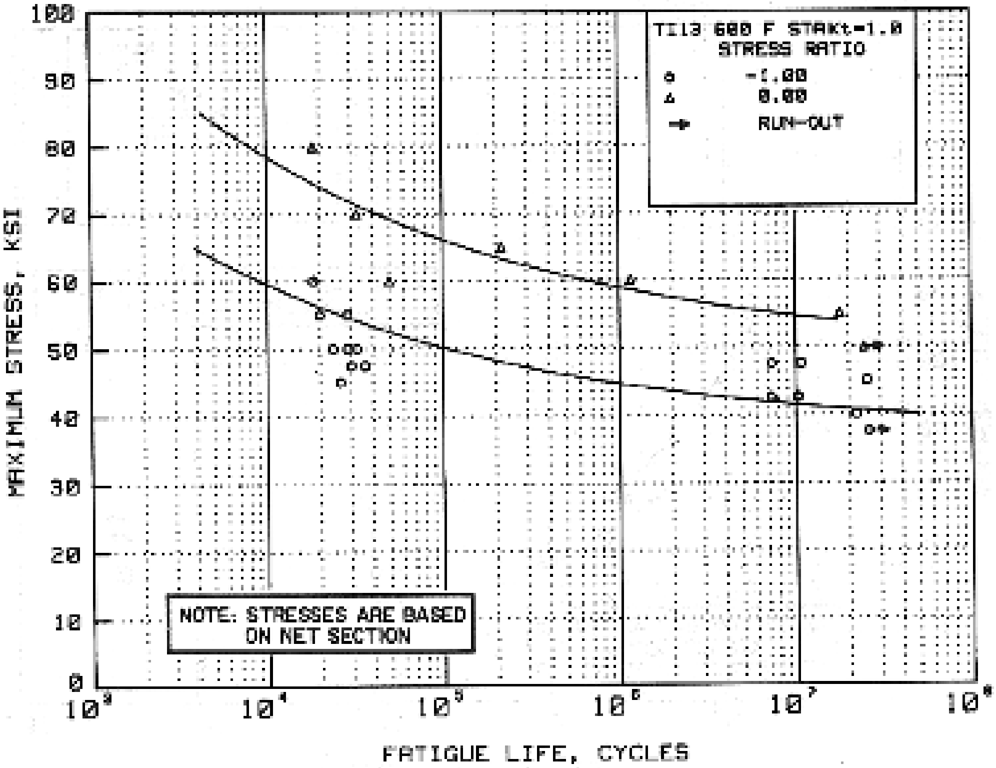

Figure 5.5.1.2.8(b). Best-fit S/N curves for unnotched, solution treated and aged Ti-13V-11Cr-3Al alloy sheet at 600°F, longitudinal direction.

<u>Correlative Information for Figure 5.5.1.2.8(b)</u>

<u>Product Form</u>: Sheet, 0.043 inch thick

<u>Properties</u>:

TUS, ksi	TYS, ksi	Temp., °F
156.30	127.0	600°F

<u>Specimen Details</u>: Unnotched, 0.310 inch wide

<u>Surface Condition</u>: As machined, edges polished with emery paper.

<u>Reference</u>: 5.5.1.1.8

<u>Test Parameters:</u>
Loading—Axial
Frequency—3600 cpm
Temperature—600°F
Atmosphere—Air

<u>No. of Heats/Lots</u>: Not specified

<u>Equivalent Stress Equation</u>:
Log N_f = 10.39-4.33 log (S_{eq}-48.5)
$S_{eq} = S_{max} (1-R)^{0.40}$
Std. Error of Estimate, Log (Life) = 0.90
Standard Deviation, Log (Life) = 1.27
R^2 = 50%

<u>Sample Size</u> = 21

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

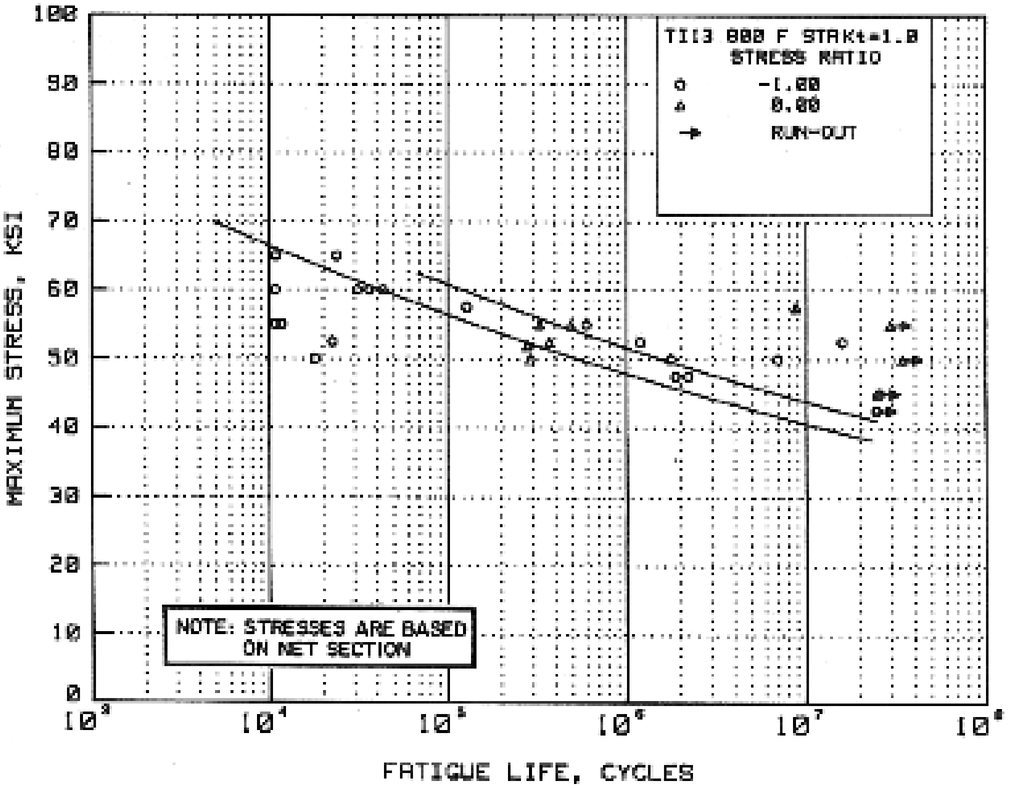

Figure 5.5.1.2.8(c). Best-fit S/N curves for unnotched, solution treated and aged Ti-13V-11Cr-3Al alloy sheet at 800°F, longitudinal direction.

Correlative Information for Figure 5.5.1.2.8(c)

Product Form: Sheet, 0.043 inch thick

Properties:

TUS, ksi	TYS, ksi	Temp., °F
149.40	122.30	800°F

Specimen Details: Unnotched, 0.30 inch wide

Surface Condition: As machined, edges polished with emery paper.

Reference: 5.5.1.1.8

Test Parameters:
Loading—Axial
Frequency—3600 cpm
Temperature—800°F
Atmosphere—Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
Log N_f = 30.03-14.03 log (S_{eq})
$S_{eq} = S_{max} (1-R)^{0.11}$
Std. Error of Estimate, Log (Life) = 0.85
Standard Deviation, Log (Life) = 1.01
R^2 = 29%

Sample Size = 24

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

5.5.2 TI-15V-3CR-3SN-3AL (TI-15-3)

5.5.2.0 *Comments* — Ti-15V-3Cr-3Sn-3Al is a solute rich (metastable) beta titanium alloy. It was developed primarily to lower the cost of titanium sheet metal parts by reducing materials and processing cost. Contrary to conventional alpha-beta alloys, this alloy is strip producible and has excellent room temperature formability characteristics. It can also be aged to a wide range of strength levels to meet a variety of application needs. Although this alloy was originally developed as a sheet alloy, it has expanded into other areas such as fasteners, foil, plate, tubing, castings, and forgings.

Manufacturing Considerations — Ti-15V-3Cr-3Sn-3Al is usually supplied in the solution-annealed condition. In this condition, the alloy has a single phase (beta) structure and, hence, is readily cold formed. After cold forming, the alloy can be resolution-treated in the 1450°F to 1550°F range and subsequently aged in the 900°F to 1100°F range, depending upon desired strength. Care should be exercised to ensure that no surface contamination results from the solution treatment. The alloy can be directly aged after forming; however, strength will vary depending upon the amount of cold work in the part. The alloy can also be hot formed. Heating times prior to hot forming should be minimized in order to prevent appreciable aging prior to forming. Ti-15V-3Cr-3Sn-3Al alloy is readily welded by standard titanium welding techniques.

Environmental Considerations — In the aged condition, Ti-15V-3Cr-3Sn-3Al appears to be immune to hot-salt stress corrosion cracking below the 500°F to 440°F range. However, some susceptibility has been noted after 100-hour stressed exposures at 600°F. The presence of salt water does not appear to affect the room temperature crack growth behavior of aged material. Alloy Ti-15V-3Cr-3Sn-3Al should not be used in the solution treated condition. Long time exposure of solution treated and cold worked material to service temperatures above approximately 300°F or solution treated material to service temperatures above approximately 400°F can result in low ductility. Under certain conditions, titanium, when in contact with cadmium, silver, mercury, or certain of their compounds, may become embrittled. Refer to MIL-S-5002 and MIL-STD-1568 for restrictions concerning such applications.

Heat Treatment — This alloy should be solution treated for 10-30 minutes in the 1450°F to 1550°F range, cooled at a rate approximating an air cool of 0.125 inch thick sheet and subsequently aged. Aging is generally conducted in the 900°F to 1100°F range, followed by an air cool. Aging times will vary depending upon aging temperature. The material can be used in service in the solution treated condition subject to the temperature limitations described above.

Specifications and Properties — A material specification for Ti-15V-3Cr-3Sn-3Al is shown in Table 5.5.2.0(a). Room-temperature mechanical properties for Ti-15V-3Cr-3Sn-3Al are shown in Table 5.5.2.0(b). The effect of temperature on physical properties is shown in Figure 5.5.2.0.

5.5.2.1 *Solution-Treated and Aged (1000°F) Condition* — Typical tensile and compressive stress-strain and compressive tangent-modulus curves are presented in Figures 5.5.2.1.6(a) and (b).

Table 5.5.2.0(a). Material Specification for Ti-15V-3Cr-3Sn-3Al

Specification	Form
AMS 4914	Sheet and strip

Table 5.5.2.0(b). Design Mechanical and Physical Properties of Ti-15V-3Cr-3Sn-3Al Sheet

Specification	AMS 4914
Form	Sheet
Condition	STA (1000°F/8 Hrs.)
Thickness, in.	≤0.125
Basis	S
Mechanical Properties:	
F_{tu}, ksi:	
L	145
LT	145
F_{ty}, ksi:	
L	140
LT	140
F_{cy}, ksi:	
L	139
LT	144
F_{su}, ksi	92
F_{bru}[a], ksi:	
(e/D = 1.5)	216
(e/D = 2.0)	276
F_{bry}[a], ksi:	
(e/D = 1.5)	203
(e/D = 2.0)	233
e, percent:	
L	7
LT	7
E, 10^3 ksi:	
L	15.2
LT	15.7
E_c, 10^3 ksi:	
L	15.3
LT	16.0
G, 10^3 ksi	...
μ	...
Physical Properties:	
ω, lb/in.^{3}	0.172
C, K, and α	See Figure 5.5.2.0

[a] Bearing values are "dry pin" values per Section 1.4.7.1.

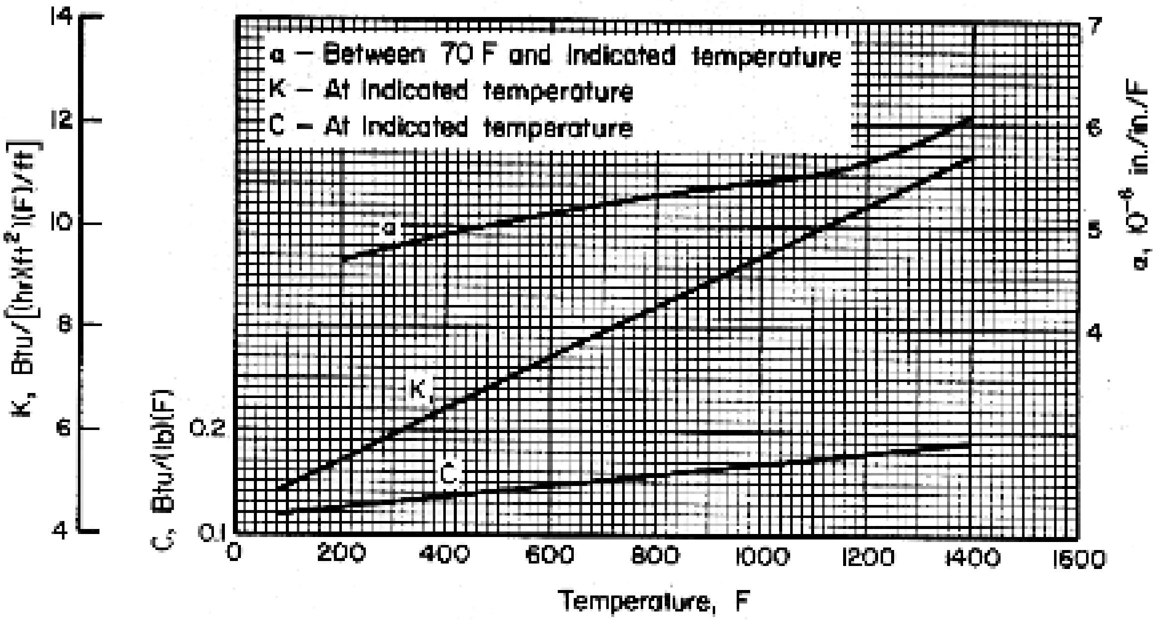

Figure 5.5.2.0. Effect of temperature on the physical properties of Ti-15V-3Cr-3Sn-3Al alloy.

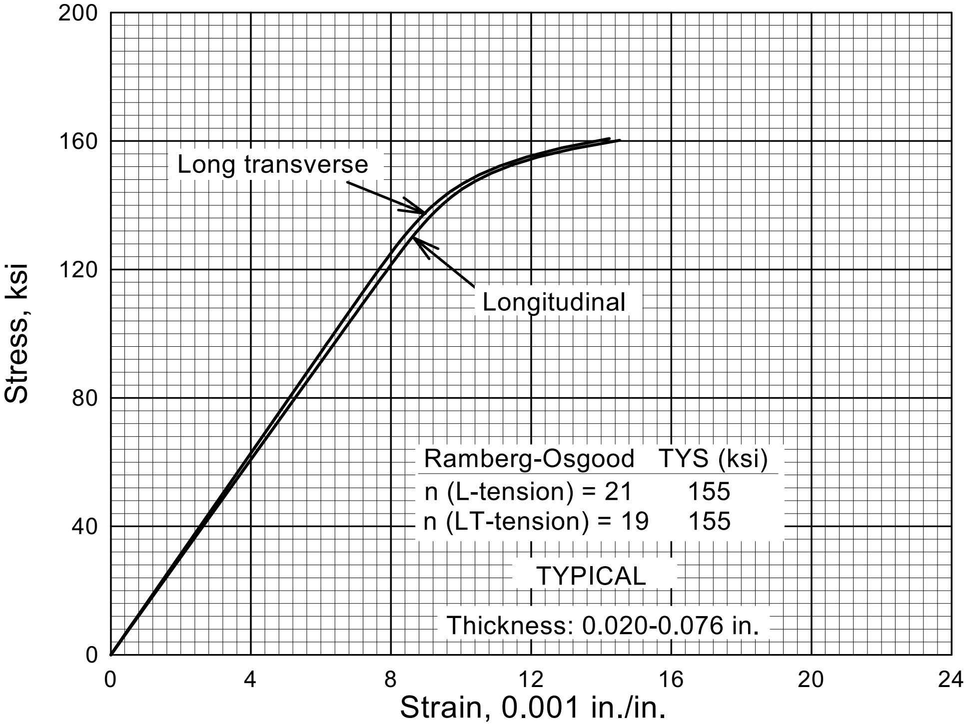

Figure 5.5.2.1.6(a). Typical tensile stress-strain curves at room temperature for solution treated and aged (1000°F) Ti-15V-3Cr-3Sn-3Al alloy sheet.

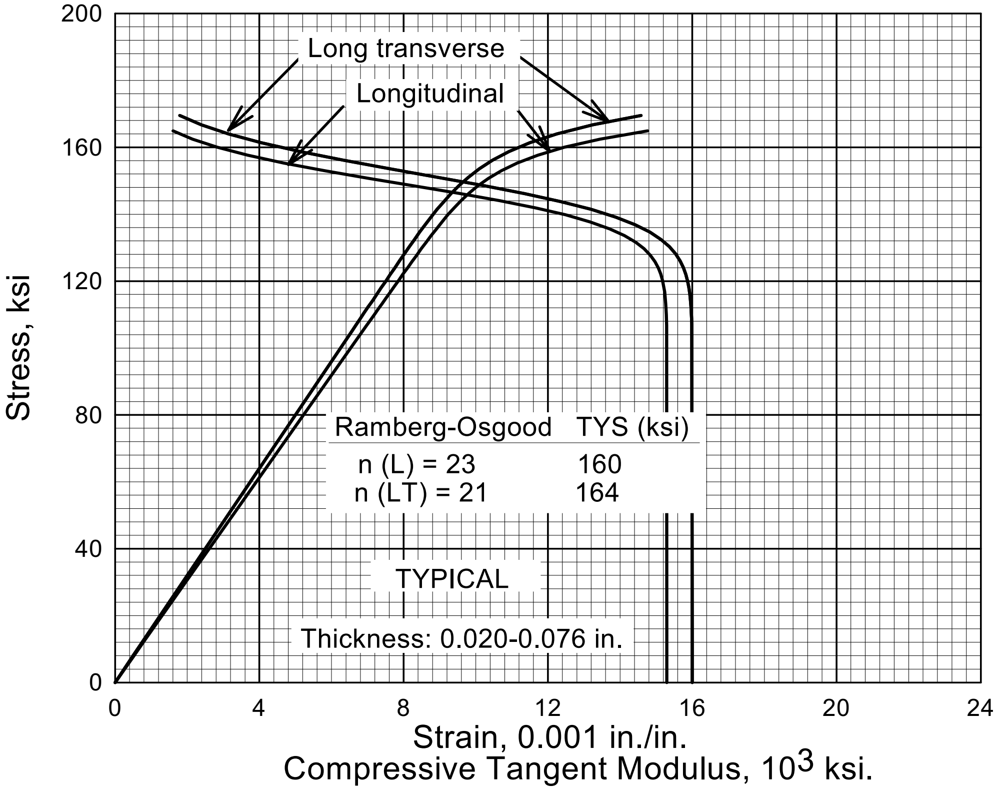

Figure 5.5.2.1.6(b). Typical compressive stress-strain and compressive tangent-modulus curves at room temperature for solution treated and aged (1000°F) Ti-15V-3Cr-3Sn-3Al alloy sheet.

5.5.3 TI-10V-2FE-3AL (TI-10-2-3)

5.5.3.0 *Comments and Properties* — Ti-10V-2Fe-3Al is a solute lean beta (near beta) titanium alloy that was developed primarily as a high-strength forging alloy. It has excellent forging characteristics, possessing flow properties at 1500°F similar to Ti-6Al-4V at 1700°F. This characteristic provides advantages, such as lower die cost and better die fill capability. This alloy also provides the best combination of strength and toughness of any of the commercially available titanium alloys. For example, at the 180 ksi tensile ultimate strength level, the alloy has a K_{Ic} value of 40 ksi-in.$^{1/2}$ minimum.

In addition to this high-strength condition, the alloy can also be processed to intermediate strength levels for higher fracture toughness. This alloy has also been reported to exhibit a shape-memory effect.

Manufacturing Considerations — Ti-10V-2Fe-3Al is usually supplied as bar or billet product which has been finish forged (or rolled) in the alpha-beta field. In order to optimize the microstructure for the high-strength condition, the forging is usually given a pre-form forge above the beta transus, followed by a 15 to 25 percent reduction below the beta transus. Ideally, the beta forging operation is finished through the beta transus, followed by a quench. The intent of the two-step forging process is to develop a structure without grain boundary alpha, but with elongated primary alpha needles in an aged beta matrix. The alloy is considered to be deep hardenable, capable of generating high strengths in section thicknesses up to approximately 5 inches. The alloy is also readily weldable by conventional titanium welding techniques.

Environmental Consideration — In the solution treated plus aged condition, the material exhibits excellent resistance to stress corrosion cracking, typically exhibiting a $K_{Iscc} > 0.8\ K_{Ic}$. In the solution-treated condition, the material should not be subjected to long-term exposure in the 500°F to 800°F range, since such exposure could result in high-strength, low-ductility conditions. Exposure to cadmium, silver, mercury, or certain other compounds should be avoided. Refer to MIL-STD-1568 and MIL-S-5002.

Heat Treatment — For the high-strength condition, the alloy is generally solution treated approximately 65°F below the beta transus (which is typically 1460 to 1480°F), followed by a water quench and an 8-hour age at 900°F to 950°F. Overaging in the 950°F to 1150°F range may also be used to obtain lower strength levels.

Beta Flecks — Ti-10V-2Fe-3Al is a segregation prone alloy which can exhibit a microstructural phenomenon known as "beta-flecks". Certain areas may possess a lower beta transus than the matrix (due primarily to beta stabilizer enrichment) and, as such, can fully transform during heat treatment just below the matrix transus. In severe cases, this condition can lead to lower ductility and a reduction in fatigue strength due to grain boundary alpha formation in the "flecked" region. Care should be exercised to procure only material which has been melted under strict control to prevent severe "fleck" formation.

Specifications and Properties — Material specifications for Ti-10V-2Fe-3Al are shown in Table 5.5.3.0(a). Room temperature mechanical properties for Ti-10V-2Fe-3Al are presented in Table 5.5.3.0(b) and (c) for die and hand forging.

5.5.3.1 *Solution Treated and Aged (900 to 950°F) Condition* — Typical tensile and compressive stress-strain and compressive tangent-modulus curves are presented in Figure 5.5.3.1.6.

Table 5.5.3.0(a). Material Specifications for Ti-10V-2Fe-3Al

Specification	Form
AMS 4983	Forging
AMS 4984	Forging
AMS 4986	Forging

5.5.3.2 ***Solution Treated and Aged (950 to 1000°F) Condition*** — Typical tensile and compressive stress-strain and compressive tangent-modulus curves are shown in Figure 5.5.3.2.6.

Table 5.5.3.0(b). Design Mechanical and Physical Properties of Ti-10V-2Fe-3Al Die Forging

Specification	AMS 4983	AMS 4984
Form	Conventional die forging	
Condition	Solution treated and aged (900-950°F)	
Thickness, in.	<1.000	≤3.000
Basis	S	S
Mechanical Properties:		
F_{tu}, ksi:		
L	180	173
LT	180[a]	173[a]
ST	...	173[a]
F_{ty}, ksi:		
L	160	160
LT	160[a]	160[a]
ST	...	160[a]
F_{cy}, ksi:		
L	168	168
LT	166	166
ST	...	166
F_{su}, ksi	101	97
F_{bru}[b], ksi:		
(e/D = 1.5)	244	234
(e/D = 2.0)	295	284
F_{bry}[b], ksi:		
(e/D = 1.5)	227	227
(e/D = 2.0)	261	261
e, percent:		
L	4	4
LT	4[a]	4[a]
ST	...	4[a]
E, 10^3 ksi	15.9	
E_c, 10^3 ksi	16.3	
G, 10^3 ksi	...	
μ	...	
Physical Properties:		
ω, lb/in.^{3}	0.168	
α, 10^{-6} in./in./°F	5.4 (68-800°F)	
C and K	...	

[a] Applicable providing LT or ST dimension is ≥2.500 inches.
[b] Bearing values are "dry pin" values per Section 1.4.7.1.

Table 5.5.3.0(c). Design Mechanical and Physical Properties of Ti-10V-2Fe-3Al Hand Forging

Specification	AMS 4986	
Form	Hand forging	
Condition	Solution treated and aged (950-1000°F)	
Thickness, in.	≤3.000	3.001-4.000
Basis	S	S
Mechanical Properties:		
F_{tu}, ksi:		
L	160	160
LT	160[a]	160
F_{ty}, ksi:		
L	145	145
LT	145[a]	145
F_{cy}, ksi:		
L	154	...
LT	...	...
F_{su}, ksi	97[b]	...
$F_{bru}{}^{c}$, ksi:		
(e/D = 1.5)	241	...
(e/D = 2.0)	293	...
$F_{bry}{}^{c}$, ksi:		
(e/D = 1.5)	218	...
(e/D = 2.0)	245	...
e, percent:		
L	6	6
LT	6[a]	6
RA, percent:		
L	10	10
LT	10[a]	10
E, 10^3 ksi	15.9	
E_c, 10^3 ksi	16.3	
G, 10^3 ksi	...	
μ	...	
Physical Properties:		
ω, lb/in.^{3}	0.168	
a, 10^{-6} in./in./°F	5.4 (68-800°F)	
C and K	...	

a Applicable providing LT dimension is ≥2.500 inches.
b Shear strength determined in accordance with ASTM B 769.
c Bearing values are “dry pin” per Section 1.4.7.1.

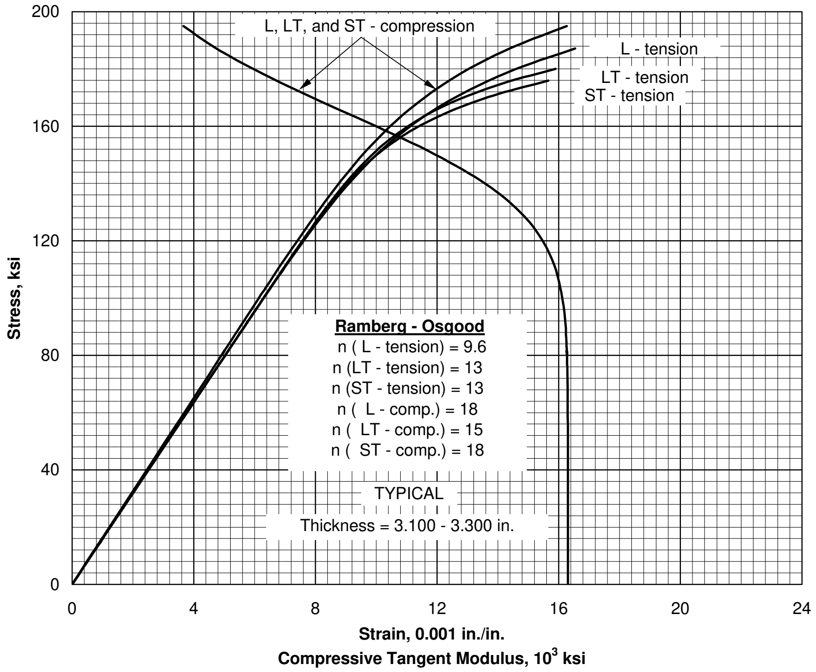

Figure 5.5.3.1.6. Typical tensile stress-strain, compressive stress-strain, and compressive tangent-modulus curves for solution treated and aged (900-950°F) Ti-10V-2Fe-3Al die forging.

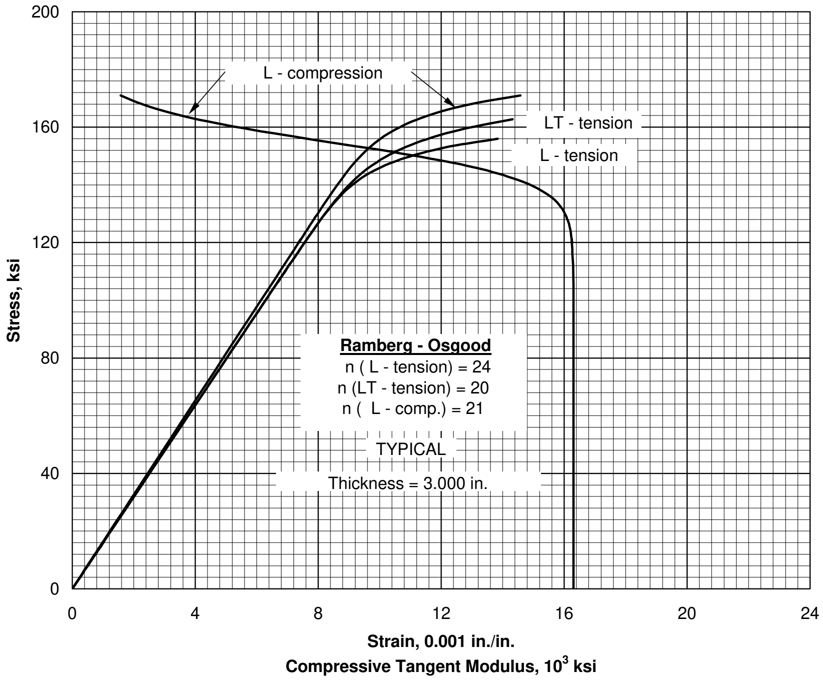

Figure 5.5.3.2.6. Typical stress-strain, compressive stress-strain, and compressive tangent-modulus curves for solution treated and aged (950-1000°F) Ti-10V-2Fe-3Al hand forging.

5.6 ELEMENT PROPERTIES

5.6.1 BEAMS — See Equation 1.3.2.3, Section 1.5.2.5, and References 1.7.1(a) and (b) for general information on stress analysis of beams.

5.6.1.1 Simple Beams — Beams of solid, tubular, or similar cross sections can be assumed to fail through exceeding an allowable modulus of rupture in bending (F_b). In the absence of specific data, the ratio F_b/F_{tu} can be assumed to be 1.25 for solid sections.

5.6.1.1.1 *Round Tubes* — For round tubes, the value of F_b will depend on the D/t ratio as well as the ultimate tensile stress. The bending modulus of rupture of 6Al-4V titanium alloy is given in Figure 5.6.1.1.1.

5.6.1.1.2 *Unconventional Cross Sections* — Sections other than solid or tubular should be tested to determine the allowable bending stress.

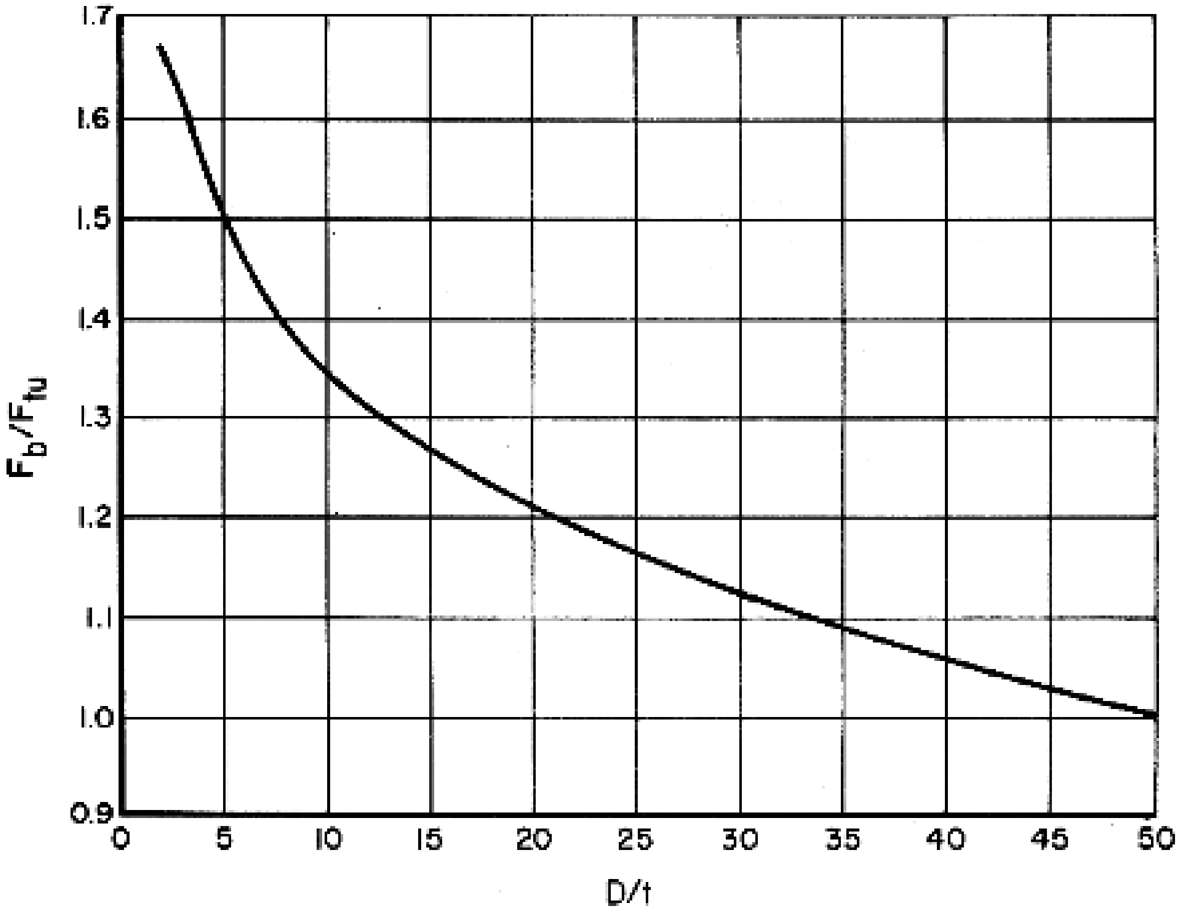

Figure 5.6.1.1.1. Bending modulus of rupture for solution-treated and aged Ti-6Al-4V alloy round tubing manufactured from bar material.

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CHAPTER 6

HEAT-RESISTANT ALLOYS

6.1 GENERAL

Heat-resistant alloys are arbitrarily defined as iron alloys richer in alloy content than the 18 percent chromium, 8 percent nickel types, or as alloys with a base element other than iron and which are intended for elevated-temperature service. These alloys have adequate oxidation resistance for service at elevated temperatures and are normally used without special surface protection. So-called "refractory" alloys that require special surface protection for elevated-temperature service are not included in this chapter.

This chapter contains strength properties and related characteristics of wrought heat-resistant alloy products used in aerospace vehicles. The strength properties are those commonly used in structural design, such as tension, compression, bearing, and shear. The effects of elevated temperature are presented. Factors such as metallurgical considerations influencing the selection of metals are included in comments preceding the specific properties of each alloy or alloy group. Data on creep, stress-rupture, and fatigue strength, as well as crack-growth characteristics, are presented in the applicable alloy section.

There is no standardized numbering system for the alloys in this chapter. For this reason, each alloy is identified by its most widely accepted trade designation.

For convenience in presenting these alloys and their properties, the heat-resistant alloys have been divided into three groups, based on alloy composition. These groups and the alloys for which specifications and properties are included are shown in Table 6.1.

The heat treatments applied to the alloys in this chapter vary considerably from one alloy to another. For uniformity of presentation, the heat-treating terms are defined as follows:

Stress-Relieving — Heating to a suitable temperature, holding long enough to reduce residual stresses, and cooling in air or as prescribed.

Annealing — Heating to a suitable temperature, holding, and cooling at a suitable rate for the purpose of obtaining minimum hardness or strength.

Solution-Treating — Heating to a suitable temperature, holding long enough to allow one or more constituents to enter into solid solution, and cooling rapidly enough to hold the constituents in solution.

Aging, Precipitation-Hardening — Heating to a suitable temperature and holding long enough to obtain hardening by the precipitation of a constituent from the solution-treated condition.

The actual temperatures, holding times, and heating and cooling rates used in these treatments vary from alloy to alloy and are described in the applicable specifications.

Table 6.1. Heat-Resistant Alloys Index

Section	Designation
6.2	**Iron-Chromium-Nickel-Base Alloys**
	A-286
6.2.1	N-155
6.2.2	
6.3	**Nickel-Base Alloys**
6.3.1	Hastelloy X
6.3.2	Inconel 600 (Inconel)
6.3.3	Inconel 625
6.3.4	Inconel 706
6.3.5	Inconel 718
6.3.6	Inconel X-750 (Inconel X)
6.3.7	René 41
6.3.8	Waspaloy
6.3.9	Haynes 230
6.3.10	Haynes HR-120
6.4	**Cobalt-Base Alloys**
6.4.1	L-605 (Haynes Alloy 25)
6.4.2	HS 188

6.1.1 MATERIAL PROPERTIES

6.1.1.1 *Mechanical Properties* — The mechanical properties of the heat-resistant alloys are affected by relatively minor variations in chemistry, processing, and heat treatment. Consequently, the mechanical properties shown for the various alloys in this chapter are intended to apply only to the alloy, form (shape), size (thickness), and heat treatment indicated. When statistical values are shown, these are intended to represent a fair cross section of all mill production within the indicated scope.

Strength Properties — Room-temperature strength properties for alloys in this chapter are based primarily on minimum tensile property requirements of material specifications. Values for nonspecification strength properties are derived. The variation of properties with temperature and other data or interest are presented in figures or tables, as appropriate.

The strength properties of the heat-resistant alloys generally decrease with increasing temperatures or increasing time at temperature. There are exceptions to this statement, particularly in the case of age-hardening alloys; these alloys may actually show an increase in strength with temperature or time, within a limited range, as a result of further aging. In most cases, however, this increase in strength is temporary and, furthermore, cannot usually be taken advantage of in service. For this reason, this increase in strength has been ignored in the preparation of elevated temperature curves as described in Chapter 9.

At cryogenic temperatures, the strength properties of the heat-resistant alloys are generally higher than at room temperature, provided some ductility is retained at the low temperatures. For additional information on mechanical properties at cryogenic temperatures, other references, such as the Cryogenic Materials Data Handbook (Reference 6.1.1.1), should be consulted.

Ductility — Specified minimum ductility requirements are presented for these alloys in the room-temperature property tables. The variation in ductility with temperature is somewhat erratic for the heat-resistant alloys. Generally, ductility decreases with increasing temperature from room temperature up to about 1200°F to 1400°F, where it reaches a minimum value, then it increases with higher temperatures. Prior creep exposure may also affect ductility adversely. Below room temperature, ductility decreases with decreasing temperature for some of these alloys.

Stress-Strain Relationships — The stress-strain relationships presented are typical curves prepared as described in Section 9.3.2.

Creep — Data covering the temperatures and times of exposure and the creep deformations of interest are included as typical information in individual material sections. These presentations may be in the form of creep stress-lifetime curves for various deformation criteria as specified in Chapter 9 or as creep nomographs.

Fatigue — Fatigue S/N curves for unnotched and notched specimens at room temperature and elevated temperatures are shown in each alloy section. Fatigue crack propagation data are also presented.

6.1.1.2 *Physical Properties* —Selected physical-property data are presented for these alloys. Processing variables and heat treatment have only a slight effect on these values; thus, the properties listed are applicable to all forms and heat treatments.

6.2 IRON-CHROMIUM-NICKEL-BASE ALLOYS

6.2.0 GENERAL COMMENTS — The alloys in this group, in terms of cost and in maximum service temperature, generally fall between the austenitic stainless steels and the nickel- and cobalt-base alloys. They are used in airframes, principally, in the temperature range 1000 to 1200°F, in those applications in which the stainless steels are inadequate and service requirements do not justify the use of the more costly nickel or cobalt alloys.

6.2.0.1 *Metallurgical Considerations*

Composition — The complex-base alloys comprising this group range from those in which iron is considered the base element to those which border on the nickel-base alloys. All of them contain sufficient alloying elements to place them in the "Superalloy" category, yet contain enough iron to reduce their cost considerably.

Chromium, in amounts ranging from 10 to 20 percent or higher, primarily increases oxidation resistance and contributes to strengthening of these alloys. Nickel and cobalt strengthen and toughen these materials. Molybdenum, tungsten, and columbium contribute to hardness and strength, particularly at elevated temperatures. Titanium and aluminum are added to provide age-hardening.

Heat Treatment — The complex-base alloys are heat treated with conventional equipment and fixtures such as would be used for austenitic stainless steels. Since these alloys are susceptible to carburization during heat treatment, it is good practice to remove all grease, oil, cutting, lubricant, etc., from the surface before heating. A low-sulfur and neutral or slightly oxidizing furnace atmosphere is recommended for heating.

6.2.0.2 *Manufacturing Considerations* — The iron-chromium-nickel-base alloys closely resemble the austenitic stainless steels insofar as forging, cold forming, machining, welding, and brazing are concerned. Their higher strength may require the use of heavier forging or forming equipment, and machining is somewhat more difficult than for the stainless steels. Pertinent comments are included under the individual alloys.

6.2.1 A-286

6.2.1.0 *Comments and Properties* — A-286 is a precipitation-hardening iron-base alloy designed for parts requiring high strength up to 1300°F and oxidation resistance up to 1500°F. It is used in jet engines and gas turbines for parts such as turbine buckets, bolts, and discs, and sheet metal assemblies. A-286 is available in the usual mill forms.

A-286 is somewhat harder to hot or cold work than the austenitic stainless steels. Its forging range is 2150 to 1800°F; when finishing below 1800°F, light reductions (under 15 percent) must be avoided to prevent grain coarsening during subsequent heat treatment. A-286 is readily machined in the partially or fully aged condition but is soft and "gummy" in the solution-treated condition. A-286 should be welded in the solution-treated condition. Fusion welding is difficult for large section sizes and moderately difficult for small cross sections and sheet. Cracking may be encountered in the welding of heavy sections or parts under high restraint. A dimensional contraction of 0.0008 inch per inch is experienced during aging. Oxidation resistance of A-286 is equivalent to that of Type 310 stainless steel up to 1800°F.

Some material specifications for A-286 alloy are presented in Table 6.2.1.0(a). Room-temperature mechanical and physical properties are shown in Table 6.2.1.0(b). The effect of temperature on physical properties is shown in Figure 6.2.1.0.

6.2.1.1 ***Solution-Treated and Aged Condition*** — Elevated-temperature data are presented in Figures 6.2.1.1.1, 6.2.1.1.3, and 6.2.1.1.4(a) through (c). Stress rupture properties are specified at 1200°F; the appropriate specifications should be consulted for detailed requirements. Figures 6.2.1.1.8(a) through (e) are fatigue S/N curves for several elevated temperatures.

Table 6.2.1.0(a). Material Specifications for A-286 Alloy

Specification	Form	Condition
AMS 5525	Sheet, strip, and plate	Solution treated (1800°F)
AMS 5731	Bar, forging, tubing, and ring	Solution treated (1800°F)
AMS 5732	Bar, forging, tubing, and ring	Solution treated (1800°F) and aged
AMS 5734	Bar, forging, and tubing	Solution treated (1650°F)
AMS 5737	Bar, forging, and tubing	Solution treated (1650°F) and aged

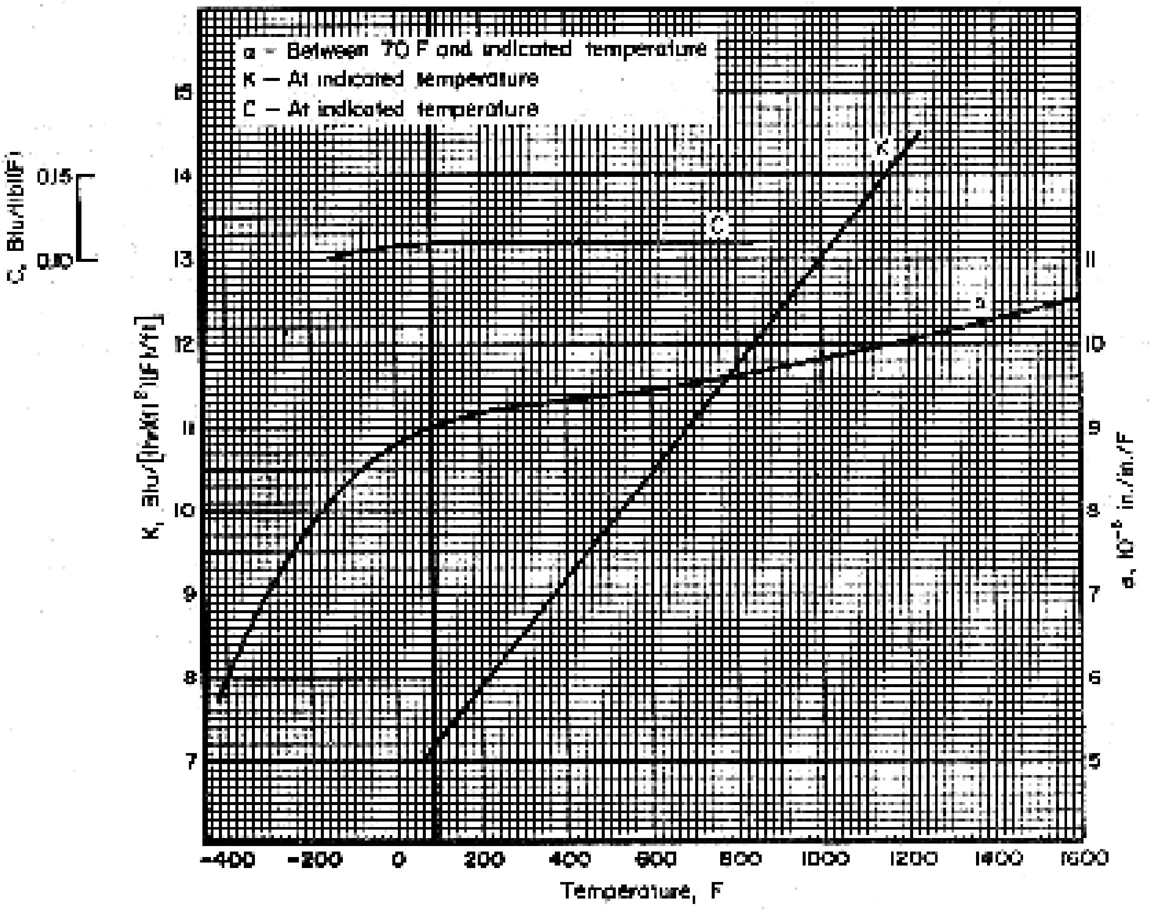

Figure 6.2.1.0. Effect of temperature on the physical properties of A-286.

Table 6.2.1.0(b). Design Mechanical and Physical Properties of A-286 Alloy

Specification	AMS 5525	AMS 5731 AMS 5732		AMS 5734 AMS 5737	
Form	Sheet, strip, and plate	Bar			
Condition	Solution treated and aged				
Thickness or diameter, in.	>0.004	≤2.499	2.500-5.000	≤2.499	2.500-5.000
Basis	S[a]	S	S	S	S
Mechanical Properties:					
F_{tu}, ksi:					
L	...	130	130	140	140
LT	140	130[b]	130	140[b]	140
ST	...	...	130	...	140
F_{ty}, ksi:					
L	...	85	85	95	95
LT	95	85[b]	85	95[b]	95
ST	...	...	85	...	95
F_{cy}, ksi:					
L	...	85	85	95	95
LT	95	...	...	...	...
F_{su}, ksi	91	85	85	91	91
F_{bru}, ksi:					
(e/D = 1.5)	210	195	195	210	210
(e/D = 2.0)	266	247	247	266	266
F_{bry}, ksi:					
(e/D = 1.5)	142	127	127	142	142
(e/D = 2.0)	171	153	153	171	171
e, percent:					
L	...	15	15	12	12
LT	15	15[b]	15	12[b]	12
ST	...	...	15	...	12
RA, percent:					
L	...	20	20	15	15
LT	...	20[b]	20	15[b]	15
ST	...	...	20	...	15
E, 10^3 ksi	29.1				
E_c, 10^3 ksi	29.1				
G, 10^3 ksi	11.1				
μ	0.31				
Physical Properties:					
ω, lb/in.^{3}	0.287				
C, K, and α	See Figure 6.2.1.0				

a Test direction longitudinal for widths less than 9 inches; transverse for widths 9 inches and over.
b Applicable to widths ≥2.500 inches only.

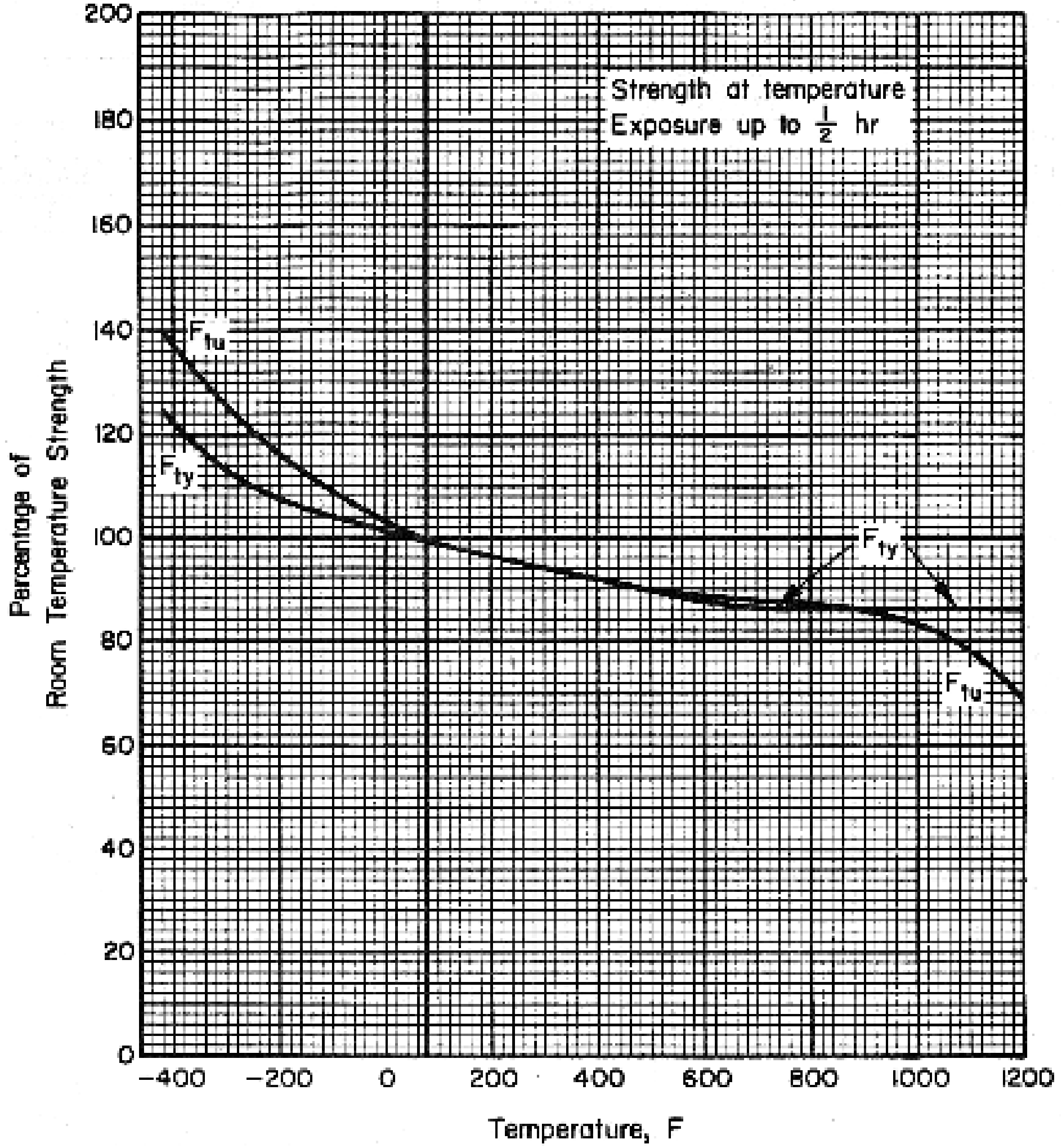

Figure 6.2.1.1.1. Effect of temperature on the tensile yield strength (F_{ty}) and tensile ultimate strength (F_{tu}) of A-286 alloy (1800°F solution treatment temperature).

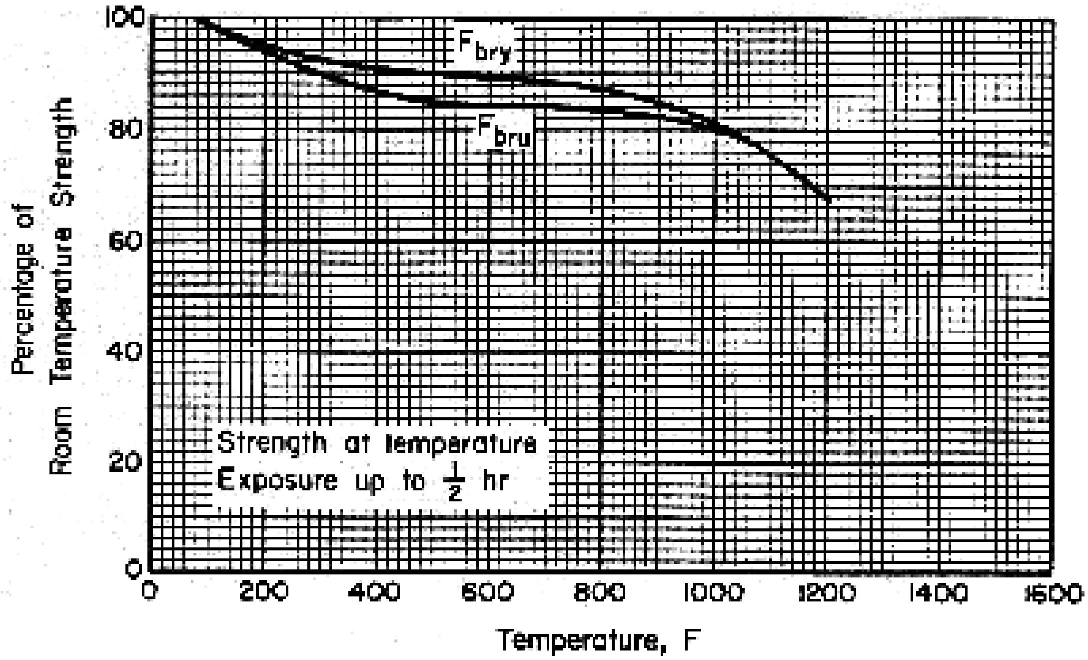

Figure 6.2.1.1.3. Effect of temperature on the bearing ultimate strength (F_{bru}) and the bearing yield strength (F_{bry}) for A-286 alloy (1800°F solution treatment temperature).

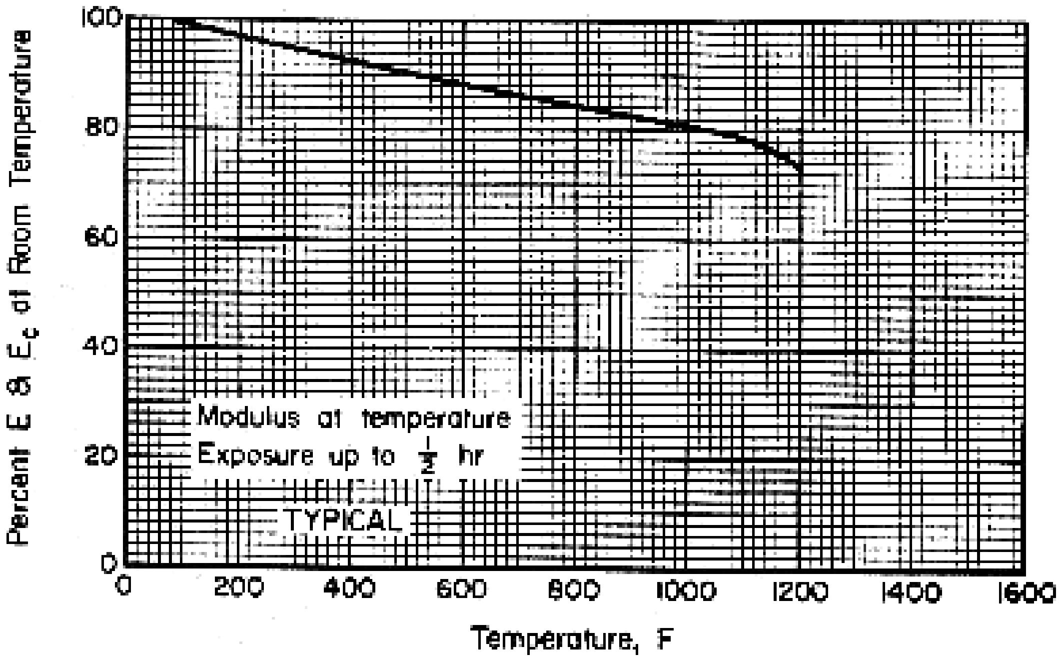

Figure 6.2.1.1.4(a). Effect of temperature on the tensile and compressive moduli (E and E_c) for A-286 alloy (1800°F solution treatment temperature).

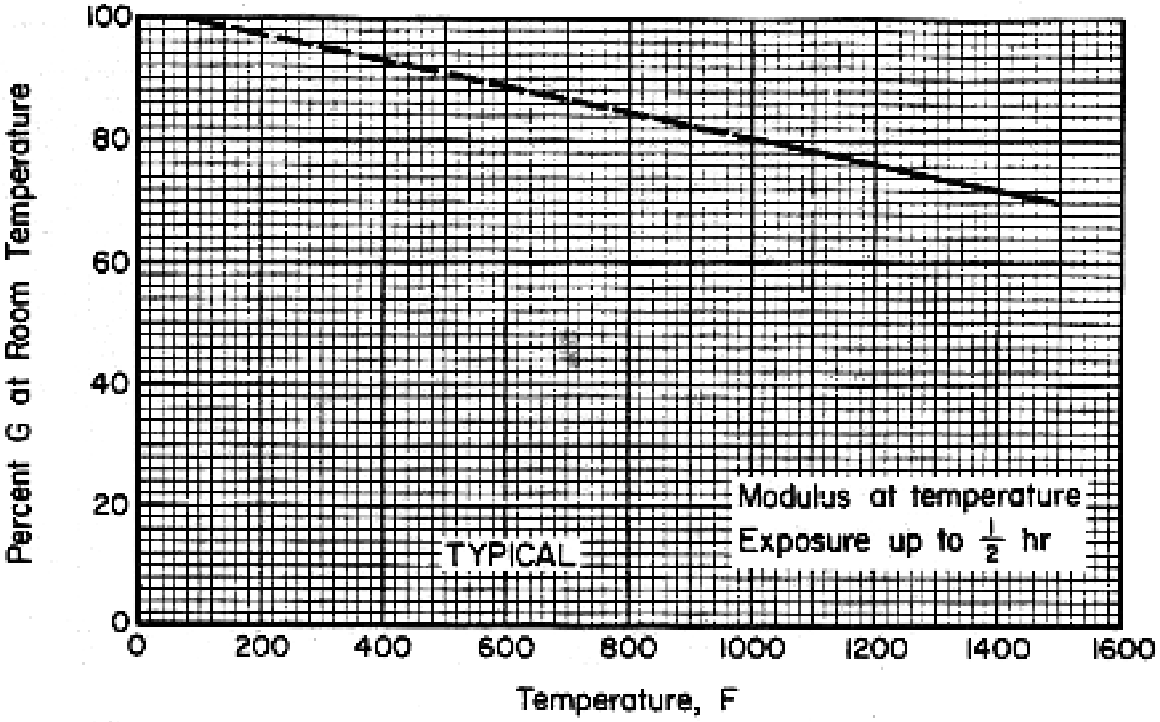

Figure 6.2.1.1.4(b). Effect of temperature on the shear modulus (G) of A-286 alloy.

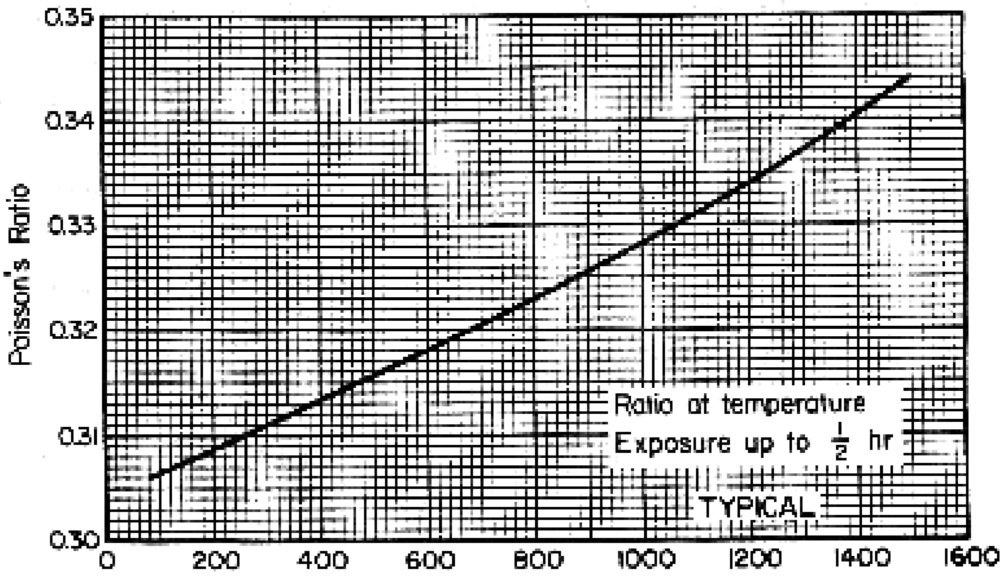

Figure 6.2.1.1.4(c). Effect of temperature on Poisson's ratio (μ) for A-286 alloy.

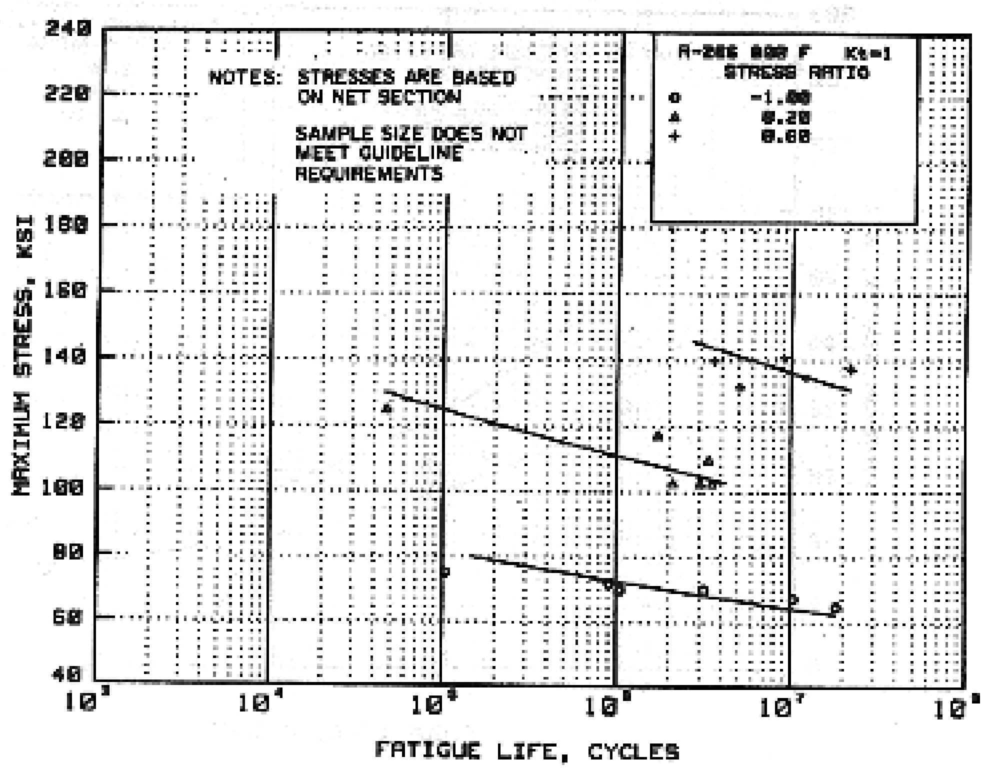

Figure 6.2.1.1.8(a). Best-fit S/N curves for unnotched A-286 bar at 800°F, longitudinal direction.

Correlative Information for Figure 6.2.1.1.8(a)

Product Form: Bar, air melted

Properties:

TUS, ksi	TYS, ksi	Temp., °F
141.4	95.3	800

Specimen Details: Unnotched
0.250 inch diameter

Heat Treatment: 1650°F for 2 hours, oil quenched and 1300°F for 16 hours, air cooled.

Surface Condition: Not given

Reference: 6.2.1.1.8

Test Parameters:
Loading - Axial
Frequency - 3600 cpm
Temperature - 800°F
Environment - Air

No. of Heats/Lots: 1

Equivalent Stress Equation:
Log N_f = 45.1-19.5 log (S_{eq})
$S_{eq} = S_{max}\ (1\text{-}R)^{0.47}$
Std. Error of Estimate, Log (Life) = 0.418
Standard Deviation, Log (Life) = 0.717
R^2 = 65.9%

Sample Size = 17

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

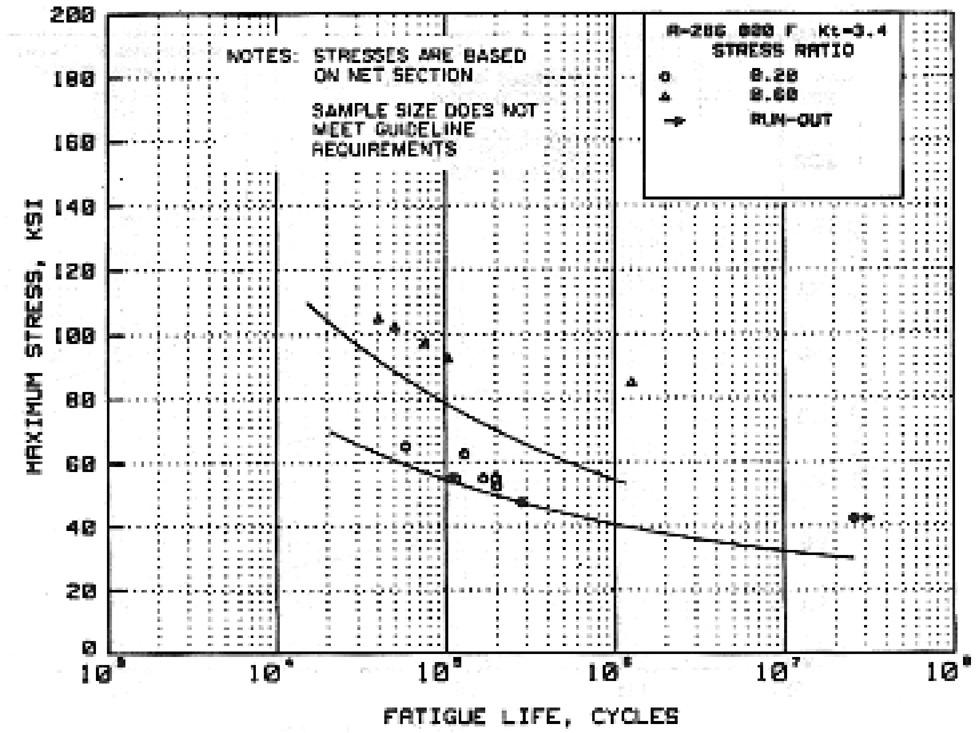

Figure 6.2.1.1.8(b). Best-fit S/N curves for notched, K_t = 3.4, A-286 alloy bar at 800°F, longitudinal direction.

Correlative Information for Figure 6.2.1.1.8(b)

Product Form: Bar, air melted

Properties:

TUS, ksi	TYS, ksi	Temp., °F
141.4	95.3	800
		Unnotched

Specimen Details: Notched, V-Groove,
K_t = 3.4
0.375 inch gross diameter
0.250 inch net diameter
0.010 inch root radius, r
60° flank angle, ω

Heat Treatment: 1650°F for 2 hours, oil quenched and 1300°F for 16 hours, air cooled.

Surface Condition: As machined

Reference: 6.2.1.1.8

Test Parameters:
Loading - Axial
Frequency - 3600 cpm
Temperature - 800°F
Environment - Air

No. of Heats/Lots: 1

Equivalent Stress Equation:
$\log N_f = 11.4 - 4.4 \log (S_{eq} - 20)$
$S_{eq} = S_{max} (1-R)^{0.75}$
Std. Error of Estimate, Log (Life) = 0.271
Standard Deviation, Log (Life) = 0.387
R^2 = 50.9%

Sample Size = 13

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

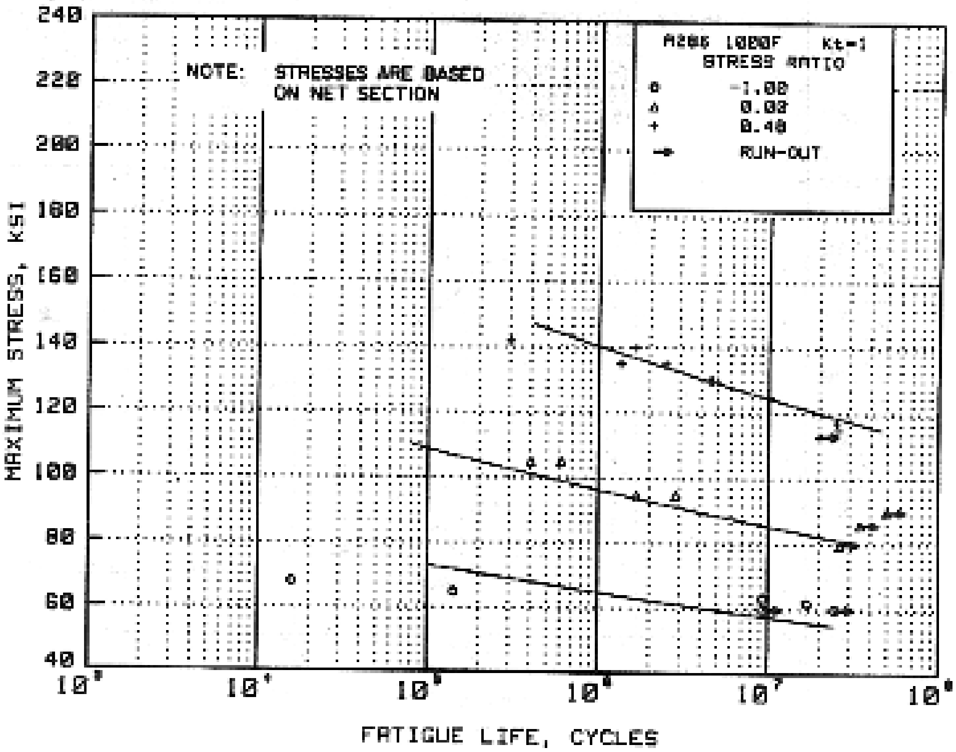

Figure 6.2.1.1.8(c). Best-fit S/N curves for unnotched A-286 bar at 1000°F, longitudinal direction.

Correlative Information for Figure 6.2.1.1.8(c)

Product Form: Bar, air melted

Properties:

TUS, ksi	TYS, ksi	Temp., °F
137.2	100.6	1000

Specimen Details: Unnotched
0.250 inch diameter

Heat Treatment: 1650°F for 2 hours, oil quenched and 1300°F for 16 hours, air cooled.

Surface Condition: Not given

Reference: 6.2.1.1.8

Test Parameters:
Loading - Axial
Frequency - 3600 cpm
Temperature - 1000°F
Environment - Air

No. of Heats/Lots: 1

Equivalent Stress Equation:
Log N_f = 44.2-19.3 log (S_{eq})
$S_{eq} = S_{max} (1-R)^{0.57}$
Std. Error of Estimate, Log (Life) = 0.566
Standard Deviation, Log (Life) = 0.835
R^2 = 54.0%

Sample Size = 18

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

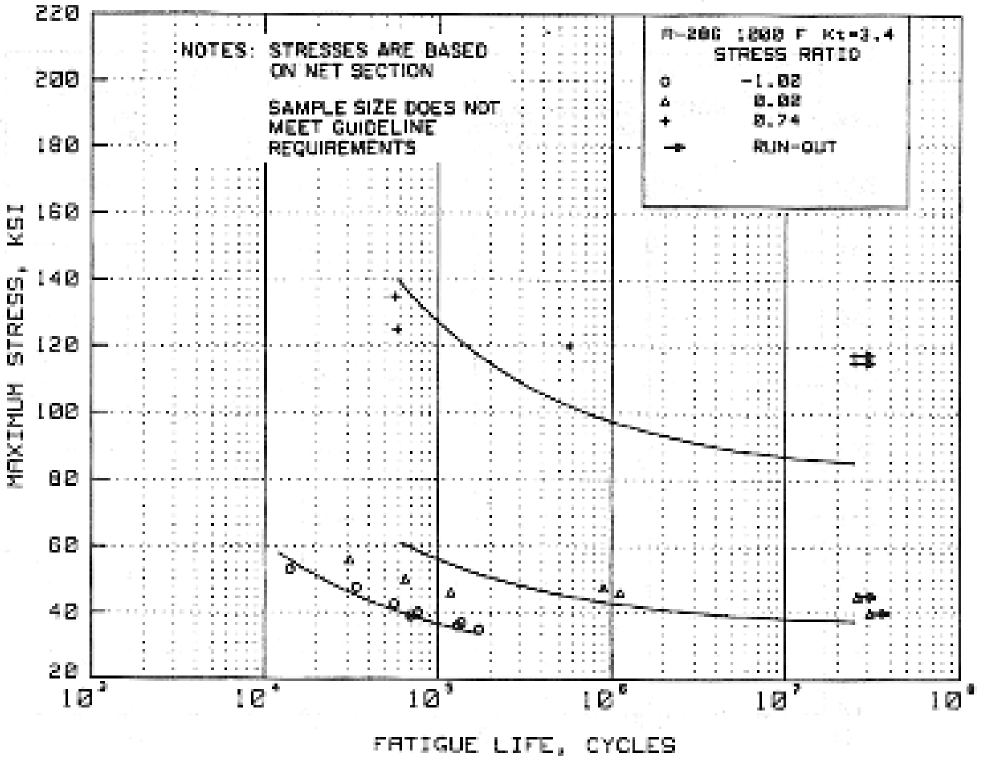

Figure 6.2.1.1.8(d). Best-fit S/N curves for notched, K_t = 3.4, A-286 alloy bar at 1000°F, longitudinal direction.

Correlative Information for Figure 6.2.1.1.8(d)

Product Form: Bar, air melted

Properties:	TUS, ksi	TYS, ksi	Temp.,°F
	137.2	100.6	1000
			Unnotched

Specimen Details: Notched, V-Groove, K_t = 3.4
0.375 inch gross diameter
0.250 inch net diameter
0.010 inch root radius, r
60° flank angle, ω

Heat Treatment: 1650°F for 2 hours, oil quenched and 1300°F for 16 hours, air cooled.

Surface Condition: As machined

Reference: 6.2.1.1.8

Test Parameters:
Loading - Axial
Frequency - 3600 cpm
Temperature - 1000°F
Environment - Air

No. of Heats/Lots: 1

Equivalent Stress Equation:
$\text{Log } N_f = 7.86 - 2.19 \log (S_{eq} - 35.8)$
$S_{eq} = S_{max} (1-R)^{0.61}$
Std. Error of Estimate, Log (Life) = 0.365
Standard Deviation, Log (Life) = 0.510
$R^2 = 48.7\%$

Sample Size = 17

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

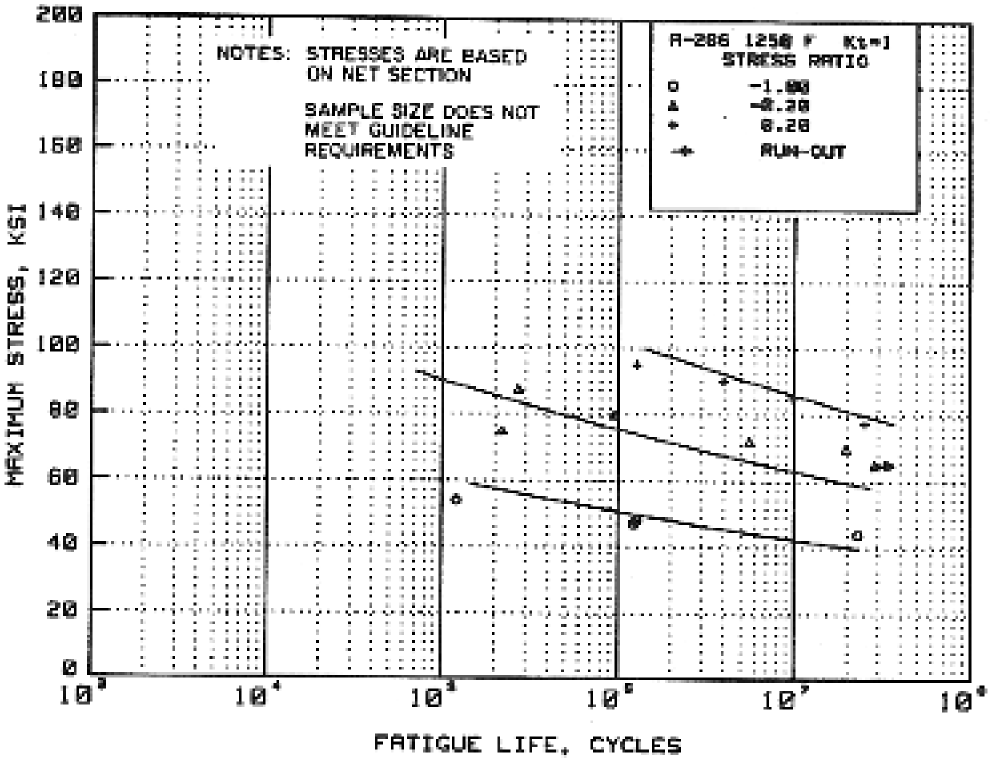

Figure 6.2.1.1.8(e). Best-fit S/N curves for unnotched A-286 bar at 1250°F, longitudinal direction.

Correlative Information for Figure 6.2.1.1.8(e)

Product Form: Bar, air melted

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	109.6	96.5	1250

Specimen Details: Unnotched
0.250 inch diameter

Heat Treatment: 1650°F for 2 hours, oil quenched and 1300°F for 16 hours, air cooled.

Surface Condition: Not given

Reference: 6.2.1.1.8

Test Parameters:
Loading - Axial
Frequency - 3600 cpm
Temperature - 1250°F
Environment - Air

No. of Heats/Lots: 1

Equivalent Stress Equation:
$\text{Log } N_f = 30.8\text{-}12.8 \log (S_{eq})$
$S_{eq} = S_{max} (1\text{-}R)^{0.77}$
Std. Error of Estimate, Log (Life) = 0.513
Standard Deviation, Log (Life) = 0.788
$R^2 = 57.6\%$

Sample Size = 13

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

6.2.2 N-155

6.2.2.0 *Comments and Properties* — N-155 alloy, also known as Multimet, is designed for applications involving high stress up to 1500°F. It has good oxidation properties and good ductility and can be fabricated readily by conventional methods. This alloy has been used in many aircraft applications, including afterburner parts, combustion chambers, exhaust assemblies, turbine parts, and bolting.

N-155 is forged readily between 1650°F and 2200°F. It is easily formed by conventional methods; intermediate anneals may be required to restore its ductility. This alloy is machinable in all conditions; low cutting speeds and ample flow of coolant are required. The weldability of N-155 is comparable to that of the austenitic stainless steels. The oxidation resistance of N-155 sheet is good up to 1500°F.

Some materials specifications for N-155 are presented in Table 6.2.2.0(a). Room-temperature mechanical and physical properties for N-155 sheet and tubing in the solution-treated (annealed) condition are presented in Table 6.2.2.0(b). Bars and forgings are not specified by room-temperature properties but have specific elevated-temperature requirements. The effect of temperature on physical properties is shown in Figure 6.2.2.0.

Table 6.2.2.0(a). Material Specifications for N-155 Alloy

Specification	Form	Condition
AMS 5532	Sheet	Solution treated
AMS 5585	Tubing (welded)	Solution treated
AMS 5768	Bar and forging	Solution treated and aged
AMS 5769	Bar and forging	Solution treated

6.2.2.1 *Solution-Treated Condition* — Elevated-temperature curves are presented in Figures 6.2.2.1.1(a) and (b), as well as 6.2.2.1.4(a) and (b). Stress-rupture properties are specified at 1500°F for sheet and at 1350°F for bars and forgings; the appropriate specifications should be consulted for detailed requirements.

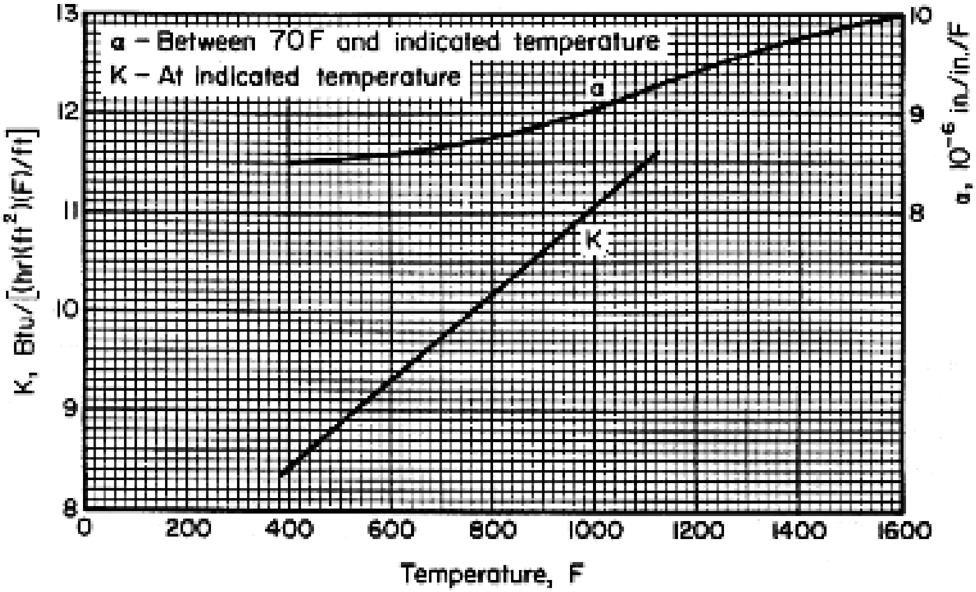

Figure 6.2.2.0. Effect of temperature on the physical properties of N-155 alloy.

Table 6.2.2.0(b). Design Mechanical and Physical Properties of N-155 Alloy

Specification	AMS 5532		AMS 5585
Form	Sheet	Strip and plate	Tubing
Condition	Solution treated		
Thickness, in.	≤0.187	...	...
Basis	S[a]	S[a]	S
Mechanical Properties:			
F_{tu}, ksi:			
L	...	...	100
LT	100	100	...
F_{ty}, ksi:			
L	...	...	49[b]
LT	49[b]	...	...
F_{cy}, ksi:			
L	...	...	...
LT	...	...	...
F_{su}, ksi	...	...	...
F_{bru}, ksi:			
(e/D = 1.5)	...	...	...
(e/D = 2.0)	...	...	...
F_{bry}, ksi:			
(e/D = 1.5)	...	...	...
(e/D = 2.0)	...	...	...
e, percent:			
L	...	...	[c]
LT	40	40	...
E, 10^3 ksi	29.2		
E_c, 10^3 ksi	29.2		
G, 10^3 ksi	11.2		
μ	See Figure 6.2.2.1.4(b)		
Physical Properties:			
ω, lb/in.^{3}	0.300		
C, Btu/(lb)(°F)	0.103 (70 to 212°F)		
K, Btu/[(hr)(ft^2)(°F)/ft]	See Figure 6.2.2.0		
α, 10^{-6} in./in./°F	See Figure 6.2.2.0		

a Test direction longitudinal for widths less than 9 inches: transverse for widths 9 inches and over.
b Typical value reduced to minimum.
c Strip = 35.
Full section 0.625 thick = 40.
Full section >0.625 thick = 30.

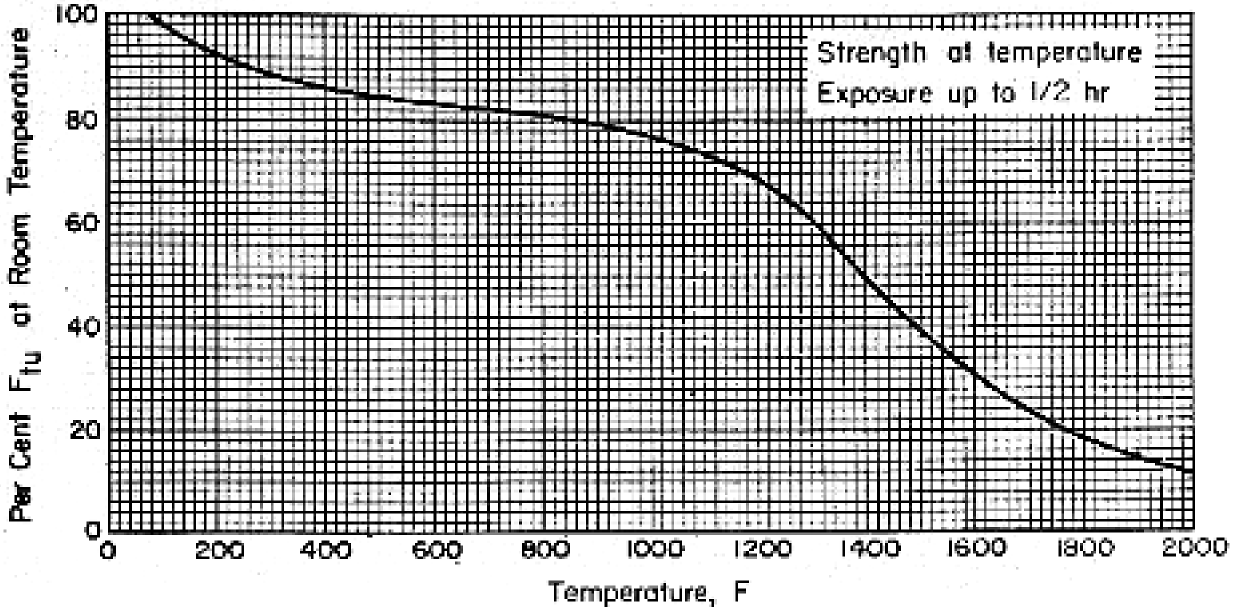

Figure 6.2.2.1.1(a). Effect of temperature on the tensile ultimate strength (F_{tu}) of N-155 alloy.

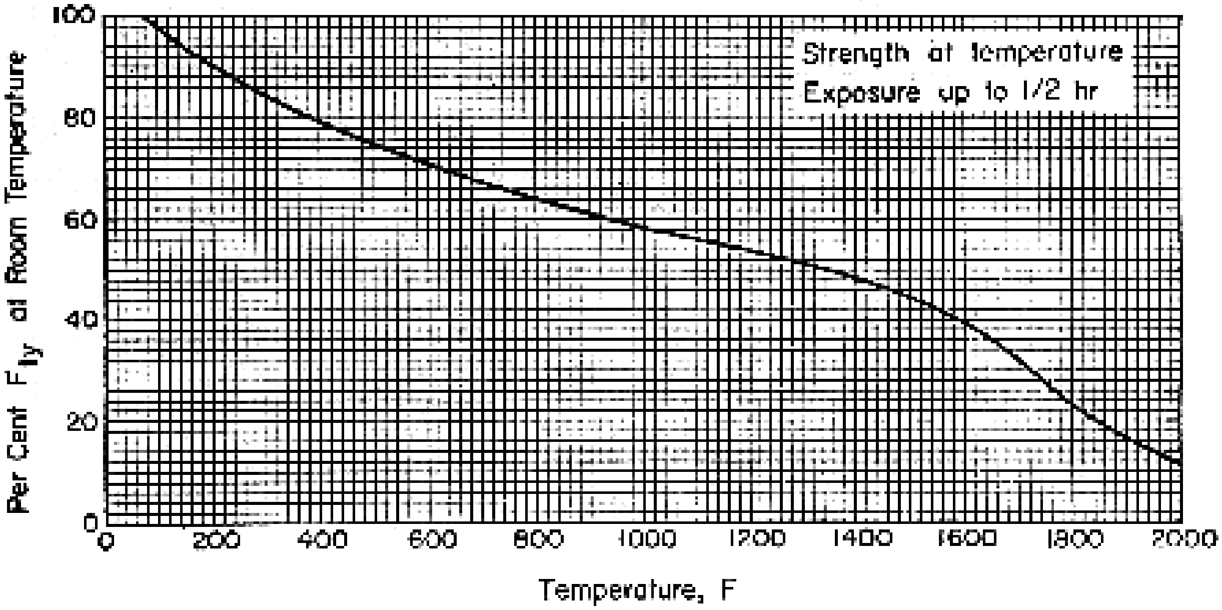

Figure 6.2.2.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of N-155 alloy.

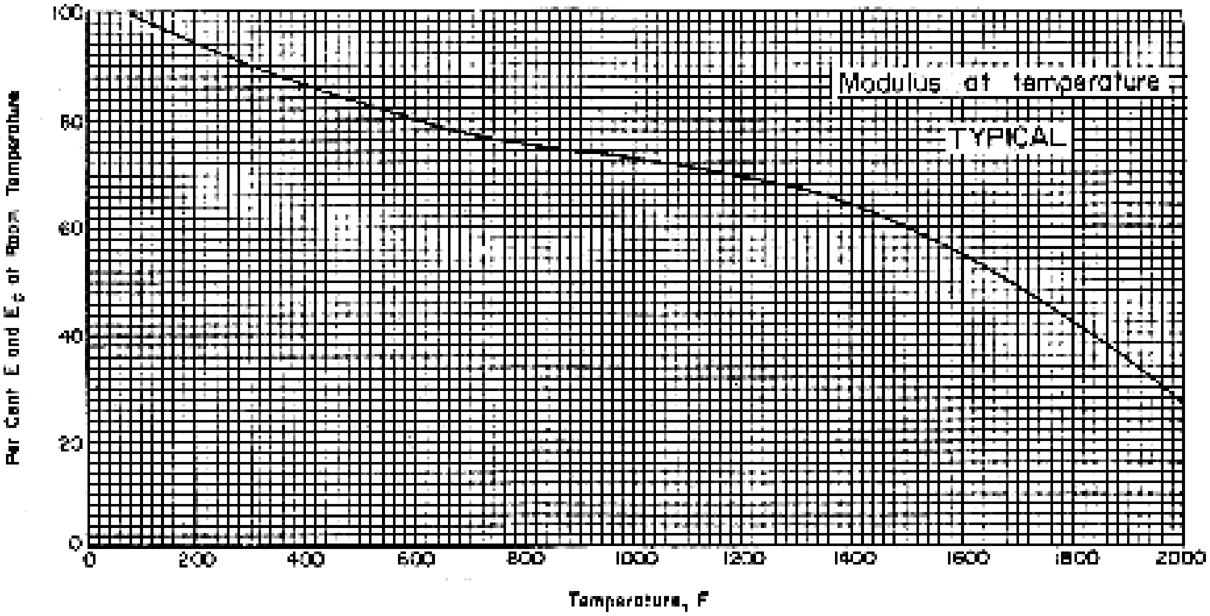

Figure 6.2.2.1.4(a). Effect of temperature on the tensile and compressive moduli (E and E_c) of N-155 alloy.

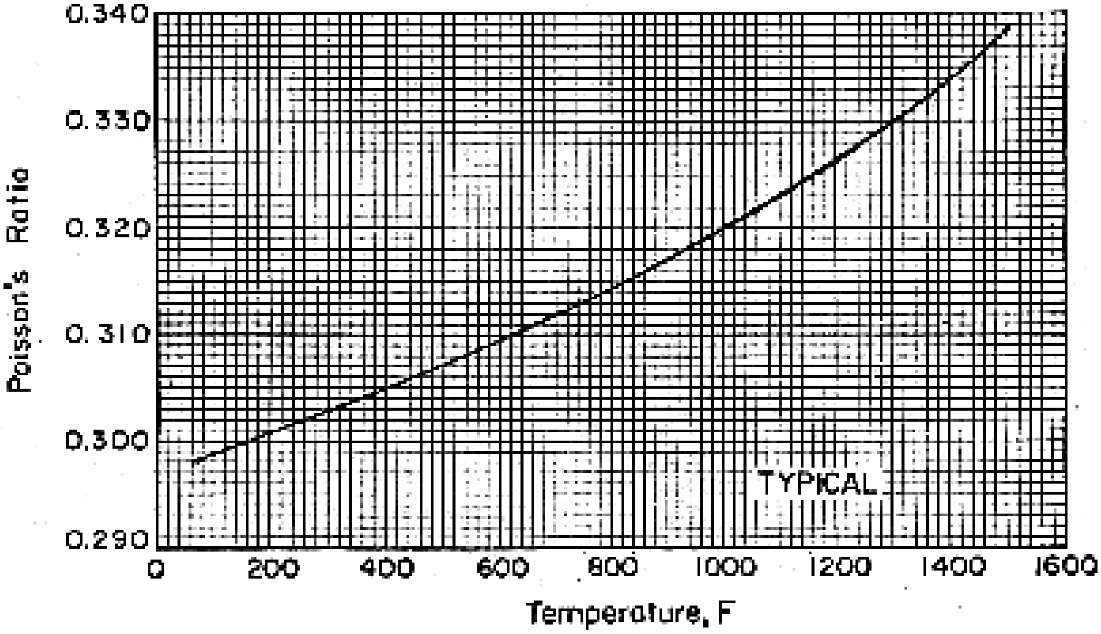

Figure 6.2.2.1.4(b). Effect of temperature on Poisson's ratio (μ) for N-155 alloy.

6.3 NICKEL-BASE ALLOYS

6.3.0 GENERAL COMMENTS — Nickel is the base element for most of the higher temperature heat-resistant alloys. While it is more expensive than iron, nickel provides an austenitic structure that has greater toughness and workability than ferritic structures of the same strength level.

6.3.0.1 *Metallurgical Considerations*

Composition — The common alloying elements for nickel are cobalt, iron, chromium, molybdenum, titanium, and aluminum. Cobalt, when substituted for a portion of the nickel in the matrix, improves high-temperature strength; small additions of iron tend to strengthen the nickel matrix and reduce the cost; chromium is added to increase strength and oxidation resistance at very high temperatures; molybdenum contributes to solid solution strengthening. Titanium and aluminum are added to most nickel-base heat resistant alloys to permit age-hardening by the formation of Ni_3 (Ti, Al) precipitates; aluminum also contributes to oxidation resistance.

The nature of the alloying elements in the age-hardenable nickel-base alloys makes vacuum melting of these alloys advisable, if not mandatory. However, the additional cost of vacuum melting is more than compensated for by the resulting improvements in elevated-temperature properties.

Heat Treatment — The nickel-base alloys are heat treated with conventional equipment and fixtures such as would be used with austenitic stainless steels. Since nickel-base alloys are more susceptible to sulfur embrittlement than are iron-base alloys, it is essential that sulfur-bearing materials such as grease, oil, cutting lubricants, marking paints, etc., be removed before heat treatment. Mechanical cleaning, such as wire brushing, is not adequate and if used should be followed by washing with a suitable solvent or by vapor degreasing. A low-sulfur content furnace atmosphere should be used. Good furnace control with respect to time and temperature is desirable since overheating some of the alloys as little as 35°F impairs strength and corrosion resistance.

When it is necessary to anneal the age-hardenable-type alloys, a protective atmosphere (such as argon) lessens the possibility of surface contaminations or depletion of the precipitation-hardening elements. This precaution is not so critical in heavier sections since the oxidized surface layer is a smaller percentage of the cross section. After solution annealing, the alloys are generally quenched in water. Heavy sections may require air cooling to avoid cracking from thermal stresses.

In stress-relief annealing of a structure or assembly composed of an aluminum-titanium hardened alloy, it is vitally important to heat the structure rapidly through the age-hardening temperature range, 1200°F to 1400°F (which is also the low ductility range) so that stress relief can be achieved before any aging takes place. Parts which are to be used in the fully heat-treated condition would have to be solution treated, air cooled, and subsequently aged. In this case, the stress-relief treatment would be conducted in the solution-temperature range. Little difficulty has been encountered with distortion under rapid heating conditions, and distortion of weldments of substantial size has been less than that observed with conventional slow heating methods.

6.3.0.2 *Manufacturing Considerations*

Forging — All of the alloys considered, except for the casting compositions, can be forged to some degree. The matrix-strengthened alloys can be forged with proper consideration of cooling rates, atmosphere, etc. Most of the precipitation-hardenable grades can be forged, although heavier equipment is required and a smaller range of reductions can be safely attained.

Cold Forming — Almost all of the wrought-nickel-base alloys in sheet form are cold formable. The lower strength alloys offer few problems, but the higher strength alloys require higher forming pressures and more frequent anneals.

Machining — All of the alloys in this section are readily machinable, provided the optimum conditions of heat treatment, type of tool speed, feed, depth of cut, etc., are achieved. Specific recommendations on these points are available from various producers of these alloys.

Welding — The matrix-strengthening-type alloys offer no serious problems in welding. All of the common resistance- and fusion-welding processes (except submerged arc) have been successfully employed. For the age-hardenable type of alloy, it is necessary to observe some further precautions:

(1) Welding should be confined to annealed material where design permits. In full age-hardened material, the hazard of cracking in the weld and/or the parent metal is great.

(2) If design permits joining some portions only after age hardening, the parts to be joined should be "safe ended" with a matrix-strengthened-type alloy (with increased cross section) and then age hardened; welding should then be carried out on the "safe ends."

(3) Parts severely worked or deformed should be annealed before welding.

(4) After welding, the weldment will often require stress relieving before aging.

(5) Material must be heated rapidly to the stress-relieving temperature.

(6) In a number of the age-hardenable alloys, fusion welds may exhibit only 70 to 80 percent of the rupture strength of the parent metal. The deficiency can often be minimized by design, such as locating welds in areas of lowest temperature and/or stress. The use of special filler wires to improve weld-rupture properties is under investigation.

Brazing — The solid-solution-type chromium-containing alloys respond well to brazing, using techniques and brazing alloys applicable to the austenitic stainless steels. Generally, it is necessary to braze annealed material and to keep stresses low during brazing, especially when brazing with low melting alloys, to avoid embrittlement. As with the stainless steels, dry hydrogen, argon, or helium atmospheres (-80°F dew point or lower) are used successfully, and vacuum brazing is now receiving increasing attention.

The aluminum-titanium age-hardened nickel-base alloys are difficult to braze, even using extremely dry reducing- and inert-gas atmospheres, unless some method of fluxing, solid or gaseous, is used. An alternative technique which is commonly used is to preplate the areas to be brazed with ½ to 1 mil of nickel. For some metal combinations, a few fabricators prefer to apply an iron preplate. In either case, the plating prevents the formation of aluminum or titanium oxide films and results in better joints.

Most of the high-temperature alloys of the nickel-base type are brazed with Ni-Cr-Si-B and Ni-Cr-Si types of brazing alloy. Silver brazing alloys can be used for lower temperature applications. However, since the nickel-base alloys to be brazed are usually employed for higher temperature applications, the higher melting point, stronger, and more oxidation-resistant brazing alloys of the Nicrobraz type are generally used. Some of the gold-base and palladium-base brazing alloys may be useful under some circumstances in intermediate-temperature applications.

6.3.1 HASTELLOY X

6.3.1.0 *Comments and Properties* — Hastelloy X is a nickel-base alloy used for combustor-liner parts, turbine-exhaust weldments, afterburner parts, and other parts requiring oxidation resistance and moderately high strength above 1450°F. It is not hardenable except by cold working and is used in the solution-treated (annealed) condition. Hastelloy X is available in all the usual mill forms.

Hastelloy X is somewhat difficult to forge; forging should be started at 2150°F to 2200°F and continued as long as the material flows freely. It should be in the annealed condition for optimum cold forming, and severely formed detail parts should be solution treated at 2150°F for 7 to 10 minutes and cooled rapidly after forming. Machinability of Hastelloy X is similar to that of austenitic stainless steel; the alloy is tough and requires low cutting speeds and ample cutting fluids. Hastelloy X can be resistance or fusion welded or brazed; large or complex fusion weldments require stress relief at 1600°F for 1 hour. Hastelloy X has good oxidation resistance up to 2100°F. It age hardens somewhat during long exposure between 1200°F and 1800°F.

Some material specifications for Hastelloy X are presented in Table 6.3.1.0(a). Room-temperature mechanical and physical properties for Hastelloy X sheet are presented in Table 6.3.1.0(b). AMS 5754 does not specify tensile properties for bars and forgings. Figure 6.3.1.0 shows the effect of temperature on physical properties.

Table 6.3.1.0(a). Material Specifications for Hastelloy X

Specification	Form	Condition
AMS 5536	Sheet and plate	Solution heat treated (annealed)
AMS 5754	Bar and forging	Solution heat treated (annealed)

6.3.1.1 *Annealed Condition* — The effect of temperature on various mechanical properties is presented in Figures 6.3.1.1.1 and 6.3.1.1.4. In addition, certain stress-rupture requirements at 1500°F are specified in AMS 5536 and 5754 for Hastelloy X. Typical tensile stress-strain curves at room and elevated temperatures are presented in Figure 6.3.1.1.6(a). Typical compressive stress-strain and tangent-modulus curves at room and elevated temperatures are presented in Figure 6.3.1.1.6(b).

Table 6.3.1.0(b). Design Mechanical and Physical Properties of Hastelloy X Sheet and Plate

Specification	AMS 5536						
Form	Sheet[a] and plate						
Condition	Solution treated (annealed)						
Thickness, in.	<0.010	0.010-0.019	0.020-0.100		0.101-0.187	0.188-2.000	>2.000
Basis	S	S	A	B	S	S	S
Mechanical Properties:							
F_{tu}, ksi:							
L	...	...	...	...	...	...	...
LT	105	105	102	106	105	100	95
F_{ty}, ksi:							
L	...	...	...	...	...	...	...
LT	45	45	44	47	45	40	40
F_{cy}, ksi:							
L	...	...	...	...	...	...	...
LT	...	...	...	...	...	...	...
F_{su}, ksi	...	...	...	...	...	...	...
F_{bru}, ksi:							
(e/D = 1.5)	...	...	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...	...	...
F_{bry}, ksi:							
(e/D = 1.5)	...	...	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...	...	...
e, percent (S-basis):							
L	...	...	...	...	...	...	...
LT	...	29	35	...	35	35	35
E, 10^3 ksi	29.8						
E_c, 10^3 ksi	29.8						
G, 10^3 ksi	11.3						
μ	0.32						
Physical Properties:							
ω, lb/in.^{3}	0.297						
C, Btu/(lb)(°F)	See Figure 6.3.1.0						
K, Btu/[(hr)(ft^2)(°F)/ft]	See Figure 6.3.1.0						
α, 10^{-6} in./in./°F	See Figure 6.3.1.0						

[a] Test direction longitudinal for widths less than 9 inches: transverse for widths 9 inches and over.

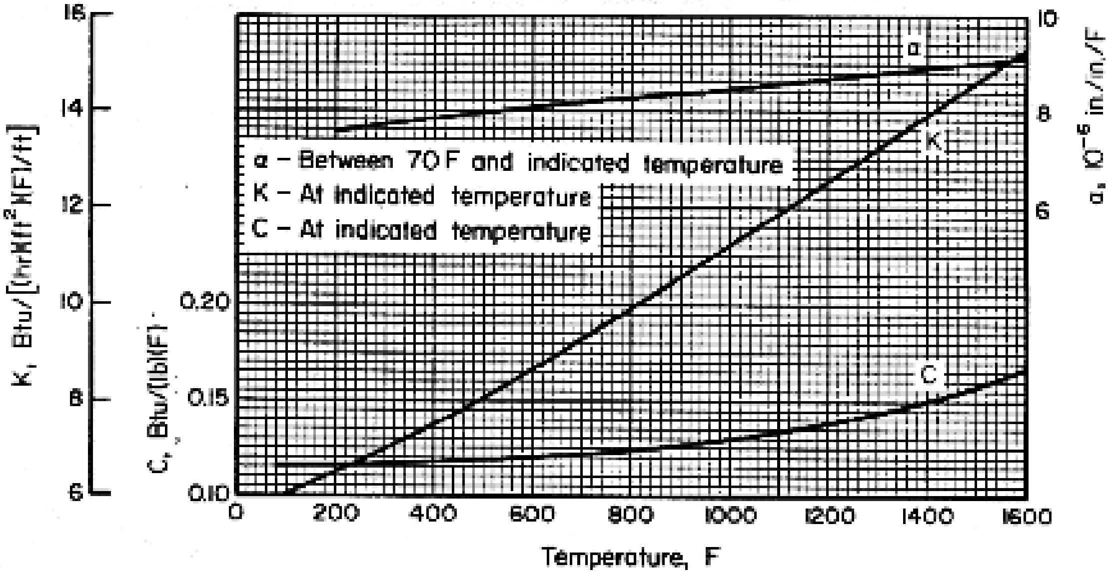

Figure 6.3.1.0. Effect of temperature on the physical properties of Hastelloy X.

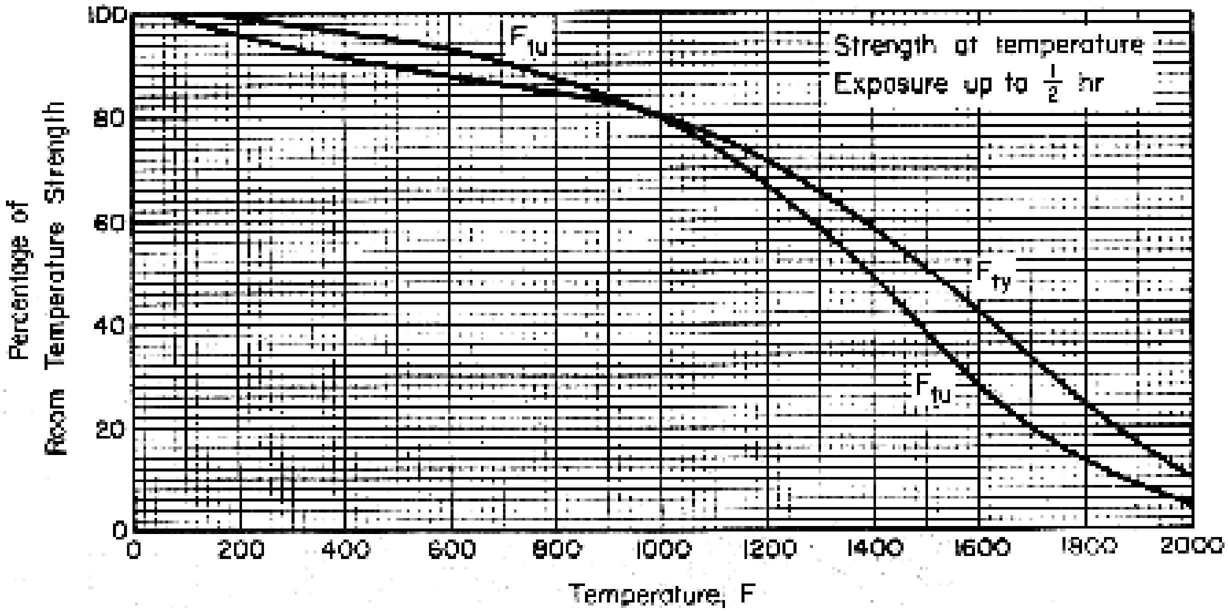

Figure 6.3.1.1.1. Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of Hastelloy X sheet.

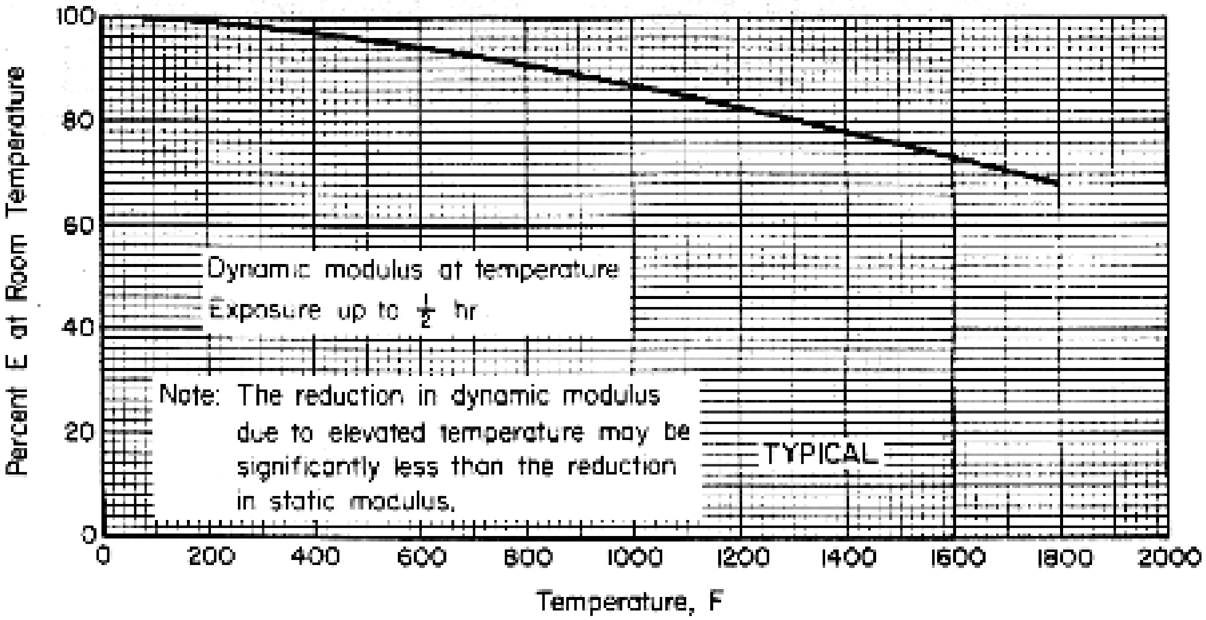

Figure 6.3.1.1.4. Effect of temperature on dynamic modulus (E) of Hastelloy X sheet.

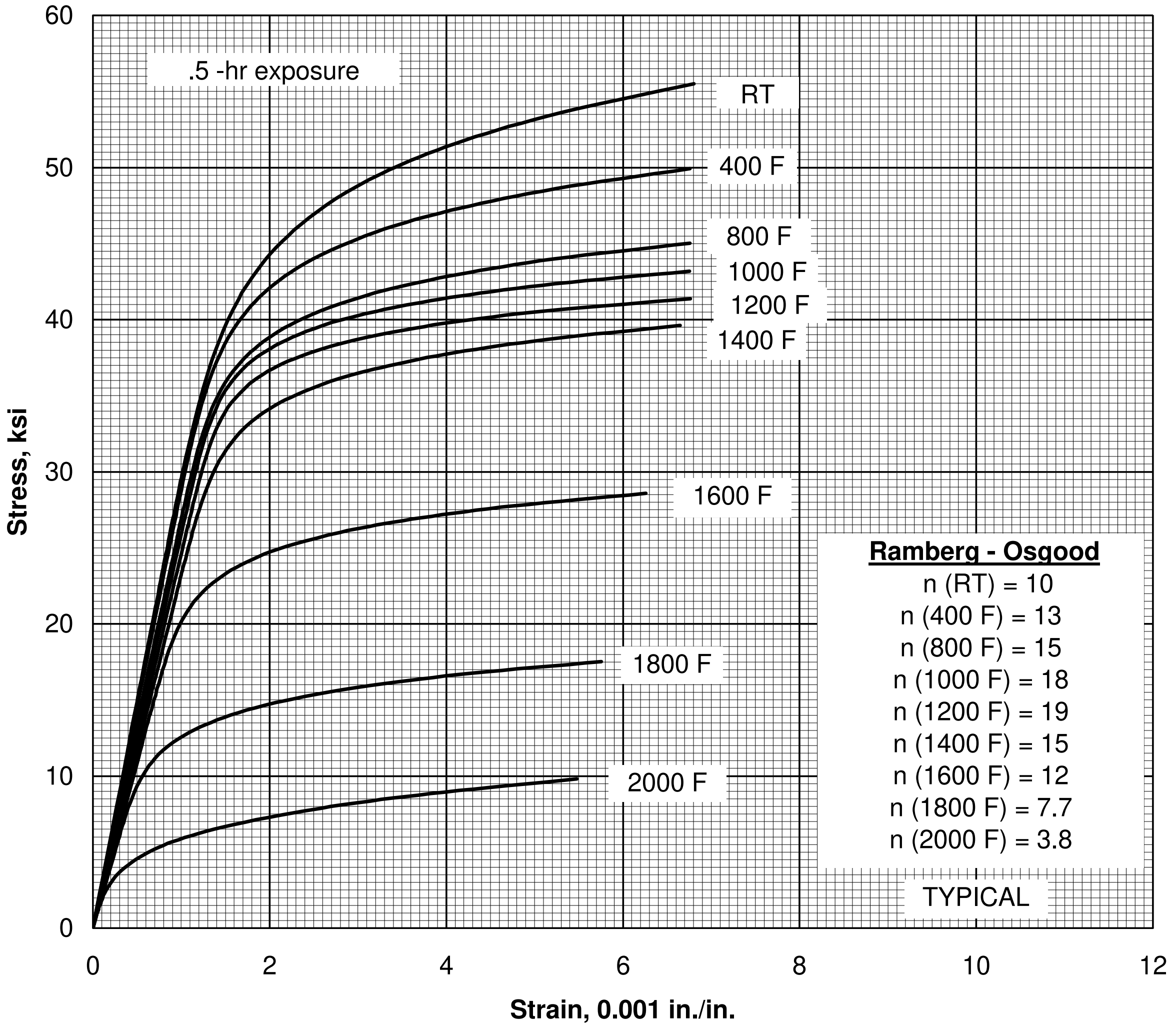

Figure 6.3.1.1.6(a). Typical tensile stress-strain curves for Hastelloy X sheet at room and elevated temperatures.

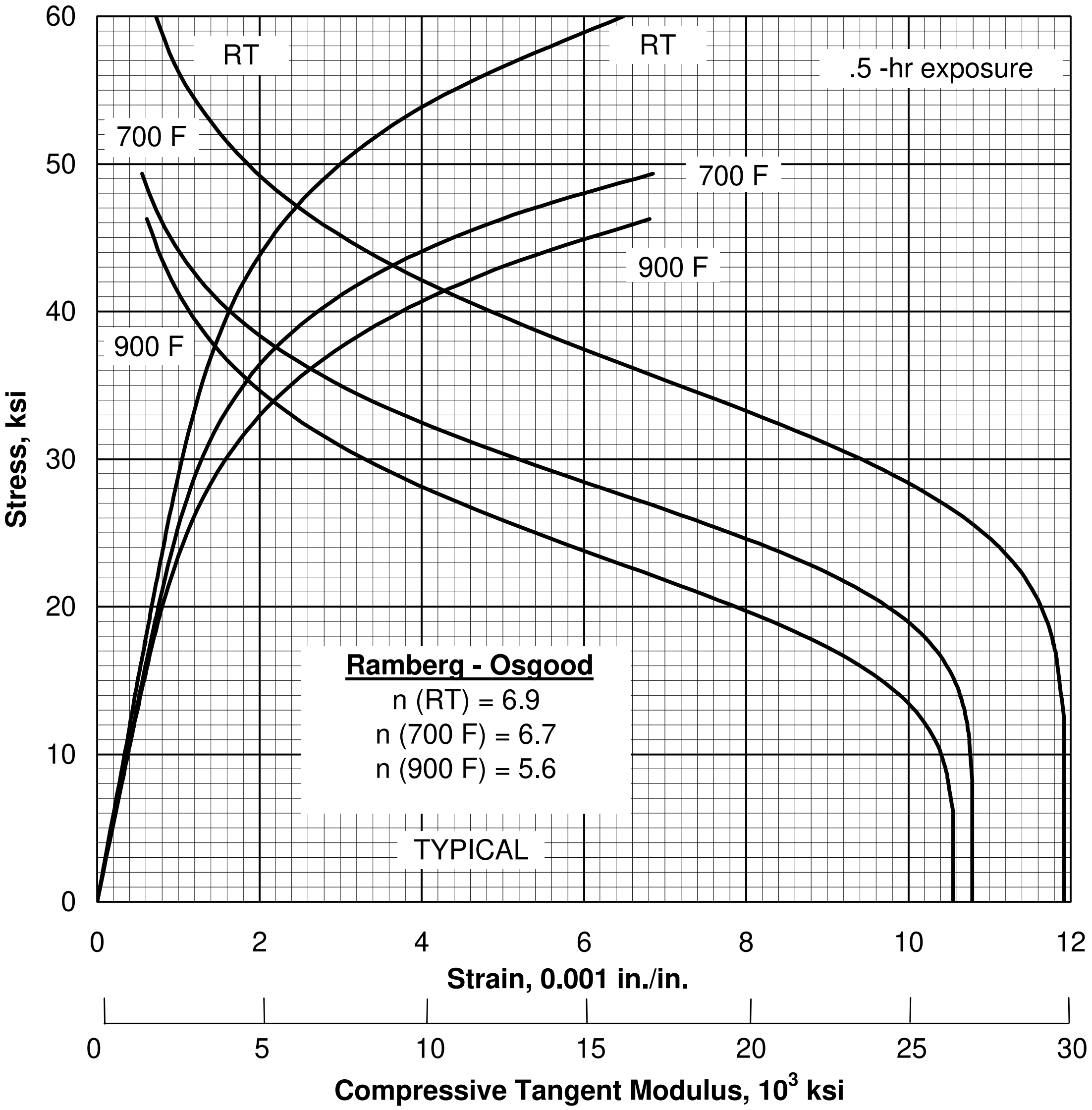

Figure 6.3.1.1.6(b). Typical compressive stress-strain and compressive tangent-modulus curves for Hastelloy X bar at room and elevated temperatures.

6.3.2 INCONEL 600

6.3.2.0 *Comments and Properties* — Inconel 600 is a corrosion- and heat-resistant nickel-base alloy used for low-stressed parts operating up to 2000°F. It is not hardenable except by cold working and is usually used in the annealed condition. Inconel 600 is available in all the usual mill forms.

Inconel 600 is readily forged between 1900°F and 2250°F; "hot-cold" working between 1200°F and 1600°F is harmful and should be avoided; cold working below 1200°F results in improved properties. This alloy is readily formed but should be annealed after severe forming operations. The maximum annealing temperature is 1800°F if minimum yield-strength requirements are to be met consistently. Inconel 600 is susceptible to rapid grain growth at 1800°F or higher, and exposures at these temperatures should be brief if large grain size is objectionable.

Inconel 600 is somewhat difficult to machine because of its toughness and capacity for work hardening; high-speed steel or cemented-carbide tools should be used, and tools should be kept sharp. This alloy can be resistance or fusion welded or brazed (using nonsilver containing brazing alloy); large or complex fusion weldments should be stress relieved at 1600°F for 1 hour. Oxidation resistance of Inconel 600 is excellent up to 2000°F in sulfur-free atmospheres. This alloy is subject to attack in sulfur-containing atmospheres.

Table 6.3.2.0(a). Material Specifications for Inconel 600

Specification	Form	Condition
AMS 5540	Plate, sheet, and strip	Annealed
ASTM B166	Bar and rod	Various
AMS 5580	Tubing, seamless	Annealed
ASTM B564	Forging	Annealed

Some material specifications for Inconel 600 are presented in Table 6.3.2.0(a). Room-temperature mechanical and physical properties are shown in Tables 6.3.2.0(b), (c), and (d). Figure 6.3.2.0 shows the effect of temperature on the physical properties.

6.3.2.1 *Annealed Condition* — Elevated-temperature data for this condition are shown in Figures 6.3.2.1.1 through 6.3.2.1.4.

Table 6.3.2.0(b). Design Mechanical and Physical Properties of Inconel 600

Specification	AMS 5540	AMS 5580		ASTM B564
Form	Sheet, strip, and plate	Tubing		Forging
Condition	Annealed	Cold drawn		Annealed
Thickness, in.	0.020-2.000	...		...
Outside Diameter, in.	...	$\leq$5.000	5.001-6.625	...
Basis	S	S	S	S
Mechanical Properties:				
F_{tu}, ksi:				
L	...	80	80	80
LT	80	...	...	...
F_{ty}, ksi:				
L	...	35	30	35
LT	35	...	...	...
F_{cy}, ksi:				
L	...	35	30	35
LT	35	...	...	...
F_{su}, ksi	51	51	51	51
F_{bru}, ksi:				
(e/D = 1.5)	...	...	...	...
(e/D = 2.0)	152	152	152	152
F_{bry}, ksi:				
(e/D = 1.5)	...	...	...	...
(e/D = 2.0)	...	...	...	...
e, percent:				
L	...	30	35	30
LT	30	...	...	...
E, 10^3 ksi	30.0			
E_c, 10^3 ksi	30.0			
G, 10^3 ksi	11.0			
μ	0.29			
Physical Properties:				
ω, lb/in.^{3}	0.304			
C, K, and α	See Figure 6.3.2.0			

Table 6.3.2.0(c). Design Mechanical and Physical Properties of Inconel 600 Bar and Rod

Specification	ASTM B166				
Form	Round			Square, hexagon, and rectangle	
Condition	Cold-worked				
Thickness, in.	≤0.499	0.500-1.000	1.001-2.500	≤0.250	0.251-0.499
Basis	S	S	S	S	S
Mechanical Properties[a]:					
F_{tu}, ksi:					
L	120	110	105	100	95
LT	...	...	...	...	...
F_{ty}, ksi:					
L	90	85	80	80	70
LT	...	...	...	...	...
F_{cy}, ksi:					
L	...	...	...	...	...
LT	...	...	...	...	...
F_{su}, ksi	...	...	...	...	...
F_{bru}, ksi:					
(e/D = 1.5)	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...
F_{bry}, ksi:					
(e/D = 1.5)	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...
e, percent:					
L	7[b]	10	12	5[b]	7
E, 10^3 ksi	30.0				
E_c, 10^3 ksi	30.0				
G, 10^3 ksi	11.0				
μ	0.29				
Physical Properties:					
ω, lb/in.^{3}	0.304				
C, K, and α	See Figure 6.3.2.0				

[a] Mechanical property requirements apply only when specified by purchaser.
[b] Not applicable to thickness <0.094 inch.

Table 6.3.2.0(d). Design Mechanical and Physical Properties of Inconel 600 Bar and Rod

Specification	ASTM B166				
Form	Round			Square, hexagon, and rectangle	Bar and rod
Condition	Hot-worked				Annealed
Thickness, in.	0.250-0.500	0.501-3.000	>3.000	All	All
Basis	S	S	S	S	S
Mechanical Properties[a]:					
F_{tu}, ksi:					
L	95	90	85	85	80
LT	...	...	...	...	...
F_{ty}, ksi:					
L	45	40	35	35	35
LT	...	...	...	...	...
F_{cy}, ksi:					
L	...	...	...	...	35
LT	...	...	...	...	...
F_{su}, ksi	...	...	...	...	51
F_{bru}, ksi:					
(e/D = 1.5)	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	152
F_{bry}, ksi:					
(e/D = 1.5)	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...
e, percent:					
L	20	25	30	...	30[b]
E, 10^3 ksi	30.0				
E_c, 10^3 ksi	30.0				
G, 10^3 ksi	11.0				
μ	0.29				
Physical Properties:					
ω, lb/in.^{3}	0.304				
C, K, and α	See Figure 6.3.2.0				

a Mechanical property requirements apply only when specified by purchaser.
b Not applicable to thickness >0.094 inch.

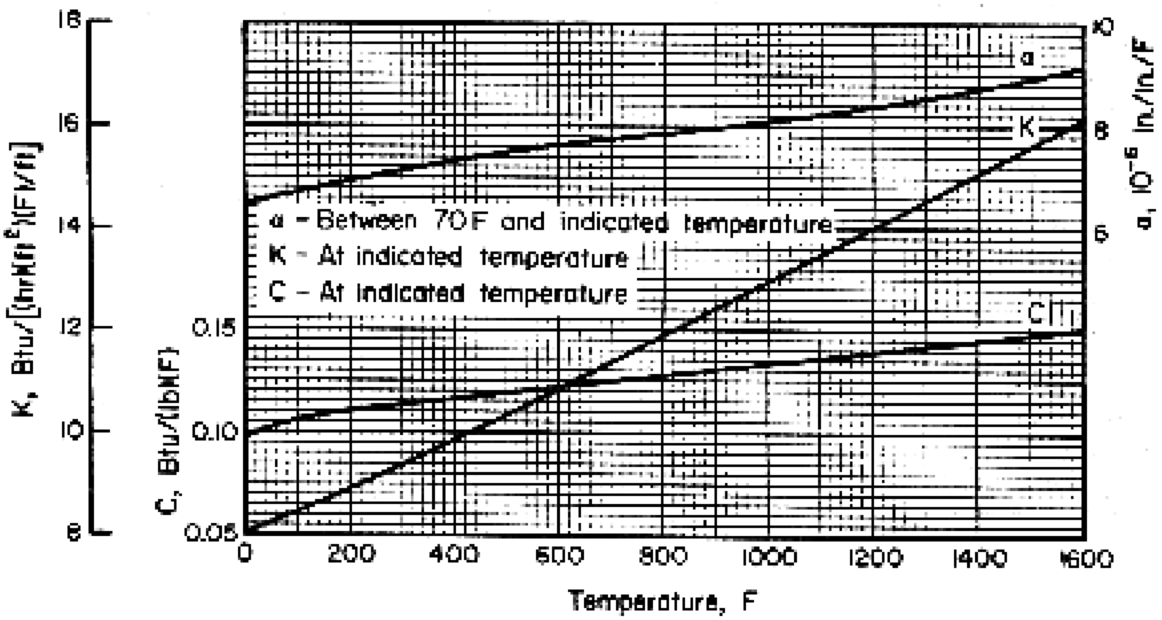

Figure 6.3.2.0. Effect of temperature on the physical properties of Inconel 600.

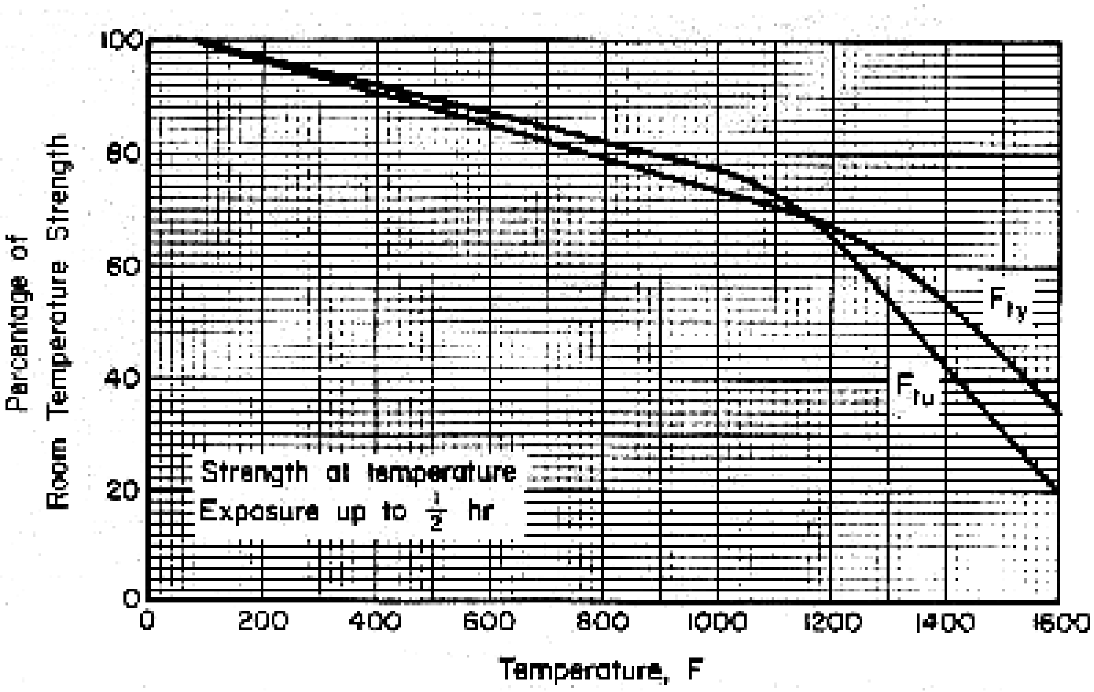

Figure 6.3.2.1.1. Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of Inconel 600.

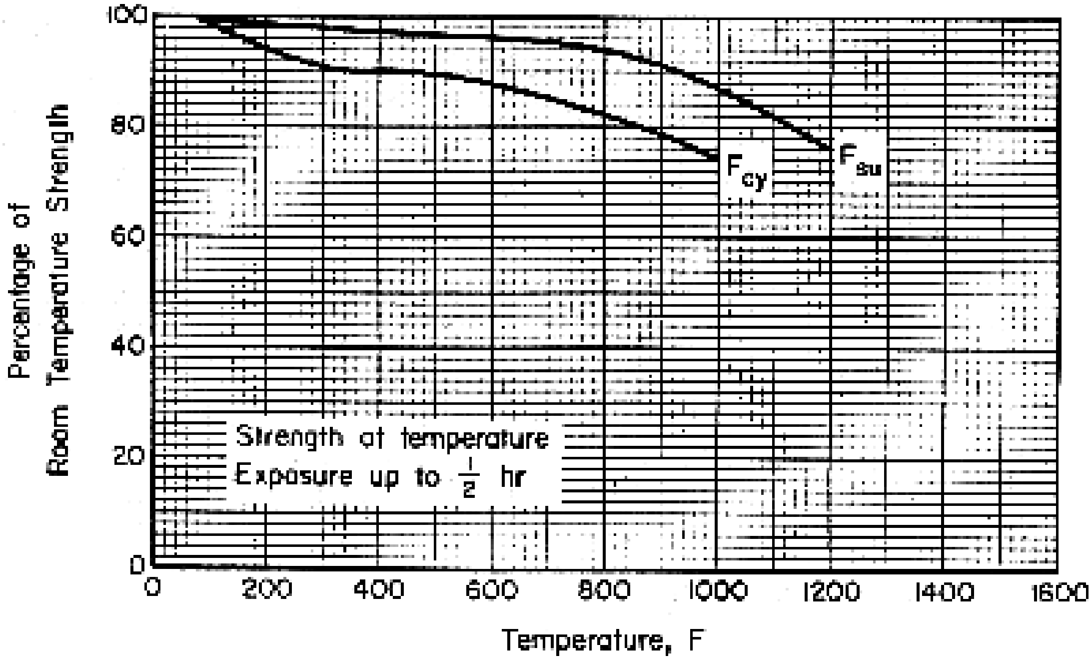

Figure 6.3.2.1.2. Effect of temperature on the compressive yield strength (F_{cy}) and the shear ultimate strength (F_{su}) of Inconel 600.

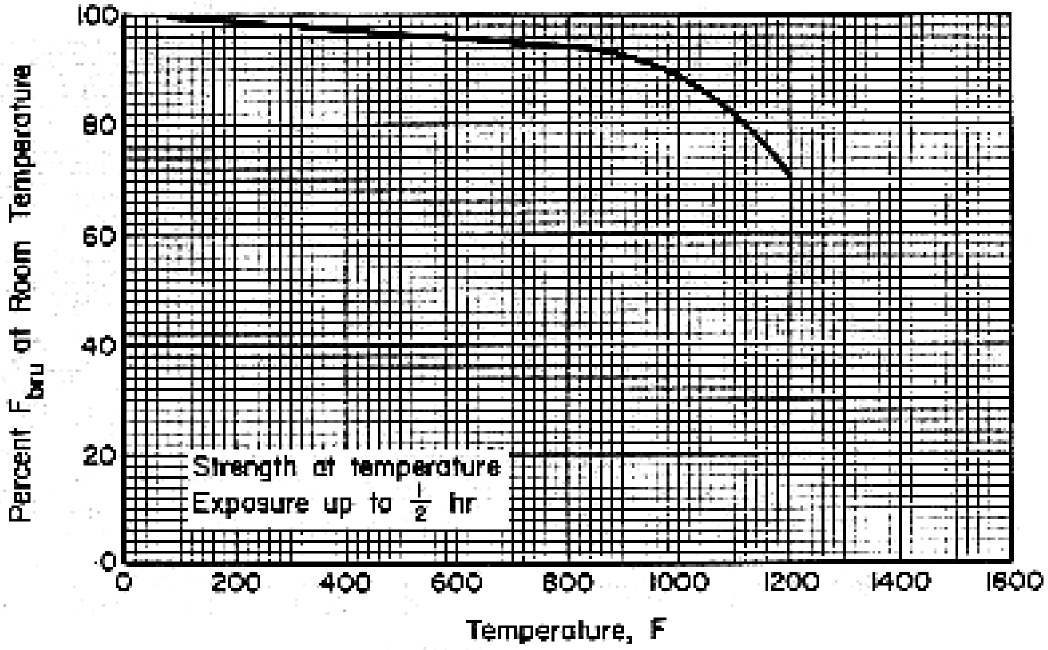

Figure 6.3.2.1.3. Effect of temperature on the bearing ultimate strength (F_{bru}) of Inconel 600.

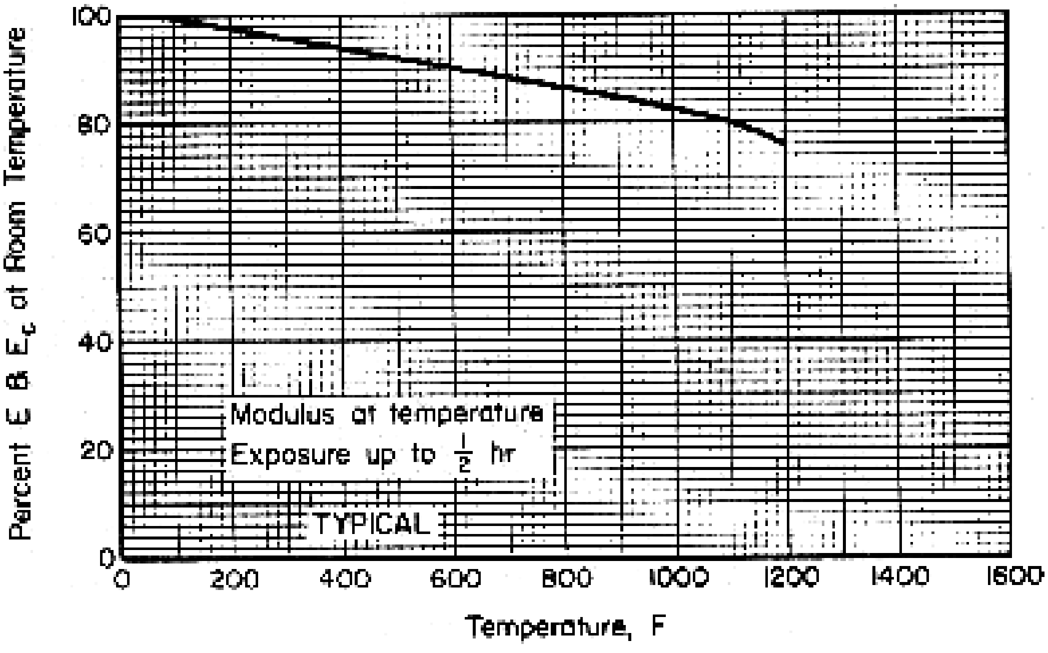

Figure 6.3.2.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of Inconel 600.

6.3.3 INCONEL 625

6.3.3.0 *Comments and Properties* — Inconel 625 is a solid-solution, matrix strengthened nickel-base alloy primarily for applications requiring good corrosion and oxidation resistance at temperatures up to approximately 1800°F and also where such parts may require welding.

The strength of the alloy is derived from the strengthening effect of molybdenum and columbium; thus, precipitation hardening is not required and the alloy is used in the annealed condition. The strength is greatly affected by the amount of cold work prior to annealing and by the annealing temperature. The material is usually annealed at 1700 to 1900°F for time commensurate with thickness. The properties in this section are restricted to that annealing range.

Because the alloy was developed to retain high strength at elevated temperatures, it resists deformation at hot working temperatures but can be readily fabricated with adequate equipment. The combination of strength, corrosion resistance, and ability to be fabricated, including welding by common industrial practices, are the alloy's outstanding features.

Some material specifications for Inconel 625 are listed in Table 6.3.3.0(a). Room-temperature mechanical and physical properties for Inconel 625 are listed in Tables 6.3.3.0(b) and (c). Figure 6.3.3.0 shows the effect of temperature on the physical properties.

Table 6.3.3.0(a). Material Specifications for Inconel 625

Specification	Form	Condition
AMS 5599	Sheet, strip, and plate	Annealed
AMS 5666	Bar, forging, and ring	Annealed

6.3.3.1 *Annealed Condition* — Elevated-temperature curves for tensile ultimate strength, tensile yield strength, tensile and compressive moduli, and Poisson's ratio are presented in Figures 6.3.3.1.1(a) and (b), as well as 6.3.3.1.4(a) and (b). Typical stress-strain and tangent-modulus curves are shown in Figures 6.3.3.1.6(a) through (d). Fatigue S/N curves are presented in Figures 6.3.3.1.8(a) through (d).

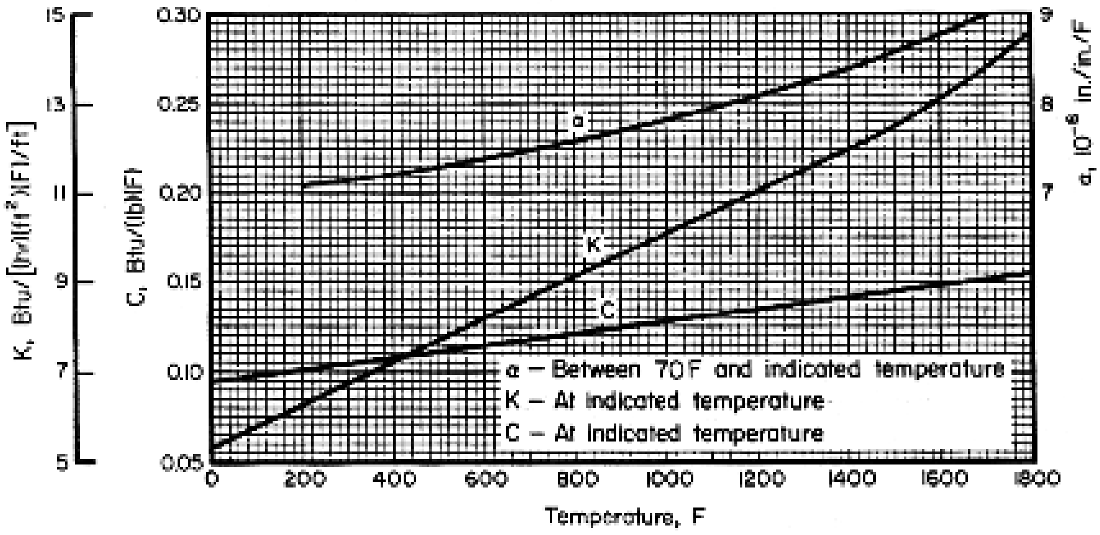

Figure 6.3.3.0. Effect of temperature on the physical properties of Inconel 625.

Table 6.3.3.0(b). Design Mechanical and Physical Properties of Inconel 625 Sheet and Plate

Specification	AMS 5599									
Form	Sheet and plate									
Condition	Annealed									
Thickness, in.	≤0.062		0.063-0.109		0.110-0.140		0.141-0.187		0.188-0.250	0.251-1.000
Basis	A	B	A	B	A	B	A	B	S	S
Mechanical Properties:										
F_{tu}, ksi:										
L	119	127	119	126	119	125	118	123	119	...
LT	120[a]	128	120[a]	127	120[a]	126	119	124	120	120
F_{ty}, ksi:										
L	56	62	55	61	54	60	53	59	59	...
LT	57	63	56	62	55	61	54	60	60	60
F_{cy}, ksi:										
L	59	65	58	64	57	63	55	62	62	...
LT	59	66	58	65	57	64	56	63	63	...
F_{su}, ksi	79	84	79	84	79	83	79	82	79	...
F_{bru}, ksi:										
(e/D = 1.5)	202	216	202	214	202	212	201	209	202	...
(e/D = 2.0)	263	281	263	279	263	276	261	272	263	...
F_{bry}[b], ksi:										
(e/D = 1.5)	88	97	86	95	84	94	83	92	92	...
(e/D = 2.0)	109	121	107	119	105	117	103	115	115	...
e, percent (S-basis):										
LT	30	...	30	...	30	...	30	...	30	30
E, 10^3 ksi	29.8									
E_c, 10^3 ksi	29.8									
G, 10^3 ksi	11.8									
μ	0.28									
Physical Properties:										
ω, lb/in.^{3}	0.305									
C, K, and α	See Figure 6.3.3.0									

a S-basis. The rounded T_{99} values are higher than specification values as follows: F_{tu}(≤0.062) = 123 ksi, F_{tu} (0.063-0.109) = 122 ksi, and F_{tu} (0.110-0.140) = 121 ksi.

b Bearing values are "dry pin" values per Section 1.4.7.1.

Table 6.3.3.0(c). Design Mechanical and Physical Properties of Inconel 625 Bar

Specification	AMS 5666			
Form	Bar			
Condition	Annealed			
Thickness or diameter, in.	0.500-0.999	1.000-1.999	2.000-2.999	3.000-3.999
Basis	S	S	S	S
Mechanical Properties:				
F_{tu}, ksi:				
L	120	120	120	120
ST	...	...	118	118
F_{ty}, ksi:				
L	60	60	60	60
ST	...	...	57	57
F_{cy}, ksi:				
L	60	59	56	53
ST	...	...	60	60
F_{su}, ksi	79	79	79	79
F_{bru}[a], ksi:				
(e/D = 1.5)	192	192	192	192
(e/D = 2.0)	234	234	234	234
F_{bry}[a], ksi:				
(e/D = 1.5)	88	88	88	88
(e/D = 2.0)	102	102	102	102
e, percent (S-basis):				
L	30	30	30	30
E, 10^3 ksi	29.8			
E_c, 10^3 ksi	29.8			
G, 10^3 ksi	11.8			
μ	0.28			
Physical Properties:				
ω, lb/in.^{3}	0.305			
C, K, and α	See Figure 6.3.3.0			

[a] Bearing values are "dry pin" values per Section 1.4.7.1.

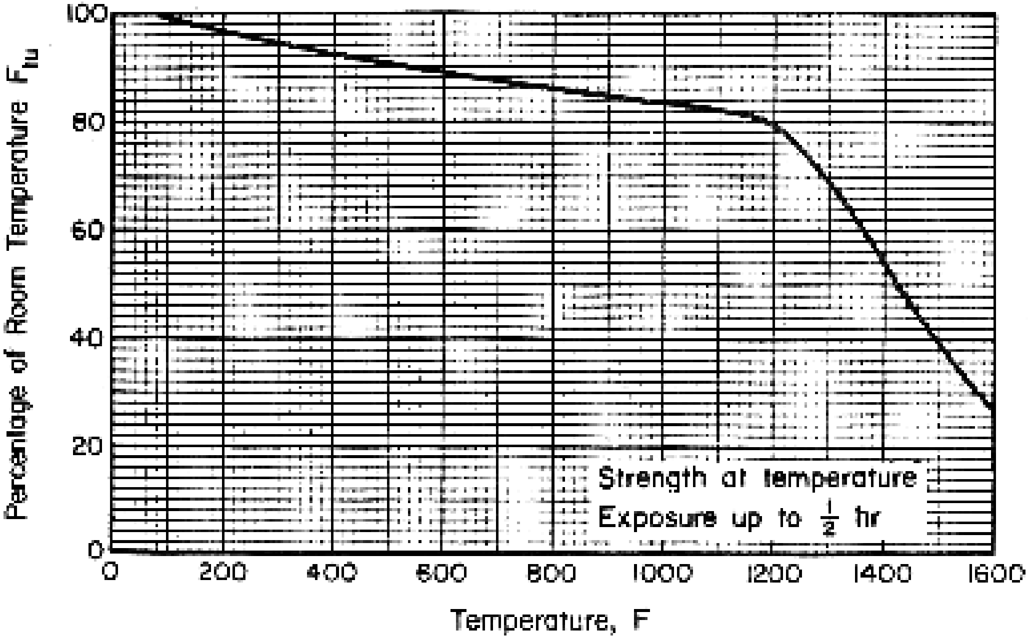

Figure 6.3.3.1.1(a). Effect of temperature on the tensile ultimate strength (F_{tu}) of annealed Inconel 625 sheet and bar.

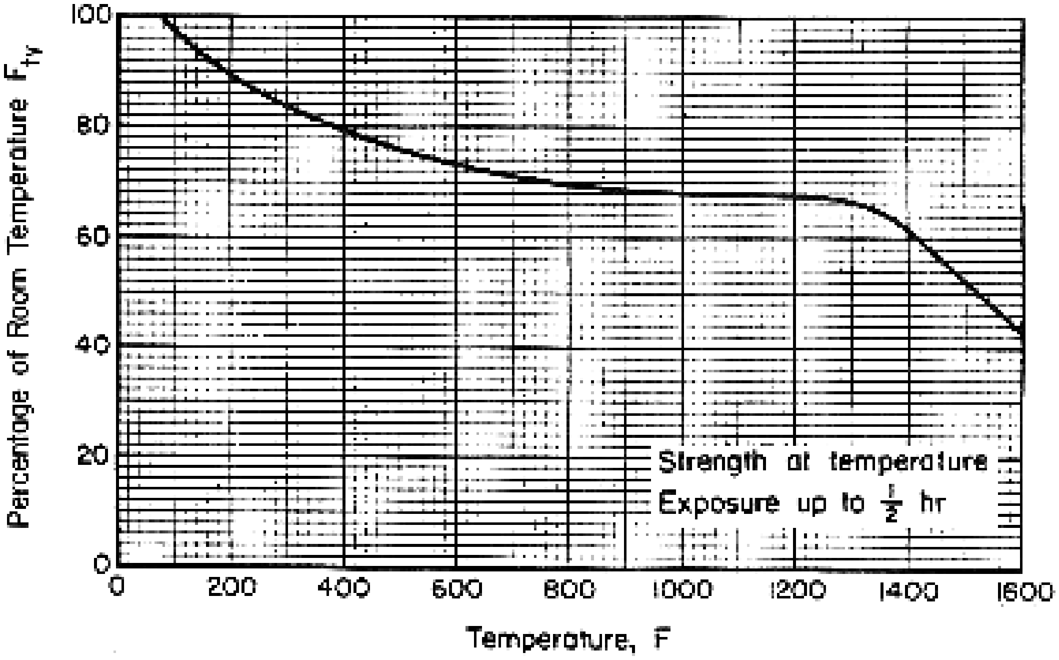

Figure 6.3.3.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of annealed Inconel 625 sheet and bar.

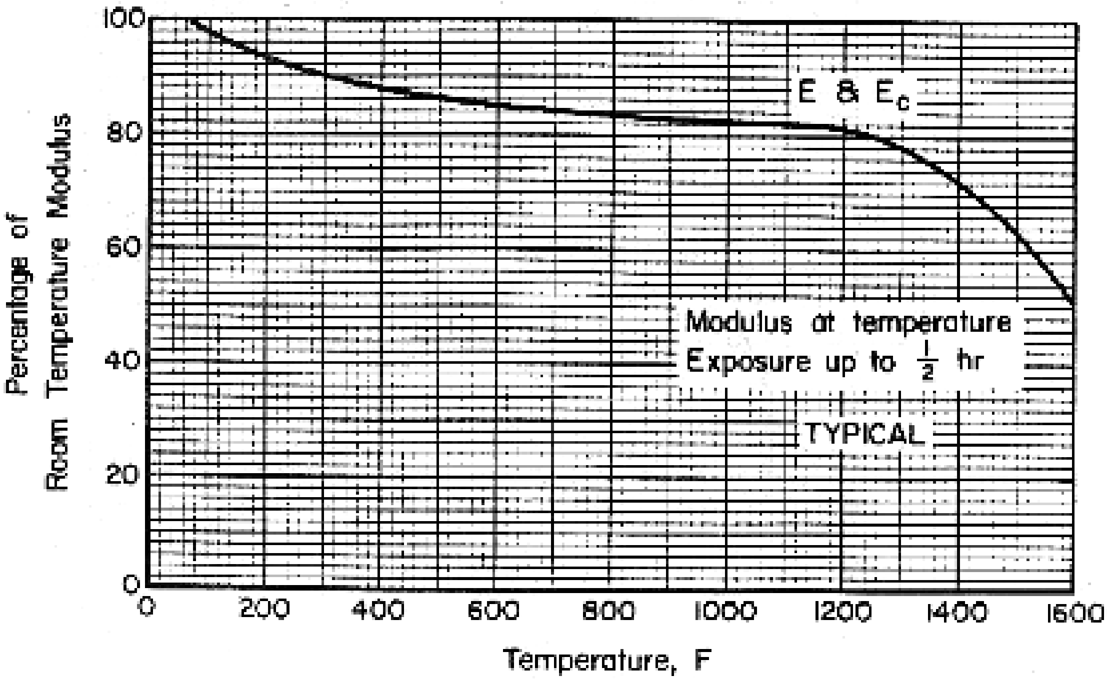

Figure 6.3.3.1.4(a). Effect of temperature on the tensile and compressive moduli (E and E_c) of annealed Inconel 625.

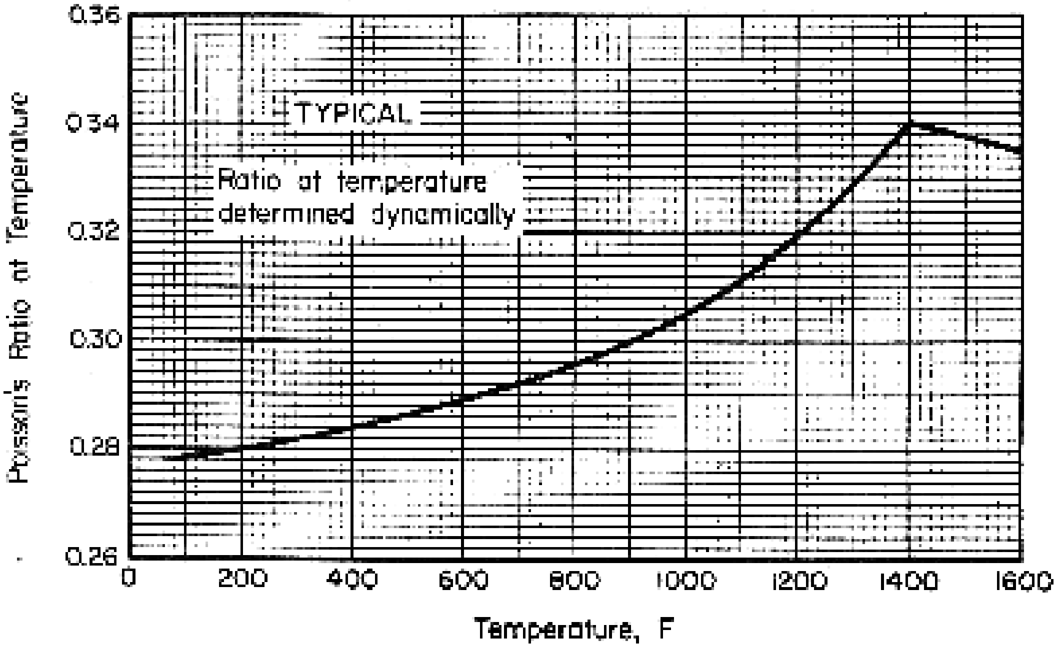

Figure 6.3.3.1.4(b). Effect of temperature on Poisson's ratio (μ) for annealed Inconel 625 bar.

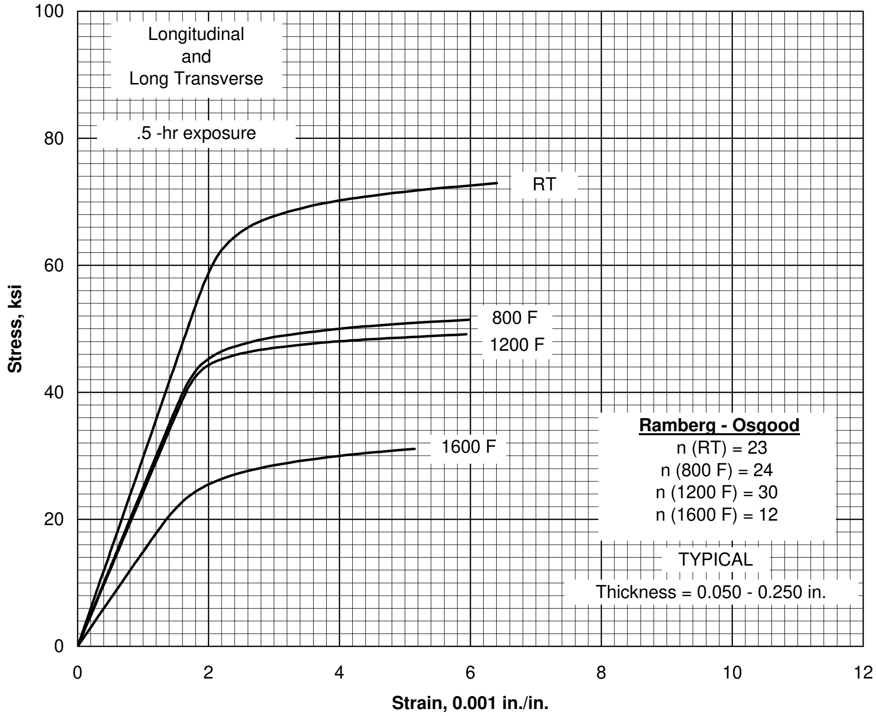

Figure 6.3.3.1.6(a). Typical tensile stress-strain curves for annealed Inconel 625 sheet at room and elevated temperatures.

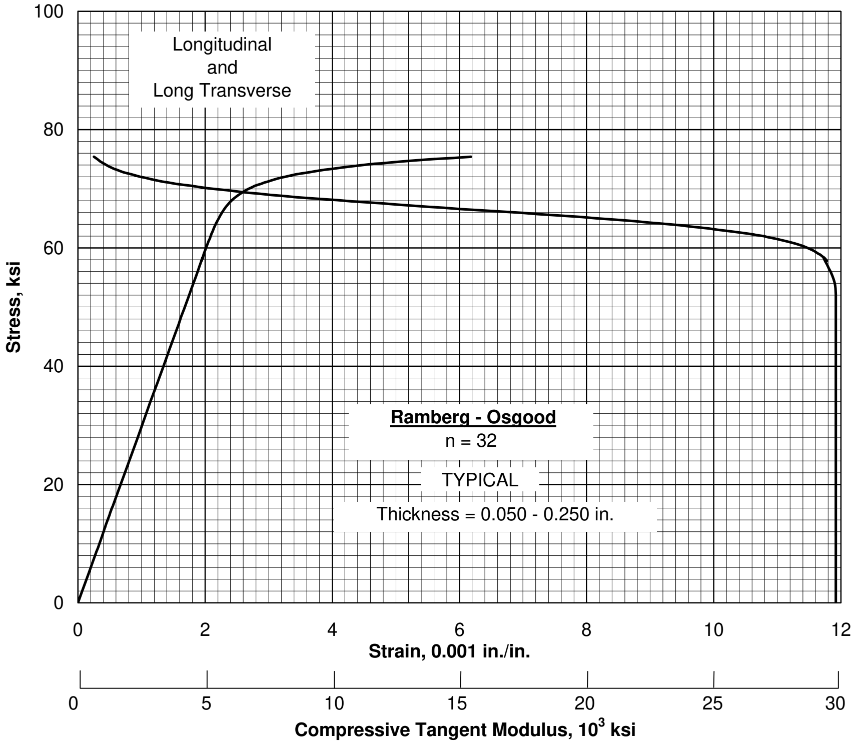

Figure 6.3.3.1.6(b). Typical compressive stress-strain and compressive tangent-modulus curves for annealed Inconel 625 sheet at room temperature.

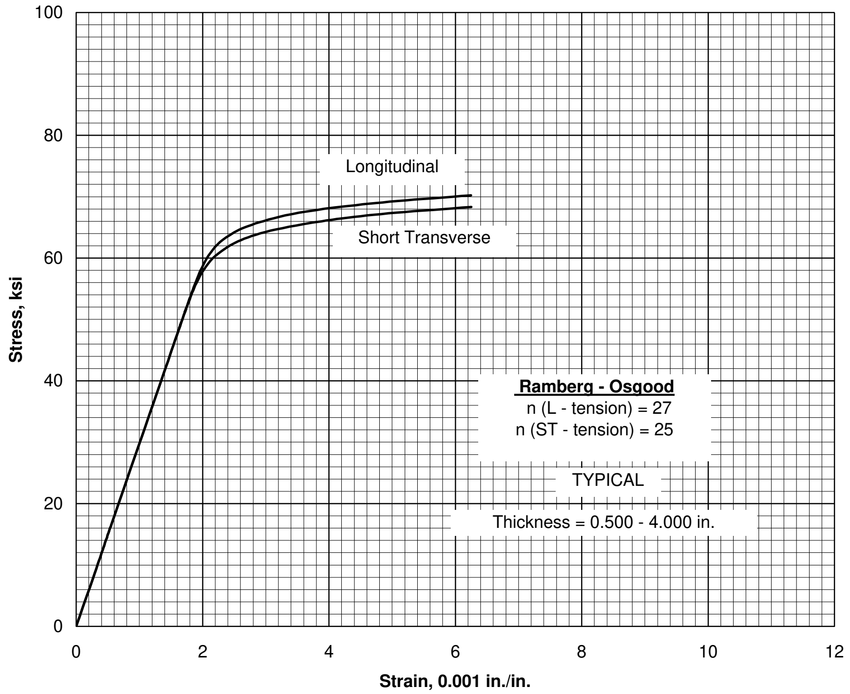

Figure 6.3.3.1.6(c). Typical tensile stress-strain curves for annealed Inconel 625 bar at room temperature.

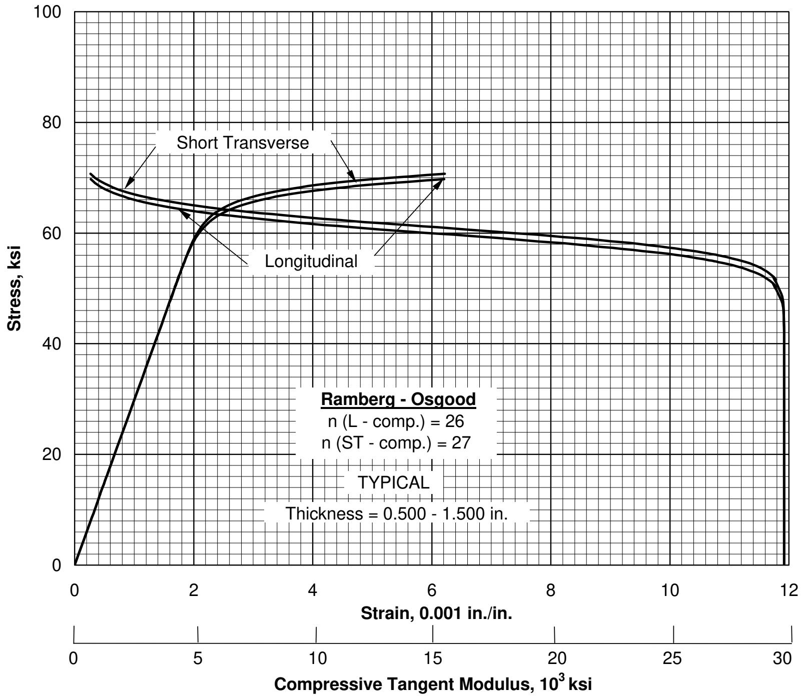

Figure 6.3.3.1.6(d). Typical compressive stress-strain and compressive tangent-modulus curves for annealed Inconel 625 bar at room temperature.

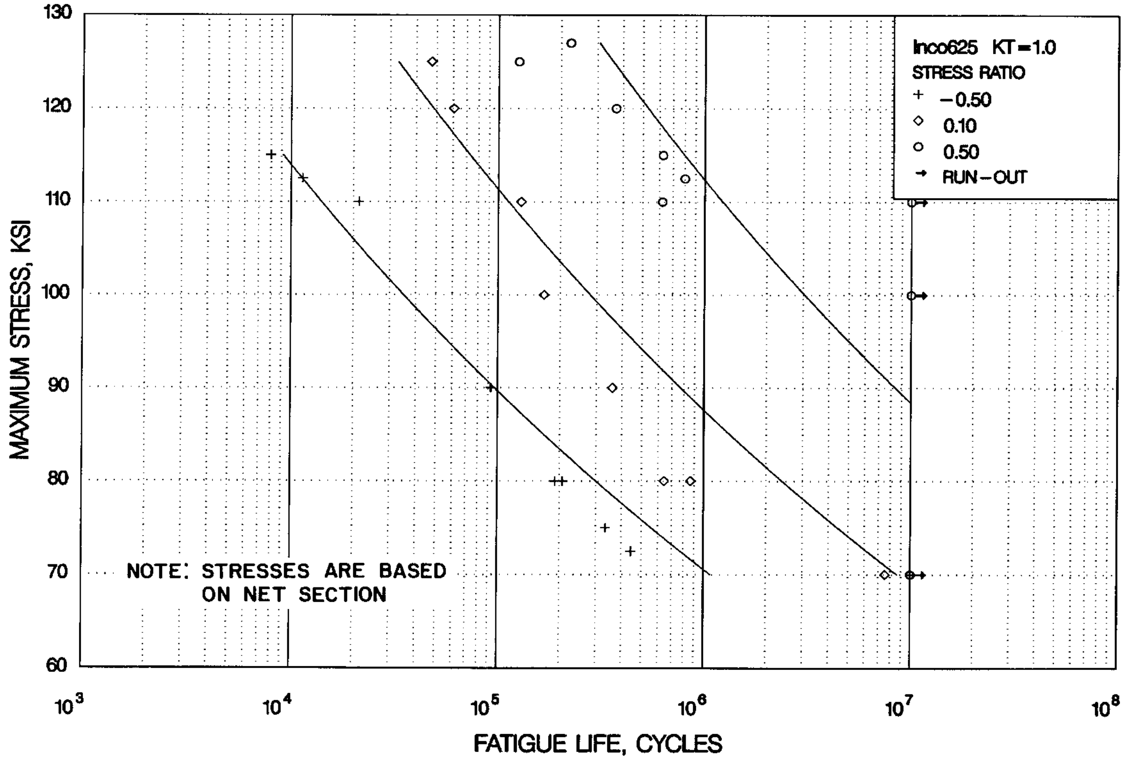

Figure 6.3.3.1.8(a). Best-fit S/N curves for annealed unnotched Inconel 625 bar, longitudinal direction.

<u>Correlative Information for Figure 6.3.3.1.8(a)</u>

<u>Product Form</u>: Bar, 0.75 inch diameter

<u>Properties</u>:

<u>TUS, ksi</u>	<u>TYS, ksi</u>	<u>Temp., °F</u>
133.2	73.8	RT

<u>Specimen Details</u>: Unnotched
0.250 inch diameter

<u>Surface Condition</u>: Longitudinally polished

<u>Reference</u>: 6.3.3.1.8(a)

<u>Test Parameters:</u>
Loading - Axial
Frequency - Unspecified
Temperature - RT
Environment - Air

<u>No. of Heats/Lots</u>: 1

<u>Equivalent Stress Equation</u>:
$\text{Log } N_f = 24.49\text{-}9.62 \log (S_{eq})$
$S_{eq} = S_{max} (1\text{-}R)^{0.42}$
Std. Error of Estimate, Log (Life) = $22.71 (1/S_{eq})$
Standard Deviation, Log (Life) = 0.985
$R^2 = 90\%$

<u>Sample Size</u> = 27

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

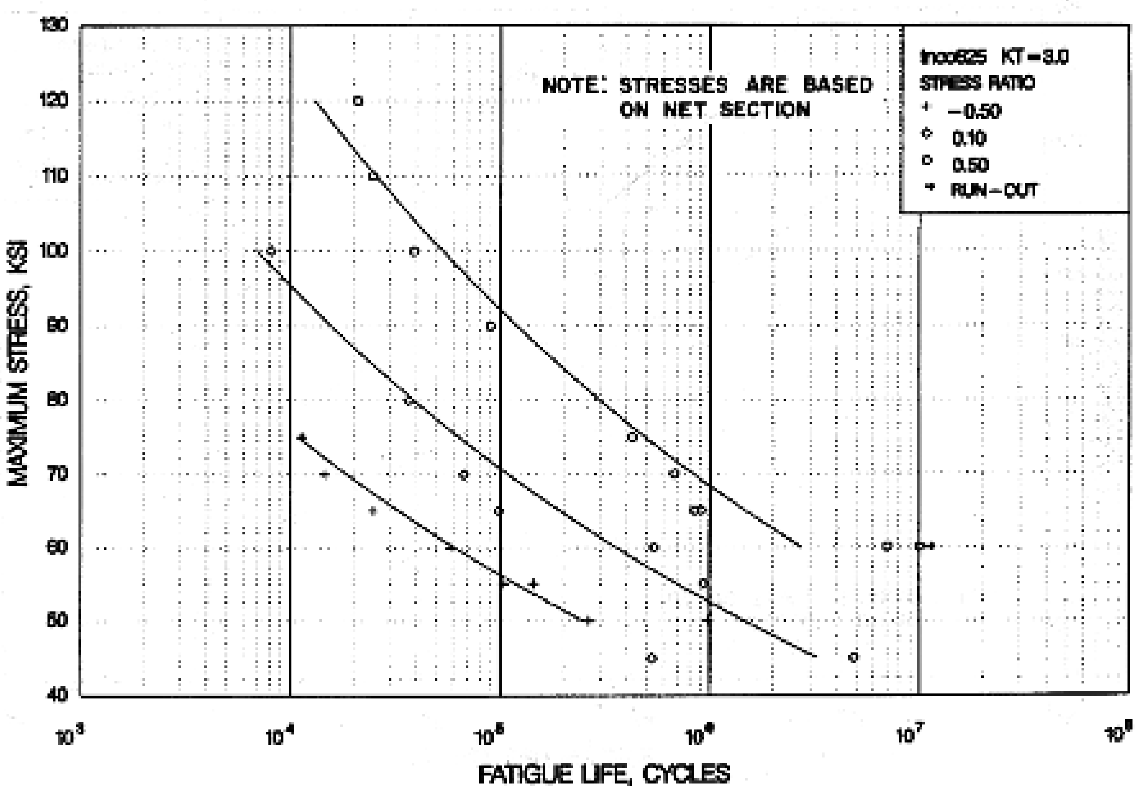

Figure 6.3.3.1.8(b). Best-fit S/N curves for annealed notched Inconel 625 bar, K_t = 3.0, longitudinal direction.

Correlative Information for Figure 6.3.3.1.8(b)

Product Form: Bar, 0.75 inch diameter

Properties:

TUS, ksi	TYS, ksi	Temp., °F
133.2	73.8	RT

Specimen Details: V-Groove, K_t = 3.0
0.375 inch gross diameter
0.250 inch net diameter
0.013 inch root radius
60° flank angle

Surface Condition: Polished

Reference: 6.3.3.1.8(a)

Test Parameters:
Loading - Axial
Frequency - Unspecified
Temperature - RT
Atmosphere - Air

No. of Heats/Lots: 1

Equivalent Stress Equation:
$\text{Log } N_f = 19.08 - 7.70 \text{ Log } (S_{eq})$
$S_{eq} = S_{max} (1-R)^{0.45}$
Std. Error of Estimate, Log (Life) = 14.31 $(1/S_{eq})$
Standard Deviation, Log (Life) = 0.959
R^2 = 92%

Sample Size = 26

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

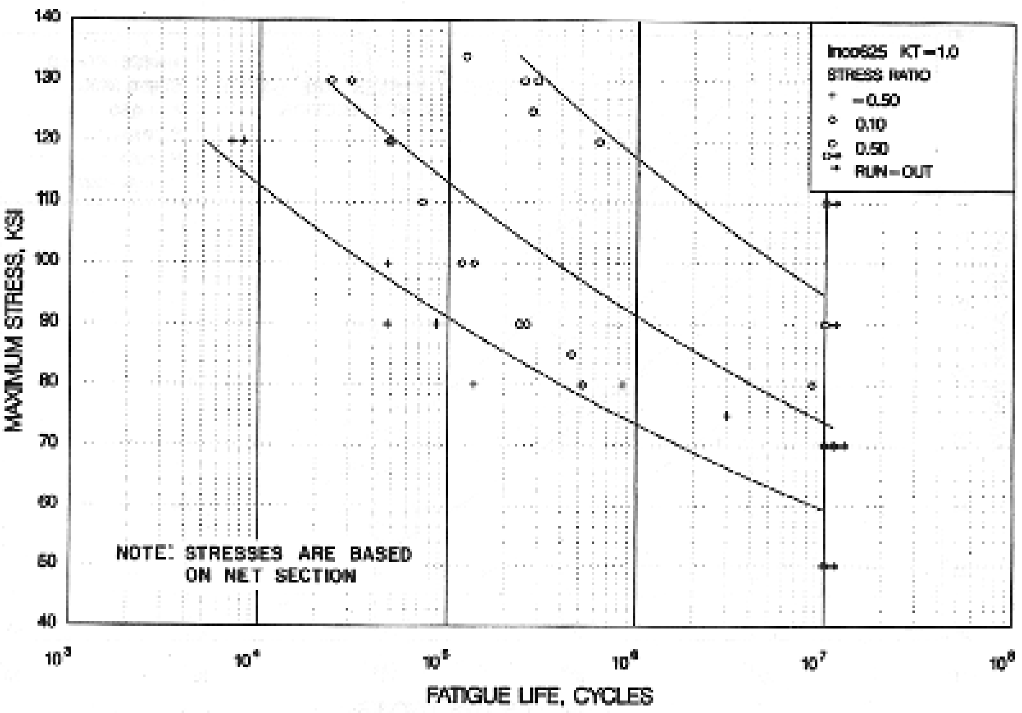

Figure 6.3.3.1.8(c). Best-fit S/N curves for annealed unnotched Inconel 625 sheet, long-transverse direction.

<u>Correlative Information for Figure 6.3.3.1.8(c)</u>

<u>Product Form</u>: Sheet, 0.093 and 0.125 inch thick

<u>Properties</u>:

TUS, ksi	TYS, ksi	Temp., °F
135.4	74.6	RT
136.7	69.8	

<u>Specimen Details</u>: Unnotched
0.500 inch wide
0.250 inch wide

<u>Surface Condition</u>: As ground

<u>References</u>: 6.3.3.1.8(a) and (b)

<u>Test Parameters:</u>
Loading - Axial
Frequency - Unspecified
Temperature - RT
Environment - Air

<u>No. of Heats/Lots</u>: 2

<u>Equivalent Stress Equation</u>:
Log $N_f = 26.91 - 10.77 \log (S_{eq})$
$S_{eq} = S_{max} (1-R)^{0.43}$
Std. Error of Estimate, Log (Life) = 37.39 $(1/S_{eq})$
Standard Deviation, Log (Life) = 0.933
$R^2 = 75\%$

<u>Sample Size</u> = 34

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

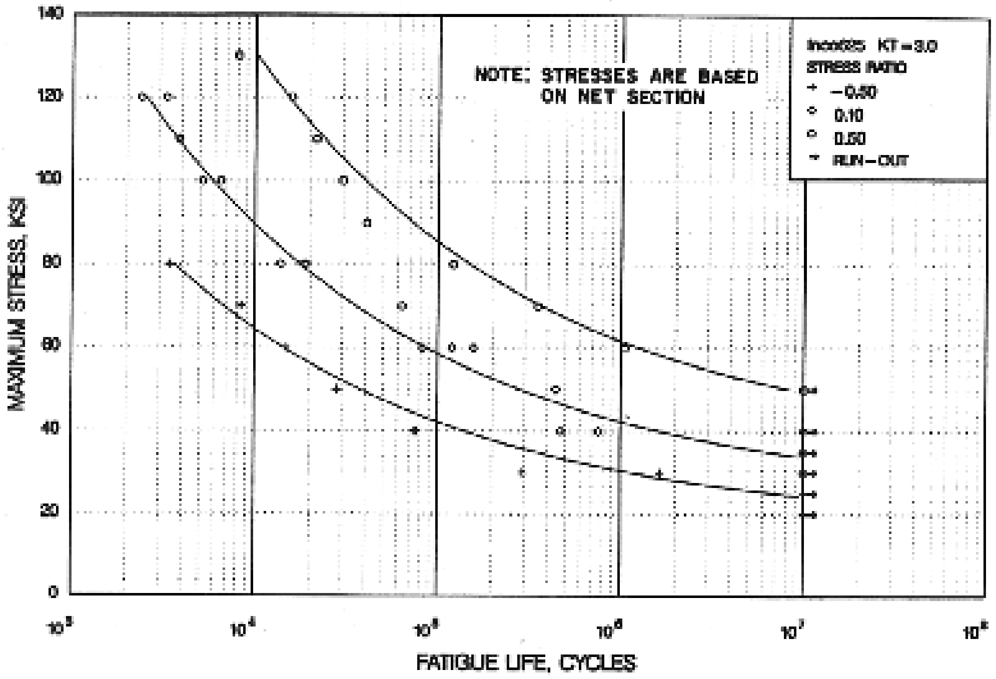

Figure 6.3.3.1.8(d). Best-fit S/N curves for annealed notched Inconel 625 sheet, K_t = 3.0, long transverse direction.

<u>Correlative Information for Figure 6.3.3.1.8(d)</u>

<u>Product Form</u>: Sheet, 0.093 and 0.125 inch thick

<u>Properties</u>:

TUS, ksi	TYS, ksi	Temp.,°F
135.4	74.6	RT
136.7	69.8	

<u>Specimen Details</u>: Edge notched, $K_t = 3.0$
0.625 inch gross width
0.030 inch root radius
0.375 inch net width
60° flank angle

<u>Surface Condition</u>: As ground

<u>References</u>: 6.3.3.1.8(a) and (b)

<u>Test Parameters:</u>
Loading - Axial
Frequency - Unspecified
Temperature - RT
Atmosphere - Air

<u>No. of Heats/Lots</u>: 2

<u>Equivalent Stress Equation</u>:
$\text{Log } N_f = 10.35\text{-}3.56 \text{ Log } (S_{eq}\text{-}22.89)$
$S_{eq} = S_{max} (1\text{-}R)^{0.64}$
Std. Error of Estimate, Log (Life) =
$10.52 (1/S_{eq})$
Standard Deviation, Log (Life) = 0.816
$R^2 = 96\%$

<u>Sample Size</u> = 37

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

6.3.4 INCONEL 706

6.3.4.0 *Comments and Properties* — Inconel 706 is a vacuum-melted precipitation-hardened, nickel-base alloy with characteristics similar to Inconel 718 except that Inconel 706 has greatly improved machinability. The alloy has good formability and weldability. Like Inconel 718, Inconel 706 has excellent resistance to postweld strain-age cracking.

Depending upon choice of heat treatment, this alloy may be used for applications requiring either (1) high resistance to creep and stress rupture up to 1300°F or (2) high-tensile strength at cryogenic temperatures or elevated temperatures for short times. The creep-resistant heat treatment is characterized by an intermediate stabilizing treatment before precipitation hardening. Inconel 706 also has good resistance to oxidation and corrosion over a broad range of temperatures and environments.

Because of close relationship between heat treatment properties and application, the form and applications are listed with specifications in Table 6.3.4.0(a). Room-temperature mechanical and physical properties are in Table 6.3.4.0(b). The effect of temperature on physical properties is shown in Figure 6.3.4.0.

Table 6.3.4.0(a). Material Specifications for Inconel 706

Specification	Form	Application	
AMS 5605	Sheet, strip, and plate	Tensile	1800°F solution treated
AMS 5606	Sheet, strip, and plate	Creep-rupture	1750°F solution treated
AMS 5701	Bar, forging, and ring	Tensile	1800°F solution treated
AMS 5702	Bar, forging, and ring	Creep-rupture	1750°F solution treated
AMS 5703	Bar, forging, and ring	Creep-rupture	1750°F solution treated, stabilized and precipitation treated

6.3.4.1 *Solution-Treated and Aged Condition (Creep Rupture Heat Treatment)* — Effect of temperature on mechanical properties is shown in Figures 6.3.4.1.1, 6.3.4.1.4, and 6.3.4.1.5. Typical tensile stress-strain curves are shown in Figure 6.3.4.1.6(a) and typical compressive stress-strain and tangent-modulus curves in Figure 6.3.4.1.6(b). A full-range tensile stress-strain curve is shown in Figure 6.3.4.1.6(c). Stress-rupture properties are specified at 1200°F; the appropriate specification should be consulted for detailed requirements.

Table 6.3.4.0(b). Design Mechanical and Physical Properties of Inconel 706

Specification	AMS 5605		AMS 5606	AMS 5701		AMS 5702 and AMS 5703	
Form	Sheet, strip, and plate			Bar and forging			
Condition	Heat treated per indicated specification						
Thickness or diameter, in.	≤0.187	0.188-1.000	All	<2.500	2.500-4.000	<2.500	2.500-4.000
Basis	S	S	S	S	S	S	S
Mechanical Properties:							
F_{tu}, ksi:							
L	...	...	...	170	170	170	165
LT	175	170	170	...	...	...	...
F_{ty}, ksi:							
L	...	...	...	140	135	130	130
LT	145	140	135	...	...	...	...
F_{cy}, ksi:							
L	...	...	...	146	141	136	136
LT	152	146	141	...	...	...	...
F_{su}, ksi	109	106	106	106	106	106	103
F_{bru}[a], ksi:							
(e/D = 1.5)	271	263	263	263	263	263	256
(e/D = 2.0)	344	334	334	334	334	334	325
F_{bry}[a], ksi:							
(e/D = 1.5)	202	195	188	195	188	181	181
(e/D = 2.0)	243	234	226	234	226	218	218
e, percent:							
L	...	...	...	12	12	12	12
LT	12	12	12	...	...	...	...
RA, percent:							
L	...	...	...	15	15	15	15
E, 10^3 ksi	30.4						
E_c, 10^3 ksi	30.4						
G, 10^3 ksi	11.0						
μ	0.38						
Physical Properties:							
ω, lb/in.^{3}	0.292						
C, K, and α	See Figure 6.3.4.0						

[a] Bearing values are "dry pin" values per Section 1.4.7.1.

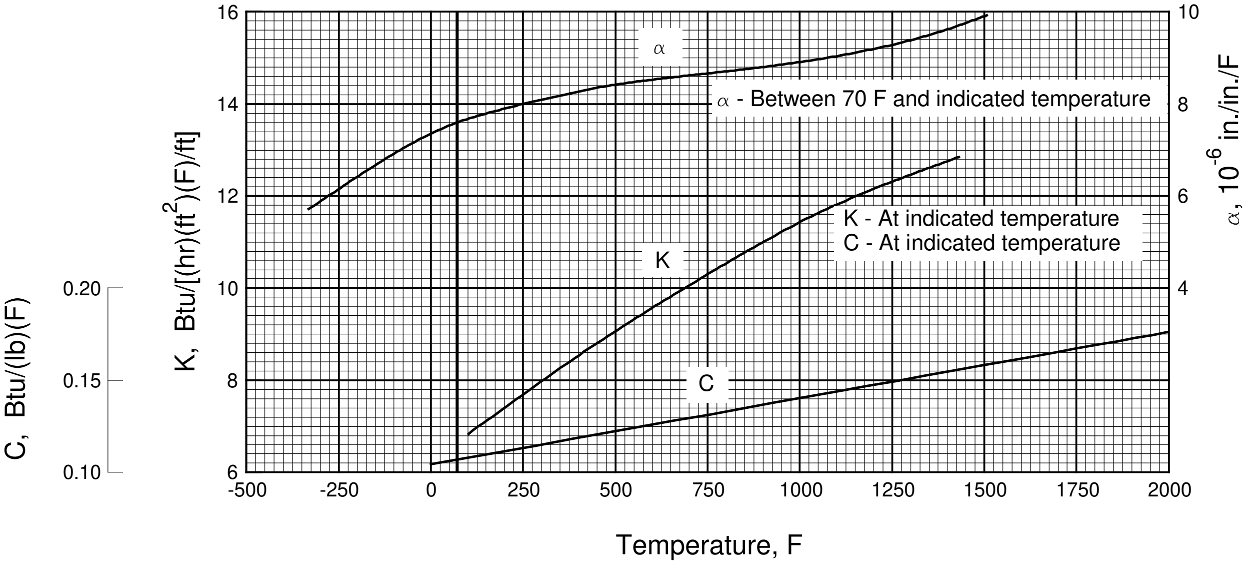

Figure 6.3.4.0. Effect of temperature on the physical properties of solution-treated and aged Inconel 706.

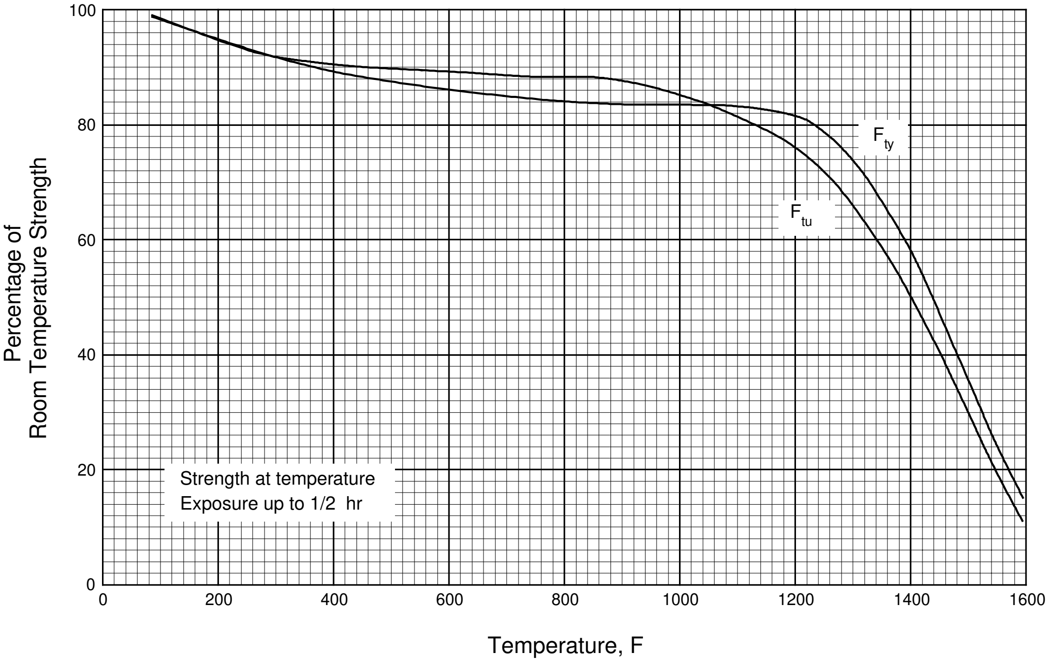

Figure 6.3.4.1.1. Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of solution treated and aged (creep rupture heat treatment) of Inconel 706.

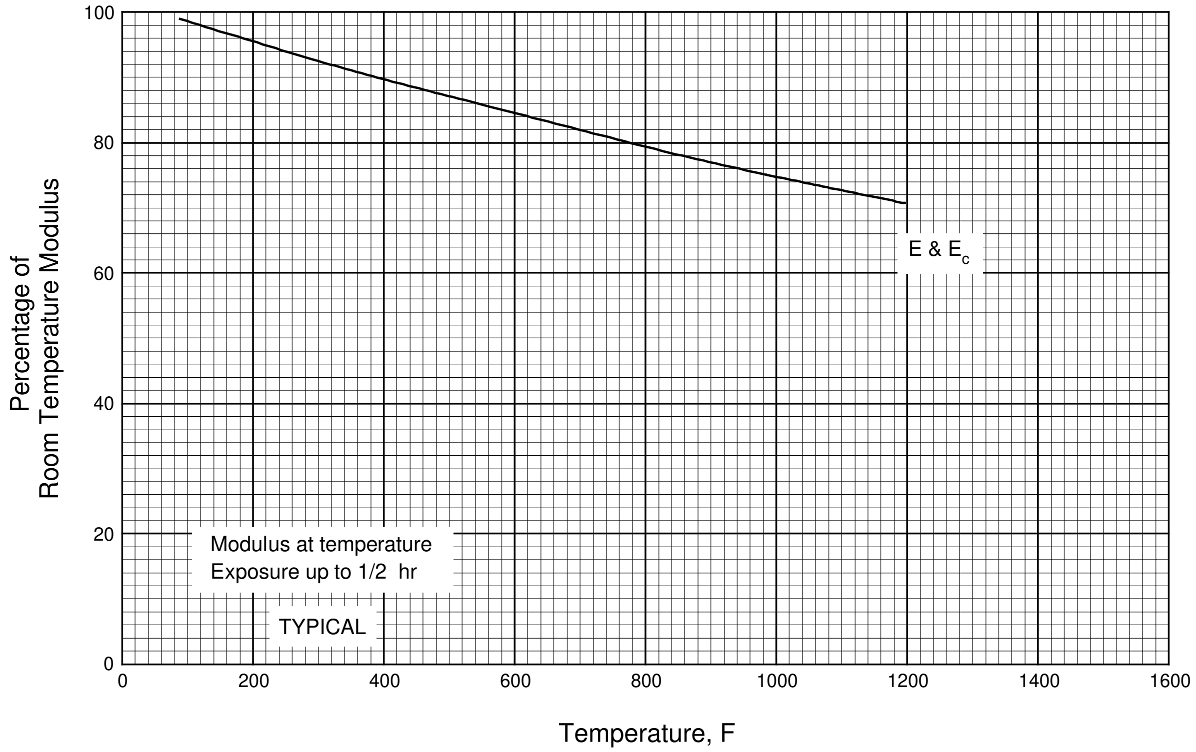

Figure 6.3.4.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of Inconel 706.

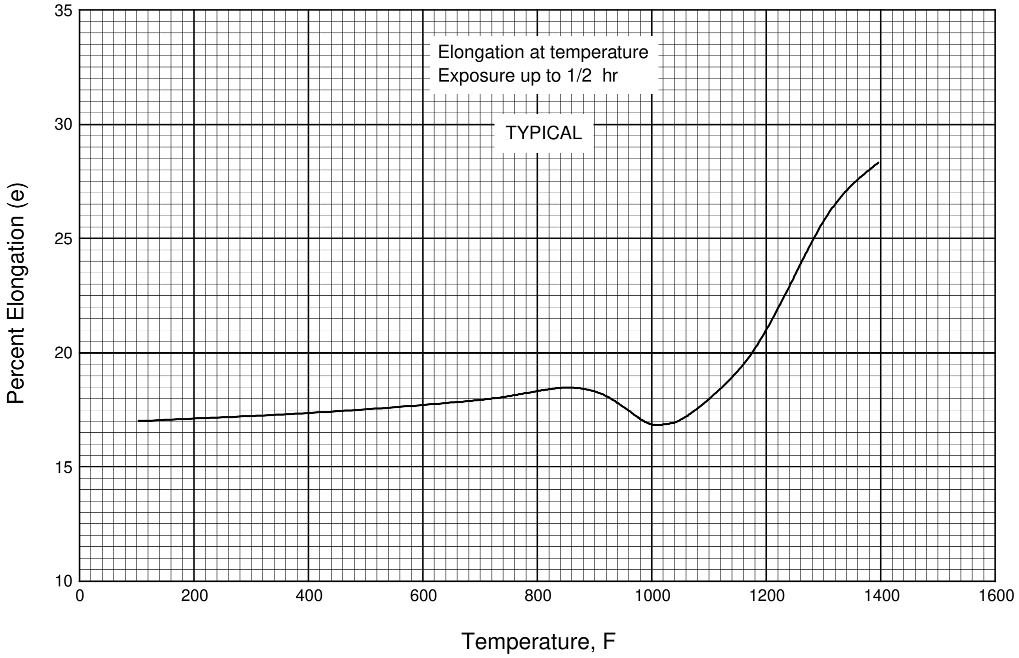

Figure 6.3.4.1.5. Effect of temperature on the elongation (e) of solution treated and aged Inconel 706 (creep rupture heat treatment).

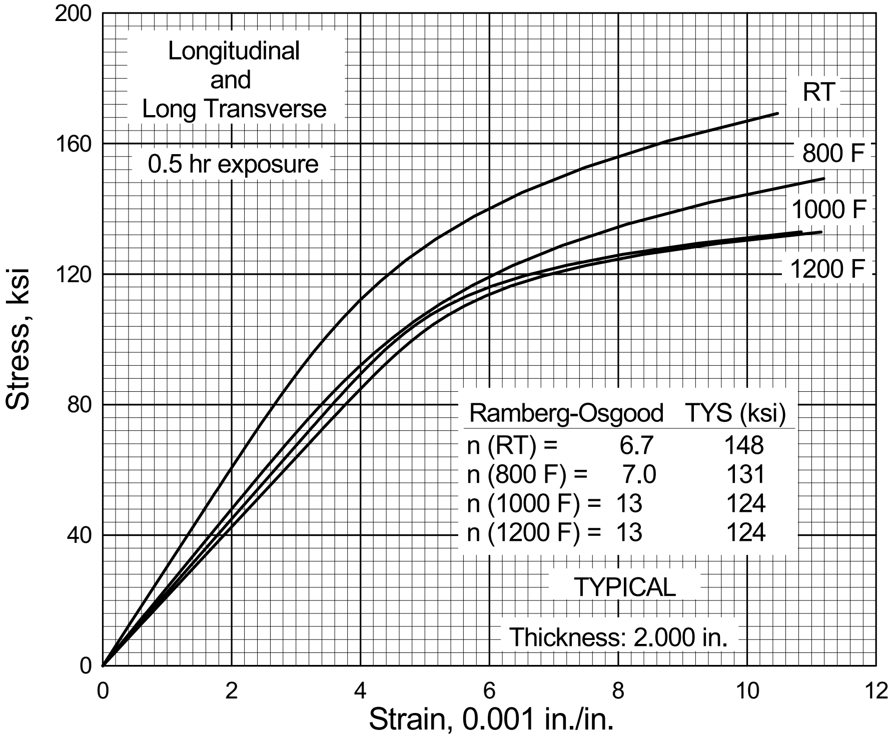

Figure 6.3.4.1.6(a). Typical tensile stress-strain curves for solution-treated and aged Inconel 706 (creep rupture heat treatment) forged bar.

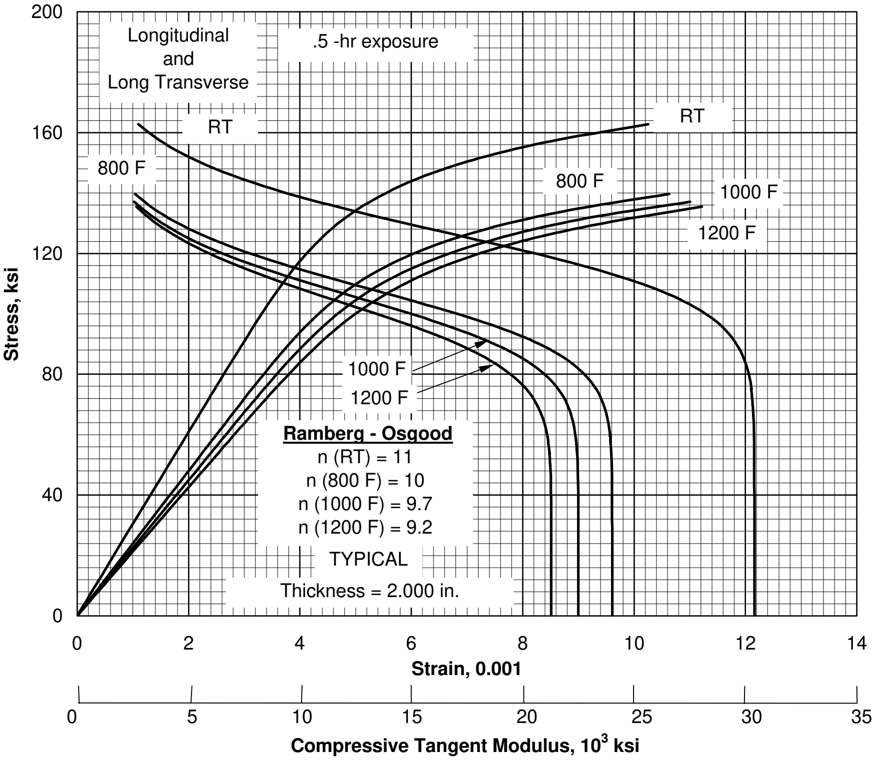

Figure 6.3.4.1.6(b). Typical compressive stress-strain and compressive tangent-modulus curves for solution-treated and aged Inconel 706 (creep rupture heat treatment) forged bar.

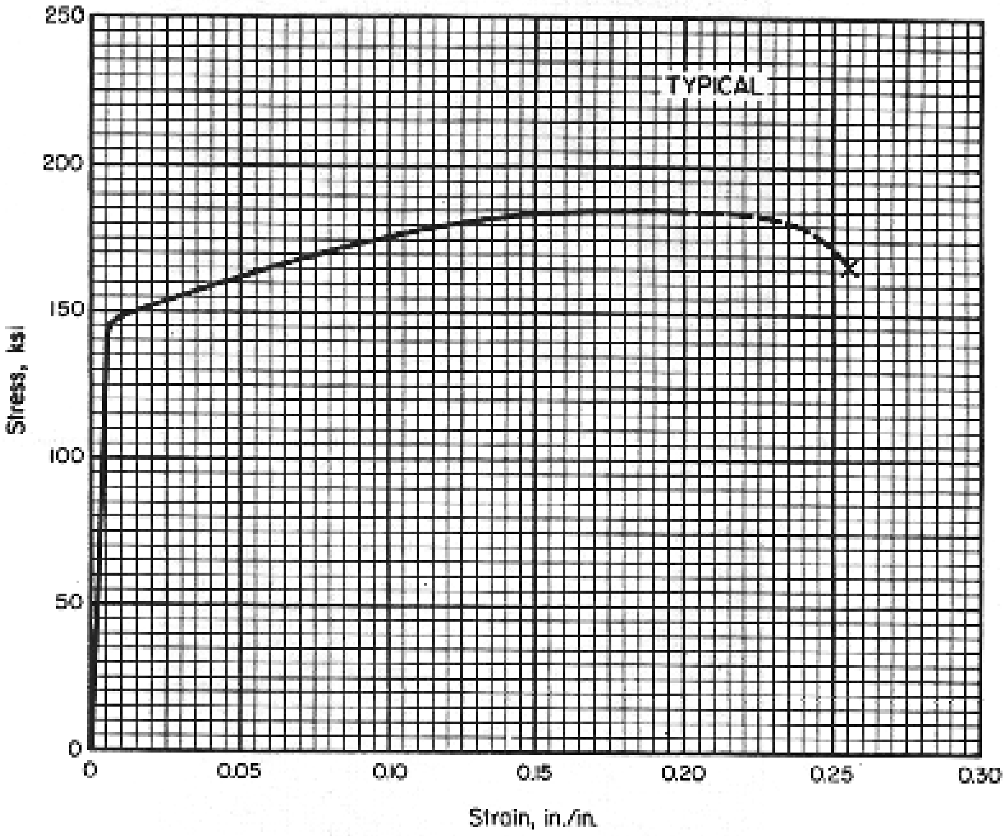

Figure 6.3.4.1.6(c). Typical tensile stress-strain curve (full range) for Inconel 706 bar and sheet at room temperature (creep rupture heat treatment).

6.3.5 INCONEL 718

6.3.5.0 *Comments and Properties* — Inconel 718 is a vacuum-melted, precipitation-hardened nickel-base alloy. It can be welded easily and excels in its resistance to strain-age cracking. It is also readily formable. Depending on choice of heat treatments, this alloy finds applications requiring either (1) high resistance to creep and stress rupture to 1300°F or (2) high strength at cryogenic temperatures. It also has good oxidation resistance up to 1800°F. Inconel 718 is available in all wrought forms and investment castings.

Because of the close relationship between heat treatment, properties, and applications, both the product form and application are listed with the specifications in Table 6.3.5.0(a). Room-temperature mechanical and physical properties are presented in Tables 6.3.5.0(b) through (d). The effect of temperature on physical properties is presented in Figure 6.3.5.0.

Table 6.3.5.0(a). Material Specifications for Inconel 718

Specification	Form	Application
AMS 5589	Tubing	Creep-rupture
AMS 5590	Tubing	Short-time
AMS 5596	Sheet, strip, plate	Creep-rupture
AMS 5597	Sheet, strip, plate	Short-time
AMS 5662, 5663	Bar, forging	Creep-rupture
AMS 5664	Bar, forging	Short-time
AMS 5383	Investment castings	Short-time

6.3.5.1 *Solution-Treated and Aged Condition* — Elevated-temperature curves are presented in Figures 6.3.5.1.1 and 6.3.5.1.4(a) through (c). Typical tensile and compressive stress-strain curves as well as typical compressive tangent-modulus curves for sheet and castings are shown in Figures 6.3.5.1.6(a) through (c). Figure 6.3.5.1.6(d) is a typical stress-strain curve (full range) for Inconel 718 investment casting. Creep and stress-rupture curves for forging are shown in Figures 6.3.5.1.7(a) through (e). Supplemental creep and stress-rupture information for forging is presented in Table 6.3.5.1.7. Fatigue S/N curves are presented in Figures 6.3.5.1.8(a) through (g). Fatigue-crack-propagation data for die forging and plate are presented in Figures 6.3.5.1.9(a) through (c).

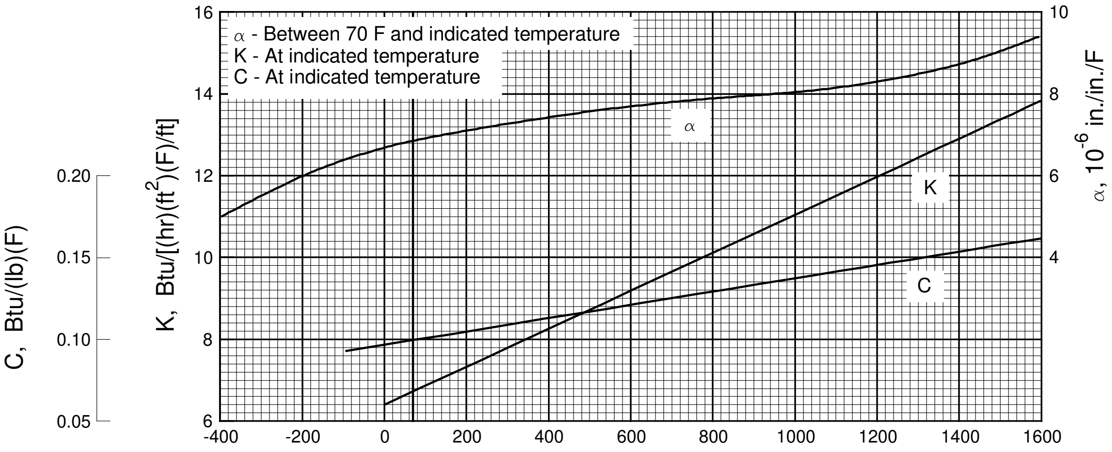

Figure 6.3.5.0. Effect of temperature on the physical properties of Inconel 718.

Table 6.3.5.0(b). Design Mechanical and Physical Properties of Inconel 718

Specification	AMS 5596				AMS 5597	AMS 5589	AMS 5590
Form	Sheet		Plate		Sheet and plate	Tubing	
Condition	Solution treated and aged per indicated specification						
Thickness, in.	0.010-0.187		0.188-0.249	0.250-1.000	0.010-1.000	O.D. > 0.125 Wall > 0.015	
Basis	A	B	S	S	S	S	S
Mechanical Properties[a]:							
F_{tu}, ksi:							
L	180	192	180	...	...	185	170
LT	180[b]	191	180	180	180	...	...
F_{ty}, ksi:							
L	145	156	148	...	...	150	145
LT	147	158	150	150	150	...	...
F_{cy}, ksi:							
L	155	167	158	...	...	...	...
LT	158	170	161	...	...	...	...
F_{su}, ksi	124	132	124	...	...	...	...
F_{bru}[c], ksi:							
(e/D = 1.5)	291	309	291	...	...	...	...
(e/D = 2.0)	380	403	380	...	...	...	...
F_{bry}[c], ksi:							
(e/D = 1.5)	208	223	212	...	...	...	...
(e/D = 2.0)	241	259	246	...	...	...	...
e, percent (S-basis):							
L	...	...	...	...	...	12	15
LT	12	...	12	12	12	...	...
E, 10^3 ksi	29.4						
E_c, 10^3 ksi	30.9						
G, 10^3 ksi	11.4						
μ	0.29						
Physical Properties:							
ω, lb/in.^{3}	0.297						
C, K, and α	See Figure 6.3.5.0						

[a] Design allowables were based upon data from samples of material, supplied in the solution treated condition, which were aged to demonstrate heat treatment response by suppliers. Properties obtained by the user may be different, if the material has been formed or otherwise cold worked.

[b] S-basis. The rounded T_{99} value is 183 ksi.

[c] Bearing values are “dry pin” values per Section 1.4.7.1.

Table 6.3.5.0(c). Design Mechanical and Physical Properties of Inconel 718 Bar and Forging

Specification	AMS 5662 and AMS 5663								AMS 5664	
Form	Bar							Forging	Bar	Forging
Condition	Solution treated and aged per indicated specification									
Thickness, in.	0.250-1.000	1.001-1.500	1.501-2.000	2.001-2.500	2.501-3.000	3.001-4.000	4.001-5.000	≤5.000	≤10.000	≤10.000
Basis	S	S	S	S	S	S	S	S	S	S
Mechanical Properties:										
F_{tu}, ksi:										
L	185	185	185	185	185	185	185	185	185	180
LT[a]	180	180	180	180	180	180	180	180	180	180
ST[a]	...	...	...	...	180	180	180	...	...	180
F_{ty}, ksi:										
L	150	150	150	150	150	150	150	150	150	150
LT[a]	150	150	150	150	150	150	150	150	150	150
ST[a]	...	...	...	...	146	150	150	...	...	150
F_{cy}, ksi:										
L	156	156	156	156	156	156	156	...	...	...
ST	...	...	...	156	156	156	156	...	...	...
F_{su}, ksi	111	114	116	118	119	121	123	...	...	...
F_{bru}[b], ksi:										
(e/D = 1.5)	309	309	309	309	309	309	309	...	...	...
(e/D = 2.0)	394	394	394	394	394	394	394	...	...	...
F_{bry}[b], ksi:										
(e/D = 1.5)	216	216	216	216	216	216	216	...	...	...
(e/D = 2.0)	257	257	257	257	257	257	257	...	...	...
e, percent:										
L	12	12	12	12	12	12	12	12	10	12
LT[b]	6	6	6	6	6	6	6	10	10	12
ST[b]	...	...	...	...	6	6	6	...	10	12
RA, percent:										
L	15	15	15	15	15	15	15	15	12	15
LT[b]	8	8	8	8	8	8	8	12	12	15
ST[b]	...	...	...	...	8	8	8	...	12	15
E, 10^3 ksi:	29.4									
E_c, 10^3 ksi:	30.9									
G, 10^3 ksi	11.4									
μ	0.29									
Physical Properties:										
ω, lb/in.^{3}	0.297									
C, K, and α	See Figure 6.3.5.0									

a Applicable providing LT or ST direction is ≥2.500 inches.

b Bearing values are "dry pin" values per Section 1.4.7.1.

Table 6.3.5.0(d). Design Mechanical and Physical Properties of Inconel 718 Investment Castings

Specification	AMS 5383
Form	Investment Casting
Condition	ST
Location within casting	Any
Thickness, in.	≤0.500
Basis	S
Mechanical Properties:	
F_{tu}, ksi	120
F_{ty}, ksi	105
F_{cy}, ksi	105
F_{su}, ksi	88[a]
F_{bru}[b], ksi:	
(e/D = 1.5)	202
(e/D = 2.0)	248
F_{bry}[b], ksi:	
(e/D = 1.5)	161
(e/D = 2.0)	188
e, percent	3
RA, percent	8
E, 10^3 ksi	29.4
E_c, 10^3 ksi	30.9
G, 10^3 ksi	11.4
μ	0.29
Physical Properties:	
ω, lb/in.^{3}	0.297
C, K, and α	See Figure 6.3.5.0

a Determined in accordance with ASTM Procedure B769.
b Bearing values are “dry pin” values per Section 1.4.7.1.

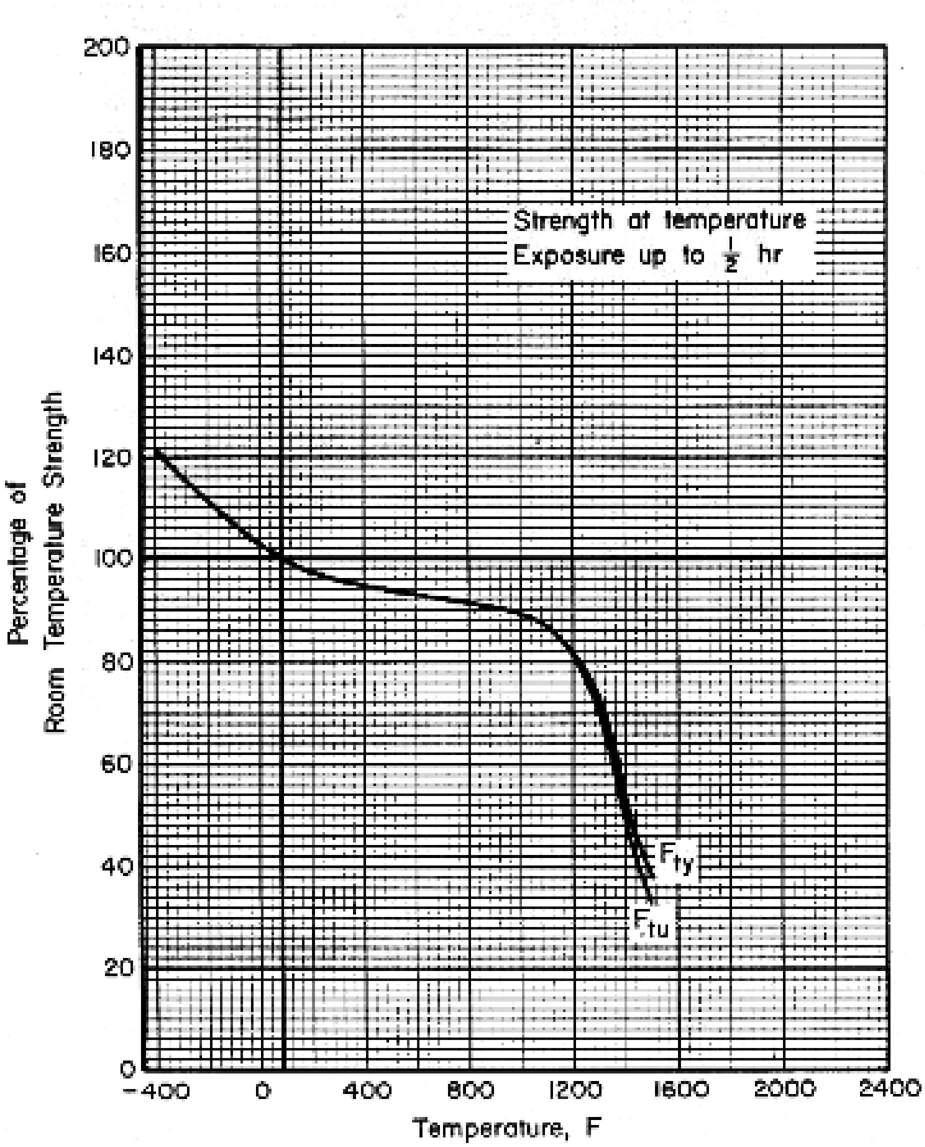

Figure 6.3.5.1.1. Effect of temperature on the tensile ultimate strength (F_{tu}) and tensile yield strength (F_{ty}) of solution-treated and aged Inconel 718.

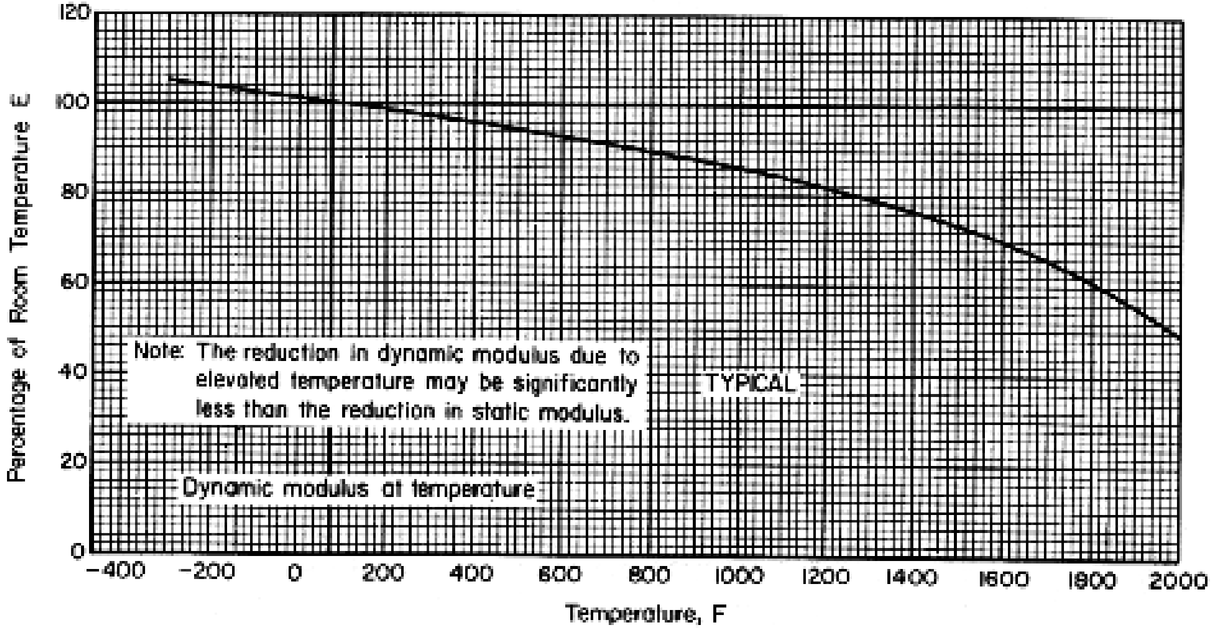

Figure 6.3.5.1.4(a). Effect of temperature on dynamic tensile modulus (E) of solution-treated and aged Inconel 718.

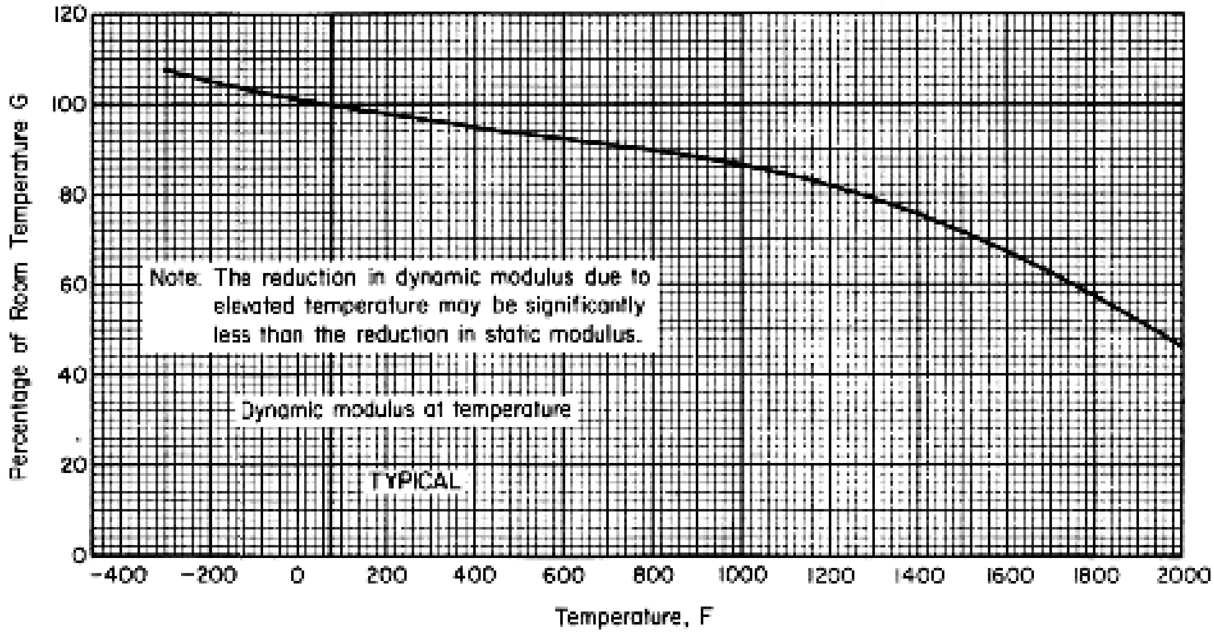

Figure 6.3.5.1.4(b). Effect of temperature on dynamic shear modulus (G) of solution-treated and aged Inconel 718.

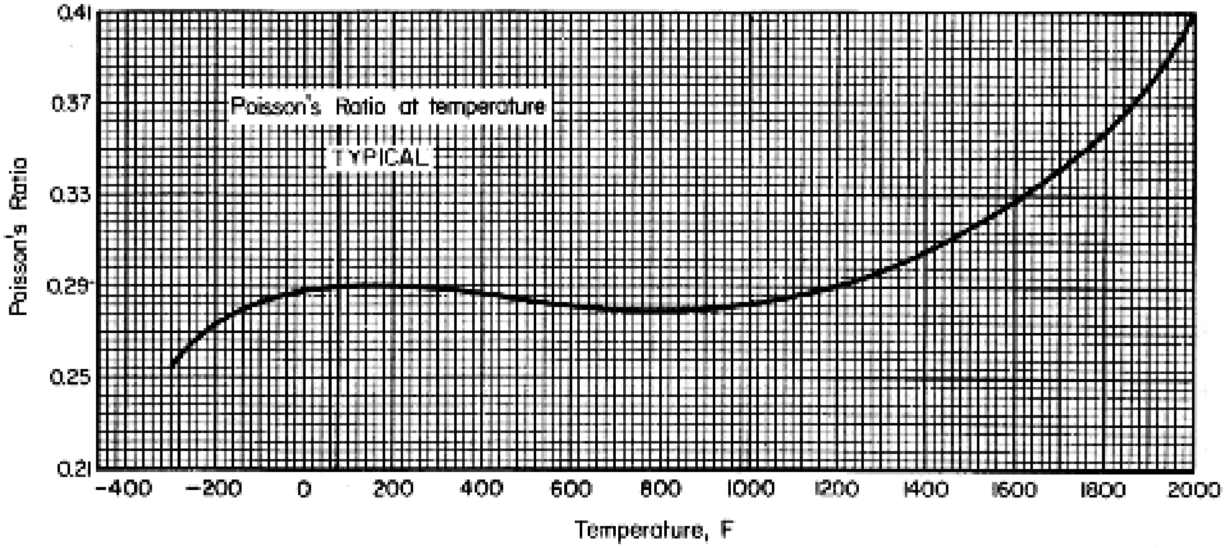

Figure 6.3.5.1.4(c). Effect of temperature on Poisson's ratio (μ) for solution-treated and aged Inconel 718.

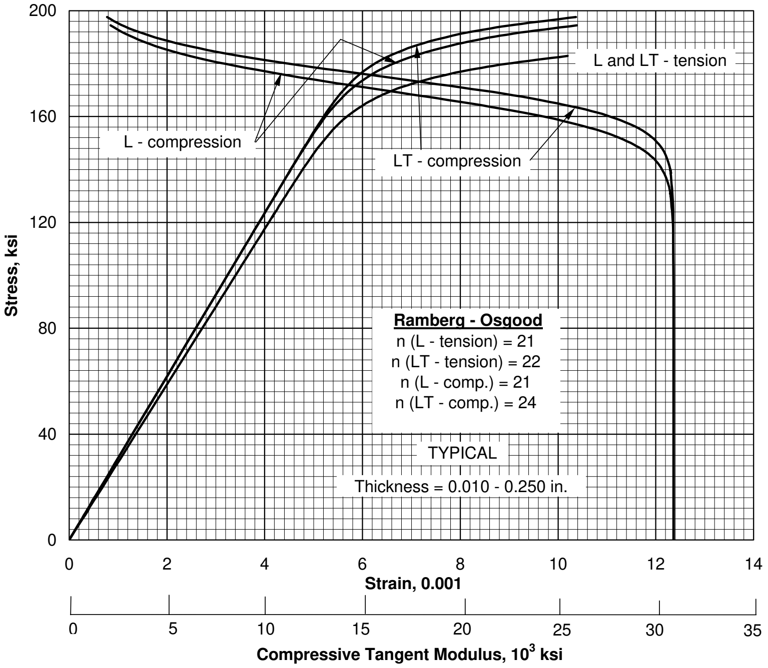

Figure 6.3.5.1.6(a). Typical tensile stress-strain, compressive stress-strain, and compressive tangent-modulus curves for solution-treated and aged Inconel 718 sheet (AMS 5596) at room temperature.

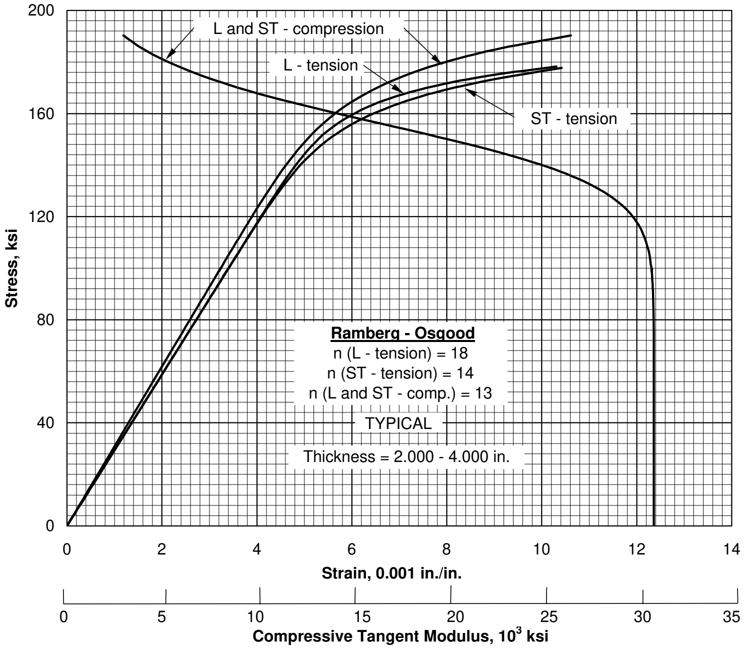

Figure 6.3.5.1.6(b). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for solution-treated and aged (creep-rupture application) Inconel 718 bar (AMS 5662 and AMS 5663) at room temperature.

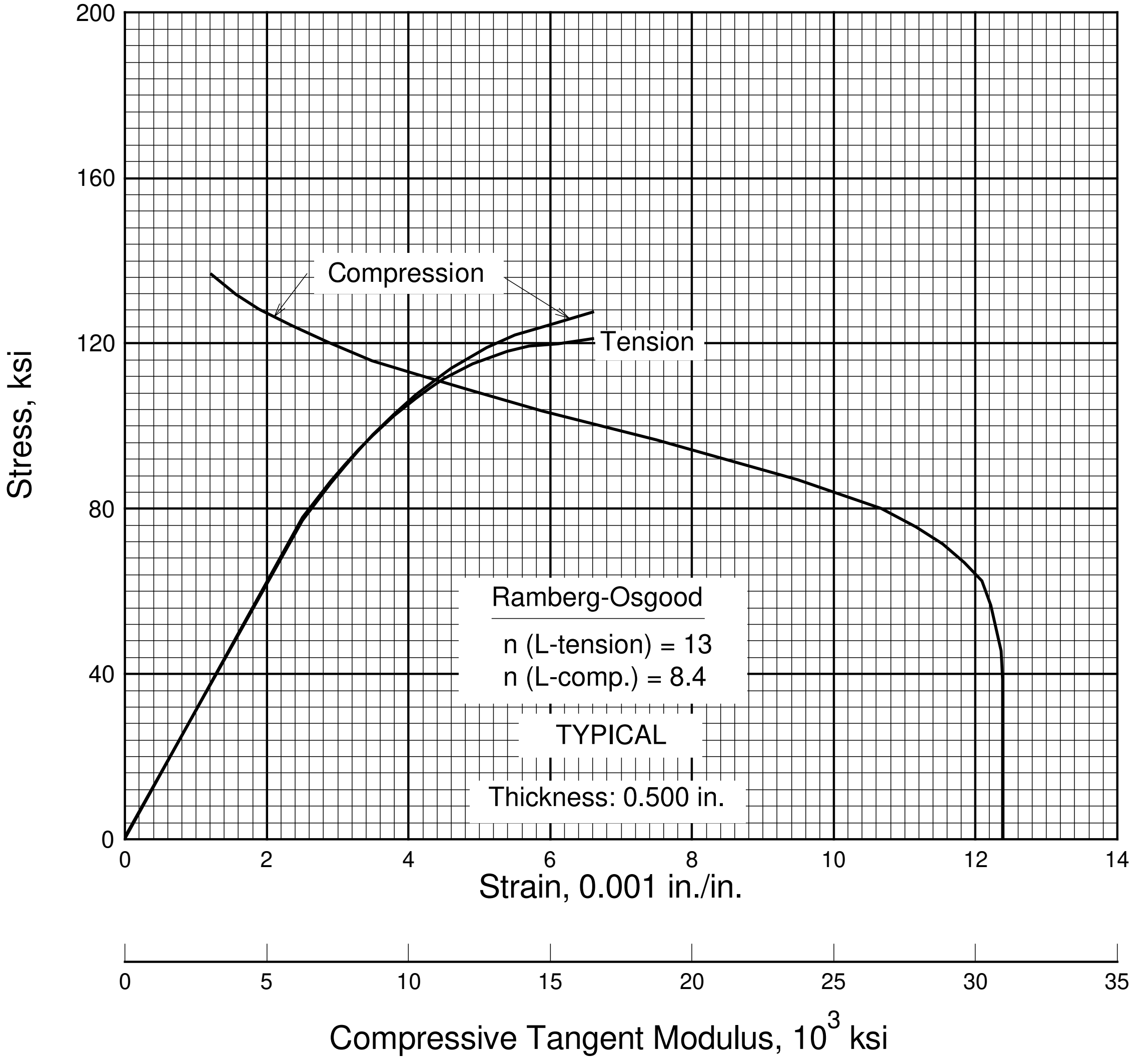

Figure 6.3.5.1.6(c). Typical tensile stress-strain, compressive stress-strain, and compressive tangent-modulus curves for solution treated and aged Inconel 718 investment casting (AMS 5383) at room temperature.

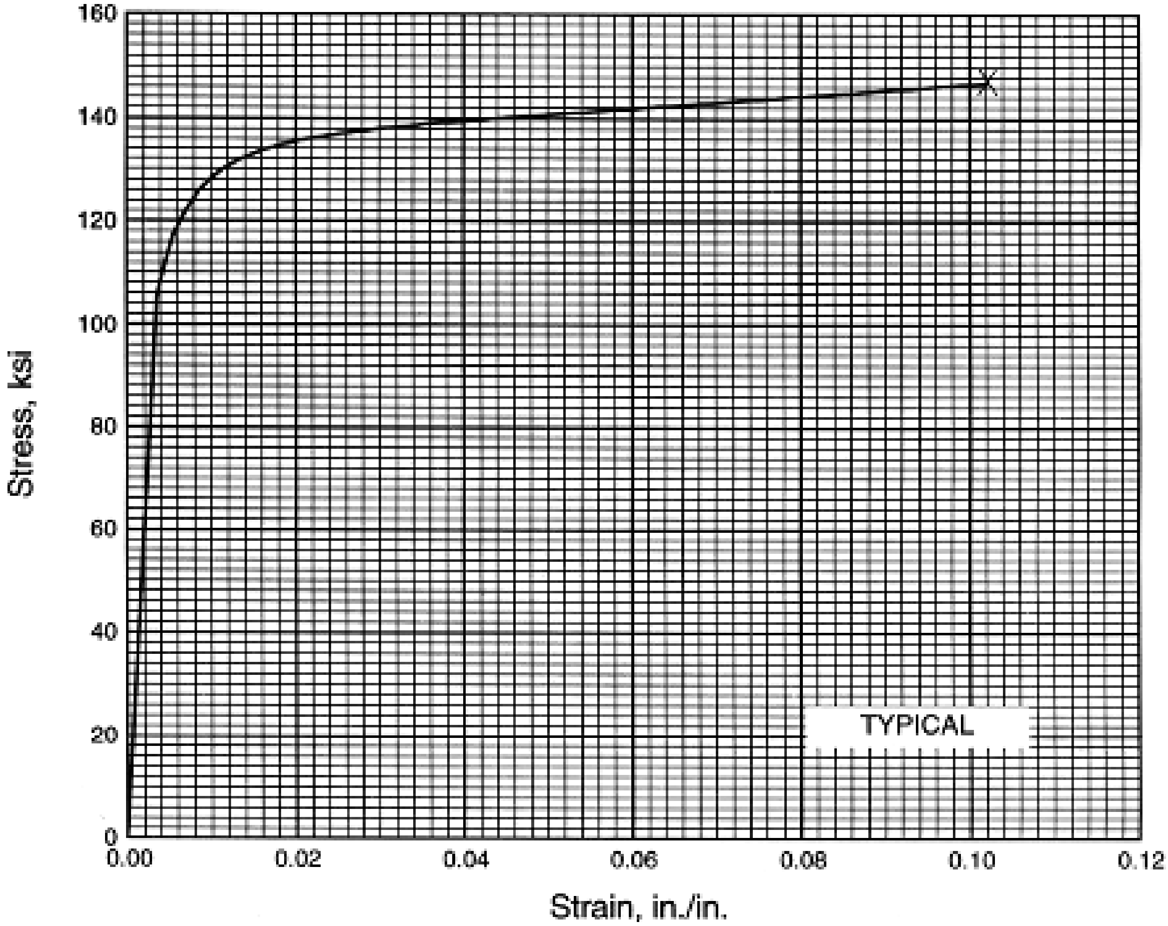

Figure 6.3.5.1.6(d). Typical tensile stress-strain curve (full range) for solution treated and aged Inconel 718 investment casting (AMS 5383) at room temperature.

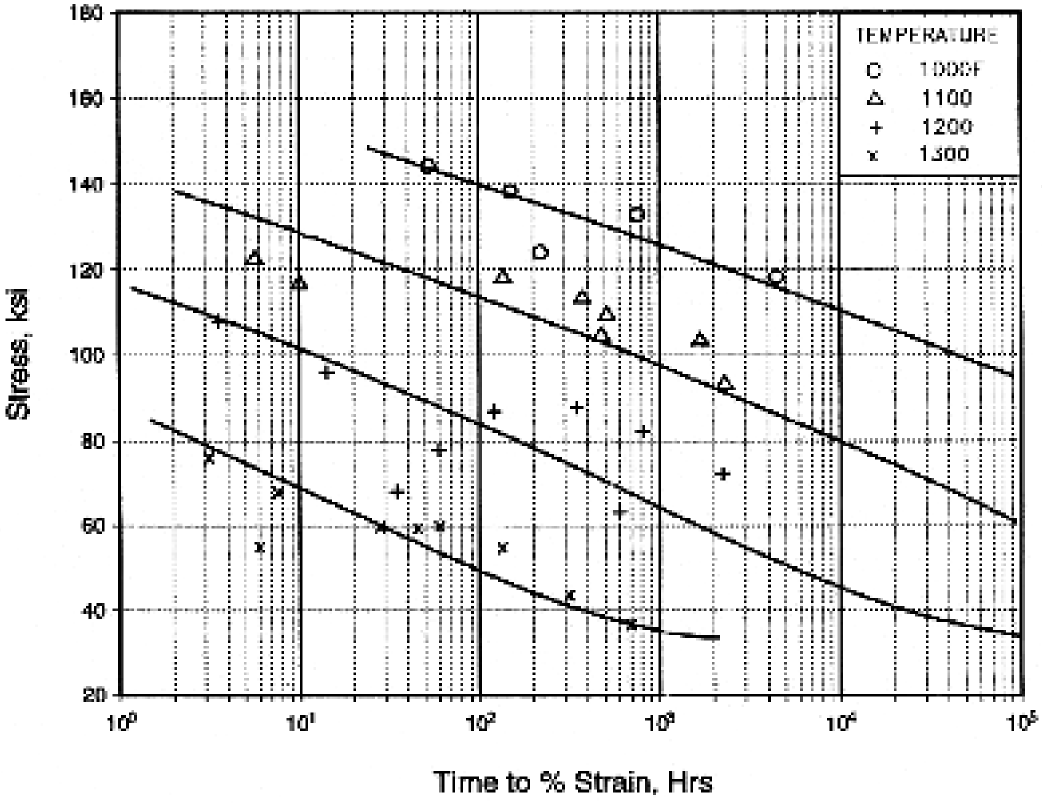

Figure 6.3.5.1.7(a). Average isothermal 0.10% creep curves for Inconel 718 forging.

Correlative Information for Figure 6.3.5.1.7(a)

Makeup of Data Collection:
Heat Treatment: 2 [See Table 6.3.5.1.7(f)]
Number of Vendors = Unknown
Number of Lots = 2
Number of Test Laboratories = 1
Number of Tests = 32

Specimen Details:
Type - Unnotched round bar
Gage Length - N.A.
Gage Thickness - 0.25 inch to 0.375 inch

0.10 Percent Creep Equation:
$\text{Log } t = c + b_1 T + b_2 X + b_3 X^2 + b_4 X^3$
$T = °R$
$X = \log(\text{stress, ksi})$
$c = 185.16$
$b_1 = -0.01778$
$b_2 = -255.25$
$b_3 = 146.28$
$b_4 = -28.65$

Analysis Details:
Inverse Matrix = [See Table 6.3.5.1.7(f)]
Std. Error of Estimate, Log (Hrs) = 0.56
Standard Deviation, Log (Hrs) = 0.99
$R^2 = 68\%$

[Caution: The creep rupture model may provide unrealistic predictions for temperatures and stresses beyond those represented above.]

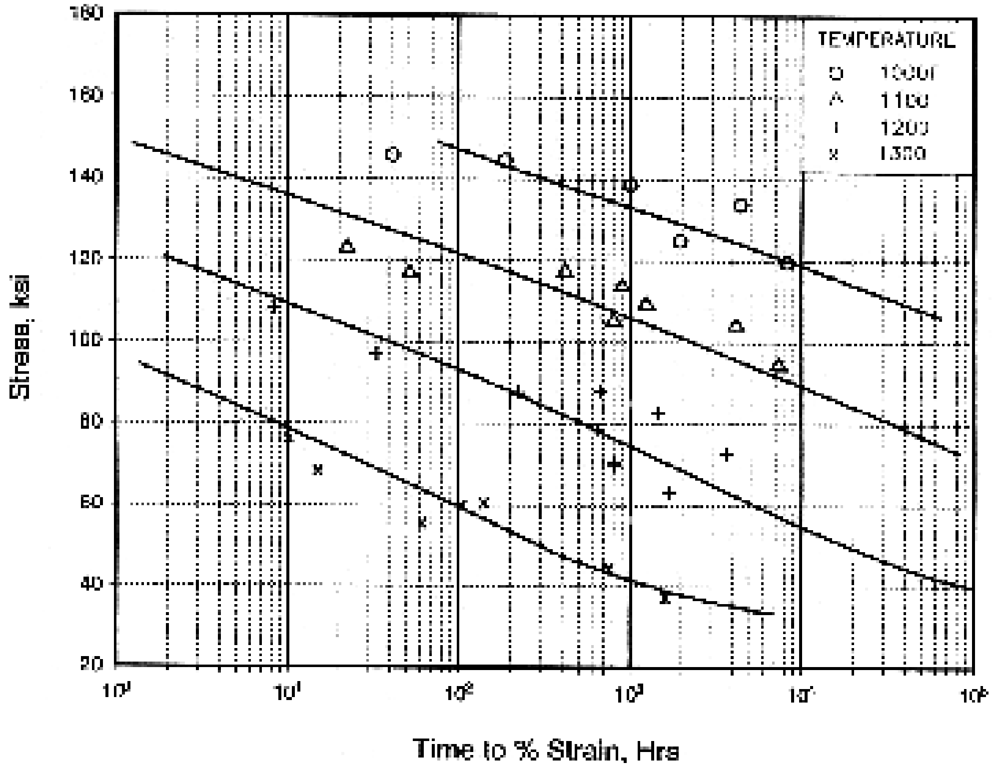

Figure 6.3.5.1.7(b). Average isothermal 0.20% creep curves for Inconel 718 forging.

Correlative Information for Figure 6.3.5.1.7(b)

Makeup of Data Collection:
Heat Treatment: 2 [See Table 6.3.5.1.7(f)]
Number of Vendors = Unknown
Number of Lots = 2
Number of Test Laboratories = 1
Number of Tests = 31

Specimen Details:
Type - Unnotched round bar
Gage Length - N.A.
Gage Thickness - 0.25. inch - 0.375 inch

0.20 Percent Creep Equation:
$\text{Log } t = c + b_1 T + b_2 X + b_3 X^2 + b_4 X^3$
$T = °R$
$X = \log(\text{stress, ksi})$
$c = 185.67$
$b_1 = -0.01778$
$b_2 = -255.25$
$b_3 = 146.28$
$b_4 = -28.65$

Analysis Details:
Inverse Matrix = [See Table 6.3.5.1.7(f)]
Std. Error of Estimate, Log (Hrs) = 0.41
Standard Deviation, Log (Hrs) = 0.98
$R^2 = 82\%$

[Caution: The creep rupture model may provide unrealistic predictions for temperatures and stresses beyond those represented above.]

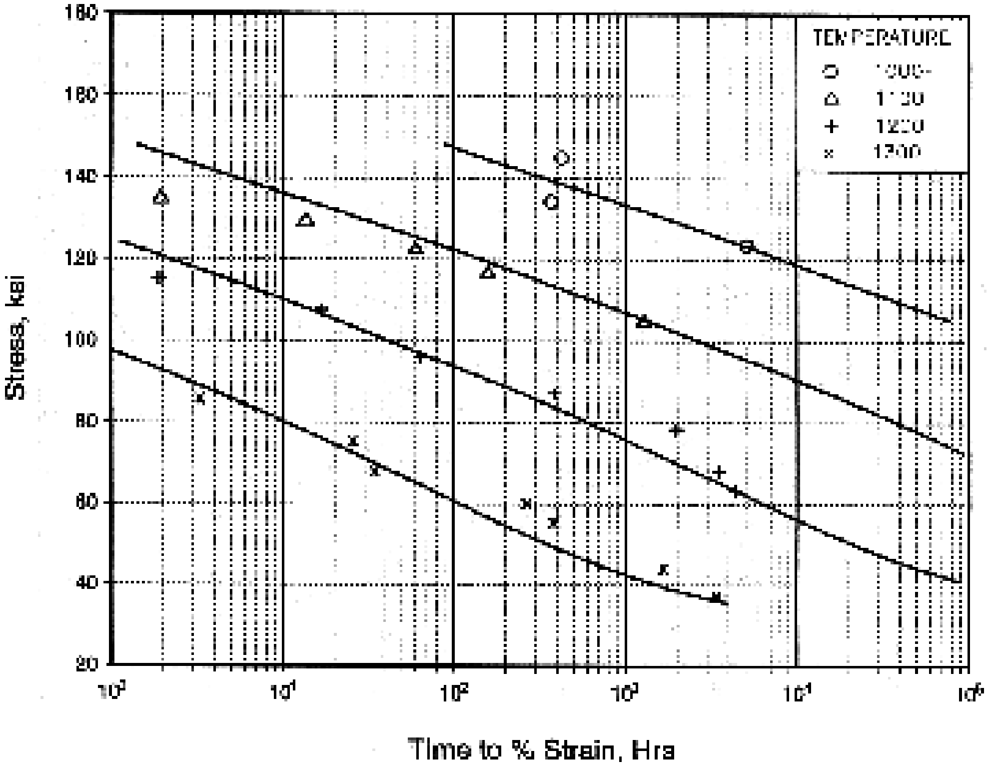

Figure 6.3.5.1.7(c). Average isothermal 0.50% creep curves for Inconel 718 forging.

Correlative Information for Figure 6.3.5.1.7(c)

Makeup of Data Collection:
Heat Treatment: 2 [See Table 6.3.5.1.7(f)]
Number of Vendors = Unknown
Number of Lots = 2
Number of Test Laboratories = 1
Number of Tests = 22

Specimen Details:
Type - Unnotched round bar
Gage Length - N.A.
Gage Thickness - 0.250 inch - 0.375 inch

0.50 Percent Creep Equation:
$\text{Log } t = c + b_1 T + b_2 X + b_3 X^2 + b_4 X^3$
$T = °R$
$X = \log(\text{stress, ksi})$
$c = 185.75$
$b_1 = -0.01778$
$b_2 = -255.25$
$b_3 = 146.28$
$b_4 = -28.65$

Analysis Details:
Inverse Matrix = [See Table 6.3.5.1.7(f)]
Std. Error of Estimate, Log (Hrs) = 0.34
Standard Deviation, Log (Hrs) = 1.10

[Caution: The creep rupture model may provide unrealistic predictions for temperatures and stresses beyond those represented above.]

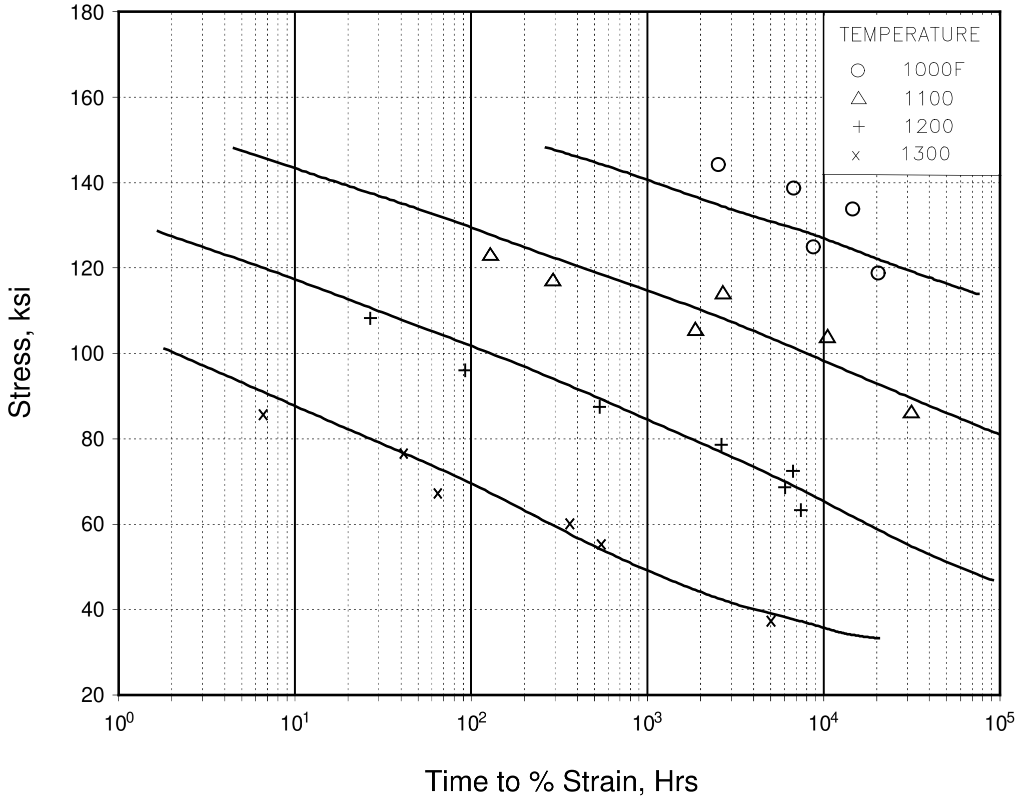

Figure 6.3.5.1.7(d). Average isothermal 5.00% creep curves for Inconel 718 forging.

Correlative Information for Figure 6.3.5.1.7(d)

Makeup of Data Collection:
Heat Treatment: 2 [See Table 6.3.5.1.7(f)]
Number of Vendors = Unknown
Number of Lots = 2
Number of Test Laboratories = 1
Number of Tests = 24

Specimen Details:
Type - Unnotched round bar
Gage Length - N.A.
Gage Thickness - 0.250 inch - 0.375 inch

5.00 Percent Creep Equation:
$\text{Log } t = c + b_1 T + b_2 X + b_3 X^2 + b_4 X^3$
$T = °R$
$X = \log(\text{stress, ksi})$
$c = 186.16$
$b_1 = -0.01778$
$b_2 = -255.25$
$b_3 = 146.28$
$b_4 = -28.65$

Analysis Details:
Inverse Matrix = [See Table 6.3.5.1.7(f)]
Std. Error of Estimate, Log (Hrs) = 0.37
Standard Deviation, Log (Hrs) = 1.02

[Caution: The creep rupture model may provide unrealistic predictions for temperatures and stresses beyond those represented above.]

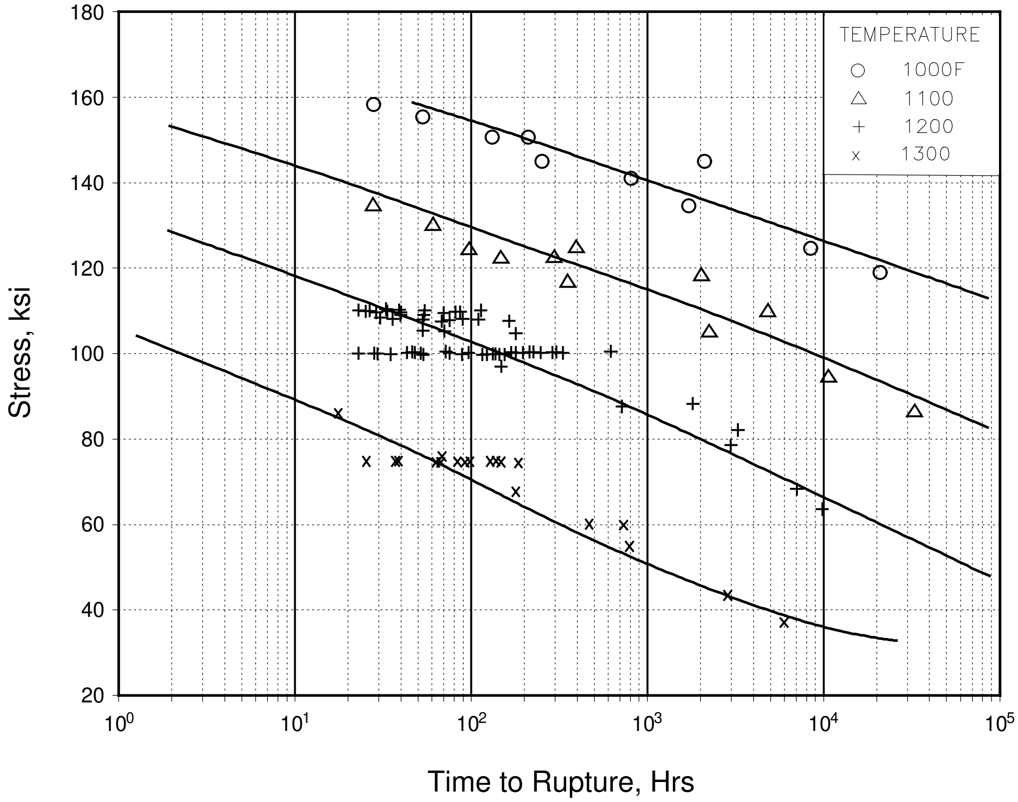

Figure 6.3.5.1.7(e). Average isothermal stress rupture curves for Inconel 718 forging.

Correlative Information for Figure 6.3.5.1.7(e)

Makeup of Data Collection:
Heat Treatment: 2 [See Table 6.3.5.1.7(f)]
Number of Vendors = Unknown
Number of Lots = 7
Number of Test Laboratories = 2
Number of Tests = 162

Specimen Details:
Type - Unnotched round bar
Gage Length - N.A.
Gage Thickness - 0.250 inch - 0.375 inch

Stress Rupture Creep Equation:
$\text{Log } t = c + b_1 T + b_2X + b_3X^2 + b_4X^3$
$T = °R$
$X = \log(\text{stress, ksi})$
$c = 186.27$
$b_1 = -0.01778$
$b_2 = -255.25$
$b_3 = 146.28$
$b_4 = -28.65$

Analysis Details:
Std. Error of Estimate, Log (Hrs) = 0.29
Standard Deviation, Log (Hrs) = 0.63
Within Heat Treatment Variance = 0.071
Ratio of Between to Within Heat Treatment Variance = (at spec pt.) <0.10

[Caution: The creep rupture model may provide unrealistic predictions for temperatures and stresses beyond those represented above.]

Table 6.3.5.1.7. Supplemental Information on the Creep and Stress Rupture Properties of Inconel 718 Forging

Heat Treatment Details

Heat Treatment No.	Cycle No.	Temperature, °F	Time, Hours	Cool
2	1	1800	1	AC, WQ
	2	1325	8	FC (100°F/hr)
	3	1150	8	AC
21	1	1700-1850	1	AC
	2	1325	8	FC (100°F/hr)
	3	1150	8	AC

Stress Rupture Equation and Inverse Matrix for the Creep Stress = 0.10, 0.20, 0.50, and 5.00% and Stress Rupture Conditions

$$\log t = c + b_1T + b_2X + b_3X^2 + b_4X^3 + b_5Y_1 + b_6Y_2 + b_7Y_3 + b_8Y_4 + b_9Y_5$$

where Y_1 = 1; Y_2, Y_3, Y_4, Y_5 = 0 for Creep Strain = 0.10% Data
Y_2 = 1; Y_1, Y_3, Y_4, Y_5 = 0 for Creep Strain = 0.20% Data
Y_3 = 1; Y_1, Y_2, Y_4, Y_5 = 0 for Creep Strain = 0.50% Data
Y_4 = 1; Y_1, Y_2, Y_3, Y_5 = 0 for Creep Strain = 5.00% Data
Y_1, Y_2, Y_3, Y_4, Y_5 = 0 for Stress Rupture Data

Column **Row**	1	2	3	4	5	6	7	8	9
1	1.809E+00	-1.108E-03	-1.978E+00	6.499E-01	-5.748E-02	-1.606E+00	-1.444E+00	-1.015E+00	-9.777E-01
2	-1.108E-03	6.834E-07	1.212E-03	-3.979E-04	3.517E-05	9.843E-04	8.852E-04	6.219E-04	5.993E-04
3	-1.978E+00	1.212E-03	3.482E+00	-1.657E+00	2.032E-01	1.634E+00	1.359E+00	6.886E-01	5.921E-01
4	6.499E-01	-3.979E-04	-1.657E+00	9.145E-01	-1.220E-01	-4.892E-01	-3.610E-01	-6.305E-02	3.594E-03
5	-5.748E-02	3.517E-05	2.032E-01	-1.220E-01	1.697E-02	3.801E-02	2.248E-02	-1.245E-02	-2.618E-02
6	-1.606E+00	9.843E-04	1.634E+00	-4.892E-01	3.801E-02	1.471E+00	1.303E+00	9.401E-01	9.124E-01
7	-1.444E+00	8.852E-04	1.359E+00	-3.610E-01	2.248E-02	1.303E+00	1.222E+00	8.806E-01	8.600E-01
8	-1.015E+00	6.219E-04	6.886E-01	-6.305E-02	-1.245E-02	9.401E-01	8.806E-01	7.491E-01	6.987E-01
9	-9.777E-01	5.993E-04	5.921E-01	3.594E-03	-2.618E-02	9.124E-01	8.600E-01	6.987E-01	1.195E+00

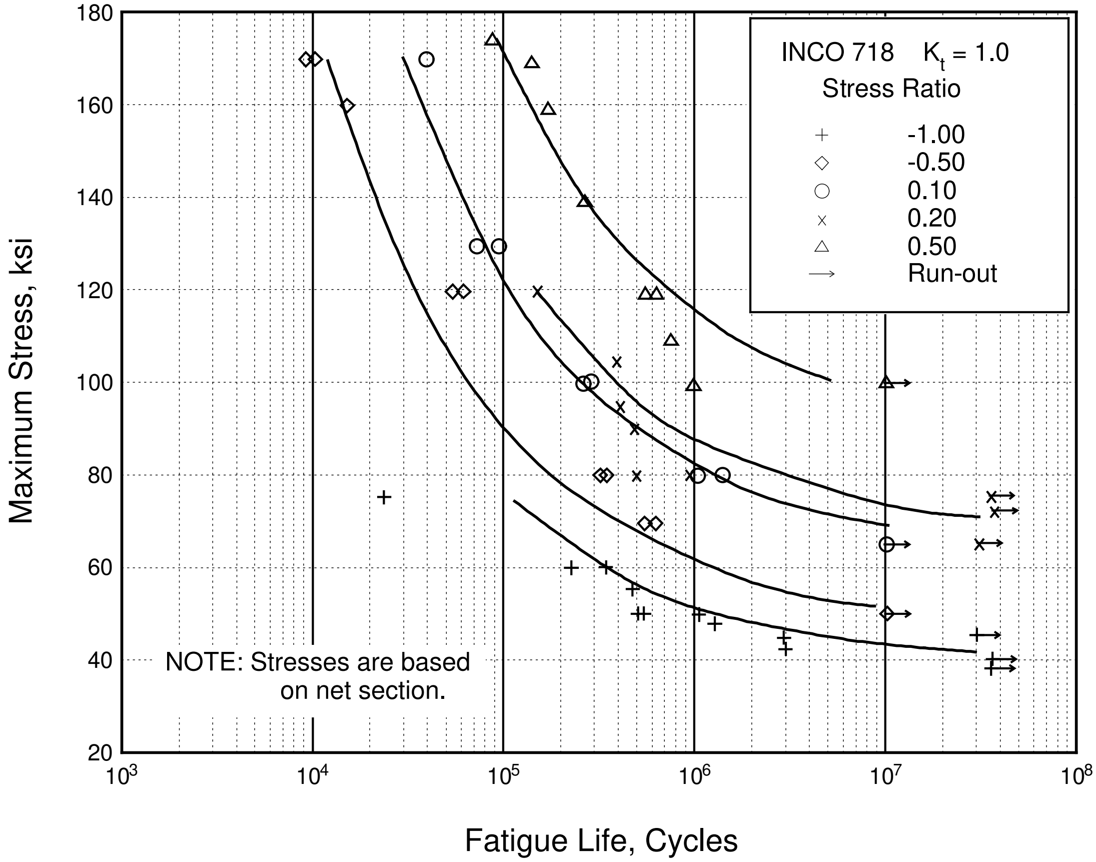

Figure 6.3.5.1.8(a). Best-fit S/N curves for unnotched Inconel 718 sheet at room temperature, long transverse direction.

<u>Correlative Information for Figure 6.3.5.1.8(a)</u>

<u>Product Form</u>: Sheet, 0.066 inch and 0.109 inch

<u>Properties</u>:

TUS, ksi	TYS, ksi	Temp., °F
197.0	164.0	RT
208.7	184.2	RT

<u>Specimen Details</u>: Unnotched
0.30 inch net width
0.50 inch net width

<u>Heat Treatment</u>: See AMS 5596

<u>Surface Condition</u>: #400 grit belt polished

<u>References</u>: 6.2.1.1.8 and 6.3.5.1.8(a)

<u>Test Parameters</u>:
Loading—Axial
Frequency—Unspecified
Temperature—RT
Environment—Air

<u>No. of Heats/Lots</u>: 2

<u>Equivalent Stress Equation</u>:
$\text{Log } N_f = 8.63 - 2.07 \text{ Log } (S_{eq} - 58.48)$
$S_{eq} = S_{max}(1-R)^{.58}$
Std. Error of Est., Log (Life) = $26.73\ (1/S_{eq})$
Standard Deviation, Log (Life) = 0.904
$R^2 = 90.3\%$

<u>Sample Size</u> = 53

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

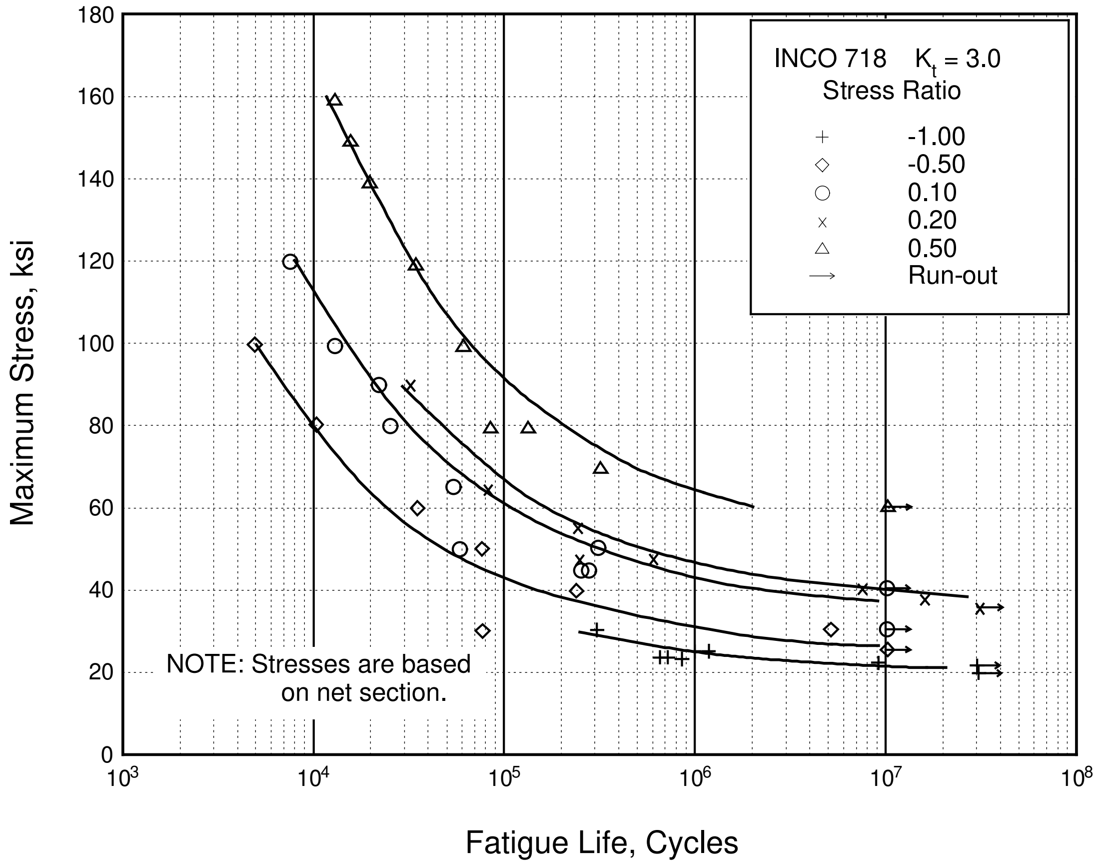

Figure 6.3.5.1.8(b). Best-fit S/N curves for notched, K_t = 3.0, Inconel 718 sheet at room temperature, long transverse direction.

Correlative Information for Figure 6.3.5.1.8(b)

Product Form: Sheet, 0.066 inch and 0.109 inch

Properties:

TUS, ksi	TYS, ksi	Temp., °F
197.0	164.0	RT
208.7	184.2	RT

Specimen Details: Notched 60° V-Groove
K_t = 3.0
0.300 inch net width
0.220 inch root width
0.625 inch net width
0.030 inch root radius

Heat Treatment: See AMS 5596

Surface Condition: As machined

References: 6.2.1.1.8 and 6.3.5.1.8(a)

Test Parameters:
Loading—Axial
Frequency—Unspecified
Temperature—RT
Environment—Air

No. of Heats/Lots: 2

Equivalent Stress Equation:
$\text{Log } N_f = 8.17 - 2.23 \text{ Log } (S_{eq} - 30.58)$
$S_{eq} = S_{max}(1-R)^{.68}$
Std. Error of Est., Log (Life) = $14.07 \, (1/S_{eq})$
Standard Deviation, Log (Life) = 0.977
R^2 = 93.7%

Sample Size = 49

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

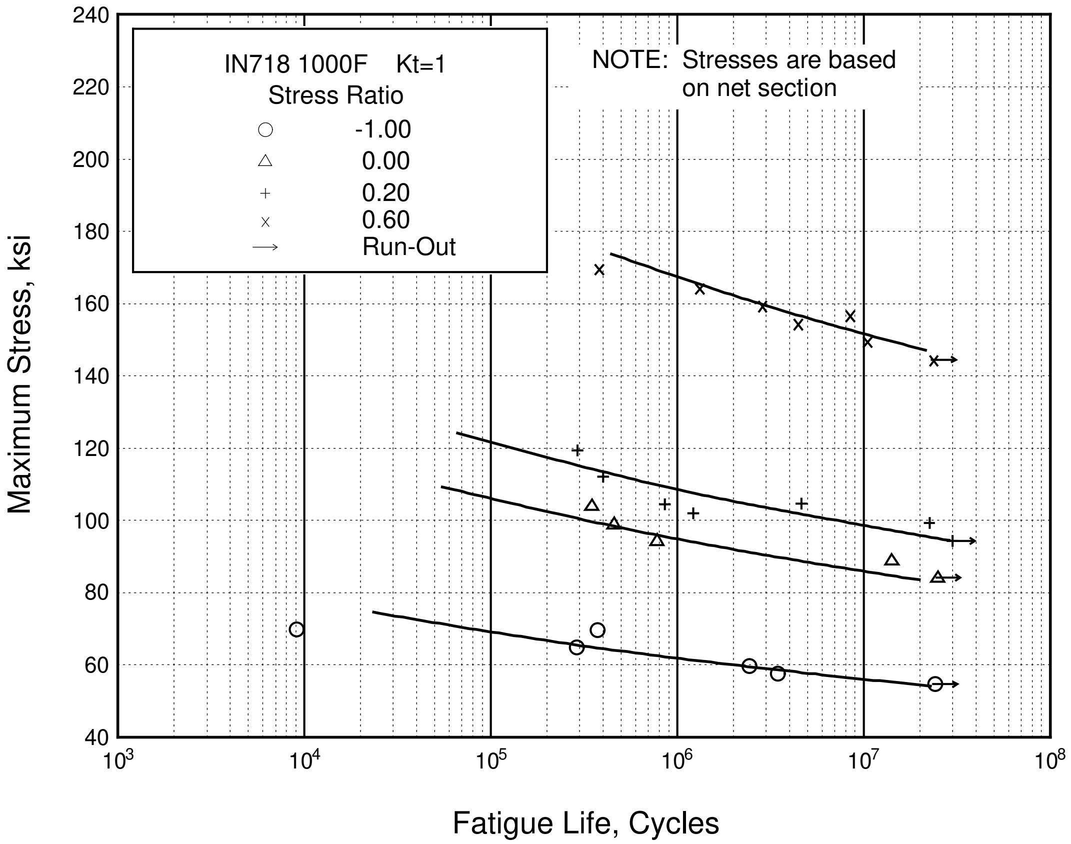

Figure 6.3.5.1.8(c). Best-fit S/N curves for unnotched Inconel 718 sheet at 1000 F, long transverse direction.

Correlative Information for Figure 6.3.5.1.8(c)

Product Form: Sheet, 0.066 inch

Properties:	TUS, ksi	TYS, ksi	Temp.,°F
	165.0	141.8	1000

Specimen Details: Unnotched
0.30 inch net width

Heat Treatment: See AMS 5596

Surface Condition: #400 grit belt polished

Reference: 6.2.1.1.8

Test Parameters:
Loading—Axial
Frequency—60 Hz
Temperature—1000°F
Environment—Air

No. of Heats/Lots: 1

Equivalent Stress Equation:
Log N_f = 23.51 - 10.57 Log (S_{eq} - 50)
$S_{eq} = S_{max}(1\text{-}R)^{0.62}$
Std. Error of Estimate, Log (Life) = 0.414
Standard Deviation, Log (Life) = 0.776
R^2 = 71.5%

Sample Size = 21

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

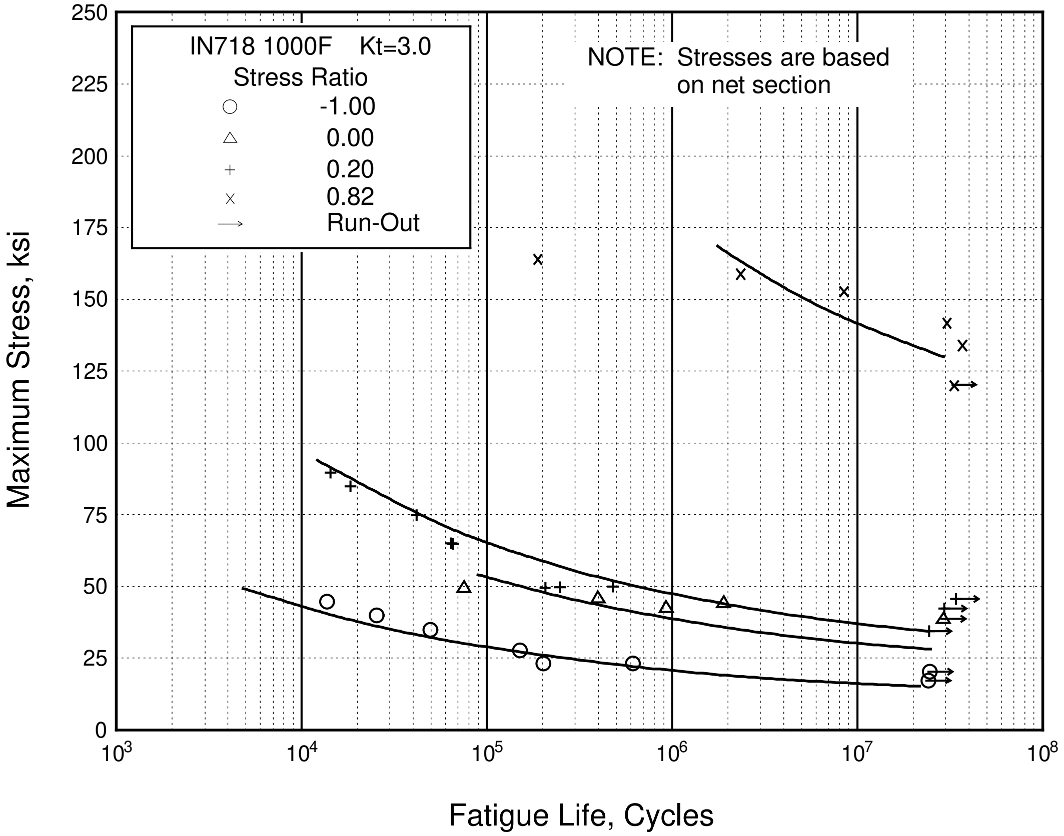

Figure 6.3.5.1.8(d). Best-fit S/N curves for notched, K_t = 3.0, Inconel 718 sheet at 1000°F, long transverse direction.

Correlative Information for Figure 6.3.5.1.8(d)

Product Form: Sheet, 0.066 inch

Properties:

TUS, ksi	TYS, ksi	Temp., °F
165.0	141.8	1000 Unnotched

Specimen Details: Notched, V-Groove, K_t = 3.0
0.448 inch gross width
0.300 inch net width
0.022 inch root radius, r
60° flank angle, ω

Heat Treatment: See AMS 5596

Surface Condition: As machined

Reference: 6.2.1.1.8

Test Parameters:
Loading—Axial
Frequency—60 Hz
Temperature—1000°F
Environment—Air

No. of Heats/Lots: 1

Equivalent Stress Equation:
$\text{Log } N_f = 11.02 - 3.93 \text{ Log } (S_{eq} - 20)$
$S_{eq} = S_{max}(1-R)^{0.91}$
Std. Error of Estimate, Log (Life) = 0.404
Standard Deviation, Log (Life) = 0.988
R^2 = 83.3%

Sample Size = 23

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

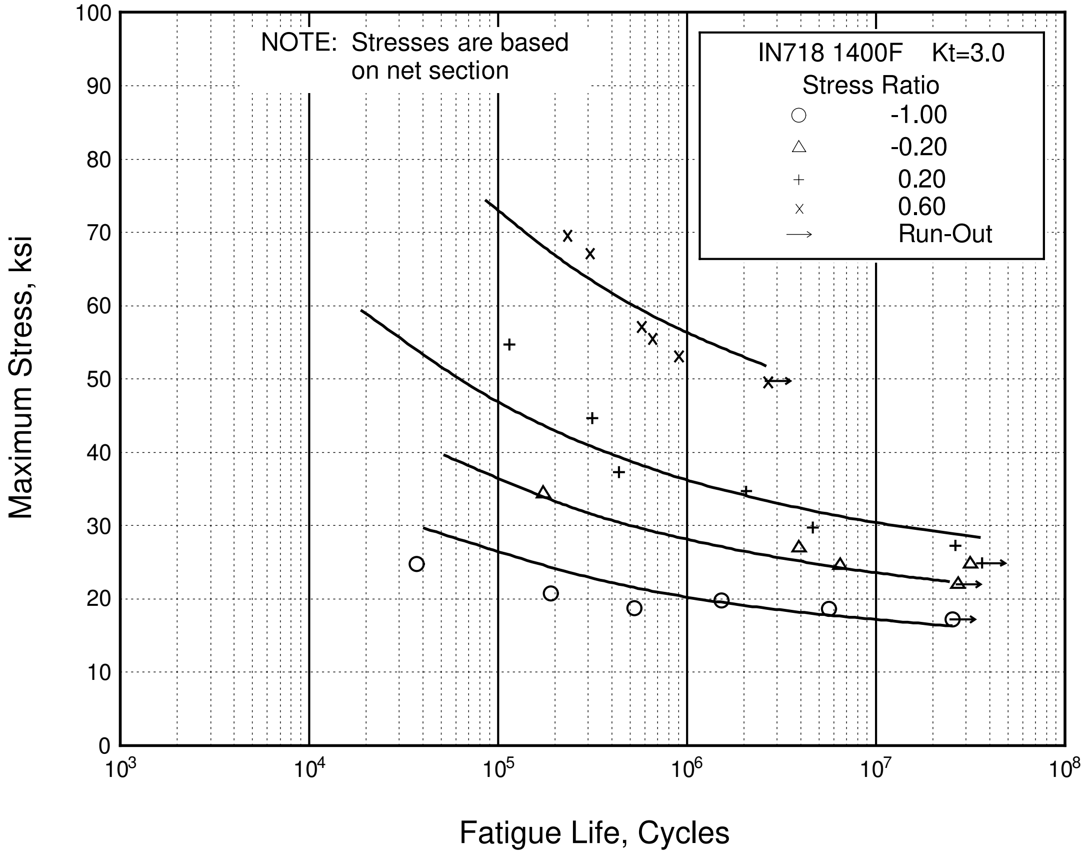

Figure 6.3.5.1.8(e). Best-fit S/N curves for notched, K_t = 3.0, Inconel 718 sheet at 1400°F, long transverse direction.

Correlative Information for Figure 6.3.5.1.8(e)

Product Form: Sheet, 0.066 inch

Properties:

TUS, ksi	TYS, ksi	Temp., °F
113.0	100.1	1400
		Unnotched

Specimen Details: Notched, V-Groove, K_t = 3.0
0.448 inch gross width
0.30 inch net width
0.022 inch root radius, r
60° flank angle, ω

Heat Treatment: See AMS 5596

Surface Condition: As machined.

Reference: 6.2.1.1.8

Test Parameters:
Loading—Axial
Frequency—60 Hz
Temperature—1400°F
Environment—Air

No. of Heats/Lots: 1

Equivalent Stress Equation:
$\text{Log } N_f = 10.29 - 4.02 \text{ Log } (S_{eq} - 20)$
$S_{eq} = S_{max}(1-R)^{0.62}$
Std. Error of Estimate, Log (Life) = 0.442
Standard Deviation, Log (Life) = 0.717
$R^2 = 62.0\%$

Sample Size = 20

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

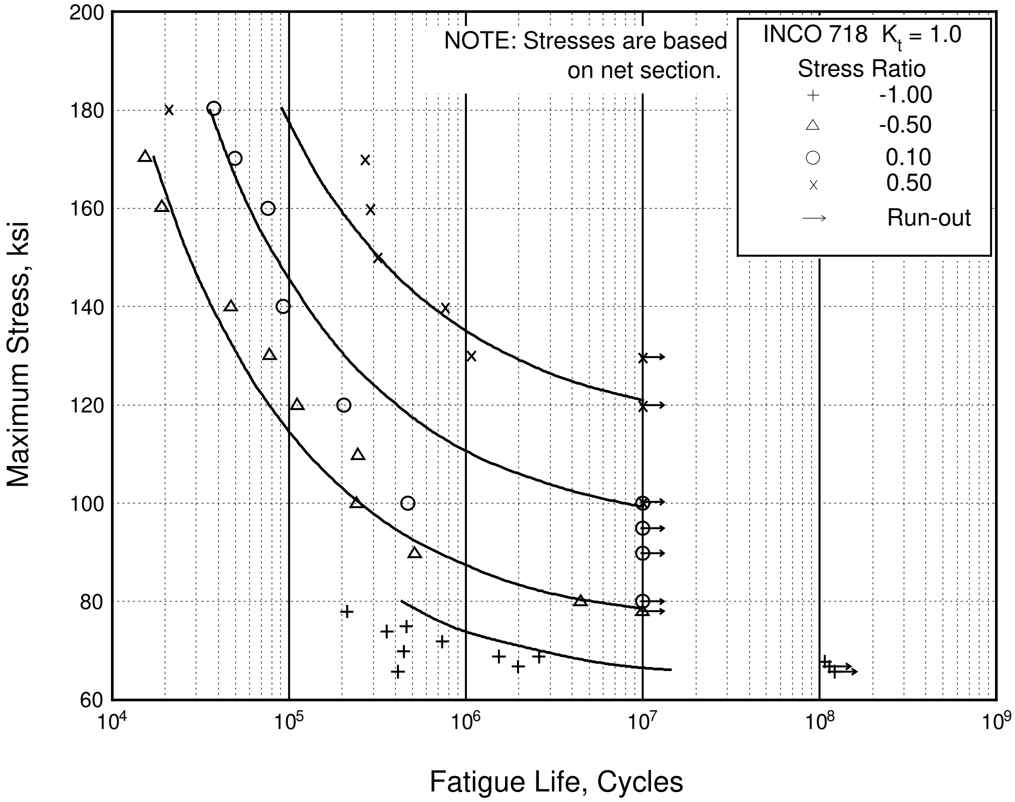

Figure 6.3.5.1.8(f). Best-fit S/N curves for unnotched Inconel 718 bar and plate at room temperature, longitudinal direction.

Correlative Information for Figure 6.3.5.1.8(f)

Product Form: Bar, 0.75 inch diameter; plate, 0.5, 0.75, and 1.0 inch thick

Properties:	TUS, ksi	TYS, ksi	Temp.,°F
	204.4	177.7	RT
	200.0	166.7	RT

Specimen Details: Unnotched
0.250 inch diameter
0.200 inch diameter

Heat Treatment: See AMS 5662 and AMS 5596

Surface Condition: Unspecified, RMS 8-11

References: 6.3.3.1.8(a) and 6.3.5.1.8(b)

Test Parameters:
Loading - Axial
Frequency - Unspecified
Temperature - RT
Environment - Air

No. of Heats/Lots: 4

Equivalent Stress Equation:
$\log N_f = 8.18 - 2.07 \log (S_{eq} - 63.0)$
$S_{eq} = S_a + 0.40\ S_m$
Std. Error of Est., Log (Life) = $38.56\ (1/S_{eq})$
Standard Deviation, Log (Life) = 0.980
R^2 = 67.7%

Sample Size = 44

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

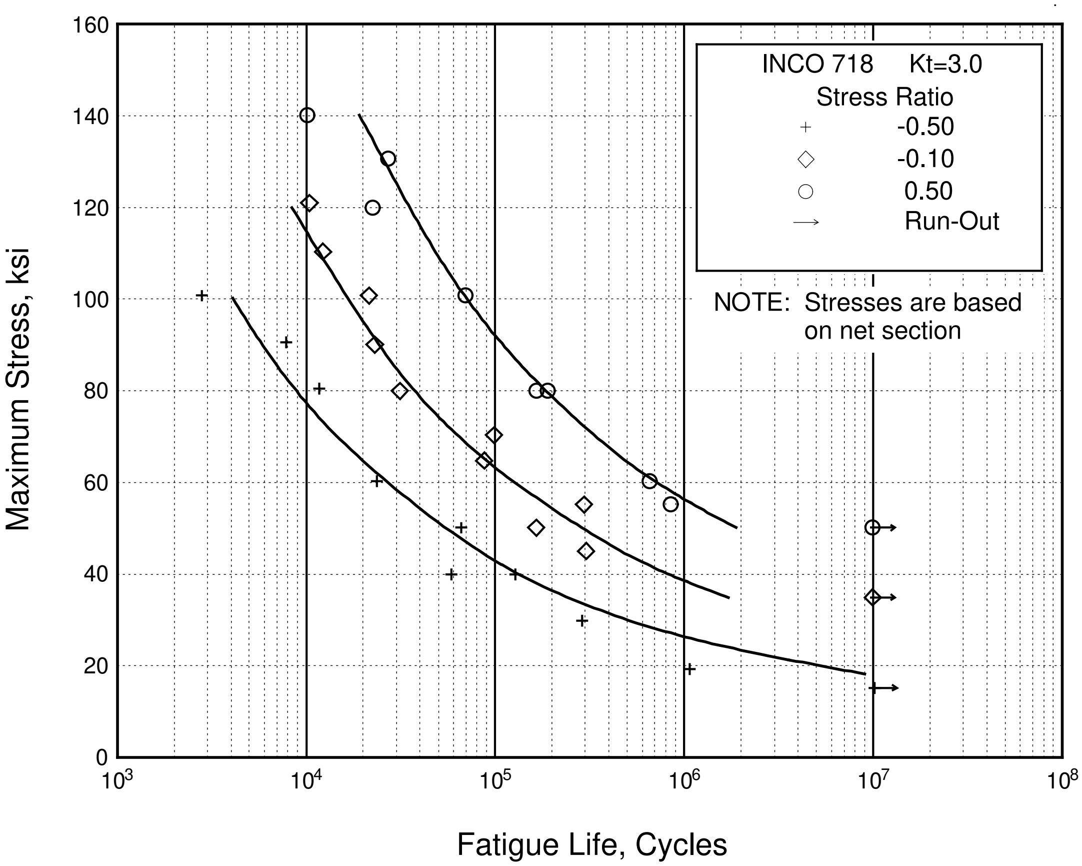

Figure 6.3.5.1.8(g). Best-fit S/N curves for notched, K_t = 3.0, Inconel 718 bar at room temperature, longitudinal direction.

Correlative Information for Figure 6.3.5.1.8(g)

Product Form: Bar, 0.75 inch diameter

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	204.4	177.7	RT

Specimen Details: Notched, 60° V Notch
0.252 inch diameter
0.013 inch diameter

Heat Treatment: See AMS 5662 and AMS 5596

Surface Condition: Unspecified

Reference: 6.3.3.1.8(a)

Test Parameters:
Loading—Axial
Frequency—Unspecified
Temperature—RT
Environment—Air

No. of Heats/Lots: 1

Equivalent Stress Equation:
Log N_f = 9.45 - 3.17 Log (S_{eq} - 8.6)
$S_{eq} = S_a + 0.16\ S_m$
Std. Error of Est., Log (Life) = 6.97 ($1/S_{eq}$)
Standard Deviation, Log (Life) =0.945
R^2 = 93.6%

Sample Size = 31

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

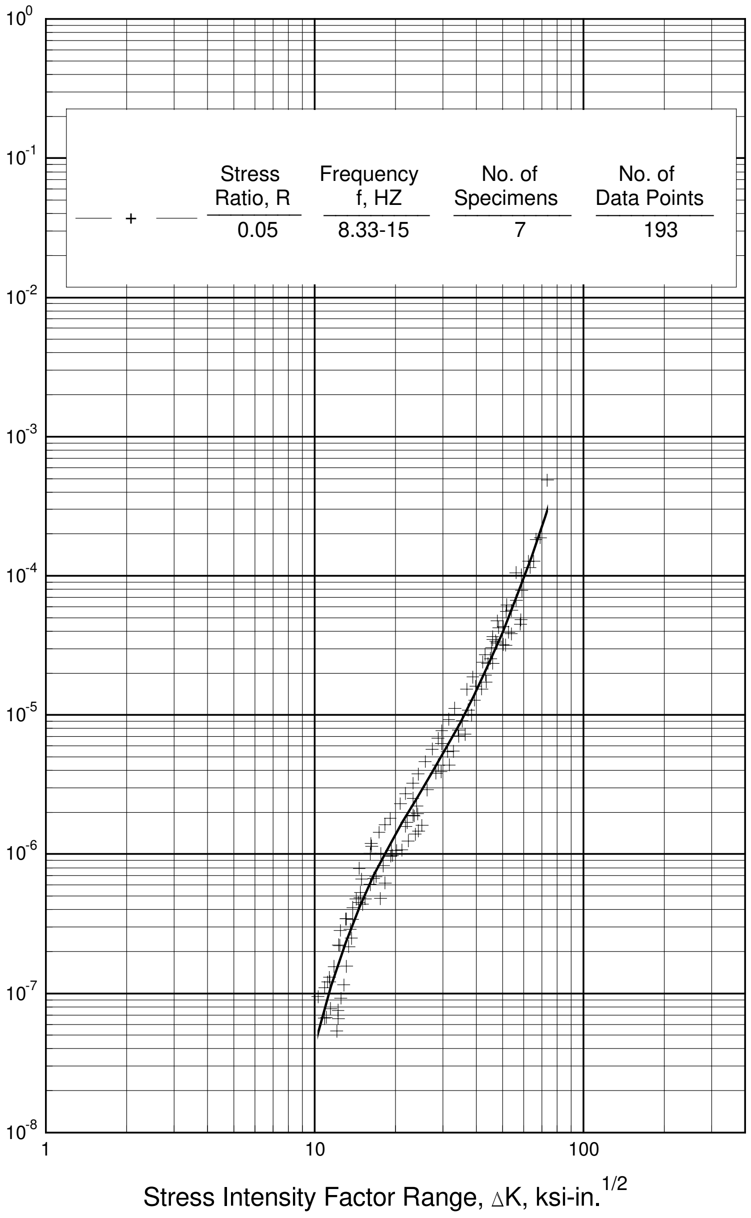

Figure 6.3.5.1.9(a). Fatigue-crack-propagation data for Inconel 718 die forging (upset ratio = 5) and 0.5-inch thick plate. [References—6.3.5.1.9(a) through (e).]

Specimen Thickness:	*0.298-0.502 inch*	*Environment:*	*Lab air*
Specimen Width:	*1.153-2.000 inches*	*Temperature:*	*RT*
Specimen Type:	*C(T)*	*Orientation:*	*L-T and T-L*

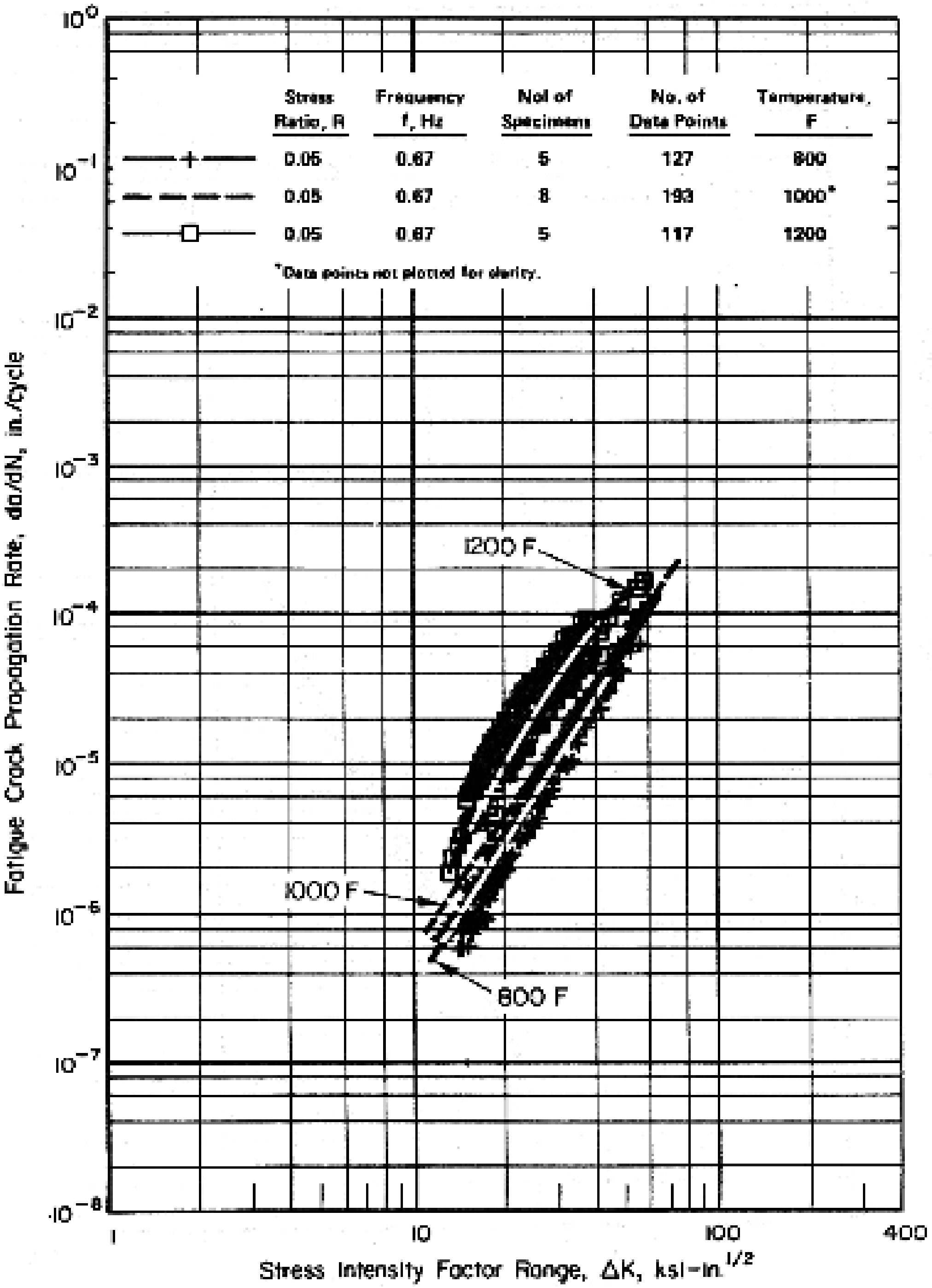

Figure 6.3.5.1.9(b). Fatigue-crack-propagation data for Inconel 718 die forging (upset ratio = 5) and 0.5-inch thick plate. [References—6.3.5.1.9(b) and 6.3.5.1.9(d) through (g).]

Specimen Thickness:	*0.298-0.502 inch*	*Environment:*	*Lab air*
Specimen Width:	*1.157-2.001 inches*	*Temperature:*	*800-1200 °F*
Specimen Type:	*C(T)*	*Orientation:*	*L-T and T-L*

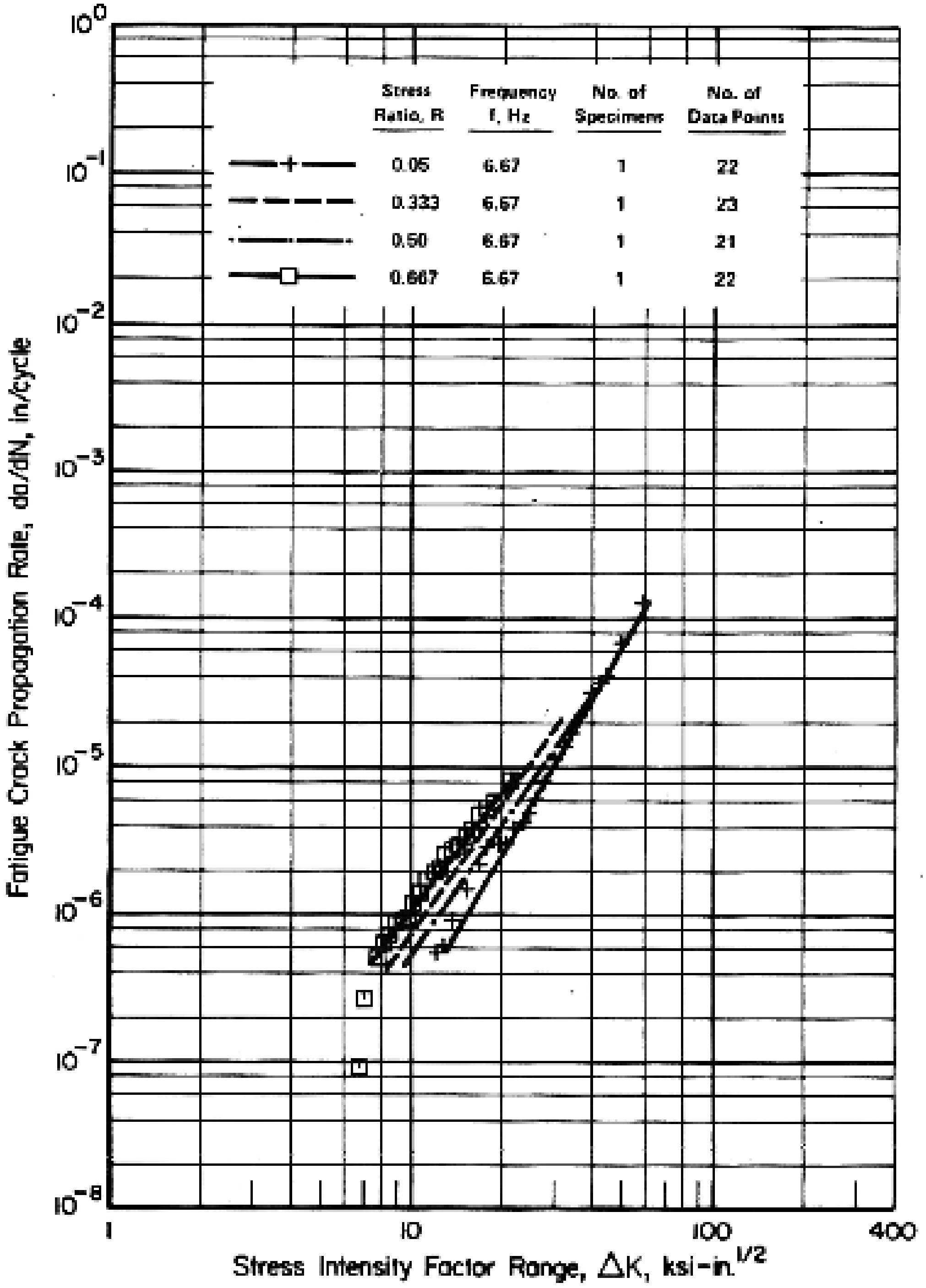

Figure 6.3.5.1.9(c). Fatigue-crack-propagation data for Inconel 718 0.5-inch thick plate. [Reference—6.3.5.1.9(f).]

Specimen Thickness:	*0.298-0.479 inch*	*Environment:*	*Lab air*
Specimen Width:	*1.151-1.993 inches*	*Temperature:*	*1000 °F*
Specimen Type:	*C(T)*	*Orientation:*	*L-T and T-L*

6.3.6 INCONEL X-750

6.3.6.0 *Comments and Properties* — Inconel X-750 is a high-strength oxidation-resistant nickel-base alloy. It is used for parts requiring high strength up to 1000°F or high creep strength up to 1500°F and for low-stressed parts operating up to 1900°F. It is hardenable by various combinations of solution treatment and aging, depending on its form and application. Inconel X-750 is available in all the usual wrought mill forms.

Inconel X-750 can be readily forged between 1900°F and 2225°F; "hot-cold" working between 1200°F and 1600°F is harmful and should be avoided. This alloy is readily formed but should be solution treated at 1925°F for 7 to 10 minutes after severe forming operations. It is somewhat more difficult to machine than austenitic stainless steels. Rough machining is easier in the solution-treated condition; finish machining in the partly or fully aged condition. Fusion welding is difficult for large section sizes and moderately difficult for small cross sections and sheet. It must be welded in the annealed or solution-treated condition; weldments should be stress relieved at 1650°F for 2 hours before aging. Nickel brazing, followed by precipitation heat treatment of the brazed assembly, results in strength nearly equal to fully heat-treated material.

Oxidation resistance of Inconel X-750 is good to 1900°F; but the beneficial effects of aging are lost above 1500°F. This alloy is subject to attack in sulfur-containing atmospheres.

A variety of heat treatments has been developed for Inconel X-750. Each provides special properties and renders the material in the best metallurgical condition for the intended application. Only two of these heat treatments, for applications requiring high strength up to 1100°F, are described below.

Annealed and Aged for Sheet, Strip, and Plate — Mill annealed plus 1300°F for 20 hours, and A.C. per AMS 5542.

Equalized and Aged for Bar and Forging — 1625°F for 4 hours, A.C., plus 1300°F for 24 hours, and A.C. per AMS 5667.

Other heat treatments are available for maximum creep-rupture strength.

Some material specifications for Inconel X-750 are shown in Table 6.3.6.0(a). Room-temperature mechanical and physical properties are shown in Table 6.3.6.0(b).

Table 6.3.6.0(a). Material Specifications for Inconel X-750

Specification	Form	Condition
AMS 5542	Sheet, strip, and plate	Annealed
AMS 5667	Bar and forging	Equalized

The effect of temperature on the physical properties of this alloy is shown in Figure 6.3.6.0.

6.3.6.1 *Annealed and Aged* — Elevated-temperature curves for tensile and yield ultimate strengths are shown in Figures 6.3.6.1.1 through 6.3.6.1.3.

6.3.6.2 *Equalized and Aged* — Elevated-temperature curves are presented in Figures 6.3.6.2.1(a) and (b), as well as 6.3.6.2.4(a) and (b).

Table 6.3.6.0(b). Design Mechanical and Physical Properties of Inconel X-750

Specification	AMS 5542				AMS 5667	
Form	Strip		Sheet	Plate	Bars and forgings	
Condition	Annealed and aged				Equalized and aged	
Thickness or diameter, in.	$\leq$0.009	$\geq$0.010	0.010-0.187	0.188-4.000	<4.000	4.000-10.000
Basis	S	S	S	S	S	S
Mechanical Properties:						
F_{tu}, ksi:						
L	...	...	...	...	165	160
LT	150	155	165	155	...	...
F_{ty}, ksi:						
L	...	...	...	...	105	100
LT	...	...	105	100	...	...
F_{cy}, ksi:						
L	...	...	...	...	105	100
LT	...	...	105	100	...	...
F_{su}, ksi	...	...	107	100	102	99
F_{bru}, ksi:						
(e/D = 1.5)	...	...	247	232	247	240
(e/D = 2.0)	...	...	313	294	313	304
F_{bry}, ksi:						
(e/D = 1.5)	...	...	157	150	157	150
(e/D = 2.0)	...	...	189	180	189	180
e, percent:						
L	...	...	...	...	20	15
LT	...	15	20	20	...	...
RA, percent:						
L	...	...	...	...	25	17
E, 10^3 ksi	30.6					
E_c, 10^3 ksi	30.6					
G, 10^3 ksi	11.8					
μ	0.30					
Physical Properties:						
ω, lb/in.^{3}	0.298					
C, K, and α	See Figure 6.3.6.0					

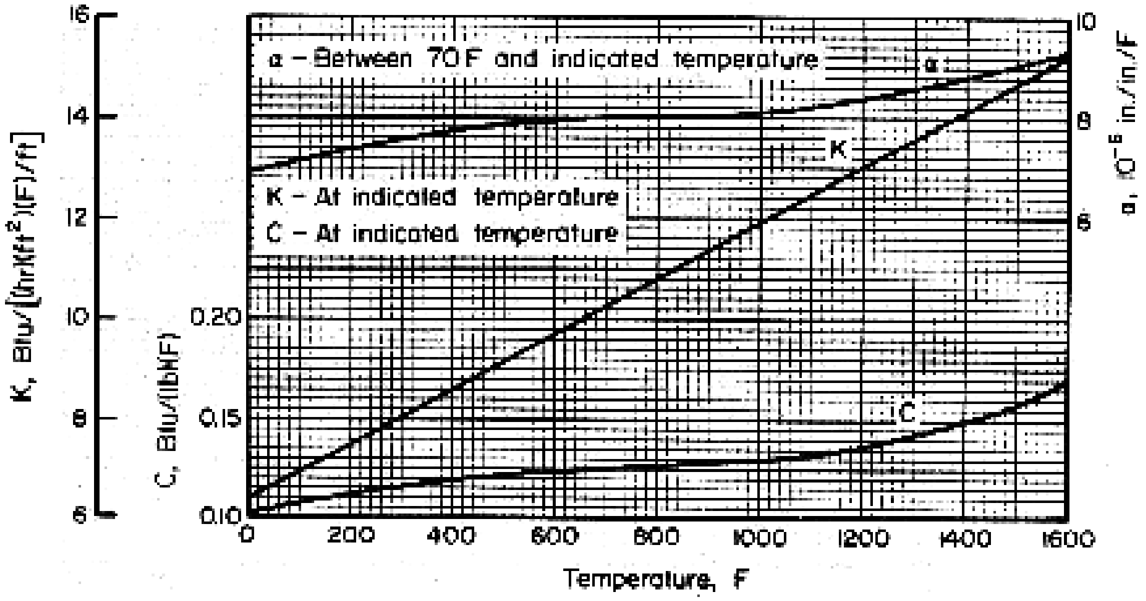

Figure 6.3.6.0. Effect of temperature on the physical properties of Inconel X-750.

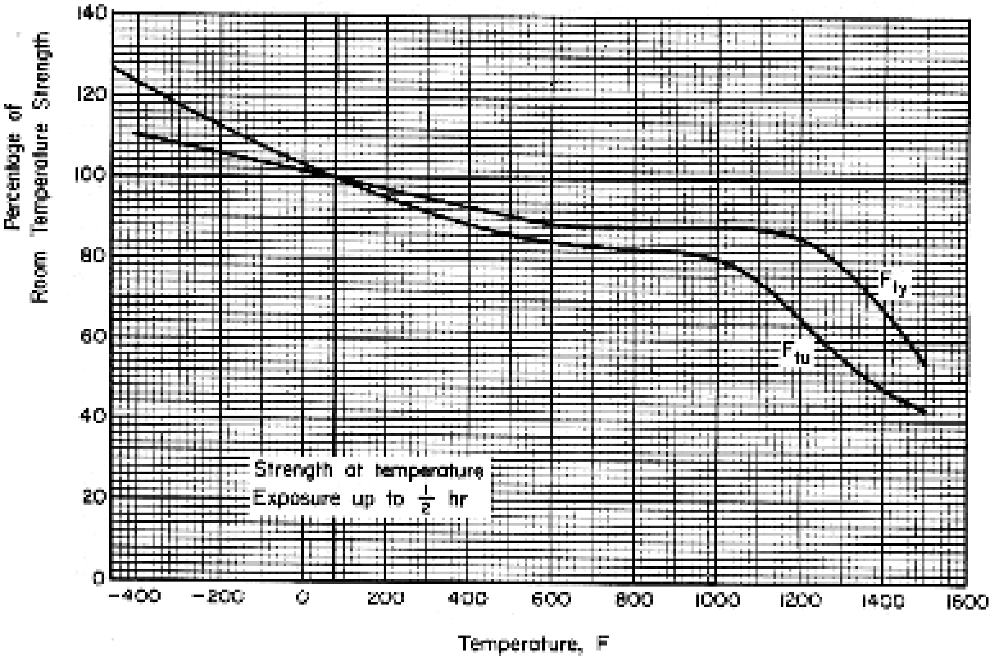

Figure 6.3.6.1.1. Effect of temperature on the tensile ultimate strength (F_{tu}) and tensile yield strength (F_{ty}) of Inconel X-750 sheet and plate (AMS 5542).

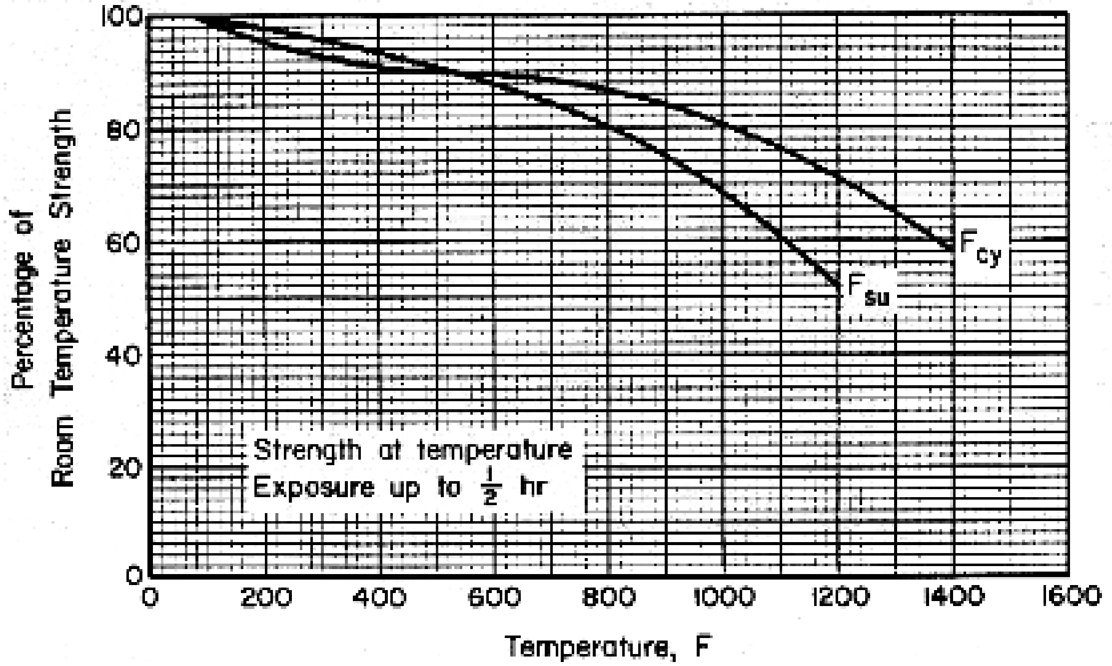

Figure 6.3.6.1.2. Effect of temperature on the compressive yield strength (F_{cy}) and the shear ultimate strength (F_{su}) of Inconel X-750.

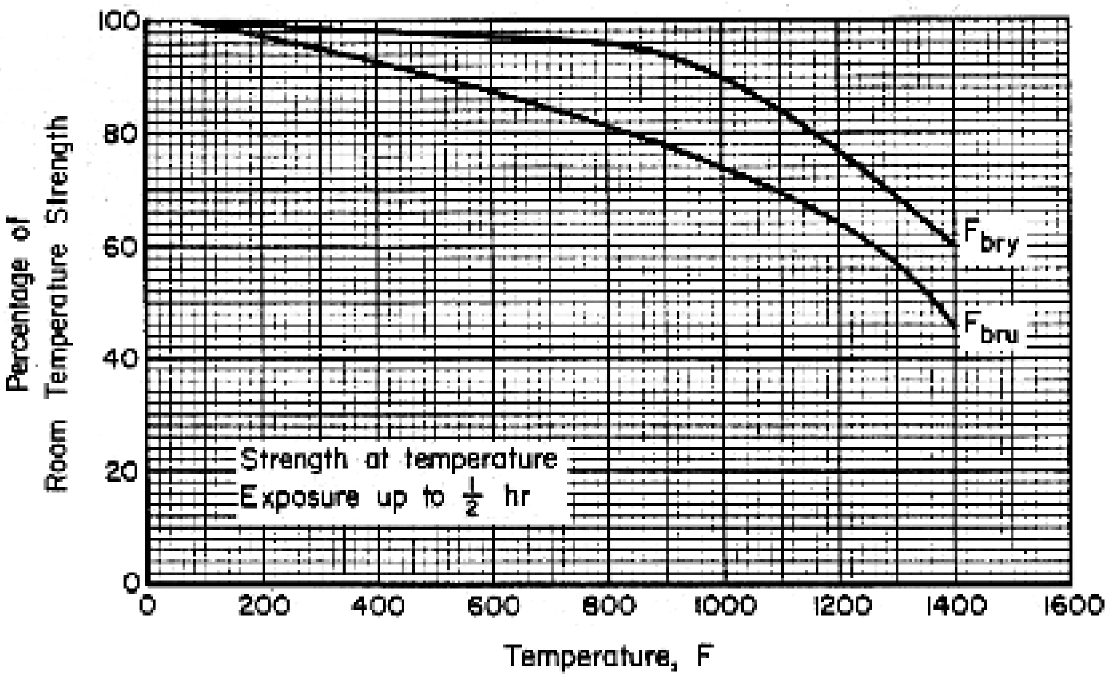

Figure 6.3.6.1.3. Effect of temperature on the bearing ultimate strength (F_{bru}) and the bearing yield strength (F_{bry}) of Inconel X-750.

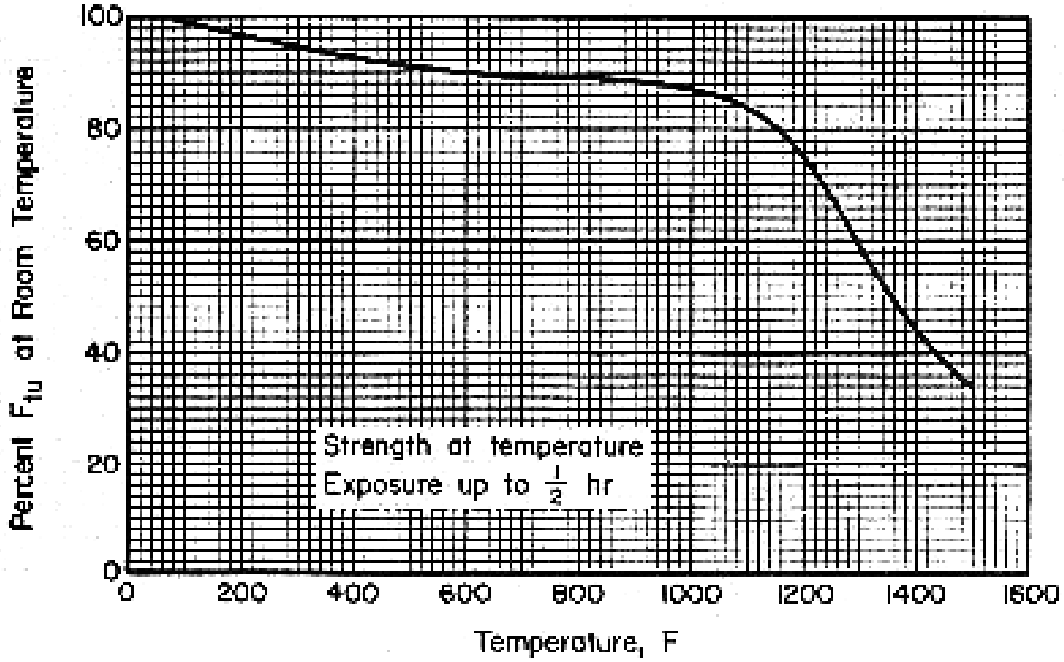

Figure 6.3.6.2.1(a). Effect of temperature on the tensile ultimate strength (F_{tu}) of Inconel X-750 bar (AMS 5667).

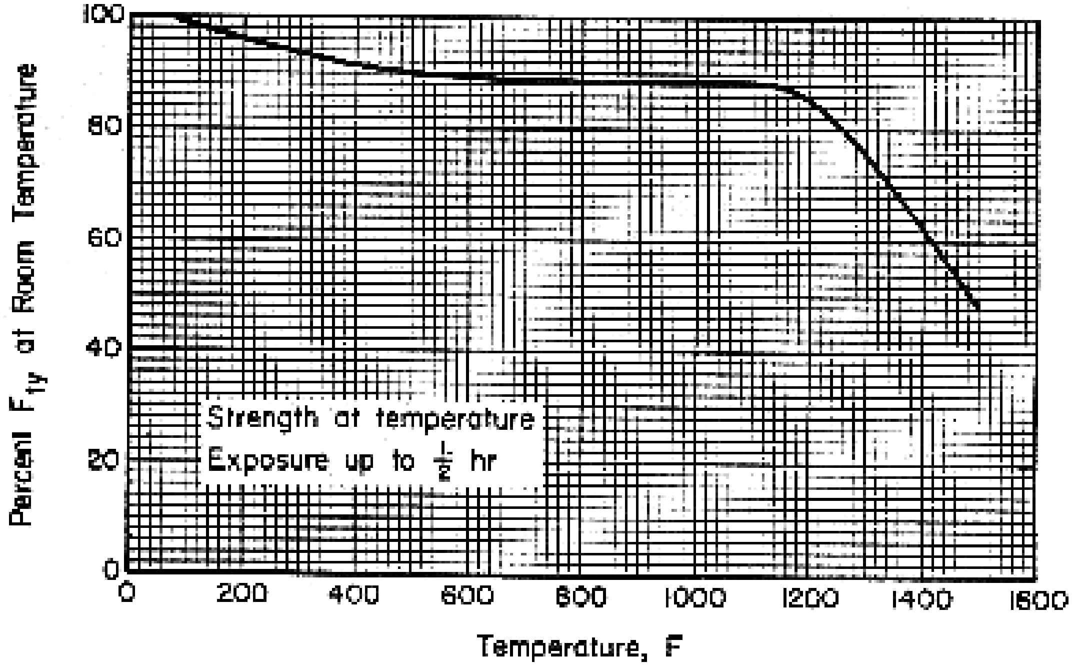

Figure 6.3.6.2.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of Inconel X-750 bar (AMS 5667).

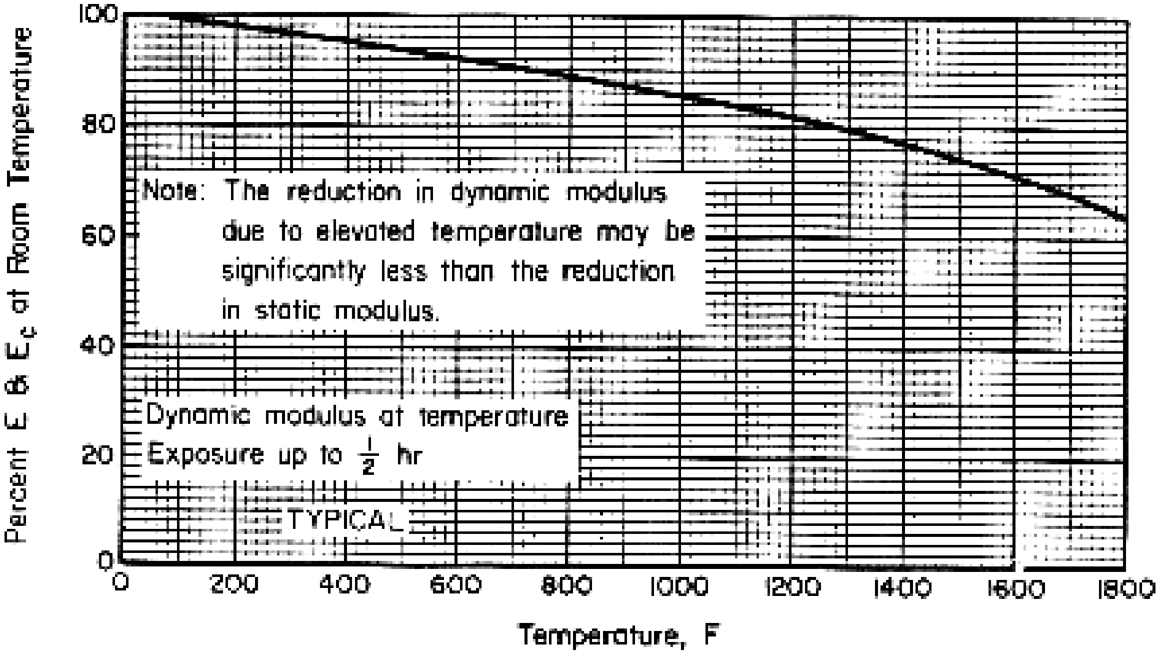

Figure 6.3.6.2.4(a). Effect of temperature on the tensile and compressive moduli (E and E_c) of Inconel X-750.

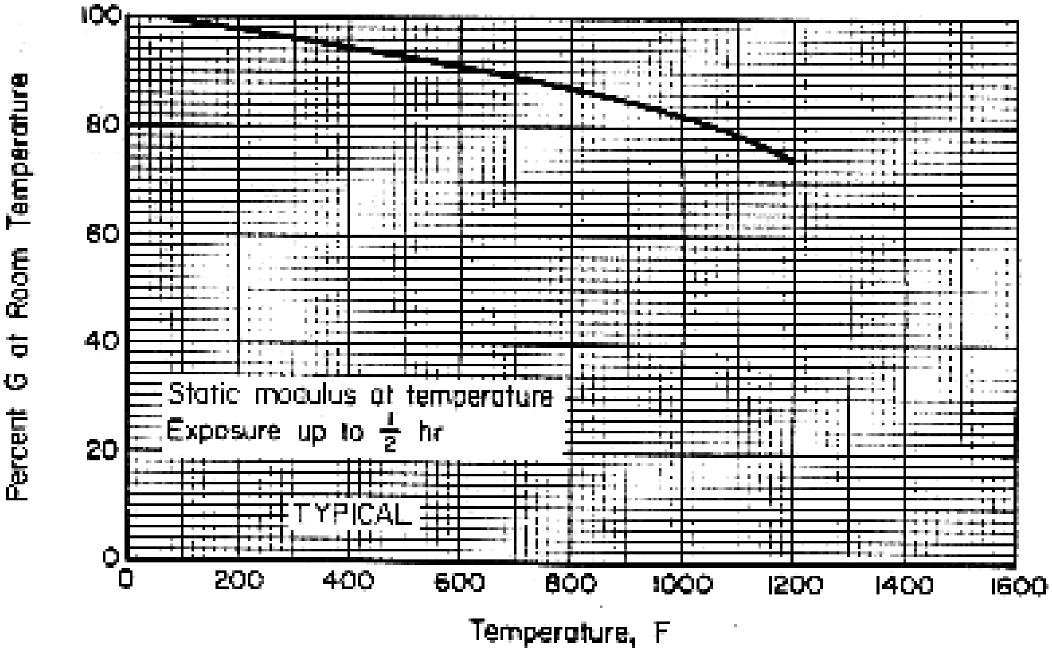

Figure 6.3.6.2.4(b). Effect of temperature on the shear modulus (G) of Inconel X-750.

6.3.7 RENÉ 41

6.3.7.0 *Comments and Properties* — René 41 is a vacuum-melted precipitation-hardening nickel-base alloy designed for highly stressed parts operating between 1200°F and 1800°F. Its applications include afterburner parts, turbine castings, wheels, buckets, and high-temperature bolts and fasteners. René 41 is available in the form of sheet, bars, and forgings.

René 41 is forged between 1900°F and 2150°F; small reductions must be made when breaking up an as-cast structure; cracking may be encountered in finishing below 1850°F. René 41 work hardens rapidly, and frequent anneals are required; to anneal, heat rapidly to 1950°F for 30 minutes and quench.

René 41 is difficult to machine. In the soft solution-annealed condition it is gummy; therefore, it should be in the fully aged condition for optimum machinability, and tungsten carbide cutting tools should be used. René 41 can be welded satisfactorily in the solution-treated condition; after welding, the parts should be solution treated for stress relief.

René 41 should not be exposed to temperatures above 2050°F during latter stages of hot working or during subsequent operations, otherwise severe intergranular cracking may be encountered.

The oxidation resistance of René 41 is good to 1800°F. Lengthy exposure above the aging temperature (1400°F to 1650°F) results in loss of strength and room-temperature ductility.

Some material specifications for René 41 are shown in Table 6.3.7.0(a). Room temperature mechanical and physical properties are shown in Table 6.3.7.0(b). The effect of temperature on physical properties is shown in Figure 6.3.7.0.

Table 6.3.7.0(a). Material Specifications for René 41

Specification	Form	Condition
AMS 5545	Plate, sheet, and strip	Vacuum melted, solution treated
AMS 5712	Bar and forging	Vacuum melted, solution treated and aged
AMS 5713	Bar and forging	Vacuum melted, solution treated and aged

6.3.7.1 *Solution Treated at 1975°F and Aged at 1400°F Condition* — Tensile and stress-rupture requirements at elevated temperatures are specified for René 41. The appropriate specification should be consulted for detailed requirements. Other elevated-temperature data for René 41 in this condition are presented in Figures 6.3.7.1.1 through 6.3.7.1.5. A creep nomograph for René 41 alloy sheet is shown in Figure 6.3.7.1.7.

Table 6.3.7.0(b). Design Mechanical and Physical Properties of René 41

Specification	AMS 5545				AMS 5712 and AMS 5713
Form	Sheet			Plate	Bar and forging
Condition	Solution treated and aged (1400°F)				
Thickness or diameter, in.	≤0.020	0.021-0.187		0.188-0.375	≤1.000
Basis	S	A[a]	B[a]	S	S
Mechanical Properties:					
F_{tu}, ksi:					
L	...	170[b]	185	...	170
LT	160	170[b]	185	170	...
F_{ty}, ksi:					
L	...	123	132	...	130
LT	120	123	132	130	...
F_{cy}, ksi:					
L	...	132	142	...	133
LT	...	135	145	...	...
F_{su}, ksi	...	105	114	105	110
F_{bru}, ksi:					
(e/D = 1.5)	...	244	266	244	...
(e/D = 2.0)	...	310	338	310	...
F_{bry}, ksi:					
(e/D = 1.5)	...	197	211	208	...
(e/D = 2.0)	...	245	263	259	...
e, percent (S-basis):					
L	...	...	...	...	8
LT	6	10	...	10	...
RA, percent (S-basis):					
L	...	...	...	...	10
E, 10^3 ksi	31.6				
E_c, 10^3 ksi	31.6				
G, 10^3 ksi	12.1				
μ	0.31				
Physical Properties:					
ω, lb/in.^{3}	0.298				
C, K, and α	See Figure 6.3.7.0				

a Design allowables were based upon data from samples of material, supplied in solution treated condition, which were aged to demonstrate heat treat response by suppliers. Properties obtained by the user may be different if the material has been formed or otherwise cold worked.

b S-basis. The rounded T_{99} value is 178 ksi.

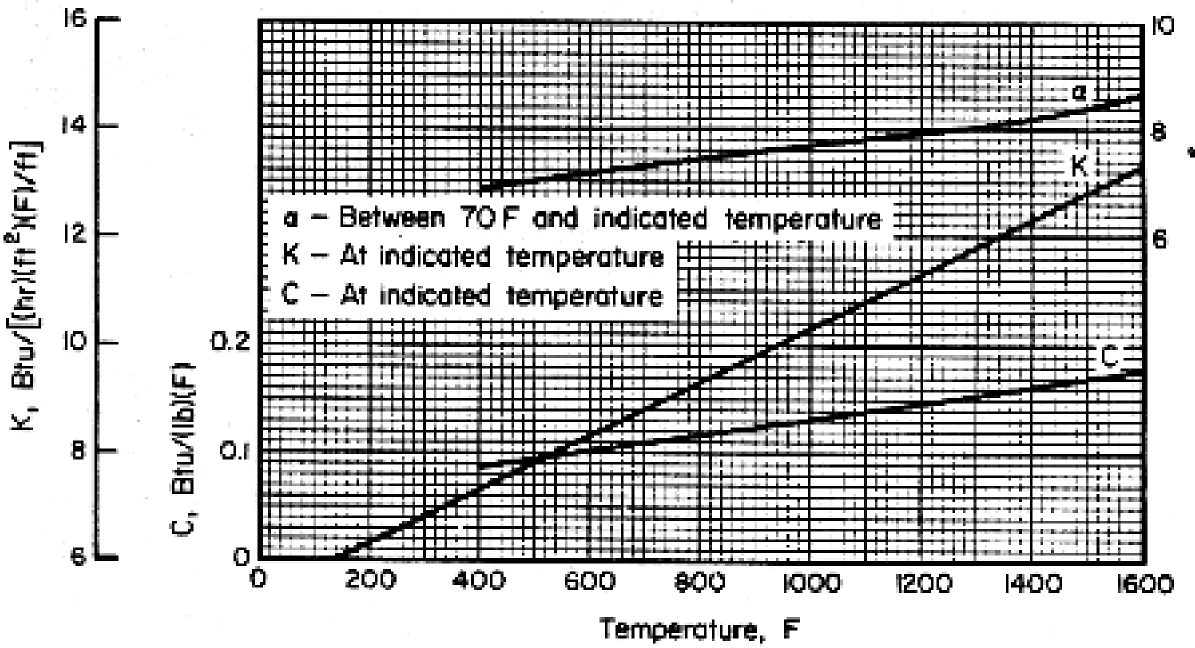

Figure 6.3.7.0. Effect of temperature on the physical properties of René 41.

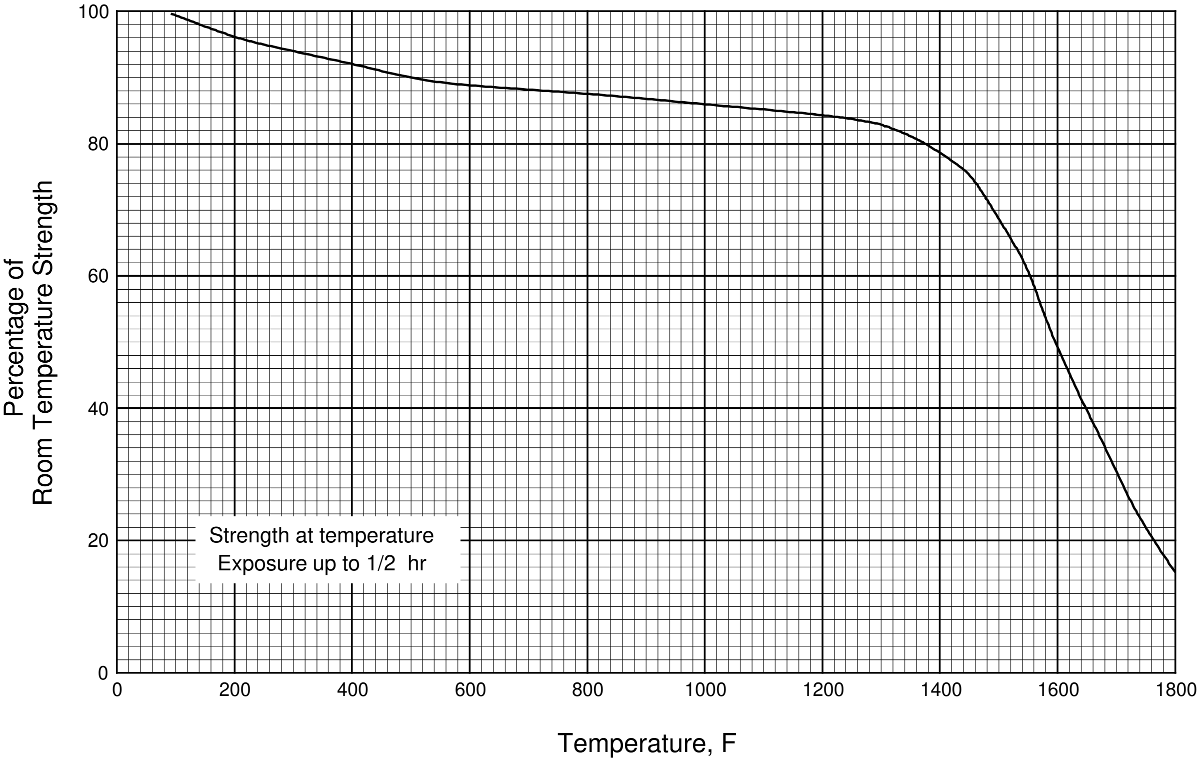

Figure 6.3.7.1.1. Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of René 41.

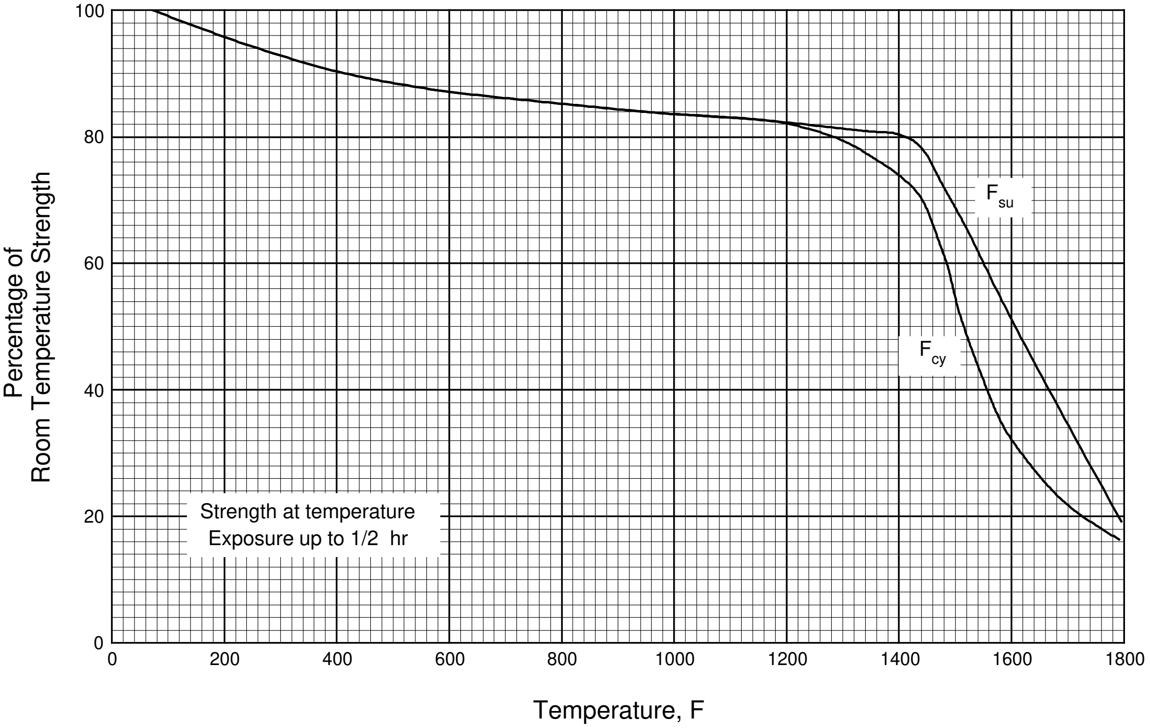

Figure 6.3.7.1.2. Effect of temperature on the compressive yield strength (F_{cy}) and the shear ultimate strength (F_{su}) of René 41.

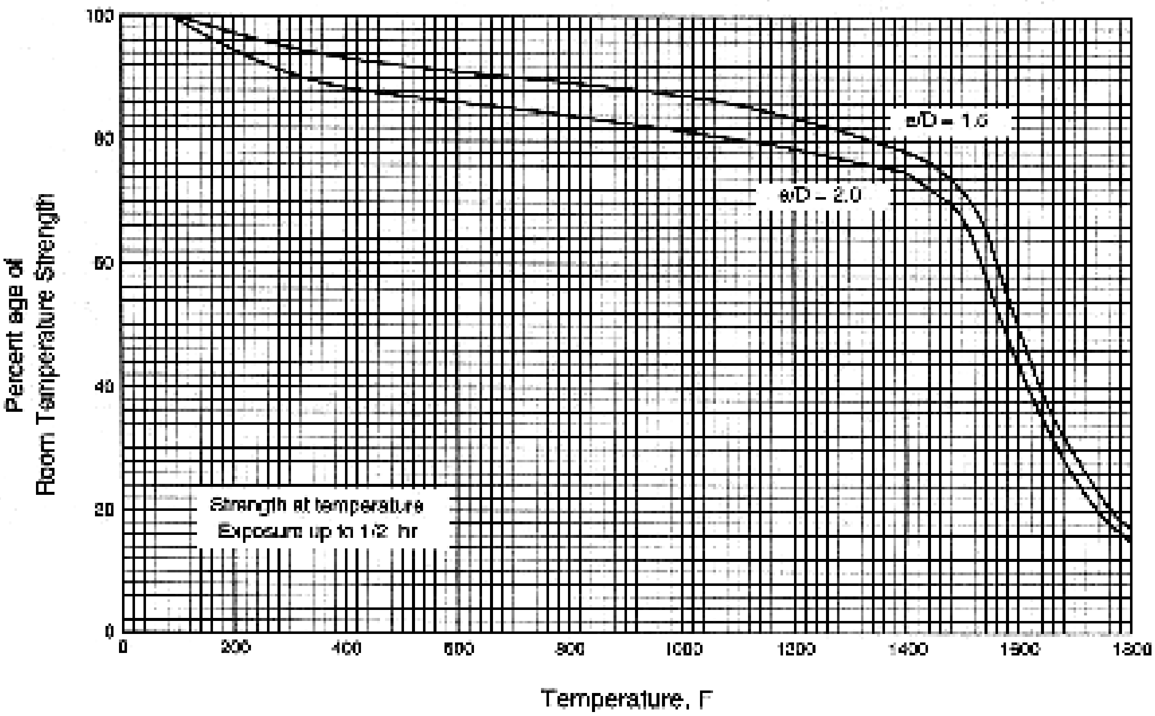

Figure 6.3.7.1.3(a). Effect of temperature on the bearing ultimate strength (F_{bru}) of René 41.

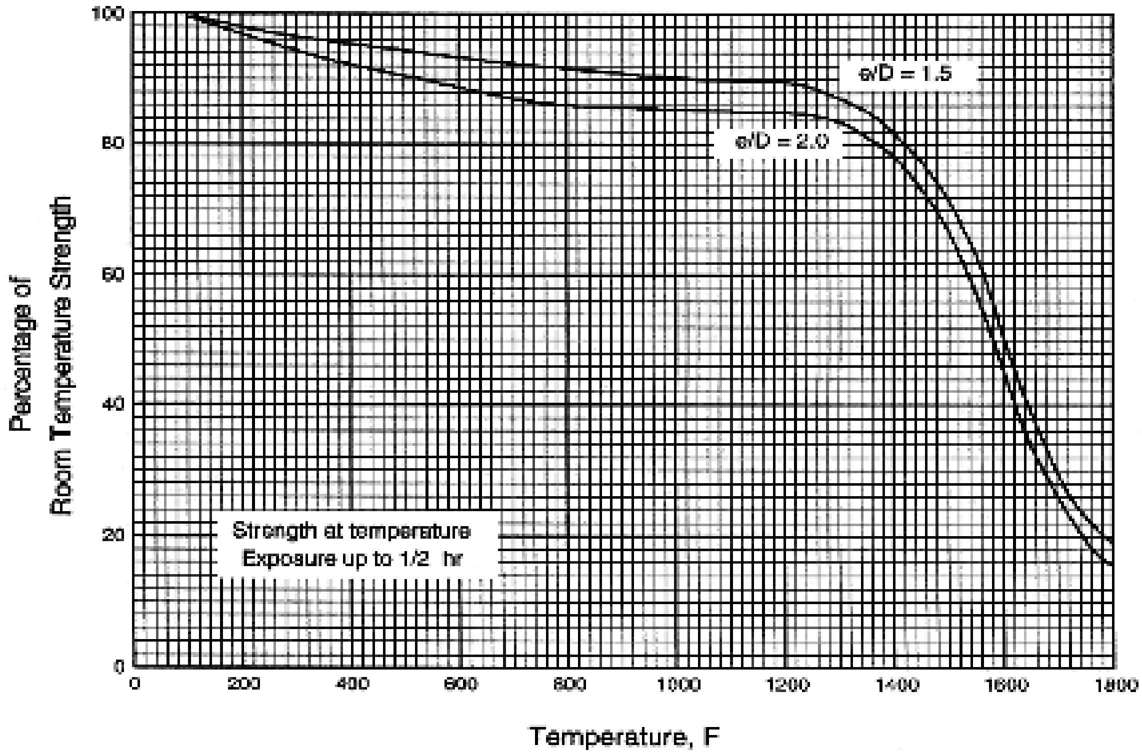

Figure 6.3.7.1.3(b). Effect of temperature on the bearing yield strength (F_{bry}) of René 41.

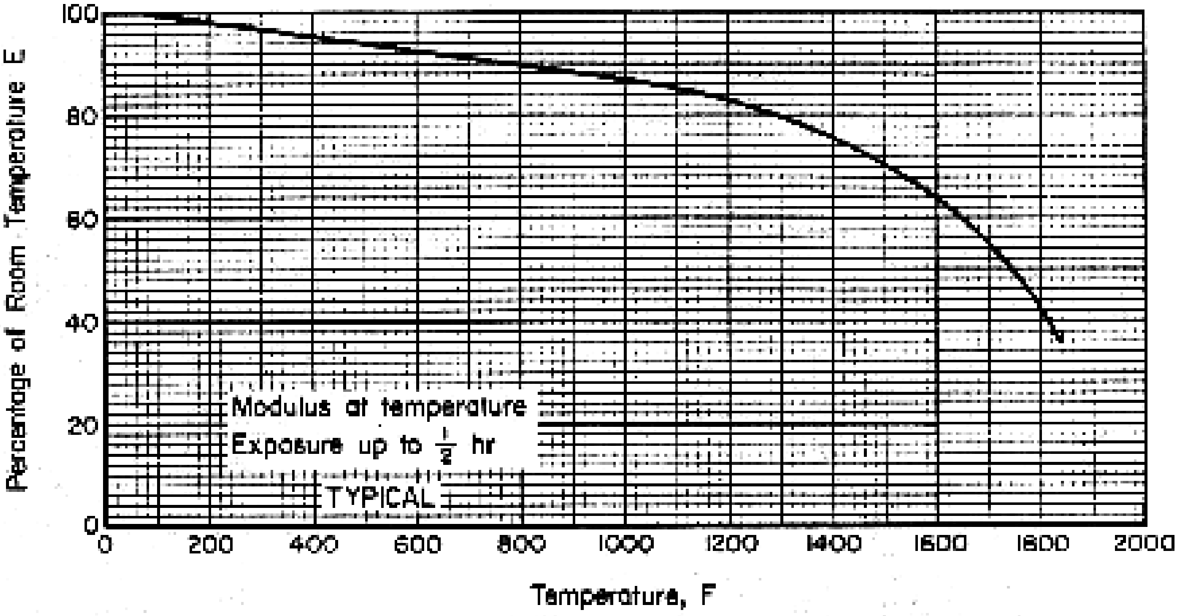

Figure 6.3.7.1.4. Effect of temperature on the tensile modulus (E) of René 41.

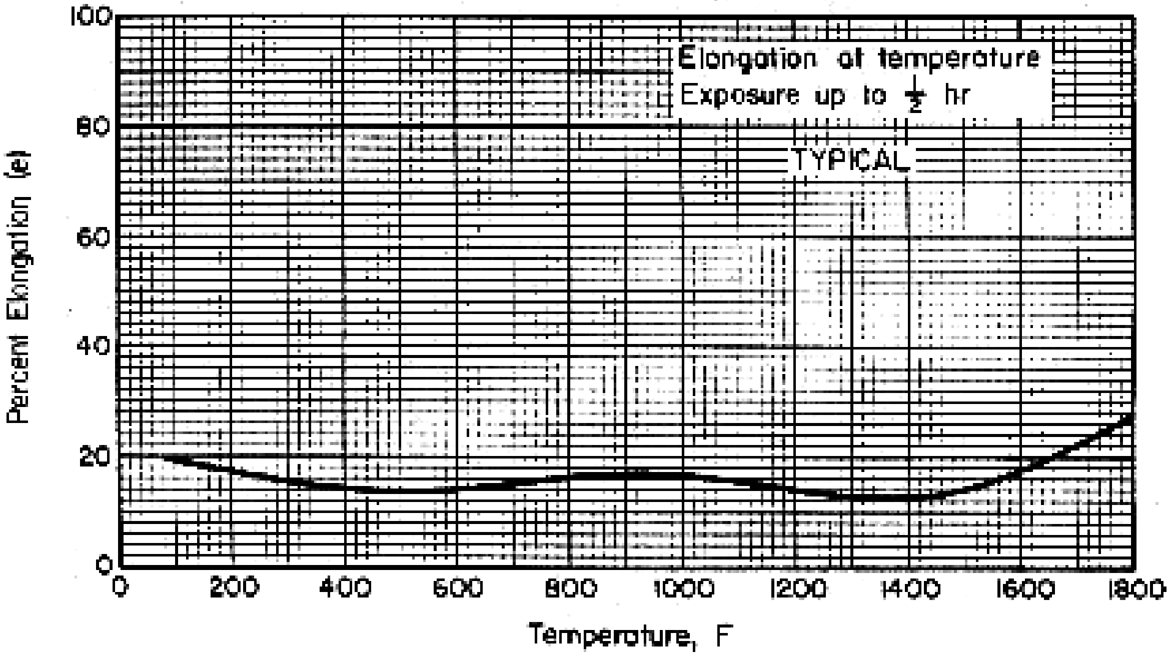

Figure 6.3.7.1.5. Effect of temperature on the elongation (e) of René 41 (>0.020 thickness) sheet.

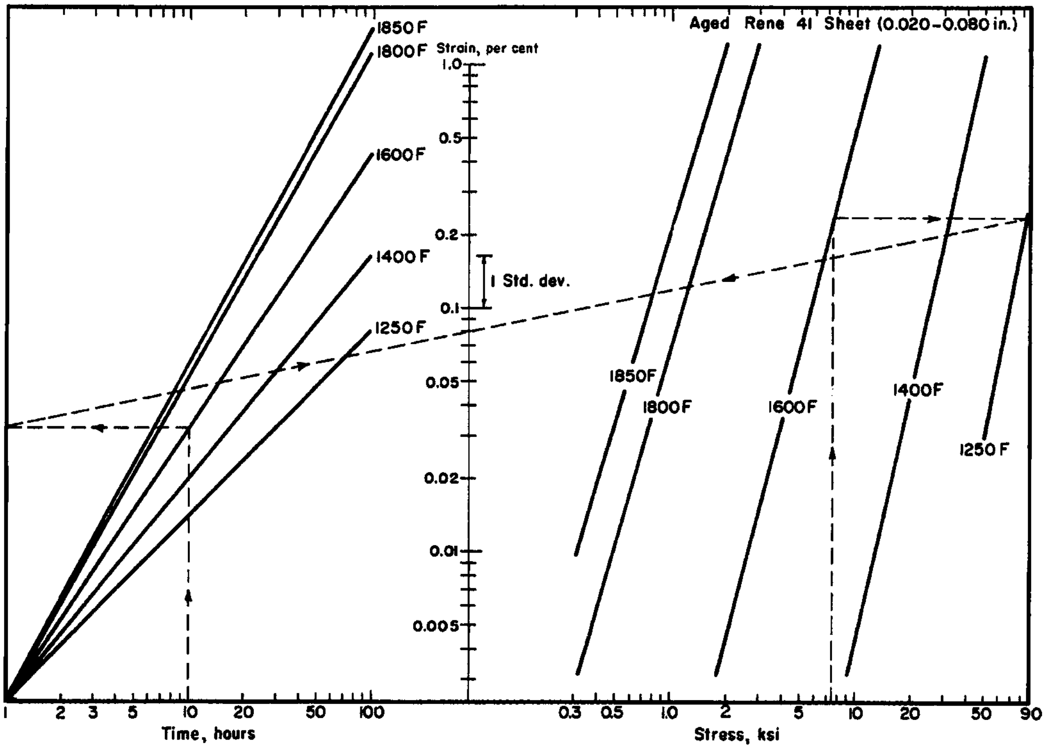

Figure 6.3.7.1.7. Typical creep properties of René 41 sheet.

Correlative Information for Figure 6.3.7.1.7

Equation
Creep Strain, percent:

$$\varepsilon=\left(6.223\times10^{7}\exp(-\frac{50760}{T})\right)\left(\sigma^{0.3928\exp(\frac{2554}{T})}\right)\left(t^{4.1557\exp(\frac{-3934}{T})}\right)$$ [a]

Temperature (T) = Fahrenheit + 460

Example

Temp., T = 1600°F
Stress, σ = 7.5 ksi
Time, t = 10 hours
Creep Strain, ε = 0.080

---

[a] This equation should only be used in the same temperature ranges indicated in the nomograph. Creep strains computed outside these temperature ranges may yield unreasonable values.

6.3.8 WASPALOY

6.3.8.0 Comments and Properties — Waspaloy is a vacuum-melted precipitation-hardened nickel-base alloy which is strengthened by the precipitation of titanium and aluminum compounds and the solid-solution strengthening effects of chromium, molybdenum, and cobalt. The alloy is designed for highly stressed parts operating at temperatures up to 1550°F, such as aircraft gas turbine blades and discs and rocket engine parts. It is available in all the usual mill forms.

The optimum range for forging is 1900°F to 2050°F. Avoid working the alloy below 1900°F due to danger of cracking and also decreasing the stress-rupture life. Sufficient soaking time between heating is necessary to ensure complete recrystallization; however, avoid excessive long-time soaking at the high forging temperature. Furnace atmospheres should be either neutral or slightly oxidizing to prevent carburization and to minimize scaling.

Waspaloy is relatively difficult to machine. Drilling, turning, etc., can best be accomplished in solution-treated and partially aged condition. Generally, carbine tools are preferred, and positive feeds are required to avoid work hardening. For finish machining, grinding is preferable.

Waspaloy is susceptible to hot cracking or “hot-shortness” above 2150°F; therefore, extreme care should be exercised in the design of weldments so that restraint can be minimized. Waspaloy should be welded in the annealed condition, with minimum heat input, and with rapid cooling by means of chill bars and gas backup. This alloy has good resistance to oxidation at temperatures up to 1750°F and to combustion products encountered in aircraft gas turbines.

Two heat treatments are used for this material. One is for optimum tensile strength (solution treated 1825°F to 1900°F, stabilize 1550°F, 24 hours air cool, and age 16 hours at 1400°F air cool), and the other for stress-rupture properties (solution treated 1975°F, stabilized 1550°F, 24 hours air cool, age 1400°F, 16 hours air cool).

Some material specifications for Waspaloy are shown in Table 6.3.8.0(a). Room-temperature mechanical properties are shown in Table 6.3.8.0(b). Physical properties at room and elevated temperatures are shown in Figure 6.3.8.0.

Table 6.3.8.0(a). Material Specifications for Waspaloy

Specification	Form
AMS 5544	Plate, sheet, and strip
AMS 5704	Forgings
AMS 5706	Bar, forging, ring
AMS 5707	Bar, forging, ring
AMS 5708	Bar, forging, ring
AMS 5709	Bar, forging, ring[a]

a Primarily for applications requiring high stress-rupture strength.

6.3.8.1 Aged Condition — Stress rupture requirements at elevated temperatures are specified in material specifications. The appropriate specification should be consulted for detailed requirements. The effect of temperature on various mechanical properties is shown in Figures 6.3.8.1.1, 6.3.8.1.4, as well as 6.3.8.1.5(a) and (b). The effect of temperature on the Ramberg-Osgood parameter, n (tension), is shown in Figure 6.3.8.1.6(a). Typical tensile stress-strain curves are shown in Figure 6.3.8.1.6(b).

Table 6.3.8.0(b). Design Mechanical and Physical Properties of Waspaloy

Specification	AMS 5544		AMS 5704	AMS 5706 and AMS 5707
Form	Sheet, strip, and plate		Forging	Bar, forging, and ring
Condition	Solution, stabilization, and precipitation heat treated			
Thickness, in.	≤0.020	>0.020	≤3.500	≤3.500
Basis	S	S	S	S
Mechanical Properties:				
F_{tu}, ksi:				
L	...	...	175	160
LT	170	175	...	...
F_{ty}, ksi:				
L	...	...	120	110
LT	110	115	...	...
F_{cy}, ksi:				
L	...	...	...	...
LT	...	...	...	...
F_{su}, ksi	...	...	...	...
F_{bru}, ksi:				
(e/D = 1.5)	...	...	...	...
(e/D = 2.0)	...	...	...	...
F_{bry}, ksi:				
(e/D = 1.5)	...	...	...	...
(e/D = 2.0)	...	...	...	...
e, percent:				
L	...	...	15	15
LT	15	20	...	...
RA, percent:				
L	...	...	18	18
E, 10^3 ksi	30.6			
E_c, 10^3 ksi	...			
G, 10^3 ksi	...			
μ	...			
Physical Properties:				
ω, lb/in.^{3}	0.298			
C, Btu/(lb)(°F)	See Figure 6.3.8.0			
K, Btu/[(hr)(ft^2)(°F)/ft]	See Figure 6.3.8.0			
α, 10^{-6} in./in./°F	See Figure 6.3.8.0			

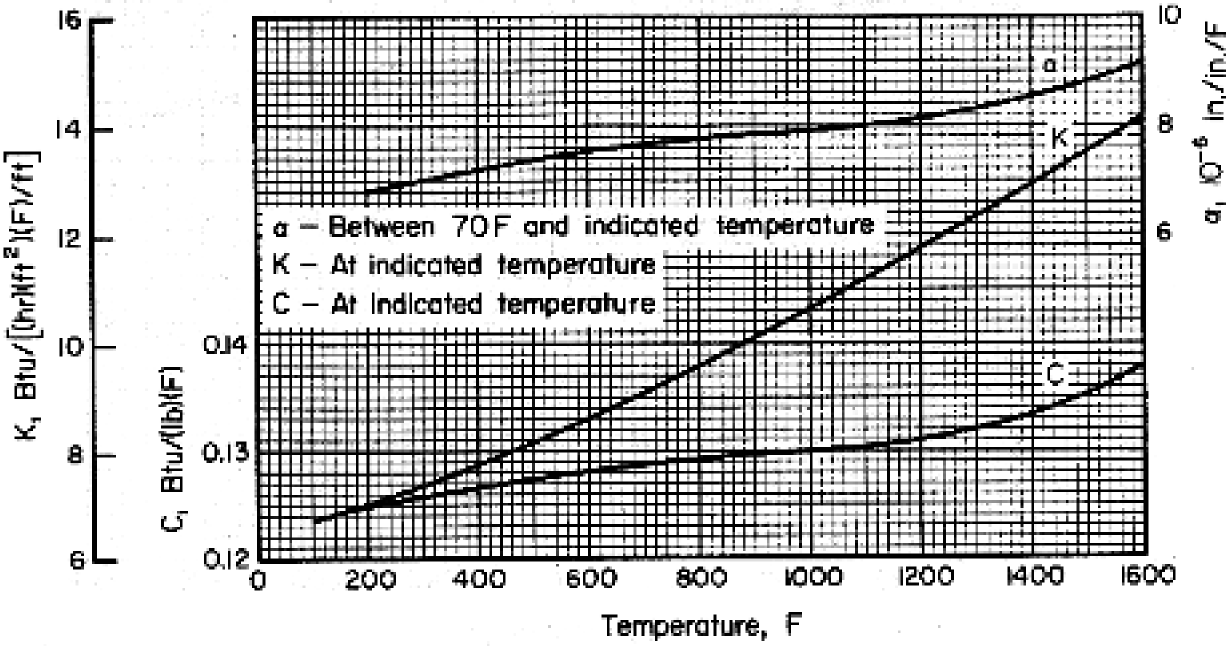

Figure 6.3.8.0. Effect of temperature on the physical properties of Waspaloy.

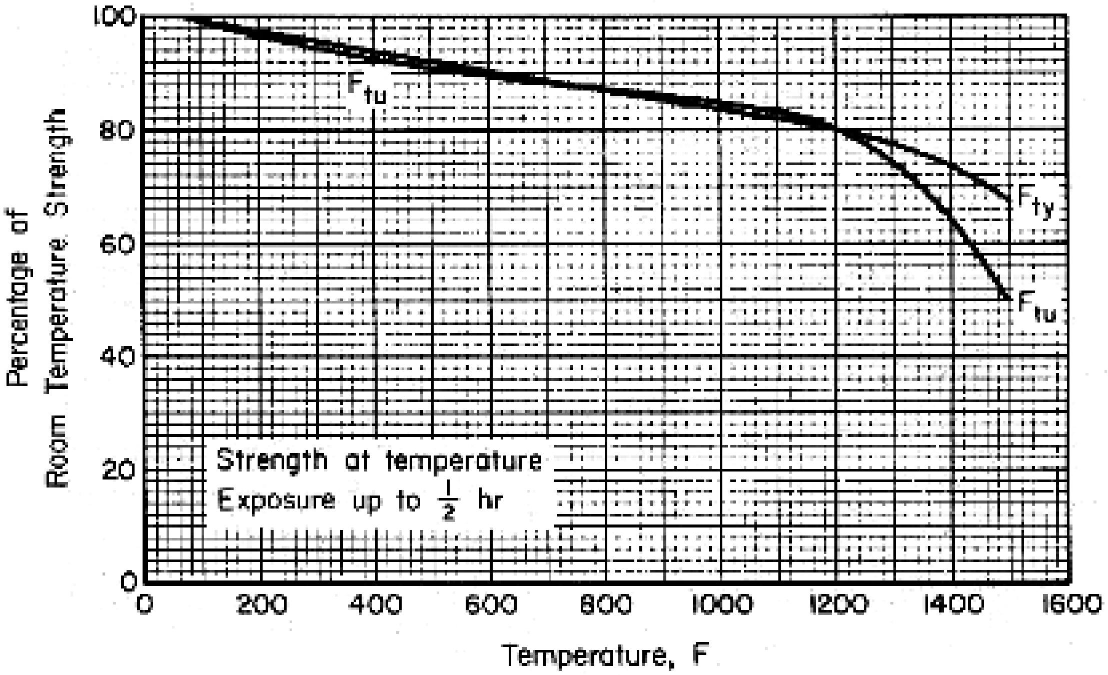

Figure 6.3.8.1.1. Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of Waspaloy.

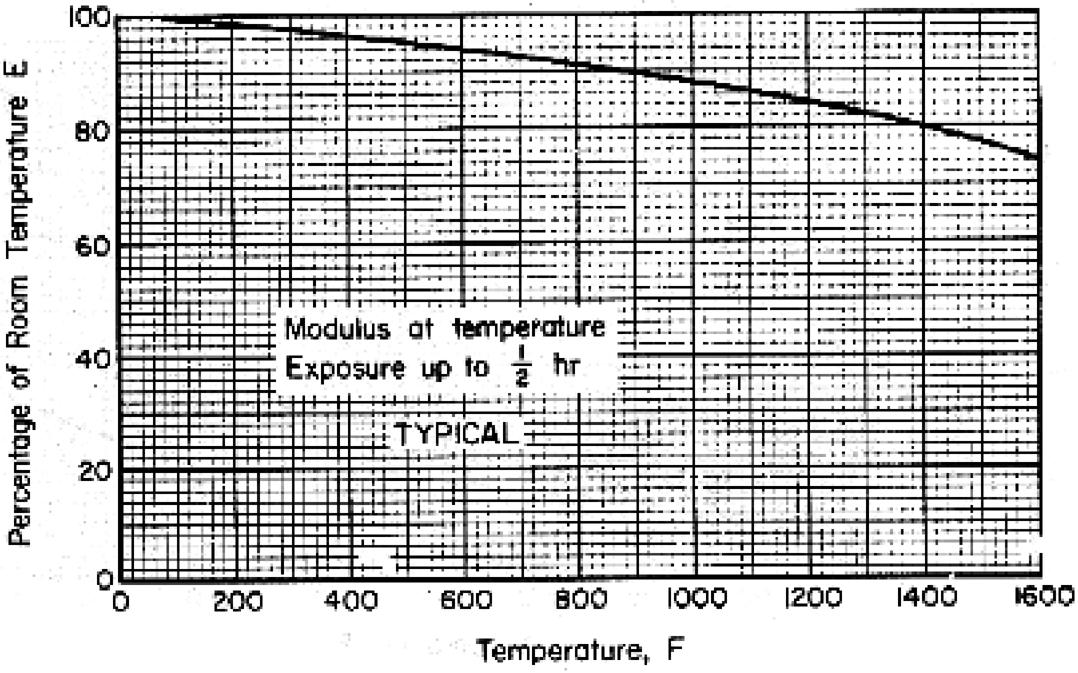

Figure 6.3.8.1.4. Effect of temperature on the modulus of elasticity (E) of Waspaloy.

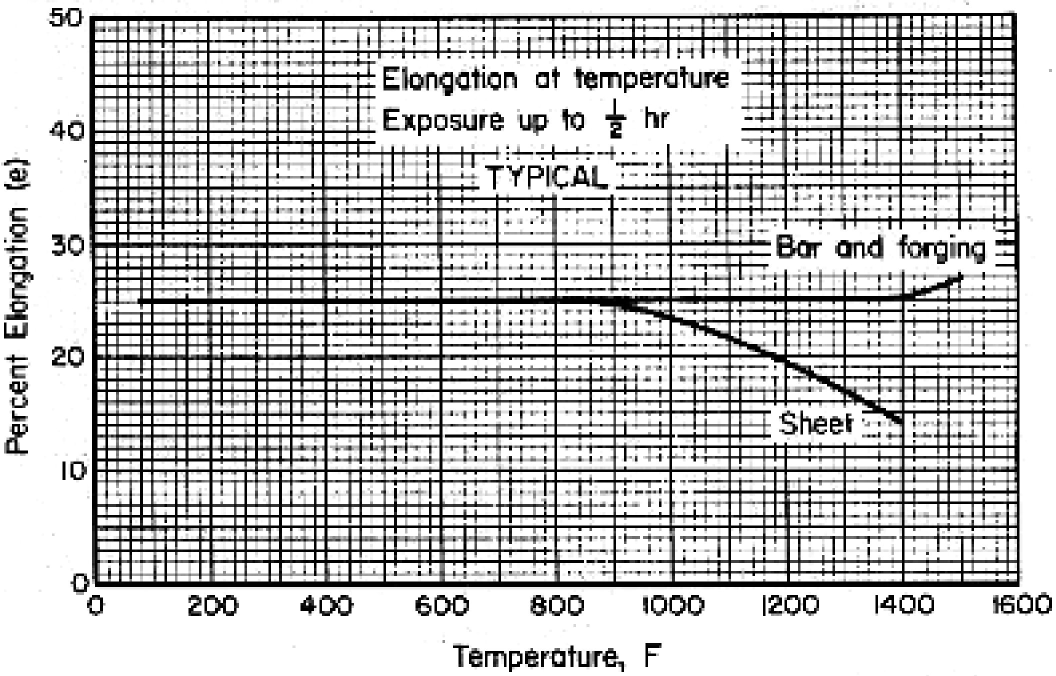

Figure 6.3.8.1.5(a). Effect of temperature on elongation (e) of Waspaloy.

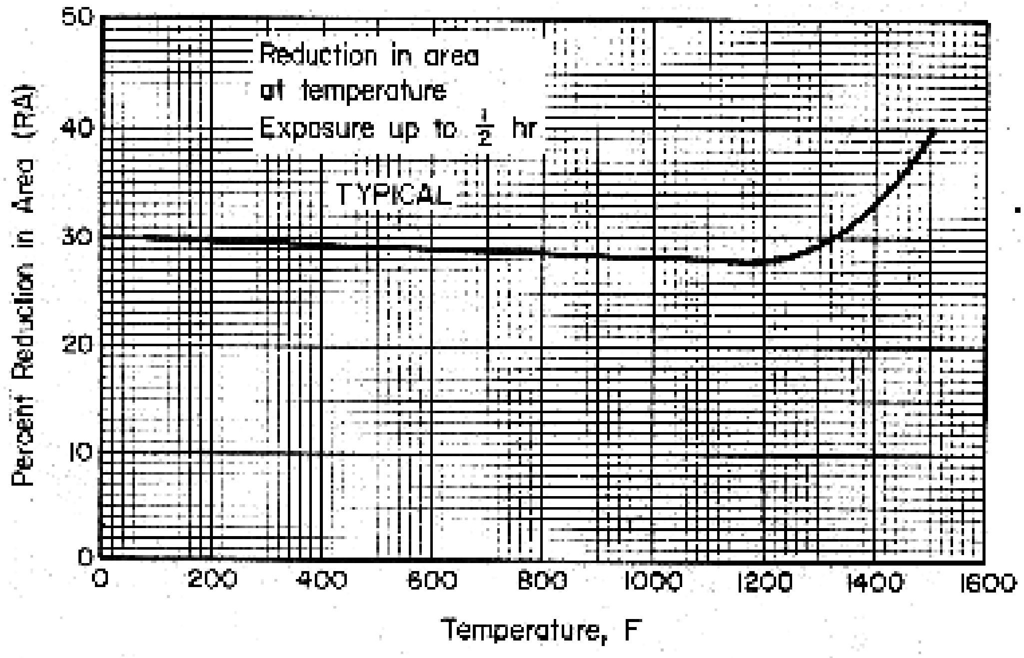

Figure 6.3.8.1.5(b). Effect of temperature on reduction in area (RA) of Waspaloy bar and forging.

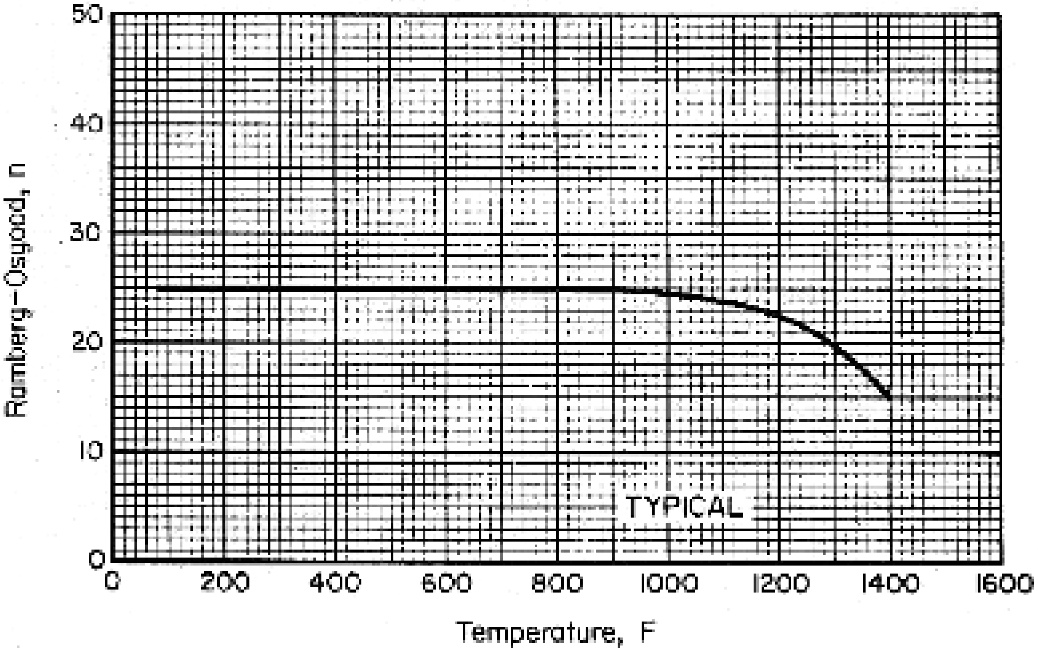

Figure 6.3.8.1.6(a). Effect of temperature on Ramberg-Osgood parameter (n in tension) of Waspaloy.

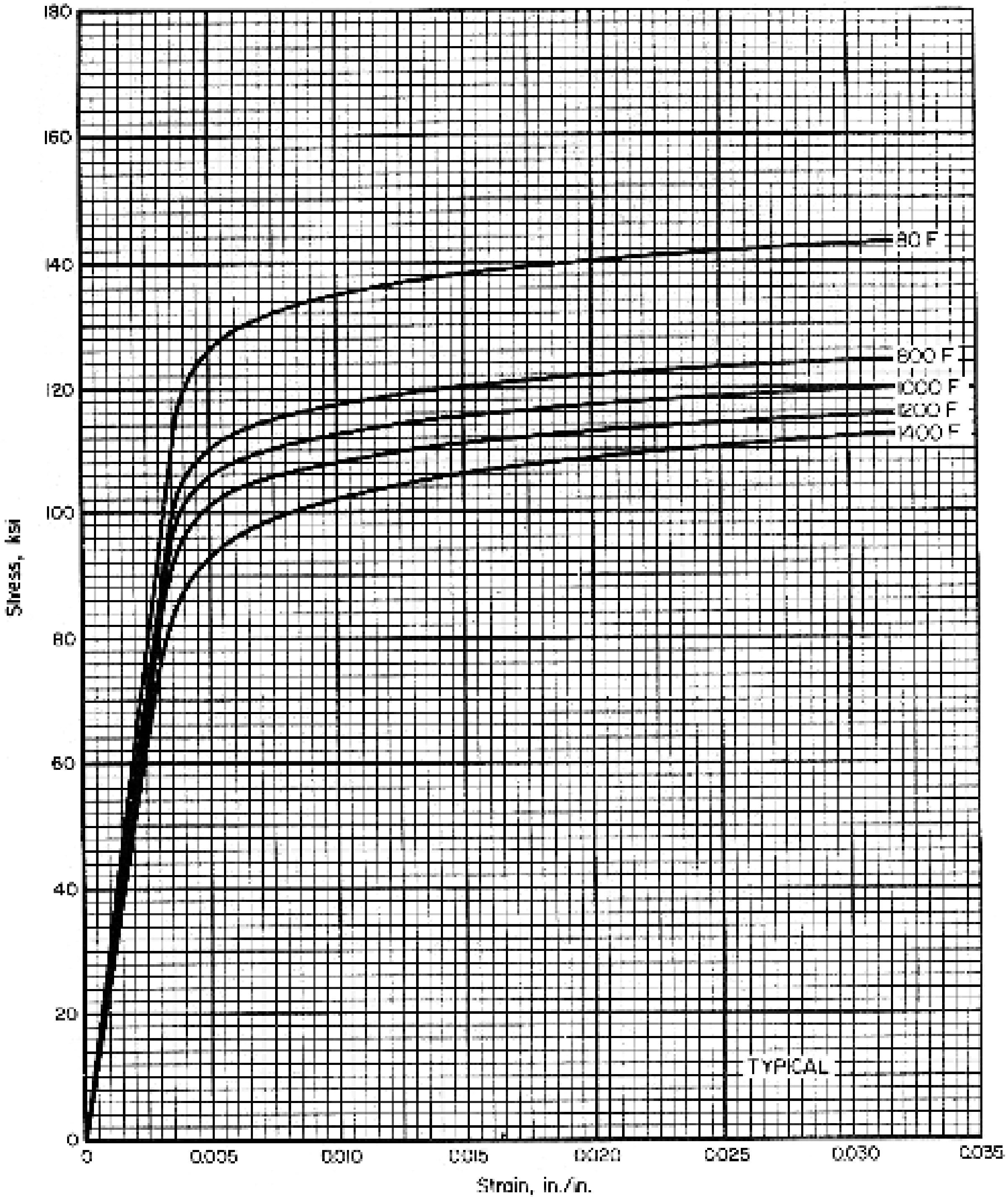

Figure 6.3.8.1.6(b). Typical tensile stress-strain curves for Waspaloy at room and elevated temperatures (all products).

6.3.9. HAYNES® 230®*

6.3.9.0. *Comments and Properties* — HAYNES® 230® alloy provides excellent oxidation resistance up to 2100°F for prolonged exposures with superior long term stability, high temperature strength and good fabricability. It is produced in the form of plate, sheet, strip, foil, billet, bar, wire welding products, pipe, tubing, remelt bar, and may be cast using traditional air-melt sand mold or vacuum-melt investment foundry techniques. Products are used for gas turbine components in the aerospace industry, catalyst grid supports in the chemical process industry, and various other high-temperature applications.

Environmental Considerations — HAYNES 230 alloy has excellent corrosion resistance to both air and combustion gas oxidizing environments. It also exhibits excellent nitriding resistance and good resistance to carburization and hydrogen embrittlement.

Machining — HAYNES 230 alloy has similar machining characteristics to other solid-solution-strengthened nickel-based alloys. This group of materials is classified moderate to difficult to machine, however, they can be machined using conventional methods at satisfactory rates. They work-harden rapidly, requiring slower speeds and feeds with heavier cuts than would be used for machining stainless steels. See HAYNES publication H-3159 for more detailed information.

Joining — HAYNES 230 alloy has excellent forming and welding characteristics similar to HASTELLOY® X alloy. It is readily welded using GTAW (Gas Tungsten-Arc Welding), GMAW (Gas Metal-Arc Welding), SMAW (Shielded Metal-Arc Welding), and resistance techniques. HAYNES 230-W™ alloy is the recommended filler metal.

Heat Treatment — This alloy is normally final solution heat-treated between 2150°F and 2275°F. Annealing during fabrication can be performed at slightly lower temperatures, but a final subsequent solution heat treatment followed by rapid cooling is needed to produce optimum properties and structure.

Specifications and Properties — Material specifications are shown in Table 6.3.9.0(a).

Table 6.3.9.0(a). Material Specifications for HAYNES 230 Alloy Wrought

Specification	Form
AMS 5878	Plate, sheet, and strip
AMS 5891	Bar and forging

Room temperature mechanical and physical properties are shown in Tables 6.3.9.0(b) and (c).

6.3.9.1. *Annealed Condition* — Elevated temperature mechanical properties are shown in Figures 6.3.9.1.1(a) and (b). Typical stress-strain and full-range curves are shown in Figure 6.3.9.1.6(a) and (b).

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*HAYNES® and HASTELLOY® are registered trademarks of HAYNES International.

Table 6.3.9.0(b). Design Mechanical and Physical Properties of HAYNES 230 Alloy Sheet and Plate

Specification	AMS 5878					
Form	Sheet		Plate			
Condition	2250 Anneal		2200 Anneal			
Thickness or diameter, in.	≤0.125		≤0.400		0.401 to 1.500	
Basis	A	B	A	B	A	B
Mechanical Properties:						
F_{tu}, ksi:						
L	...	...	...	...	...	...
LT	114	117	115[a]	120	111	114
F_{ty}, ksi:						
L	...	...	...	...	...	...
LT	49	53	50	55	48	51
F_{cy}, ksi:						
L	...	...	...	...	...	...
LT	...	...	...	...	...	...
F_{su}, ksi						
F_{bru}, ksi:						
(e/D = 1.5)	...	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...	...
F_{bry}, ksi:						
(e/D = 1.5)	...	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...	...
e, percent:						
LT	39	42	40	43	39	42
E, 10^3 ksi	...					
E_c, 10^3 ksi	...					
G, 10^3 ksi	...					
μ	...					
Physical Properties:						
ω, lb/in.^{3}	0.324					
C, K, and α	See Figures 6.3.9.0(a),(b), and (c)					

[a] S-basis. The rounded T_{99} value for F_{tu} (L) = 117 ksi.

Table 6.3.9.0(c). Design Mechanical and Physical Properties of HAYNES230 Bar

Specification	AMS 5891											
Form	Bar											
Condition	2250 Anneal											
Thickness, in.	≤1.000		1.001 to 2.000		2.001 to 3.000		3.001 to 4.000		4.001 to 5.000		5.001 to 6.000	
Basis	A	B	A	B	A	B	A	B	A	B	A	B
Mechanical Properties:												
F_{tu}, ksi: L	110	118	110	117	110	115	110	114	109	112	107	110
F_{ty}, ksi: L	45[a]	51	45[a]	51	45[a]	51	45[a]	51	45[a]	51	45[a]	51
F_{cy}, ksi	...	...	...	...	...	...	...	...	...	...	...	...
F_{su}, ksi	...	...	...	...	...	...	...	...	...	...	...	...
F_{bru}, ksi:												
(e/D = 1.5)	...	...	...	...	...	...	...	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...	...	...	...	...	...	...	...
F_{bry}, ksi:												
(e/D = 1.5)	...	...	...	...	...	...	...	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...	...	...	...	...	...	...	...
e, percent: L	35	46	35	46	35	46	35	46	35	46	35	46
E, 10^3 ksi	...											
E_c, 10^3 ksi	...											
G, 10^3 ksi	...											
μ	...											
Physical Properties:												
ω, lb/in.^{3}	0.324											
C, K and α	See Figures 6.3.9.0(a), (b), and (c)											

[a] S-basis. The rounded T_{99} values for F_{ty} (L) = 48 ksi.

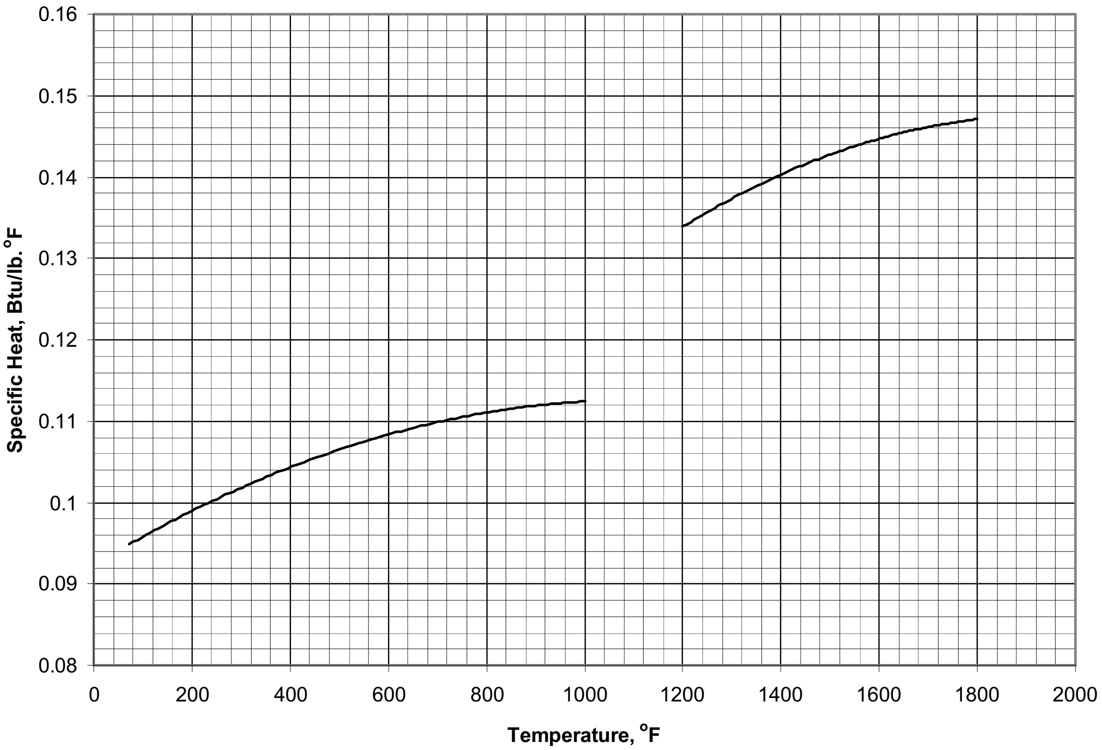


Figure 6.3.9.0(a). Effect of temperature on specific heat of HAYNES 230 alloy.

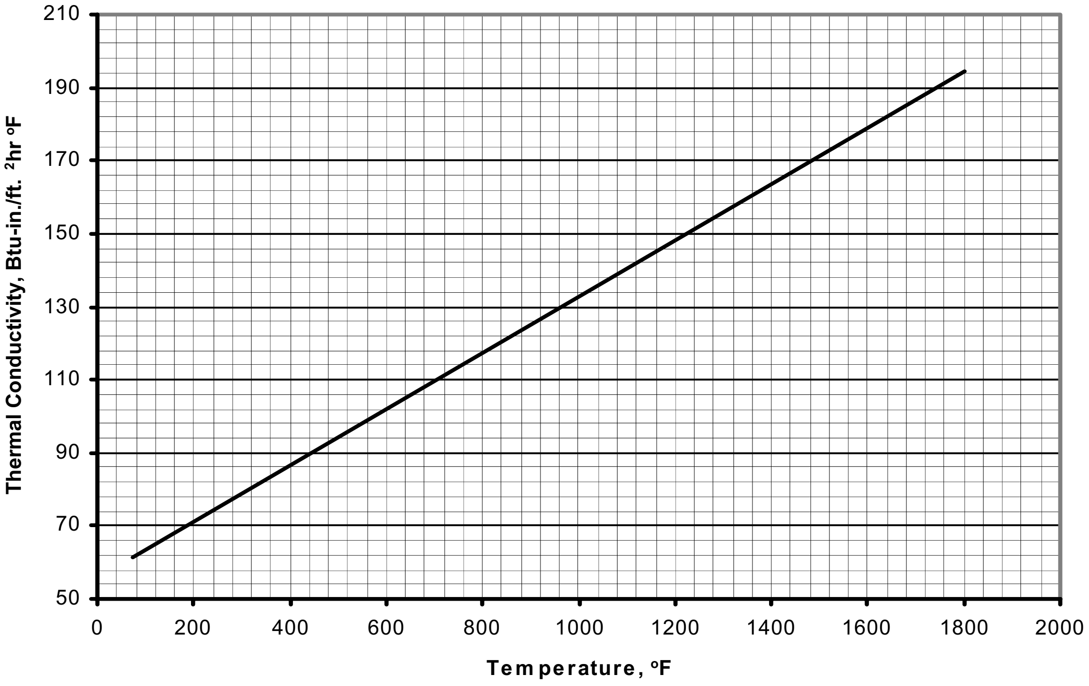


Figure 6.3.9.0(b). Effect of temperature on thermal conductivity of HAYNES 230 alloy.

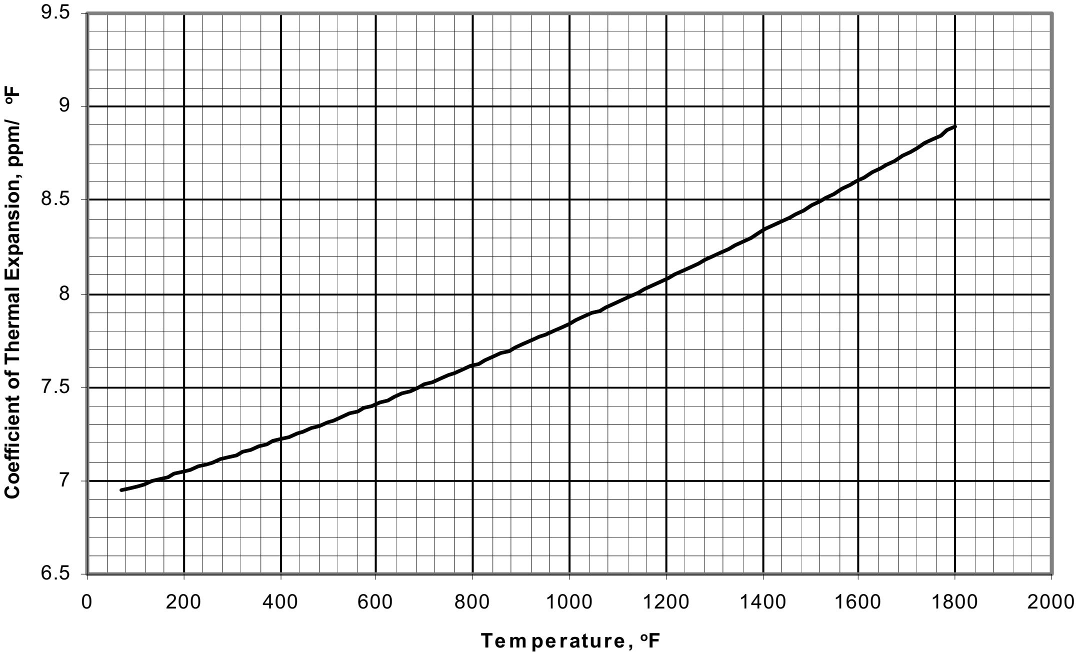


Figure 6.3.9.0(c). Effect of temperature on mean coefficient of thermal expansion of HAYNES 230 alloy between 70° F and the temperature indicated.

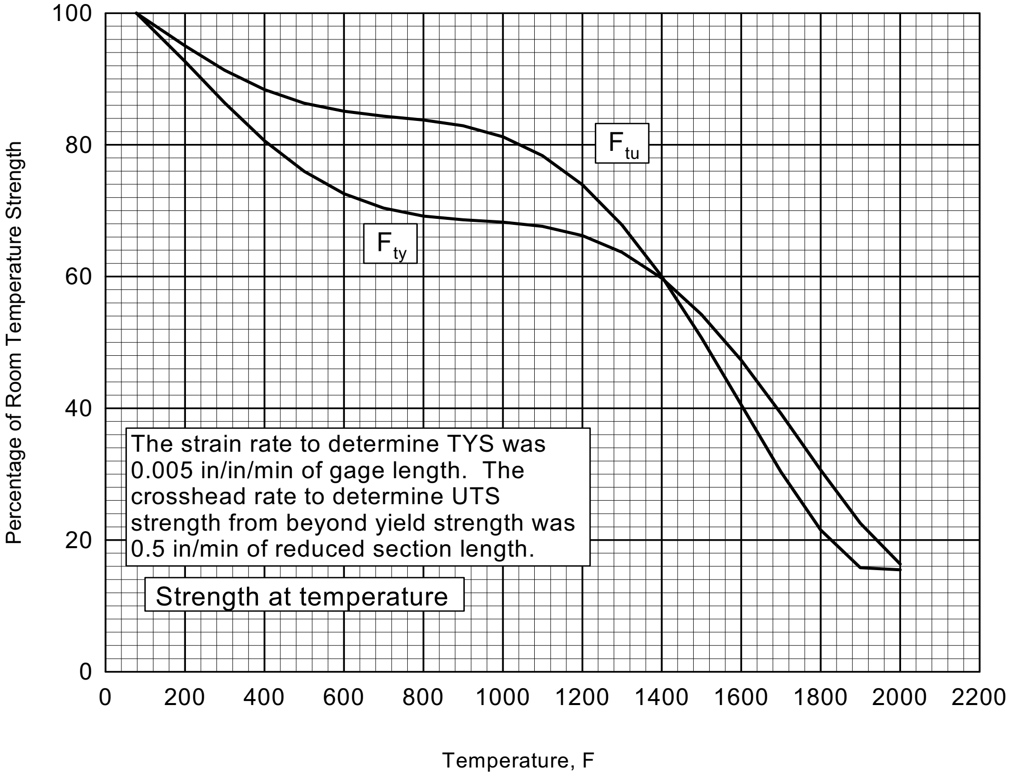


Figure 6.3.9.1.1(a). Effect of temperature on tensile properties of Haynes 230 alloy plate.

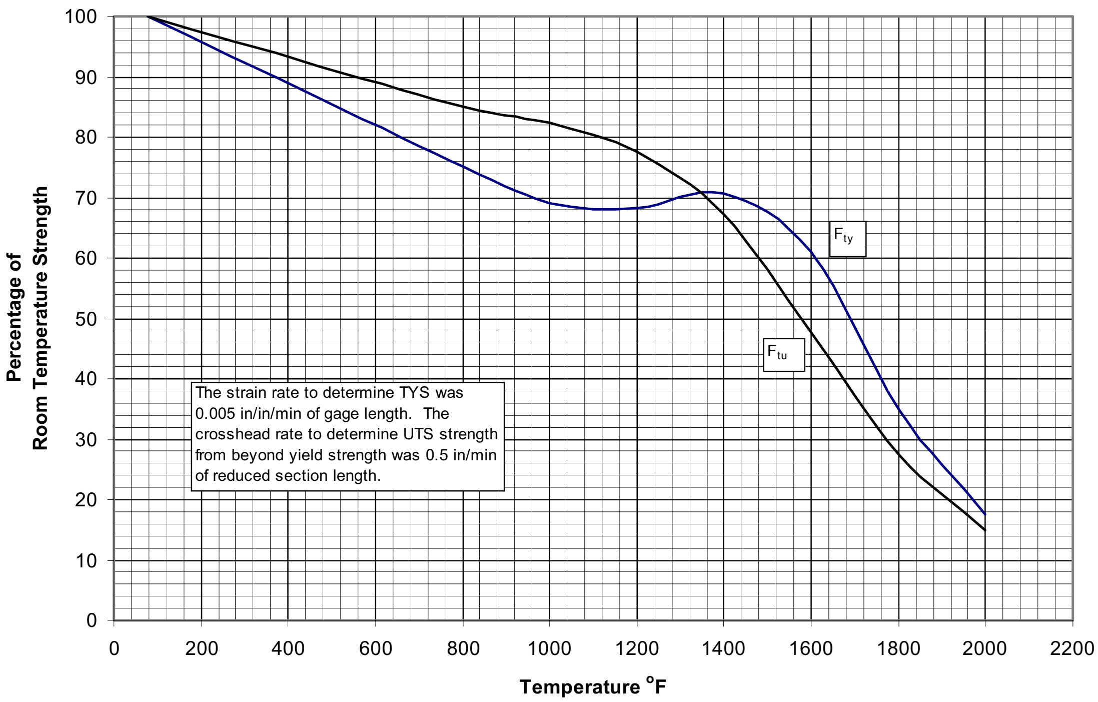


Figure 6.3.9.1.1(b). Effect of temperature on tensile properties of HAYNES 230 alloy bar ranging up to 1.3 inches in diameter.

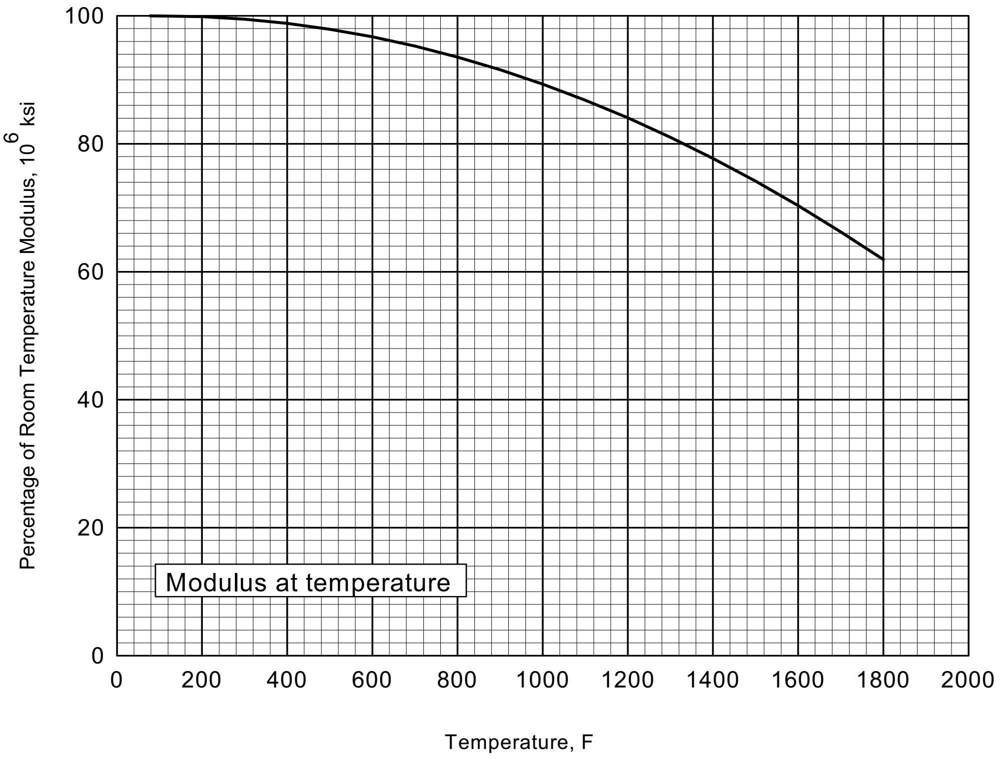


Figure 6.3.9.1.4. Effect of temperature on modulus of Haynes 230 alloy plate.

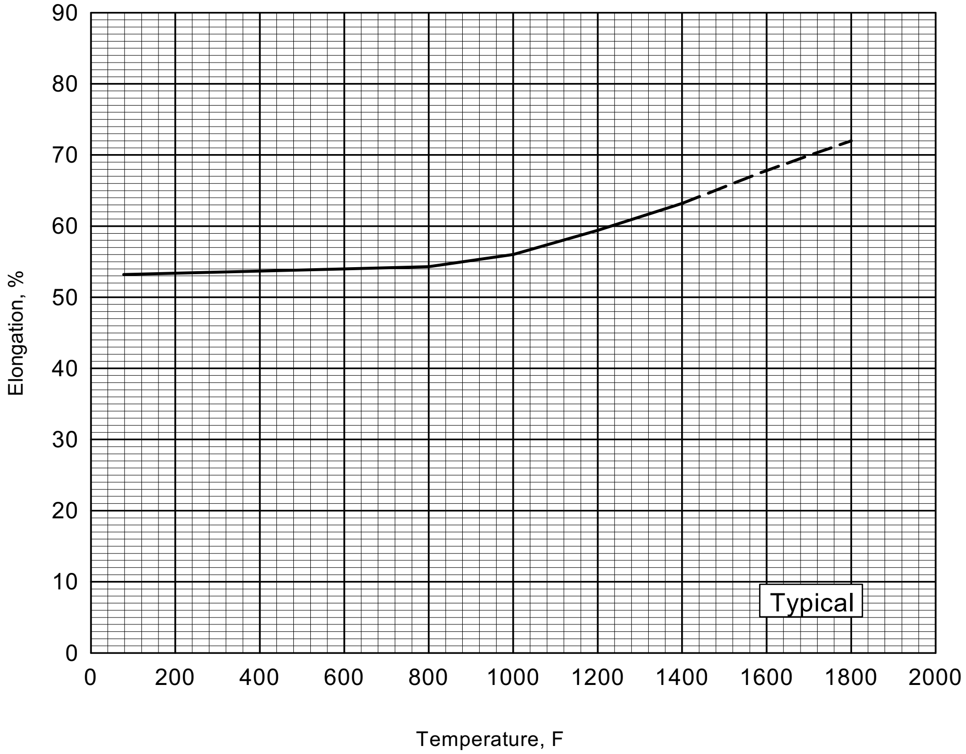


Figure 6.3.9.1.5. Effect of temperature on elongation of Haynes 230 alloy plate.

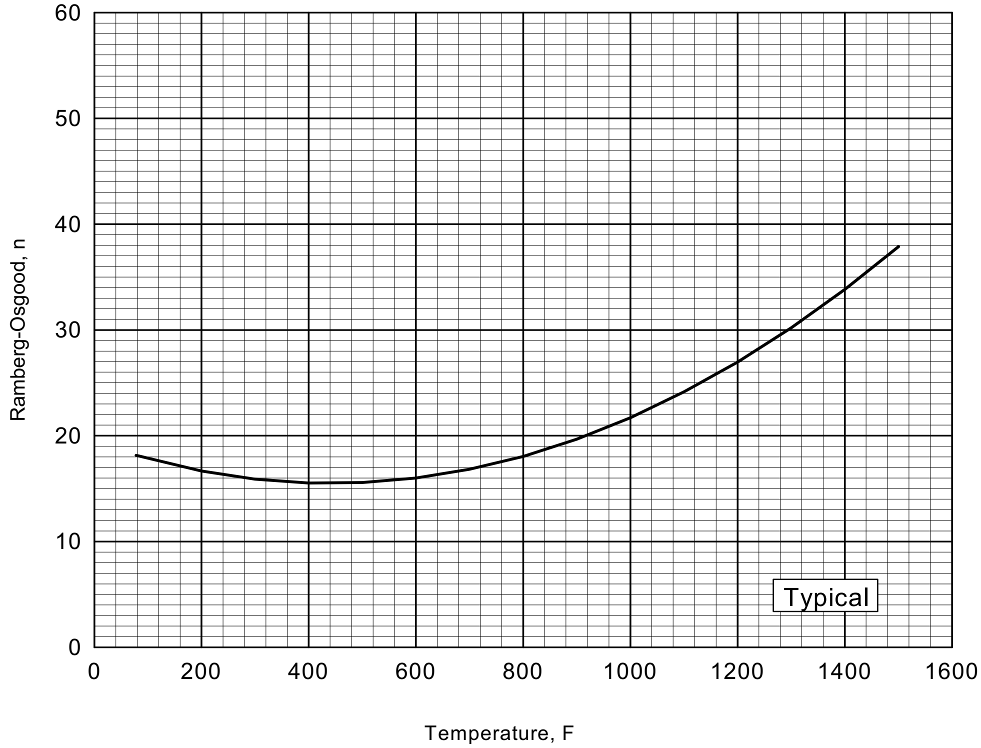


Figure 6.3.9.1.6(a). Effect of temperature on Ramberg-Osgood parameter (n in tension) of Haynes 230 alloy plate.

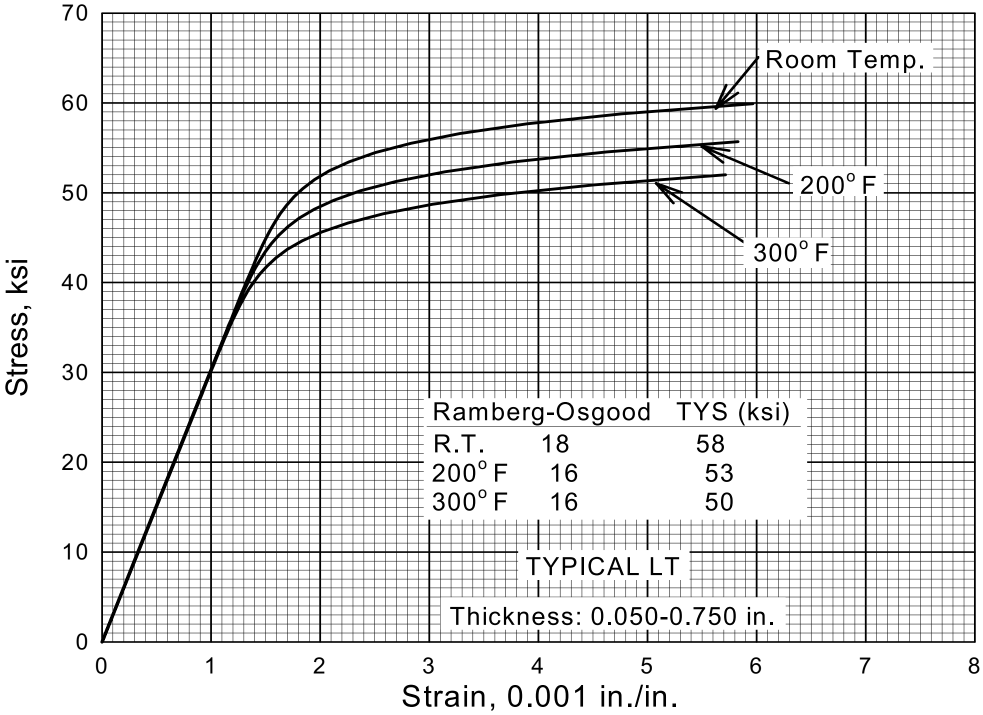


Figure 6.3.9.1.6(b). Typical tensile stress-strain curves for Haynes 230 plate at room temperature, 200°F, and 300°F.

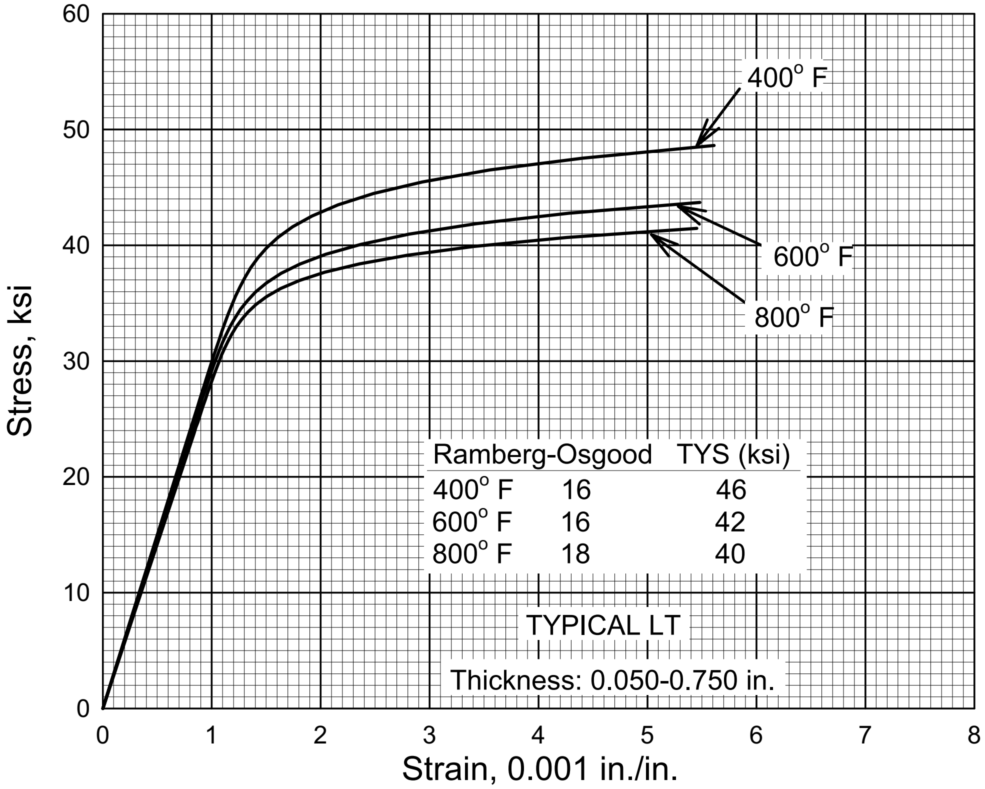
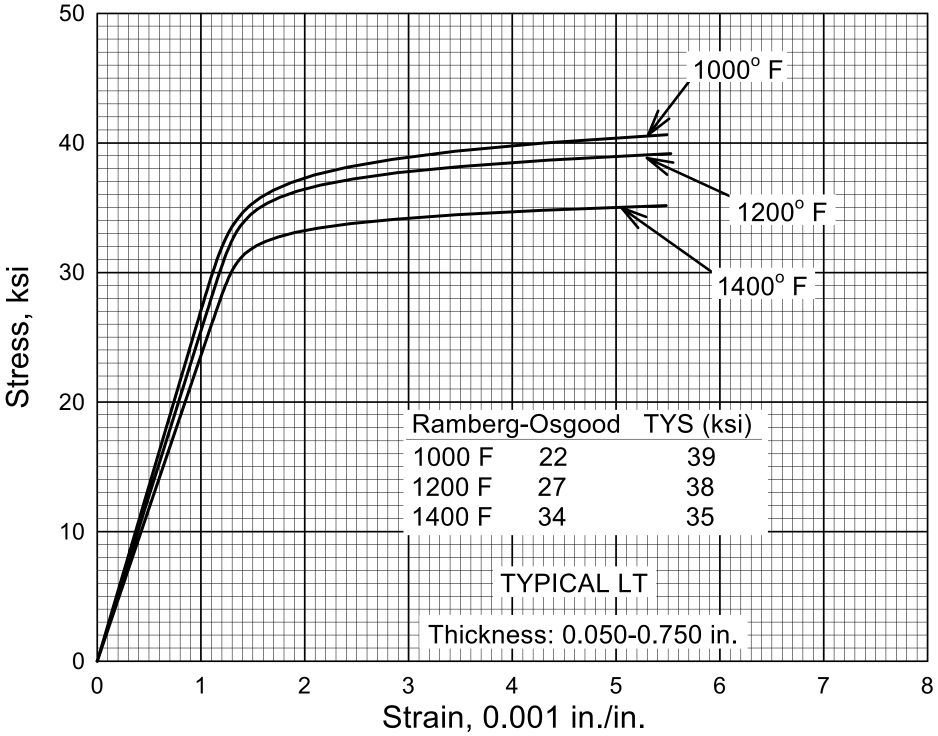


Fig 6.3.9.1.6(c). Typical tensile stress-strain curves for Haynes 230 plate at 400°F, 600°F, and 800°F.



Ramberg-Osgood		TYS (ksi)
1000 F	22	39
1200 F	27	38
1400 F	34	35

Figure 6.3.9.1.6(d). Typical tensile stress-strain curves for Haynes 230 plate at 1000°F, 1200°F, and 1400°F.

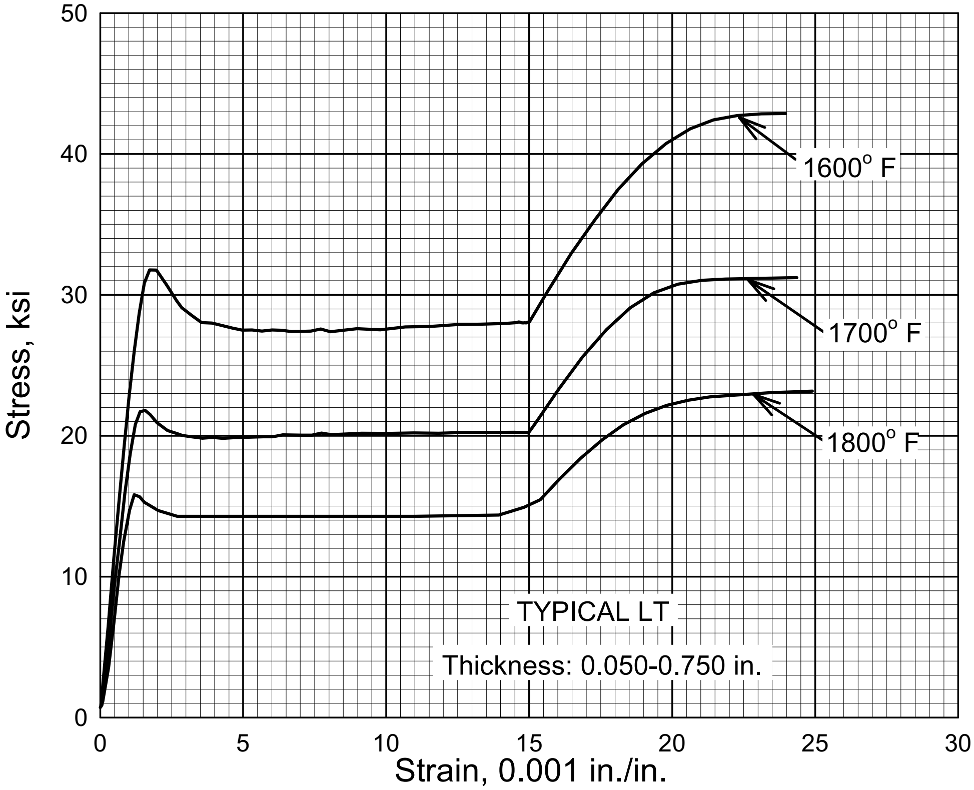


Figure 6.3.9.1.6(e). Typical tensile stress-strain curves for Haynes 230 plat at 1600°F, 1700°F, and 1800°F.

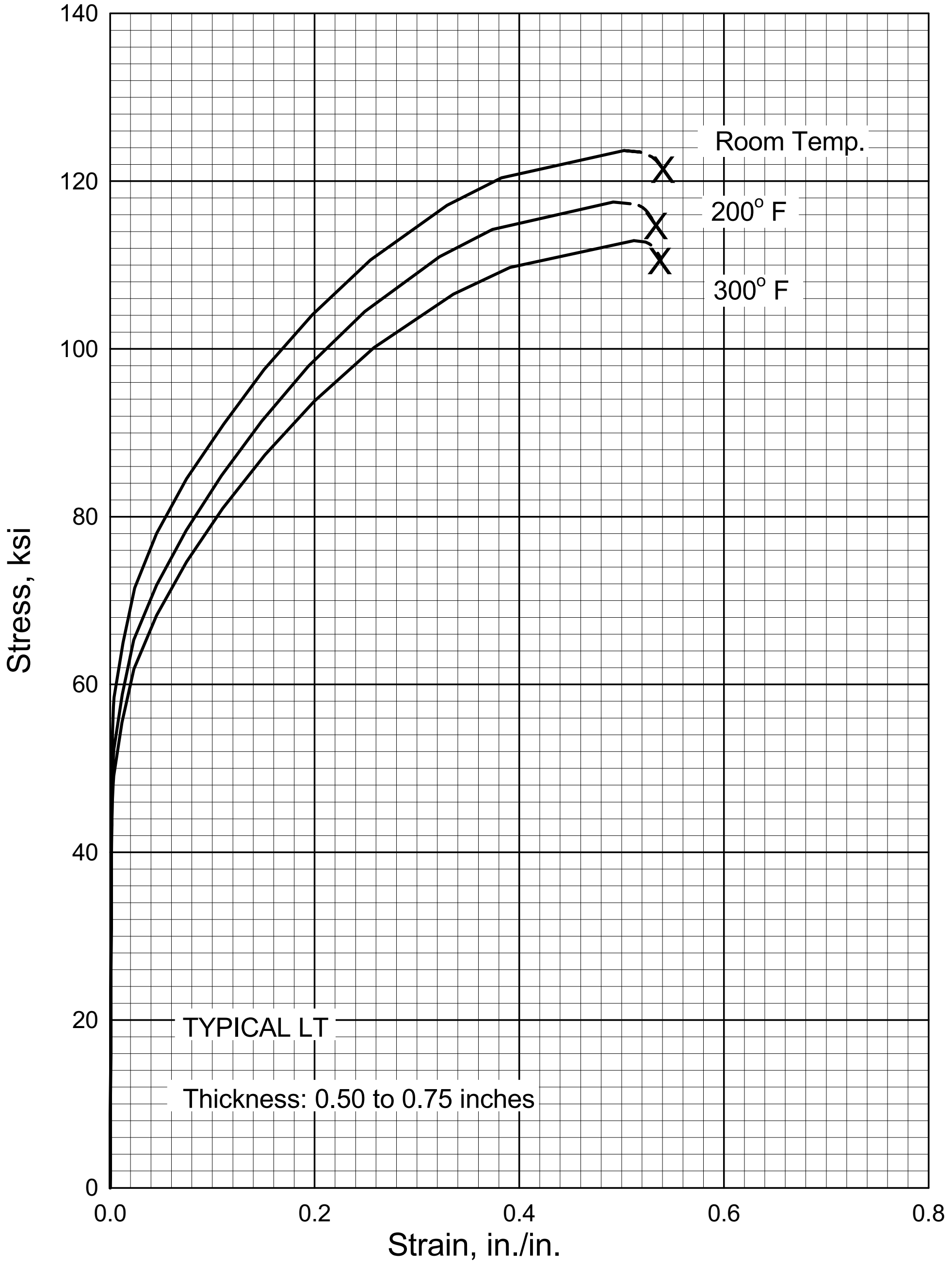


Figure 6.3.9.1.6(f). Full range tensile stress-strain curves for Haynes 230 plate at room temperature, 200°F, and 300°F.

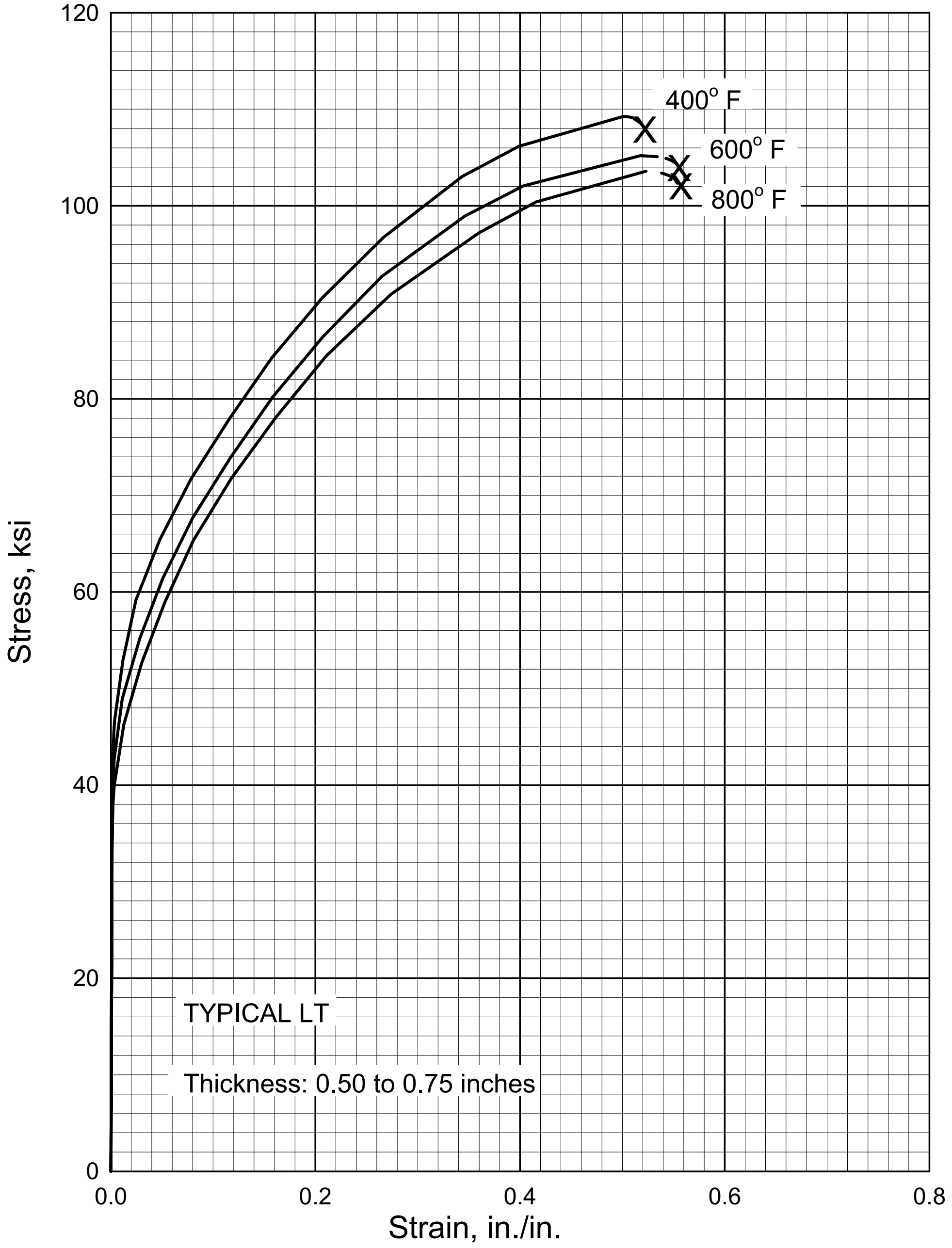


Figure 6.3.9.1.6(g). Full range tensile stress-strain curves for Haynes 230 plate at 400°F, 600°F, and 800°F.

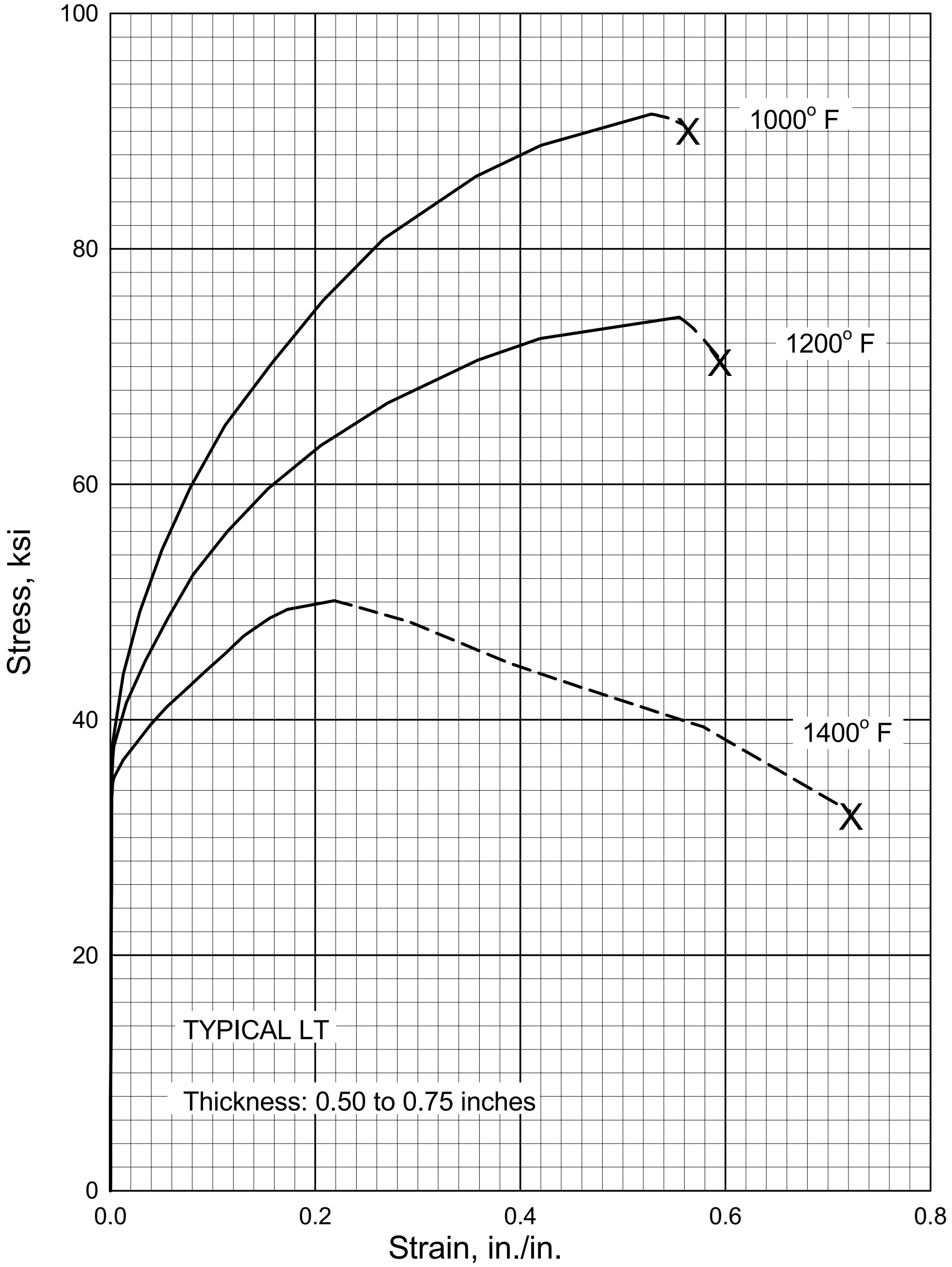


Figure 6.3.9.1.6(h). Full range tensile stress-strain curves for Haynes 230 plate at 1000°F, 1200°F, and 1400°F.

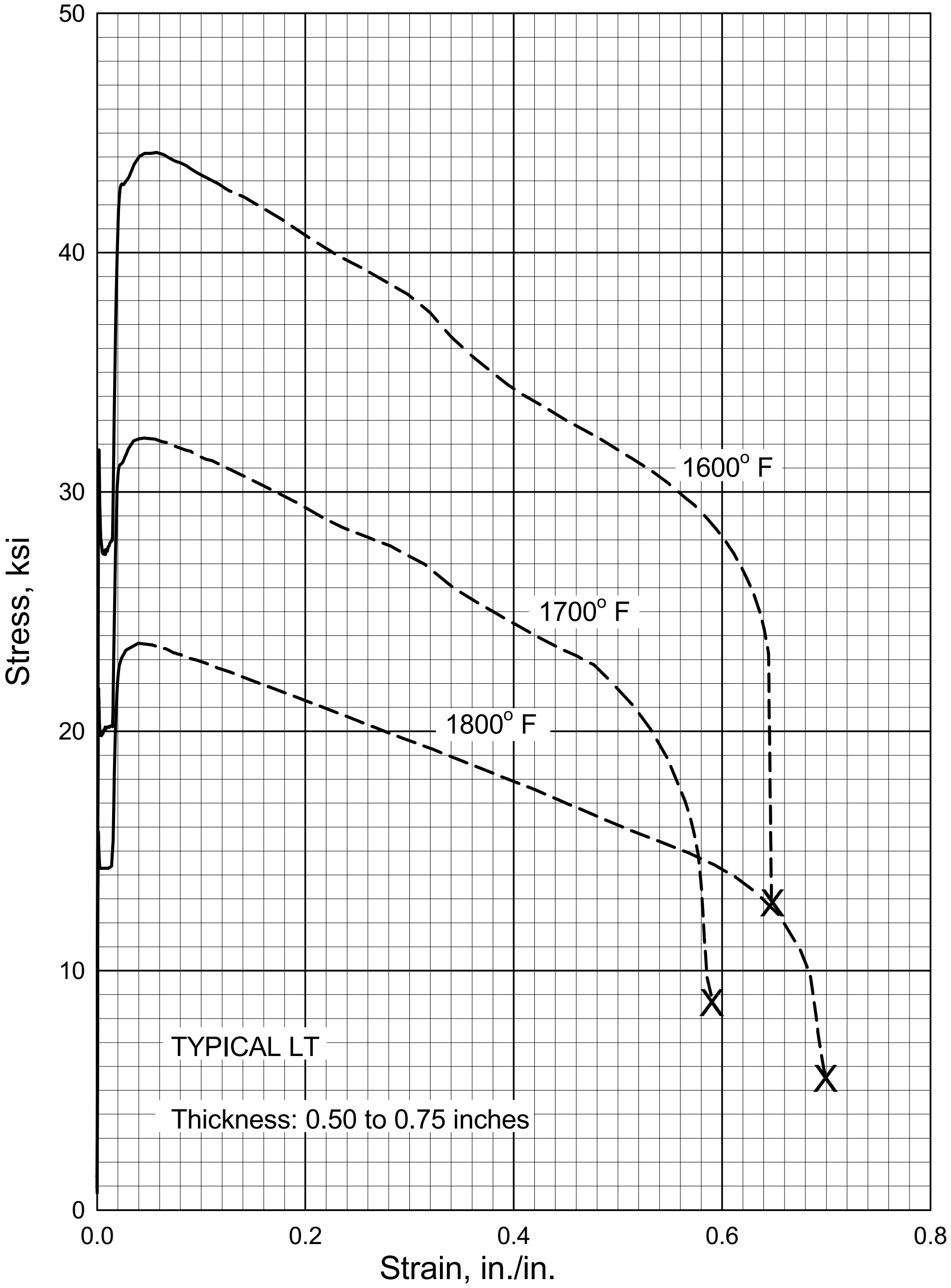


Figure 6.3.9.1.6(i). Full range tensile stress-strain curves for Haynes 230 plate at 1600°F, 1700°F, and 1800°F.

6.3.10 HAYNES® HR-120®*

6.3.10.0 *Comments and Properties* — HAYNES HR-120 alloy is a solid-solution strengthened Fe-Ni-Cr alloy with excellent high temperature strength, very good resistance to carburizing and sulfiding environments, and readily formed hot or cold.

Environmental Considerations — HAYNES HR-120 alloy has very good sulfide and carburization resistance. Oxidation resistance is comparable to other Fe-Ni-Cr materials such as alloys 330 and 800H, yet with a greater strength at temperatures up to 2000°F.

Machining — This alloy is readily machinable using conventional practices similar to those for 300 series austenitic stainless steels. Minor adjustments may be required to yield optimum results. See HAYNES publication H-3125B for more detailed information.

Joining — Welding characteristics are similar to the HASTELLOY® alloys. The alloy is readily welded using GTAW (Gas Tungsten-Arc Welding), GMAW (Gas Metal-Arc Welding), and SMAW (Shielded Metal-Arc Welding) techniques. HAYNES® 556™ alloy is the recommended filler wire (AMS5831) for GTAW and GMAW processes. Multimet® alloy covered electrode (AMS 5795) is recommended for SMAW processes. HASTELLOY® X alloy filler wire (AMS 5798) and covered electrode (AMS 5799) may also be used.

Heat Treatment — This alloy is solution annealed between 2150°F and 2250°F and rapidly cooled.

Specifications and Properties — Material specifications are shown in Table 6.3.10.0(a).

Table 6.3.10.0(a). Material Specifications for HAYNES HR-120 Alloy Wrought Products

Specification	Form
AMS 5916	Sheet, strip and plate

Room temperature mechanical and physical properties are shown in Table 6.3.10.0(b).

6.3.10.1 *Annealed Condition* — Elevated temperature tensile properties are shown in Figure 6.3.10.1.1(a). Stress rupture curves are shown in Figures 6.3.10.1.7(a) and (b)

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* HAYNES® and HASTELLOY® are registered trademarks of HAYNES International.

Table 6.3.10.0(b). Design Mechanical and Physical Properties of HAYNES HR-120 Alloy Sheet, Strip and Plate

Specification	AMS 5916		
Form	Sheet, Strip, and Plate		
Condition	Annealed		
Thickness or diameter, in.	>0.015 to 0.749		0.750 to 2.000
Basis	A	B	S
Mechanical Properties:			
F_{tu}, ksi:			
L	...	...	...
LT	90[a]	101	90
F_{ty}, ksi:			
L	...	...	...
LT	40[a]	44	40
F_{cy}, ksi:			
L	...	...	...
LT	...	...	...
F_{su}, ksi	...	...	...
F_{bru}[b], ksi:			
(e/D = 1.5)	...	...	...
(e/D = 2.0)	...	...	...
F_{bry}[a], ksi:			
(e/D = 1.5)	...	...	...
(e/D = 2.0)	...	...	...
e, percent (S-basis):			
LT	30	...	30
E, 10^3 ksi	see Figure 6.3.10.0(a)		
E_c, 10^3 ksi	...		
G, 10^3 ksi	...		
μ	...		
Physical Properties:			
ω, lb/in.^{3}	0.324		
C, K, and α	See Figures 6.3.9.0(b),(c), and (d)		

a S-basis. The rounded T_{99} value for F_{tu} (LT) = 94 ksi, F_{ty} (LT) = 41 ksi
b Bearing values are "dry pin" values per Section 1.4.7.1.

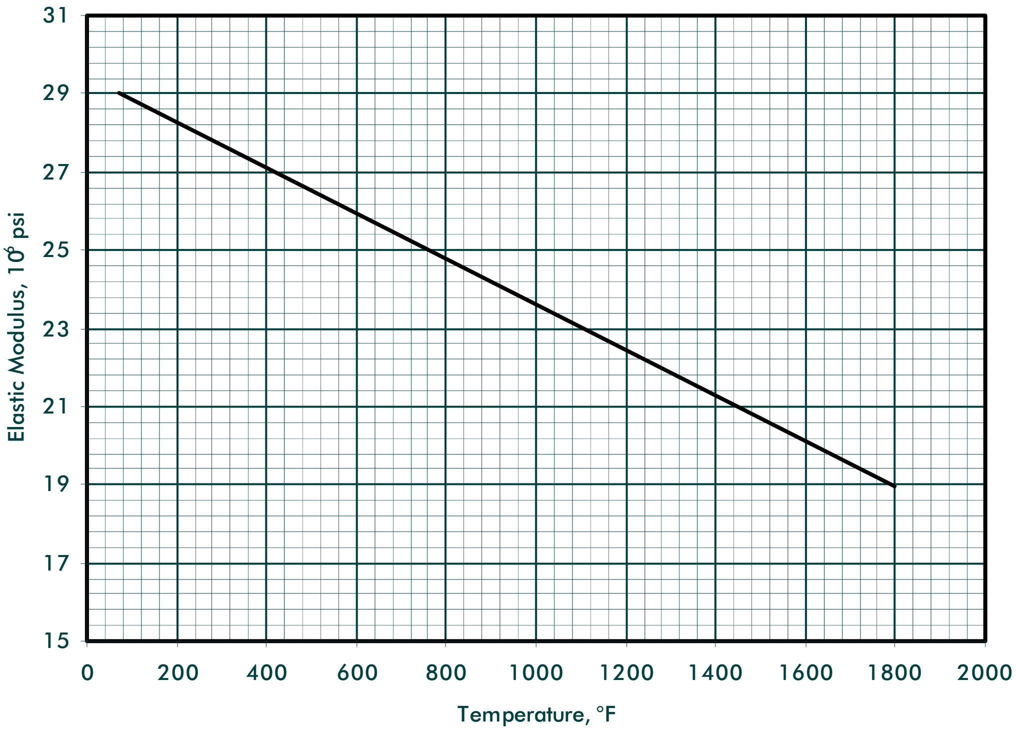


Figure 6.3.10.0(a). Effect of temperature on elastic modulus of HAYNES HR-120 alloy.

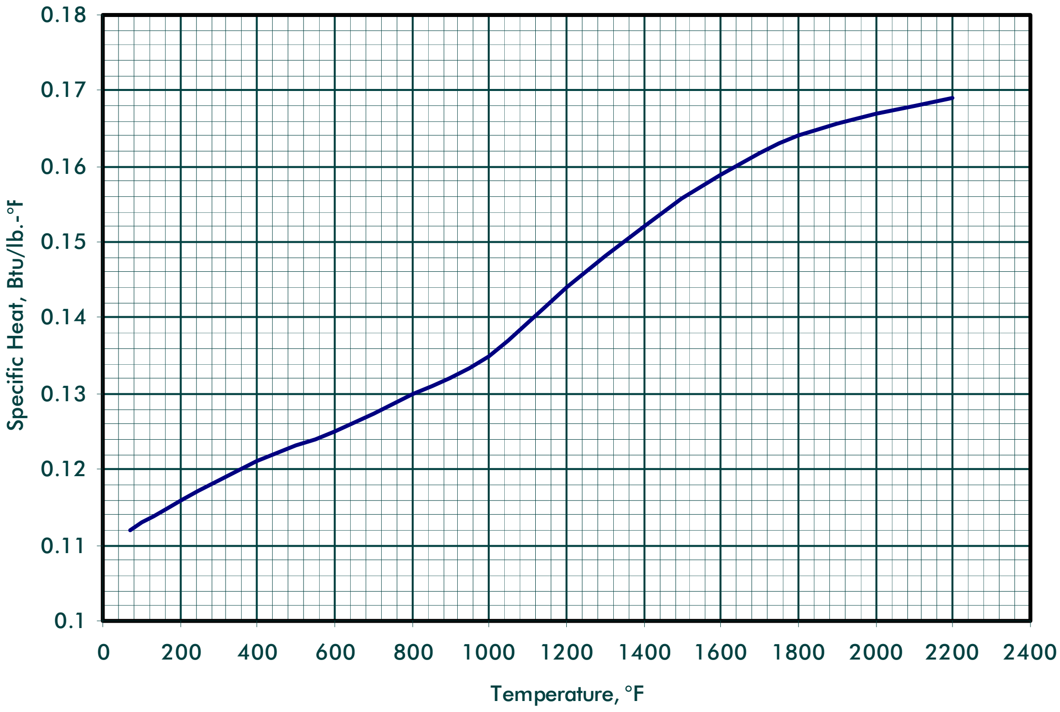


Figure 6.3.10.0(b). Effect of temperature on specific heat of HAYNES HR-120 alloy.

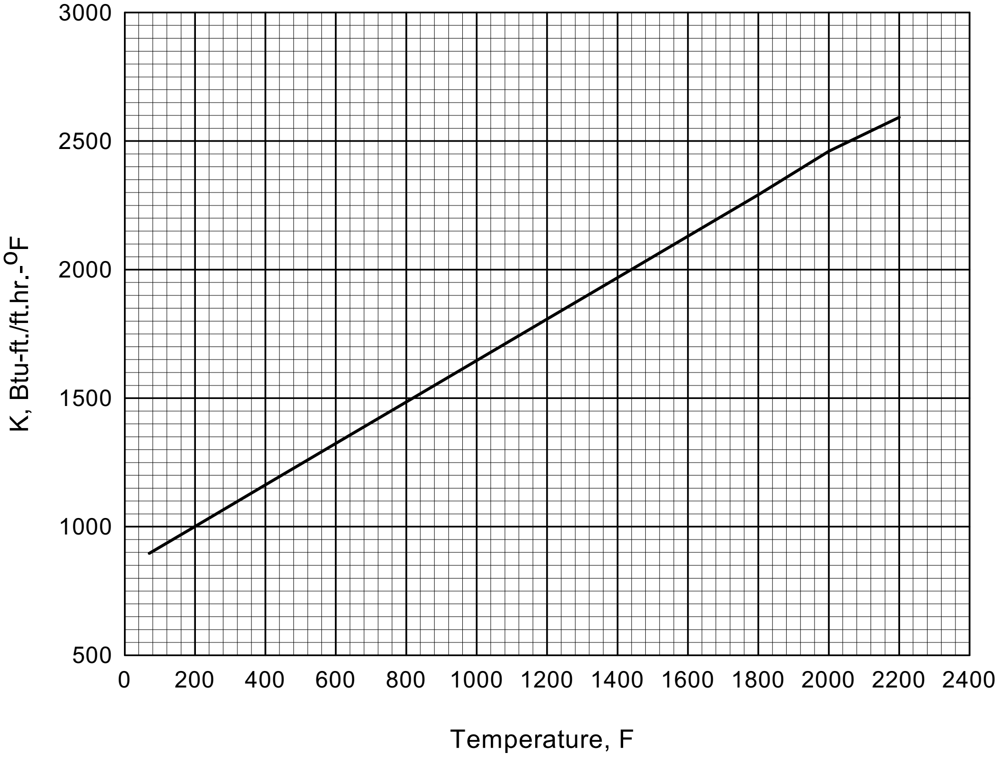


Figure 6.3.10.0(c). Effect of temperature on thermal conductivity of HAYNES HR-120 alloy.

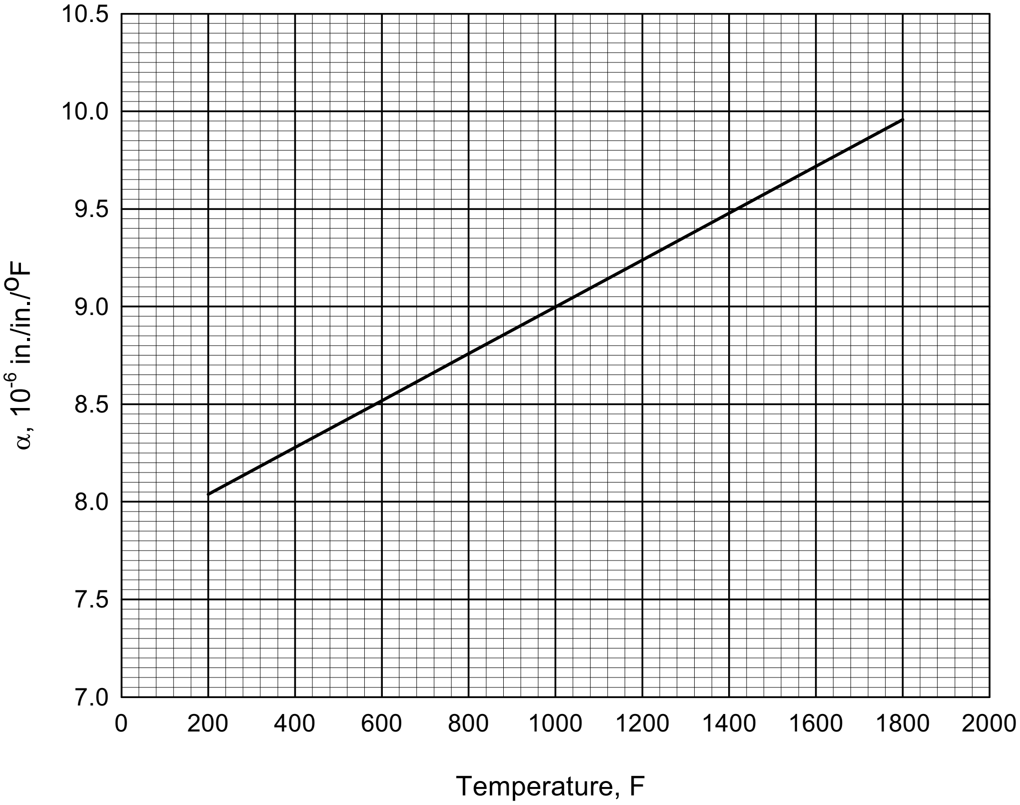


Figure 6.3.10.0(d). Effect of temperature on coefficient of thermal expansion of HAYNES HR-120 alloy.

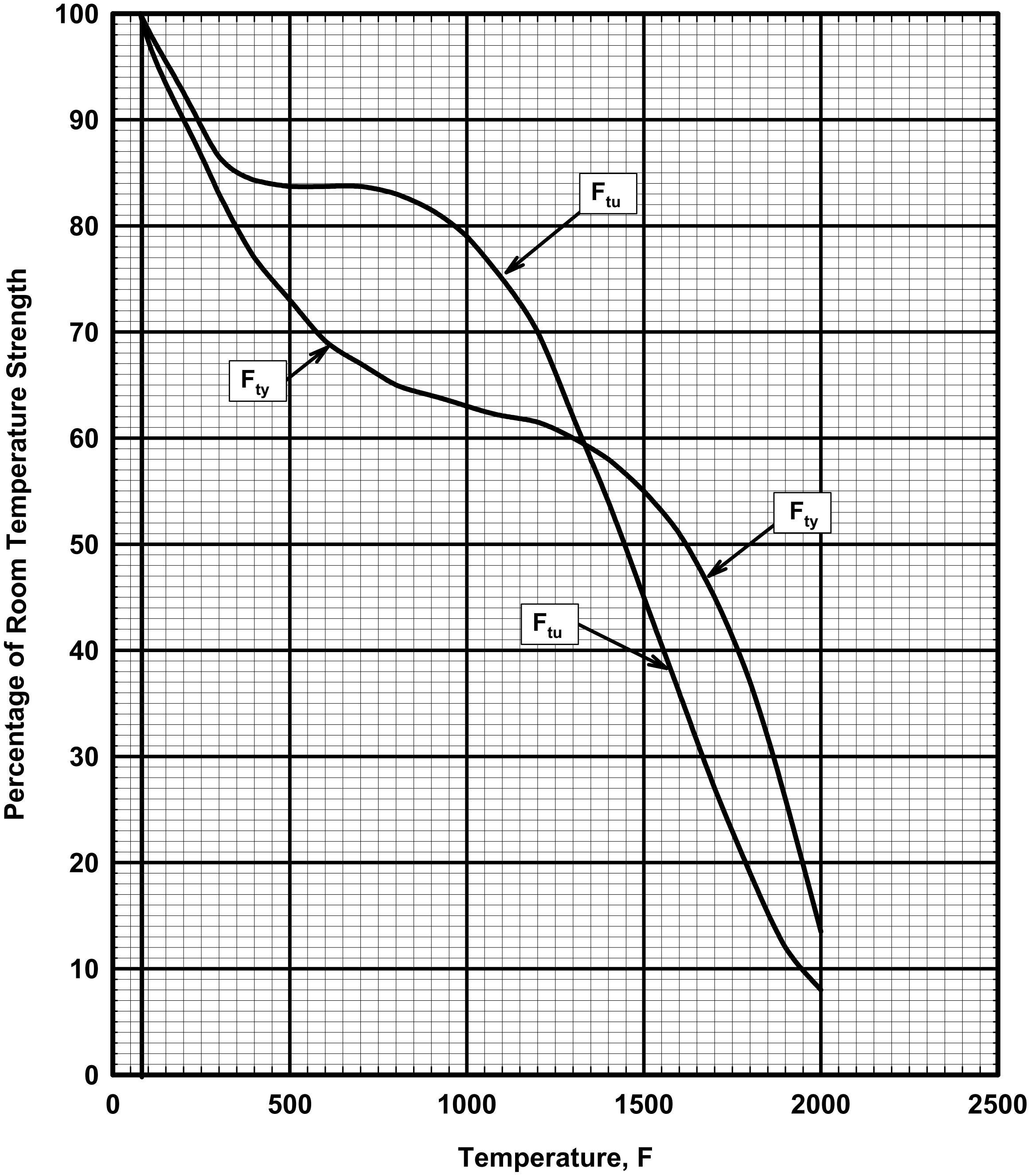


Figure 6.3.10.1.1(a). Effect of temperature on tensile properties of HAYNES HR-120 alloy.

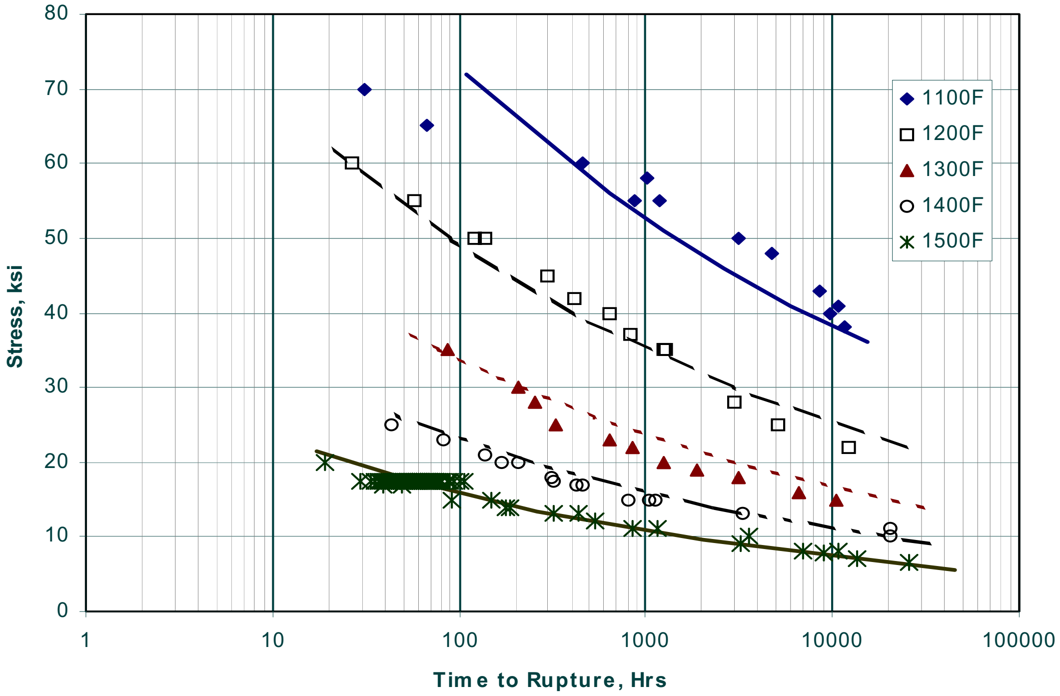
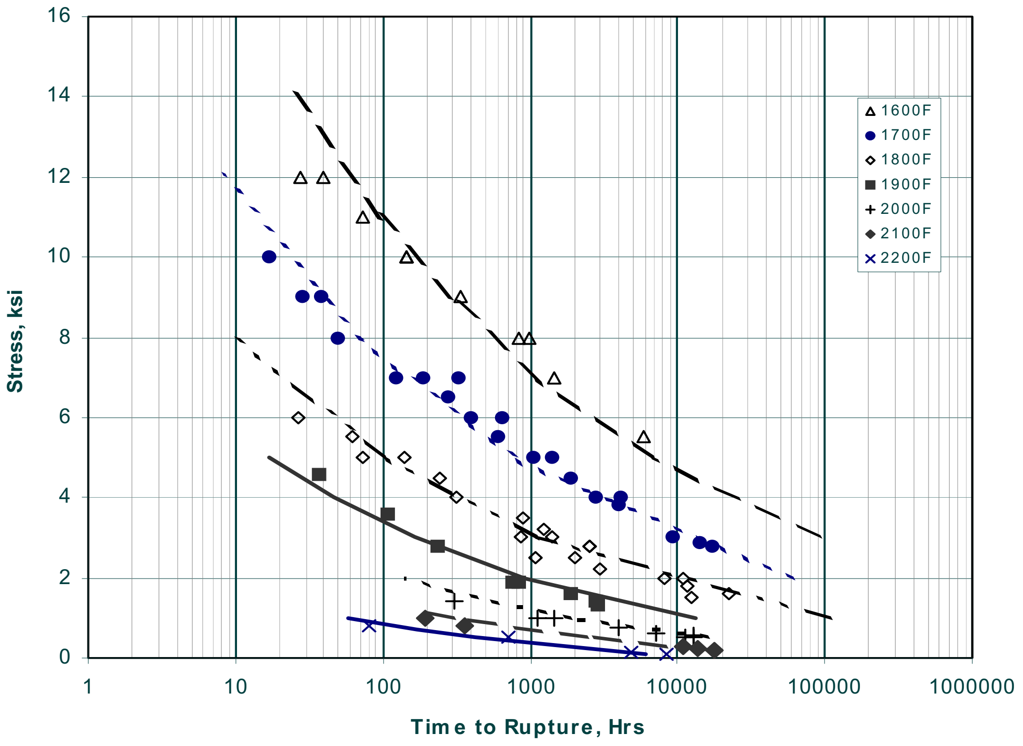


Figure 6.3.10.1.7(a). Average isothermal stress rupture curves for HAYNES HR-120 alloy for temperatures from 1100°F to 1500°F.



Correlativ

Figure 6.3.10.1.7(b). Average isothermal stress rupture curves for HAYNES HR-120 alloy for temperatures from 1600°F to 2200°F.

e Information for Figures 6.3.10.1.7(a) and (b)

Makeup of Data Collection:
Heat Treatment: Annealed
Number of Vendors = 1
Number of Lots =
Number of Test Laboratories = 1
Number of Tests = 283

Specimen Details:
Type - ≤ 0.375 inch thick - Flat
> 0.375 inch thick -
0.25 inch rd reduced section
Adjusted Gage Length -
2.6 inches for flat specimens
1.35 inches for rd. specimens
Gage Thickness - 0.125" for flat specimens for sheets with thickness of 0.125" or greater. Sheet thickness for specimens from sheet with thickness < 0.125".

Stress Rupture Equation:
$\text{Log } t = c + b_1/T + b_2X/T + b_3X^2/T + b_4X^3/T$
$T = °R$
$X = \log (\text{stress, ksi})$
$c = -16.671$
$b_1 = 49{,}051$
$b_2 = -8{,}375.3$
$b_3 = -2{,}403.7$
$b_4 = 619.59$

Analysis Details:
Standard Deviation = 0.598
Standard Error of Estimate = 0.155
Ratio of Between to Within Heat Treatment Variance = < 0.10 (at spec pt.)
$R^2 = 96.6\%$

[Caution: The stress rupture model may provide unrealistic times to rupture for stresses beyond those represented above.]

6.4 COBALT-BASE ALLOYS

6.4.0 GENERAL COMMENTS — The use of cobalt in wrought heat-resistant alloys is usually limited to additions of cobalt to alloys of other bases. Very few of the heat-resistant alloys can be considered as cobalt base, since cobalt is seldom the predominating element. For airframe applications, some workability is usually required; the alloys considered in this section are limited to those available in wrought form.

6.4.0.1 *Metallurgical Considerations*

Composition — The common alloying elements for cobalt are chromium, nickel, carbon, molybdenum, and tungsten. Chromium is added to increase strength and oxidation resistance at very high temperatures; nickel to increase toughness; carbon to increase the hardness and strength, especially when combined with chromium and the other carbide formers, molybdenum and tungsten; molybdenum and tungsten also contribute to solid-solution strengthening.

Vacuum melting is not required for these alloys. For this reason, the cobalt-base alloys are often competitively priced with vacuum-melted nickel-base alloys although the price of cobalt is higher than that of nickel.

Heat Treatment — The cobalt-base alloys are heat treated with conventional equipment and fixtures such as those used with austenitic stainless steels. The use of good heat-treating practices is recommended, although this is not so critical as in the case of the nickel-based alloys.

6.4.0.2 *Manufacturing Considerations*

Forging — Because these alloys are designed to have very high strength at temperatures near the forging range, they require the use of heavy forging equipment. However, the forgeability of these alloys is good over a fairly wide range of temperatures. Hot-cold working is neither required nor recommended for these alloys.

Cold Forming — These alloys, when in the solution-treated condition, have excellent ductility and are readily cold formed. Because of their capacity for work hardening, they require higher forming pressures and frequent anneals.

Machining — These alloys are tough and they work harden rapidly; consequently, heavy-duty vibration-free machine tools, sharp cutting tools (high-speed steel or carbide tipped), and low cutting speeds are required.

Welding — The weldability of the cobalt-base alloys is comparable with that of the austenitic stainless steels. Welding may be accomplished by all commonly used welding processes. Large or complex weldments require stress relief.

Brazing — These alloys can be brazed using the same techniques and precautions applicable to stainless steels and nickel-base alloys. Alloys which contain aluminum or titanium require extremely dry, inert gas atmospheres, very high vacuum or a thin (0.002 to 0.0010 inch thick) nickel plating to prevent surface oxidation. It is also necessary to braze the material in the annealed condition and to keep the stresses low during brazing to avoid embrittlement, especially when brazing with low melting alloys.

6.4.0.3 *Special Precautions* — If the cobalt-base alloys have not been exposed to neutron radiation, no special safety precautions in handling are required. However, neutron irradiation creates a very dangerous radioactive isotope, cobalt 60, which has a half life of about 5.2 years. Special precautions must be employed to protect personnel from the radioactive material.

6.4.1 L-605

6.4.1.0 *Comments and Properties* — L-605, also known as Haynes Alloy 25, is a corrosion and heat-resistant cobalt-base alloy used for moderately stressed parts operating between 1000 and 1900°F. Its applications include gas turbine blades and rotors, combustion chambers, and afterburner parts. L-605 is not hardenable except by cold working and is usually used in the annealed condition. It is available in all the usual mill forms.

L-605 forges moderately well between 1900°F and 2250°F. In the annealed condition, it has excellent formability at room temperature; severely formed parts should be annealed at 2225°F for 7 to 10 minutes. L-605 is difficult to machine. Its toughness and capacity for work hardening necessitate the use of sharp tools and low cutting speeds; high-speed steel or carbide cutting tools are recommended. L-605 can be fusion or resistance welded or brazed; large or complex fusion weldment should be stress relieved at 1300°F for 2 hours. This alloy has excellent oxidation resistance up to 1900°F.

Some material specifications for L-605 are shown in Table 6.4.1.0(a). Room-temperature mechanical and physical properties are shown in Table 6.4.1.0(b). The effect of temperature on physical properties is shown in Figure 6.4.1.0.

Table 6.4.1.0(a). Material Specifications for L-605

Specification	Form	Condition
AMS 5537	Sheet	Solution treated (annealed)
AMS 5759	Bar and forging	Solution treated (annealed)

6.4.1.1 *Solution Treated Condition* — Elevated temperature properties for this condition are shown in Figures 6.4.1.1.1 through 6.4.1.1.5. A creep nomograph is shown in Figure 6.4.1.1.7. Stress-rupture requirements at elevated temperatures are specified in material specifications. The appropriate specification should be consulted for detailed requirements.

Table 6.4.1.0(b). Design Mechanical and Physical Properties of L-605

Specification	AMS 5537			AMS 5759
Form	Sheet		Plate	Bar and forging
Condition	Solution treated			
Thickness, in.	0.010-0.187		0.188-0.375	≤1.000
Basis	A	B	S	S
Mechanical Properties:				
F_{tu}, ksi:				
L	126	131	...	125
LT	130	135	130	...
F_{ty}, ksi:				
L	57	62	...	45
LT	55[a]	60	55	...
F_{cy}, ksi:				
L	41	45	...	42
LT	56	61	...	...
F_{su}, ksi	91	95	91	88
F_{bru}, ksi:				
(e/D = 1.5)	186	193	186	...
(e/D = 2.0)	232	241	232	...
F_{bry}, ksi:				
(e/D = 1.5)	88	96	88	...
(e/D = 2.0)	113	123	113	...
e, percent (S-basis):				
L	...	...	...	30
LT	[b]	...	45	...
E, 10^3 ksi	32.6			
E_c, 10^3 ksi	32.6			
G, 10^3 ksi	12.6			
μ	0.29			
Physical Properties:				
ω, lb/in.^{3}	0.330			
C, Btu/(lb)(°F)	0.090 (70-212°F)			
C, K, and α	See Figure 6.4.1.0			

[a] S-basis. The rounded T_{99} value: F_{ty} = 56 ksi.
[b] 30 - ≤0.020; 35 - 0.021 to 0.032; 40 - 0.033 to 0.043; 45 - ≥0.043.

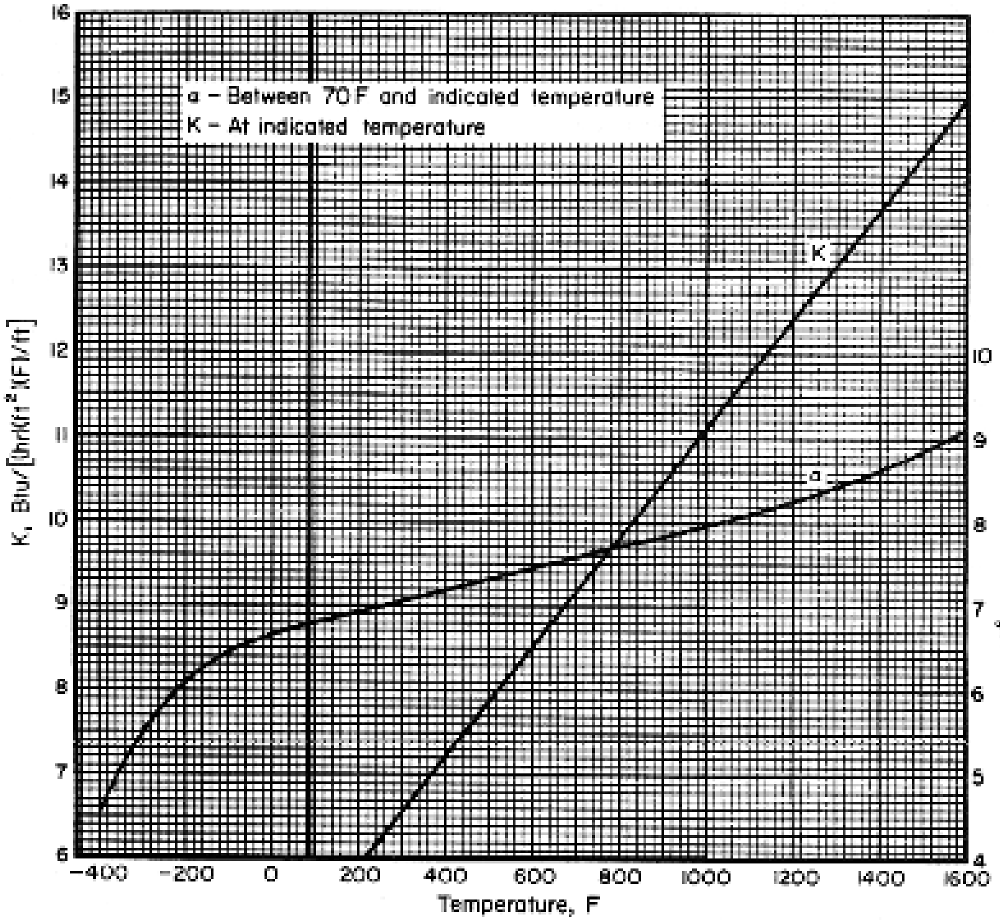


Figure 6.4.1.0. Effect of temperature on the physical properties of L-605.

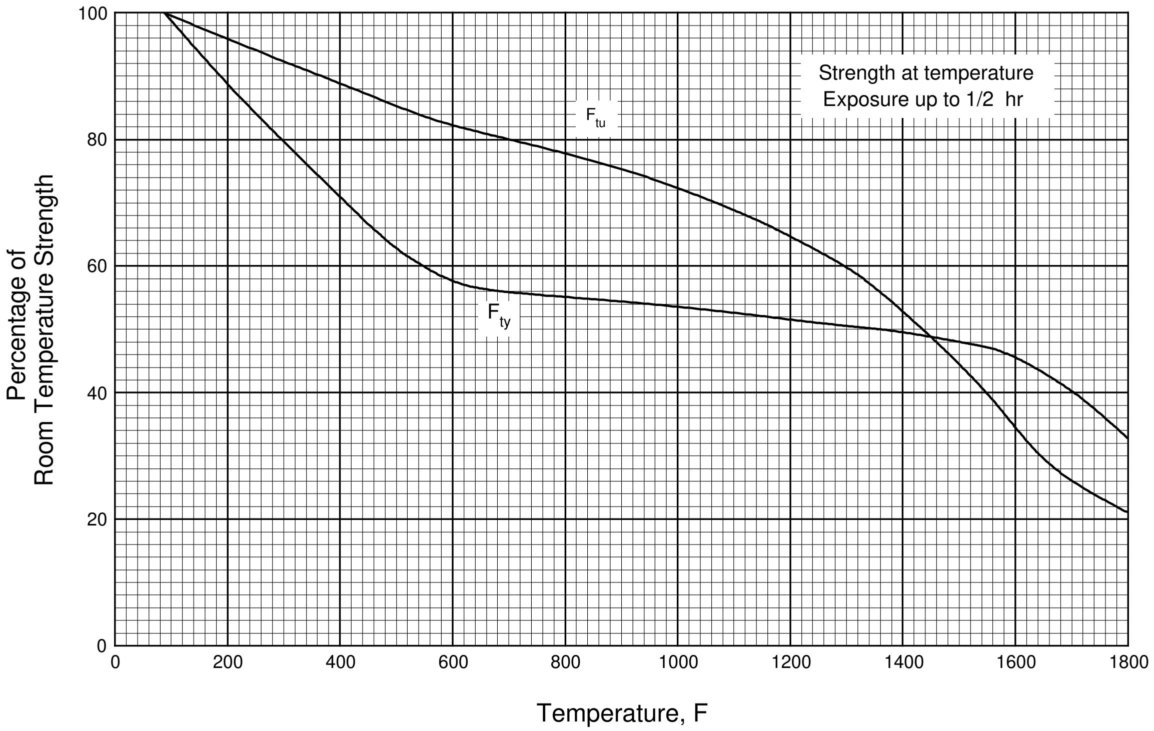


Figure 6.4.1.1.1. Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of L-605.

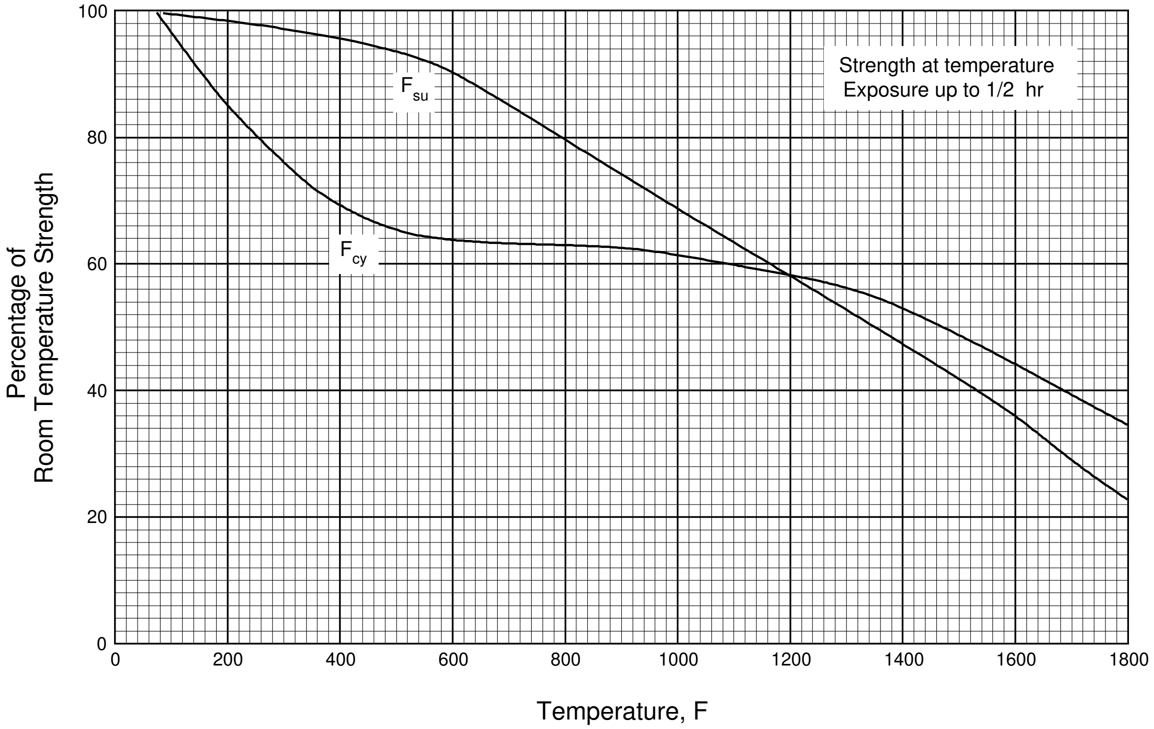


Figure 6.4.1.1.2. Effect of temperature on the compressive yield strength (F_{cy}) and the shear ultimate strength (F_{su}) of L-605.

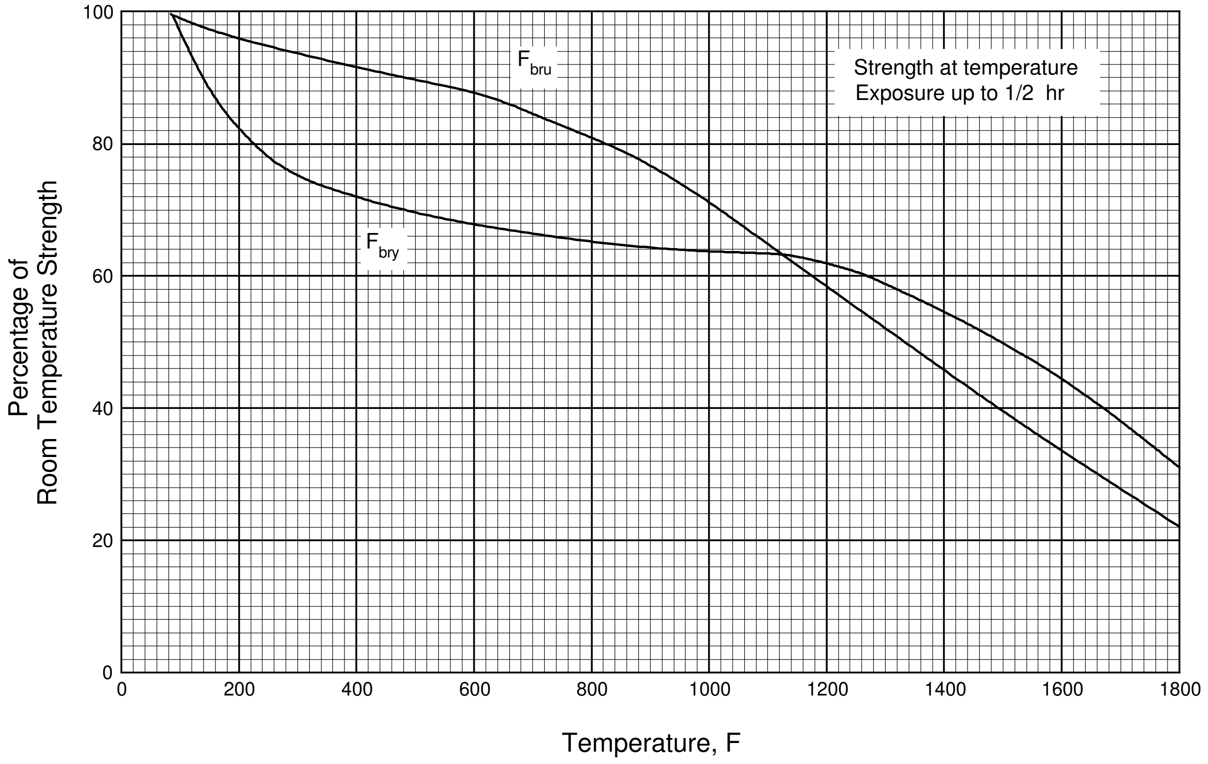


Figure 6.4.1.1.3. Effect of temperature on the bearing ultimate strength (F_{bru}) and the bearing yield strength (F_{bry}) of L-605 sheet.

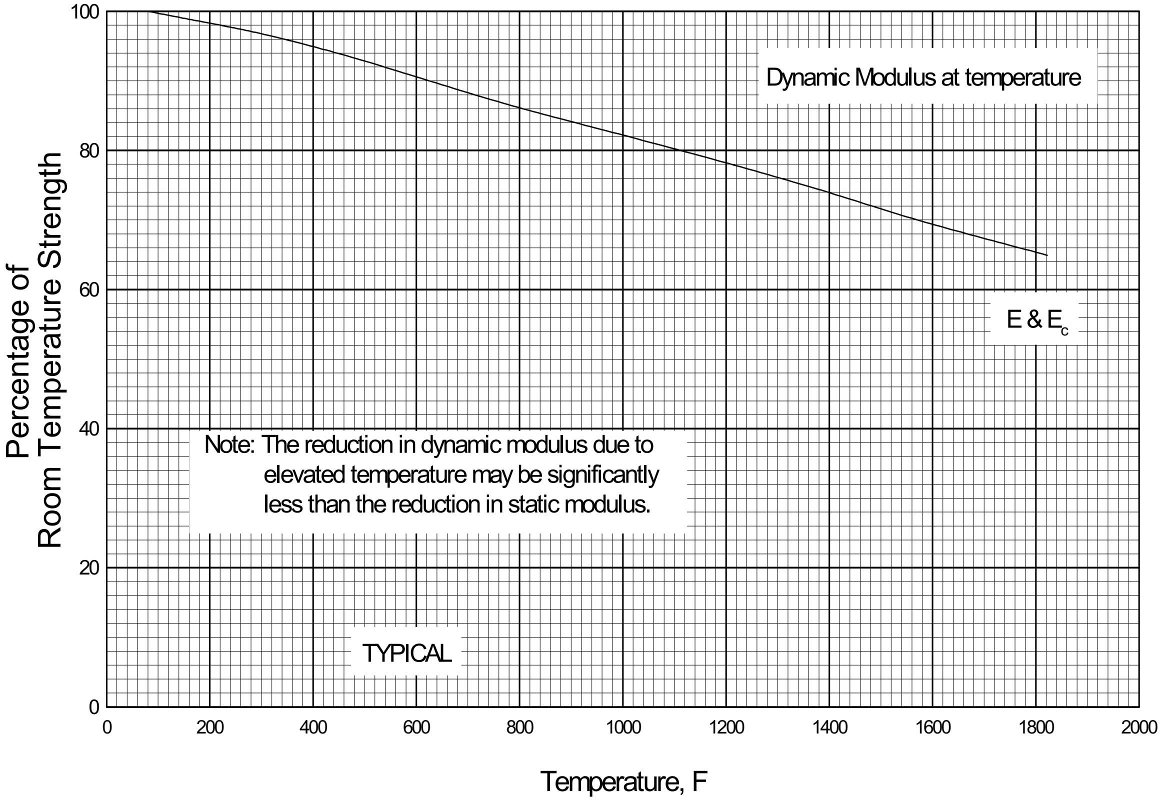


Figure 6.4.1.1.4(a). Effect of temperature on dynamic moduli (E and E_c) of L-605 sheet.

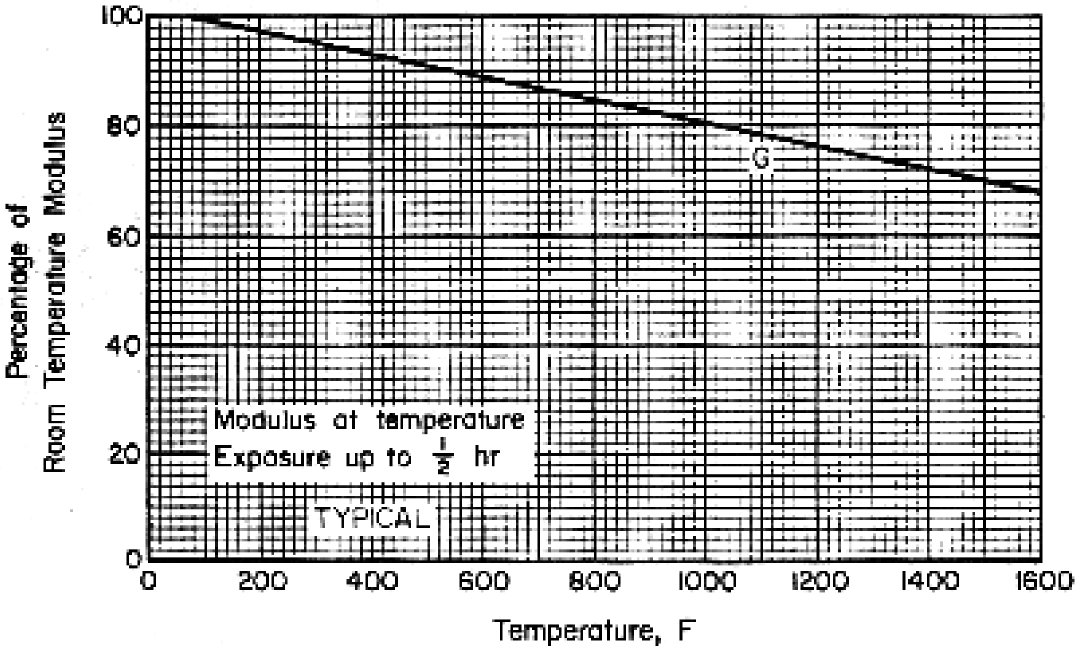


Figure 6.4.1.1.4(b). Effect of temperature on the shear modulus (G) of L-605 sheet.

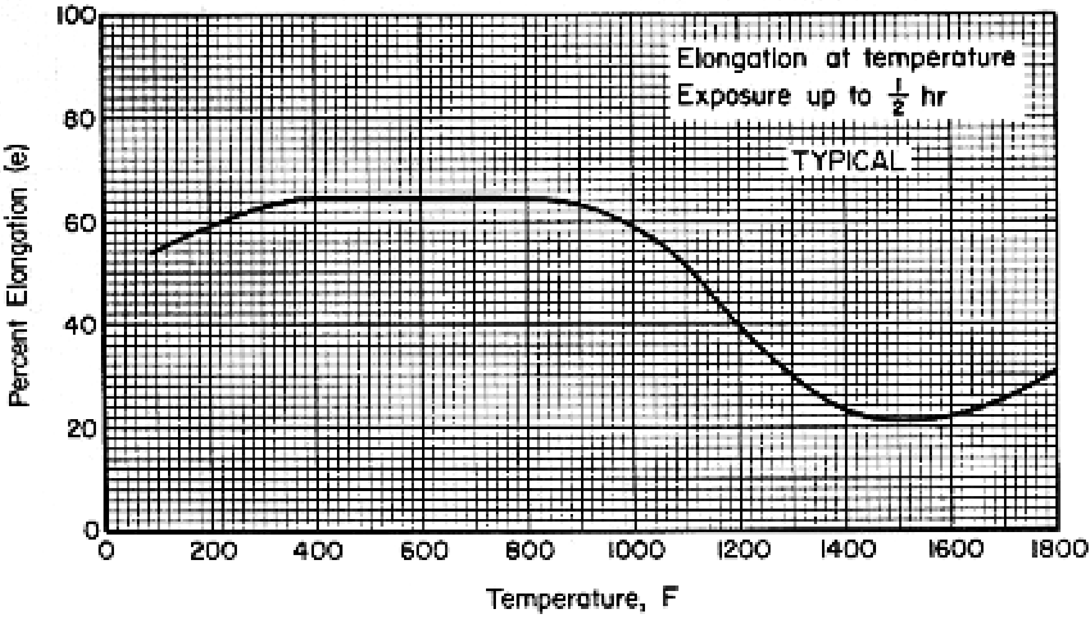


Figure 6.4.1.1.5. Effect of temperature on the elongation (e) of L-605 (>0.020 thickness) sheet.

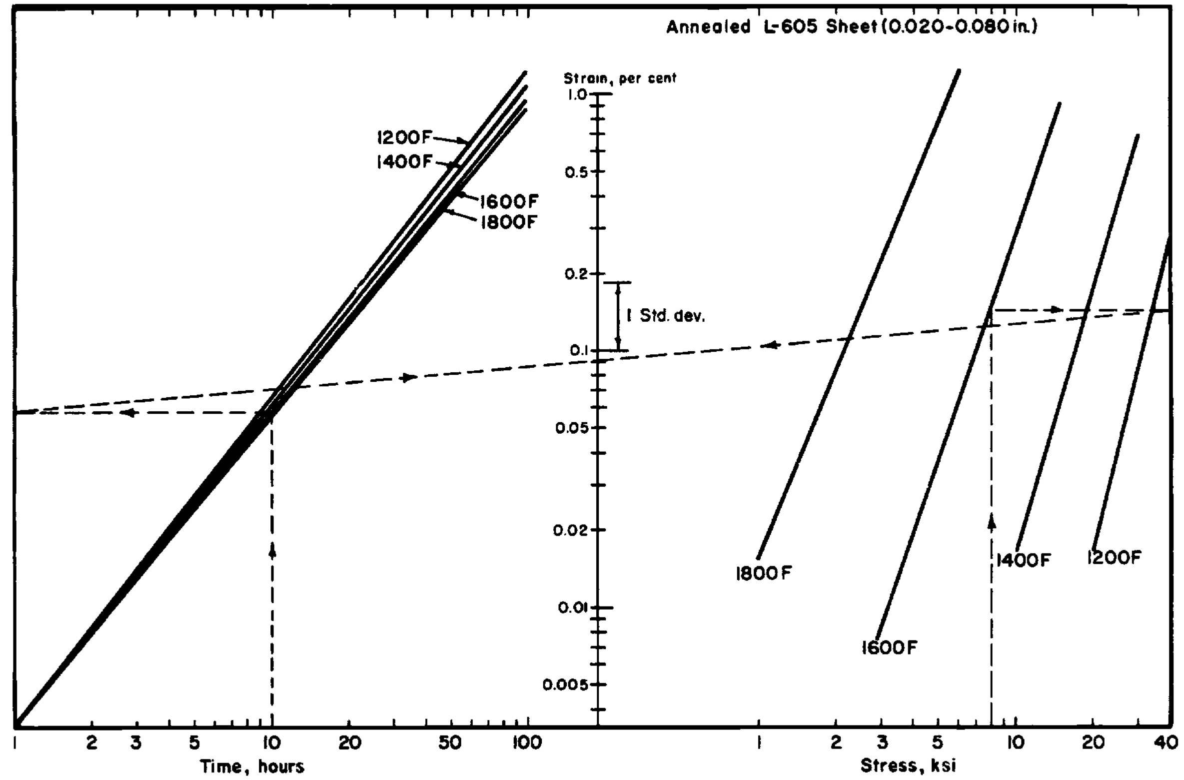


Figure 6.4.1.1.7. Typical creep properties of L-605 sheet.

Correlative Information for Figure 6.4.1.1.7

Equation
Creep Strain, percent:

$$\varepsilon = \left(3.516 \times 10^{8} \exp(-\frac{56040}{T})\right)\left(\sigma^{0.2791 \exp(\frac{3943}{T})}\right)\left(t^{0.4172 \exp(\frac{413.4}{T})}\right)^{a}$$

Temperature (T) = Fahrenheit + 460

Example

Temp., T = 1600 °F
Stress, σ = 8 ksi
Time, t = 10 hours
Creep Strain, ε = 0.091

---

[a] This equation should only be used in the same temperature ranges indicated in the nomograph. Creep strains computed outside these temperature ranges may yield unreasonable values.

6.4.2 HS 188

6.4.2.0 *Comments and Properties* — HS 188 is a corrosion- and heat-resistant cobalt-base alloy used for moderately stressed parts up to 2100°F. The alloy exhibits outstanding oxidation resistance up to 2100°F resulting from the addition of minute amounts of lanthanum to the alloy system. The alloy exhibits excellent post-aged ductility after prolonged heating of 1000 hours at temperatures up to 1600°F inclusive.

HS 188 is not hardenable except by cold working and is used in the solution-treated condition. The alloy can be forged and welded. Welding can be accomplished by both manual and automatic welding methods including electron beam, gas tungsten air, and resistance welding. Like other cobalt base alloys, machining is difficult necessitating the use of sharp tools and low cutting speeds; high speed steel or carbide cutting tools are recommended. Gas turbine applications include transition ducts, combustion cans, spray bars, flame--holders, and liners.

Material specifications for HS 188 are presented in Table 6.4.2.0(a). Room-temperature mechanical and physical properties are shown in Table 6.4.2.0(b). The effect of temperature on physical properties is shown in Figure 6.4.2.0.

Table 6.4.2.0(a). Material Specifications for HS 188

Specification	Form	Condition
AMS 5608	Sheet and plate	Solution treated (annealed)
AMS 5772	Bar and forging	Solution treated (annealed)

6.4.2.1 *Solution-Treated Condition* — Elevated-temperature properties are presented in Figures 6.4.2.1.1(a) and (b), 6.4.2.1.2, 6.4.2.1.4(a) through (c), and 6.4.2.1.5. Typical tensile stress-strain curves at room temperature are presented in Figure 6.4.2.1.6(a). Typical compressive stress-strain and tangent-modulus curves at room and elevated temperatures are presented in Figure 6.4.2.1.6(b). Strain control fatigue data for bar are presented in Figures 6.4.2.1.8(a) through (d).

Table 6.4.2.0(b). Design Mechanical and Physical Properties of HS 188 Sheet

Specification	AMS 5608	
Form	Sheet	
Condition	Solution Treated	
Thickness, in.	<0.020	0.020-0.187
Basis	S	S
Mechanical Properties:		
F_{tu}, ksi:		
L	125	125
LT	125	125
F_{ty}, ksi:		
L	57	57
LT	55	55
F_{cy}, ksi:		
L	...	...
LT	55	55
F_{su}, ksi	111	111
F_{bru}, ksi:		
(e/D = 1.5)	...	...
(e/D = 2.0)	...	...
F_{bry}, ksi:		
(e/D = 1.5)	...	...
(e/D = 2.0)	...	...
e, percent:		
LT	40	45
E, 10^3 ksi	33.6	
E_c, 10^3 ksi	33.6	
G, 10^3 ksi	12.8	
μ	0.31	
Physical Properties:		
ω, lb/in.^{3}	0.324	
C, K, and α	See Figure 6.4.2.0	

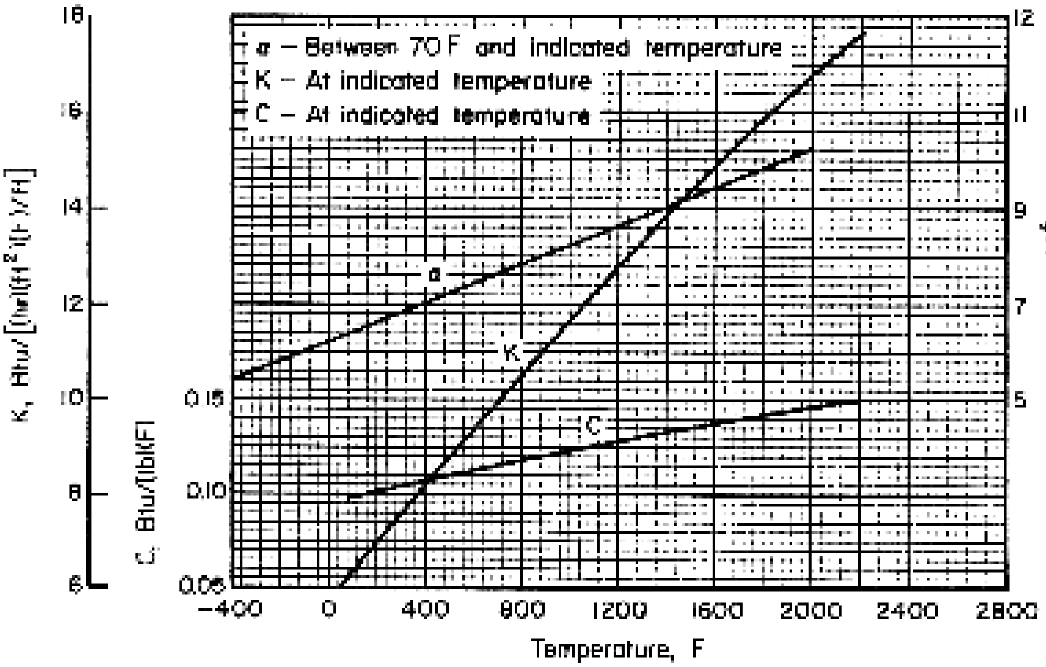


Figure 6.4.2.0. Effect of temperature on the physical properties of HS 188.

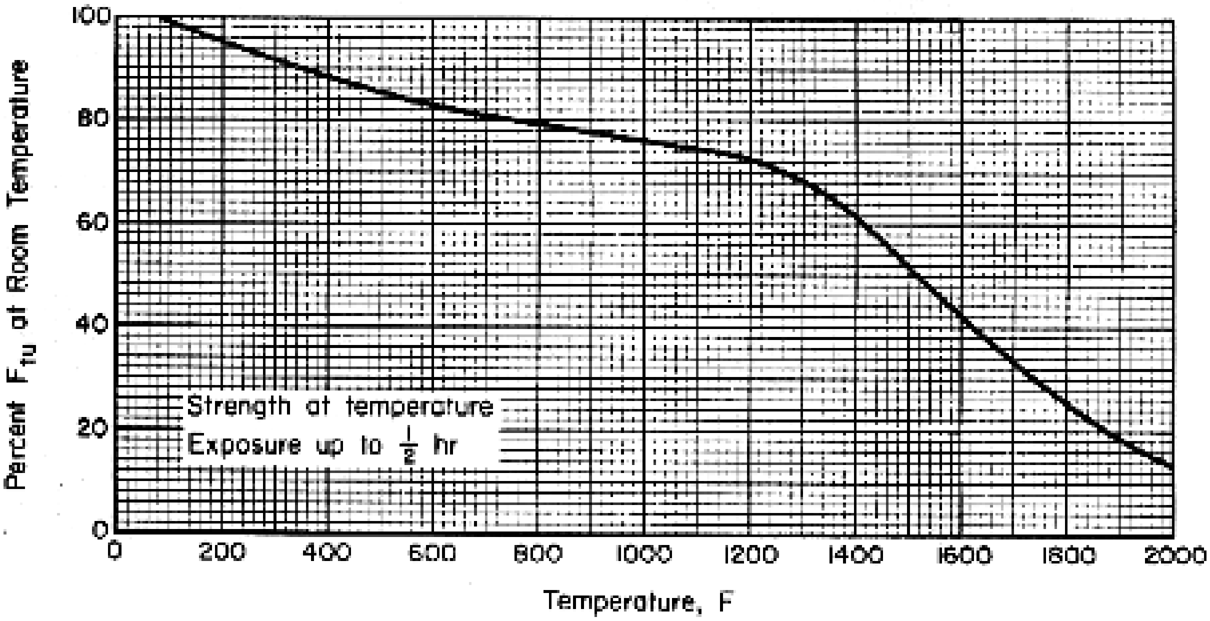


Figure 6.4.2.1.1(a). Effect of temperature on tensile ultimate strength (F_{tu}) of HS 188 sheet.

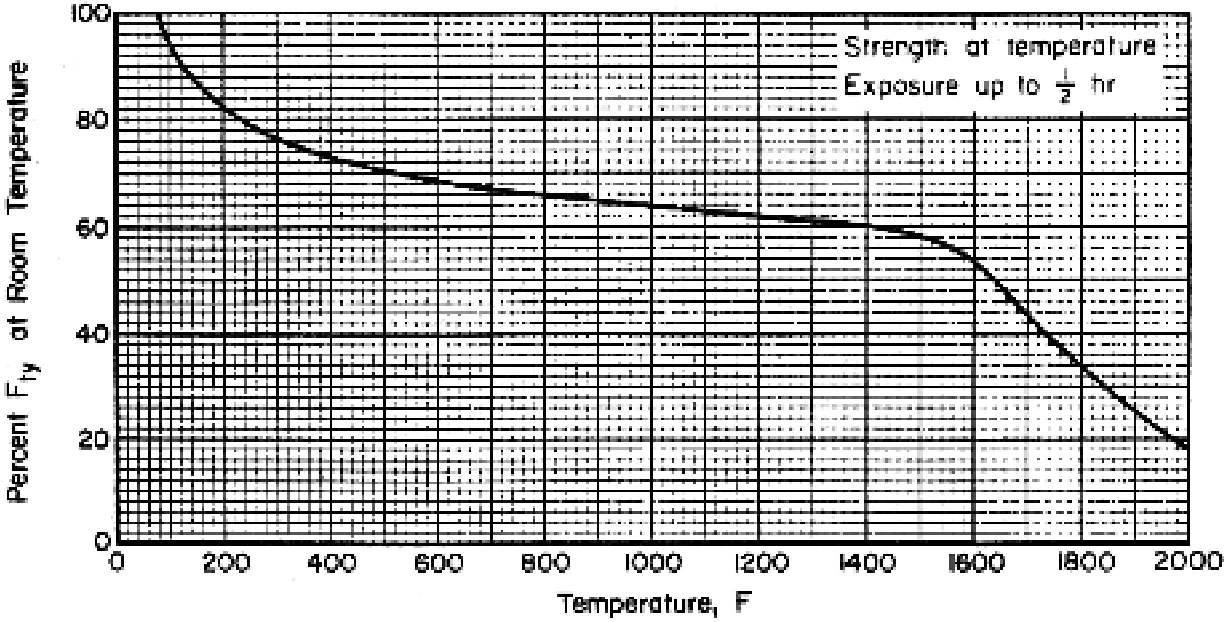


Figure 6.4.2.1.1(b). Effect of temperature on tensile yield strength (F_{ty}) of HS 188 sheet.

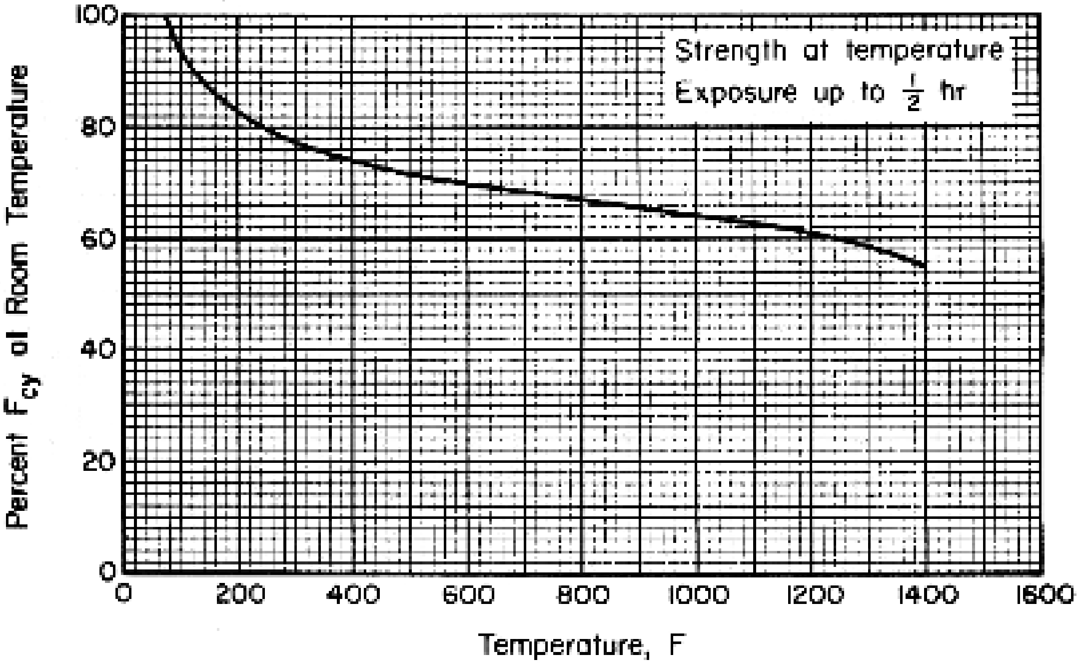


Figure 6.4.2.1.2. Effect of temperature on compressive yield strength (F_{cy}) of HS 188 sheet.

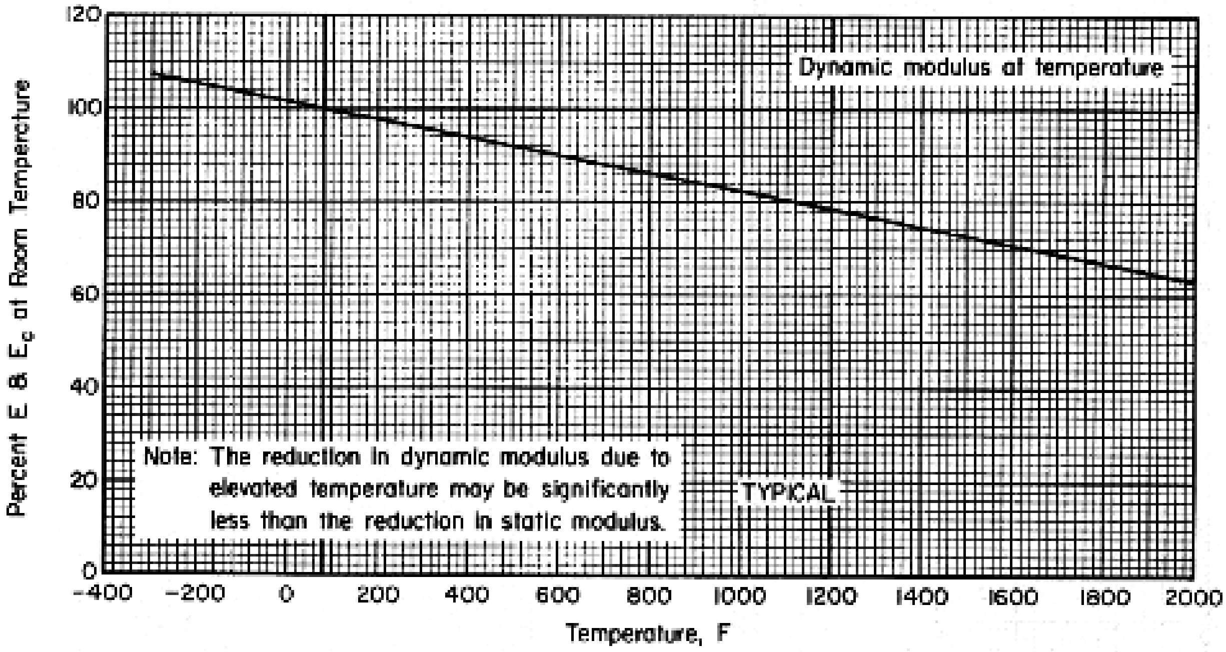


Figure 6.4.2.1.4(a). Effect of temperature on dynamic moduli (E and E_c) of HS 188.

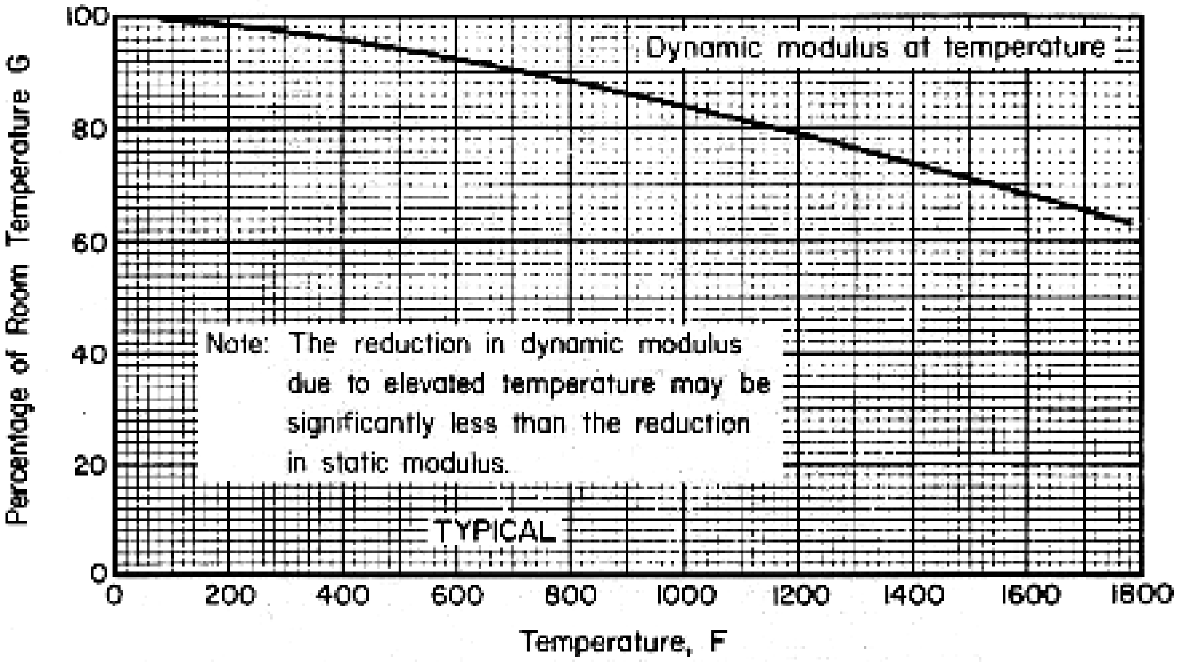


Figure 6.4.2.1.4(b). Effect of temperature on dynamic shear modulus (G) for HS 188.

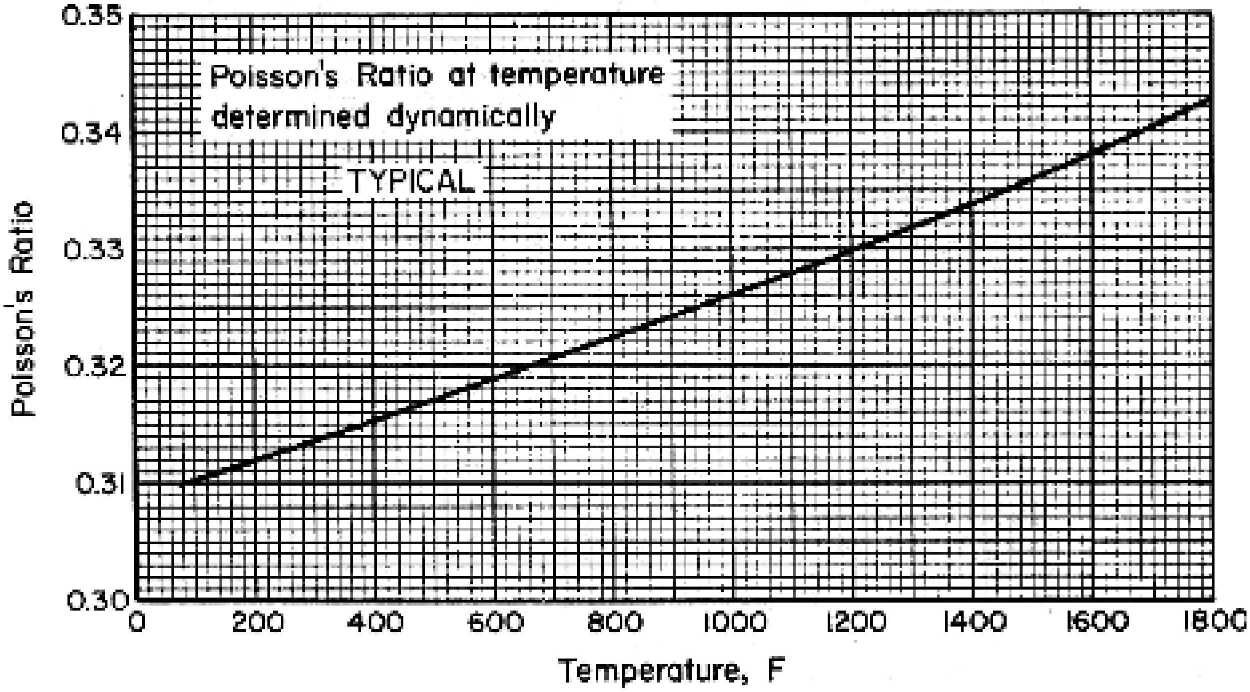


Figure 6.4.2.1.4(c). Effect of temperature on Poisson's ratio (μ) for HS 188.

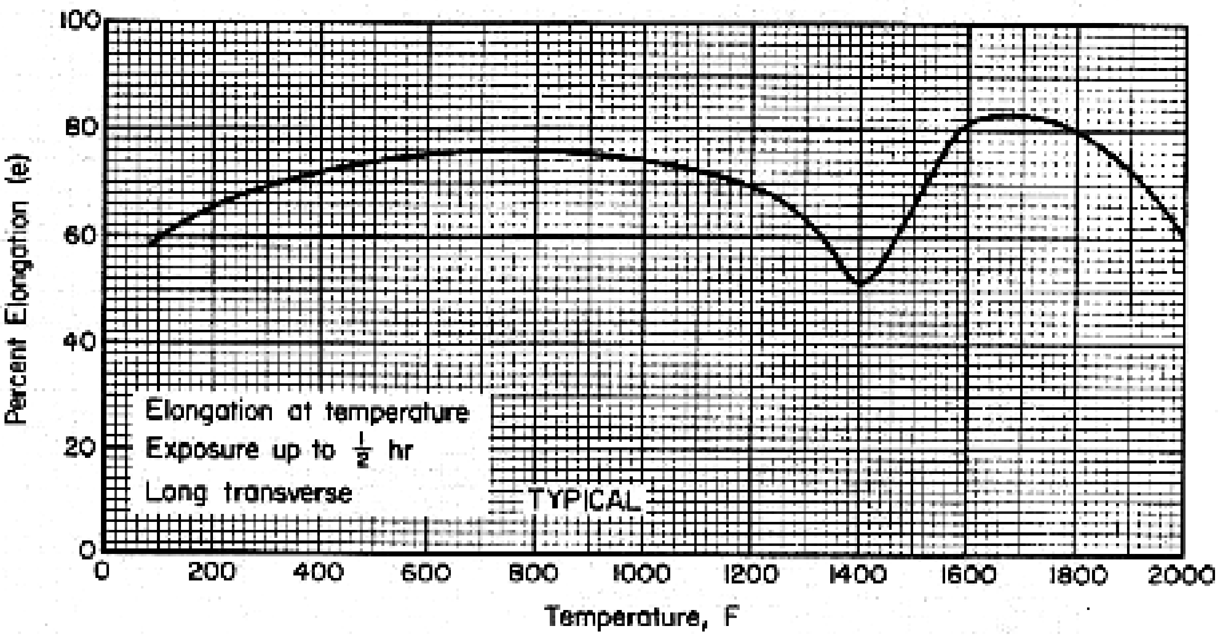


Figure 6.4.2.1.5. Effect of temperature on elongation (e) of HS 188 sheet.

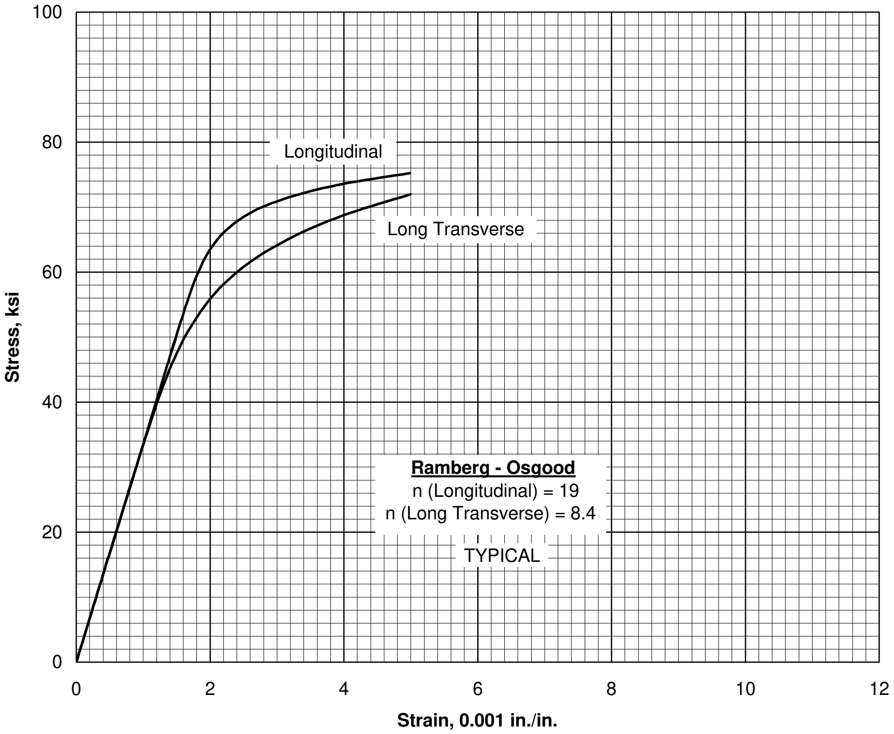


Figure 6.4.2.1.6(a). Typical tensile stress-strain curves for HS 188 sheet at room temperature.

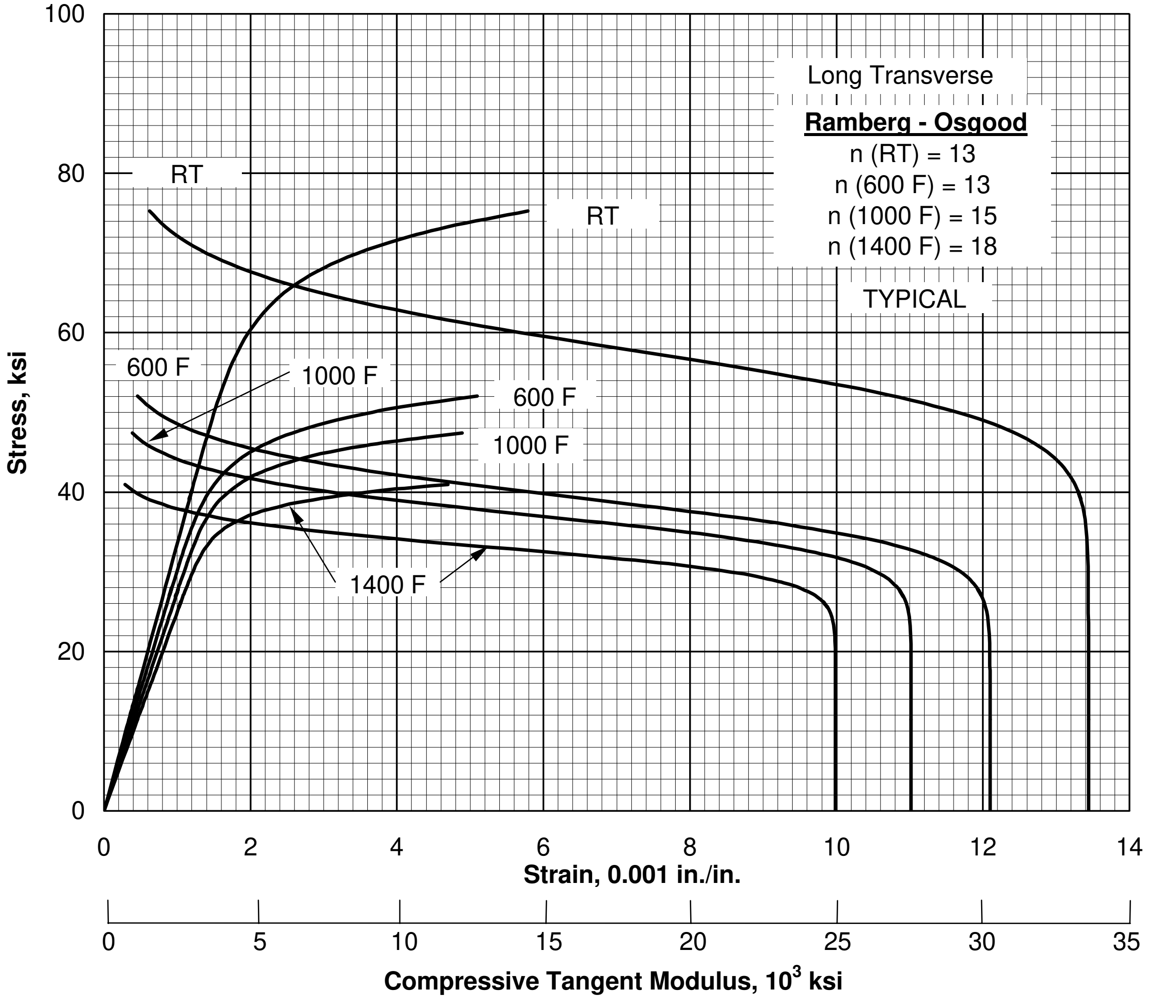


Figure 6.4.2.1.6(b). Typical compressive stress-strain and compressive tangent-modulus curves for HS 188 sheet at various temperatures.

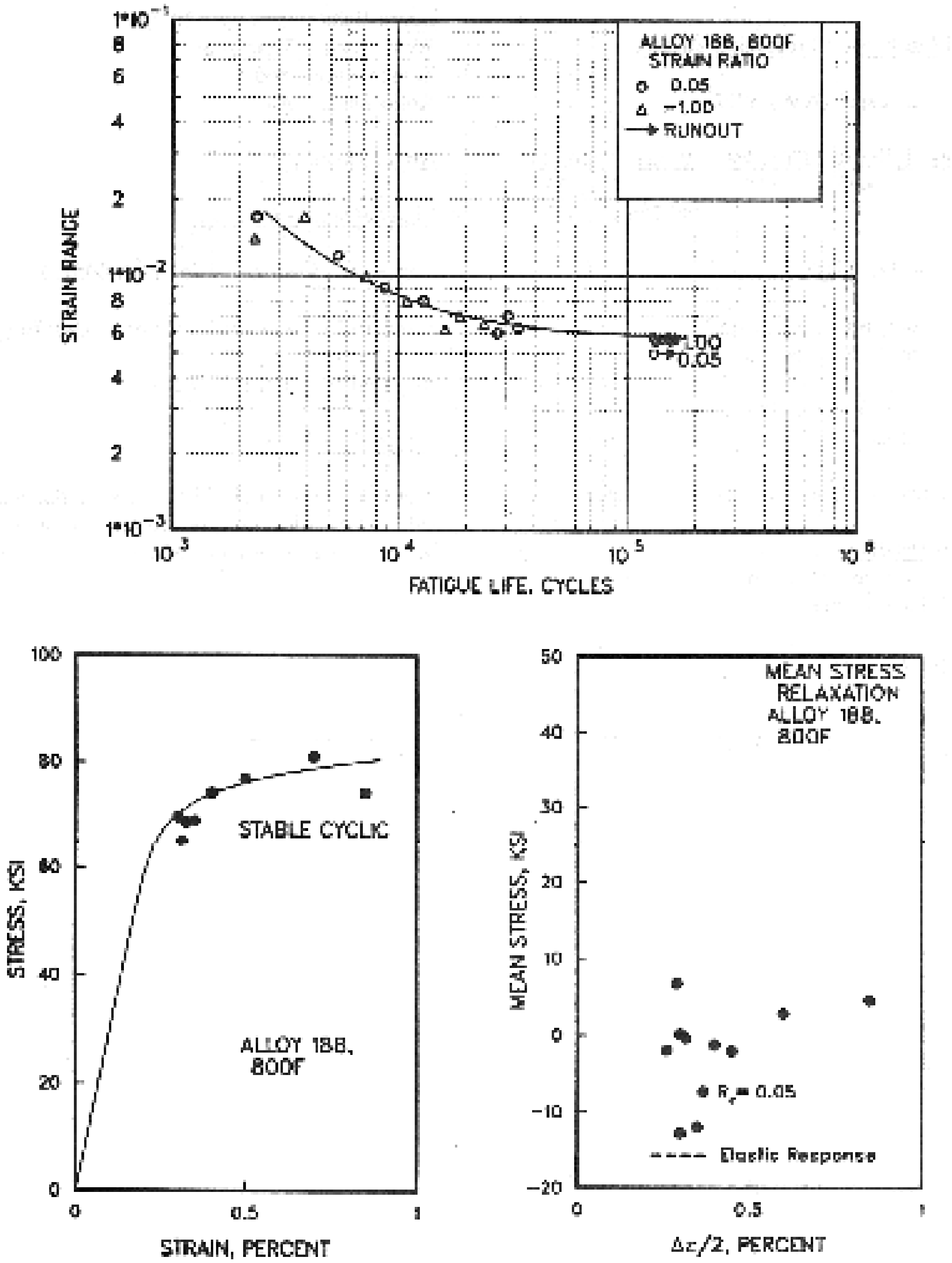


Figure 6.4.2.1.8(a). Best-fit ε/N curve, cyclic stress-strain curve, and mean stress relaxation curve for HS 188 bar, longitudinal orientation at 800°F.

Correlative Information for Figure 6.4.2.1.8(a)

Product Form/Thickness: Bar, 0.5 inch thick diameter

Thermal Mechanical Processing History:
Solution annealed (AMS 5772)

Properties:

TUS, ksi	TYS, ksi	E, ksi	Temp., °F
102*	55*		75
		29,766	800

Stress-Strain Equations:
Cyclic (Companion Specimens)
Proportional Limit = 60 ksi

$(\Delta\sigma/2) = 109\ (\Delta\varepsilon_p/2)^{0.06}$
Mean Stress Relaxation

Inadequate data at low strain range values

Specimen Details: Uniform gage test section 0.250 inch diameter

Reference: 3.8.1.1.8

Test Parameters:
Strain Rate/Frequency - 20 cpm
Wave Form - Triangular
Temperature - 800°F
Atmosphere - Air

No. of Heats/Lots: 2

Equivalent Strain Equation:
$\text{Log } N_f = 1.678 - 0.905 \log(\Delta\varepsilon - 0.00572)$
Std. Error of Est., Log (Life) = $0.00176\ (1/\varepsilon_{eq})$
Standard Deviation, Log (Life) = 0.65
$R^2 = 82\%$

Sample Size: 18

[Caution: The equivalent strain model may provide unrealistic life predictions for strain ratios and ranges beyond those represented above.]

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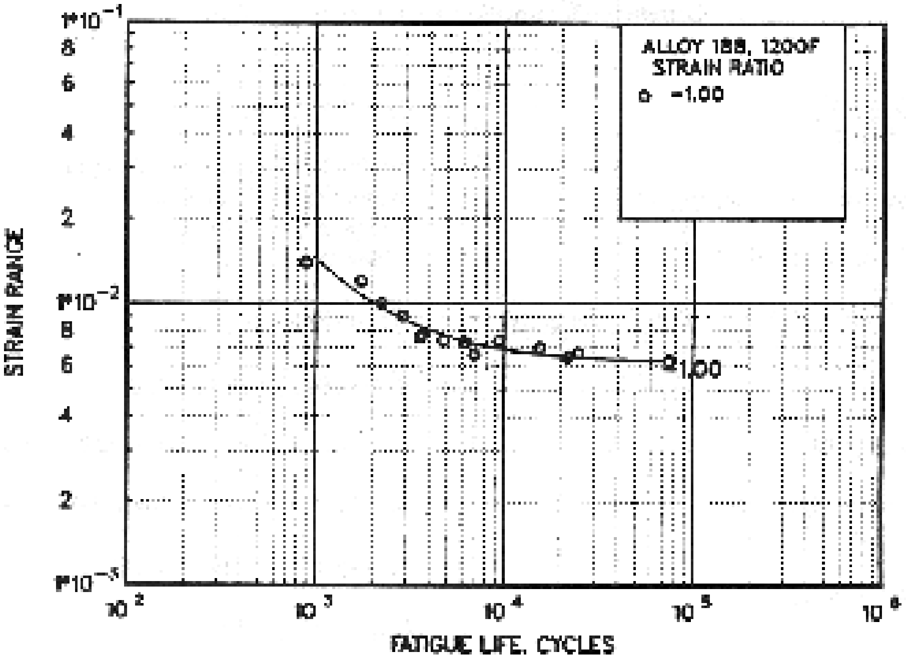
* Minimum values from AMS 5772.



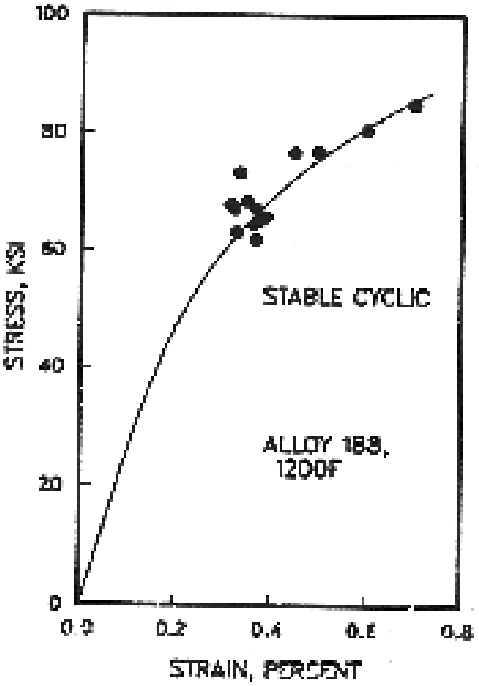


Figure 6.4.2.1.8(b). Best-fit ε/N curve and cyclic stress-strain curve for HS 188 bar, longitudinal orientation at 1200°F.

Correlative Information for Figure 6.4.2.1.8(b)

Product Form/Thickness: Bar, 1.5 inch thick

Thermal Mechanical Processing History:
Solution annealed (AMS 5772)

Properties:

TUS, ksi	TYS, ksi	E, ksi	Temp., °F
120*	55*		75
		20,050	1200

Stress-Strain Equations:
Cyclic (Companion Specimens)
Proportional Limit = 45 ksi

$(\Delta\sigma/2) = 293\ (\Delta\varepsilon_p/2)^{0.22}$

Specimen Details: Uniform gage test section
0.250 inch diameter

Reference: 3.8.1.1.8

Test Parameters:
Strain Rate/Frequency - 20 cpm
Wave Form - Triangular
Temperature - 1200°F
Atmosphere - Air

No. of Heats/Lots: 1

Equivalent Strain Equation:
$\text{Log } N_f = 1.073 - 0.925 \log (\Delta\varepsilon - 0.00622)$
Std. Error of Est., Log (Life) = $0.00134\ (1/\varepsilon_{eq})$
Standard Deviation, Log(Life) = 0.61
R^2 = 91%

Sample Size: 14

[Caution: The equivalent strain model may provide unrealistic life predictions for strain ratios and ranges beyond those represented above.]

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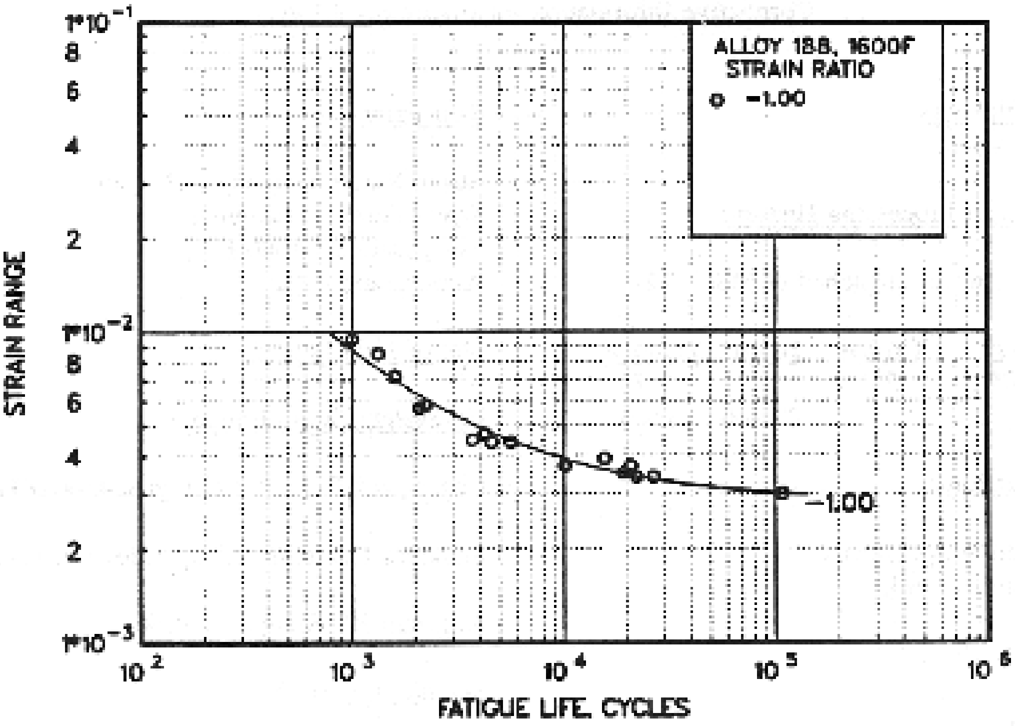
* Minimum values from AMS 5772.



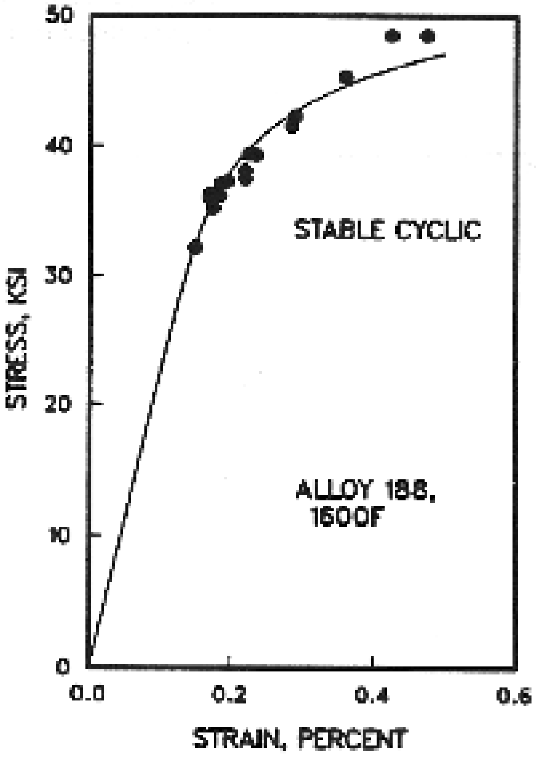


Figure 6.4.2.1.8(c). Best-fit ε/N curve and cyclic stress-strain curve for HS 188 bar, longitudinal orientation at 1600°F.

Correlative Information for Figure 6.4.2.1.8(c)

Product Form/Thickness: Bar, 1.5 inch thick

Thermal Mechanical Processing History:
Solution treated, water quenched (AMS 5772)

Properties:

TUS, ksi	TYS, ksi	E, ksi	Temp., °F
120*	55*		75
		22,406	1600

Stress-Strain Equations:
Cyclic (Companion Specimens)
Proportional Limit = 36 ksi

$(\Delta\sigma/2) = 81.6\ (\Delta\varepsilon_p/2)^{0.094}$

Specimen Details: Uniform gage test section
0.250 inch diameter

Reference: 3.8.1.1.8

Test Parameters:
Strain Rate/Frequency - 20 cpm
Wave Form - Triangular
Temperature - 1600°F
Atmosphere - Air

No. of Heats/Lots: 1

Equivalent Strain Equation:
$\text{Log } N_f = 0.011 - 1.343 \log (\Delta\varepsilon - 0.00283)$
Std. Error of Estimate, Log (Life) = 0.116
Standard Deviation, Log(Life) = 0.582
$R^2 = 96\%$

Sample Size: 16

[Caution: The equivalent strain model may provide unrealistic life predictions for strain ratios and ranges beyond those represented above.]

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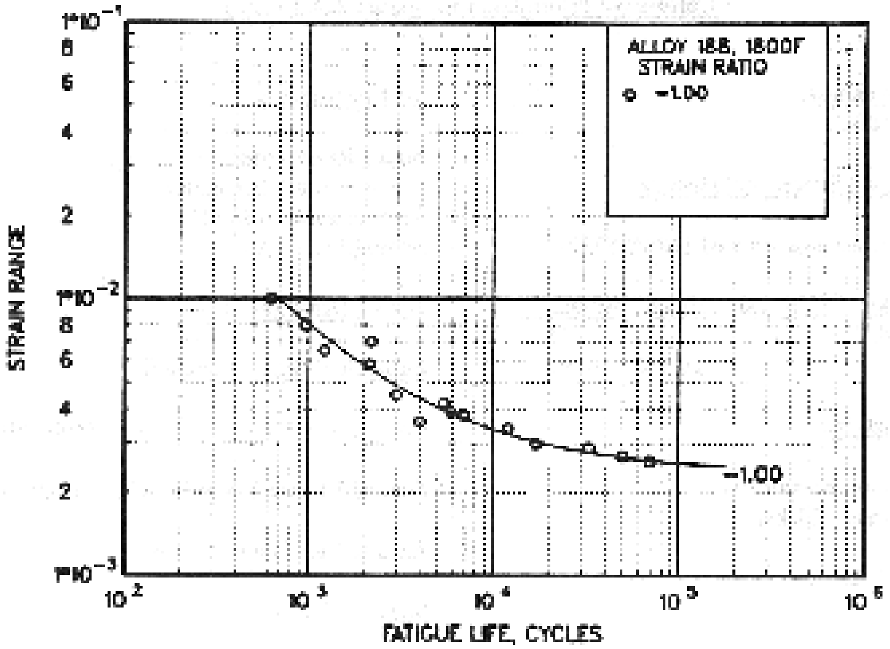
* Minimum values from AMS 5772.



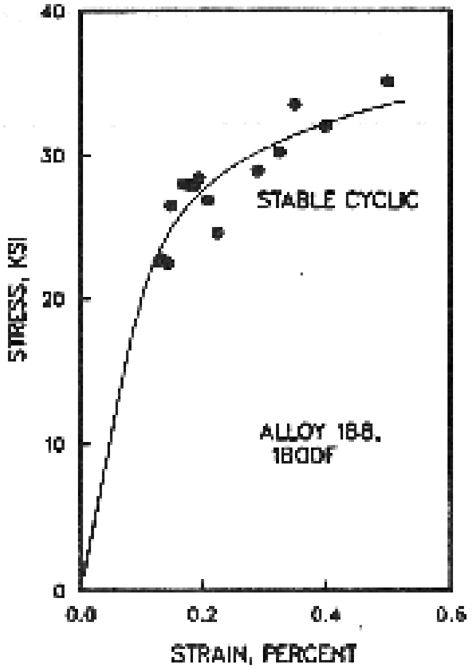


Figure 6.4.2.1.8(d). Best-fit ε/N curve and cyclic stress-strain curve for HS 188 bar, longitudinal orientation at 1800°F.

Correlative Information for Figure 6.4.2.1.8(d)

Product Form/Thickness: Bar, 1.5 inch thick

Thermal Mechanical Processing History:
Solution treated, water quenched (AMS 5772)

Properties:

TUS, ksi	TYS, ksi	E, ksi	Temp., °F
120*	55*		75
		20,353	1800

Stress-Strain Equations:
Cyclic (Companion Specimens)
Proportional Limit = 23 ksi

$(\Delta\sigma/2) = 66.3\ (\Delta\varepsilon_p/2)^{0.12}$

Specimen Details: Uniform gage test section
0.250 inch diameter

Reference: 3.8.1.1.8

Test Parameters:
Strain Rate/Frequency - 20 cpm
Wave Form - Triangular
Temperature - 1800°F
Atmosphere - Air

No. of Heats/Lots: 1

Equivalent Strain Equation:
$\text{Log } N_f = 0.047 - 1.317 \log (\Delta\varepsilon - 0.00239)$
Std. Error of Estimate, Log (Life) = 0.0126
Standard Deviation, Log(Life) = 0.063
$R^2 = 96\%$

Sample Size: 15

[Caution: The equivalent strain model may provide unrealistic life predictions for strain ratios and ranges beyond those represented above.]

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* Minimum values from AMS 5772.

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6.3.5.1.9(f) James, L. A., "Fatigue-Crack Propagation Behavior of Inconel 718", Report HEDL-TME-75-80, Hanford Engineering Development Laboratory (September 1975).

6.3.5.1.9(g) James, L. A., "Heat-to-Heat and/or Melt Practice Variations in Crack Growth Behavior of Alloy 718", Mechanical Properties Test Data for Structural Materials, Quarterly Progress Report for Period Ending January 31, 1978, Report ORNL-5380, pp. 153-160, Oak Ridge National Laboratory (March 1978).

CHAPTER 7

MISCELLANEOUS ALLOYS AND HYBRID MATERIALS

7.1 GENERAL

This chapter contains the engineering properties and related characteristics of miscellaneous alloys and hybrid materials. In addition to the usual properties, some characteristics relating to the special uses of these alloys are described. For example, the electrical conductivity is reported for the bronzes and information is included on toxicity of particles of beryllium and its compounds, such as beryllium oxide.

The organization of this chapter is in sections by base metal and subdivided as shown in Table 7.1.

Table 7.1. Miscellaneous Alloys Index

Section	Designation
7.2	**Beryllium**
7.2.1	Standard Grade Beryllium
7.3	**Copper and Copper Alloys**
7.3.1	Manganese Bronzes
7.3.2	Copper Beryllium
7.4	**Multiphase Alloys**
7.4.1	MP35N Alloy
7.4.2	MP159 Alloy
7.5	**Aluminum Alloy Sheet Laminates**
7.5.1	2024-T3 Aramid Fiber Reinforced Sheet Laminate
7.5.2	7475-T761 Aramid Fiber Reinforced Sheet Laminate

7.2 BERYLLIUM

7.2.0 GENERAL

This section contains the engineering properties and related characteristics of beryllium used in aerospace structural applications. Beryllium is a lightweight, high modulus, moderate temperature capability metal that is used for specific aerospace applications. Structural designs utilizing beryllium sheet should allow for anisotropy, particularly the very low short transverse properties. Additional information on the fabrication of beryllium may be found in References 7.2.0(a) through (i).

7.2.1 STANDARD GRADE BERYLLIUM

7.2.1.0 ***Comments and Properties*** — Standard grade beryllium bars, rods, tubing, and machined shapes are produced from vacuum hot-pressed powder with 1½ percent maximum beryllium oxide content. These products are also available in numerous other compositions for special purposes but are not covered in this document. Sheet and plate are fabricated from vacuum hot-pressed powder with 2 percent maximum beryllium oxide content.

7.2.1.1 *Manufacturing Considerations*

Hot Shaping — Beryllium hot-pressed block can be forged and rolled but requires temperatures of 700°F and higher because of brittleness. A temperature range of 1000°F to 1400°F is recommended. Hot shaping procedures are given in more detail in Reference 7.2.0(b).

Forming — Beryllium sheet should be formed at 1300°F to 1350°F, holding at temperature no more than 1.5 hours, for minimum springback. Forming above 1450°F will result in a reduction in strength.

Machining — Carbide tools are most often used in machining beryllium. Mechanical metal removal techniques generally cause microcracks and metallographic twins. Finishing cuts are usually 0.002 to 0.005 inch in depth to minimize surface damage. Although most machining operations are performed without coolant, to avoid contamination of the chips, the use of coolant can reduce the depth of damage and give longer tool life. See Reference 7.2.0(c) for more information. Finish machining should be followed by chemical etching at least 0.002-inch from the surface to remove machining damage. See References 7.2.0(h) and (i). A combination of 1350°F stress relief followed by an 0.0005-inch etch may be necessary for close-tolerance parts. Damage-free metal removal techniques include chemical milling and electrochemical machining. The drilling of sheet may lead to delamination and breakout unless the drillhead is of the controlled torque type and the drills are carbide burr type.

Joining — Parts may be joined mechanically by riveting, but only by squeeze riveting to avoid damage to the beryllium, by bolting, threading, or by press fitting specifically designed to avoid damage. Parts also may be joined by brazing, soldering, braze welding, adhesive bonding, and diffusion bonding. Fusion welding is not recommended. Brazing may be accomplished with zinc, aluminum-silicon, or silver-base filler metals. Many elements, including copper, may cause embrittlement when used as brazing filler metals. However, specific manufacturing techniques have been developed by various beryllium fabricators to use many of the common braze materials. For each method of joining specific detailed procedures must be followed, Reference 7.2.0(f).

Surface Treatment — A surface treatment such as chemical etching to remove the machined surface of metal is recommended to ensure the specified properties. All design allowables herein represent material so treated. This surface treatment is especially important when beryllium is to be mechanically joined. References 7.2.0(d), (h), and (i) contain information on etching solutions and procedures.

Toxicity Hazard — Particles of beryllium and its compounds, such as beryllium oxide, are toxic, so special precautions to prevent inhalation must be taken. References 7.2.1.1(a) through (e) outline the hazard and methods to control it.

Specifications and Properties — Material specifications for standard grade beryllium are presented in Table 7.2.1.0(a).

Table 7.2.1.0(a). Material Specifications for Standard Grade Beryllium

Specification	Form
AMS 7906	Bar, rod, tubing, and mechanical shapes
AMS 7902	Sheet and plate

Room-temperature mechanical and physical properties are shown in Tables 7.2.1.0(b) and (c). Notch tensile test data are available in Reference 7.2.1.1(g). The effect of temperature on physical properties is shown in Figure 7.2.1.0.

7.2.1.1 ***Hot-Pressed Condition*** — The effect of temperature on the mechanical properties of hot-pressed beryllium is presented in Figures 7.2.1.1.1 and 7.2.1.1.4.

Table 7.2.1.0(b). Design Mechanical and Physical Properties of Beryllium Bar, Rod, Tubing, and Mechanical Shapes

Specification	AMS 7906
Form	Bar, rod, tubing, and machined shapes
Condition	Hot pressed (ground and etched)
Thickness or diameter, in.	...
Basis	S
Mechanical Properties:	
F_{tu}, ksi:	
L	47
LT	47
F_{ty}, ksi:	
L	35
LT	35
F_{cy}, ksi:	
L	...
LT	...
F_{su}, ksi	...
F_{bru}, ksi:	
(e/D = 1.5)	...
(e/D = 2.0)	...
F_{bry}, ksi:	
(e/D = 1.5)	...
(e/D = 2.0)	...
e, percent:	
L	2
LT	2
E, 10^3 ksi	42
E_c, 10^3 ksi	42
G, 10^3 ksi	20
μ	0.10
Physical Properties:	
ω, lb/in.^{3}	0.067
C, K, and α	See Figure 7.2.1.0

Table 7.2.1.0(c). Design Mechanical and Physical Properties of Beryllium Sheet and Plate

Specification	AMS 7902			
Form	Sheet	Plate		
Condition	Stress relieved (ground and etched)			
Thickness or diameter, in.	0.020-0.250	0.251-0.450	0.451-0.600	≥0.601
Basis	S	S	S	S
Mechanical Properties:				
F_{tu}, ksi:				
L	70	65	60	40
LT	70	65	60	40
F_{ty}, ksi:				
L	50	45	40	30
LT	50	45	40	30
F_{cy}, ksi:				
L	...	...	...	...
LT	...	...	...	...
F_{su}, ksi	...	...	...	...
F_{bru}, ksi:				
(e/D = 1.5)	...	...	...	...
(e/D = 2.0)	...	...	...	...
F_{bry}, ksi:				
(e/D = 1.5)	...	...	...	...
(e/D = 2.0)	...	...	...	...
e, percent:				
L	10	4	3	1
LT	10	4	3	1
E, 10^3 ksi	42.5			
E_c, 10^3 ksi	42.5			
G, 10^3 ksi	20.0			
μ	0.10 (L and LT)			
Physical Properties:				
ω, lb/in.^{3}	0.067			
C, K, and α	See Figure 7.2.1.0			

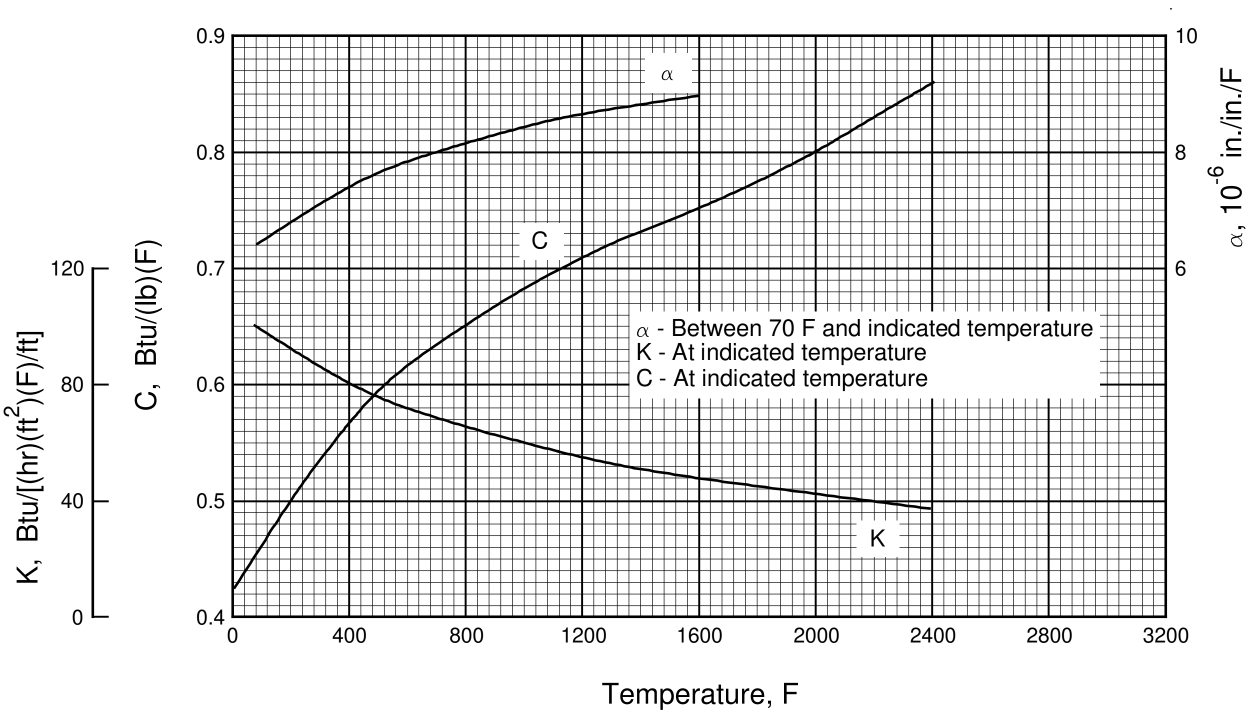

Figure 7.2.1.0. Effect of temperature on the physical properties of beryllium (2% maximum BeO).

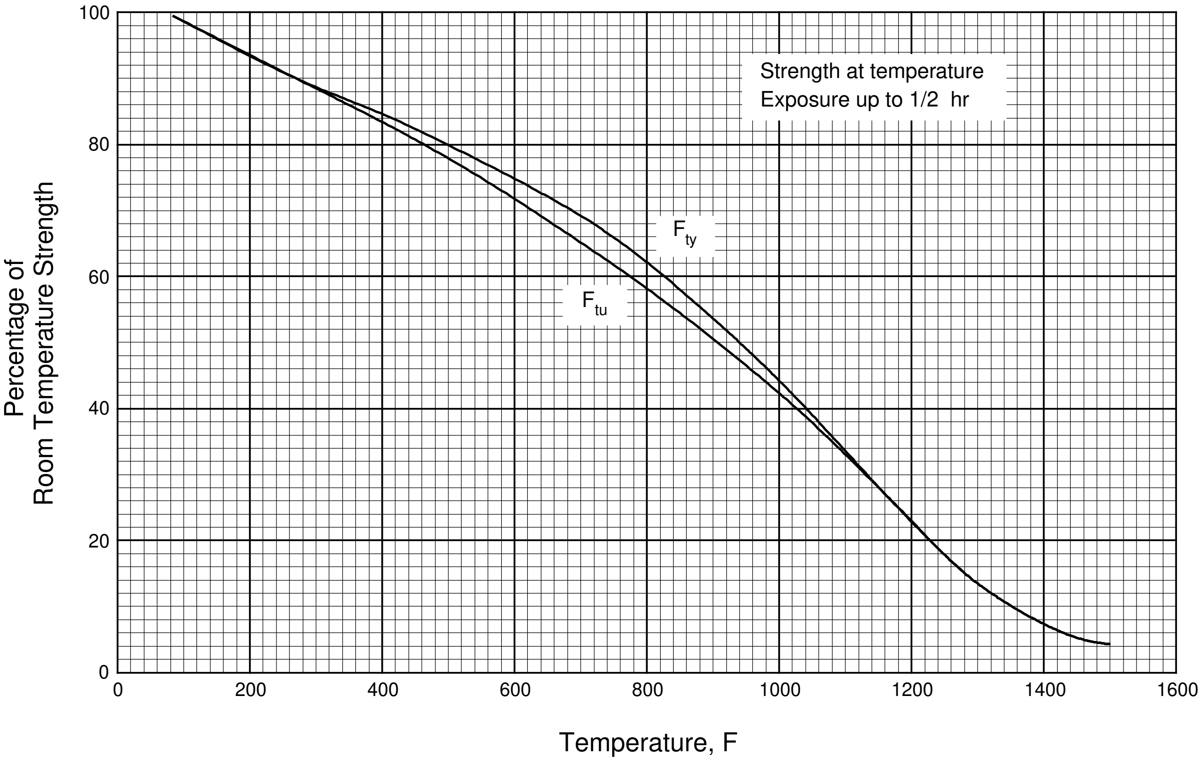

Figure 7.2.1.1.1. Effect of temperature on the tensile ultimate strength (F_{tu}) and tensile yield strength (F_{ty}) of hot-pressed beryllium bar, rod, tubing, and machined shapes.

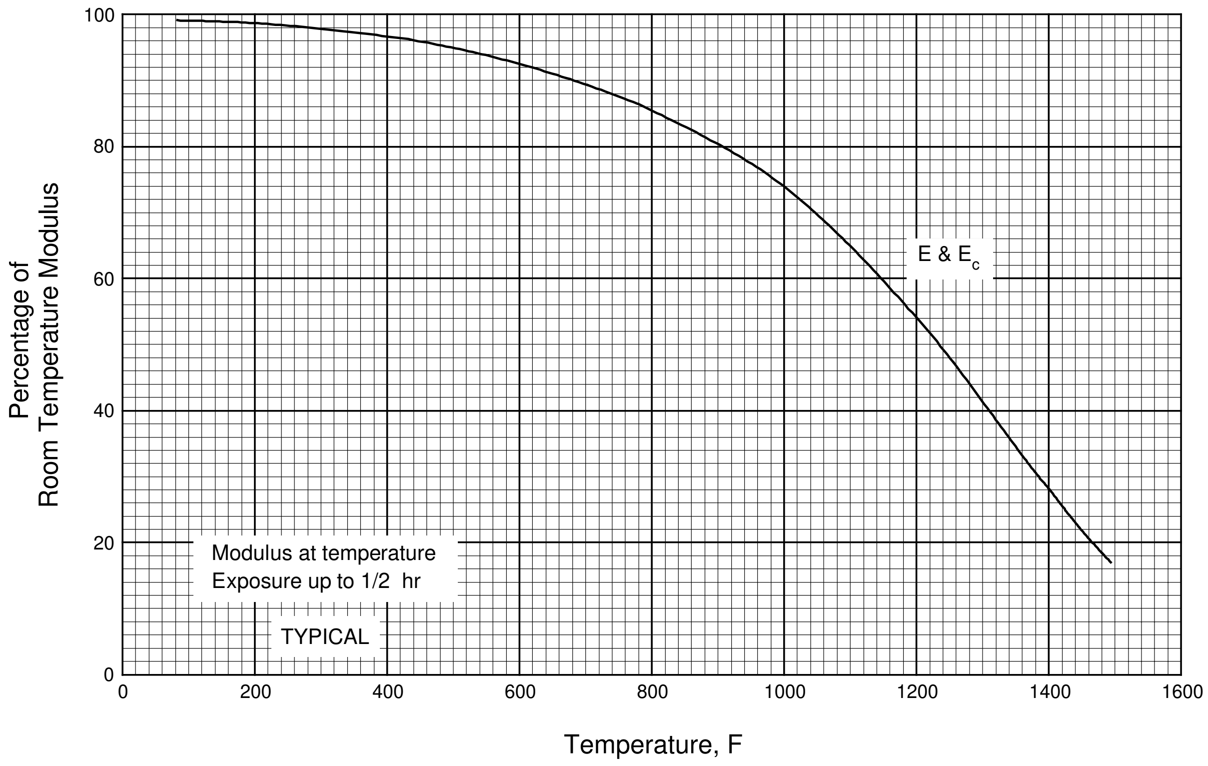

Figure 7.2.1.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of hot-pressed beryllium bar, rod, tubing, and machined shapes.

7.3 COPPER AND COPPER ALLOYS

7.3.0 GENERAL

The properties of major significance in designing with copper and copper alloys are electrical and thermal conductivity, corrosion resistance, and good bearing qualities (antigalling). Copper and copper alloys are non-magnetic and can be readily joined by welding, brazing and soldering. The use of copper alloys is usually predicated upon two or more of the above properties plus the ease of casting and hot and cold working into desirable shapes.

The thermally unstable range for copper and copper alloys generally begins somewhat above room temperature (150°F). Creep, stress relaxation and diminishing stress rupture strength are factors of concern above 150°F. Copper alloys frequently are used at temperatures up to 480°F. The range between 480°F and 750°F is considered very high for copper alloys, since copper and many of its alloys begin to oxidize slightly above 350°F and protection may be required. Bronzes containing Al, Si, and Be oxidize to a lesser extent than the red copper alloys. Precipitation hardened alloys such as copper beryllium retain strength up to their aging temperatures of 500°F to 750°F.

Copper alloys used for bearing and wear resistance applications include, in the order of their increasing strength and load-carrying capacity, copper-tin-lead, copper-tin, silicon bronze, manganese bronze, aluminum bronze, and copper beryllium. Copper beryllium and manganese bronzes are included in MIL-HDBK-5.

Copper-base bearing alloys are readily cast by a number of techniques: statically sand cast, centrifugally cast into tubular shapes, and continuously cast into various shapes. Tin bronze, sometimes called phosphor bronze because phosphorous is used to deoxidize the melt and improve castability, is a low-strength alloy. It is generally supplied as a static (sand) casting or centrifugal casting (tubular shapes from rotating graphite molds). Manganese bronze is considerably stronger than tin bronze, is easily cast in the foundry, has good toughness and is not heat treated. Aluminum bronze alloys, especially those with nickel, silicon, and manganese over 2 percent, respond to heat treatment, resulting in greater strength, and higher galling and fatigue limits than manganese bronze. Aluminum bronze is used in the static and centrifugal cast form or parts may be machined from wrought rod and bar stock. Copper beryllium is the highest strength copper-base bearing material, due to its response to precipitation hardening. Copper beryllium is also available in static and centrifugal cast form but is generally used as wrought shapes, such as extrusions, forgings, and mill shapes.

Copper beryllium, because of its high strength, is also useful as a spring material. In this application its high elastic limit, high fatigue strength as well as good electrical conductivity are significant. Copper beryllium resists softening up to 500°F, which is higher than other common copper alloys. Copper beryllium springs are usually fabricated from strip or wire. Consult References 7.3.0(a) through (c) for more information.

7.3.1 MANGANESE BRONZES

7.3.1.0 *Comments and Properties* — The manganese bronzes are also known as the high-strength yellow brasses and leaded high-strength yellow brasses. These alloys contain zinc as the principal alloying element with smaller amounts of iron, aluminum, manganese, nickel, and lead present. These bronzes are easily cast.

Some material specifications for manganese bronzes are presented in Table 7.3.1.0(a). A cross index to CDA and former QQ-C-390 designations is presented in Table 7.3.1.0(b). Room-temperature mechanical properties are shown in Tables 7.3.1.0(c) and (d).

Table 7.3.1.0(a). Material Specifications for Manganese Bronzes

Specification	Form
AMS 4860	Casting
AMS 4862	Casting

Table 7.3.1.0(b). Cross Index

Copper Alloy UNS No.	CDA Alloy No.	Former QQ-C-390 Alloy No.
C86300	863	C7
C86500	865	C3

Table 7.3.1.0(c). Design Mechanical and Physical Properties of C86500 Manganese Bronze

Specification	AMS 4860
Form	Sand and centrifugal casting
Condition	As cast
Location within casting	Any area
Basis	S
Mechanical Properties:	
F_{tu}, ksi	65[a]
F_{ty}, ksi	25[a]
F_{cy}, ksi	...
F_{su}, ksi	...
F_{bru}, ksi:	
(e/D = 1.5)	...
(e/D = 2.0)	...
F_{bry}, ksi:	
(e/D = 1.5)	...
(e/D = 2.0)	...
e, percent	20[a]
E, 10^3 ksi	15.0
E_c, 10^3 ksi	...
G, 10^3 ksi	...
μ	...
Physical Properties:	
ω, lb/in.^{3}	0.301
C, Btu/(lb)(°F)	0.09 (at 68°F)
K, Btu/[(hr)(ft^2)(°F)/ft]	50 (at 68°F)
α, 10^{-6} in./in/°F	11.3 (68 to 212°F)
Electrical conductivity, % IACS	22.0

a When specified, conformance to tensile property requirements is determined by testing specimens cut from casting.

Table 7.3.1.0(d). Design Mechanical and Physical Properties of C86300 Manganese Bronze

Specification	AMS 4862
Form	Sand and centrifugal casting
Condition	As cast
Location within casting	Any area
Basis	S
Mechanical Properties:	
F_{tu}, ksi	110[a]
F_{ty}, ksi	60[a]
F_{cy}, ksi	...
F_{su}, ksi	...
F_{bru}, ksi:	
(e/D = 1.5)	...
(e/D = 2.0)	...
F_{bry}, ksi:	
(e/D = 1.5)	...
(e/D = 2.0)	...
e, percent	12[a]
E, 10^3 ksi	14.2
E_c, 10^3 ksi	...
G, 10^3 ksi	...
μ	...
Physical Properties:	
ω, lb/in.^{3}	0.283
C, Btu/(lb)(°F)	0.09 (at 68°F)
K, Btu/[(hr)(ft^2)(°F)/ft]	20.5 (at 68°F)
α, 10^{-6} in./in/°F	12.0 (68 to 500°F)
Electrical conductivity, % IACS	8.0

a When specified, conformance to tensile property requirements is determined by testing specimens cut from casting.

7.3.2 COPPER BERYLLIUM

7.3.2.0 *Comments and Properties* — Copper beryllium refers to a family of copper-base alloys containing beryllium and cobalt or nickel which cause the alloys to be precipitation hardenable. Data for only one high-strength alloy, designated C17200, which contains 1.90 percent (nominal) beryllium, are presented in this section. This alloy is suitable for parts requiring high strength, good wear, and corrosion resistance. Alloy C17200 is available in the form of rod, bar, shapes, mechanical tubing, strip, and casting.

Manufacturing Considerations — The heat treatable tempers of rod and bar are designated TB00 (AMS 4650) for solution-treated or TD04 (AMS 4651) for solution-treated plus cold worked conditions. After fabrication operations, the material may be strengthened by precipitation heat treatment (aging). Rod and bar are also available from the mill in the TF00 (AMS 4533) and TH04 (AMS 4534) conditions. Mechanical tubing is available from the mill in TF00 (AMS 4535) condition. Machining operations on rod, bar, and tubing are usually performed on material in the TF00 or (TH04) conditions. This eliminates the volumetric shrinkage of 0.02 percent, which occurs during precipitation hardening, as a factor in maintaining final dimensional tolerances. This material has good machinability in all conditions.

Strip is also available in the heat treatable condition. Parts are stamped or formed in a heat treatable temper and subsequently precipitation heat treated. For strip, the heat treatable tempers are designated TB00 (AMS 4530, ASTM B194), TD01 (ASTM B194), TD02 (AMS 4532, ASTM B194), and TD04 (ASTM B194), indicating a progressively greater amount of cold work by the mill. When parts produced from these tempers are precipitation heat treated by the user, the designations become TF00, TH01, TH02, and TH04, respectively. Strip is also available from the mill for the hardened conditions. Design values for these conditions are not included.

Environmental Considerations — The copper beryllium alloys have good corrosion resistance and are not susceptible to hydrogen embrittlement. The maximum service temperature for C17200 copper beryllium products is 500°F for up to 100 hours.

Specifications and Properties — A cross-index to previous and current temper designations for C17200 alloy is presented in Table 7.3.2.0(a).

Table 7.3.2.0(a). Cross-Index to Previous and Current Temper Designations for C17200 Copper Beryllium

Previous Temper	Current ASTM Temper
A	TB00
AT	TF00
¼H	TD01
¼HT	TH01
½H	TD02
½HT	TH02
H	TD04
HT	TH04

Material specifications for alloy C17200 are presented in Table 7.3.2.0(b). Room-temperature mechanical properties are shown in Tables 7.3.2.0(c) through (g). The effect of temperature on physical properties is depicted in Figure 7.3.2.0.

Table 7.3.2.0(b). Material Specifications for C17200 Copper Beryllium Alloy

Specification	Form
ASTM B194	Strip (TB00, TD01, TD02, TD04)
AMS 4530[a]	Strip (TB00)
AMS 4532[a]	Strip (TD02)
AMS 4650	Bar, rod, shapes, and forgings (TB00)
AMS 4533	Bar and rod (TF00)
AMS 4535	Mechanical tubing (TF00)
AMS 4651	Bar and rod (TD04)
AMS 4534	Bar and rod (TH04)

a Noncurrent specification.

The temper index for C17200 alloy is as follows:

Section	Temper
7.3.2.1	TF00
7.3.2.2	TH04

7.3.2.1 ***TF00 Temper*** — Typical tensile and compressive stress-strain and tangent-modulus curves are presented in Figures 7.3.2.1.6(a) and (b).

7.3.2.2 ***TH04 Temper*** — Typical tensile and compressive stress-strain and tangent-modulus curves are presented in Figure 7.3.2.2.6.

Table 7.3.2.0(c). Design Mechanical and Physical Properties of Copper Beryllium Strip

Specification	ASTM B194 AMS 4530[a]	ASTM B194	ASTM B194 AMS 4532[a]	ASTM B194
Form	Strip			
Condition	TF00	TH01	TH02	TH04
Thickness, in.	≤0.188	≤0.188	≤0.188	≤0.188
Basis	S	S	S	S
Mechanical Properties:				
F_{tu}, ksi:				
L	165	175	185	190
LT	...	...	...	...
F_{ty}, ksi:				
L	140	150	160	165
LT	...	...	...	...
F_{cy}[b], ksi: (Estimate)				
L	140	150	160	165
LT	140	150	160	165
F_{su}[b], ksi (Estimate)	90	90	92	95
F_{bru}[b], ksi: (Estimate)				
(e/D = 1.5)	214	227	240	247
(e/D = 2.0)	280	297	314	323
F_{bry}[b], ksi: (Estimate)				
(e/D = 1.5)	196	210	224	231
(e/D = 2.0)	210	225	240	247
e, percent:				
L	3	2.5	1	1
E, 10^3 ksi	18.5			
E_c, 10^3 ksi	...			
G, 10^3 ksi	7.3			
μ	0.27			
Physical Properties:				
ω, lb/in.^{3}	0.298			
C, K, and α	See Figure 7.3.2.0 for TF00 temper			

[a] Noncurrent specification.
[b] These properties do not represent values derived from tests, but are estimates.

Table 7.3.2.0(d). Design Mechanical and Physical Properties of C17200 Copper Beryllium Rod and Bar

Specification	AMS 4650 and AMS 4533				
Form	Rod and bar				
Condition	TF00				
Thickness, in.	≤1.500	1.501-2.000	2.001-3.000	3.001-3.500	3.501-4.000
Basis	S	S	S	S	S
Mechanical Properties:					
F_{tu}, ksi:					
L	165	165	165	165	165
ST	...	158	158	158	158
F_{ty}, ksi:					
L	140	140	140	140	140
ST	...	137	137	137	137
F_{cy}, ksi:					
L	150	149	145	143	139
ST	...	142	142	142	142
F_{su}, ksi	...	94	94	94	94
F_{bru}[a], ksi:					
(e/D = 1.5)	226	226	226	226	226
(e/D = 2.0)	290	290	290	290	290
F_{bry}[a], ksi:					
(e/D = 1.5)	200	200	200	200	200
(e/D = 2.0)	225	225	225	225	225
e, percent:					
L	4[b]	4[b]	4[b]	3	3
E, 10^3 ksi	18.5				
E_c, 10^3 ksi	18.7				
G, 10^3 ksi	7.3				
μ	0.27				
Physical Properties:					
ω, lb/in.^{3}	0.298				
C, K, and α	See Figure 7.3.2.0				

[a] Bearing values are "dry pin" values per Section 1.4.7.1.
[b] AMS 4650 specifies *e* = 3 percent.

Table 7.3.2.0(e). Design Mechanical and Physical Properties of C17200 Copper Beryllium Rod and Bar

Specification	AMS 4651			
Form	Rod and bar			
Condition	TH04			
Thickness, in.	≤0.375	0.376-1.000	1.001-1.500	1.501-2.000
Basis	S	S	S	S
Mechanical Properties:				
F_{tu}, ksi:				
L	185	180	175	175
ST	...	...	...	169
F_{ty}, ksi:				
L	145	145	145	145
ST	...	...	...	140
F_{cy}, ksi:				
L	...	148	148	148
ST	...	...	...	154
F_{su}, ksi	...	89	90	93
F_{bru}[a], ksi:				
(e/D = 1.5)	...	242	235	235
(e/D = 2.0)	...	306	298	298
F_{bry}[a], ksi:				
(e/D = 1.5)	...	207	207	207
(e/D = 2.0)	...	225	225	225
e, percent:				
L	1	1	2	2
E, 10^3 ksi	18.5			
E_c, 10^3 ksi	18.7			
G, 10^3 ksi	7.3			
μ	0.27			
Physical Properties:				
ω, lb/in.^{3}	0.298			
C, K, and α	...			

[a] Bearing values are "dry pin" values per Section 1.4.7.1.

Table 7.3.4.0(f). Design Mechanical and Physical Properties of C17200 Copper Beryllium Rod and Bar

Specification	AMS 4534											
Form	Rod and bar											
Condition	TH04											
Thickness, in.	≤0.375		0.376-0.999		1.000-1.499		1.500-1.999		2.000-2.499		2.500-3.000	
Basis	A	B	A	B	A	B	A	B	A	B	A	B
Mechanical Properties:												
F_{tu}, ksi:												
L	182	188	180	186	177[a]	184	177	183	175	181	172	178
ST	...	...	...	...	...	...	167	173	168	174	167	173
F_{ty}, ksi:												
L	157	165	154	162	150[a]	162	150	158	147	155	145	152
ST	...	...	...	...	...	...	145	153	142	150	140	147
F_{cy}, ksi:												
L	...	...	157	166	153	164	153	162	150	158	148	155
ST	...	...	...	...	...	...	160	168	156	165	154	162
F_{su}, ksi	...	...	89	92	91	95	94	97	95	98	94	96
F_{bru}[b], ksi:												
(e/D = 1.5)	...	...	242	250	238	247	238	246	235	243	231	239
(e/D = 2.0)	...	...	306	317	302	313	302	312	298	308	293	303
F_{bry}[b], ksi:												
(e/D = 1.5)	...	...	220	231	214	228	214	226	210	221	207	217
(e/D = 2.0)	...	...	239	251	233	248	233	245	228	240	225	236
e, percent (S-basis):												
L	3	...	3	...	3	...	3	...	3	...	3	...
E, 10^3 ksi	18.5											
E_c, 10^3 ksi	18.7											
G, 10^3 ksi	7.3											
μ	0.27											
Physical Properties:												
ω, lb/in.^{3}	0.298											
C, K, and α	...											

[a] S-basis. A values are F_{tu}(L) = 178 ksi and F_{ty} = 152 ksi.
[b] Bearing values are "dry pin" values per Section 1.4.7.1.

Table 7.3.2.0(g). Design Mechanical and Physical Properties of C17200 Copper Beryllium Mechanical Tubing

Specification	AMS 4535			
Form	Mechanical tubing			
Condition	TF00			
Outside Diameter, in.	≤2.499		2.500-12.000	
Wall Thickness, in.	≤0.749		0.750-2.000	
Basis	A	B	A	B
Mechanical Properties:				
F_{tu}, ksi:				
L	161	167	161	167
LT	...	...	157	163
F_{ty}, ksi:				
L	126	136	126	136
LT	...	...	124	134
F_{cy}, ksi:				
L	134	145	134	145
LT	...	...	135	146
F_{su}, ksi	92	95	92	95
$F_{bru}{}^{a}$, ksi:				
(e/D = 1.5)	228	237	228	237
(e/D = 2.0)	287	298	287	298
$F_{bry}{}^{a}$, ksi:				
(e/D = 1.5)	183	197	183	197
(e/D = 2.0)	206	222	206	222
e, percent (S-basis):				
L	3	...	3	...
E, 10^3 ksi	18.5			
E_c, 10^3 ksi	18.7			
G, 10^3 ksi	7.3			
μ	0.27			
Physical Properties:				
ω, lb/in.^{3}	0.298			
C, Btu/(lb)(°F)	See Figure 7.3.4.0			

a Bearing values are "dry pin" values per Section 1.4.7.1.

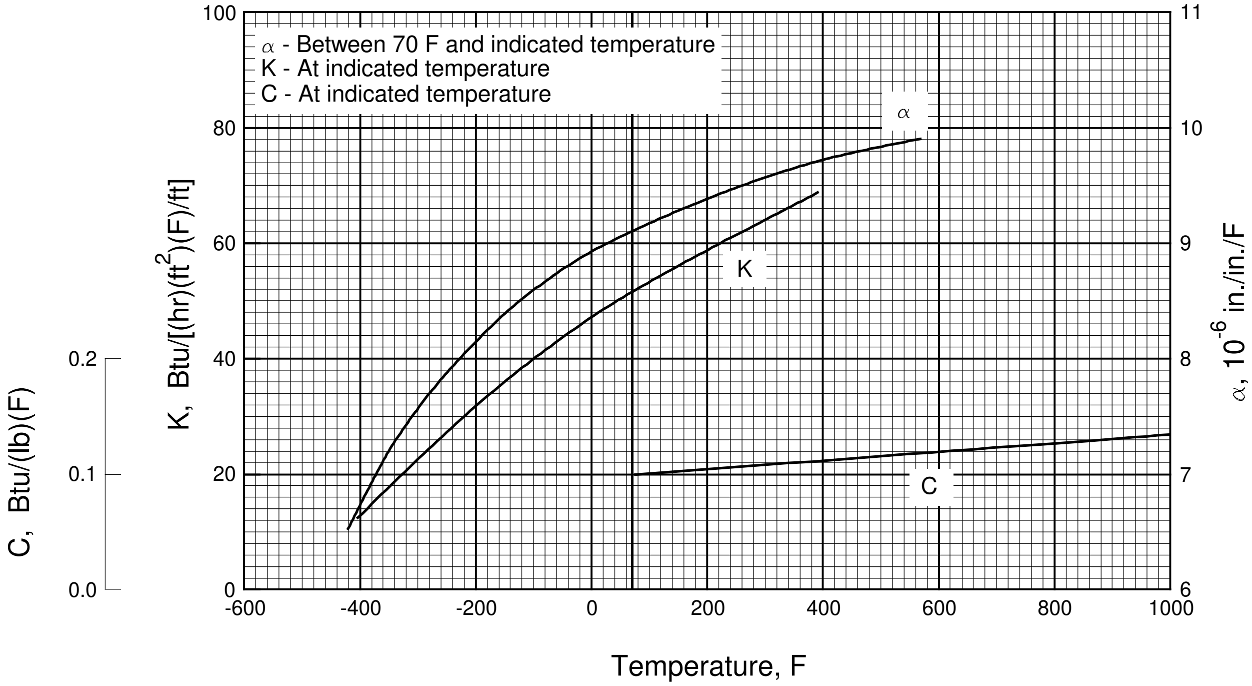

Figure 7.3.2.0. Effect of temperature on the physical properties of copper beryllium (TF00).

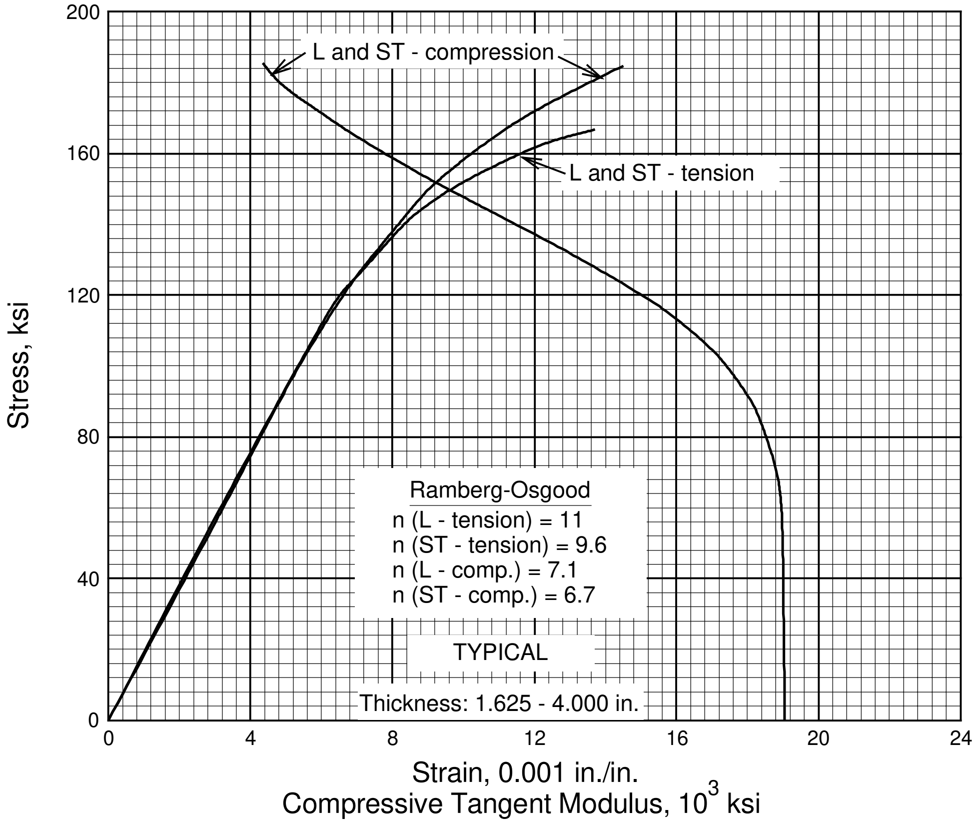

Figure 7.3.2.1.6(a). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for C17200 copper beryllium bar and rod in TF00 temper.

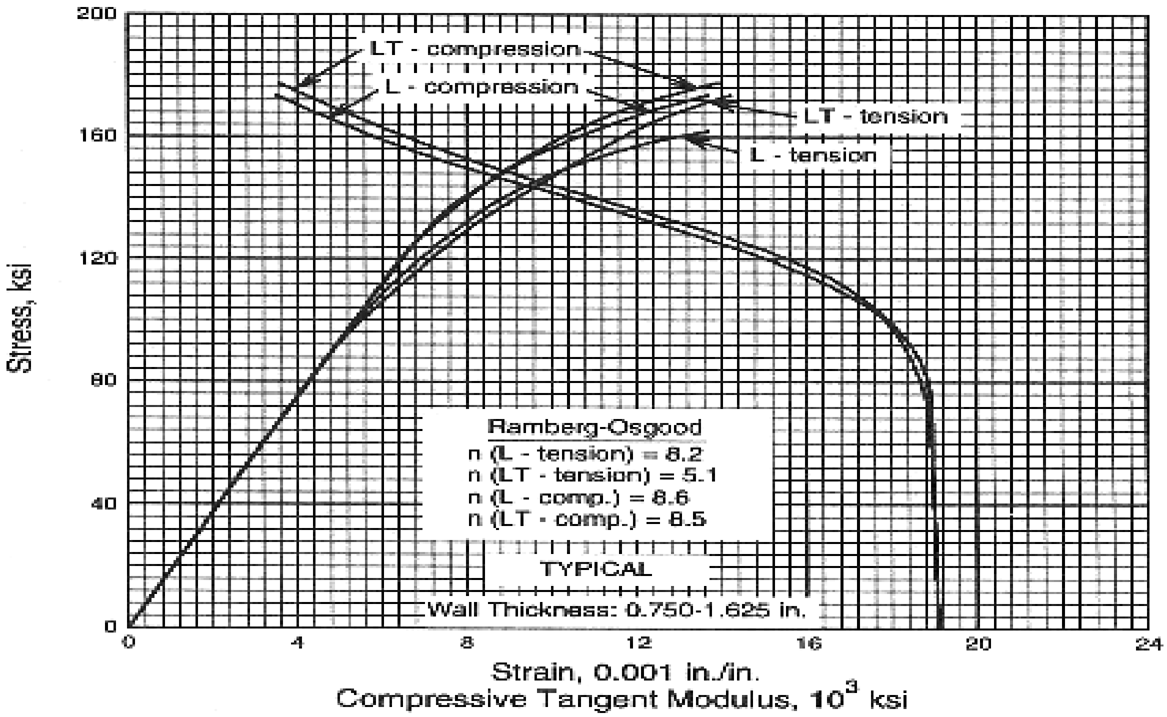

Figure 7.3.2.1.6(b). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for C17200 copper beryllium mechanical tubing in TF00 temper.

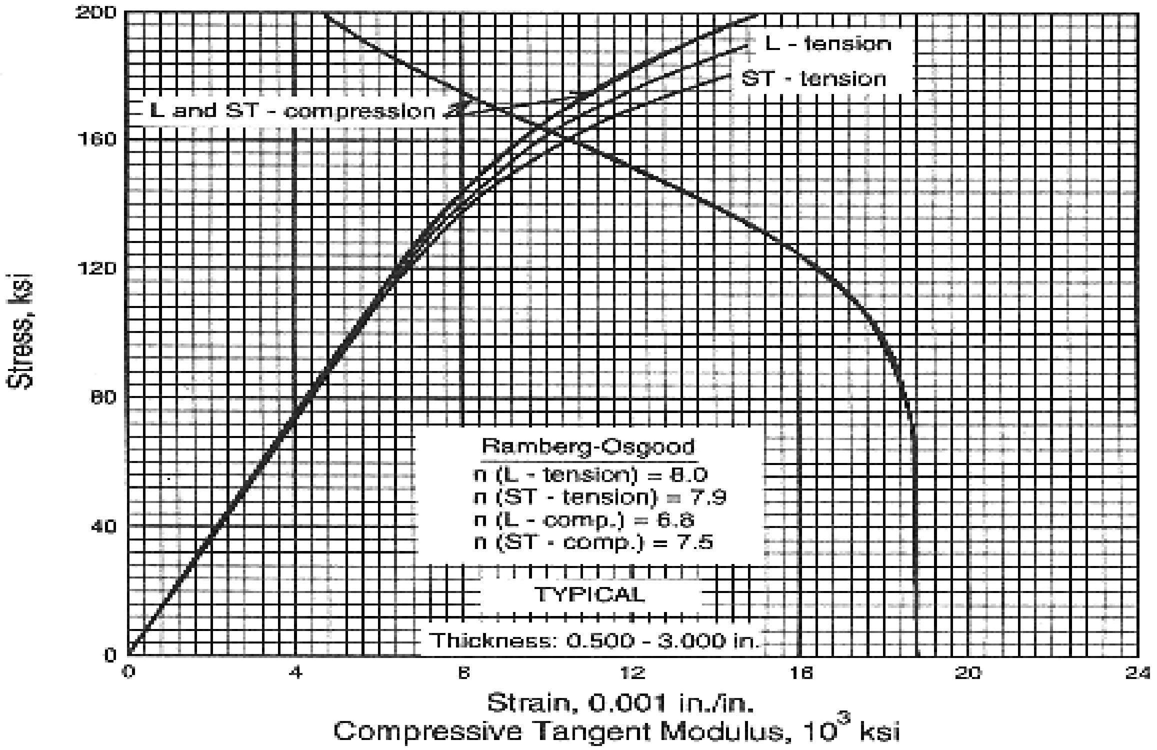

Figure 7.3.2.2.6. Typical tensile and compressive stress-strain and compressive tangent-modulus curves for C17200 copper beryllium bar and rod in TH04 temper.

7.4 MULTIPHASE ALLOYS

7.4.0 GENERAL

This section contains the engineering properties of the "Multiphase" alloys. These alloys, based on the quaternary of cobalt, nickel, chromium, and molybdenum, can be work-strengthened and aged to ultrahigh strengths with good ductility and corrosion resistance.

7.4.1 MP35N ALLOY

7.4.1.0 *Comments and Properties* — MP35N is a vacuum induction, vacuum arc remelted alloy which can be work-strengthened and aged to ultrahigh strengths. This alloy is suitable for parts requiring ultrahigh strength, good ductility and excellent corrosion and oxidation resistance up to 700°F.

Manufacturing Considerations — The work hardening characteristics of MP35N are similar to 304 stainless steel. Drawing, swaging, rolling, and shear forming are excellent deforming methods for work strengthening the alloy. The machinability of MP35N is similar to the nickel-base alloys.

Environmental Considerations — MP35N has excellent corrosion, crevice corrosion and stress corrosion resistance in seawater. Due to the passivity of MP35N, a galvanically active coating, such as aluminum or cadmium, may be required to prevent galvanic corrosion of aluminum joints. Initial tests have indicated that MP35N does not appear to be susceptible to hydrogen embrittlement.

Short time exposure to temperatures above 700°F causes a decrease in ductility (elongation and reduction of area) at temperature. Mechanical properties at room temperature are not affected significantly by unstressed exposure to temperatures up to 50 degrees below the aging temperature (1000 to 2000°F) for up to 100 hours.

Heat Treatment — After work strengthening, MP35N is aged at 1000 to 1200°F for 4 to 4½ hours and air cooled.

Material specifications for MP35N are presented in Table 7.4.1.0(a). The room-temperature mechanical and physical properties for MP35N are presented in Tables 7.4.1.0(b) and (c). The effect of temperature on physical properties is shown in Figure 7.4.1.0.

Table 7.4.1.0(a). Material Specifications for MP35N Alloy

Specification	Form
AMS 5844	Bar (solution treated, and cold drawn)
AMS 5845	Bar (solution treated, cold drawn and aged)

7.4.1.1 *Cold Worked and Aged Condition* — Elevated temperature curves for various mechanical properties are shown in Figures 7.4.1.1.1, 7.4.1.1.4 (a) and (b), and 7.4.1.1.5. Typical tensile stress-strain curves at room and elevated temperatures are shown in Figure 7.4.1.1.6.

Table 7.4.1.0(b). Design Mechanical and Physical Properties of MP35N Alloy Bar

Specification	AMS 5845			
Form	Bar			
Condition	Solution treated, cold drawn, and aged			
Diameter, in.[a]	≤0.800		0.801-1.000	1.001-1.750
Basis	A	B	S	S
Mechanical Properties:				
F_{tu}, ksi:				
L	260[b]	275	260	260
LT	...	...	...	...
F_{ty}, ksi:				
L	230[c]	266	230	230
LT	...	...	...	...
F_{cy}, ksi:				
L	...	...	...	...
LT	...	...	...	...
F_{su}, ksi	145	147	145	...
F_{bru}, ksi:				
(e/D = 1.5)	...	...	...	...
(e/D = 2.0)	...	...	...	...
F_{bry}, ksi:				
(e/D = 1.5)	...	...	...	...
(e/D = 2.0)	...	...	...	...
e, percent (S basis):				
L	8	...	8	8
RA, percent (S basis):				
L	35	...	35	35
E, 10^3 ksi	34.0			
E_c, 10^3 ksi	...			
G, 10^3 ksi	11.7			
μ	...			
Physical Properties:				
ω, lb/in.^{3}	0.304			
C, Btu/(lb)(°F)	0.18 (32 to 70°F)			
K and α	See Figure 7.4.1.0			

[a] Tensile specimens are located at T/2 location for bars 0.800 inch and under in diameter or distance between parallel sides and at T/4 location of larger size bars. The strength of bar, especially large diameter, may vary significantly from center to surface; consequently, caution should be exercised in machining parts from bars over 0.800 inch in diameter since strengths may be lower than design values depending on depth of material removed from surface.

[b] The T_{99} value of 266 ksi is higher than specification minimum.

[c] The T_{99} value of 256 ksi is higher than specification minimum.

Table 7.4.1.0(c). Design Mechanical and Physical Properties of MP35N Alloy Bar

Specification	AMS 5844	
Form	Bar	
Condition	Solution treated and cold drawn	
Diameter, in.[a]	≤1.000	1.001-1.750
Basis	S	S
Mechanical Properties:		
F_{tu}, ksi:		
L	260	260
LT	...	...
F_{ty}, ksi:		
L	230	230
LT	...	...
F_{cy}, ksi:		
L	...	...
LT	...	...
F_{su}, ksi	145	...
F_{bru}, ksi:		
(e/D = 1.5)	...	...
(e/D = 2.0)	...	...
F_{bry}, ksi:		
(e/D = 1.5)	...	...
(e/D = 2.0)	...	...
e, percent:		
L	8	8
RA, percent:		
L	35	35
E, 10^3 ksi	34.0	
E_c, 10^3 ksi	...	
G, 10^3 ksi	11.7	
μ	...	
Physical Properties:		
ω, lb/in.^{3}	0.304	
C, Btu/(lb)(°F)	0.18 (32 to 70°F)	
K and α	See Figure 7.4.1.0	

[a] Tensile specimens are located at T/2 location for bars 0.800 inch and under in diameter or distance between parallel sides and at T/4 location for larger size bars. The strength of bar, especially large diameter may vary significantly from center to surface; consequently, caution should be exercised in machining parts from bars over 0.800 inch in diameter since strengths may be lower than design values depending on depth of material removed from surface.

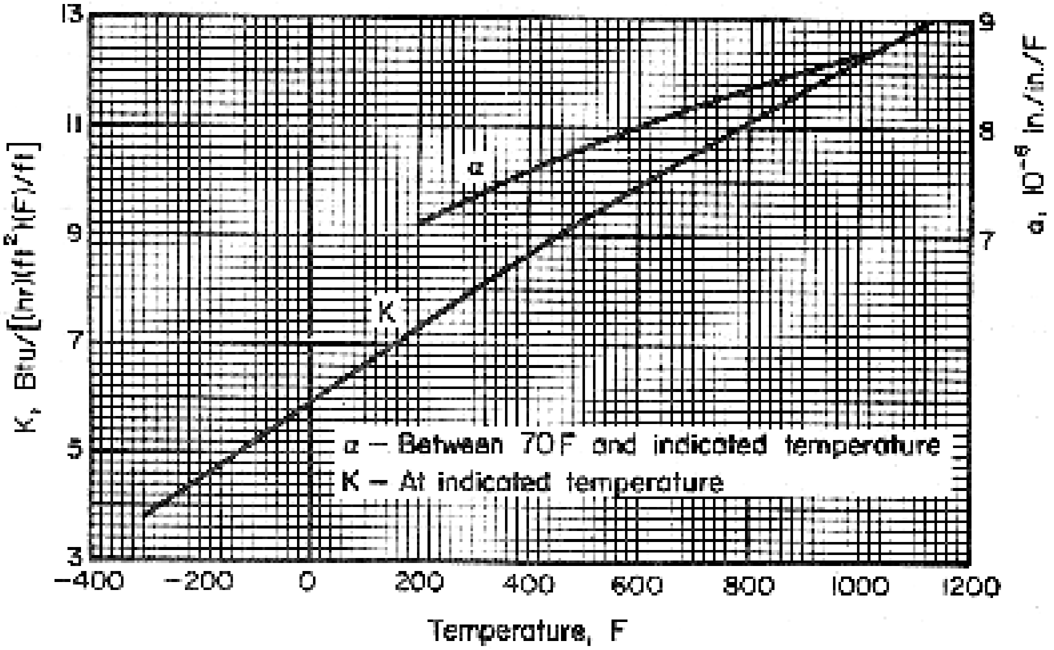

Figure 7.4.1.0. Effect of temperature on the physical properties of MP35N alloy.

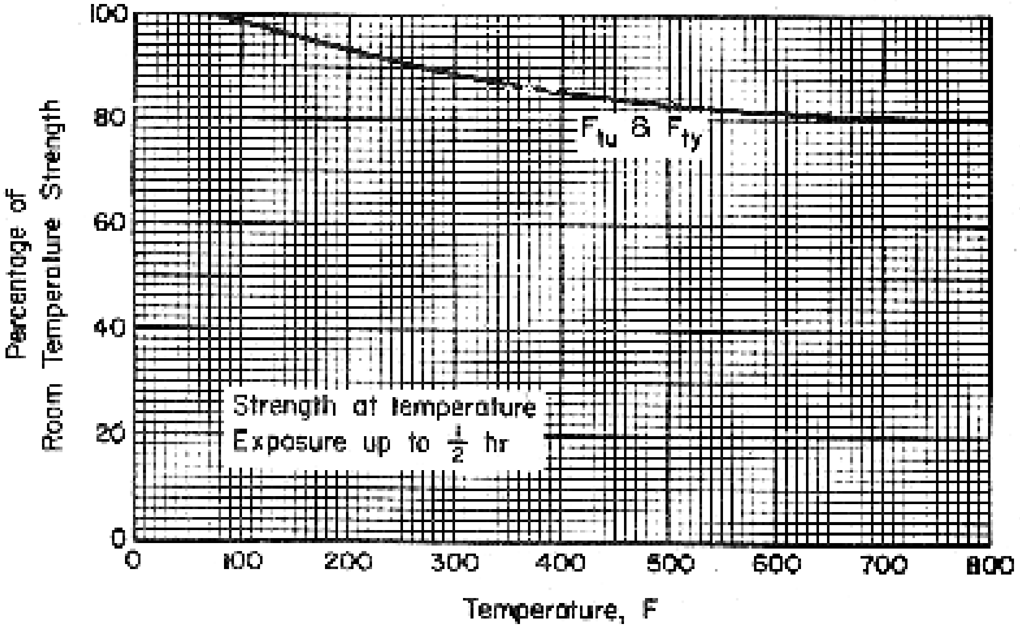

Figure 7.4.1.1.1. Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of cold worked and aged MP35N bar, F_{tu} = 260 ksi.

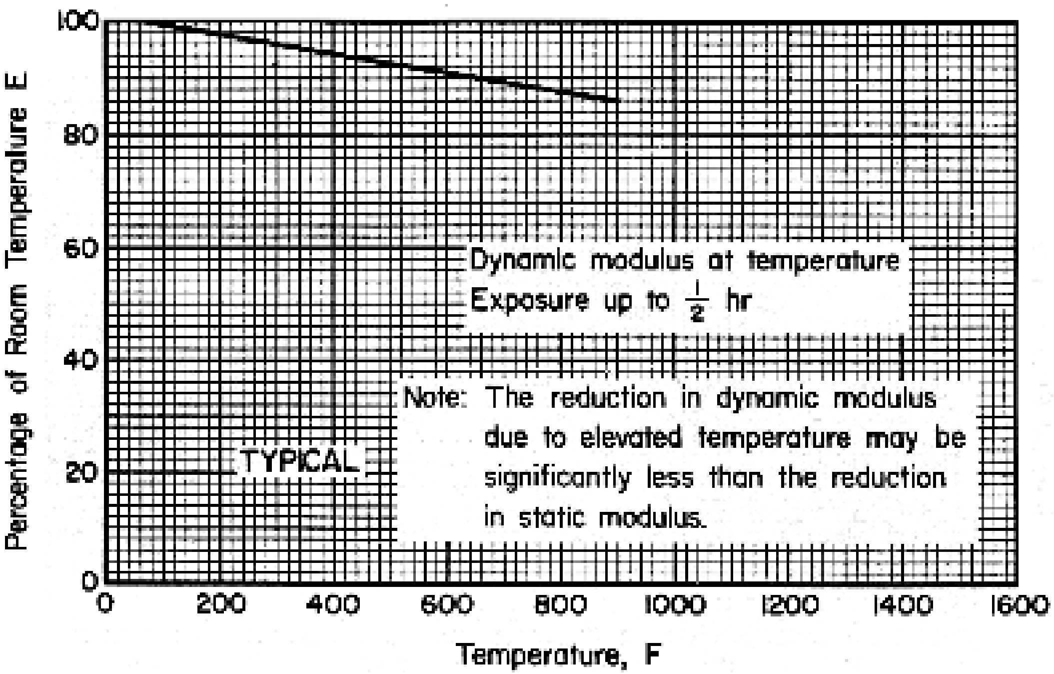

Figure 7.4.1.1.4(a). Effect of temperature on the dynamic tensile modulus (E) of MP35N alloy bar.

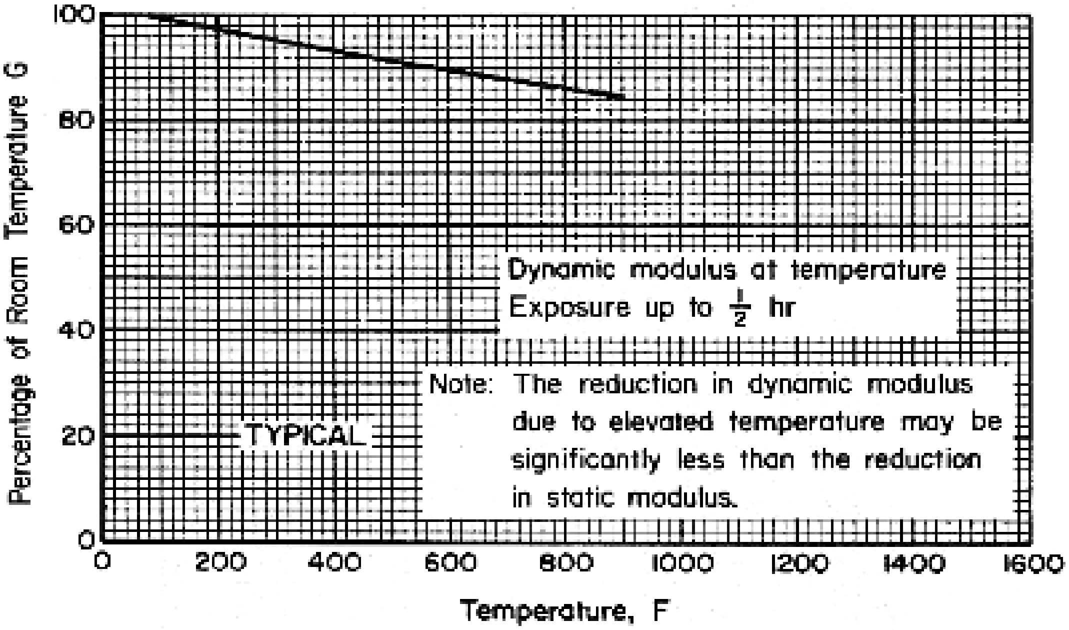

Figure 7.4.1.1.4(b). Effect of temperature on the dynamic shear modulus (G) of MP35N alloy bar.

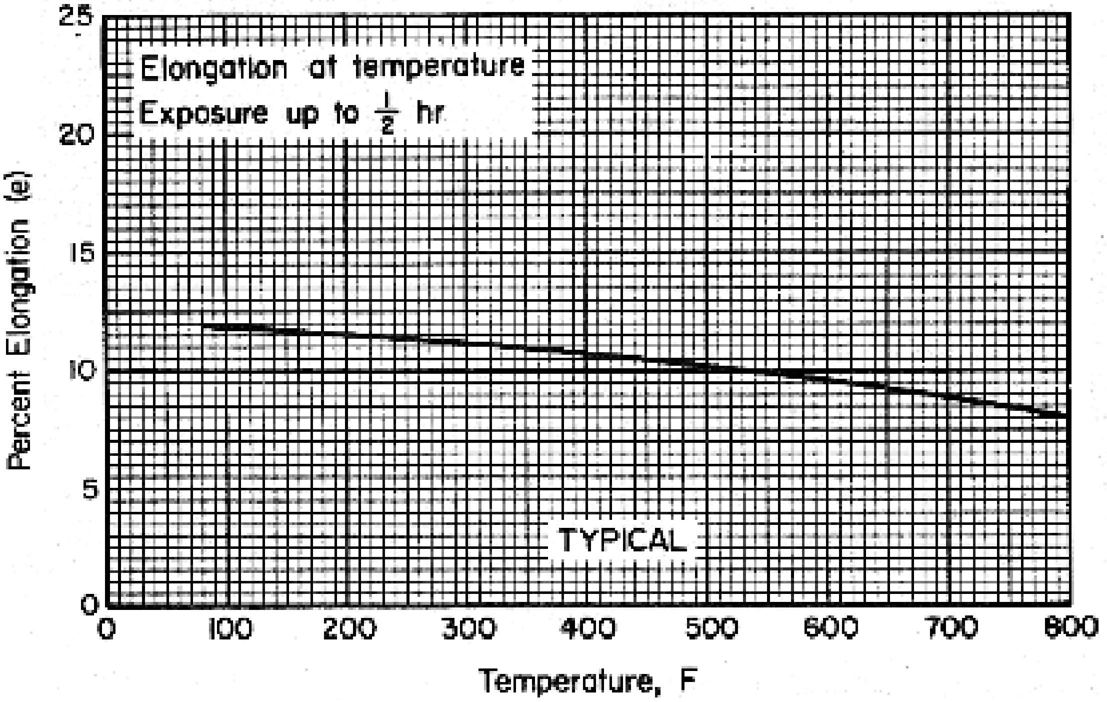

Figure 7.4.1.1.5. Effect of temperature on the elongation (e) of cold worked and aged MP35N bar, F_{tu} = 260 ksi.

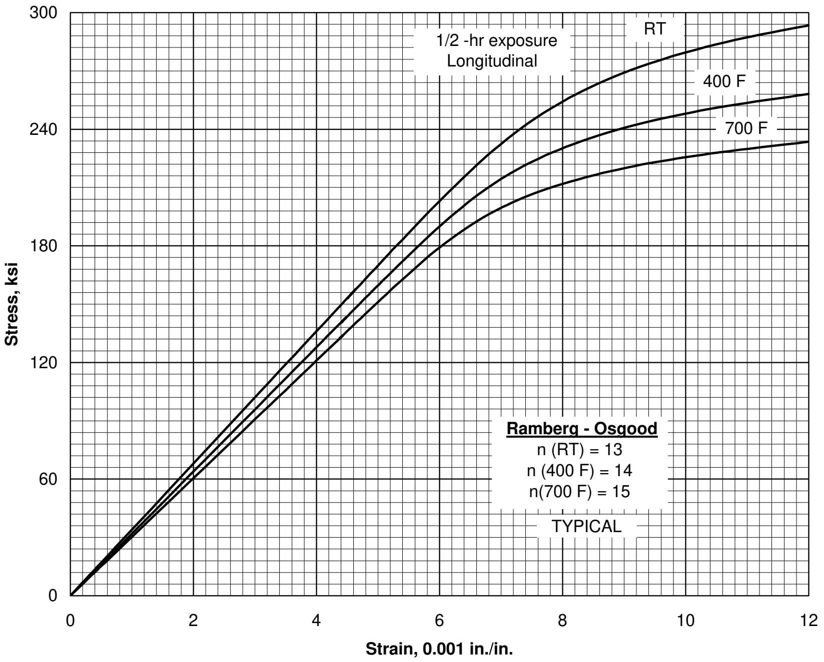

Figure 7.4.1.1.6. Typical tensile stress-strain curves at room and elevated temperatures for cold worked and aged MP35N bar, F_{tu} = 260 ksi.

7.4.2 MP159 ALLOY

7.4.2.0 *Comments and Properties* — MP159 is a vacuum induction, vacuum arc remelted alloy, based on cobalt, nickel, chromium, iron, and molybdenum, which can be work-strengthened and aged to ultrahigh strength. This alloy is suitable for parts requiring ultrahigh strength, good ductility, and excellent corrosion and oxidation resistance up to 1100°F. The alloy maintains its ultrahigh strength very well at temperatures up to 1100°F.

Manufacturing Considerations — The work hardening characteristics of MP159 are similar to MP35N and 304 stainless steel. Drawing, swaging, rolling, and shear forming are excellent deforming methods for work strengthening the alloy. The machinability of MP159 is similar to MP35N and the nickel-base alloys.

Environmental Considerations — MP159 has excellent corrosion, crevice corrosion, and stress corrosion resistance in various hostile environments. Due to the passivity of MP159, a galvanically active coating, such as aluminum or cadmium, may be required to prevent galvanic corrosion of aluminum joints. Initial tests have indicated that MP159 does not appear to be susceptible to hydrogen embrittlement.

Heat Treatment — After work strengthening, MP159 is aged at 1200 to 1250°F ± 25°F for 4 to 4½ hours and air cooled.

Material specifications for MP159 are presented in Table 7.4.2.0(a). The room temperature mechanical and physical properties for MP159 are presented in Tables 7.4.2.0(b) and (c). The effect of temperature on thermal expansion is shown in Figure 7.4.2.0.

Table 7.4.2.0(a). Material Specifications for MP159 Alloy

Specification	Form
AMS 5842	Bar (solution treated and cold drawn)
AMS 5843	Bar (solution treated, cold drawn, and aged)

7.4.2.1 *Cold Worked and Aged Condition* — The effect of temperature on tension modulus of elasticity and shear modulus is presented in Figure 7.4.2.1.4. A typical stress-strain curve at room temperature is shown in Figure 7.4.2.1.6.

Table 7.4.2.0(b). Design Mechanical and Physical Properties of MP159 Alloy Bar

Specification	AMS 5843				
Form	Bar				
Condition	Solution treated, cold drawn, and aged				
Diameter, in.[a]	≤0.500		0.501-0.800		0.801-1.750
Basis	A	B	A	B	S
Mechanical Properties:					
F_{tu}, ksi:					
L	260[b]	269	260[b]	269	260
LT	...	...	...	...	...
F_{ty}, ksi:					
L	250[c]	262	250[c]	262	250
LT	...	...	...	...	...
F_{cy}, ksi:					
L	...	...	...	...	...
LT	...	...	...	...	...
F_{su}, ksi	131	144	...	...	...
F_{bru}, ksi:					
(e/D = 1.5)	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...
F_{bry}, ksi:					
(e/D = 1.5)	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...
e, percent (S basis):					
L	6	...	6	...	6
RA, percent (S basis):					
L	32	...	32	...	32
E, 10^3 ksi	35.3				
E_c, 10^3 ksi	...				
G, 10^3 ksi	11.3				
μ	0.37 (solution treated condition)				
Physical Properties:					
ω, lb/in.^{3}	0.302				
C and K	...				
α, 10^{-6} in./in./°F	See Figure 7.4.2.0				

[a] Tensile specimens are located at T/2 location for bars 0.800 inch and under in diameter or distance between parallel sides and at T/4 location for larger size bars. The strength of bar, especially large diameter, may vary machining parts from bars over 0.800-inch in diameter since strengths may be lower than design values depending on depth of material removed from surface.

[b] S-Basis. The rounded T_{99} value of 265 ksi is higher than specification minimum.

[c] S-Basis. The rounded T_{99} value of 253 ksi is higher than specification minimum.

Table 7.4.2.0(c). Design Mechanical and Physical Properties of MP159 Alloy Bar

Specification	AMS 5842	
Form	Bar	
Condition	Solution treated, cold drawn, and aged	
Diameter, in.[a]	≤0.500	0.501-1.750
Basis	S	S
Mechanical Properties:		
F_{tu}, ksi:		
L	260	260
LT	...	...
F_{ty}, ksi:		
L	250	250
LT	...	...
F_{cy}, ksi:		
L	...	...
LT	...	...
F_{su}, ksi	131	...
F_{bru}, ksi:		
(e/D = 1.5)	...	...
(e/D = 2.0)	...	...
F_{bry}, ksi:		
(e/D = 1.5)	...	...
(e/D = 2.0)	...	...
e, percent:		
L	6	6
RA, percent:		
L	32	32
E, 10^3 ksi	35.3	
E_c, 10^3 ksi	...	
G, 10^3 ksi	11.3	
μ	0.37 (solution treated condition)	
Physical Properties:		
ω, lb/in.^{3}	0.302	
C and *K*	...	
α, 10^{-6} in./in./°F	See Figure 7.4.2.0	

[a] Tensile specimens are located at T/2 location for bars 0.800 inch and under in diameter or distance between parallel sides and at T/4 location for larger size bars. The strength of bar, especially large diameter may vary significantly from center to surface; consequently, caution should be exercised in machining parts from bars over 0.800 inch in diameter since strengths may be lower than design values depending on depth of material removed from surface.

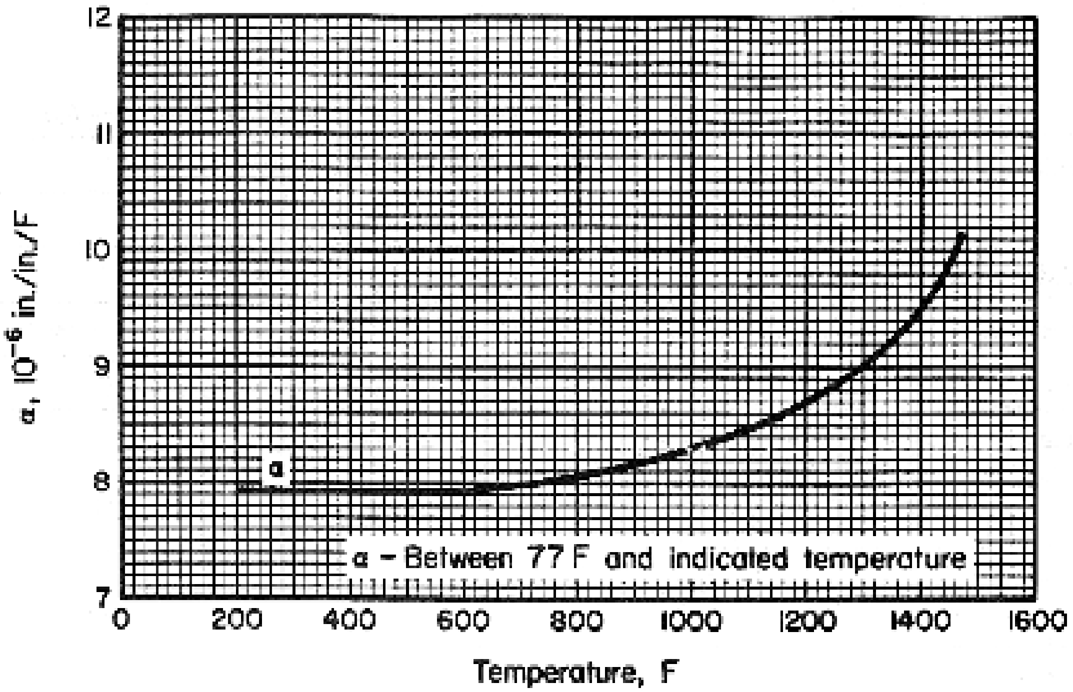

Figure 7.4.2.0. Effect of temperature on thermal expansion (α) of MP159 alloy bar.

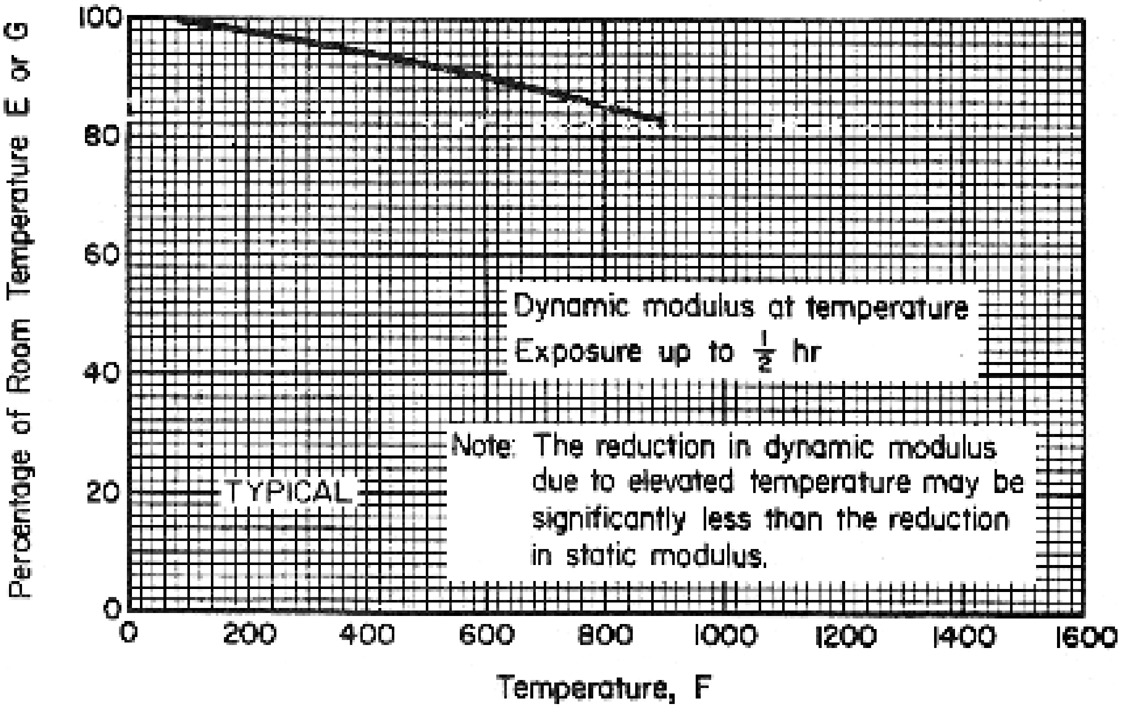

Figure 7.4.2.1.4. Effect of temperature on the tensile modulus (E) and shear modulus (G) of MP159 alloy bar.

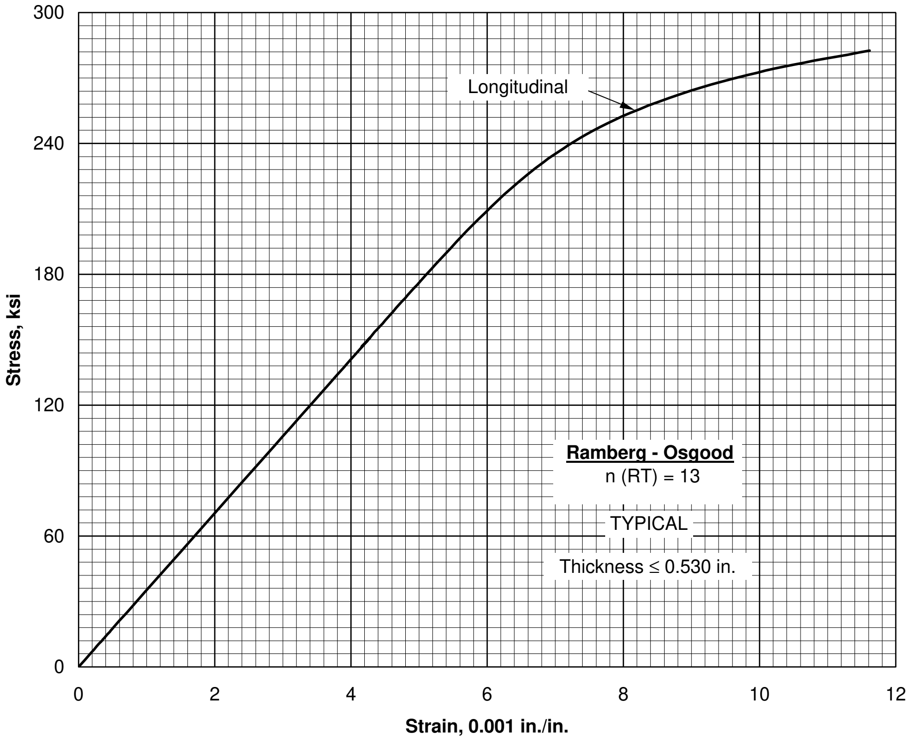

Figure 7.4.2.1.6. Typical tensile stress-strain curve at room temperature for cold worked and aged MP159 alloy bar.

7.5 ALUMINUM ALLOY SHEET LAMINATES

7.5.0 GENERAL

This section contains the engineering properties of aluminum alloy sheet laminates. These products consist of thin high-strength aluminum alloy sheets alternating with fiber layers impregnated with adhesive. These sheet laminates provide a very efficient structure for certain applications and exhibit excellent fatigue resistance.

Tensile and compressive properties for the aluminum alloy sheet laminates were determined using test specimens similar to those used for testing conventional aluminum alloy sheet with one exception. The Iosipescu shear specimen was the most appropriate configuration for the determination of shear strength. Shear yield strength and shear ultimate strength were determined using the Iosipescu test procedure. Shear yield strength was determined at 0.2% offset from load-deformation curves. Bearing tests were conducted according to ASTM E 238, which is applicable to conventional aluminum alloy products. Bearing specimens exhibited several different types of failure and bearing strength was influenced by failure mode. Consequently, a more suitable bearing test procedure for aramid fiber reinforced aluminum alloy sheet laminates is currently being developed. However, the design values for bearing strength determined according to ASTM E 238 are conservative and are considered suitable for design. These sheet laminates exhibit low elongation as measured by the tensile test. Consequently, a more realistic measure of ductility is total strain at failure, ε_t, defined as the measure of strain determined from the tensile load-deformation curve at specimen failure. This measurement includes both elastic and plastic strains. The minimum total strain at failure value from the material specification will be presented in the room temperature design allowable table. These sheet laminates are generally anisotropic. Therefore, design values for each grain orientation of the aluminum alloy sheet will be presented for all mechanical properties, except F_{su} and F_{sy}. The longitudinal direction is parallel to the rolling direction of the aluminum alloy sheet or length of sheet laminate, while the long transverse direction is 90° to the longitudinal direction or parallel to the width of the sheet laminate. The design values for F_{cy}, F_{sy}, F_{su}, F_{bry}, and F_{bru} were derived conventionally in accordance with the guidelines.

7.5.1 2024-T3 ARAMID FIBER REINFORCED SHEET LAMINATE

7.5.1.0 *Comments and Properties* — This product consists of thin 2024-T3 sheets alternating with aramid fiber layers embedded in a special resin. Nominal thickness of aluminum sheet is 0.012 inch with a prepreg nominal thickness of 0.0085 inch. The primary advantage of this product is the significant improvement in fatigue and fatigue crack growth properties compared to conventional aluminum alloy structures. The product also has good damping capacity and resistance to impact. Compared to 7475-T761 aramid fiber-reinforced sheet laminate, this product has better formability and damage tolerance characteristics.

Manufacturing Considerations — This product can be fabricated by conventional metal practices for machining, sawing, drilling, joining with fasteners and can be inspected by conventional procedures.

Environmental Considerations — This product has good corrosion resistance. The maximum service temperature is 200°F.

Specification and Properties — A material specification is presented in Table 7.5.1.0(a). Room-temperature mechanical properties are presented in Table 7.5.1.0(b).

Table 7.5.1.0(a). Material Specifications for 2024-T3 Aramid Fiber Reinforced Sheet Laminate

Specification	Form
AMS 4254	Sheet laminate

7.5.1.1 *T3 Temper* — Typical tensile and compressive stress-strain and tangent-modulus curves are shown in Figures 7.5.1.1.6(a) through (l).

Table 7.5.1.0(b). Design Mechanical and Physical Properties of 2024-T3 Aluminum Alloy, Aramid Fiber Reinforced, Sheet Laminate

Specification	AMS 4254			
Form	Aramid fiber reinforced sheet laminate			
Laminate lay-up	2/1	3/2	4/3	5/4
Nominal thickness, in.	0.032	0.053	0.074	0.094
Basis	S	S	S	S
Mechanical Properties:				
F_{tu}, ksi:				
L	90	96	101	101
LT	48	44	43	42
F_{ty}, ksi:				
L	48	49	49	49
LT	33	30	30	30
F_{cy}, ksi:				
L	35	35	34	33
LT	33	30	30	30
F_{su}[a], ksi	[b]	[b]	[b]	[b]
F_{sy}[a], ksi	16	15	14	14
F_{bru}[c], ksi:				
L (e/D = 1.5)	78	73	73	68
LT (e/D = 1.5)	89	84	80	75
L (e/D = 2.0)	93	86	83	77
LT (e/D = 2.0)	95	89	81	76
F_{bry}[c], ksi:				
L (e/D = 1.5)	53	52	51	50
LT (e/D = 1.5)	56	52	52	52
L (e/D = 2.0)	63	63	61	59
LT (e/D = 2.0)	66	61	61	60
ε_t[d], percent:				
L	2	2	2	2
LT	12	12	12	14
E, 10^3 ksi:				
L	9.9	9.9	9.7	9.6
LT	8.1	7.5	7.1	7.0
E_c, 10^3 ksi:				
L	9.5	9.4	9.3	9.1
LT	8.0	7.5	7.2	7.0
G, 10^3 ksi:				
L	2.7	2.5	2.4	2.2
LT	2.6	2.4	2.4	2.2
μ:				
L	0.33	0.34	0.34	0.32
LT	0.29	0.27	0.26	0.25
Physical Properties:				
ω, lb/in.^{3}	0.086	0.084	0.082	0.081
C, K, and α	...	...	...	...

a Shear values determined from data obtained using Iosipescu shear specimens.
b Shear ultimate strengths not determinable due to excessive deflection of specimen.
c Bearing values are "dry pin" values per Section 1.4.7.1 determined in accordance with ASTM E238.
d Total (elastic plus plastic) strain at failure determined from stress-strain curve.

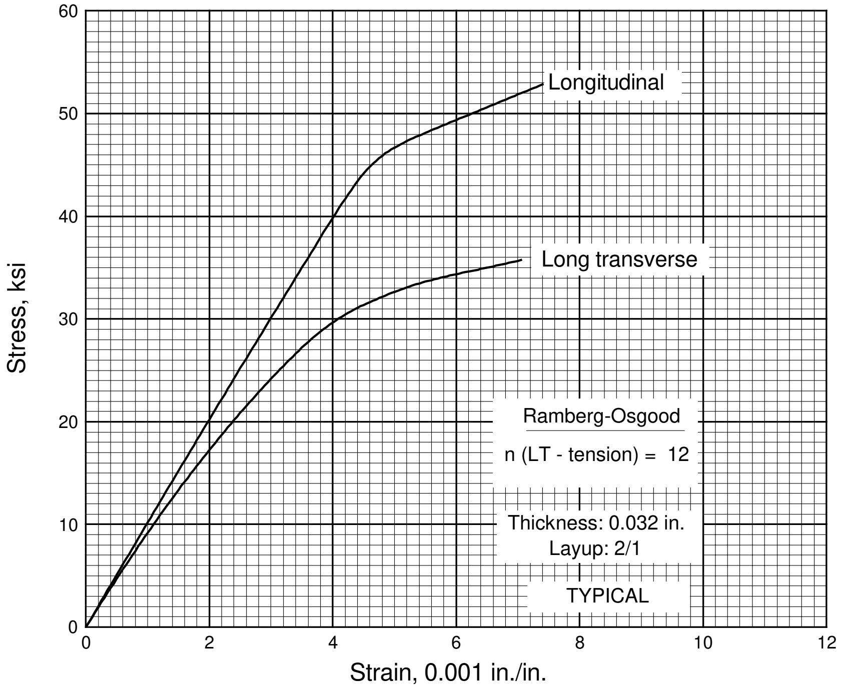

Figure 7.5.1.1.6(a). Typical tensile stress-strain curves for 2024-T3 aluminum alloy, aramid fiber-reinforced, sheet laminate.

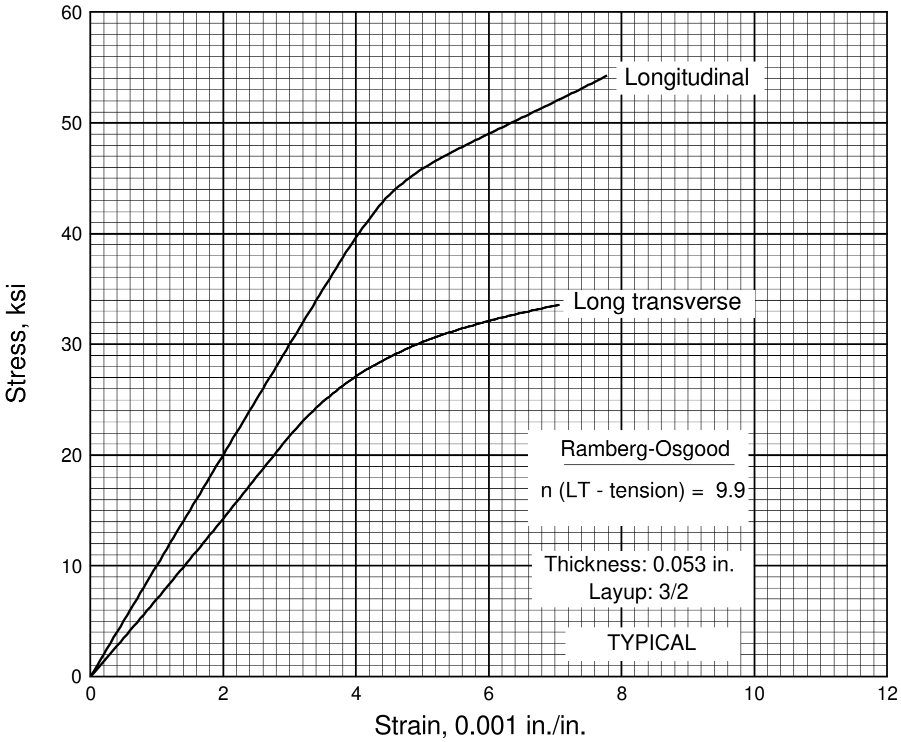

Figure 7.5.1.1.6(b). Typical tensile stress-strain curves for 2024-T3 aluminum alloy, aramid fiber-reinforced, sheet laminate.

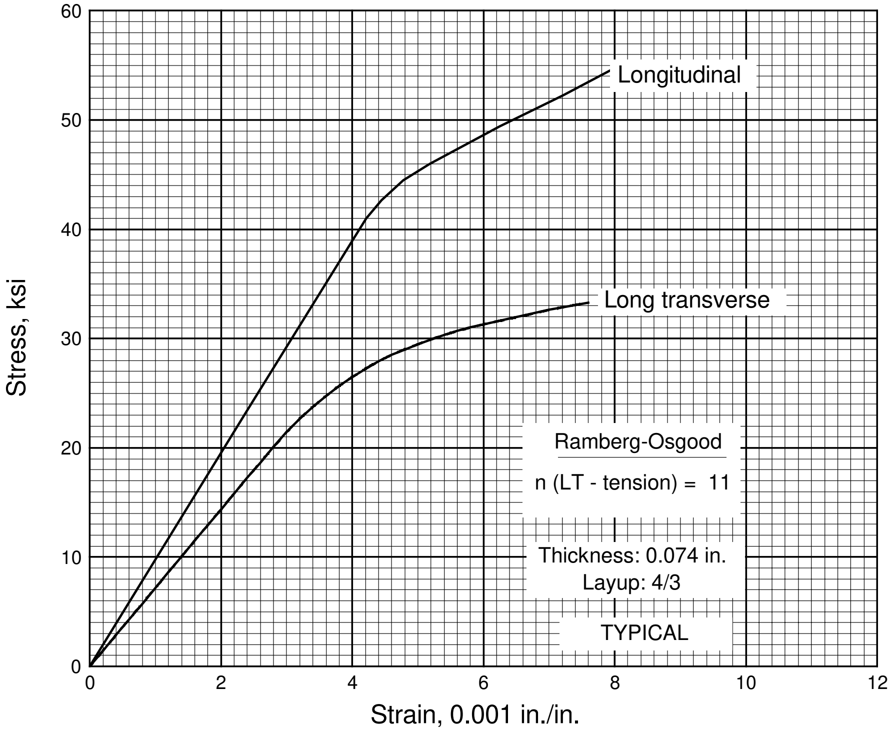

Figure 7.5.1.1.6(c). Typical tensile stress-strain curves for 2024-T3 aluminum alloy, aramid fiber-reinforced, sheet laminate.

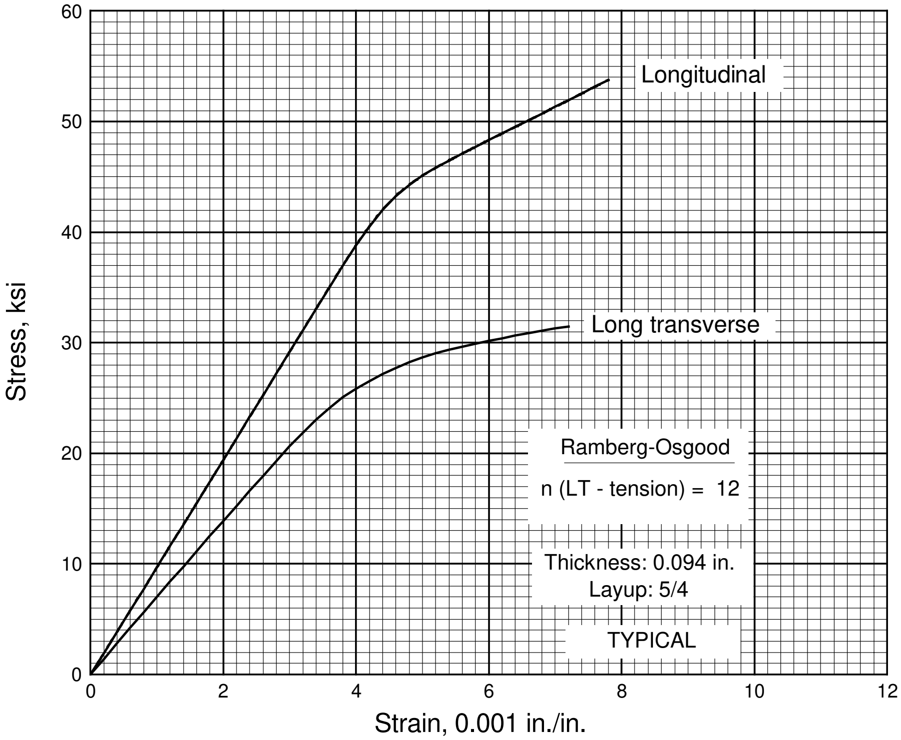

Figure 7.5.1.1.6(d). Typical tensile stress-strain curves for 2024-T3 aluminum alloy, aramid fiber-reinforced, sheet laminate.

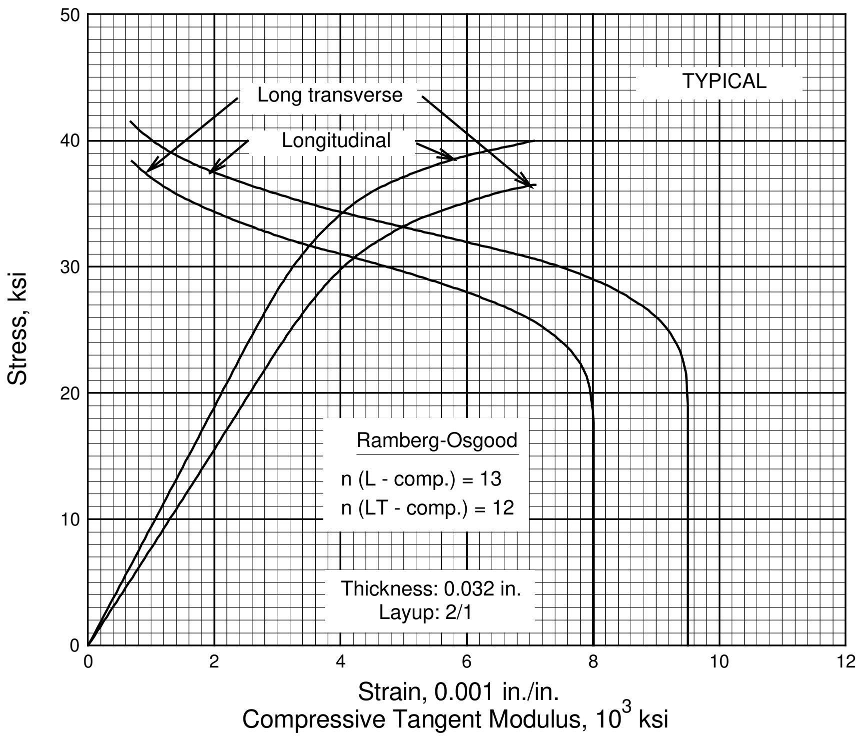

Figure 7.5.1.1.6(e). Typical compressive stress-strain and compressive tangent-modulus curves for 2024-T3 aluminum alloy, aramid fiber-reinforced, sheet laminate.

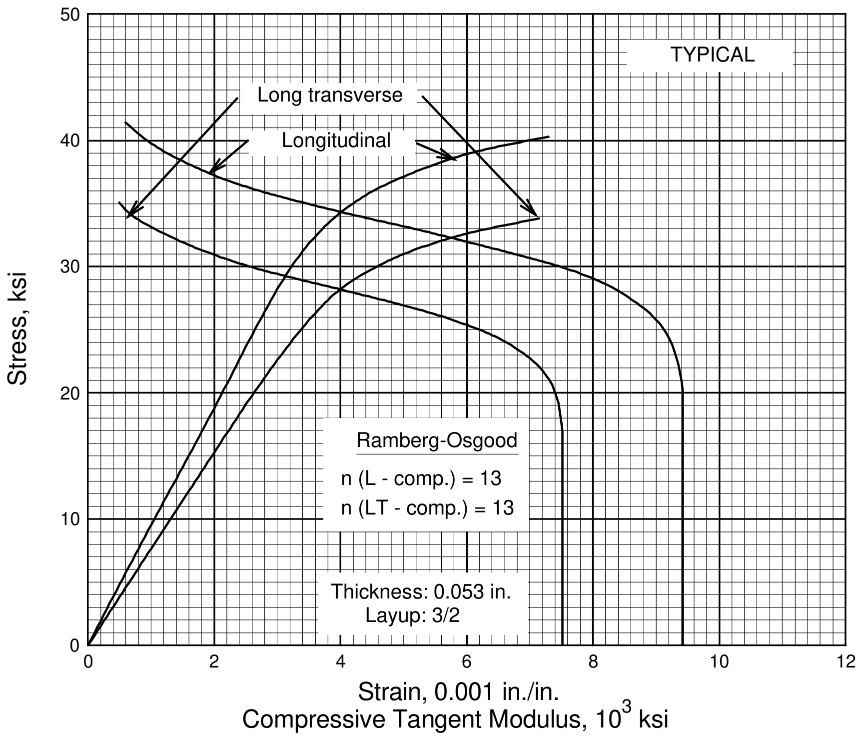

Figure 7.5.1.1.6(f). Typical compressive stress-strain and compressive tangent-modulus curves for 2024-T3 aluminum alloy, aramid fiber-reinforced, sheet laminate.

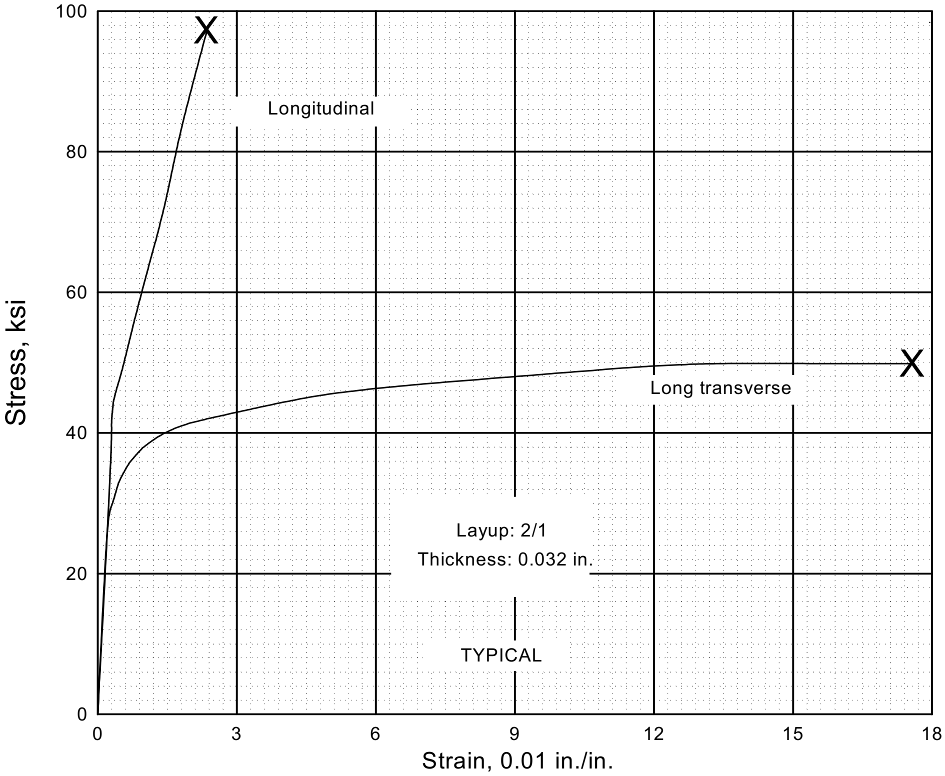

Figure 7.5.1.1.6(i). Typical tensile stress-strain curves (full range) for 2024-T3 aluminum alloy, aramid fiber-reinforced, sheet laminate.

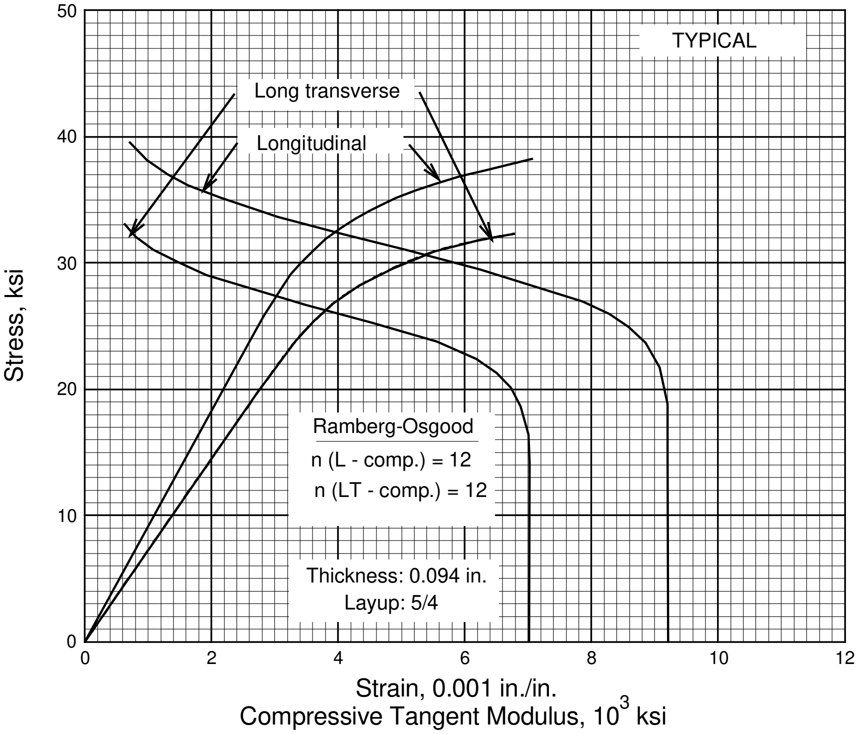

Figure 7.5.1.1.6(h). Typical compressive stress-strain and compressive tangent-modulus curves for 2024-T3 aluminum alloy, aramid fiber-reinforced, sheet laminate.

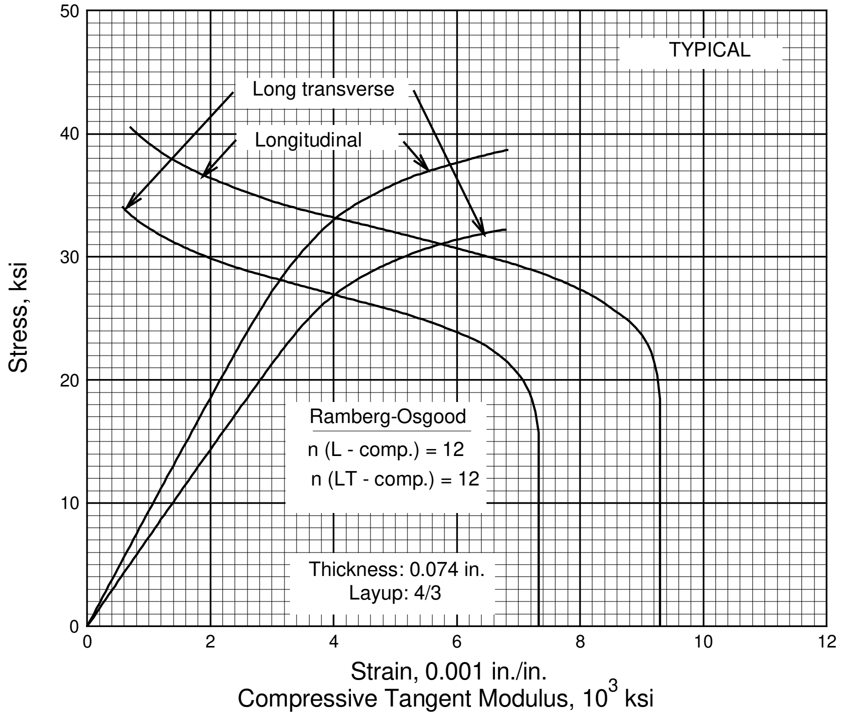

Figure 7.5.1.1.6(g). Typical compressive stress-strain and compressive tangent-modulus curves for 2024-T3 aluminum alloy, aramid fiber-reinforced, sheet laminate.

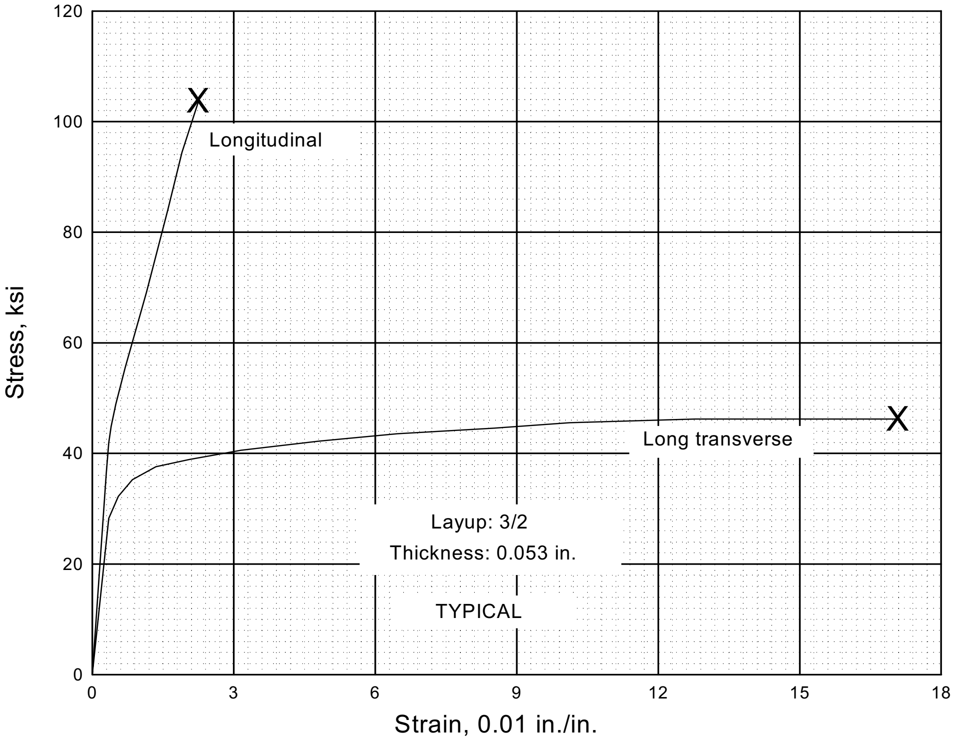

Figure 7.5.1.1.6(j). Typical tensile stress-strain curves (full range) for 2024-T3 aluminum alloy, aramid fiber-reinforced, sheet laminate.

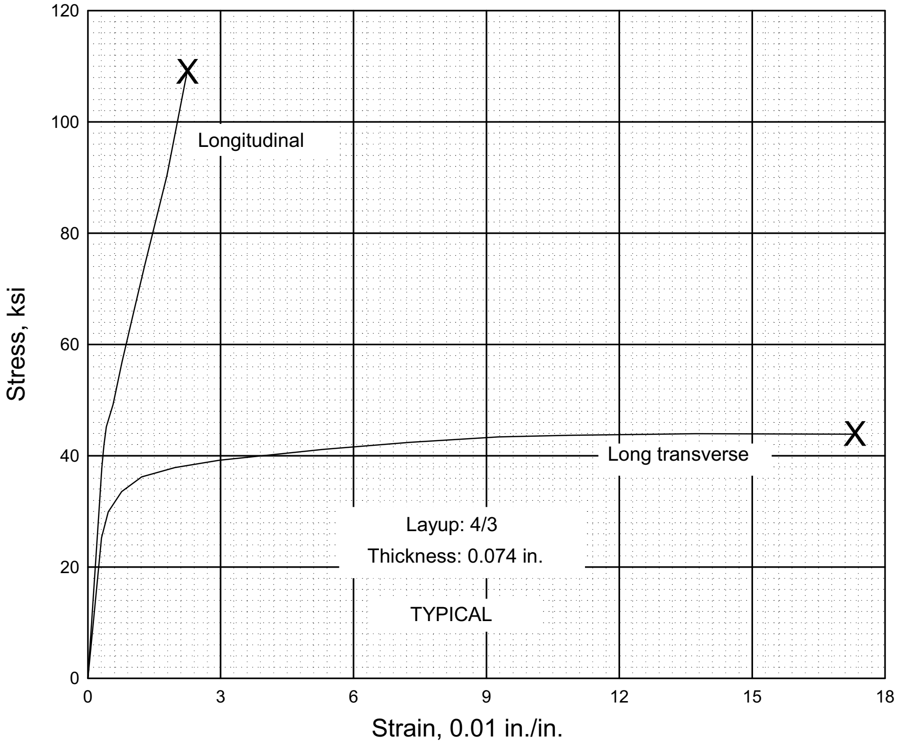

Figure 7.5.1.1.6(k). Typical tensile stress-strain curves (full range) for 2024-T3 aluminum alloy, aramid fiber-reinforced, sheet laminate.

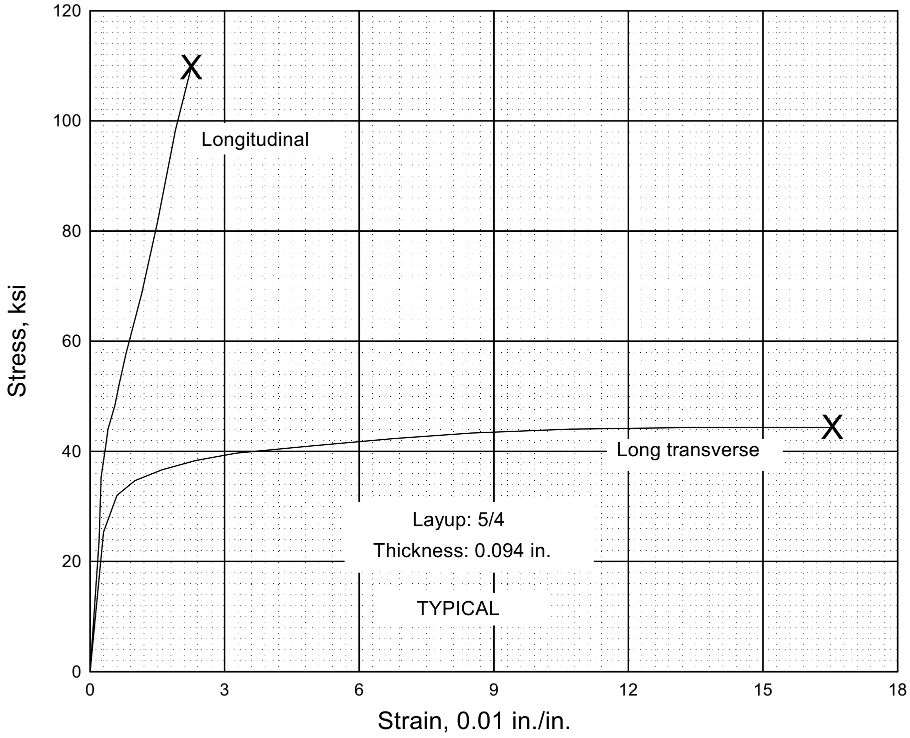

Figure 7.5.1.1.6(l). Typical tensile stress-strain curves (full range) for 2024-T3 aluminum alloy, aramid fiber-reinforced, sheet laminate.

7.5.2 7475-T761 ARAMID FIBER REINFORCED SHEET LAMINATE

7.5.2.0 *Comments and Properties* — This product consists of thin 7475-T761 sheets alternating with aramid fiber layers embedded in a special resin. Nominal thickness of aluminum sheet is 0.012 inch with a prepreg nominal thickness of 0.0085 inch. The primary advantage of this product is the significant improvement in fatigue and fatigue crack growth properties compared to conventional aluminum alloy structures. The product also has good damping capacity and resistance to impact.

Manufacturing Considerations — This product can be fabricated by conventional metal practices for machining, sawing, drilling, joining with fasteners and can be inspected by conventional procedures.

Environmental Considerations — This product has good corrosion resistance. The maximum service temperature is 200°F.

Specifications and Properties — A material specification is presented in Table 7.5.2.0(a). Room-temperature mechanical properties are presented in Table 7.5.2.0(b).

Table 7.5.2.0(a). Material Specifications for 7475-T761 Aramid Fiber Reinforced Sheet Laminate

Specification	Form
AMS 4302	Sheet laminate

7.5.2.1 *T761 Temper* — Tensile and compressive stress-strain and tangent modulus curves are shown in Figures 7.5.2.1.6(a) through (f). Full-range tensile stress-strain curves are presented in Figures 7.5.2.1.6(g) through (j).

Table 7.5.2.0(b). Design Mechanical and Physical Properties of 7475-T761 Aluminum Alloy, Aramid Fiber Reinforced, Sheet Laminate

Specification	AMS 4302			
Form	Aramid fiber reinforced sheet laminate			
Laminate lay-up	2/1	3/2	4/3	5/4
Nominal thickness, in.	0.032	0.053	0.074	0.094
Basis	S	S	S	S
Mechanical Properties:				
F_{tu}, ksi:				
L	103	111	114	116
LT	56	51	50	48
F_{ty}, ksi:				
L	76	82	82	84
LT	48	43	42	40
F_{cy}, ksi:				
L	46	46	44	44
LT	51	48	47	45
F_{su}[a], ksi	35	33	33	32
F_{sy}[a], ksi	24	23	22	21
F_{bru}[b], ksi:				
L (e/D = 1.5)	91	83	84	82
LT (e/D = 1.5)	96	85	86	80
L (e/D = 2.0)	104	87	88	84
LT (e/D = 2.0)	108	88	86	80
F_{bry}[b], ksi:				
L (e/D = 1.5)	73	70	66	69
LT (e/D = 1.5)	76	69	69	67
L (e/D = 2.0)	83	81	77	79
LT (e/D = 2.0)	84	76	75	72
e_t[c], percent:				
L	1.5	1.8	1.7	1.8
LT	6.1	6.4	6.3	6.6
E, 10^3 ksi:				
L	9.8	9.9	10.0	9.8
LT	7.7	7.1	6.7	6.7
E_c, 10^3 ksi:				
L	9.6	9.6	9.6	9.7
LT	7.8	7.3	7.0	6.9
G, 10^3 ksi:				
L	2.8	2.6	2.3	2.3
LT	2.6	2.4	2.3	2.3
μ:				
L	0.35	0.35	0.35	0.35
LT	0.25	0.25	0.25	0.25
Physical Properties:				
ω, lb/in.^{3}	0.085	0.083	0.082	0.081
C, K, and α	...	...	...	...

a Shear values determined from data obtained using Iosipescu shear specimens.

b Bearing values are “dry pin” values per Section 1.4.7.1 determined in accordance with ASTM E 238.

c Total (elastic plus plastic) strain at failure determined from stress-strain curve. Values are minimum but not included in AMS 4302.

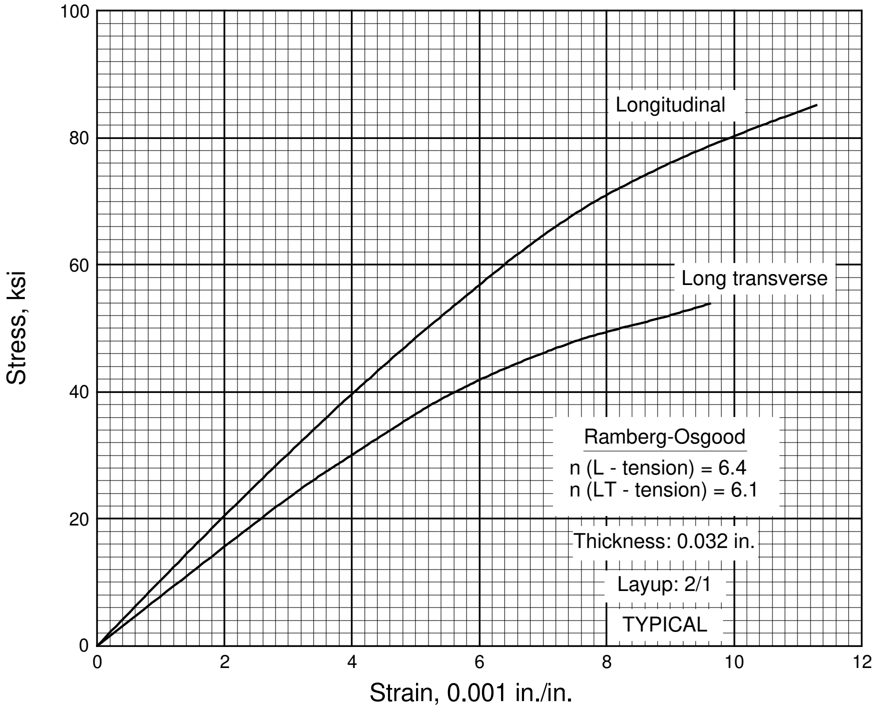

Figure 7.5.2.1.6(a). Typical tensile stress-strain curves for 7475-T761 aluminum alloy, aramid fiber-reinforced, sheet laminate.

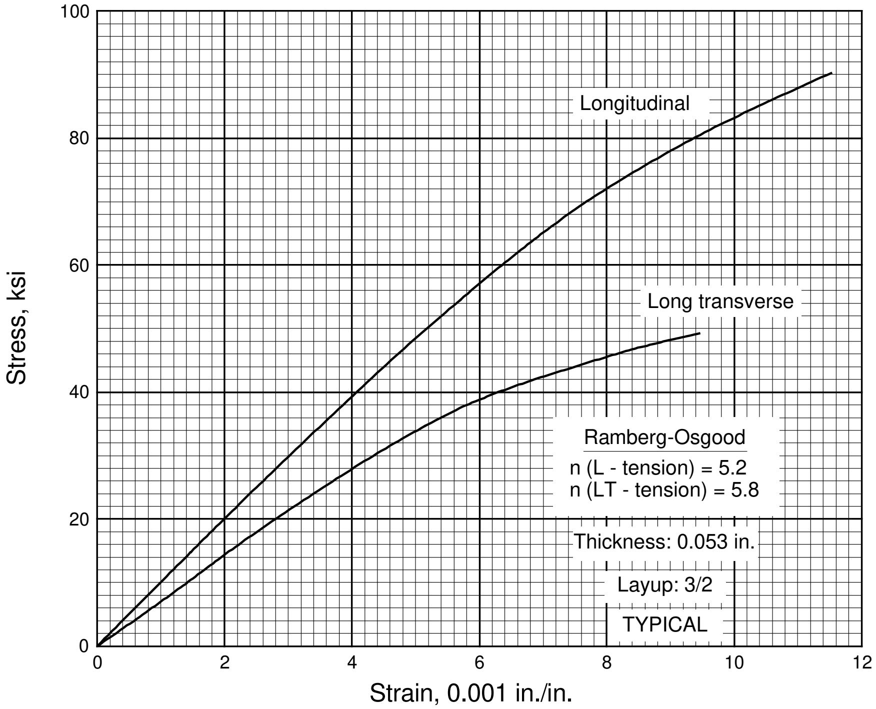

Figure 7.5.2.1.6(b). Typical tensile stress-strain curves for 7475-T761 aluminum alloy, aramid fiber-reinforced, sheet laminate.

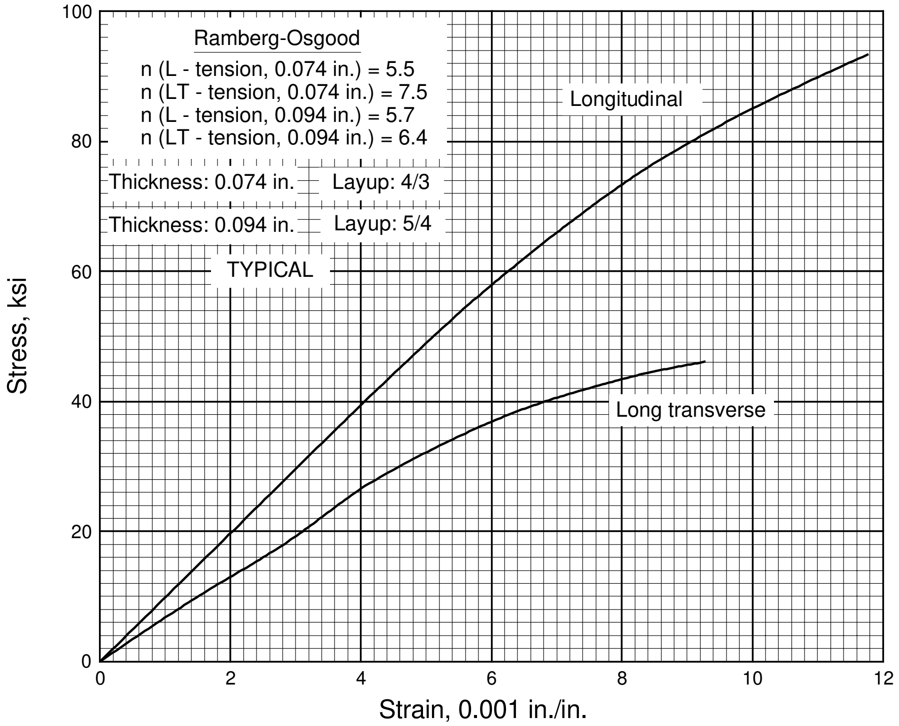

Figure 7.5.2.1.6(c). Typical tensile stress-strain curves for 7475-T761 aluminum alloy, aramid fiber-reinforced, sheet laminate.

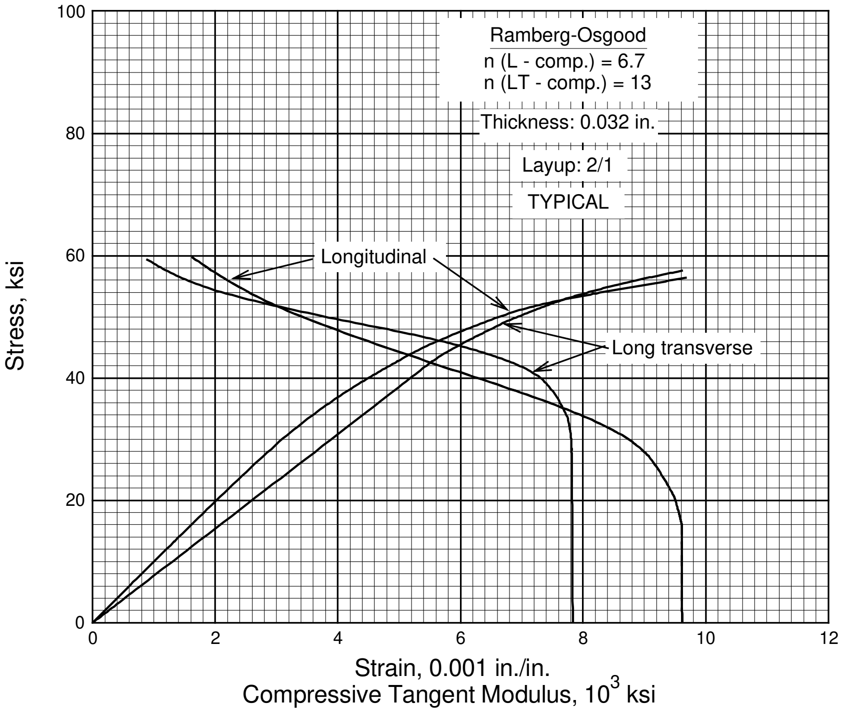

Figure 7.5.2.1.6(d). Typical compressive stress-strain and compressive tangent-modulus curves for 7475-T761 aluminum alloy, aramid fiber-reinforced, sheet laminate.

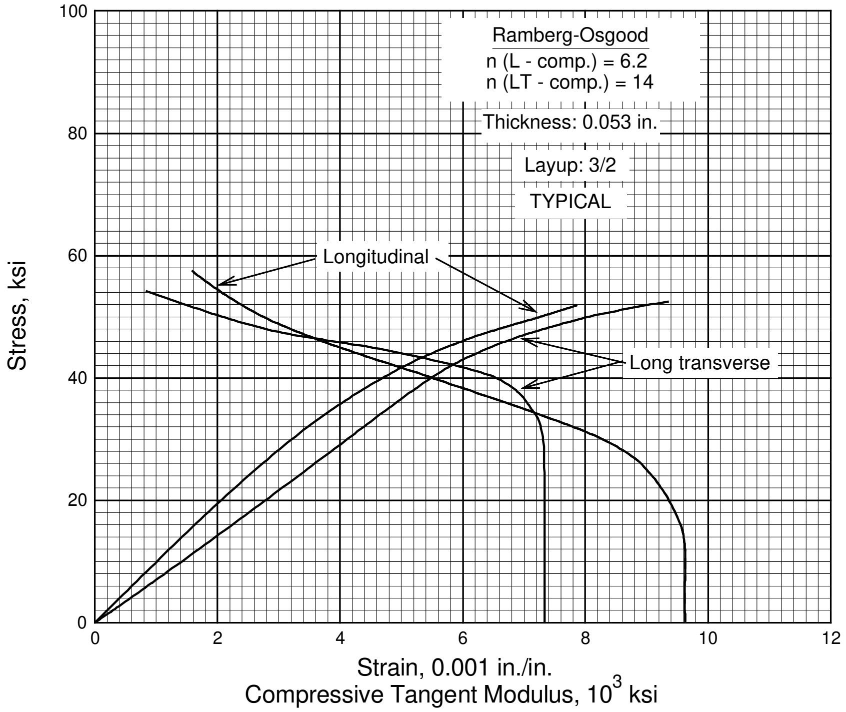

Figure 7.5.2.1.6(e). Typical compressive stress-strain and compressive tangent-modulus curves for 7475-T761 aluminum alloy, aramid fiber-reinforced, sheet laminate.

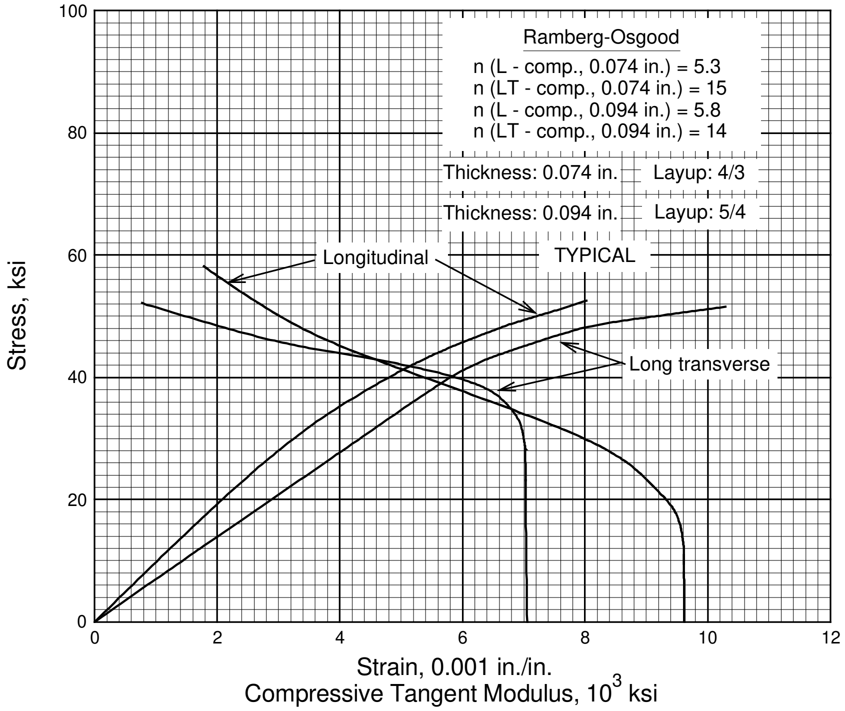

Figure 7.5.2.1.6(f). Typical compressive stress-strain and compressive tangent-modulus curves for 7475-T761 aluminum alloy, aramid fiber-reinforced, sheet laminate.

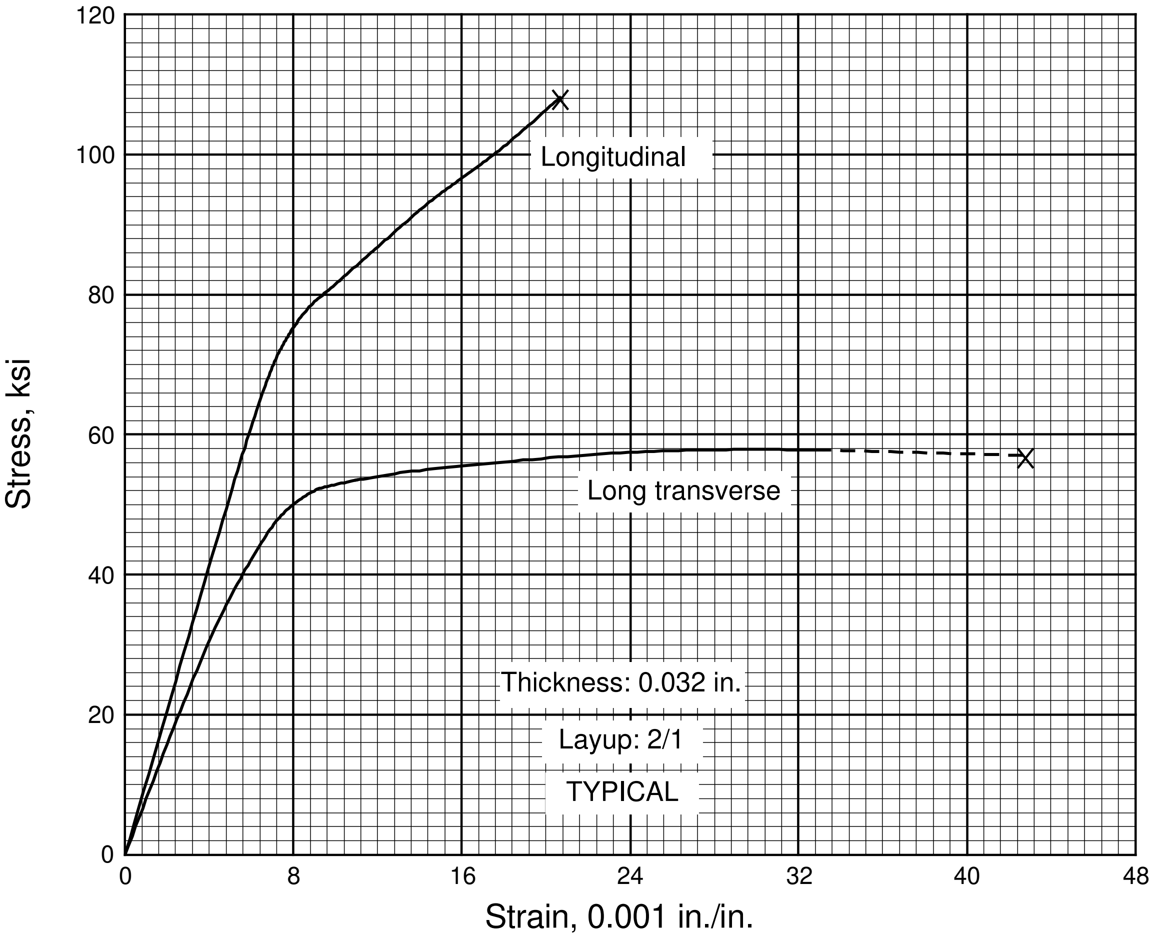

Figure 7.5.2.1.6(g). Typical tensile stress-strain curves (full range) for 7475-T761 aluminum alloy, aramid fiber-reinforced, sheet laminate.

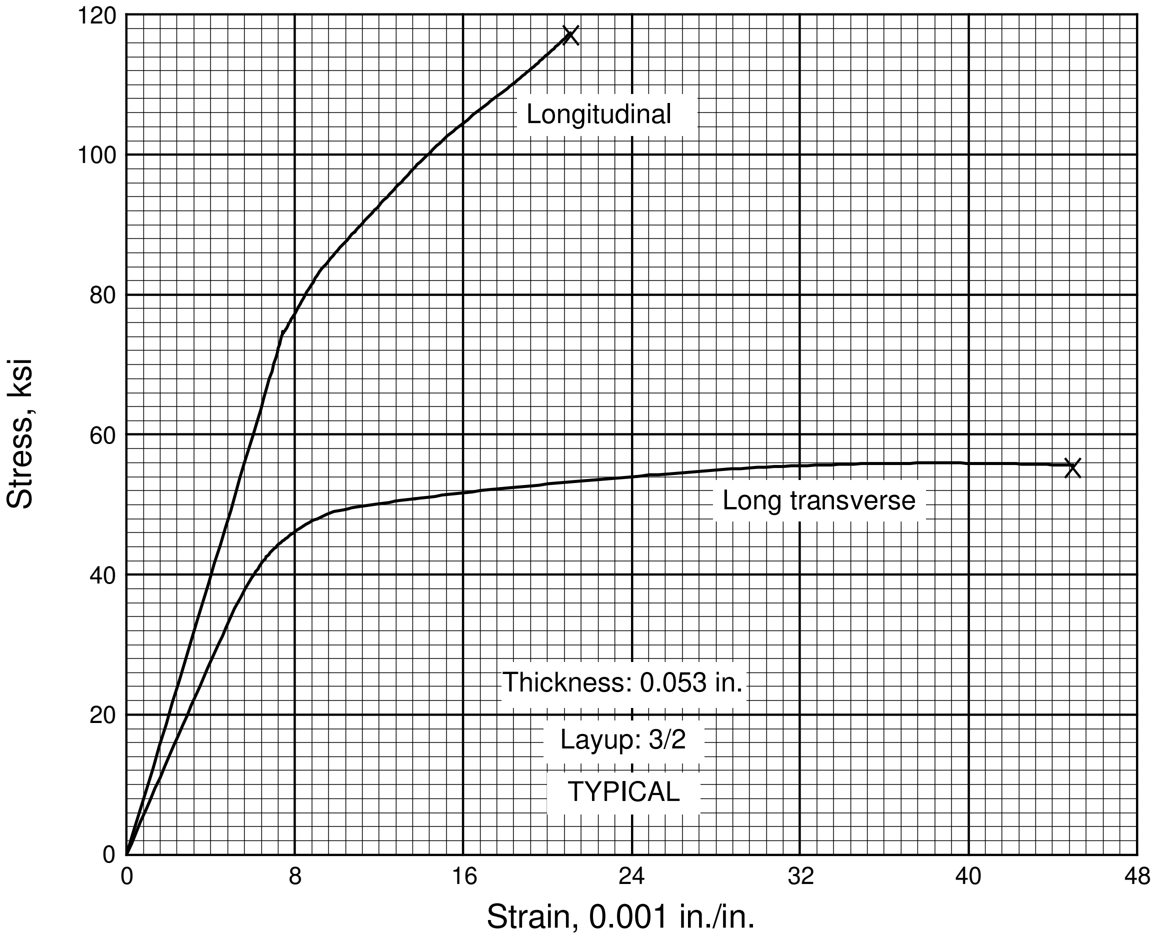

Figure 7.5.2.1.6(h). Typical tensile stress-strain curves (full range) for 7475-T761 aluminum alloy, aramid fiber-reinforced, sheet laminate.

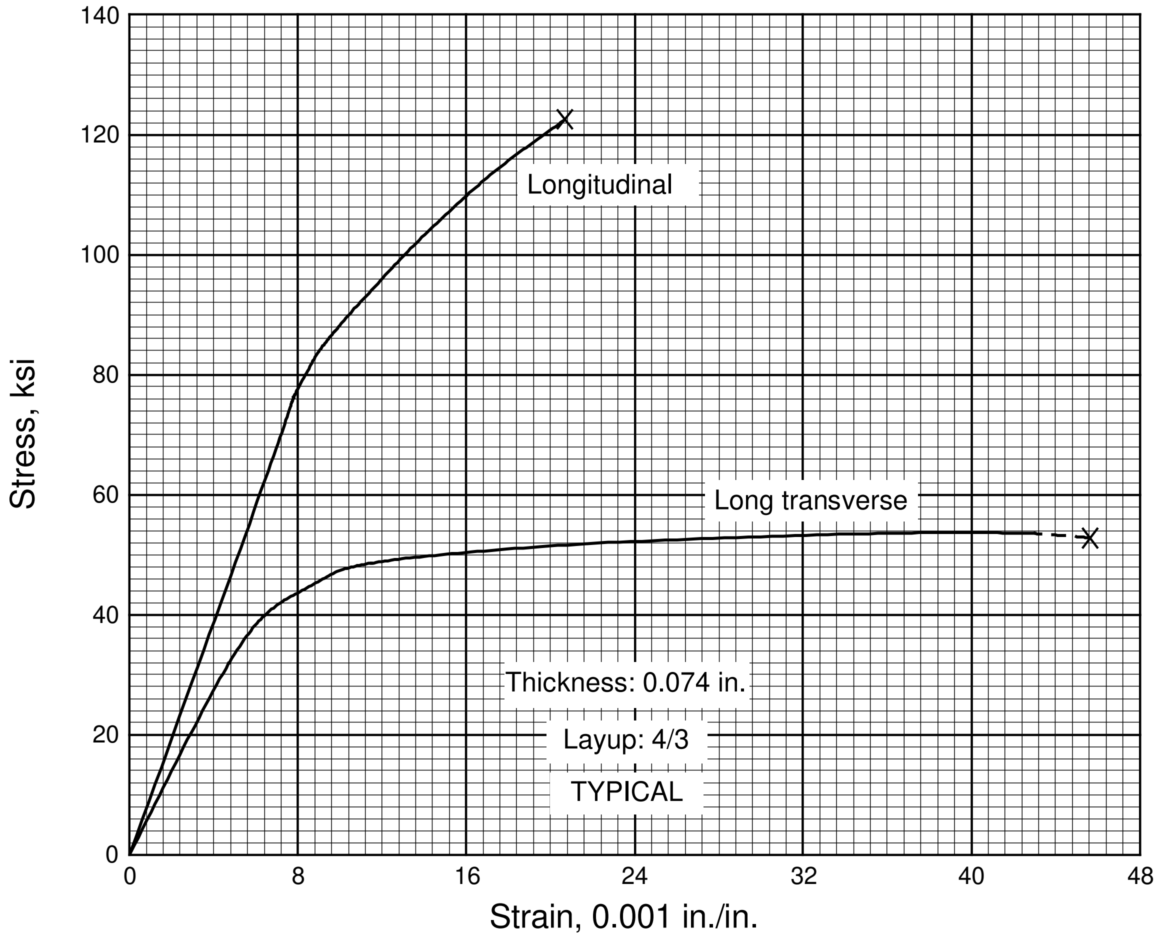

Figure 7.5.2.1.6(i). Typical tensile stress-strain curves (full range) for 7475-T761 aluminum alloy, aramid fiber-reinforced, sheet laminate.

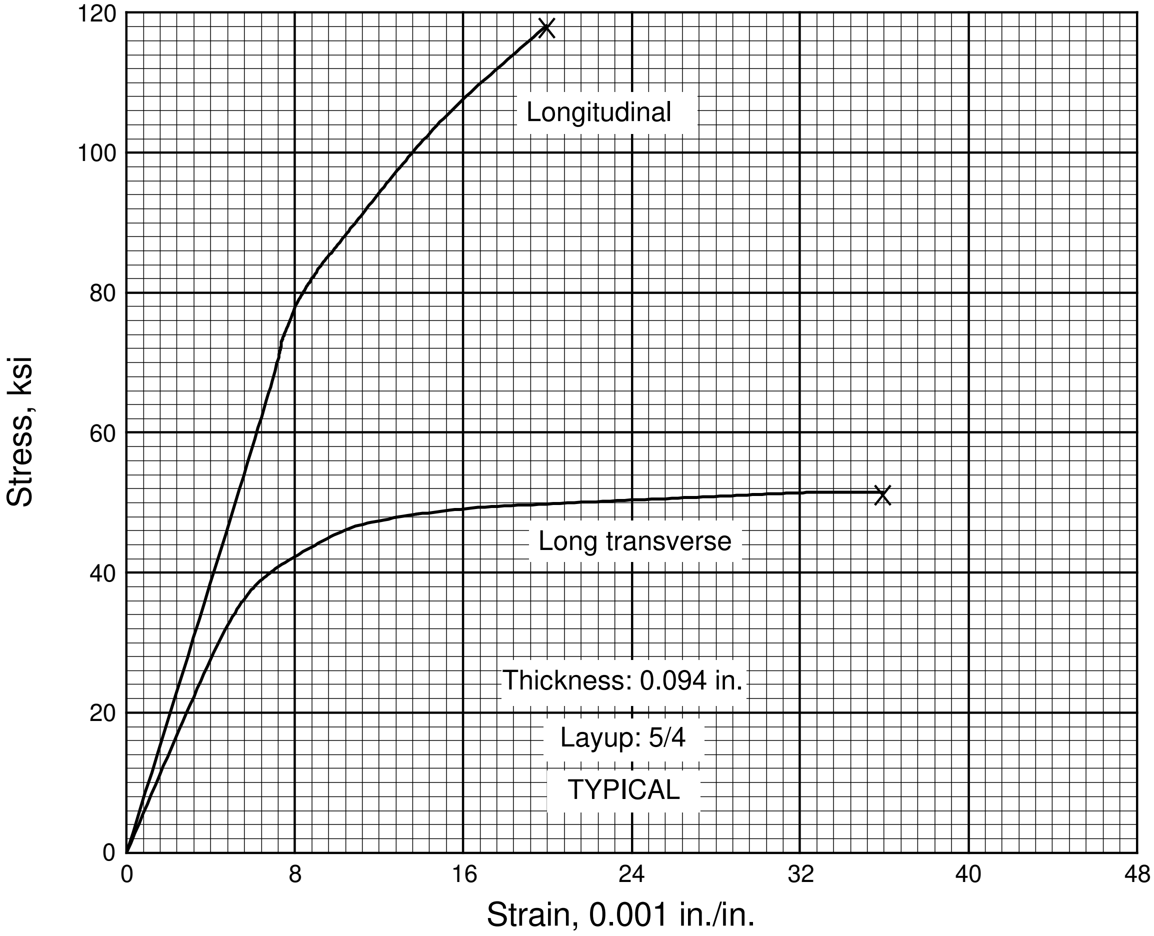

Figure 7.5.2.1.6(j). Typical tensile stress-strain curves (full range) for 7475-T761 aluminum alloy, aramid fiber-reinforced, sheet laminate.

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CHAPTER 8

STRUCTURAL JOINTS

This chapter, while comprising three major sections, primarily is concerned with joint allowables. Section 8.1 is concerned with mechanically fastened joints; Section 8.2, with metallurgical joints (various welding and brazing processes). Section 8.3 contains information for structural component data; it is concerned with bearings, pulleys, and cables.

With particular reference to Section 8.1, the introductory section (8.1.1) contains fastener indexes that can be used as a quick reference to locate a specific table of joint allowables. Following this introductory section are five sections comprising the five major fastener categories, as shown in Table 8.0.1.

Table 8.0.1. Structural Joints Index (Fastener Type)

Section	Fastener Type
8.1.2	Solid Rivets
8.1.2.1	Protruding head
8.1.2.2	Flush head
8.1.3	Blind fasteners
8.1.3.1	Protruding head
8.1.3.2	Flush head
8.1.4	Swaged collar fasteners
8.1.4.1	Protruding head
8.1.4.2	Flush head
8.1.5	Threaded fasteners
8.1.5.1	Protruding head
8.1.5.2	Flush head
8.1.6	Special fasteners
8.1.6.1	Fastener sleeves

In each of the five major sections, there are subsections that describe the factors to be considered in determining the strength of fasteners and joints. After each major section, pertinent tables are presented.

Similarly, Section 8.2 has an introductory section (8.2.1), followed by two major sections comprising different metallurgical joints as shown in Table 8.0.2.

Table 8.0.2. Structural Joints Index (Joining Methods)

Section	Joining Methods
8.2.2	Welded joints
8.2.2.1	Fusion
8.2.2.2	Flush and pressure
8.2.2.3	Spot and seam
8.2.3	Brazing
8.2.3.1	Copper
8.2.3.2	Silver

Following each 4-digit section, applicable tables and figures for the particular section are presented.

8.1 MECHANICALLY FASTENED JOINTS

To determine the strength of mechanically fastened joints, it is necessary to know the strength of the individual fasteners (both by itself, and when installed in various thicknesses of the various materials). In most cases, failures in such joints occur by tensile failure of the fasteners, shearing of the fasteners and by bearing and/or tearing of the sheet or plate.

8.1.1 INTRODUCTION AND FASTENER INDEXES — Five categories of mechanical fasteners are presently contained in this Handbook, generically defined as follows:

Solid Rivets — Solid rivets are defined as one piece fasteners installed by mechanically upsetting one end.

Blind Fasteners — Blind fasteners are usually multiple piece devices that can be installed in a joint which is accessible from one side only. When a blind fastener is being installed, a self-contained mechanical, chemical, or other feature forms an upset on its inaccessible or blind side. These fasteners must be destroyed to be removed. This fastener category includes such fasteners as blind rivets, blind bolts, etc.

Swaged Collar Fasteners — Swaged collar fasteners are multiple piece fasteners, usually consisting of a solid pin and a malleable collar which is swaged or formed onto the pin to clamp the joint. This fastener usually is permanently installed. This fastener class includes such fasteners as “Hi-Shear” rivets, “Lockbolts”, and “Cherrybucks”.

Threaded Fasteners — Fasteners in this category are considered to be any threaded part (or parts) that after assembly in a joint can be easily removed without damage to the fastener or to the material being joined. This classification includes bolts, screws, and a wide assortment of proprietary fasteners.

Special Fasteners — As the name implies, this category of fastener is less commonly used in primary aircraft structure than the four categories listed above. Examples of such fastening systems are sleeves, inserts, panel fasteners, etc.

In the following 3-digit sections, descriptive information is presented relative to the establishment of design allowables in joints containing these four categories of fasteners. Following each such section are the various tables of joint allowables or associated information for computing joint allowables as described.

Tables 8.1.1(a) through (e) are fastener indexes that list the joint allowables tables for each fastener category. These indexes are provided to make it easier to locate the allowables table for a given fastener and sheet material combination. Each of the indexes generally is similarly structured in the following manner. The left-hand column describes the fastener by referring to the NASM part number or to a vendor part number when the fastener is not covered by either series. The second column contains the table number for the allowables table for each fastener. The fastener column has been so arranged that when protruding head and countersunk head fasteners are included in a given fastener index table, the protruding head tables appear first in the second column. The third column identifies generally the base material of the fastener. Generic terms usually are used, such as steel, aluminum, titanium, etc. The fourth column identifies the specific sheet or plate material.

It is recommended that Section 9.7 be reviewed in its entirety since it contains detailed information on the generation and analysis of joint data that results in the joint allowables tables contained in this section.

8.1.1.1 *Data Sources* — The data shown in subsequent tables are provided by one or more manufacturers as listed in the table. There may be more than one producer of a fastener type, but data support is provided by only the footnoted source. **Warning: Caution should be exercised to ensure that use of static joint strength data is applicable only for the data producer(s) indicated by the footnote on each table.**

8.1.1.2 *Fastener Shear Strengths* — Fastener shear strengths accepted and documented by the aerospace industry and government agencies are listed in Table 8.1.1.1. Some existing tables in MIL-HDBK-5 may reflect other values; however, new fastener proposals will be classified in accordance with the above-noted table.

8.1.1.3 *Edge Distance Requirements* — The joint allowables in MIL-HDBK-5 are based on joint tests having edge distances of twice the nominal hole diameter, 2D. Therefore, the allowables are applicable only to joints having 2D edge distance.

Table 8.1.1(a). Fastener Index for Solid Rivets

Fastener Identification[a]	Table Number	Rivet Material	Sheet Material	Page No.
Rivet Hole Size	8.1.2(a)	...	...	8-12
Shear Strength of Solid Rivets	8.1.2(b)	...	...	8-13
Unit Bearing Strength	8.1.2.1(a)	...	...	8-14
Shear Strength Corection Factors	8.1.2.1(b)	Aluminum	...	8-15
NAS1198 (MC)[b]	8.1.2.1(c)	A-286	A-286	8-16
MS20427M (MC)	8.1.2.2(a)	Monel	AISI 301/302	8-17
MS20427M (D)[b]	8.1.2.2(b)	Monel	AISI 301/302	8-18
MS20426AD (D)	8.1.2.2(c)	Aluminum	Aluminum	8-19
MS20426D (D)	8.1.2.2(d)	Aluminum	Aluminum	8-20
MS20426DD (D)	8.1.2.2(e)	Aluminum	Aluminum	8-21
MS20426 (MC)	8.1.2.2(f)	Aluminum	Clad 2024-T42	8-22
MS20426B (MC)	8.1.2.2(g)	Aluminum	AZ31B-H24	8-23
MS20427M (MC)	8.1.2.2(h)	Monel	Com Pure Titanium	8-24
BRFS-D (MC)	8.1.2.2(i)	Aluminum	Clad 2024-T3	8-25
BRFS-AD (MC)	8.1.2.2(j)	Aluminum	Clad 2024-T3	8-26
BRFS-DD (MC)	8.1.2.2(k)	Aluminum	Clad 2024-T3	8-27
BRFS-T (MC)	8.1.2.2(l)	Ti-45Cb	Clad 7075-T6/Ti-6Al-4V	8-28
MS14218E (MC)	8.1.2.2(m)	Aluminum	Clad 2024-T3	8-29
NAS1097E (MC)	8.1.2.2(n)	Aluminum	Clad 2024-T3/7075-T6	8-30
MS14218AD (MC)	8.1.2.2(o)	Aluminum	Clad 2024-T3	8-31
MS14219E (MC)	8.1.2.2(p)	Aluminum	Clad 2024-T3	8-32
MS14219E (MC)	8.1.2.2(q)	Aluminum	Clad 7075-T6	8-33
MS20426E (MC)	8.1.2.2(r)	Aluminum	Clad 2024-T3	8-34
MS20426E (MC)	8.1.2.2(s)	Aluminum	Clad 7075-T6	8-35
AL905KE (MC)	8.1.2.2(t)	Aluminum	Clad 2024-T3	8-36

a In some cases, entries in this table identify the subject matter in certain tables.
b MC, machine countersunk holes; D, dimpled holes.

Table 8.1.1(b). Fastener Index for Blind Fasteners

Fastener Identification	Table Number	Fastener Sleeve Material	Sheet or Plate Material	Page No.
		Protruding-head, Friction-Lock Blind Rivets		
CR 6636	8.1.3.1.1(a)	A-286	Various	8-38
MS20600M	8.1.3.1.1(b)	Monel	AISI 301	8-39
MS20600M	8.1.3.1.1(c)	Monel	Clad 2024-T3/7075-T6	8-40
MS20600AD and MS20602AD	8.1.3.1.1(d)	Aluminum	Clad 2024-T3	8-41
MS20600B	8.1.3.1.1(e)	Aluminum	AZ31B-H24	8-42
		Protruding-head, Mechanical-Lock Blind Rivets		
NAS1398C	8.1.3.1.2(a)	A-286	Alloy Steel	8-43
CR 2643	8.1.3.1.2(a)	A-286	Alloy Steel	8-43
NAS1398 MS or MW	8.1.3.1.2(b)	Monel	AISI 301-½ Hard	8-44
NAS1398 MS or MW	8.1.3.1.2(c)	Monel	Clad 7075-T6	8-45
NAS1398B	8.1.3.1.2(d_1)	Aluminum	Clad 2024-T3	8-46
NAS1398D	8.1.3.1.2(d_1)	Aluminum	Clad 2024-T3	8-46
NAS1738B and NAS1738E	8.1.3.1.2(d_2)	Aluminum	Clad 2024-T3	8-47
NAS1398B	8.1.3.1.2(e)	Aluminum	AZ31B-H24	8-48
NAS1738B and NAS1738E	8.1.3.1.2(e)	Aluminum	AZ31B-H24	8-48
CR 2A63	8.1.3.1.2(f)	Aluminum	Clad 2024-T81	8-49
CR 4623	8.1.3.1.2(g)	A-286	Clad 7075-T6	8-50
CR 4523	8.1.3.1.2(h)	Monel	Clad 7075-T6	8-51
NAS1720KE and NAS1720KE ( ) L	8.1.3.1.2(i)	Aluminum	Clad 7075-T6	8-52
NAS1720C and NAS1720C ( ) L	8.1.3.1.2(j)	A-286	Clad 2024-T3	8-53
AF3243	8.1.3.1.2(k)	Aluminum	Clad 2024-T3	8-54
HC3213	8.1.3.1.2(l)	Aluminum	Clad 2024-T3	8-55
HC6223	8.1.3.1.2(m)	Aluminum	Clad 2024-T3	8-56
HC6253	8.1.3.1.2(n)	Aluminum	Clad 2024-T3	8-57
AF3213	8.1.3.1.2(o)	Aluminum	Clad 2024-T3	8-58
CR3213	8.1.3.1.2(p)	Aluminum	Clad 2024-T3	8-59
CR3243	8.1.3.1.2(q)	Aluminum	Clad 2024-T3	8-60
HC3243	8.1.3.1.2(r)	Aluminum	Clad 2024-T3	8-61
AF3223	8.1.3.1.2(s)	Aluminum	Clad 2024-T3	8-62
CR3223	8.1.3.1.2(t)	Aluminum	Clad 2024-T3	8-63

Table 8.1.1(b). Fastener Index for Blind Fasteners (Continued)

Fastener Identification	Table Number	Fastener Sleeve Material	Sheet or Plate Material	Page No.
		Flush-head, Friction-Lock Blind Rivets		
CR 6626 (MC)[a]	8.1.3.2.1(a)	A-286	Various	8-64
MS20601M (MC)	8.1.3.2.1(b)	Monel	17-7PH (TH1050)	8-65
MS20601M (D)[a]	8.1.3.2.1(c)	Monel	AISI 301	8-66
MS20601M (MC)	8.1.3.2.1(d_1)	Monel	AISI 301-Ann	8-67
MS20601M (MC)	8.1.3.2.1(d_2)	Monel	AISI 301-¼ Hard	8-68
MS20601M (MC)	8.1.3.2.1(d_3)	Monel	AISI 301-½ Hard	8-69
MS20601M (MC)	8.1.3.2.1(e)	Monel	7075-T6	8-70
MS20601AD and MS20603AD (MC)	8.1.3.2.1(f)	Aluminum	Clad 2024-T3	8-71
MS20601B (MC)	8.1.3.2.1(g)	Aluminum	AZ31B-H24	8-72
		Flush-head, Mechanical-Lock Spindle Blind Rivets		
NAS1399C (MC)	8.1.3.2.2(a)	A-286	Alloy Steel	8-73
CR 2642 (MC)	8.1.3.2.2(a)	A-286	Alloy Steel	8-73
NAS1399 MS or MW (MC)	8.1.3.2.2(b)	Monel	AISI 301-½ Hard	8-74
NAS1921C (MC)	8.1.3.2.2(c)	A-286	Clad 7075-T6	8-75
NAS1399 MS or MW (MC)	8.1.3.2.2(d)	Monel	Clad 7075-T6	8-76
NAS1921M (MC)	8.1.3.2.2(e)	Monel	Clad 7075-T6	8-77
CR 2A62 (MC)	8.1.3.2.2(f)	Aluminum	Clad 2024-T81	8-78
NAS1921B (MC)	8.1.3.2.2(g)	Aluminum	Clad 7075-T6	8-79
NAS1399B (MC)	8.1.3.2.2(h)	Aluminum	Clad 2024-T3	8-80
NAS1399D (MC)	8.1.3.2.2(h)	Aluminum	Clad 2024-T3	8-80
NAS1739B and NAS1379E (MC)	8.1.3.2.2(i)	Aluminum	Clad 2024-T3	8-81
NAS1739B and NAS1739E (D)	8.1.3.2.2(i)	Aluminum	Clad 2024-T3	8-81
NAS1399B (MC)	8.1.3.2.2(j)	Aluminum	AZ31B-H24	8-82
NAS1739B and NAS1739E (MC)	8.1.3.2.2(j)	Aluminum	AZ31B-H24	8-82
CR 4622 (MC)	8.1.3.2.2(k)	A-286	Clad 7075-T6	8-83
CR 4522 (MC)	8.1.3.2.2(l)	Monel	Clad 7075-T6/T651	8-84
NAS1721KE and NAS1721KE ( )L (MC)	8.1.3.2.2(m)	Aluminum	Clad 2024-T3	8-85
NAS1721C and NAS1721C ( ) L (MC)	8.1.3.2.2(n)	A-286	Clad 7075-T6	8-86
HC3212 (MC)	8.1.3.2.2(o)	Aluminum	Clad 2024-T3	8-87
MBC 4807 and MBC 4907 (MC)	8.1.3.2.2(p)	Aluminum	Clad 2024-T3	8-88
MBC 4801 and MBC 4901	8.1.3.2.2(q)	Aluminum	Clad 2024-T3	8-89
HC6222 (MC)	8.1.3.2.2(r)	Aluminum	Clad 2024-T3	8-90
HC6252 (MC)	8.1.3.2.2(s)	Aluminum	Clad 2024-T3	8-91
HC6224 (MC) (A-286 pin)	8.1.3.2.2(t_1)	5056 Al	Clad 2024-T3	8-92
HC3214 (MC) (8740 pin)	8.1.3.2.2(t_2)	5056 Al	Clad 2024-T3	8-93
AF3212 (MC)	8.1.3.2.2(u)	Aluminum	Clad 2024-T3	8-94
CR3212 (MC)	8.1.3.2.2(v)	Aluminum	Clad 2024-T3	8-95
AF3242 (MC)	8.1.3.2.2(w)	Aluminum	Clad 2024-T3	8-96
CR3242 (MC)	8.1.3.2.2(x)	Aluminum	Clad 2024-T3	8-97
HC3242 (MC)	8.1.3.2.2(y)	Aluminum	Clad 2024-T3	8-98
AF3222 (MC)	8.1.3.2.2(z)	Aluminum	Clad 2024-T3	8-99
CR3222 (MC)	8.1.3.2.2(aa)	Aluminum	Clad 2024-T3	8-100

[a] MC, machine countersunk holes; D, dimpled holes.

Table 8.1.1(b). Fastener Index for Blind Fasteners (Continued)

Fastener Identification	Table Number	Fastener Sleeve Material	Sheet or Plate Material	Page No.
		Flush-head Blind Bolts		
MS21140 (MC)	8.1.3.2.3(a)	A-286	Clad 7075-T6/T651	8-101
MS90353 (MC)	8.1.3.2.3(b_1)	Alloy Steel	Clad 2024-T3/T351	8-102
MS90353 (MC)	8.1.3.2.3(b_2)	Alloy Steel	Clad or Bare 7075-T6 or T651	8-103
FF-200, FF-260 and FF-312 (MC)	8.1.3.2.3(c)	Alloy Steel	Clad 2024-T42/ 7075-T6	8-104
NS 100 (MC)	8.1.3.2.3(d)	Alloy Steel	Clad 7075-T6	8-105
SSHFA-200 and SSHFA-260(MC)	8.1.3.2.3(e)	Aluminum	Clad 2024-T42/ 7075-T6	8-106
PLT-150 (MC)	8.1.3.2.3(f)	Alloy Steel	Clad 7075-T6/T651	8-107
NAS1670-L (MC)	8.1.3.2.3(g)	Alloy Steel	Clad 7075-T6/T651	8-108
NAS1674-L (MC)	8.1.3.2.3(h)	Aluminum	Clad 7075-T6	8-109

a MC, machine countersunk holes; D, dimpled holes.

Table 8.1.1(c). Fastener Index for Swaged-Collar/Upset-Pin Fasteners

Fastener Identification	Table Number	Fastener Pin Material	Sheet or Plate Material	Page No.
Ultimate Single-Shear and Tensile Strengths	8.1.4	Alloy Steel and Alum.	...	8-112
CSR 925	8.1.4.1(a)	Titanium	Clad 7075-T6	8-113
CSR 925	8.1.4.1(b)	Titanium	Clad 2024-T3	8-114
NAS1436-NAS1442 (MC)[a]	8.1.4.2(a)	Alloy Steel	Clad 7075-T6/T651	8-115
NAS7024-NAS7032 (MC)	8.1.4.2(b)	Alloy Steel	Clad 7075-T6/T651	8-116
CSR 924 (MC)	8.1.4.2(c)	Titanium	Clad 7075-T6	8-117
CSR 924 (MC)	8.1.4.2(d)	Titanium	Clad 2024-T3	8-118
HSR 201 (MC)	8.1.4.2(e)	A-286	Clad 7075-T6	8-119
HSR 101 (MC)	8.1.4.2(f)	Titanium	Clad 7075-T6	8-120
GPL 3SC-V (MC)	8.1.4.2(g)	Titanium	Clad 7075-T6	8-121
GPL 3SC-V (MC)	8.1.4.2(h)	Titanium	Clad 2024-T3	8-122
LGPL 2SC-V (MC)	8.1.4.2(i)	Titanium	Clad 7075-T6	8-123
LGPL 2SC-V (MC)	8.1.4.2(j)	Titanium	Clad 2024-T3	8-124

[a] MC, machine countersunk holes.

Table 8.1.1(d). Fastener Index for Threaded Fasteners

Fastener Identification[a]	Table Number	Fastener Sleeve Material	Sheet	Page No.
Single Shear Strength	8.1.5(a)	Steel	...	8-127
Tensile Strength	8.1.5(b_1)	Steel	...	8-128
Tensile Strength	8.1.5(b_2)	...	...	8-129
Unit Bearing Strength	8.1.5.1	Alloy Steel	...	8-130
AN 509 Screws (MC)[b]	8.1.5.2(a_1)	Alloy Steel	Clad 2024-T3	8-131
AN 509 Screws (MC)	8.1.5.2(a_2)	CRES	Clad 7075-T6	8-132
PBF 11 (MC)	8.1.5.2(b)	Alloy Steel	Ti-6Al-4V	8-133
TL 100 (MC)	8.1.5.2(c)		Clad 7075-T6	8-134
TLV 10 (MC)	8.1.5.2(d)	Titanium	Clad 7075-T6	8-135
HPB-V (MC)	8.1.5.2(e)	Titanium	Clad 7075-T6	8-136
KLBHV with KFN 600 (MC)	8.1.5.2(f)	Titanium	Clad 7075-T6	8-137
HL-61-70 (MC)	8.1.5.2(g)	CRES	Clad 7075-T6	8-138
HL-719-79 (MC)	8.1.5.2(h)	Alloy Steel	Clad 7075-T6	8-139
HL-11 (MC)	8.1.5.2(i)	Titanium	Clad 7075-T6	8-140
HL-911 (MC)	8.1.5.2(j)	Titanium	Clad 7075-T6	8-141
NAS4452S and KS 100-FV with NAS4445DD (MC)	8.1.5.2(k)	Alloy Steel or Titanium	Clad 7075-T6	8-142
HPG-V (MC)	8.1.5.2(l)	Titanium	Clad 7075-T6	8-143
NAS4452V with NAS4445 DD (MC)	8.1.5.2(m)	Titanium	Clad 7075-T6	8-144
HL18Pin, HL70 Collar (MC)	8.1.5.2(n)	Alloy Steel	Clad 7075-T6	8-145
HL19 Pin, HL70 Collar (MC)	8.1.5.2(o)	Alloy Steel	Clad 7075-T6	8-146

[a] In some cases entries in this table identify the subject matter in certain tables.

[b] MC, machine countersunk holes; D, dimpled holes.

Table 8.1.1(e). Fastener Index for Special Fasteners

Fastener Identification	Table Number	Fastener Pin Material	Sheet or Plate Material	Page No.
ACRES Sleeves	...	A-286	Clad 7075-T6	8-147
MIL-B-8831/4 (MC)[a]	8.1.6.2(a)	Steel Pin, Aluminum Sleeve	Clad 7075-T6	8-148
MIL-B-8831/4 (MC)	8.1.6.2(b)	Steel Pin, Aluminum Sleeve	Clad 2024-T3	8-149

[a] MC, machine countersunk holes.

Table 8.1.1.1. Fastener Shear Strengths

F_{su}, ksi	Examples of Current Alloys Which Meet Level[a]	Current Usage		
		Driven Rivets	Blind Fasteners	Solid Shank Fasteners
28	5056	X	X	
30	2117	X	X	
34	2017	X	X	
36	2219	X	X	
38	2017	X	X	
41	2024 and 7050-T73	X		
43	7050-T731	X	X	X
46	7075		X	
49	Monel	Undriven		
50	Ti/Cb	X		
55	Monel		X	
75	Alloy Steel and CRES		X	X
78	A-286			X
90	A-286	Undriven		
95	Alloy Steel, A-286, Ti-6Al-4V	X	X	X
108	Alloy Steel and Ti-6Al-2Sn			X
110	A-286			X
112	Alloy Steel		X	X
125	Alloy Steel and CRES			X
132	Alloy Steel			X
145	MP35N			X
156	Alloy Steel			X
180	Alloy Steel			X

a Different tempers and thermal treatments are used to obtain desired fastener shear strengths.

8.1.2 SOLID RIVETS — The recommended diameter dimensions of the upset tail on solid rivets will be at least 1.5 times the nominal shank diameter except for 2024-T4 rivets which will be at least 1.4 times the nominal shank diameter. Tail heights will be a minimum of 0.3 diameter. Shear strengths for driven rivets may be based on areas corresponding to the nominal hole diameter provided that the nominal hole diameter is not larger than the values listed in Table 8.1.2(a). If the nominal hole diameter is larger than the listed value, the listed value will be used. Shear strength values for solid rivets of a number of rivet materials are given in Table 8.1.2(b).

8.1.2.1 *Protruding-Head Solid Rivet Joints* — The unit load at which shear or bearing type of failure occurs is calculated separately and the lower of the two governs the design.

The design bearing stress for various materials at both room and elevated temperatures is given in the strength properties stated for each alloy or group of alloys and is applicable to riveted joints wherein cylindrical holes are used and where t/D is greater than or equal to 0.18; where t/D is less than 0.18, tests to substantiate yield and ultimate bearing strengths must be performed. These bearing stresses are applicable only for the design of rigid joints where there is no possibility of relative motion of the parts joined without deformation of such parts. Design bearing stresses at low temperatures will be higher than those specified for room temperature; however, no quantitative data are available.

For convenience, “unit” sheet bearing strengths for rivets, based on a bearing stress of 100 ksi and nominal hole diameters, are given in Table 8.1.2.1(a).

In computing protruding-head rivet design shear strengths, the shear strength values obtained from Table 8.1.2(b) should be multiplied by the correction factors given in Table 8.1.2.1(b). This compensates for the reduction in rivet shear strength resulting from high bearing stresses on the rivet at t/D ratios less than 0.33 for single-shear joints and 0.67 for double-shear joints.

For those rivet material sheet material combinations where test data shows the above to be unconservative or for rivet materials other than those shown in Table 8.1.2(b), joint allowables should be established by test in accordance with Section 9.7. From such tests tabular presentation of ultimate load and yield load allowables are made.

Unless otherwise specified, yield load is defined in Section 9.7.1.1 as the load which results in a joint permanent set equal to 0.04D, where D is the decimal equivalent of the hole diameter defined in Table 9.7.1.1(a).

Table 8.1.2.1(c) provides ultimate and yield strength data on protruding-head A-286 solid rivets in aged A-286 sheet, for a variety of conditions of exposure.

8.1.2.2 *Flush-Head Solid Rivet Joints* — Tables 8.1.2.2(a) through (t) contain joint allowables for various flush-head solid rivet/sheet material combinations. Prior to 2003 the allowable ultimate loads were established from test data using the average ultimate test load divided by a factor of 1.15. (See Section 9.7 for current statistical procedures and possible variations.) Shear strength cutoff values may be either the procurement specification shear strength (S value) of the fastener, or if no specification exists, a statistical value determined from test results as described in Section 9.7.

Yield load allowables are established from test data. Unless otherwise specified, the yield load is defined as the load which results in a joint permanent set equal to 0.04D, where D is the decimal equivalent of the hole diameter defined in Table 9.7.1.1.

For machine countersunk joints, the sheet gage specified in the tables is that of the countersunk sheet. When the noncountersunk sheet is thinner than the countersunk sheet, the bearing allowable for the noncountersunk sheet-fastener combination should be computed, compared to the table value, and the lower of the two values selected. Increased attention should be paid to detail design in cases where t/D < 0.25 because of possibly greater incidence of difficulty in service life.

Table 8.1.2(a). Standard Rivet-Hole Drill Sizes and Nominal Hole Diameters

Rivet Size, in.	1/16	3/32	1/8	5/32	3/16	1/4	5/16	3/8
Drill No.	51	41	30	21	11	F	P	W
Nominal Hole Diameter, in.	0.067	0.096	0.1285	0.159	0.191	0.257	0.323	0.386

Table 8.1.2(b). Single Shear Strength of Solid Rivets[a]

Undriven			Driven			Rivet Size							
Rivet Material	F_{su} (ksi)		Rivet Material	F_{su}[b] (ksi)	Rivet Designation	1/16	3/32	1/8	5/32	3/16	1/4	5/16	3/8
	Min	Max				Driven Single Shear Strength, lbs[c]							
5056-H32	24	n/a	5056-H321[d]	28[e]	B[f]	99	203	363	556	802	1450	2290	3275
2117-T4	26	n/a	2117-T3	30[e]	AD	106	217	389	596	860	1555	2455	3510
2017-T4	35	42	2017-T3	38[e]	D	134	275	493	755	1085	1970	3115	4445
2024-T4	37	n/a	2024-T31	41[g]	DD	145	297	532	814	1175	2125	3360	4795
7050-T73	41	46	7050-T731[d]	43[e]	E[h]	152	311	558	854	1230	2230	3520	5030
Monel	49	59	Monel	52[e]	M	183	376	674	1030	1490	2695	4260	6085
Ti-45Cb	50	59	Ti-45Cb	53[e]	T	187	384	687	1050	1515	2745	4340	6200
A-286	85	95	A-286	90[e]	-	317	651	1165	1785	2575	4665	7375	10500

[a] All rivets must be sufficiently driven to fill the rivet hole at the shear plane. Driving changes the rivet strength from the undriven to the driven condition and thus provides the above driven shear strengths.

[b] Shear stresses are for the as driven condition on B-basis probability.

[c] Based on nominal hole diameter specified in Table 8.1.2(a).

[d] The temper designations last digit (1), indicates recognition of strengthening derived from driving.

[e] The bucktail's minimum diameter is 1.5 times the nominal hole diameter in Table 8.1.2(a).

[f] Should not be exposed to temperatures over 150°F.

[g] Driven in the W (fresh or ice box) condition to minimum 1.4D bucktail diameter.

[h] E (or KE, as per NAS documents).

Table 8.1.2.1(a). Unit Bearing Strength of Sheet on Rivets, F_{br} = 100 ksi

Sheet thickness, in.	Unit Bearing Strength for Indicated Rivet Diameter, lbs							
	1/16	3/32	1/8	5/32	3/16	1/4	5/16	3/8
0.012	80	...	...	...	...	...	...	...
0.016	107	...	...	...	...	...	...	...
0.018	121	173	...	...	...	...	...	...
0.020	134	192	...	...	...	...	...	...
0.025	168	240	321	...	...	...	...	...
0.032	214	307	411	509	...	...	...	...
0.036	241	346	462	572	688	...	...	...
0.040	268	384	514	636	764	...	...	...
0.045	302	432	578	716	860	...	...	...
0.050	335	480	642	795	955	1285	...	...
0.063	422	605	810	1002	1203	1619	2035	...
0.071	476	682	912	1129	1356	1825	2293	2741
0.080	536	768	1028	1272	1528	2056	2584	3088
0.090	603	864	1156	1431	1719	2313	2907	3474
0.100	670	960	1285	1590	1910	2570	3230	3860
0.125	838	1200	1606	1988	2388	3212	4038	4825
0.160	1072	1536	2056	2544	3056	4112	5168	6176
0.190	1273	1824	2442	3021	3629	4883	6137	7334
0.250	1670	2400	3210	3975	4775	6425	8075	9650

Table 8.1.2.1(b). Shear Strength Correction Factors for Solid Protruding Head Rivets[a]

Rivet Diameter, in.	1/16	3/32	1/8	5/32	3/16	1/4	5/16	3/8
	Single-Shear Rivet Strength Factors							
Sheet thickness, in.:								
0.016	0.964	...	...	...	...	...	...	...
0.018	0.981	0.912	...	...	...	...	...	...
0.020	0.995	0.933	...	...	...	...	...	...
0.025	1.000	0.970	0.920	...	...	...	...	...
0.032	...	1.000	0.964	0.925	...	...	...	...
0.036	...	...	0.981	0.946	0.912	...	...	...
0.040	...	...	0.995	0.964	0.933	...	...	...
0.045	...	...	1.000	0.981	0.953	...	...	...
0.050	...	...	...	0.995	0.970	0.920	...	...
0.063	...	...	...	1.000	1.000	0.961	0.922	...
0.071	...	...	...	...	...	0.979	0.944	0.909
0.080	...	...	...	...	...	0.995	0.964	0.933
0.090	...	...	...	...	...	1.000	0.981	0.953
0.100	...	...	...	...	...	...	0.995	0.972
0.125	...	...	...	...	...	...	1.000	1.000
	Double-Shear Rivet Strength Factors							
Sheet thickness, in.:								
0.016	0.687	...	...	...	...	...	...	...
0.018	0.744	0.518	...	...	...	...	...	...
0.020	0.789	0.585	...	...	...	...	...	...
0.025	0.870	0.708	0.545	...	...	...	...	...
0.032	0.941	0.814	0.687	0.560	...	...	...	...
0.036	0.969	0.857	0.744	0.630	0.518	...	...	...
0.040	0.992	0.891	0.789	0.687	0.585	...	...	...
0.045	1.000	0.924	0.834	0.744	0.653	...	...	...
0.050	...	0.951	0.870	0.789	0.708	0.545	...	...
0.063	...	1.000	0.937	0.872	0.808	0.679	0.550	...
0.071	...	...	0.966	0.909	0.852	0.737	0.622	0.508
0.080	...	...	0.992	0.941	0.891	0.789	0.687	0.585
0.090	...	...	1.000	0.969	0.924	0.834	0.744	0.653
0.100	...	...	...	0.992	0.951	0.870	0.789	0.708
0.125	...	...	...	1.000	1.000	0.935	0.870	0.805
0.160	...	...	...	...	...	0.992	0.941	0.891
0.190	...	...	...	...	...	1.000	0.981	0.939
0.250	...	...	...	...	...	...	1.000	1.000

[a] Sheet thickness is that of the thinnest sheet in single-shear joints and the middle sheet in double-shear joints. Values based on tests of aluminum rivets, Reference 8.1.

Table 8.1.2.1(c). Static Joint Strength of Protruding Head A-286 Solid Rivets in A-286 Alloy Sheet at Various Temperatures

Rivet Type	NAS1198 (F_{su} = 90 ksi)								
Sheet Material	A-286, solution treated and aged, F_{tu} = 140 ksi								
Temperature	Room Temperature			1200°F, Stabilized 15 Minutes			1200°F, Rapid Heating in 20 Seconds, Tested in 15 Seconds		
Rivet Diameter, in. (Nominal Hole Diameter, in.)	1/8 (0.1285)	5/32 (0.159)	3/16 (0.191)	1/8 (0.1285)	5/32 (0.159)	3/16 (0.191)	1/8 (0.1285)	5/32 (0.159)	3/16 (0.191)
Sheet thickness, in.:	Ultimate Strength[a], lbs.								
0.020	478	...	...	331	...	...	470[b]	...	...
0.025	590	740	...	426	626	...	587[b]	726[b]	...
0.032	745	932	1132	560	801	962	752[b]	930[b]	1117[b]
0.040	923	1152	1397	682	1002	1204	783	1164[b]	1397[b]
0.050	1023	1428	1677	...	1044	1505	...	1198	1729[b]
0.063	1131	1578	1821	...	...	1507	...	...	...
0.071	1170	1660	1909	...	...	...	...	...	...
0.080	...	1752	2008	...	...	...	...	...	...
0.090	...	1790	2118	...	...	...	...	...	...
0.100	...	...	2229	...	...	...	...	...	...
0.125	...	...	2504	...	...	...	...	...	...
0.160	...	...	2580	...	...	...	...	...	...
Rivet shear strength[c]	1170	1790	2580	682	1044	1507	783	1198	1729
Sheet thickness, in.:	Yield Strength[a,d], lbs.								
0.020	447	...	...	300	...	...	300	...	...
0.025	590	695	...	374	464	...	374	464	...
0.032	745	932	974	479	593	713	478	593	712
0.040	867	1152	1167	598	741	890	598	740	889
0.050	938	1331	1407	...	925	1112	...	924	1110
0.063	1031	1447	1649	...	...	1400	...	...	...
0.071	1089	1518	1723	...	...	...	...	...	...
0.080	...	1597	1806	...	...	...	...	...	...
0.090	...	1686	1898	...	...	...	...	...	...
0.100	...	...	1990	...	...	...	...	...	...
0.125	...	...	2221	...	...	...	...	...	...
0.160	...	...	2543	...	...	...	...	...	...

a Test data from which the yield and ultimate strengths were derived can be found in Reference 8.1.2.1.
b Yield value is less than 2/3 of indicated ultimate.
c Rivet shear strength is documented in NAS1198 as 90 ksi.
d Permanent set at yield load: 0.005 inch.
Note: Because of difficulties encountered upsetting countersunk head rivets in thin A-286 sheet, such conditions should be avoided in design.

Table 8.1.2.2(a). Static Joint Strength of 100° Flush Head Monel Solid Rivets in Machine-Countersunk Stainless Steel Sheet

Rivet Type	MS20427M (F_{su} = 49 ksi)									
Sheet Material	AISI 302-Annealed			AISI 301-¼ Hard			AISI 301-½ Hard AISI 301-Full Hard			
Rivet Diameter, in. (Nominal Hole Diameter, in.)	1/8 (0.1285)	5/32 (0.159)	3/16 (0.191)	1/8 (0.1285)	5/32 (0.159)	3/16 (0.191)	3/32 (0.096)	1/8 (0.1285)	5/32 (0.159)	3/16 (0.191)
	Ultimate Strength, lbs									
Sheet thickness, in.:										
0.040	439[a,b]	...	...	439[b]	...	...	251[b]	439[b]	...	...
0.050	526[a]	673[a,b]	...	468	673[b]	...	322	447	673[b]	...
0.063	635[a]	820[a]	...	595	732	...	355	538	688	...
0.071	...	915[a]	1110[a,b]	635	830	990[b]	...	615	741	984[b]
0.080	...	973[a]	1246[a]	...	936	1118	...	635	850	995
0.090	...	...	1380[a]	...	973	1255	...	...	973	1132
0.100	...	...	1400	...	...	1400	...	...	...	1280
0.125	...	...	...	...	...	...	...	...	...	1400
Rivet shear strength[c]	635	973	1400	635	973	1400	355	635	973	1400
	Yield Strength[d], lbs									
Sheet thickness, in.:										
0.040	259	...	...	368	...	...	212	324	...	...
0.050	324	402	...	442	570	...	293	360	498	...
0.063	408	506	...	492	686	...	355	480	557	...
0.071	...	570	685	561	714	958	...	561	630	780
0.080	...	643	771	...	764	1012	...	635	765	848
0.090	...	...	865	...	893	1062	...	...	893	1000
0.100	...	...	965	...	...	1160	...	...	...	1160
0.125	...	...	...	...	...	...	...	...	...	1400
Head height (ref.), in.	0.048	0.061	0.077	0.048	0.061	0.077	0.042	0.048	0.061	0.077

a Yield value is less than 2/3 of the indicated ultimate strength value.

b Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.

c Rivet shear strength is documented in MS20427M.

d Permanent set at yield load: 0.005 inch.

Table 8.1.2.2(b). Static Joint Strength of 100° Flush Head Monel Solid Rivets in Dimpled Stainless Steel Sheet

Rivet Type	MS20427M (F_{su} = 49 ksi)										
Sheet Material	AISI 302 - annealed				AISI 301 - 1/4 hard			AISI 301 - 1/2 hard			
Rivet Diameter, in.	1/8	5/32	3/16	1/4	1/8	5/32	3/16	3/32	1/8	5/32	3/16
(Nominal Hole Diameter, in.)	(0.1285)	(0.159)	(0.191)	(0.257)	(0.1285)	(0.159)	(0.191)	(0.096)	(0.1285)	(0.159)	(0.191)
	Ultimate Strength, lbs.										
Sheet thickness, in.:											
0.020	348	...	...	...	497	...	...	348	497	...	...
0.025	441	536	...	...	595	766	...	355	595	766	...
0.032	568	698	846	...	635	931	1163	...	635	931	1163
0.040	635	884	1046	1370	...	973	1382	...	...	973	1382
0.050	...	973	1320	1730	...	...	1405	...	...	...	1405
0.063	...	...	1405	2240	...	...	...	...	...	...	...
0.071	...	...	...	2490	...	...	...	...	...	...	...
0.080	...	...	...	2540	...	...	...	...	...	...	...
Rivet shear strength[a]	635	973	1405	2540	635	973	1405	355	635	973	1405
	Yield Strength[b], lbs.										
Sheet thickness, in.:											
0.020	336	...	...	...	449	...	...	329	449	...	...
0.025	427	518	...	...	533	681	...	355	533	681	...
0.032	550	679	801	...	635	842	1049	...	635	842	1049
0.040	635	856	1020	1326	...	973	1252	...	...	973	1252
0.050	...	973	1280	1678	...	...	1405	...	...	...	1405
0.063	...	...	1405	2140	...	...	...	...	...	...	...
0.071	...	...	...	2420	...	...	...	...	...	...	...
0.080	...	...	...	2540	...	...	...	...	...	...	...
Head height (max.), in.	0.048	0.061	0.077	0.103	0.048	0.061	0.077	0.042	0.048	0.061	0.077

[a] Rivet shear strength from Table 8.1.2(b).

[b] Permanent set at yield load: 0.005 inch.

Table 8.1.2.2(c). Static Joint Strength of 100° Flush Head Aluminum Alloy (2117-T3) Solid Rivets in Dimpled Aluminum Alloy Sheet[a,b]

Rivet Type	MS20426AD (F_{su} = 30 ksi)								
Sheet Material	2024-T3 2024-T42 2024-T62 2024-T81		2024-T3 2024-T42		2024-T62 2024-T81		2024-T86 7075-T6		
Rivet Diameter, in. (Nominal Hole Diameter, in.)	3/32 (0.096)	1/8 (0.1285)	5/32 (0.159)	3/16 (0.191)	5/32 (0.159)	3/16 (0.191)	1/8 (0.1285)	5/32 (0.159)	3/16 (0.191)
	Ultimate Strength, lbs.								
Sheet thickness, in.:									
0.016	177	...	...	...	...	...	...	...	...
0.020	209	299	...	...	...	...	302	...	...
0.025	217	360	474	...	462	...	383	462	...
0.032	...	388	568	722	596	725	388	596	725
0.040	...	...	596	839	...	862	...	...	862
0.050	...	...	...	862	...	...	...	...	...
Rivet shear strength[c]	217	388	596	862	596	862	388	596	862
	Yield Strength[d], lbs.								
Sheet thickness, in.:									
0.016	154	...	...	...	...	...	...	...	...
0.020	184	257	...	...	...	...	257	...	...
0.025	209	315	324	...	324	...	315	410	...
0.032	...	367	430	512	430	512	367	525	640
0.040	...	...	506	644	...	644	...	...	782
0.050	...	...	...	757	...	...	...	...	...
Head height (max.), in.	0.036	0.042	0.055	0.070	0.055	0.070	0.042	0.055	0.070

[a] These allowables apply to double dimpled sheets and to the upper sheet dimpled into a machine-countersunk lower sheet. Sheet gage is that of the thinnest sheet for double dimpled joints and of the upper dimpled sheet for dimpled, machine-countersunk joints. The thickness of machine-countersunk sheet must be at least one tabulated gage thicker than the upper sheet. In no case will allowables be obtained by extrapolation for gages other than those shown.

[b] Test data from which the yield strengths listed were derived and can be found in Reference 8.1.2.2.

[c] Rivet shear strength from Table 8.1.2(b).

[d] Permanent set at yield load: the greater of 0.005 inch or 2.5% of nominal diameter.

Table 8.1.2.2(d). Static Joint Strength of 100° Flush Head Aluminum Alloy (2017-T3) Solid Rivets in Dimpled Aluminum Alloy Sheet[a,b]

Rivet Type	MS20426D (F_{su} = 38 ksi)								
Sheet Material	2024-T3 and 2024-T42			2024-T86 and 7075-T6			2024-T62 and 2024-T81		
Rivet Diameter, in.	5/32	3/16	1/4	5/32	3/16	1/4	5/32	3/16	1/4
(Nominal Hole Diameter, in.)	(0.159)	(0.191)	(0.257)	(0.159)	(0.191)	(0.257)	(0.159)	(0.191)	(0.257)
	Ultimate Strength, lbs.								
Sheet thickness, in.:									
0.025	419	...	...	530	...	...	419	...	...
0.032	600	681	...	672	822	...	600	681	...
0.040	738	905	845	755	1000	1108	738	905	1108
0.050	755	1090	1332	...	1090	1508	755	1090	1508
0.063	...	...	1695	...	...	1803	...	...	1803
0.071	...	...	1853	...	...	1930	...	...	1930
0.080	...	...	1970	...	...	1970	...	...	1970
Rivet shear strength[c]	755	1090	1970	755	1090	1970	755	1090	1970
	Yield Strength[d], lbs.								
Sheet thickness, in.:									
0.025	336	...	...	450	...	...	336	...	...
0.032	483	546	...	581	...	...	483	546	...
0.040	589	730	845	675	705	978	589	730	845
0.050	681	888	1187	...	867	1508	681	888	1187
0.063	...	...	1415	...	1007	1803	...	...	1415
0.071	...	...	1656	...	...	1930	...	...	1656
0.080	...	...	1870	...	...	1970	...	...	1870
Head height (max.), in.	0.055	0.070	0.095	0.055	0.070	0.095	0.055	0.070	0.095

a These allowables apply to double dimpled sheets and to the upper sheet dimpled into a machine-countersunk lower sheet. Sheet gage is that of the thinnest sheet for double dimpled joints and of the upper dimpled sheet for dimpled, machine-countersunk joints. The thickness of machine-countersunk sheet must be at least one tabulated gage thicker than the upper sheet. In no case will allowables be obtained by extrapolation for gages other than those shown.

b Test data from which the yield strengths listed were derived and can be found in Reference 8.1.2.2.

c Rivet shear strength from Table 8.1.2(b).

d Permanent set at yield load: the greater of 0.005 inch or 2.5% of nominal diameter.

Table 8.1.2.2(e). Static Joint Strength of 100° Flush Head Aluminum Alloy (2024-T31) Solid Rivets in Dimpled Aluminum Alloy Sheet[a,b]

Rivet Type	MS20426DD (F_{su} = 41 ksi)					
Sheet Material	2024-T3 2024-T42		2024-T62 2024-T81		2024-T86 7075-T6	
Rivet Diameter, in.	3/16	1/4	3/16	1/4	3/16	1/4
(Nominal Hole Diameter, in.) . .	(0.191)	(0.257)	(0.191)	(0.257)	(0.191)	(0.257)
	Ultimate Strength, lbs.					
Sheet thickness, in.:						
0.032	744	...	786	...	786	...
0.040	941	879	982	1300	982	1300
0.050	1110	1359	1152	1705	1152	1705
0.063	1175	1727	1175	2010	1175	2010
0.071	...	1883	...	2125	...	2125
0.080	...	2025	...	...	...	...
0.090	...	2125	...	...	...	...
Rivet shear strength[c]	1175	2125	1175	2125	1175	2125
	Yield Strength[d], lbs.					
Sheet thickness, in.:						
0.032	582	...	649	...	786	...
0.040	666	879	816	962	982	978
0.050	738	1308	961	1308	1152	1543
0.063	925	1564	1068	1564	1175	1958
0.071	...	1711	...	1711	...	2125
0.080	...	1928	...	...	...	...
0.090	...	2121	...	...	...	...
Head height (max.), in.	0.070	0.095	0.070	0.095	0.070	0.095

a These allowables apply to double dimpled sheets and to the upper sheet dimpled into a machine-countersunk lower sheet. Sheet gage is that of the thinnest sheet for double dimpled joints and of the upper dimpled sheet for dimpled, machine-countersunk joints. The thickness of machine-countersunk sheet must be at least one tabulated gage thicker than the upper sheet. In no case will allowables be obtained by extrapolation for gages other than those shown.

b Test data from which the yield strengths listed were derived and can be found in Reference 8.1.2.2.

c Rivet shear strength from Table 8.1.2(b).

d Permanent set at yield load: the greater of 0.005 inch or 2.5% of nominal diameter.

Table 8.1.2.2(f). Static Joint Strength of 100° Flush Head Aluminum Alloy Solid Rivets in Machine-Countersunk Aluminum Alloy Sheet

Rivet Type	MS20426AD (2117-T3) (F_{su} = 30 ksi)				MS20426D (2017-T3) (F_{su} = 38 ksi)			MS20426DD (2024-T31) (F_{su} = 41 ksi)	
Sheet Material	Clad 2024-T42								
Rivet Diameter, in. (Nominal Hole Diameter, in.)	3/32 (0.096)	1/8 (0.1285)	5/32 (0.159)	3/16 (0.191)	5/32 (0.159)	3/16 (0.191)	1/4 (0.257)	3/16 (0.191)	1/4 (0.257)
	Ultimate Strength[a], lbs								
Sheet thickness, in.:									
0.032	178[b]	...	...	...	...	...	...	...	...
0.040	193	309[b]	...	...	...	...	...	...	...
0.050	206	340	479[b]	...	580[b,c]	...	...	...	...
0.063	216	363	523	705[b]	657[c]	859[b,c]	...	886 [b]	...
0.071	...	373	542	739	690	917[c]	...	942	...
0.080	...	...	560	769	720	969[c]	...	992	...
0.090	...	...	575	795	746	1015	1552[b,c]	1035	1647[b,c]
0.100	...	...	...	818	...	1054	1640[c]	1073	1738[c]
0.125	...	...	...	853	...	1090	1773	1131	1877
0.160	...	...	...	...	...	...	1891	...	2000
0.190	...	...	...	...	...	...	1970	...	2084
Rivet shear strength[d]	217	388	596	862	755	1090	1970	1175	2125
	Yield Strength[a,e], lbs								
Sheet thickness, in.:									
0.032	132	...	...	...	...	...	...	...	...
0.040	153	231	...	...	...	...	...	...	...
0.050	188	261	321	...	345	...	...	...	...
0.063	213	321	402	471	401	515	...	614	...
0.071	...	348	453	538	481	557	...	669	...
0.080	...	...	498	616	562	623	...	761	...
0.090	...	...	537	685	633	746	861	842	1053
0.100	...	...	...	745	...	854	1017	913	1115
0.125	...	...	...	836	...	1018	1313	1021	1357
0.160	...	...	...	...	...	...	1574	...	1694
0.190	...	...	...	...	...	...	1753	...	1925
Head height (ref.), in.	0.036	0.042	0.055	0.070	0.055	0.070	0.095	0.070	0.095

a Test data from which the yield and ultimate strength listed were derived can be found in Reference 8.1.2.2.
b Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.
c Yield value is less than 2/3 of the indicated ultimate strength value.
d Rivet shear strength is documented in MS20426.
e Permanent set at yield load: the greater of 0.005 inch or 2.5% of nominal diameter.

Table 8.1.2.2(g). Static Joint Strength of 100° Flush Head Aluminum Alloy (5056-H321) Solid Rivets in Machine-Countersunk Magnesium Alloy Sheet

Rivet Type	MS20426B (F_{su} = 28 ksi)				
Sheet Material	AZ31B-H24				
Rivet Diameter, in. (Nominal Hole Diameter, in.)	3/32 (0.096)	1/8 (0.1285)	5/32 (0.159)	3/16 (0.191)	1/4 (0.257)
	Ultimate Strength, lbs				
Sheet thickness, in.:					
0.032	172[a,b]	...	...	...	...
0.040	180	304[a,b]	...	...	...
0.050	190	318	467[a,b]	...	...
0.063	203	337	490	679[a,b]	...
0.071	...	348	503	697[a]	...
0.080	...	360	519	715	...
0.090	...	363	536	737	1244[b]
0.100	...	...	554	757	1271
0.125	...	...	556	802	1343
0.160	...	...	...	...	1440
0.190	...	...	...	...	1450
Rivet shear strength[c]	203	363	556	802	1450
	Yield Strength[d], lbs				
Sheet thickness, in.:					
0.032	104	...	...	...	...
0.040	127	172	...	...	...
0.050	152	214	268	...	...
0.063	186	259	334	409	...
0.071	...	287	369	459	...
0.080	...	318	406	504	...
0.090	...	353	450	555	792
0.100	...	...	491	606	856
0.125	...	...	556	735	1030
0.160	...	...	...	...	1273
0.190	...	...	...	...	1450
Head height (ref.), in.	0.036	0.042	0.055	0.070	0.095

a Yield value is less than 2/3 of the indicated ultimate strength value.

b Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.

c Rivet shear strength is documented in MS20426.

d Permanent set at yield load: the greater of 0.005 inch or 2.5% of nominal diameter.

Table 8.1.2.2(h). Static Joint Strength of 100° Flush Head Monel Solid Rivets in Machine-Countersunk Titanium Alloy Sheet

Rivet Type	MS20427M (F_{su} = 49 ksi)			
Sheet Material	Commercially Pure Titanium, F_{tu} = 80 ksi			
Rivet Diameter, in. (Nominal Hole Diameter, in.)	1/8 (0.1285)	5/32 (0.159)	3/16 (0.191)	1/4 (0.257)
	Ultimate Strength, lbs			
Sheet thickness, in.:				
0.040	531[a]	...	...	...
0.050	573	818[a]	...	...
0.063	626	885	...	...
0.071	635	926	1242[a]	...
0.080	...	973	1302	...
0.090	...	...	1360	...
0.100	...	...	1400	2260[a]
0.125	...	...	...	2460
0.160	...	...	...	2540
Rivet shear strength[b]	635	973	1400	2540
	Yield Strength[c], lbs			
Sheet thickness, in.:				
0.040	376	...	...	...
0.050	472	582	...	...
0.063	598	736	...	...
0.071	635	835	933	...
0.080	...	945	1130	...
0.090	...	...	1268	...
0.100	...	...	1400	1860
0.125	...	...	...	2340
0.160	...	...	...	2540
Head height (max.), in.	0.048	0.061	0.077	0.103

[a] Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.

[b] Rivet shear strength is documented in MS20427.

[c] Permanent set at yield load: the greater of 0.005 inch or 2.5% of nominal diameter.

Table 8.1.2.2(i). Static Joint Strength of 120° Flush Shear Head Aluminum Alloy (2017-T3) Solid Rivets in Machine-Countersunk Aluminum Alloy Sheet

Rivet Type	BRFS-D[a] (F_{su} = 38 ksi)				
Sheet Material	Clad 2024-T3				
Rivet Diameter, in. (Nominal Hole Diameter, in.)[b]	3/32 (0.096)	1/8 (0.1285)	5/32 (0.159)	3/16 (0.191)	1/4 (0.257)
	Ultimate Strength, lbs				
Sheet thickness, in.:					
0.020	139	...	...	...	...
0.025	176	233	...	...	...
0.032	226	300	367	...	...
0.040	275	378	465	552	...
0.050	...	477	585	697	930
0.063	...	494	741	886	1182
0.071	...	...	755	1005	1338
0.080	...	...	...	1090	1513
0.090	...	...	...	...	1711
0.100	...	...	...	...	1902
0.125	...	...	...	...	1970
Rivet shear strength[c]	275	494	755	1090	1970
	Yield Strength[d], lbs				
Sheet thickness, in.:					
0.020	137	...	...	...	...
0.025	171	229	...	...	...
0.032	207	294	359	...	...
0.040	231	357	453	547	...
0.050	...	398	550	680	918
0.063	...	451	614	814	1149
0.071	...	...	655	857	1295
0.080	...	...	...	914	1430
0.090	...	...	...	...	1513
0.100	...	...	...	...	1592
0.125	...	...	...	...	1790
Head height (ref.), in.	0.018	0.023	0.030	0.039	0.049

[a] Data supplied by Briles Rivet Corp.

[b] Fasteners installed in hole diameters of 0.0975, 0.1285, 0.1615, 0.1945, 0.257, +0.0005, -0.001, respectively.

[c] Shear strength based on Table 8.1.2(b) and F_{su} = 38 ksi.

[d] Permanent set at yield load: 4% of nominal diameter.

Table 8.1.2.2(j). Static Joint Strength of 120° Flush Shear Head Aluminum Alloy (2117-T3) Solid Rivets in Machine-Countersunk Aluminum Alloy Sheet

Rivet Type	BRFS-AD[a] (F_{su} = 30 ksi)				
Sheet Material	Clad 2024-T3				
Rivet Diameter, in. (Nominal Hole Diameter, in.)[b]	3/32 (0.096)	1/8 (0.1285)	5/32 (0.159)	3/16 (0.191)	1/4 (0.257)
	Ultimate Strength, lbs				
Sheet thickness, in.:					
0.020	119	...	...	...	...
0.025	144	201	...	...	...
0.032	171	250	316	...	...
0.040	204	292	386	474	...
0.050	217	343	451	571	806
0.063	...	388	536	675	987
0.071	...	...	596	737	1073
0.080	...	...	...	812	1169
0.090	...	...	...	862	1278
0.100	...	...	...	...	1371
0.125	...	...	...	...	1550
Rivet shear strength[c]	217	388	596	862	1550
	Yield Strength[d], lbs				
Sheet thickness, in.:					
0.020	119	...	...	...	...
0.025	144	201	...	...	...
0.032	171	250	316	...	...
0.040	204	292	386	474	...
0.050	217	343	451	571	806
0.063	...	388	536	675	987
0.071	...	...	596	737	1073
0.080	...	...	...	812	1169
0.090	...	...	...	862	1278
0.100	...	...	...	...	1371
0.125	...	...	...	...	1550
Head height (ref.), in.	0.018	0.023	0.030	0.039	0.049

[a] Data supplied by Briles Rivet Corp.

[b] Fasteners installed in hole diameters of 0.0975, 0.1285, 0.1615, 0.1945, 0.257, +0.0005, -0.001, respectively.

[c] Shear strength based on Table 8.1.2(b) and F_{su} = 38 ksi.

[d] Permanent set at yield load: 4% of nominal diameter.

Table 8.1.2.2(k). Static Joint Strength of 120° Flush Shear Head Aluminum Alloy (2024-T31) Solid Rivets in Machine-Countersunk Aluminum Alloy Sheet

Rivet Type	BRFS-DD[a] (F_{su} = 41 ksi)	
Sheet Material	Clad 2024-T3	
Rivet Diameter, in. (Nominal Hole Diameter, in.)[b]	3/16 (0.191)	1/4 (0.257)
	Ultimate Strength, lbs	
Sheet thickness, in.:		
0.040	598	...
0.050	772	1000
0.063	994	1300
0.071	1130	1480
0.080	1180	1690
0.090	...	1920
0.100	...	2120
Rivet shear strength[c]	1180	2120
	Yield Strength[d], lbs	
Sheet thickness, in.:		
0.040	598	...
0.050	772	1000
0.063	949	1300
0.071	1000	1480
0.080	1060	1680
0.090	...	1760
0.100	...	1850
Head height (ref.), in.	0.039	0.049

a Data supplied by Briles Rivet Corp.
b Fasteners installed in hole diameters of 0.1935 and 0.257, ±0.0005.
c Shear strength based on Table 8.1.2(b) and F_{su} = 41 ksi.
d Permanent set at yield load: 4% of nominal diameter.

Table 8.1.2.2(l). Static Joint Strength of 120° Flush Shear Head Ti-45 Cb Solid Rivets in Machine-Countersunk Aluminum Alloy and Titanium Sheet

Rivet Type	BRFS-T[a] (F_{su} = 53 ksi)					
Sheet Material	Clad 7075-T6			Annealed Ti-6Al-4V		
Rivet Diameter, in. (Nominal Hole Diameter, in.)[b]	1/8 (0.1285)	5/32 (0.159)	3/16 (0.191)	1/8 (0.1285)	5/32 (0.159)	3/16 (0.191)
	Ultimate Strength, lbs					
Sheet thickness, in.:						
0.025	288	...	...	400	...	...
0.032	369	456	...	513	635	...
0.040	461	572	685	564	796	952
0.050	577	713	858	602	867	1190
0.063	610	891	1080	650	927	1270
0.071	628	914	1220	680	964	1310
0.080	649	939	1300	687	1005	1360
0.090	671	967	1330	...	1050	1420
0.100	687	996	1370	...	...	1470
0.125	...	1050	1450	...	...	1520
0.160	...	...	1520	...	...	...
Rivet shear strength[c]	687	1050	1520	687	1050	1520
	Yield Strength[d], lbs					
Sheet thickness, in.:						
0.025	288	...	...	400	...	...
0.032	369	456	...	513	635	...
0.040	461	572	685	564	796	952
0.050	577	713	858	602	867	1190
0.063	610	891	1080	650	927	1270
0.071	628	914	1220	680	964	1310
0.080	649	939	1300	687	1005	1360
0.090	671	967	1330	...	1050	1420
0.100	687	996	1370	...	...	1470
0.125	...	1050	1450	...	...	1520
0.160	...	...	1520	...	...	...
Head height (ref.), in.	0.023	0.030	0.039	0.023	0.030	0.039

a Data supplied by Briles Rivet Corp.

b Allowables developed from tests with hole diameters noted, except 5/32 and 3/16 diameters were 0.161 and 0.1935 ±0.0005, respectively.

c Rivet shear strength based on Table 8.1.2(b) and F_{su} = 53 ksi.

d Permanent set at yield load: 4% of nominal hole diameter.

Table 8.1.2.2(m). Static Joint Strength of 120° Flush Shear Head Aluminum Alloy (7050-T731) Solid Rivets in Machine-Countersunk Aluminum Alloy Sheet

Rivet Type	MS14218E[a] (F_{su} = 43 ksi)						
Sheet Material	Clad 2024-T3						
Rivet Diameter, in. (Nominal Hole Diameter, in.)[b]	1/8 (0.1285)	5/32 (0.159)	3/16 (0.191)	7/32 (0.228)	1/4 (0.257)	9/32 (0.290)	5/16 (0.323)
	Ultimate Strength, lbs						
Sheet thickness, in.:							
0.025	215[c]	...	...	...	...	...	...
0.032	307	346[c]	...	...	...	...	...
0.040	434	478	529[c]	...	...	...	...
0.050	508	673	732	806 [c]	...	...	...
0.063	536	781	1045	1135	1200	1285[c]	...
0.071	554	803	1110	1365	1445	1530	1630[c]
0.080	558	827	1140	1565	1735	1835	1930
0.090	...	854	1175	1605	1990	2200	2320
0.100	...	...	1205	1645	2030	2525	2725
0.125	...	...	1230	1740	2140	2650	3205
0.160	...	...	...	1755	2230	2820	3400
0.190	...	...	...	...	...	2840	3525
Rivet shear strength[d]	558	854	1230	1755	2230	2840	3525
	Yield Strength[e], lbs						
Sheet thickness, in.:							
0.025	215	...	...	...	...	...	...
0.032	307	346	...	...	...	...	...
0.040	388	478	529	...	...	...	...
0.050	487	601	721	806	...	...	...
0.063	536	760	912	1085	1200	1285	...
0.071	552	803	1030	1225	1377	1530	1630
0.080	558	827	1140	1385	1554	1755	1930
0.090	...	854	1175	1560	1750	1970	2200
0.100	...	...	1205	1645	1950	2200	2445
0.125	...	...	1230	1735	2140	2650	3060
0.160	...	...	...	1755	2230	2810	3400
0.190	...	...	...	...	...	2840	3525
Head height (ref.), in.	0.027	0.035	0.044	0.053	0.061	0.069	0.077

a Data supplied by Briles Rivet Corp.

b Allowables developed from tests with hole diameters noted, except 5/32, 3/16, and 5/16 diameters were 0.161, 0.1935, and 0.316, respectively. Hole tolerances were +0.0005, -0.001 inch.

c Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.

d Shear strength based on Table 8.1.2(b) and F_{su} = 43 ksi.

e Permanent set at yield load: 4% of nominal hole diameter.

Table 8.1.2.2(n). Static Joint Strength of 100° Flush Shear Head Aluminum Alloy (7050-T73) Solid Rivets in Machine-Countersunk Aluminum Alloy Sheet

Rivet Type	NAS1097-E[a] (F_{su} = 41 ksi)							
Sheet Material	Clad 2024-T3				Clad 7075-T6			
Nominal Rivet Diameter, in. (Nominal Hole Diameter, in.)[b]	1/8 (0.1285)	5/32 (0.159)	3/16 (0.191)	1/4 (0.257)	1/8 (0.1285)	5/32 (0.159)	3/16 (0.191)	1/4 (0.257)
	Ultimate Strength, lbs							
Sheet thickness, in.:								
0.025	227[c]	...	...	...	278[c]	...	...	...
0.032	326	367[c]	...	...	354	441[c]	...	...
0.040	437	505	561[c]	...	439	547	661[c]	...
0.050	466	679	773	908[c]	456	674	823	1120[c]
0.063	485	717	1005	1275	477	700	980	1330
0.071	497	731	1025	1500	490	716	999	1570
0.080	507	747	1045	1750	505	734	1020	1760
0.090	521	765	1065	1840	520	754	1045	1790
0.100	531	781	1085	1870	531	774	1070	1825
0.125	...	814	1135	1935	...	814	1130	1905
0.160	...	...	1175	2030	...	...	1175	2020
0.190	...	...	...	2110	...	...	...	2115
0.250	...	...	...	2125	...	...	...	2125
Rivet shear strength[d]	531	814	1175	2125	531	814	1175	2125
	Yield Strength[e], lbs							
Sheet thickness, in.:								
0.025	192	...	...	...	222	...	...	...
0.032	283	311	...	...	307	356	...	...
0.040	349	439	479	...	372	475	542	...
0.050	398	538	674	767	398	572	724	894
0.063	462	617	799	1105	431	612	836	1205
0.071	497	665	857	1310	451	638	867	1400
0.080	507	720	921	1400	474	666	900	1490
0.090	521	765	995	1500	499	698	938	1540
0.100	531	781	1065	1595	525	729	976	1595
0.125	...	814	1135	1835	...	808	1070	1720
0.160	...	...	1175	2030	...	...	1175	1895
0.190	...	...	...	2110	...	...	...	2050
0.250	...	...	...	2125	...	...	...	2125
Head height (ref.), in.	0.029	0.037	0.046	0.060	0.029	0.037	0.046	0.060

a Data supplied by Lockheed-Georgia Company.

b Fasteners installed in hole diameters of 0.130, 0.158, 0.191, and 0.254 ± 0.003 inch, respectively.

c Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.

d Shear strength based on Table 8.1.2(b) and F_{su} = 41 ksi.

e Permanent set at yield load: 4% of nominal hole diameter.

Table 8.1.2.2(o). Static Joint Strength of 120° Flush Shear Head Aluminum Alloy (2117-T3) Solid Rivets in Machine-Countersunk Aluminum Alloy Sheet

Rivet Type	MS14218AD[a] (F_{su} = 30 ksi)					
Sheet Material	Clad 2024-T3					
Rivet Diameter, in. (Nominal Hole Diameter, in.)[b]	3/32 (0.096)	1/8 (0.1285)	5/32 (0.159)	3/16 (0.191)	7/32 (0.228)	1/4 (0.257)
	Ultimate Strength, lbs					
Sheet thickness, in.:						
0.020	125[c]	...	...	...	...	...
0.025	153	212[c]	...	...	...	...
0.032	188	263	334[c]	...	...	...
0.040	216	322	408	498[c]	...	...
0.050	217	380	498	609	740[c]	849[c]
0.063	...	388	588	751	910	1040
0.071	...	...	596	817	1015	1155
0.080	...	...	...	842	1125	1290
0.090	...	...	...	862	1205	1425
0.100	...	...	...	...	1225	1520
0.125	...	...	...	...	...	1555
Rivet shear strength[d]	217	388	596	862	1225	1555
	Yield Strength[e], lbs					
Sheet thickness, in.:						
0.020	125	...	...	...	...	...
0.025	153	212	...	...	...	...
0.032	188	263	334	...	...	...
0.040	216	319	408	498	...	...
0.050	217	370	492	609	740	849
0.063	...	388	574	733	910	1040
0.071	...	...	596	794	1005	1155
0.080	...	...	...	842	1090	1275
0.090	...	...	...	862	1180	1380
0.100	...	...	...	...	1225	1480
0.125	...	...	...	...	...	1555
Head height (ref.), in.	0.022	0.027	0.035	0.044	0.053	0.061

[a] Data supplied by Briles Rivet Corp.

[b] Load allowables developed from tests with hole diameters noted, except 3/32, 5/32, and 3/16 diameters were 0.098, 0.161, and 0.1935, respectively. Hole tolerance was +0.0005, -0.001 inch.

[c] Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.

[d] Shear strength based on Table 8.1.2(b) and F_{su} = 30 ksi.

[e] Permanent set at yield load: 4% of nominal hole diameter.

Table 8.1.2.2(p). Static Joint Strength of 120° Flush Tension Type Head Aluminum Alloy (7050-T731) Solid Rivets in Machine-Countersunk Aluminum Alloy Sheet

Rivet Type	MS14219 E^{a} (F_{su} = 43 ksi)							
Sheet Material	Clad 2024-T3							
Rivet Diameter, in. (Nominal Hole Diameter, in.)^{b}	3/32 (0.096)	1/8 (0.1285)	5/32 (0.159)	3/16 (0.191)	7/32 (0.228)	1/4 (0.257)	9/32 (0.290)	5/16 (0.523)
	Ultimate Strength, lbs							
Sheet thickness, in.:								
0.032	210^{c}	...	...	...	...	...	...	...
0.040	279	339^{c}	...	...	...	...	...	...
0.050	310	473	527^{c}	...	...	...	...	...
0.063	311	538	743	819^{c}	...	...	...	...
0.071	...	558	788	979	1065^{c}	...	...	...
0.080	...	...	834	1105	1280	...	...	...
0.090	...	...	854	1165	1520	1625^{c}	...	...
0.100	...	...	...	1230	1605	1890	2020^{c}	2120^{c}
0.125	...	...	...	...	1755	2145	2580	2965
0.160	...	...	...	...	...	2230	2840	3415
0.190	...	...	...	...	...	...	...	3525
Rivet shear strength^{d}	311	588	854	1230	1755	2230	2840	3525
	Yield Strength^{e}, lbs							
Sheet thickness, in.:								
0.032	210	...	...	...	...	...	...	...
0.040	277	339	...	...	...	...	...	...
0.050	301	468	527	...	...	...	...	...
0.063	309	538	728	819	...	...	...	...
0.071	...	543	788	979	1065	...	...	...
0.080	...	...	823	1100	1280	...	...	...
0.090	...	...	833	1165	1490	1625	...	...
0.100	...	...	...	1190	1605	1875	2020	2120
0.125	...	...	...	...	1705	2145	2580	2945
0.160	...	...	...	...	...	2200	2765	3390
0.190	...	...	...	...	...	...	...	3455
Head height (ref.), in.	0.034	0.041	0.053	0.068	0.077	0.090	0.100	0.104

a Data supplied by Briles Rivet Corp.
b Load allowables developed from tests with hole diameters noted, except 5/32, 3/16, and 5/16 diameter were 0.161, 0.1935, and 0.316, respectively. Hole tolerances were + 0.0005, -0.001 inch.
c Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.
d Rivet shear strength based on Table 8.1.2(b) and F_{su} = 43 ksi.
e Permanent set at yield load: 4% of nominal hole diameter.

Table 8.1.2.2(q). Static Joint Strength of 120° Flush Tension Type Head Aluminum Alloy (7050-T731) Solid Rivets in Machine-Countersunk Aluminum Alloy Sheet

Rivet Type	MS14219 E[a] (F_{su} = 43 ksi)							
Sheet Material	Clad 7075-T6							
Rivet Diameter, in. (Nominal Hole Diameter, in.)[b]	3/32 (0.096)	1/8 (0.1285)	5/32 (0.159)	3/16 (0.191)	7/32 (0.228)	1/4 (0.257)	9/32 (0.290)	5/16 (0.523)
	Ultimate Strength, lbs							
Sheet thickness, in.:								
0.032	272[c]	...	...	...	...	...	...	...
0.040	297	455[c]	...	...	...	...	...	...
0.050	311	522	704[c]	...	...	...	...	...
0.063	...	558	803	1065[c]	...	...	...	...
0.071	...	...	832	1140	1435[c]	...	...	...
0.080	...	...	854	1180	1600	...	...	...
0.090	...	...	...	1220	1650	2030[c]	...	...
0.100	...	...	...	1230	1700	2090	2565[c]	2860[c]
0.125	...	...	...	...	1755	2230	2740	3295
0.160	...	...	...	...	...	...	2840	3525
Rivet shear strength[d]	311	558	854	1230	1755	2230	2840	3525
	Yield Strength[e], lbs							
Sheet thickness, in.:								
0.032	272	...	...	...	...	...	...	...
0.040	296	455	...	...	...	...	...	...
0.050	308	522	704	...	...	...	...	...
0.063	...	550	802	1065	...	...	...	...
0.071	...	...	823	1140	1435	...	...	...
0.080	...	...	845	1170	1600	...	...	...
0.090	...	...	...	1205	1650	2030	...	...
0.100	...	...	...	1220	1685	2090	2565	2860
0.125	...	...	...	...	1740	2195	2715	3295
0.160	...	...	...	...	...	...	2815	3480
Head height (ref.), in.	0.034	0.041	0.053	0.068	0.077	0.090	0.100	0.104

a Data supplied by Briles Rivet Corp.

b Allowables developed from tests with hole diameters noted, except 3/32, 5/32, 3/16, and 5/16 diameters were 0.098, 0.161, 0.1935, and 0.316, respectively. Hole tolerances were +0.0005, -0.001 inch.

c Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.

d Rivet shear strength based on Table 8.1.2(b) and F_{su} = 43 ksi.

e Permanent set at yield load: 4% of nominal hole diameter.

Table 8.1.2.2(r). Static Joint Strength of Solid 100° Flush Head Aluminum Alloy (7050-T73) Solid Rivets in Machine Countersunk Aluminum Alloy Sheet

Rivet Type	MS20426E (F_{su} = 41 ksi)[a]			
Sheet Material	Clad 2024-T3			
Rivet Diameter, in.	1/8	5/32	3/16	1/4
(Nominal Hole Diameter, in.)[b]	(0.1285)	(0.159)	(0.191)	(0.257)
	Ultimate Strength, lbs			
Sheet thickness, in.:				
0.040	386[c]	...	...	...
0.050	419	592[c]	...	...
0.063	463	647	870[c]	...
0.071	491	680	910	...
0.080	521	718	955	...
0.090	531	760	1005	1610[c]
0.100	...	802	1055	1680
0.125	...	814	1175	1845
0.160	...	...	...	2085
0.190	...	...	...	2125
Rivet shear strength[d]	531	814	1175	2125
	Yield Strength[e], lbs			
Sheet thickness, in.:				
0.040	262	...	...	...
0.050	327	404	...	...
0.063	412	510	612	...
0.071	464	574	690	...
0.080	517	647	777	...
0.090	531	728	875	1175
0.100	...	794	972	1310
0.125	...	814	1160	1635
0.160	...	...	...	2070
0.190	...	...	...	2125
Head Height (ref.), in.	0.042	0.055	0.070	0.095

a Data supplied by Lockheed Ga. Co. and Air Force Materials Laboratory.

b Load allowables developed from tests with hole diameters of 0.130, 0.158, 0.191, and 0.256 ± 0.003 inch.

c The values in the table above the horizontal line in each column are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires the specific approval of the procuring agency.

d Shear strength based on area computed from nominal hole diameters in Table 8.1.2(b) and F_{su} = 41 ksi.

e Permanent set at yield load: 4% of the nominal hole diameter.

Table 8.1.2.2 (s). Static Joint Strength of Solid 100° Flush Head Alumunim Alloy (7050-T73) Solid Rivets in Machine Countersunk Aluminum Alloy Sheet

Rivet Type	MS20426E (F_{su} = 41 ksi)[a]			
Sheet Material	Clad 7075-T6			
Rivet Diameter, in.	1/8	5/32	3/16	1/4
(Nominal Hole Diameter, in.)[b]	(0.1285)	(0.159)	(0.191)	(0.257)
	Ultimate Strength, lbs			
Sheet thickness, in.:				
0.040	318[c]	...	...	...
0.050	393	492[c]	...	...
0.063	440	606	745[c]	...
0.071	469	642	840	...
0.080	502	683	898	...
0.090	531	728	952	1430[c]
0.100	...	773	1005	1570
0.125	...	814	1140	1755
0.160	...	...	1175	2010
0.190	...	...	...	2125
Rivet shear strength[d]	531	814	1175	2125
	Yield Strength[e], lbs			
Sheet thickness, in.:				
0.040	257	...	...	...
0.050	330	399	...	...
0.063	423	515	607	...
0.071	469	586	693	...
0.080	502	666	789	...
0.090	531	728	896	1175
0.100	...	773	1005	1320
0.125	...	814	1140	1680
0.160	...	...	1175	2010
0.190	...	...	...	2125
Head height (ref.), in.	0.042	0.055	0.070	0.095

a Data supplied by Lockheed Ga. Co., Air Force Materials Laboratory, Allfast, Cherry Fasteners, Douglas Aircraft Co., and Huck Mfg. Co.

b Load allowables developed from tests with hole diameters of 0.130, 0.158, 0.191, and 0.256 ± 0.003 inch.

c The values in the table above the horizontal line in each column are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires the specific approval of the procuring agency.

d Shear strength based on area computed from nominal hole diameters in Table 8.1.2(b) and F_{su} = 41 ksi.

e Permanent set at yield load: 4% of the nominal hole diameter.

Table 8.1.2.2(t). Static Joint Strength of 105 degree Flush Shear Head Aluminum Alloy (7050) Solid Rivet in 100 degree Machine-Countersunk Alloy Sheet

Rivet Type	AL 905 KE[a] (F_{su} = 41 ksi)			
Sheet Material	Clad 2024-T3			
Rivet Diameter, in. (Nominal Hole Diameter, in.)[b]	1/8 (0.1285)	5/32 (0.159)	3/16 (0.191)	1/4 (0.257)
	Ultimate Strength, lbs.			
Sheet thickness, in.:				
0.032	325[c]	---	---	---
0.040	396	502[c]	---	---
0.050	452	612	750[c]	---
0.063	498	696	923	1280[c]
0.071	526	731	980	1425
0.080	531	771	1030	1585
0.090	---	814	1080	1735
0.125	---	---	1175	1985
0.160	---	---	---	2125
Rivet Shear Strength[d]	531	814	1175	2125
	Yield Strength, lbs[e]			
Sheet thickness, in.:				
0.032	268	---	---	---
0.040	326	415	---	---
0.050	399	504	619	---
0.063	493	620	759	1060
0.071	526	692	845	1175
0.080	531	771	942	1305
0.090	---	814	1050	1450
0.125	---	---	1175	1955
0.160	---	---	---	2125
Head height [ref.],[f] in.	0.029	0.037	0.046	0.060

a Data supplied by Ateliers De La Haute Garonne SARL.

b Loads developed from tests with hole diameters of 0.1285, 0.161, 0.193, and 0.257, +/- 0.001 inch.

c The values above the horizontal line in each column are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring activity.

d Rivet shear strength is based upon Table 8.1.2(b) and F_{su} = 41 ksi.

e Permanent set at yield load: 4% of nominal diameter.

f Head height values reflect driven rivet configuration.

8.1.3 BLIND FASTENERS — The strengths shown in the following tables are applicable only for the grip lengths and hole tolerances recommended by the respective fastener manufacturers. For some fastener systems, permanent set at yield load may be increased if hole sizes greater than those listed in the applicable table are used. This condition may exist even though the test hole size lies within the manufacturer's recommended hole size range.

The strength values were established from test data and are applicable to "joints" with $e/D \geq 2.0$. For joints with e/D ratios less than 2.0, tests to substantiate the use of yield and ultimate strength allowables must be made. Ultimate strength values of protruding- and flush-head blind fasteners were obtained as described in Section 9.7. The analyses prior to 2003 included dividing the average ultimate load from test data by 1.15. This factor was not applicable to shear strength cutoff values which represented either the procurement specification shear strength (S values) of the fastener, or if no specification existed, a statistical value determined from test results as described in Chapter 9.

Unless otherwise specified, prior to 2003 the yield load was defined as the load which resulted in a joint permanent set equal to 0.04D, where D is the decimal equivalent of the hole or fastener shank diameter, as defined in Table 9.7.1.1. Some tables are footnoted to show the previous criteria used for those particular tables.

For machine countersunk joints, the sheet gage specified in the tables is that of the countersunk sheet. When the noncountersunk sheet is thinner than the countersunk sheet, the bearing allowable for the noncountersunk sheet-fastener combination should be computed, compared to the table value, and the lower of the two values selected. Increased attention should be paid to detail design in cases where $t/D < 0.25$ because of the possibility of unsatisfactory service life.

Joint allowable strengths of blind fasteners in double-dimpled or dimpled into machine countersunk applications should be established on the basis of specific tests acceptable to the procuring or certifying agency.

Reference should be made to the requirements of the applicable procuring or certifying agency relative to the use of blind fasteners such as the limitations of usage in design standard MS33522.

8.1.3.1 *Protruding-Head Blind Fasteners*

8.1.3.1.1 *Friction-Lock Blind Rivets* — Tables 8.1.3.1.1(a) through 8.1.3.1.1(e) contain joint allowables for various protruding-head, friction-lock blind rivet/sheet material combinations.

8.1.3.1.2 *Mechanical-Lock Spindle Blind Rivets* — Tables 8.1.3.1.2(a) through (t) contain joint allowables for various protruding-head, mechanical-lock spindle blind rivet/sheet material combinations.

8.1.3.2 *Flush-Head Blind Fasteners*

8.1.3.2.1 *Friction-Lock Blind Rivets* — Tables 8.1.3.2.1(a) through (g) contain joint allowables for various flush-head, friction-lock blind rivet/sheet material combinations.

8.1.3.2.2 *Mechanical-Lock Spindle Blind Rivets* — Tables 8.1.3.2.2(a) through (aa) contain joint allowables for various flush-head, mechanical-lock spindle blind rivet/sheet material combinations.

8.1.3.2.3 *Flush-Head Blind Bolts* — Tables 8.1.3.2.3(a) through (h) contain joint allowables for various flush-head blind bolt/sheet material combinations.

Table 8.1.3.1.1(a). Static Joint Strength of Blind Protruding Head A-286 Rivets in Alloy Steels, Titanium Alloy and A-286 Alloy Sheet

Rivet Type	CR 6636[a] (F_{su} = 75 ksi)			
Sheet Material	Alloy Steel, F_{tu} = 125 ksi, Titanium Alloys, F_{tu} = 120 ksi, and A-286 Alloy, F_{tu} = 140 ksi			
Rivet Diameter, in. (Nominal Hole Diameter, in.)	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)	1/4 (0.258)
	Ultimate Strength[b], lbs			
Sheet thickness, in.:				
0.008	169	...	...	...
0.012	290	341	...	...
0.016	412	493	566	...
0.020	532	645	748	924
0.025	688	816	967	1221
0.032	796	1050	1278	1650
0.040	879	1233	1570	2129
0.050	945	1354	1807	2673
0.063	970	1461	1980	3168
0.071	...	1490	2062	3350
0.080	...	...	2150	3515
0.090	...	...	...	3663
0.100	...	...	...	3779
0.112	...	...	...	3890
Rivet shear strength[c]	970	1490	2150	3890

a Data supplied by Cherry Fasteners.

b Yield strength is in excess of 80% of ultimate. This is based on a previous Navy "BuAer" definition that yield strength would not be considered to be critical if it exceeded 1.15 x 2.3 of design ultimate strength. There was no requirement for submission of the yield data for inclusion in ANC-5.

c Shear strength based on areas computed from nominal hole diameters in Table 8.1.2(a) and F_{su} = 75 ksi.

Table 8.1.3.1.1(b). Static Joint Strength of Protruding Head Monel Rivets in Stainless Steel Sheet

Rivet Type	MS20600M (F_{su} = 55 ksi)							
Sheet Material	ANSI 301-Annealed				AISI 301-½ Hard			
Rivet Diameter, in. (Nominal Hole Diameter, in.)	1/8 (0.130)	5/32 (0.162)	3/16 (0.154)	1/4 (0.258)	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)	1/4 (0.258)
	Ultimate Strength, lbs							
Sheet thickness, in.:								
0.010	...	...	...	...	195	...	...	...
0.012	...	...	...	...	225	287	...	...
0.016	...	...	...	...	290	367	453	...
0.020	332[a]	...	...	...	358	450	552	774
0.025	396[a]	494[a]	...	...	440	552	675	940
0.032	472[a]	627[a]	768[a]	...	522	690	1040	1163
0.040	526[a]	729[a]	942[a]	1290[a]	580	810	1200	1430
0.050	594[a]	810[a]	1070[a]	1585[a]	635	903	1325	1760
0.063	681[a]	919[a]	1280[a]	1875[a]	678	980	1385	2090
0.071	700[a]	984[a]	1370[a]	1980[a]	701	1013	1438	2220
0.080	713	1055[a]	1470[a]	2110[a]	713	1050	1486	2340
0.090	...	1080[a]	1530[a]	2240[a]	...	1081	1540	2450
0.100	...	1090	1580	2380[a]	...	1090	1580	2540
0.125	...	...	...	2700[a]	...	...	...	2710
0.160	...	...	...	2855	...	...	...	2855
Rivet shear strength[b]	713	1090	1580	2855	713	1090	1580	2855
	Yield Strength[c], lbs							
Sheet thickness, in.:								
0.010	...	...	...	...	195	...	...	...
0.012	...	...	...	...	225	287	...	...
0.016	...	...	...	...	290	367	453	...
0.020	128	...	...	...	358	450	551	774
0.025	160	199	...	...	440	552	675	940
0.032	205	254	306	...	522	690	836	1163
0.040	257	318	382	514	580	810	1040	1430
0.050	321	397	477	642	635	903	1200	1760
0.063	405	501	601	810	678	980	1325	2090
0.071	456	564	678	912	701	1013	1385	2220
0.080	514	635	764	1025	713	1050	1438	2340
0.090	...	715	860	1155	...	1081	1486	2450
0.100	...	795	955	1285	...	1090	1540	2540
0.125	...	...	...	1605	...	...	...	2710
0.160	...	...	...	2055	...	...	...	2855

a Yield value is less than 2/3 of the indicated ultimate strength value.
b Rivet shear strength based on areas computed from nominal hole diameters in Table 8.1.2(a) and F_{su} = 55 ksi.
c Permanent set at yield load: the greater of 0.005 inch or 2.5% of nominal diameter.

Table 8.1.3.1.1(c). Static Joint Strength of Blind Protruding Head Monel Rivets in Aluminum Alloy Sheet

Rivet Type	MS20600M (F_{su} = 55 ksi)							
Sheet Material	2024-T3				7075-T6			
Rivet Diameter, in. (Nominal Hole Diameter, in.)	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)	1/4 (0.258)	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)	1/4 (0.258)
	Ultimate Strength, lbs							
Sheet thickness, in.:								
0.025	268	...	...	...	297	...	...	...
0.032	365	429	...	...	405	472	...	...
0.040	478	569	650	...	485	631	720	...
0.050	545	738	860	1070	545	747	955	1190
0.063	622	844	1110	1430	622	844	1110	1590
0.071	652	903	1180	1665	652	903	1180	1840
0.080	684	968	1255	1910	684	968	1255	1940
0.090	713	1010	1345	2060	713	1010	1345	2060
0.100	...	1050	1415	2180	...	1050	1415	2180
0.125	...	1090	1545	2480	...	1090	1545	2480
0.160	...	...	1580	2735	...	...	1580	2735
0.190	...	...	...	2855	...	...	...	2855
Rivet shear strength[a]	713	1090	1580	2855	713	1090	1580	2855
	Yield Strength[b], lbs							
Sheet thickness, in.:								
0.025	234	...	...	...	272	...	...	...
0.032	297	370	...	...	343	430	...	...
0.040	368	460	556	...	425	533	644	...
0.050	458	570	688	936	492	657	797	1090
0.063	529	715	863	1170	529	759	996	1350
0.071	552	786	970	1315	552	786	1075	1520
0.080	577	818	1090	1470	577	818	1110	1700
0.090	605	853	1155	1650	605	853	1155	1915
0.100	...	888	1200	1830	...	888	1200	1970
0.125	...	976	1300	2110	...	976	1300	2110
0.160	...	...	1450	2310	...	...	1450	2310
0.190	...	...	...	2480	...	...	...	2480

a Shear strength based on areas computed from nominal hole diameters in Table 8.1.2(a) and F_{su} = 55 ksi.
b Permanent set at yield load: the greater of 0.005 inch or 2.5% of nominal diameter.

Table 8.1.3.1.1(d). Static Joint Strength of Blind Protruding Head Alloy (2117-T3) Rivets in Aluminum Alloy Sheet

Rivet Type	MS20600AD and MS20602AD (F_{su} = 30 ksi)			
Sheet Material	Clad 2024 T3			
Rivet Diameter, in. (Nominal Hole Diameter, in.)	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)	1/4 (0.258)
	Ultimate Strength, lbs			
Sheet thickness, in.:				
0.025	233	...	...	...
0.032	277	368	...	...
0.040	321	425	544	...
0.050	388	506	643	961
0.063	...	596	753	1110
0.071	...	...	823	1200
0.080	...	...	862	1305
0.090	...	...	...	1415
0.100	...	...	...	1550
Rivet shear strength[a]	388	596	862	1550
	Yield Strength[b], lbs			
Sheet thickness, in.:				
0.025	226	...	...	...
0.032	264	356	...	...
0.040	304	406	523	...
0.050	362	475	610	925
0.063	388	560	709	1058
0.071	...	596	771	1135
0.080	...	...	862	1230
0.090	...	...	...	1330
0.100	...	...	...	1450

[a] Rivet shear strength based on areas computed from nominal hole diameters in Table 8.1.2(a) and F_{su} = 30 ksi.

[b] Permanent set at yield load: the greater of 0.005 inch or 2.5% of nominal diameter.

Table 8.1.3.1.1(e). Static Joint Strength of Blind Protruding Head Aluminum Alloy (5056) Rivets in Magnesium Alloy Sheet

Rivet Type	MS20600B (F_{su} = 28 ksi)			
Sheet Material	AZ31B-H24			
Rivet Diameter, in. . . . . (Nominal Hole Diameter, in.)	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)	1/4 (0.258)
	Ultimate Strength[a], lbs			
Sheet thickness, in.:				
0.025	178	...	...	...
0.032	218	282	...	...
0.040	256	339	420	...
0.050	290	392	502	714
0.063	330	449	584	870
0.071	352	481	627	942
0.080	363	512	667	1025
0.090	...	550	714	1090
0.100	...	556	757	1160
0.125	...	...	802	1315
0.160	...	...	...	1450
Rivet shear strength[b]	363	556	802	1450

a Yield strength is in excess of 80% of ultimate. This is based on a previous Navy "Bureau of Aeronautics" definition that yield strength was not considered to be critical if it exceeded 1.15 x 2/3 of design ultimate strength. There was no requirement for submission of the yield data for inclusion in ANC-5.

b Shear strength based on areas computed from nominal hole diameters in Table 8.1.2(a) and F_{su} = 28 ksi.

Table 8.1.3.1.2(a). Static Joint Strength of Blind Protruding Head Locked Spindle A-286 Rivets in Alloy Steel Sheet

Rivet Type	NAS1398C[a] and NAS1398C, Code A[b] (F_{su} = 75 ksi)			CR 2643[a] (F_{su} = 95 ksi)		
Sheet Material	Alloy Steel F_{tu} = 180 ksi					
Rivet Diameter, in. (Nominal Hole Diameter, in.)	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)
	Ultimate Strength[c], lbs					
Sheet thickness, in.:						
0.025	697	...	...	697	...	...
0.032	785	1112	...	807	1112	...
0.040	860	1211	1628	911	1246	1639
0.050	956	1325	1772	1043	1406	1833
0.063	970	1480	1958	1215	1615	2090
0.071	...	1490	2070	1230	1748	2240
0.080	...	...	2150	...	1885	2420
0.090	...	...	...	...	...	2610
0.100	...	...	...	...	...	2720
Rivet shear strength	970[d]	1490[d]	2150[d]	1230[e]	1885[e]	2720[e]

a Data supplied by Cherry Fasteners.

b Confirmatory data supplied by Olympic Fastening Systems, Inc.

c Yield strength is in excess of 80% of ultimate. This is based on a previous Navy "Bureau of Aeronautics" definition that yield strength would not be considered to be critical if it exceeded 1.15 x 2/3 of design ultimate strength. There was no requirement for submission of the yield data for inclusion in ANC-5.

d Rivet shear strength is documented in NAS1400.

e Shear strength based on areas computed from nominal hole diameters in Table 8.1.2(a) and F_{su} = 95 ksi.

Table 8.1.3.1.2(b). Static Joint Strength of Blind Protruding Head Locked Spindle Monel Rivets in Stainless Steel Sheet

Rivet Type	NAS1398 MS or MW[a] and NAS1398 MS or MW, Code A[b] (F_{su} = 55 ksi)		
Sheet Material	AISI 301-½ Hard		
Rivet Diameter, in. . . . . (Nominal Hole Diameter, in.)	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)
	Ultimate Strength[c], lbs		
Sheet thickness, in.:			
0.025	462	...	...
0.032	568	734	...
0.040	594	870	1094
0.050	632	915	1270
0.063	678	971	1335
0.071	706	1009	1380
0.080	710	1048	1428
0.090	...	1090	1532
0.100	...	...	1580
Rivet shear strength[d]	710	1090	1580

[a] Data supplied by Cherry Fasteners.

[b] Confirmatory data supplied by Olympic Fastening Systems, Inc.

[c] Yield strength is in excess of 80% of ultimate strength. This is based on a previous Navy "Bureau of Aeronautics" definition that yield strength was not considered to be critical if it exceeded 1.15 x 2/3 of design ultimate strength. There was no requirement for submission of the yield strength data for inclusion in ANC-5.

[d] Rivet shear strength is documented in NAS1400.

Table 8.1.3.1.2(c). Static Joint Strength of Blind Protruding Head Locked Spindle Monel Rivets in Aluminum Alloy Sheet

Rivet Type	NAS1398 MS or MW[a] and NAS1398 MS or MW, Code A[b] (F_{su} = 55 ksi)		
Sheet Material	Clad 7075-T6		
Rivet Diameter, in. . . . . (Nominal Hole Diameter, in.)	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)
	Ultimate Strength[c], lbs		
Sheet thickness, in.:			
0.025	318	...	...
0.032	404	506	...
0.040	466	624	774
0.050	546	720	922
0.063	647	845	1072
0.071	710	921	1168
0.080	...	1009	1272
0.090	...	1090	1387
0.100	...	...	1507
0.125	...	...	1580
Rivet shear strength[d]	710	1090	1580

a Data supplied by Cherry Fasteners.

b Confirmatory data supplied by Olympic Fastening Systems, Inc.

c Yield strength is in excess of 80% of ultimate. This is based on a previous Navy “Bureau of Aeronautics” definition that yield strength would not be considered to be critical if it exceeded 1.15 x 1/3 of design ultimate strength. There was no requirement for submission of the yield data for inclusion in ANC-5.

d Rivet shear strength is documented in NAS1400.

Table 8.1.3.1.2(d_1). Static Joint Strength of Blind Protruding Head Locked Spindle Aluminum Alloy Rivets in Aluminum Alloy Sheet

Rivet Type	NAS1398B[a] (F_{su} = 30 ksi)				NAS1398D[a] (F_{su} = 38 ksi)			
Sheet Material	Clad 2024-T3							
Rivet Diameter, in. (Nominal Hole Diameter, in.)	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)	1/4 (0.258)	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)	1/4 (0.258)
	Ultimate Strength, lbs.							
Sheet thickness, in.:								
0.025	228	...	...	...	228	...	...	...
0.032	289	364	412	...	304	364	...	...
0.040	337	448	553	670	355	470	553	...
0.050	388	521	662	914	418	548	696	914
0.063	...	596	781	1145	494	647	816	1205
0.071	...	...	854	1240	...	710	894	1303
0.080	...	...	862	1350	...	755	975	1420
0.090	...	...	...	1475	...	...	1069	1545
0.100	...	...	...	1550	...	...	1090	1670
0.125	...	...	...	...	...	...	...	1970
Rivet shear strength[b]	388	596	862	1550	494	755	1090	1970

a Data supplied by Cherry Fasteners.
b Rivet shear strength documented in NAS1400.

Table 8.1.3.1.2(d_2). Static Joint Strength of Blind Protruding Head Locked Spindle Aluminum Alloy Rivets in Aluminum Alloy Sheet

Rivet Type	NAS1738B and NAS1738E[a] (F_{su} = 34 ksi)		
Sheet Material	Clad 2024-T3		
Rivet Diameter, in. (Nominal Hole Diameter, in.)	1/8 (0.144)	5/32 (0.178)	3/16 (0.207)
	Ultimate Strength, lbs		
Sheet thickness, in.:			
0.025	267	305	330
0.032	368	428	473
0.040	427	567	636
0.050	480	650	815
0.063	547[b]	735	912
0.071	554[b]	785[b]	976
0.080	...	837[b]	1042[b]
0.090	...	...	1115[b]
0.100	...	...	1128[b]
Rivet shear strength[c]	554	837	1128
	Yield Strength[d], lbs		
Sheet thickness, in.:			
0.020	185	213	228
0.025	242	285	317
0.032	298	386	433
0.040	321	453	568
0.050	336	489	625
0.063	336	508	680
0.071	336	508	684
0.080	...	508	684
0.090	...	...	684
0.100	...	...	684

[a] Data supplied by Cherry Fasteners.

[b] Yield value is less than 2/3 of the indicated ultimate.

[c] Rivet shear strength was documented in NAS1740 prior to Revision (1), dated January 15, 1974.

[d] Permanent set at yield load: the greater of 0.005 inch or 2.5% of nominal diameter.

Table 8.1.3.1.2(e). Static Joint Strength of Blind Protruding Head Locked Spindle Aluminum Alloy Rivets in Magnesium Alloy Sheet

Rivet Type	NAS1398B[a] (F_{su} = 30 ksi)				NAS1738B and NAS1738E[a] (F_{su} = 34 ksi)		
Sheet Material	AZ31B-H24						
Rivet Diameter, in. (Nominal Hole Diameter, in.)	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)	1/4 (0.258)	1/8 (0.144)	5/32 (0.178)	3/16 (0.207)
	Ultimate Strength, lbs.						
Sheet thickness, in.:							
0.025	163	...	...	...	202	...	...
0.032	208	256	310	...	261	321	372
0.040	255	324	388	519	325	401	465
0.050	298	394	485	654	372	501	579
0.063	352	461	588	822	425	570	708
0.071	385	501	639	924	458	609	756
0.080	388	550	695	1020	495	656	809
0.090	...	596	755	1109	536[b]	709	866
0.100	...	...	820	1191	554[b]	759	925
0.125	...	...	862	1397	...	837[b]	1072[b]
0.160	...	...	...	1550	...	...	1128[b]
Rivet shear strength	388[c]	596[c]	862[c]	1550[c]	554[d]	837[d]	1128[d]
	Yield Strength[e], lbs.						
Sheet thickness, in.:							
0.025	...	...	...	...	155	...	...
0.032	...	...	...	...	198	243	282
0.040	...	...	...	...	248	304	353
0.050	...	...	...	...	302	380	441
0.063	...	...	...	...	325	460	556
0.071	...	...	...	...	336	478	614
0.080	...	...	...	...	336	499	638
0.090	...	...	...	...	336	508	664
0.100	...	...	...	...	336	508	684
0.125	...	...	...	...	...	508	684
0.160	...	...	...	...	...	...	684

a Data supplied by Cherry Fasteners.
b Yield value is less than 2/3 of the indicated ultimate strength value.
c Rivet shear strength is documented in NAS1400.
d Rivet shear strength was documented in NAS1740 prior to Revision (1), dated January 15, 1974.
e Permanent set at yield load: the greater of 0.005 inch or 2.5% of nominal diameter.

Table 8.1.3.1.2(f). Static Joint Strength of Blind Protruding Head Locked Spindle Aluminum Alloy (2219) Rivets in Aluminum Alloy Sheet

Rivet Type	CR 2A63[a] (F_{su} = 36 ksi)		
Sheet Material	Clad 2024-T81		
Rivet Diameter, in. (Nominal Hole Diameter, in.)	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)
	Ultimate Strength, lbs		
Sheet thickness, in.			
0.025	256	...	...
0.032	295	404	...
0.040	340	458	592
0.050	395	527	675
0.063	467	617	783
0.071	478	672	848
0.080	...	734	922
0.090	...	741	1005
0.100	...	...	1063
Rivet shear strength[b]	478	741	1063
	Yield Strength[c], lbs		
Sheet thickness, in.:			
0.025	256	...	...
0.032	295	404	...
0.040	336	458	592
0.050	383	521	675
0.063	440	598	770
0.071	445	646	827
0.080	...	683	890
0.090	...	690	963
0.100	...	...	984

a Data supplied by Cherry Fasteners.

b Shear strength values based on indicated nominal hole diameters and F_{su} = 36 ksi.

c Permanent set at yield load: 4% of nominal hole diameter.

Table 8.1.3.1.2(g). Static Joint Strength of Blind Protruding Head Locked Spindle A-286 Rivets in Aluminum Alloy Sheet

Rivet Type	CR4623[a] (F_{su} = 75 ksi)			
Sheet Material	Clad 7075-T6			
Rivet Diameter, in. . . . . (Nominal Hole Diameter, in.)[b]	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)	1/4 (0.258)
Sheet thickness, in.:	Ultimate Strength, lbs.			
0.020	237	...	...	...
0.025	298	367	...	...
0.032.	385	478	566	...
0.040	486	601	714	939
0.050	610	757	902	1185
0.063	772	958	1145	1505
0.071	856	1080	1290	1705
0.080	903	1220	1455	1925
0.090	956	1340	1645	2175
0.100	995	1405	1830	2425
0.125	...	1545	2055	3035
0.160	...	...	2215	3570
0.190	...	...	...	3885
0.250	...	...	...	3920
Rivet shear strength[c]	995	1545	2215	3920
Sheet thickness, in.:	Yield Strength[d], lbs.			
0.020	237	...	...	...
0.025	296	367	...	...
0.032	381	475	565	...
0.040	478	594	709	938
0.050	596	745	890	1180
0.063	690	932	1125	1490
0.071	747	1005	1270	1680
0.080	812	1085	1385	1895
0.090	857	1175	1495	2140
0.100	879	1265	1600	2360
0.125	...	1365	1870	2715
0.160	...	...	1995	3215
0.190	...	...	...	3425
0.250	...	...	...	3690

a Data supplied by Cherry Fasteners.
b Allowable loads developed from test with hole diameters as listed.
c Fastener shear strength based on nominal hole diameters and F_{su} = 75 ksi from data analysis.
d Permanent set at yield load: 4% of nominal hole diameter.

Table 8.1.3.1.2(h). Static Joint Strength of Blind Protruding Head Locked Spindle Monel Rivets in Aluminum Alloy Sheet

Rivet Type	CR 4523[a] (F_{su} = 65 ksi)			
Sheet Material	Clad 7075-T6			
Rivet Diameter, in (Nominal Hole Diameter, in.)[b]	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)	1/4 (0.258)
Sheet thickness, in.:	Ultimate Strength, lbs.			
0.020	221	...	...	...
0.025	284	344	...	...
0.032	373	456	533	...
0.040	475	582	684	878
0.050	602	740	875	1130
0.063	701	945	1120	1455
0.071	729	1055	1270	1655
0.080	760	1095	1440	1885
0.090	796	1140	1540	2135
0.100	831	1180	1590	2390
0.125	863	1290	1725	2760
0.160	...	1340	1905	3005
0.190	...	...	1920	3215
0.250	...	...	...	3400
Rivet shear strength[c]	863	1340	1920	3400
Sheet thickness, in.:	Yield Strength[d], lbs.			
0.020	221	...	...	...
0.025	279	344	...	...
0.032	360	447	530	...
0.040	453	561	667	878
0.050	569	706	841	1110
0.063	659	893	1065	1405
0.071	707	965	1205	1590
0.080	729	1035	1340	1795
0.090	752	1105	1430	2030
0.100	776	1135	1520	2260
0.125	834	1205	1645	2590
0.160	...	1305	1765	2880
0.190	...	...	1870	3015
0.250	...	...	...	3290

a Data supplied by Cherry Fasteners.
b Allowable loads developed from test with hole diameters as listed.
c Fastener shear strength based on nominal hole diameters and F_{su} = 65 ksi from data analysis.
d Permanent set at yield load: 4% of nominal hole diameter.

Table 8.1.3.1.2(i). Static Joint Strength of Blind Protruding Head Locked Spindle Aluminum Alloy (7050) Rivets in Aluminum Alloy Sheet

Rivet Type	NAS 1720KE and NAS 1720KE( )L[a,b] (F_{su} = 33 ksi)		
Sheet Material	Clad 2024-T3		
Rivet Diameter, in.	1/8	5/32	3/16
(Nominal Hole Diameter, in.)[c]	(0.130)	(0.162)	(0.194)
Sheet thickness, in.:	Ultimate Strength, lbs.		
0.020	174	...	...
0.025	219	272	...
0.032	282	350	417
0.040	354	440	525
0.050	376	552	659
0.063	392	585	816
0.071	402	597	831
0.080	413	611	847
0.090	425	626	866
0.100	437	641	884
0.125	450	680	929
0.160	...	700	950
Rivet shear strength[d]	450	700	950
Sheet thickness, in.:	Yield Strength[e], lbs.		
0.020	174	...	...
0.025	215	272	...
0.032	261	340	417
0.040	314	406	504
0.050	366	489	603
0.063	382	570	732
0.071	391	582	809
0.080	402	595	825
0.090	414	610	843
0.100	426	625	861
0.125	450	662	905
0.160	...	700	950

a Data supplied by Avdel Corp.
b Fasteners should not be used for structural applications where the t/D is less than 0.15.
c Loads developed from tests with hole diameters of 0.130, 0.162, and 0.194, +0.0005, -0.0000 inch.
d Rivet shear strength is documented in NAS 1722.
e Permanent set at yield load: 4% of nominal diameter.

Table 8.1.3.1.2(j). Static Joint Strength of Blind Protruding Head Locked Spindle A-286 Rivets in Aluminum Alloy Sheet

Rivet Type	NAS1720C and NAS1720C( )L[a,b] (F_{su} = 75 ksi)		
Sheet Material	Clad 7075-T6		
Rivet Diameter, in. (Nominal Hole Diameter, in.)[c]	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)
	Ultimate Strength, lbs.		
Sheet thickness, in:			
0.025	329	...	...
0.032	399	528	...
0.040	499	621	799
0.050	625	778	930
0.063	789	982	1170
0.071	847	1105	1320
0.080	870	1245	1490
0.090	896	1320	1680
0.100	921	1350	1865
0.125	985	1430	1955
0.160	1000	1500	2090
0.190	...	...	2200
Rivet shear strength[d]	1000	1500	2200
	Yield Strength[e], lbs.		
Sheet thickness, in.:			
0.025	329	...	...
0.032	390	386	...
0.040	453	607	779
0.050	531	704	895
0.063	632	831	1045
0.071	687	909	1140
0.080	701	996	1245
0.090	717	1070	1360
0.100	733	1090	1475
0.125	773	1140	1575
0.160	829	1210	1655
0.190	...	...	1730

a Data supplied by Avdel Corp.
b Fasteners should not be used for structural applications where the t/D is less than 0.15.
c Loads developed from tests with hole diameters of 0.130, 0.162, and 0.194, ±.0001 inch.
d Rivet shear strength is documented in NAS1722.
e Permanent set at yield load: 4% of nominal diameter.

Table 8.1.3.1.2(k). Static Joint Strength of Blind Protruding Head Locked Spindle Aluminum Alloy Rivets in Aluminum Alloy Sheet

Rivet Type	AF3243 (F_{su} = 51 ksi approx.)[a]		
Sheet Material	Clad 2024-T3		
Rivet Diameter, in. (Nominal Hole Diameter, in.)[b]	1/8 (0.144)	5/32 (0.178)	3/16 (0.207)
	Ultimate Strength, lbs.		
Sheet thickness, in.:			
0.025	242	---	---
0.032	302	382	453
0.040	371	467	551
0.050	456	572	674
0.063	538	710	834
0.071	556	795	932
0.080	577	828	1040
0.090	600	856	1110
0.100	622	885	1140
0.125	679	955	1225
0.160	759	---	1335
Rivet shear strength[c]	814	1245	1685
	Yield Strength, lbs[d]		
Sheet thickness, in.:			
0.025	242	---	---
0.032	302	382	453
0.040	371	467	551
0.050	456	572	674
0.063	538	710	834
0.071	556	795	932
0.080	577	828	1040
0.090	600	856	1110
0.100	622	885	1140
0.125	679	955	1225
0.160	759	---	1335

THIS FASTENER HAS ONLY BEEN TESTED IN THE SHEET GAGES SHOWN IN THIS TABLE. DESIGN DATA FOR SHEET GAGES OR DIAMETERS OTHER THAN THOSE SHOWN HERE CANNOT BE EXTRAPOLATED.

a Data supplied by Allfast Fastening Systems Inc.
b Loads developed from tests with hole diameters of 0.144, 0.178, and 0.207, +/-0.001 inch.
c Rivet shear strength is documented on AF3243 standards drawing.
d Permanent set at yield load: 4% of nominal diameter.

Table 8.1.3.1.2(l). Static Joint Strength of Blind Protruding Head Locked Spindle Aluminum Alloy Rivets in Aluminum Alloy Sheet

Rivet Type	HC3213 (F_{su} = 51 ksi approx.)[a]		
Sheet Material	Clad 2024-T3		
Rivet Diameter, in. (Nominal Hole Diameter, in.)[b]	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)
	Ultimate Strength, lbs.		
Sheet thickness, in.:			
0.020	225	---	---
0.025	265	351	---
0.032	320	419	527
0.040	383	498	621
0.050	461	596	738
0.063	538	723	891
0.071	558	801	985
0.080	581	840	1090
0.090	607	872	1180
0.100	632	904	1220
0.125	664	983	1315
0.160	---	1030	1445
0.190	---	---	1480
Rivet shear strength[c]	664	1030	1480
	Yield Strength, lbs[d]		
Sheet thickness, in.:			
0.020	182	---	---
0.025	222	284	---
0.032	278	354	431
0.040	343	434	527
0.050	423	534	647
0.063	436	658	803
0.071	444	668	898
0.080	453	679	951
0.090	463	691	965
0.100	473	704	980
0.125	497	734	1015
0.160	---	777	1065
0.190	---	---	1110

[a] Data supplied by Huck International Inc.

[b] Loads developed from tests with hole diameters of 0.130, 0.162, and 0.194, +/- 0.001 inch.

[c] Rivet shear strength is documented on HC3213 standards drawing.

[d] Permanent set at yield load: 4% of nominal diameter.

Table 8.1.3.1.2(m). Static Joint Strength of Protruding Head Locked Spindle Aluminum Alloy Blind Rivets in Aluminum Alloy Sheet

Rivet Type	HC6223[a] (F_{su} = 50 ksi) Nominal		
Sheet and Plate Material	Clad 2024-T3		
Rivet Diameter, in. (Nominal Hole Diameter, in.)	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)
	Ultimate Strength, lbs		
Sheet thickness, in.:			
0.016	...	...	...
0.020	...	...	...
0.025	272	...	...
0.032	367	437	...
0.040	427	573	661
0.050	476	664	864
0.063	539	743	975
0.071	578	792	1033
0.080	622	846	1099
0.090	664	907	1171
0.100	...	967	1244
0.125	...	1030	1425
0.160	...	...	1480
0.190	...	...	...
Rivet shear strength[b]	664	1030	1480
	Yield Strength[c], lbs		
Sheet thickness, in.:			
0.016	...	...	...
0.020	...	...	...
0.025	255	...	...
0.032	320	406	...
0.040	394	498	605
0.050	417	613	743
0.063	437	648	901
0.071	449	664	920
0.080	463	681	940
0.090	478	700	963
0.100	...	720	986
0.125	...	768	1044
0.160	...	...	1125
0.190	...	...	...

a Data supplied by Huck International, Inc.
b Rivet shear strength is documented in MIL-R-7885D.
c Permanent set at yield load: 4% of nominal hole diameter.

Table 8.1.3.1.2(n). Static Joint Strength of Protruding Head Locked Spindle Aluminum Alloy Blind Rivets in Aluminum Alloy Sheet

Rivet Type	HC6253[a] (F_{su} = 50 ksi)		
Sheet Material	Clad 2024-T3		
Rivet Diameter, in. (Nominal Hole Diameter, in.)	1/8 (0.144)	5/32 (0.178)	3/16 (0.207)
	Ultimate Strength, lbs		
Sheet thickness, in.:			
0.016	...	...	...
0.020	...	...	...
0.025	...	...	...
0.032	344	419	...
0.040	436	532	613
0.050	513	674	777
0.063	559	789	992
0.071	588	824	1055
0.080	620	864	1101
0.090	656	908	1152
0.100	691	952	1204
0.125	781	1063	1332
0.160	814	1217	1512
0.190	...	1245	1666
0.250	...	...	1685
Rivet shear strength[b]	814	1245	1685
	Yield Strength[c], lbs		
Sheet thickness, in.:			
0.016	...	...	...
0.020	...	...	...
0.025	...	...	...
0.032	344[d]	419[d]	...
0.040	403	532[d]	613[d]
0.050	462	619	731
0.063	523	715	879
0.071	541	774	948
0.080	560	805	1025
0.090	583	832	1079
0.100	605	859	1110
0.125	660	928	1190
0.160	738	1024	1302
0.190	...	1245	1397
0.250	...	...	1588

[a] Data supplied by Huck International, Inc.

[b] Rivet shear strength is documented in MIL-R-7885D.

[c] Permanent set at yield load: 4% of nominal hole diameter.

[d] Calculated yield reduced to match ultimate strength.

Table 8.1.3.1.2(o). Static Joint Strength of Blind Protruding Head Locked Spindle Aluminum Alloy Rivets in Aluminum Alloy Sheet

Rivet Type	AF3213 (F_{su} = 51 ksi approx.)[a]		
Sheet Material	Clad 2024-T3		
Rivet Diameter, in. (Nominal Hole Diameter, in.)[b]	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)
	Ultimate Strength, lbs.		
Sheet thickness, in.:			
0.020	223	---	---
0.025	262	347	---
0.032	317	416	522
0.040	380	494	616
0.050	411	592	733
0.063	441	640	875
0.071	459	663	902
0.080	480	689	933
0.090	503	717	968
0.100	526	746	1000
0.125	583	818	1085
0.160	---	918	1205
0.190	---	---	1310

THIS FASTENER HAS ONLY BEEN TESTED IN THE SHEET GAGES SHOWN IN THIS TABLE. DESIGN DATA FOR SHEET GAGES OR DIAMETERS OTHER THAN THOSE SHOWN HERE CANNOT BE EXTRAPOLATED.

Rivet shear strength[c]	664	1030	1480
	Yield Strength, lbs[d]		
Sheet thickness, in.:			
0.020	223	---	---
0.025	262	347	---
0.032	317	416	522
0.040	362	494	616
0.050	378	562	733
0.063	398	588	814
0.071	411	604	833
0.080	425	622	854
0.090	441	641	878
0.100	457	661	901
0.125	496	710	960
0.160	---	779	1040
0.190	---	---	1110

[a] Data supplied by Allfast Fastening Systems Inc.

[b] Loads developed from tests with hole diameters of 0.130, 0.162, and 0.194, +/- 0.001 inch.

[c] Rivet shear strength is documented on AF3213 standards drawing.

[d] Permanent set at yield load: 4% of nominal diameter.

Table 8.1.3.1.2(p). Static Joint Strength of Blind Protruding Head Locked Spindle Aluminum Alloy Rivets in Aluminum Alloy Sheet

Rivet Type	CR3213 (F_{su} = 51 ksi approx.)[a]		
Sheet Material	Clad 2024-T3		
Rivet Diameter, in. (Nominal Hole Diameter, in.)[b]	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)
	Ultimate Strength, lbs.		
Sheet thickness, in.:			
0.020	250	---	---
0.025	280	389	---
0.032	322	441	576
0.040	370	501	648
0.050	430	576	737
0.063	492	673	853
0.071	513	733	925
0.080	536	769	1005
0.090	562	801	1080
0.100	587	833	1115
0.125	652	913	1215

THIS FASTENER HAS ONLY BEEN TESTED IN THE SHEET GAGES SHOWN IN THIS TABLE. DESIGN DATA FOR SHEET GAGES OR DIAMETERS OTHER THAN THOSE SHOWN HERE CANNOT BE EXTRAPOLATED.

Rivet shear strength[c]	664	1030	1480
	Yield Strength, lbs[d]		
Sheet thickness, in.:			
0.020	214	---	---
0.025	238	332	---
0.032	272	375	491
0.040	298	424	550
0.050	315	463	623
0.063	338	491	672
0.071	351	508	692
0.080	367	527	716
0.090	384	549	741
0.100	401	570	767
0.125	445	624	831

[a] Data supplied by Textron Aerospace Fasteners.
[b] Loads developed from tests with hole diameters of 0.130, 0.162, and 0.194, +/- 0.001 inch.
[c] Rivet shear strength is documented on CR3213 standards drawing.
[d] Permanent set at yield load: 4% of nominal diameter.

Table 8.1.3.1.2(q). Static Joint Strength of Blind Protruding Head Locked Spindle Aluminum Alloy Rivets in Aluminum Alloy Sheet

Rivet Type	CR3243 (F_{su} = 51 ksi approx.)[a]		
Sheet Material	Clad 2024-T3		
Rivet Diameter, in. (Nominal Hole Diameter, in.)[b]	1/8 (0.144)	5/32 (0.178)	3/16 (0.207)
	Ultimate Strength, lbs.		
Sheet thickness, in.:			
0.025	317	---	---
0.032	366	494	617
0.040	421	562	696
0.050	489	647	795
0.063	579	758	924
0.071	623	826	1000
0.080	640	902	1090
0.090	660	957	1190
0.100	679	981	1280
0.125	728	1040	1350
Rivet shear strength[c]	814	1245	1685
	Yield Strength, lbs[d]		
Sheet thickness, in.:			
0.025	272	---	---
0.032	317	425	527
0.040	368	488	600
0.050	432	567	692
0.063	451	664	811
0.071	462	677	884
0.080	475	693	911
0.090	489	710	931
0.100	503	728	951
0.125	538	771	1000

THIS FASTENER HAS ONLY BEEN TESTED IN THE SHEET GAGES SHOWN IN THIS TABLE. DESIGN DATA FOR SHEET GAGES OR DIAMETERS OTHER THAN THOSE SHOWN HERE CANNOT BE EXTRAPOLATED.

[a] Data supplied by Textron Aerospace Fasteners.

[b] Loads developed from tests with hole diameters of 0.144, 0.178, and 0.207, +/-0.001 inch.

[c] Rivet shear strength is documented on CR3243 standards drawing.

[d] Permanent set at yield load: 4% of nominal diameter.

Table 8.1.3.1.2(r). Static Joint Strength of Blind Protruding Head Locked Spindle Aluminum Alloy Rivets in Aluminum Alloy Sheet

Rivet Type	HC3243 (F_{su} = 51 ksi approx.)[a]		
Sheet Material	Clad 2024-T3		
Rivet Diameter, in. (Nominal Hole Diameter, in.)[b]	1/8 (0.144)	5/32 (0.178)	3/16 (0.207)
	Ultimate Strength, lbs.		
Sheet thickness, in.:			
0.025	252	---	---
0.032	312	397	473
0.040	380	481	571
0.050	465	586	693
0.063	546	723	852
0.071	576	803	950
0.080	610	844	1060
0.090	647	891	1125
0.100	685	937	1175
0.125	779	1050	1310
0.160	814	1215	1500
0.190	---	1245	1665
0.250	---	---	1685
Rivet shear strength[c]	814	1245	1685
	Yield Strength, lbs[d]		
Sheet thickness, in.:			
0.025	252	---	---
0.032	312	397	473
0.040	371	481	571
0.050	401	569	693
0.063	440	617	790
0.071	464	646	824
0.080	491	680	863
0.090	521	717	906
0.100	551	754	949
0.125	626	846	1055
0.160	730	976	1205
0.190	---	1085	1335
0.250	---	---	1595

a Data supplied by Huck International Inc.
b Loads developed from tests with hole diameters of 0.144, 0.178, and 0.207, +/-0.001 inch.
c Rivet shear strength is documented on HC3243 standards drawing.
d Permanent set at yield load: 4% of nominal diameter.

Table 8.1.3.1.2(s). Static Joint Strength of Blind Protruding Head Locked Spindle Aluminum Alloy Rivets in Aluminum Alloy Sheet

Rivet Type	AF3223 (F_{su} = 50 ksi approx.)[a]		
Sheet Material	Clad 2024-T3		
Rivet Diameter, in. (Nominal Hole Diameter, in.)[b]	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)
	Ultimate Strength, lbs.		
Sheet thickness, in.:			
0.025	272	...	...
0.032	331	431	...
0.040	390	516	640
0.050	421	606	767
0.063	461	656	883
0.071	486	687	920
0.080	514	722	962
0.090	545	760	1005
0.100	576	799	1050
0.125	653	896	1170
0.160	664	1030	1330
0.190	...	...	1460
Rivet shear strength[c]	664	1030	1460
	Yield Strength[d], lbs.		
Sheet thickness, in.:			
0.025	243	...	...
0.032	312	387	...
0.040	390	485	580
0.050	421	606	727
0.063	448	656	883
0.071	463	678	920
0.080	481	700	958
0.090	500	723	987
0.100	519	747	1015
0.125	566	806	1085
0.160	633	889	1185
0.190	...	...	1270

a Data supplied by Allfast Fastening Systems Inc.

b Loads developed from tests with hole diameters of 0.130, 0.162, and 0.194, +/- 0.001 inch.

c Rivet shear strength as documented in Allfast Fastening Systems Inc P-127.

d Permanent set at yield load: 4% of nominal diameter.

Table 8.1.3.1.2(t). Static Joint Strength of Protruding Head 5056 Aluminum Alloy Rivets in Clad Aluminum Alloy Sheet

Rivet Type	CR3223 (F_{su} = 50 ksi approx.)[a]		
Sheet Material	Clad 2024-T3		
Rivet Diameter, in. (Nominal Hole Diameter, in.)[b]	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)
	Ultimate Strength, lbs.		
Sheet thickness, in.:			
0.025	257	...	...
0.032	316	408	...
0.040	383	492	606
0.050	450	596	731
0.063	486	701	894
0.071	509	729	987
0.080	534	760	1025
0.090	562	795	1065
0.100	590	830	1105
0.125	659[c]	917	1210
0.160	664[c]	1030[c]	1355[c]
0.190	...	...	1480[c]
Rivet shear strength[d]	664	1030	1480
	Yield Strength[e], lbs.		
Sheet thickness, in.:			
0.025	221	...	...
0.032	279	351	...
0.040	321	434	525
0.050	333	498	649
0.063	350	519	720
0.071	360	531	736
0.080	371	545	752
0.090	384	561	771
0.100	396	577	790
0.125	428	616	837
0.160	472	671	903
0.190	...	...	959

[a] Data supplied by Textron Aerospace Fasteners.
[b] Loads developed from tests with hole diameters of 0.130, 0.162, and 0.194, +/- 0.0005 inch.
[c] Yield value is less than 2/3 of indicated ultimate strength value.
[d] Rivet shear strength as documented in Textron Aerospace Fasteners PS-CMR-3000.
[e] Permanent set at yield load: 4% of nominal diameter.

Table 8.1.3.2.1(a). Static Joint Strength of Blind 100° Flush Head A-286 Rivets in Machine-Countersunk Alloy Steel, Titanium Alloy, and A-286 Alloy Sheet

Rivet Type	CR 6626^{a} (F_{su} = 75 ksi)			
Sheet Material	Alloy Steel, F_{tu} = 125 ksi, Titanium Alloy, F_{tu} = 120 ksi, and A-286 Alloy, F_{tu} = 140 ksi			
Rivet Diameter, in. (Nominal Hole Diameter, in.)	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)	1/4 (0.258)
	Ultimate Strength, lbs			
Sheet thickness, in.:				
0.040	582^{b,c}	...	...	...
0.050	693	898^{b,c}	...	...
0.063	842	1082	1351^{b,c}	...
0.071	891	1189	1478	...
0.080	949	1303	1633	...
0.090	970	1379	1798	2558^{b,c}
0.100	...	1461	1916	2772
0.112	...	1490	2026	3036
0.125	...	...	2150	3333
0.140	...	...	...	3531
0.160	...	...	...	3795
0.190	...	...	...	3890
Rivet shear strength^{d}	970	1490	2150	3890
	Yield Strength^{e}, lbs			
Sheet thickness, in.:				
0.040	355	...	...	...
0.050	499	557	...	...
0.063	681	784	858	...
0.071	771	923	1031	...
0.080	858	1082	1223	...
0.090	920	1202	1424	1700
0.100	...	1297	1643	1997
0.112	...	1417	1779	2327
0.125	...	...	1925	2690
0.140	...	...	...	3053
0.160	...	...	...	3432
0.190	...	...	...	3845
Head height (ref.), in.	0.042	0.055	0.070	0.095

a Data supplied by Cherry Fasteners.
b Yield value is less than 2/3 of the indicated ultimate strength value.
c Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.
d Rivet shear strength based on areas computed from nominal hole diameters in Table 8.1.2(a) and F_{su} = 75 ksi.
e Permanent set at yield load: the greater of 0.005 inch or 2.5% of nominal diameter.

Table 8.1.3.2.1(b). Static Joint Strength of Blind 100° Flush Head Monel Rivets in Machine-Countersunk Stainless Steel

Rivet Type	MS20601M (R.T. F_{su} = 55 ksi)											
Sheet Material	17-7PH, TH 1050											
Temperature	Room				500°F				700°F			
Rivet Diameter, in. (Nominal Hole Diameter, in.)	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)	1/4 (0.258)	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)	1/4 (0.258)	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)	1/4 (0.258)
	Ultimate Strength, lbs											
Sheet thickness, in.:												
0.040	373[a,b]	...	...	...	373[a,b]	...	...	...	373[a,b]	...	...	...
0.050	429	574[a,b]	...	...	429	574[a,b]	...	...	429	574[a,b]	...	...
0.063	495	664	866[a,b]	...	495	664	866[a,b]	...	495	664	866[a,b]	...
0.071	535	714	924	...	535	714	924	...	535	714	924	...
0.080	579	771	991	...	579	771	991	...	574	771	991	...
0.090	630	833	1065	1615[a,b]	625	833	1065	1615[a,b]	590	833	1065	1615[a,b]
0.100	...	896	1140	1720	...	896	1140	1720	...	884	1140	1720
0.125	...	...	1325	1970	...	...	1325	1970	...	904	1290	1970
0.160	...	...	...	2320	...	...	...	2320	...	...	1305	2300
0.180	...	...	...	2520	...	...	...	2500	...	...	...	2360
Rivet shear strength[c]	713	1090	1580	2855	648	993	1430	2590	590	904	1305	2360
	Yield Strength[d], lbs											
Sheet thickness, in.:												
0.040	213	...	...	...	213	...	...	...	213	...	...	...
0.050	303	332	...	...	303	332	...	...	303	332	...	...
0.063	439	476	518	...	439	476	518	...	439	476	518	...
0.071	528	569	621	...	528	569	621	...	528	569	621	...
0.080	579	696	741	...	579	696	741	...	574	696	741	...
0.090	630	833	910	1030	625	833	910	1030	590	833	910	1030
0.100	...	896	1075	1212	...	896	1075	1212	...	884	1075	1212
0.125	...	...	1325	1731	...	...	1325	1731	...	904	1290	1731
0.160	...	...	...	2320	...	...	...	2320	...	...	1305	2300
0.180	...	...	...	2520	...	...	...	2500	...	...	...	2360
Head height (ref.), in.	0.042	0.055	0.070	0.095	0.042	0.055	0.070	0.095	0.042	0.055	0.070	0.095

[a] Yield value is less than 2/3 of the indicated ultimate strength value.

[b] Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.

[c] Rivet shear strength based on areas computed from nominal hole diameters in Table 8.1.2(a) and F_{su} values at 55 ksi, 50 ksi, and 45 ksi at room temperature, 500°F and 700°F, respectively.

[d] Permanent set at yield load: the greater of 0.005 inch or 2.5% of nominal diameter.

Table 8.1.3.2.1(c). Static Joint Strength of Blind 100° Flush Head Monel Rivets in Dimpled Stainless Steel Sheet

Rivet Type	MS20601M (F_{su} = 55 ksi)							
Sheet Material	AISI 301-Annealed				AISI 301-1/4 Hard			
Rivet Diameter, in. (Nominal Hole Diameter, in.)	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)	1/4 (0.258)	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)	1/4 (0.258)
	Ultimate Strength, lbs.							
Sheet thickness, in.:								
0.010	224	...	...	...	277	377	...	...
0.012	254	338	...	...	302	428	560	...
0.016	313	412	519	...	358	485	632	...
0.020	375	486	610	...	415	542	705	1135
0.025	447	576	722	1045	482	642	808	1230
0.032	516	705	876	1255	543	750	963	1400
0.040	536	793	1055	1490	585	833	1110	1660
0.050	565	825	1150[a]	1790	628	910	1240	1930
0.063	...	868	1200[a]	2065	...	964	1330	2175
0.071	...	...	...	2100	...	973	1375	2275
0.080	...	...	...	2150	...	...	1405	2340
0.090	...	...	...	2200	...	...	...	2440
0.100	...	...	...	...	...	...	...	2510
Rivet shear strength[a]	635	973	1405	2540	635	973	1405	2540
	Yield Strength[b], lbs.							
Sheet thickness, in.:								
0.010	188	...	...	...	244	291	...	...
0.012	214	281	...	...	259	335	423	...
0.016	270	352	438	...	333	428	535	...
0.020	328	422	518	...	398	528	639	896
0.025	397	506	627	873	443	612	774	1080
0.032	498	627	770	1070	505	689	912	1330
0.040	536	772	939	1310	576	779	1015	1590
0.050	565	825	1150	1590	619	883	1145	1770
0.063	...	868	1200	1970	...	954	1305	2000
0.071	...	...	...	2100	...	973	1350	2140
0.080	...	...	...	2150	...	...	1400	2305
0.090	...	...	...	2200	...	...	...	2395
0.100	...	...	...	...	...	...	...	2475
Head height (ref.), in.	0.042	0.055	0.070	0.095	0.042	0.055	0.070	0.095

[a] Rivet shear strength from Table 8.1.2(b).

[b] Permanent set at yield load: the greater of 0.005 inch or 2.5% of nominal diameter.

Table 8.1.3.2.1(d_1). Static Joint Strength of Blind 100° Flush Head Monel Rivets in Machine-Countersunk Stainless Steel Sheet

Rivet Type	MS20601M (F_{su} = 55 ksi)			
Sheet Material	AISI 301-Annealed			
Rivet Diameter, in. . . . . (Nominal Hole Diameter, in.)	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)	1/4 (0.258)
	Ultimate Strength, lbs			
Sheet thickness, in.:				
0.040	469[a,b]	...	...	...
0.050	555[a]	721[a,b]	...	...
0.063	...	864[a]	1075[a,b]	...
0.071	...	...	1187[a]	...
0.080	...	...	...	...
0.090	...	...	...	2040[b]
Rivet shear strength[c]	713	1090	1580	2855
	Yield Strength[d], lbs			
Sheet thickness, in.:				
0.040	231	...	...	...
0.050	321	359	...	...
0.063	...	500	566	...
0.071	...	...	678	...
0.080	...	...	...	...
0.090	...	...	...	1135
Head height (ref.), in.	0.042	0.055	0.070	0.095

[a] Yield value is less than 2/3 of the indicated ultimate strength value.

[b] Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.

[c] Rivet shear strength based on areas computed from nominal hole diameters in Table 8.1.2(a) and F_{su} = 55 ksi.

[d] Permanent set at yield load: the greater of 0.005 inch or 2.5% of nominal diameter.

Table 8.1.3.2.1(d_2). Static Joint Strength of Blind 100° Flush Head Monel Rivets in Machine-Countersunk Stainless Steel Sheet

Rivet Type	MS20601M (R.T. F_{su} = 55 ksi)											
Sheet Material	AISI 301-¼ Hard											
Temperature	Room				500°F				700°F			
Rivet Diameter, in. (Nominal Hole Diameter, in.)	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)	1/4 (0.258)	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)	1/4 (0.258)	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)	1/4 (0.258)
	Ultimate Strength, lbs											
Sheet thickness, in.:												
0.040	373[a,b]	...	...	...	373[a,b]	...	...	...	373[a,b]	...	...	...
0.050	450	574[a,b]	...	...	450[a]	574[a,b]	...	...	450[a]	574[a,b]	...	...
0.063	538	704	866[a,b]	...	538	704[a]	866[a,b]	...	538	704[a]	866[a,b]	...
0.071	584	773	960	...	584	773	960[a]	...	584	773	960[a]	...
0.080	637	838	1065	...	637	838	1065[a]	...	590	838	1065[a]	...
0.090	695	910	1155	1645[b]	648	910	1155	1645[a,b]	...	904	1155	1645[a,b]
0.100	713	984	1240	1800	...	984	1240	1800[a]	...	...	1240	1800[a]
0.125	...	1090	1460	2135	...	993	1430	2135	...	...	1305	2135
0.160	...	...	1580	2550	...	...	...	2550	...	...	...	2360
0.180	...	...	...	2780	...	...	...	2590	...	...	...	...
Rivet shear strength[c]	713	1090	1580	2855	648	993	1430	2590	590	904	1305	2360
	Yield Strength[d], lbs											
Sheet thickness, in.:												
0.040	231	...	...	...	192	...	...	...	192	...	...	...
0.050	336	359	...	...	279	298	...	...	279	298	...	...
0.063	459	531	566	...	425	440	471	...	425	440	471	...
0.071	530	625	698	...	525	546	576	...	525	546	576	...
0.080	607	725	835	...	607	683	690	...	590	683	690	...
0.090	693	832	966	1135	648	832	872	945	...	832	872	945
0.100	713	943	1095	1345	...	943	1060	1115	...	...	1060	1115
0.125	...	1090	1420	1815	...	993	1420	1670	...	...	1305	1670
0.160	...	...	1580	2430	...	...	...	2430	...	...	...	2360
0.180	...	...	...	2775	...	...	...	2590	...	...	...	...
Head height (ref.), in.	0.042	0.055	0.070	0.095	0.042	0.055	0.070	0.095	0.042	0.055	0.070	0.095

a Yield value is less than 2/3 of the indicated ultimate strength value.

b Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.

c Rivet shear strength based on areas computed from nominal hole diameters in Table 8.1.2(a) and F_{su} = 55 ksi at R.T., F_{tu} = 50 ksi at 500°F, and F_{su} = 45 ksi at 700°F.

d Permanent set at yield load: the greater of 0.005 inch or 2.5% of nominal diameter.

Table 8.1.3.2.1(d_3). Static Joint Strength of Blind 100° Flush Head Monel Rivets in Machine-Countersunk Stainless Steel Sheet

Rivet Type	MS20601M (R.T. F_{su} = 55 ksi)											
Sheet Material	AISI 301-½ Hard											
Temperature	Room				500°F				700°F			
Rivet Diameter, in. (Nominal Hole Diameter, in.)	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)	1/4 (0.258)	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)	1/4 (0.258)	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)	1/4 (0.258)
	Ultimate Strength, lbs											
Sheet thickness, in.:												
0.040	350[a,b]	...	...	...	350[a,b]	...	...	...	350[a,b]	...	...	...
0.050	444	540[a,b]	...	...	444	540[a,b]	...	...	444	540[a,b]	...	...
0.063	538	694	821[b]	...	538	694	821[b]	...	538	694	821[b]	...
0.071	584	773	935	...	584	773	935	...	575	773	935	...
0.080	637	838	1065	...	624	838	1065	...	586	838	1065	...
0.090	695	910	1155	1585[b]	648	910	1155	1585[b]	590	886	1155	1585[b]
0.100	713	984	1240	1780	...	962	1240	1780	...	904	1240	1780
0.125	...	1090	1460	2135	...	993	1410	2135	...	...	1305	2135
0.160	...	...	1580	2550	...	...	1430	2500	...	...	...	2345
0.180	...	...	...	2780	...	...	...	2590	...	...	...	2360
Rivet shear strength[c]	713	1090	1580	2855	648	993	1430	2590	590	904	1305	2360
	Yield Strength[d], lbs											
Sheet thickness, in.:												
0.040	231	...	...	...	231	...	...	...	231	...	...	...
0.050	336	359	...	...	336	359	...	...	336	359	...	...
0.063	459	531	566	...	459	531	566	...	459	531	566	...
0.071	530	625	698	...	530	625	698	...	530	625	698	...
0.080	607	725	835	...	607	725	835	...	586	725	835	...
0.090	693	832	966	1135	648	832	966	1135	590	832	966	1135
0.100	713	943	1095	1345	...	943	1095	1345	...	904	1095	1345
0.125	...	1090	1420	1815	...	993	1410	1815	...	...	1305	1815
0.160	...	...	1580	2430	...	...	1430	2430	...	...	...	2345
0.180	...	...	...	2775	...	...	...	2590	...	...	...	2360
Head height (ref.), in.	0.042	0.055	0.070	0.095	0.042	0.055	0.070	0.095	0.042	0.055	0.070	0.095

a Yield value is less than 2/3 of the indicated ultimate strength value.

b Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.

c Rivet shear strength based on areas computed from nominal hole diameters in Table 8.1.2(a) and F_{su} = 55 ksi at R.T., F_{su} = 50 ksi at 500°F, and F_{su} = 45 ksi at 700°F.

d Permanent set at yield load: the greater of 0.005 inch or 2.5% of nominal diameter.

Table 8.1.3.2.1(e). Static Joint Strength of Blind 100° Flush-Head Monel Rivets in Machine-Countersunk Aluminum Alloy Sheet

Rivet Type	MS20601M (F_{su} = 55 ksi)			
Sheet Material	7075-T6			
Rivet Diameter, in. (Nominal Hole Diameter, in.)	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)	1/4 (0.258)
	Ultimate Strength, lbs			
Sheet thickness, in.:				
0.040	320[a,b]	...	...	...
0.050	393	494[a,b]	...	...
0.063	487	612[a]	747[a,b]	...
0.071	545	684	832[a]	...
0.080	565	766	930[a]	...
0.090	587	840	1040	1425[a,b]
0.100	610	867	1150	1570[a]
0.125	...	937	1270	1940
0.160	...	...	1385	2260
0.190	...	...	...	2390
Rivet shear strength[c]	713	1090	1580	2855
	Yield Strength[d], lbs			
Sheet thickness, in.:				
0.040	146	...	...	...
0.050	228	226	...	...
0.063	395	369	343	...
0.071	496	495	444	...
0.080	526	640	615	...
0.090	561	769	806	660
0.100	595	811	1000	912
0.125	...	918	1195	1560
0.160	...	...	1375	2105
0.190	...	...	...	2310
Head height (ref.), in.	0.042	0.055	0.070	0.095

a Yield value is less than 2/3 of the indicated ultimate strength value.

b Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.

c Rivet shear strength based on areas computed from nominal hole diameters in Table 8.1.2(a) and F_{su} = 55 ksi.

d Permanent set at yield load: the greater of 0.005 inch or 2.5% of nominal diameter.

Table 8.1.3.2.1(f). Static Joint Strength of Blind 100° Flush Head Aluminum Alloy (2117-T3) Rivets in Machine-Countersunk Aluminum Alloy Sheet

Rivet Type	MS20601AD and MS20603AD (F_{su} = 30 ksi)			
Sheet Material	Clad 2024-T3			
Rivet Diameter, in. (Nominal Hole Diameter, in.)	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)	1/4 (0.258)
	Ultimate Strength, lbs			
Sheet thickness, in.:				
0.040	159[a]	...	...	...
0.050	236	258[a]	...	...
0.063	327	369	398[a]	...
0.071	360	439	485	...
0.080	388	511	577	...
0.090	...	561	684	795[a]
0.100	...	596	768	945
0.125	...	...	862	1270
Rivet shear strength[b]	388	596	862	1550
	Yield Strength[c], lbs			
Sheet thickness, in.:				
0.040	110	...	...	...
0.050	198	185	...	...
0.063	300	308	296	...
0.071	336	384	391	...
0.080	377	468	497	...
0.090	...	524	614	621
0.100	...	592	709	793
0.125	...	...	862	1150
Head height (ref.), in.	0.042	0.055	0.070	0.095

[a] Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.

[b] Rivet shear strength based on areas computed from nominal hole diameters in Table 8.1.2(a) and F_{su} = 30 ksi.

[c] Permanent set at yield load: the greater of 0.005 inch or 2.5% of nominal diameter.

Table 8.1.3.2.1(g). Static Joint Strength of Blind 100° Flush Head Aluminum Alloy (5056-H321) Rivets in Machine-Countersunk Magnesium Alloy Sheet

Rivet Type	MS20601B (F_{su} = 28 ksi)			
Sheet Material	AZ31B-H24			
Rivet Diameter, in. (Nominal Hole Diameter, in.)	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)	1/4 (0.258)
	Ultimate Strength, lbs			
Sheet thickness, in.:				
0.040	167[a]	...	...	...
0.050	208	257[a]	...	...
0.063	262	324	390[a]	...
0.071	295	366	440	...
0.080	333	413	495	...
0.090	363	464	557	749[a]
0.100	...	516	620	833
0.125	...	556	774	1040
0.160	...	...	802	1332
0.190	...	...	...	1450
Rivet shear strength[b]	363	556	802	1450
	Yield Strength[c], lbs			
Sheet thickness, in.:				
0.040	158	...	...	...
0.050	197	244	...	...
0.063	248	308	370	...
0.071	279	346	417	...
0.080	315	391	469	...
0.090	354	440	527	710
0.100	...	489	587	789
0.125	...	556	734	986
0.160	...	...	802	1262
0.190	...	...	...	1450
Head height (ref.), in.	0.042	0.055	0.070	0.095

a Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.

b Rivet shear strength based on areas computed from nominal hole diameters in Table 8.1.2(a) and F_{su} = 28 ksi.

c Permanent set at yield load: the greater of 0.005 inch or 2.5% of nominal diameter.

Table 8.1.3.2.2(a). Static Joint Strength of Blind 100° Flush Head Locked Spindle A-286 Rivets in Machine-Countersunk Alloy Steel Sheet

Rivet Type	NAS1399C[a] (F_{su} = 75 ksi)			CR 2642[a] (F_{su} = 95 ksi)		
Sheet Material	Alloy Steel, F_{tu} = 180 ksi					
Rivet Diameter, in. (Nominal Hole Diameter, in.)	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)
	Ultimate Strength, lbs.					
Sheet thickness, in.:						
0.040	380[b,c]	...	...	380[b,c]	...	...
0.050	475[b]	588[b,c]	...	475	588[b,c]	...
0.063	698	741[b]	890[b,c]	698	741	890[b,c]
0.071	840	908	1004[b]	840	908	1004[b]
0.080	970	1108	1171[b]	1002	1108	1171
0.090	...	1333	1438	1185	1333	1438
0.100	...	1490	1710	1230	1559	1710
0.125	...	...	2150	...	1885	2380
0.160	...	...	...	...	...	2720
Rivet shear strength	970[d]	1490[d]	2150[d]	1230[e]	1885[e]	2720[e]
	Yield Strength[f], lbs.					
Sheet thickness, in.:						
0.040	137	...	...	180	...	...
0.050	292	219	...	320	278	...
0.063	494	468	387	536	513	432
0.071	614	620	570	665	675	628
0.080	755	793	776	816	860	847
0.090	...	983	1003	981	1063	1090
0.100	...	1176	1236	1144	1267	1337
0.125	...	...	1809	...	1777	1950
0.160	...	...	...	...	...	2720
Head height (ref.), in.	0.042	0.055	0.070	0.042	0.055	0.070

a Data supplied by Cherry Fasteners.
b Yield value is less than 2/3 of the indicated ultimate strength value.
c Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.
d Rivet shear strength is documented in NAS1400.
e Shear strength is based on areas computed from nominal hole diameters in Table 8.1.2(a) and F_{su} = 95 ksi.
f Permanent set at yield load: the greater of 0.005 inch or 2.5% of nominal diameter.

Table 8.1.3.2.2(b). Static Joint Strength of Blind 100° Flush Head Locked Spindle Monel Rivets in Machine-Countersunk Stainless Steel Sheet

Rivet Type	NAS1399 MS or MW[a] (F_{su} = 55 ksi)		
Sheet Material	AISI 301-1/2 Hard		
Rivet Diameter, in. (Nominal Hole Diameter, in.)	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)
	Ultimate Strength, lbs.		
Sheet thickness, in.:			
0.040	287[b,c]	...	...
0.050	363	445[b,c]	...
0.063	491	569	671[b,c]
0.071	569	668	755[b]
0.080	657	776	886
0.090	710	898	1032
0.100	...	1019	1182
0.125	...	1090	1580
Rivet shear strength[d]	710	1090	1580
	Yield Strength[e], lbs.		
Sheet thickness, in.:			
0.040	163	...	...
0.050	243	253	...
0.063	348	384	401
0.071	413	463	496
0.080	487	554	606
0.090	568	655	726
0.100	...	753	846
0.125	...	1004	1156
Head height (ref.), in.	0.042	0.055	0.070

a Data supplied by Cherry Fasteners.

b Yield value is less than 2/3 of the indicated ultimate strength value.

c Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.

d Rivet shear strength is documented in NAS1400.

e Permanent set at yield load: the greater of 0.005 inch or 2.5% of nominal diameter.

Table 8.1.3.2.2(c). Static Joint Strength of 100° Flush Head Locked Spindle A-286 Blind Rivets in Machine-Countersunk Aluminum Alloy Sheet

Rivet Type	NAS1921C[a] (F_{su} = 80 ksi)		
Sheet Material	Clad 7075-T6		
Rivet Diameter, in. (Nominal Hole Diameter, in.)	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)
	Ultimate Strength, lbs		
Sheet thickness, in.			
0.050	612[b]	...	...
0.063	749[b]	956[b]	...
0.071	831[b]	1060[b]	...
0.080	923[b]	1180[b]	1450[b]
0.090	1110[b]	1305[b]	1605[b]
0.100	1090[b]	1435[b]	1755[b]
0.125	...	1670[b]	2130[b]
0.160	...	...	2400[b]
Rivet shear strength[c]	1090	1670	2400
	Yield Strength[d], lbs		
Sheet thickness, in.:			
0.050	365	...	...
0.063	466	571	...
0.071	528	649	...
0.080	598	737	873
0.090	639	835	990
0.100	686	931	1105
0.125	804	1065	1325
0.160	...	...	1605
Head height (ref.), in.	0.042	0.055	0.070

[a] Data supplied by Huck Manufacturing Company.

[b] Yield value is less than 2/3 of indicated ultimate strength value.

[c] Rivet shear strength is documented in NAS1900.

[d] Permanent set at yield load: 4% of nominal diameter (revised May 1, 1985 from the greater of 0.012 inch or 4% of nominal diameter).

Table 8.1.3.2.2(d). Static Joint Strength of Blind 100° Flush Head Locked Spindle Monel Rivets in Machine-Countersunk Aluminum Alloy Sheet

Rivet Type	NAS1399 MS or MW[a] (F_{su} = 55 ksi)		
Sheet Material	Clad 7075-T6		
Rivet Diameter, in. (Nominal Hole Diameter, in.)	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)
	Ultimate Strength, lbs.		
Sheet thickness, in.:			
0.040	323[b,c]	...	...
0.050	404[b]	499[b,c]	...
0.063	500[b]	631[b]	757[b,c]
0.071	557	703[b]	855[b]
0.080	610	784	958[b]
0.090	636	873	1065[b]
0.100	662	937	1175
0.125	710	1015	1370
0.160	...	1090	1505
0.190	...	...	1580
Rivet shear strength[d]	710	1090	1580
	Yield Strength[e], lbs.		
Sheet thickness, in.:			
0.040	139	...	...
0.050	223	218	...
0.063	331	353	351
0.071	397	436	451
0.080	472	529	563
0.090	556	633	687
0.100	562	737	811
0.125	574	873	1120
0.160	...	894	1260
0.190	...	...	1280
Head height (ref.), in.	0.042	0.055	0.070

[a] Data supplied by Cherry Fasteners.

[b] Yield value is less than 2/3 of the indicated ultimate strength value.

[c] Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.

[d] Rivet shear strength is documented in NAS1400.

[e] Permanent set at yield load: 4% of nominal diameter (revised May 1, 1985, from the greater of 0.005 inch or 2.5% of nominal diameter).

Table 8.1.3.2.2(e). Static Joint Strength of 100° Flush Head Locked Spindle Monel Blind Rivets in Machine-Countersunk Aluminum Alloy Sheet

Rivet Type	NAS 1921 M[a] (F_{su} = 75 ksi)		
Sheet Material	Clad 7075-T6		
Rivet Diameter, in. (Nominal Hole Diameter, in.)	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)
	Ultimate Strength, lbs		
Sheet thickness, in.			
0.050	595[b]	...	...
0.063	732[b]	927[b]	...
0.071	816[b]	1035[b]	...
0.080	913[b]	1158[b]	1400[b]
0.090	946[b]	1289[b]	1570[b]
0.100	980[b]	1415[b]	1720[b]
0.125	1020	1525[b]	2055[b]
0.160	...	1565[b]	2245[b]
0.190	...	...	2260
Rivet shear strength[c]	1020	1565	2260
	Yield Strength[d], lbs		
Sheet thickness, in.:			
0.050	354	...	...
0.063	447	554	...
0.071	504	625	...
0.080	569	707	843
0.090	607	796	952
0.100	626	885	1060
0.125	686	972	1265
0.160	...	1080	1430
0.190	...	...	1540
Head height (ref.), in.	0.042	0.055	0.070

[a] Data supplied by Huck Manufacturing Company.

[b] Yield value is less than 2/3 of indicated ultimate strength value.

[c] Rivet shear strength is documented in NAS 1900.

[d] Permanent set at yield load: 4% of nominal diameter (revised May 1, 1985 from the greater of 0.012 inch or 4% of nominal diameter).

Table 8.1.3.2.2(f). Static Joint Strength of Blind 100° Flush Head Aluminum Alloy (2219) Rivets in Machine-Countersunk Aluminum Alloy Sheet

Rivet Type	CR 2A62[a] (F_{su} = 36 ksi)		
Sheet Material	Clad 2024-T81		
Rivet Diameter, in. (Nominal Hole Diameter, in.)	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)
	Ultimate Strength, lbs		
Sheet thickness, in.			
0.050	203	...	...
0.063	289	319	...
0.071	342	385	...
0.080	393	461	503
0.090	416	542	603
0.100	439	610	701
0.125	478	682	894
0.160	...	741	1013
0.190	...	...	1063
Rivet shear strength[b]	478	741	1063
	Yield Strength[c], lbs		
Sheet thickness, in.:			
0.050	169	...	...
0.063	247	267	...
0.071	295	326	...
0.080	349	394	423
0.090	409	468	514
0.100	424	544	603
0.125	448	658	827
0.160	...	670	960
0.190	...	...	1002
Head height (ref.), in.	0.042	0.055	0.070

a Data supplied by Cherry Fasteners.

b Shear strength values are based on indicated nominal hole diameters and F_{su} = 36 ksi.

c Permanent set at yield load: 4% of nominal diameter.

Table 8.1.3.2.2(g). Static Joint Strength of Blind 100 degree Flush Head Locked Aluminum Alloy Rivets in Machine-Countersunk Aluminum Alloy Sheet

Rivet Type	NAS1921B0()-0(), NAS1921B0()S0(), NAS1921B0()S0()U[a] (F_{su} = 36 ksi)		
Sheet Material	Clad 7075-T6		
Rivet Diameter, in. (Nominal Hole Diameter, in.)	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)
	Ultimate Strength, lbs.		
Sheet thickness, in.:			
0.040	171[b]	---	---
0.050	232	267[b]	---
0.063	313	366	411[b]
0.071	360	427	484
0.080	416	498	566
0.090	477	571	658
0.100	494	647	748
0.125	---	755	978
0.160	---	---	1090
Rivet shear strength[c]	495	755	1090
	Yield Strength, lbs[d]		
Sheet thickness, in.:			
0.040	110	---	---
0.050	161	171	---
0.063	247	254	270
0.071	303	315	330
0.080	354	395	399
0.090	373	484	506
0.100	393	549	611
0.125	---	610	803
0.160	---	---	906
Head height [ref.], in.	0.042	0.055	0.070

[a] Data supplied by Huck Manufacturing Company.

[b] Values above the horizontal line in each column are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring activity.

[c] Rivet shear strength is documented in NAS1900.

[d] Permanent set at yield load: 4% of nominal diameter.

Table 8.1.3.2.2(h). Static Joint Strength of Blind 100° Flush Head Locked Spindle Aluminum Alloy Rivets in Machine-Countersunk Aluminum Alloy Sheet

Rivet Type	NAS1399B[a] (5056) (F_{su} = 30 ksi)			NAS1399D[a] (2017) (F_{su} = 36 ksi)		
Sheet Material	Clad 2024-T3					
Rivet Diameter, in. (Nominal Hole Diameter, in.)	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)
	Ultimate Strength, lbs.					
Sheet thickness, in.:						
0.040	149[b,c]	...	...	149[b,c]	...	...
0.050	223[b]	230[b,c]	...	223[b]	230[b,c]	...
0.063	310[b]	349[b]	356[b,c]	319[b]	349[b]	356[b,c]
0.071	366	415[b]	448[b]	379[b]	420[b]	448[b]
0.080	388	492[b]	544[b]	423	506[b]	547[b]
0.090	...	578	646[b]	459	600[b]	660[b]
0.100	...	596	751[b]	494	652	775[b]
0.125	...	...	862	...	755	969
0.160	...	...	...	...	...	1090
Rivet shear strength[d]	388	596	862	494	755	1090
	Yield Strength[e], lbs.					
Sheet thickness, in.:						
0.040	72	...	...	72	...	...
0.050	114	113	...	114	113	...
0.063	197	182	170	197	182	170
0.071	247	245	220	247	245	220
0.080	304	316	304	304	316	304
0.090	...	396	399	367	396	399
0.100	...	473	493	431	473	493
0.125	...	...	729	...	672	729
0.160	...	...	...	...	...	1060
Head height (ref.), in.	0.042	0.055	0.070	0.042	0.055	0.070

a Data supplied by Cherry Fasteners.
b Yield value is less than 2/3 of the indicated ultimate strength value.
c Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.
d Rivet shear strength is documented in NAS1900.
e Permanent set at yield load: 4% of nominal diameter (revised May 1, 1985, from the greater of 0.005 inch or 2.5% of nominal diameter).

Table 8.1.3.2.2(i). Static Joint Strength of Blind 100° Flush Head Locked Spindle Aluminum Alloy Rivets in Machine-Countersunk and Dimpled Aluminum Alloy Sheet

Rivet Type	NAS1739B[a] and NAS1739E[a,b] (F_{su} = 34 ksi)			NAS1739B[c] and NAS1739E[b,c] (F_{su} = 34 ksi)		
Sheet Material	Clad 2024-T3					
Rivet Diameter, in. (Nominal Hole Diameter, in.)	1/8 (0.144)	5/32 (0.178)	3/16 (0.207)	1/8 (0.144)	5/32 (0.178)	3/16 (0.207)
	Ultimate Strength, lbs.					
Sheet thickness, in.:						
0.020	...	...	...	246	334	418
0.025	...	...	...	281	376	465
0.032	212[d]	...	...	330	436	536
0.040	266	326[d]	...	386	506	616
0.050	344	410	...	456	592	716
0.063	441	533	606[d]	546	703	845
0.071	504	608	696	...	771	926
0.080	554	693	794	...	837	1015
0.090	...	787	900	...	...	1110
0.100	...	837	1015	...	...	...
0.125	...	...	1128	...	...	...
Rivet shear strength[e]	554	837	1128	554	837	1128
	Yield Strength[f], lbs.					
Sheet thickness, in.:						
0.020	...	...	...	...	...	...
0.025	...	...	...	...	...	...
0.032	159	...	...	...	...	...
0.040	212	247	...	...	...	...
0.050	279	331	...	...	...	...
0.063	365	437	492	...	...	...
0.071	418	503	568	...	...	...
0.080	448	577	654	...	...	...
0.090	...	659	750	...	...	...
0.100	...	689	845	...	...	...
0.125	...	...	960	...	...	...
Head height (ref.), in.	0.035	0.047	0.063	0.035	0.047	0.063

[a] Machine-countersunk holes.

[b] Data supplied by Cherry Fasteners. Confirmatory data for machine-countersunk holes provided by Allfast Fastening Systems, Inc.

[c] Dimpled holes. These allowables apply to double dimpled sheets and to the upper sheet dimpled into a machine-countersunk lower sheet. Sheet gauge is that of the thinnest sheet for double dimpled joints and of the upper dimpled, machine-countersunk joints. The thickness of the machine-countersunk sheet must be at least one tabulated gauge thicker than the upper sheet. In no case will allowables be obtained by extrapolation for gauges other than those shown.

[d] The values in the table above the horizontal line in each column are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.

[e] Rivet shear strength is documented in NAS1740.

[f] Permanent set at yield load: 4% of nominal diameter (revised May 1, 1985, from the greater of 0.005 inch or 2.5% of nominal diameter).

Table 8.1.3.2.2(j). Static Joint Strength of Blind 100° Flush Head Locked Spindle Aluminum Alloy Rivets in Machine-Countersunk Magnesium Alloy Sheet

Rivet Type	NAS1399B[a] (F_{su} = 30 ksi)				NAS1739B and NAS 1739E[a] (F_{su} = 34 ksi)		
Sheet Material	AZ31B-H24						
Rivet Diameter, in. (Nominal Hole Diameter, in.)	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)	1/4 (0.258)	1/8 (0.144)	5/32 (0.178)	3/16 (0.207)
	Ultimate Strength, lbs.						
Sheet thickness, in.:							
0.032	...	...	...	...	188[b,c]	...	...
0.040	178[b,c]	...	...	...	235[b]	292[b,c]	...
0.050	223[b]	274[b,c]	...	...	295	362[b]	...
0.063	292[b]	349[b]	418[b,c]	...	371	457	530[b,c]
0.071	334[b]	399[b]	471[b]	...	418	514	600[b]
0.080	383[b]	459[b]	536[b]	...	471	580	671
0.090	388	526[b]	613[b]	803[b,c]	531	651	756
0.100	...	593[b]	693[b]	892[b]	554	725[b]	843
0.125	...	596	862	1153[b]	...	837[b]	1052[b]
0.160	...	...	...	1532[b]	...	...	...
Rivet shear strength	388[d]	596[d]	862[d]	1550[d]	554[e]	837[e]	1128[e]
	Yield Strength[f], lbs.						
Sheet thickness, in.:							
0.032	...	...	...	...	106	...	...
0.040	49	...	...	...	147	164	...
0.050	94	76	...	...	197	227	...
0.063	158	152	128	...	262	307	340
0.071	197	200	186	...	300	355	399
0.080	242	254	250	...	314	414	462
0.090	291	315	323	277	330	459	534
0.100	...	375	396	376	336	478	608
0.125	...	530	580	621	...	508	667
0.160	...	...	...	968	...	...	...
Head height (ref.), in.	0.042	0.055	0.070	0.095	0.035	0.047	0.063

a Data supplied by Cherry Fasteners.
b Yield value is less than 2/3 of the indicated ultimate strength value.
c Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.
d Rivet shear strength is documented in NAS1400.
e Rivet shear strength is documented in NAS1740 dated March 1968.
f Permanent set at yield load: the greater of 0.005 inch or 2.5% of nominal diameter.

Table 8.1.3.2.2(k). Static Joint Strength of Blind 100° Flush Head Locked Spindle A-286 Rivets in Machine-Countersunk Aluminum Alloy Sheet

Rivet Type	CR 4622[a] (F_{su} = 75 ksi)			
Sheet Material	Clad 7075-T6			
Rivet Diameter . . . . (Nominal Hole Diameter, in.)[b]	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)	1/4 (0.258)
	Ultimate Strength, lbs			
Sheet thickness, in.:				
0.050	595[c]	...	...	...
0.063	733[c]	932[c]	...	...
0.071	817[c]	1035[c]	...	...
0.080	913	1160[c]	1410[c]	...
0.090	947	1290[c]	1570[c]	...
0.100	982	1420	1725[c]	2360[c]
0.125	995	1525	2060	2880[c]
0.160	...	1545	2215	3605
0.190	...	...	...	3810
0.250	...	...	...	3920
Rivet shear strength[d]	995	1545	2215	3920
	Yield Strength[e], lbs			
Sheet thickness, in.:				
0.050	211	...	...	...
0.063	348	339	...	...
0.071	489	470	...	...
0.080	608	620	574	...
0.090	664	787	774	...
0.100	720	947	970	853
0.125	860	1120	1400	1505
0.160	...	1365	1695	2410
0.190	...	...	...	2740
0.250	...	...	...	3405
Head height (ref.), in.	0.041	0.054	0.069	0.095

a Data supplied by Cherry Fasteners.

b Allowable loads developed from test with nominal hole diameters as listed.

c Yield value is less than 2/3 of the indicated ultimate strength value.

d Fastener shear strength based upon nominal hole diameters and F_{su} = 75 ksi from data analysis.

e Permanent set at yield load: 4% of nominal diameter.

Table 8.1.3.2.2(l). Static Joint Strength of Blind 100° Flush Head Locked Spindle Monel Rivets in Machine-Countersunk Aluminum Alloy Sheet and Plate

Rivet Type	CR 4522[a] (F_{su} = 65 ksi)			
Sheet and Plate Material	Clad 7075-T6 and T651			
Rivet Diameter (Nominal Hole Diameter, in.)[b]	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)	1/4 (0.258)
	Ultimate Strength, lbs			
Sheet or plate thickness, in.:				
0.050	529[c]	...	...	...
0.063	632[c]	828[c]	...	...
0.071	694[c]	906[c]	...	...
0.080	754	995[c]	1240[c]	...
0.090	776	1095	1360[c]	...
0.100	797	1170	1475[c]	...
0.125	852	1240	1695	2485[c]
0.160	863	1335	1810	2975
0.190	...	1340	1910	3105
0.250	...	...	1920	3365
0.312	...	...	...	3400
Rivet shear strength[d]	863	1340	1920	3400
	Yield Strength[e], lbs			
Sheet or plate thickness, in.:				
0.050	169	...	...	...
0.063	346	273	...	...
0.071	454	408	...	...
0.080	561	562	483	...
0.090	621	732	688	...
0.100	682	874	888	...
0.125	833	1060	1300	1355
0.160	863	1325	1615	2225
0.190	...	1340	1885	2585
0.250	...	...	1920	3300
0.312	...	...	...	3400
Head height (ref.), in.	0.042	0.055	0.070	0.095

a Data supplied by Cherry Fasteners.
b Allowable loads developed from test with nominal hole diameters as listed.
c Yield value is less than 2/3 of the indicated ultimate strength value.
d Fastener shear strength based upon nominal hole diameters and F_{su} = 65 ksi from data analysis.
e Permanent set at yield load: 4% of nominal diameter.

Table 8.1.3.2.2(m). Static Joint Strength of Blind 100° Flush Head Locked Spindle Aluminum Alloy (7050) Rivets in Machine-Countersunk Aluminum Alloy Sheet

Rivet Type	NAS1721KE and NAS1721KE ( )L[a] (F_{su} = 33 ksi)		
Sheet Material	Clad 2024-T3		
Rivet Diameter, in. (Nominal Hole Diameter, in.)[b]	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)
	Ultimate Strength, lbs.		
Sheet thickness, in.:			
0.040	221[c,d]	...	...
0.050	277[d]	342[c,d]	...
0.063	351	435[d]	518[c,d]
0.071	396	491[d]	586[d]
0.080	448	555	662[d]
0.090	450	626	747
0.100	...	697	832
0.125	...	700	950
Rivet shear strength[e]	450	700	950
	Yield Strength[f], lbs.		
Sheet thickness, in.:			
0.040	62	...	...
0.050	150	99	...
0.063	263	240	182
0.071	333	327	287
0.080	386	425	404
0.090	403	534	534
0.100	...	600	665
0.125	...	653	874
Head height (ref.), in.	0.042	0.055	0.070

[a] Data supplied by Avdel Corp.

[b] Loads developed from tests with hole diameters of 0.130, 0.162, and 0.194, ±0.001 inch.

[c] The values in the table above the horizontal line in each column are for knife-edge conditions, and the use of fasteners in this condition is undesirable. The use of knife-edge conditions in the design of military aircraft requires the specific approval of the procuring agency.

[d] Yield value is less than 2/3 of indicated ultimate value.

[e] Rivet shear strength is documented in NAS1722.

[f] Permanent set at yield load: 4% of nominal diameter.

Table 8.1.3.2.2(n). Static Joint Strength of Blind 100° Flush Head Locked Spindle A-286 Rivets in Machine-Countersunk Aluminum Alloy Sheet

Rivet Type	NAS1721C and NAS1721C( )L[a] (F_{su} = 75 ksi)		
Sheet Material	Clad 7075-T6		
Rivet Diameter, in. (Nominal Hole Diameter, in.)[b]	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)
	Ultimate Strength, lbs.		
Sheet thickness, in.:			
0.040	454[c, d]	...	...
0.050	585[d]	707[c,d]	...
0.063	751[d]	919[d]	1075[c,d]
0.071	853[d]	1045[d]	1230[d]
0.080	881[d]	1190[d]	1405[d]
0.090	896	1345[d]	1595[d]
0.100	912	1365[d]	1785[d]
0.125	951	1415	1970
0.160	1000	1485	2055
0.190	...	1500	2125
0.250	...	...	2200
Rivet shear strength[e]	1000	1500	2200
	Yield Strength[f], lbs.		
Sheet thickness, in.:			
0.040	77	...	...
0.050	220	122	...
0.063	375	352	246
0.071	470	471	425
0.080	578	604	585
0.090	615	753	763
0.100	641	902	942
0.125	707	997	1330
0.160	799	1110	1470
0.190	...	1210	1585
0.250	...	...	1820
Head height (ref.), in.	0.042	0.055	0.070

a Data supplied by Avdel Corp.

b Loads developed from tests with hole diameters of 0.130, 0.162, and 0.194, ±0.001 inch.

c The values in the table above the horizontal line in each column are for knife-edge conditions and the use of fasteners in this condition is undesirable. The use of knife-edge conditions in the design of military aircraft requires the specific approval of the procuring agency.

d Yield value is less than 2/3 of indicated ultimate value.

e Rivet shear strength is documented in NAS1722.

f Permanent set at yield load: 4% of nominal diameter.

Table 8.1.3.2.2(o). Static Joint Strength of Blind Flush Head Locked Aluminum Alloy Rivets in Machine-Countersunk Aluminum Alloy Sheets

Rivet Type	HC3212 (F_{su} = 51 ksi approx.)[a]		
Sheet Material	Clad 2024-T3		
Rivet Diameter, in. (Nominal Hole Diameter, in.)[b]	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)
	Ultimate Strength, lbs.		
Sheet thickness, in.:			
0.040	280[c,d]	---	---
0.050	318	436[c,d]	---
0.063	367	497	643[c,d]
0.071	397	535	688
0.080	431	577	739
0.090	469	624	795
0.100	507	671	851
0.125	602	789	992
0.160	664	954	1190
0.190	---	1030	1355
0.250	---	---	1480
Rivet shear strength[e]	664	1030	1480
	Yield Strength, lbs[f]		
Sheet thickness, in.:			
0.040	151	---	---
0.050	244	236	---
0.063	366	387	382
0.071	397	480	494
0.080	431	577	619
0.090	454	624	758
0.100	476	671	851
0.125	532	740	979
0.160	610	837	1095
0.190	---	921	1195
0.250	---	---	1395
Head height [ref.], in.	0.042	0.055	0.070

[a] Data supplied by Huck International Inc.

[b] Loads developed from tests with hole diameters of 0.130, 0.162, and 0.194, +/- 0.001 inch.

[c] The values in the table above the horizontal line in each column are for knife-edge conditions and the use of fasteners in this condition is undesirable. The use of knife-edge conditions in the design of military aircraft requires specific approval of the procuring activity.

[d] Yield value is less than 2/3 of indicated ultimate strength value.

[e] Rivet shear strength is documented on HC3212 standards drawing.

[f] Permanent set at yield load: 4% of nominal diameter.

Table 8.1.3.2.2(p). Static Joint Strength of Blind 100° Flush Head Locked Spindle 2014 Aluminum Alloy Rivets in Machine Countersunk Aluminum Alloy Sheet

Rivet Type	MBC 4807 and 4907 (F_{su} = 33 ksi approx.)[a]		
Sheet Material	Clad 2024-T3		
Rivet Diameter, in.	1/8	5/32	3/16
(Nominal Hole Diameter, in.)[b]	(0.130)	(0.162)	(0.194)
	Ultimate Strength, lbs.		
Sheet thickness, in.:			
0.040	183[c]	...	...
0.050	243	286[c]	...
0.063	320	382	437[c]
0.071	368	441	508
0.080	412	508	588
0.090	435	582	677
0.100	450	641	766
0.125	...	700	937
0.160	...	...	950
Rivet shear strength[d]	450	700	950
	Yield Strength, lbs.[e]		
Sheet thickness, in.:			
0.040	102	...	...
0.050	173	160	...
0.063	264	274	263
0.071	309	345	347
0.080	333	423	441
0.090	360	486	546
0.100	387	519	651
0.125	...	602	765
0.160	...	...	904
Head height (ref.), in.	0.041	0.053	0.068

[a] Data supplied by Avdel Systems Ltd.

[b] Loads developed from tests with hole diameters of 0.130, 0.162, and 0.194, +/- 0.001 inch.

[c] The values in the table above the horizontal line in each column are for knife-edge conditions, and the use of fasteners in this condition is undesirable. The use of knife-edge conditions in the design of military aircraft requires the specific approval of the procuring agency.

[d] Rivet shear strength is documented in NAS 1722, and rivets meet the requirements of NAS 1721.

[e] Permanent set at yield load: 4% of nominal diameter.

Table 8.1.3.2.2(q). Static Joint Strength of Blind Protruding Head Locked Spindle 2014 Aluminum Alloy Rivets in Aluminum Alloy Sheet

Rivet Type	MBC 4801 and 4901 (F_{su} = 33 ksi approx.)[a]		
Sheet Material	Clad 2024-T3		
Rivet Diameter, in. (Nominal Hole Diameter, in.)[b]	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)
	Ultimate Strength, lbs.		
Sheet thickness, in.:			
0.025	247	...	...
0.032	284	389	...
0.040	326	441	571
0.050	378	507	650
0.063	415	589	751
0.071	437	617	814
0.080	450	649	864
0.090	...	684	906
0.100	...	700	948
0.125	...	...	950
Rivet shear strength[c]	450	700	950
	Yield Strength, lbs.[d]		
Sheet thickness, in.:			
0.025	238	...	...
0.032	277	375	...
0.040	321	431	552
0.050	368	500	635
0.063	381	572	743
0.071	389	583	810
0.080	399	594	828
0.090	...	607	843
0.100	...	619	858
0.125	...	...	896

a Data supplied by Avdel Systems Ltd.
b Loads developed from tests with hole diameters of 0.130, 0.162, and 0.194, ±0.001 inch.
c Rivet shear strength is documented in NAS 1722, and rivets meet the requirements of NAS 1720.
d Permanent set at yield load: 4% of nominal diameter.

Table 8.1.3.2.2(r). Static Joint Strength of 100° Flush Head Locked Spindle Aluminum Alloy Blind Rivets in Machine-Countersunk Aluminum Alloy Sheet

Rivet Type	HC6222[a] (F_{su} = 50 ksi) Nominal		
Sheet Material	Clad 2024-T3		
Rivet Diameter, in. . . . . (Nominal Hole Diameter, in.) . . .	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)
	Ultimate Strength, lbs		
Sheet thickness, in.:			
0.040	270[b]	...	...
0.050	317	420[b]	...
0.063	377	496	624[b]
0.071	414	542	680
0.080	456	594	743
0.090	503	652	812
0.100	550	711	882
0.125	664	856	1055
0.160	...	1030	1299
0.190	...	...	1480
0.250	...	...	...
Rivet shear strength[d]	664	1030	1480
	Yield Strength[e], lbs		
Sheet thickness, in.:			
0.040	196	237[c]	...
0.050	252	306	...
0.063	323	395	464
0.071	368	451	530
0.080	417	512	605
0.090	445	581	687
0.100	459	650	770
0.125	494	714	972
0.160	...	775	1045
0.190	...	...	1108
0.250	...	...	...
Head height (ref.), in.	0.042	0.055	0.070

[a] Data supplied by Huck International, Inc.

[b] Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.

[c] Yield value is less than 2/3 of the indicated ultimate.

[d] Rivet shear strength is documented in MIL-R-7885D.

[e] Permanent set at yield load: 4% of nominal hole diameter.

Table 8.1.3.2.2(s). Static Joint Strength of 100° Flush Head Locked Spindle Aluminum Alloy Blind Rivets in Machine-Countersunk Aluminum Alloy Sheet

Rivet Type	HC6252[a] (F_{su} = 50 ksi)		
Sheet Material	Clad 2024-T3		
Rivet Diameter, in. (Nominal Hole Diameter, in.)	1/8 (0.144)	5/32 (0.178)	3/16 (0.207)
	Ultimate Strength, lbs		
Sheet thickness, in.:			
0.032	265[b,c]	...	...
0.040	304	408[b,c]	...
0.050	352	467	...
0.063	414	544	665[c]
0.071	452	591	720
0.080	495	645	782
0.090	543	704	851
0.100	591	763	920
0.125	701	911	1092
0.160	814	1097	1332
0.190	...	1237	1505
0.250	...	1245	1685
Rivet shear strength[d]	814	1245	1685
	Yield Strength[e], lbs		
Sheet thickness, in.:			
0.032	154	...	...
0.040	214	240	...
0.050	288	332	...
0.063	384	451	500
0.071	444	524	586
0.080	494	607	682
0.090	513	698	788
0.100	531	758	895
0.125	576	814	1048
0.160	640	893	1139
0.190	...	961	1218
0.250	...	1096	1376
Head height (ref.), in.	0.035	0.047	0.063

a Data supplied by Huck International, Inc.

b Yield value is less than 2/3 of the indicated ultimate.

c Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring activity.

d Rivet shear strength is documented in MIL-R-7885D.

e Permanent set at yield load: 4% of nominal hole diameter.

Table 8.1.3.2.2(t_1). Static Joint Strength of 100° Flush Shear Head Locked Spindle Aluminum Alloy Blind Rivets in Machine-Countersunk Aluminum Alloy Sheet

Rivet Type	HC6224[a] (F_{su} = 50 ksi) Nominal		
Sheet Material	Clad 2024-T3		
Rivet Diameter, in. . . . . (Nominal Hole Diameter, in.)[b] . .	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)
	Ultimate Strength, lbs		
Sheet thickness, in.:			
0.032	230	294[c]	
0.040	282	358	437[c]
0.050	347	439	534
0.063	431	544	660
0.071	456	608	737
0.080	493	681	824
0.090	535	716	921
0.100	576	768	979
0.125	664	897	1135
0.160	...	1030	1350
0.190	...	...	1480
Rivet shear strength[d]	664	1030	1480
	Yield Strength[e], lbs		
Sheet thickness, in.:			
0.032	185	209	
0.040	248	288	320
0.050	328	387	438
0.063	431	516	592
0.071	448	595	687
0.080	457	681	794
0.090	467	697	912
0.100	477	710	979
0.125	503	742	1030
0.160	...	786	1080
0.190	...	...	1125
Head height (ref.), in.	0.028	0.037	0.046

[a] Data supplied by Huck International, Inc.

[b] Loads developed from tests with hole diameters of 0.130, 0.162, and 0.194 ± 0.0002.

[c] Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring activity.

[d] Rivet shear strength is documented in MIL-R-7885D.

[e] Permanent set at yield load: 4% of nominal hole diameter.

TABLE 8.1.3.2.2(t_2). Static Joint Strength of 100° Flush Shear Head Locked Spindle Aluminum Alloy Blind Rivets in Machine-Countersunk Aluminum Alloy Sheet

Rivet Type	HC3214[a](Fsu = 50 ksi)Nominal		
Sheet Material	Clad 2024-T3		
Rivet Diameter, in	1/8	5/32	3/16
(Nominal Hole Diameter, in)	(0.130)	(0.162)	(0.194)
	Ultimate Strength, lbs.		
Sheet thickness, in:			
0.032	214	272[b]	
0.040	264	333	405[b]
0.050	325	410	497
0.063	406	511	617
0.071	427	572	691
0.080	464	621	774
0.090	504	671	856
0.100	544	721	916
0.125	644	846	1066
0.160	664	1020	1275
0.190	...	1030	1455
0.250	...	...	1480
Rivet shear strength[c]	664	1030	1480
	Yield Strength[d], lbs		
Sheet thickness, in:			
0.032	196	230	
0.040	256	305	348
0.050	325	399	461
0.063	406	511	607
0.071	427	572	691
0.080	453	621	774
0.090	475	678	856
0.100	497	705	916
0.125	552	773	1030
0.160	628	868	1140
0.190	...	950	1240
0.250	...	...	1435
Head height (ref), in	0.028	0.037	0.046

a Data supplied by Huck International Inc.

b Values above the horizontal line in each column are for knife-edge conditions, the use of fasteners in this condition is undesirable. The use of knife-edge conditions in the design of military aircraft requires the specific approval of the procuring activity.

c Rivet shear strength is based upon nominal hole diameter and F_{su} = 50 ksi.

d Permanent set at yield: 4% of nominal hole diameter.

Table 8.1.3.2.2(u). Static Joint Strength of Blind Flush Head Locked Spindle Aluminum Alloy Rivets in Machine-Countersunk Aluminum Alloy Sheets

Rivet Type	AF3212 (F_{su} = 51 ksi approx.)[a]		
Sheet Material	Clad 2024-T3		
Rivet Diameter, in. (Nominal Hole Diameter, in.)[b]	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)
	Ultimate Strength, lbs.		
Sheet thickness, in.:			
0.040	143[c]	---	---
0.050	247	224[c]	---
0.063	383	393	370[c]
0.071	414	497	494
0.080	435	614	634
0.090	457	647	790
0.100	480	676	902
0.125	537	746	987
0.160	616	846	1105
0.190	---	931	1205
0.250	---	---	1410

THIS FASTENER HAS ONLY BEEN TESTED IN THE SHEET GAGES SHOWN IN THIS TABLE. DESIGN DATA FOR SHEET GAGES OR DIAMETERS OTHER THAN THOSE SHOWN HERE CANNOT BE EXTRAPOLATED.

Rivet shear strength[d]	664	1030	1480
	Yield Strength, lbs[e]		
Sheet thickness, in.:			
0.040	143	---	---
0.050	235	224	---
0.063	310	371	370
0.071	330	431	491
0.080	353	486	572
0.090	379	518	662
0.100	404	549	713
0.125	468	629	808
0.160	557	740	914
0.190	---	835	1055
0.250	---	---	1280
Head height [ref.], in.	0.042	0.055	0.070

a Data supplied by Allfast Fastening Systems Inc.
b Loads developed from tests with hole diameters of 0.130, 0.162, and 0.194, +/- 0.001 inch.
c The values in the table above the horizontal line in each column are for knife-edge conditions, and the use of fasteners in this condition is undesirable. The use of knife-edge conditions in the design of military aircraft requires specific approval of the procuring activity.
d Rivet shear strength is documented on AF3212 standards drawing.
e Permanent set at yield load: 4% of nominal diameter.

Table 8.1.3.2.2(v). Static Joint Strength of Blind Flush Head Locked Spindle Aluminum Alloy Rivets in Machine-Countersunk Aluminum Alloy Sheet

Rivet Type	CR3212 (F_{su} = 51 ksi approx.)[a]		
Sheet Material	Clad 2024-T3		
Rivet Diameter, in. (Nominal Hole Diameter, in.)[b]	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)
	Ultimate Strength, lbs.		
Sheet thickness, in.:			
0.040	297[c, d]	---	---
0.050	342[d]	462[c, d]	---
0.063	401[d]	535[d]	683[c, d]
0.071	437[d]	580[d]	737[d]
0.080	477	630[d]	798[d]
0.090	513	687[d]	865[d]
0.100	536	743	932
0.125	594	834	1100

THIS FASTENER HAS ONLY BEEN TESTED IN THE SHEET GAGES SHOWN IN THIS TABLE. DESIGN DATA FOR SHEET GAGES OR DIAMETERS OTHER THAN THOSE SHOWN HERE CANNOT BE EXTRAPOLATED.

	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)
Rivet shear strength[e]	664	1030	1480
	Yield Strength, lbs[f]		
Sheet thickness, in.:			
0.040	131	---	---
0.050	181	204	---
0.063	247	286	317
0.071	287	336	377
0.080	333	393	444
0.090	361	456	520
0.100	371	518	595
0.125	394	576	783
Head height [ref.], in.	0.042	0.055	0.070

[a] Data supplied by Textron Aerospace Fasteners.

[b] Loads developed from tests with hole diameters of 0.130, 0.162, and 0.194, +/- 0.001 inch.

[c] The values in the table above the horizontal line in each column are for knife-edge conditions, and the use of fasteners in this condition is undesirable. The use of knife-edge conditions in the design of military aircraft requires specific approval of the procuring activity.

[d] Yield value is less than 2/3 of indicated ultimate strength value.

[e] Rivet shear strength is documented on CR3212 standards drawing.

[f] Permanent set at yield load: 4% of nominal diameter.

Table 8.1.3.2.2(w). Static Joint Strength of Blind Flush Head Locked Spindle Aluminum Alloy Rivets in Machine-Countersunk Aluminum Alloy Sheet

Rivet Type	AF3242 (F_{su} = 51 ksi approx.)[a]		
Sheet Material	Clad 2024-T3		
Rivet Diameter, in. (Nominal Hole Diameter, in.)[b]	1/8 (0.144)	5/32 (0.178)	3/16 (0.207)
	Ultimate Strength, lbs.		
Sheet thickness, in.:			
0.032	193[c]	---	---
0.040	250	299[c]	---
0.050	321	387	---
0.063	414	501	573[c]
0.071	470	571	654
0.080	524	651	746
0.090	550	738	849
0.100	577	804	951
0.125	643	886	1120
0.160	736	1000	1250
0.190	814	---	1365

THIS FASTENER HAS ONLY BEEN TESTED IN THE SHEET GAGES SHOWN IN THIS TABLE. DESIGN DATA FOR SHEET GAGES OR DIAMETERS OTHER THAN THOSE SHOWN HERE CANNOT BE EXTRAPOLATED.

	1/8 (0.144)	5/32 (0.178)	3/16 (0.207)
Rivet shear strength[d]	814	1245	1685
	Yield Strength, lbs[e]		
Sheet thickness, in.:			
0.032	192	---	---
0.040	250	298	---
0.050	321	387	---
0.063	414	501	573
0.071	470	571	654
0.080	524	651	746
0.090	550	738	849
0.100	577	804	951
0.125	643	886	1120
0.160	736	1000	1250
0.190	814	---	1365
Head height (ref.), in.	0.035	0.047	0.063

[a] Data supplied by Allfast Fastening Systems Inc.

[b] Loads developed from tests with hole diameters of 0.144, 0.178, and 0.207, +/-0.001 inch.

[c] The values in the table above the horizontal line in each column are for knife-edge conditions, and the use of fasteners in this condition is undesirable. The use of knife-edge conditions in the design of military aircraft requires the specific approval of the procuring activity.

[d] Rivet shear strength is documented on AF3242 standards drawing.

[e] Permanent set at yield load: 4% of nominal diameter.

Table 8.1.3.2.2(x). Static Joint Strength of Blind Flush Head Locked Spindle Aluminum Alloy Rivets in Machine-Countersunk Aluminum Alloy Sheet

Rivet Type	CR3242 (F_{su} = 51 ksi approx.)[a]		
Sheet Material	Clad 2024-T3		
Rivet Diameter, in. (Nominal Hole Diameter, in.)[b]	1/8 (0.144)	5/32 (0.178)	3/16 (0.207)
	Ultimate Strength, lbs.		
Sheet thickness, in.:			
0.032	245[c,d]	---	---
0.040	302	378[c,d]	---
0.050	374	467	---
0.063	467	582	681[c]
0.071	568	653	764
0.080	584	732	856
0.090	602	872	959
0.100	620	894	1165
0.125	664	950	1230

THIS FASTENER HAS ONLY BEEN TESTED IN THE SHEET GAGES SHOWN IN THIS TABLE. DESIGN DATA FOR SHEET GAGES OR DIAMETERS OTHER THAN THOSE SHOWN HERE CANNOT BE EXTRAPOLATED.

Rivet shear strength[e]	814	1245	1685
	Yield Strength, lbs[f]		
Sheet thickness, in.:			
0.032	158	---	---
0.040	206	245	---
0.050	265	318	---
0.063	330	413	472
0.071	361	471	540
0.080	395	514	616
0.090	434	562	678
0.100	473	609	734
0.125	569	729	873
Head height (ref.), in.	0.035	0.047	0.063

[a] Data supplied by Textron Aerospace Fasteners.

[b] Loads developed from tests with hole diameters of 0.144, 0.178, and 0.207, +/-0.001 inch.

[c] The values in the table above the horizontal line in each column are for knife-edge conditions, and the use of fasteners in this condition is undesirable. The use of knife-edge conditions in the design of military aircraft requires the specific approval of the procuring activity.

[d] Yield value is less than 2/3 of indicated ultimate strength value.

[e] Rivet shear strength is documented on CR3242 standards drawing.

[f] Permanent set at yield load: 4% of nominal diameter.

Table 8.1.3.2.2(y). Static Joint Strength of Blind Flush Head Locked Spindle Aluminum Alloy Rivets in Machine-Countersunk Aluminum Alloy Sheet

Rivet Type	HC3242 (F_{su} = 51 ksi approx.)[a]		
Sheet Material	Clad 2024-T3		
Rivet Diameter, in. (Nominal Hole Diameter, in.[b]	1/8 (0.144)	5/32 (0.178)	3/16 (0.207)
	Ultimate Strength, lbs.		
Sheet thickness, in.:			
0.032	267[c,d]	---	---
0.040	310	411[c,d]	---
0.050	363	477	---
0.063	433	563	682[c]
0.071	475	616	744
0.080	522	675	813
0.090	560	741	889
0.100	597	803	966
0.125	690	918	1130
0.160	814	1075	1320
0.190	---	1215	1480
0.250	---	---	1685

THIS FASTENER HAS ONLY BEEN TESTED IN THE SHEET GAGES SHOWN IN THIS TABLE. DESIGN DATA FOR SHEET GAGES OR DIAMETERS OTHER THAN THOSE SHOWN HERE CANNOT BE EXTRAPOLATED.

Rivet shear strength[e]	814	1245	1685
	Yield Strength, lbs[f]		
Sheet thickness, in.:			
0.032	138	---	---
0.040	218	217	---
0.050	317	340	---
0.063	433	500	529
0.071	475	598	643
0.080	510	675	772
0.090	527	741	889
0.100	543	781	966
0.125	585	833	1075
0.160	644	906	1160
0.190	---	968	1235
0.250	---	---	1375
Head height (ref.), in.	0.035	0.047	0.063

a Data supplied by Huck International Inc.

b Loads developed from tests with hole diameters of 0.144, 0.178, and 0.207, +/-0.001 inch.

c The values in the table above the horizontal line in each column are for knife-edge conditions, and the use of fasteners in this condition is undesirable. The use of knife-edge conditions in the design of military aircraft requires the specific approval of the procuring activity.

d Yield value is less than 2/3 of indicated ultimate strength value.

e Rivet shear strength is documented on HC3242 standards drawing.

f Permanent set at yield load: 4% of nominal diameter.

Table 8.1.3.2.2(z). Static Joint Strength of Blind Flush Head Locked Spindle Aluminum Alloy Rivets in Aluminum Alloy Sheet

Rivet Type	AF3222 (F_{su} = 50 ksi approx.)[a]		
Sheet Material	Clad 2024-T3		
Rivet Diameter, in. (Nominal Hole Diameter, in.)[b]	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)
	Ultimate Strength, lbs.		
Sheet thickness, in.:			
0.040	202[c]	...	...
0.050	287	316[c]	...
0.063	388	452	492[c]
0.071	412	536	593
0.080	439	608	706
0.090	469	645	832
0.100	498	683	891
0.125	573	775	1000
0.160	664	905	1155
0.190	...	1015	1290
0.250	...	1030	1480
Rivet shear strength[d]	664	1030	1480
	Yield Strength[e], lbs.		
Sheet thickness, in.:			
0.040	160	...	...
0.050	216	249	...
0.063	290	341	383
0.071	335	397	451
0.080	379	460	527
0.090	421	531	611
0.100	462	591	696
0.125	566	720	880
0.160	664	901	1095
0.190	...	1015	1280
0.250	...	1030	1480
Head height (ref.), in.	0.042	0.055	0.070

[a] Data supplied by Allfast Fastening Systems Inc.

[b] Loads developed from tests with hole diameters of 0.130, 0.162, and 0.194, +/- 0.001 inch.

[c] Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in the design of military aircraft requires specific approval of the procuring agency.

[d] Rivet shear strength as documented in Allfast Fastening Systems Inc. P-127.

[e] Permanent set at yield load: 4% of nominal diameter.

Table 8.1.3.2.2(aa). Static Joint Strength of Flush Head 5056 Aluminum Alloy Rivets in Clad Aluminum Alloy Sheet

Rivet Type	CR3222 (F_{su} = 50 ksi approx.)[a]		
Sheet Material	Clad 2024-T3		
Rivet Diameter, in. (Nominal Hole Diameter, in.)[b]	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)
	Ultimate Strength, lbs.		
Sheet thickness, in.:			
0.040	286[c,d]	...	...
0.050	328[d]	445[c,d]	...
0.063	382[d]	513[d]	658[c,d]
0.071	416	555[d]	708[d]
0.080	454	602[d]	764[d]
0.090	496	654	827[d]
0.100	528	706	889
0.125	589	821	1045
0.160	664	928	1215
0.190	...	1020	1325
0.250	...	1030	1480
Rivet shear strength[e]	664	1030	1480
	Yield Strength[f], lbs.		
Sheet thickness, in.:			
0.040	158	...	...
0.050	199	247	...
0.063	252	313	373
0.071	285	354	422
0.080	322	399	476
0.090	362	450	537
0.100	384	501	598
0.125	425	597	750
0.160	483	669	881
0.190	...	731	955
0.250	...	854	1100
Head height (ref.), in.	0.041	0.054	0.069

a Data supplied by Textron Aerospace Fasteners.

b Loads developed from tests with hole diameters of 0.130, 0.162, and 0.194, +/- 0.0005 inch.

c Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in the design of military aircraft requires the specific approval of the procuring agency.

d Yield values is less than 2/3 of indicated ultimate strength value.

e Rivet shear strength as documented in Textron Aerospace Fasteners PS-CMR-3000.

f Permanent set at yield load: 4% of nominal diameter.

Table 8.1.3.2.3(a). Static Joint Strength of Blind 100° Flush Head A-286 Bolts in Machine-Countersunk Aluminum Alloy Sheet and Plate

Fastener Type	MS21140[a] (F_{su} = 95 ksi)				
Sheet and Plate Material	Clad 7075-T6 and T651				
Fastener Diameter, in. (Nominal Shank Diameter, in.)	5/32 (0.163)	3/16 (0.198)	1/4 (0.259)	5/16 (0.311)	3/8 (0.373)
	Ultimate Strength, lbs				
Sheet or plate thickness, in.:					
0.071	1165[b,c]	...	...	...	...
0.080	1330[b]	1600[b,c]	...	...	...
0.090	1515[b]	1805[b]	...	...	...
0.100	1700[b]	2020[b]	2615[b,c]	...	...
0.125	1980[b]	2595[b]	3295[b]	3935[b,c]	...
0.160	...	2925[b]	4335[b]	5080[b]	6010[b,c]
0.190	...	...	5005[b]	6150[b]	7205[b]
0.200	...	...	...	6520[b]	6580[b]
0.250	...	...	...	7215[b]	9810[b]
0.312	...	...	...	...	10380[b]
Fastener shear strength[d]	1980	2925	5005	7215	10380
	Yield Strength[e], lbs				
Sheet or plate thickness, in.:					
0.071	478	...	...	...	...
0.080	584	627	...	...	...
0.090	702	730	...	...	...
0.100	819	901	1025	...	...
0.125	1115	1260	1435	1540	...
0.160	...	1760	2090	2285	2430
0.190	...	...	2655	2965	3235
0.200	...	...	...	3190	3510
0.250	...	...	...	4320	4860
0.312	...	...	...	...	6460
Head height (ref.), in.	0.074	0.082	0.108	0.140	0.168

[a] Data supplied by Huck Manufacturing Company.

[b] Yield value is less than 2/3 of the indicated ultimate strength value.

[c] Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.

[d] Fastener shear strength is documented in MIL-F-8975.

[e] Permanent set at yield load: 4% of nominal diameter (revised May 1, 1986, from the greater of 0.012 inch or 4% of nominal diameter).

Table 8.1.3.2.3(b$_1$). Static Joint Strength of Blind 100° Flush Head Alloy Steel Fasteners in Machine-Countersunk Aluminum Alloy Sheet and Plate

Fastener Type	MS90353, MS90353S, and MS90353U[a] (F_{su} = 112 ksi)				
Sheet and Plate Material	Clad 2024-T3 and T351				
Fastener Diameter, in. . . . . (Nominal Shank Diameter, in.) .	5/32 (0.163)	3/16 (0.198)	1/4 (0.259)	5/16 (0.311)	3/8 (0.373)
	Ultimate Strength, lbs				
Sheet or plate thickness, in.:					
0.071	1120[b,c]	...	...	...	...
0.080	1305[b]	1480[b,c]	...	...	...
0.090	1510[b]	1735[b]	...	...	...
0.100	1740[b]	2000[b]	2380[b,c]	...	...
0.125	2080[b]	2670[b]	3210[b]	3625[b,c]	...
0.160	2340[b]	3195[b]	4440[b]	5060[b]	5700[b,c]
0.190	...	3450[b]	5090[b]	6310[b]	7180[b]
0.250	...	...	5900[b]	7860[b]	9890[b]
0.312	...	...	...	8500[b]	11600[b]
0.375	...	...	...	...	12200[b]
Fastener shear strength[d]	2340	3450	5900	8500	12200
	Yield Strength[e], lbs				
Sheet or plate thickness, in.:					
0.071	403	...	...	...	...
0.080	513	501	...	...	...
0.090	636	652	...	...	...
0.100	759	799	1045	...	...
0.125	989	1170	1525	1620	...
0.160	1170	1510	2200	2430	2610
0.190	...	1700	2700	3120	3440
0.250	...	...	3330	4170	5095
0.312	...	...	...	4955	6175
0.375	...	...	...	...	7135
Head height (ref.), in.	0.072	0.080	0.105	0.137	0.165

a Data supplied by Huck Manufacturing Company.

b Yield strength value is less than 2/3 of indicated ultimate strength value.

c Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.

d Fastener shear strength is documented in MIL-F-81177.

e Permanent set at yield load: 4% of nominal diameter.

Table 8.1.3.2.3(b_2). Static Joint Strength of Blind 100° Flush Head Alloy Steel Fasteners in Machine-Countersunk Aluminum Alloy Sheet and Plate

Rivet Type	MS90353[a] (F_{su} = 112 ksi)				
Sheet and Plate Material	Clad or Bare 7075-T6 and T651				
Fastener Diameter, in. (Nominal Hole Diameter, in.)	5/32 (0.163)	3/16 (0.198)	1/4 (0.259)	5/16 (0.311)	3/8 (0.373)
	Ultimate Strength, lbs				
Sheet or plate thickness, in.:					
0.071	1360[b,c]	...	...	...	...
0.080	1535[c]	1830[b,c]	...	...	...
0.090	1710[c]	2090[c]	...	...	...
0.100	1880[c]	2330[c]	2970[b,c]	...	...
0.125	2200[c]	2825[c]	3805[c]	4490[b,c]	...
0.160	2340	3365	4760[c]	5850[c]	6960[b,c]
0.190	...	3450	5370[c]	6790[c]	8310[c]
0.250	...	...	5900	8290[c]	10450[c]
0.312	...	...	...	8500	12200
0.375	...	...	...	...	12200
Fastener shear strength[d]	2340	3450	5900	8500	12200
	Yield Strength[e], lbs				
Sheet or plate thickness, in.:					
0.071	557	...	...	...	...
0.080	666	757	...	...	...
0.090	787	875	...	...	...
0.100	909	1025	1240	...	...
0.125	1215	1395	1640	1860	...
0.160	1640	1910	2315	2590	2850
0.190	...	2355	2895	3290	3675
0.250	...	...	4055	4680	5345
0.312	...	...	...	6125	7075
0.375	...	...	...	...	8830
Head height (ref.), in.	0.072	0.080	0.105	0.137	0.165

[a] Data supplied by Huck Manufacturing Company.

[b] Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.

[c] Yield value is less than 2/3 of indicated ultimate strength value.

[d] Fastener shear strength is documented in MIL-F-81177.

[e] Permanent set at yield load: 4% of nominal diameter revised May 1, 1986, from the greater of 0.012 inch or 4% of nominal diameters.

Table 8.1.3.2.3(c). Static Joint Strength of Blind 100° Flush Head Alloy Steel Fasteners in Machine-Countersunk Aluminum Alloy Sheet and Plate

Fastener Type	FF-200[a]		FF-260[a]		FF-312[a]	
Sheet and Plate Material	Clad 2024-T42	Clad 7075-T6	Clad 2024-T42	Clad 7075-T6	Clad 2024-T42	Clad 7075-T6
Fastener Diameter, in. (Nominal Shank Diameter, in.)	3/16 (0.198)	3/16 (0.198)	1/4 (0.259)	1/4 (0.259)	5/16 (0.311)	5/16 (0.311)
	Ultimate Strength, lbs					
Sheet or plate thickness, in.:						
0.071	1220[b,c]	1360[b,c]	...	...	...	...
0.080	1380[b]	1500[b]	...	...	...	...
0.090	1520[b]	1620[b]	...	...	...	...
0.100	1650[b]	1740[b]	2250[b,c]	2700[b,c]	...	...
0.125	1890[b]	1960	2940[b]	3220[b]	2720[c]	3080[b,c]
0.160	2160	2200	3390[b]	3570[b]	3600[b]	3940[b]
0.190	2400	2420	3730[b]	2860[b]	4490[b]	4810[b]
0.250	2620	2620	4260[b]	4320	5550[b]	6000[b]
0.312	...	...	4500	4500	6000[b]	...
Fastener shear strength[d]	2620	2620	4500	4500	6000	6000
	Yield Strength[e], lbs					
Sheet or plate thickness, in.:						
0.071	685	850	...	...	...	...
0.080	770	930	...	...	...	...
0.090	870	1025	...	...	...	...
0.100	980	1130	1120	1280	...	...
0.125	1200	1350	1380	1600	1440	1540
0.160	1500	1640	1700	2050	1820	1980
0.190	1800	1960	2010	2470	2200	2520
0.250	2400	2550	2600	3190	2950	3710
0.312	...	...	3200	3880	3690	...
Head height (ref.), in.	0.077		0.102		0.134	

[a] Data supplied by Monogram Aerospace Fasteners.

[b] Yield value is less than 2/3 of indicated ultimate strength value.

[c] Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.

[d] Fastener shear strength is documented in NAS1675.

[e] Permanent set at yield load: the greater of 0.012 inch or 4% of nominal diameter.

Table 8.1.3.2.3(d). Static Joint Strength of Blind 100° Flush Head Alloy Steel Fasteners in Machine-Countersunk Aluminum Alloy Sheet

Fastener Type	NS 100[a]		
Sheet Material	Clad 7075-T6		
Fastener Diameter, in. . . . . (Nominal Shank Diameter, in.)	5/32 (0.163)	3/16 (0.198)	1/4 (0.259)
	Ultimate Strength, lbs		
Sheet thickness, in.:			
0.063	1085[b,c]	...	...
0.071	1295[b]	1400[b,c]	...
0.080	1525[b]	1710[b]	...
0.090	1695[b]	2020[b]	...
0.100	1830[b]	2335[b]	2715[b,c]
0.125	2170[b]	2745[b]	3765[b]
0.160	2190	3325[b]	4615[b]
0.190	...	3325[b]	5280[b]
0.250	...	...	5690[b]
Fastener shear strength[d]	2190	3325	5690
	Yield Strength[e], lbs		
Sheet thickness, in.:			
0.063	516	...	...
0.071	602	690	...
0.080	698	805	...
0.090	804	936	...
0.100	911	1065	1300
0.125	1180	1390	1725
0.160	1500	1835	2320
0.190	...	2165	2830
0.250	...	...	3725
Head height (ref.), in.	0.069	0.077	0.102

[a] Data supplied by Monogram Aerospace Fasteners.

[b] Yield value is less than 2/3 of the indicated ultimate strength value.

[c] Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.

[d] Fastener shear strength values are A basis from analysis of test data.

[e] Permanent set at yield load: 4% of nominal diameter (revised May 1, 1985, from the greater of 0.012 inch or 4% of nominal diameter).

Table 8.1.3.2.3(e). Static Joint Strength of Blind 100° Flush Head Aluminum Alloy Fasteners in Machine-Countersunk Aluminum Alloy Sheet

Fastener Type	SSHFA-200[a] (F_{su} = 50 ksi)		SSHFA-260[a] (F_{su} = 50 ksi)	
Sheet Material	Clad 2024-T42	Clad 7075-T6	Clad 2024-T42	Clad 7075-T6
Fastener Diameter, in. (Nominal Shank Diameter, in.)	3/16 (0.198)	3/16 (0.198)	1/4 (0.259)	1/4 (0.259)
	Ultimate Strength, lbs			
Sheet thickness, in.:				
0.050	500[b]	590[b]	...	...
0.063	640	750	...	...
0.071	790	880	...	...
0.080	1040	1060	1310[b]	1480[b]
0.090	1270	1270	1480	1650
0.100	1450	1450	1680	1850
0.125	1550	1550	2010	2250
0.160	...	...	2300	2650
0.190	...	...	2520	...
0.250	...	...	2650	...
Fastener shear strength[c]	1550	1550	2650	2650
	Yield Strength[d], lbs			
Sheet thickness, in.:				
0.050	500	520	...	...
0.063	630	700	...	...
0.071	740	800	...	...
0.080	860	915	940	1160
0.090	990	1040	1080	1300
0.100	1130	1180	1230	1460
0.125	1340	1420	1550	1790
0.160	...	...	1980	2240
0.190	...	...	2420	...
0.250	...	...	2650	...
Head height (ref.), in.	0.061	0.061	0.088	0.088

[a] Data supplied by Monogram Aerospace Fasteners.

[b] Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.

[c] Fastener shear strength is documented in NAS1675.

[d] Permanent set at yield load: the greater of 0.012 inch or 4% of nominal diameter.

Table 8.1.3.2.3(f). Static Joint Strength of Blind 100° Flush Head Alloy Steel Fasteners in Machine-Countersunk Aluminum Alloy Sheet and Plate

Fastener Type	PLT-150[a] (F_{su} = 112 ksi) (H-11 Nut and screw, Inconel X-750 or A-286 Sleeve)			
Sheet or Plate Material	Clad 7075-T6 and T651			
Fastener Diameter, in. (Nominal Shank Diameter, in.)	5/32 (0.163)	3/16 (0.198)	1/4 (0.259)	3/8 (0.373)
	Ultimate Strength, lbs			
Sheet or plate thickness, in.:				
0.063	1120[b,c]	...	...	...
0.071	1320[b]	1470[b,c]	...	...
0.080	1550[b]	1755[b]	...	...
0.090	1730[b]	2060[b]	...	...
0.100	1885[b]	2350[b]	2820[b,c]	...
0.125	2300[b]	2850[b]	3825[b]	...
0.160	2340[b]	3450[b]	4790[b]	6695[b,c]
0.190	...	...	5570[b]	8440[b]
0.250	...	...	5900[b]	10700[b]
0.312	...	...	...	12250[b]
Fastener shear strength[d]	2340	3450	5900	12250
	Yield Strength[e], lbs			
Sheet or plate thickness, in.:				
0.063	534	...	...	...
0.071	615	730	...	...
0.080	705	830	...	...
0.090	805	953	...	...
0.100	906	1075	1345	...
0.125	1235	1390	1750	...
0.160	1545	1910	2310	3160
0.190	...	...	2965	3850
0.250	...	...	3840	5395
0.312	...	...	...	6985
Head height (ref.), in.	0.069	0.077	0.102	0.160

[a] Data supplied by Voi-Shan Industries (Inconel X-750 Sleeve) and Monogram Aerospace Fasteners (A-286 Sleeve).

[b] Yield value is less than 2/3 of the indicated ultimate strength value.

[c] Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.

[d] Fastener shear strength based on area computed from nominal shank diameter in Table 9.4.1.2(a) and F_{su} = 112 ksi.

[e] Permanent set at yield load: 4% of nominal diameter (revised May 1, 1985, from the greater of 0.012 inch or 4% of nominal diameter).

Table 8.1.3.2.3(g). Static Joint Strength of Blind 100° Flush Head Alloy Steel Fasteners in Machine-Countersunk Aluminum Alloy Sheet and Plate

Fastener Type	NAS1670-L[a]				
Sheet and Plate Material	Clad 7075-T6 and T651				
Fastener Diameter, in.[b] . . . . (Nominal Shank Diameter, in.)	5/32 (0.163)	3/16 (0.198)	1/4 (0.259)	5/16 (0.311)	3/8 (0.373)
	Ultimate Strength, lbs				
Sheet or plate thickness, in.:					
0.063	1110[c,d]	...	...	...	...
0.071	1230[c]	1530[c,d]	...	...	...
0.080	1365[c]	1700[c]	...	...	...
0.090	1525[c]	1885[c]	...	...	...
0.100	1678[c]	2065[c]	2800[c,d]	...	...
0.125	1678	2530[c]	3400[c]	4165[c,d]	...
0.160	1678	2620[c]	4255[c]	5190[c]	6350[c,d]
0.190	...	2620	4500[c]	6000[c]	7395[c]
0.250	...	...	4500	6000	9625[c]
0.312	...	...	...	...	9750
0.375	...	...	...	...	9750
Fastener shear strength[e]	1678	2620	4500	6000	9750
	Yield Strength[f], lbs				
Sheet or plate thickness, in.:					
0.063	500	...	...	...	...
0.071	601	647	...	...	...
0.080	711	788	...	...	...
0.090	802	941	...	...	...
0.100	887	1085	1255	...	...
0.125	1105	1340	1770	1930	...
0.160	1405	1700	2250	2720	3055
0.190	...	2020	2655	3200	3890
0.250	...	...	3480	4185	5020
0.312	...	...	...	...	6280
0.375	...	...	...	...	7520
Head height (ref.), in.	0.069	0.077	0.102	0.134	0.160

[a] Data supplied by Monogram Aerospace Fasteners.

[b] Fasteners installed in 0.165/0.166, 0.200/0.201, 0.261/0.262, 0.312/0.313, 0.375/0.376 inch holes.

[c] Yield value is less than 2/3 of the indicated ultimate strength value.

[d] Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.

[e] Fastener shear strength is documented in NAS1675.

[f] Permanent set at yield load: 4% of nominal diameter.

Table 8.1.3.2.3(h). Static Joint Strength of Blind 100° Flush Head Aluminum Alloy Fasteners in Machine-Countersunk Aluminum Alloy Sheet

Fastener Type	NAS1674-L[a]		
Sheet Material	Clad 7075-T6		
Fastener Diameter, in. (Nominal Shank Diameter, in.)[b]	5/32 (0.163)	3/16 (0.198)	1/4 (0.259)
	Ultimate Strength, lbs		
Sheet thickness, in.:			
0.050	548[c]	...	...
0.063	756[c]	853	...
0.071	882[c]	1010	...
0.080	960	1185	...
0.090	...	1375	1645
0.100	...	1550	1900
0.125	...	...	2535
0.160	...	...	2650
Fastener shear strength[d]	960	1550	2650
	Yield Strength[e], lbs		
Sheet thickness, in.:			
0.050	356	...	...
0.063	481	666	...
0.071	561	774	...
0.080	650	892	...
0.090	...	1025	1275
0.100	...	1155	1450
0.125	...	...	1880
0.160	...	...	2480
Head height (ref.), in.	0.049	0.061	0.088

[a] Data supplied by Monogram Aerospace Fasteners.

[b] Fasteners installed in 0.165/0.166, 0.199/0.200, 0.260/0.261 inch holes.

[c] Yield value is less than 2/3 of the indicated ultimate strength value.

[d] Fastener shear strength is documented in NAS1675.

[e] Permanent set at yield load: 4% of nominal diameter.

8.1.4 SWAGED COLLAR/UPSET-PIN FASTENERS — The strengths shown in the following tables are applicable only when grip lengths and hole tolerances are as recommended by respective fastener manufacturers. For some fastener systems, permanent set at yield load may be increased if hole sizes greater than those listed in the applicable table are used. This condition may exist even though the test hole size lies within the manufacturer's recommended hole size range (refer to Section 9.4.1.3.3).

The ultimate allowable shear load for lockbolts and lockbolt stumps may be obtained from Table 8.1.4 for the appropriate shear stress level. Tensile strengths of lockbolts and lockbolt stumps also are contained in Table 8.1.4.

For lockbolts under combined loading of shear and tension installed in material having a thickness large enough to make the shear cutoff strength critical for shear loading, the following interaction equations are applicable:

Steel lockbolts, $R_t + R_s^{10} = 1.0$
7075-T6 lockbolts, $R_t + R_s^{5} = 1.0$

where R_t and R_s are the ratios of applied load to allowable load in tension and shear, respectively.

Unless otherwise specified, yield load is defined in Section 9.4.1.3.3 as the load which results in a joint permanent set equal to 4% D, where D is the decimal equivalent of the fastener shank diameter, as defined in 9.4.1.2(a).

8.1.4.1 *Protruding-Head Swaged Collar Fastener Joints* — Tables 8.1.4.1(a) and (b) contain joint allowables for various protruding-head swaged collar fastener/sheet material combinations. It has been shown that protruding shear head (representative configurations are NAS 2406 to NAS 2412 and M43859/1) fastener joints may not develop the full bearing strength of joint material. Therefore, static allowable loads for protruding shear head fasteners must be established from test data using the criteria specified in Section 9.4.1. For shear joints with protruding tension head fasteners, the load per fastener at which shear or bearing type of failure occurs is calculated separately and the lower of the two governs the design. Allowable shear loads are obtained from Table 8.1.4.

The design bearing stresses for various materials at room and other temperatures are given in strength properties stated for each alloy or group of alloys, and are applicable to joints with pins in cylindrical holes and where $t/D \geq 0.18$. Where $t/D < 0.18$, tests to substantiate yield and ultimate bearing strengths must be performed. These bearing stresses are applicable only for design of rigid joints where there is no possibility of relative motion of the parts joined without deformation of such parts.

For convenience, "unit" sheet bearing strengths for pins, based on bearing stress of 100 ksi and nominal fastener diameters, are given in Table 8.1.5.1. The strength for a specific combination of fastener, sheet thickness, and sheet material is obtained by multiplying the proper "unit" strength by the ratio of material allowable bearing stress (ksi) to 100.

8.1.4.2 *Flush-Head Swaged Collar Fastener Joints* — Tables 8.1.4.2(a) through (j) contain joint allowables for various flush-head swaged collar fastener/sheet material combinations. The allowable loads for flush-head swaged collar fasteners were established from test data using the following criteria, unless otherwise noted in the footnotes of individual tables.

Ultimate Load — Design allowable ultimate load as defined in Section 9.7.1.5. Prior to 2003 this value was computed as the average ultimate test load divided by a factor of 1.15. This factor is not applicable to shear strength cutoff values which may be either the procurement specification shear strength (S value) of the fastener or, if no specification exists, a statistical value determined from test results.

The allowable loads shown for flush-head swaged collar fasteners are applicable to joints having e/D equal to or greater than 2.0.

For machine countersunk joints, the sheet gage specified in the tables is that of countersunk sheet. When the noncountersunk sheet is thinner than the countersunk sheet, the bearing allowable for the noncountersunk sheet-fastener combination should be computed, compared to the table value, and the lower of the two values selected.

Table 8.1.4. Ultimate Single-Shear and Tensile Strengths of Lockbolts and Lockbolt Stumps[a]

Nominal Diameter (inches)	Heat Treated Alloy Steel[b](160 ksi)			7075-T6[c]	
	Single-Shear Strength, lbs.	Tensile Strength, lbs.		Single-Shear Strength, lbs.	Tensile Strength, lbs.
		Tensile Type[d]	Shear Type[e]	Tensile Type[d]	
		NAS 1456 thru 1462 NAS 1465 thru 1472 NAS 1475 thru 1482 NAS 1486 thru 1492 NAS 1496 thru 1502	NAS 1414 thru 1422 NAS 1424 thru 1432 NAS 1436 thru 1442 NAS 1446 thru 1452	NAS 1516 thru 1522 NAS 1525 thru 1532 NAS 1535 thru 1542 NAS 1546 thru 1552 NAS 1556 thru 1562	
5/32	2007[f]/1822[g]	1100[f]	705[g]	960[f]	740[f]
3/16	2623	2210	1105	1260	1195
1/4	4660	4080	2040	2185	2200
5/16	7290	6500[d]	3250	3450	3500
3/8	10490	10100[h]	5050	4970	5455

[a] Lockbolts are pull-gun driven; lockbolt stumps are hammer or squeeze driven.

[b] Used with 2024-T4 aluminum alloy collar, NAS 1080.

[c] Used with 6061-T6 aluminum alloy collar.

[d] Tensile type have a higher head and more grooves than the shear type and can be either protruding or 100° flush head. Strength value listed refers to lowest strength fastener configuration within this type.

[e] Shear type have shorter head and less grooves than the tensile type and can be either protruding or 100° flush head. Strength values listed refer to lowest strength fastener configuration within this type.

[f] Available as lockbolt only (0.164 dia. for #8 lockbolts).

[g] Available as lockbolt stump only (0.156 dia. for 5/32 stumps).

[h] Five groove design on lockbolts.

Table 8.1.4.1(a). Static Joint Strength of Protruding Shear Head Ti-6Al-4V Cherrybuck Fasteners in Aluminum Alloy Sheet

Fastener Type	CSR 925[a] (F_{su} = 95 ksi)		
Sheet Material	Clad 7075-T6		
Fastener Diameter, in. . . . . (Nominal Shank Diameter, in.)[b] . . .	5/32 (0.164)	3/16 (0.190)	1/4 (0.250)
	Ultimate Strength, lbs.		
Sheet thickness, in.:			
0.050	995	...	...
0.063	1227	1442	...
0.071	1371	1607	...
0.080	1532	1792	2415
0.090	1711	2001	2688
0.100	1890	2205	2960
0.125	2007	2694	3641
0.160	...	...	4595
0.190	...	...	4660
Fastener shear strength[c]	2007	2694	4660
	Yield Strength[d], lbs.		
Sheet thickness, in.:			
0.050	861	...	...
0.063	1013	1225	...
0.071	1107	1334	...
0.080	1213	1455	2067
0.090	1331	1592	2246
0.100	1448	1727	2425
0.125	1741	2068	2873
0.160	...	...	3499
0.190	...	...	4036

a Data supplied by Cherry Fasteners.
b Fasteners installed in clearance holes (0.0005" - 0.002").
c Fastener shear strength based on area computed from nominal shank diameters in Table 9.7.1.1 and F_{su} = 95 ksi.
d Permanent set at yield load: 4% of nominal diameter.

Table 8.1.4.1(b). Static Joint Strength of Protruding Shear Head Ti-6Al-4V Cherrybuck Fasteners in Aluminum Alloy Sheet

Fastener Type	CSR 925[a] (F_{su} = 95 ksi)		
Sheet Material	Clad 2024-T3		
Fastener Diameter, in. . . . . (Nominal Shank Diameter, in.)[b] . .	5/32 (0.164)	3/16 (0.190)	1/4 (0.250)
	Ultimate Strength, lbs.		
Sheet thickness, in.:			
0.050	807	...	...
0.063	1020	1180	...
0.071	1150	1335	...
0.080	1300	1505	1970
0.090	1465	1695	2220
0.100	1630	1885	2470
0.125	2007	2360	3095
0.160	...	2694	3975
0.190	...	...	4660
Fastener shear strength[c]	2007	2694	4660
	Yield Strength[d], lbs.		
Sheet thickness, in.:			
0.050	619	...	...
0.063	747	889	...
0.071	827	981	...
0.080	916	1085	1495
0.090	1015	1200	1645
0.100	1115	1315	1795
0.125	1360	1600	2175
0.160	...	2000	2705
0.190	...	...	3155

a Data supplied by Cherry Fasteners.

b Fasteners installed in clearance holes (0.0005" - 0.002").

c Fastener shear strength based on area computed from nominal diameters in Table 9.7.1.1 and F_{su} = 95 ksi.

d Permanent set at yield load: 4% of nominal diameter.

Table 8.1.4.2(a). Static Joint Strength of 100° Flush Shear Head Alloy Steel Lockbolt Fasteners in Machine-Countersunk Aluminum Alloy Sheet and Plate

Fastener Type	NAS 1436-1442[a] (F_{su} = 95 ksi)			
Sheet and Plate Material	Clad 7075-T6 and T651			
Fastener Diameter, in. (Nominal Shank Diameter, in.)	3/16 (0.190)	1/4 (0.250)	5/16 (0.312)	3/8 (0.375)
	Ultimate Strength, lbs			
Sheet or plate thickness, in.:				
0.071	1684	...	...	...
0.080	1875	...	...	...
0.090	2077	...	...	...
0.100	2286	3075	...	...
0.125	2620	3750	4811	...
0.160	...	4625	5994[b]	7350
0.190	...	4650	6993	8554
0.250	...	...	7300	10435
0.312	...	...	...	10500
Fastener shear strength[c]	2620	4650	7300	10500
	Yield Strength[d], lbs			
Sheet or plate thickness, in.:				
0.071	1405	...	...	...
0.080	1598	...	...	...
0.090	1717	...	...	...
0.100	1850	2395	...	...
0.125	2232	2790	3327	...
0.160	...	3415	3851	5656
0.190	...	3765	4666	6342
0.250	...	...	5248	7910
0.312	...	...	...	8946
Head height (max.), in.	0.049	0.063	0.071	0.081

[a] Data supplied by Huck Manufacturing Company.
[b] Yield value is less than 2/3 of the indicated ultimate strength value.
[c] Fastener shear strength is documented in NAS 1413.
[d] Permanent set at yield load: the greater of 0.012 inch or 4% of nominal diameter.

Table 8.1.4.2(b). Static Joint Strength of 100° Flush Shear/Tension Head Alloy Steel Lockbolt Fasteners in Machine-Countersunk Aluminum Alloy Sheet and Plate

Fastener Type	NAS 7024-7032[a,b] (F_{su} = 108 ksi)					
Sheet and Plate Material	Clad 7075-T6 and T651					
Fastener Diameter, in. . . . . (Nominal Shank Diameter, in.) .	1/8 (0.125)	5/32 (0.156)	3/16 (0.190)	1/4 (0.250)	5/16 (0.312)	3/8 (0.375)
	Ultimate Strength, lbs					
Sheet or plate thickness, in.:						
0.040	563[c]	...	...	...	...	...
0.050	846[d]	881[c]	1071[c]	...	...	...
0.063	1040[d]	1341[d]	1398	...	...	...
0.071	1147	1494[d]	1743[d]	2001[c]	...	...
0.080	1231	1645[d]	2083[d]	2256	...	...
0.090	1289	1813	2288[d]	2823	3071[c]	...
0.100	1325	1921	2493[d]	3390[d]	3425	4225[c]
0.125	...	2070	2878	4140[d]	5200[d]	5500
0.160	...	...	3060	4930	6490	8080[d]
0.190	...	...	...	5280	7530	8725[d]
0.250	...	...	...	5300	7870	10010
0.312	...	...	...	...	8220	11270
0.324	...	...	...	...	8280	11340
0.375	...	...	...	...	...	11620
0.433	...	...	...	...	...	11930
Fastener shear strength[e]	1325	2070	3060	5300	8280	11930
	Yield Strength[f], lbs					
Sheet or plate thickness, in.:						
0.040	426	...	...	...	...	...
0.050	537	666	804	...	...	...
0.063	682	846	1024	...	...	...
0.071	770	957	1159	1508	...	...
0.080	870	1082	1311	1708	...	...
0.090	981	1221	1430	1931	2392	...
0.100	1092	1360	1649	2152	2669	3177
0.125	...	1705	2071	2709	3363	4010
0.160	...	...	2595	3486	4340	4975
0.190	...	...	...	4050	5170	5760
0.250	...	...	...	4140	6210	7340
0.312	...	...	...	...	7040	8730
0.324	...	...	...	...	7200	8810
0.375	...	...	...	...	...	9160
0.433	...	...	...	...	...	9560
Head height (ref.), in.	0.042	0.050	0.060	0.077	0.094	0.111

a Data supplied by Huck Manufacturing Company.
b Used with NAS1080K aluminum alloy collar.
c Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.
d Yield value is less than 2/3 of indicated ultimate strength value.
e Fastener shear strength is documented in NAS1413.
f Permanent set at yield load: the greater of 0.012 inch or 4% of nominal diameter.

Table 8.1.4.2(c). Static Joint Strength of 100° Flush Shear Head Ti-6Al-4V Cherrybuck Fasteners in Machine-Countersunk Aluminum Alloy Sheet

Fastener Type	CSR 924[a] (F_{su} = 95 ksi)		
Sheet Material	Clad 7075-T6		
Fastener Diameter, in. (Nominal Shank Diameter, in.)[b]	5/32 (0.164)	3/16 (0.190)	1/4 (0.250)
	Ultimate Strength, lbs.		
Sheet thickness, in.:			
0.050	941	...	...
0.063	1207	1383	...
0.071	1385	1588	...
0.080	1557	1779	2281
0.090	1775	2050	2594
0.100	1876	2263	2919
0.125	1950	2542	3765
0.160	2007	2660	4387
0.190	...	2694	4525
0.250	...	...	4660
Fastener shear strength[b]	2007	2694	4660
	Yield Strength[c], lbs.		
Sheet thickness, in.:			
0.050	659	...	...
0.063	887	985	...
0.071	1022	1148	...
0.080	1116	1325	1625
0.090	1189	1480	1894
0.100	1257	1545	2162
0.125	1393	1733	2619
0.160	1608	1978	2950
0.190	...	2191	3231
0.250	...	...	3794
Head height (ref.), in.	0.034	0.046	0.060

[a] Data supplied by Cherry Fasteners.

[b] Fastener shear strength based on area computed from nominal shank diameter in Table 9.7.1.1 and F_{su} = 95 ksi.

[c] Permanent set at yield load: 4% of nominal diameter.

Table 8.1.4.2(d). Static Joint Strength of 100° Flush Shear Head Ti-6Al-4V Cherrybuck Fasteners in Machine-Countersunk Aluminum Alloy Sheet

Fastener Type	CSR 924[a] (F_{su} = 95 ksi)		
Sheet Material	Clad 2024-T3		
Fastener Diameter, in. (Nominal Shank Diameter, in.)[b]	5/32 (0.164)	3/16 (0.190)	1/4 (0.250)
	Ultimate Strength, lbs.		
Sheet thickness, in.:			
0.050	737	...	...
0.063	1019	1118	...
0.071	1152	1319	...
0.080	1279[c]	1509	1837
0.090	1419[c]	1673[c]	2168
0.100	1560[c]	1834[c]	2500
0.125	1898[c]	2242[c]	3036[c]
0.160	2007[c]	2680[c]	3786[c]
0.190	...	2694	4404[c]
0.250	...	...	4660
Fastener shear strength[d]	2007	2694	4660
	Yield Strength[e], lbs.		
Sheet thickness, in.:			
0.050	511	...	...
0.063	712	778	...
0.071	786	922	...
0.080	840	1039	1276
0.090	900	1109	1513
0.100	960	1178	1750
0.125	1110	1352	1979
0.160	1321	1596	2300
0.190	...	1805	2575
0.250	...	...	3125
Head height (ref.), in.	0.034	0.046	0.060

a Data supplied by Cherry Fasteners.
b Fasteners installed in clearance holes (0.0005 - 0.002).
c Yield load is less than 2/3 of indicated ultimate.
d Fastener shear strength based on area computed from nominal shank diameter in Table 9.7.1.1 and F_{su} = 95 ksi.
e Permanent set at yield load: 4% of nominal diameter.

Table 8.1.4.2(e). Static Joint Strength of 100° Flush Shear Head A-286 Rivets in Machine-Countersunk Aluminum Alloy Sheet

Fastener Type	HSR201[a] (F_{su} = 95 ksi)		
Sheet Material	7075-T6		
Fastener Diameter, in. . . . . (Nominal Shank Diameter, in.)[b] . .	5/32 (0.164)	3/16 (0.190)	1/4 (0.250)
	Ultimate Strength, lbs.		
Sheet thickness, in.:			
0.050	1055	1095	...
0.063	1330	1545	2030
0.071	1500	1740	2285
0.080	1690	1955	2575
0.090	1900	2200	2895
0.100	2007	2445	3220
0.125	...	2694	4025
0.160	...	...	4660
Fastener shear strength[c]	2007	2694	4660
	Yield Strength[d], lbs.		
Sheet thickness, in.:			
0.050	835	870	...
0.063	1055	1225	1605
0.071	1185	1380	1810
0.080	1340	1550	2040
0.090	1505	1745	2295
0.100	1675	1940	2550
0.125	...	2420	3190
0.160	...	...	4180
Head height (nom.), in.	0.040	0.046	0.060

[a] Data supplied by Hi-Shear Corporation.

[b] Hole Size: Fastener installed in 0.000 interference to 0.005 clearance.

[c] Fastener shear strength based on area computed from nominal shank diameter in Table 9.7.1.1 and F_{su} = 95 ksi.

[d] Permanent set at yield load: 4% of nominal diameter.

Table 8.1.4.2(f). Static Joint Strength of 100° Flush Shear Head Ti-8Mo-8V-2Fe-3Al Rivets in Machine-Countersunk Aluminum Alloy Sheet

Rivet Type	HSR101[a] (F_{su} = 95 ksi)		
Sheet Material	7075-T6		
Rivet Diameter, in. . . . . (Nominal Shank Diameter, in.)[b] . .	5/32 (0.164)	3/16 (0.190)	1/4 (0.250)
	Ultimate Strength, lbs.		
Sheet thickness, in.:			
0.050	1040	1205	...
0.063	1310	1520	2000
0.071	1480	1715	2255
0.080	1665	1930	2540
0.090	1875	2170	2855
0.100	2007	2410	3175
0.125	...	2694	3965
0.160	...	...	4660
Rivet shear strength[c]	2007	2694	4660
	Yield Strength[d], lbs.		
Sheet thickness, in.:			
0.050	797	921	...
0.063	1005	1165	1530
0.071	1130	1310	1725
0.080	1275	1475	1945
0.090	1435	1660	2185
0.100	1595	1845	2430
0.125	...	2310	3035
0.160	...	...	3885
Head height (nom.), in.	0.040	0.046	0.060

a Data supplied by Hi-Shear Corporation.
b Hole Size: Fastener installed in 0.000 interference to 0.005 clearance.
c Fastener shear strength based on area computed from nominal shank diameter in Table 9.7.1.1 and 1/4 = 0.250 and F_{su} = 95 ksi.
d Permanent set at yield load: 4% of nominal diameter.

Table 8.1.4.2(g). Static Joint Strength of 100° Flush Shear Head Ti-6Al-4V Lockbolt Fasteners in Machine-Countersunk Aluminum Alloy Sheet

Rivet Type	GPL3SC-V Pin[a,b] (F_{su} = 95 ksi), 2SC-3C Collar			
Sheet Material	Clad 7075-T6			
Rivet Diameter, in. (Nominal Shank Diameter, in)[c]	3/16 (0.190)	1/4 (0.250)	5/16 (0.312)	3/8 (0.375)
	Ultimate Strength, lbs.			
Sheet thickness, in.:				
0.050	1105	...	...	...
0.063	1500	1800[d]	...	...
0.071	1740	2125	2430	...
0.080	2020	2485	2865	3170[d]
0.090	2200	2885	3365	3780
0.100	2355	3310	3865	4390
0.125	2694	3945	5135	5880
0.160	...	4660	6245	8005
0.190	...	...	7010	8955
0.250	...	...	7290	10490
Rivet shear strength[e]	2694	4660	7290	10490
	Yield Strength[f], lbs.			
Sheet thickness, in.:				
0.050	948	...	...	...
0.063	1160	1585	...	...
0.071	1290	1755	2265	...
0.080	1435	1945	2500	3090
0.090	1600	2160	2765	3415
0.100	1760	2375	3030	3740
0.125	2095	2910	3705	4535
0.160	...	3585	4640	5670
0.190	...	...	5440	6635
0.250	...	...	6270	8230
Head height (ref.), in.	0.048	0.063	0.070	0.081

a Data supplied by Huck Manufacturing Company and Voi-Shan Industries.

b Aluminum coated per NAS 4006.

c Hole Size: Fastener installed in 0.005" interference to 0.0005" clearance.

d Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.

e Fastener shear strength based on area computed from nominal shank diameter in Table 9.7.1.1 and 1/4 = 0.250 and F_{su} = 95 ksi.

f Permanent set at yield load: 4% of nominal diameter.

Table 8.1.4.2(h). Static Joint Strength of 100° Flush Shear Head Ti-6Al-4V Lockbolt Fasteners in Machine-Countersunk Aluminum Alloy Sheet and Plate

Rivet Type	GPL3SC-V Pin[a,b] (F_{su} = 95 ksi), 2SC-3C Collar			
Sheet Material	Clad 2024-T3			
Rivet Diameter, in. . . . . (Nominal Shank Diameter, in.)[c] .	3/16 (0.190)	1/4 (0.250)	5/16 (0.312)	3/8 (0.375)
Sheet thickness, in.:	Ultimate Strength, lbs.			
0.050	938	...	...	...
0.063	1255	1535[d]	...	...
0.071	1455	1795	2085	...
0.080	1680	2085	2440	2740[f]
0.090	1920[e]	2410	2845	3230
0.100	2080[e]	2735	3245	3725
0.125	2460[e]	3470[e]	4270	4930
0.160	2694	4175[e]	5505[e]	6645
0.190	...	4590[e]	6260[e]	7885[e]
0.250	...	4660	7230	9705[e]
0.312	...	...	7290	10490
0.375	...	...	...	...
Rivet shear strength[f]	2694	4660	7290	10490
Sheet thickness, in.:	Yield Strength[g], lbs.			
0.050	777	...	...	...
0.063	945	1285	...	...
0.071	1050	1435	1810	...
0.080	1140	1590	2030	2440
0.090	1230	1760	2260	2750
0.100	1320	1910	2475	3065
0.125	1545	2205	2975	3705
0.160	1860	2620	3495	4475
0.190	...	2975	3935	5010
0.250	...	3685	4820	6075
0.312	...	...	5740	7175
Head height (ref.), in.	0.048	0.063	0.070	0.081

a Data supplied by Huck Manufacturing Company and Voi-Shan Industries.
b Aluminum coated per NAS 4006.
c Hole size: Fasteners installed in 0.005" interference to 0.0005" clearance.
d Values above line are for knife-edge condition and the use of fasteners in this condition is undersirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.
e Yield load is less than 2/3 of indicated ultimate.
f Fastener shear strength based on area computed from nominal shank diameter in Table 9.7.1.1 and F_{su} = 95 ksi.
g Permanent set at yield load: 4% of nominal diameter.

Table 8.1.4.2(i). Static Joint Strength of 100° Flush Shear Head Ti-6Al-4V Lockbolt Fasteners in Machine-Countersunk Aluminum Alloy Sheet and Plate

Rivet Type	LGPL2SC-V Pin[a,b] (F_{su} = 95 ksi), 3SLC-C Collar			
Sheet Material	Clad 7075-T6			
Rivet Diameter, in. . . . . (Nominal Shank Diameter, in.)[c] .	3/16 (0.190)	1/4 (0.250)	5/16 (0.312)	3/8 (0.375)
Sheet thickness, in.:	Ultimate Strength, lbs.			
0.050	1040	...	...	...
0.063	1370	1710[d]	...	...
0.071	1575	1980	2345	...
0.080	1805	2280	2715	3105[d]
0.090	2060	2615	3130	3620
0.100	2315	2950	3550	4130
0.125	2590	3790	4605	5375
0.160	2694	4430	6070	7150
0.190	...	4660	6750	8660
0.250	...	...	7290	10154
0.312	...	...	...	10490
Rivet shear strength[e]	2694	4660	7290	10490
Sheet thickness, in.:	Yield Strength[f], lbs.			
0.050	948	...	...	...
0.063	1160	1585	...	...
0.071	1290	1755	2265	...
0.080	1435	1945	2500	3090
0.090	1600	2160	2765	3415
0.100	1760	2375	3030	3740
0.125	2095	2910	3705	4535
0.160	2395	3585	4640	5670
0.190	...	3900	5440	6635
0.250	...	...	6270	8230
0.312	...	...	...	9255
Head height (ref.), in.	0.048	0.063	0.070	0.081

a Data supplied by Huck Manufacturing Company and Voi-Shan Industries.

b Aluminum coated per NAS 4006.

c Hole size: Fasteners installed in 0.005" interference to 0.0005" clearance.

d Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.

e Fastener shear strength based on area computed from nominal shank diameter in Table 9.7.1.1 and F_{su} = 95 ksi.

f Permanent set at yield load: 4% of nominal diameter.

Table 8.1.4.2(j). Static Joint Strength of 100° Flush Shear Head Ti-6Al-4V Lockbolt Fasteners in Machine-Countersunk Aluminum Alloy Sheet and Plate

Rivet Type	LGPL2SC-V Pin[a,b] (F_{su} = 95 ksi), 3SLC-C Collar			
Sheet Material	Clad 2024-T3			
Rivet Diameter, in. (Nominal Shank Diameter, in.)[c]	3/16 (0.190)	1/4 (0.250)	5/16 (0.312)	3/8 (0.375)
Sheet thickness, in.:	Ultimate Strength, lbs.			
0.050	836	...	...	...
0.063	1180	1350[d]	...	...
0.071	1395	1630	1775	...
0.080	1640	1950	2155	2270[d]
0.090	1900[e]	2300	2595	2800
0.100	2115[e]	2650	3035	3335
0.125	2340	3530[e]	4140	4640
0.160	2655	4000	5645[e]	6500
0.190	2694	4355	6085	8080[e]
0.250	...	4660	6965	9180
0.312	...	...	7290	10270
0.375	...	...	...	10490
Rivet shear strength[f]	2694	4660	7290	10490
Sheet thickness, in.:	Yield Strength[g], lbs.			
0.050	733	...	...	...
0.063	901	1220	...	...
0.071	1005	1360	1745	...
0.080	1125	1515	1930	2270
0.090	1250	1685	2140	2635
0.100	1380	1855	2355	2895
0.125	1640	2280	2895	3530
0.160	1910	2795	3640	4430
0.190	2140	3100	4230	5200
0.250	...	3700	4985	6440
0.312	...	...	5760	7375
0.375	...	...	...	8325
Head height (ref.), in.	0.048	0.063	0.070	0.081

a Data supplied by Huck Manufacturing Company and Voi-Shan Industries.
b Aluminum coated per NAS 4006.
c Hole size: Fasteners installed in 0.0005" interference to 0.0005" clearance.
d Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.
e Yield load is less than 2/3 of indicated ultimate.
f Fastener shear strength based on area computed from nominal shank diameter in Table 9.7.1.1 and F_{su} = 95 ksi.
g Permanent set at yield load: 4% of nominal diameter.

8.1.5 THREADED FASTENERS — The strengths shown in the following tables are applicable only when grip lengths and hole tolerances are as recommended by the respective fastener manufacturers. For some fastener systems, permanent set at yield load may be increased if hole sizes greater than those listed in the applicable table are used. This condition may exist even though the test hole size lies within the manufacturer's recommended hole size range (refer to Section 9.7.1.1).

The ultimate single shear strength of threaded fasteners at full diameter is shown in Table 8.1.5(a). The ultimate tensile strength of threaded fasteners is shown in Tables 8.1.5(b_1) and (b_2). In both tables values shown are a product of the indicated strength and area, with the area based on the following:

Shear — Based on basic shank diameter.

Tension — Based on the nominal minor diameter of the thread as published in Table 2.21 of Handbook H-28.

For any given threaded fastener the allowable load will be chosen using an appropriate category corresponding to minimum tensile strength, shear strength, or other requirements of the pertinent procurement specification.

It is recognized that some procurement specifications may provide higher tensile strengths than those reported in Tables 8.1.5(b_1) and (b_2), since they may be based on a larger effective area than shown in the table. The values listed herein have been judged acceptable for design, acknowledging that they may be slightly conservative since they are based on the nominal minor diameter area.

Unless otherwise specified, the yield load is defined in Section 9.7.1.1 for threaded fasteners as the load at which the joint permanent is set equal to 0.04D, where D is the decimal equivalent of the fastener shank diameter as defined in Table 9.4.1.2(a).

8.1.5.1 *Protruding-Head Threaded Fastener Joints* — It has been shown that protruding shear head (representative configuration is NAS 1982) fastener joints may not develop the full bearing strength of the joint material. Therefore, static allowable loads for protruding shear head fasteners must be established from test data using the criteria specified in Section 9.7. For shear joints with protruding tension head fasteners, the load per fastener at which shear or bearing type of failure occurs is separately calculated, and the lower of the two values so determined governs the design. Allowable shear loads may be obtained from Table 8.1.5(a).

The design bearing stresses for various materials at room and other temperatures are given in the properties for each alloy or group of alloys, and are applicable to joints with fasteners in cylindrical holds and where $t/D \geq 0.18$. Where $t/D < 0.18$, tests to substantiate yield and ultimate bearing strengths must be performed. These bearing stresses are applicable only for design of rigid joints where there is no possibility of relative motion of the parts joined without deformation of such parts.

For convenience, "unit" sheet bearing strengths for threaded fasteners, based on a strength of 100 ksi and nominal fastener diameters, are given in Table 8.1.5.1. The strength for a specific combination of fasteners, sheet thickness, and sheet material is obtained by multiplying the proper "unit" strength by the ratio of material allowable bearing stress (ksi) to 100.

The following interaction formula is applicable to AN3 series bolts under combined shear and tension loading: $R_s^3 + R_t^2 = 1.0$, where R_s and R_t are ratios of applied load to allowable load in shear and tension, respectively.

8.1.5.2 *Flush-Head Threaded Fastener Joints* — Tables 8.1.5.2(a) through (o) contain joint allowables for various flush-head threaded fastener/sheet material combinations. Unless otherwise noted, the allowable loads for flush-head threaded fasteners were established from test data using the following criteria;

Ultimate Load — Design allowable ultimate load as defined in Section 9.7.1.5. Prior to 2003 this value was computed as the average ultimate test load divided by a factor of 1.15. This factor is not applicable to shear strength cutoff values which may be either procurement specification shear strength (S value) of the fastener or, if no specification exists, a statistical value determined from test results. It should coincide with shear values from Table 8.1.5(a).

The allowables shown for flush-head threaded fasteners are applicable to joints having e/D equal to or greater than 2.0.

For machine countersunk joints, the sheet gage specified in the tables is that of the countersunk sheet. When the noncountersunk sheet is thinner than the countersunk sheet, the bearing allowable for the noncountersunk sheet-fastener combination should be computed, compared to the table value, and the lower of the two values selected.

Table 8.1.5(a). Ultimate Single Shear Strength of Threaded Fasteners

Shear Stress of Fastener, ksi			35	38	75	90	95	108	125	132	145	156
Fastener Diameter		Basic Shank Area										
in.	Size[a]		Ultimate Single Shear Strength, lbs.									
0.112	#4	0.0098520	345	374	739	887	936	1060	1230	1300	1425	1535
0.125	1/8	0.012272	430	466	920	1105	1165	1325	1530	1620	1775	1910
0.138	#6	0.014957	523	568	1120	1345	1420	1615	1870	1970	2165	2330
0.156	5/32	0.019175	671	729	1435	1725	1820	2070	2395	2530	2780	2990
0.164	#8	0.021124	739	803	1580	1900	2005	2280	2640	2785	3060	3295
0.188	3/16	0.027612	966	1045	2070	2485	2620	2980	3450	3645	4005	4310
0.190	#10	0.028353	992	1075	2125	2550	2690	3060	3540	3740	4110	4420
0.216	#12	0.036644	1280	1390	2745	3295	3480	3955	4580	4840	5315	5720
0.219	7/32	0.037582	1315	1425	2815	3380	3570	4060	4700	4960	5445	5860
0.250	1/4	0.049087	1715	1865	3680	4420	4660	5300	6140	6480	7115	7660
0.312	5/16	0.076699	2680	2915	5750	6900	7290	8280	9590	10100	11100	11950
0.375	3/8	0.11045	3865	4200	8280	9935	10450	11900	13800	14550	16000	17200
0.438	7/16	0.15033	5260	5710	11250	13500	14250	16200	18750	19800	21750	23450
0.500	1/2	0.19635	6870	7460	14700	17650	18650	21200	24500	25900	28450	30600
0.562	9/16	0.24850	8700	9440	18600	22350	23600	26800	31050	32800	36000	38750
0.625	5/8	0.30680	10700	11650	23000	27600	29150	33100	38350	40500	44500	47900
0.750	3/4	0.44179	15450	16750	33100	39750	42000	47700	55200	58300	64000	68900
0.875	7/8	0.60132	21050	22850	45100	54100	57100	64900	75200	79400	87200	93800
1.000	1	0.78540	27450	29850	58900	70700	74600	84800	98200	103500	113500	122500
1.125	1-1/8	0.99402	34750	37750	74600	89500	94400	107000	124000	131000	144000	155000
1.250	1-1/4	1.2272	43000	46600	92000	110000	116500	132500	153000	162000	177500	191000
1.375	1-3/8	1.4849	52000	56400	111000	133500	141000	160000	185500	196000	215000	231500
1.500	1-1/2	1.7671	61800	67100	132500	159000	167500	190500	220500	233000	256000	275500

a Fractional equivalent or screw number.

Table 8.1.5(b_1). Ultimate Tensile Strength of Threaded Fasteners

Tensile Stress of Fastener, ksi			55	62	62.5	125	140	160	180
Fastener Diameter in.	Fastener Diameter Size[a]	Nominal Minor Area[b]	MIL-S-7742 Ultimate Tensile Strength, lbs.[c,d]						
0.112	4-40	0.0050896	280	316	318	636	713	814	916
0.138	6-32	0.0076821	423	476	480	960	1075	1225	1380
0.164	8-32	0.012233	673	758	765	1525	1710	1955	2200
0.190	10-32	0.018074	994	1120	1130	2255	2530	2890	3250
0.250	1/4-28	0.033394	1835	2070	2085	4170	4680	5340	6010
0.312	5/16-24	0.053666	2950	3325	3350	6710	7510	8590	9660
0.375	3/8-24	0.082397	4530	5110	5150	10300	11500	13150	14800
0.438	7/16-20	0.11115	6110	6890	6950	13850	15550	17750	20000
0.500	1/2-20	0.15116	8310	9370	9450	18900	21150	24150	27200
0.562	9/16-18	0.19190	10550	11900	11950	23950	26850	30700	34500
0.625	5/8-18	0.24349	13350	15100	15200	30400	34050	38950	43800
0.750	3/4-16	0.35605	19550	22050	22250	44500	49800	57000	64100
0.875	7/8-14	0.48695	26750	30150	30400	60900	68200	77900	87700
1.000	1-12	0.63307	34800	39250	39550	79100	88600	101000	114000
1.125	1-1/8-12	0.82162	45200	50900	51400	102500	115000	131500	147500
1.250	1-1/4-12	1.0347	56900	64200	64700	129000	144500	165500	186000
1.375	1-3/8-12	1.2724	70000	78900	79500	159000	178000	203500	229000
1.500	1-1/2-12	1.5345	84400	95100	95900	191500	214500	245500	276000

[a] Fractional equivalent or number and threads per inch.

[b] The tension fastener allowables above are based on the nominal minor diameter thread area for MIL-S-7742 threads from Table 2.2.1 of Handbook H-28.

[c] Values shown above heavy line are for 2A threads, all other values are for 3A threads.

[d] Nuts and fastener heads designed to develop the ultimate tensile strength of the fastener are required to develop the tabulated tension loads.

Table 8.1.5(b_2). Ultimate Tensile Strength of Threaded Fasteners (Continued)

Tensile Stress of Fastener, ksi			160	180	220	260
Fastener Diameter		Maximum Minor	MIL-S-8879			
in.	Size[a]	Area[b]	Ultimate Tensile Strength, lbs.[c,d]			
0.112	4-40	0.0054367	869	979	1195	1410
0.138	6-32	0.0081553	1305	1465	1790	2120
0.164	8-32	0.012848	2055	2310	2825	3340
0.190	10-32	0.018602	2975	3345	4090	4840
0.250	1/4-28	0.034241	5480	6160	7530	8900
0.312	5/16-24	0.054905	8780	9880	12050	14250
0.375	3/8-24	0.083879	13400	15100	18450	21800
0.438	7/16-20	0.11323	18100	20350	24900	29400
0.500	1/2-20	0.15358	24550	27600	33750	39900
0.562	9/16-18	0.19502	31200	35100	42900	50700
0.625	5/8-18	0.24700	39500	44500	54300	64200
0.750	3/4-16	0.36082	57700	64900	79400	93800
0.875	7/8-14	0.49327	78900	88800	108500	128000
1.000	1-12	0.64156	102500	115500	141000	166500
1.125	1-1/8-12	0.83129	133000	149500	182500	216000
1.250	1-1/4-12	1.0456	167000	188000	230000	271500
1.375	1-3/8-12	1.2844	205500	231000	282500	333500
1.500	1-1/2-12	1.5477	247500	278500	340500	402000

[a] Fractional equivalent or number and threads per inch.

[b] The tension fastener allowables above are based on the maximum minor diameter thread area for MIL-S-8879 threads from Tables II and III of MIL-S-8879.

[c] Values are for 3A threads.

[d] Nuts and fastener heads designed to develop the ultimate tensile strength of the fastener are required to develop the tabulated tension loads.

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Table 8.1.5.1. Unit Bearing Strength of Sheet and Plate in Joints With Threaded Fasteners or Pins; F_{br} = 100 ksi

	Unit Bearing Strength of Sheet for Fastener Diameter Indicated, lbs.[a]													
Fastener, Diameter, in.	0.156	0.164	0.188	0.190	0.250	0.312	0.375	0.438	0.500	0.562	0.625	0.750	0.875	1.000
Thickness, in.														
0.032	500	525	...	...	...	...	...	...	...	...	...	...	...	...
0.036	563	590	675	684	...	...	...	...	...	...	...	...	...	...
0.040	625	656	750	760	...	...	...	...	...	...	...	...	...	...
0.045	704	738	845	855	...	...	...	...	...	...	...	...	...	...
0.050	781	820	940	950	1250	...	...	...	...	...	...	...	...	...
0.063	985	1033	1180	1197	1575	1969	...	...	...	...	...	...	...	...
0.071	1110	1164	1330	1349	1775	2219	2662	...	...	...	...	...	...	...
0.080	1250	1312	1500	1520	2000	2500	3000	3500	...	...	...	...	...	...
0.090	1407	1476	1690	1710	2250	2812	3375	3938	4500	...	...	...	...	...
0.100	1562	1640	1875	1900	2500	3125	3750	4375	5000	...	...	...	...	...
0.125	1953	2050	2340	2375	3125	3906	4688	5469	6250	7030	7812	...	...	...
0.160	2500	2624	3000	3040	4000	5000	6000	7000	8000	9000	10000	12000	...	...
0.200	3125	3280	3750	3800	5000	6250	7500	8750	10000	11250	12500	15000	17500	20000
0.250	3916	4100	4688	4750	6250	7812	9375	10940	12500	14060	15625	18750	21875	25000
0.312	4867	5117	5866	5928	7800	9734	11700	13670	15600	17530	19500	23400	27300	31200
0.375	5850	6150	7050	7125	9375	11700	14063	16425	18750	21075	23400	28125	32810	37500
0.500	7800	8200	9400	9500	12500	15600	18750	21900	25000	28100	31250	37500	43750	50000
0.625	9750	10250	11750	11875	15625	19500	23440	27375	31250	35125	39062	46875	54690	62500
0.750	11700	12300	14100	14250	18750	23400	28125	32850	37500	42150	46875	56250	65625	75000
0.875	13650	14350	16450	16625	21875	27300	32810	38325	43750	49175	56690	65625	76560	87500
1.000	15600	16400	18800	19000	25000	31200	37600	43800	50000	56200	62500	75000	87500	100000

[a] Bearing strengths shown are based on nominal fastener diameter.

Table 8.1.5.2(a_1). Static Joint Strength of 100° Flush Head Alloy Steel Screws in Machine-Countersunk Aluminum Alloy Sheet and Plate

Fastener Type	AN509[a] steel screw (F_{su} = 75 ksi) w/MS20365 or equiv. steel nut				
Sheet and Plate Material	Clad 2024-T3 and T351				
Fastener Diameter, in. . . . . (Nominal Shank Diameter, in.) .	3/16 (0.190)	1/4 (0.250)	5/16 (0.312)	3/8 (0.375)	½ (0.500)
	Ultimate Strength[e], lbs				
Sheet or plate thickness, in.:					
0.080	1576[b,c]	...	...	...	...
0.090	1726[b]	...	...	...	...
0.100	1877[b]	2567[b,c]	...	...	...
0.125	2126[b]	3054[b]	3922[b,c]	4579[b,c]	...
0.160	...	3536[b]	4722[b]	5878[b]	...
0.190	...	3682	5405[b]	6872[b]	9408[b,c]
0.250	...	...	5750	8280[b]	12201[b]
0.312	...	...	...	8280[b]	14141[b]
0.375	...	...	...	...	14730
Fastener shear strength[d]	2126	3682	5750	8280	14730
	Yield Strength[e,f], lbs				
Sheet or plate thickness, in.:					
0.080	903	...	...	...	...
0.090	989	...	...	...	...
0.100	1084	1490	...	...	...
0.125	1296	1748	2001	2559	...
0.160	1615	2116	2334	2939	...
0.190	...	2484	2702	3361	6012
0.250	...	...	3404	4197	7306
0.312	...	...	...	5092	8452
0.375	...	...	...	...	9996
Head height (ref.), in.	0.080	0.106	0.133	0.159	0.213

a This fastener is no longer manufactured; do not specify for new designs.
b Yield value is less than 2/3 of the indicated ultimate strength value.
c Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.
d Fastener shear strength based on area computed from nominal shank diameters in Table 9.7.1.1 and F_{su} = 75 ksi.
e Test data from which the yield and ultimate strengths were derived can be found in Reference 8.1.5.2.
f Permanent set at yield load: the greater of 0.012 inch or 4% of nominal diameter.

Table 8.1.5.2(a_2). Static Joint Strength of 100° Flush Head Alloy Steel Screws in Machine-Countersunk Aluminum Alloy Sheet and Plate

Fastener Type	AN509[a] steel screw (F_{su} = 75 ksi) w/MS20365 or equiv. steel nut				
Sheet and Plate Material	Clad 7075-T6 and T651				
Fastener Diameter, in. . . . . (Nominal Shank Diameter, in.) .	3/16 (0.190)	1/4 (0.250)	5/16 (0.312)	3/8 (0.375)	½ (0.500)
	Ultimate Strength[b], lbs				
Sheet or plate thickness, in.:					
0.080	1632[c,d]	...	...	...	...
0.090	1762[c]	...	...	...	...
0.100	1892	2723[c,d]	...	...	...
0.125	2126	3109[c]	4180[c,d]	5216[c,d]	...
0.160	...	3551[c]	4858[c]	6193[c]	...
0.190	...	3682	5433[c]	6996[c]	...
0.250	...	...	5750	8280[c]	12421[c,d]
0.312	...	...	...	8280	14185[c]
0.375	...	...	...	...	14730
Fastener shear strength[e]	2126	3682	5750	8280	14730
	Yield Strength[b,f], lbs				
Sheet or plate thickness, in.:					
0.080	965	...	...	...	...
0.090	1063	...	...	...	...
0.100	1179	1600	...	...	...
0.125	1462	1895	2098	2699	...
0.160	...	2363	2501	3088	...
0.190	...	2926	3018	3601	...
0.250	...	...	4312	4868	8041
0.312	...	...	...	6624	9437
0.375	...	...	...	...	11686
Head height (ref.), in.	0.080	0.106	0.133	0.159	0.213

a This fastener is no longer manufactured; do not specify for new designs.

b Test data from which the yield and ultimate strengths were derived can be found in Reference 8.1.5.2.

c Yield value is less than 2/3 of the indicated ultimate strength value.

d Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.

e Fastener shear strength based on area computed from nominal shank diameters in Table 9.7.1.1 and F_{su} = 75 ksi.

f Permanent set at yield load: the greater of 0.012 inch or 4% of nominal diameter.

Table 8.1.5.2(b). Static Joint Strength of 100° Flush Head Stainless Steel (PH13-8Mo-H1000) Fasteners in Machine-Countersunk Titanium Alloy Sheet and Plate

Fastener Type	PBF 11[a] (F_{su} = 125 ksi)			
Sheet and Plate Material	Annealed Ti-6Al-4V			
Rivet Diameter, in. . . . . (Nominal Shank Diameter, in.)[b] . . .	5/32 (0.164)	1/4 (0.250)	3/8 (0.375)	1/2 (0.500)
	Ultimate Strength, lbs			
Sheet or plate thickness, in.:				
0.040	1535[c]	...	...	...
0.050	1963	...	...	...
0.063	2528	3656	...	...
0.071	2640	4213	...	...
0.080	...	4813	6820	...
0.090	...	5438	7818	...
0.100	...	6140	8775	11250[c]
0.125	...	...	11264	14575
0.160	...	...	13810	19250
0.190	...	...	...	23200
0.200	...	...	...	24540
Fastener shear strength[d]	2640	6140	13810	24540
	Yield Strength[e], lbs			
Sheet or plate thickness, in.:				
0.040	1237	...	...	...
0.050	1543	...	...	...
0.063	1947	2969	...	...
0.071	2049	3350	...	...
0.080	...	3756	5667	...
0.090	...	4219	6370	...
0.100	...	4600	7101	9500
0.125	...	...	8789	11825
0.160	...	...	10645	15025
0.190	...	...	...	17825
0.200	...	...	...	18400
Head height (nom.), in.	0.040	0.060	0.077	0.101

a Data supplied by Huck Manufacturing Company and PB Fasteners.

b Fasteners installed in clearance holes (0.0025-0.0030).

c Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.

d Fastener shear strength based on areas computed from indicated nominal shank diameter F_{su} = 125 ksi.

e Permanent set at yield load: 4% of nominal diameter.

Table 8.1.5.2(c). Static Joint Strength of 100° Flush Head Tapered Alloy Steel Fasteners in Machine-Countersunk Aluminum Alloy Sheet and Plate

Fastener Type	TL 100[a] (F_{su} = 108 ksi)					
Sheet and Plate Material	Clad 7075-T6 and T651					
Fastener Diameter, in. . . . . (Nominal Shank Diameter, in.) . .	3/16 (0.1969)	1/4 (0.2585)	5/16 (0.3214)	3/8 (0.3860)	7/16 (0.4490)	½ (0.5122)
	Ultimate Strength, lbs					
Sheet or plate thickness, in.:						
0.100	2435	...	...	...	...	...
0.125	2913	3745	4443	...	...	...
0.160	3290	4831	6017	7016	7993	...
0.190	...	5269	7017	8511	9737	10900
0.250	...	5670	8148	11120	13220	14890
0.285	...	...	8760	11360	15000	17240
0.312	...	...	...	11570	15280	19000
0.344	...	...	...	11800	15560	19800
0.375	...	...	...	12030	15820	20110
0.500	...	...	...	12640	16870	21320
Fastener shear strength[b]	3290	5670	8760	12640	17100	22250
	Yield Strength[c], lbs					
Sheet or plate thickness, in.:						
0.100	1960	...	...	...	...	...
0.125	2350	2990	3818	...	...	...
0.160	2840	3550	4650	5650	6703	...
0.190	...	3970	5308	6596	7806	9045
0.250	...	4830	6450	8209	9903	11560
0.285	...	...	7060	9090	10930	12840
0.312	...	...	...	9680	11780	13930
0.344	...	...	...	10010	12710	14930
0.375	...	...	...	10430	13200	16000
0.500	...	...	...	...	15160	18490
Head height (max.), in.	0.048	0.063	0.070	0.081	0.100	0.110

[a] Data supplied by Briles Manufacturing Company.

[b] Fastener shear strength based on areas computed from indicated nominal shank diameter and F_{su} = 108 ksi.

[c] Permanent set at yield load: the greater of 0.012 inch or 4% of nominal diameter.

Table 8.1.5.2(d). Static Joint Strength of 100° Flush Head Tapered STA Ti-6Al-4V Fasteners in Machine-Countersunk Aluminum Alloy Sheet

Fastener Type	TLV 10[a] (F_{su} = 95 ksi)			
Sheet Material	Clad 7075-T6			
Fastener Diameter, in. (Nominal Shank Diameter, in.)	1/8 (0.1437)	5/32 (0.1688)	3/16 (0.1965)	1/4 (0.2583)
	Ultimate Strength, lbs			
Sheet thickness, in.:				
0.032	488[b]	...	...	...
0.040	610	713[b]	826[b]	...
0.050	768	896	1050	...
0.063	967	1145	1312	1730[b]
0.071	1120	1290	1491	1960
0.080	1260	1470	1690	2223
0.090	1377	1670	1910	2505
0.100	1441	1845	2130	2800
0.125	1530	2010	2580	3540
0.160	1540	2125	2800	4410
0.190	...	...	2880	4750
0.250	...	...	...	4980
Fastener shear strength[c]	1540	2125	2880	4980
	Yield Strength[d], lbs			
Sheet thickness, in.:				
0.032	488	...	...	...
0.040	610	713	826	...
0.050	753	890	1050	...
0.063	925	1118	1301	1730
0.071	1035	1240	1467	1960
0.080	1138	1377	1637	2192
0.090	1238	1522	1806	2455
0.100	1321	1639	1976	2711
0.125	1480	1880	2331	3304
0.160	1540	2111	2683	3986
0.190	...	...	2880	4437
0.250	...	...	...	4980
Head height (max.), in.	0.033	0.041	0.048	0.063

[a] Data supplied by Lockheed Georgia Company.

[b] Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.

[c] Fastener shear strength based on areas computed from indicated nominal shank diameter and F_{su} = 95 ksi.

[d] Permanent set at yield load: the greater of 0.012 inch or 4% of fractional diameter.

Table 8.1.5.2(e). Static Joint Strength of 70° Flush Head Tapered Ti-6Al-4V Fasteners in Non-Matching Machine-Countersunk Aluminum Alloy Sheet and Plate

Fastener Type	HPB-V[a] (F_{su} = 95 ksi)			
Sheet and Plate Material	Clad 7075-T6 and T651			
Fastener Diameter . . . . (Nominal Shank Diameter, in.)[b]	3/16 (0.1976)	1/4 (0.2587)	5/16 (0.3211)	3/8 (0.3850)
Sheet Countersink Angle	82°	82°	82°	75°
	Ultimate Strength, lbs			
Sheet or plate thickness, in.:				
0.063	1355	...	...	...
0.071	1554	2041	...	...
0.080	1710	2296	...	...
0.090	1847	2583	3207	...
0.100	1984	2864	3567	4269
0.125	2319	3293	4454	5336
0.160	2792	3908	5176	6611
0.190	2913	4444	5836	7396
0.250	...	4993	7155	8968
0.312	...	...	7692	10613
0.375	...	...	...	11058
0.500	...	...	...	11058
Fastener shear strength[c]	2913	4993	7692	11058
	Yield Strength[d], lbs			
Sheet or plate thickness, in.:				
0.063	1269	...	...	...
0.071	1429	1874	...	...
0.080	1613	2108	...	...
0.090	1812	2376	2949	...
0.100	1984	2637	3279	3928
0.125	2319	3299	4093	4906
0.160	2718	3908	5176	6285
0.190	2913	4397	5836	7396
0.250	...	4993	6980	8968
0.312	...	...	7692	10257
0.375	...	...	...	11058
0.500	...	...	...	11058
Head height (max.), in.	0.057	0.067	0.076	0.086

[a] Data supplied by PB Fasteners.

[b] Fasteners installed in interference holes (0.0015-0.0048).

[c] Fastener shear strength based on areas computed from the indicated nominal shank diameter and F_{su} = 95 ksi.

[d] Permanent set at yield load: the greater of 0.012 inch or 4% of nominal diameter.

Table 8.1.5.2(f). Static Joint Strength of 100° Flush Shear Head Ti-6Al-4V Fasteners in Machine-Countersunk Aluminum Alloy Sheet

Fastener Type	KLBHV Pin (F_{su} = 95 ksi), KFN 600 Nut[a]				
Sheet Material	Clad 7075-T6				
Fastener Diameter, in. (Nominal Shank Diameter, in.)[b]	5/32 (0.164)	3/16 (0.190)	1/4 (0.250)	5/16 (0.3125)	3/8 (0.375)
	Ultimate Strength, lbs				
Sheet thickness, in.:					
0.040	748[c]	...	...	...	...
0.050	987	1112	...	...	...
0.063	1291	1462	1813[c]	...	...
0.071	1428	1679	2100	...	...
0.080	1571	1888	2438	2902	...
0.090	1722	2058	2794	3322	3867
0.100	1883	2231	3150	3810	4402
0.125	2007	2694	3725	4924	5724
0.160	...	...	4531	4901	7397
0.190	...	...	4660	6790	8452
0.200	...	...	...	7083	8789
0.250	...	...	...	7290	10490
Fastener shear strength[d]	2007	2694	4660	7290	10490
	Yield Strength[e], lbs				
Sheet thickness, in.:					
0.040	594	...	...	...	...
0.050	740	859	...	...	...
0.063	931	1079	1419	...	...
0.071	1049	1213	1600	...	...
0.080	1176	1368	1806	2267	...
0.090	1283	1534	2031	2540	3052
0.100	1375	1675	2250	2824	3375
0.125	1606	1942	2813	3517	4219
0.160	...	...	3306	4455	5386
0.190	...	...	3725	4983	6385
0.200	...	...	...	5168	6581
0.250	...	...	...	6038	7636
Head height (ref.), in.	0.043	0.048	0.063	0.070	0.081

a Data supplied by Kaynar Manufacturing Co., Inc.

b Fasteners installed in interference holes (0.003-0.055).

c Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.

d Fastener shear strength based on areas computed from indicated nominal shank diameter and F_{su} = 95 ksi.

e Permanent set at yield load: 4% of the nominal diameter.

Table 8.1.5.2(g). Static Joint Strength of 100° Flush Shear AISI 431[a] Hi-Lok Fasteners in Aluminum Alloy Sheet and Plate

Rivet Type	HL 61 Pin (F_{su} = 125 ksi), HL 70 Collar[b]			
Sheet and Plate Material	Clad 7075-T6 and T651			
Rivet Diameter (Nominal Shank Diameter, in.)	3/16 (0.190)	1/4 (0.250)	5/16 (0.312)	3/8 (0.375)
	Ultimate Strength, lbs			
Sheet or plate thickness, in.:				
0.090	2327	...	...	...
0.100	2430	3740	...	...
0.125	2695	4080	...	...
0.160	3070	4560	6500[c]	...
0.190	3390	4970	7160	9100
0.250	3544	5800	8320	10230
0.312	...	6140	9590	11390
0.375	...	...	...	12580
0.500	...	...	...	13810
Fastener shear strength[d]	3544	6140	9590	13810
	Yield Strength[e], lbs			
Sheet or plate thickness, in.:				
0.090	1840	...	...	...
0.100	1943	2900	...	...
0.125	2195	3240	...	...
0.160	2540	3700	4030	...
0.190	2840	4020	5430	7120
0.250	3110	4870	6590	8500
0.312	...	5350	7580	9700
0.375	...	...	7890	10410
0.500	...	...	...	12070
Head height (max.), in.	0.049	0.063	0.077	0.051

[a] AISI 431 is prohibited from use in Air Force and Navy structure by MIL-STD-1568 and SD-24, respectively, because of its sensitivity to heat treatment. Use of fasteners made of this material in design of military aerospace structures requires the specific approval of the procuring agency.

[b] Data supplied by Hi-Shear Corporation.

[c] Yield value is less than 2/3 of the indicated ultimate strength value.

[d] Fastener shear strength based on areas computed from the indicated nominal shank diameter and F_{su} = 125 ksi.

[e] Permanent set at yield load: the greater of 0.012 inch or 4% of nominal diameter.

Table 8.1.5.2(h). Static Joint Strength of 100° Flush Shear Head Alloy Steel Hi-Lok Fasteners in Machine-Countersunk Aluminum Alloy Sheet and Plate

Fastener Type	HL 719 Pin (F_{su} = 108 ksi), HL 79 Collar[a]				
Sheet and Plate Material	7075-T6 and T651				
Fastener Diameter, in. (Nominal Shank Diameter, in.)[b]	5/32 (0.164)	3/16 (0.190)	1/4 (0.250)	5/16 (0.312)	3/8 (0.375)
	Ultimate Strength, lbs				
Sheet or plate thickness, in.:					
0.040	734[c]	...	...	...	...
0.050	1044	1131	...	...	...
0.063	1384	1565	1813	...	...
0.071	1518	1820	2216	...	...
0.080	1668	1998	2594	2916	...
0.090	1764	2193	3015	3532	3724
0.100	1825	2345	3338	4059	4516
0.125	1979	2524	3980	5229	6167
0.160	2195	2774	4350	6347	7928
0.190	...	2989	4634	6702	9087
0.250	...	3062	5200	7512	9985
0.312	...	...	5300	8146	10870
0.375	...	...	...	8280	11760
Fastener shear strength[d]	2281	3062	5300	8280	11930
	Yield Strength[e], lbs				
Sheet or plate thickness, in.:					
0.040	690	...	...	...	...
0.050	861	1000	...	...	...
0.063	1086	1261	1664	...	...
0.071	1224	1421	1876	...	...
0.080	1346	1601	2114	2647	...
0.090	1478	1771	2378	2978	3578
0.100	1610	1924	2642	3309	3976
0.125	1845	2308	3210	4136	4970
0.160	2022	2583	3920	5124	6362
0.190	...	2750	4344	5886	7330
0.250	...	3062	4785	6925	9160
0.312	...	...	...	7496	10130
0.375	...	...	...	8158	10820
Head height (nom.), in.	0.040	0.046	0.060	0.067	0.077

[a] Data supplied by Hi-Shear Corporation.

[b] Fasteners installed in interference holes (0.001-0.002).

[c] Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.

[d] Fastener shear strength based on areas computed from indicated nominal shank diameter and F_{su} = 108 ksi.

[e] Permanent set at yield load: the greater of 0.012 inch or 4% of nominal diameter.

Table 8.1.5.2(i). Static Joint Strength of 100° Flush Shear Head Ti-6Al-4V Fasteners in Machine-Countersunk Aluminum Alloy Sheet and Plate

Fastener Type	HL 11 Pin (F_{su} = 95 ksi), HL 70 Collar[a]			
Sheet and Plate Material	Clad 7075-T6 and T651			
Fastener Diameter, in. . . . . (Nominal Shank Diameter, in.)	5/32 (0.164)	3/16 (0.190)	1/4 (0.250)	5/16 (0.312)
	Ultimate Strength, lbs			
Sheet or plate thickness, in.:				
0.040	734[b]	837[b]	...	...
0.050	941	1083	1343[b]	...
0.063	1207	1393	1762	2170[b]
0.071	1385	1588	2012	2463
0.080	1557	1779	2281	2823
0.090	1775	2050	2594	3193
0.100	1876	2263	2919	3631
0.125	1950	2542	3765	4594
0.160	2007	2660	3970	5890
0.190	...	2694	4165	6105
0.250	...	...	4530	6580
0.312	...	...	4660	7050
0.375	...	...	...	7290
Fastener shear strength[c]	2007	2694	4660	7290
	Yield Strength[d], lbs			
Sheet or plate thickness, in.:				
0.040	674	794	...	...
0.050	835	982	1325	...
0.063	1038	1230	1655	2141
0.071	1130	1355	1813	2338
0.080	1230	1480	2062	2620
0.090	1342	1625	2250	2880
0.100	1440	1750	2470	3420
0.125	1670	2020	2930	3860
0.160	1891	2360	3480	4620
0.190	...	2560	3840	5150
0.250	...	...	4440	6170
0.312	...	...	4660	6900
0.375	...	...	...	7290
Head height (nom.), in.	0.040	0.046	0.060	0.067

[a] Data supplied by Hi-Shear Corporation.

[b] Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.

[c] Fastener shear strength based on areas computed from indicated nominal shank diameter and F_{su} = 95 ksi.

[d] Permanent set at yield load: the greater of 0.012 inch or 4% of nominal diameter.

Table 8.1.5.2(j). Static Joint Strength of 100° Flush Shear Head Ti-6Al-6V-2Sn Fasteners in Machine-Countersunk Aluminum Alloy Sheet and Plate

Fastener Type	HL 911 Pin (F_{su} = 108 ksi), HL 70 Collar[a]				
Sheet and Plate Material	Clad 7075-T6 and T651				
Fastener Diameter, in. (Nominal Shank Diameter, in.)	5/32 (0.164)	3/16 (0.190)	1/4 (0.250)	5/16 (0.312)	3/8 (0.375)
	Ultimate Strength, lbs				
Sheet or plate thickness, in.:					
0.040	780[b]	...	...	...	...
0.050	982	1137	1456[b]	...	...
0.063	1264	1458	1863	2287[b]	...
0.071	1426	1642	2094	2570	3096[b]
0.080	1622	1866	2425	2920	3473
0.090	1740	2105	2750	3339	3965
0.100	1794	2310	3063	3777	4415
0.125	1915	2455	3875	4770	5666
0.160	2098	2660	4219	6181	7339
0.190	2252	2840	4450	6483	8788
0.250	2281	3062	4925	7067	9589
0.312	...	...	5300	7670	10362
0.375	...	...	...	8280	11079
0.500	...	...	...	...	11930
Fastener shear strength[c]	2281	3062	5300	8280	11930
	Yield Strength[d], lbs				
Sheet or plate thickness, in.:					
0.040	734	...	...	...	...
0.050	882	1044	1394	...	...
0.063	1076	1300	1750	2190	...
0.071	1184	1406	1938	2472	2995
0.080	1320	1540	2188	2774	3332
0.090	1392	1680	2375	3066	3768
0.100	1480	1810	2569	3358	4120
0.125	1700	2085	3031	4010	5019
0.160	1870	2380	3563	4818	6074
0.190	1978	2530	3937	5354	6749
0.250	2178	2740	4375	6269	8183
0.312	...	...	4687	6883	9209
0.375	...	...	...	7418	9870
0.500	...	...	...	...	11039
Head height (nom.), in.	0.040	0.046	0.060	0.067	0.077

[a] Data supplied by Hi-Shear Corporation.

[b] Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.

[c] Fastener shear strength based on areas computed from indicated nominal shank diameter and F_{su} = 108 ksi.

[d] Permanent set at yield load: the greater of 0.012 inch or 4% of nominal diameter.

Table 8.1.5.2(k). Static Joint Strength of 100° Flush Head Ti-6Al-6V-2Sn or Alloy Steel, Shear Type Fasteners in Machine-Countersunk Aluminum Alloy Sheet

Fastener Type	NAS 4452S and KS 100-FV Pins[a] (F_{su} = 108 ksi), NAS 4445DD Nut			
Sheet Material	7075-T6			
Fastener Diameter, in. (Nominal Shank Diameter, in.)	1/8 (0.138)	5/32 (0.164)	3/16 (0.190)	1/4 (0.250)
	Ultimate Strength, lbs			
Sheet thickness, in.:				
0.040	644	...	...	...
0.050	857	976	1065	...
0.063	1131	1305	1458	1750[b]
0.071	1268	1512	1697	2062
0.080	1428	1703	1964	2406
0.090	1499	1910	2227	2794
0.100	1539	2084	2458	3181
0.125	1615	2200	2848	4063
0.160	...	2281	3036	4900
0.190	...	...	3062	5113
0.250	...	...	...	5300
Fastener shear strength[c]	1615	2281	3062	5300
	Yield Strength[d], lbs			
Sheet thickness, in.:				
0.040	609	...	...	...
0.050	766	906	1029	...
0.063	946	1157	1325	1706
0.071	1044	1278	1505	1956
0.080	1152	1412	1668	2219
0.090	1261	1555	1848	2500
0.100	1320	1694	2014	2762
0.125	1444	1904	2397	3350
0.160	...	2106	2661	4100
0.190	...	...	2845	4419
0.250	...	...	...	4925
Head height (max.), in.	0.037	0.040	0.049	0.063

[a] Data supplied by Huck Manufacturing Company.

[b] Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.

[c] Fastener shear strength is documented in NAS 4444.

[d] Permanent set at yield load: the greater of 0.012 inch or 4% of nominal diameter.

Table 8.1.5.2(l). Static Joint Strength of 70° Flush Head Straight Shank Ti-6Al-4V Fasteners in Non-Matching Machine-Countersunk Aluminum Alloy Sheet and Plate

Fastener Type	HPT-V[a] (F_{su} = 95 ksi)			
Sheet and Plate Material	Clad 7075-T6 and T651			
Fastener Diameter (Nominal Shank Diameter, in.)[b]	3/16 (0.193)	1/4 (0.255)	5/16 (0.3175)	3/8 (0.380)
Sheet Countersink Angle	82°	82°	82°	75°
	Ultimate Strength, lbs			
Sheet or plate thickness, in.:				
0.063	1348	...	...	...
0.071	1546	1970	...	...
0.080	1704	2275	...	...
0.090	1814	2580	3125	...
0.100	1948	2873	3528	4100
0.125	2265	3282	4465	5270
0.160	2700	3868	5171	6642
0.190	2779	4361	5826	7393
0.250	...	4851	7056	8880
0.312	...	...	7521	10396
0.375	...	...	...	10774
Fastener shear strength[c]	2779	4851	7521	10774
	Yield Strength[d], lbs			
Sheet or plate thickness, in.:				
0.063	1180	...	...	...
0.071	1378	1651	...	...
0.080	1590	1944	...	...
0.090	1702	2321	2631	...
0.100	1818	2620	3024	3350
0.125	2112	3055	4133	4664
0.160	2496	3601	4848	6209
0.190	2734	4062	5413	6902
0.250	...	4745	6552	8288
0.312	...	...	7378	9631
0.375	...	...	...	10584
Head height (max.), in.	0.060	0.070	0.080	0.090

[a] Data supplied by PB Fasteners.

[b] Fasteners installed in interference holes (0.0045-0.0055).

[c] Fastener shear strength based on areas computed from the indicated nominal shank diameter and F_{su} = 95 ksi.

[d] Permanent set at yield load: the greater of 0.012 inch or 4% of nominal diameter.

Table 8.1.5.2(m). Static Joint Strength of 100° Flush Shear Head STA Ti-6Al-4V Fasteners in Machine-Countersunk Aluminum Alloy Sheet

Fastener Type	NAS 4452V Pin (F_{su} = 95 ksi), NAS 4445D Nut[a]				
Sheet Material	Clad 7075-T6				
Fastener Diameter, in. (Nominal Shank Diameter, in.)	5/32 (0.164)	3/16 (0.190)	1/4 (0.250)	5/16 (0.312)	3/8 (0.375)
	Ultimate Strength, lbs				
Sheet or plate thickness, in.:					
0.040	766[b]	...	...	...	...
0.050	1092	1173	...	...	...
0.063	1450	1639	1886[b]	...	...
0.071	1633	1889	2290	...	...
0.080	1805	2136	2710	3028	...
0.090	1955	2368	3135	3651	...
0.100	2007	2557	3515	4230	4669
0.125	...	2694	4273	5485	6428
0.160	...	...	4660	6776	8426
0.190	...	...	...	7290	9708
0.250	...	...	...	...	10490
Fastener shear strength[c]	2007	2694	4660	7290	10490
	Yield Strength[d], lbs				
Sheet thickness, in.:					
0.040	712	...	...	...	...
0.050	891	1034	...	...	...
0.063	1103	1295	1712	...	...
0.071	1223	1445	1932	...	...
0.080	1349	1604	2169	2715	...
0.090	1475	1768	2420	3056	...
0.100	1489	1920	2658	3383	4082
0.125	...	2241	3196	4145	5072
0.160	...	...	3812	5076	6321
0.190	...	...	...	5746	7265
0.250	...	...	...	...	8802
Head height (max.), in.	0.040	0.049	0.063	0.077	0.091

[a] Data supplied by Huck Manufacturing Company.

[b] Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.

[c] Fastener shear strength is documented in NAS 4444.

[d] Permanent set at yield load: the greater of 0.012 inch or 4% of nominal diameter.

Table 8.1.5.2(n). Static Joint Strength of Protruding Shear Head Alloy Steel Hi-Lok Fasteners in Aluminum Alloy Sheet

Fastener Type	HL 18 Pin (F_{su} = 95 ksi), HL 70 Collar[a]			
Sheet Material	Clad 7075-T6			
Fastener Diameter, in. (Nominal Shank Diameter, in.)[b]	5/32 (0.164)	3/16 (0.190)	1/4 (0.250)	5/16 (0.312)
Sheet thickness, in.:	Ultimate Strength, lbs.			
0.050	1078	...	...	...
0.063	1353	1559	...	...
0.071	1520	1776	...	...
0.080	1718	1957	2593	...
0.090	1890	2224	2937	...
0.100	1930	2473	3250	4050
0.125	2007	2580	4063	5075
0.160	...	2694	4450	6509
0.190	...	...	4620	6880
0.250	...	...	4660	7290
Rivet shear strength[c]	2007	2694	4660	7290
Sheet thickness, in.:	Yield Strength[d], lbs.			
0.050	976	...	...	...
0.063	1251	1426	...	...
0.071	1430	1624	...	...
0.080	1589	1848	2344	...
0.090	1746	2065	2687	...
0.100	1875	2242	3031	3660
0.125	...	2563	3750	4734
0.160	...	...	4406	6051
0.190	...	...	...	6686

[a] Data supplied by Hi-Shear Corporation.
[b] Fasteners installed in clearance holes (0.0005-0.0025).
[c] Fastener shear strength based on areas computed from indicated nominal shank diameter and F_{su} = 95 ksi.
[d] Permanent set at yield load: the greater of 0.012 inch or 4% of nominal diameter.

Table 8.1.5.2(o). Static Joint Strength of 100° Flush Shear Head Alloy Steel Hi-Lok Fasteners in Machine-Countersunk Aluminum Alloy Sheet

Fastener Type	HL 19 Pin (F_{su} = 95 ksi), HL 70 Collar[a]			
Sheet Material	Clad 7075-T6			
Fastener Diameter, in. (Nominal Shank Diameter, in.)[b]	5/32 (0.164)	3/16 (0.190)	1/4 (0.250)	5/16 (0.312)
Sheet thickness, in.:	Ultimate Strength, lbs.			
0.050	968	...	...	...
0.063	1251	1408	...	...
0.071	1400	1606	...	...
0.080	1595	1823	2344	...
0.090	1815	2050	2675	...
0.100	1903	2300	3000	3660
0.125	2005	2570	3781	4685
0.160	...	2694	4420	6051
0.190	...	...	4625	6832
0.250	...	...	4660	7290
Rivet shear strength[c]	2007	2694	4660	7290
Sheet thickness, in.:	Yield Strength[d], lbs.			
0.050	839	...	...	...
0.063	1031	1191	...	...
0.071	1141	1336	...	...
0.080	1279	1480	2013	...
0.090	1416	1632	2219	...
0.100	1540	1805	2420	3143
0.125	1807	2173	3000	3777
0.160	...	2545	3670	4800
0.190	...	...	4144	5514
0.250	...	...	...	6686
Head height (nom.), in.	0.040	0.046	0.060	0.067

[a] Data supplied by Hi-Shear Corporation.

[b] Fasteners installed in clearance holes (0.0005-0.0025).

[c] Fastener shear strength based on areas computed from indicated nominal shank diameter and F_{su} = 95 ksi.

[d] Permanent set at yield load: the greater of 0.012 inch or 4% of nominal diameter.

8.1.6 SPECIAL FASTENERS — Due to the special nature of this classification of fastener, care must be exercised in their application. Consideration should be given to the proposed fastener application and its compatibility with data presented in this section. In particular, test and analysis methods used for fasteners in this section may necessarily be different than those used in preceding sections.

8.1.6.1 Fastener Sleeves — Fastener sleeves are precision-formed, tubular elements designed to replace oversize fasteners used in the repair of damaged or enlarged holes.

8.1.6.1.1 A-286 ACRES Sleeves in 7075-T6 Aluminum Alloy Sheet and Plate — Analysis of static lap joint data indicates that a single 100° low profile head, A-286 [ACRES Sleeve (part number JK5512C)] installed with titanium or steel Hi-Loks and alloy steel lockbolts (up to 108 ksi F_{su}) provided static joint allowable shear loads equivalent to those developed by the above-noted fasteners when tested without sleeves. Fasteners and sleeves were installed to the same comparable hole tolerance and fit condition as fasteners when tested alone. The analysis was restricted to static lap joint data (in accordance with MIL-STD-1312 Test 4) and equivalency to fastener systems other than those listed above is not implied. Other properties such as tensile strength, preload, fatigue strength, and corrosion characteristics should be verified by test data. When using sleeves, knife-edge conditions should be avoided.

8.1.6.2 Sleeve Bolts — Tables 8.1.6.2(a) and (b) contain joint allowables for various sleeve bolt/sheet material combinations. Sleeve bolts are made of precision-formed aluminum alloy sleeve elements assembled on standard taper shank bolts. When the assembly is placed in a cylindrical hole and the bolt is drawn into the sleeve, the sleeve expands, thus filling the hole and causing an interference-fit condition.

The allowable loads were established from test data using the following criteria:

Ultimate Load — Design allowable ultimate load as defined in Section 9.7.1.5. Prior to 2003 this value was computed as the average ultimate test load divided by a factor of 1.15. This factor is not applicable to shear strength cutoff values which are defined by the procurement specification.

Yield Load — Design allowable yield load as defined in Section 9.7.1.5. Prior to 2003 this value was computed as the average yield test load or the load which results in a joint permanent set equal to 0.04D, where D is the hole size.

The allowable loads shown for flush-head fasteners are applicable to joints having e/D equal to or greater than 2.0.

For machine countersunk joints, the sheet gage specified in the tables herein is that of the countersunk sheet. When the noncountersunk sheet is thinner than the countersunk sheet, the bearing allowable for the noncountersunk sheet-fastener combination should be computed, compared to the table value, and the lower of the two values selected.

Table 8.1.6.2(a). Static Joint Strength of 100° Reduced Flush Head, Alloy Steel Pin, Aluminum Alloy Sleeve, Fastener in Machine-Countersunk Aluminum Alloy Sheet and Plate

Fastener Type	MIL-B-8831/4[a] (F_{su} = 108 ksi)					
Sheet Material	Clad 7075-T6					
Fastener Diameter, in. (Nominal Hole Diameter, in.)[b,c]	3/16 (0.2390)	1/4 (0.3032)	5/16 (0.3695)	3/8 (0.4350)	7/16 (0.5022)	½ (0.5735)
Sheet thickness, in.:	Ultimate Strength, lbs.					
0.100	2585	...	...	...	...	...
0.125	3205	4100	5035	...	...	...
0.160	3290	5205	6385	7560	8790	...
0.190	...	5670	7535	8925	10360	11900
0.250	...	...	8760	11640	13495	15480
0.312	...	...	...	12395	16195	19180
0.375	...	...	...	12640	16625	21265
0.500	...	...	...	...	17100	22250
Rivet shear strength[d]	3290	5670	8760	12640	17100	22250
Sheet thickness, in.:	Yield Strength[e], lbs.					
0.100	2080	...	...	...	...	...
0.125	2570	3300	4075	...	...	...
0.160	3255	4170	5135	6105	7125	...
0.190	...	4915	6040	7175	8360	9635
0.250	...	...	7855	9310	10825	12450
0.312	...	...	...	11520	13375	15360
0.375	...	...	...	12355	15620	18320
0.500	...	...	...	...	...	21570
Sleeve head height (ref.), in.	0.062	0.075	0.082	0.093	0.115	0.120

[a] Data supplied by P.B. Fasteners.

[b] Nominal hole diameter based on $\left(\frac{\text{max. expanded sleeve} - \text{min. hole}}{2}\right) + \text{min. hole}$ using larger expanded diameter from MIL-B-8831/4 dated 23 August 1982.

[c] Fasteners installed to interference levels of 0.0025-0.008 in.

[d] Fastener shear strength is documented in NAS 1724 as 108 ksi.

[e] Permanent set at yield load: 4% of nominal hole diameter.

Table 8.1.6.2(b). Static Joint Strength of 100° Reduced Flush Head, Alloy Steel Pin, Aluminum Alloy Sleeve, Fastener in Machine-Countersunk Aluminum Alloy Sheet and Plate

Fastener Type	MIL-B-8831/4[a] (F_{su} = 108 ksi)					
Sheet Material	Clad 2024-T3					
Fastener Diameter, in. . . . . (Nominal Hole Diameter, in.)[b,c] .	3/16 (0.2390)	1/4 (0.3032)	5/16 (0.3695)	3/8 (0.4350)	7/16 (0.5022)	1/2 (0.5735)
Sheet thickness, in.:	Ultimate Strength, lbs.					
0.100	2175	...	...	...	...	...
0.125	2720	3450	4205	...	...	...
0.160	3290	4415	5380	6335	7315	...
0.190	...	5240	6390	7525	8685	9920
0.250	...	5480	7945	9895	11425	13050
0.312	...	5655	8165	11085	14260	16285
0.375	...	5670	8385	11345	14845	19070
0.500	...	...	8760	11865	15445	19755
0.625	...	...	...	12385	16045	20440
0.750	...	...	...	12640	16645	21225
0.875	...	...	...	...	17100	21805
1.000	...	...	...	...	...	22250
Rivet shear strength[d]	3290	5670	8760	12640	17100	22250
Sheet thickness, in.:	Yield Strength[e], lbs.					
0.100	1575	...	...	...	...	...
0.125	1880	2505	3200	...	...	...
0.160	2310	3050	3865	4720	5655	...
0.190	...	3515	4435	5395	6430	7595
0.250	...	4450	5570	6735	7980	9360
0.312	...	5055	6745	8115	9580	11185
0.375	...	5560	7460	9525	11205	13040
0.500	...	...	8680	11010	13655	16720
0.625	...	...	...	12385	15315	18625
0.750	...	...	...	12640	16645	20520
0.875	...	...	...	...	17100	21805
1.000	...	...	...	...	...	22250
Sleeve head height (ref.), in. . . .	0.062	0.075	0.082	0.093	0.115	0.120

a Data supplied by P.B. Fasteners.

b Nominal hole diameter based on $\left(\frac{\text{max. expanded sleeve} - \text{min. hole}}{2}\right)$ + min. hole using larger expanded diameter from MIL-B-8831/4 dated 23 August 1982.

c Fasteners installed to interference levels of 0.002-0.008 in.

d Fastener shear strength is documented in NAS 1724 as 108 ksi.

e Permanent set at yield load: 4% of nominal hole diameter.

8.2 METALLURGICAL JOINTS

In the design of metallurgical joints, the strength of the joining material (for example, weld metal) and the adjacent parent material must be considered. The joint should be analyzed on the basis of its loading, the specified allowable strengths, dimensions and geometry.

8.2.1 INTRODUCTION AND DEFINITIONS — The allowable strength for both the adjacent parent metal and the weld metal is given below in the particular section dealing with the method of forming used, and the material being joined. The following subparagraphs define certain joining processes.

Welding — Welding consists of joining two or more pieces of metal by applying heat, pressure or both, with or without filler material, to produce a localized union through fusion or recrystallization across the joint interface. Examples of common welding processes include: fusion [inert-gas, shielded-arc welding with tungsten electrode (TIG) and inert-gas shielded metal-arc welding using covered electrodes (MIG)], resistance (spot and seam), and flash. Several terms used in describing various sections of a welded joint are illustrated in Figure 8.2.1.

Brazing — Brazing consists of joining metals by the application of heat causing the flow of a thin layer, capillary thickness, of nonferrous filler metal into the space between the pieces. Bonding results from the intimate contact produced by the dissolution of a small amount of base metal in the molten filler metal, without fusion of the base metal.

8.2.2 WELDED JOINTS — The weld metal section of a joint should be analyzed on the basis of its loading, specified allowable strength, dimensions and geometry. The effects of the parent metal are to be accounted for as specified herein.

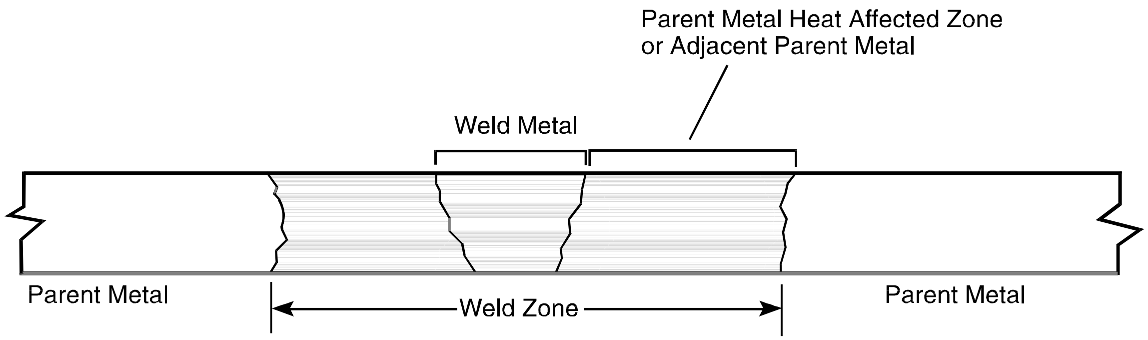


Figure 8.2.1. Schematic diagram of weld and parent metal.

8.2.2.1 *Fusion Welding—Arc and Gas* — Section 9.4.2 contains a detailed discussion of one acceptable method of establishing fusion welding allowables. As stated in that section, other methods can be employed as approved by certifying agencies. The following subsections contain specific information for a number of materials.

8.2.2.1.1 *Strength of Fusion Welded Joints of Steel Alloys* — Allowable fusion weld-metal strengths of steel alloys are shown in Table 8.2.2.1.1(a). Design allowable stresses for the weld metal are based on 85 percent of the respective minimum tensile ultimate test values.

For steel joints welded after heat treatment, the allowable strengths near the weld are given in Tables 8.2.2.1.1(b) and (c).

Table 8.2.2.1.1(a). Strength of Fusion Welded Joints of Steel Alloys

Material	Heat Treatment Subsequent to Welding	Welding Rod or Electrode	F_{su}, ksi	F_{tu}, ksi
Carbon and alloy steels	None	AMS 6457	32	51
		AWSA5.1 classes E6010 and E6013	32	51
Alloy steels	None	AMS 6452	43	72
Alloy steels	Stress relieved	AWSA5.5 class E10013 MIL-E-22200/10, classes MIL-10018-M1	50	85

Table 8.2.2.1.1(b). Allowable Ultimate Tensile Stresses Near Fusion Welds in 4130, 4140, or 8630 Steels[a]

Section Thickness ¼ inch or less	
Type of Joint	Ultimate Tensile Stress, ksi
Tapered joints of 30° or less[b]	90
All others	80

a Welded after heat treatment or normalized after weld.

b Gussets or plate inserts considered 0° taper with centerline.

Table 8.2.2.1.1(c). Allowable Bending Modulus of Rupture Near Fusion Weld in 4130, 4140, 4340, or 8630 Steels[a]

Type of Joint	Bending Modulus of Rupture, ksi
Tapered joints of 30° or less[b]	F_b from Figure 2.8.1.1 for F_{tu} = 90 ksi
All others	0.9 of the values of F_b from Figure 2.8.1.1 for F_{tu} = 90 ksi

a Welded after heat treatment or normalized after weld.

b Gussets or plate inserts considered 0° taper with centerline.

For materials heat treated after welding, the allowable strength in the parent metal near a welded joint may equal the allowable strength for the material in the heat treated condition as given in the tables of design mechanical properties of the specific alloys; however, it should be noted that the weld metal allowables are based on 85 percent of these values.

8.2.2.2 *Flash and Pressure Welding* — The ultimate tensile allowable strength and bending allowable modulus of rupture for flash and pressure welds are given in Tables 8.2.2.2(a) and (b). A higher efficiency may be permitted in special cases by the applicable procuring or certifying agency upon approval of the manufacturer's process specification.

8.2.2.3 *Spot and Seam Welding* — Permission to use spot and seam welding on structural parts is governed by the requirements of the procuring or certifying agency. Table 8.2.2.3 gives the recommended allowable edge distance for spot and seam welds.

8.2.2.3.1 *Design Shear Strengths for Spot and Seam Welds in Uncoated Steels and Nickel and Cobalt Alloys* — The design shear strength for spot welds for these materials are given in Tables 8.2.2.3.1(a) and (b). The thickness ratio of the thickest sheet to the thinnest outer sheet in the combination should not exceed 4:1.

8.2.2.3.1.1 *Effects of Spot-Welds on the Parent Metal Strength of 300 Series Stainless Steel* — In applications of spot welding where ribs, intercostals, or doublers are attached to sheet, either at splices or at other joints on the sheet panels, the allowable ultimate strength of the spot-welded stainless steel sheet will be determined by multiplying the ultimate tensile strength of the sheet (A or S-value) by the appropriate efficiency factors shown in Figures 8.2.2.3.1.1(a) through (c). Efficiencies for gages under 0.012 will be determined by test.

8.2.2.3.2 *Design Shear Strengths for Spot and Seam Weldings in Aluminum Alloys* — The acceptable aluminum and aluminum alloy combinations for spot and seam welding are given in Table 8.2.2.3.2(a).

Design shear-strength for spot welds in aluminum alloys are given in Tables 8.2.2.3.2(b) and (c). The thickness ratio of the thickest to the thinnest outer sheet in the combination should not exceed 4:1.

Design shear-strength for spot-welded joints, based on tearing of the sheet, is given in Table 8.2.2.3.2(d) for some aluminum alloys, together with the "maximum" pitches that permit attainment of these strengths. Joints having larger pitches fail in the spot welds rather than by tearing of the sheet, and are governed by Tables 8.2.2.3.2(b) and (c). The design shear strengths listed are also applicable to seam welds.

8.2.2.3.2.1 Effects of Spot Welds on Parent Metal Strength of Aluminum Alloys — In applications of spot welding other than splices, where ribs, intercostals, or doublers are attached to sheet, the allowable ultimate strength of the spot-welded sheet may be determined by multiplying the ultimate tensile strength of the sheet (A or S-values) by the appropriate efficiency factor shown on Figure 8.2.2.3.2.1. Efficiencies for gages under 0.020 will be determined by test.

8.2.2.3.2.2 Fatigue Strength of Spot-Welded Joints in Aluminum Alloys — The fatigue strength of spot-welded joints in aluminum alloy are given in Figures 8.2.2.3.2.2(a) through 8.2.2.3.2.2(e).

8.2.2.3.3 *Design Shear Strengths for Spot and Seam Welds in Magnesium Alloys* — Design shear-strength for spot welds in magnesium alloys are given in Table 8.2.2.3.3. The thickness ratio of the thickest sheet to the thinnest outer sheet in the combination should not exceed 4:1.

8.2.2.3.4 *Design Shear Strengths for Spot and Seam Welds in Titanium and Titanium Alloys* — Design shear strength for spot welds in titanium and titanium alloys are given in Tables 8.2.2.3.4(a) and (b). The thickness ratio of the thickest sheet to the thinnest outer sheet in the combination should not exceed 4:1.

Table 8.2.2.2(a). Allowable Ultimate Tensile Stress for Flash Welds in Steel Tubing

Tubing	Allowable Ultimate Tensile Stress of Welds
Normalized tubing — not heat treated (including normalizing) after welding	1.0 F_{tu} (based on F_{tu} of normalized tubing)
Heat-treated tubing welded after heat treatment	1.0 F_{tu} (based on F_{tu} of normalized tubing)
Tubing heat treated (including normalizing) after welding. F_{tu} of unwelded material in heat-treated condition:	
< 100 ksi	0.9 F_{tu}
100 to 150 ksi	0.6 F_{tu} + 30
> 150 ksi	0.8 F_{tu}

Table 8.2.2.2(b). Allowable Bending Modulus of Rupture for Flash Welds in Steel Tubing

Tubing	Allowable Bending Modulus of Rupture of Welds (F_b from Figure 2.8.1.1 using values of F_{tu} listed)
Normalized tubing — not heat treated (including normalizing after welding	1.0 F_{tu} (based on F_{tu} of normalized tubing)
Heat-treated tubing welded after heat treatment	1.0 F_{tu} (based on F_{tu} of normalized tubing)
Tubing heat treated (including normalizing) after welding. F_{tu} of unwelded material in heat-treated condition:	
< 100 ksi	0.9 F_{tu}
100 to 150 ksi	0.6 F_{tu} + 30
> 150 ksi	0.8 F_{tu}

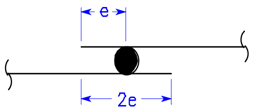
Table 8.2.2.3. Recommended Minimum Edge Distance and Spacing for Spot-Welded Joints[a]

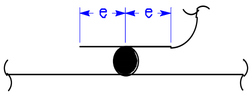
Nominal Thickness[b] of Thinner Sheet, inch	Minimum Lap Joint[c,d] Edge Distance, inch	Minimum Spacing[e], inch
0.016	0.19	0.19
0.020	0.20	0.30
0.025	0.22	0.38
0.032	0.25	0.46
0.040	0.28	0.52
0.050	0.31	0.58
0.063	0.38	0.67
0.071	0.41	0.73
0.080	0.44	0.79
0.090	0.47	0.89
0.100	0.50	1.00
0.125	0.56	1.25
0.160	0.69	1.60

[a] Reference Aluminum Association and American Welding Society Handbook.

[b] Intermediate gages will require interpolation between adjacent gages.

[c] Edge distances are measured materials in contact; this can be to a free edge or to a sheet metal radius where one material bends away from another. Edge distances less than those specified above may be used provided there is no expulsion of weld material or bulging of the edge of the sheet; however, these joints may have less static strength and shorter fatigue life.





[d] Minimum contacting overlap is twice the minimum edge distance.

[e] Less than minimum recommended spacing may cause shunting that leads to deterioration of weld strengths and joint life.

Table 8.2.2.3.1(a). Spot-Weld Design Shear Strength[a,b] in Thin Sheet and Foil for Uncoated Steels[c] and Nickel and Cobalt Alloys (Welding Specification MIL-W-6858)

Thickness of Thinnest Outer Sheet, in.	Spots/inch		Material Ultimate Tensile Strength, ksi			
	Standard (Ns)[d]	Range[e,f]	Above 185	150 to 185	90 to 149	Below 90
			Design Shear Strength, pounds per linear inch (Xm)			
0.001	40	1-50	72	64	52	36
0.002	20	1-30	144	128	104	72
0.003	12	1-17	240	208	164	120
0.004	10	1-14	324	280	228	152
0.005	9	1-13	392	340	272	188
0.006	7	1-10	432	380	304	220
0.007	6	1-8	504	440	352	256
0.008	5	1-7	552	488	392	284

a Strength based on 80 percent of minimum values specified in Specification MIL-W-6858.

b The allowable tensile strength of spot-welds is 25 percent of the design shear strength. Higher values may be used, however, if these are substantiated by tests acceptable to the procuring or certifying agency.

c Refers to plain carbon steels containing not more than 0.15 percent carbon, austenitic, heat and corrosion resistant, and precipitation hardening steels. The reduction in strength of spot-welds due to the cumulative effects of time-temperature-stress factors is not greater than the reduction in strength of the parent metal.

d When the number of spots per inch is within 15 percent of the standard spot per inch requirement, the design shear strengths tabulated above will apply.

e When the number of spots differs from the standard spots per inch by 15 percent or greater, but does not exceed the noted range of spots per inch, applicable design strength will be determined as noted below:

$$\frac{Xm}{Ns}(K)\,Nr = Xr$$

where

Xm = design shear strength in accordance with the above table
Ns = standard spots per inch in accordance with the above table
Nr = required spots per inch (production part)
Xr = actual design shear strength requirement
K = 1.15 when number of spots per inch is reduced more than 15 percent of the standard spacing of the above table
K = 0.90 when number of spots is increased more than 15 percent of the standard spacing but within range of the tabular spacing.

f When the number of spots per inch is above the range indicated in the table, the design shear strength will remain constant at the value obtained at the top of the range.

Table 8.2.2.3.1(b). Spot-Weld Design Shear Strength[a,b] in Panels for Uncoated Steels[c] and Nickel and Cobalt Alloys (Welding Specification MIL-W-6858)

	Design Shear Strength, pounds per spot			
Material Ultimate Tensile Strength, ksi	Above 185	150 to 185	90 to 149	Below 90
Nominal thickness of thinner sheet, in.:				
0.009	160	140	104	80
0.010	196	164	128	92
0.012	280	220	160	120
0.016	384	320	236	172
0.018	472	392	272	200
0.020	508	424	312	224
0.022	584	488	360	264
0.025	696	580	424	320
0.028	820	684	508	372
0.032	1000	836	620	452
0.036	1200	1004	736	552
0.040	1400	1168	852	652
0.045	1680	1436	1028	804
0.050	1960	1700	1204	956
0.056	2304	2040	1416	1168
0.063	2840	2472	1688	1408
0.071	3360	2984	2028	1664
0.080	3880	3528	2404	1964
0.090	4480	4072	2812	2308
0.100	5040	4576	3200	2640
0.112	5600	5092	3636	3036
0.125	6228	5664	4052	3440

[a] Strength based on 80 percent of minimum values specified in Specification MIL-W-6858.

[b] The allowable tensile strength of spot-welds is 25 percent of the design shear strength. Higher values may be used, however, if these are substantiated by tests acceptable to the procuring or certifying agency.

[c] Refers to plain carbon steels containing not more than 0.15 percent carbon and to austenitic heat and corrosion resistant, precipitation hardening steels. The reduction in strength of spot-welds due to the cumulative effects of time-temperature-stress factors is not greater than the reduction in strength of the parent metal.

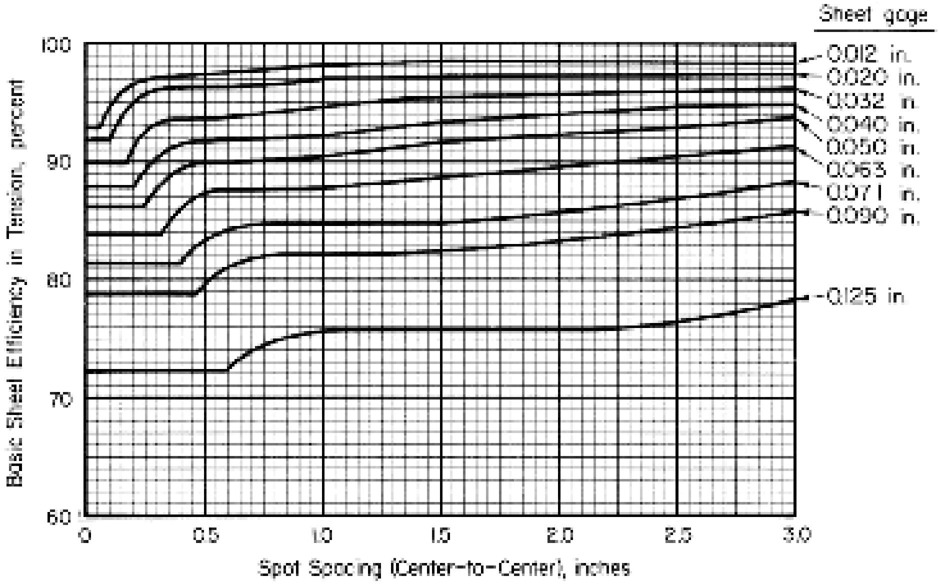


Figure 8.2.2.3.1.1(a). Efficiency of the parent metal in tension for spot-welded AISI 301-A, and AISI 347-A, and AISI 301-1/4 stainless steel.

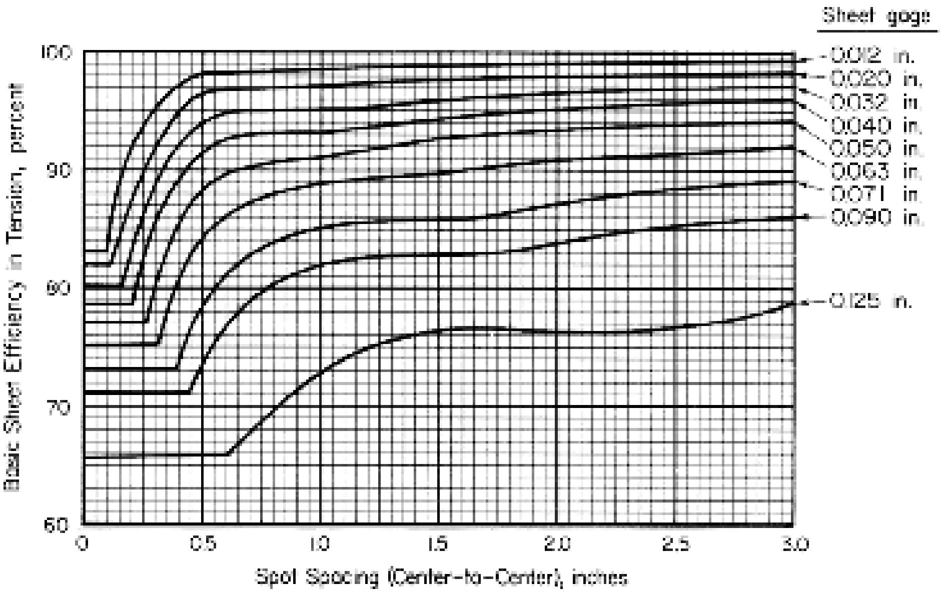


Figure 8.2.2.3.1.1(b). Efficiency of the parent metal in tension for spot-welding AISI 301-1/2H stainless steel.

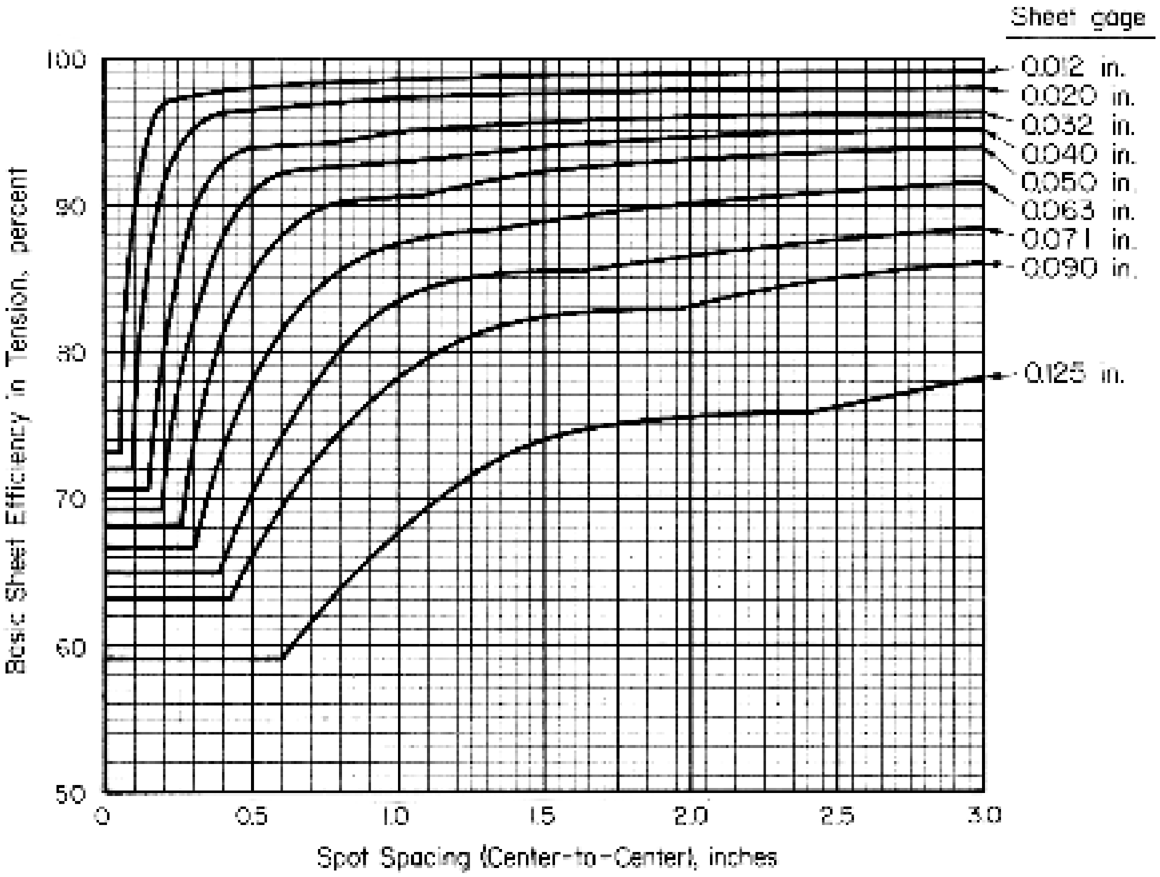


Figure 8.2.2.3.1.1(c). Efficiency of the parent metal in tension for spot-welded AISI 301-H stainless steel.

Table 8.2.2.3.2(a). Acceptable Aluminum and Aluminum Alloy Combination[a] for Spot and Seam Welding

Specification		AMS-QQ-A-250/1	AMS-4029[b]	AMS-QQ-A-250/3	AMS-QQ-A-250/4[b]	AMS-QQ-A-250/5	AMS-QQ-A-250/2	AMS-QQ-A-250/8	AMS-QQ-A-250/11	AMS-QQ-A-250/12[b]	AMS-QQ-A-250/13[c]
Material		1100	Bare 2014	Clad 2014	Bare 2024	Clad 2024	3003	5052	6061	Bare 7075	Clad 7075
Specification	Material										
AMS-QQ-A-250/1	1100	...	...	...	...	...	...	...	...	...	...
AMS-4029	Bare 2014[b]	...	*	*	*	...	...	...	...	*	...
AMS-QQ-A-250/3	Clad 2014	...	*	...	*	...	...	...	...	*	...
AMS-QQ-A-250/4	Bare 2024[b]	...	*	*	*	...	...	...	...	*	...
AMS-QQ-A-250/5	Clad 2024	...	...	...	...	...	...	...	...	...	...
AMS-QQ-A-250/2	3003	...	...	...	...	...	...	...	...	...	...
AMS-QQ-A-250/8	5052	...	...	...	...	...	...	...	...	...	...
AMS-QQ-A-250/11	6061	...	...	...	...	...	...	...	...	...	...
AMS-QQ-A-250/12	Bare 7075[b]	...	*	*	*	...	...	...	...	*	...
AMS-QQ-A-250/13	Clad 7075[b]	...	...	...	...	...	...	...	...	...	...

[a] The various aluminum and aluminum-alloy materials referred to in this table may be spot-welded in any combinations except the combinations indicated by the asterisk(*) in the table. The combinations indicated by the asterisk (*) may be spot-welded only with the specific approval of the procuring or certifying agency.

[b] This table applies to construction of land- and carrier-based aircraft only. The welding of bare, high-strength alloys in construction of seaplanes and amphibians is prohibited unless specifically authorized by the procuring or certifying agency.

[c] Clad heat-treated and aged 7075 material in thicknesses less than 0.020 inch will not be welded without specific approval of the procuring or certifying agency.

Table 8.2.2.3.2(b). Spot-Weld Design Shear Strength in Thin Sheet and Foil for Bare and Clad Aluminum Alloys[a,b,c] (Welding Specification MIL-W-6858)

Thickness of Thinnest Outer Sheet, in.	Spots/inch		Material Ultimate Tensile Strength, ksi	
			56 and Above	Below 56
	Standard (Ns)[d]	Range[e,f]	Design Shear Strength, pounds per linear inch (Xm)	
0.001...................	40	1-50	24	16
0.002...................	20	1-30	48	32
0.003...................	12	1-17	80	52
0.004...................	10	1-14	108	72
0.005...................	9	1-13	132	92
0.006...................	7	1-10	148	100
0.007...................	6	1-8	168	112
0.008...................	5	1-7	188	128

a The reduction in strength of spot-welds due to the cumulative effects of time-temperature-stress factors is not greater than the reduction in strength of the parent metal.

b Strength based on 80 percent of minimum values specified in Specification MIL-W-6858.

c The allowable tensile strength of spot-welds is 25 percent of the design shear strength. Higher values may be used, however, if these are substantiated by tests acceptable to the procuring or certifying agency.

d When the number of spots per inch is within 15 percent of the standard spot per inch requirement, the design shear strengths tabulated above will apply.

e When the number of spots differs from the standard spots per inch by 15 percent or greater, but does not exceed the noted range of spots per inch, applicable design strength will be determined as noted below:

$$\frac{XM}{Ns}(K)\,Nr = Xr$$

where

Xm = design shear strength in accordance with the above table
Ns = standard spots per inch in accordance with the above table
Nr = required spots per inch (production part)
Xr = actual design shear strength requirement
K = 1.15 when number of spots per inch is reduced more than 15 percent of the standard spacing of the above table
K = 0.90 when number of spots is increased more than 15 percent of the standard spacing but within range of the tabular spacing.

f When the number of spots per inch is above the range indicated in the table, the design shear strength will remain constant at the value obtained at the top of the range.

Table 8.2.2.3.2(c). Spot-Weld Design Shear Strength in Panels for Bare and Clad Aluminum Alloys[a,b,c] (Welding Specification MIL-W-6858)

	Design Shear Strength, pounds per spot			
Material Ultimate Tensile Strength, ksi...	56 and Above	35 to 56	19.5 to 34.9	Below 19.5
Nominal thickness of thinner sheet, in.:				
0.010	48	40	...	...
0.012	60	52	24	16
0.016	88	80	56	40
0.018	100	92	68	52
0.020	112	108	80	64
0.022	128	124	96	76
0.025	148	140	116	88
0.028	172	164	140	108
0.032	208	188	168	132
0.036	244	220	204	156
0.040	276	248	240	180
0.045	324	296	280	208
0.050	372	344	320	236
0.056	444	412	380	272
0.063	536	488	456	316
0.071	660	576	516	360
0.080	820	684	612	420
0.090	1004	800	696	476
0.100	1192	936	752	540
0.112	1424	1072	800	588
0.125	1696	1300	840	628
0.140	2020	1538	...	...
0.160	2496	1952	...	...
0.180	2980	2400	...	...
0.190	3228	2592	...	...
0.250	5880	5120	...	...

a The reduction in strength of spot-welds due to the cumulative effects of time-temperature-stress factors is not greater than the reduction in strength of the parent metal.
b Strength based on 80 percent of minimum values specified in Specification MIL-W-6858.
c The allowable tensile strength of spot-welds is 25 percent of the design shear strength. Higher values may be used, however, if these are substantiated by tests acceptable to the procuring or certifying agency.

Table 8.2.2.3.2(d). Maximum Static Strength of Spot-Welded Joints in Aluminum Alloys and Corresponding Maximum Design Spot-Weld Pitch[a,b]

	Single Row Joints						Multiple Row Joints					
Material..........	7075-T6 clad		2024-T3 clad		6061-T6		7075-T6 clad		2024-T3 clad		6061-T6	
Thickness of Thinnest Sheet, in.	Strength, lbs/in.	Pitch, in.	Strength, lbs/in.	Pitch, in.	Strength, lbs/in.	Pitch, in.	Strength, lbs/in.	Pitch÷No. of Rows, in.	Strength, lbs/in.	Pitch÷No. of Rows, in.	Strength, lbs/in.	Pitch÷No. of Rows, in.
0.010...........	288	0.167	250	0.192	210	0.190	438	0.110	384	0.125	329	0.122
0.012...........	346	0.173	300	0.200	252	0.206	526	0.114	461	0.130	395	0.132
0.016...........	461	0.191	400	0.220	336	0.238	701	0.126	614	0.143	526	0.152
0.020...........	577	0.194	500	0.224	420	0.257	876	0.128	768	0.146	658	0.164
0.025...........	721	0.205	625	0.237	525	0.267	1095	0.135	960	0.154	822	0.170
0.032...........	923	0.225	800	0.260	672	0.280	1402	0.148	1229	0.169	1053	0.179
0.040...........	1059	0.261	918	0.301	778	0.319	1752	0.158	1536	0.180	1316	0.188
0.050...........	1230	0.302	1067	0.349	910	0.378	2190	0.170	1920	0.194	1645	0.209
0.063...........	1452	0.369	1259	0.426	1082	0.451	2759	0.194	2419	0.222	2073	0.235
0.071...........	1589	0.415	1378	0.479	1187	0.485	3110	0.212	2726	0.242	2336	0.247
0.080...........	1742	0.471	1511	0.543	1306	0.524	3504	0.234	3072	0.267	2632	0.260
0.090...........	1913	0.525	1660	0.605	1438	0.556	3942	0.255	3456	0.290	2961	0.270
0.100...........	2084	0.572	1808	0.659	1580	0.596	4380	0.272	3840	0.310	3290	0.284
0.112...........	2289	0.622	1986	0.717	1728	0.620	4906	0.290	4301	0.331	3685	0.291
0.125...........	2511	0.675	2179	0.788	1900	0.684	5475	0.310	4800	0.353	4112	0.316

a For multiple row joints row spacing is at minimum and same pitch in all rows.

b For pitches greater than those shown, strength is governed by Tables 8.2.2.3.2(b) and (c).

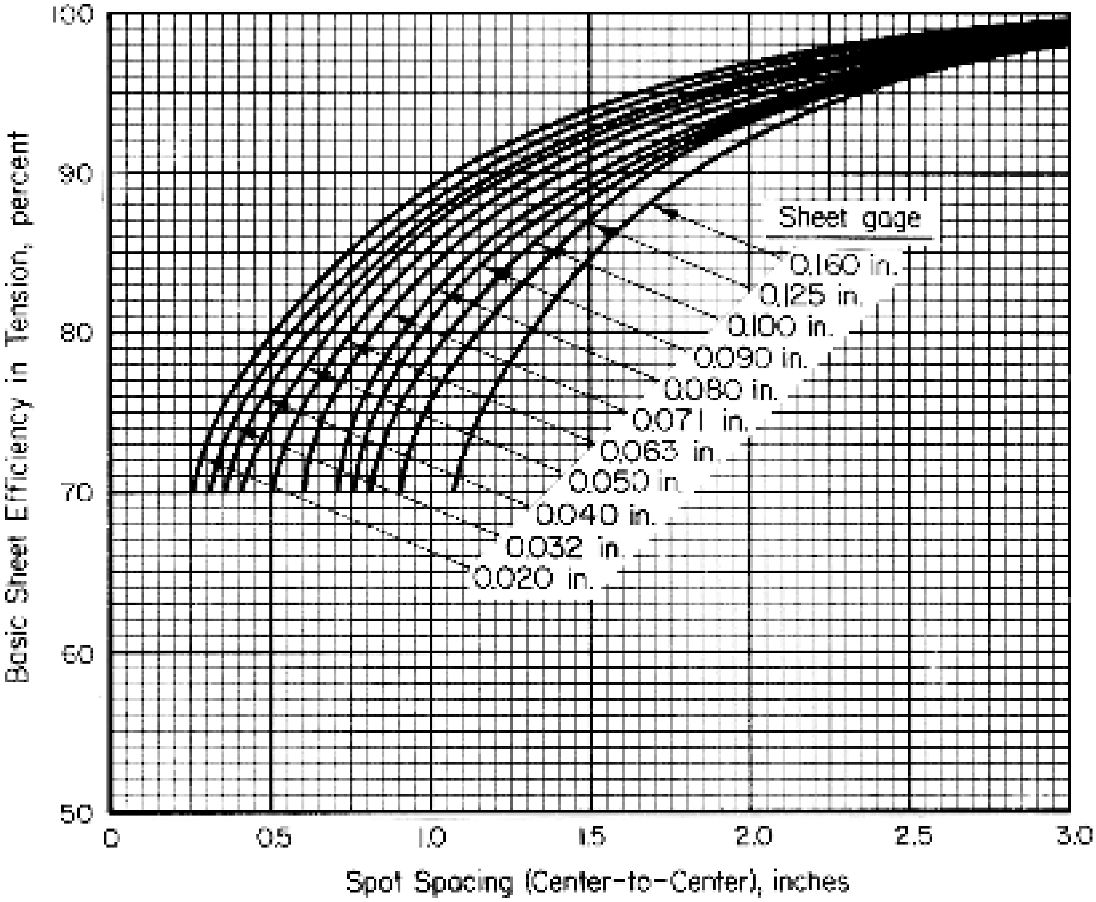


Figure 8.2.2.3.2.1. Efficiency of the parent metal in tension for spot-welded aluminum alloys.

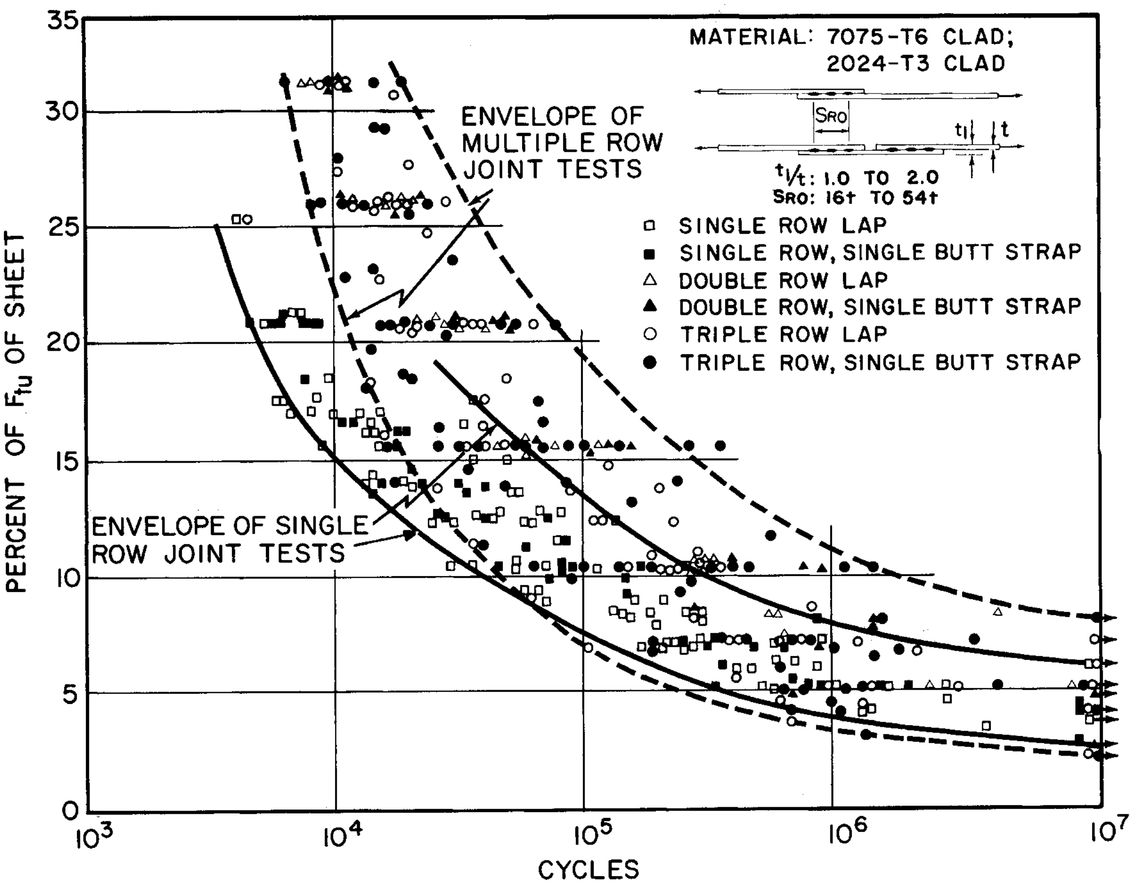


Figure 8.2.2.3.2.2(a). Fatigue strength of spot-welded joints in aluminum alloy sheet. Load Ratio = 0.05 (static failure by tearing sheet).

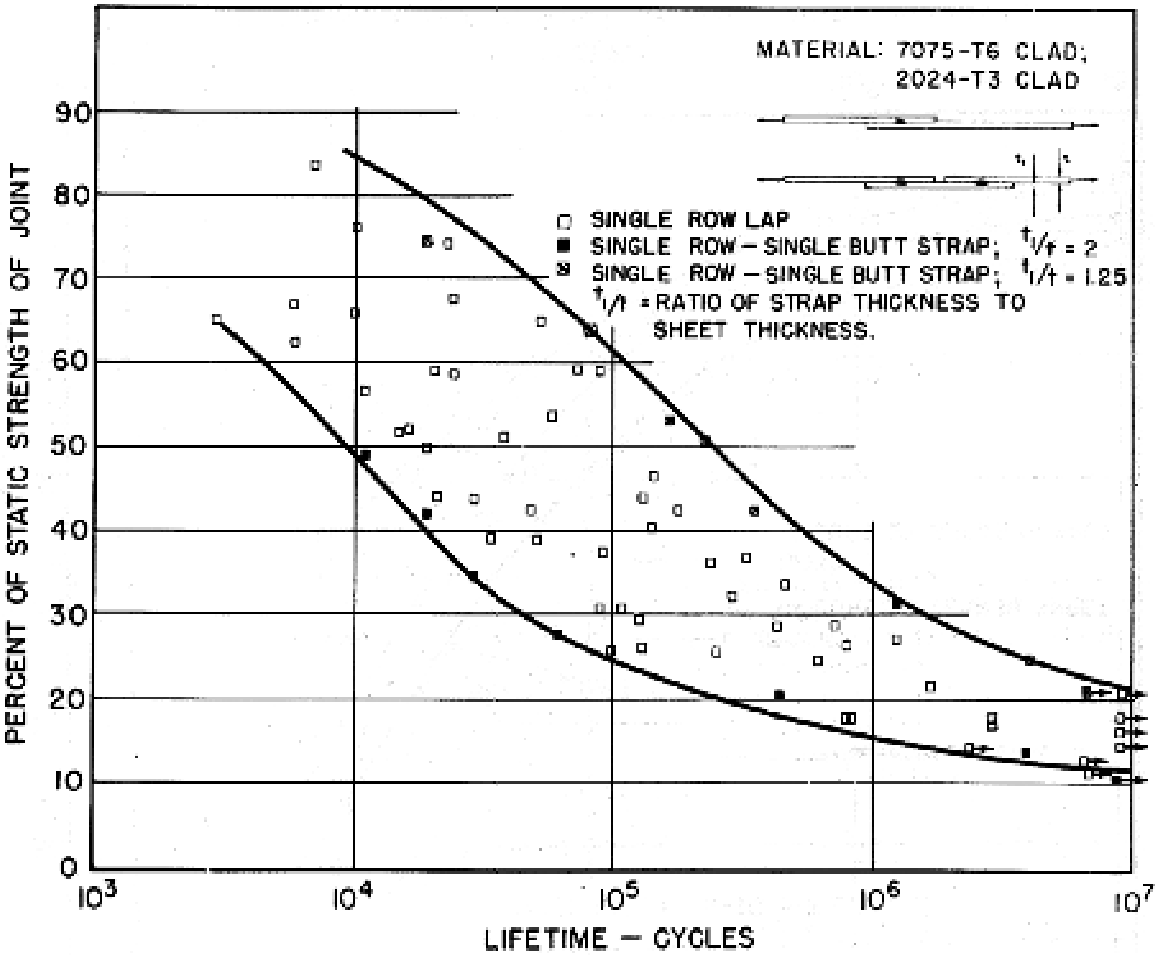


Figure 8.2.2.3.2.2(b). Fatigue strength of spot-welded joints in aluminum alloy sheet. Load Ratio = 0.05 (static failure by shear in the spot welds).

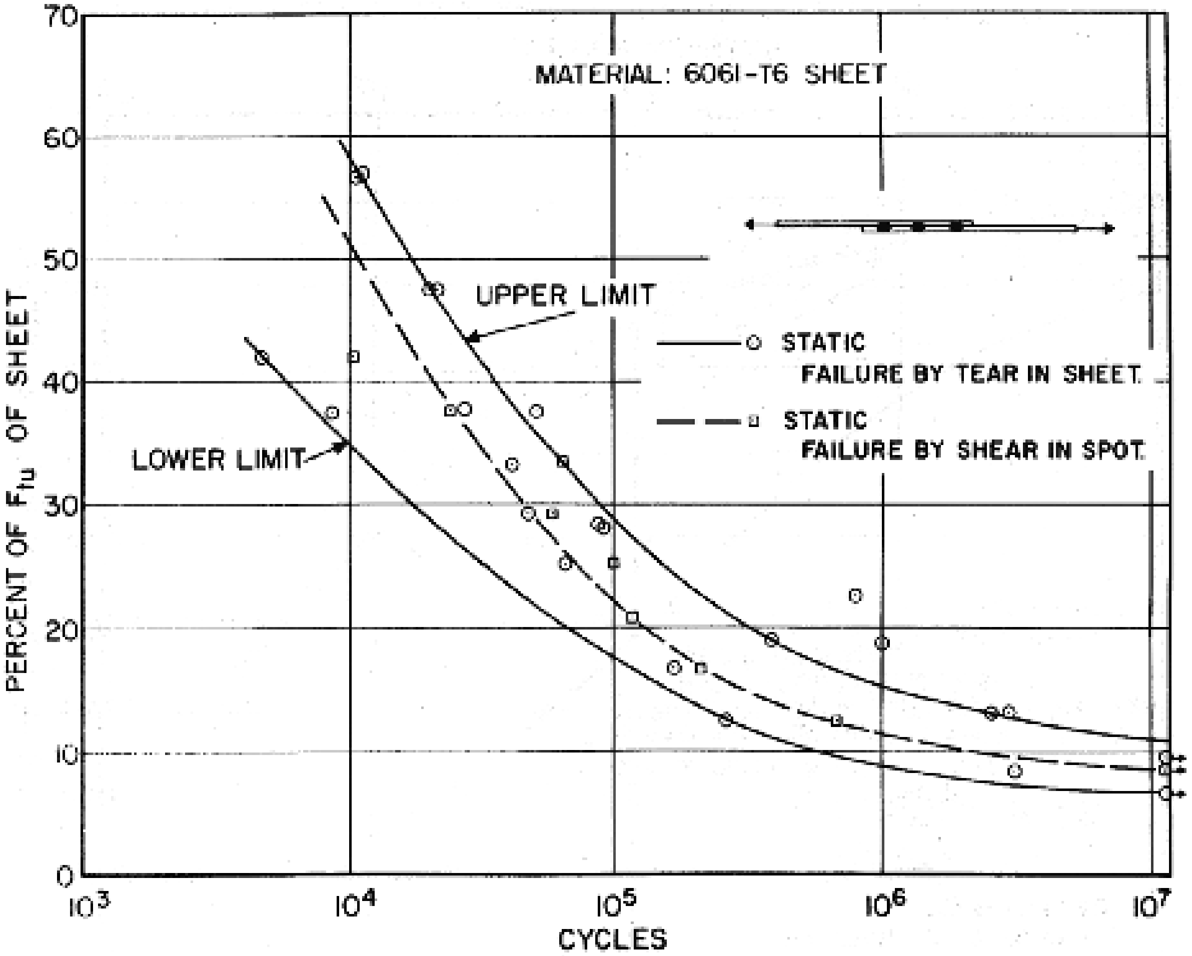


Figure 8.2.2.3.2.2(c). Fatigue strength of triple row spot-welded lap joints in 6061-T6 aluminum alloy sheet. Load Ratio = 0.05.

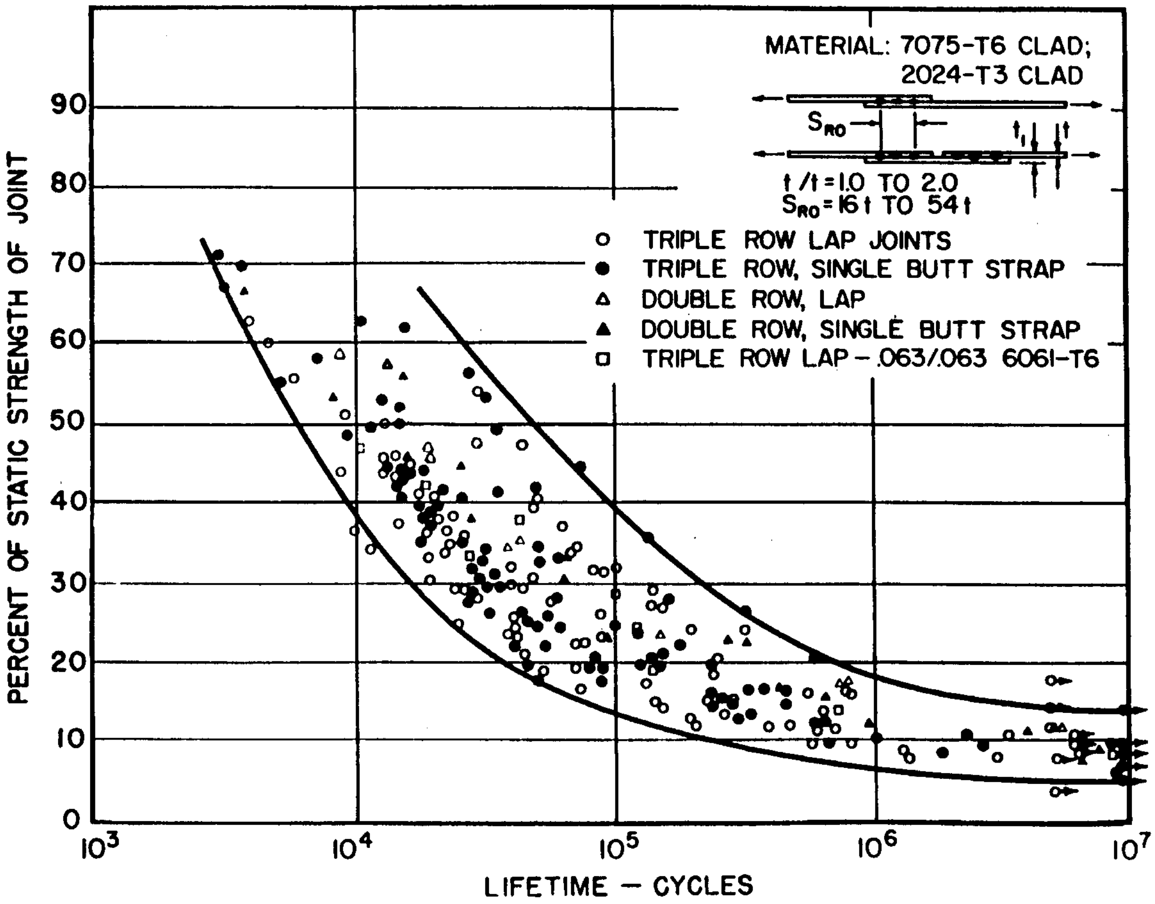


Figure 8.2.2.3.2.2(d). Fatigue strength of spot-welded multiple row joints in aluminum alloy sheet. Load Ratio = 0.05 (static failure by shear in the spot welds).

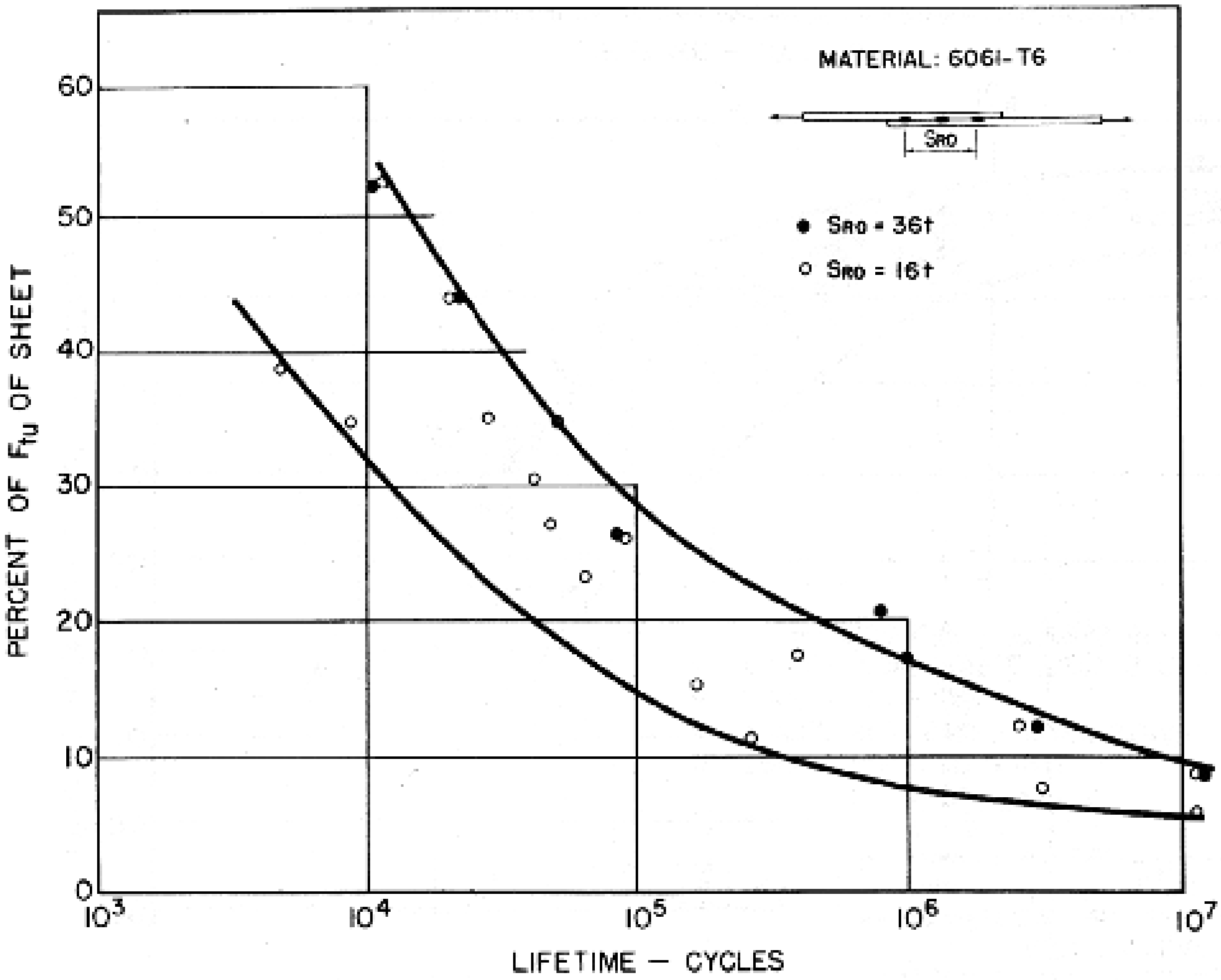


Figure 8.2.2.3.2.2(e). Fatigue strength of triple row spot-welded lap joints in 6061-T6 aluminum alloy sheet. Load Ratio = 0.05 (static failure by tear in sheets).

Table 8.2.2.3.3. Spot-Weld Design Shear Strength in Panels for Magnesium Alloys[a,b,c] (Welding Specification MIL-W-6858)

	Design Shear Strength, pounds per spot	
Material Ultimate Tensile Strength, ksi...	Greater than 19.5	Less than 19.5
Nominal thickness of thinner sheet, in.:		
0.012	24	16
0.016	56	40
0.018	68	52
0.020	80	64
0.022	96	76
0.025	116	88
0.028	140	108
0.032	168	132
0.036	204	156
0.040	240	180
0.045	280	208
0.050	320	236
0.056	380	272
0.063	456	316
0.071	516	360
0.080	612	420
0.090	696	476
0.100	752	540
0.112	800	588
0.125	840	628

[a] Strength based on 80 percent of minimum values specified in Specification MIL-W-6858.

[b] The allowable tensile strength of spot-welds is 25 percent of the design shear strength. Higher values may be used, however, if these are substantiated by tests acceptable to the procuring or certifying agency.

[c] Magnesium alloys AZ31B and HK31A may be spot-welded in any combination.

Table 8.2.2.3.4(a). Spot-Weld Design Shear Strength in Thin Sheet and Foils for Titanium and Titanium Alloys[a,b,c] (Welding Specification MIL-W-6858)

Thickness of Thinnest Outer Sheet, in.	Spots/inch		Materials Ultimate Tensile Strength, ksi			
	Standard (Ns)[d]	Range[e,f]	Above 185	150 to 185	90 to 149	Below 90
			Design Shear Strength, pounds per linear inch (Xm)			
0.001	40	1-50	72	64	52	36
0.002	20	1-30	144	128	104	72
0.003	12	1-17	240	208	164	120
0.004	10	1-14	324	280	228	152
0.005	9	1-13	392	340	272	188
0.006	7	1-10	432	380	304	220
0.007	6	1-8	504	440	352	256
0.008	5	1-7	552	488	392	284

[a] The reduction in strength of spot-welds due to the cumulative effects of time-temperature-stress factors is not greater than the reduction in strength of the parent metal.

[b] Strength based on 80 percent of minimum values specified in Specification MIL-W-6858.

[c] The allowable tensile strength of spot-welds is 25 percent of the design shear strength. Higher values may be used, however, if these are substantiated by tests acceptable to the procuring or certifying agency.

[d] When the number of spots per inch is within 15 percent of the standard spot per inch requirement, the design shear strengths tabulated above will apply.

[e] When the number of spots differs from the standard spots per inch by 15 percent or greater, but does not exceed the noted range of spots per inch, applicable design strength will be determined as noted below:

$$XM/Ns(K)Nr = Xr$$

where

Xm = design shear strength in accordance with the above table
Ns = standard spots per inch in accordance with the above table
Nr = required spots per inch (production part)
Xr = actual design shear strength requirement
K = 1.15 when number of spots per inch is reduced more than 15 percent of the standard spacing of the above table
K = 0.90 when number of spots is increased more than 15 percent of the standard spacing but within range of the tabular spacing.

[f] When the number of spots per inch is above the range indicated in the table, the design shear strength will remain constant at the value obtained at the top of the range.

Table 8.2.2.3.4(b). Spot-Weld Design Shear Strength in Panels for Titanium and Titanium Alloy[a,b,c] (Welding Specification MIL-W-6858)

	Design Shear Strength, pounds per spot	
Material Ultimate Tensile Strength, ksi	Above 100	100 and Below
Nominal thickness of thinner sheet, in.:		
0.010	164	128
0.012	220	160
0.016	320	236
0.018	392	272
0.020	424	312
0.022	488	360
0.025	580	424
0.028	684	508
0.032	836	620
0.036	1004	736
0.040	1168	852
0.045	1438	1028
0.050	1702	1204
0.056	2040	1416
0.063	2400	1688
0.071	2702	1914
0.080	3048	2160
0.090	3430	2435
0.100	3810	2702
0.112	4260	3030
0.125	4760	3380

a The reduction in strength of spot-welds due to the cumulative effects of time-temperature-stress factors is not greater than the reduction in strength of the parent metal.

b Strength based on 80 percent of minimum value specified in Specification MIL-W-6858.

c The allowable tensile strength of spot-wells is 25 percent of the design shear strength. Higher values may be used, however, if these are substantiated by tests acceptable to the procuring or certifying agency.

8.2.3 BRAZING

8.2.3.1 *Copper Brazing* — The allowable shear strength for copper brazing of steel alloys will be 15 ksi, for all conditions of heat treatment. Higher values may be allowed upon approval of the procuring or certifying agency.

The effect of the brazing process on the strength of the parent or base metal of steel alloys will be considered in the structural design. Where copper furnace brazing is employed, the calculated allowable strength of the base metal which is subjected to the temperatures of the brazing process will be in accordance with the following:

Material	Allowable Strength
Heat-treated material (including normalized) used in "as-brazed" condition	Mechanical properties of normalized material
Heat-treated material (including normalized) reheat-treated during or after brazing	Mechanical properties corresponding to heat treatment performed

8.2.3.2 *Silver Brazing* — Silver-brazed areas should not be subjected to temperatures exceeding 900°F. Silver brazing alloys are listed in specification QQ-B-654. Deviation from this specification may be allowed upon approval of the procuring or certifying agency.

The allowable shear strength for silver brazing of steel alloys will be 15 ksi, provided that clearances or gaps between parts to be brazed do not exceed 0.010 in. Deviation from this specified allowable value may be allowed upon approval of the procuring or certifying agency.

The effect of silver brazing on the strength of the parent or base metal is the same as shown for copper brazing in Section 8.2.3.1.

8.3 BEARINGS, PULLEYS, AND WIRE ROPE

Bearings — Design, strengths, selection criteria, and other data for plain and antifriction bearings are found in AFSC Design Handbook AFSC DH-2-1, Chapters 3 and 6.

Pulleys — Pulley strengths and design data are to be utilized in accordance with Specification MIL-P-7034.

Wire Rope — Strengths and design data for wire rope are to be selected from the following specifications, whichever is appropriate: MIL-W-83420 or MIL-W-87161.

REFERENCES

8.1 Hartman, E. C. and Westcoat, C., "The Shear Strength of Aluminum Alloy Driven Rivets as Affected by Increasing D/t Ratios," U.S. National Advisory Committee for Aeronautics, Technical Note No. 942, 23 pp (July 1944).

8.1.2.1 Fugazzi, G. R., "Results of Test Evaluation Program to Develop Design Joint Strength Load Allowable Values for A-286 Solid Rivets Under Room and Elevated Temperature Conditions," Almay Research and Testing Corporation Report No. G8058, 63 pp (November 1964).

8.1.2.2 "Report on Flush Riveted Joint Strength," Airworthiness Requirements Committee, A/C Industries Association of America, Inc., Airworthiness Project 12 (Revised May 25, 1948).

8.1.5.2 "Report on Flush Screw Joint Strength," Airworthiness Requirements Committee, A/C Industries Association of American, Inc., Airworthiness Project 20 (Revised April 6, 1953).

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CHAPTER 9

GUIDELINES FOR THE PRESENTATION OF DATA

This chapter contains Guidelines for judging adequacy of data, procedures for analyzing data in determining property values for inclusion in previous chapters, and formats for submitting results of analyses to the MIL-HDBK-5 Coordination Group for approval. The index that follows should be helpful in locating sections of these Guidelines applicable to specific properties:

9.1 GENERAL INFORMATION

This section of the Guidelines covers general information. Information specific to individual properties can be found in pertinent sections. Abbreviations, symbols, and definitions can be found in Appendix A.

9.1.1 INTRODUCTION — Design properties in MIL-HDBK-5 are used in the design of aerospace structures and elements. Thus, it is exceedingly important that the values presented in MIL-HDBK-5 reflect as accurately as possible the actual properties of the products covered.

Throughout the Guidelines, many types of statistical computations are referenced. Since these may not be familiar to all who may be analyzing data in the preparation of MIL-HDBK-5 proposals, a detailed description of each operation is required. To present the detailed description in the individual sections, however, would unnecessarily complicate the orderly presentation of the overall computational procedures. Therefore, the detailed description of the statistical techniques have been covered in Sections 9.5, 9.6, and 9.7.

9.1.2 APPLICABILITY — Minimum data requirements and analytical procedures defined in these Guidelines for establishment of MIL-HDBK-5 design properties and elevated temperature curves for these properties should be used to obtain approval of such values or curves when proposed to the MIL-HDBK-5 Coordination Group or a certifying agency. However, the minimum data requirements and analytical procedures are not mandatory; to the extent of precluding use of other analytical procedures which can be substantiated. Any exceptions or deviations must be reported when requesting approval of these values or curves by the Coordination Group or certifying agency.

9.1.3 APPROVAL PROCEDURES — The MIL-HDBK-5 Coordination Group (a voluntary, joint Government-Industry activity) meets twice yearly. At each meeting, this group acts upon proposed changes or additions to the document submitted in writing in advance of the meeting. The agenda is normally mailed to attendees four weeks prior to the meeting date, and the minutes four weeks following the meeting. Attachments for either the agenda or the minutes should be delivered to the Secretariat well in advance of the mailing date.

Attachments containing proposed changes or additions to the document will include specific notations of changes or additions to be made; adequate documentation of supporting data; analytical procedures used; discussion of analysis of data; and a listing of exceptions or deviations from the requirements of these Guidelines.

Approval procedures for establishment of MIL-HDBK-5 equivalent design values are defined by the individual certifying agency.

9.1.4 DOCUMENTATION REQUIREMENTS — The purpose of adequate documentation of proposals submitted to the MIL-HDBK-5 Coordination Group is to permit an independent evaluation of proposals by each interested attendee and to provide a historical record of actions of the Coordination Group. For this reason, both supporting data and a description of analytical procedures employed must be made available to attendees, either as an integral portion of an attachment to the agenda or minutes, or by reference to other documents that may reasonably be expected to be in the possession of MIL-HDBK-5 Meeting attendees. A specific example of the latter would be certain reports of Government-sponsored research or material evaluations for which distribution included the MIL-HDBK-5 attendance list. In some cases involving large quantities of supporting data, it may suffice (at the discretion of the Coordination Group) to furnish a single copy of these data to the Secretariat, from whom they would be available to interested attendees.

All relevant reference documents (specifications, testing standards, data submissions, etc.) for proposals must be provided in English, to facilitate interpretation and evaluation by the MIL-HDBK-5 Coordination Group. If metric units are used as the primary system of units in these documents, they should be supplied along with a soft conversion to English units. The following English units are standard within MIL-HDBK-5:

- Coefficient of thermal expansion, 10^{-6} in./in./F
- Density, lb./in^3
- Fracture toughness, ksi-in$^{1/2}$
- Frequency, Hz (cycles per second), or cpm (cycles per minute)
- Load, lbs., or kips (10^3 lbs.)
- Modulus of elasticity (Tension and Compression), 10^3 ksi
- Shear Modulus, 10^3 ksi
- Specific heat, Btu/(lb.)(F)
- Strain, in./in.
- Stress or strength, ksi
- Temperature, °F
- Thermal conductivity, Btu/[(hr)(ft^2)(F)/ft]
- Thickness, in.
- Time, hrs.

Refer to Section 9.2.3.1 for the terminology used within MIL-HDBK-5 for mechanical properties.

9.1.5 SUMMARY — The objective of this summary is to provide a global overview of Chapter 9 without defining specific statistical details. This overview will be most helpful to those unfamiliar with the statistical procedures used in MIL-HDBK-5 and to those who would like to learn more about the philosophy behind the MIL-HDBK-5 guidelines.

Chapter 9 is the "rule book" for MIL-HDBK-5. Since 1966, these guidelines have described statistical procedures used to calculate mechanical properties for alloys included in the Handbook. Recommended changes in the guidelines are reviewed first by the Guidelines Task Group (GTG) and later approved by the entire coordination committee. Recommended changes in statistical procedures within the guidelines are evaluated first by the Statistics Working Group (SWG), which supports the GTG. Similarly, recommended changes in fastener analysis procedures are examined by the Fastener Task Group (FTG) before approval by the coordination committee.

Chapter 9 is divided into subchapters that cover the analysis methods used to define room and elevated temperature properties. The room temperature mechanical properties are tensile, compression, bearing, shear, fatigue, fracture toughness, elongation and elastic modulus. The elevated temperature properties are the same, except that creep and stress rupture properties are added to the list. Analysis procedures for fatigue, fatigue crack growth and mechanically fastened joints are also covered since these data are commonly used in aircraft design. The presentation of these data varies depending upon the data type. For instance, the room temperature mechanical properties (tensile, compression, bearing, shear, elongation, elastic modulus, and fracture toughness) are provided in a tabular format, while the fatigue, elevated temperature properties, and typical stress-strain curves are presented in graphical format.

The majority, by far, of the data in MIL-HDBK-5 are room temperature design properties: including tensile (F_{tu}, F_{ty}), shear (F_{su}), compression (F_{cy}), bearing ultimate and yield strengths (F_{bru} and F_{bry}), elongation and elastic modulus. Room temperature design properties are the primary focus in the Handbook because most aircraft, commercial and military, typically operate at near-ambient temperatures and because most material specifications include only room temperature property requirements.

Many different statistical techniques may be useful in analysis of mechanical-property data. Brief descriptions of procedures that will be used most frequently in this application are given in Section 9.5, 9.6, and 9.7. More detailed descriptions of these and other statistical techniques and tables in their various forms can be found in a number of workbooks and texts; Reference 9.1.5 is a particularly useful one.

Before an alloy can be considered for inclusion in MIL-HDBK-5, it must be covered by a commercial or government specification. There are two main reasons for this: (1) the alloy, and its method of manufacture, must be "reduced to standard practice" to increase confidence that the material, if obtained from different suppliers, will still demonstrate similar mechanical properties, and (2) specification minimum properties are included in MIL-HDBK-5 tables as design properties in situations where there are insufficient data to determine statistically based material design values.

Design minimum mechanical properties tabulated in MIL-HDBK-5 are calculated either by "direct" or "indirect" statistical procedures. The minimum sample size required for the direct computation of T_{99} and T_{90} values (from which A and B-basis design properties are established) is 100. These 100 observations must include data from at least 10 heats and lots (as defined in the next paragraph). A T_{99} value is a statistically computed, one-sided lower tolerance limit, representing a 95 percent confidence lower limit on the first percentile of the distribution. Similarly, a T_{90} value is a statistically computed, one-sided lower tolerance limit, representing a 95 percent lower confidence limit on the tenth percentile of the distribution. If the sample cannot be described by a Pearson[1] or Weibull distribution, the T_{99} and T_{90} values must be computed by nonparametric (distribution free) means, which can only be done if there are at least 299 observations. (In most cases, only minimum tensile ultimate and yield strength values are determined by the direct method.) T_{90} values are not computed if there are insufficient data to compute T_{99} values, even though a much smaller sample size is required to compute nonparametric T_{90} values. This is because the general consensus within the MIL-HDBK-5 committee has been that a large number of observations (in the realm of 100) are needed from a large number of heats and lots (e.g. 10) for a particular material to properly characterize the variability in strength of that product.

A lot represents all of the material of a specific chemical composition, heat treat condition or temper, and product form that has passed through all processing operations at the same time. Multiple lots can be obtained from a single heat. A heat of material, in the case of batch melting, is all of the material that is cast at the same time from the same furnace and is identified with the same heat number. In the case of continuous melting, a single heat of material is generally poured without interruption. The exception is for ingot metallurgy wrought aluminum products, where a single heat is commonly cast in sequential aluminum ingots, which are melted from a single furnace charge and poured in one or more drops without changes in the processing parameters.

Minimum compression, bearing, and shear strengths are typically determined through the indirect method. This is done to reduce cost, because as few as 10 data points (from 3 heats and 10 lots) can be used, in combination with "paired" direct properties to compute a design minimum value. In this indirect method, the compression, bearing, and shear strengths are paired with tensile values determined in the same region of the product to produce a ratio. Statistical analyses of these ratios are conducted to obtain lower bound estimates of the relationship between the primary property and the ratioed property. These ratios are then multiplied with the appropriate F_{tu} or F_{ty} in the Handbook to obtain the F_{su}, F_{cy}, F_{bru}, F_{bry} values for shear, compression, and bearing (ultimate and yield), respectively.

When procedures other than those described are employed in preparation of data proposals, they should be described adequately in the proposal.

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[1] A Pearson distribution analysis with zero skewness is comparable to the normal analysis method used in earlier versions of MIL-HDBK-5.

Many mechanical property tables in the Handbook include data for specific grain directions and thickness ranges. This is done to better represent anisotropic materials, such as wrought products, that often display variations in mechanical properties as a function of grain direction and/or product thickness. Therefore, it is common practice to test for variability in mechanical properties as a function of product thickness. This is done through the use of regression analysis for both direct and indirect properties. If a regression is found to be significant, properties may be computed separately (without regression) for reduced thickness ranges.

To compliment the mechanical property tables, the Handbook also contains typical stress-strain curves. These curves are included to illustrate each material's yield behavior and to graphically display differences in yield behavior for different grain directions, tempers, etc. These curves are identified as typical because they are based upon only a few test points. Typical curves are shown for both tension and compression and are extended to just beyond the 0.2 percent yield stress. Each typical curve also contains a shape factor called the Ramberg-Osgood number (n). These numbers can be used in conjunction with a material's elastic modulus to empirically develop a stress-strain curve. Typical tensile full-range stress-strain curves are also provided that illustrate deformation behavior from the proportional limit to fracture. In addition, compression tangent-modulus curves are provided to describe compression instability.

Effect of temperature and thermal exposure curves are included throughout the Handbook. The curves are presented as a percentage of the room temperature design value. For these curves, there is a minimum data requirement and statistical procedures have been established to construct the curves. The creep rupture plots are shown as typical isothermal curves of stress versus time. The physical properties are shown as a function of temperature for each property, i.e., specific heat, thermal conductivity, etc. Physical properties are reported as average actual values, not a percentage of a room temperature value.

In addition to the mechanical properties, statistically based S/N fatigue curves are provided in the Handbook, since many airframe structures experience dynamic loading conditions. The statistical procedures are fairly rigorous. For example, the procedure describes how to treat outliers and run-outs (discontinued tests), and which models to use to best-fit a specific set of data. Each fatigue figure includes relevant information such as K_t, R value, material properties, sample size and equivalent stress equation. Each figure should be closely examined by the user to properly identify the fatigue curves required for a particular design.

Design properties for mechanical fasteners and mechanically fastened elements are also included in MIL-HDBK-5. A unique analysis procedure has been developed for mechanical fasteners because fasteners generally do not develop the full bearing strength of materials in which they are installed. Joint allowables are determined from test data using the statistical analysis procedures described in section 9.7.

9.1.6 Data Basis —There are four types of room-temperature mechanical properties included in MIL-HDBK-5. They are listed here, in order, from the least statistical confidence to the highest statistical confidence, as follows:

Typical Basis — A typical property value is an average value and has no statistical assurance associated with it.

S-Basis — This designation represents the specification minimum value specified by the governing industry specification (as issued by standardization groups such as SAE Aerospace Materials Division, ASTM, etc.) or federal or military standards for the material. (See MIL-STD-970 for order of preference of specifications.) For certain products heat treated by the user (for example, steels hardened and tempered to a designated F_{tu}), the S-basis value may reflect a specified quality-control requirement. Traditionally, the statistical assurance of S-basis values has not been known. However, the statistical assurance associated with S-basis values established since 1975 is known within the limitations of the qualification sample and the analysis method used to evaluate the data. Within those constraints S-basis values established since 1975 may be viewed as estimated A-basis values.

Wherever possible, the statistical validity of these estimated A-basis (S-basis) values should be verified as soon as sufficient heats and lots of material are available from the major producers to establish more rigorous A-basis properties by the methods described in MIL-HDBK-5. If the more rigorous A-basis property exceeds the S-basis value, the major suppliers and users of the material may benefit from updating or replacing the specification because then they will be able to take full advantage of the capabilities of the material within the design allowable tables in MIL-HDBK-5.

In the opposite (and fortunately infrequent) situation where the more rigorous A-basis property falls well below the S-basis value, the repercussions may be greater for both the user and producer. Actual design margins (as compared to originally perceived design margins) on primary structure may be reduced below desirable levels if the S-basis value must be downgraded to a lower A-basis value. The perceived adequacy of a material for a particular application may be reduced if the S-basis value is reduced to match a lower A-basis value. However, under most circumstances, the S-basis value should be reduced to match the A-basis value if process improvements cannot be instituted to raise the A-basis value to the level of the original S-basis value.

B-Basis — This designation indicates that at least 90 percent of the population of values is expected to equal or exceed the statistically calculated mechanical property value, with a confidence of 95 percent. This statistically calculated number is computed using the procedures specified in Section 9.5.

A-Basis — The lower value of either the statistically calculated number T_{99}, or the specification minimum (S-basis). The statistically calculated number indicates that at least 99 percent of the population is expected to equal or exceed the statistically calculated mechanical property value with a confidence of 95 percent. This statistically calculated number is computed using the procedures specified in Section 9.5.

Sections 9.2.4.2 and 9.5.1.1 contain discussions of data requirements for direct computation of design properties based on current process capability of the majority of suppliers of a given material and product form. To assure that the A- and B-basis values, defined above, represent true current process capability of a material, all available original test data for current material that is produced and supplied to the appropriate government, industry, or equivalent company specifications are included in calculating these values. (However, to be considered for inclusion in MIL-HDBK-5, a material must be covered by an industry, Federal, or Military specification per Section 9.1.6.) Only positive proof of improper processing or testing is cause for exclusion of original test data, except that the number of tests per lot will not exceed the usual frequency of testing for the product. It is recognized, however, that extensive acceptance testing resulting in elimination of low-strength material from the population may justify establishment of higher mechanical property values for the remaining material. Since this is a function of both the type of product and the nature and frequency of the acceptance tests practiced by each company, it is impractical to attempt to include these considerations in this document.

Usually, only tensile ultimate and yield strengths in a specified testing direction are determined in such a manner that they can be termed A- and B-basis values, in accordance with definitions given above. Only tensile ultimate strength, tensile yield strength, elongation, and reduction of area (for some alloys) are normally specified in the governing specifications and can be termed S-basis values. However, ratioing procedures (described in Section 9.5.4) have been established, by which other property values such as compression, shear, and bearing are computed to have approximately the same assurance levels as A-, B-, or S-basis values for tensile ultimate and yield strength. Property values determined in this manner are presented as having the same data basis as tensile ultimate and yield strengths in the same column of the table.

Current practice regarding the use of the above data bases in the presentation of room-temperature design properties is as follows:

(1) Room-temperature design properties for tensile ultimate and yield strengths are presented as A- and B- or S-basis values. Calculated T_{99} values that are higher than corresponding S-basis

values are presented as footnotes in MIL-HDBK-5 property tables, and these T_{99} values are not qualified for general use in design unless the specification requirements are increased to equal the T_{99} value. However, T_{99} values that are equal to or lower than corresponding S-basis values replace S-basis values as the A-basis values in the document.

(2) The S-basis value is used for elongation and reduction of area.

(3) If an A-basis value is presented for a strength property, the corresponding B-basis value is also presented.

(4) A- and B-basis values, when available, replace S-basis values, based upon item (1) conditions.

(5) A- and B-basis values, based upon data representing samples of material supplied in the annealed, solution treated, or as-fabricated conditions, which were heat treated to demonstrate response to heat treatment by suppliers, are incorporated into MIL-HDBK-5 with an explanatory footnote. It is recognized that structural fabrication and processing can alter mechanical properties. The use of A- and B-basis values for structural design requires consideration of such effects. These material property values are derived from the statistically computed T_{99} and T_{90} values defined earlier.

(6) Strength at room temperature after thermal exposure is presented graphically as a percentage of the tabulated design property.

(7) Design data for all other properties, such as elastic modulus, Poisson's ratio, creep, fatigue, and physical properties, are presented on a typical basis unless indicated otherwise.

9.1.7 Rounding Procedures —When the lower tolerance bound (T_{99} or T_{90}) results in a fractional number, the actual mechanical property value used in the room temperature tables is determined by rounding according to Section 6.4 of ASTM E29, Standard Practice for Using Significant Digits in Test Data to Determine Conformance with Specifications. However, if the S value is lower, it is shown in the table and the rounded T_{99} value is included in a footnote.

9.2 MATERIAL, SPECIFICATION, TESTING, AND DATA REQUIREMENTS

9.2.1 MATERIAL REQUIREMENTS — The product used for the determination of minimum design values for incorporation into MIL-HDBK-5 must be production material. The material must have been produced using production facilities and standard fabrication and processing procedures. If a test program to determine requisite mechanical properties is initiated before a public specification describing this product is available, precautionary measures must be taken to ensure that the product supplied for the test program conforms to the specification, when published, and represents production material.

Dimensionally discrepant castings or special test configurations may be used for the development of derived properties with prior approval by the MIL-HDBK-5 Coordination Group, providing these castings meet the requirements of the applicable material specification. Design values for separately cast test specimens are not presented in MIL-HDBK-5.

9.2.2 SPECIFICATION REQUIREMENTS — To be considered for inclusion in MIL-HDBK-5, a product must be covered by an industry specification (AMS specification issued by SAE Aerospace Materials Division or an ASTM standard published by the American Society for Testing and Materials), or a government specification (Military or Federal). If a public specification for the product is not available, action should be initiated to prepare a draft specification. Standard manufacturing procedures will have been established for the fabrication and processing of production material before a draft specification is prepared. The draft specification will describe a product which is commercially available on a production basis. An AMS draft specification should be submitted to the SAE Aerospace Materials Division and an ASTM standard should be transmitted to the American Society for Testing and Materials for publication. See Section 9.4 for requirements to substantiate the S-basis properties.

9.2.3 REQUIRED TEST METHODS/PROCEDURES — Testing standards used in MIL-HDBK-5 are summarized in Table 9.2.3. In most cases, testing standards maintained by the American Society for Testing and Materials, ASTM, are referenced. The primary exception is fastener testing, where NASM-1312 is used as the reference standard. The mostly recently approved version of each standard is used as the baseline for all test data reviewed for inclusion in MIL-HDBK-5.

Table 9.2.3. Summary of Required Testing Standards within MIL-HDBK-5

Property to be Determined or Procedure to be Followed	Designation	Title of Testing Standard	Relevant Section(s) within Guidelines
Bearing	ASTM E 238	Method for Pin-Type Bearing Test of Metallic Materials	9.2.3.2, 1.4.7.1, 3.1.2
Classification of Extensometers	ASTM E 83	Method of Verification and Classification of Extensometers	9.1.3.3, 9.2.4.4.2
Coefficient of Thermal Expansion	ASTM E 228	Test Method for Linear Thermal Expansion of Solid Materials with a Vitreous Silica Dilatometer	9.2.3.4
Compression	ASTM E 9	Compression Testing of Metallic Materials	1.7.1
Creep and Rupture	ASTM E 139	Rec. Practice for Conducting Creep, Creep-Rupture, & Stress-Rupture Tests of Metallic Materials	9.2.3.9
Density	ASTM C 693	Test Method for Density of Glass by Buoyancy	9.2.3.4
Elastic Modulus – Compression	ASTM E 111	Test Method for Young's Modulus, Tangent Modulus, and Chord Modulus	9.2.3.3, 9.8.1.3.1
Elastic Modulus – Shear	ASTM E 143	Test Method for Shear Modulus at Room Temperature	9.8.1.3.1
Elastic Modulus – Tension	ASTM E 111	Test Method for Young's Modulus, Tangent Modulus, and Chord Modulus	9.2.3.3, 9.8.1.3.1
Elongation	ASTM E 8	Test Method for Tension Testing of Metallic Materials	1.4.3.5
Exfoliation Corrosion	ASTM G 34	Test Method for Exfoliation Corrosion Susceptibility in 2XXX and 7XXX Series Aluminum Alloys (EXCO Test)	3.1.2.3.1
Fastener Mechanical Properties	NASM-1312	Fastener Test Methods	9.2.3.10.1
Fatigue - Load Control	ASTM E 466	Recommended Practice for Constant Amplitude Axial Fatigue Tests of Metallic Materials	9.6.1
Fatigue - Strain Control	ASTM E 606	Recommended Practice for Constant Amplitude Low Cycle Fatigue Testing	9.6.1
Fatigue Crack Growth	ASTM E 647	Test Method for Measurement of Fatigue Crack Growth Rates	9.2.3.6

Table 9.2.3. Summary of Required Testing Standards within MIL-HDBK-5, Continued

Property to be Determined or Procedure to be Followed	Designation	Title of Testing Standard	Relevant Section(s) within Guidelines
Fracture Toughness - Plane Strain	ASTM E 399	Test Method for Plane-Strain Fracture Toughness of Metallic Materials	9.6.3
Fracture Toughness - Plane Stress	ASTM E 561	Recommended Practice for R Curve Determination	9.6.3
Poisson's Ratio	ASTM E 132	Test Method for Poisson's Ratio at Room Temperature	9.8.1.3.1
Reduction in Area	ASTM E 8	Test Method for Tension Testing of Metallic Materials	1.4.3.5
Shear – Pin	ASTM B 769	Test Method for Shear Testing of Aluminum Alloys	9.2.3.2, 3.1.2
Shear – Slotted	ASTM B 831	Standard Test Method for Shear Testing of Thin Aluminum Alloy Products	9.2.2
Specific Heat	ASTM D 2766	Test Method for Specific Heat of Liquids and Solids	9.2.3.4
Stress Corrosion Cracking	ASTM G 47	Test Method for Determining Susceptibility to Stress-Corrosion Cracking of High Strength Aluminum Alloy Products	3.1.2.3.1
Tension	ASTM E 8	Test Method for Tension Testing of Metallic Materials	1.4.4.1
	ASTM A 370	Standard Test Methods and Definitions for Mechanical Testing of Steel Products	1.4.4.1
	ASTM B 557	Test Methods of Tension Testing Wrought and Cast Aluminum- and Magnesium-Alloy Products	1.4.4.1
Tension - Elevated Temperatures	ASTM E 21	Recommended Practice for Elevated Temperature Tension Tests of Metallic Materials	1.4.4.1
Thermal Conductivity	ASTM C 714	Test Method for Thermal Diffusivity of Carbon and Graphite by a Thermal Pulse Method	9.2.3.4

9.2.3.1 ***Mechanical-Property Terms*** — Mechanical properties that are presented as room-temperature design properties are listed in Table 9.2.3.1. It is important that use of a subscripted, capital letter *"F"* should be limited to designation of minimum values. Its use to designate an individual test value can lead to confusion and should be avoided in MIL-HDBK-5 data proposals.

The absence of a directionality symbol implies that the property value is applicable to each of the grain directions when the product dimensions exceed approximately 2.5 inches.

Table 9.2.3.1. Mechanical Property Terms

		Symbol	
Property	Units	Room-Temperature Minimum Value	Individual or Typical Value
Tensile Ultimate Strength	ksi	F_{tu}	TUS
Tensile Yield Strength	ksi	F_{ty}	TYS
Compressive Yield Strength	ksi	F_{cy}	CYS
Shear Ultimate Strength	ksi	F_{su}	SUS
Shear Yield Strength*	ksi	F_{sy}	SYS
Bearing Ultimate Strength	ksi	F_{bru}	BUS
Bearing Yield Strength	ksi	F_{bry}	BYS
Elongation	percent	e	elong.
Total Strain at Failure*	percent	e_t	strain at failure
Reduction of Area	percent	RA	red. of area

* As applicable.

The listed mechanical property symbols should be followed by one of the following additional symbols for wrought alloys, not castings.

L — Longitudinal direction; parallel to the principal direction of flow in a worked metal.

T — Transverse direction; perpendicular to the principal direction of flow in a worked metal; may be further defined as LT or ST.

LT — Long-transverse direction; the transverse direction having the largest dimension, often called the "width" direction.

ST — Short-transverse direction; the transverse direction having the smallest dimension, often called the "thickness" direction.

Values of F_{bru} and F_{bry} should indicate the appropriate edge distance/hole diameter (e/D) ratio. Design properties are presented for two such ratios: e/D = 1.5 and e/D = 2.0.

Data for use in establishing these properties should be based on ASTM standard testing practices. The test practice and any deviations therefrom should be reported when submitting proposals to the MIL-HDBK-5 Coordination Group for consideration.

9.2.3.2 ***Testing Direction and Specimen Location*** — Table 9.2.3.2 lists the primary testing direction for various products. When performing derived property test programs it is imperative that the test specimens be taken from the same sheet, plate, bar, extrusion, forging, or casting. Derived property test specimens must also be located in close proximity. If derived property coupons or specimens are machined prior to heat treatment, all specimens representing a lot must be heat treated simultaneously in the same heat treat load through all heat treating operations. This procedure is necessary to provide precise mechanical property relationships (ratios).

Table 9.2.3.2. Primary[a] Testing Direction for Various Alloy Systems

Product Form	Carbon and Low Alloy Steels	Non-Heat Treatable Alum. Alloys	Heat Treatable Alum. Alloys	Magnesium Alloys	Titanium Alloys	Corrosion and Heat Resistant Alloys	Other Alloys
Sheet and Plate	LT	L	LT	L	[c]	LT	[b]
Bar	L	L	L	L	[c]	L	[b]
Tubing	L	L	L	L	L	L	[b]
Extrusion	L	L	L	L	[c]	L	[b]
Die Forging	[b]	L	L	L	[c]	[b]	[b]
Hand Forging	[b]	LT	LT	LT	[c]	[b]	[b]

[a] Although material specifications may contain mechanical-property requirements for two or three grain directions, the primary test direction indicates the grain direction which is tested regularly.

[b] See applicable material specification.

[c] Since there is no primary test direction for titanium alloys, mechanical property ratios will be formed using strength values which represent the same grain directions in the numerator and denominator. The design allowable is computed as the product of the reduced ratio and the F_{ty} or F_{tu} value for the grain direction represented by the reduced ratio.

Test specimens must be located within the cross section of the product in accordance with the applicable material specification, or applicable sampling specification, such as AMS 2355, AMS 2370, and AMS 2371 (See list of references at the end of Chapter 9). Subsize tensile and compressive test specimens may be used if necessary. Specimen drawings should be provided along with each data proposal, with English units included. The applicable testing standard should be identified along with the specimen drawings. If the standard is not routinely available in English, an English translation of the standard should be provided.

Test specimens must be excised in longitudinal, long transverse, and short transverse (when applicable) grain directions. Mechanical properties must also be obtained in the 45° grain direction for materials that have significantly different properties in this direction than the standard grain directions. For some product configurations, it may be impractical to obtain transverse bearing specimens. For aluminum die forgings, the longitudinal grain direction is defined as orientations parallel, within ±15°, to the predominate grain flow. The preferred definition for long transverse grain direction is perpendicular, within ±15°, to the longitudinal (predominate) grain direction and parallel, within ±15°, to the parting plane. (Both conditions must be met to satisfy this definition.) The short transverse grain direction is defined as perpendicular, within ±15°, to the longitudinal (predominate) grain direction and perpendicular, within ±15°, to the parting plane. (Both conditions must be met.)

9.2.3.3 *Tension, Compression, Shear and Bearing* — All tests must be performed in accordance with applicable ASTM specifications, or their equivalent. Tensile (ASTM E8, A370, and B557), compression (ASTM E9), shear (ASTM B769), and bearing (ASTM E238) tests must be conducted at room temperature to determine tensile yield and ultimate strengths, compressive yield strength, shear ultimate strength, and bearing yield and ultimate strengths for e/D = 1.5 and e/D = 2.0 for each grain direction and each lot of material. All data must be identified by lot, or heat, or melt. For materials used exclusively in high temperature applications, such as gas turbine or rocket engines, the determination of design values for compression, shear, and bearing strengths may be waived by the MIL-HDBK-5 Coordination Group. In lieu of data for these properties, sufficient elevated temperature data for tensile yield and ultimate strengths, as well as modulus of elasticity, will be submitted so that elevated temperature curves can be constructed. Data should be submitted for the useful temperature range of the product. See Section 9.2.4.4.3 for data requirements for elevated temperature curves.

The pin shear testing of aluminum alloys should be done in conformance to ASTM B 769, or an equivalent public specification. Grain orientations and loading directions for shear specimens must be defined in accordance with ASTM B 769, or an equivalent specification. Slotted shear testing of thin aluminum alloys should be done in conformance to ASTM B 831. Bearing tests for products from all alloy systems will be conducted in accordance with ASTM E 238, or an equivalent public specification, using "clean pin" test procedures. For aluminum alloy plate, bearing specimens are oriented flatwise and for aluminum alloy die and hand forgings, bearing specimens must be oriented edgewise, as described in Section 3.1.2.1.1.

9.2.3.4 Other Static Properties

9.2.3.4.1 Modulus and Poisson's Ratio — Tensile and compressive modulus of elasticity values must be determined using a Class B-1 or better extensometer. Measurements must be made on at least three lots of material. The method of determining or verifying the classification of extensometers is identified in ASTM E 83. ASTM E 111 is the standard test method for the determination of Young's Modulus, tangent modulus, and chord modulus of structural materials. A modulus value will also be obtained for the 45 degree grain orientation for materials that are anticipated to have significantly different properties in this direction than the standard grain directions. Modulus values are "typical". Poisson's ratio values must be determined in accordance with ASTM E132.

9.2.3.4.2 Physical Properties — Density, specific heat, thermal conductivity, and mean coefficient of thermal expansion are physical properties normally included in MIL-HDBK-5. Physical properties are presented in the room-temperature property tables if they are not presented in effect-of-temperature curves (see Section 9.8.3.3). The basis for physical properties is "typical". Table 9.2.3.4.2 displays units and symbols used in MIL-HDBK-5, and also shows recommended ASTM test procedures for measuring these properties. Since other procedures are sometimes employed in measuring physical properties, the methods actually used to develop the values proposed for inclusion in MIL-HDBK-5 should be reported in the supporting data proposal. For specific heat and thermal conductivity values reported in the room temperature property table, the reference temperature of measurement is also shown [for example, for 2017 aluminum the specific heat is 0.23 (at 212°F)]. For tabulated values of mean thermal expansion, temperature range of the coefficient is shown [for example, 12.5 (70 to 212°F)]. The reference temperature of 70°F is used as the standard for mean coefficient of thermal expansion curves shown in MIL-HDBK-5.

Table 9.2.3.4.2. Units, Symbols, and ASTM Test Procedures Used to Compute and Present Physical Property Data in MIL-HDBK-5

Property	Units	Symbol	Recommended ASTM Test Procedures
Density	lb/in.^{3}	ω	C 693
Specific heat	Btu/lb-°F	C	D 2766
Thermal conductivity	Btu(hr-ft^2-°F/ft)	K	C 714[a]
Mean coefficient of thermal expansion	10^{-6}(in./in./°F)	α	E 228

[a] ASTM C 714 is a test for thermal diffusivity from which thermal conductivity can be computed.

9.2.3.5 Dynamic and Time Dependent Properties

9.2.3.5.1 Fatigue — Both strain-controlled and load-controlled axial fatigue data are included in MIL-HDBK-5. Constant amplitude test data are the primary focus. Well-documented, initial and/or periodic overstrain data may also be included. Data obtained under strain control are considered only for unnotched, uniform-gage-length specimens, while both notched and unnotched specimens are considered for load-control conditions. The relevant standards for strain and load control fatigue testing are ASTM E606 and ASTM E466, respectively.

9.2.3.5.2 Fatigue Crack Growth — Fatigue-crack-propagation data may be generated by several types of fracture mechanics test specimens as described in ASTM E647. The principal criteria for acceptance of data are twofold. One is that a valid stress-intensity-factor formulation be available for the specimen; the other is that nominal net-section stresses, as calculated by concepts of elementary strength of materials, be less than eighty percent (80%) of the tensile yield strength of the material.

Basic data are generated as crack lengths, a, and associated cycle counts, N. These data are interpreted as crack-growth rates determined as slopes, or average slopes, of sequential subsets of data. For MIL-HDBK-5, da/dN is calculated as the weighted average incremental slope approximation

$$\left(\frac{da}{dN}\right) \approx \left(\frac{\Delta a}{\Delta N}\right)_{i-1} + \frac{N_i - N_{i-1}}{\left(N_{i+1} - N_{i-1}\right)}\left[\left(\frac{\Delta a}{\Delta N}\right)_i - \left(\frac{\Delta a}{\Delta N}\right)_{i-1}\right] \quad i=2,\ldots,n-1 \qquad [9.2.3.5.2(a)]$$

from the measured crack-growth data as illustrated in Figure 9.2.3.5.2. However, alternative methods, such as polynomial fitting of the "a" versus "N" curve, are acceptable for computation of da/dN values. By this indexing and calculating procedure "n" measurements provide "n-2" slope or rate values at all but first and last measurement points. The directly associated stress-intensity factor, K, for each slope computation is computed in accordance with Equation 9.2.3.5.2(b) where g(a,w) is a geometric scaling function dependent on crack and specimen geometry, and S is nominal stress.

$$K = S\sqrt{a}\ g(a,w) \quad , \qquad [9.2.3.5.2(b)]$$

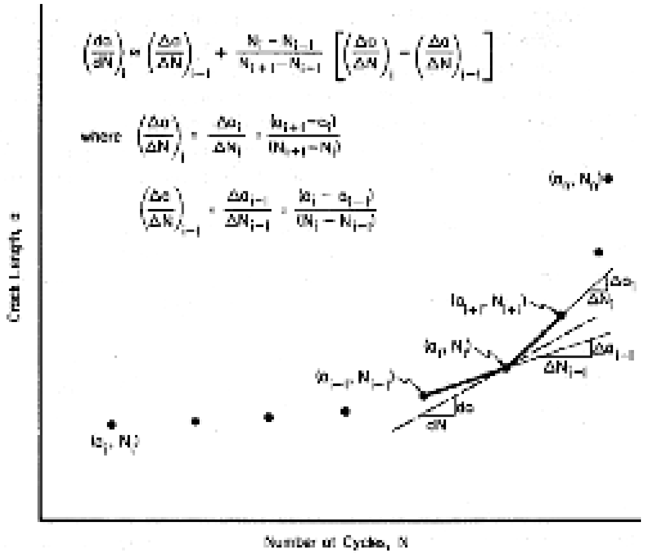


Figure 9.2.3.5.2. Analytical definition of crack-growth rate calculation.

9.2.3.5.3 Fracture Toughness — The degree of lateral constraint at the crack tip determines whether plane strain (high lateral constraint) or plane stress test methods should be used.

Plane-Strain Fracture Toughness — For materials which are inherently brittle, or for structure and flaw configurations which are in triaxial tension due to their thickness or bulk restraint, quasi-plane-strain-stress conditions can be obtained in a finite-sized structural element. Triaxial stress state implicit to plane strain effectively embrittles the material by providing maximum restraint against plastic deformation. In this condition, component behavior is essentially elastic until fracture stress is reached and is readily amenable to analysis in terms of elastic fracture mechanics. This mode of fracture is frequently characteristic of the very high strength metals.

While a wide variety of fracture specimens are available for specified testing objectives, the notch-bend specimen and compact specimen generally offer the greatest convenience and material economics for testing. Details of recommended testing practice are presented in ASTM E399.

Plane-Stress and Transitional-Fracture Toughness — In ductile materials and relatively thin structural elements, stress state may approach plane-stress conditions. As a result, crack tip plasticity and stable-crack growth may be expected in cracked structural components under load prior to reaching a critical stress-intensity factor value. Furthermore, due to the interaction of plasticity and geometry, characteristic fracture toughness of a material may vary with the stress state, as illustrated in Figure 9.2.3.5.3(a).

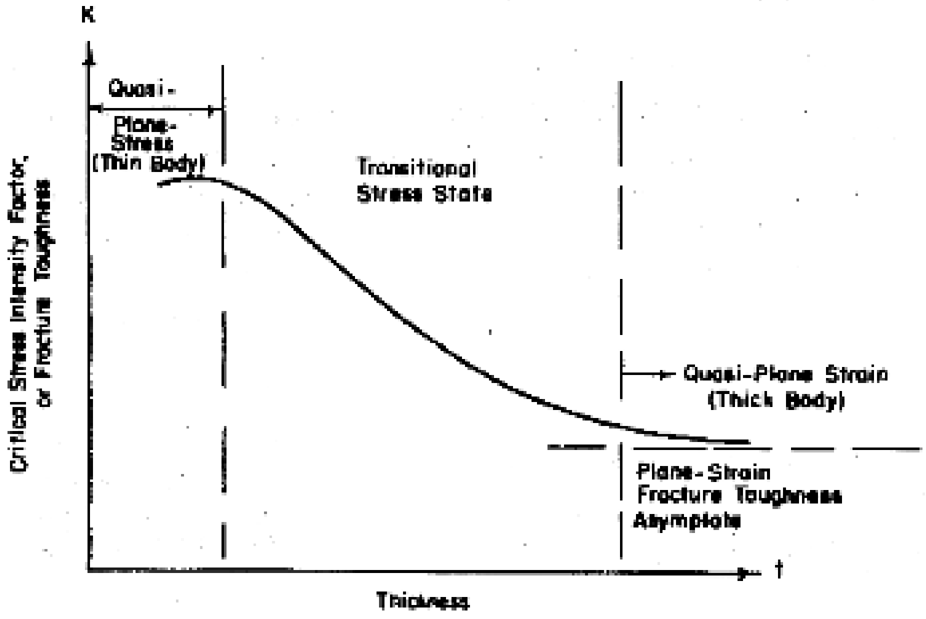
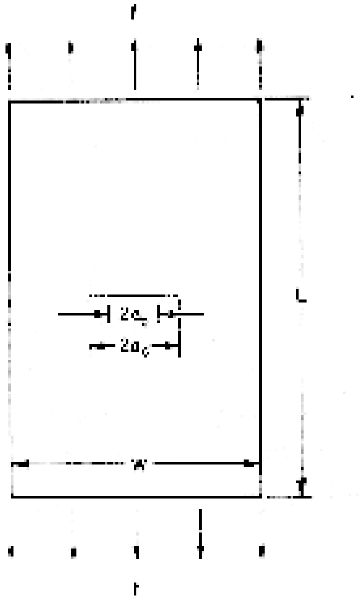


Figure 9.2.3.5.3(a). Variation of fracture toughness with thickness or stress state (size effect).

It is convenient to consider critical stress-intensity factor values, varying with thickness or stress state, as indices of crack-damage resistance. The stress-intensity factor can be used as a consistent measure of crack damage, not only for fracture instability, but also for other levels of crack damage severity, provided the damage is consistently specified and detected. This concept implies that plane-stress and transitional-fracture toughness of metallic materials, while not necessarily a fixed value for the material, is a characteristic value for a given product form, thickness, grain direction, temperature, and strain rate.

Because of the complexity of crack behavior in plane-stress and transitional-stress states, test methods for evaluating material toughness have not been completely standardized; however, several useful methods do exist. One of the most widely used techniques, the R-curve procedure, is documented in ASTM E561. Although each configuration generates nearly consistent results when data are properly evaluated, it is recommended that each general flaw configuration be interpreted and applied within its own design context.

Middle Tension Panels — Because it simulates typical crack conditions in thin-sheet structures, the middle tension panel is a popular testing configuration for evaluating crack behavior. This specimen is illustrated in Figure 9.2.3.5.3(b).



Typical Constraints:

Free length of specimen between grips, $L \geq 2W$

Stress intensity factor (max) during precracking, $K_{fatigue} \leq K_{app}/2$

Figure 9.2.3.5.3(b). Middle tension panel.

The crack-tip plasticity and slow-stable growth of the crack which are attendant to plane-stress or transitional stress state conditions may cause a deviation from abrupt fracture which is normally associated with crack extension under ideal plane conditions, as illustrated in Figure 9.2.3.5.3(c).

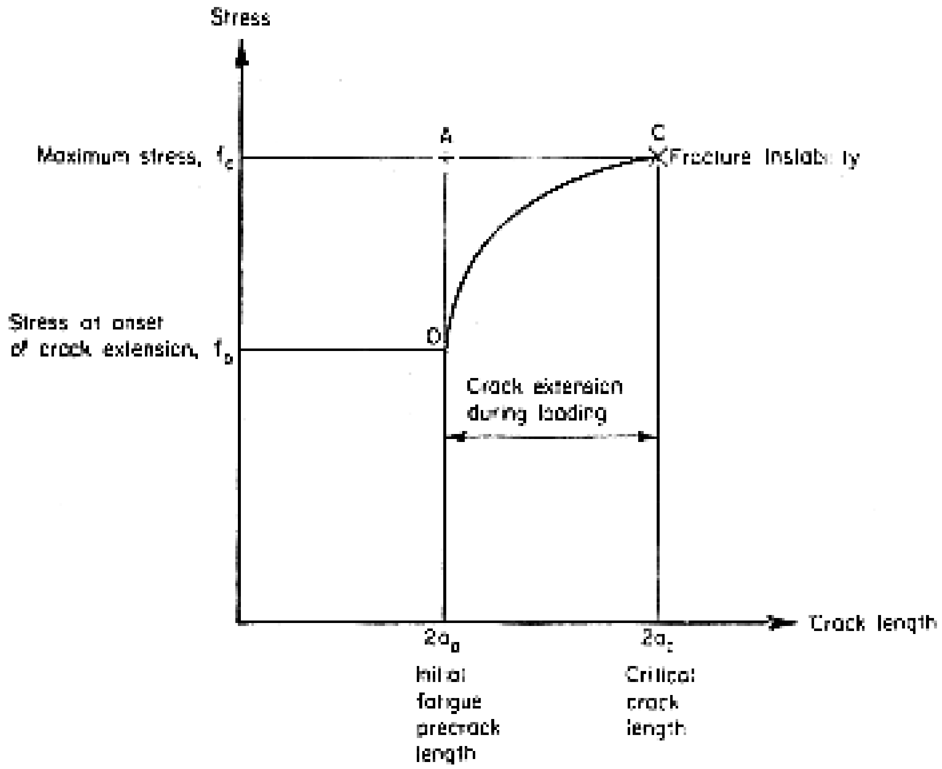


Figure 9.2.3.5.3(c). Crack growth curve.

Two limiting damage levels are noted in this figure. Point O is the threshold or onset of slow, stable tear where the crack slowly extends after reaching a threshold stress level. Point C is fracture instability. Both levels of crack damage can be associated with a different stress intensity factor, or damage index, for product forms and thicknesses of interest. These damage levels can be identified either directly with the K value as determined from instantaneous stress-crack length coordinate dimensions at these points, or approximately by the coordinates of Point A, which is residual strength, or apparent toughness concept of relating initial crack length to final fracture stress.

The stress intensity factor, K, associated with any of these damage levels is determined from

$$K = f\sqrt{a} \cdot Y, \text{ ksi } \sqrt{\text{in}} \qquad [9.2.3.5.3(a)]$$

where, for this configuration,

a = half-length of middle crack

$Y = (\pi \sec \pi a/W)^{1/2}$.

The locus of data points can be represented by a parametric stress-intensity factor curve, as shown in Figure 9.2.3.5.3(d), where each curve represents a different stress-intensity factor formulation. The slow growth curve is superimposed on this figure to illustrate the general relationship between the threshold of stable crack extension, apparent instability, and fracture instability for a typical crack.

Because of experimental difficulties associated with precise detection of threshold and instability points, points O and C, apparent toughness, or residual strength concept of crack damage is used in this presentation. This is the locus of data points "A", noted in Figure 9.2.3.5.3(c), which determine apparent fracture toughness.

$$K_{app} = f_c\left(\pi a_o \sec \pi a_o / W\right)^{\frac{1}{2}} \quad . \qquad [\,9.2.3.5.3(b)]$$

See Reference 9.2.3.5.3 for additional information.

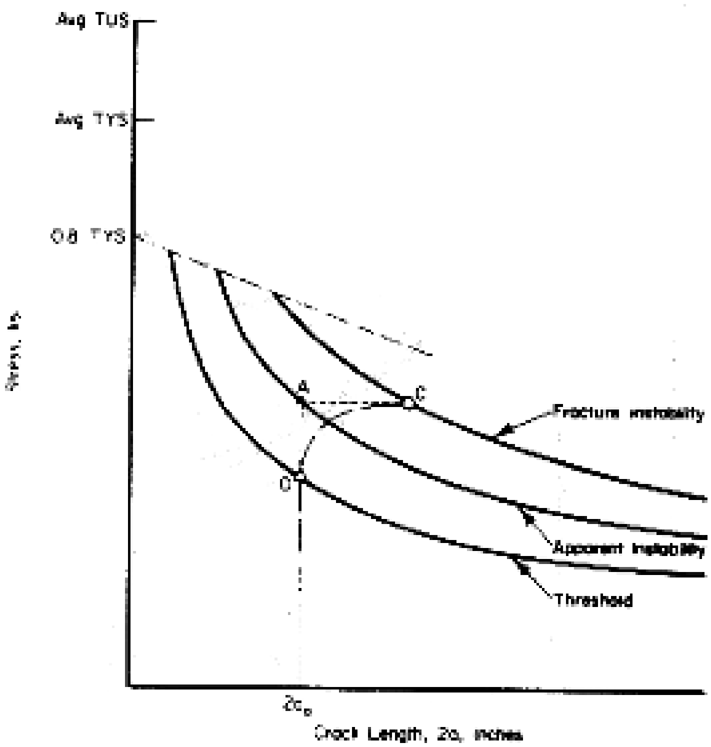


Figure 9.2.3.5.3(d). Stress intensity factor curves as parametric indices of crack damage.

9.2.3.5.4 *Creep and Creep Rupture* — The following paragraphs provide guidelines on testing methods for developing creep and creep-rupture data.

Test Methods—Test methods must conform to ASTM E139. However, it is recognized that this standard allows considerable latitude in procedures such that the mean trends and variability in the results can be significantly affected.

In case a significant difference is found in results from different testing sources, the following should be evaluated:

- Material Condition
- Specimen Dimensions and Configuration (geometry effect)
- Specimen Surface Preparation (residual stresses)
- Specimen Alignment (concentricity, fixturing, load train, and loading method)
- Temperature Control (number, type, and location of sensors, reference junction temperature control, monitoring and recording)
- Extensometers (type, fixturing, and recording)
- Strain Recording (records inelastic strain on loading and creates a record to be evaluated for test stability)
- Documentation (testing procedures)
- General Laboratory Conditions, Personnel Qualifications, Calibration Intervals.

The submittor of a proposal should provide documentation sufficient to permit a comparative evaluation of data. Inability to do so may cause rejection of some associated data, or the entire proposal.

9.2.3.6 *Mechanically Fastened Joints* —Although many fasteners for which joint allowables are given in MIL-HDBK-5 are covered by MIL and NAS specifications (which provide for minimum shear strength values), many proprietary fasteners are listed wherein minimum shear strength values are established by the manufacturer. In either case, sufficient testing is necessary to establish minimum values. The intent of this subsection is to provide minimum test procedures to document shear strength of fasteners appearing in MIL-HDBK-5, regardless of specification source.

Shear strengths will be determined from shear-critical single-shear test results or double-shear test results. Double-shear test results performed in accordance with NASM 1312, Test 13, are preferred over single-shear results, except for blind fasteners and driven rivets. For these latter fasteners, shear-critical tests will be conducted with all components in the installed condition in hardened steel test plates. NASM 1312, Test 20, is the required test method. Furthermore, when fasteners of a given configuration and material are identical in every respect except for head size and shape, fastener shear test data are necessary only on one head style.

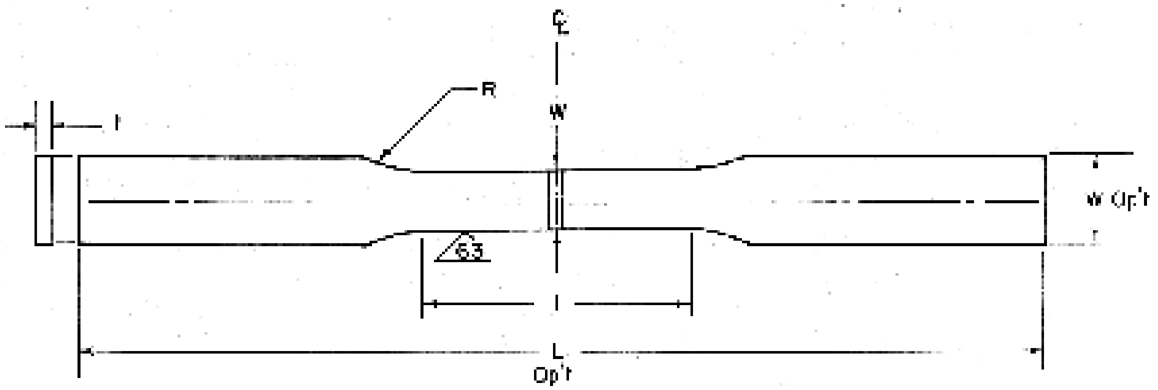
Room-temperature testing equipment and procedures should comply with the provisions of NASM 1312, Tests 4, 13, and 20 (See list of references at the end of Chapter 9 for both single- and double-shear tests).

Specimen design should be as provided in NASM 1312, Test 4, Figure 1.

9.2.3.7 *Fusion-Welded Joints* — Two types of transverse-weld tensile coupon configurations are recommended. Use flat coupons for materials up to 0.5-inch thickness. For weld joint thicknesses greater than 0.5-inch, round coupons are recommended. These two configurations are shown in Figure 9.2.3.7(a) and (b), respectively. Exact specimen dimensions are dependent on thickness of the weldment being evaluated, but geometric similitude is maintained within each type of specimen. Appropriate dimensions are given for the reduced test section of each coupon. The dimensions of gripping areas at each end are optional and may be modified to accommodate standard test fixtures.

Remove the weld heads from all flat coupons unless standards have been established regarding weld reinforcement configuration. When data are required for welds with reinforcements intact, their configurations must be specified. When round coupons are used in thick weldments, location within the weldment becomes an additional variable which must be described and associated with data.

At present, coupon configuration requirements for evaluation of properties other than transverse tensile have not been sufficiently defined to be utilized on an industry-wide basis. Due to the nature of fatigue testing, no specific test configurations are recommended. Configurations selected according to standard base metal practices have been used and may be satisfactory. Weld reinforcements are of particular significance in fatigue testing, and should be removed or specified in detail, together with a description of the coupon used.

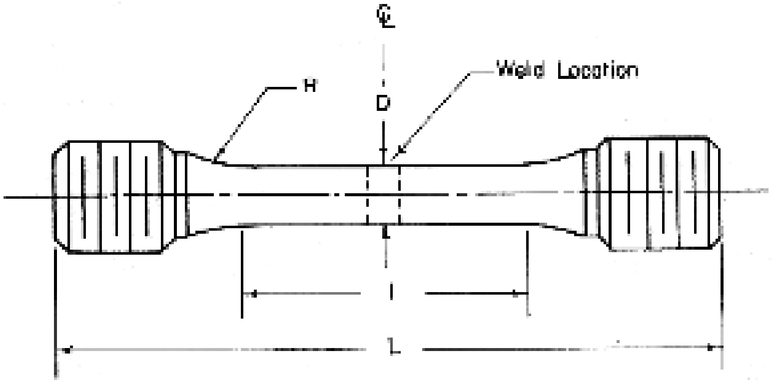


t	w	l	R
< .188	0.5	2.25	1 min.
0.188 to 0.25	0.75	3.0	1.5 min
0.25 to 0.5	1.0	4.0	2 min.

NOTES:

1. Dimension "W" and "L" optional.
2. Weld bead on or off optional
3. Fillet radii must fair smoothly into reduced section
4. Material and grain direction per test requirements.
5. Specimens warped from welding or heat treatment shall not be straightened
6. Reduced section machined surfaces 63
7. The reduced section and grip ends must be symmetrical about the longitudinal ℄ within ±0.01.
8. Tolerances except otherwise noted Linear ±0.03, Angular ± 1°.

Figure 9.2.3.7(a). Flat transverse-weld tensile coupon.



D	I	R
0.250	1.25	0.250
0.505	2.0	0.50

Notes:

1. Dimension "L" and thread size optional.
2. Fillet radii must fair smoothly into reduced section
3. Reduced section machined surface 32
4. Heat treatment to be performed prior to finish machining.
5. The reduced section and grip ends must be symmetrical about the longitudinal ℄ within ±0.01.
6. Tolerances except otherwise noted: Linear ± 0.03, Angular ±1°

Figure 9.2.3.7(b). Round transverse-weld tensile coupon.

Fracture toughness coupons should conform to the latest requirements defined by ASTM E 399. Crack location with respect to weldment is of particular importance, and the criteria for validity of specimen must be met. Coupons used for evaluation of other weldment properties, such as fillet-weld shear strength and creep or stress rupture, also require definition in order to be used for design strengths.

Availability of accepted test methods for base metal evaluation, as evidence by federal and ASTM standards, has resulted in their general application to testing of weldments. These standards control test equipment, data accuracy, and loading rates. Reference to existing base metal test methods are generally considered satisfactory for mechanical property testing of weldments except for configuration definition. The testing practice and any deviations should be reported when data samples are generated. In no case may a test result be discarded on the basis of a defect found after final inspection—for example, during post-test examination of fractured surfaces.

9.2.4 DATA REQUIREMENTS — Data requirements for the various types of data included in MIL-HDBK-5 are described in this section. Data requirements for determination of mechanical and physical properties within MIL-HDBK-5 are summarized in Table 9.2.4. The customary statistical basis of each material property is listed, along with the relative importance of each data type within the Handbook. Potential extenuating circumstances, such as special material usage requirements, are also considered. Where applicable for each data type, the minimum sample size and the minimum number of heats and lots are identified. Applicable MIL-HDBK-5 introductory or guideline sections are also referenced.

9.2.4.1 S-basis Values —To incorporate a new product into MIL-HDBK-5 on an S-basis it is recommended that at least 30 test samples from at least three heats or lots of material be provided for each thickness range and product form. These requirements are applicable to each alloy, product form and heat treat condition or temper. Section 9.2.3 delineates the requirements for a test program to generate mechanical property data suitable for computation of derived properties. A test matrix, based on these requirements, is shown in Table 9.2.4.1.

9.2.4.2 *A- and B-basis Values* — The direct calculation of statistical minimum properties (T_{99} and T_{90} values) requires a substantial quantity of data to determine (1) the form of distribution and (2) reliable estimates of the population parameters describing the distribution. Prior experience with the material under consideration will help in determining sample size requirements. Each material should be represented by a sample containing at least 100 observations, assuming these data are distributed according to a three-parameter Weibull distribution or a Pearson Type III distribution, or 299 observations if neither of these families of distributions adequately describe the data. The sample must include multiple lots, representing at least ten production heats, casts, or melts, from a majority of important producers. See Table 9.2.4.2 for definitions of lot, heat, cast, and melt. The sample should be distributed as evenly as possible over the size range applicable to the tolerance bound for the mechanical property. In order to avoid an undesirable biasing of the sample in favor of lots represented by more observations than other lots, the number of observations from each lot must be nearly equal.

If grouped data are reported in intervals of 1 ksi or less, they may be “ungrouped” and analyzed as described below. The uniform smoothing method for ungrouping grouped data should be used. For the uniform smoothing method, observations in an interval are spread uniformly over that interval. The i^{th} observation in an interval is set equal to

$$a_i = L + \frac{i}{n+1}(U - L) \quad i = 1,2,\ldots, n$$

where

n = the number of observations in the interval
L = the lower end point of the interval
U = the upper end point of the interval.

The amount of data must be adequate to assure that the sample is representative of the population. Although censoring is highly undesirable, parametric techniques will “tolerate” a limited degree of censoring. In contrast, nonparametric techniques will not “tolerate” censoring. Determination of a T_{99} value by nonparametric techniques requires at least 299 individual observations that represent 10 heats, casts, or melts. Additional data are very desirable. The selection of the number 299 is not arbitrary. Rather, 299 represents the smallest sample for which the lowest observation is a 95 percent confidence, 99 percent exceedance tolerance bound, or T_{99} value. For smaller samples, the T_{99} value falls below the lowest observation and thus cannot be determined without knowledge of the form of the distribution. The lowest of 29 observations corresponds to a 95 percent confidence, 90 percent exceedance tolerance bound, or T_{90} value. The T_{90} value must be based on data from at least 10 heats, casts, or melts. It is important to note that B-basis properties are not included in the Handbook without A-basis properties.

Table 9.2.4. Summary of Data Requirements within MIL-HDBK-5

Mechanical or Physical Property	Customary Statistical Basis	Relative Importance in MIL-HDBK-5	Extenuating Circumstances for Special Material Usage Requirements	Minimum Data Requirements			Applicable Handbook Sections
				Sample Size	No. of Heats	No. of Lots	
Bearing Yield and Ultimate Strength[a] (Derived)	Same as Tensile Properties	Mandatory	Except for elevated temperature applications	20	3	10	1.4.7.1, 3.1.2, 9.2.3.2, 9.2.3.3
Coefficient of Thermal Expansion	Typical	Strongly recommended	Especially for anticipated range of usage	Triplicate measurements			9.2.3.4.2, 9.2.4.4
Compression Yield Strength[a] (Derived)	Same as Tensile Properties	Mandatory		20	3	10	1.7.1, 9.2.3.2, 9.2.3.3
Creep and Rupture	Raw Data w/ Best-Fit Curves	Recommended	Especially for elevated temperature applications	6 tests per creep strain level and temp, at least 4 temps over usage range			9.2.3.5.4, 9.2.5.2
Density	Typical	Mandatory		Duplicate measurements			9.2.3.4.2, 9.2.4.4
Effect of Temperature Curves	Same as Room Temperature Properties	Recommended	Especially for elevated temperature applications	5[b]	2[c]	5	9.2.3.3, 9.2.4.4.3
Effect of Thermal Exposure	Same as Baseline Properties	Recommended	Especially for elevated temperature applications	5[b]	2[c]	5	9.8.5.5, 9.8.5.6
Elastic Modulus (Tension and Compression)	Typical	Mandatory	Clad materials must have primary and secondary modulus properties defined	9	3	Multiple	9.2.3.4.1, 9.2.4.4.1, 9.8.3.2
Elastic Modulus (T and C) - Elevated Temperatures	Typical	Mandatory	For anticipated usage range	9	3	Multiple	9.8.3.2
Elongation	S-basis	Mandatory	Two-inch gage length preferred	30	3	10	1.4.3.5
Fastener Yield and Ultimate Load	B-basis	Mandatory		100	3	10	9.2.3.6, 9.2.4.6.1
Fastener Shear Strength	B-basis	Mandatory	At least 15 tests per fastener diameter	100	3	10	9.2.3.6, 9.2.4.6.1, 9.7.1

a Optional direct property determination involves same minimum data requirements as tension yield and ultimate.
b Tests per temperature, at least 4 temperatures over usage range.
c 5 heats required for single form and thickness.

Table 9.2.4. Summary of Data Requirements within MIL-HDBK-5, Continued

Mechanical or Physical Property	Customary Statistical Basis	Relative Importance in MIL-HDBK-5	Extenuating Circumstances for Special Material Usage Requirements	Minimum Data Requirements			Applicable Handbook Sections
				Sample Size	No. of Heats	No. of Lots	
Fatigue-Load Control	Raw Data w/ Best-Fit Curves	Recommended	Especially for high-cycle fatigue critical applications	6 tests per R ratio, 3 R ratios, no minimum heat or lot requirements			9.2.5.1
Fatigue-Strain Control	Raw Data w/ Best-Fit Curves	Recommended	Especially for low-cycle fatigue critical applications	10 tests for $R_\varepsilon = -1.0$, 6 tests other strain ratios			9.2.5.1
Fatigue Crack Growth	Raw Data w/ Best-Fit Curves	Recommended	Especially for damage tolerance critical applications	Duplicate da/dN results for relevant stress ratios and stress intensity range			9.2.4.5.2
Fracture Toughness - Plane Strain	Max., Avg., Min., Coef. of Variance, S-basis	Recommended	Mandatory for materials with spec. min. requirements for plain strain fracture toughness	30	3	10	9.2.3.5.3, 9.2.4.6.1, 9.6.3, 9.9.3.1
Fracture Toughness - Plane Stress	Raw Data w/ Best-Fit Curves	Recommended	Mandatory for materials with spec minimum requirements for plane stress fracture toughness	d	2	5	9.2.3.5.3, 9.2.4.5.3, 9.6.3, 9.9.3.2
Poisson's Ratio	Typical	Strongly recommended		Duplicate measurements			9.8.3.2
Reduction In Area	Typical	Recommended		When tested, use same criteria as for elongation			9.8.3
Shear Ultimate Strength[a]	Same as Tensile Properties	Mandatory	Except for elevated temperature applications	20	3	10	1.4.6.4, 9.2.3.2
Specific Heat	Typical	Strongly recommended	Important to document over anticipated usage range	Duplicate measurements			9.2.3.4.2, 9.2.4.4

d Minimum sample size not specified, testing should be conducted at 6 or more panel widths to confidently represent trends over the panel widths of interest. Refer to ASTM E561 for testing details.

Table 9.2.4. Summary of Data Requirements within MIL-HDBK-5, Concluded

Mechanical or Physical Property	Customary Statistical Basis	Relative Importance in MIL-HDBK-5	Extenuating Circumstances for Special Material Usage Requirements	Minimum Data Requirements			Applicable Handbook Sections
				Sample Size	No. of Heats	No. of Lots	
Stress Corrosion Cracking	Letter Rating	Recommended	Especially for susceptible aluminum alloys	Conform to replication requirements in G47			3.1.2.3
Stress/Strain Curves (To Yield)	Typical	Mandatory	Desirable to have accurate plastic strain offsets from 10^{-6} to 3×10^{-2}	6	3	6	9.8.4.1
Stress/Strain Curves (Full Range)	Typical	Mandatory		6	3	6	9.8.4.1, 9.8.4.3
Tension Yield and Ultimate Strength	S-basis	Mandatory		30	3	Multiple	1.4.4.1
Tension Yield and Ultimate Strength	A- and B-basis	Strongly recommended	Especially for strength critical applications; a parametric representation of data is possible	100	10	10	1.4.4.1
Tension Yield and Ultimate Strength	A- and B-basis	Strongly recommended	Especially for strength critical applications; a parametric representation of data is not possible	299	10	10	1.4.4.1
Tension Yield and Ultimate Strength - Elevated Temps	Typical	Recommended	Mandatory for elevated temperature applications	e	2	5	1.4.4.1
Thermal Conductivity	Typical	Strongly recommended	Important to document over anticipated usage range	Duplicate measurements			9.2.3.4.2, 9.2.4.4

e Minimum sample size not specified, testing should be conducted at 6 or more temperatures to confidently represent trends over the temperature range of interest. Testing in regions where properties are expected to change rapidly with changes in temperature must be done at temperature intervals sufficiently small to clearly identify mean trends.

Table 9.2.4.1 Test Matrix to Provide Required Mechanical Property Data for Determination of Design Values for Derived Properties

Lot Number[a,b,c]	Test Specimen Requirements												
	TUS & TYS[d,e,f,g]			CYS[d,e,g]			SUS[h]			BUS & BYS[i], e/D = 1.5		BUS & BYS[i], e/D = 2.0	
	L	LT	ST[j]	L	LT	ST[j]	L	LT	ST[j]	L	LT[j]	L	LT[j]
A	2[k]	2	2	2	2	2	2	2	2	2	2	2	2
B	2	2	2	2	2	2	2	2	2	2	2	2	2
C	2	2	2	2	2	2	2	2	2	2	2	2	2
D	2	2	2	2	2	2	2	2	2	2	2	2	2
E	2	2	2	2	2	2	2	2	2	2	2	2	2
F	2	2	2	2	2	2	2	2	2	2	2	2	2
G	2	2	2	2	2	2	2	2	2	2	2	2	2
H	2	2	2	2	2	2	2	2	2	2	2	2	2
I	2	2	2	2	2	2	2	2	2	2	2	2	2
J	2	2	2	2	2	2	2	2	2	2	2	2	2

[a] Ten lots, representing at least three production heats, or casts or melts, are required.

[b] Thicknesses of ten lots will span thickness range of product form covered by material specification.

[c] For a single lot, multiple heat treat lots will not be used to meet 10-lot requirement.

[d] If elastic modulus values for E and E_c are not available, elastic modulus tests should be conducted on three lots.

[e] Stress-strain data from at least three lots will be submitted.

[f] Full-range tensile stress-strain data from at least one lot will be submitted, but data from three or more lots are preferred.

[g] Mechanical properties will also be obtained in the 45° grain orientation for materials that are anticipated to have significantly different properties in this direction than the standard grain directions.

[h] It is recommended that sheet and strip ≥ 0.050 inch in thickness be selected for shear tests conducted according to ASTM B831. Shear testing of sheet <0.050 inch in thickness may result in invalid results due to buckling around the pin hole areas during testing.

[i] It is recommended that minimum sheet and strip selected for bearing tests comply with the t/D ratio (0.25-0.50) specified in ASTM E238. For failure modes, see Figure 9.3.3.4.

[j] As applicable, depending on product form and size.

[k] At least two specimens are recommended; however, a single test is acceptable if retesting can be accomplished to replace invalid tests.

Table 9.2.4.2. Definitions of Heat, Melt, and Cast

Material	Heat, Melt, or Cast
Ingot Metallurgy Wrought Products Excluding Aluminum Alloys	A heat is material which, in the case of batch melting, is cast at the same time from the same furnace and is identified with the same heat number; or, in the case of continuous melting, is poured without interruption.
Ingot Metallurgy Wrought Aluminum Alloy Products	A cast consists of the sequential aluminum ingots which are melted from a single furnace charge and poured in one or more drops without changes in the processing parameters. (The cast number is for internal identification and is not reported.)
Powder Metallurgy Wrought Products Including Metal-Matrix Composites	A heat is a consolidated (vacuum hot pressed) billet having a distinct chemical composition.
Cast Alloy Products Including Metal-Matrix Composites	A melt is a single homogeneous batch of molten metal for which all processing has been completed and the temperature has been adjusted and made ready to pour castings. (For metal-matrix composites, the molten metal includes unmelted reinforcements such as particles, fibers, or whiskers.)

9.2.4.3 ***Derived Property Values*** — Minimum compression, bearing and shear strength values are typically derived by pairing compression, bearing and shear test results with tensile test values determined in the same region of the product. The computation of a derived value for each significant test direction requires at least ten paired measurements from ten lots of material obtained from at least three production heats, casts, or melts for each product form and heat-treat condition or temper. If two lots are from the same heat, cast, or melt and have the same product form and thickness, they must be heat-treated separately in order to constitute two lots. Therefore, it is recommended that two lots with the same product form and thickness come from a different heat, cast, or melt.

Ten lots of material, as shown in Table 9.2.4, from at least three production heats, casts or melts for each product form and heat treat condition will be tested to determine required mechanical properties. (See Table 9.2.4.2 for definitions of heat, melt and cast.) A lot is defined as all material of a specific chemical composition, heat treat condition or temper, and product form which has been processed at the same time through all processing operations. Different sizes and configurations from a heat cast or melt will be considered different lots. For a single lot of material, only one heat treat lot may be used to meet the ten-lot requirement. Thicknesses of the 10 lots to be tested will span the thickness range of the product form covered by the material specification (or for the thickness range for which design values are to be established). Test specimens for paired ratios will be located in close proximity and will be taken from the same sheet, plate, bar, extrusion, forging, or casting. If coupons or specimens are machined prior to heat treatment, all coupons or specimens from the same lot will be heat treated simultaneously in the same heat-treat load through all heat-treating operations. Some or all of the lots may be heat treated together provided they are of the same product form that represent different thicknesses or heats, casts, or melts.

In the cases where multiple observations are available from a single lot, the average of those observations will be treated as an individual observation. Since some variation in strength may be expected from one specimen location to another, use of lot averages minimizes the effect of this variable.

9.2.4.4 Other Static Properties —Data requirements for defining elastic properties, stress-strain curves, and effect of temperature curves are described in the following sections.

A precise density value in pounds per cubic inch will be provided. Although not required, physical property data for coefficient of expansion, thermal conductivity, and specific heat should be submitted, when available. Also, information regarding manufacturing (fabrication and processing), environmental effects (corrosion resistance), heat treat condition and applicable specification will be provided so that a comments and properties section can be prepared.

9.2.4.4.1 Modulus of Elasticity —Tensile and compressive modulus of elasticity values will be determined from at least three lots of material. Elastic modulus values are those obtained using a Class B-1 or better extensometer. The method of determining or verifying the classification of extensometers is identified in ASTM E 83. ASTM E 111 is the standard test method for the determination of Young's Modulus, tangent modulus, and chord modulus of structural materials. A modulus value will also be obtained for the 45 degree grain orientation for materials that are anticipated to have significantly different properties in this direction than the standard grain directions.

Typical values for elastic moduli at room temperature are tabulated in MIL-HDBK-5 room-temperature property tables. Values for these properties at other temperatures may be approximated by multiplying the room-temperature value by appropriate percentages from effect-of-temperature curves in MIL-HDBK-5.

9.2.4.4.2 Typical Stress-Strain Curves — Room temperature tensile and compressive load-deformation curves or stress-strain data for each grain direction, from at least three lots will be provided. Room temperature, full-range, tensile load deformation curves or stress-strain data for each grain direction will also be provided. Full-range stress-strain data will be provided from at least one lot, but data from three lots are preferable. For heat resistant materials for which elevated temperature data for tensile yield and ultimate strengths are required, room and elevated temperature stress-strain data will be provided.

Preparation of each typical stress-strain curve requires (1) several representative original stress-strain curves, (2) average values for yield strength from original stress-strain curves, or, when available, product average values for yield strength, and (3) typical elastic-modulus values at test temperature.

Original stress-strain curves are utilized to obtain a representative curve shape, which may be characterized by the Ramberg-Osgood parameter. The minimum number of original stress-strain curves required is dependent on the degree of variation from one curve to another. If curves are found to be similar in shape, and the range of products (thickness, etc.) is small, one curve from each of three plots should be adequate. Otherwise, the number of original curves should be increased as necessary, to insure an adequate sampling.

Original stress-strain curves determined using an ASTM E 83 Class A extensometer (Tuckerman, Martens, etc.) are preferred for preparation of typical stress-strain curves up to 0.005-in./in. plastic strain or higher. When curves having this precision and accuracy are not available (particularly for full-range and elevated-temperature curves), curves determined using Class B-1 extensometers may be used as indicated in ASTM E 83.

Product average values for yield strength, ultimate strength, and elongation are average values rounded to the nearest whole number, determined from production lots of product form. Product average values represent current production capabilities; hence, these are supplied by producers.

The modulus value used in constructing a stress-strain curve must agree with the value obtained from the room-temperature table value multiplied by the appropriate percentage from the elevated temperature curve.

For some materials, the shape of the stress-strain curve, yield strength, and elastic modulus vary with test direction. When this is the case, individual curves should be prepared for each test direction, and each curve should be labeled accordingly. Likewise, tensile and compressive stress-strain curves usually differ, and individual curves should be prepared for each type of loading. If two or more finished curves are found to be identical, they may be combined in presenting the finished curves.

The selection of test temperatures to be represented by typical stress-strain curves should be guided by the temperatures at which the product is typically used. In the absence of other information, these temperatures should include room temperature, other temperatures at which tensile properties are determined in conformance with the requirement of applicable procurement specifications, and appropriate temperatures within the useful application range for the product.

9.2.4.4.3 Elevated Temperature Curves — An idealistic approach to the establishment of elevated temperature curves would be to have A-basis design values at a sufficient number of temperatures to define corresponding temperature curves on an A-basis. If such data were available, finished curves would be constructed by plotting A-values on a percentage scale and analytically defining a smooth curve, and the procedures described in Section 9.8.5.1.1 would not be applicable. Unfortunately, the cost of generating the required data is prohibitive, and idealism must be tempered with practicality. For this reason, data requirements and the procedures described in Sections 9.8.5.1.1 and 9.8.5.1.2 allow some latitude to make fullest use of whatever data may be available.

These procedures, as described in the indicated sections, are intended both to establish the general shape of curves, and to adjust their scaling in such manner that the resulting product of a percentage value from the curve and a corresponding value from the room-temperature property table will yield a design value, at some designated temperature, that will be a good approximation of a directly computed design value at that temperature.

To establish the shape of an elevated-temperature curve, the sample will include observations from at least five lots* of material, composed of at least two heats at each of several temperatures. Choice of temperatures will be guided by probable range of service temperatures anticipated for the material, as well as by its metallurgical characteristics. For materials used at cryogenic temperatures, testing is normally conducted at -110°F, -320°F, and -423°F; however, no attempt will be made to extrapolate the curve below the lowest temperature for which adequate data are available. For elevated temperature applications, data should normally be available at temperature intervals from 200°F to 300°F except in regions of time-temperature-dependent metallurgical change, where temperature intervals of perhaps 100°F to 150°F are appropriate. Extrapolation beyond the range of temperatures covered by adequate data is not allowed.

For a number of alloys, most specifically heat-resisting alloys, procurement specifications may designate minimum property values at temperatures other than room temperature, and either A- or S-basis

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* For single form and thickness, data from no more than one heat treat lot per heat may be used to meet the five lot requirement.

values may be available at both room temperature and secondary testing temperatures. When this is the case, the elevated temperature curve may be scaled by means of these values.

9.2.4.5 Dynamic and Time Dependent Properties

9.2.4.5.1 Fatigue — Most fatigue data generated in load control may be considered for inclusion in MIL-HDBK-5. However, load-control experiments on unnotched samples can produce ratcheting failures rather than true fatigue failures. This can be a problem with materials that cyclically soften. In the absence of cyclic stress-strain data, the acceptability of short-life data obtained under load control on unnotched specimens can be difficult to evaluate. Therefore, results from specimens tested at a maximum stress level greater than the average tensile ultimate strength of the material should not be used. In addition, test results obtained under load control that have produced average fatigue lives on unnotched specimens of less than 10^3 cycles should be excluded. Short-life, load-control data generated on notched samples tested at high stress levels may be considered.

Fatigue data generated under strain control over a wide range of strain ratios and ranges can be acceptable also. High-strain-range tests producing low fatigue lives can be considered, assuming that documented bending strains were held within ASTM E 606 limits and buckling failures were not produced. Documenting the stress response associated with each test result is important. The stress data that are reported should reflect the material's stable response, including effects of cyclic hardening or softening and of mean stress relaxation provided such data were obtained at other than $R_\varepsilon = -1$. The normal convention is to report the stress values associated with one-half the material's fatigue life to crack initiation. Several criteria are commonly used to define crack initiation in a test under strain control. The primary requirements for inclusion in MIL-HDBK-5 are that the criteria be specific and applied consistently. If multiple sources of data are being considered, the potential problem of inconsistent crack initiation criteria must be addressed before that data are merged.

If strain-control data only are reported with fatigue test results obtained under strain control, these data must be supported by well-documented cyclic stress-strain curves and mean stress relaxation data for that specific material.

For fatigue experiments under load control, data are normally generated at specific stress ratios or mean stress levels. If the stress ratio is held constant, a fatigue curve is generated by performing a series of experiments at prescribed maximum stress levels, such that the desired range of fatigue lives is achieved. If mean stress levels are held constant, a range of maximum stress levels is also used, but the stress ratio for each maximum stress level is different. Presentation of the latter type of data in a traditional S_{max}-versus-log N_f display, with individual stress ratio curves, can be cumbersome because of the large number of stress ratios involved. For this reason, constant mean-stress fatigue data should be identified by mean stress level, even though they are plotted on a standard S_{max}-versus-log N_f display. The illustrations should be clearly labeled to properly identify the mean-stress or stress-ratio levels.

To evaluate analytically the effects of stress or strain ratio on the fatigue performance of a particular material, it is recommended that data be available for at least three stress or strain ratios, or alternatively, three mean-stress or strain levels. Similarly, at least three stress or strain levels are recommended to evaluate the effects of mean stress on fatigue performance. In the case of data under strain control, a specific strain ratio or mean strain may not define a mean-stress level uniquely. For $R_\varepsilon = -1.0$ (mean strain = 0), the stress ratio is usually very close to $R = -1.0$ (mean stress = 0) – if it is not, the data should be examined carefully for validity. For strain ratios greater than $R_\varepsilon = -1.0$, the stress ratio is usually less than the strain ratio, and the difference is generally greater at the greatest strain ranges. For very large strain ranges in ductile

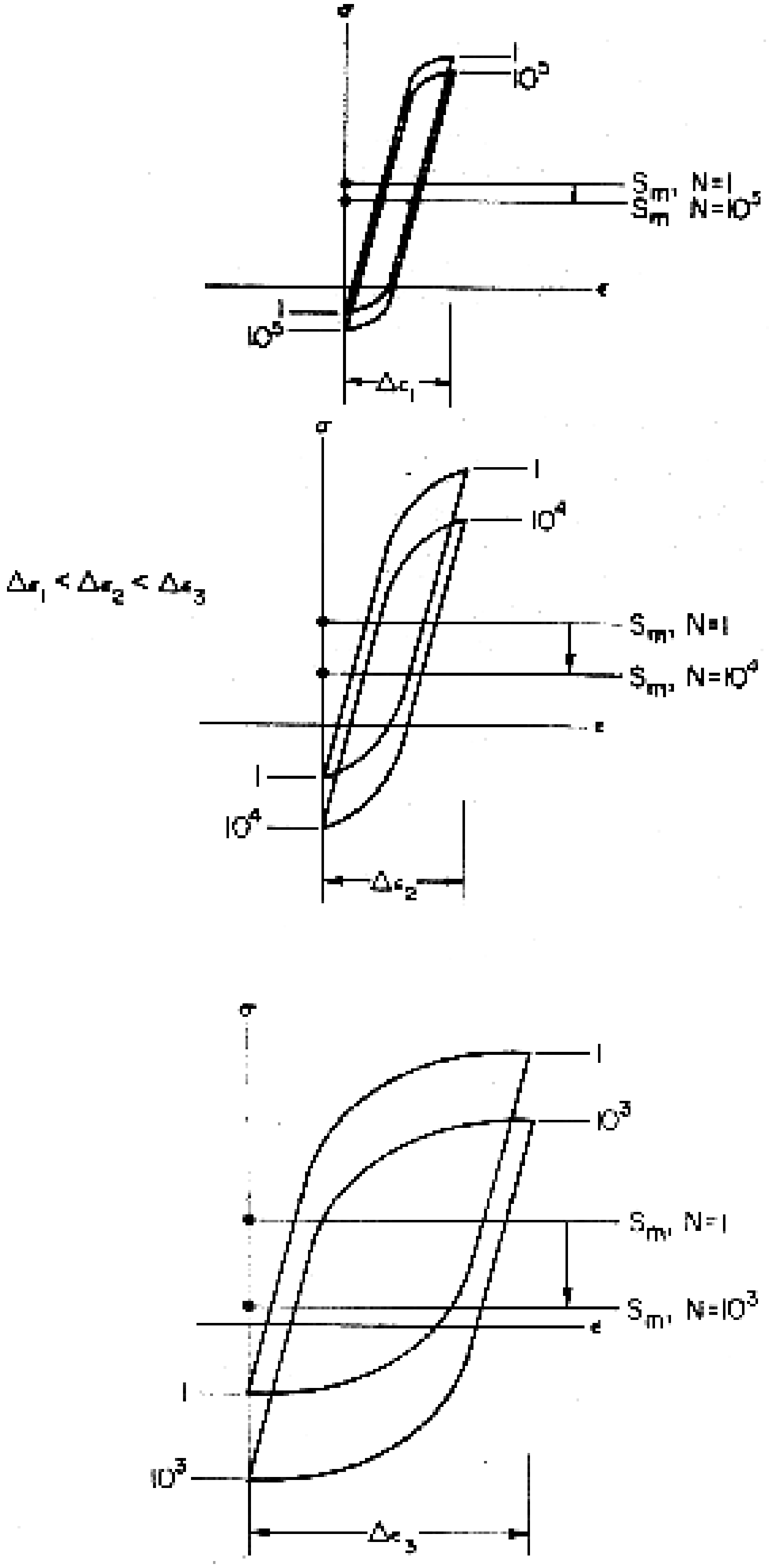

Figure 9.2.4.5.1. Schematic of stabilized mean stress relaxation for different strain ranges at $R_\varepsilon = 0$.

materials, the stable stress ratio will approach R = -1.0 (mean stress = 0), regardless of the strain ratio, R_ε. Mean stress relaxation behavior is illustrated in Figure 9.2.4.5.1.

There should be at least six non-runout fatigue test results for each condition, and these data should be distributed over at least two orders of magnitude in fatigue life. These requirements are the minimum sample sizes normally required to consider developing a fatigue data display. Meeting the minimum data requirements does not ensure an acceptable set of fatigue curves. In cases involving highly scattered data, substantially larger sample sizes may be required to achieve a meaningful description of mean fatigue trends. The statistical procedures used to evaluate the significance of a fatigue data collection are described in Section 9.6.1.7.

9.2.4.5.2 Fatigue Crack Growth — In order to establish a positive trend in rate behavior, it is recommended that rate data be generated over a range of at least two orders of magnitude. In general, this will be associated with a domain of stress-intensity-factor range from one half to a full order of magnitude. Good experimental techniques, coupled with this data-range criterion, should provide a concise and consistent data display for linear or other analysis.

When planning experimental programs to achieve the best, most complete derivation of fatigue-crack-propagation data, the range of ΔK over which tests are conducted should include those which will provide crack-growth rates as low as 10^{-8} inches/cycle. Furthermore, if possible, multiple heats of material should be included. Ideally, to properly document the effects of stress ratio, fatigue crack growth data should also be generated over a range of R ratios (0.1, 0.4, and 0.7 are typically good values). If data representing negative R ratios are available, they should also be included.

9.2.4.5.3 Fracture Toughness — For materials covered by public specifications that include minimum fracture toughness requirements, at least three specimens each from a minimum of ten lots of material for each test direction (at least 30 observations total) are required for inclusion in MIL-HDBK-5.

Middle Tension Panels — To identify the material tested, it is necessary to report alloy temper, product form, and grain directions being tested. Reference tensile properties, actually representative of specimen or material lot (i.e., not specification or MIL-HDBK-5 A and B values), are also necessary information. These will include yield strength, ultimate strength, and elongation.

The specimen configuration is described by measured thickness, panel width, and free length between grips. The minimum flaw details to be reported are fatigue stress levels used in generating the fatigue crack and length of the fatigue crack existent prior to the rising load fracture test.

The test procedure will be described briefly, identifying environment (temperature, humidity, salinity, etc.), loading rate, and the mode of buckling restraint.

The report of test results will include maximum load and stress, and estimated critical crack length (indicate method of detection, such as visual observation, film record, or compliance calibration). It is recommended that whenever practical, a record of load versus crack length be obtained to assess slow stable crack extension prior to fracture.

9.2.4.5.4 Creep and Creep Rupture —A sufficient number of creep and/or creep rupture tests should be performed to clearly define creep and/or creep rupture trends as a function of applied stress for the range of temperatures of interest. Typically, at least eight tests should be completed for each temperature, and at least 20 tests performed for each multi-temperature regression that is performed. The “spacing” of the temperatures tested generally should be close enough that the highest stress level at a given temperature (which can be expected to produce the shortest average creep times) is greater than or equal to the lowest stress level at the next higher temperature, and vice versa.

Another factor to consider when defining a series of creep tests is heat-to-heat variability. The creep test program may be based on as few as two heats of material if the heat-to-heat component of variability is less than 25% of the within-heat variability. On the other hand, the creep test program should be based on at least five heats of material if the heat-to-heat component of variability is greater than 65% of the within-heat variability. In any case, the heats of material that are tested should be distributed randomly and essentially equally throughout the test matrix. Additional experimental design suggestions for creep testing are included in Section 9.2.5.2.

For isostrain creep, collected data will include stress, temperature, modulus and plastic strain on initial loading, and strain-time pairs sufficient to define a curve. While strain-time pairs will be only those for the isostrain of interest, after inelastic strain on loading has been included in the reported strain, it may be that reported data may not correspond to isostrain levels. Consequently, isostrain-time pairs may be read from a smooth curve drawn through the values recorded during the test.

For rupture, collected data will include stress, temperature, time-to-rupture, percent elongation, and reduction of area. Percent elongation and reduction of area can then be used to define rupture ductility curves or equations.

9.2.4.6 *Mechanically Fastened Joints*

9.2.4.6.1 Introduction of a New Fastener System —When introducing a new fastener for possible inclusion in MIL-HDBK-5, the sponsor will submit a written request (on company letterhead) to the Chairman, MIL-HDBK-5 Coordination Group, providing the following information:

(1) A description of the fastener such as: (a) type of fastener (driven rivet, blind fastener, swaged collar, etc.), (b) fastener material (alloy and temper), (c) unique or new features, (d) nominal sizes and actual diameters, and (e) part drawings and functional description.

(2) Reason for fastener usage or intended usage such as: (a) higher strength, (b) higher or lower temperature capability, (c) improved fatigue performance, and (d) lower installed cost.

(3) Development and use status. (It is not required that the fastener system actually be in use on production airframe structure, but there should be a high level of interest and an intent to use the fastener.) (a) What are current or planned airframe applications? (b) How long has the fastener been produced on a production (nonexperimental) basis? Include preliminary lap joint test data that demonstrates that sufficient diameters and grips are available to conduct a design allowable test program (i.e., data for at least one test for each diameter/grip combination contained in the proposed test plan).

(4) Specification status. Under what type of specification is the fastener covered (NASM or Company)?

(5) In what sheet or plate material will the fastener be installed? (The proposed allowables should be for the same or similar sheet or plate material that the sponsor is using or plans to use.)

(6) Shank deformation. Does shank deform during installation? Verification is desirable. (a) If a blind fastener, is it hole filling or nonhole filling? Verification of hole fill is desirable. (b) If a solid shank fastener, are design values to be presented for clearance or interference holes?

(7) Has the sponsor conducted any testing on the fastener system (especially joint allowables) and will the sponsor provide data to the MIL-HDBK-5 Coordination Group?

(8) Has the sponsor reviewed (or will the sponsor review) test program plan, actual testing, analysis of data, and specifications?

(9) Are the fastener holes to be cold worked or a sleeve inserted? If so, the reproducibility of this part of the fastener installation process must be verified.

9.2.4.6.2 Sample Fasteners —At time of approval of a fastener static joint strength proposal, fastener manufacturer will submit, to the Chairman, MIL-HDBK-5 Coordination Group, 10 fasteners each from maximum and minimum diameter and grip size tested in the allowables program. These 40 samples will be from the same production lots as those used in the test program. Samples will be packaged suitable for storage with full identification of contents on the container. The information may also include any storage time limitation due to coating or lubricant life. The information required to complete the report described in Section 9.3.3.4 must also be included.

9.2.4.6.3 General Data Requirements —The types of data required to develop a fastener system design curve are shown schematically in Figure 9.2.4.6.3. There are three facets to consider, which are described in following subsections: (1) shear strength of the fastener, Region 3; (2) sheet critical strength, bearing and transition regions, Regions 1 and 2; and (3) tensile properties of sheet and plate material used in the joint. Each of these facets is described in the next 3 subsections. The next two subsections address data requirements for determination of the tensile strength of a fastener, and an assembled joint. Recommended data formats are discussed in Section 9.3.3.4.

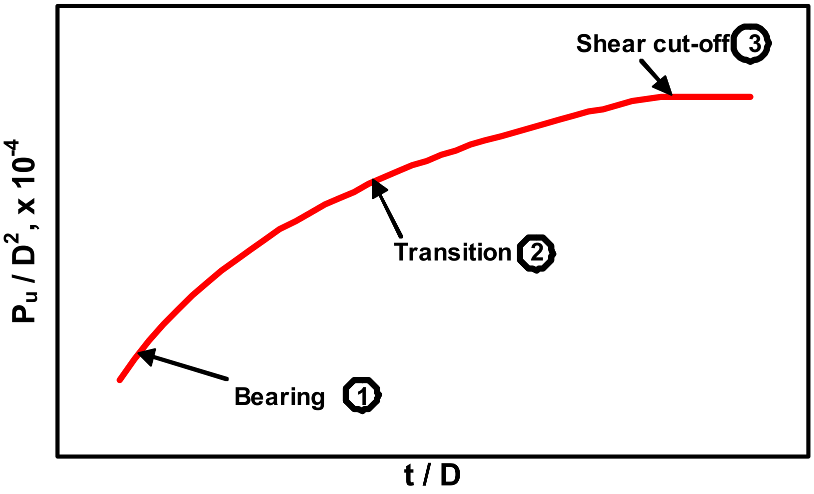

Figure 9.2.4.6.3 Schematic diagram of P_u/D^2 versus t/D.

Shear Strength of Fastener — At least 15 shear tests are required for each fastener diameter for which allowables are to be established. Fasteners for each diameter will be selected from at least three production lots that represent at least two heats of the fastener component materials. The major components of multi-piece fasteners will meet the two heat requirement.

A product lot will consist of finished fasteners of the same part number, class, grip and diameter, which conform to the following:

(1) fabricated by the same process
(2) major components each made from material of the same heat
(3) major components heat treated in one continuous run or order
(4) produced as one continuous run or order

The major components of multi-piece fasteners of the production lot will individually meet the definition above.

Fasteners developed from materials not previously used for fastener applications will require additional testing in order to determine statistically reliable minimum shear strengths. Test values should be developed in accordance with the test methods noted above using hole sizes specified in those methods or Table 9.7.1, as appropriate. Test values will represent a minimum of 10 tests from each of 10 production lots made of at least 3 heats of material (100 tests). Fasteners tested should be evenly distributed over the diameter range under consideration with grip ranging from 2 to 3 diameters for solid and blind rivets and any appropriate length for solid shank fasteners. Shear strength (F_{su}) should be computed based on hole size for solid and blind rivets and measured shank diameter for non-hole filling blind fasteners and pins.

In the sheet critical range, fasteners with different head shapes, head sizes (NAS 1097, MS 29694, or MS 20426), material, or heat treatment will be considered different fasteners and will require separate tests. Sheet materials with different heat treatments or compositions will be considered different materials and also will require separate tests. In the case of aluminum alloys, data obtained with clad sheet may be used to determine allowables for clad and bare sheet; however, allowables obtained from tests on bare sheet can be used only to determine allowables for bare sheet. In the case of all sheet materials, data from tests using sheet at one heat-treat level may be used to determine allowables for sheet having higher strength heat treatments. However, the reverse is not permissible.

Tensile Properties of Sheet — At least three sheet tension test results as required by NASM 1312, Test 4, will be provided for each sheet or plate used to make single-shear test specimens described in the previous subsection. Tensile ultimate and yield strengths and percent elongation will be reported in accordance with ASTM E 8. Grain direction will be that applicable to the procurement specification tensile test requirements. Tabulated data will identify single-shear specimens made from sheet to which each group of sheet-tension specimens apply by appropriate coding.

Tensile Strength of Fastener — Tensile strength will be determined for all fastener systems except solid and blind rivets from tests performed in accordance with NASM 1312, Test 8. Tensile test requirements and analytical methods will be the same as for shear strength determination (see Section 9.2.4.6.1).

Assembled Joint Strength — The requirement for data from two fabricating and testing sources applies to assembled joint strength. Approximately 75 percent of required data will come from one source; the remainder from a second source. Data will cover the t/D (thickness/diameter) range that results in bearing, transitional and shear-type failures as shown in Figure 9.2.4.6.4. It is suggested that the second source concentrate testing in the bearing and transition regions. Selection of sheet thickness will be made in such a way that, for each fastener diameter, an even distribution of data is achieved over the t/D range with about 20 percent of the data taken at t/D values for which joint failure will be by fastener shear (not applicable to dimpled joints). Minimum sheet thickness should be restricted to one thickness below knife edge for flush head fasteners and no tests below t/D or 0.18. Sheet thickness/fastener grip combinations will be selected to include a uniform distribution of minimum and maximum grip conditions throughout the t/D range tested. Specimen fabrication and testing will be allocated to provide data from each source, distributed across the sheet critical and transition ranges.

All diameters of a given fastener for which joint allowable loads are established will be included in the test plan. Since a fastener system usually comprises 2 to 5 diameters, the quantity of joint specimens to be tested will be expected to vary, depending upon number of fastener diameters. Quantity of data will include results from at least the following valid tests: two diameters, 42 tests; three diameters, 57 tests; four diameters, 72 tests; five diameters, 87 tests. In allocating test joint specimens among fastener diameters, for a three- or four-diameter fastener line a larger quantity of specimens will be used for the largest and smallest diameters with somewhat less testing for intermediate diameter(s). In the case of a five-diameter fastener line, larger quantities of specimens should be allocated to the largest, middlemost, and smallest diameters with somewhat less testing for the two remaining intermediate diameters. For each diameter and t/D combination tested, a minimum of three specimens should be used. In addition, approximately an equal number of tests must be run at each t/D.

9.2.4.6.5 Confirmatory Data — If a manufacturer wishes to have their company name added to the footnote of an existing table as a supplier of confirmatory data, or to add to an existing product, function, or modification, the following procedure will be used:

(1) Repeat, in total (quantities and conditions), the original test program from which the table was developed.

(2) The T90 curves, (yield and ultimate), of the original data set will establish the baseline performance requirements, regardless of the construction method employed for the published table, in accordance with section 9.7.1.4.

(3) The T90 curves, (yield and ultimate), of the proposed supplier's data set will be constructed, and compared to the baseline curves of the original data set in accordance with the criteria defined in section 9.2.4.x.x. (The same criteria defined for sunset clause conformance.)

(4) If the proposed supplier's data set conforms to the criteria of section 9.2.4.x.x, then the design allowable table will be modified in accordance with Item 17(c) of section 9.9.5.

(5) Note that the published data values of the original table will not be modified.

If a manufacturer wishes the company name to be added to the footnote of an existing design allowable table with four or more diameters as a supplier of confirmatory data, but does not produce or market the fastener in all diameters contained in the design allowable table, the following procedure will be used:

(1) The new supplier will test at least three successive diameters, including the smallest diameter in the design table, or at least three successive diameters including the largest diameter in the design allowable table. Test quantities will be the same as defined in section 9.2.4.6.3.

(2) The T90 curves, (yield and ultimate), of the original data set will establish the baseline performance requirements, regardless of the construction method employed for the published table, in accordance with section 9.7.1.4.

(3) The T90 curves, (yield and ultimate), of the proposed supplier's data set will be constructed, and compared to the baseline curves of the original data set in accordance with the criteria defined in section 9.2.4.7.2. (The same criteria defined for sunset clause conformance).

(4) The following footnote will be added to the design allowable table: "Confirmatory data provided by XYZ Company." This footnote will be flagged to the supplier's part number and applicable fastener diameters.

(5) Note that the published data values of the original table will not be modified.

9.2.4.7 Fusion-Welded Joints — The type of data required (i.e., tension, shear, fatigue, etc.) and general welding conditions of interest must be established first.

The data sample must be adequate to determine form and distribution of the population from which it was drawn. If the weldment population definition is broad and allows considerable latitude in the range of parameters defined, it is obvious that larger sample sizes will be required. Certain minimum requirements can be stated, however, based on statistical considerations.

For data to be directly analyzed on a statistical basis, a typical weldment population exhibiting nearly normal distribution characteristics should be represented by a sample containing a minimum of 100 random observations. These observations should include at least 10 subsamples representing random variables such as base material lots, filler material lots, weld processing variables, and weld machine operators and setups.

Direct analysis of a data sample not normally distributed requires at least 300 observations to establish a minimum value on an A-basis. A B-value may be established from the smaller sample defined above. As in the previous case, the observations should be representative of the total population.

Due to the number of variables inherent in a welding process, it is advisable to make as broad a sampling as practicable within the population definition. The range of material and processing parameters included in the sample will obviously influence sample size. The total number of observations should be sufficient to identify factors that may be significant within the population, such as joint thickness, weld repair, filler material, and heat-treat condition.

9.2.5 EXPERIMENTAL DESIGN — General guidance on experimental design for fatigue , creep-rupture and fusion-welded joints is included in the following subsections.

9.2.5.1 Fatigue —In view of the data requirements in Section 9.2.3.5.1 and 9.2.5.1, fatigue data generated for inclusion in MIL-HDBK-5 should be the result of a well-planned test program. The following general discussion of fatigue test planning is based in large part on the concepts presented in References 9.2.5.1(a) and (b), and ASTM E739. Those interested in the detailed aspects of fatigue test planning should refer to these and other sources. The discussion that follows pertains to fatigue testing under either load control or strain control.

Traditionally, fatigue testing under load control has been performed to evaluate the fatigue performance of engineering materials and components subjected to numerous load fluctuations. Notched specimens are often used to evaluate the effect of stress concentrations upon fatigue life in load-control testing. The nominal stresses during load-control testing are generally below the materials yield strength and the resulting fatigue lives are usually greater than 10^4 cycles. Load-control tests with high mean- stress levels may develop unconstrained cyclic plasticity which may lead to racheting failures (see Figure 9.6.1(b) in Section 9.6.1). Unless cyclic strains are monitored in load-control tests, it is not possible to know exactly when unconstrained cyclic plasticity will develop. In general, however, there are test conditions that should be avoided when operating under load control, as follows:

(1) Unnotched-specimen fatigue tests in which fatigue lives less than 10^3 cycles to failure are expected.

(2) Fatigue tests involving net-section maximum stresses greater than the yield strength or over 95 percent of the typical monotonic ultimate strength of the material.

Strain-controlled fatigue testing has emerged since the mid-1950s because the fatigue damage process was found to be highly dependent upon cumulative plastic deformation. Cycling a material between two strain limits can alter the material's stress-strain response (cyclic hardening or softening) compared to the monotonic response. Fatigue testing under strain control should be considered in cases where constrained inelastic cyclic strains may occur in the actual component. Strain control should also be used for any conditions where unconstrained cyclic plasticity may lead to racheting failures in load-control testing.

Fatigue data obtained under load control for use in MIL-HDBK-5 should be generated for at least three stress ratios (see Figure 9.2.5.1). Fatigue lives ranging from approximately 10^3 to 10^6 cycles are most commonly of interest while the stress ratios chosen should normally span the range from about R = -1.0 to 0.50 or greater.

Fatigue data obtained under strain control are commonly generated at $R_\varepsilon = -1.0$. These data will be considered for MIL-HDBK-5, but generating data for at least two other strain ratios is also desirable.

The stabilized value of mean stress attained in a strain-control test at R_ε greater than -1.0 will be different from that observed at the beginning of the test for materials that undergo cyclic mean stress relaxation. The degree of stress relaxation will depend on strain range and strain ratio, the magnitude being greater at larger strain ranges or larger strain ratios. Complete relaxation to a zero mean stress is the limiting case. When testing at strain ratios greater than -1.0, it is appropriate to limit the strain ranges to values below those at which total cyclic mean-stress relaxation occurs.

The amount of cyclic stress relaxation also varies with the anticipated fatigue life. Large-strain-range, low-cycle tests usually exhibit the greatest mean stress relaxation. Because of this behavior, it is usually appropriate to run the positive mean strain experiments at strain ranges less than or equal to the level that produces complete mean stress relaxation.

A given series of fatigue tests conducted under strain control should be targeted to describe the useful life range for the material. The life range explored need only be limited on the low side by the maximum strain ranges that can be performed without specimen buckling problems, and on the high side by the maximum strain rates that are allowable, in combination with the permissible duration of individual tests. Life ranges of 10 to 10^6 cycles are reasonable to explore in strain-control tests with many materials and specimen geometries (see Figure 9.2.5.1). Strain-control tests performed for inclusion in MIL-HDBK-5 should normally be conducted with symmetric waveforms, with no hold times at frequencies ranging from 0.10 to 5 Hz— depending on the response of extensometry and recording equipment. It is important to document the strain rates and conformance of the testing techniques with ASTM E 606.

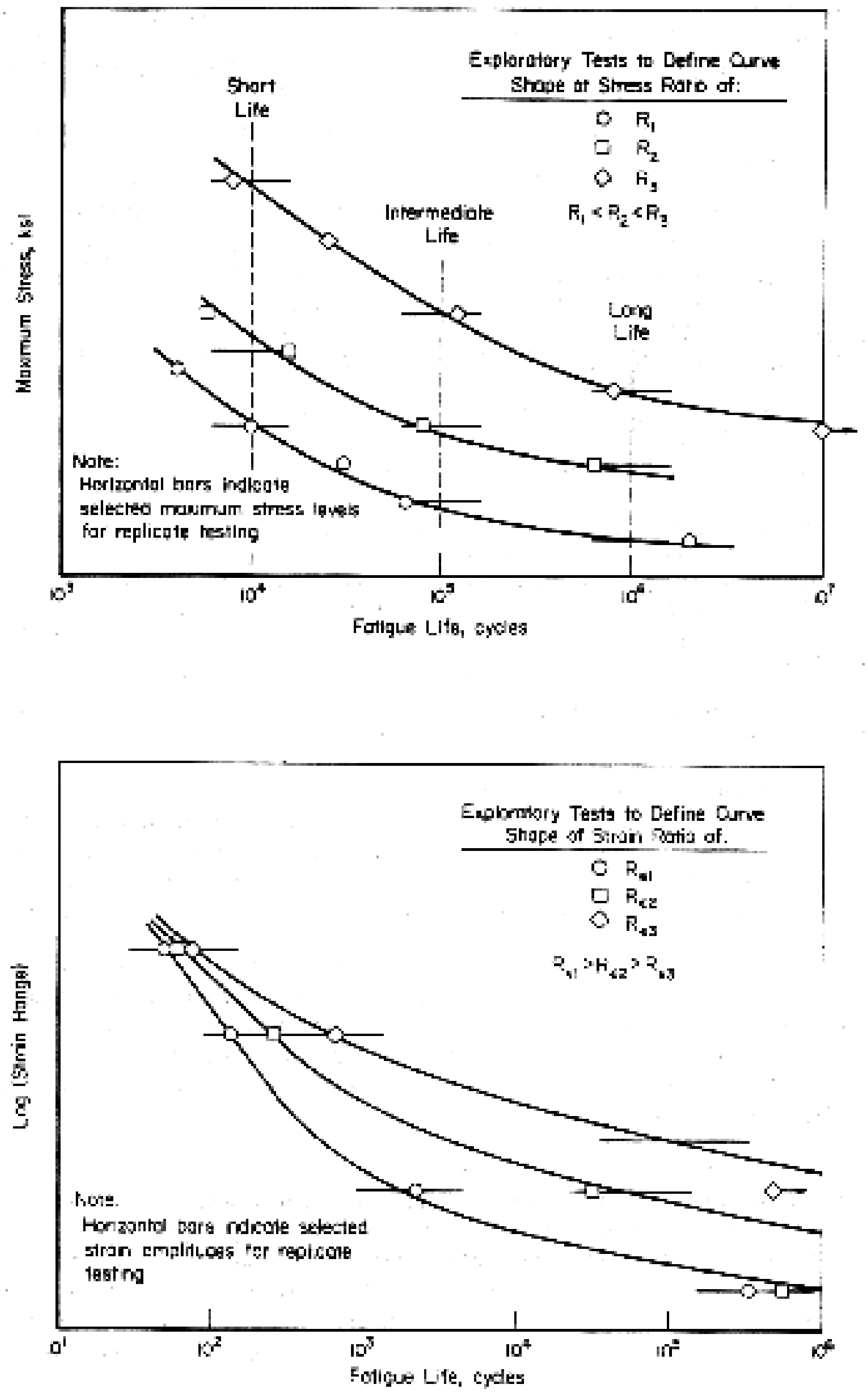

Figure 9.2.5.1. Schematic fatigue data displays (showing the initial exploratory tests as symbols and the strain levels subsequently chosen for replicate fatigue testing as bars; the length of the bars denoting observed data variability).

Long-life fatigue tests are a special situation in strain-control testing because of the extended test periods that may be required, especially if maximum test frequencies must be kept at or below 1 Hz. For example, a test run at 1 Hz involving one million cycles requires about 11-1/2 days. Decreasing the duration of long-life, strain-control fatigue tests are desirable whenever possible; otherwise, a few tests in the 10^6 to 10^7 cycle range can take as much time as the rest of the life curve.

Switching from strain-control testing to load-control testing at a greater frequency at some point in the life of the specimen is becoming a common practice. This switch is typically done when the cyclic response is nominally elastic. Usually the frequency can be increased by a factor of 10 or more but even a factor of 2 or 3 is certainly worthwhile.

When the control mode and/or frequency are changed, certain criteria should be observed. When generating a strain-control fatigue curve, ranging from the short-life regime (10 to 10^3 cycles) to the long-life regime (10^6 to 10^8 cycles), the fatigue tests can be placed in three groups for consideration.

At the short-life end of the curve, the material response will typically vary throughout the test. In this regime, a significant amount of inelastic strain may be present, cyclic hardening or softening may occur as well as mean stress shifts. In short, no consistent relationships exist between stress and strain and, therefore, no control mode change is recommended in this life regime.

For intermediate life tests, some inelastic strain may be present and, for a period of time, the stress-strain relationship may vary. Generally, however, a stabilized, consistent relationship is eventually achieved. Under these conditions, it may be possible to switch the test mode to load control at a higher frequency.

In the long-life regime, very little inelastic strain will normally be present, and stress-strain stabilization is achieved very rapidly. Here, switching from the strain-control mode to the load-control mode can be accomplished.

The material behavior cited above can only be evaluated by starting all of the tests in the strain-control mode and then switching the mode and frequency when stabilized stress-strain behavior is achieved. An evaluation of the strain rate behavior of the material in the strain-control mode (within the normal response capabilities of the equipment) may be desirable to determine if the stress-strain relationship is likely to change when the frequency is changed.

In summary, do not switch control modes in the low life regime of the fatigue curve. When some inelastic strain is present, switching may be employed if stable stress-strain response can be obtained and a negligible strain rate effect at the test temperature and strain range of interest can be demonstrated (i.e., it can be shown that fatigue life and stress range are not influenced by loading rate). One very good check is to produce overlapping data points in this regime where some tests are run to failure in the strain-control mode while others are switched to high-frequency load-control mode after stabilization is obtained. This is necessary to provide assurance that the switching procedure is not influencing results.

At the very long-life end of the curve, the essentially elastic behavior of the material is most conducive to switching of control modes. The greatest benefit of the increased frequency can also be obtained here. If results have shown that switching is successful at the intermediate strain range level, then the probability of the long-life tests being at least as successful is high. If, however, the material exhibits a measurable inelastic strain and is slow to stabilize even after many cycles, caution should be exercised in making the decision for a control mode change.

When the determination that a test should be switched from strain control to load control has been made, the following sequence is recommended:

(1) Note the maximum and minimum stabilized load levels.

(2) Gradually reduce the strain range to zero. This process should take several cycles (at least 10). If a measurable inelastic strain is present, the strain range reduction should take sufficient cycles so the magnitudes of the maximum and minimum loads are reduced symmetrically.

(3) At this point (strain range at zero) the load may or may not be at zero, depending on the conditions of strain ratio and strain range to which the specimen was exposed. If a residual load is present, the load should be adjusted to zero by carefully changing the strain level.

(4) Next, the test system should be switched to the load-control mode and the test restarted. The strain-control cycling may have been performed using a triangular waveform. The higher frequency testing under load control generally employs a sine wave. The waveshape difference is only of secondary importance, and most machines can easily control a high frequency sine wave. The actual frequency used should be well within the capability of the test equipment so that the load can be accurately measured and controlled. Furthermore, care must be taken to avoid frequency effects, e.g., self-heating, and strain-rate effects. This is commonly a problem with tests involving a significant amount of inelastic strain.

When reproducing the maximum and minimum stresses that existed under strain-control testing, first introducing the mean load on the specimen and then gradually increasing the load range symmetrically from this point is generally preferred. Whatever procedures are used should be clearly defined and well documented.

The tendency of the load-control results to be slightly more conservative than those generated in strain-control testing is worth repeating. When a specimen develops a fatigue crack, a test that is being conducted under strain-control mode will generally exhibit a reduced tensile load as the crack propagates. Under load-control testing, the load remains constant and the crack will grow faster, resulting in a lesser life. For this reason, all data generated by this technique should be so noted and identified on data tables and graphs.

Essentially two steps are involved in the generation of a fatigue curve for a specific stress or strain ratio. First, the general shape of the curve should be determined. Nonreplicated fatigue tests completed at not more than four to six maximum stress levels are usually sufficient to define the basic shape of the curve above the fatigue limit. After the shape of the curve is found from test results, or estimated from fatigue data on similar materials, then the mean curve should be verified through carefully planned replicate fatigue tests.

If the lower maximum stress levels or strain ranges chosen result in nonfailures or runouts[**], do not repeat these stress levels while defining the general shape of the fatigue curve. Simply focus on relatively evenly spaced stress or strain levels that generally provide fatigue failures.

In performing these exploratory fatigue tests, obtaining the test specimens from a random sample that adequately represents the material is important. In that context, specimens should be taken from several different lots if possible. Particular care should also be given to minimizing nuisance variables such as test machine effects, frequency effects, surface finish irregularities, residual stress effects, or environmental

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[**] A specific fatigue cycle limit should be chosen as a runout point, and that limit should be used for all further tests on that material, regardless of the stress or strain ratio. For materials that typically display constant amplitude fatigue limits (many steels do), a runout limit as low as 3 x 10^6 cycles may be satisfactory. Normally, however, a runout limit of 10^7 cycles is preferred, especially for materials that typically do not show a definite fatigue limit (many aluminums do not) and for experiments conducted at reasonably high cyclic frequencies (10^7 cycles is accumulated in less than 4 days of continuous cycling at 30 Hz). Fatigue tests for cast metals are traditionally continued to 2 x 10^7 cycles as a fatigue limit.

variations. Unfortunately, variables such as specimen fabrication can influence fatigue results to such an extent that the effect being studied is eclipsed. Composition, thermal-mechanical processing and the origin of the material should be well documented. The same type documentation should apply to the fabrication of the specimens. ASTM E 606 provides an example of a machining procedure in Appendix X3.

In addition, fabricating fatigue specimens also involves many special considerations. For example, simulating a component fabrication process for making the specimens may be desired, e.g., heat treating before or after machining. The specimens may be ground or lathe turned. A mechanical polish or electro-polish may be employed. Special processing such as shot peening, stress relieving, plating or coating may be used. All of these procedures (including their sequence) must be documented.

The formation of surface residual stresses should be recognized as one of the most influential effects of machining, although it is frequently overlooked. Any mechanical removal of material from the specimen can produce residual stresses on the surface. Even when special care is taken to remove material very gradually, residual stresses (either surface or profile) may approach the yield point of the material. Under certain conditions these stresses can have a dramatic effect on the fatigue life of the specimen. Whenever the test environment and strain range are such that these stresses are not dissipated, they can alter the stress on the surface of the specimen. Crack initiation and propagation life will therefore be affected. Machining processes for producing fatigue specimens, therefore, should be evaluated not only on the basis of machining tolerances and surface finish, but also on the magnitude, consistency, and profile of these residual stresses.

Fatigue tests that exhibit little inelastic strain are especially influenced by the procedures employed in specimen preparation. Test results in these intermediate- and long-life regimes can be very confusing and misleading if the residual stresses are not considered. These stresses should at least be measured and documented and, in some cases, it may be desirable to stress relieve or electro-polish the specimens.

After the general shape of the fatigue curve has been identified (as shown in Figure 9.2.3.6 for three different stress and strain ratios), replicate tests at specific stress or strain levels may be performed to improve the statistical definition of the fatigue curve. Normally, replications at three levels are sufficient, if no fatigue limit is anticipated (or no attempt is to be made to define one).

The replicated stress or strain levels should be selected to represent initial estimates (based on the exploratory experiments) that would be expected to provide average fatigue lives at the extremes of the life interval of interest and at an intermediate fatigue life. For example, if load-control tests are to be performed and the fatigue performance between 10^4 and 10^6 cycles to failure is of concern, select three maximum stress levels for each stress ratio that appear likely to provide average fatigue lives of about 10^4, 10^5, and 10^6 cycles to failure, respectively.

Figure 9.2.5.1 illustrates this maximum stress and strain level selection process. As this figure suggests, specifying the levels with great precision is not necessary (or justified). The use of levels that have been established from exploratory testing may be appropriate. Use the same levels as those used on one of the exploratory tests if it results in a fatigue life near one of the life ranges of interest. The order of fatigue testing at these stress levels should be randomized for each series of replicates.

If further definition of the fatigue curve is desired in the long-life regime, replication at a fourth maximum stress level may be helpful[*]. To select this stress level, examine the number of runouts obtained at the lowest of the three replicated stress levels. If the number of runouts is less than 50 percent at the lowest stress level, select another, somewhat lower stress level for replication (5 to 10 percent is suggested). Alternatively, if the number of runouts at the lowest of the three replicated stress levels is above 50 percent, select a fourth

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[*] It is assumed here that long-life fatigue tests will be run in load control or started in strain control and switched to load control as discussed earlier.

replicated stress level that is somewhat higher (again, 5 to 10 percent is suggested). Using such an approach, defining a fatigue limit stress at the selected runout level in clearly defined statistical terms will, in many cases, be possible.

The amount of replication required at each maximum stress level or strain range is the key remaining issue. Reference 9.2.5.1(a) recommends a minimum of 50 to 75 percent replication for design allowables data. This translates into two to four specimens at each stress or strain level. If the data displays minor variability, two specimens per level may be sufficient. If the data are highly variable, even four specimens per level may still not clearly define a statistically significant mean fatigue curve (see Section 9.6.1.7).

Adding the number of specimens recommended for curve shape definition and the number recommended for replication, the normal minimum number of fatigue tests per curve ranges from 8 to 16. Therefore, the development of fatigue curves for three stress or strain ratios for a fatigue data display in MIL-HDBK-5 might be based on 24 to 48 specimens. If additional stress or strain ratios are to be considered, the number of recommended tests would expand further, although fewer tests may be employed at these R-ratios.

More fatigue specimens are recommended for test in developing a fatigue data display for use in MIL-HDBK-5 than are actually required by current minimum data standards (see Section 9.2.4.5.1). This discrepancy exists primarily because the satisfaction of current minimum data standards does not ensure a statistically significant set of fatigue curves. The chance of producing a significant set of fatigue curves is much greater if the recommended fatigue test planning procedure is used and the designed test matrix is carefully completed.

Strain control fatigue data for a particular material must be accompanied by sufficient information to allow the construction of a cyclic stress-strain curve. Normally, such a curve can be constructed from stress-strain pairs recorded from stable hysteresis loops. Pairs obtained from a number of different tests covering a wide range of plastic strain ranges will allow construction of a complete cyclic stress-strain curve. Results from replicated incremental step tests may also be used to construct cyclic stress-strain tests [Reference 9.2.5.1(c)].

9.2.5.2 Creep-Rupture — A design of experiments approach to creep data development is highly recommended because it provides the maximum amount of useful data for the least expenditure of time and testing funds. If such an approach is not used, it is likely that several times as many test data will not serve as well in developing desired mathematical models of creep behavior as data developed through design of experiments. This section is devoted to a description of design of experiments approach which can be used to develop regression models to mathematically portray creep rupture life and creep as a function of temperature and stress.

One method for planning testing is to develop a test layout in matrix form, with temperatures in rows and expected creep lives in columns. Then, through testing, simply fill out blocks within the matrix. There should be a minimum of eight observations per isothermal line, or twenty observations per Larson-Miller or other regression model. This ensures coverage of all conditions of interest.

Choosing the Number of Temperatures and Life Intervals—Before the test matrix can be formed, interval sizes must be considered, first for temperature and then life.

(a) Temperature—A range of temperatures is usually required. For example, if experiments must range from 1000°F through 1500°F, a choice must be made whether to perform tests at six levels (1000°F, 1100°F, 1200°F, 1300°F, 1400°F, 1500°F), or maybe at three levels (1000°F, 1300°F, 1500°F). The decision can be quite complicated and based on such phenomena as:

(1) The relative closeness of the isothermal lines
(2) Parallel or divergent isothermal lines
(3) The precipitation of secondary phases within the life ranges of interest.

However, this selection can be greatly simplified with very little user risk. Start with the lowest temperature, and then choose the next temperature line such that at least one level of testing stress, on log stress-log life plot, will be common to both temperatures. Then, proceed to the next temperature line, etc., ensuring like stress values on adjacent temperature levels.

(b) Life—Divide a log-life cycle into four equidistant segments. For example, between 100 hours and 1000 hours, the divisions would be approximately 180 hours, 320 hours, and 560 hours on the log-life scale. These divisions are far enough apart to insure a well-defined curve and a minimum overlap of data. To convert from temperature and life desired to temperature and test stress requires that there be some prior knowledge of this relationship. If there is no prior knowledge, a series of "probe" tests must be made to locate the isothermal lines on a log-log plot.

Choosing the Number of Heats—Batch variations in chemistry, heat treating, etc., can cause considerable variations in the mechanical properties of an alloy. This difference is referred to as heat-to-heat components, as opposed to within-heat components of variance.[**] Heat-to-heat standard deviation is usually 50 to 70 percent of within-heat standard deviation. The root sum square of the two components of variance produces a measure of scatter about the regression that, when added to curve fitting error, gives the regression parameter called SEE (Standard Error of Estimate). SEE is a product of regression analysis; it is rarely determined as defined above. It is this parameter which fixes design minimums about the regression estimates of the typical or mean values.

To make a mathematically sound decision on the minimum number of heats that should be used in a given analysis, it is necessary that an estimate of heat-to-heat and within-heat variance be known. This can usually be estimated from like alloys, or calculated from development data. Simulation has shown the following minimum number of heats to be satisfactory:

(1) When the heat-to-heat component of variance is less than 25 percent of within-heat variance, use two heats equally.

(2) When the heat-to-heat component of variance is between 25-65 percent of within-heat variance, use three heats equally.

(3) When the heat-to-heat component of variance is greater than 65 percent of within-heat variance, use five heats equally.

Heats should be distributed randomly and essentially equally throughout the test matrix to insure an unbiased heat distribution.

When regression models are developed from data that were not taken from an experimental model, heats are rarely chosen randomly. Therefore, unless there are large samples of data in all areas of the regression matrix, this imbalance of heat sample sizes must be accounted for as described in Section 9.6.4.2

[**] The within heat variance is the pooled variability of data from all heats, where the variability for each heat is calculated about its own average regression line. The heat-to-heat variance is calculated from the variability of each heat's average regression line about the overall average regression line of all heats. All heat average curves are assumed to be parallel in log life.

Order of testing must also be randomized so that any time-, operator-, or machine-oriented effects are randomly distributed within the test matrix as described in Reference 9.2.5.2.

9.2.5.3 *Fusion-Welded Joints* — Data generation involves developing a testing program based on considerations of design data requirements, population definition, subpopulation definition, welding procedures, testing procedures, and minimum test data requirements. Data generation is in two parts:

(1) Determination of the properties of weld coupons cut from simple panels welded in accordance with a welding process specification.

(2) Determination of the strength of welded structural components and the relation between the structural component strength and the coupon strength determined in (1).

9.2.5.3.1 *Basic Population Definition* — A basic population definition is selected, satisfying the general welding conditions previously established. The procedure for population definition requires a detailed review of applicable welding conditions to select a single population which will provide data consistent with requirements of the specification. The example shown in Figure 9.2.5.3.1 for 6061 aluminum weldments is typical of a basic population definition. In this example, tooling and heat input have not been specified.

9.2.5.3.2 *Subpopulation Definition* — Appropriate subpopulations must be selected. Obvious subpopulations or associated populations in Figure 9.2.5.3.1 would be alternative weld/heat treating sequences, filler materials, welding processes, weld repair, joint thickness, and weld classes (quality level). Selection of these preplanned subpopulations is dependent upon previous knowledge of their potential effect on weldment properties. However, those mentioned are most frequently encountered subpopulations required.

9.2.5.3.3 *Welding Procedure* — The variables defining the selected basic and subpopulations must be controlled within (but no better than) their prescribed ranges during test program welding. This requires welding in accordance with a referenced specification and any additional requirements which may limit the population. The generation of data requires that welding be conducted under production conditions rather than closely controlled laboratory conditions. Data for development of design properties must realistically represent the variation allowed in referenced specification and/or supplemental requirements for each variable.

Weldments from which data are generated should represent the product of several welders, welding machines, and weld setups. It is required to select test samples from weldments produced at different times by different operators guided only by specified requirements.

BASE MATERIAL

Alloy: 6061 Aluminum per AMS-QQ-A-250/11
Form: Sheet
Preweld Heat Treat Condition: T4 or T6
Postweld Heat Treat Condition: As-Welded
Material Thickness: 0.09 inch
Filler Material: 4043 per QQ-B-655

WELDING VARIABLES

- Joint Preparation
  - Joint Type: Butt
  - Edge Preparation: Square Groove
  - Cleaning: Deoxidize, solvent wipe and hand scrape
- Tooling: None Specified
- Welding Conditions
  - Process: Mechanized GTA
- Sequence: Single Pass
- Position: Flat
- Heat Input: Not Specified
- Weld Repair: None

WELDMENT QUALITY

- Inspection Methods
  - Visual
  - Radiographic, Mil-Std-453
  - Penetrant, Mil-I-6866
- Acceptance Levels
  - External
    - Weld Beads: Removed Flush
    - Underfill and Undercut: None Allowed
    - Cracks: None Allowed
    - Pores: *Maximum size 0.02-inch, one per inch
    - Mismatch: 10% of Thickness Maximum
  - Internal
    - Pores and Inclusions: *Maximum Size 50% T or 0.12 inch whichever is lesser. Maximum accumulated amount less than 2% of cross section area.

*Sharp-tailed or crack-like indications not allowed, appropriate acceptance levels will be added.

Figure 9.2.5.3.1. Example population definition.

9.3 SUBMISSION OF DATA

9.3.1 RECOMMENDED PROCEDURES —This section specifies the procedure for submission of mechanical property data for statistical analysis; specifically data supplied for the determination of T_{99} and T_{90} values for F_{tu} and F_{ty} and for data supplied to obtain derived property values for F_{cy}, F_{su}, F_{bru} and F_{bry}. The amount of data to be supplied for both of these are indicated in other sections of Chapter 9, such as Table 9.2.4.1 for derived property values. This section covers the format for submission of data.

9.3.2 COMPUTER SOFTWARE — The data may be supplied on 3.5 inch disks or CD-ROM in a PC-compatible format. The data files may also be submitted as attachments to an e-mail message. It is recommended that the software applications in Table 9.3.2 be used to construct the data files. Along with the electronic version, provide a hard (paper) copy of the data and any other supporting documentation such as specimen dimensions, gage length etc. This information will be stored in the MIL-HDBK-5 archives for future reference. Company-specific data will be treated as proprietary information at the request of the submitting organization.

Table 9.3.2. Software Applications for Data Submission

- ASCII text editor
- Current Spreadsheet or Database Applications
- The Chairman or Secretary of MIL-HDBK-5 can be contacted concerning software compatibility questions.

The data supplied on these disks or sent by e-mail are to be supplied in English units. For example, physical dimensions should be reported in units of inches to the nearest thousandth of an inch (X.XXX), stress should be reported in units of ksi to the nearest one hundredth of a ksi (X.XX), strain is to be reported in percent to the nearest tenth of a percent (X.X) and modulus is to be reported in units of 10^3 ksi to the nearest tenth of a msi (X.X). If necessary, refer to Table 1.2.2 to convert to English units of measure.

9.3.3 GENERAL DATA FORMATS — Table 9.3.3 shows the information that should be supplied in electronic form along with the mechanical test results. The alloy type, temper/heat treatment, product form, specimen location and specification number will be identified. Columns (or data fields), in order, will contain grain direction, product thickness, unit of product thickness, lot number, and heat number. Columns will be added towards the right of the heat number and will containthe individual test results as discussed in Sections 9.3.3.1 and 9.3.3.4.

When specifying grain direction for wrought product strengths, etc., use the conventions identified in Table 9.2.4.3: L for longitudinal, LT for long transverse, and ST for short transverse. Products that are anticipated to have significantly different properties in directions other than those stated above should be tested in the appropriate directions and the results reported.

There are several types of product forms identified in the Handbook; therefore, the term product form should be properly defined and reported in this column. Examples for wrought products are sheet, plate, bar, and forging. Examples for cast products are sand casting , investment casting, and permanent mold casting. For wrought products, specimen location should be t/2 or t/4. For cast products, specimen location should indicate designated or nondesignated areas.

Table 9.3.3. General Data Format

Alloy Trade Name　　Temper/Heat Treatment　　Product Form

Industry/Government Specification No.

Grain Direction	Product Thickness	Unit (in.), or Area (in.^{2})	Lot No.	Heat No.	Specimen Location (or Designation)	TUS, ksi	TYS, ksi	CYS, ksi	e, %

9.3.3.1 ***Data Format for the Computation of T_{99} and T_{90} Values*** — The tensile test results that are to be reported for determination of A and B-basis properties are tensile ultimate strength (TUS), tensile yield strength (TYS), elongation (e), reduction of area (RA), and elastic modulus. The results of these tests are to be reported as shown in Table 9.3.3.1 along with alloy designation, specification, lot and/or heat number, product thickness, grain direction, etc. as previously shown in Table 9.3.3. The number of tests required for determining A and B-basis properties are identified in Section 9.2.4.1.

9.3.3.2 ***Data Format for Derived Properties*** — For the derived property values, several types of tests may be conducted such as tensile, compression, shear and bearing, as shown in Table 9.2.4.1. The results of these tests are to be reported as shown in Table 9.3.3.2 along with alloy designation, specification, lot and/or heat number, product thickness, grain direction, etc. as previously shown in Table 9.3.3. The ultimate strength properties are to be contained in one file as shown in Table 9.3.3.2(a) while the yield strength properties are to be contained in another file as shown in Table 9.3.3.2(b).

Generally, two tests are preferred (one required) for a given test type and product thickness. The results of these tests are to be reported in columns adjacent to each other. For example, TUS Test #1 and TUS Test #2 are on the same row for a given thickness and heat. An additional column should be created to report the specimen number for the second test. This column should be just to the left of the test result. The same procedure is to be used for the other properties. The abbreviations (see Appendix A) for the other test types are CYS for compressive yield, SUS for shear ultimate, and BUS and BYS for bearing ultimate and bearing yield strengths, respectively. For the bearing properties, also identify the e/D ratio of either 1.5 or 2.0.

Table 9.3.3.1. Data Format for Determination of A and B-Basis Values of F_{tu} and F_{ty}

Alloy Trade Name		Heat No.	Lot No.	UTS, ksi	TYS, ksi	Elongation %	Red. of Area, %	Elastic Modulus, ksi
	The information to be entered between these two columns							
	depends upon the product form, see Table 9.3.3.							

Table 9.3.3.2(a). Derived Ultimate Properties

Alloy Trade Name		Heat No.	Lot No.	TUS Test 1	TUS Test 2*	SUS Test 1	SUS Test 2*	BUS e/D=1.5 Test 1	BUS e/D=1.5 Test 2*	BUS e/D-2.0 Test 1	BUS e/D=2.0 Test 2*
	The information to be entered between these two columns depends upon the product form, see Table 9.3.3.										

* Two tests are preferred, only one is required.

Table 9.3.3.2(b). Derived Yield Properties

Alloy Trade Name		Heat No.	Lot No.	TYS Test 1	TYS Test 2*	CYS Test 1	CYS Test 2*	BYS e/D=1.5 Test 1	BYS e/D=1.5 Test 2*	BYS e/D-2.0 Test 1	BYS e/D=2.0 Test 2*
	The information to be entered between these two										
	columns depends upon the product form, see Table 9.3.3.										

* Two tests are preferred, only one is required.

9.3.3.3 *Data Format for the Construction of Typical Stress-Strain Curves* — The individual tensile and compression stress-strain data should also be submitted in electronic form, if possible, so that typical tensile and compression stress-strain curves, compression tangent-modulus and typical (full-range) stress-strain curves can be constructed. In order to construct a typical stress-strain curve, the individual specimen curves must be documented up to slightly beyond the 0.2 percent offset yield strength. To construct a typical (full-range) stress-strain curve, the individual curves must be documented through to failure.

The data for the stress-strain curves must be supplied on separate electronic media from the mechanical property data. The data should be stored in a file which contains the load (or stress) in the first column and the displacement (or strain) in the second column. Each load or displacement stress-strain pair should be identified with its corresponding specimen identification number.

For the load-displacement curves, the load should be reported in pounds (X.) and the displacement should be reported in units of thousandth of an inch (X.XXX). For stress-strain curves, the stress should be reported to the nearest hundredth of a ksi (X.XX) and strain should be reported to the nearest X.XX $x10^{-6}$ units.

A hard copy of the load displacement curve should also be submitted for each stress-strain curve.

9.3.3.4 *Data Format for Fasteners* — A report will be submitted to MIL-HDBK-5 Coordination Group summarizing the test program, results, analysis, and suggested table of joint allowables for MIL-HDBK-5. The following information will be provided in the report:

(1) A description of sheet and plate material with heat-treatment details and mechanical property test data for each sheet thickness used in the program in accordance with the requirements of Section 9.2.4.6.3.

(2) A description of fastener, including drawings and specifications. If the fastener is not covered by a government or industry specification, a copy of an appropriate draft specification will be attached to the report.

(3) A statement of compliance with NASM 1312, including a detailed statement of any differences from this standard.

(4) Basic test data [see Figure 9.7.1.4(a)], including that required in NASM 1312, and representative load deflection curves.

(5) Values for fastener shear calculation: as defined in Section 9.7.1.3 and fastener shear stress curves, where applicable.

(6) Designation of allowable shear strength reliability (90 or 99 percent value).

(7) Calculated t/D, P_u/D^2, and P_y/D^2 values [see Figure 9.7.1.4(a) for sample format].

(8) Seven or more graphs, as required, of P/D^2 versus t/D, as described in detail in Section 9.7.1.4, including the proposed design allowable curves for yield and ultimate load.

(9) Calculations of allowable loads (see Figure 9.7.1.5 for sample format).

(10) The suggested allowable load tables in the format shown in Section 9.9.5.

(11) Failure identification mode for failure of each fastener and/or joint is required, as shown in Figure 9.3.3.4. If failure is unique or not covered in the figure, so indicate.

(12) Off-set used to obtain yield data.

(13) Draft, in NAS or MS format, of specification for applicable fastener system.

9.3.3.5 ***Data Format for Other Properties*** — Data submission format for data types not discussed in Section 9.3.3.1 through 9.3.3.4 have not been standardized. The Chairman or Secretary of MIL-HDBK-5 can be contacted concerning most convenient data submission formats.

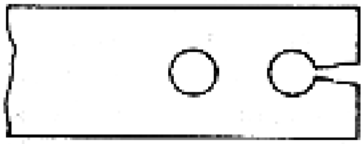
1. SHEET FAILURE

(a) Bearing Deformation of Hole

(b) Tearing of Sheet Allowing Fastener Pull-Through, Head Pull-Through or Nut Collar of Formed Head Pull-Through

(c) Tearing of Sheet at Edge Margin

(d) Shear Out of Sheet Through Edge Margin

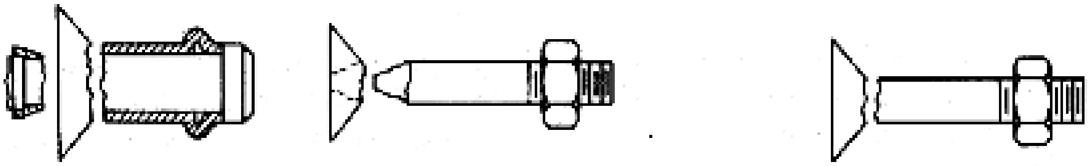


(e) Hoop Tension Failure of Sheet

2. FASTENER HEAD FAILURE

(a) Head Dished in Tension

(b) Partial Shear Failure of Head



(c) Shear Failure of Head

(d) Tensile Failure at Head to Shank Junction

Figure 9.3.3.4. Failure identification code.

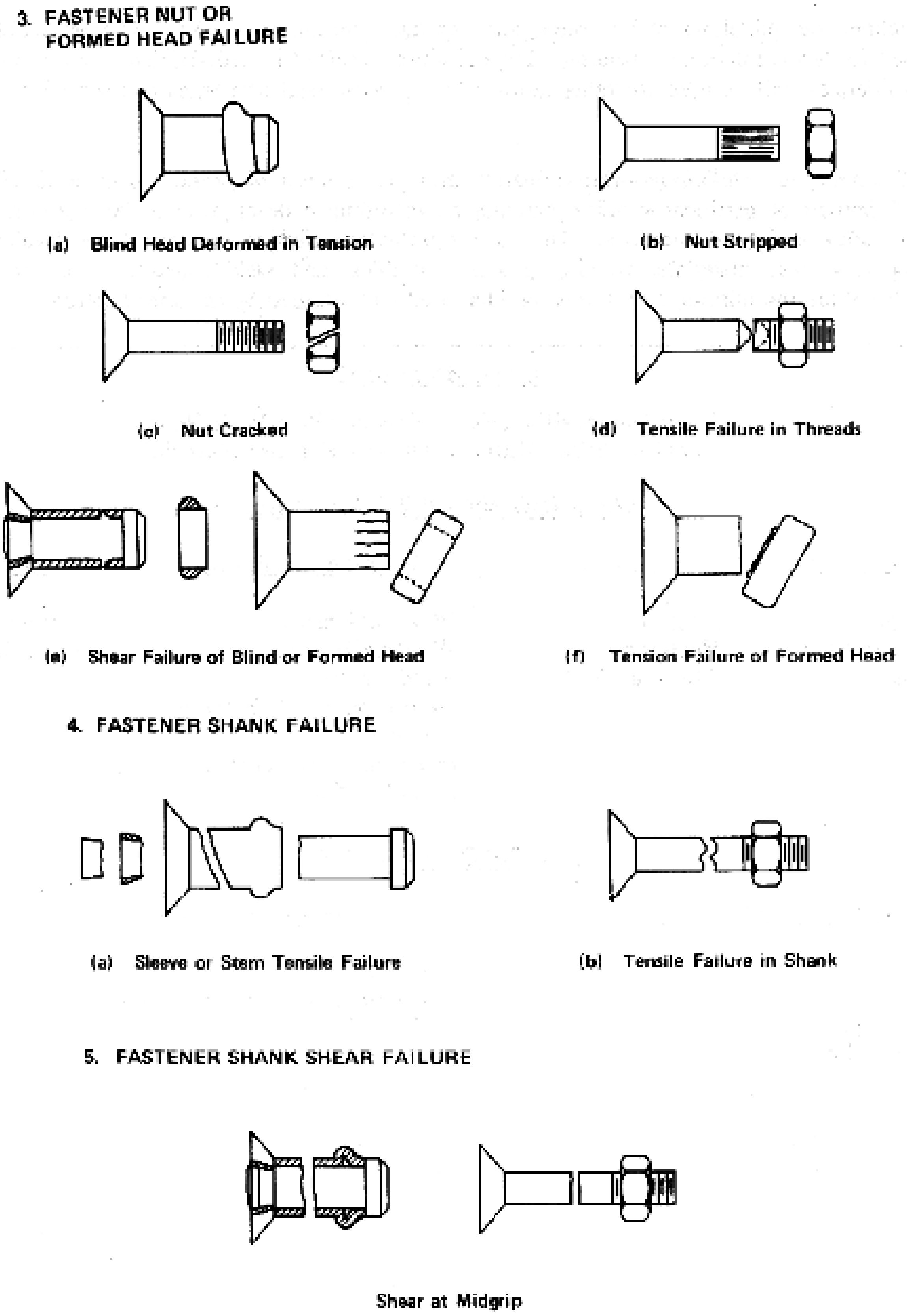


Figure 9.3.3.4. Failure identification code—Continued.

9.4 SUBSTANTIATION OF S-BASIS MINIMUM PROPERTIES

A product must be covered by an industry specification prior to being considered for inclusion into MIL-HDBK-5. Within a specification, one of the basic requirements is to provide minimum properties (S-basis) which includes tension yield, tension ultimate, elongation and compression yield (when specified). The statistical significance to the S-basis properties is typically not known. However, since ~ 1975, the minimum mechanical properties in the SAE/AMS specifications have been statistically justified with a procedure described in their documents. With that in mind, a procedure has been established to provide a level of statistical significance to S-basis properties contained within the Handbook.

A material being submitted for inclusion into MIL-HDBK-5 must include the basis of the specification properties as part of the substantiation package. This substantiation package should include the number of test samples, the number of lots, and the method used to determine any property covered in the specification, even if it will not be reported in MIL-HDBK-5. This could include the development of minimum as well as maximum properties. Consideration will be given to the specified sizes, product forms, heat treatments and other variables affecting the physical and mechanical properties. It is also expected that the test material chemistry be in the nominal specification range and not tailored to the chemistry extremes.

It is recommended that the substantiation of properties be based on a procedure similar to SAE/AMS in which the analysis of data or other appropriate documentation supports a statistical S-basis value, where at least 99 percent of the population of values is expected to equal or exceed the minimum value with a confidence of 95 percent. The data requirements for an S-basis value are described in Section 9.2.4.1. The S-basis value may be computed by assuming the distribution of the sample population to be normal and using the following equation:

$$\text{Minimum S} = \bar{X} - s \cdot k_{99}$$

where

$\bar{X}$ = sample mean
s = standard deviation
k_{99} = one-sided tolerance-limit factor corresponding to a proportion at least 0.99 of a normal distribution and a confidence coefficient of 0.95 based on the number of specimens (See Table 9.10.1).

All data analyses must to be performed in English units. Strength data recorded in metric units should be converted to English units, to the nearest 0.01 ksi, before data analyses are undertaken. If desired by the data supplier, metric equivalent tables and figures can be included as part of the working data submitted with a data proposal, but the tables and/or figures proposed for inclusion in MIL-HDBK-5 will contain only English units.

When the tensile and compressive properties vary significantly with thickness, regression analysis should be used.

Although the establishment of an S-basis value should be based upon the statistically computed value, the S-basis value may be slightly lower, based on experience and judgement.

9.5 ANALYSIS PROCEDURES FOR STATISTICALLY COMPUTED MINIMUM STATIC PROPERTIES

Procedures used to determine tolerance bounds for mechanical properties vary somewhat from one sample to another. All involve a number of steps that are illustrated by the flowchart in Figure 9.5. These steps can be summarized as follows:

(1) Specify the population to which the property applies
(2) Decide on the procedure for computing the property
(3) Compute the property.

These steps are described in greater detail in Sections 9.5.1 through 9.5.8, and a number of examples of the several procedures are presented in Section 9.8.1.

9.5.1 SPECIFYING THE POPULATION— For computational purposes, definition of a population must be sufficiently restrictive to ensure that computed tolerance bounds for design properties are realistic and useful. This is done by establishing a range of products and test conditions for which a mechanical property can be characterized by a single statistical distribution. In most cases a homogeneous population of data for a measured test parameter should not include more than one alloy, heat-treated condition, or test temperature.

It is not necessarily obvious whether such a population may include more than one product form or size, grain direction or processing history. Strip, plate, bars, and forgings of one alloy may have essentially the same TYS, while for another material the TYS may differ greatly among those product forms. To resolve these questions, appropriate statistical tests of significance should be applied to the respective groups of data. These tests are described in detail in Sections 9.5.3 and 9.5.4. Section 9.8 presents examples of their use in MIL-HDBK-5 data analyses.

The step-by-step procedure for specifying the population is illustrated in Figure 9.5.1 and described below. This procedure is used to determine whether several available data sets may be combined for the purpose of computing design allowables. The procedure is applicable to data collections for which regression analysis is required, as well as those for which regression is not required. In the latter case, an acceptability test is employed to eliminate unacceptable data sets. This procedure is described in Section 9.5.4.3 and 9.5.4.4. A corresponding acceptability test for the regression setting is described in Section 9.5.1.2.

9.5.1.1 ***Deciding Between Direct and Indirect Computation*** — The only room-temperature design properties that are regularly determined by direct computation are F_{tu} and F_{ty}. This procedure is usually limited to a specified or usual testing direction because there are seldom enough data available to determine properties in other test directions. Two rules govern the choice between direct and indirect computation:

(1) F_{tu} and F_{ty} in the specified or usual testing direction may be determined by direct computation only.

(2) F_{tu} and F_{ty} in other testing directions (as well as F_{cy}, F_{su}, F_{bru}, and F_{bry} in all directions) may be determined by direct computation only if (a) the data are adequate to determine the distribution form and reliable estimates of population parameters, or (b) the sample includes 299 or more individual, representative observations of the property to be determined.

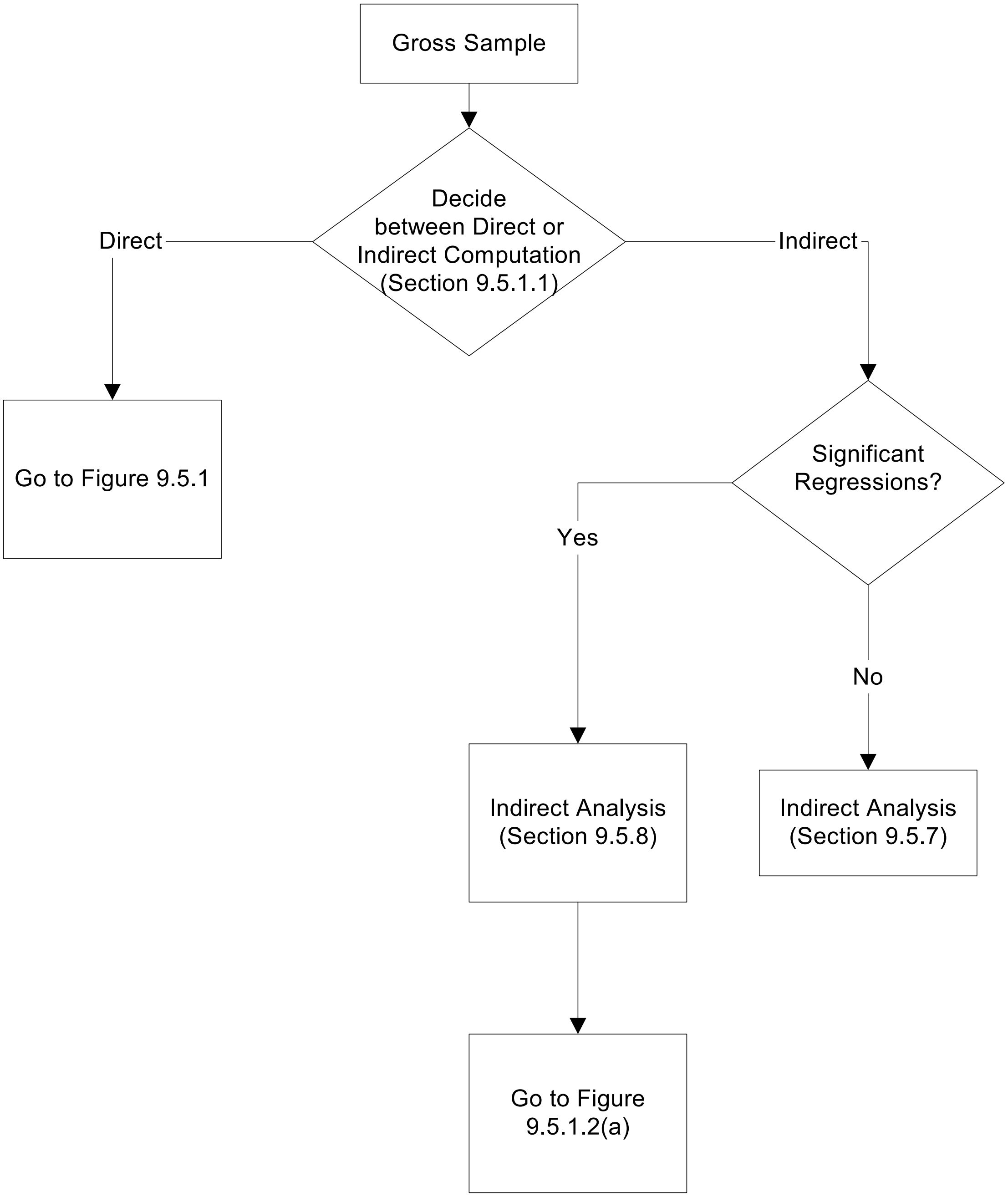


Figure 9.5 Determination of Method of Design Allowable Analysis.

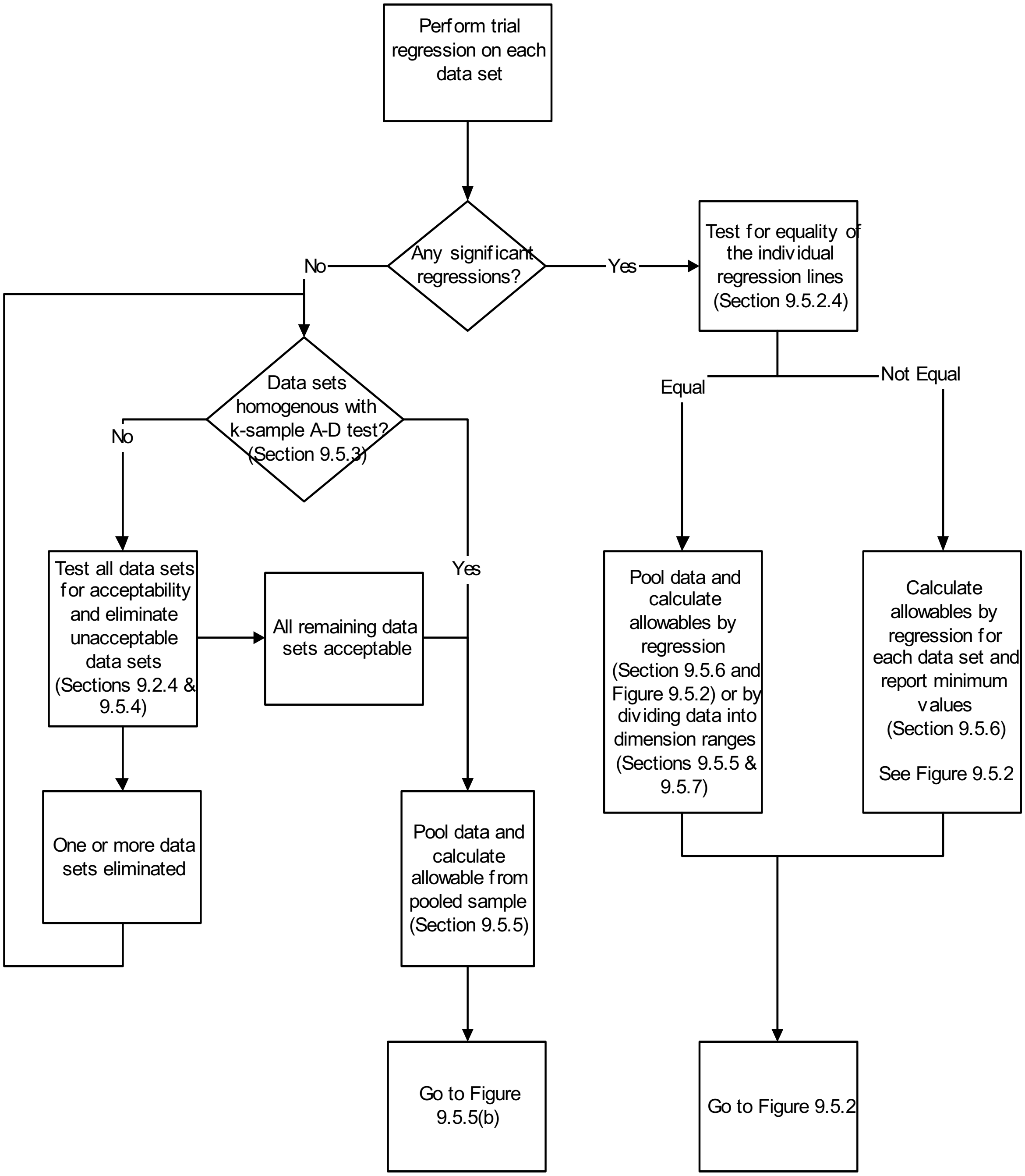


Figure 9.5.1. Determination of Direct Design Allowables.

For example, assume that available data for a relatively new alloy comprise 50 observations of TUS in the specified testing direction. This sample is not considered large enough to determine the distribution form and reliable estimates of population mean and standard deviation. Since only direct computation is permitted in this instance, determination of T_{99} and T_{90} values must be postponed until a larger sample is available. However, these properties may be considered for presentation on the S basis at the discretion of the MIL-HDBK-5 Coordination Group, contingent on availability of an acceptable procurement specification for the material.

If the number of observations increases to 100, this quantity may be adequate to allow determination of T_{99} and T_{90} values, provided data can be described by a Pearson Type III (gamma) (subsequently referred to as simply "Pearson") or Weibull distribution. If the distribution cannot be described parametrically, at least 299 observations are required so that computation can proceed without knowledge of the distributional form.

If the above example involved observations of SUS instead of TUS, the same criteria would apply for direct computation. However, F_{su} could be determined by indirect computation with as few as ten paired observations of SUS and TUS (representing at least ten lots and three heats), provided F_{tu} has been established.

9.5.1.2 *Testing for Regression Effects and Homogeneity* — In most cases, there will be a fairly clear-cut division between one population and another. For example, L and T properties either are or are not nearly identical. However, wrought product properties may sometimes vary linearly or curvilinearly with some dimensional characteristic, such as thickness. Examples are effect of thickness on TUS, effect of temperature on TUS, and effect of stress on cycles or time to rupture. It is necessary, therefore, to first test the data for the relationship between the property and the material dimension.

Before employing a regression analysis in the determination of material properties, one must ascertain that the average of the property to be regressed varies continuously and linearly or quadratically with some dimensional parameter x (such as x = t, 1/t, etc., where t is thickness). If the variation of average is attributable to other causes, regression should not be used.

Regression analysis, as described herein, also assumes that residuals are normally distributed about the regression line. Residuals are the differences between observed data values and the values which are predicted by the fitted regression equation. Validity of this normality assumption should be evaluated by performing the Anderson-Darling test presented in Section 9.5.4.1.

The procedures for fitting a regression equation of the form,

$$\text{TUS} = a + bx,$$

or

$$(\text{SUS/TUS}) = a + bx,$$

or

$$(\text{SUS/TUS}) = a + bx + cx^2,$$

to n data points are described in Section.9.5.2. In addition to estimates for a and b (and possibly c), this procedure produces two F statistics. One statistic (F_1) tests the significance of regression. The other statistic (F_2) tests the adequacy of a linear model for describing the relationship between the material property and the dimensional parameter. If F_2 indicates a lack of fit of the model to the data, a transformation of the data may account for the nonlinearity. If F_1 indicates an insignificant regression, one of the other appropriate analysis techniques, as described in Section 9.5.5 for direct computation, or 9.5.7 for indirect computaion, should be used.

If any one of a group of data sets analyzed by regression shows a significant effect on properties due to the selected material dimension, all regressions should be tested for equality to determine whether the data sets may be combined and considered a homogeneous population. The procedure described in Section 9.5.2.4 should be used to perform this test.

If the regressions are accepted as equal, then T_{99} and T_{90} values can be calculated in one of two ways: (1) by regression; or (2) by dividing data into thickness ranges and calculating T_{99} and T_{90} values for each range. If the regressions are not equal, T_{99} and T_{90} values should be calculated separately for each data set and minimum T_{99} and T_{90} values determined for all data sets should be reported. The method for determining T_{99} and T_{90} by regression is described in Section 9.5.6. Figures 9.5.1.2(a) and (b) illustrate the procedures used to determine design allowables when regression is required.

If none of the individual data sets (e.g. different producers) show significant regression due to the chosen material dimension, the different data sets should be tested for homogeneity using a k-sample Anderson-Darling test as described in Section 9.5.3.1. If data sets are found to be homogenous, data should be pooled and T_{99} and T_{90} values should be calculated using the single combined data set. If data from the various producers constitute more than one population, the following procedure should be used.

(1) Data sets which do not comply to the minimum number of observations as stated in Sections 9.2.4.2 should be excluded from any further evaluation until they meet the minimum requirements.

(2) Each remaining data set should be tested for acceptability using the three-parameter Weibull acceptability test described in Section 9.5.4.3. If there is statistical evidence that one or more statistically distinct data sets do not meet the specification minimum value, the results will be brought to the Material Data Review Working Group where a decision will be made on whether or not these data sets should be included in the computation of material property values.

(3) All remaining data sets should be tested for homogeneity using the k-sample Anderson-Darling test. If the data sets are found to be homogeneous, T_{99} and T_{90} values can be calculated using a single combined data set. If the populations are not homogeneous, material property values must be determined by calculating T_{99} and T_{90} values for each data set. In the latter case, the data set with the lowest T_{99} and T_{90} values will generally be used to establish minimum design values.

9.5.2 REGRESSION ANALYSIS — Mathematical techniques for performing a simple linear regression analysis are contained in Section 9.5.2.1. Similar techniques for performing a quadratic regression analysis are contained in 9.5.2.2. Statistical tests to determine whether a linear or quadratic regression adequately describes the data are described in Section 9.5.2.3. A test for equality of several regression lines is presented in Section 9.5.2.4. Example analyses are presented in Section 9.8 using hypothetical data to illustrate the regression calculations. Figure 9.5.1.2(b) provides guidance in choosing an appropriate regression analysis to use for calculating design allowables.

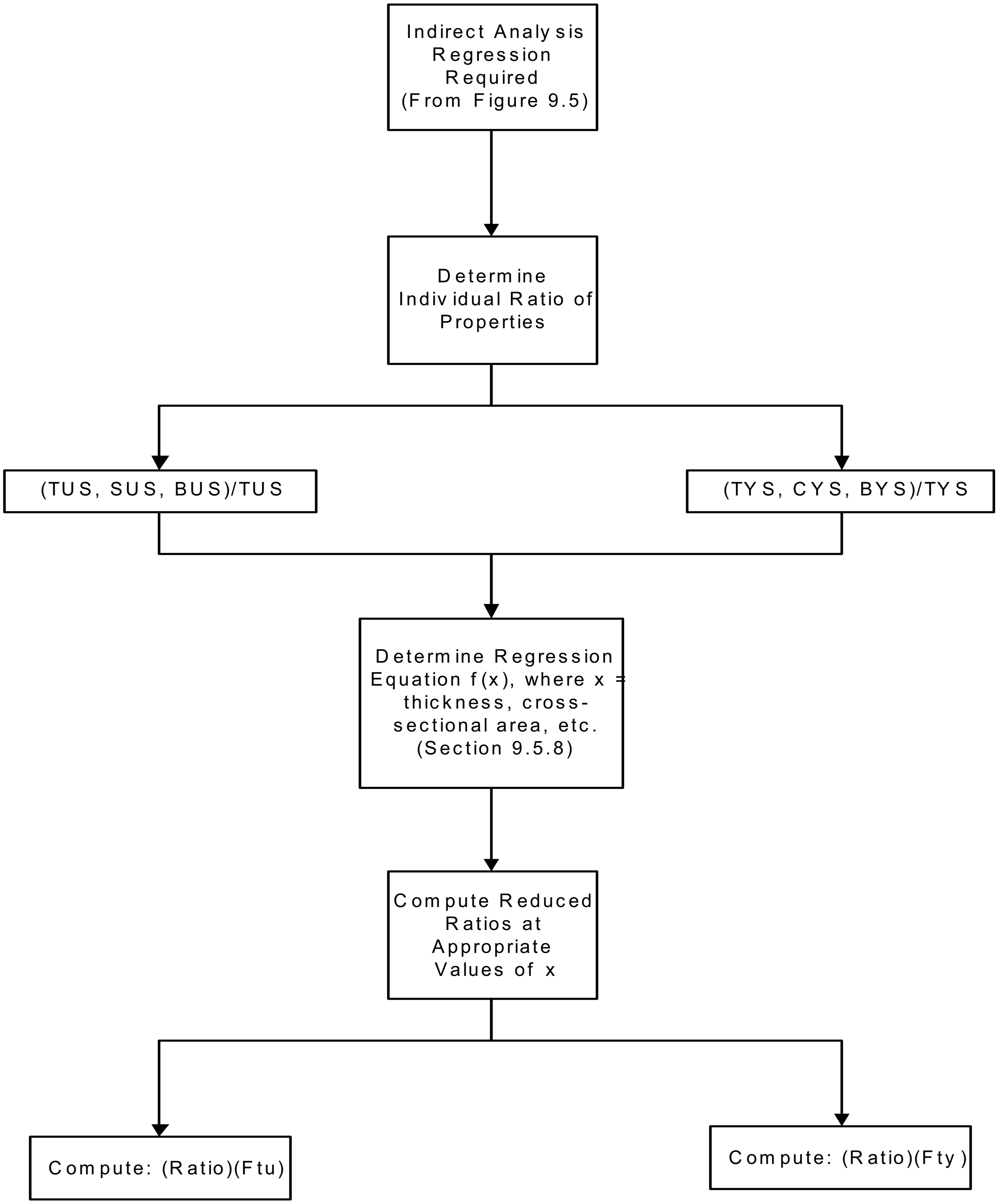


Figure 9.5.1.2(a). Determination of Indirect Design Allowables When Regression is Required.

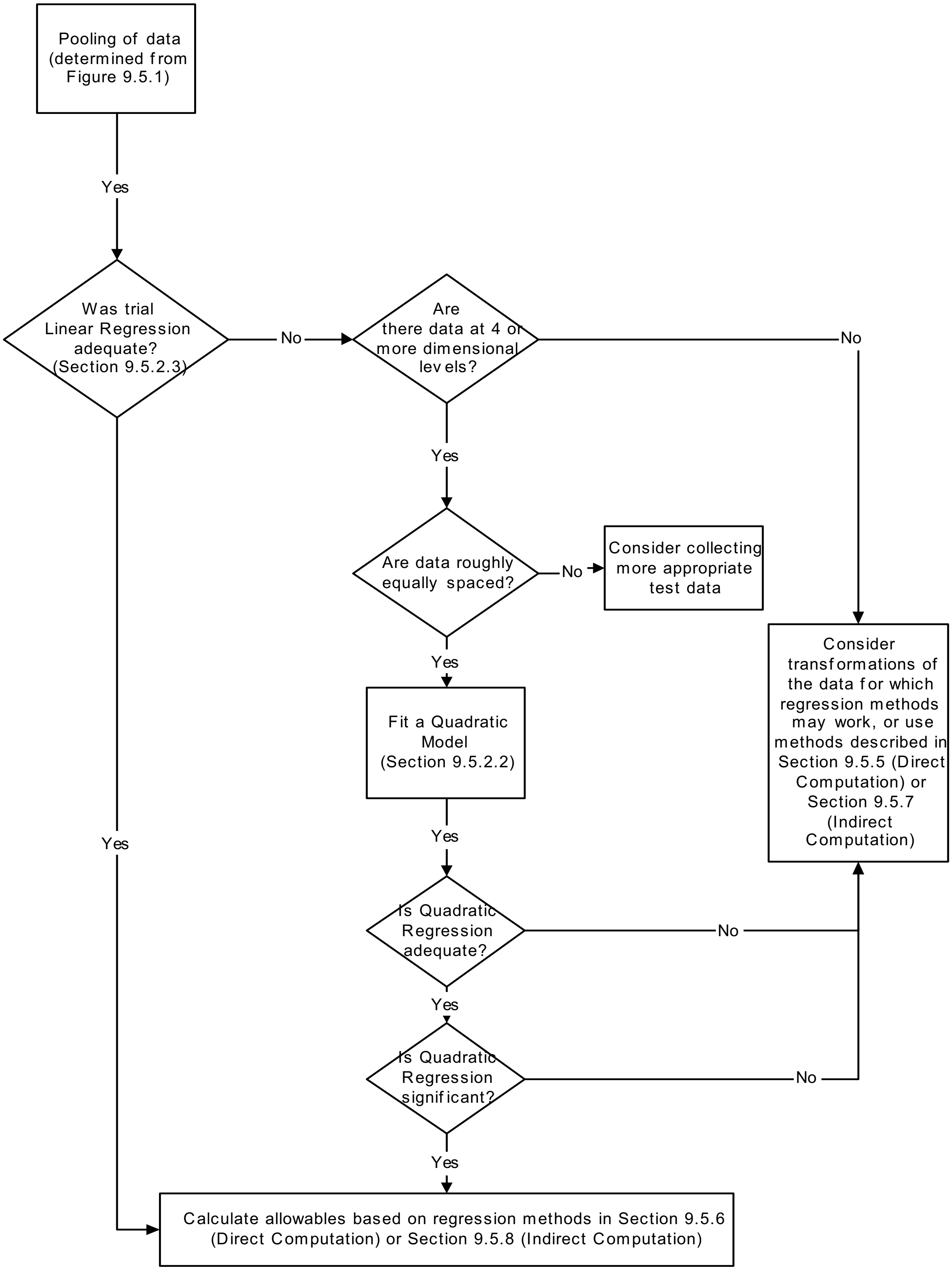


Figure 9.5.1.2(b). Determination of Direct Allowables When Regression is Required

Regression is sometimes employed with transformed variables; that is, it may be necessary to work with log(TUS), t^2, or $1/(T+460)$, for example. When this is the case, the analyst must remember to transform variables back to the original engineering units after final computations.

Regression analysis, as described herein, also assumes that residuals are normally distributed about the regression line. Residuals are the differences between observed data values and the values which are predicted by the fitted regression equation. Validity of this normality assumption should be evaluated by performing the Anderson-Darling test presented in Section 9.5.4.1.

9.5.2.1 ***Linear Regression*** — Linear regression is appropriate when there is an approximate linear relationship between two measurable characteristics. Such a relationship is expressed algebraically by an equation that, in the case of two measurable characteristics x and y, has the form

$$y = \alpha + \beta x + \varepsilon \qquad [9.5.2.1(a)]$$

where

x = independent variable
y = dependent variable
α = true intercept of the regression equation
β = true slope of the regression equation
ε = measurement or experimental error by which y differs from the ideal linear relationship.

Aside from the error term, ε, this is the equation of a straight line. The parameter α determines the point where this line intersects the y-axis, and the β represents its slope. The variables x and y may represent either direct measurements or some transformation measurements of the characteristics under consideration.

Knowing or assuming such an approximate linear relationship, the problem becomes one of estimating the parameters α and β of the regression equations. It is necessary to have a random sample consisting of n pairs of observations, which is denoted by $(x_1, y_1),(x_2, y_2),\ldots, (x_n, y_n)$. Such a sample can be represented graphically by n points plotted on a coordinate system, in which x is plotted horizontally and y vertically. A subjective solution can be obtained by drawing a line that, by visual inspection, appears to fit the points satisfactorily. An objective solution is given by the method of least squares.

The method of least squares is a numerical procedure for obtaining a line having the property that the sum of squares of vertical deviations of the sample points from this line is less than that for any other line. In this analysis, the least-squares line is represented by the equation

$$\hat{y} = a + bx \quad , \qquad [9.5.2.1(b)]$$

in which

$\hat{y}$ = predicted value of y for any value of x
a and b = estimates of the parameters α and β in the true regression equation obtained by the least squares method presented below.

It can be shown with the aid of calculus that the values of a and b that minimize the sum of squares of the vertical deviations are given by the formulas:

$$a = \frac{\Sigma y - b\Sigma x}{n} \qquad [9.5.2.1(c)]$$

$$b = \frac{S_{xy}}{S_{xx}} \qquad [9.5.2.1(d)]$$

where

$$S_{xy} = \Sigma xy - \frac{\Sigma x \; \Sigma y}{n} \quad , \qquad [9.5.2.1(e)]$$

and

$$S_{xx} = \Sigma x^2 - \frac{(\Sigma x)^2}{n} \quad . \qquad [9.5.2.1(f)]$$

The root mean square error of y is expressed as

$$S_y = \sqrt{\frac{\Sigma(y - \hat{y})^2}{n - 2}} \qquad [9.5.2.1(g)]$$

where ŷ is the predicted value of y defined above. This quantity is an estimate of the standard deviation of the distribution of y about the regression line. A convenient computational formula for s_y is

$$s_y = \sqrt{\frac{S_{yy} - b^2 S_{xx}}{n - 2}} \qquad [9.5.2.1(h)]$$

where

$$S_{yy} = \Sigma y^2 - \frac{(\Sigma y)^2}{n} \qquad [9.5.2.1(i)]$$

The quantity $R^2 = (b^2 S_{xx})/S_{yy}$ measures the proportion of total variation in the y data, about its average, that is explained by the regression. An R^2 equal to 1 indicates that the regression model describes the data perfectly, which is rare in practice. R^2 provides a rough idea of how well data is described by a linear regression. A more precise determination of the adequacy of a linear regression is discussed in Section 9.5.2.3.

9.5.2.2 *Quadratic Regression* — Quadratic regression is appropriate when there is an approximate quadratic relationship between two measurable characteristics. Such a relationship is expressed algebraically by an equation that, in the case of two measurable characteristics x and y, has the form

$$y = \alpha + \beta x + \gamma x^2 + \varepsilon, \qquad [9.5.2.2(a)]$$

where

x = independent variable
y = dependent variable
α = true intercept of the regression equation
β = true coefficient of the linear term in the regression equation
γ = true coefficient of the quadratic term in the regression equation
ε = measurement or experimental error by which y differs from the ideal linear relationship.

Aside from the error term, ε, this is the equation of a parabola. The parameter α determines the point where this curve intersects the y-axis. The variable x and y may represent either direct measurements or some transformation measurements of the characteristics under consideration.

Knowing or assuming such an approximately quadratic relationship, the problem becomes one of estimating the parameters α, β, and γ of the regression equation. It is necessary to have a random sample consisting of n pairs of observations, which is denoted by (x_1,y_1), (x_2,y_2), ..., (x_n,y_n). Such a sample can be represented graphically by n points plotted on a coordinate system, in which x is plotted horizontally, y vertically. A subjective solution can be obtained by drawing a curve that, by visual inspection, appears to fit the points satisfactorily. An objective solution is given by the method of least squares.

The method of least squares is a numerical procedure for obtaining a second-degree polynomial having the property that the sum of squares of vertical deviations of the sample points from this curve is less than that for any other second-degree polynomial. In this analysis, the least squares curve is represented by the equation

$$\hat{y} = a + bx + cx^2 \quad , \qquad [9.5.2.2(b)]$$

in which

$\hat{y}$ = predicted value of y for any value of x
a, b, and c = estimates of the parameters α, β and γ in the true regression equation obtained by the least squares method presented below.

It can be shown with the aid of calculus that the values of a, b, and c that minimize the sum of squares of the vertical deviations are given by the formulas:

$$a = \bar{y} - b\left(\sum \frac{x}{n}\right) - c\left(\sum \frac{x^2}{n}\right)$$

$$b = \frac{\left(\sum X_1Y\right)\left(\sum X_2^2\right) - \left(\sum X_2Y\right)\left(\sum X_1X_2\right)}{D}$$

$$c = \frac{\left(\sum X_2Y\right)\left(\sum X_1^2\right) - \left(\sum X_1Y\right)\left(\sum X_1X_2\right)}{D} \qquad [9.5.2.2(c)]$$

where

$$D = \left(\sum X_1^2\right)\left(\sum X_2^2\right) - \left(\sum X_1 X_2\right)^2 \qquad [9.5.2.2(d)]$$

and where $X_1 = x - \Sigma x/n$, $X_2 = x^2 - \Sigma x^2/n$, $Y = y - \Sigma y/n$, all symbols being summed are subscripted by i, and all summations are over i=1 to n.

The root mean square error of y is expressed as

$$s_y = \sqrt{\frac{\sum (y-\hat{y})^2}{n - 3}} \qquad [9.5.2.2(e)]$$

where ŷ is the predicted value of y defined above. This quantity is an estimate of the standard deviation of the distribution of y about the regression curve. A convenient computational formula for s_y is

$$s_y = \sqrt{\left(\sum Y^2 - b\sum X_1 Y - c\sum X_2 Y\right) / (n-3)} \qquad [9.5.2.2(f)]$$

The quantity $R^2 = 1-(n-3)\, s_y^2 / \Sigma Y^2$ measures the proportion of total variation in the y data, about its average, that is explained by the regression. An R^2 equal to 1 indicates that the regression model describes the data perfectly, which is rare in practice. R^2 provides a rough idea of how well the data are described by a quadratic regression.

Another quantity, Q, is required to compute allowables by quadratic regression analysis. Q is defined as

$$Q = q_1 + 2q_2 x_o + (2q_3 + q_4)\, x_o^2 + 2q_5\, x_o^3 + q_6\, x_o^4 \qquad [9.5.2.2(g)]$$

where x_0 is the value of the independent variable for which the allowable is being calculated and q_1, q_2, q_3, q_4, q_5 and q_6 are defined as:

$q_1 = k\,[\,ce - d^2]$,

$q_2 = k\,[\,cd - be]$,

$q_3 = k\,[\,bd - c^2]$,

$q_4 = k\,[\,ae - c^2]$,

$q_5 = k\,[\,bc - ad]$, and

$q_6 = k\,[\,ac - b^2]$

where[*]

$a = n,$

$b = \Sigma\, x_i,$

$c = \Sigma\, x_i^2,$

$d = \Sigma\, x_i^3,$

$e = \Sigma\, x_i^4,$ and

$k = [\,(ace + 2bcd) - (\,c^3 + ad^2 + b^2e)\,]^{-1}.$

9.5.2.3 *Tests for Adequacy of a Regression* — It is possible that the relationship between the dependent variable y and the independent variable x may not be well approximated by the chosen model (linear or quadratic). In that case, the predicted values, modeled by a line or a quadratic curve, would not "fit" the data very well. It is also possible that the relationship between x and y, although well described by the chosen model, is not very strong. That is, there may not be much change in the y values over the range of x considered. This is measured by the "significance" of the regression. Both the lack of fit and the significance of a linear regression equation can be evaluated through an analysis of variance as described in this section.

To evaluate the adequacy of a regression model requires satisfying two conditions. First, it is necessary that there are multiple observations at one or more values of the independent variable x. Second, in the case of a linear regression, there must be three or more distinct x values; in the case of a quadratic regression, there must be four or more distinct x values.

The analysis of variance for testing lack of fit and significance of regression is based on the assumption that the measurement errors, ε_i, in the relationship between y_i and x_i [see 9.5.2.1(a) and 9.5.2.2(a)] are independent and normally distributed with an overall mean of zero and a constant variance of σ^2. Assuming uniformity of variance of measurement errors over the range of the independent variable, the normality assumption concerning unobservable ε_i can be checked by performing the Anderson-Darling test for normality on the observed residuals

$$e_i = y_i - \hat{y}_i,$$

i=1,…, n, where

$$\hat{y}_i = a + bx_i$$

---

[*] Although it is not necessary for the computations, the values q_1, q_2, q_3, q_4, q_5, and q_6 represent elements

of the inverted matrix $(X'X)^{-1} = \begin{bmatrix} q_1 & q_2 & q_3 \\ q_2 & q_4 & q_5 \\ q_3 & q_5 & q_6 \end{bmatrix}$, where $X'X = \begin{bmatrix} n & \sum x_i & \sum x_i^2 \\ \sum x_i & \sum x_i^2 & \sum x_i^3 \\ \sum x_i^2 & \sum x_i^3 & \sum x_i^4 \end{bmatrix}.$

in the case of linear regression, and

$$\hat{y}_i = a + bx_i + cx_i^2$$

in the case of quadratic regression. See Sections 9.5.2.1 and 9.5.2.2 for details on the computation of a, b, and c, and see Section 9.5.4.1 for details on the Anderson-Darling test for normality. By plotting the residuals, e_i, against the respective x_i, an informal check on the assumption of constant variance is possible as well. In such a plot, residuals should vary approximately equally over the range of x_i values.

The analysis of variance table for testing lack of fit and significance of a linear regression is shown below. In this table, n represents the total number of data points for which x and y are available, k represents the number of distinct x values. Formulas for calculating the terms provided in the table are described below.

Source of Variation	Degrees of Freedom Linear	 Quadratic	Sum of Squares, SS	Mean Squares, MS	F_{calc}
Regression	1	2	SSR	MSR	F_1
Error	n-2	n-3	SSE	MSE	
Lack of Fit	k-2	k-3	SSLF	MSLF	F_2
Pure Error	n-k	n-k	SSPE	MSPE	
Total	n-1	n-1	SST		

The sums of squares (SS terms) for the Regression, Error, and Total lines of the analysis of variance table are calculated using the following:

$$SSR = \sum (\hat{y}_i - \bar{y})^2$$
$$SST = \sum (y_i - \bar{y})^2$$
$$SSE = \sum (y_i - \hat{y}_i)^2$$

To calculate the sums of squares for lack of fit (SSLF) and pure error (SSPE) requires a relabeling of the data, ordered by x value. To this point, the measured values y_i have been arbitrarily ordered. For these calculations, let Y_{uj} represent the jth data value at the uth x level, and let n_u represent the number of data values at the uth x level. Let

$$\overline{Y}_u = \sum_{j=1}^{n_u} Y_{uj} / n_u$$

Also, let

$$\hat{Y}_{uj} = \hat{y}_i,$$

or the predicted y value corresponding to the x value paired with Y_{uj}. (Notice that

$$\hat{Y}_{u1} = \hat{Y}_{u2} = \hat{Y}_{u3} = \cdots = \hat{Y}_{un},$$

because each of these y values have the same x value paired with it.)

Then

$$\text{SSLF} = \sum_{u=1}^{k} \sum_{j=1}^{n_u} \left(\overline{Y}_u - \hat{Y}_{uj}\right)^2,$$

and

$$\text{SSPE} = \text{SSE} - \text{SSLF}.$$

The sums of squares are then divided by their respective degrees of freedom to compute mean squares follows:

Mean Square	Linear Regression	Quadratic Regression
MSR	SSR	SSR/2
MSE	SSE/(n-2)	SSE/(n-3)
MSLF	SSLF/(k-2)	SSLF/(k-3)
MSPE	SSPE/(n-k)	SSPE/(n-k)

These mean squares are used to compute two F statistics which test for lack of fit and significance of regression. (Note: If the requirements described at the beginning of this section are not satisfied, then it is not possible to test for lack of fit.)

The two F statistics, F_1 and F_2, are defined as ratios of the mean squares as specified below:

$$F_1 = \text{MSR/MSE}$$

$$F_2 = \text{MSLF/MSPE}.$$

F_2 and Table 9.10.2 are used to test for lack of fit. If F_2 is greater than the 95th percentile of the F distribution with k – 2 numerator degrees of freedom (k – 3 for quadratic regression) and n – k denominator degrees of freedom (from Table 9.10.2), then there is significant lack of fit. In this case it may be concluded (with a 5 percent risk of error) that linear regression does not adequately describe the relationship between x and y. Otherwise, lack of fit can be considered insignificant and the chosen model can be assumed.

If lack of fit is not significant, the significance of regression may be tested using F_1 and Table 9.10.2. If F_1 is greater than the 95th percentile of the F distribution with 1 numerator degree of freedom (2 for quadratic regression) and n – 2 denominator degrees of freedom (n – 3 for quadratic regression), then regression is significant and the selected model may be assumed. Otherwise, regression is not significant and x is considered to have little or no predictive value for y.

9.5.2.4 *Testing for Equality of Several Regressions* — The procedure presented in this section is designed to test the hypothesis that the true regression equations corresponding to two or more independent data sets are equal (linear or quadratic). It is appropriately applied to test the equality of several regressions in determining whether corresponding data sets should be combined for the purpose of calculating design allowables. To test k regressions for equality, the following procedure should be performed.

Perform separate regression analyses for each data set. The same model form should be used in all regressions (all linear or all quadratic). Add error sum of squares (SSE) values from each of the separate regressions to obtain SSE(F), the error sum of squares for the full model which allows separate slope and intercept parameters for each data set. Then fit a single regression to the combined data from all data sets to obtain SSE(R), error sum of squares for the reduced model which contains a single set of coefficients a and b (and c for quadratic models) which apply to all data sets. The F statistic for testing the equality of the k regressions is

$$F = \frac{SSE(R) - SSE(F)}{2(k - 1)} \div \frac{SSE(F)}{n - 2k}$$

for simple linear models, and

$$F = \frac{SSE(R) - SSE(F)}{3(k - 1)} \div \frac{SSE(F)}{n - 3k}$$

for quadratic models, where n denotes total number of observations in all k data sets combined. In the linear case, if F is greater than the 95th percentile of the F distribution with 2(k - 1) numerator degrees of freedom and n - 2k denominator degrees of freedom (from Table 9.10.2), the hypothesis that the regressions are equal is rejected. In the quadratic case, if F is greater than the 95th percentile of the F distribution with 3(k - 1) numerator degrees of freedom, and n - 3k denominator degrees of freedom, the hypothesis that the regressions are equal is rejected. See Reference 9.5.2.4 for more detail.

Example of Computations — In this example, x represents thickness and y represents the TYS values determined from a group of tensile tests. Values of x and y are as follows:

X	Y
0.100	121
0.100	119
0.200	114
0.200	108
0.300	112
0.300	108
0.400	112
0.400	106
0.500	101
0.500	99

From these data, the following quantities may be calculated:

$n = 10$
$\Sigma x = 3$
$\Sigma y = 1100.0$
$\Sigma x^2 = 1.1$
$\Sigma y^2 = 121452$
$\Sigma xy = 321.6$
$(\Sigma x)^2 = 9$
$(\Sigma y)^2 = 121000$
$(\Sigma x)(\Sigma y) = 3300$
$S_{xx} = 0.20$
$S_{xy} = -8.4$
$S_{yy} = 452.$

The slope of the regression line is:

$$b = \frac{S_{xy}}{S_{xx}} = \frac{-8.4}{0.20} = -42 \quad .$$

The y-intercept of the regression line is:

$$a = \frac{\Sigma y - b\Sigma x}{n} = \frac{1100}{10} - \frac{(-42)(3)}{10} = 110 + 12.6 = 122.6 \quad .$$

Thus the final equation of the least squares regression line is:

$$\hat{y} = a + b\,x = 122.6 - 42x \quad .$$

The total of the y data at each x level is needed to calculate lack of fit and pure error sums of squares. These totals are as follows:

x_i	T_i
0.1	240
0.2	222
0.3	220
0.4	218
0.5	200

There are data values at $k = 5$ different x levels, with $n_i = 2$ values at each level and

$$\sum_{i=1}^{k} (T_i^2/n_i) = \frac{(240)^2}{2} + \ldots + \frac{(200)^2}{2} = 121404 \quad .$$

Thus,

$$SSLF = 121404 - (1100)^2/10 - 352.8 = 51.2$$

and

$$SSPE = 99.2 - 51.2 = 48.$$

The mean square values are computed by dividing corresponding sums of squares by their degrees of freedom. The F_1 and F_2 statistics are then calculated as ratios of mean squares. The analysis of variance table is shown below.

Source of Variation	Degree of Freedom, DF	Sum of Square, SS	Mean Squares, MS	F_{calc}
Regression	1	352.8	352.8	$F_1 = 28.5$
Error	8	99.2	12.4	
Lack of Fit	3	51.2	17.07	$F_2 = 1.78$
Pure Error	5	48.0	9.6	
Total	9	452.0		

Using this equation, the following values of ŷ may be computed for the values of x listed previously.

x	ŷ
0.100	118.4
0.200	114.2
0.300	110.0
0.400	105.8
0.500	101.6

The root mean square error is computed as follows:

$$S_y = \sqrt{\frac{\Sigma(y - \hat{y})^2}{n - 2}} = \sqrt{\frac{99.2}{8}}$$

or

$$S_y = \sqrt{\frac{S_{yy} - b^2 S_{xx}}{n - 2}} = \sqrt{\frac{452 - (-42)^2(0.2)}{8}} = 3.52 \quad .$$

R^2 is computed as follows:

$$R^2 = \frac{b^2 S_{xx}}{S_{yy}} = \frac{(-42)^2(0.2)}{452} = 0.78$$

Thus, 78 percent of the variability in the y data about its average is explained by the linear relationship between y and x.

The sum of squares for the regression, total and error lines are computed as follows:

$$SSR = (-42)^2 (0.20) = 352.8$$
$$SST = 452$$
$$SSE = 452 - 352.8 = 99.2.$$

The F_2 value of 1.78 with $k - 2 = 3$ and $n - k = 5$ degrees of freedom is less than the value of 5.41 from Table 9.6.4.9 corresponding to 3 numerator and 5 denominator degrees of freedom. This indicates that lack of fit can be considered insignificant. Thus, it is reasonable to assume that a linear regression adequately describes the data. The F_1 value of 28.5 with 1 and $n - 2 = 8$ degrees of freedom is greater than the value of 5.32 from Table 9.10.2 corresponding to 1 numerator and 8 denominator degrees of freedom, so the slope of the regression is found to be significantly different from zero.

9.5.3 Combinability of Data — A test of significance is employed to make a decision on a statistical basis. In this section, three tests (k-sample Anderson-Darling test, “F” test, and “t” test) are described for use in determining whether the populations from which two or more samples are drawn are identical. The k-sample Anderson-Darling test is the most general and does not depend on a specific assumed distribution, and may be used to evaluate combinability of two or more data sets.

The “F” and “t” tests should only be used to evaluate combinability of two samples that can be assumed to be normally distributed. The “F” test is used first to determine whether the two sample variances differ significantly or not (with a 5 percent risk of error). If the two sample variances do not differ significantly, the “t” test is used to determine whether the two sample means differ significantly. If either the two sample variances or the two sample means differ significantly (with a 5 percent risk of error), one may conclude (with a 9.75 percent joint risk of error) that the populations from which the two samples were drawn are not identical. Otherwise, the hypothesis that the two populations are identical is not rejected. The tests given are exact when:

(1) The observations within each sample are taken randomly from a single population of possible observations, and

(2) The characteristic measured is normally distributed within this population.

To carry out a similar procedure without requiring the assumption of an underlying normal distribution, or if three or more samples are to be compared, the k-sample Anderson-Darling test should be employed. This test is a nonparametric procedure and simply tests the hypothesis that populations from which the samples are drawn are identical.

9.5.3.1 *The k-Sample Anderson-Darling Test* — The k-sample Anderson-Darling test is designed to test the hypothesis that populations from which two or more independent random samples were drawn are identical. The test is appropriately applied to determine whether two or more products differ with regard to strength distributions. The test is a nonparametric statistical procedure and, thus, requires no assumptions other than the samples are true independent random samples from their respective populations.

Consider the products $A_1, A_2, ..., A_k$. Let $X_{11}, X_{12}, ..., X_{1n_1}$, denote a sample of n_1 data points from product A_1, let $X_{21}, X_{22}, ..., X_{2n_2}$ denote a sample of the n_2 data points from product A_2, and so forth. Furthermore, let $N = n_1 + n_2 + ... + n_k$ represent the total number of data points in the combined samples.

Let L denote the total number of distinct data points in the combined samples and $Z_{(1)}, Z_{(2)}, ..., Z_{(L)}$ denote the distinct values in the combined data set ordered from least to greatest. The k-sample Anderson-Darling statistic is defined by

$$\mathrm{ADK} = \frac{N-1}{N^2(k-1)} \sum_{i=1}^{k} \left[\frac{1}{n_i} \sum_{j=1}^{L} h_j \frac{(NF_{ij} - n_i H_j)^2}{H_j(N - H_j) - Nh_j/4} \right]$$

where

h_j = the number of values in the combined samples equal to $Z_{(j)}$

H_j = the number of values in the combined samples less than $Z_{(j)}$ plus one-half the number of values in the combined samples equal to $Z_{(j)}$

and

F_{ij} = the number of values in sample corresponding to product A_i which are less than $Z_{(j)}$ plus one-half the number of values in the sample corresponding to product A_i which are equal to $Z_{(j)}$.

Under the hypothesis of no differences in the sampled populations, the mean of ADK is approximately one and the variance is approximately

$$\sigma_N^2 = \mathrm{Var(ADK)} = \frac{aN^3 + bN^2 + cN + d}{(k-1)^2 (N-1)(N-2)(N-3)}$$

with

$a = (4g - 6)(k - 1) + (10 - 6g)S$

$b = (2g - 4)k^2 + 8Tk + (2g - 14T - 4)S - 8T + 4g - 6$

$c = (6T + 2g - 2)k^2 + (4T - 4g + 6)k + (2T - 6)S + 4T$

$d = (2T + 6)k^2 - 4Tk$

where

$$S = \sum_{i=1}^{k} \frac{1}{n_i}$$

$$T = \sum_{i=1}^{N-1} \frac{1}{i}$$

and

$$g = \sum_{i=1}^{N-2} \sum_{j=i+1}^{N-1} \frac{1}{(N-i)j}$$

If

$$ADK \geq 1 + \sigma_N \left[1.645 + \frac{0.678}{\sqrt{k - 1}} - \frac{0.362}{k - 1} \right]$$

one may conclude (with a 5 percent risk error) that samples were drawn from different populations. Otherwise, the hypothesis that samples were selected from identical populations is not rejected. For more information on the k-sample Anderson-Darling test, see Reference 9.5.3.1.

9.5.3.2 ***The F Test*** — The F test is used to determine whether the strength of two products differs with regard to variability.

Consider two products, A and B. These might represent two different processes, thickness ranges, or test directions. The statistics for the samples drawn from these products are:

	Product A	Product B
Sample size	n_A	n_B
Sample standard deviation	s_A	s_B
Sample mean	X_A	X_B

F is the ratio of the two sample variances, thus,

$$F = s_A^2/s_B^2 \qquad [9.5.3.2]$$

If the true variances of Products A and B are identical at a significance level of $\alpha = 0.05$, F should lie within the interval defined by

$F_{0.975}$ (for n_A - 1 and n_B - 1 degrees of freedom),

and

$1/F_{0.975}$ (for n_B - 1 and n_A - 1 degrees for freedom).*

If F does not lie within this interval, it can be concluded that the two products differ with regard to their variability. Values of $F_{0.975}$ are presented in Table 9.10.3.

** Since a two-sided interval is being defined for the population variance, the fractile of the F distribution corresponding to I-α/2 should be used, i.e., $F_{0.975}$.

Example of Test Computation — The following sample statistics are reported:

	Product A	Product B
Sample size	20	30
Sample standard deviation, ksi	4.0	5.0
Sample mean, ksi	100.0	102.0

Perform an F test as follows:

$$F = s_A{}^2/s_B{}^2 = 4^2/5^2 = 0.64$$

$$df = n_A - 1 = 19$$

$$n_B - 1 = 29$$

$$\left.\begin{array}{l} F_{0.975\ (19,29)} = 2.23 \\ 1/F_{0.975\ (29,19)} = 1/2.40 = 0.42 \end{array}\right\} \quad \text{From Table 9.10.3}$$

Since 0.64 lies within the interval of 0.42 to 2.23 one can conclude that there is no reason to believe that Products A and B differ with regard to their variability.

9.5.3.3 ***The t Test*** — The t test is used to determine whether two products differ with regard to average strength. If they do, one may conclude that the two products do not belong to the same population.

In making the t test, it is assumed that the variances of two products are nearly equal, as first determined from the F test. If the F test shows that the variances are significantly different, there is no need to conduct the t test.

Consider the same products, A and B. The statistics for samples drawn from these products are:

	Product A	Product B
Sample size	n_A	n_B
Sample standard deviation, ksi	s_A	s_B
Sample mean, ksi	$\overline{X}_A$	$\overline{X}_B$

$D_{\bar{x}}$ is the absolute difference between the two sample means.

$$D_{\overline{X}} = \left| \overline{X}_A - \overline{X}_B \right| \qquad [9.5.3.3(a)]$$

If the true means of products A and B are identical, $D_{\bar{x}}$ should not exceed u, which is determined as indicated by the following equation for a significance level of $\alpha = 0.05$.

$$u = t_{0.975} s_p \sqrt{\frac{n_A + n_B}{n_A n_B}} \qquad [9.5.3.3(b)]$$

where

$t_{0.975}$ has $n_A + n_B - 2$ degrees of freedom*

and

$$s_p = \sqrt{\frac{(n_A - 1)s_A^2 + (n_B - 1)s_B^2}{n_A + n_B - 2}} \qquad [9.5.3.3(c)]$$

Values of $t_{0.975}$ are found in Table 9.10.4.

Example of Test Computation — The following sample statistics are the same as those in Section 9.5.3.2:

	Product A	Product B
Sample size	20	30
Sample standard deviation, ksi	4.0	5.0
Sample mean, ksi	100.0	102.0

It was determined in Section 9.5.3.2 that the variances of Products A and B do not differ significantly. The t test computations to test the sample means are:

$$df = n_A + n_B - 2 = 48$$

$t_{0.975}$ (for 48 df) = 2.011 (from Table 9.10.4)

$$s_p = \sqrt{\frac{(n_A - 1)s_A^2 + (n_B - 1)s_B^2}{n_A + n_B - 2}} = \sqrt{\frac{(19)(4)^2 + (29)(5)^2}{48}} = 4.63 \text{ ksi}$$

$$\sqrt{\frac{n_A + n_B}{n_A n_B}} = \sqrt{\frac{20 + 30}{(20)(30)}} = 0.2887$$

$$u = t_{0.975} s_p \sqrt{\frac{n_A + n_B}{n_A n_B}} = (2.011)(4.63)(0.2887) = 2.7 \text{ ksi}$$

$$D_{\bar{x}} = |\bar{X}_A - \bar{X}_B| = 2.0 \text{ ksi}$$

Since $D_{\bar{x}}$ (2.0) is not greater than u (2.7), it may be concluded that there is no reason to believe that Products A and B differ with regard to their average strength. On the basis of both tests in this example, the conclusion would be that the two products were drawn from the same population.

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* Since a two-sided interval is being defined from the population means, the fractile of the t distribution corresponding to $1-\alpha/2$ should be used, i.e., $t_{0.975}$.

9.5.4 Determining the Form of Distribution — The computational procedure selected to establish design-allowable values by statistical techniques is dependent upon distribution of strength measurements in the available sample. Both three-parameter Weibull and Pearson Type III distributions may be used. Some procedures in the Handbook still require that residuals from a model be normally distributed (such as determination of design allowables by regression analysis). As noted previously, references to normal, Weibull, or Pearson Type III distributions will be interpreted as applying either to original measurements or to an appropriate transformation of them. This section contains a discussion and illustration of methods used to establish whether or not a population follows a normal, Weibull, or Pearson Type III distribution.

Various goodness-of-fit test procedures are described in Sections 9.5.4.1 through 9.5.4.9. The purpose of each is to indicate whether an initial distribution assumption should be rejected. The methods presented are based on the "AndersonDarling" goodness-of-fit family of tests. These tests are objective and indicate (at 5 percent risk of error) whether the sample is drawn from the tested distribution. Unfortunately, these tests may reject the assumed distribution even though the distribution may provide a reasonable approximation within the lower tail. For this reason, the sequential Weibull procedure permits upper tail censoring when found to be appropriate, and the goodness-of-fit test described below allows for this. Nonetheless, some subjective reasoning should be employed after using a goodness-of-fit test.

After a goodness-of-fit test has been performed (especially if the distributional assumption has been rejected), it is generally required that a cumulative probability plot of data be provided to graphically illustrate the degree to which the assumed distribution fits the data. Methods for development of normal probability plots (Section 9.5.4.2), Pearson probability plots (Section 9.5.4.6), and Weibull probability plots (Section 9.5.4.9) are presented.

Sample size is denoted by n, sample observations by $X_1, ..., X_n$, and sample observations ordered from least to greatest by $X_{(1)}, ..., X_{(n)}$. Data must be ungrouped.

9.5.4.1 "Anderson-Darling" Test for Normality — The "Anderson-Darling" test for normality is used to determine whether the curve which fits a given set of data can be approximated by a normal curve. The essence of the test is a numerical comparison of the cumulative distribution function for observed data with that for the fitted normal curve over the entire range of the property being measured. Let

$$Z_{(i)} = \left(X_{(i)} - \overline{X}\right)/s \quad i = 1,...,n$$

where $X_{(i)}$ is the i^{th} smallest sample observation, $\overline{X}$ is the sample average, and s is the sample standard deviation. Equations for computing sample statistics are presented in Appendix A.

The "Anderson-Darling" test statistic is

$$AD = \left[\sum_{i=1}^{n} \frac{1-2i}{n}\left[\ln\left(F_o\left(Z_{(i)}\right)\right) + \ln\left(1 - F_o\left(Z_{(n+1-i)}\right)\right)\right]\right] - n$$

where F_o is the standard normal distribution function*. If

$$AD > 0.752/\left(1 + 0.75/n + 2.25/n^2\right)$$

---

* The standard normal distribution function F_o is that function such that $F_o(x)$ is equal to the area under the standard normal curve to the left of the value x.

one may conclude (at 5 percent risk of error) that the population from which the sample was drawn is not normally distributed. Otherwise, the hypothesis that the population is normally distributed is not rejected. For further information on this test procedure, see References 9.5.4.1(a) and (b).

The same procedure can be used to test the normality of the residuals

$$e_i = y_i - (a + bx_i) \quad i = 1,...,n$$

from a regression (see Section 9.5.2.1) assuming uniformity of variance of the residuals over the range of the independent variable. When calculating the test statistic AD, define

$$Z_{(i)} = e_{(i)}/s_y \quad i = 1,...,n$$

where $e_{(i)}$, i = 1,...,n are the ordered residuals from smallest to largest and s_y is the root mean square error of the regression defined in Section 9.5.5.1 or 9.5.5.2. The justification for this procedure may be found in Reference 9.5.4.1(c).

9.5.4.2 *Normal Probability Plot* —To graphically illustrate the degree to which a normal distribution fits a set of data, a normal probability plot may be formed by plotting the measured value of each test point versus $\overline{X} + s\,F_o^{-1}(P/100)$ where F_o^{-1} is the inverse standard normal cumulative distribution function.* The line representing the fitted normal distribution is the line passing through the points with equal horizontal and vertical coordinates. If the horizontal axis is labeled with cumulative probabilities (P values) as in Table 9.10.5 rather than $F_o^{-1}(P/100)$ values, the plot will be identical to a plot formed on normal probability paper.

Figure 9.5.4.2 illustrates the use of a normal probability plot on Alclad 2524-T3 Aluminum Alloy Sheet and Plate data in the 0.063-0.128 inch thickness range. There are 309 measured test values with $\overline{X}$ = 45.24 and s = 1.923. There appears to be a systematic departure from the model (the measured values are higher than expected) in both tails, suggesting that the distribution of the measured values departs from a normal distribution. This model was rejected by the Anderson-Darling test for normality.

9.5.4.3 *Three-Parameter Weibull Acceptability Test* — The three-parameter Weibull acceptability test is designed to determine whether an acceptable proportion of a producer's population is likely to exceed the specification limit for corresponding material property. Because this test is only used to screen data sets and is not used in the actual calculation of lower tolerance bounds, it is not required that the data be well-described by a Weibull distribution to apply this test. To carry out this test, an upper confidence bound (UCB) is calculated for the first percentile of the producer's population. This UCB value is calculated in the same manner as a T_{99} value is calculated (in Section 9.5.5.2) with the following modifications:

(1) In solving for the threshold $\tau(\theta)$ (Section 9.5.5.2.1), θ should be set equal to 0.10.

(2) The value of V_{99} should be taken from Table 9.10.6 rather than Table 9.10.7 when using the formula for T_{99} (Equation [9.5.5.2(a)]) to calculate the UCB value.

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* The point $F_o^{-1}(P/100)$ is that value such that the area under the standard normal curve to the left of $F_o^{-1}(P/100)$ is P/100.

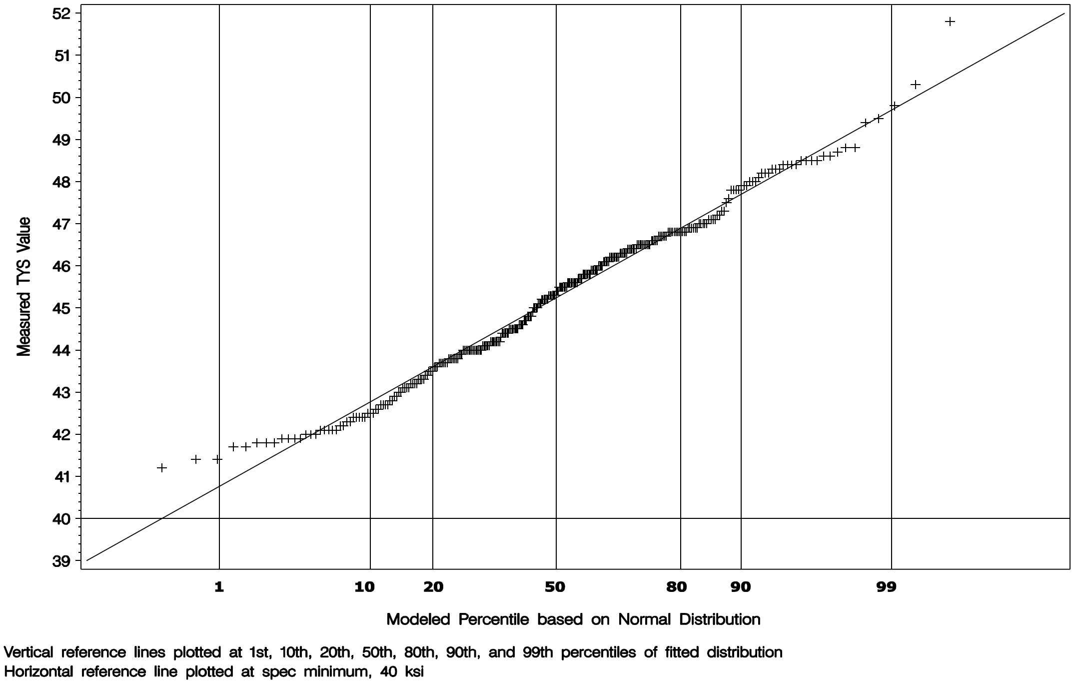


Figure 9.5.4.2 Probability plot for a normal distribution fitted to a complete TYS data set for Alclad 2524-T3 aluminum alloy sheet in the 0.063-0.128 inch thickness range - rejected.

If UCB is greater than or equal to the specification limit, it is concluded that the producer's data is acceptable. If UCB is less than the specification limit, it is concluded (with a 5 percent risk of error) that the producer's data do not meet the specification minimum value.

In statistical terms, this method tests (at 5 percent significance level) the hypothesis that at least 99 percent of the producer's population is greater than the specification limit. If the hypothesis is not rejected (UCB greater than or equal to specification limit), then it is concluded that the producer's data is acceptable. If the hypothesis is rejected (UCB less than the specification limit), it is concluded that the producer's data is unacceptable.

This technique is applicable only when data have not been censored from the sample. It also assumes that the data are distributed according to a three-parameter Weibull distribution (although normally distributed data and Pearson distributed data are also accommodated by this test). If the data sample is highly skewed, background data should be reviewed to determine whether the skewness is caused by a mixed population. If it is not, the Weibull test procedure can be applied. This test should be applied to both tensile yield and ultimate strengths (in appropriate grain directions), and if a producer's data is unacceptable for either property, that producer's data for both properties should be excluded for the purpose of computing T_{99} and T_{90} values.

9.5.4.4 ***Anderson-Darling Test for Pearsonality*** – This section describes a test to determine whether data from a population are satisfactorily described by the Pearson Type III (or gamma) distribution.

First compute estimates of the population mean, standard deviation, and skewness (denoted by $\overline{X}$, S, and q), as described in Section 9.5.5.1. Then calculate the following Anderson-Darling statistic:

$$\mathrm{AD} = -\sum_{i=1}^{n}\left[\frac{(2i-1)}{n}\ln\left(F_{\bar{X},S,q}(X_{(i)})\right) - 2F_{\bar{X},S,q}(X_{(i)})\right] - \frac{3n}{2}$$

where

$$F_{\mu,\sigma,q}(x) = \begin{cases} H\left[\dfrac{4}{q}\left(\dfrac{2}{q}+\dfrac{x-\mu}{\sigma}\right)\right] & q > 0.1265 \\[2ex] 1 - H\left[\dfrac{4}{q}\left(\dfrac{2}{q}+\dfrac{x-\mu}{\sigma}\right)\right] & q < -0.1265 \\[2ex] \Phi\left\{\left[\sqrt[3]{\dfrac{\frac{4}{q}\left(\frac{2}{q}+\frac{x-\mu}{\sigma}\right)}{\frac{8}{q^2}}} - 1 + \dfrac{2}{9\cdot\frac{8}{q^2}}\right] \Bigg/ \sqrt{\dfrac{2}{9\cdot\frac{8}{q^2}}}\right\} & 0.025 < q \le 0.1265 \\[2ex] 1 - \Phi\left\{\left[\sqrt[3]{\dfrac{\frac{4}{q}\left(\frac{2}{q}+\frac{x-\mu}{\sigma}\right)}{\frac{8}{q^2}}} - 1 + \dfrac{2}{9\cdot\frac{8}{q^2}}\right] \Bigg/ \sqrt{\dfrac{2}{9\cdot\frac{8}{q^2}}}\right\} & -0.1265 \le q < 0.025 \\[2ex] \Phi\left(\dfrac{x-\mu}{\sigma}\right) & |q| \le 0.025 \end{cases}$$

H(x) is the cumulative distribution function of a chi-square distribution with $8/q^2$ degrees of freedom. Note that F(x) is the cumulative distribution function of a chi-square distribution with $8/q^2$ degrees of freedom when $q > 0.1265$, and a standard normal distribution when $|q| \le 0.025$. Because of numerical computing inconsistencies for large degrees of freedom, a normal approximation to the chi-square distribution is recommended for $0.025 < |q| \le 0.1265$.

If the *AD* is greater than the critical value of

$$0.3167 + 0.034454 \cdot \ln(n) \cdot \left[\exp(q) - 1\right]^2,$$

then the data are rejected by the Anderson-Darling test for Pearsonality.

9.5.4.5 *The Pearson Backoff Option* – If the data are rejected by the Pearson AD test, the backoff method may be applied. The following formula should be used to calculate the AD statistic of the backoff method:

$$\mathrm{AD}_{\mathrm{backoff}}(\mu) = \frac{1}{n}\sum_{i=1}^{n} i^2\left[\ln\left(b_{i+1,i}\right) - \ln\left(b_{i,i}\right)\right] - 2\sum_{i=1}^{n} i\left(b_{i+1,i} - b_{i,i}\right) + \frac{n}{2}\sum_{i=1}^{n}\left(b_{i+1,i}{}^2 - b_{i,i}{}^2\right)$$

where

$$b_{i,j} = \min\left[F_{\mu,S,q}(x_{(i)}),\ \frac{j}{n}\right] \text{ for } j<n,\ b_{n,n} = F_{\mu,S,q}(x_{(n)}) \text{ , and } b_{n+1,n}=1.$$

(Notice that this formula has an argument representing the assumed mean of the distribution being tested against.)

Calculate $AD_{backoff}(\overline{X} - \tau)$ for τ equal to 0.1, 0.2, 0.3, 0.4, and 0.5. If any of these values is below the critical value of

$$0.03238 + 0.00001795 \cdot \ln(n)^2 \cdot \left[\exp(q) + 0.2355\right]^2 ,$$

then $\tau_{backoff}$, is defined as the smallest of these τ's satisfying the inequality. (Note: In calculating the backoff, if q is negative and $\tau_{backoff} > \overline{X} - 2 \cdot S/Q - X_{(n)}$, then the backoff method cannot be applied. S and Q are defined in Section 9.5.5.1.)

If a backoff is identified, then T_{99} and T_{90} should be calculated by the following formulas:

$$T_{99} = \overline{X} - k_{99}(q,n) \cdot S - \tau_{backoff}$$

$$T_{90} = \overline{X} - k_{90}(q,n) \cdot S - \tau_{backoff}$$

where k_{90}(q,n) and k_{99}(q,n) are defined in Section 9.5.5.1.

9.5.4.6 Pearson Probability Plot — To graphically illustrate the degree to which a Pearson Type III (or gamma) distribution fits a set of data, the following procedure for creation of a Pearson probability plot is recommended. This method is appropriate for distributions estimated using uncensored data.

The rank of each point selected for plotting is the number of lower test points plus the plotted point plus one-half the number of other test points equal to the plotted point. Its cumulative probability, P (in percent), is equal to the rank multiplied by 100, divided by one more than the total number of test points:

$$\text{P (in percent)} = \frac{(\text{rank})(100)}{n + 1}$$

The measured value of each test point is plotted versus F^{-1} (P/100) where

$$F^{-1}(P/100) = \begin{cases} \overline{X} + s \cdot \left[\dfrac{q}{4} \cdot H^{-1}(P/100) - \dfrac{2}{q} \right] & \text{when} \quad q > 0.1265 \\[2ex] \overline{X} + s \cdot \left[\dfrac{q}{4} \cdot H^{-1}\left[1 - (P/100)\right] - \dfrac{2}{q} \right] & \text{when} \quad q < -0.1265 \\[2ex] \overline{X} + s \cdot \dfrac{2}{q} \cdot \left\{ \left[\sqrt{\dfrac{2}{9 \cdot \dfrac{8}{q^2}}} \cdot F_o^{-1}(P/100) + 1 - \dfrac{2}{9 \cdot \dfrac{8}{q^2}} \right]^3 - 1 \right\} & 0.025 < q \le 0.1265 \\[2ex] \overline{X} + s \cdot \dfrac{2}{q} \cdot \left\{ \left[\sqrt{\dfrac{2}{9 \cdot \dfrac{8}{q^2}}} \cdot F_o^{-1}(1 - P/100) + 1 - \dfrac{2}{9 \cdot \dfrac{8}{q^2}} \right]^3 - 1 \right\} & -0.1265 \le q < -0.025 \\[2ex] \overline{X} + s \cdot F_o^{-1}(P/100) & |q| \le 0.025 \end{cases}$$

and $\overline{X}$, s, and q are population parameter estimates obtained according to the procedures outlined in Section 9.5.5.1. H^{-1} is the cumulative distribution function of a chi-square distribution with $8/q^2$ degrees of freedom and F_o^{-1} is the inverse standard normal cumulative distribution function. A straight line is then drawn to represent the fitted Pearson distribution. This line may be established by plotting any two points with equal vertical and horizontal coordinates and drawing a line through these two points. The horizontal axis is then labeled with cumulative probabilities (P or P/100) rather than F^{-1} values.

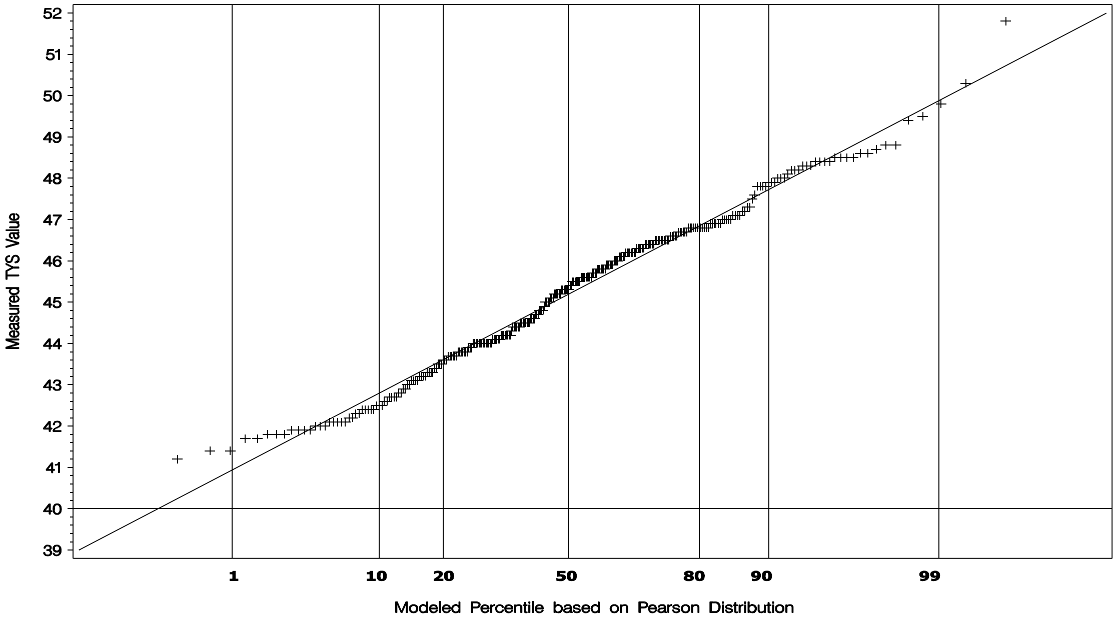
If the backoff option is used, the selected distribution can then be described as the best-fit distribution shifted by a small constant, $\tau_{backoff}$. In this case, the predicted values should also be shifted by the same constant. That is, plot the measured values versus

$$F^{-1}(P/100) - \tau_{backoff} \quad .$$

The plotted points should finally be compared with the line to determine whether there appears to be a reasonably good fit. If the backoff option is used, then only deviations where the data fall below the fitted line should be considered as relevant.

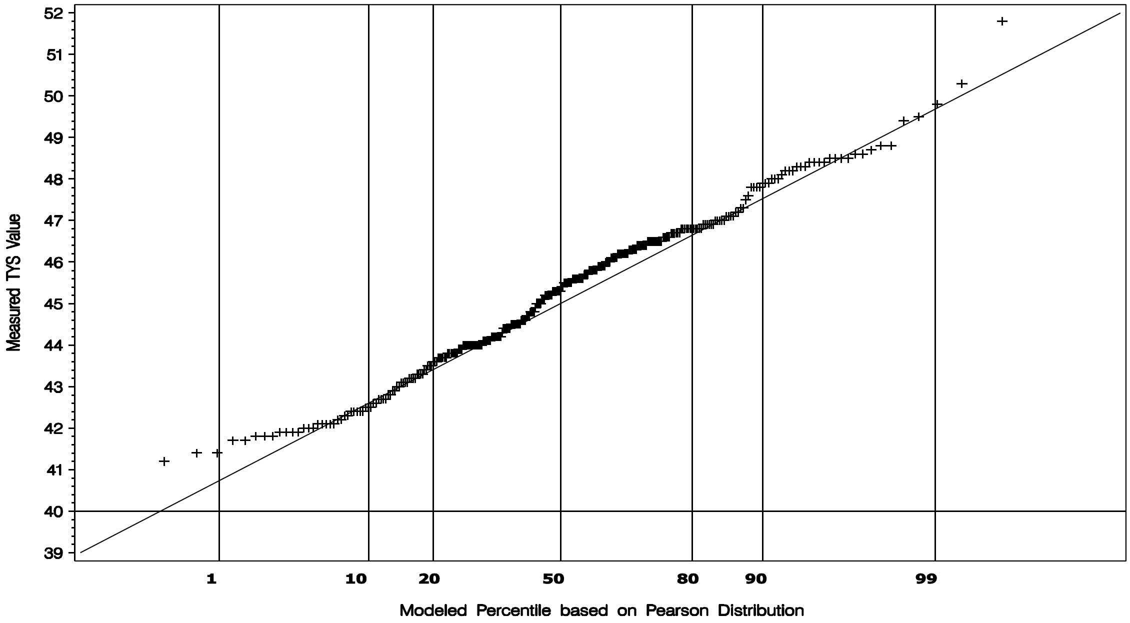
Figure 9.5.4.6(a) illustrates the use of a Pearson probability plot on Aluminum Alloy Sheet and Plate data in the 0.063-0.128 inch thickness range. The estimates of the mean, standard deviation, and skewness parameters are 45.24, 1.92, and 0.12, respectively. There appears to be a systematic departure from the model (the measured values are higher than expected) in both tails, suggesting that the distribution of the measured values is not well approximated by a Pearson distribution. Appropriately, this model was rejected by the A-D test for Pearsonality.

Figure 9.5.4.6(b) shows a probability plot for the same data, using the distribution estimated with the backoff option of the sequential Pearson procedure, which identified a backoff of 0.2 ksi. The only difference between the two plots is that the predicted values in Figure 9.5.4.6(a) are shifted 0.2 ksi to the left in Figure 9.5.4.6(b). Although the curve of data in Figure 9.5.4.6(b) is further away (on average) from the y=x reference line than the curve of data in Figure 9.5.4.6(a), only negative deviations from the reference line are recognized in the A-D goodness-of-fit test for a distribution estimated by the backoff method. In



Vertical reference lines plotted at 1st, 10th, 20th, 50th, 80th, 90th, and 99th percentiles of fitted distribution
Horizontal reference line plotted at spec minimum, 40 ksi

Figure 9.5.4.6(a). Probability plot for a Pearson distribution fitted to a complete TYS data set for Alcad 2524-T3 aluminum alloy sheet in the 0.063-0.128 inch thickness range - rejected.



Vertical reference lines plotted at 1st, 10th, 20th, 50th, 80th, 90th, and 99th percentiles of fitted distribution
Horizontal reference line plotted at spec minimum, 40 ksi

Figure 9.5.4.6(b). Probability plot for a Pearson distribution fitted to complete TYS data for Alcad 2524-T3 aluminum alloy plate in the 0.063-0.128 inch thickness range using 0.2 ksi backoff - accepted.

Figure 9.5.4.6(b), only a small proportion of the data are below the predicted values, resulting in an insignificant deviation. The "backoff" model was accepted by the A-D test.

9.5.4.7 *Modified "Anderson-Darling" Test for Weibullness* — The "Anderson-Darling" test for three-parameter Weibullness is used to determine whether the curve which fits a given set of data can be approximated by a three-parameter Weibull curve. The essence of the test is a numerical comparison of the cumulative distribution function for observed data with that for a fitted Weibull curve over the entire range of property being measured. This test differs from the original version of the Anderson-Darling test in that it emphasizes the lower tail. This method can be applied with complete or censored data.

The first two steps produce estimates of the parameters of a three-parameter Weibull distribution. Be sure to acknowledge the appropriate degree of censoring in computing the threshold, shape, and scale parameters as described in Sections 9.5.4.7.1 and 9.5.4.7.2. Using the procedure outlined in 9.5.4.7.1, compute the threshold for the goodness-of-fit test, τ_{50}. Then, using the method described in 9.5.4.7.2, compute the maximum likelihood estimates of the shape and scale parameters for $\{X_{(i)} - \tau_{50} : i=1,...,r\}$ where r equals n for the uncensored data and r represents the smallest integer greater than or equal to 4n/5 for 20 percent censoring and n/2 for 50 percent censoring. Denote these estimates by β_{50} and α_{50}, respectively. Calculate the (censored or uncensored) A-D statistic is described in Section 9.5.4.7.3.

9.5.4.7.1 *Estimating the Threshold Parameter* — This section describes a method for estimating the threshold of a three-parameter Weibull distribution. The same approach is taken for estimating the threshold, whether the purpose is to test goodness-of-fit (Section 9.5.4.7), or to directly calculate T_{99} or T_{90} values (Section 9.5.5.2). This method applies to uncensored and upper-tail censored data; however, different columns of Table 9.10.8 are used. (References 9.5.4.7.1(a) and 9.5.4.7.1(b) provide details of this method for uncensored data.)

Let K equal the greatest integer less than or equal to min {4n/15, (1-p)n/3}, where p represents the proportion of the upper tail that is censored (p equals 0, 0.2, or 0.5). Define the function R(τ) by

$$R(\tau) = \sum_{i=K+1}^{3K-2} L_i(\tau) / \sum_{i=1}^{3K-2} L_i(\tau)$$

where

$$L_i(\tau) = \frac{1}{D_i}\left[\ln\left(X_{(i+1)} - \tau\right) - \ln\left(X_{(i)} - \tau\right)\right]$$

with

$$D_1 = n \ln\left(1 + \frac{1}{n-1}\right),$$

$$D_2 = \left(\frac{n(n-1)}{2}\right) \ln\left(1 + \frac{1}{n(n-2)}\right) ,$$

$$D_3 = \left(\frac{n(n-1)(n-2)}{6}\right) \ln\left(1 + \frac{2n - 3}{(n-1)^3\ (n-3)}\right) ,$$

$$D_4 = \left(\frac{n(n-1)(n-2)(n-3)}{24}\right) \ln\left(1 + \frac{6n^4 - 48n^3 + 140n^2 - 176n + 81}{n(n-4)\ (n-2)^6}\right) ,$$

and

$$D_i = \ln\left[-\ln\left(1 - \frac{i + 0.5}{n + 0.25}\right)\right] - \ln\left[-\ln\left(1 - \frac{i - 0.5}{n + 0.25}\right)\right]$$

for i=5,6,...,3K-2. Finally, let $\overline{X}$ and S represent the sample mean and sample standard deviation, respectively.

Determine γ using the appropriate column of Table 9.10.8. The first set of columns in Table 9.10.8 is provided for estimating the threshold, τ_{50}, associated with the Anderson-Darling goodness-of-fit test described here. The second and third sets of columns are provided for estimating τ_{99} and τ_{90}, which are needed to determine T_{99} and T_{90}, as described in Section 9.5.5.2. Each set of columns includes a column for uncensored data, 20 percent upper-tail censored data, and 50 percent upper-tail censored data.

The estimated threshold parameter, τ, is the solution to the equation $R(\tau) = \gamma$. The function $R(\tau)$ is a monotonically decreasing continuous function of τ. A simple method for finding the solution is as follows. Start with $L = \min(0, \overline{X} - 100S)$ and $H = 0.999999X_{(1)}$. If $R(L) \leq \gamma$, then set $\tau = L$ or if $R(H) \geq \gamma$ then set $\tau = H$. Otherwise reduce the (L,H) interval by calculating $M = (L+H)/2$ and setting $L = M$ if $R(M) \geq \gamma$ or by setting $H = M$ if $R(M) < \gamma$. If $H - L \leq 2\overline{X}/10^6$, then set $\tau = M$ and stop. Otherwise, reduce the (L,H) interval again.

9.5.4.7.2 *Estimating the Shape and Scale Parameters* — This section describes a method for estimation of the shape and scale parameters of the two-parameter Weibull distribution based on data which may be censored in the upper tail. Estimates of the shape and scale parameters are based on the original data corrected for the estimated threshold, τ. That is, the calculations in this section are performed based on $Z_{(1)}$, ..., $Z_{(n)}$, where $Z_{(i)} = X_{(i)} - \tau$, with τ estimated as in Section 9.5.4.7.1. The assumption is made here that if the data are censored, then only the r smallest observations in the sample are observed ($1 \leq r \leq n$), where r is some pre-specified number (often based on a percentage); this is called Type II censoring. Thus, the input to this procedure is a total sample size, n, a censored sample size, r, and the sample remaining after censoring $Z_{(1)}$, ..., $Z_{(r)}$. Define

$$g(\beta) = \frac{\sum_{i=1}^{r} Z_{(i)}^{\beta} \ln Z_{(i)} + (n-r)\, Z_{(r)}^{\beta} \ln Z_{(r)}}{\sum_{i=1}^{r} Z_{(i)}^{\beta} + (n-r)\, Z_{(r)}^{\beta}} - \frac{1}{\beta} - \frac{1}{r}\sum_{i=1}^{r} \ln Z_{(i)}$$

Note: When implementing the equation for $g(\beta)$ in software, it may be necessary to divide each Z term that is raised to the β power by a normalizing factor, C, in order to avoid computational difficulties. The factor, C, can be any type of average calculated from the Z values (e.g., geometric mean of the uncensored Z values). Because the C-factor algebraically cancels out of the equation for $g(\beta)$, its use does not change the meaning of the equation in any way.

The shape parameter estimate, β, is the solution to the equation $g(\beta) = 0$. The function $g(\beta)$ is a monotonically increasing continuous function of β. A simple method for finding the solution is as follows. Let S_y denote the standard deviation of Y_1, ..., Y_r where $Y_i = \ln(Z_i)$ for i=1, ..., r. Calculate $I = 1.28/S_y$ as an initial guess at the solution and calculate g(I). If $g(I) > 0$, then find the smallest positive integer k such that $g(I/2^k) < 0$ and let $L = I/2^k$ and $H = I/2^{k-1}$. If $g(I) < 0$, then find the smallest positive integer k such that $g(2^k I) > 0$ and let $L = 2^{k-1} I$, and $H = 2^k I$. Reduce the (L,H) interval by calculating $M = (L+H)/2$ and setting

L = M if g(M) $\leq$ 0 and/or by setting H = M if g(M) $\geq$ 0. If H-L $\leq$ 2I/10^6, then set β = M and stop. Otherwise, reduce the (L,H) interval again.

Once β has been determined, the scale parameter estimate is defined by

$$\alpha = \left(\frac{1}{r} \left(\sum_{i=1}^{r} Z_{(i)}^{\beta} + (n-r)\ Z_{(r)}^{\beta} \right) \right)^{\frac{1}{\beta}} .$$

9.5.4.7.3 *Calculating the Anderson-Darling Statistic* — Once the parameters have been estimated in Sections 9.5.4.7.1 and 9.5.4.7.2, calculate the Anderson-Darling statistic by the following steps.

For i=1,...,r, let

$$F_i = 1 - \exp\left(- \left(\frac{X_{(i)} - \tau_{50}}{\alpha_{50}} \right)^{\beta_{50}} \right) ,$$

let F_{n+1} = 1, and let

$$C_i = \frac{2i-1}{n}.$$

Define the A-D statistic as

$$AD = -\sum_{i=1}^{r} \left(C_i \ln F_i - 2F_i \right) + \frac{r^2}{n} \ln F_{r+1} - 2r\ F_{r+1} + \frac{n}{2} F_{r+1}^2 - \frac{n}{2} F_1^2 .$$

If

$$AD \geq \begin{cases} 0.3951 + 4.186 \times 10^{-5}\ n & \text{(Uncensored)} \\ 0.2603 + 4.182 \times 10^{-5}\ n & \text{(20 percent censored)} \\ 0.1761 + 1.842 \times 10^{-5}\ n & \text{(50 percent censored)} \end{cases} \qquad [9.5.4.7.3]$$

one may conclude (at 5 percent risk of error) that the population from which the sample was drawn is not a three-parameter Weibull population. Otherwise, the hypothesis that the population is a three-parameter Weibull population is not rejected. Equation 9.5.4.7.3 was derived under the assumption that the threshold parameter is estimated, not known. For further information on this test procedure, see Reference 9.5.4.7.3.

9.5.4.8 ***Identifying Proper Backoff for Weibull Method*** — Begin with the estimates τ_{50}, α_{50}, and β_{50} obtained according to the procedures outlined in Sections 9.5.4.7.1 and 9.5.4.7.2. Let $F_\tau(x)$ represent the cumulative distribution function of the three-parameter Weibull distribution with threshold parameter τ, and scale and shape parameters, α_{50} and β_{50}, respectively:

$$F_\tau(x) = 1 - \exp\left(- \left(\frac{x - \tau}{\alpha_{50}} \right)^{\beta_{50}} \right) .$$

Define the special "backoff" Anderson Darling statistic by

$$\mathrm{ADB}(\tau) = n \sum_{i=1}^{n} \left[\left(\frac{i}{n} \right)^2 (\ln b_i - \ln a_i) - \frac{2i}{n}(b_i - a_i) + \frac{1}{2}(b_i^2 - a_i^2) \right],$$

where $a_i = \min\{F_\tau(x_{(i)}), i/n\}$, $b_i = \min\{F_\tau(x_{(i+1)}), i/n\}$ for $i < n$, and $b_n = 1$. Let $\tau_{backoff}$ be the smallest value among 0.1, 0.2, 0.3, 0.4, and 0.5 such that

$$\mathrm{ADB}(\tau_{50} - \tau_{backoff}) < 0.0359 + 1.2 \times 10^{-5}\, n\,. \qquad [9.5.4.8]$$

If none of the five values satisfies Equation 9.5.4.8, the backoff procedure cannot be used to compute T_{99} and T_{90}. Otherwise, $\tau_{backoff}$ is subtracted from T_{99} and T_{90} as calculated from the complete sample.

9.5.4.9 *Weibull Probability Plots* —To graphically illustrate the degree to which a three-parameter Weibull distribution fits a set of data, the following procedure for creation of a Weibull probability plot is recommended. This method is appropriate for distributions estimated using censored or uncensored data. A method for displaying the fit using a distribution estimated by a backoff option is also described.

The rank of each point selected for plotting is the number of lower test points plus the plotted point plus one-half the number of other test points equal to the plotted point. Its cumulative probability, P (in percent), is equal to the rank multiplied by 100, divided by one more than the total number of test points:

$$P \text{ (in percent)} = \frac{(\text{rank})(100)}{n + 1}$$

The measured value of each test point is plotted versus F^{-1} (P/100) where

$$F^{-1}(P/100) = \tau_{50} + \alpha_{50} \left[-\ln\left(1 - (P/100)\right)\right]^{\frac{1}{\beta_{50}}}$$

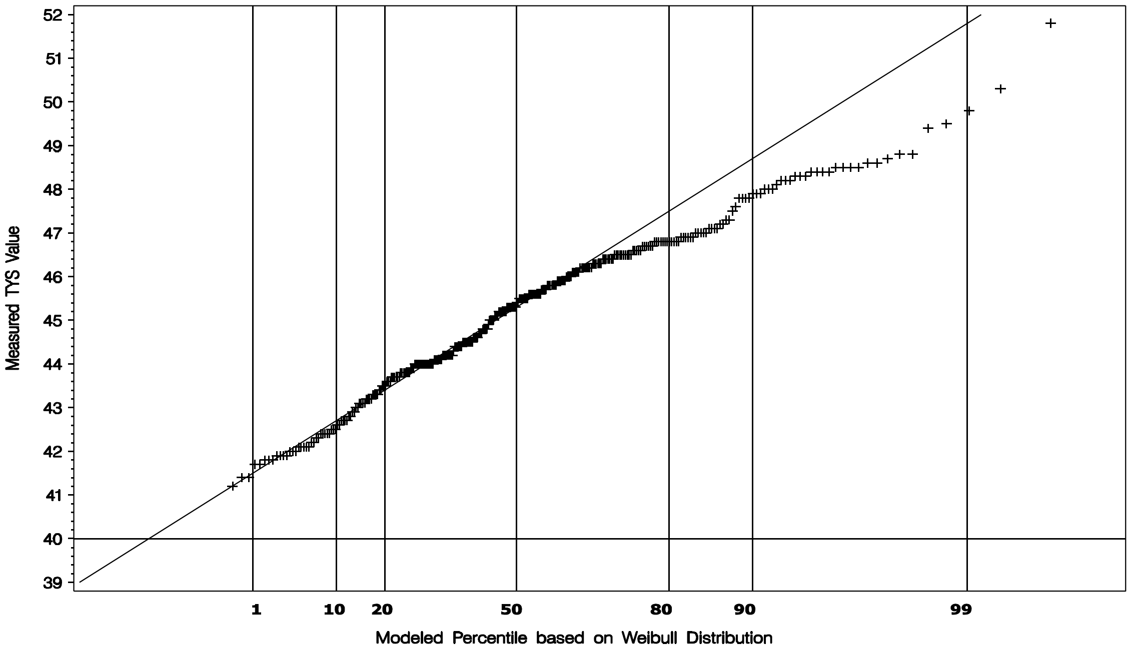
and τ_{50}, α_{50}, and β_{50} are population parameter estimates obtained according to the procedures outlined in Sections 9.5.4.7.1 and 9.5.4.7.2 . A straight line is then drawn to represent the fitted Weibull distribution. This line may be established by plotting any two points with equal vertical and horizontal coordinates and drawing a line through these two points. The horizontal axis is then labeled with cumulative probabilities rather than F^{-1} values.

If the backoff option is used, the selected distribution can then be described as the best-fit distribution shifted by a small constant, $\tau_{backoff}$. In this case, the predicted values should also be shifted by the same constant. That is, plot the measured values versus

$$F^{-1}(P/100) - \tau_{backoff}\ .$$

The plotted points should finally be compared with the line to determine whether there appears to be a reasonably good fit. With sample sizes on the order of 100 test points, only those points lying between about 10 and 90 percent probability should be considered in making this evaluation. With sample sizes of 1000 test points, these limits can be extended to about 1 and 99 percent. If the distribution was estimated using a method for censored data, then only the uncensored portion of the data used to estimate the distribution should be considered when assessing lack of fit. For instance, if the 20 percent censoring method is selected for use by the sequential Weibull method, then only the lower 80 percent of the data should be examined for agreement with the line of best fit. If the backoff option was used, then only deviations where the data fall below the fitted line should be considered as departures.

Figure 9.5.4.9(a) illustrates the use of a Weibull probability plot on Alclad 2524-T3 Aluminum Alloy Sheet and Plate data in the 0.063-0.128 inch thickness range. This is a probability plot based on a Weibull distribution estimated using the 50 percent censoring method. The estimates of the threshold, scale, and shape parameters based on 50 percent censoring are 40.87, 5.26, and 2.09, respectively. Notice that the lower tail does not exhibit serious departures from the model, but significant departures are apparent in the upper tail. But, as mentioned above, only the lower 50 percent of the data should be included in an assessment of this probability plot, because the rest are not used in fitting the model. The model estimated by this method was accepted by the Anderson-Darling test for Weibullness.

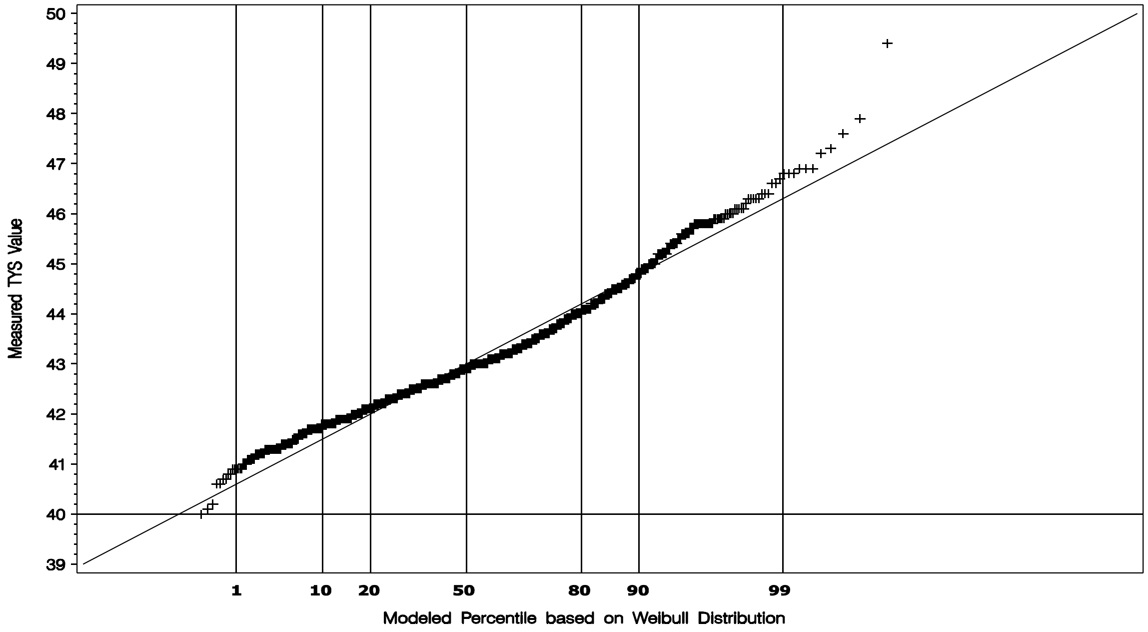


Vertical reference lines plotted at 1st, 10th, 20th, 50th, 80th, 90th, and 99th percentiles of fitted distribution
Horizontal reference line plotted at spec minimum, 40 ksi

Figure 9.5.4.9(a). Probability plot for a Weibull distribution fitted with 50 percent censored TYS data for Alcad 2524-T3 aluminum alloy sheet in the 0.063-0.128 inch thickness range - accepted.

Figures 9.5.4.9(b) and 9.5.4.9(c) illustrate the value of the backoff method and the construction and interpretation of the associated probability plots. Alclad 2524-T3 Aluminum Alloy Sheet and Plate tensile yield data in the 0.250 – 0.310 inch thickness range is used for illustration. There are 1202 measured test values. The estimates of the threshold, scale, and shape parameters of the best-fit Weibull distribution, based on the uncensored data, are 40.00, 3.50, and 2.62, respectively. The departures from the reference line in Figure 9.5.4.9(b) suggest that this Weibull distribution does not provide a good fit for the measured values, and it was rejected by Anderson-Darling test for Weibullness.

Figure 9.5.4.9(c) shows a probability plot of the same data, using the distribution estimated with the backoff option of the sequential Weibull procedure, which identified a backoff of 0.2 ksi. The only difference between the two plots is that the predicted values in Figure 9.5.4.9(b) are shifted 0.2 ksi to the left in Figure 9.5.4.9(c). Although the curve of data in Figure 9.5.4.9(c) is further away (on average) from the y=x reference line than the curve of data in Figure 9.5.4.9(b), only negative deviations from the reference line are recognized in the Anderson-Darling goodness-of-fit test for a distribution estimated by the backoff method. In Figure 9.5.4.9(c), only a small proportion of the data in the very middle of the distribution are below the predicted values, resulting in an insignificant departure from Weibullness.



Vertical reference lines plotted at 1st, 10th, 20th, 50th, 80th, 90th, and 99th percentiles of fitted distribution
Horizontal reference line plotted at spec minimum, 40 ksi

Figure 9.5.4.9(b). Probability plot for a Weibull distribution fitted to a complete TYS data set for Alcad 2524-T3 aluminum alloy plate in the 0.250-0.310 inch thickness range - rejected.

9.5.5 DIRECT COMPUTATION WITHOUT REGRESSION —To permit computation of lower tolerance bounds in more of these cases, the Weibull approach was expanded to incorporate two different levels of upper-tail censoring and a last-resort conservative "backoff" option. Also, a modified version of the A-D test was developed which places more emphasis on the lower tail than the upper tail (Section 9.5.4.7).

During the development of the Weibull procedure (Section 9.5.5.2), it became evident how inadequate the traditional normal procedure is for computing tolerance bounds when the data come from a 9.5.5 illustrates the shortcomings of the normal procedure for computing T_{99} and T_{90} for distributions[*] ranging in skewness from minus 1 to plus 1. The second column provides estimates of the probability that skewed

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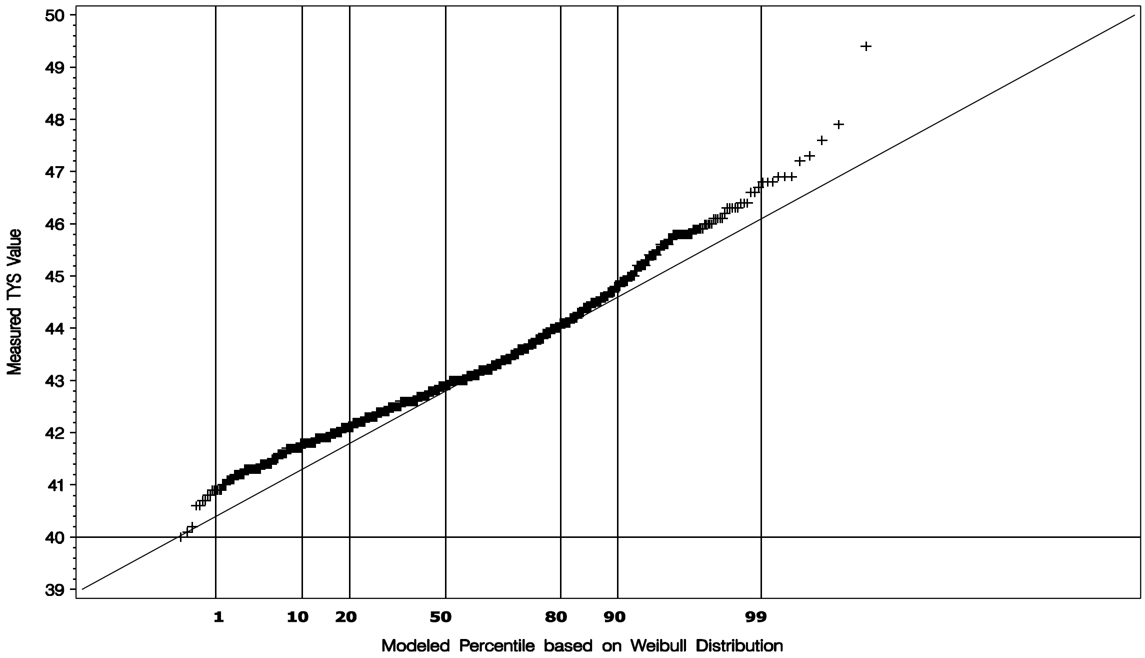
[*] Table 9.5.5 is based on data generated from Weibull distributions with varying skewness. All distributions are standardized to a mean of 100 and standard deviation of 5.0.



Vertical reference lines plotted at 1st, 10th, 20th, 50th, 80th, 90th, and 99th percentiles of fitted distribution
Horizontal reference line plotted at spec minimum, 40 ksi

Figure 9.5.4.9(c). Probability plot for a Weibull distribution fitted to complete TYS data for Alcad 2524-T3 aluminum alloy plate in the 0.250-0.310 inch thickness range using 0.2 ksi backoff - accepted.

distribution – even if a goodness-of-fit test is applied to screen out non-normal distributions. Table a sample of size 100 will be "accepted" as normal. Notice that for very skewed Weibull distributions, the proportion accepted by the normal Anderson-Darling test is small, but it increases for distributions with skewness near zero. The third column of Table 9.5.5 estimates the coverage, which is the probability (or confidence) that the method will yield a T_{99} below the true first percentile. This should be 95 percent. If the distribution is negatively skewed then the coverage can be substantially lower than the claimed 95 percent. The fourth column estimates the systematic bias of the procedure. Bias for T_{99} represents the difference between the 95th percentile of the T_{99} values produced by the normal procedure minus the true first percentile. (Bias is presented in units of standard deviations. This can be converted to, say, ksi units, if the standard deviation is known.) It can be interpreted as the amount that would have to be subtracted from the T_{99} values produced by the procedure to get an appropriate answer. The problem is, in practice, one never knows true skewness. Notice that as bias goes up, coverage goes down. The last two columns provide coverage and bias estimates for T_{90}. Although still significant, the errors associated with T_{90} are much smaller than those for T_{99}. Figure 9.5.5(a) displays the bias of T_{90} and T_{99} for skewness between minus1 and plus 1 (again, in units of standard deviations).

Normal-based methods can be very good for estimating the mean of a distribution - which is not very sensitive to skewness. However, in MIL-HDBK-5, much of the emphasis is on estimating the first and tenth percentiles - which are very sensitive to skewness. Table 9.5.5 and Figure 9.5.5(a) are provided to emphasize the notion that applying the normal method can result in very poor tolerance bound estimates due to undetected skewness. It is for this reason that the traditional normal method for computing tolerance bounds is not provided in the Handbook as a recommended procedure.

On the other hand, because methods based on the Weibull distribution are computationally intensive and have less intuitive appeal than methods based on the normal distribution, an alternative procedure was

Table 9.5.5. Performance of Normal Method for Calculating T_{90} and T_{99} on Samples of Varying Skewness

		T_{99}		T_{90}	
Skewness	Percent Accepted	Percent Coverage	Bias (Std. Dev.)	Percent Coverage	Bias (Std. Dev.)
-1.00	16	3	1.0	66	0.22
-0.75	40	11	0.7	78	0.16
-0.50	68	43	0.4	83	0.12
-0.25	91	82	0.2	88	0.08
0.00	98	98	-0.1	93	0.04
0.25	91	100	-0.4	97	-0.02
0.50	65	100	-0.6	99	-0.06
0.75	21	100	-0.7	100	-0.06
1.00	4	100	-0.7	100	-0.10

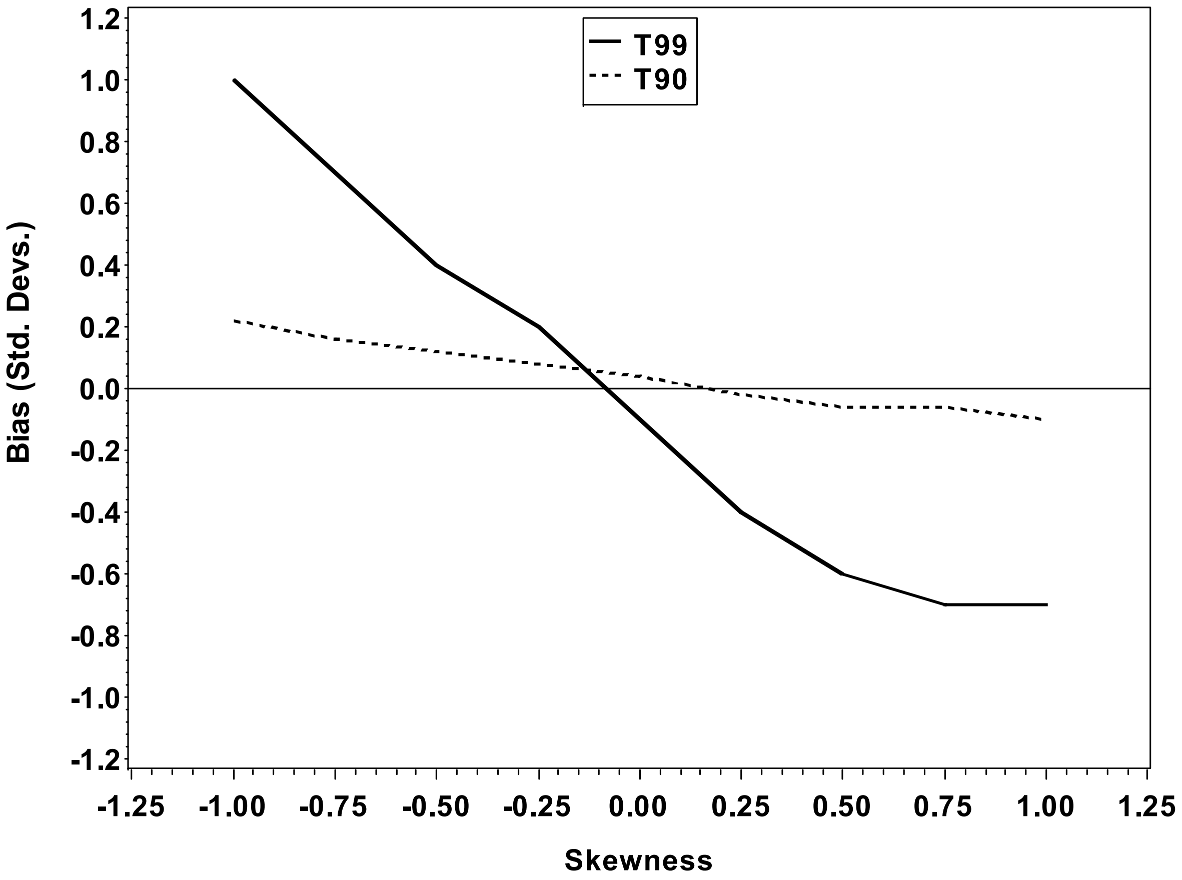


Figure 9.5.5(a). Estimated Bias of T_{99} and T_{90} Using Normal Method on Skewed Data.

developed based on the Pearson Type III family of distributions. The Pearson family includes the normal distribution as a special case. The Pearson method was incorporated into the Guidelines in 1999.

The sequential Weibull procedure (Section 9.5.5.2) and the sequential Pearson procedure (Section 9.5.5.1) were developed based on distributions with skewness between minus 1 and 1. Therefore, the Weibull and Pearson procedures should not be applied if the sample skewness is outside this range. If no systematic effects (e.g., thickness) are identified as significant by regression, then only the nonparametric method (Section 9.5.5.3) should be applied.

Current analysis procedures for computing lower tolerance bounds (T_{90}, T_{99}) are described in Figure 9.5.5(b). Three methods are permitted: the sequential Pearson procedure, the sequential Weibull procedure, and the nonparametric procedure. The remainder of this section provides an overview and a roadmap to these procedures. Figure 9.5.5(c) describes the procedure for translating T_{99} and T_{90} values to A and B values, and values for publication in the mechanical property tables in this Handbook.

In what follows, certain procedures require artificial censoring of the measured data. That is, because the real engineering interest for design lies in lower percentiles of the distribution of a material's properties, some of the following procedures ignore a portion of the observations in the upper tail. Specifically, we use the notation $X_{(1)} \leq X_{(2)} \leq \ldots \leq X_{(n)}$ to denote the ordered sample, and will frequently refer to the censored sample:

$$X_{(1)} \leq X_{(2)} \leq \ldots \leq X_{(r)}.$$

The ratio r/n represents the proportion of the sample which is uncensored. Alternatively, (1-r/n) represents the proportion of the sample which is censored. The terms r and n will be used throughout subsequent sections without redefinition. In the case of uncensored data, r=n.

If the sequential Pearson analysis procedure is applied, the first step is to perform an Anderson-Darling goodness-of-fit test for Pearsonality as described in Section 9.5.4.4. If the assumption of normality is not rejected, the lower tolerance bounds may be computed using the methods described in Section 9.5.5.1. If the assumption of Pearsonality is rejected, then the Pearson backoff method (Section 9.5.4.5) should be attempted. This method decreases the estimate of the mean, while holding the standard deviation and skewness estimates constant, until the percentiles of the resulting model are sufficiently less than the sample percentiles. To avoid accepting an extremely inadequate fit, the decrease in the mean is limited to 0.5 ksi.

Section 9.5.4.5 describes the method for identifying a proper backoff, denoted by $\tau_{backoff}$, for the sequential Pearson method. If the appropriate backoff is less than or equal to 0.5 ksi, the lower tolerance bounds should be calculated by first computing bounds based on the complete sample as specified in Section 9.5.5.1, and then subtracting $\tau_{backoff}$. If an appropriate backoff less than or equal to 0.5 ksi is not identified, then the sequential Weibull procedures described in Section 9.5.5.2 or the nonparametric procedure described in Section 9.5.5.3 should be considered. In most cases it has been found that strength data fit a Pearson distribution better than a Weibull distribution. However, there are times when a Weibull distribution does provide a better fit. Probability plots are helpful in determining which procedure provides the best fit when there is a difference in the T_{99} and T_{90} values for the two methods.

When the sequential Weibull procedure is applied, a modified Anderson-Darling goodness-of-fit-test is conducted as described in Section 9.5.4.7 for the uncensored sample. If the assumption of Weibullness is not rejected, the lower tolerance bound should be computed using methods described in Section 9.5.5.2 for complete samples. (The risk that one may conclude erroneously that a true Weibull distribution is non-

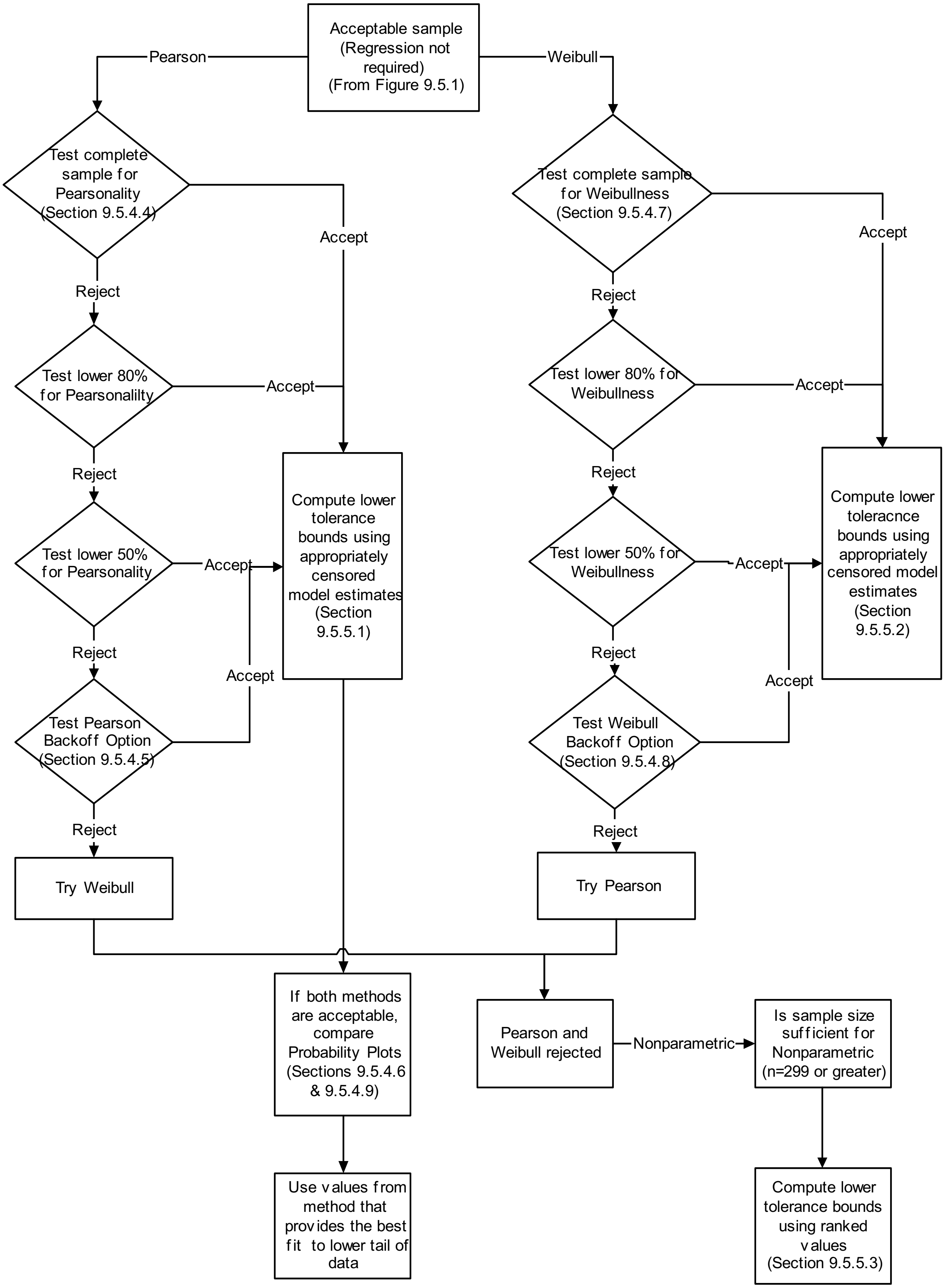


Figure 9.5.5(b). Procedure for Direct Computation of T_{99} and T_{90} When Regression is Not Required.

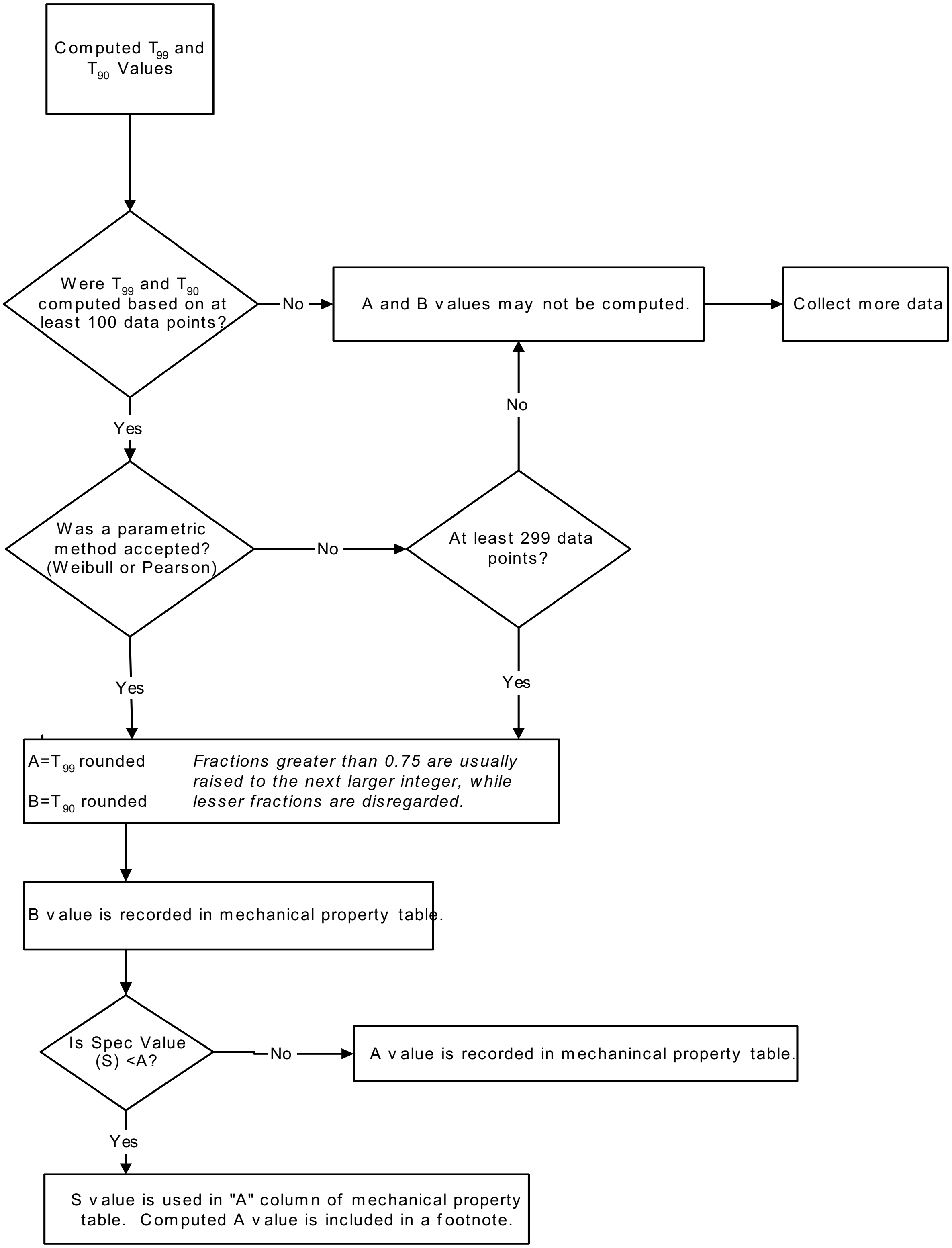


Figure 9.5.5(c). Procedure for Converting T_{99} and T_{90} values [from Figure 9.2.6(a)] to A and B Values, and Mechanical Property Table Values.

Weibull is set at 5 percent.) If the assumption of Weibullness is rejected for the complete sample, then the next step is to test the lower 80 percent of the data for Weibullness by trimming the top 20 percent of the measurements and applying a censored version of the Anderson-Darling test. Use the version of the test described in Section 9.5.4.7 for 20 percent censoring. If this test is not rejected, then the lower tolerance bounds should be computed using the methods described in Section 9.5.5.2 for 20 percent censoring. If the assumption of Weibullness is rejected here, then 50 percent censoring should be attempted, in the same manner as described for 20 percent censoring.

If the Weibull model is still rejected with 50 percent censoring, then a last resort conservative Weibull method should be attempted. This method decreases the initial Weibull threshold estimate while holding the shape and scale parameters constant, until the percentiles of the resulting model are sufficiently less than the sample percentiles. To avoid accepting an extremely inadequate fit, the decrease is limited to 0.5 ksi.

Section 9.5.4.8 describes the method for identifying a proper backoff (the decrease from the initial Weibull threshold estimate), denoted by $\tau_{backoff}$, for this method. If the appropriate backoff is less than or equal to 0.5 ksi, the lower tolerance bounds should be calculated by first computing bounds based on the complete sample as specified in Section 9.5.5.2, and then subtracting the $\tau_{backoff}$ value. If an appropriate backoff less than or equal to 0.5 ksi is not identified for either the sequential Pearson or sequential Weibull procedures, then the nonparametric procedures described in 9.5.5.3, should be considered

In those cases where sufficient data are available, one may choose to calculate the lower tolerance bounds by the nonparametric procedure. A T_{99} bound requires 299 data values and a T_{90} bound requires 29 data values.* The nonparametric procedure is described in Section 9.5.5.3. If the sample size is too small for the nonparametric method, sequential Pearson procedure described in Section 9.5.5.1 or the the sequential Weibull procedure described in Section 9.5.5.2, should be considered.

In those cases where sample sizes are insufficient to apply the nonparametric method, and the goodness-of-fit tests will not allow application of the sequential Weibull or sequential Pearson procedures, the lower tolerance bounds cannot be calculated.

9.5.5.1 *Sequential Pearson Procedure* —This procedure should be used when a lower tolerance bound (T_{99}, T_{90}) is to be computed directly (not paired with another property for computational purposes) and the population may be interpreted to signify either the property measured (TUS, etc.) or some transformation of the measured value that is normally distributed. This procedure is applicable to F_{tu} and F_{ty}. It may also be used for F_{cy}, F_{su}, F_{bru}, and F_{bry} if sufficient quantity of data is available.

To compute lower tolerance bounds for a population from the Pearson Type III (or gamma) family of distributions, it is necessary to have estimates of the mean, standard deviation, and skewness of the population. In what follows, these are denoted respectively by $\overline{X}$, S, and q. These estimates are also necessary for applying the Anderson-Darling (AD) test for Pearsonality (described in 9.5.4.4) and for the backoff part of the test (described in 9.5.4.5). Background information on the Pearson Type III distribution may be found in References 9.5.5.1(a) and 9.5.5.1(b).

In what follows, $X_{(1)}$, $X_{(2)}$, …, $X_{(n)}$ represent the sorted observations, from smallest to largest. Calculate the sample mean and sample standard deviation as usual:

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* However, according to current guidelines, a T_{90} value cannot be calculated for inclusion in MIL-HDBK-5 with fewer than 100 data values. See Section 9.2.9.1.

$$\overline{X}=\frac{1}{n}\sum_{i=1}^{n}X_i$$

$$S=\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(X_i-\overline{X}\right)^2}$$

The skewness is calculated as follows. First calculate the sample skewness:

$$Q=\sqrt{\frac{n}{(n-1)^3}}\bullet\frac{\sum_{i=1}^{n}(X_i-\overline{X})^3}{S^3}$$

If $Q = 0$, then let $q = 0$. If $Q \neq 0$, calculate the estimated threshold

$$T=\overline{X}-2\bullet S/Q$$

and use the following rules to define q:

a. If $Q > 0$ and $X_{(1)} < T$, then let $q = 2\bullet S/(\overline{X}-0.99999X_{(1)})$.

b. If $Q < 0$ and $X_{(n)} > T$, then let $q = 2\bullet S/(\overline{X}-1.00001X_{(n)})$.

c. Otherwise, $q = Q$.

If the data are not rejected by the Anderson-Darling test for Pearsonality (described in 9.5.4.4), then T_{99} and T_{90} should be calculated by the following formulae:

$$\begin{aligned} T_{99} &= \overline{X} - k_{99}(q,n)\cdot S \\ T_{90} &= \overline{X} - k_{90}(q,n)\cdot S \end{aligned}$$

where

$$\begin{aligned} k_{99}(q,n) = {} & z_{99}(q) \\ & + \exp\left[2.556 - 1.229\,q + 0.987\,q^2 - 0.6542\cdot\ln(n) + 0.0897\,q\cdot\ln(n) - 0.1864\,q^2\cdot\ln(n)\right] \end{aligned}$$

$$\begin{aligned} k_{90}(q,n) = {} & z_{90}(q) \\ & + \exp\left[1.541 - 0.943\,q - 0.6515\,q^2 - 0.6004\cdot\ln(n) + 0.0684\,q\cdot\ln(n) + 0.0864\,q^2\cdot\ln(n)\right] \end{aligned}$$

$$z_{99}(q)=\frac{2}{q}\left[1-\left(1-\frac{q^2}{36}-2.326348\cdot\frac{q}{6}\right)^3\right]-0.013133\,q^2-0.003231\,q^3+0.003139\,q^4+0.001007\,q^5$$

$$z_{90}(q)=\frac{2}{q}\left[1-\left(1-\frac{q^2}{36}-1.281552\cdot\frac{q}{6}\right)^3\right]+0.003814\,q^2-0.002466\,q^3-0.000633\,q^4+0.000122\,q^5$$

The above formulas for $z_{99}(q)$ and $z_{90}(q)$ should be used for $q \neq 0$. If $q = 0$, then $z_{99}(q) = 2.326348$ and $z_{90}(q) = 1.281552$.

If the data are rejected by the Anderson-Darling test for Pearsonality, but accepted under the backoff option of the test (9.5.4.5) with a reduction in the mean of $\tau_{backoff}$, then the above formulas should be applied to compute then T_{99} and T_{90} with the following slight modification:

$$T_{99} = \overline{X} - k_{99}(q,n) \cdot S - \tau_{backoff},$$
$$T_{90} = \overline{X} - k_{90}(q,n) \cdot S - \tau_{backoff}.$$

9.5.5.2. *Sequential Weibull Procedure* — This section describes procedures required for modeling data with the three-parameter Weibull distribution. Section 9.5.4.7.1 describes a method for estimating the threshold parameter, τ. Section 9.5.4.7.2 describes a method for estimating the shape and scale parameters, β and α, respectively. Both methods permit estimation with upper-tail censored data. For a good exposition of such procedures, see Reference 9.5.4.1(a).

This procedure should be used when a mechanical property value is to be computed directly (not paired with another property for computational purposes) and the population may be interpreted to signify either the property measured (TUS, etc.) or some transformation of the measured value that follows a three-parameter Weibull distribution. This procedure is applicable to F_{tu} and F_{ty}. It may also be used for F_{cy}, F_{su}, F_{bru}, and F_{bry} if a sufficient quantity of data is available.

In order to compute the lower tolerance bounds for a three-parameter Weibull population, it is necessary to have (1) an estimate of population threshold, (2) estimates of population shape and scale parameters, and (3) tables of one-sided tolerance limit factors for the three-parameter Weibull distribution. The method for estimating the population threshold is presented in Section 9.5.4.7.1, and Section 9.5.4.7.2 contains the method for estimating population shape and scale parameters. Both of these procedures permit estimation with complete or censored data (20 or 50 percent censoring). A tabulation of tolerance limit factors by sample size, censoring level, and population proportion covered by the tolerance interval is presented in Table 9.10.7. For further information on these procedures and tabled values, see References 9.5.5.2.(a) and (b).

Let $X_1,..,X_n$ denote sample observations in any order and let $X_{(1)},...,X_{(n)}$ denote sample observations ordered from smallest to largest. The first step in calculating T_{99} and T_{90} for a three-parameter Weibull population is to obtain an estimate of the population threshold. The population threshold is theoretically the minimum achievable value for the property being measured. However, the real population is being empirically modeled by some Weibull population with a threshold. Since this empirical model is not perfect, there may be a small percentage of observations in the population that fall below the model threshold. Separate threshold estimates, denoted by τ_{99} and τ_{90}, will be obtained for T_{99} and T_{90} using the methods described in Section 9.5.4.7.1.

The second step in calculating mechanical properties for a three-parameter Weibull population is to obtain estimates of population shape and scale parameters for each property. Shape parameter estimates will be denoted by β_{99} and β_{90} and scale parameter estimates will be denoted by α_{99} and α_{90}. Estimation of shape and scale parameters is performed using a maximum likelihood procedure for the two-parameter Weibull distribution, after subtracting off the estimated threshold. (The two-parameter Weibull is equivalent to the three-parameter Weibull with threshold zero.)

Using the method outlined in Section 9.5.4.7.2, compute the maximum likelihood estimates of the shape and scale parameters for the censored or uncensored sample $\{X_{(i)} - \tau_{99} : i=1,...,r\}$, where r equals n for uncensored data and r represents the smallest integer greater than or equal to 4n/5 for 20 percent censoring and n/2 for 50 percent censoring. Denote these estimates by β_{99} and α_{99}, respectively. Using the same procedure, compute estimates β_{90} and α_{90} based on the sample $\{X_{(i)} - \tau_{90} : i=1,...,r\}$.

With population parameter estimates discussed above at hand, the computation of the lower tolerance bounds is carried out by use of the formulas:

$$T_{99} = \tau_{99} + Q_{99} \exp\left[- V_{99}/\left(\beta_{99}\sqrt{n}\right) \right], \qquad [9.5.5.2(a)]$$

$$T_{90} = \tau_{90} + Q_{90} \exp\left[- V_{90}/\left(\beta_{90}\sqrt{n}\right) \right], \qquad [9.5.5.2(b)]$$

where

Q_{99} = $\alpha_{99} (0.01005)^{1/\beta_{99}}$
Q_{90} = $\alpha_{90} (0.10536)^{1/\beta_{90}}$
V_{99} = the value in the V_{99} column of Table 9.10.8 corresponding to a sample of size n and the appropriate degree of censoring, and
V_{90} = the value in the V_{90} column of Table 9.10.8 corresponding to a sample of size n and the appropriate degree of censoring.

Note that the level of censoring used in estimating the threshold, shape, and scale parameters must be used in determining V_{99} and V_{90}. Also, because this censoring level is determined by the goodness-of-fit test (9.5.4.7), the same censoring level is used for both T_{99} and T_{90}.

If the property that follows a three-parameter Weibull distribution represents a transformation, the lower tolerance bounds (T_{99}, T_{90}) computed by the above formulas must be transformed back to the original units in which the mechanical property is conventionally reported.

9.5.5.3 *Nonparametric Procedure* — This procedure should be used when a mechanical-property value is to be computed directly (not paired with another property for computational purposes) and the form of the distribution of population is unknown (not Pearson Type III or three-parameter Weibull). Distribution should not be considered unknown (1) if tests show it to be Pearson or three-parameter Weibull, (2) if it can be transformed to a Pearson or three-parameter Weibull distribution, or (3) if it can be separated into Pearson or three-parameter Weibull subpopulations. This procedure is applicable to F_{tu} and F_{ty}. It may also be used for F_{cy}, F_{su}, F_{bru}, and F_{bry} if sufficient quantity of data is available.

Nonparametric (or distribution-free) data analysis assumes a random selection of test points and uses only the ranks of individual test points and the total number of test points. If test points have been deleted from a sample, the random basis is violated; consequently, this procedure must not be used when there is reason to suspect that the sample may have been censored.

As an example, assume that a sample consists of 299 test points selected in a random manner. The test point having the lowest value has rank 1, the test point having the next lowest value has rank 2, etc. Thus, an array of ranked test points might appear as follows:

Rank of Test Point	Value of Test Point, ksi
1	73.3
2	74.1
3	75.2
4	75.3
5	75.6
299	85.7

For each rank from a sample of size, n, it is possible to predict, with 0.95 confidence, the least fraction of population that exceeds the value of the test point having rank r. Since only two fractions, or probabilities, are of interest in determination of T_{99} and T_{90} values, only the ranks of test points having the probability and confidence of T_{99} and T_{90} values are presented in Table 9.10.9. To use this table with a sample size of 299, for example, one would designate the value of the lowest (r=1) test measurement as T_{99} and the 22nd lowest (r=22) test measurement as T_{90}. For sample sizes between tabulated values, interpolation is permissible. For sample sizes smaller than 299, T_{99} is smaller than the value of the lowest point and cannot be determined in this manner.

9.5.6 DIRECT COMPUTATION BY REGRESSION ANALYSIS — This section describes the procedure used to determine design allowables by regression analysis if it has been determined that a significant representation relationship exists (see Section 9.5.1.2). Thus a dimensional parameter x (such as x=t, 1/t, etc., where t is thickness) has been determined to be related to the property being considered.

9.5.6.1 *PERFORMING THE REGRESSION* — The following steps must be performed prior to determining design allowables by regression analysis:

(1) Express the property as a simple linear (or quadratic) function of the dimensional parameter and obtain estimates of the coefficient using the least squares regression procedure in Section 9.5.2.1 (or Section 9.5.2.2); for example

$$\text{TUS} = a + bx$$

or

$$(\text{SUS}/\text{TUS}) = a + bx + cx^2$$

where x is thickness or area and a, b, and c are constants from the least squares equation.

(2) Determine the root mean square error of regression (s_y). See 9.5.2.1(h) and 9.5.2.2(e).

The direct computational procedure takes into account errors in the model estimates. If a linear relationship has been determined, compute T_{99} for F_{tu} at $x = x_o$, using Equation [9.5.6.1(a)]

$$T_{99} = a + bx_0 - k'_{99} s_y \qquad [9.5.6.1(a)]$$

where a, b, and s_y are computed in the regression of TUS data, k'_{99} is $\sqrt{(1+\Delta)\ /n}$ times the 95th percentile of the noncentral t distribution with noncentrality parameter $2.326/\sqrt{(1+\Delta)\ /n}$ and n - 2 degrees of freedom, and

$$\Delta = \frac{\left(x_o - \Sigma\ x/n\right)^2}{\Sigma\left(x - \Sigma\ x/n\right)^2/n} \quad . \qquad [9.5.6.1(b)]$$

The equation for computing a T_{90} is similar with k'_{90} being used in place of k'_{99}. k'_{90} is $\sqrt{(1+\Delta)\ /n}$ times the 95th percentile of the noncentral t distribution with noncentrality parameter $1.282/\sqrt{(1+\Delta)\ /n}$ and n - 2 degrees of freedom, where Δ is defined above. If calculation of the appropriate noncentral t percentile is not possible, the following approximations to k'_{99} and k'_{90} may be used:

$$k'_{99} = 2.326 + \exp\{0.659 - 0.514\ \ln(n) + (0.481 - 1.42/n)\ln(3.71 + \Delta) + 6.58/n\} \qquad [9.5.6.1(c)]$$

$$k'_{90} = 1.282 + \exp\{0.595 - 0.508\ \ln(n) + (0.486 - 0.986/n)\ln(1.82 + \Delta) + 4.62/n\}. \qquad [9.5.6.1(d)]$$

These approximations are accurate to within 1.0 percent for $n \geq 10$ and $\Delta \leq 10$. The square root of Δ is the number of standard deviations between x_o and the arithmetic mean of the x-values. Thus, a Δ value of 10 would represent an extreme x_o value, which is more than three standard deviations from the mean x-value.

If a quadratic relationship has been determined, calculate T_{99} for F_{tu} at $x = x_o$ using Equation [9.5.6.1(e)]

$$T_{99} = a + bx_o + cx_o^2 - \left(t_{0.95,\ n-3,\ \frac{2.326}{\sqrt{Q}}}\right)\sqrt{Q}\ s_y \qquad [9.5.6.1(e)]$$

where a, b, c, s_y, and Q are computed by quadratic regression, and the factor $t_{0.95,n-3,\frac{2.326}{\sqrt{Q}}}$ is the 95th percentile of the noncentral t distribution with noncentrality parameter $2.326/\sqrt{Q}$ and n-3 degrees of freedom.

To calculate T_{90} in the presence of a quadratic relationship, use Equation 9.5.6.1(f)

$$T_{90} = a + bx_o + cx_o^2 - \left(t_{0.95,\ n-3,\ \frac{1.282}{\sqrt{Q}}}\right)\sqrt{Q}\ s_y \qquad [9.5.6.1(f)]$$

where a, b, c, s_y, and Q are computed by quadratic regression, and the factor $t_{0.95,n-3,\frac{1.282}{\sqrt{Q}}}$ is the 95th percentile of the noncentral t distribution with noncentrality parameter $1.282/\sqrt{Q}$ and n-3 degrees of freedom.*

The procedures described above permit the determination of design allowables only for specific values of x. When it is desired to present a single allowable covering a range of product thickness (for example, 1.001- to 2.000-inch plate), the lowest allowable for the range should be used. Thus, if TUS(LT) decreases continuously with increasing thickness, the TUS(LT) corresponding to x = 2.000 inches would be presented in MIL-HDBK-5. If the decrease is large, a decrease in product thickness interval can be made: for example, by splitting the 1.001- to 2.000-inch interval into two intervals of 1.001 to 1.500 and 1.501 to 2.000 inches.

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* Note that critical values for the noncentral t distribution are not tabulated in MIL-HDBK-5.

9.5.7 INDIRECT COMPUTATION WITHOUT REGRESSION (REDUCED RATIOS/DERIVED PROPERTIES) — Ideally, it is desirable to determine F_{cy}, F_{su}, F_{bru}, F_{bry}, as well as F_{tu} and F_{ty} in other than specified test direction by direct computation as described in Sections 9.5.2, and, if sufficient quantity of data is available, direct computation procedures will be used. Unfortunately, the cost of generating required data for these properties is usually prohibitive. Consequently, this section describes an indirect method of computation to determine the mechanical property values.

A derived property is a mechanical property value determined by its relationship to an established tensile property (F_{tu} or F_{ty}, A, B, or S-basis). This indirect method of computation is applicable to F_{tu} and F_{ty} in grain directions other than the specified testing direction, as delineated in the applicable material specification, and for all grain directions for F_{cy}, F_{su}, F_{bru}, and F_{bry}.

The procedure involves pairing of TUS, SUS, or BUS measurements with TUS measurements for which F_{tu} has been established or the pairing of TYS, CYS, and BYS measurements with TYS measurements for which F_{ty} has been established. Average values for each lot will be used when more than one measurement per lot is available.

This technique is based on the premise that the mean ratio of paired observations representing related properties provides an estimate of the ratio of corresponding population means. The ratio consists of measurements of the property to be derived as the numerator and measurement of the established tensile property as the denominator. Thus, TUS or TYS in the specified testing direction always appears in the denominator of the ratio of observed values.

The grain direction to be used for the denominator is the specified test direction as delineated in the applicable material specification. For most materials, routine quality control (certification) tests are usually conducted only in one grain direction even though the specification may contain mechanical property requirements for two or three grain directions. The typically specified or primary test directions for different product forms of each alloy system are shown in Table 9.2.3.2 and discussed in Section 9.5.7.1. Section 9.5.7.2 discusses the treatment of test specimen location. Section 9.5.7.3 discusses the treatment of clad plates, and Section 9.5.7.4 discusses the computation procedure for minimum design values.

9.5.7.1 *Treatment of Grain Direction* — Tensile allowables are usually listed according to grain direction in material specifications although some specifications do not indicate a grain direction, which implies isotropy. For MIL-HDBK-5, it is recommended that tension allowables be shown for each grain direction. When the material is shown to be isotropic, then the same properties should be shown for each direction.

Compression allowables are shown by grain direction similar to tension allowables. An example of computing compression allowables for heat treatable plate is shown below. The reduced ratio, R, for longitudinal grain direction, is determined from ratios, r, formed from paired observations for each lot of material, CYS(L)/TYS(LT). Although a longitudinal ratio is being obtained, the divisor is long transverse because this is the specified testing direction (refer to Table 9.2.3.2). The reduced ratio, R, for long transverse grain direction, is determined from ratios, r, formed from paired observations for each lot of material, CYS(LT)/TYS(LT). Similarly the reduced ratios, R, for short transverse grain direction, are determined from ratios, r, formed from paired observations for each lot of material, CYS(ST)/TYS(LT). The ratios, r, determined in the above manner are used in conjunction with Equation 9.5.7.4(b) to obtain a reduced ratio, R, for each grain direction. Equating the reduced ratios, design allowable values are determined from the resulting relationships,

$$R = \frac{F_{cy}(L)}{F_{ty}(LT)}$$

or

$$F_{cy}(L) = RF_{ty}(LT)$$

similarly

$$F_{cy}(LT) = RF_{ty}(LT)$$

and

$$F_{cy}(ST) = RF_{ty}(LT) \quad .$$

Shear and bearing allowables are usually shown without reference to grain direction. These properties will be analyzed according to grain direction, and design allowables will be based on the lowest reduced ratio obtained for longitudinal, long transverse and short transverse (when applicable) directions. An exception is aluminum hand forgings for which shear values will be presented according to grain direction.

In computing the derived properties, paired ratios representing different grain directions will not be combined in the determination of a reduced ratio. This is based on the premise that, if the ratio for two paired measurements is to provide an estimate of population mean ratio, then paired measurements must represent the same grain direction as that of the corresponding population means.

For aluminum die forgings, the longitudinal grain direction is defined as orientations parallel, within ±15°, to the predominate grain flow. The long transverse grain direction is defined as perpendicular, within ±15°, to the longitudinal (predominate) grain direction and parallel, within ±15°, to the parting plane. (Both conditions must be met.) The short transverse grain direction is defined as perpendicular, within ±15°, to the longitudinal (predominate) grain direction and perpendicular, within ±15°, to the parting plane. (Both conditions must be met.) When possible, compression, bearing, and shear tests for three grain directions will be conducted.

9.5.7.2 ***Treatment of Test Specimen Location*** — Testing specifications require a change in test specimen location from t/2 for ≤1.500- to t/4 for >1.500-inch thickness for certain products. Although this change in specimen location may result in t/4 mechanical property ratios which are significantly different from t/2 ratios (different populations), as for aluminum plate, the t/2 and t/4 mechanical property ratios should be treated together for analysis to determine derived properties.

9.5.7.3 ***Treatment of Clad Aluminum Alloy Plate*** — For clad aluminum alloy plate, 0.500 inch and greater in thickness, tensile properties are determined using round tensile specimens; consequently, tensile properties represent core material. To present design values which represent the average tensile properties across the thickness of the clad plate, an adjustment must be made in the tensile yield and ultimate strength values (S- or A- and B-basis), representing core strength, in the primary test direction(s). These strengths will be reduced by a factor equal to twice the percentage of the nominal cladding thickness per side. These adjustments in the tensile yield and ultimate strengths will be made prior to the computation of derived properties, except for short transverse properties. The following footnote, flagged to the appropriate thickness ranges, will be incorporated into the design allowable table: “These values, except in the ST direction, have been adjusted to represent the average properties across the whole section, including X percent per side nominal cladding thickness.”

9.5.7.4 *Computational Procedure* — Four basic steps are involved in determining design allowable properties by indirect computation:

(1) Determine the ratios of paired observations for each lot of material.
(2) Compute the statistics, $\bar{r}$ and s, for the ratios of paired observations.
(3) Determine the lower confidence interval estimate (reduced ratio) for the mean ratio.
(4) Use the reduced ratio as the ratio of the derived to the established design allowable.

The ratio of two paired observations is obtained by dividing the measurement of the property to be derived [for example, CYS (LT) for heat-treatable aluminum sheet] by the measurement for established tensile property [for example, TYS (LT)] in the specified testing direction. Equations for computing average and standard deviation of the ratios are the same as those in Appendix A.

The ratio of the two population means [for CYS (LT) and TYS (LT), respectively] is expected to exceed the lower confidence limit defined as

$$\bar{r} - t_{1-\alpha} s / \sqrt{n} \qquad [\,9.5.7.4(a)]$$

where

n is the number of ratios
$\bar{r}$ is the average of n ratios
s is the standard deviation of the ratios
$t_{1-\alpha}$ is the 1-α fractile of the t distribution for n - 1 degrees of freedom. At the risk level of $\alpha = 0.05$, the appropriate t value is $t_{0.95}$.

Since the lower confidence interval estimate is used as the ratio between the design allowable properties, the reduced ratio, R, may be defined as

$$R = \bar{r} - t_{0.95}\, s/\sqrt{n} \quad . \qquad [\,9.5.7.4(b)]$$

Values of $t_{0.95}$ for various degrees of freedom, n - 1, are tabulated in Table 9.10.4.

The reduced ratio may now be used to establish the design allowable for the property to be derived using the example of aluminum sheet,

$$R = \frac{F_{cy}(\mathrm{LT})}{F_{ty}(\mathrm{LT})} = \frac{\text{allowable to be derived}}{\text{established allowable in specified test direction}} \quad .$$

The derived allowable property is computed by cross multiplying:

$$F_{cy}\,(\mathrm{LT}) = R\, F_{ty}\,(\mathrm{LT})\ .$$

The basis (A, B, or S), defined in Section 9.1.6, for computed or derived property is assumed to be the same as the basis for F_{ty} or F_{tu} tensile property in the right-hand side of the equation. If only the S-basis (integer) properties are available to compute the derived properties, these values must be used. However, the unrounded S-basis F_{ty} or F_{tu} values computed with the method in Section 9.4 must be used to compute the derived properties if there are 100 or more observations representing 10 heats, casts, or melts; this will ensure the proper statistical confidence in the derived values. The lower of either the S-basis value computed from Section 9.4 or the T_{99} value must be used to compute the A-basis derived properties.

In a sample of ratios for a given product, effect of thickness on the ratio should be examined. If there is no effect of thickness, ratios for the various thicknesses can be pooled to compute the average and reduced ratio. If there is an effect of thickness, then a regression with thickness should be computed and the average and reduced ratios determined from the regression. See Section 9.5.8 for procedure.

9.5.8 INDIRECT COMPUTATION USING REGRESSION — Regression may also be used to determine reduced ratios when an allowable for a property, such as SUS, is computed indirectly from an already established allowable for TUS. The following assumptions are inherent to the reduced ratio procedure:

(1) The two properties must be distributed according to a bivariate normal distribution.

(2) The coefficient of variation must be the same for the two properties within particular bounds.

(3) The average of the ratio of the two properties must be well described by a linear function of the independent variable.

It is also important that paired data be available over the entire range of the dimensional parameter for which there is data for the direct property (TUS). Note that the confidence level associated with allowables computed using the reduced ratio technique may be somewhat below 95 percent.

To compute the reduced ratio at $x = x_o$, in the case of linear regression, use Equation [9.5.8(a)],

$$\text{Reduced Ratio} = a + bx_0 - \left(t_{0.95,n-2}\right) s_y \sqrt{\frac{1+\Delta}{n}} \qquad [9.5.8(a)]$$

where Δ is defined in Equation 9.5.6.1(b), a, b, and s_y are computed in the regression of SUS/TUS data (discussed in Section 9.5.6.1), and $t_{.95,n-2}$ is selected from Table 9.10.4 corresponding to n-2 degrees of freedom. The allowable for F_{su} at x_o is then computed as the product of the reduced ratio and the established allowable for F_{tu}:

$$F_{su} = (\text{Reduced Ratio})(F_{tu}) .$$

To compute the reduced ratio at $x = x_o$, in the case of quadratic regression, use Equation [9.5.8(b)],

$$\text{Reduced Ratio} = a + bx_o + cx_o^2 - t_{0.95,n-3}\, s_y \sqrt{Q} \qquad [9.5.8(b)]$$

where a, b, c, s_y, and Q are computed in the quadratic regression of SUS/TUS data (discussed in Section 9.5.6.1), and $t_{.95,n-3}$ is selected from Table 9.10.3 corresponding to n-3 degrees of freedom.

The allowable for F_{su} at x_o is then computed as the product of the reduced ratio and the established allowable for F_{tu}:

$$F_{su} = (\text{Reduced Ratio})(F_{tu}) .$$

9.6 ANALYSIS PROCEDURES FOR DYNAMIC AND TIME DEPENDENT PROPERTIES

9.6.1 LOAD AND STRAIN CONTROL FATIGUE DATA — Fatigue has been defined as "the process of progressive localized permanent structural change occurring in a material subjected to conditions that produce fluctuating stresses and strains at some point or points, and which may culminate in cracks or complete fracture after a sufficient number of fluctuations."

For many years, tests have been performed on specimens having simple geometries in attempts to characterize the fatigue properties of particular materials. Fatigue tests have been conducted for many reasons. Basic fatigue-life information may be desired for design purposes, or to evaluate the differences between materials. The effects of heat treatments, mechanical working, or material orientation may also be studied through comparative fatigue testing.

Many types of machines and specimen designs have been used to develop fatigue data. Machine types include mechanical, electromechanical, hydraulic, and ultrasonic. Specimens have been designed for testing in cyclic tension and/or compression, bending, and torsion. Cyclic loading conditions have been produced by rotating bending, axial loading and cantilever bending. In- and out-of-phase biaxial and multiaxial fatigue conditions have also been examined using specially designed specimens. Tests have been conducted in a variety of simulated environments including temperatures ranging from cryogenic to near melting point levels. The fatigue data included in MIL-HDBK-5 are limited to constant-amplitude axial fatigue data on simple laboratory specimens tested according to ASTM E 606. Data obtained under both strain control and load (stress) control are included. Figure 9.6.1(a) shows examples of trends for stress-life and strain-life fatigue data. Generally, stress-life data for unnotched specimens are limited to stress levels that produce intermediate-to-long fatigue lives because of unstable cyclic creep and tensile failure that can occur at high stress ratios in load-control testing. This phenomenon is shown in Figure 9.6.1(b). Strain-life curves are often focused on strain ranges that produce short-to-intermediate fatigue lives because of strain rate and frequency limitations which require long testing times to generate long-life fatigue data under strain control. However, there is no inherent limit to the life range that can be evaluated in strain-control testing.

For fatigue to occur, a material must undergo cyclic plasticity, at least on a localized level. The relationship between total strain, plastic strain, and elastic strain is shown in Figure 9.6.1(c). Low-cycle fatigue tests involve relatively high levels of cyclic plasticity. Intermediate-life fatigue tests usually involve plastic strains of the same order as the elastic strains. Long-life fatigue tests normally involve very low levels of cyclic plasticity. These trends are shown in Figure 9.6.1(d). In the MIL-HDBK-5 fatigue analysis guidelines, engineering strain is denoted as e and true or local strain is denoted as ε. These symbols are used interchangeably within MIL-HDBK-5 for small strain values.

The limited plasticity involved in intermediate and long-life fatigue tests often results in a similar stress-strain response for both fully reversed strain-control and fully reversed load-control tests. A fatigue test, under strain control that produces a stable maximum stress of X, should produce (on the average) a fatigue life that is comparable to that obtained for a sample tested under load control at a maximum stress of X. Strictly speaking, the results are likely to be most comparable in terms of crack initiation life and not total life. If the comparison is made in terms of total life, the load-control results will tend to be more conservative than those generated by strain-control testing. When a specimen cracks in a test under strain control, it will usually display a decrease in maximum tensile load. Under load control, the maximum tensile load will remain constant but stress will increase as the crack grows, resulting in a shorter period of crack growth before the specimen fails.

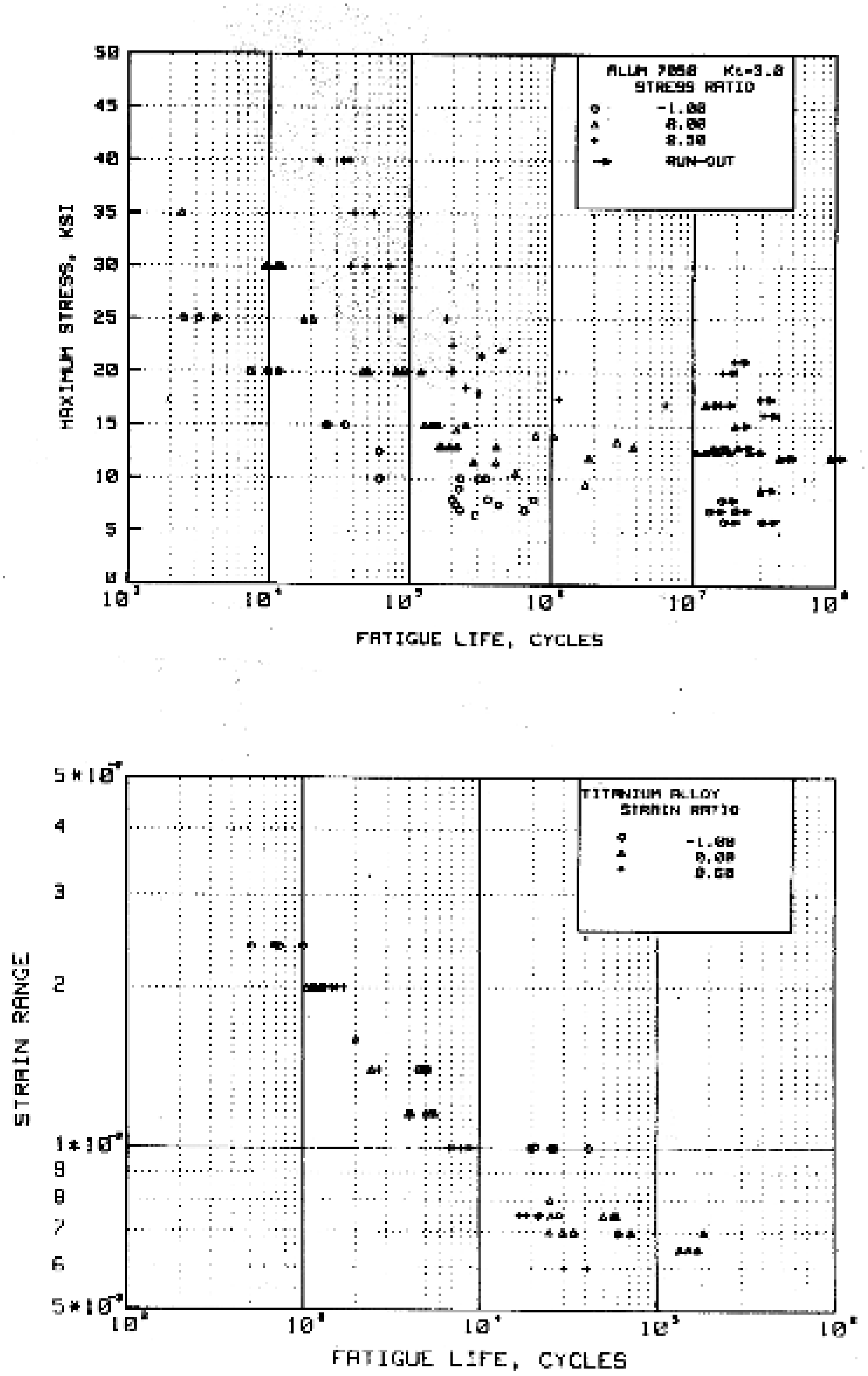

Figure 9.6.1(a). Examples of stress-life and strain-life fatigue trends.

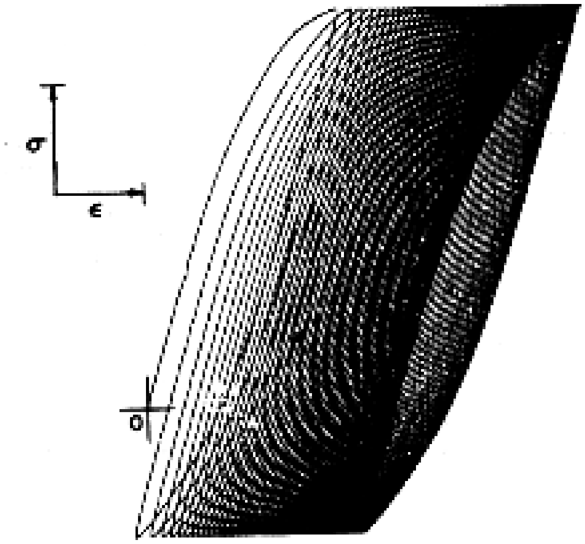

Figure 9.6.1(b). Example of cyclic creep phenomenon that can occur in a load control test with a high tensile mean stress [Reference 9.6.1].

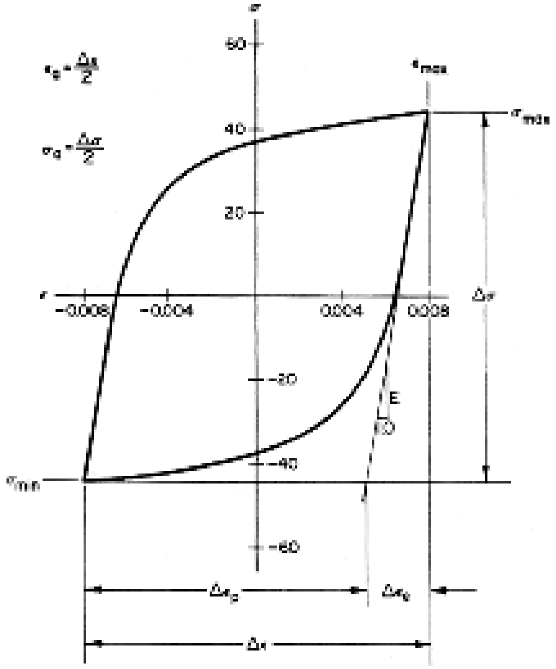

Figure 9.6.1(c). A typical hysteresis loop for a material tested in fatigue under strain control illustrating the relationship between stress and strain parameters.

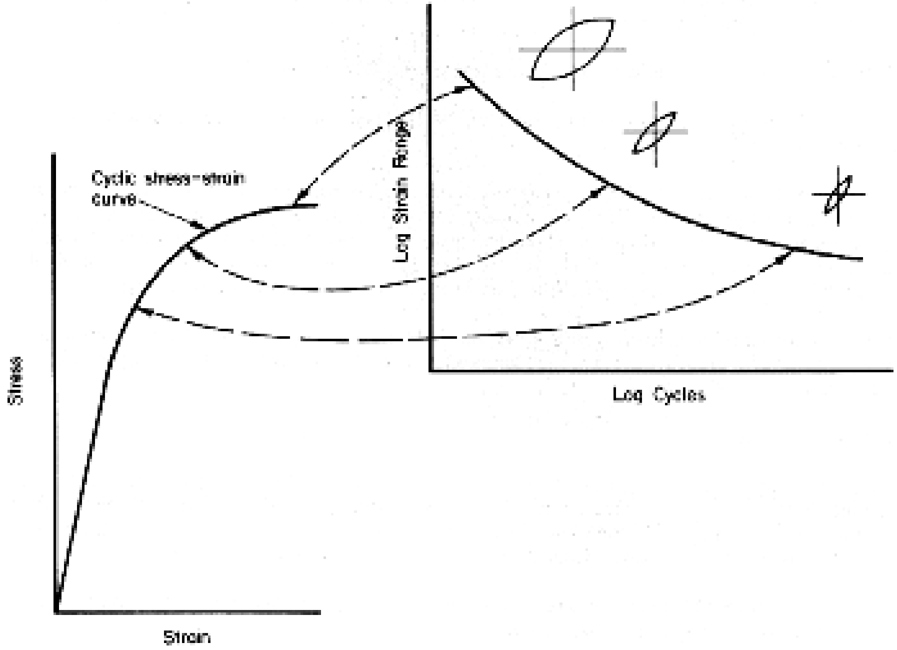

Figure 9.6.1(d). An example of a strain-life fatigue curve and the stress-strain response at short, intermediate, and long fatigue lives.

A number of factors can significantly influence fatigue properties for a particular material—whether the data are developed under load or under strain control. The surface condition (such as surface roughness) of the test specimens is an important factor. The methods used for fabricating the specimens are also important—principally because such methods influence the state of surface residual stresses and residual stress profiles. Other factors such as mean stress or strain, specimen geometry (including notch type), heat treatment, environment, frequency and temperature can also be significant variables. In MIL-HDBK-5, fatigue data are always presented in separate displays for different theoretical stress concentration factors. However, data sets may be presented for various combinations of variables if preliminary analyses indicate that the data sets are compatible. In any case, it is very important to fully document both the input data and their resulting illustrations in MIL-HDBK-5 with regard to variables that can influence fatigue.

The selection of the specific procedures and methods that are outlined in this guideline for fatigue data presentation should not be construed as an endorsement of these procedures and methods for life prediction of components. The selection was made for consistency in data presentation only. For the purpose of life prediction, other methods and models are also commonly employed. Depending on the material, component and loading history, other models may be more appropriate for the particular situation. It is beyond the scope of these guidelines to make recommendations with respect to a specific life prediction methodology (e.g., the construction of design allowable fatigue curves).

9.6.1.1 ***Data Collection and Interpretation*** — If a set of strain- or load-control data for a material of interest meet the minimum requirements, the data should be processed for analysis. Load-control data reports should clearly specify the net section stresses, stress ratios, and associated cycles to failure. Strain-control data reports should clearly specify the strain levels used, the stable stress response values, and the associated cycles to initiation and/or failure, along with a clear and concise definition of the failure criterion. Acceptable definitions of failure in a strain-control fatigue test report include:

(1) Total specimen separation

(2) Decrease of 50 percent in the maximum or stabilized tensile load value.

Acceptable definitions of crack initiation in a strain-control fatigue test report include:

(1) First significant deviation from the stabilized load range or a stabilized rate-of-change of the load range. Detection reliability is dependent upon the sensitivity of the monitoring equipment and consequently values as small as 1 to 5 percent are used in some cases, while values as great as 10 to 20 percent are used in other cases.

(2) Verifiable results from a calibrated nondestructive inspection device, such as an electrical potential drop system.

The definition of crack initiation or failure used in a particular study must be clearly and quantitatively documented. Correlative information that is important for load or strain-control test data includes detailed specimen dimensions, fabrication procedures (and their sequence), surface finish, product form, environment, frequency, waveform, surface residual stresses, and temperature. Other useful information includes average material tensile properties, product dimensions, and manufacturer.

All fatigue data that are not listed as invalid by the author of the test report will be prepared for analysis, except for specimens tested at a maximum stress level greater than the average tensile ultimate strength of the material. The identity of different sources should be retained to determine whether combinations of data are appropriate. If all conditions from the different sources are virtually identical, the data should be analyzed together. Data should be identified as invalid if defects in specimen preparation or testing procedures are discovered.

Runouts should be designated differently from failure data, since runouts are given special consideration in the regression analysis used to define mean fatigue curves. Runouts are generally defined as tests that have accumulated some predetermined number of cycles and have been subsequently stopped to reduce test time. Tests which have been stopped due to distinct problems encountered during testing are termed interrupted tests. Typical problems include power failures, temperature deviations, and load spikes. Interrupted tests are generally valid up until time at which the problem occurred. In this context, interrupted tests are treated the same as runouts in determining the mean fatigue-life trends of a data collection. However, if the interruption occurs long before expected failure of the specimen, the information contributed by the interrupted test is minimal, and the data point should be discarded.

Data from specimens which exhibit failures outside of the gage section may, in certain circumstances, be included in the analysis and treated as interrupted tests. Failures occurring just outside the gage section are essentially normal failures and should be included for analysis. In strain-control tests, however, the crack initiation is not sensed by the extensometer. Failures at threads, shoulders, or button heads may be indicative of a problem with the specimen design or test procedure.

Strain-control fatigue data must be accompanied by sufficient information to construct a cyclic stress-strain curve. The cyclic stress-strain curve may be established based on incremental stress-strain results or multiple specimen data for which stable stress amplitudes are defined for the complete range of strain ranges. The method used to define the cyclic stress-strain curve must be recorded so that it can be included in the correlative information along with the strain-life fatigue data displays.

9.6.1.2 *Analysis of Data* — Once a collection of data is reviewed (see Section 9.6.1.1) and compiled for the material of interest, analysis of that data may begin. An outline of the analysis procedure that is normally followed is given in Figure 9.6.1.2. Each of the elements in the flow chart are discussed in the following sections.

The same basic analysis procedure is used for strain- and load-control data except these data types are normally analyzed separately even if they represent the same material and product form. The only case where load- and strain-control data can be combined is the situation where some specimens have been switched from strain- to load-control testing. In this case, the load- and strain-control data may be analyzed on an equivalent strain basis. In all other cases, load-control data should be analyzed on an equivalent stress basis. Load-control data generated at different stress concentrations should always be analyzed separately.

9.6.1.3 *Fatigue Life Models* — To clarify the fatigue data trends for a specific stress or strain ratio, a linear regression model can be applied as follows:

$$\log(N_i \text{ or } N_f) = A_1 + A_2 \log(S_{max} \text{ or } \Delta\varepsilon). \qquad [9.6.1.3(a)]$$

Note that fatigue life is specified as the dependent variable. The alternative approach, using stress or strain as the dependent variable, is sometimes used, but this procedure will not be employed in developing mean fatigue curves in MIL-HDBK-5. The use of fatigue life or, more specifically, logarithm (base 10) of fatigue life as the dependent variable will be used since stress or strain is the controlled parameter in a fatigue experiment, and the resultant fatigue life is a random variable.

If Equation 9.6.1.3(a) does not adequately describe long-life data trends, a nonlinear model (or a more complicated linear model) may be warranted. For example, long-life, load-control data might be modeled by the nonlinear expression

$$\log N_j = A_1 + A_2(S_{max} - A_3) \qquad [9.6.1.3(a)]$$

or by the more complicated equation [Reference 9.6.1.3]

$$\log N_f = A_1 + A_2 \log S_{max} + A_3 \sqrt{\log S_{max} + A_4} \quad . \qquad [9.6.1.3(c)]$$

These more complex forms should only be employed in instances where they are warranted based on a distinct fatigue limit at long lives and when the simpler linear model was inadequate.

Standard least squares regression analysis and the procedure for detecting outliers in Section 9.6.1.6 require that the variance be relatively constant at all fatigue life values. Traditionally, the logarithm of fatigue life is approximated by a normal distribution. However, the variability or scatter of fatigue life is generally not constant, but increases with increasing fatigue life. To ensure the reliable use of the outlier detection procedure, a weighting scheme designed to produce a more uniform distribution of residuals is suggested in Section 9.6.1.5.

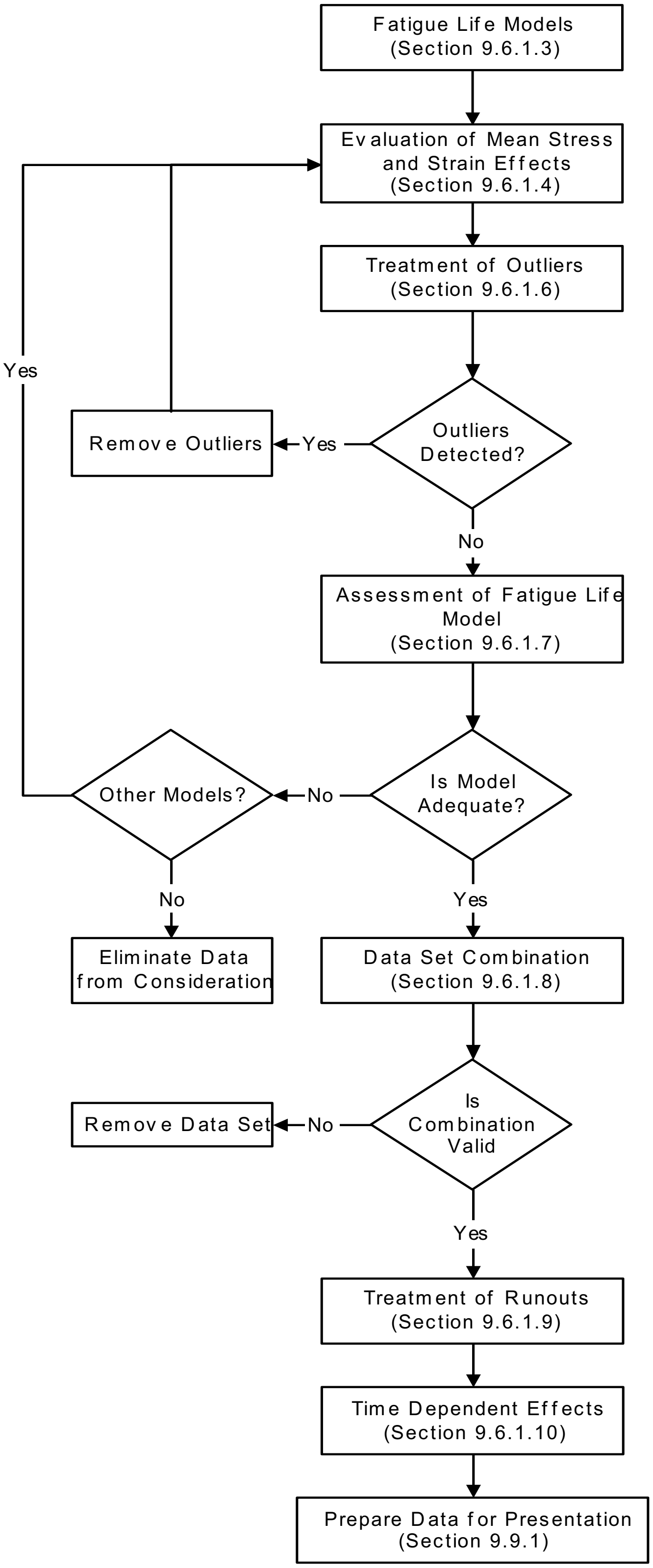

Figure 9.6.1.2. Flow chart of general fatigue analysis procedure.

9.6.1.4 ***Evaluation of Mean Stress and Strain Effects***—Commonly, load-controlled fatigue data generated over a range of stress ratios can be represented by the following equivalent stress-fatigue life formulation:

$$\log N_f = A_1 + A_2 \log (S_{eq} - A_4) \qquad [\,9.6.1.4(a)]$$

where

$$S_{eq} = (\Delta S)^{A_3} (S_{max})^{1-A_3}$$

$$S_{eq} = S_{max}(1 - R)^{A_3}$$

The equivalent stress model (and the related equivalent strain model) are derived from Reference 9.6.1.4(a).

Equation 9.6.1.4(a) is nonlinear in its general form and must, therefore, normally be optimized through use of a nonlinear regression package. However, the above equation can be solved through a linear analysis, if A_3 and A_4 are optimized through an iterative solution. The parameter A_3 normally lies in the range of 0.30 to 0.70, while A_4 represents, in essence, the fatigue limit stress. In cases where the optimum value of A_4 is negative or insignificant, it should be omitted. Unnotched data, especially aluminum alloy data, can frequently be represented without using the nonlinear A_4 term. Parameter optimization is discussed more thoroughly in Section 9.6.1.5.

If A_4 is zero or set equal to zero, Equation 9.6.1.4(a) becomes linear in log S_{max} and log (1-R), and it can be written as follows:

$$\log N_f = A_1 + A_2 \log S_{max} + B \log (1-R) \qquad [\,9.6.1.4(b)]$$

where $B = A_2A_3$. Thus, if A_4 is zero, then

$$A_3 = B/A_2$$

Strain-controlled fatigue data generated over a range of strain ratios often can be consolidated by the following equivalent strain formulation:

$$\log N_f = A_1 + A_2 \log (\varepsilon_{eq} - A_4) \qquad [\,9.6.1.4(c)]$$

where

$$\varepsilon_{eq} = (\Delta\varepsilon)^{A_3} (S_{max}/E)^{1-A_3} \quad .$$

Note that Equation 9.6.1.4(c) is very similar in form to Equation 9.6.1.4(a). It is important to note, however, that the maximum stress value used in Equation 9.6.1.4(c) is not a controlled quantity. It is a measured quantity and its magnitude depends primarily on the amount of cyclic softening or hardening that occurs in combination with mean stress relaxation. Although S_{max} can be predicted with reasonable accuracy if the cyclic response of the material is well established, using the stable measured values of S_{max}, when analyzing strain-control data for presentation in MIL-HDBK-5, is preferred.

The equivalent stress and strain approaches are very useful for computing mean fatigue life estimates for conditions intermediate to those for which the test data have been generated. Caution should be used, however, in making life predictions for stress/strain conditions beyond the range of those represented in the data base. Also, when only two stress/strain ratios are used in the equivalence formulation, fatigue life estimates at conditions other than those two ratios (either intermediate or beyond) may be unreliable.

If the basic formulations just described do not realistically represent the data, alternative equivalent stress or strain formulations should be considered. Two formulations [References 9.6.1.4(b) and (c)], in particular, may apply in these specific instances where equivalent stress is defined as:

$$S_{eq} = S_a + A_3\ S_m \qquad [9.6.1.4(d)]$$

or

$$S_{eq} = S_a + S_m^{A_3} \qquad [9.6.1.4(e)]$$

and equivalent strain is defined as:

$$\varepsilon_{eq} = \varepsilon_a + A_3\ S_m/E \qquad [9.6.1.4(f)]$$

or

$$\varepsilon_{eq} = \varepsilon_a + (S_m/E)^{A_3} \qquad [9.6.1.4(g)]$$

where

S_{eq}	= equivalent stress	ε_{eq}	= equivalent strain
S_a	= alternating stress	S_m	= mean stress
ε_a	= alternating strain	E	= elastic modulus (from each test result).

Other data consolidation parameters may also be used provided they do not violate other guideline requirements, and they can be proven adequate. Adequacy may be assessed by employing the procedures described in Section 9.6.1.7.

To evaluate the adequacy of one equivalent stress or strain formulation compared to another, it is useful to construct a plot of residuals versus stress or strain identifying individual stress or strain ratios. In this way the usefulness of a given formulation for modeling stress or strain ratio effects is visually apparent.

9.6.1.5 *Estimation of Fatigue-Life Model Parameters* — The fatigue-life model parameters are estimated to obtain the best-fit S/N or ε/N curve for the data. The procedure used to determine the parameters includes a statistical method for adjusting the fatigue model for the nonconstant variance commonly observed in long-life fatigue data. The motivation for this adjustment is the fact that constant variance is an inherent assumption in least squares regression analysis. To estimate the parameters in Equation 9.6.1.4(a) or Equation 9.6.1.4(c) and adjust the model to incorporate nonuniform variance, the following six-step procedure is performed.

Step 1 - Initial Parameter Estimates. If A_4 is assumed to be zero, then a linear least squares regression analysis is performed to obtain the initial parameter estimates for A_1, A_2, and A_3. If A_4 is to be estimated from the data, a nonlinear least squares regression analysis is performed to obtain the initial parameter estimates for A_1, A_2, A_3, and A_4. Runout observations above the minimum equivalent stress (strain) at which a failure occurred should be included in the calculation of the initial parameter estimates and residuals.

To facilitate convergence of the nonlinear least squares fit when A_4 is to be estimated from the data, the following procedure may be used to obtain starting values. Set A_3 equal to 0.5 and calculate equivalent stress (strain) values for each observation. Set A_4 equal to one-half the smallest equivalent stress (strain) not associated with a runout. Using these values of A_3 and A_4 as constants, obtain least squares estimates of A_1 and A_2 using a linear regression routine.

Step 2 - Fitting the Variability Model. The magnitude of the residuals from these fatigue-life models typically increases with decreasing stress or strain as illustrated in Figure 9.6.1.5(a). The residuals plotted are the observed log(life) values minus the predicted log(life) values.

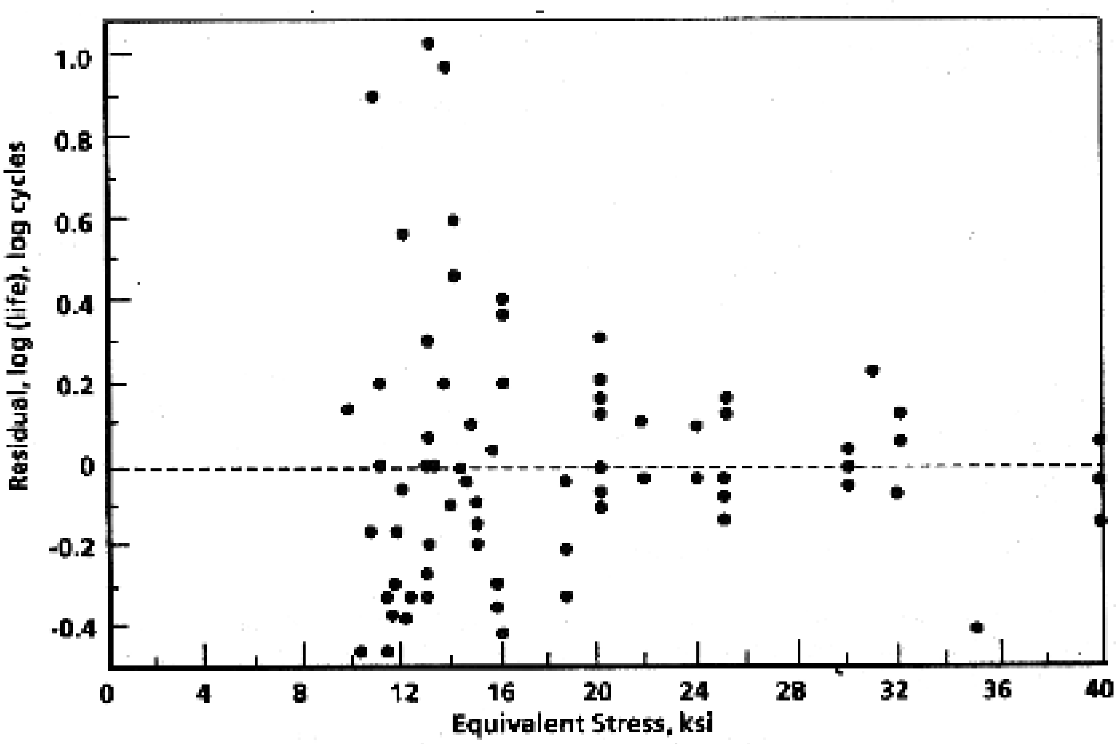

Figure 9.6.1.5(a). Example plot showing increasing magnitude of residuals with decreasing stress/strain levels.

To evaluate the fatigue-life model for nonuniform variance, it is useful to construct a model to estimate the standard deviation of log(life) as a function of equivalent stress (strain). If there is nonuniform variance, such a model can then be used to perform a weighted regression to estimate the fatigue life model parameters where the weight for each observations inversely proportional to its estimated variance.

The suggested standard deviation model is

$$\frac{|R|}{\sqrt{2/\pi}} = \sigma_o + \sigma_1 \left[\frac{1}{S_{eq}}\right] = g(S_{eq}) \qquad [9.6.1.5(a)]$$

or

$$\frac{|R|}{\sqrt{2/\pi}} = \sigma_o + \sigma_1 \left[\frac{1}{\varepsilon_{eq}}\right] = h(\varepsilon_{eq}) \qquad [9.6.1.5(b)]$$

where R (observed log(life) minus predicted log(life)) represents the residuals from the fatigue life model fitted in Step 1. This model assumes that the standard deviation of log(life) is a linear function of the reciprocal of equivalent stress (strain). The absolute values of the residuals are divided by $\sqrt{2/\pi}$ so that $g(S_{eq})$ or $h(\varepsilon_{eq})$ is an estimate of the standard deviation of log(life).

The intercept, σ_o, and the slope, σ_1, are first estimated by ordinary least squares. If the least squares estimate of σ_o is negative, σ_o should be set to zero and σ_1 should be estimated by performing a least squares regression through the origin (no intercept term). A 90 percent confidence interval for σ_1 should also be obtained. If the lower bound of the confidence interval for σ_1 is positive, there is evidence of nonuniform variance and one should proceed to Step 3A. If the confidence interval for σ_1 contains zero, there is no evidence of nonuniform variance and one should proceed to Step 3B. If the upper bound of the confidence interval for σ_1 is negative, this indicates abnormal behavior requiring further examination of the data set before proceeding with the analysis.

Figure 9.6.1.5(b) is a plot of the absolute values of the residuals from Figure 9.6.1.5(a) versus the reciprocal of equivalent stress. The slope and vertical intercept of the least squares line displayed in this plot are the estimated parameters σ_1 and σ_o.

Step 3A - Fitting the Weighted Fatigue Model. Adjust the fatigue model for nonconstant variance by dividing each term in the model by $g(S_{eq})$ or $h(\varepsilon_{eq})$, the estimated standard deviation of the dependent regression variable. If the four-parameter fatigue model is being used, the adjusted model becomes

$$\left[\frac{\log(N)}{g(S_{eq})}\right] = A_1 \left[\frac{1}{g(S_{eq})}\right] + A_2 \left[\frac{\log(S_{eq} - A_4)}{g(S_{eq})}\right] \qquad [9.6.1.5(c)]$$

or

$$\left[\frac{\log(N)}{g(\varepsilon_{eq})}\right] = A_1 \left[\frac{1}{g(\varepsilon_{eq})}\right] + A_2 \left[\frac{\log(\varepsilon_{eq} - A_4)}{g(\varepsilon_{eq})}\right] \qquad [9.6.1.5(d)]$$

where S_{eq} and ε_{eq} are defined in Equations 9.6.1.4(a) and 9.6.1.4(c). Perform a nonlinear least squares regression analysis (no intercept) using the adjusted model to obtain new estimates of A_1, A_2, A_3, and A_4.

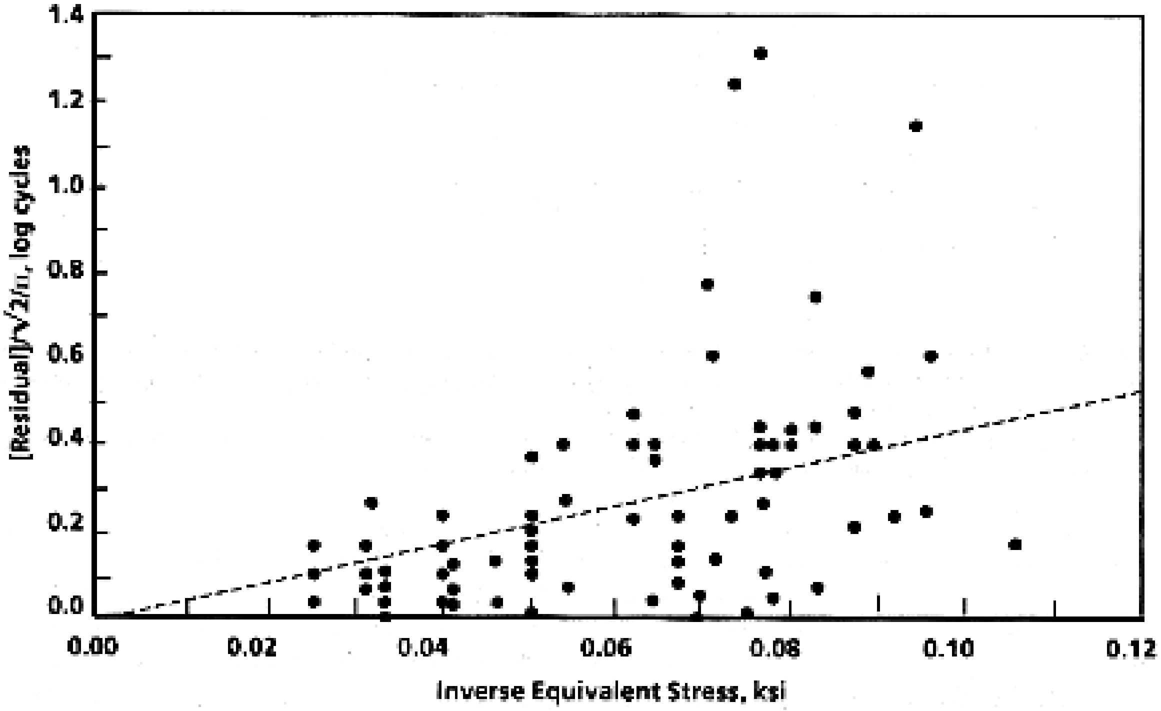

Figure 9.6.1.5(b). Example plot showing the magnitude of the residuals versus the inverse of equivalent stress/strain levels.

When performing this regression, all runouts above the minimum S_{eq} or ε_{eq} at which a failure occurred should be included in the analysis and treated as failures. The inclusion of runouts in this step should be determined based on equivalent stress (strain) values using the value of A_3 estimated in Step 1. Assuming that the equivalent stress/strain model is valid, this qualifying stress/strain level allows the use of all runouts above stresses or strains at which failures have been observed. Below this level, there is no statistical evidence that discontinued tests would have failed. Therefore, runouts below the minimum S_{eq} or ε_{eq} value at which a failure occurred are not assigned finite life values in estimating the parameters.

It should be noted that the regression analysis performed using the adjusted model [Equation 9.6.1.5(c) or (d)] is equivalent to performing a weighted least squares regression analysis using the original fatigue life model [Equation 9.6.1.4(c)] and weights equal to $1/g^2(S_{eq})$ or $1/g^2(\varepsilon_{eq})$. Also, it may be desirable in certain situations to fit alternative standard deviation models to the residuals from Step 1. In this case, simply redefine $g(S_{eq})$ or $g(\varepsilon_{eq})$ to be equal to the desired model and follow Steps 1 through 3 above. Upon completion of Step 3A, proceed to Step 4.

Step 3B - Fitting the Unweighted Fatigue Model. Using the initial estimate of A_3 obtained in Step 1, calculate equivalent stress (strain) values for all observations including runouts. All runouts above the minimum equivalent stress (strain) at which a failure occurred should be included in the analysis and treated as failures. (See Step 3A for an explanation of this rationale.) Using the same regression techniques employed in Step 1, obtain least squares estimates of the parameters A_1, A_2, A_3, and A_4.

Step 4 - Testing the Significance of Model Parameters. Obtain a 90 percent confidence interval for A_4. If the lower bound of the confidence interval is negative, there is no evidence that A_4 is different from zero. In this case, assume A_4 is equal to zero and repeat Step 3A or 3B, eliminating A_4 from the model.

Next, obtain a 90 percent confidence interval for A_2. If the upper bound of the confidence interval is negative, this indicates that the relationship between log(life) and equivalent stress (strain) is significant. If the upper bound of the confidence interval is positive, there is no evidence of a significant relationship between log(life) and equivalent stress (strain) and the data set should be examined further before proceeding with the analysis.

Step 5 - Re-estimating A_1 and A_2. If a weighted least squares analysis was performed in Step 3A, A_1 and A_2 should be re-estimated to include the effect of the new value of A_3 on the calculation of weights and the inclusion of runouts. First, recompute the weights $g(S_{eq})$ or $g(\varepsilon_{eq})$ using the value of A_3 obtained in Step 3A. Then perform a linear regression (no intercept) to obtain updated estimates of A_1 and A_2 in Equation 9.3.4.10(c) or (d) treating A_3 as a constant. The inclusion of runouts in this linear regression should be determined based on equivalent stress (strain) values using the value of A_3 obtained in Step 3A.

Step 6 - Estimating the Standard Deviation and Calculating Standardized Residuals. The method for estimating the "standard deviation of log(life)" (SD) depends on whether there is evidence of nonuniform variance in the fatigue life data. If an unweighted regression was performed in Step 3B to obtain the model parameters, SD should be set equal to the root mean square error (RMSE) associated with the fitted and unweighted fatigue life model. In this case, SD may be calculated as

$$SD = RMSE = \sqrt{\sum_{i=1}^{n} R_i^2/(n-k)} \qquad [\,9.6.1.5(e)]$$

where k is the number of parameters estimated in Step 3, and

$$R_i = \log N_i - \widehat{\log N_i} \qquad [9.6.1.5(f)]$$

where R_i is the residual, $\log N_i$ is the logarithm of observed number of cycles, and $\widehat{\log N_i}$ is the logarithm of predicted number of cycles associated with the ith observation.

If a weighted regression was performed in Step 3A to obtain the model parameters, SD should be reported as linear function of the reciprocal of equivalent stress (strain). This function should be obtained by multiplying the fitted standard deviation model $g(S_{eq})$ or $g(\varepsilon_{eq})$ from Step 2 by the root mean square error (RMSE) associated with the fitted and weighted fatigue life model to obtain an updated standard deviation model. In this case, SD may be calculated as

$$SD = RMSE * (\sigma_0 + \sigma_1/S_{eq}) \qquad [9.6.1.5(g)]$$

or

$$SD = RMSE * (\sigma_0 + \sigma_1/\varepsilon_{eq}) \qquad [9.6.1.5(h)]$$

where

$$\text{RMSE} = \sum \text{WR}_i^2/(n - k) \quad , \qquad [9.6.1.5(i)]$$

k is the number of parameters estimated in Step 3, and

$$\text{WR}_i = \frac{\log N_i - \widehat{\log N_i}}{g\left(S_{eq,i} \text{ or } \varepsilon_{eq,i}\right)} \qquad [9.6.1.5(j)]$$

with WR_i denoting the weighted residual and $S_{eq,i}(\varepsilon_{eq,i})$ the equivalent stress (strain) associated with the "ith" observation.

As a final step associated with the estimation of fatigue life model parameters, standardized residuals should be calculated for use in the judging the appropriateness of the fitted model. Standardized residuals are calculated as

$$\text{SR}_i = R_i/\text{SD} \qquad [9.6.1.5(k)]$$

where the form of the residual R_i is given in Equation 9.6.1.5(f) and the estimated standard deviation SD is given by either Equation 9.6.1.5(e) or 9.6.1.5(h), (j) or (k).

Figure 9.6.1.5(c) is a plot of the standardized residuals for the same data plotted in Figure 9.6.1.5(d) but based on a standard deviation model to correct the nonuniform variance. Note that the pattern of nonconstant variance has been eliminated.

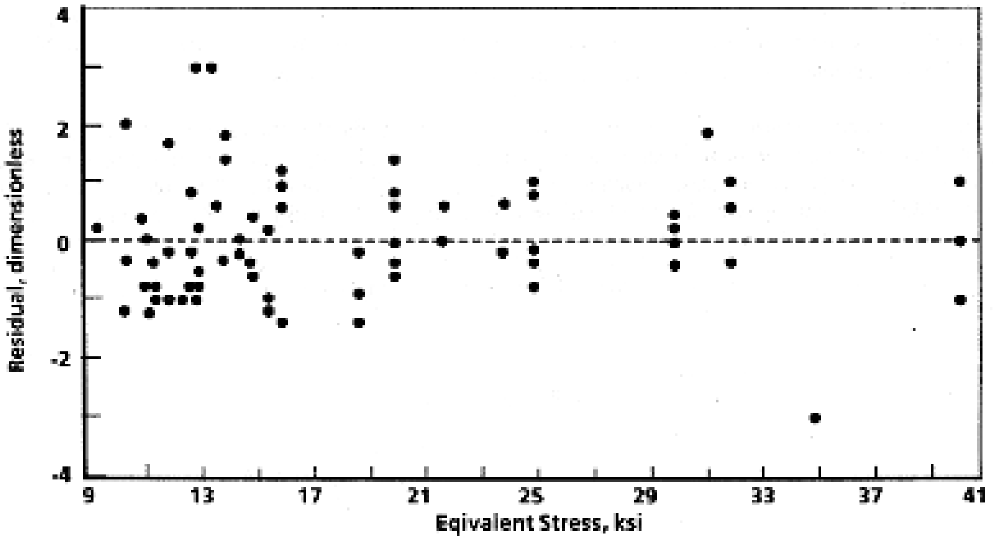

Figure 9.6.1.5(c). Example plot showing constant variance of standardized residuals.

Note - When performing any of the regression analyses described above to estimate the parameters A_1, A_2, A_3, and A_4, the estimate of A_4 should be restricted to be greater than or equal to zero. Some regression programs allow such restrictions as an option. If such an option is not available and if the estimate of A_4 is negative, set A_4 equal to zero and refit the model treating A_4 as a constant. Also note that the parameter estimates obtained from the regression analysis of Step 3A or 3B need not necessarily be reported as the final parameter estimates. If the data set includes runout observations, final estimates of the A_1 and A_2 parameters may be calculated using the maximum likelihood techniques presented in Section 9.6.1.9, provided that software for performing this procedure is available.

9.6.1.6 *Treatment of Outliers* — An outlying observation (or outlier) is one that appears to deviate markedly from other observations in the sample in which it occurs. Outliers may essentially be classified into two groups:

(1) An extreme value of the random variable inherent in the data (in this case fatigue life). If this is true, the value should be retained in future analyses.

(2) An unusual result caused by a gross deviation in material or prescribed experimental procedure or an error in calculating or recording any experimental data.

An outlier of the second type is sometimes correctable by a review of the test sample and/or test records, which may provide sufficient evidence for rejection of the observation. An outlying value from a failure that occurred in the fillet of an unnotched fatigue test sample is an example of a potentially rejectable result based on physical evidence alone. The more difficult case is one where an observation is an obvious outlier and no physical reasons can be identified to justify its exclusion.

Assuming uniform variance in the standardized residuals over the complete range in equivalent stress or strain, the problem of identifying certain observations as potential outliers should be addressed as follows. Calculate the studentized residuals,

$$T_i = \frac{SR_i}{(1 - h_i)^{1/2}} \left[\frac{RMSE}{RMSE(i)}\right] \qquad [9.6.1.6(a)]$$

for i = 1, ..., n where SR_i is the standardized residual from Equation 9.6.1.5(k), RMSE is the root mean square error based on the entire sample as calculated in either Equation 9.6.1.5(e) or Equation 9.6.1.5(i), and RMSE(i) is the root mean square error based on the sample which excludes the ith observation as calculated by either Equation 9.6.1.5(e) or Equation 9.6.1.5(i).

The value h_i is calculated using the formula

$$h_i = \frac{X_{1i}^2 \left(\Sigma X_{2j}^2\right) - 2\, X_{1i}X_{2i} \left(\Sigma X_{1j}X_{2j}\right) + X_{2j}^2\left(\Sigma X_{1j}^2\right)}{\left(\Sigma X_{1j}^2\right)\left(\Sigma X_{2j}^2\right) - \left(\Sigma X_{1j}X_{2j}^2\right)} \qquad [9.6.1.6(b)]$$

where X_{1i} is the value of 1/SD for the ith specimen, X_{2i} is the value of $\log(S_{eq}-A_4)/SD$ for the ith specimen and all summations are over j = 1, ..., n. Note that

$$\mathrm{RMSE}^2(i) = \frac{(n - k)\mathrm{RMSE}^2 - SR_1^2/(1 - h_i)}{(n - k - 1)} \qquad [9.6.1.6(c)]$$

where RMSE is the root mean square error based on the entire sample as calculated in either Equation 9.6.1.5(e) or Equation 9.6.1.5(k) and k is the number of parameters estimated in Step 3 of Section 9.6.1.5.

It can be shown that each T_i has a central t distribution with n-k-1 degrees of freedom. Applying the Bonferroni inequality [Reference 9.6.1.6] to obtain a conservative critical value leads to the following outlier test. Calculate the maximum absolute studentized residual

$$G = \max \left[T_i\right] \qquad [9.6.1.6(d)]$$

and declare the data value corresponding to G to be an outlier if

$$G > t(\alpha/2n,\ n - k - 1) \qquad [9.6.1.6(e)]$$

where $t(\alpha/2n, n\text{-}k\text{-}1)$ is the upper $\alpha/2n$ percentile point of the central t distribution with n-k-1 degrees of freedom and α represents the significance level of the outlier test. Under the hypothesis that no outliers are present in the data, the probability is less than α that the data value corresponding to G will be falsely declared an outlier.

In applying this test to fatigue life data, a significance level of $\alpha = 0.05$ is used and the test is first applied to the entire sample. If an outlier is detected, the outlying observation is removed from the sample and the entire analysis is repeated on the smaller sample of n-1 observations starting with Step 1 of Section 9.6.1.5. (When a nonlinear least squares fit is performed in Step 1, use the current estimates for A_1, A_2, A_3, and A_4 as starting values rather than following the starting value algorithm.) This process of removing outliers and repeating the analysis continues until no outliers are detected in the remaining sample. For strain-control data, apply the procedure described above replacing S_{eq} with ε_{eq} throughout.

The data analyst may also wish to carry out the outlier test procedure using a significance level of $\alpha = 0.20$ in order to identify additional observations that may warrant investigation. To identify even more suspect observations, a larger significance level may be used. Any data values identified by this procedure should be examined but retained in the data set unless physical evidence justifies their exclusion.

9.6.1.7 ***Assessment of the Fatigue Life Model*** — The fit of the fatigue model S/N curve to the data may be assessed in two ways—the adequacy of the equivalent stress/strain model and the adequacy of the fatigue life model. The equivalent stress model lack of fit test and the overall lack of fit test described below provide a reasonable assessment of the fatigue life model.

When three or more stress (strain) ratios are used, the fit of the equivalent stress (strain) model may be tested by determining the relationship between the standardized residuals from Equation 9.6.1.5(k) and stress (strain) ratio. A difference in the means of the standardized residuals at each stress (strain) ratio indicates that the equivalent stress (strain) model is inadequate. To determine whether or not there is a statistically significant difference in the means of the standardized residuals at each stress (strain) ratio, an analysis of variance should be performed on the standardized residuals using stress (strain) ratio as the treatment variable. A statistical F-test should be used to determine if the effect of stress ratio is significant at the 5 percent level [Reference 9.6.1.7]. The equivalent stress (strain) model should be considered inadequate when the effect of stress (strain) ratio is significant according to the statistical F-test.

The plot of the standardized residuals versus stress ratio shown in Figure 9.6.1.7(a) illustrates such a relationship between the standardized residuals and stress ratio. Since there would be no such relationship if the equivalent stress model were adequate, the plot indicates that the equivalent stress model must have been misspecified in this case. In addition to the lack of fit shown by differences in standardized residual means, other types of lack of fit could exist. Therefore, it would be prudent to examine stress-life plots in addition to performing the statistical test for lack of fit of the equivalent stress model.

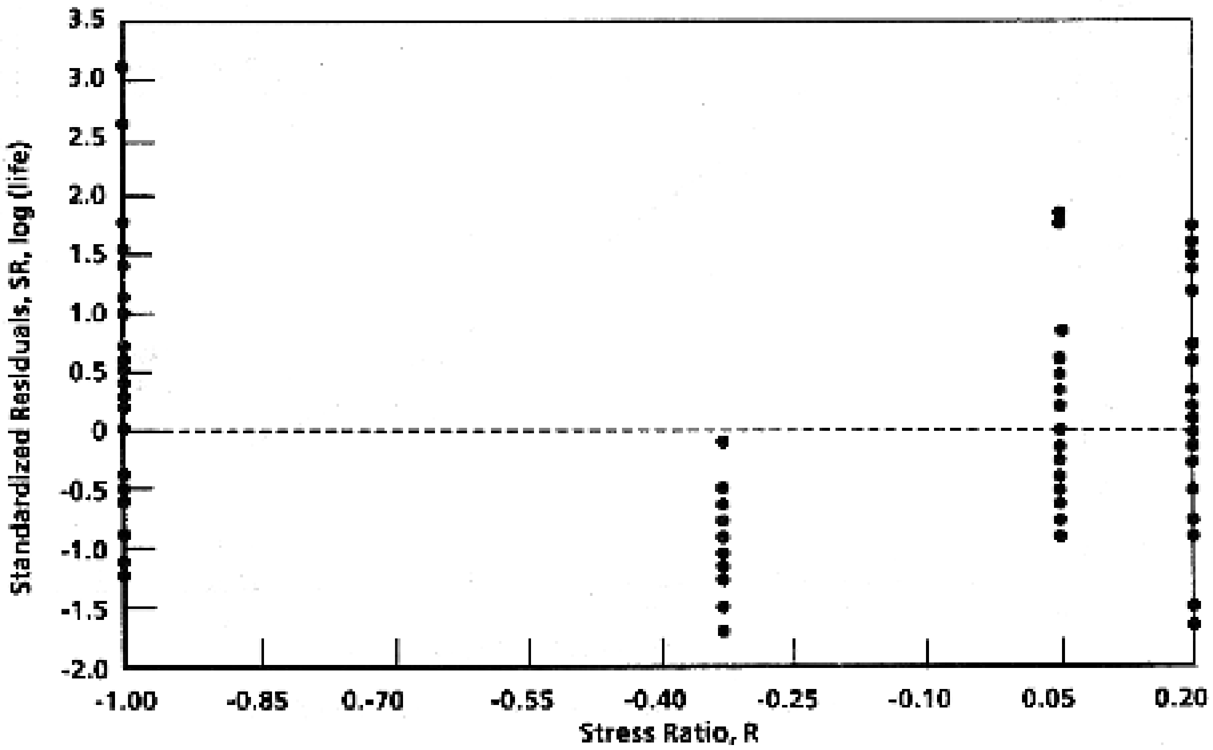

Figure 9.6.1.7(a). Standardized residuals versus stress ratio.

If the equivalent stress (strain) model is inappropriate, then a new equivalent stress (strain) model should be selected. When a suitable stress (strain) model is not available, an alternative strategy is to present the data with best fit regression lines for each stress (strain) ratio. To be acceptable, each curve must meet minimum data requirements and satisfy significance checks as discussed in Section 9.6.1.5. This approach is less desirable than the equivalent stress (strain) modeling approach because it requires the estimation of fatigue trends using a graphical technique for intermediate conditions where no data exist. It should, therefore, be used only in cases where significant fatigue data collections cannot be handled by standard procedures.

Once an equivalent stress (strain) model has been found that describes the general fatigue data trends for all stress (strain) ratios, an overall test of the fit of the fatigue model should be performed. The stress-life plot shown in Figure 9.6.1.7(b) is characteristic of an overall lack of fit. To identify such a lack of fit, the Durbin-Watson test may be used [Reference 9.6.1.7]. The statistic D should be computed according to the formula

$$D_i = \frac{\sum_{i=2}^{n} (SR_i - SR_{i-1})^2}{\sum_{i=1}^{n} SR_i^2} \qquad [9.6.1.7(a)]$$

where SR_i is the ith standardized residual [Equation 9.6.1.5(k)] ordered by increasing values of equivalent stress(strain).

If

$$D < 2 - 4.73/n^{0.555} \qquad [9.6.1.7(b)]$$

conclude that there is a significant lack of fit at the 5 percent significance level. This equation was derived from the conservative critical value (d_L) reported in Table A.6 of Montgomery and Peck [Reference 9.6.1.7]. When an overall lack of fit is determined from this test, the modeling procedure should be repeated with a more appropriate fatigue model.

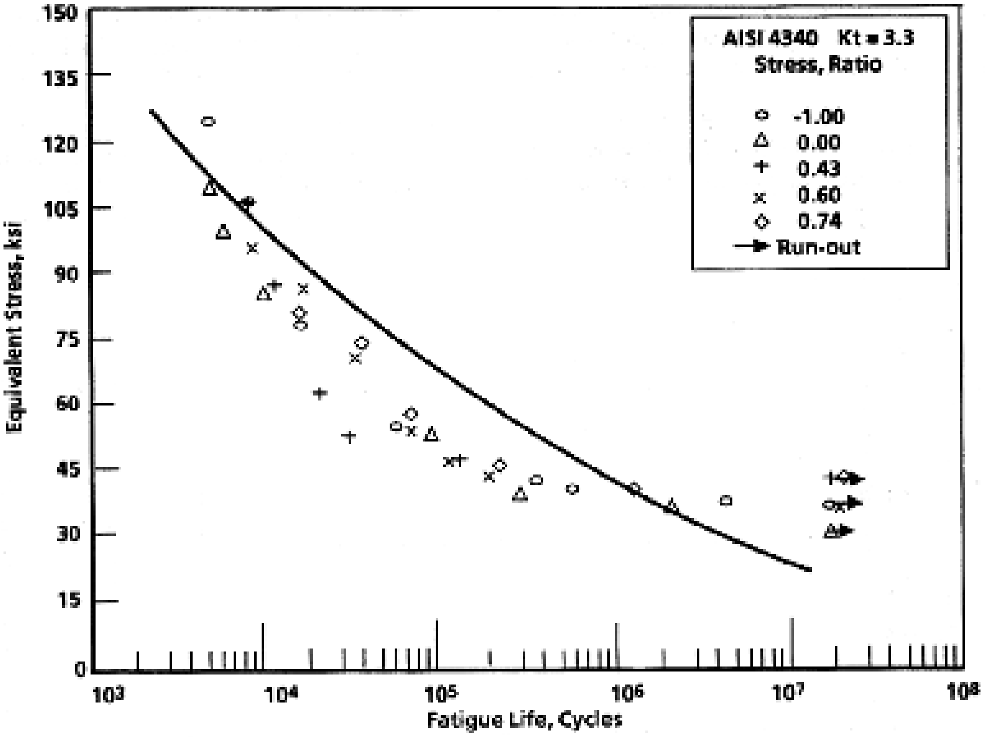

Figure 9.6.1.7(b). Stress-life plot showing lack of fit.

9.6.1.8 ***Data Set Combination*** — In many cases, data from different sources, orientations, etc., may need to be combined for analysis. When data set combinations of this sort are performed, the validity of the combination should be tested with the method described below. The test is similar to that used to determine the adequacy of the equivalent stress (strain) model in the previous section.

If there is a relationship between the standardized residuals from Equation 9.6.1.5(k) and the data set from which they were obtained, such as that shown in Figure 9.6.1.8, then the data sets should normally not be combined. To determine whether or not the mean of the standardized residuals is significantly different for any of the data sets, an analysis of variance should be performed on the standardized residuals using data set as the treatment variable. The analysis of variance F-test should be used to determine if the combined data sets are significantly different at the 5 percent level.

When the data sets are found to be significantly different, at least one of the data sets should normally be removed from the data set combination. In this situation, the data analyst may wish to apply a standard multiple comparison procedure to the standardized residual data to determine which standardized residual means are significantly different from the others. For a discussion of standard multiple comparison procedures, see pages 185-201 of Winer [Reference 9.6.1.8].

There may be situations where differences between data sets are found to be statistically significant, yet these differences are so small as to be unimportant from an engineering standpoint. If a particular analysis reveals such a case, exceptions may be taken, if clearly noted and explained in the fatigue data proposal.

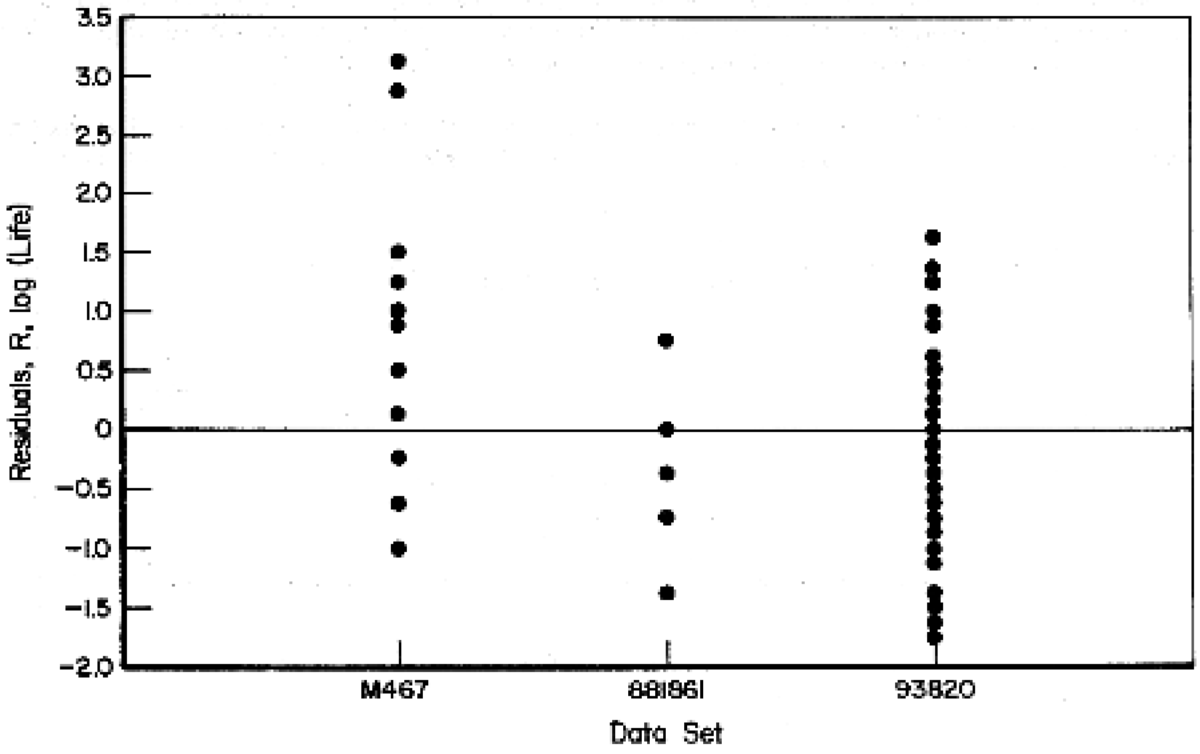

Figure 9.6.1.8. Standardized residual plot showing different mean trends between data sets.

9.6.1.9 ***Treatment of Runouts*** — It is difficult to incorporate information from runouts (or interrupted tests) when using the least squares criterion to fit fatigue life models to data since the failure times for these observations are not known. The runouts must be either ignored or treated as failures and neither of these alternatives adequately incorporates the information contained in the runout observations. Both of these approaches tend to produce smaller predicted lives at a given equivalent stress (strain) value than is appropriate. The treatment of runouts presented below is more appropriate but requires that two of the fatigue life model parameters be estimated by maximum likelihood techniques rather than by least squares procedures.

The maximum likelihood procedure is employed to obtain new estimates for the parameters A_1 and A_2 in Equation 9.6.1.4(a) or 9.6.1.4(c). For the purpose of this analysis, fatigue life (cycles to failure) is assumed to be log normally distributed and the parameters A_3 and A_4 are considered to be constants which are equal to the values obtained using the procedures of Section 9.6.1.5.

The estimated values of A_1 and A_2 obtained previously are used as initial values. The maximum likelihood procedure then determines the values of A_1 and A_2 which maximize the log-likelihood function

$$L(A_1,A_2,\sigma) = \sum_{i=1}^{n} (1 - d_i)\left[\left[\log\left(f(w_i)/\sigma\right)\right]\right] + d_i \log S(w_i) \qquad [9.6.1.9(a)]$$

where

$$f(w) = \frac{1}{\sqrt{2\pi}} \exp\left[-\frac{w^2}{2}\right] \qquad [9.6.1.9(b)]$$

is the standard normal density function,

$$S(w) = \int_{w}^{\infty} f(t)\ dt \qquad [9.6.1.9(c)]$$

is the survival function for the standard normal distribution, d_i is equal to 1 if the ith observation is a runout and zero otherwise, σ is a scale parameter to be estimated, and

$$w_i = \left[\frac{\log(N)}{SD}\right] - A_1\left[\frac{1}{SD}\right] - A_2\left[\frac{\log(S_{eq} - A_4)}{SD}\right] \qquad [9.6.1.9(d)]$$

where N is the cycles to failure and SD is the standard deviation for the ith observation as calculated from Equation 9.6.1.5(e) or Equation 9.6.1.5(h).

For more information on the maximum likelihood procedure, see Reference 9.6.1.9(a). For use in standard data analysis, the maximum likelihood procedure is conveniently implemented in some statistical software packages such as SAS [see Reference 9.6.1.9(b)].

When runouts are present, the fitted curve produced by maximum likelihood will generally predict longer average cycles to failure at given equivalent stress (strain) values than the fitted curve produced by least squares. Although it would be desirable to update all of the parameters in the fatigue model with maximum likelihood, algorithms to perform maximum likelihood on nonlinear models are not readily available. For this reason, the least squares estimates of the parameters A_3 and A_4 must be used.

9.6.1.10 ***Recognition of Time Dependent Effects*** — All prior discussion has been based on the assumption that time dependent effects in the fatigue data sample of interest are negligible. When dealing with elevated temperature fatigue properties of materials (or room temperature fatigue properties in a corrosive environment, for example), this assumption may not be realistic. Analysis methods that are approved for use in MIL-HDBK-5 do not account for time-dependent effects. Therefore, every effort must be made to identify data that embody significant time-dependent effects.

There are no absolute methods presently available for sensing time-dependent effects in fatigue data; however, there are some useful approximation techniques. One of the more useful approaches applied to "suspect" data is to include time-dependent terms in the regression model. If the terms are significant, there is reason to believe that the population contains time dependent data. Subdividing the data into subsets that do not show time dependent effect may be possible. If this is not possible, the data set should either be rejected or included with a disclaimer restricting usage of the data to predict performance at other frequencies or temperatures.

One other possible indicator of time dependent effects is an abnormal equivalent stress (strain) model. If data for different stress or strain ratios do not fit the customary models (as described in Section 9.6.1.4), or abnormal optimum parameters are defined the problem may be caused by time dependent effects. In the case of the primary equivalent stress (strain) formulation equation the exponent normally is between zero and one. If the A_3 exponent approaches or exceeds one, the influence of maximum stress on fatigue life is negligible. This is a very unusual result that usually indicates problems with the data sample. The problem may result from mixed sources, where the data from each source were generated at different stress (strain) ratios. Rejection of such data sets is discussed in Section 9.6.1.8. In the case of the primary equivalent stress model [Equation 9.6.1.4(a)], if the exponent (A_3) approaches or is less than zero, it indicates the influence of maximum stress on fatigue life is "too strong". This result implies that creep is affecting the data.

If data are available for a material at a range of different temperatures it may be possible to analyze these sets separately and make comparisons between best-fit mean trend lines for increasing temperatures. If the different mean trend lines are not consistent with the higher-temperature curves converging or diverging from the lower-temperature curves, there is probably a significant time-dependent effect in the data. The suspect data should either be excluded or included with a disclaimer as previously cited. If data are excluded for time-dependent effects, the preliminary analyses of those data should be included in the data proposal and reasons for their exclusion should be given.

9.6.2 FATIGUE CRACK GROWTH DATA — Fatigue-crack-propagation data, recorded in the form of crack-length measurements and cycle counts (a_i, N_i) can be presented as crack-growth curve drawn through the data points as shown in Figure 9.6.2(a).

Although data presented in this form indicate general trends, they are not generally useful for design purposes since a variety of stress levels, stress ratios, initial crack conditions, and environmental conditions are encountered.

It has been found convenient to model fatigue-crack-propagation damage behavior as rate process and formulate a dependent variable based on the slope of this growth curve, or an approximation to it, namely,

$$\frac{da}{dN} \simeq \frac{\Delta a}{\Delta N} \qquad [\,9.6.2(a)]$$

Results obtained from the theory of linear elastic fracture mechanics have suggested that rate process at the crack tip might be represented as a function of a stress-intensity factor, K, which, in general form, may be written as

$$K = S\sqrt{a}\ g(a,w) \quad , \qquad [9.6.2(b)]$$

where g(a,w) is a geometric scaling function dependent on crack and specimen geometry, and S is nominal stress. As a result, the independent variable is usually considered as some function of K. At present, in MIL-HDBK-5 the independent variable is considered to be simply the range of the stress intensity factor, ΔK, and data are considered to be parametric on the stress ratio, R, such that

$$da/dN \approx \Delta a/\Delta N = g(\Delta K,R) \quad , \qquad [\ 9.6.2(c)]$$

where $\Delta K = K_{max} - K_{min}$. Values of maximum and minimum stress intensity factors, K_{max} and K_{min}, respectively, are computed with Equation 9.6.2(b) using respective maximum and minimum cyclic stresses.

A crack growth rate curve, as shown in Figure 9.6.2(b), is obtained by plotting the locus of points (da/dN, ΔK) derived from the crack-growth curve [see Figure 9.6.2(a)] at selected values of crack length, a. Crack-growth-rate curves are generally plotted on log-log coordinates.

Within the general curve shape described above, systematic variations in data point locations are observed. When data from tests conducted at several different stress ratios are present, the plot of crack-growth rate versus stress-intensity-factor range will be layered into distinct bands. Layering of data points may also occur as a result of variation in such parameters as test frequency, environment, temperature, and specimen grain direction.

9.6.2.1 *Data Collection and Interpretation* — Reporting of basic crack-growth data will be as complete as possible. In addition to reporting cyclic loading conditions, such as maximum cyclic load and/or stress levels, stress ratio, test frequency, and specimen dimensions, it is particularly important to identify environmental conditions associated with the tests. The number of specimens and number of respective heats should also be identified. Table 9.9.2 serves as an example of the type of information which should be available (or at least is desirable) for each collection of FCP data.

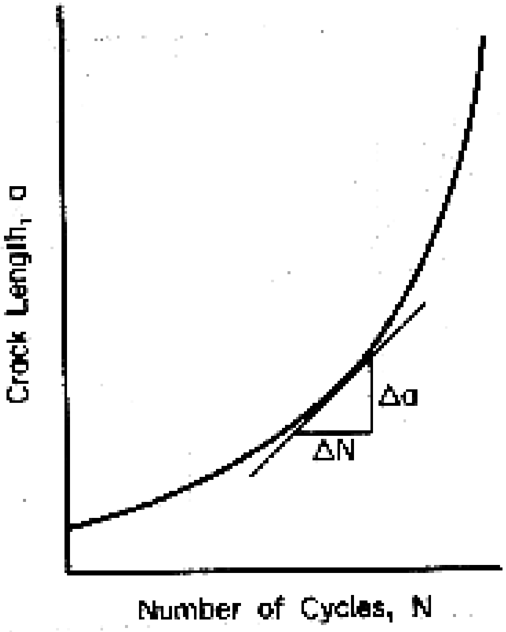

Figure 9.6.2(a). Crack-growth curve.

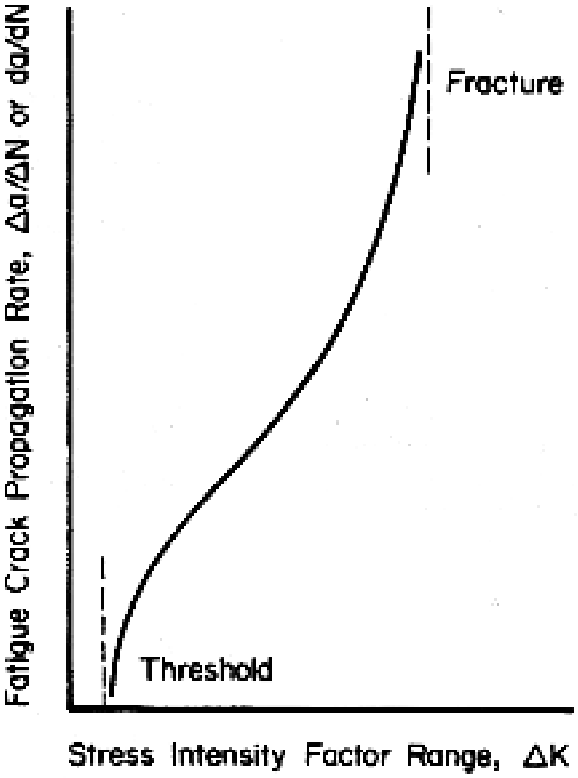

Figure 9.6.2(b). Crack-growth-rate curve.

9.6.3 FRACTURE TOUGHNESS DATA — Fracture toughness of a material is its ability to resist flaw propagation and fracture. This characteristic is a generic quality, somewhat elusive to assess quantitatively. Of several measures of fracture toughness which have evolved for appraising the sensitivity of metals to the presence of small flaws, those based on crack stress or strain analysis appear to be more meaningful for use in design applications. Significant quantification of fracture and flaw propagation behavior of high-strength metals has been achieved through the concept of stress intensity factors. Typical room-temperature values and effect-of-temperature curves for critical stress intensity factors are presented in MIL-HDBK-5 for "information only" where data are available. Basic concepts, testing considerations, and interpretations of fracture toughness are briefly described in the following subsections.

A primary factor in fracture behavior of a material is stress state, i.e., plane-stress or plane-strain. In accord with previous definitions, these stress states may be interpreted mechanically as a size or thickness effect within the material. The ideal plane-stress condition occurs in the two-dimensional ($\sigma_z = 0$) case, in which all stresses are restricted to one plane. Typically material loaded in plane-stress can accommodate extensive plastic deformation adjacent to the flaw prior to fracture, and at fracture exhibit a relatively high K value, as computed by a relationship such as Equation 9.6.2. At the opposite extreme is the ideal plane-strain case, in which the third dimension is essentially infinite so that bulk restraint of the material permits no out-of-plane strains. As a result, plastic deformation is restricted and the material fractures in a nearly elastic manner at a relatively low K value. In real materials, these ideal extremes can be closely approximated by "quasi" conditions of "thin" and "thick" bodies. Variation in stress intensity at fracture over these extremes, and the transition stage between, may be represented as shown previously in Figure 9.2.3.5.3(a).

9.6.3.1 Plane-Strain Fracture Toughness Data — For materials which are inherently brittle, or for structures and flaw configurations which are in triaxial tension due to their thickness or bulk restraint, quasi-plane-strain-stress conditions can be obtained in a finite-sized structural element. Triaxial stress state implicit to plane strain effectively embrittles the material by providing maximum restraint against plastic deformation. In this condition, component behavior is essentially elastic until fracture stress is reached and is readily amenable to analysis in terms of elastic fracture mechanics. This mode of fracture is frequently characteristic of the very high strength metals.

9.6.3.1.1 *Data Collection and Interpretation* — While a wide variety of fracture specimens are available for specified testing objectives, the notch-bend specimen and compact specimen generally offer the greatest convenience and material economics for testing. Details of recommended testing practice are presented in ASTM E399.

9.6.3.2 Plane Stress and Transitional Fracture Toughness — It is convenient to consider critical stress-intensity factor values, varying with thickness or stress state, as indices of crack-damage resistance. The stress-intensity factor can be used as a consistent measure of crack damage, not only for fracture instability, but also for other levels of crack damage severity, provided the damage is consistently specified and detected. This concept implies that plane-stress and transitional-fracture toughness of metallic materials, while not necessarily a fixed value for the material, is a characteristic value for a given product form, thickness, grain direction, temperature, and strain rate.

9.6.3.2.1 *Data Collection and Interpretation* — Because of the complexity of crack behavior in plane-stress and transitional-stress states, test methods for evaluating material toughness have not been completely standardized; however, several useful methods do exist. Although each configuration generates nearly consistent results when data are properly evaluated, it is recommended that each general flaw configuration be interpreted and applied within its own design context.

Middle Tension Panels — Because it simulates typical crack conditions in thin-sheet structures, the middle tension panel is a popular testing configuration for evaluating crack behavior. This specimen was illustrated earlier in Figure.9.2.3.5.3(b).

The crack-tip plasticity and slow-stable growth of the crack which commonly occur with plane-stress or transitional stress state conditions may cause a deviation from abrupt fracture, which is normally associated with crack extension under ideal plane conditions, as illustrated earlier in Figure 9.2.3.5.3(c).

Two limiting damage levels are noted in this figure. Point O is the threshold or onset of slow, stable tear where the crack slowly extends after reaching a threshold stress level. Point C is fracture instability. Both levels of crack damage can be associated with a different stress intensity factor, or damage index, for product forms and thicknesses of interest. These damage levels can be identified either directly with the K value as determined from instantaneous stress-crack length coordinate dimensions at these points, or approximately by the coordinates of Point A, which is residual strength, or apparent toughness concept of relating initial crack length to final fracture stress.

The stress intensity factor, K, associated with any of these damage levels is determined from Equation 9.6.2(b) where, for this configuration,

a = half-length of center-through crack
$g(a,w) = (\pi \sec \pi a/W)^{1/2}$.

The locus of data points can be represented by a parametric stress-intensity factor curve, as shown in Figure 9.2.3.5.3(d), where each curve represents a different stress-intensity factor formulation. The slow growth curve is superimposed on this figure to illustrate the general relationship between the threshold of stable crack extension, apparent instability, and fracture instability for a typical crack.

Because of experimental difficulties associated with precise detection of threshold and instability points, points O and C, apparent toughness, or residual strength concept of crack damage is used in this presentation. This is the locus of data points "A", noted earlier in Figure 9.2.3.5.3(d), which determine apparent fracture toughness.

$$K_{app} = f_c\left(\pi a_o \ \sec\pi a_o/W\right)^{\frac{1}{2}} \quad . \qquad [\,9.6.3.2.1]$$

See Reference 9.2.3.5.3 for additional information.

9.6.3.2.2 *Analysis of Data* — Since precise definitions of damage mechanisms and their associated instability conditions have not been devised for crack behavior in plane-stress and transitional stress states, only general constraints can be suggested for screening data. To assure that crack damage or fracture instability occurs under predominantly linear elastic conditions the basic criterion is that net section stress must be less than 80 percent of tensile yield strength, TYS, actually representative of that material. Additional criteria may be imposed by stress and boundary constraints characteristic to specific specimen configurations.

Middle Tension Panels — To maintain consistency with the Damage Tolerant Design Handbook [Reference 9.6.3.2.2], a related damage tolerance data document for Air Force contractors, a singular criterion,

$$f_c \leq 0.8\ (TYS)\ (1 - 2a/W) \qquad [9.6.3.2.2]$$

corresponding to the above net section stress requirement, is imposed on fracture data from middle tension panels. Data which satisfy this criterion are used with Equation 9.6.3.2.1 to define apparent fracture toughness.

The validity of elastic fracture in a given set of data may also be substantiated by additional tests conducted to demonstrate that elastic fracture conditions have been achieved and that the associated K value is nearly constant. For example, once a tentative value of K_{app} has been determined, it can be confirmed by testing additional panels of larger width (at least 50 percent larger) with the same initial crack length, or by testing the same panel width containing a smaller initial crack length (approximately two-thirds of the previous). These additional K_{app} values must confirm to the original tentative value. In any case, it is recommended that tests can be conducted at a variety of crack lengths and panel widths whenever practical to obtain a more complete characterization of panel behavior.

9.6.4 CREEP AND CREEP-RUPTURE DATA — Creep is defined as time-dependent deformation of a material under an applied load. It is usually regarded as an elevated temperature phenomenon, although some materials creep at room temperature. If permitted to continue indefinitely, creep terminates in rupture. (First stage or logarithmic creep exhibited by many materials at lower temperatures is not the subject of this section.) Creep in service usually occurs under varying conditions of temperature and complex (multiaxial) stress, leading to an infinite number of stress-temperature-time combinations. Creep data for use in general design are usually obtained under conditions of constant uniform temperature and uniaxial stress. This type of data is the subject of this section.

9.6.4.1 Data Collection and Interpretation — After a desired group of creep and/or creep-rupture data have been experimentally developed or isolated in preproduction files, it is necessary to carefully collect and interpret these data in accordance with the following guidelines:

State-of-the-art for interpreting these types of creep and rupture data requires that a certain amount of judgment be allowed. The general approach will be to optimize one of several empirical equations that best follows the trend of data, using life (or time) as the dependent variable. Independent variables will include stress and temperature for rupture and isostrain creep curves, and will also include strain for isostrain creep curves.

Rupture ductility can be an exception to the above because of complex behavior and data scatter. At least a cautionary note should be given in the introductory material on times and temperatures included in rupture data. Some materials exhibit such low elongation in certain time-temperature regions that normal, reasonable values of design creep strain cannot be achieved without risk of fracture.

Interpretation of creep and rupture data should also include variables that are reflected in background data reporting requirements (discussed in the next subsection). Depending on the information content of the data, and the type of variable, it may be desirable to develop a series of equations, or to include additional physical variables in the regression analysis. The proposal should demonstrate that these additional variables have been evaluated and appropriately treated in the analysis.

The individual interpreting the data should also take note of the following special types of data, and consider the following recommendations on their use:

> Specification Data—Virtually all alloys used for high-temperature applications are controlled and purchased by a process control variable generally called "spec point". Therefore, there will often be large quantities of data available from quality control data records at the specification condition. Data will contain many heats, and serve as an excellent measurement source of scatter. Therefore, in

regression modeling, specification data are often the major source of scatter measurements. Slope measurements must come from the experimental design matrix.

Specification data can also be used to (1) determine, through analysis-of-variance techniques, fractions of scatter due to heat-to-heat variations, etc., (2) determine, through distribution analysis, if data are normal, log normal, etc., and (3) find out, if data are not normal, what transformation is required.

Outliers—These can be excluded only if tests are demonstrably invalid, or if the effect on the equation and statistical parameters is unreasonable. Since exclusion of outliers normally involves a certain degree of judgment, it should only be done by a knowledgeable, experienced individual.

Discontinued Tests—These can be included if longer lived, or excluded if shorter lived, than average life of the data subset (lot, section thickness, etc.) to which they belong.

Stepped-Tests—If load on the specimen had been increased or decreased after initial loading, this test result will be excluded.

Truncating Data—Certain equations, notably parametrics, often do not properly represent a mix of shorter and longer time data. These equations can severely overpredict creep and rupture lives less than ten to thirty hours. Similarly a preponderance of short time data can cause long lives to be overpredicted. Eliminating such data requires truncating the data (or subset). This is done by removing all data above (or below) a fixed stress level, even though normally acceptable data are excluded.

Background Data Reporting—The significance and reliability of creep data generated at elevated temperatures for heat-resistant alloys are, to a major extent, a function of detailed factors which relate to the material, its processing, and its testing. Hence, it is necessary to evaluate not only the property data, but also correlative information concerning these factors.

It is not possible to specify individual items of correlative information, or the minimum thereof, which must be provided with elevated temperature property data to make those data properly meaningful. Individual alloy systems, product forms, and testing practices can all be quite unique with regard to associated information which should be provided with the data. A certain minimum amount of information is required for all data, including:

(1) Identity of alloy
(2) Chemical composition of the specific material tested
(3) Form of product (sheet, forging, etc.)
(4) Heat-treatment condition
(5) Producer(s)
(6) Specification to which product was produced (AMS specifications are normally considered standard*)
(7) Date when part was made.

---

* Company specification data may be included with federal, military, and industry specification data if it is properly documented and can be shown to compare favorably in creep or stress-rupture behavior.

Lack of such information is sufficient basis for rejection of a particular data set.

In addition, it is vital that the individual submitting data consider those factors which contribute to uniqueness of the alloy, processing, and/or testing, and give thought to information which is pertinent to that uniqueness. Thus, grain size can be a significant variable, not only between cast turbine blades, but within a single blade. Thermomechanical working processes may result in significantly different properties (not only higher, but lower as well); and test specimen design can affect resultant data. It is mandatory that knowledgeable personnel be involved when data are submitted for evaluation and potential use. Any correlative data that can be provided will aid the analyst in identifying valid reasons for rejection of data which may not fit the trends of other data (outliers). Such apparent outliers may be indicated through analysis of between-heat variance as described in Section 9.6.4.2.

These examples illustrate the need for adequate information:

(1) Creep-rupture specimens are being machined from cast high-strength, nickel-base alloy turbine blades. At center span location, specimens are 0.070- to 0.090-inch diameter, while at the trailing edge, specimens are flat and 0.020-inch thick. Flat specimens are typically about one Larson-Miller parameter weaker than round specimens, which is attributable both to thickness effects of the thin specimens and to finer grain size at the trailing edge. In addition, trailing edge specimens exhibit more scatter. Hence, availability of associated information is vital when considering data from specimens machined from cast turbine blades.

(2) Comparison of creep-rupture properties of Waspaloy and Superwaspaloy shows that the latter is much weaker at temperatures approaching the upper bounds of utility of the alloy. The significantly lower properties at higher temperatures are attributed to a finer grain size of Superwaspaloy and also to a recovery process that may well be occurring at these temperatures. This alloy is subjected to extensive thermomechanical working, and some strengthening gained by the associated warm working is lost at higher testing temperatures. This effect clearly indicates that processing history significantly affects levels of mechanical properties and, hence, must be adequately documented when property data are submitted.

9.6.4.2 ***Analysis of Data*** — After an acceptable data collection has been obtained and interpreted, it is possible to proceed in analyzing those data and developing mathematical models of creep and creep-rupture behavior. The objective of the procedures described in the following paragraphs is to calculate creep and rupture life as a function of test conditions and other significant variables. This calculation is done to provide an average curve and a measure of expected variability about the average. The approach that is discussed involves regression analysis to optimize the fit of an equation to the data set. The following information provides guidelines in the application of regression analysis to creep and rupture data and recommends approaches to specific problems that are frequently encountered.

General—It is assumed that life or time is the dependent variable for rupture or isostrain creep equation analysis, respectively, and logarithmic transformation of the dependent variable is normally distributed.

The data set will nearly always contain a variety of stresses and temperatures. If the data set is the product of a very well-balanced test design, good results may be obtained by independently fitting each temperature. Since this type of data set is often not available, and the approach sacrifices the opportunity for interpolation, the discussion will assume that at least temperature and stress are used as independent variables.

In order to achieve good results, it may be necessary to consider other variables. Some variables are continuous physical variables that are incorporated into regression variables, e.g., section size. Other variables may occur as discrete subsets that require modifying the regression analysis (this is discussed under

Subsets of Data). In such cases, it may be necessary to group data per subset for data reporting if regression analysis cannot easily accommodate the observed subsets.

Selection of Equations—For isostrain and rupture time, as a function of stress and temperature, a number of relationships have been proposed. Some useful ones are:

(1) $\log t = c + b_1/T + b_2X/T + b_3X^2/T + b_4X^3/T$ [9.6.4.2(a)]

(2) $\log t = c + b_1/T + b_2X + b_3X^2 + b_4X^3$ [9.6.4.2(b)]

(3) $\log t = c + b_1\, T + b_2X + b_3X^2 + b_4X^3$ [9.6.4.2(c)]

(4) $\log t = c + (T\text{-}T_a)(b_1 + b_2X + b_3X^2 + b_4X^3)$. [9.6.4.2(d)]

These are the Larson-Miller, Dorn, Manson-Succop, and Manson-Haferd, respectively, where

c = the regression constant
b_1 = coefficients (b_1 through b_4)
t = time
T = absolute temperature (T_a is the temperature of convergence of the isostress lines)
X = log S (stress).

While all forms may be used to model a data set with varying degrees of goodness of fit, experience and practice indicate the Larson-Miller relationship adequately models most materials, and is usually the preferred equation form.

If data for a given material is available at a variety of creep strain levels as well as the stress rupture point, only one model should be used to describe data trends for each strain level. The decision as to which of the four customary models is chosen should be based on a comparative analysis of data for the most comprehensive data collection, whether that collection be for a specific creep strain level or stress rupture point. In addition, the constant term found in the optimum analysis should be held the same for all creep strain levels. If this is done, it will be possible to construct a composite plot of stress versus parameter for all creep strain levels and the stress-rupture level.

If none of these standard forms satisfactorily follows data trends, various combinations of stress and temperature may be tried. For example, terms can be selected from a matrix obtained using cross products of T^{-1}, T^o, T^1 with S^{-1}, S^o and S^1. Methods for generalizing and applying these equations are discussed in Reference 9.6.4.2.

The exact form of the functions should reflect data and reasonable boundary conditions. Quadratic, quartic, etc., can be expected to give poor boundary conditions, e.g., zero life at zero stress, and should be avoided. Extrapolation by users of the equation is inevitable (though it is not recommended), so other general equations must be checked for unusual behavior beyond the data—this can be done, in many cases, by differentiating to obtain maxima and minima. In general, short times should give strengths approximately corresponding to tensile yield and ultimate strength; zero stress should predict infinite life.

Metallurgical instabilities and transition regions may present difficulties in some analyses. Methods for handling such problems have been discussed in Reference 9.6.4.2.

Optimum Fit—Guidelines for an optimum fit are:

(1) Minimum number of terms. With two independent variables, σ and T, six regression variables are reasonable, each additional physical variable allowing two additional regression variables.

(2) Reasonable curve characteristics for material behavior, including extrapolation.

(3) Minimum standard error and maximum correlation coefficient (as long as 1 and 2 are not violated). Standard errors are typically between 0.1 and 0.2.

(4) Uniform deviations (see a later paragraph on Weights for a brief discussion of nonuniform deviations and their analytical treatment).

Subsets of Data—A non-normal or multimodal population, or an excessive standard error may indicate the presence of subsets. However, an apparently typical data set may contain subsets that should receive special consideration.

One type can be treated by adding physical variables to the regression analysis. For example, different thicknesses of sheet material may give different average lives. Including sheet thickness in the regression should not only improve fit but also avoid the risk of misrepresenting behavior of the material. Section thickness, distance from surface, and grain size are other examples of subsets that can be treated as regression variables. Section thickness and distance from surface refer to location of the specimen in terms of geometry of the original material, e.g., finish work thickness, final heat thickness, etc.

A second type is not typically subject to use as a regression variable. Examples of these are orientation (L, LT, and ST), or different heats (chemistry). A decision must be made whether to treat these as unique subsets to be analyzed separately (if properties are different) or as randomly distributed subsets. Orientation will usually be analyzed separately, while heats will usually be randomly distributed subsets. Other methods (e.g., fixed intercept, centered above mean values for each creep level) may be more suited for a given data set and may be tried. The specific procedure used must be indicated in the data package.

The theory of treatment of randomly distributed subsets has been developed in Reference 9.2.5.2, while application to lots of material (actually "heats" in chemistry) is considered in Reference 9.6.4.2. Treating subsets as random affects calculation of both average curve and standard error. While effect on standard error may become insignificant as the number of subsets exceeds ten (depending on the relative contribution to total standard error), effect on the trend of the calculated average remains. Lots whose average lives are uniformly displaced (parallel) in logarithm of life, or are not significantly non-parallel, are discussed in Reference 9.6.4.2(a). There is no known published reference for treating non-parallel lots. Data permitting, individual lots can be fitted, within-lot variances pooled, and average and variance of lot averages calculated for selected stress-temperature combinations. After calculating total variance and desired lower level tolerance limit* ($\overline{X}$ - ks) at each stress level, curves can be drawn and, if desired, equations be fit to X's and ($\overline{X}$ - ks) 's. It should be noted that the equation for ($\overline{X}$ - ks) is not likely to properly reflect uncertainty in coefficients obtained by normal fitting procedures. Alternately, all data for non-parallel lots can be pooled and variance weighted, providing sufficient lots are represented and average curve is reasonably similar to the first approach.

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* Tolerance limits used here are one-sided and are normally developed for tolerance levels of 90 or 99 percent at a confidence level of 95 percent.

Consistency in Creep and Stress Rupture Trends—When creep data are somewhat limited, an independent analysis of each creep strain level may produce inconsistent trends between different creep strain levels and stress rupture mean curve. There may be cases where very minor extrapolations will produce creep curves that cross over each other or the stress rupture curve. In some instances, this problem can be eliminated, without a significant loss in quality of fit at each creep strain level, by forcing a prescribed relationship to exist between creep curves and stress rupture curve. Parallelism in log(time) is the simplest relationship that can be assumed, but it is also a relationship that is often supported by data trends. A linearly increasing or decreasing separation of creep curves and stress rupture curve in log(time) as a function of stress is also a possibility, but it takes a large quantity of data to verify such trends. If large quantities of data are available, then it is generally preferable to analyze each creep strain level individually. Therefore, about the only practical relationship to assume between individual creep curves and the stress rupture curve is parallelism in log(time).

Parallelism in log(time) can be achieved through the addition of a dummy variable to the stress rupture equation for each creep strain level being added to the regression analysis. For example, in the case of the Larson-Miller equation, which (in its third order form) is normally written as

$$\log t = c + b_1/T + b_2X/T + b_3\,X^2/T + b_4\,X^3/T, \qquad [9.6.4.2(a)]$$

where

t = time, hrs

T = absolute temperature, °R

X = log (stress), ksi,

the equation can be modified to include additional terms for each creep level, as follows

$$\log t = c + b_1/T + b_2X/T + b_3X^2/T + b_4X^3/T + b_5\,Y_1 + b_6\,Y_2 + \ldots b_{4+i}\,Y_i \qquad [9.6.4.2(e)]$$

where the value of Y_i new terms are either 0 or 1. If a creep strain level 1 data point is considered, $Y_1 = 1$ and all other Y's are 0. Similarly, if a creep strain level 2 data point is considered, $Y_2 = 1$ and all other Y's are 0. If a stress rupture data point is considered, all the Y's are 0. In this way, the optimized values of additional b's represent average A in log(time) that each creep curve falls below the stress rupture curve.

The usefulness of such an approach must be verified through an examination of quality of fit for each creep strain level compared to raw data trends.

Weights—Rupture and isostrain creep curves will not normally require weights to obtain uniform variables. Analysis, including strain as a variable, frequently will. Variables other than strain, temperature, and stress will require evaluation for uniform variance. Reference 9.6.4.2(a) provides further discussion of weighting.

Rejection of Analyses—Regression analyses of specific creep or stress-rupture data sets should normally be rejected if the R^2 statistic for analysis is <75 percent, or there are fewer data than five times the number of temperature levels, or there are <20 data points total available for regression.

If data for several different creep strain levels are analyzed in combination with stress rupture data, R^2 levels below 75 percent for one or two creep strain levels may be acceptable, if the overall R^2 exceeds 75 percent. Separate analyses of low creep strain data may show relatively high variation with R^2 values below 75 percent. In these cases, if there are sufficient data to produce significant regression coefficients at a 95 percent confidence level, the result may still be acceptable for inclusion in MIL-HDBK-5.

9.7 ANALYSIS PROCEDURES FOR STRUCTURAL JOINT PROPERTIES

This section of the guidelines covers analysis procedures for determination of structural joint properties. Reference to the following related sections may be useful:

Test Methods
 9.2.3.6 Mechanically Fastened Joints
 9.2.3.7 Fusion-Welded Joints

Data Requirements
 9.2.4.6 Mechanically Fastened Joints
 9.2.4.7 Fusion-Welded Joints

Examples of Data Analyses and Data Presentation
 9.9.5 Mechanically Fastened Joints
 9.9.6 Fusion-Welded Joints

It is important to recognize that these guidelines for the analysis and presentation of fastener design allowable properties in MIL-HDBK-5 are substantially different than the version that has been used for at least 20 years. These new guidelines are based on standardized statistical procedures, and involve the development of B-basis yield and ultimate load fastener allowables. Fastener tables included in MIL-HDBK-5 prior to Revision J will not be systematically reviewed or updated in accordance with these new guidelines. However, new fastener data proposals, or revisions to existing fastener allowable tables, will be based on the statistical procedures described in this section of the Handbook.

These new procedures were adopted to:

- Migrate toward a consistent level of statistical confidence in tabulated fastener design properties.

- Provide a method that accounts for (but is not driven by) singularity points in the data.

- Allow for greater confidence and accuracy in fastener design allowables as sample sizes increase.

- Ensure that fastener data analysis procedures will provide repeatable, unbiased results when used by different analysts.

Fastener tables approved prior to Revision J of MIL-HDBK-5 include ultimate load design allowables that are approximately equivalent to B-basis design properties. The yield properties shown in these same tables cannot realistically be equated with B-basis design properties; these previously established yield properties should be treated as conservative average fastener yield loads. To avoid confusion the basis of all fastener properties presented in Chapter 8 of MIL-HDBK-5 must be clearly delineated, as illustrated in Section 9.9.5.

9.7.1 MECHANICALLY FASTENED JOINTS — Some mechanical fasteners will not develop full bearing strengths of materials in which they are installed. Joint allowables for these fasteners must therefore be determined from test data. Fasteners for which allowable loads must be determined are:

(1) flush-head fasteners in dimpled or countersunk sheet,
(2) fasteners with hollow or multiple-piece shanks,
(3) protruding-head fasteners with shear-type heads[*], and
(4) protruding-head bolts and rivets when thickness-to-diameter ratio (t/D) is less than 0.18.

These guidelines define data generation (quality/quantity), analysis methods, and presentation format applicable to mechanically fastened joint allowables. They reflect a need to (1) ensure that the aerospace industry is interested in new fastener systems which are incorporated in MIL-HDBK-5, and (2) ensure that confirmatory data to substantiate allowable loads meet certain stated requirements that simplify the process of acceptance through coordination. To accomplish these needs, fastener systems proposed for inclusion in MIL-HDBK-5 may be introduced (sponsored) by airlines, airframe or engine prime contractors, and Government agencies (DoD, FAA, or NASA); i.e., one of the users. When introducing a new fastener, the sponsoring organization will supply information specified in Section 9.2.4.5.3. The sponsoring organization is also expected to review the test program plan, actual testing, and data analysis. At least 25 percent of the specimen fabrication and testing will be performed at a second facility. It also is expected that fasteners and fastener materials will be obtained from three production runs per diameter as documented in the report. The sponsoring organization will submit a report documenting design allowables to the MIL-HDBK-5 Coordination Group for evaluation. (See Section 9.2.4.5.3.)

Proposals not meeting the requirements described herein will be rejected or require more time-consuming evaluation, inevitably delaying approval and release of proposed allowables. Therefore, use of these guidelines in preparing proposals for MIL-HDBK-5 is essential.

In case of conflict, provisions of this document take precedence over reference documents for any tests or analyses made to provide, substantiate, or revise MIL-HDBK-5 fastener allowables.

9.7.1.1 Definitions — Terms used in Section 9.7.1 vary among users of this Handbook. To provide consistency, these terms are defined herein in accordance with the intent of MIL-HDBK-5.

(a) Deformable Shank Fasteners—A fastener whose shank is deformed in the grip area during normal installation processes.

(b) Nominal Hole Diameters—Nominal hole diameters for deformable shank solid, blind rivet and blind fasteners will be according to Table 9.7.1.1. When tests are made with hole diameters other than those tabulated, hole sizes used will be noted in the report and on the proposed joint allowables table.

(c) Nondeformable Shank Fasteners—A fastener whose shank does not deform in the grip area during normal installation processes.

(d) Nominal Shank Diameter—Nominal shank diameter of fasteners with shank diameters equal to those used for standard size bolts and screws (NAS 618 sizes) will be the decimal equivalents of stated fractional or numbered sizes. These diameters are those listed in the fourth column of Table 9.7.1.1. Nominal shank diameters for nondeformable shank blind

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[*] For example, protruding-head fasteners with reduced head heights similar to those shown for NAS 529 rivets.

fasteners are listed in the fifth column of Table 9.7.1.1. Nominal shank diameters for other fasteners will be the average of required maximum and minimum shank diameters.

(e) Yield Load—Joint yield loads for all fasteners are defined as loads which result in 0.04D permanent set in the joint when the fastener is tested in nominal hole size as defined in Table 9.7.1.1. For some fastening systems, tests in larger hole sizes, although within manufacturer's recommended hole size limits, may result in joint permanent sets greater than 0.04D[*] at yield load.

There are many generically named fasteners for which joint allowables are provided. These fasteners are listed below, followed by the letter H or S. H signifies that, in the analysis, nominal hole diameter (as described above) is used. S signifies that, in the analysis, nominal shank diameter is used.

(a) Solid rivets and blind fasteners whose shanks deform during installation. (H)

(b) Solid rivets and blind fasteners whose shanks do not deform during installation. (S)

(c) Threaded and swaged-collar fasteners whose shanks do not deform during installation. (S)

(d) All interference-fit and close-tolerance fasteners. (S)

9.7.1.2 ***Yield Load Determination*** — The preferred method of determining yield load is by the secondary modulus method.[**] To obtain secondary modulus line, during the test the joint is unloaded from a load close to, and preferably above, estimated yield load to a load value in the range of about 10 to 20 percent of estimated yield load. The joint then is reloaded and secondary modulus is the slope of this second loading line. This procedure is described in NASM 1312-4 and is illustrated in Figures 9.7.1.2(a) through (e).

If curves similar to Curves A and B in Figure 9.7.1.2(b) are obtained early in the test program, strain hardening will be presumed. In that case, unloading should be delayed in subsequent tests until after anticipated yield load. Curves showing strain hardening may be extrapolated a reasonable amount to determine yield load by the secondary modulus method as shown.

The initial loading line is used to establish the intersection with the abscissa from which to measure yield offset. At times, minor irregularities occur on initial loading which necessitates redrawing of the lower part of the curve as a continuation of the normal curve, as shown in Curves C and D of Figure 9.7.1.2(c).

Unusually shaped curves are sometimes obtained. Typical of these are the illustrations in Figure 9.7.1.2(d). Data which are typified by Curves A or B are unacceptable for analysis. When the secondary modulus has a straight-line portion of recognizable length, do as shown in Curve C. When the secondary curve has two straight parts, but is more in question (as in Curve D), and there are satisfactory curves available from similar group test specimens, use the slope which approximates other curves. Otherwise, the more conservative (steepest) will be used. An acceptable alternate is to draw a straight

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[*] Or previous yield load criteria used prior to 1973. Applicable yield criteria are noted in footnote for design allowable table.

[**] The primary modulus line has been used in the past, on occasion. It is the slope of the initial loading line and frequently is observed to have greater variability than the secondary modulus line.

line between end points of the off-loading-reloading loop and consider this as the secondary modulus line, as shown in Figure 9.7.1.2(e). The primary modulus method may be used as a last resort, if there is no straight-line portion or usable loop in the secondary modulus curve.

Table 9.7.1.1. Nominal Hole and Shank Diameters, Inches

Fastener Size, Functional or Numbered	Deformable Shank Fasteners		Nondeformable Shank Fasteners	
	Solid	Blind	Solid Shank	Blind
1/16	0.067	…	…	…
3/32	0.096	0.098		0.098
#4	…	…	0.112	…
1/8	0.1285	0.130	0.125	0.130
		0.144		0.144
#6	…	…	0.138	…
5/32	0.159	0.162	0.156	0.163
		0.178		0.178
#8	…	…	0.164	…
3/16	0.191	0.194	0.188	0.198
		0.207		0.207
#10	…	…	0.190	…
#12	…	…	0.216	…
7/32	…	…	0.219	…
1/4	0.257	0.258	0.250	0.259
		0.273		0.273
5/16	0.323		0.312	0.311
3/8	0.386	…	0.375	0.373
7/16	…	…	0.438	0.436
1/2	…	…	0.500	0.497
9/16	…	…	0.562	…
5/8	…	…	0.625	…
3/4	…	…	0.750	…
7/8	…	…	0.875	…
1	…	…	1.000	…
1-1/8	…	…	1.125	…
1-1/4	…	…	1.250	…
1-3/8	…	…	1.375	…
1-1/2	…	…	1.500	…

[a] In order to standardize test and analysis procedures, nondeformable shank fasteners will be installed in net fit ±0.0005 inch holes.

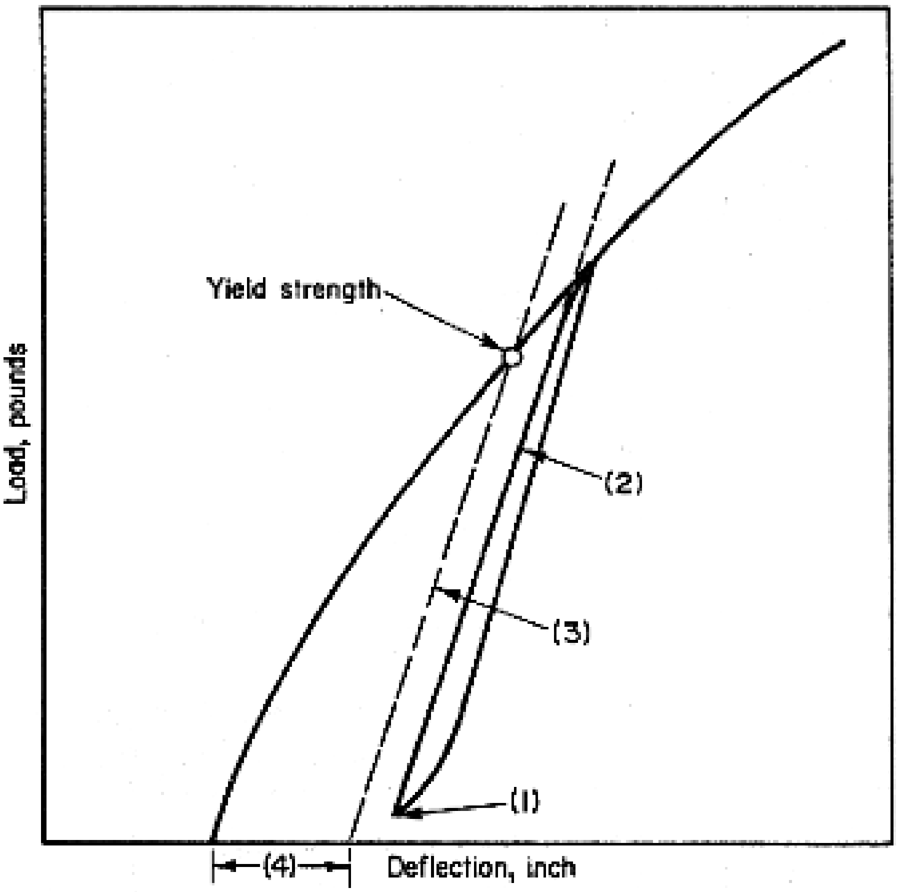

Figure 9.7.1.2(a). Illustration of secondary-modulus method of yield strength determination.

(1) Reduce load to 10-20 percent of yield load.
(2) Secondary-modulus line. The straight part of the loading side of the secondary-modulus loop indicating elastic behavior.
(3) Offset line. A line parallel to the secondary-modulus line.
(4) Offset. Equal to permanent set value specified in yield load definition in Section 9.7.1.1.

9.7.1.3 ***Shear Strength of Fastener*** — Each group of double-shear or single-shear results for a specific fastener type, size, and material will be analyzed to determine an A-value, except driven rivets which will be analyzed to obtain a B-value. Data will be checked for their conformance to a Pearson distribution through use of the Anderson-Darling test described in Section 9.5.4.4. If the assumption of a Pearson distribution is not rejected:

(a) For solid driven rivets, compute the B-value as shown in Section 9.5.5.1 and select the next lower shear strength from Table 8.1.1.1, if it is within 2 ksi of the computed value. If the computed B value is more than 2 ksi above the next lower value in Table 8.1.1.1, a new value may be proposed.

(b) For other fasteners, compute the A-value as shown in Section 9.5.5.1 and select the next lower shear strength from Table 8.1.1.1. If the computed A-value is more than 5 ksi above the next lower value in Table 8.1.1.1, a new value may be proposed.

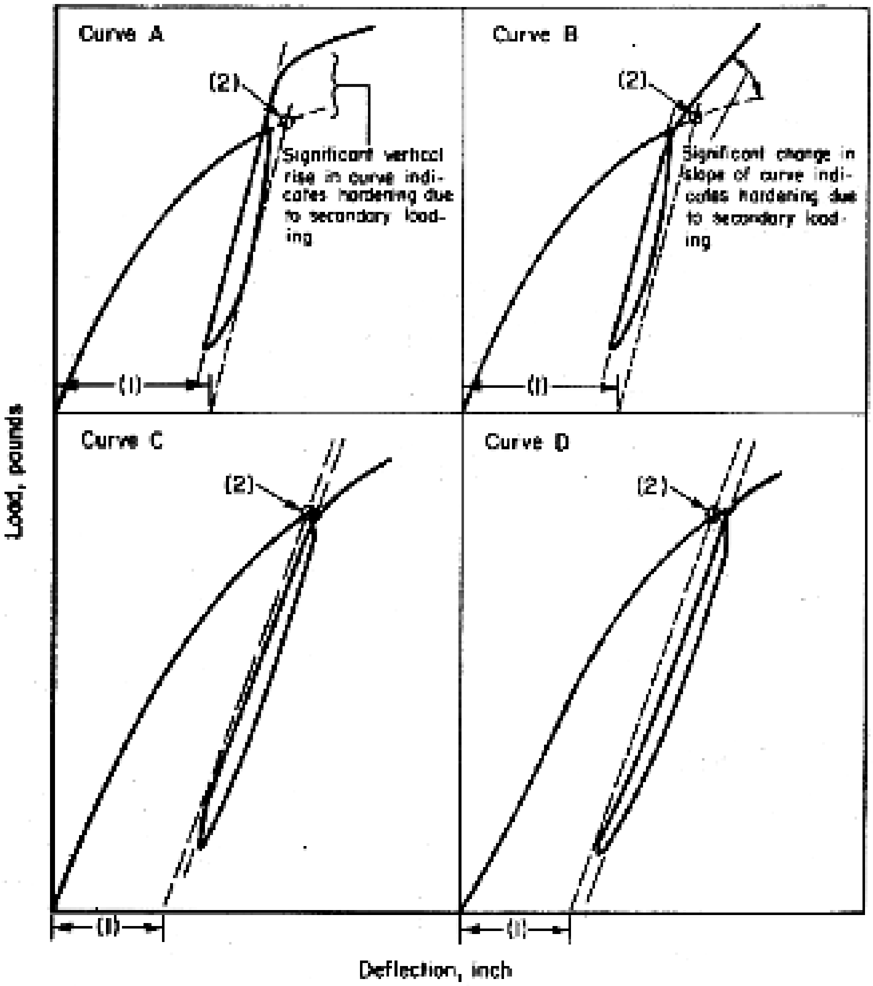

Figure 9.7.1.2(b). Sample secondary modulus load-deflection curves.

(1) Offset per 9.7.1.1.
(2) Joint yield strength.

If analysis of data shows a non-Pearson distribution, obtain additional observations (as required) and employ the nonparametric procedure as described in Section 9.5.5.3. Minimum shear strength will then be selected as described in (a) and (b) above.

The calculated design minimum shear values will be equal to or greater than the values in Table 8.1.5(a) (for the appropriate stress level) and the specification value. (For example, the computed minimum shear value for a 0.190 diameter, 95 ksi fastener will be greater than, or equal to, the allowable load value of 2,694 pounds.) The allowable load will be the lower of the appropriate Table 8.1.5(a) value or the specification value.

If Table 8.1.5(a) is not applicable (i.e., driven rivets, blind fasteners, and fasteners without shear-load requirements in the specification), the allowable load values will be converted to stresses for each diameter using nominal shank areas for S fasteners and nominal hole areas for H fasteners.

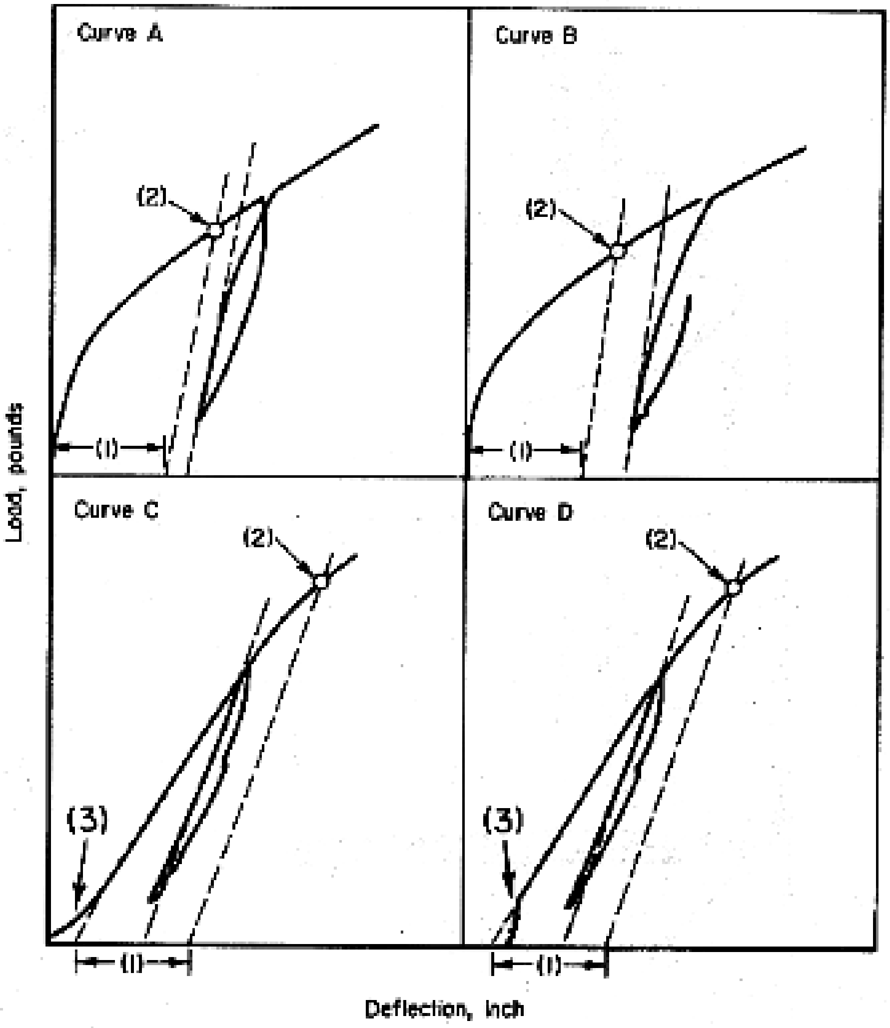

Figure 9.7.1.2(c). Sample secondary-modulus load-deflection curves.

(1) Offset per yield load definition given in Section 9.7.1.1.
(2) Joint yield strength.
(3) Disregarded irregularities, per Section 9.7.1.2.

The allowable stress for the fastener system will be established as the lowest of the above calculated stresses, or the specification stress value, whichever is lower. Allowable fastener shear strength will be the product of this stress and the appropriate (H or S) areas used above.

The shear strengths that are calculated will be clearly identified as either 90 percent (B-value) or 99 percent (A-value) allowables.

9.7.1.4 ***Sheet Critical and Transition Critical Strengths*** — The analysis of data in the bearing and transitional regions provides design allowable curves for yield and ultimate strength where sheet or plate material of the joint is generally critical. To accomplish the analysis, tables and graphs are required as detailed in this subsection. The use of computer programs to analyze data and to prepare tables of

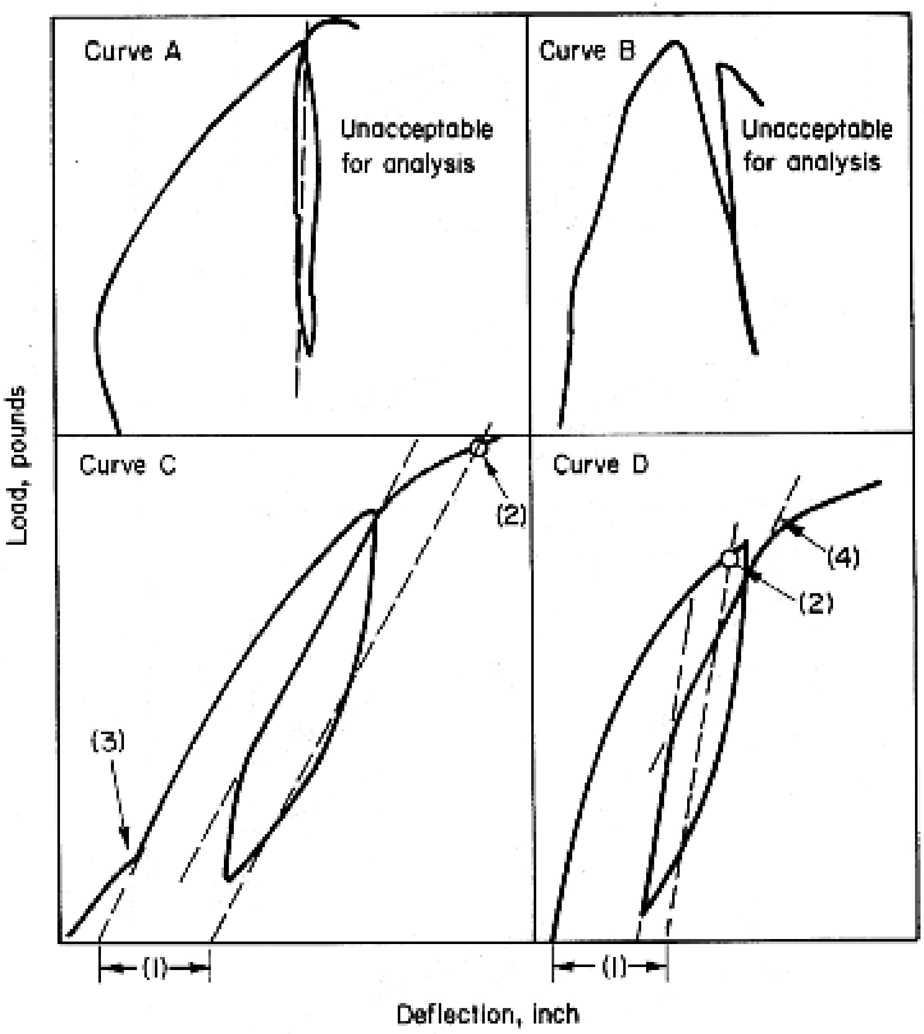

Figure 9.7.1.2(d). Sample secondary-modulus load-deflection curves.

(1) Offset, per 9.7.1.1
(2) Joint yield strength.
(3) Disregarded irregularities, per 9.7.1.2.
(4) Disregarded second slope in secondary-modulus curve.

calculations and figures, as next described, is acceptable. However, all tables and figures subsequently described should be illustrated in the report. When using a computer program for analysis, some engineering judgements may still be necessary for certain data sets in the transition thickness range.

(a) Presentation and Analysis of Basic Test Data—The values of the functions t/D, P_u/D^2, and P_y/D^2 will be calculated from the basic t, D, P_u, and P_y test data obtained on each specimen tested, using the values defined below:

t = measured sheet thickness, inch, for thinnest sheet gage of combination

D = measured hole diameter, inch, for H-type fasteners, nominal shank diameter for S-type fasteners as defined in Section 9.7.1

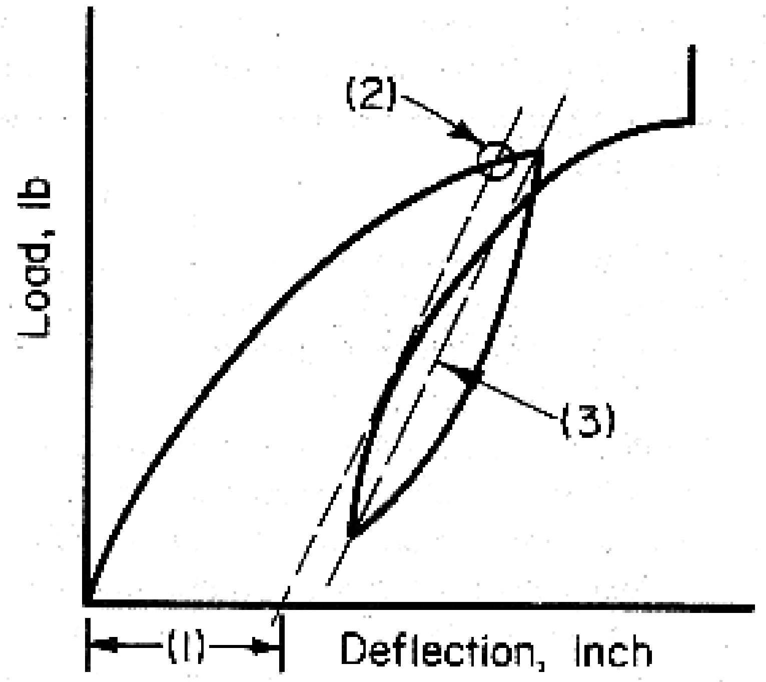

Figure 9.7.1.2(e). Sample alternative secondary-modulus load-deflection curve.

(1) Offset, per yield load definition given in Section 9.7.1.1
(2) Joint yield strength.
(3) Alternative secondary-modulus line.

P_u = test ultimate load, where ultimate load is the maximum load reached by the test specimen prior to load fall off (pounds per fastener)

P_y = test yield load, determined per Section 9.7.1, pounds per fastener.

A suggested format for reporting the basic data and the computed values of t/D, P_u/D^2, and P_y/D^2 is shown in Figure 9.7.1.4(a). The average P_u/D^2 and P_y/D^2 for each fastener diameter at each t/D will be indicated in the table.

Computation of P/D^2 and t/D from Basic Data

Test Specimen No.	D Diameter	D^2	t Gage	t/D	Yield Load, P_y	$\frac{P_y}{10^4D^2}$	Ultimate Load, P_u	$\frac{P_u}{10^4D^2}$	Type of Failure

t, D, P_u, and P_y, per Section.

Figure 9.7.1.4(a). Suggested tabular layout for basic data and computer P/D^2 and t/D data.

(b) Regression Analysis to Determine Average Ultimate and Yield Load Curves—The general assumption inherent in a P/D^2 versus t/D analysis procedures is that the dimensions of a fastener system are proportional to the fastener diameter. Therefore, a plot of the average P_u/D^2 and P_y/D^2 values for each t/D tested is expected to yield a compact band of data points through which single ultimate and yield load curves can be determined. The following regression equation can generally be used to represent average t/D trends:

$$P/D^2 = A_0 + A_1 * (t/D) + A_2 * \ln (t/D) \qquad [9.7.1.3(d)]$$

where P = applied load,

D = nominal hole or fastener shank diameter (as defined in Table 9.4.1.2),

t = sheet thickness, and

“ln” represents the natural logarithm of the quantity in parentheses.

If the data for different diameter ranges are not combinable based on an F and t test (at a 95% confidence level as described in Section 9.5.2.4) the average regression trends for each diameter must be analyzed separately. Examples of this type of analysis are shown in Figures 9.7.1.4(b) and (c), for yield and ultimate loads, respectively. In this example both the yield and ultimate load t/D trends for the 3 different diameters were statistically combinable.

If applicable, fastener shear failure and sheet critical conditions should be clearly identified and considered in the evaluation of combinability of fastener data for different diameters.

Where applicable, data obtained from different sources must also be identified. The objective in both cases is to establish realistic average ultimate-load and yield-load curves for the fastener system. With the ultimate-load curve, consideration will be given to all test data for which joint failure was by failure modes other than fastener shear.

In the event that the yield and/or ultimate load data for an individual fastener diameter are not combinable with the other available diameters, a separate regression analysis must be performed on this fastener diameter.

Also to be shown on these graphs are one or more horizontal lines representing fastener shear strength (more than one line occurs when shear strength in pounds is not proportional to shank area) and allowable sheet or plate ultimate bearing strength and bearing yield strength lines. For materials where bearing properties vary with thickness, bearing strengths plotted will include the lowest value in the applicable thickness range and the values used will be the S or A values.

Nonshear-critical test data include all data below the fastener shear strength line and all data for joints that failed in sheet bearing, pullout, head failure, combinations of shear, or any other mode of failure, other than shear of fastener shanks, even though same data may lie above the fastener shear strength line. All shear-critical data should fall above the fastener shear strength line. Average t/D curves must not extend beyond the tested t/D range.

(c) Regression Analysis to Determine Yield and Ultimate Load Design Allowable Curves – The following statistical procedure must be used for definition of yield and ultimate load design allowable curves. This procedure involves generation a B-basis allowables using a quadratic regression of the yield and ultimate load data generated from tests conducted on jointed specimens. Terms used in these statistical calculations are defined as follows:

a , b, c	Best-fit equation coefficients
df	Degrees of freedom
$F_{.05}(M\text{-}3,N\text{-}M)$	The 5th percentile of the F distribution with degrees of freedom M–3 and N-M
H	Estimated bound on ratio of MSE to MSPE
ln	Natural logarithm
M	Distinct levels of t/D
MSE	Mean Square Error
MSPE	Mean Square Pure Error
N	Total number of tests
$q_1, q_2, \ldots, q_6$	Sums of the x_i = ln(t/D)
Q(x)	A measure of the "nearness" of x to the center of the range of independent variables
RMSE	Root Mean Square Error
(x)	The multiplier on s_y in the calculation of T_{90} values for different t/D ratios
s_y	Unbiased estimated of standard deviation in average joint strengths
t/D	Sheet thickness / fastener diameter
x_i	Independent variable in quadratic regression analysis
y_{ij}	The jth test value at ith t/D ratio, used to compute dependent variable

The following statistical procedure for calculating B-basis (T_{90}) values for fasteners is based on a quadratic regression analysis of the average strength values at each t/D, using a log scale on the t/D axis. In estimating the lower tolerance bounds, the procedure uses an estimate of the standard deviation that incorporates variability within each t/D condition, and random variations between these t/D conditions.

1) Calculate averages of the replicate tests:

$$\bar{y}_i = 1/3\sum_{j=1}^{3} y_{ij}$$

(Nominally, 3 tests are conducted, but use the appropriate divisor, n_i, throughout)

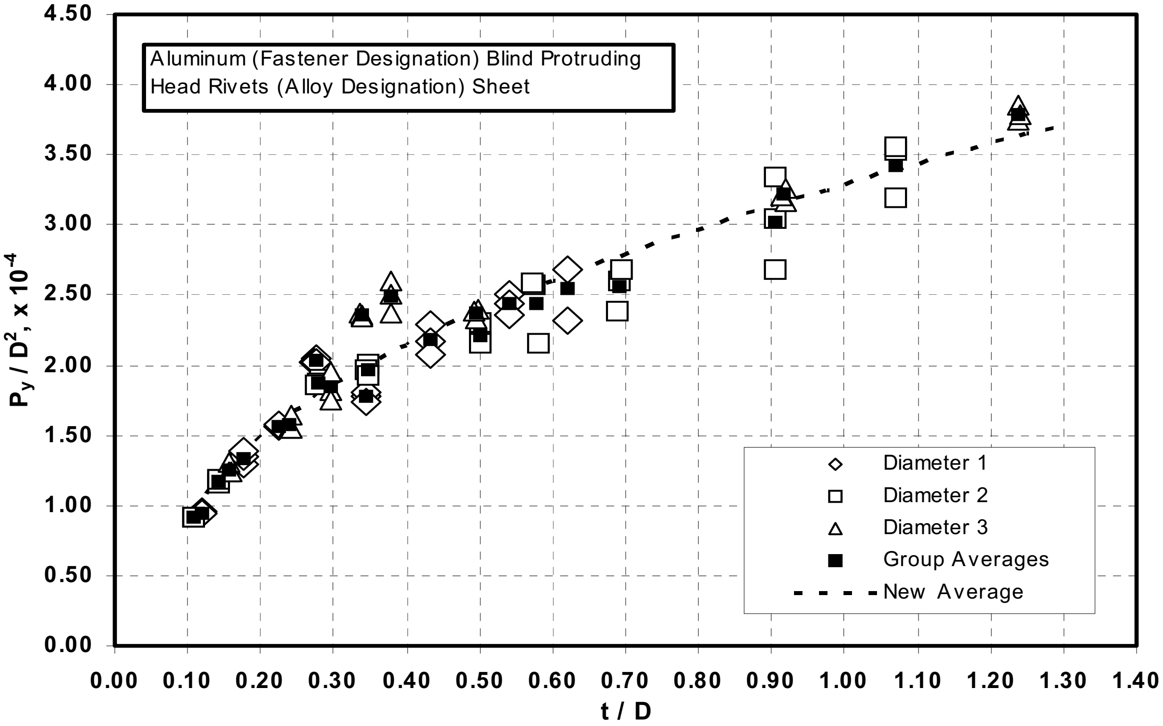

Figure 9.7.1.4(b) Example of Trial Analysis to Compare Mean t/D Yield Load Trends for 3 Different Fastener Diameters

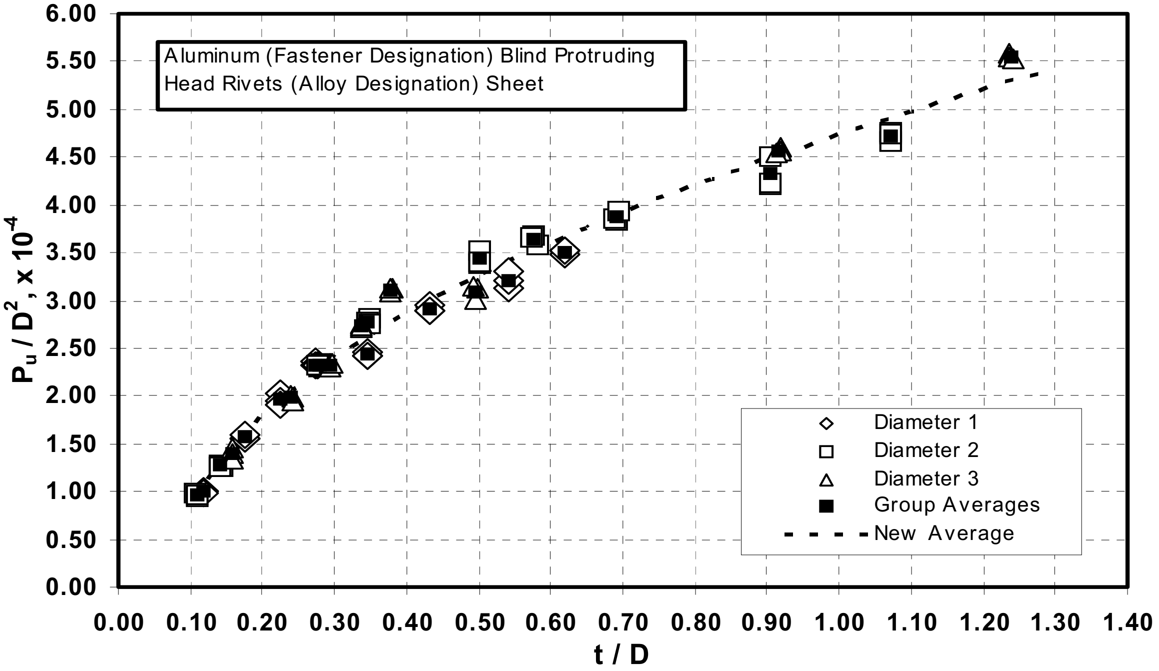

Figure 9.7.1.4(c) Example of Trial Analysis to Compare Mean t/D Ultimate Load Trends for 3 Different Fastener Diameters

2) **Fit a quadratic regression of the averages to**

$$x_i = \ln(t/D).$$

a) Let a + b ln(t/D) + c (ln(t/D))^2 be the estimated model where

$$\mathrm{a} = \bar{y} - \mathrm{b}\bar{x} - \mathrm{c}\frac{\sum_{i=1}^{M} x_i^2}{M}$$

$$\mathrm{b} = \frac{\sum_{i=1}^{M}\left(x_i\bar{y}_i - \bar{x}\bar{y}\right) - \mathrm{c}\left[\sum_{i=1}^{M}\left(x_i - \bar{x}\right)x_i^2\right]}{\sum_{i=1}^{M}\left(x_i - \bar{x}\right)^2}$$

and $\bar{y} = \sum_{i=1}^{M} \bar{y}_i$, $\bar{x} = \sum_{i=1}^{M} x_i$, and is the number of distinct levels of t/D. The logarithm of t/D is used because it often improves the fit at the lower values of t/D.

b) Let *MSE* denote the mean squared error of the regression.

$$\mathrm{MSE} = \left(RMSE\right)^2 = \frac{\sum_{i=1}^{M}\left(\bar{y}_i - \hat{\bar{y}}_i\right)^2}{(M-3)}$$

where $\hat{\bar{y}}_i = \mathrm{a} + \mathrm{b}x_i + \mathrm{c}x_i^2$

3) **Determine appropriate standard deviation for the tolerance bounds and associated degrees of freedom.**

$$\mathrm{c} = \frac{\left[\sum_{i=1}^{M} x_i^2\left(\bar{y}_i - \bar{y}\right)\right]\left[\sum_{i=1}^{M}\left(x_i - \bar{x}\right)^2\right] - \left[\sum_{i=1}^{M}\left(x_i\bar{y}_i - \bar{x}\bar{y}\right)\right]\left[\sum_{i=1}^{M}\left(x_i - \bar{x}\right)x_i^2\right]}{\left[\sum_{i=1}^{M} x_i^4 - \frac{\left(\sum_{i=1}^{M} x_i^2\right)^2}{M}\right]\left[\sum_{i=1}^{M}\left(x_i - \bar{x}\right)^2\right] - \left[\sum_{i=1}^{M}\left(x_i - \bar{x}\right)x_i^2\right]^2}$$

a) Calculate the MSPE (mean squared pure error)

$$MSPE = \frac{\sum_{i=1}^{M}\sum_{j=1}^{n_i}(y_{ij} - \bar{y}_i)^2}{(N-M)},$$

where $N = \sum_{i=1}^{M} n_i$ is the total number of tests and M is the number of distinct levels of t/D and n_i is the assumed number of replicates at the ith level of t/D. This represents the variability that can be expected at a particular condition.

b) Calculate s_y:

$$s_y = (MSE + \frac{(n_0 - 1)}{n_0} MSPE)^{1/2},$$

where $n_0 = \frac{1}{M-1}\left(N - \frac{\sum_{i=1}^{M} n_i^2}{N}\right)$. If the number of tests performed at each test condition is the same, i.e., $n_i = n_0$ or $1 \le i \le M$, then this provides an unbiased estimate of the standard deviation of individual observations under a particular, fixed condition.

c) Calculate H (the upper confidence bound on the ratio of the variability between t/D conditions to the variability within t/D condition):

$$H = \max\left(\frac{MSE}{MSPE}\frac{1}{F_{.05}(M-3, N-M)} - \frac{1}{n_0}, 0\right)$$

where $F_{.05}(M - 3, N - M)$ is the fifth percentile of an F distribution with degrees of freedom M – 3 and N – M. Percentiles of the F distribution can be obtained from Table 9.10.2.

d) Calculate degrees of freedom, *df* (Because the standard deviation is estimated by combining two different sums of squared differences, MSPE and MSE, standard statistical procedures do not apply. The formulas below rely on Satterthwaite's approximation for degrees of freedom.)

$$df = \frac{(H+1)^2}{\frac{\left(H + \frac{1}{n_0}\right)^2}{M-3} + \frac{\left[\frac{(n_0 - 1)}{n_0}\right]^2}{N-M}}.$$

The degrees of freedom is estimated using the upper confidence bound on the ratio of the variability between t/D conditions to the variability within t/D condition, instead of the point estimate of the ratio. This approach for estimating the degrees of freedom ensures that level of confidence that T_{90} is below 90 percent of the fastener strengths, at each value of x = ln(t/D), is 95 percent when the ratio of the variability between t/D conditions to the variability within t/D condition is large, and it is consistent with a similar approach used in MIL-HDBK-17.

4) **Determine noncentrality parameter for T_{90}**

a) For x = ln(t/D) in the range being characterized, calculate Q(x):

$$Q(x) = q_1 + 2q_2 x + (2q_3 + q_4)x^2 + 2q_5 x^3 + q_6 x^4,$$

where $q_1, q_2, \ldots, q_6$ are defined as sums of the x_i = ln(t/D) in 9.6.3.2 of the Guidelines. (With any regression, the further you move away from the bulk of the data, the more uncertain the estimates are. Q(x) provides a measure of the "nearness" of x to the center of the data.)

b) Then calculate R(x):

$$R(x) = \frac{H + \frac{1}{n_0}}{H + 1} Q(x).$$

5) **Finally, calculate T_{90} as in [9.5.6.1(f)]:**

$$T_{90} = a + bx + cx^2 - \left(t_{0.95, df, \frac{1.282}{\sqrt{R(x)}}}\right)\sqrt{R(x)}\, s_y,$$

where the term in parentheses is the 95th percentile of the noncentral t distribution with df degrees of freedom and noncentrality parameter $1.282/(R(x))^{1/2}$ (as in 9.5.6.1 of these Guidelines).

Examples of this analysis procedure applied to yield and ultimate fastener load test data are given in Figures 9.7.1.4(d) and (e), respectively. Note in Figure 9.7.1.4(d) that it is possible for the B-basis design curve to fall above a small percentage of the actual test results. Note also in Figure 9.7.1.4(e) that the shear cutoff value has been incorporated into the ultimate strength regression curve.

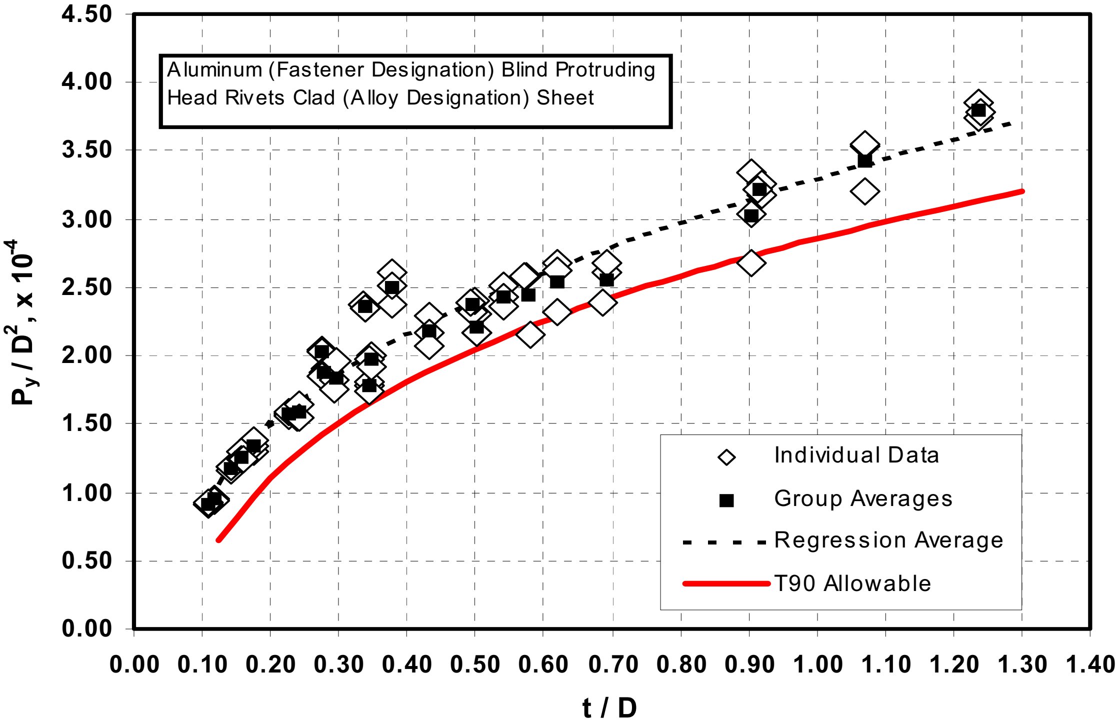

Figure 9.7.1.4(d) Example of Regression Analysis to Define B-Basis (T90) Fastener Yield Load Design Allowables

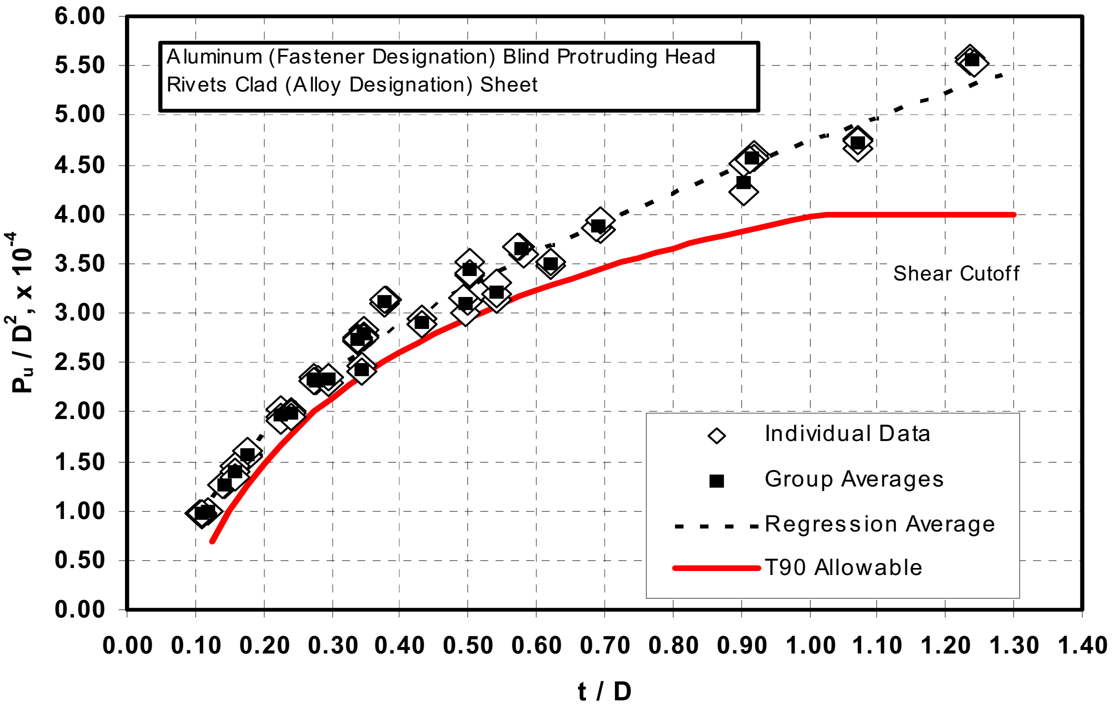

Figure 9.7.1.4(e) Example of Regression Analysis to Define B-Basis (T90) Fastener Ultimate Load Design Allowables

9.7.1.5 ***Calculation of Allowable Loads*** — Allowable yield and ultimate loads will be calculated for each thickness and diameter combination using the B-basis lower bound curves described above. Allowable loads will not be calculated for thickness/diameter combinations below the t/D range tested, or for diameters not tested.

In these calculations, thickness (per Section 9.9.5, Note 11), and diameters to be used will be the nominal shank diameter (per Section 9.7.1.1) for S-Type fasteners and recommended nominal hole diameters (per Section 9.7.1.1) for H-type fasteners. Figure 9.7.1.5 shows a suggested format for this set of calculations.

Computation of Allowables from Design Curves

D	D^2	t	t/D		$P_y/10^4D^2$	P_y	$P_u/10^4D^2$		P_u

D, t, P_u, and P_y, as described in 9.7.1.4

Figure 9.7.1.5. Suggested tabular layout for computing allowables from design curves.

The analysis of joint allowable load data for the case where data are required for procuring or regulatory agency (not for use in MIL-HDBK-5) for a limited range of sheet thickness and fastener diameter is as follows. An analysis similar to that described in Section 9.7.1.4 is required for data over the limited t/D range evaluated. In the special case where one sheet thickness and one fastener diameter have been tested in accordance with the requirements of Section 9.7.1.3, data will be analyzed as follows: the ultimate-load calculations will be made utilizing the statistical formulas listed in Section 9.7.1.3, where the k value is obtained from Table 9.10.1 for the appropriate number of test values (n) and 90 percent probability (B) value at a 95% confidence level. These ultimate-load values will be compared with values computed from bearing ultimate strengths of the joint material. In each comparison, the lower of either (1) statistical value computed from joint test data, (2) computed B-basis ultimate value from regression analysis, (3) computed bearing ultimate strength, or (4) fastener shear ultimate strength, will be the ultimate-load design allowable.

Similarly, the yield-load values will be compared with values computed from bearing yield strengths of the joint material. These yield-load values will be compared with values computed from bearing yield strengths of the joint material. In each comparison, the lower of either (1) statistical value computed from joint test data, (2) computed B-basis yield value from regression analysis, (3) computed bearing yield strength, or (4) fastener shear yield strength, will be the yield-load design allowable.

The load values so calculated will be rounded to three or four significant figures as follows:

(1) Load values less than 1000 will be rounded to 3 figures (load values less than 100, 2 figures).

(2) Load values greater than 1000 will be rounded to 4 figures. The fourth figure will be a 0 or 5.

9.7.2 FUSION-WELDED JOINT DATA — The purpose of this section of the guidelines is to provide a uniform procedure by which reliable design data on welded joints can be developed for use within the aerospace industry. Unlike most other guidelines procedures, for which reasonably complete concurrence has been found among the users of MIL-HDBK-5, those relating to fusion-welding allowables are still subject to interpretation by users in view of their own welding processes. An additional consideration is that fusion-welding allowables are highly process-dependent. Design values will not be presented in MIL-HDBK-5 since their application will be limited to the process represented by data from which the allowables were derived.

Consequently, it is the purpose of these guidelines to describe one of possibly many valid procedures, without excluding other procedures that may be authorized for determination of fusion-welding allowables. Basis for this discussion is presented in Reference 9.7.2.

These guidelines generally reflect procedures currently used within the aerospace industry. They are applicable to all types of weldable materials and welding processes. However, recommended test coupon configurations and testing methods described herein have been limited to those used in evaluation of butt-type joints.

A distinction is made in properties of weldments between those applicable to design and those used for welding development and process control. These guidelines are concerned with those properties applicable to design.

The approach followed establishes coupon-derived design properties for weldments produced under known and defined conditions. Appropriate analysis must be conducted to adapt coupon-derived data to design of the structure being considered. This is accomplished by determining the state of stress for the component joint, and/or by relating structural hardware test results to coupon-derived design properties. This approach is consistent with techniques used to obtain design data for MIL-HDBK-5, as defined in other sections of these guidelines.

Current military welding specifications do not contain adequate requirements for defining a meaningful population of weldments. Due to this lack of applicable industry-wide specifications, the necessary specification information must be presented with coupon-derived weldment design data.

Throughout the guidelines and in preparation of data, definitions of the American Welding Society will be used for terms relating to welding. The definitions utilized in MIL-HDBK-5 and in other sections of these guidelines will be used for other terms relating to material properties and statistical treatment of data.

9.7.2.1 *Data Collection and Interpretation* — Determination and presentation of properties of weldments requires adequate definition of pertinent welding parameters, including a description of base materials, welding process variables, and weld character. The most significant variables considered are divided into three basic categories: base materials, welding process variables, and weld character (see Figure 9.7.2.1). Variables listed are the minimum that must be identified and required by the specification.

In summary, the primary concern of population definition for weldments is to describe welding conditions in a manner that will assure reproducibility of this same population and will be sufficiently detailed to allow proper data analysis.

9.7.2.1.1 *Base Materials* — Base material variables include appropriate stipulation of alloy, composition form, preweld and postweld heat treat conditions, filler material, and material thickness.

9.7.2.1.2 *Welding Process Variables* — The most difficult aspect is establishing welding variables. The variables must be sufficiently detailed to represent the population of weldments produced, as well as to assure reproducibility of welds within this population. Appropriate selection of variables to be stipulated must be based on an interpretation of their effect on weldment properties and desirability of control.

BASE MATERIAL

Alloy, Composition, Form, Pre- and Post-Weld Heat Treat Condition, Material Thickness, Filler Material

WELDING PROCESS VARIABLES

Joint Preparation

- Joint Type
- Edge Preparation
- Cleaning

Tooling

- Alignment
- Restraint
- Thermal Control

Welding Conditions

- Welding Process
- Welding Method
- Welding Position
- Heat Input (Weld Setting)
- Preheat
- Interpress Temperature
- Shielding Gas

Weld Repair

- Number of Repairs
- Type of Repair

WELD CHARACTER

Inspection Methods

- NDT
  - Visual
  - Radiographic
  - Magnetic Particle
  - Ultrasonic
- DT
  - Transverse Tensile Test

Acceptance Levels

- External
  - Underfill and Undercut
  - Cracks
  - Pores
  - Reinforcements
- Internal
  - Pores
  - Inclusions
  - Cracks
- Tensile Properties
  - Minimum and Minimum Average

Figure 9.7.2.1. Summary of population definition considerations.

Using the variable of thermal control tooling as an example, it may be found that various types of tooling influence tensile properties of a weld joint by their effect on cooling rate. However, the difficulty in adequately describing thermal-control tooling for more than a single application makes it desirable to treat tooling as a random and uncontrolled variable. This same judgment of effect on properties and desirability of control must be made for each welding process variable.

9.7.2.1.3 *Weld Character* — Appropriate levels of weld character must be prescribed in order to define a population of weldments. This includes a description of internal and external quality levels, as well as minimum joint strength requirements. In most specifications there are several weld classes which identify in detail the quality level requirements. In addition, means of determining weldment characteristics are established by stipulation of both nondestructive and destructive test methods.

9.7.2.2 *Data Analysis* — Some concepts used for base-metal analyses lend themselves to analysis techniques for weldments. The procedures described in other sections of the guidelines may be used as a basis for analysis of mechanical property data for weldments in order to obtain A- and B-values. The procedures involve either direct statistical analysis of weldment data when sufficient data exist, or an indirect statistical analysis of ratios of paired properties.

The data samples required for direct statistical analysis will usually limit its use to tensile ultimate strength of weldment coupons. The indirect analysis may be used to derive other properties of interest using smaller samples. One example is to derive the minimum shear strength for the cases where only tensile distribution is known; one would operate on the ratio SUS/TUS in this case.

The indirect computation method also provides a tool for rational development of weld factors to be used in translating coupon-derived minimum properties to hardware design. In this case, ratio of hardware failure stress to control coupon failure stress is used.

9.8 EXAMPLES OF DATA ANALYSIS AND DATA PRESENTATION FOR STATIC PROPERTIES

Proposals presented to the MIL-HDBK-5 Coordination Group should include (1) new or revised table of room-temperature allowables, (2) raw data used in the analysis, and (3) supporting analysis for the proposed design values.

9.8.1 DIRECT ANALYSES OF MECHANICAL PROPERTIES — Computational procedures described in earlier sections are demonstrated here. Several hypothetical sets of input data were created for these example problems. These datasets were created to represent quality assurance test data, representing one long transverse tensile test per lot, plus other tests from a portion of the lots, at a frequency of one test per lot.

The example problems fall into two major categories. Problems I through VII illustrate techniques based on an underlying normal distribution. Problems VIII through XII illustrate techniques based on an underlying three-parameter Weibull distribution.

The input data for these example problems are described below. Because entire data sets (as opposed to means and standard deviations) are required for Problems VIII through XII, the data points for groups (1) through (4) and group (6) are listed in Tables 9.8.1(a) through (c).

INFORMATION FOR EXAMPLE PROBLEMS

Material Identification: Alloy X sheet, annealed.
Specified Testing Direction: Long Transverse (LT)

Specified Properties:
≤ 0.125 inch — F_{tu} (LT) = 140 ksi, F_{ty} (LT) = 115 ksi;

0.126-0.249 inch — F_{tu} (LT) = 135 ksi, F_{ty} (LT) = 110 ksi.

Available Test Results:

Group (1). 300 observations of TUS(LT) for thickness range 0.020-0.125 inch from Supplier A; no variation with thickness. Go to Problems I, III, VIII, and X.

Group (2). 300 observations of TYS(LT) for thickness range 0.020-0.125 inch from Supplier A; no variation with thickness. Go to Problems II and IX.

Group (3). 30 observations of TUS(LT) for thickness range 0.020-0.125 inch from Supplier B; no variation with thickness. Go to Problems I and VIII.

Group (4). 30 observations of TYS(LT) for thickness range 0.020-0.125 inch from Supplier B; no variation with thickness. Go to Problems II and IX.

Group (5). 100 observations of TUS(LT) for thickness range 0.126-0.249 inch; no variation with thickness. Go to Problems III and X.

Group (6). 30 observations of SUS(LT) for thickness range 0.020-0.249 inch; apparent decrease in SUS(LT) on increasing thickness; observations may be paired with TUS(LT) if desired. Go to Problem VII.

Table 9.8.1(a). Group (1) Data Set

Group (1)				
139.608	146.534	147.442	151.229	153.792
140.638	146.651	147.489	151.234	153.844
140.711	146.667	147.497	151.283	153.846
140.988	146.699	147.653	151.323	153.855
141.873	146.710	147.752	151.388	153.914
141.940	146.714	147.765	151.425	153.992
142.105	146.766	147.785	151.428	154.021
142.478	146.825	147.803	151.433	154.064
142.597	146.857	147.911	151.471	154.068
142.694	146.876	147.942	151.557	154.077
143.309	146.941	147.952	151.599	154.110
143.502	146.944	147.961	151.609	154.128
143.620	146.970	147.980	151.628	154.149
143.644	147.087	148.001	151.641	154.219
143.674	147.198	148.012	151.670	154.242
143.720	147.284	148.029	151.785	154.297
143.844	147.291	148.038	151.837	154.359
143.865	147.326	148.048	151.876	154.382
143.867	147.334	148.049	151.962	154.508
143.997	147.353	148.051	151.992	154.541
144.221	148.686	148.059	152.015	154.571
144.320	148.691	148.074	152.037	154.781
144.463	148.695	148.091	152.081	154.858
144.508	148.701	148.118	152.101	155.012
144.612	148.714	148.122	152.143	155.077
144.651	148.724	148.197	152.150	155.102
144.837	148.854	148.201	152.151	155.116
144.864	148.868	148.236	152.157	155.231
144.890	148.884	148.267	152.199	155.267
144.973	148.891	148.292	152.207	155.311
145.076	148.919	148.304	152.270	155.336
145.110	148.952	148.334	152.332	155.359
145.122	148.957	148.339	152.352	155.386
145.165	148.982	148.355	152.448	155.422
145.214	149.016	148.368	152.656	155.469
145.229	149.045	148.567	152.736	155.604
145.270	149.103	148.584	152.802	155.627
145.277	149.107	148.620	152.840	155.641
145.325	149.158	148.678	152.882	155.785
145.399	149.180	148.684	152.907	155.823
145.416	149.183	150.194	152.920	155.863
145.577	149.187	150.310	152.929	155.904
145.600	149.321	150.315	153.007	156.078
145.693	149.416	150.340	153.029	156.088
145.709	149.473	150.377	153.049	156.379
145.721	149.571	150.415	153.102	156.616
145.741	149.581	150.423	153.118	156.716
145.872	149.605	150.427	153.206	156.740
145.921	149.605	150.459	153.279	156.924
145.925	149.606	150.579	153.286	157.053
145.966	149.653	150.722	153.296	157.341
145.978	149.707	150.731	153.298	157.357
146.069	149.731	150.739	153.478	157.614
146.136	149.755	150.773	153.504	157.763
146.220	149.798	150.830	153.543	157.980
146.285	149.810	151.019	153.576	158.021
146.301	149.812	151.042	153.648	158.154
146.367	149.894	151.075	153.695	158.518
146.479	149.996	151.111	153.707	159.377
146.500	150.124	151.211	153.715	162.717

Table 9.8.1(b). Group (2) Data Set

Group (2)				
121.438	126.276	128.823	131.254	133.841
121.614	126.342	128.846	131.325	133.843
121.757	126.388	128.868	131.388	133.893
122.077	126.430	128.966	131.439	133.898
122.109	126.449	128.983	131.444	133.912
122.494	126.535	128.989	131.469	133.922
122.503	126.606	129.029	131.477	133.934
122.543	126.665	129.035	131.677	133.948
122.632	126.668	129.052	131.690	134.089
123.082	126.673	129.083	131.731	134.134
123.101	126.696	129.117	131.754	134.179
123.193	126.727	129.136	131.786	134.194
123.238	126.822	129.148	131.808	134.249
123.296	126.863	129.321	131.816	134.339
123.474	126.877	129.413	131.906	134.351
123.527	126.907	129.434	131.975	134.361
123.616	126.919	129.546	131.977	134.689
123.694	126.972	129.560	132.138	134.747
123.755	126.999	129.596	132.189	134.776
123.770	127.114	129.654	132.223	134.779
123.825	127.140	129.709	132.282	134.873
124.025	127.203	129.715	132.286	134.874
124.055	127.300	129.784	132.296	134.883
124.083	127.322	129.788	132.380	134.890
124.105	127.337	129.891	132.393	134.969
124.121	127.383	129.899	132.436	135.027
124.171	127.387	129.938	132.470	135.064
124.176	127.420	129.940	132.482	135.191
124.223	127.474	130.007	132.511	135.499
124.373	127.579	130.020	132.514	135.513
124.681	127.607	130.070	132.558	135.518
124.691	127.677	130.206	132.564	135.532
124.718	127.695	130.225	132.595	135.545
124.778	127.710	130.237	132.703	135.661
124.793	127.741	130.351	132.718	135.754
124.920	127.761	130.427	132.762	135.836
124.934	127.811	130.457	132.805	135.920
125.000	127.841	130.499	132.849	135.921
125.018	127.859	130.526	132.851	135.944
125.070	127.859	130.528	132.869	136.027
125.070	127.889	130.586	132.952	136.030
125.150	127.946	130.599	133.024	136.032
125.152	128.010	130.624	133.031	136.050
125.247	128.016	130.684	133.049	136.112
125.279	128.153	130.710	133.096	136.149
125.295	128.203	130.765	133.159	136.154
125.350	128.288	130.772	133.166	136.160
125.370	128.309	130.797	133.224	136.204
125.433	128.323	130.895	133.438	136.217
125.531	128.332	131.003	133.441	136.348
125.535	128.341	131.008	133.508	136.855
125.714	128.452	131.040	133.581	136.883
125.717	128.640	131.103	133.592	137.087
125.801	128.672	131.104	133.595	137.115
125.915	128.699	131.125	133.622	137.163
126.083	128.719	131.158	133.683	137.484
126.128	128.723	131.175	133.749	137.618
126.129	128.752	131.176	133.763	137.653
126.194	128.795	131.192	133.768	138.335
126.276	128.819	131.195	133.774	139.141

Table 9.8.1(c). Groups (3), (4), and (5) Data Sets

Group (3)	Group (4)	Group (5)	
141.914	120.487	135.373	145.061
143.980	122.271	135.500	145.072
145.110	124.167	135.775	145.082
145.681	124.622	136.450	145.082
145.829	124.672	137.114	145.331
145.919	125.280	137.241	145.460
145.981	125.862	137.900	145.606
148.412	126.332	138.916	145.626
148.694	128.860	139.158	145.754
148.772	129.158	139.307	145.785
148.831	129.179	139.626	145.802
148.965	130.238	139.827	145.876
149.197	130.782	139.839	146.091
149.761	130.985	140.022	146.096
150.150	131.612	140.461	146.159
151.472	131.642	140.957	146.302
151.746	132.129	141.083	146.303
152.089	132.147	141.149	146.447
152.564	132.812	141.435	146.797
152.737	133.388	141.473	146.937
152.798	133.716	141.518	146.967
153.857	134.127	141.582	147.149
153.930	135.787	141.592	147.224
154.012	135.836	141.731	147.305
154.024	136.235	141.937	147.500
154.153	136.770	142.125	147.657
155.637	137.068	142.138	147.675
157.118	137.901	142.298	147.833
162.241	137.919	142.441	148.084
164.426	138.017	142.785	148.556
		142.838	148.708
		142.859	148.954
		143.141	148.988
		143.180	149.082
		143.397	149.123
		143.426	149.590
		143.444	149.831
		143.558	149.974
		143.722	150.325
		143.886	151.484
		144.200	151.523
		144.276	151.605
		144.313	152.086
		144.418	152.467
		144.465	152.646
		144.650	152.852
		144.672	153.164
		144.847	153.675
		144.901	155.492
		144.924	157.944

EXAMPLE PROBLEMS BASED ON AN ASSUMED UNDERLYING NORMAL DISTRIBUTION[*]

PROBLEM I

Should the data in Groups (1) and (3) be combined?

Other Information: Neither property varies with thickness. Sample statistics are:

Subpopulation	n	$\overline{X}$, ksi	s, ksi
Group (1) TUS (LT), 0.020 to 0.125	300	150.0	4.00
Group (3) TUS (LT), 0.020 to 0.125	30	151.0	5.00

Prob. I—Step 1. Test to determine whether the variances differ significantly (refer to Section 9.5.3.2):

$$F = (s_1)^2/(s_3)^2 = (4.00)^2/(5.00)^2 = 0.64$$

Degrees of freedom, numerator = $n_1 - 1 = 300 - 1 = 299$.

Degrees of freedom, denominator = $n_3 - 1 = 30 - 1 = 29$.

$F_{0.975}(299,29\text{df})$ from Table 9.10.3 = 1.87 (approximately)

$1/F_{0.975}\ (29,299\text{df}) = 1/1.69 = 0.59$

Since the computed value of F(0.64) lies within the 0.95 confidence interval (0.59 to 1.87), conclude the variances do not differ significantly.

Prob. I—Step 2. Test to determine whether the averages differ significantly (refer to Section 9.5.3.3):

Difference between averages $D_{\overline{X}} = 150.0 - 151.0 = 1.0$ ksi

$$u = t_{0.975}\ S_p \sqrt{\frac{n_1 + n_3}{n_1\ n_3}}$$

Degrees of freedom = $n_1 + n_3 - 2 = 300 + 30 - 2 = 328$

$t_{0.975}$ (328 df) from Table 9.10.4 = 1.969

$$S_p = \sqrt{\frac{(n_1 - 2)\ s_1^2 + (n_3 - 1)\ s_2^2}{n_1 + n_3 - 2}} = \sqrt{\frac{(300 - 1)(4.00)^2 + (30 - 1)(5.00)^2}{300 + 30 - 2}} = 4.10\ \text{ksi}$$

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[*] The statistical tests described in Problems I through III apply specifically to the case where normality can be assumed. The more general Anderson-Darling procedure described in Problem IV can be applied to normal as well as nonnormal distributions.

$$u = 1.969 \times 4.10 \times \sqrt{\frac{n_1 + n_3}{n_1 \ n_3}} = 1.969 \times 4.10 \times \sqrt{\frac{300 + 30}{300 \times 30}} = 1.54 \text{ ksi}$$

Since the observed difference between the averages, $\overline{X}$ (1.0 ksi), is less than u (1.54 ksi), conclude the averages do not differ significantly.

Prob. I—Step 3. Since there is no reason to conclude that the subpopulations represented by Groups (1) and (3) do not belong to the same population, combine these groups.

Subpopulation	n	$\overline{X}$, ksi	s, ksi
Group (1& 3) TUS (LT), 0.020-0.125, Suppliers A and B	330	150.1	4.10

Go to Problem IV.

PROBLEM II

Should the data in Groups (2) and (4) be combined?

Other Information: Neither property varies with thickness. Sample statistics are:

Subpopulation	n	$\overline{X}$, ksi	s, ksi
Group (2) TYS (LT), 0.020-0.125, Supplier A	300	130.0	4.00
Group (4) TYS (LT), 0.020-0.125, Supplier B	30	131.0	5.00

The steps involved in this problem are identical to those in Problem I and similar conclusions were obtained from the input, namely, that Groups (2) and (4) should be combined. The sample statistics for the combined groups are:

Subpopulation	n	$\overline{X}$, ksi	s, ksi
Group (2& 4) TYS (LT), 0.020-0.125, Suppliers A and B	330	130.1	4.10

Go to Problem V.

PROBLEM III

Should the data in Groups (1) and (5) be combined?

Other Information: Neither property varies with thickness. Sample statistics are:

Subpopulation	n	$\overline{X}$, ksi	s, ksi
Group (1) TUS (LT), 0.020-0.125	300	150.0	4.00
Group (5) TUS (LT), 0.126-0.249	100	145.0	4.47

Prob. III—Step 1. Test to determine whether the variances differ significantly.

$F = (s_1)^2/(s_5)^2 = (4.00)^2/(4.47)^2 = 0.80$

Degrees of freedom, numerator $= n_1 - 1 = 300 - 1 = 299$.

Degrees of freedom, denominator $= n_5 - 1 = 100 - 1 = 99$.

$F_{0.975}$ (299,99df) from Table 9.10.3 = 1.46 (approximately)

$1/F_{0.975}(99{,}299\text{df}) = 1/1.43 = 0.700$.

Since the computed value of F (0.80) lies within the 0.95 confidence interval (0.700 to 1.46), conclude that the variances do not differ significantly.

Prob. III—Step 2. Test to determine whether the averages differ significantly.

Difference between averages, $D_{\overline{X}} = (150.0 - 145.0) = 5.0$ ksi

$$u = t_{0.975} S_p \sqrt{\frac{n_1 + n_5}{n_1 \; n_5}}$$

Degrees of freedom $= n_1 + n_{\cancel{6}5} - 2 = 300 + 100 - 2 = 398$.

$t_{0.975}$ (398 df) from Table 9.10.4 = 1.968.

$$S_p = \sqrt{\frac{(n_1 - 1)s_1^2 + (n_5 - 1)s_5^2}{n_1 + n_5 - 2}} = \sqrt{\frac{(300 - 1)(4.00)^2 + (100 - 1)(4.47)^2}{300 + 100 - 2}} = 4.20 \text{ ksi}$$

$$u = (1.968)(4.20)\sqrt{\frac{n_1 + n_5}{n_1 \; n_5}} = (1.968)(4.20)\sqrt{\frac{300 + 100}{(300)(100)}} = 0.95 \text{ ksi}$$

Since the observed difference between the averages $D_{\overline{X}}$ (5.0 ksi) is greater than u (0.95 ksi), conclude that the averages differ significantly and that the subpopulations represented by Groups (1) and (5) do not belong to the same population.

Prob. III—Step 3. Do not combine the sample statistics for these groups.

Go to Problem VI.

PROBLEM IV

What computational method should be used for the combined observations of Groups (1) and (3)?

Other Information: This property does not vary with thickness. Sample statistics for the combined observations are:

Population	n	$\overline{X}$, ksi	s, ksi
Group (1& 3) TUS (LT), 0.020-0.125	330	150.1	4.10

Form of the distribution has not been determined.

The sample is large enough to permit direct computation of A and B values by any of the three available methods. Consequently, all three computational methods will be attempted: sequential Weibull, sequential Pearson, and nonparametric.

Prob. IV—Step 1. Test to determine whether the distribution is Weibull. The Anderson-Darling test for Weibullness will be employed in this example. Use the formula:

$$Z_{(i)} = (X_{(i)} - 150.1)/4.10,$$

the values of $Z_{(1), ...,} Z_{(330)}$ must be calculated. The first three values are $Z_{(1)} = -2.56$, $Z_{(3)} = -2.31$, and $Z_{(3)} = -2.29$. Now $F_0(Z_{(1)})$, ..., $F_0(Z_{(330)})$ must be calculated by finding the area under the standard normal curve to the left of each Z value. The first three values are $F_o(Z_{(1)}) = 0.0052$, $F_o(Z_{(2)}) = 0.0104$, and $F_o(Z_{(3)}) = 0.0110$.

The Anderson-Darling test statistic is then calculated as

$$AD = \left[\sum_{i=1}^{330} \frac{1-2i}{330}\left[\ln(F_o(Z_{(i)})) + \ln(1 - F_o(Z_{(331-i)}))\right]\right] - 330 = 0.693.$$

The computed value of the test statistic is then compared to the critical value

$$0.750 = 0.752/[1 + 0.75/330 + 2.25/(330)^2]$$

Since the computed value of 0.693 is less than the critical value of 0.750, the hypothesis of normality is not rejected.

Prob. IV—Step 2. Compute F_{tu} (LT), 0.020 to 0.125, for Alloy X, using procedures for the normal distribution.

Population	n	$\overline{X}$, ksi	s, ksi
Group (1 & 3) TUS (LT), 0.020 to 0.125	330	150.1	4.10

$k_A = 2.512$
$k_B = 1.410$
F_{tu}(LT), A basis = X - k_As = 150.1 - 2.512 x 4.10 = 139.8 or 140 ksi (rounded per Section 9.5.4.1)
F_{tu}(LT), B basis = X - k_Bs = 150.1 - 1.410 x 4.10 = 144.3 or 144 ksi (rounded per Section 9.5.4.1)

PROBLEM V

What computational method should be used for the combined observations of Groups (2) and (4)?

Other Information: This property does not vary with thickness. Sample statistics for the combined observations are:

Population	n	$\overline{X}$, ksi	s, ksi
Group (2 & 4) TYS(LT), 0.20 to 0.125	330	130.1	4.10

Form of the distribution has not been determined.

The sample is large enough to permit direct computation of A and B-values. Consequently, the computational method to be used will be determined by whether or not the observations are normally distributed.

Prob. V—Step 1. Test to determine whether or not the distribution is normal. The value of the Anderson-Darling test statistic for normality is 1.315 for Group (2 & 4). Since 1.315 is greater than the critical value of 0.750, the underlying distribution cannot be assumed to be normal. Thus, the underlying distribution will be treated as a three-parameter Weibull or an unknown distributional form.

Prob. V—Step 2. Compute F_{ty}(LT), 0.020-0.125, using procedures for the unknown distribution. This procedure requires the ranking of observations from lowest to highest. Referring to Table 9.10.9, it is found that for a sample size of 330, the lowest observation (rank = 1) is an A-value and the 24th lowest (rank = 24) is a B-value. The 24 lowest observations are shown below:

Rank	TYS, ksi	Rank	TYS, ksi	Rank	TYS, ksi
1	120.5	9	122.5	17	123.5
2	121.4	10	122.5	18	123.5
3	121.6	11	122.6	19	123.6
4	121.8	12	123.1	20	123.7
5	122.1	13	123.1	21	123.8
6	122.1	14	123.2	22	123.8
7	122.3	15	123.2	23	123.8
8	122.5	16	123.3	24	124.0

Consequently, from these data the following allowables have been computed for Alloy X:

F_{ty}(LT), A-basis = 120.5 ksi.
F_{ty}(LT), B-basis = 124.0 ksi.

PROBLEM VI

What computational procedure should be used for the observations in Group (5)? The data in Group (5) represent a borderline situation. They cannot be combined with data for lesser thicknesses because there is significant difference between the TUS(LT) averages for the two thickness ranges, as shown in Problem III. The sample size is just barely adequate for direct computation if the distribution is found to be normal. If the distribution is not normal, the properties for this product would be presented on an S-basis, pending the accumulation of more data. The test for normality would be conducted as described in Problem IV, and will not be illustrated here.

EXAMPLE PROBLEMS BASED ON AN ASSUMED UNDERLYING THREE-PARAMETER WEIBULL DISTRIBUTION

PROBLEM VII

Should the data in Groups (1) and (3) be combined?

Other Information. Neither property varies with thickness. (Refer to Sections 9.5.1 and 9.5.3.)

The k-sample Anderson-Darling test will be employed in this example to determine whether or not the data in Groups (1) and (2) should be combined. There are 328 distinct values in the combined data from both groups and these are ordered from least to greatest to obtain $Z_{(1)},\ldots,Z_{(328)}$. All values of h_j are equal to 1 except for $h_{34} = 2$ and $h_{160} = 2$. Taking Group (2) to be the first (A_1)-sample and Group (1) to be the second (A_2)-sample, the first 24 Z-values are listed in the table below with the corresponding H- and F-values.

Z_j	H_j	F_{ij}	Z_j	H_j	F_{ij}	Z_j	H_j	F_{ij}
139.61	0.5	0	142.48	8.5	1	143.72	16.5	1
140.64	1.5	0	142.60	9.5	1	143.84	17.5	1
140.71	2.5	0	142.69	10.5	1	143.86	18.5	1
140.99	3.5	0	143.31	11.5	1	143.87	19.5	1
141.87	4.5	0	143.50	12.5	1	143.98	20.5	1.5
141.91	5.5	0.5	143.62	13.5	1	144.00	21.5	2
141.94	6.5	1	143.64	14.5	1	144.22	22.5	2
142.10	7.5	1	143.67	15.5	1	144.32	23.5	2

The k-sample Anderson-Darling test statistic is calculated as

$$\mathrm{ADK} = \frac{1}{330(1)}\left[\frac{1}{300}\sum_{j=1}^{328} h_j \frac{(330F_{1j} - 300H_j)^2}{H_j(330 - H_j) - 330h_j/4} + \frac{1}{30}\sum_{j=1}^{328} h_j \frac{(330\ F_{2j} - 30H_j)^2}{H_j(330 - H_j) - 330h_j/4}\right] = 0.821$$

The computed value of the test statistic is compared to the critical value of

$$2.488 = 1 + 0.759\left(1.645 + \frac{0.678}{\sqrt{1}} - \frac{0.362}{1}\right) .$$

Since the computed value of 0.821 is less than the critical value of 2.488, the hypothesis that the populations from which these groups were drawn are identical is not rejected. Thus Groups (1) and (3) will be combined for the computation of allowables.

Go to Problem X.

PROBLEM VIII

Should the data in Groups (2) and (4) be combined?

Other Information: Neither property varies with thickness.

The value of the k-sample Anderson-Darling test statistic for Groups (2) and (4) is 2.147. Since 2.147 is less than the critical value of 2.488, the hypothesis that the populations from which these groups were drawn are identical is not rejected. Thus, Groups (2) and (4) will be combined for the computation of allowables.

Go to Problem XI.

PROBLEM IX

Should the data in Groups (1) and (5) be combined?

Other Information: Neither property varies with thickness.

The k-sample Anderson-Darling test will be employed in this example. Taking Group (5) to be the first sample (A_1) and Group (1) to be the second sample (A_2), the k-sample Anderson-Darling test statistic is calculated as:

$$\mathrm{ADK} = \frac{1}{400(1)}\left[\frac{1}{100}\sum_{j=1}^{398} h_j \frac{(400\ F_{1j} - 100\ H_j)^2}{H_j(400 - H_j)\ 400\ h_j/4} + \frac{1}{300}\sum_{j=1}^{398} h_j \frac{(400\ F_{2j} - 300\ H_j)^2}{H_j\ (400 - H_j) - 400\ h_j/4}\right] = 44.195$$

Since the computed value of 44.195 is greater than the critical value of

$$2.486 = 1 + 0.758\left(1.645 + \frac{0.678}{\sqrt{1}} - \frac{0.362}{1}\right) ,$$

the hypothesis that the populations from which these groups are drawn are identical is rejected. Thus Groups (1) and (5) will not be combined for the calculation allowables.

PROBLEM X

What computational method should be used for the combined observations of Groups (1) and (3)?

Other Information: This property does not vary with thickness.

Form of the distribution has not been determined.

The sample is large enough to permit direct computation of A and B-values. Consequently, the computational method will be determined by whether or not the observations may be assumed to follow a three-parameter Weibull distribution.

Prob. X—Step 1. Test to determine whether the distribution is a three-parameter Weibull distribution. The Anderson-Darling test for three-parameter Weibullness will be employed in this example. Preliminary calculations give

$K = 88$ $\qquad W_{50} = 0.665$

$\bar{X} = 150.1$ $\qquad S = 4.10$

$X_{(1)} = 139.608$ $\qquad H = 139.6079$

$L = -259.9$

$$R(\tau) = \sum_{i=89}^{262} L_i(\tau) \Big/ \sum_{i=1}^{262} L_i(\tau) \quad .$$

It can be verified that $R(-259.9) > 0.665$ and $R(139.6079) < 0.665$. Solving the equation $R(\tau) = 0.665$ with the initial interval $(-259.9, 139.6079)$ gives $\tau_{50} = 138.70$. The function $G_{50}(\beta_{50})$ then becomes

$$G_{50}(\beta_{50}) = \frac{1}{330} \sum_{i=1}^{330} \ln(X_i - 138.70) \left[\left(\frac{X_i - 138.70}{\alpha_{50}} \right)^{\beta_{50}} - 1 \right] - \frac{1}{\beta_{50}}$$

where

$$\alpha_{50} = 10.53 \left[\frac{1}{330} \sum_{i=1}^{330} \left(\frac{X_i - 138.70}{10.53} \right)^{\beta_{50}} \right]^{1/\beta_{50}}$$

Solving the equation $G_{50}(\beta_{50}) = 0$ gives $\beta_{50} = 3.02$ which in turn gives $\alpha_{50} = 12.75$.

The values of $Z_{(1)}, \ldots, Z_{(330)}$ are obtained using the formula

$$Z_i = \left(\frac{X_{(i)} - 138.70}{12.75} \right)^{3.02} \quad .$$

The first three Z-values are $Z_{(1)} = 0.000345$, $Z_{(2)} = 0.00339$, and $Z_{(3)} = 0.00378$. The Anderson-Darling test statistic is calculated as

$$AD = \sum_{i=1}^{330} \frac{1 - 2i}{330} \left[\ln\left(1 - \exp(-Z_{(i)})\right) + \ln\left(\exp(-Z_{(331-i)})\right) \right] - 330 = 0.491 \quad .$$

The computed value of the test statistic is compared to the critical value

$$0.749 = 0.757/(1 + 1/5\sqrt{330}) \quad .$$

Since the computed value of 0.491 is less than the critical value of 0.749, the hypothesis that the observations follow a three-parameter Weibull distribution is not rejected.

Prob. X—Step 2. Compute F_{tu} (LT), 0.020-0.125, for Alloy X, using procedures for the three-parameter Weibull distribution. Preliminary calculations give

$K = 88$
$W_A = 0.698$
$W_\beta = 0.678$
$\overline{X} = 150.1$
$S = 4.10$
$X_{(1)} = 139.608$
$H = 139.6079$
$L = -259.9$

$$R(\tau) = \sum_{i=89}^{262} L_i(\tau) \Big/ \sum_{i=1}^{262} L_i(\tau)$$

Solving the equation $R(\tau) = 0.698$ with the interval (-259.9, 139.6079) gives $\tau_A = 136.43$. Solving $R(\tau) = 0.678$ gives $\tau_B = 137.98$.

Solving the equation $G_A(\beta_A) = 0$ gives $\beta_A = 3.63$ which in turn gives $\alpha_A = 15.14$. Solving the equation $G_B(\beta_B) = 0$ gives $\beta_B = 3.22$ which in turn gives $\alpha_B = 13.52$.

Using the formulas from Section 9.5.2.2 the allowables are calculated as follows:

$$Q_A = 15.14\ (0.01005)^{1/3.63} = 4.263$$
$$Q_B = 13.52\ (0.10536)^{1/3.22} = 6.719$$
$$A = 136.43 + 4.263 \exp\left(-7.259/3.63\ \sqrt{330}\right) = 140.2$$
$$B = 137.98 + 6.716 \exp\left(-4.103/3.22\ \sqrt{330}\right) = 144.2$$

PROBLEM XI

What computational method should be used for the combined observations of Groups (2) and (4)?

Other Information: This property does not vary with thickness.

Form of the distribution has not been determined.

The sample is large enough to permit direct computation of A and B values. Consequently, the computational method will be determined by whether or not the observations may be assumed to follow a three-parameter Weibull distribution.

Prob. XI—Step 1. Test to determine whether the distribution is a three-parameter Weibull distribution. The Anderson-Darling test for three-parameter Weibullness will be employed in this example. Preliminary calculations give

$K = 88$
$\overline{X} = 130.1$
$W_{50} = 0.665$
$X_{(1)} = 120.487$
$S = 4.10$
$H = 120.4869$
$L = -279.9$

$$R(\tau) = \sum_{i=89}^{262} L_i(\tau) \Big/ \sum_{i=1}^{262} L_i(\tau)$$

Solving the equation $R(\tau) = 0.665$ with initial interval (-279.9, 120.4869) gives $\tau_{50} = 119.58$. Solving the equation $G_{50}(\beta_{50}) = 0$ gives $\beta_{50} = 2.84$ which in turn gives $\alpha_{50} = 11.81$.

The values $Z_{(1)},...,Z_{(330)}$ are obtained using these estimates. The value of the Anderson-Darling test statistic is 1.392. Since the computed value of 1.392 is greater than the critical value of 0.749, the hypothesis that the observations follow a three-parameter Weibull distribution is rejected.

Prob. XI—Step 2. Compute F_{ty}(LT), 0.020 to 0.125, using procedures for an unknown distribution. This computation has been carried out in Problem V, Step 2.

9.8.2 INDIRECT ANALYSES OF MECHANICAL PROPERTIES

PROBLEM XII

What computational procedure should be used for the observations in Group (6)?

Other Information: SUS(LT) decreases with increasing thickness, while TUS(LT) does not vary with thickness. Sample statistics are:

Population	n	$\overline{X}$, ksi	s, ksi
Group (6) SUS(LT), 0.020 to 0.249	30	not determined	

The sample size for these data is too small to permit direct computation. Thus, the procedure that should be used is indirect computation by pairing observations of SUS(LT) with observations of TUS(LT). Also, since a thickness effect was suspected in the original data, a regression against thickness should be made and checked for significance.

Prob. XII—Step 1. Pair SUS(LT) with TUS(LT).

Ratios of SUS(LT)/TUS(LT) are as follows:

SUS(LT)/ TUS(LT)	Thickness, inch	SUS(LT)/ TUS(LT)	Thickness, inch
0.700	0.020	0.640	0.090
0.680	0.020	0.650	0.090
0.660	0.020	0.660	0.090
0.660	0.030	0.630	0.100
0.670	0.030	0.650	0.100
0.680	0.030	0.670	0.100
0.650	0.040	0.640	0.150
0.670	0.040	0.630	0.150
0.690	0.040	0.620	0.150
0.650	0.060	0.610	0.180
0.660	0.060	0.630	0.180
0.670	0.060	0.650	0.180
0.640	0.070	0.600	0.240
0.660	0.070	0.610	0.240
0.680	0.070	0.620	0.240

Prob. XII—Step 2. Determine regression equation in the form [SUS(LT)TUS(LT)]′=r′=a + bx, where x = thickness, using least-squares techniques. (Note—in this example, the letter r, rather than y, is used to denote the dependent variable and the prime (′) is used to indicate that the ratio is determined by regression.) The following sums were obtained from analysis of the ratios plotted in Figure 9.8.1.2.1.

Number of ratios, n = 30

$\sum(x) = 2.94$

$\sum(x^2) = 0.4260$

$\sum(r) = 19.53$

$\sum(r^2) = 12.7319$

$\sum(xr) = 1.8723$

$(\sum x)^2 = 8.6436$

$(\sum r)^2 = 381.4209$

$(\sum x)(\sum r) = 57.4182$

$S_{xx} = 0.1379$

$S_{xr} = 0.0416$

$S_{rr} = 0.0179$

Referring to the equations presented in Section 9.5.6:

$$\text{Slope, } b = \frac{S_{xr}}{S_{xx}} = \frac{-0.0416}{0.1379} = -0.302$$

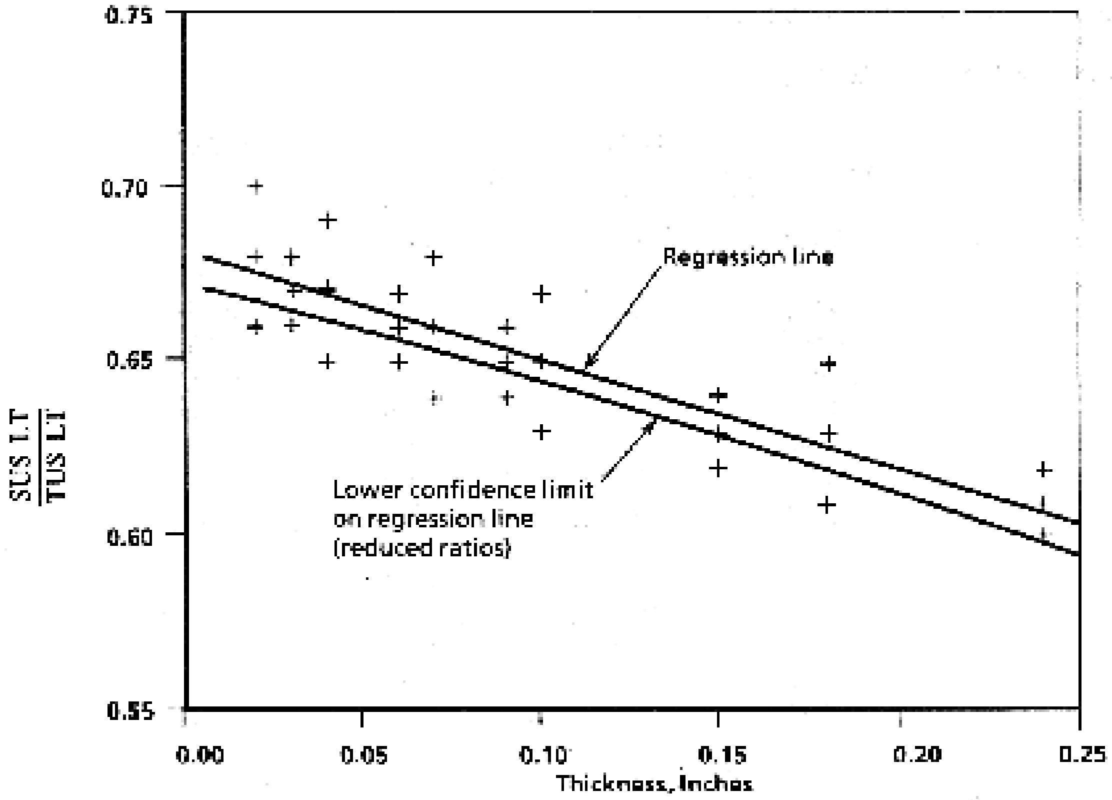


Figure 9.8.1.2.1. Ratios of input data for Problem VII.

Standard Error of Estimate,

$$\text{SEE} = \sqrt{\frac{S_{rr} - b^2 S_{xx}}{(n - 2)}}$$

$$= \sqrt{\frac{0.0179 - (-0.302)^2(0.1379)}{(30 - 2)}}$$

$$\text{SEE} = 0.014$$

The equation of the regression line is r′ = 0.6806 - 0.302x.

The regression line is shown in Figure 9.8.1.2.1.

Prob. XII—Step 3. Perform an analysis of variance to check the significance and linearity of the regression.

Since there are 30 ratios, the analysis of variance approach rather than the method involving the computation of confidence limits on the slope term can be used to evaluate linearity.

The only information missing from Step 2 required for the analysis of variance is the values of T, or the summed values of r for each x. They are as follows:

x_1	T_1	x_1	T_1
0.02	2.04	0.09	1.95
0.03	2.01	0.10	1.95
0.04	2.01	0.15	1.89
0.06	1.98	0.18	1.89
0.07	1.98	0.24	1.83

Using these values, the analysis of variance, which is illustrated in Section 9.5.6.3, can be completed as follows:

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F_{calc}
Regression	0.0126	1	0.0126	63.0
Error	0.0053	28	0.0002	
Lack of Fit	0.0004	8	0.00005	0.208
Pure Error	0.0049	20	0.00024	
Total	0.0179	29		

The second calculated F statistic of 0.208 with k - 2 = 8 and n - k = 20 degrees of freedom is less than the value of 2.45 from Table 9.10.2 corresponding to 8 numerator and 20 denominator degrees of freedom. Thus, the deviation from linearity is not significant. The first F statistic of 63.0 with 1 and 28 degrees of freedom is greater than the value of 4.20 from Table 9.10.2 corresponding to 1 numerator and 28 denominator degrees of freedom, so the slope of the regression is found to be significantly different from zero.

Prob. XII—Step 4. Compute the reduced ratio for SUS(LT)/TUS(LT). In performing this step, the reduced ratio will be computed at each of four thicknesses (0.020, 0.062, 0.125, and 0.249 inch). This is done by determining the lower confidence limit for the regression line at the desired thicknesses, using the equation from Section 9.5.3. The computation will be worked in detail for $x_0 = 0.020$ inch:

$$\text{Reduced ratio} = [\text{SUS(LT)/TUS(LT)}]' - t_{0.95}s'_r \sqrt{\frac{1}{n} + \frac{(x_0 - \Sigma x/n)^2}{(\Sigma x^2) - (\Sigma x)^2/n}}$$

$[\text{SUS(LT)/TUS(LT)}]' = r' = 0.681 - 0.302x_0$ (from Step 2, Problem VII)
$= 0.681 - 0.302 \times 0.020 = 0.6746.$

$t_{0.95}$ (for $n - 2 = 30 - 2 = 28$ degrees of freedom) = 1.701 (from Table 9.10.4)

$s'_r = 0.014$ (from Step 2)

$$\sqrt{\frac{1}{n} + \frac{(x_0 - \Sigma x/n)^2}{(\Sigma x^2) - (\Sigma x)^2/n}} = \sqrt{\frac{1}{30} + \frac{(0.020 - 2.94/30)^2}{0.4260 - 8.6436/30}} = 0.2783$$

Reduced ratio = 0.6746 - 1.701 x 0.014 x 0.2783 = 0.668.

The corresponding ratios for the other thicknesses are tabulated in Step 5. See Figure 9.8.1.2.1 for lower confidence limit curve.

Prob. XII—Step 5. Compute F_{su}. This computation will be illustrated for a thickness of 0.020 inch, using the reduced ratio from Step 4.

From Problem IV,
F_{tu}(LT) = 140 ksi (A-basis)
F_{tu}(LT) = 144 ksi (B-basis)
F_{su}(LT) = Reduced Ratio x F_{tu}(LT)
F_{su}(LT)(A-Basis) = 0.668 x 140 = 93.5 ksi
F_{su}(LT)(B-Basis) = 0.668 x 144 = 96.2 ksi.

For the four thicknesses listed,

		F_{su}(LT), ksi		
t, inch	Reduced Ratio	A-basis	B-basis	S-basis
0.020	0.668	93.5	96.2	...
0.062	0.657	92.0	94.6	...
0.125	0.638	89.3	91.9	...
0.249	0.595	...	...	80.3

Since F_{su} is shown to decrease with increasing thickness, only the lowest value applicable to the range should be presented in MIL-HDBK-5. By dividing the 0.020 to 0.125 thickness range into two ranges, a somewhat higher F_{su}(LT) value may be presented for thinner material as shown below.

The results of the computations in Problems I through VII have produced the following results (fractions greater than 0.75 are raised to the next higher ksi, while less fractions are dropped):

Thickness, inch	<0.020	0.020-0.062		0.063-0.125		0.126-0.249
Basis	S	A	B	A	B	S
F_{tu}(LT), ksi	140	140	144	140	144	135
F_{ty}(LT), ksi	115	120	124	120	124	110
F_{su}, ksi	...	92	94	89	92	80

Since SUS(LT) data were not available for thickness <0.020 inch, a design value is not presented for this range.

9.8.3 TABULAR DATA PRESENTATION — The proposal for the incorporation of design allowables into MIL-HDBK-5 will contain supporting data and computations for all design properties. Depending on quantity and availability, data may be tabulated, plotted, or referenced (to readily available technical reports, specifications, etc.). Computations should indicate adequately the manner in which design values were computed and will be presented in an orderly manner. Data sources will be identified.

All minimum mechanical property data analyses must be performed in English units. Strength data recorded in metric units should be converted to English units, to the nearest 0.01 ksi, before data analyses are undertaken. If desired by the data supplier, metric equivalent tables and figures can be included as part of the working data submitted with a data proposal, but the tables and/or figures proposed for inclusion in MIL-HDBK-5 will contain only English units.

9.8.3.1 Mechanical Properties — The table of room-temperature design values will be presented in the format indicated in Figure 9.8.3.1(a) for conventional metallic materials. This format has been designed to accommodate most of these materials; however, some modifications may be required. For example, the format shown in Figure 9.8.3.1(b) will be used for aluminum alloy sheet laminates which are generally anisotropic and have limited ductility. Design values for these hybrid materials are presented for several mechanical properties which differ from those shown for conventional metallic materials. Unused lines (for example, ST properties for sheet) are deleted. Guidance in the use of these formats may be obtained by examining tables throughout this document and by referral to the applicable procurement specification. The following instructions should be followed for the items located in Figure 9.8.3.1(a):

(1) Table number: If this is a revision of an existing table, use the same table number; otherwise, use a new table number in the proper sequence.

(2) Material designation: Use a numeric designation where available (for example, 7075 aluminum alloy). Avoid the use of trade names. Include products following the material designation, except products may be omitted from the title if there are many products covered by the table.

(3) Specification: Refer to a public specification (industry, Military, or Federal), followed by a type or class designation, if appropriate. Do not refer to proprietary specifications.

Table ①. Design Mechanical and Physical Properties of (material designation) ② (products)

Specification	③			
Form				
Condition (or Temper)	④			
Cross-Sectional Area, in.^{2}		⑤		
Location Within Casting		⑥		
Thickness or Diameter, in.		⑦		
Basis	S	A	B ⑧	S
Mechanical Properties:				
F_{tu}, ksi:				
L	120	120	124	
LT (or T) ⑨	...	... ⑩	...	
ST				
F_{ty}, ksi:				
L				
LT (or T)				
ST				
F_{cy}, ksi:				
L				
LT (or T)				
ST				
F_{su}, ksi				
F_{bru}, ksi:⑪				
(e/D = 1.5)				
(e/D = 2.0)				
F_{bry}, ksi:				
(e/D = 1.5)				
(e/D = 2.0)				
e, percent (S-basis):				
L				
LT (or T)				
ST				
RA, percent (S-basis):				
L				
LT (or T)				
ST				
E, 10^3 ksi				
E_c, 10^3 ksi				
G, 10^3 ksi				
μ				
Physical Properties:				
ω, lb/in.^{3}	⑫			
C, Btu/(lb)(°F)				
K, Btu/[(hr)(ft^2)(°F)/ft]				
α, 10^{-6} in./in./°F				

⑬ (footnotes)

Figure 9.8.3.1(a). Format for room temperature property table.

Table 7.5.X.X(b). Design Mechanical and Physical Properties of (sheet material designation) Aluminum Alloy, Aramid Fiber Reinforced, Sheet Laminate

Specification				
Form	Aramid fiber reinforced sheet laminate			
Laminate Lay-Up	2/1	3/2	4/3	5/4
Nominal Thickness, in.	0.032	0.053	0.074	0.094
Basis	S	S	S	S
Mechanical Properties[a]:				
F_{tu}, ksi:				
L				
LT				
F_{ty}, ksi:				
L				
LT				
F_{cy}, ksi:				
L				
LT				
F_{su}, ksi				
F_{sy}, ksi				
F_{bru}, ksi:				
L (e/D = 1.5)				
LT (e/D = 1.5)				
L (e/D = 2.0)				
LT (e/D = 2.0)				
F_{bry}, ksi:				
L (e/D = 1.5)				
LT (e/D = 1.5)				
L (e/D = 2.0)				
LT (e/D = 2.0)				
ε_t, percent:				
L				
LT				
E, 10^3 ksi:				
L				
LT				
E_c, 10^3 ksi:				
L				
LT				
G, 10^3 ksi:				
L				
LT				
μ:				
L				
LT				
Physical Properties:				
ω, lb/in.^{3}				
C, K, and α				

a Design values were computed using nominal thickness of sheet laminate.

Figure 9.8.3.1(b). Format for room temperature property table for aluminum alloy fiber reinforced sheet laminate.

(4) Condition: Use a standard temper designation where applicable. Otherwise, use an easily recognized description, including pertinent details if these are not available in the reference specification. Examples: T651, TH1050, Aged (1400°F), Mill Annealed.

(5) Cross-sectional area: Use only when applicable.

(6) Location within casting: Applicable only to castings. Specify "Non-designated area," or "Designated area," as applicable.

(7) Design values will be presented only for the thicknesses covered in the material specification.

(8) Basis: For each product and size, use two columns covering A- and B-basis properties or one column covering S-basis properties. A-values that are higher than the corresponding S-values are presented only in footnotes to the table. In such instances, A-values are replaced by S-values in the body of the table. When A-values are presented for some properties and S-values are presented for other properties for the same product, values will be shown in a column labeled A-basis, and individual S-values will be identified by appropriate footnotes. Elongation, total strain at failure, and reduction of area values are presented on an S-basis only. When other properties are presented on an A- and B-basis, add "(S-basis)" after "e, percent," or "ε_t percent" and "RA, percent."

(9) Grain direction: Show design values for grain directions "L, LT, and ST" or for grain directions "L and T" for the properties F_{tu}, F_{ty}, F_{cy}, e, and RA. For anisotropic materials sheet and plate, present design values for grain directions "L, 45°, and LT" for F_{tu}, F_{ty}, and F_{cy}. For aluminum alloy sheet laminates, show design values for L and LT grain directions of aluminum alloy sheet for all mechanical properties. Grain directions are not applicable to castings.

The T grain direction should be footnoted with the definition used in the specification identified at the top of the mechanical property table. For example, the T grain direction for aluminum die forgings covered in MIL, Federal and some AMS specifications will read as follows: "For die forgings, T indicates any grain direction not within ±15 degrees of being parallel to the forging flow lines." For updated AMS specifications with the preferred narrower definition of the T grain direction, the footnote should read as follows: "For die forgings, T indicates a grain direction within ±15 degrees of being perpendicular to the forging flow lines." Specimens to test the transverse properties should be located as close to the short transverse direction as possible.

Transverse F_{cy} values for aluminum die forgings will be shown as F_{cy}(T). If the values are based upon short transverse or long transverse test data, add this information to the above footnote.

(10) Missing values: For table entries that are missing or not applicable, show a series of three dots aligned with the numbers in that column.

(11) Bearing values: Add footnote "Bearing values are dry pin values per Section 1.4.7.1" when bearing allowables are based on data from clean pin tests. Supporting information supplied with the proposal should describe the bearing test cleaning procedures used in testing.

(12) Physical properties: Include a section for physical properties even if properties are not available. If physical property data are presented in an effect-of-temperature curve, use table entry, "See Figure X.X.X.0" to refer to the illustration.

(13) Footnotes: Use footnotes to indicate anything unusual or restrictive concerning the property description, properties, or individual values; to present supplementary values; or to reference other tables or sections of text. When A-values have been replaced by S-values, the following wording is suggested: "S-basis. The rounded T_{99} values are as follows: (list values)."

In addition, the proposal will contain supporting data and computations for all design properties. Depending on quantity and availability, data may be tabulated, plotted (by cumulative-probability curves or histograms), or referenced (to readily available technical reports, specifications, etc.). Computations should indicate adequately the manner in which design values were computed and will be presented in an orderly manner. Data sources will be identified.

9.8.3.2 *Modulus of Elasticity and Poisson's Ratio* — The following room-temperature elasticity values are presented in the room-temperature property tables as typical values:

Property	Units	Symbol	Recommended ASTM Test Procedures
Modulus of Elasticity			
In tension	1000 ksi	E	E 111
In compression	1000 ksi	E_c	E 111
In shear	1000 ksi	G	E 143
Poisson's Ratio	(Dimensionless)	μ	E 132

If the material is not isotropic, the applicable test direction must be specified. Deviations from isotropy must be suspected if the experimentally determined Poisson's ratio differs from the value computed by the formula

$$\mu = \frac{\bar{E}}{2G} - 1 \qquad [9.8.3.2(a)]$$

where $\bar{E}$ is the average of E and E_c.

Given E, E_c, and G, μ may be computed by this equation. Likewise, given E, E_c, and μ, G may be computed from the equation:

$$G = \frac{\bar{E}}{2(\mu + 1)} \qquad [9.8.3.2(b)]$$

In the event E_c is not available, E may be substituted for $\bar{E}$ in the above equations to provide an estimate of either μ or G.

9.8.3.3 *Physical Properties* — Density, specific heat, thermal conductivity, and mean coefficient of thermal expansion are physical properties normally included in MIL-HDBK-5. Physical properties are presented in the room-temperature property table if they are not presented in effect-of-temperature curves. The basis for physical properties is "typical". Table 9.8.3.3 displays units and symbols used in MIL-HDBK-5, and also recommended ASTM test procedures for measuring these properties. Since modifications of procedures are employed in measuring physical properties, methods used for values proposed for inclusion in MIL-HDBK-5 should be reported in the supporting data proposal. For specific heat and thermal conductivity values reported in the room temperature property table, the reference temperature of measurement is also shown [for example, for 2017 aluminum the specific heat is 0.23 (at 212°F)]. For tabulated values of mean thermal expansion, temperature range of the coefficient is shown [for example, 12.5 (70 to 212°F)]. The reference temperature of 70°F is established as standard for mean coefficient of thermal expansion curves.

Table 9.8.3.3. Units and Symbols Used to Present Physical Property Data and ASTM Test Procedures

Property	Unit	Symbol	Recommended ASTM Test Procedures
Density	lb/in.^{3}	ω	C 693
Specific heat	Btu/lb-°F	C	D 2766
Thermal conductivity	Btu(hr-ft^2-°F/ft)	K	C 714[a]
Mean coefficient of thermal expansion	10^{-6}(in./in./°F)	α	E 228

a ASTM C 714 is a test for thermal diffusivity from which thermal conductivity can be computed.

9.8.4 ROOM TEMPERATURE GRAPHICAL MECHANICAL PROPERTY DATA

9.8.4.1 ***Typical Stress-Strain*** — The stress-strain and tangent-modulus data appearing in MIL-HDBK-5 are described as "typical" stress-strain and compression tangent-modulus curves. The term typical indicates that representative stress-strain data for products covered have been adjusted to reflect precision typical values of the elastic modulus, and product average values of the 0.2 percent offset yield strength in tension or compression. Curves extend to strain somewhat beyond the 0.2 percent offset yield strength. Curves described as "full range" stress-strain curves are also included in MIL-HDBK-5. These curves extend through maximum load and beyond to rupture. Mathematical representations of curves are covered in Section 9.8.4.6.

All curves will be prominently marked "typical". With regard to tension data, only stress-strain curves are shown; however, compression data should include stress-strain curves and tangent-modulus curves. The Ramberg-Osgood n exponent should appear on all stress-strain curves if n is shown to apply in the approximate range from proportional limit to yield strength. The procedures and methods to be used are described in the following paragraphs.

Two alternative procedures are described for determining typical stress-strain curves.

(1) The "strain-departure" method, which assumes no parametric relationship between stress and plastic strain, utilizes the full stress-strain curve.

(2) The Ramberg-Osgood method, which assumes an exponential relationship between stress and plastic strain. Its use requires as few as two points from the original stress-strain curve, once the exponential relationship has been found to be applicable.

Generally, the two methods yield nearly identical results for those portions of the curve lying between proportional limit and yield stress. For plastic strains greater than about 0.002 in./in. and for bimetallic or clad products, only the strain-departure method is applicable.

Stress tangent-modulus curves may be derived graphically from compressive stress-strain curves, or computed, if the Ramberg-Osgood method is used.

9.8.4.1.1 *Strain Departure Method* — These steps, as illustrated in Table 9.8.4.1.1, should be followed to establish a typical tensile or compressive stress-strain curve using the strain-departure method:

(1) The straight-line (modulus) portion of each curve should be extended as in Figure 9.8.4.1.1(a), and the 0.002 (0.2%) offset yield strength should be indicated.

(2) At appropriate departures or offsets from the modulus line, load should be determined accurately, converted to stress, and recorded. Sufficient departure measurements should be made to accurately describe the curve to just beyond yield load for each load-strain curve.

(3) At each strain departure, the stresses should be averaged.

(4) When a product average yield strength value is available, the average stresses at each departure should be converted to product average stresses.

(5) Elastic strains should be computed for each departure. (Elastic Strain equals Total Stress/Elastic Modulus.)

(6) Elastic strains (computed) and plastic strains (departure) should be added to obtain total strain for each departure.

Table 9.8.4.1.1. Example of Use of Strain Departures to Establish Typical Stress-Strain Curve

	Stress, ksi					Strain, μ in./in.	
Departure (D) μ in./in.	Test #1	Test #2	Test #3	Average[a] (σ_A)	Product Avg.[b] (σ_T)	Elastic[c] (ε_E)	Total[d] (ε_T)
0	43.81	42.75	41.20	42.59	42.63	4022	4022
20	49.77	48.81	45.14	47.91	47.95	4524	4544
40	51.41	50.98	47.82	50.17	50.12	4728	4768
100	54.31	53.96	51.24	53.17	53.22	5021	5121
500	60.16	60.37	57.10	59.21	59.27	5592	6092
1000	62.67	62.85	59.45	61.66	61.72	5823	6823
2000	64.95	65.06	61.80	63.94[f]	64.00[e]	6038	8038
2200	65.26	65.38	62.12	64.25	64.31	6067	8267

a Average of Tests 1, 2, and 3.
b σ_T = (Product average yield strength ÷ average yield strength) x σ_A.
c $\varepsilon_E = \sigma_T/E$.
d $\varepsilon_T = \varepsilon_E + D$.
e Product average yield strength.
f Average yield strength.

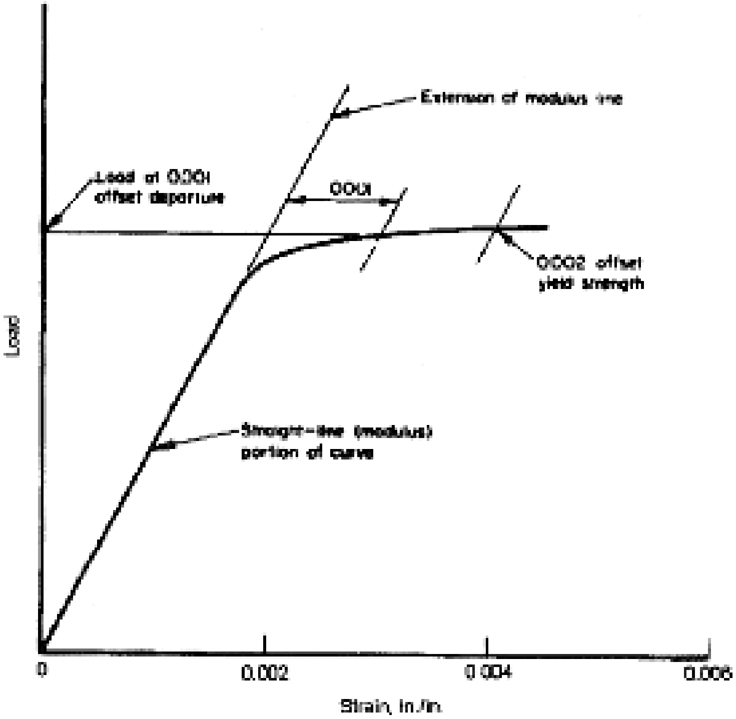


Figure 9.8.4.1.1(a). Measuring loads by strain departure method.

The following guidelines should be used to plot a typical stress-strain curve. The graph axis should be laid out such that there are 10 minor divisions for every major division with every tenth (major) division accented. The ordinate (Y-axis) is used for stress and should be scaled in units of ksi to the major division, as appropriate, to produce a total scale length of approximately 5 major divisions. The abscissa (X-axis) is used for total strain and should be scaled in units of in./in. to the major division, as appropriate, to produce a total scale length of approximately 6 major divisions.

The final step is plotting the values in Table 9.8.4.1.1 to produce the typical stress-strain curve as shown in Figure 9.8.4.1.1(b). In addition to plotting the graphs by hand, they may be plotted with computer software programs. In the latter case, input the stress-strain pairs (σ_T and ε_T) from Table 9.8.4.1.1 into the computer and then curve fit the data. In all cases, the elastic section must be linear up to the proportional limit. It is recommended that the Ramberg-Osgood equation be used to fit the data from the proportional limit to just beyond the 0.2% yield stress. If not, a power-law polynomial second order may be used to fit the data points. The stress-strain curve should extend slightly beyond the 0.2% yield strength.

To complete the figure, the Ramberg-Osgood number from Section 9.8.4.1.2 and the typical yield strength (TYS) product average must be contained in a table within the figure. If more than one curve is contained in the figure, information such as the grain direction (L, LT, and ST), and/or temperature for each curve must be indicated in the figure. Figure 9.8.4.1.1(c) shows the proper format of a figure for presentation in Chapters 2 through 7.

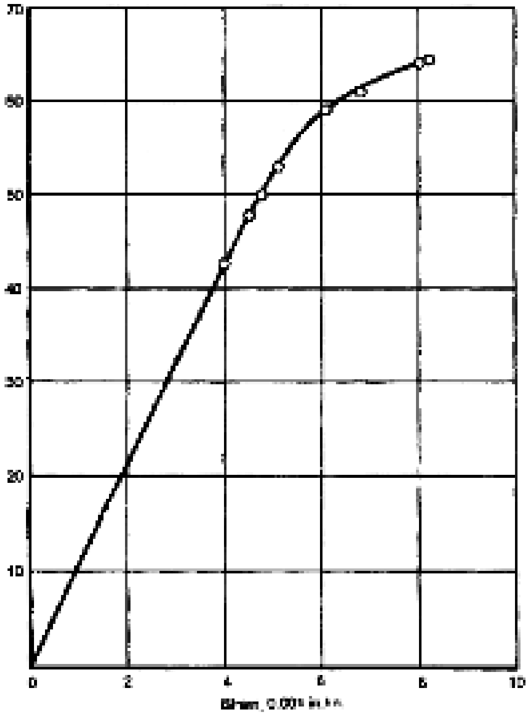
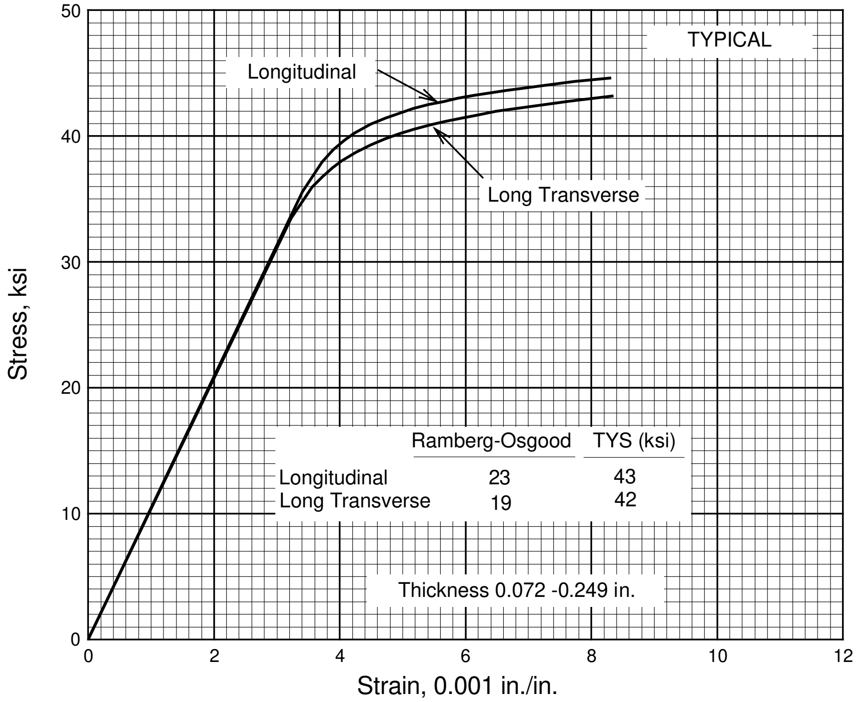


Figure 9.8.4.1.1(b). Plotted data from Table 9.8.4.1.1.



	Ramberg-Osgood	TYS (ksi)
Longitudinal	23	43
Long Transverse	19	42

Figure 9.8.4.1.1(c). Typical stress-strain curves showing the proper presentation format.

9.8.4.1.2 Ramberg-Osgood Method — This method, which is based on the work of Ramberg and Osgood [Reference 9.8.4.1.2(a)], and Hill [Reference 9.8.4.1.2(b)], assumes that an exponential relationship exists between stress and plastic strain, as expressed by

$$e_p = 0.002 \left(\frac{f}{f_{0.2ys}} \right)^n \qquad [9.8.4.1.2(a)]$$

where

f is stress,
$f_{0.2ys}$ is the 0.2 percent yield stress,
e_p is plastic strain,
n is the Ramberg-Osgood parameter**.

While this relationship may not be exact, it is sufficiently accurate for use up to the yield strength for many materials, but cannot be employed to compute full-range stress-strain curves.

Since total strain equals elastic strain plus plastic strain,

$$e_{total} = f/E + 0.002 \left(\frac{f}{f_{0.2ys}} \right)^n \qquad [9.8.4.1.2(b)]$$

where E is the typical value of modulus of elasticity from the room-temperature property tables.

Equation 9.8.4.1.2(b) can be programmed for determination and plotting by a computer, given only values for E, n, and $f_{0.2ys}$. To obtain typical curves, TYS or CYS is used for $f_{0.2ys}$. TYS and CYS values are based on product averages when available; in other cases, average values from original stress-strain curves are used. The Ramberg-Osgood parameter, n, will be determined analytically in development of typical stress-strain curves for MIL-HDBK-5.

As the first step in the analytical determination of n, a series of values of stress and strain departure (plastic strain) must be obtained from each original stress-strain curve. These may be determined by the method of strain-departure described in Section 9.8.4.1.1 or the alternate method outlined below:

(1) Determine the indicated modulus of elasticity for the individual stress-strain curves.

(2) For each curve, construct two lines parallel to the modulus line and intersecting the stress-strain curve at plastic strains of approximately 0.020 and 0.20 percent. The lines will bound the zone where stress-plastic strain pairs are determined. This zone also eliminates the small plastic strain region where nonlinearities in stress versus plastic strain sometimes exist.

(3) Digitize each stress-strain curve over the range bounded in Step 2. A series of approximately ten to 12 pairs of stress-total pairs should be taken at nearly equal intervals within this range. A resolution of 0.25 ksi stress and 0.01 percent strain is desirable here.

(4) Compute plastic strains from each collection of total strains, using the individual curve's modulus to subtract out elastic strains.

** The Ramberg-Osgood parameter, n, should not be confused with the strain hardening coefficient, which is also denoted by the letter n. The one is the reciprocal of the other. Values of the Ramberg-Osgood parameter usually lie within the range of 2 to 40. It should be noted that an occasional practice in the aircraft industry, but not followed in MIL-HDBK-5, is to subtract a small increment of strain from Equation 9.8.2.1.1.2(a) in order to compensate for the existence of a proportional limit.

Once the stress and plastic strain values are tabulated for available stress-strain curves, it is possible to proceed with determination of the Ramberg-Osgood parameter. To determine n analytically, Equation 9.8.4.1.2(a) is rearranged to solve for stress, f, the dependent variable.

$$f = Ae_p^{1/n} \qquad [9.8.4.1.2(c)]$$

where

$$A = \frac{f_{0.2ys}}{(0.002)^{1/n}} \qquad [9.8.4.1.2(d)]$$

Taking the natural logarithm of Equation 9.8.4.1.2(c), a transformed equation is obtained which can be analyzed by the method of linear least squares.

$$\ln f = \ln A + 1/n \ln e_p \qquad [9.8.4.1.2(e)]$$

The solution for n is the same as that for a linear regression least-squares estimate of the slope, b, as shown in Section 9.6.3.1, Equation 9.8.4.1.2(d) where b = 1/n, therefore,

$$n = \frac{\Sigma x^2 - \frac{(\Sigma x)^2}{N}}{\Sigma xy - \frac{\Sigma x \, \Sigma y}{N}} \qquad [9.8.4.1.2(f)]$$

where

$x = \ln e_p$
$y = \ln f$
N = number of data points.

Correspondingly, A can be obtained from Equation 9.8.4.1.2(d) as

$$\ln A = \frac{\Sigma y - \frac{1}{n} \Sigma x}{N} \qquad [9.8.4.1.2(g)]$$

Values for stress and strain departure may be input for solution of Equation 9.8.4.1.2(f) by either of two methods. In one method, $x = \ln e_p$ and $y = \ln f$ are input for each value of stress and strain departure for each stress-strain curve used in the analysis. N is the total number of points obtained from stress-departure analysis of all specimens from all heats that are analyzed. Care should be taken to ensure that the same number of data points are collected from each curve. In the other method, average stress (f) is determined for all available curves at designated values of strain departure (e_p). In this case, x and y in Equation 9.8.4.1.2(f) are $\ln e_p$ and $\ln f$, respectively, and N is the number of strain departure points. Again, the same number of data points should be computed for each stress-strain curve.

Some investigators may analyze the results of each individual specimen by the method outlined by Equations 9.8.4.1.2(c) through (g) and record individual values of the parameter n. In these cases, an alternate approach must be used to combine results and establish n. This technique is called the method of computed strain-departure.

In the method of computed strain-departure, results from individual specimen analyses are used to compute stress levels [from Equation 9.8.4.1.2(c)] at specific strain-departure levels for all specimens. In so doing, the original data are used to analytically perform the method of strain-departure of Section 9.8.4.1.1 which should be used as a guideline for doing this analysis. Once these computed stress values are obtained, they can be used to calculate the exponent, n, by Equation 9.8.4.1.2(f) using either of the two methods that are described above for the case when data are recorded by the method of strain-departure.

An approximate value of the Ramberg-Osgood parameter can be found graphically, although this approach will not be used to construct stress-strain curves for MIL-HDBK-5. Graphically determined stress-strain curves must be verified by computer analysis according to previously described techniques before inclusion in MIL-HDBK-5. A graphical procedure is described in the following paragraphs and is illustrated in Figure 9.8.4.1.2.

(1) Plot at least three pairs of stress-plastic strain points from each original stress-strain curve on log-log graph paper. As illustrated in Figure 9.8.4.1.2(a), the ordinate is conventionally used for log stress, the abscissa is log plastic strain (strain departure method is described in Section 9.8.4.1.1), and the slope is 1/n.

(2) A straight line then is drawn through the plotted points and the slope (l/n) is computed as shown in the figure.

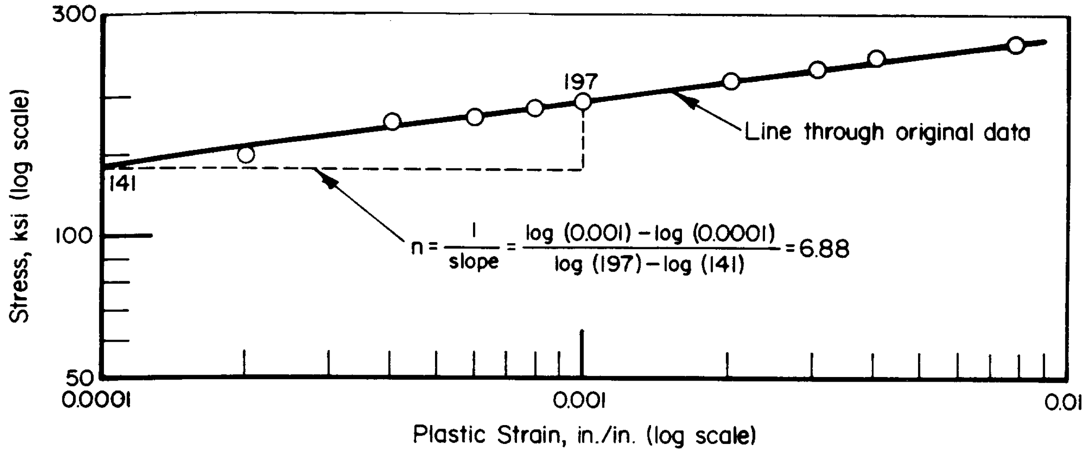


Figure 9.8.4.1.2. Graphical approximation of Ramberg-Osgood Parameter, n.

When using the above-described approaches, it is recommended that a check be made to determine how well the value of n reproduces the stress-strain curve in the approximate range from the proportional limit (defined as 0.02% ys) to $f_{0.2ys}$. This can be done by constructing the stress-strain curve using Equation 9.8.4.1.2(b), and comparing an original stress-strain curve through the yield strength with the computed curve. In checking an original stress-strain curve with the computed curve, some judgment must be exercised in the vicinity of the proportional limit since the Ramberg-Osgood relationship may not precisely represent original stress-strain curves in this area. Stress deviations greater than about 5 percent between the two curves suggest that the Ramberg-Osgood relation is not applicable.

9.8.4.2 *Compression-Tangent-Modulus Curves* — In deriving tangent-modulus curves graphically from typical compressive stress-strain curves, a number of points are marked off on the latter curves, particularly where the curve departs from linearity and in regions of greatest curvature. At each point on the curve, a line is drawn tangent to the curve as shown in Figure 9.8.4.2(a). The slope of each line is the tangent modulus corresponding to the stress coordinate of the point of tangency. The Ramberg-Osgood relationship, Equation 9.8.4.2(b),

$$e_{total} = f/E + 0.002 \left(\frac{f}{f_{0.2ys}} \right)^{n} \qquad [9.8.4.2(a)]$$

also may be employed to determine the compression tangent-modulus curve.

Tangent modulus is the first derivative of stress with respect to strain, df/de, or

$$E_t = \frac{1}{\frac{1}{E} + \frac{0.002n}{f_{0.2ys}} \left(\frac{f}{f_{0.2ys}} \right)^{n-1}} \qquad [\,9.8.4.2(b)]$$

This equation can be programmed for determination and plotting by a computer, given only values for E, n, and $f_{0.2\%ys}$. To obtain typical curves, average CYS is used for $f_{0.2\%ys}$.

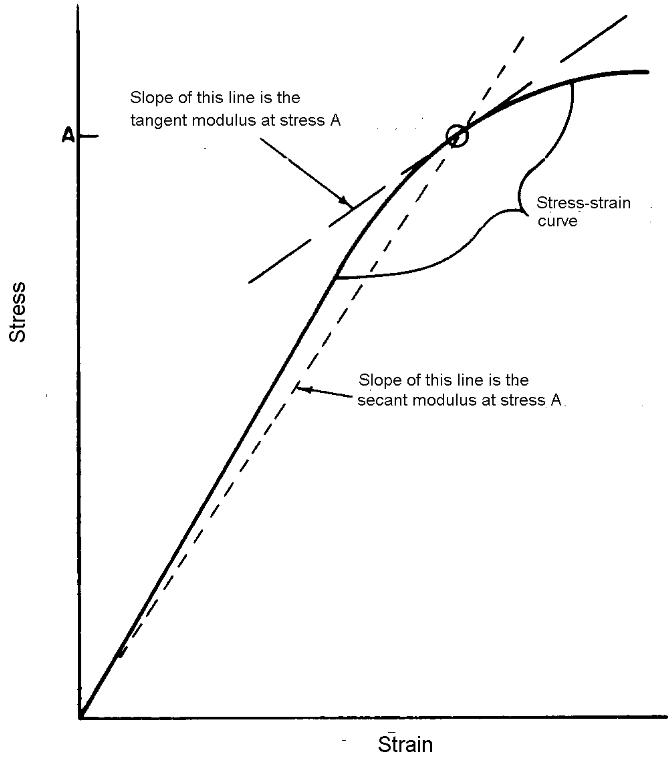


Figure 9.8.4.2(a). Determining tangent modulus and secant modulus.

The following guidelines should be used to plot a compression tangent-modulus curve. For mathematical representations of compression tangent modulus curves see Section 9.8.4.6. The graph axis should be laid out such that there are 10 minor divisions for every major division with every tenth (major) division accented. The ordinate (Y-axis) scale is plotted in the same manner as that used for the stress-strain curves in Section 9.8.4.1.1. The abscissa (X-axis) scale is usually made equal to 2, 4, or 5 x 10^3 ksi per major division, depending on material, to produce a total scale length of approximately 6 major divisions.

The compression tangent-modulus curve is illustrated in Figure 9.8.4.2(b) where stress is plotted (on the ordinate) versus tangent modulus (on the abscissa). In addition to plotting the graphs by hand, they may be plotted with computer software programs. In the latter case, input the stress-modulus pairs (σ_T and E_t) from Equation 9.8.4.2(b) into the computer or program the computer with the equation and then curve fit the data. If it will not lead to confusion, stress tangent-modulus curves may be superimposed on the corresponding stress-strain figures as illustrated in Figure 9.8.4.2(c). If, however, several stress-strain curves appear in one figure, it is advisable to present stress tangent-modulus curves in a separate figure, as illustrated in Figure 9.8.4.2(b).

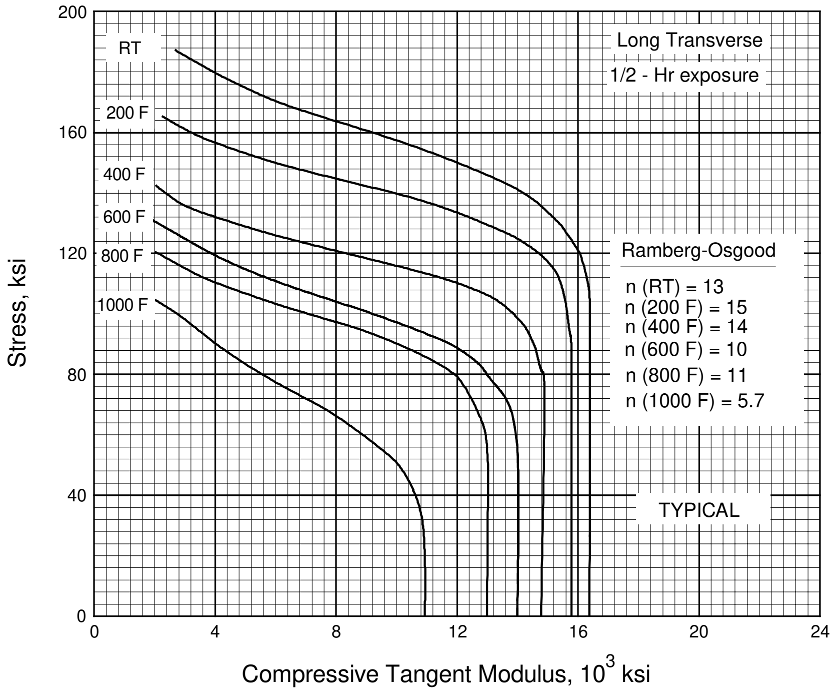


Figure 9.8.4.2(b). Typical compressive tangent-modulus curves.

The compression tangent-modulus curves for clad material should show a primary and secondary modulus as indicated in Figure 9.8.4.2(d). The stress-strain curves of clad material may indicate two modulus lines due to the cladding. The primary modulus is due to the combined modulus of both clad and base materials. However, the clad material is typically weaker than the base material and will yield at a low stress; therefore not contributing to the modulus at higher stresses. At this point, the secondary modulus becomes predominate. The compression tangent-modulus curves should show the primary and secondary modulus and indicated in Figure 9.8.4.2(d).

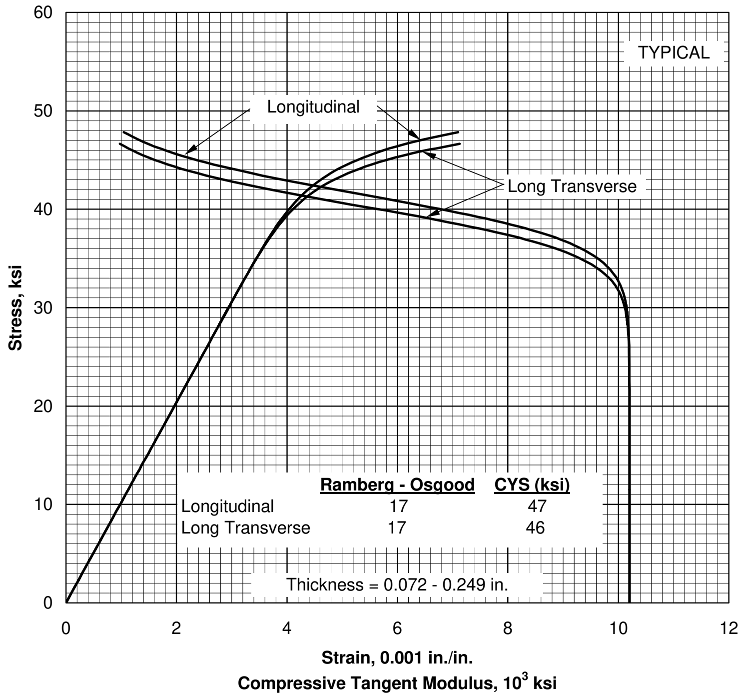


Figure 9.8.4.2(c). Typical compressive stress-strain and compressive tangent-modulus within the same figure.

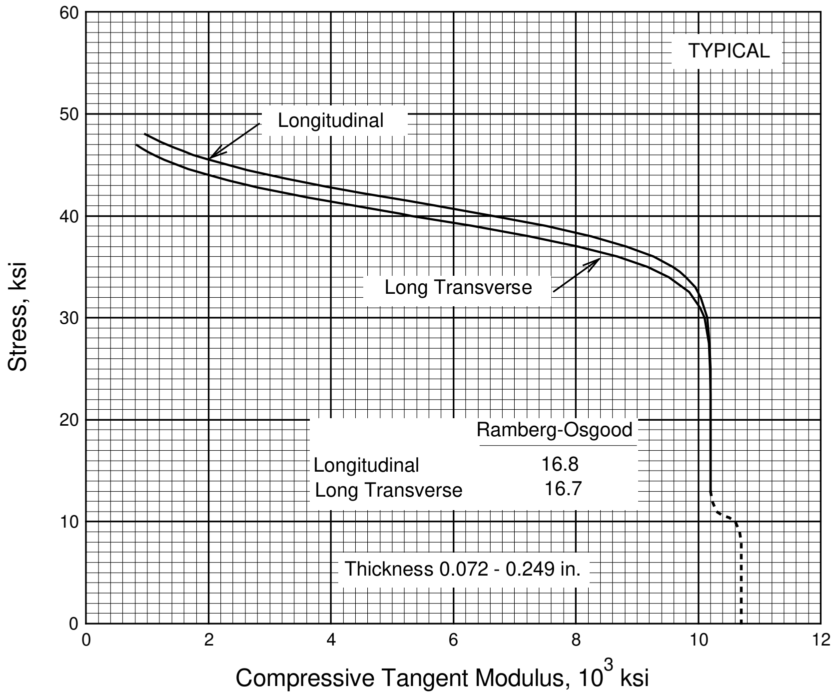


Figure 9.8.4.2(d). Typical compression tangent-modulus curves for clad aluminum alloy sheet showing the primary and secondary modulus.

To complete the figure, the Ramberg-Osgood number from Section 9.8.4.1.2 must be contained in a table within the figure. If more than one tangent modulus curve is contained in the figure, information such as the grain direction (L, LT, and ST), and/or temperature for each curve must be indicated in the figure. Figures 9.8.4.2(b), (c), and (d) show the proper format for presentation in Chapters 2 through 7.

Stress-secant modulus curves are not presently used in MIL-HDBK-5. Secant or "chord" modulus is determined as illustrated in Figure 9.8.4.2(a) and is plotted in the same manner as the tangent modulus. The equation for secant modulus is:

$$E_s = \frac{\mathrm{f}}{\mathrm{e}} = \frac{f}{\frac{f}{E} + 0.002\left(\frac{f}{f_y}\right)^n} \qquad [\,9.8.4.2\ (c)]$$

at the point of stress.

9.8.4.3 *Full-Range Tensile Stress-Strain Curves* — Preparation of each typical full-range tensile stress-strain curve requires (1) representative original full-range stress-strain curves, (2) product average values for ultimate strength, yield strength, and elongation, and (3) typical precision elastic-modulus values at test temperature. Full-range tensile stress-strain data for at least one lot of material will be provided, but data from three lots are preferred. If data for less than three lots are submitted, the full-range stress-strain curve will be labeled "BASED ON ONE LOT" or "BASED ON TWO LOTS", as appropriate.

The procedure for developing typical full-range tensile stress-strain curves is based upon strain departures obtained from several original test curves, and the product average tensile strength, yield strength, and elongation established from production data. Properties of material tested for determining strain departures should be in reasonable agreement with the product average properties.

These steps, as illustrated in Table 9.8.4.3 and Figures 9.8.4.3(a) and (b), should be followed in developing typical full-range tensile stress-strain curves.

(1) From each stress-strain test curve, measure strain departures (D) between the extension of the modulus line and the curve at stresses determined by taking appropriate percentages of the differences between ultimate stress and yield stress added to the yield stress.

$$\sigma_{(1,n)} = \mathrm{TYS} + \%\ (\mathrm{TUS} - \mathrm{TYS})$$

where TUS and TYS are values for each test. Also identify the proportional limit for each test. The proportional limit is defined as the stress level below, which the stress-strain curve is linear; as determined by σ=Eε where σ is the stress, E is Young's Modulus, and ε is the strain.

Table 9.8.4.3. Example of Strain-Departure Method to Establish Typical Full-Range Stress-Strain Curves

Percent	Test 1		Test 2		Average		Typical			
	Stress, ksi σ_1	Strain Departure[c] in./in. (D_1)	Stress, ksi σ_2	Strain Departure[c] in./in. (D_2)	Stress,[d] ksi σ_A	Strain Departure[d] in./in. (D_A)	Stress, ksi σ_T	Strain Departure[i] in./in. (D_T)	Elastic Strain[j] in/in. (ε_E)	Total Strain[k] in./in. (ε_T)
Yield Stress to Ultimate Stress										
Proportional Limit (PL)	56.5		58.5		57.5^{h}		59.6^{l}	0.0000	0.0058	0.0058
0(TYS)	58.8^{a}	0.0020	60.9^{a}	0.0020	59.8	0.0020	62.0^{e}	0.0020	0.0061	0.0081
20	61.0^{a}	0.0106	63.0^{a}	0.0094	62.0	0.0100	64.0^{e}	0.0100	0.0063	0.0163
40	63.2^{a}	0.0204	65.2^{a}	0.0194	64.2	0.0199	66.0^{e}	0.0200	0.0065	0.0265
60	65.4^{a}	0.0302	67.4^{a}	0.0302	66.4	0.0302	68.0^{e}	0.0303	0.0067	0.0370
80	67.7^{a}	0.0452	69.5^{a}	0.0436	68.6	0.0444	70.0^{e}	0.0446	0.0069	0.0515
95	69.3^{a}	0.0640	71.1^{a}	0.0626	70.2	0.0633	71.5^{e}	0.0636	0.0070	0.0706
100(TUS)	69.9^{a}	0.0848	71.7^{a}	0.0838	70.8	0.0843	72.0^{e}	0.0847	0.0071	0.0918
Ultimate Stress to Fracture Stress (FS)										
100(TUS)	69.9^{b}	0.0848	71.7^{b}	0.0838	70.8	0.0843	72.0^{g}	0.0847	0.0071	0.0918
90	69.0^{b}	0.0962	70.9^{b}	0.1014	70.0	0.0988	71.1^{g}	0.0992	0.0070	0.1062
60	66.3^{b}	0.1058	68.5^{b}	0.1156	67.4	0.1107	68.5^{g}	0.1112	0.0067	0.1179
0(FS)	60.9^{b}	0.1210	63.7^{b}	0.1378	62.3	0.1294	63.4^{f}	0.1300 (Elong.)	0.0062	0.1362

a $\sigma_{1,n}$ = TYS + % (TUS-TYS) where TUS and TYS are values for each test.
b $\sigma_{1,n}$ = TUS - (1 - %) · (TUS-FS) or $\sigma_{(1,n)}$ = FS + % (TUS-FS) where TUS and FS are values for each test.
c D = Departure (plastic strain) from modulus line at corresponding stresses.
d Averages (σ and D) of Tests 1 and 2.
e $\sigma_T = TYS_{Prod.\ Avg.} + \%\ (TUS_{Prod.\ Avg.} - TYS_{Prod.\ Avg.})$.
f $\sigma_T(FS) = (TUS_{Prod.\ Avg.}/TUS_{Avg.}) \cdot \sigma_{Avg.}(FS)$.
g $\sigma_T = TUS_{Prod.\ Avg.} - (1 - \%) \cdot (TUS_{Prod.\ Avg.} - \sigma_T(FS))$ or $\sigma_T = \sigma_T(FS) + \%\ (TUS_{Prod.Avg.} - \sigma_T(FS))$.
h Average proportional limit.
i $D_T = [((D_A - 0.002) \times (\text{Product Average Elongation} - 0.002)) \div (D_A \text{ at FS} - 0.002)] + 0.002$.
j $\varepsilon_E = \sigma_T \div E$ ($E = 10.2 \times 10^3$ ksi in this example).
k $\varepsilon_T = D_T + \varepsilon_E$.
l $\sigma_T(PL) = (TYS_{Prod.\ Avg.}/TYS_{Avg.}) \cdot \sigma_{Avg.}(PL)$.

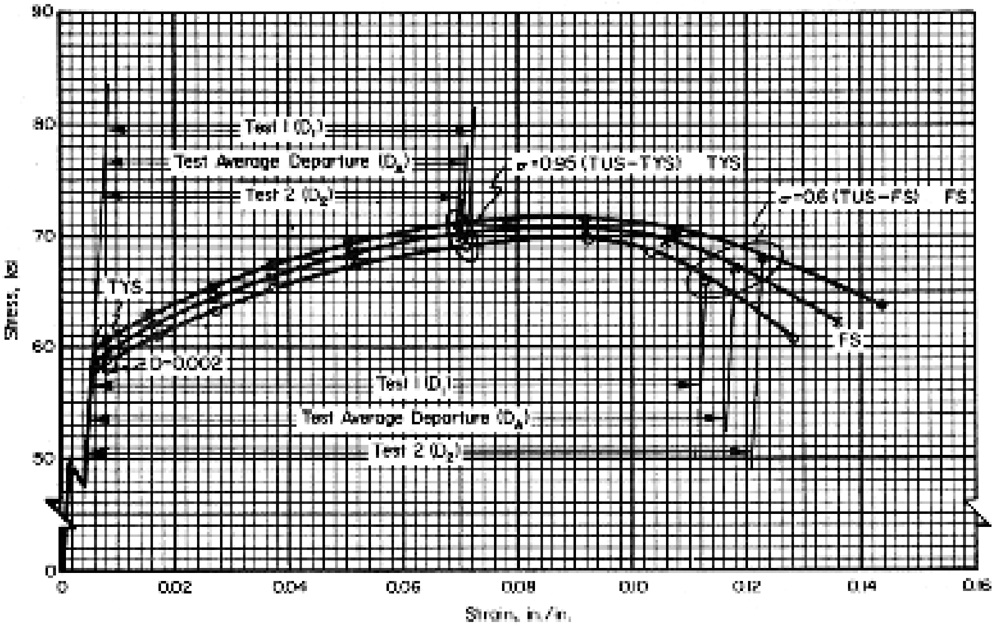


Figure 9.8.4.3(a). Strain departure method for determining average full-range stress-strain curve.

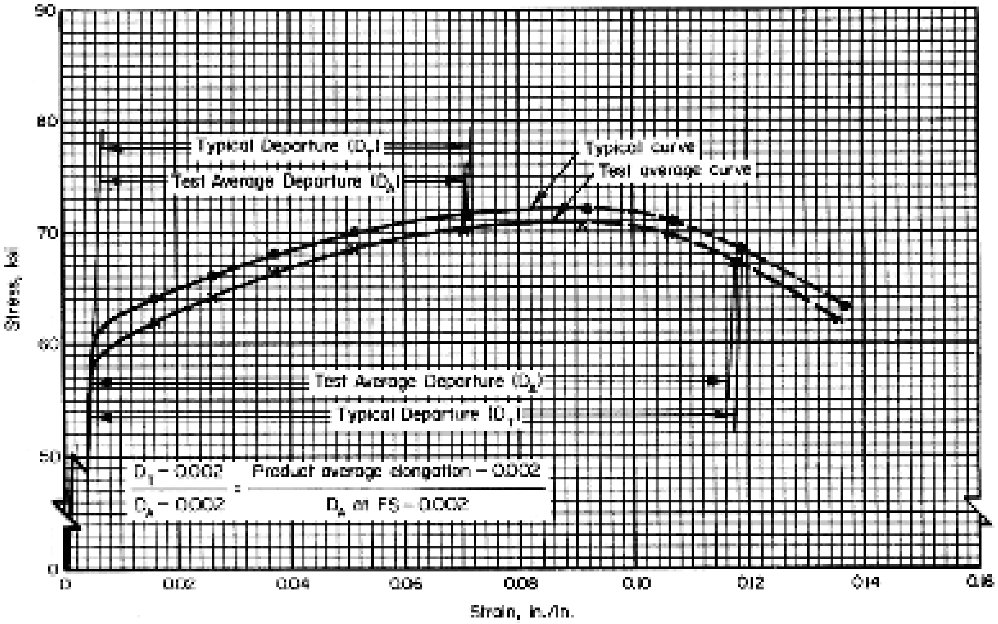


Figure 9.8.4.3(b). Method of adjusting average to typical full-range stress-strain curve.

(2) For departures beyond ultimate stress, the stresses are determined by taking the percentage of the difference between the fracture stress and ultimate stress and subtracting it from the ultimate stress.

$$\sigma_{(1,n)} = TUS - (1 - \%) \cdot (TUS - FS)$$

or

$$\sigma_{(1,n)} = FS + \% \ (TUS - FS)$$

where TUS and FS are values for each specimen.

(3) For each percentage, average the stresses and strain departures, σ_A and D_A, respectively.

(4) Compute typical stresses between TYS and TUS using product average yield strengths.

$$\sigma_T = TYS_{Prod.\,Avg.} + \% \left(TUS_{Prod.\,Avg.} - TYS_{Prod.\,Avg.}\right)$$

(5) Compute typical fracture stress, $\sigma_T(FS)$, as follows:

$$\sigma_T(FS) = \frac{TUS_{Prod.\ Avg.}}{TUS_{Avg.}} \sigma_{Avg.}(FS) \quad .$$

(6) Compute typical stresses between TUS and FS using product average ultimate strength and typical fracture stress.

$$\sigma_T = TUS_{Prod.Avg.} - (1 - \%) \cdot \left(TUS_{Prod.\,Avg.} - \sigma_T(FS)\right)$$

or

$$\sigma_T = \sigma_T(FS) + \% \left(TUS_{Prod.\,Avg.} - \sigma_T(FS)\right)$$

(7) Adjust the average departures, D_A, to typical departures, D_T, as follows:

$$D_T = \frac{(D_A - 0.002)(\text{Prod. Avg. Elong.} - 0.002)}{(D_A \text{ at Fracture Stress} - 0.002)} + 0.002 \quad .$$

(8) Compute elastic strains, ε_E, by dividing typical stresses by typical modulus.

$$\varepsilon_E = \frac{\sigma_T}{E}$$

(9) Obtain total strain, ε_T, by adding D_T and ε_E.

(10) Calculate the average proportional limit from the stress strain curves and compute the typical proportional limit.

$$\sigma_T(PL) = \left(TYS_{Prod.\ Avg.}/TYS_{Avg.}\right) \cdot \sigma_{Avg.}(PL)$$

The final step is plotting the full-range stress-strain curves. The following guidelines should be followed to plot the stress-strain curve. There should be 10 minor divisions for every major division with every tenth (major) division accented. The ordinate (Y-axis) is used for stress and should be in units of 5, 10, 20, or 50 ksi to the major division. The abscissa (X-axis) is used for strain and should be in units of 0.01, 0.02, 0.05, or 0.1 in./in. to the major division.

In addition to plotting the graphs by hand, they may be plotted with computer software programs. In the latter case, input the stress-strain pairs (σ_T and ε_T) from Table 9.8.4.3 into the computer and then curve fit the data. The elastic section must be linear up to the proportional limit. It is recommended that a power-law polynomial second order be used to fit the data from the proportional limit to fracture stress. The full-range stress-strain curve should be solid up to maximum stress and dashed from maximum stress to rupture. The fracture point should be indicated with an X. Only one typical full-range stress-strain figure should be plotted per page and should fill as much of the page as possible as illustrated in Figure 9.8.4.3(c). If more than one curve is contained in the figure, information such as the direction (ST, LT, and L), and/or temperature for each curve must be indicated.

9.8.4.4 *Minimum Stress-Strain and Stress Tangent-Modulus Curves* — Minimum stress-strain and stress tangent-modulus curves are not presented in MIL-HDBK-5, but these are sometimes required by the designer. Procedures for preparing minimum curves are identical to those for preparing typical curves, except for choice of yield-strength values. Product average, or average values of yield strength, are used to determine typical curves; minimum values (F_{ty} or F_{cy} A- or B-basis) are used to determine minimum curves. Average values of precision elastic modulus (E or E_c) are used.

9.8.4.5 *Biaxial Stress-Strain Behavior* — Procedures for analyzing and presenting biaxial stress-strain properties may be added to the guidelines at a later date. In the interim, procedures described in Reference 9.8.4.5 may be used as a general guide.

9.8.4.6 *Mathematical Representation of Stress-Strain Curves* — As an aid to computer analyses, the stress-strain curves for most materials can be represented mathematically. This method of representing stress-strain curves may be used for any stress-strain response that can be well characterized by the Ramberg-Osgood Method, and should be used as a supplement to a curve drawn by the Ramberg-Osgood Method.

To represent the stress-strain curves for a particular alloy using this method, a data summary like the one shown in Figure 9.8.4.6 should be constructed.

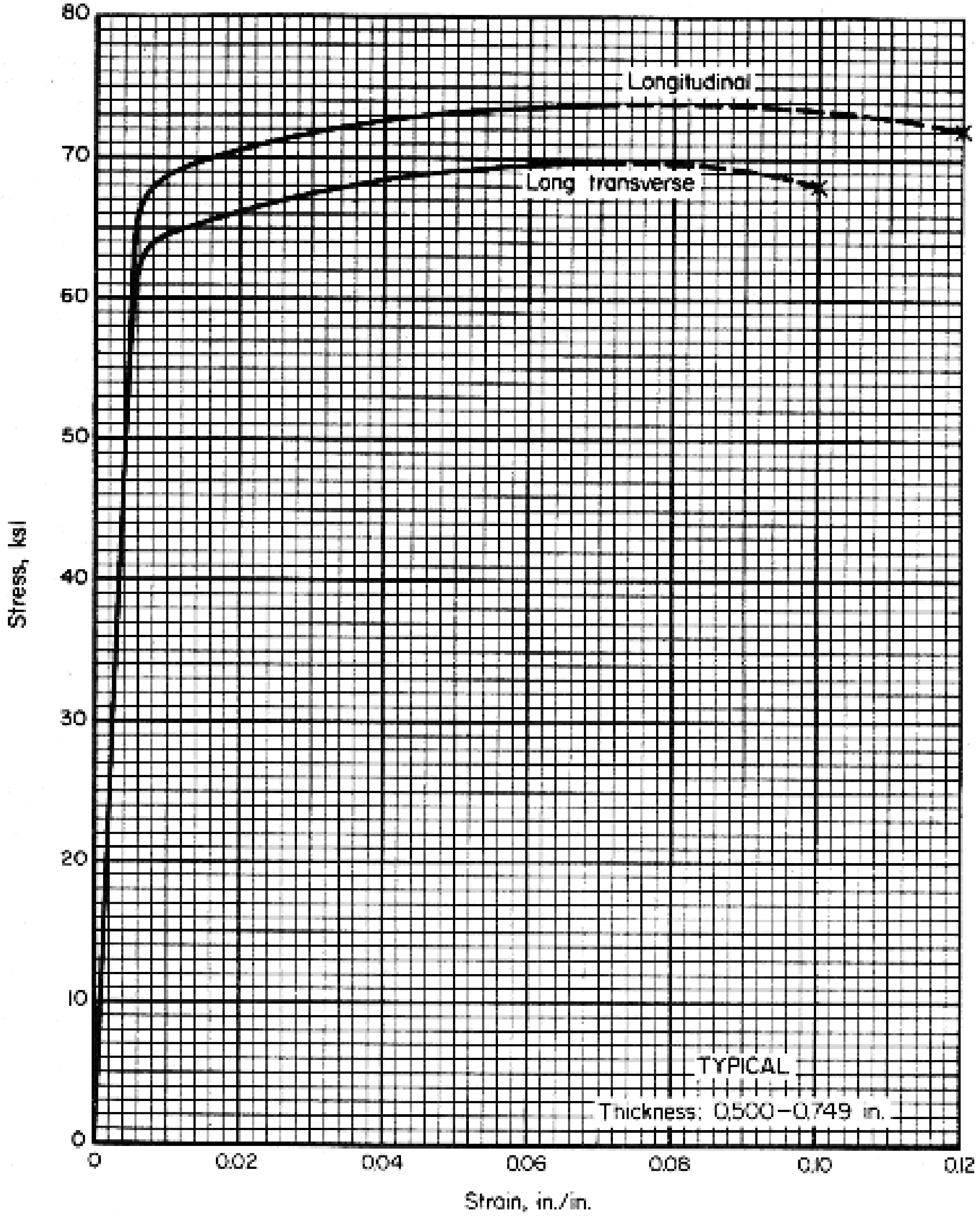


Figure 9.8.4.3(c). Typical full-range curves drawn by the strain-departure method.

Table (table number). Typical Stress-Strain Parameters for (material designation)

Temper/Product Form	Condition	Temper-ature, °F	Grain Direction	Tension			Compression	
				n	TYS, ksi	TUS	n_c	CYS, ksi
T6 Clad Sheet	0.02-0.039 in. thickness	RT	L	32	57		17	57
			LT	17	57		13	60
	0.04-0.249 in. thickness		L	27	62		15	62
			LT	20	60		17	65
	½ hr. exposure	200 F	LT				9.5	60
	100 hr. exposure						8.0	62
	½ and 2 hr. exposure	300 F					4.0	54
	1000 hr. exposure						6.4	46
	½ hr. exposure	400 F					8.2	47
	100 hr. exposure						10	20
	1000 hr. exposure						6.0	16
	½ hr. exposure	500 F					7.0	22
	½ hr. exposure	600 F					4.3	9
	10 hr. exposure						6.0	8
	100 hr. exposure						13	7
T62 Clad Plate	0.250 - 2.000 in. thickness	RT	L	29	64		27	69
			LT	29	64		27	70
T651 Plate	0.250 - 2.000 in. thickness	RT	L	30	66		15	68
			LT	19	65		18	66
T6 Bar, Rod and Shapes	> 3 in. thickness	RT	L	31	62		25	60
T6 Forging		RT	L			70		
			LT			68		
T652 Hand Forging	2.001 - 3.000 in. thickness	RT	L	18	62	67	17	63
			LT	18	62	66	18	65
			ST	13	60		22	67
T6 Extrusion	0.125 - 0.499 in. thickness	RT	L	23	62		15	64
	> 0.500 in. thickness			26	68		14	72
T62 Extrusion	< 0.499 in. thickness	RT	L	29	64	71	17	68
			LT	29	64		32	68
T651X Extrusion	0.500 - 0.749 in. thickness	RT	L	32	64	74	16	68
			LT	18	64	70	18	68

Figure 9.8.4.6. Example of stress-strain parameter table.

The parameters in the table are defined as follows:

Tension

n = Ramberg-Osgood parameter for small plastic strains in tension from the proportional limit up to the yield stress.

TYS = Typical yield stress in tension.

TUS = Typical ultimate stress in tension.

Compression

n_c = Ramberg-Osgood parameter for small plastic strains in compression up to the yield stress.

CYS = Typical yield stress in compression.

Equation 9.8.4.6(a) shows the relationship between the plastic strain and stress values that hold for many materials up to that material's yield stress. The problem with this equation is that the Ramberg-Osgood parameter (n) typically changes for plastic strains greater than 0.002. Therefore, the variation of plastic strain typically must be expressed with two different equations. For stress values in the range between the proportional limit and yield stress, plastic strain can often be expressed by

$$e_p = 0.002 \; (f \, / \, TYS)^n \qquad [9.8.4.6(a)]$$

where

f = any stress value between the proportional limit and tensile yield stress

TYS = the 0.2 percent typical yield stress

e_p = the plastic strain.

In any tabular representation of these data for a given alloy (covering all production thickness and product forms), significant information may be missing. Therefore, only 50 percent of the data are required to be available before a table may be included in MIL-HDBK-5.

The data in this table may also be used to calculate other useful quantitites. A table with all elements defined can be used to calculate the proportional limit in tension and compression, and the shear "yield" stress. Each of these calculations are covered below.

9.8.4.6.1 Proportional Limit Stress in Tension and Compression — If the proportional limit stress is equated with a plastic strain level of 0.0002 or a 0.02 percent deviation from linearity, and the Ramberg-Osgood relationship is found to be valid for small plastic strains, then the proportional limit stress ($f_{p.l.}$) can be approximated from Equation 9.8.4.6(a) as follows:

$$f_{p.l.} = TYS \; (0.10)^{\frac{1}{n}}$$

The same basic formulation could be used to define a proportional limit stress in compression, replacing TYS and CYS and n in tension with n_c in compression in Equation 9.8.4.6(b).

9.8.4.6.2 Shear Yield Stress — An estimate of the shear yield stress can be obtained from the equation:

$$F_{sy} = \frac{F_{ty}(L) + F_{ty}(LT) + F_{cy}(L) + F_{cy}(LT)}{4} \times \frac{2F_{su}}{F_{tu}(L) + F_{tu}(LT)} \qquad [9.8.4.6.2]$$

where

(p) = Primary load direction for shear
$F_{ty}(L)$ = Tensile yield stress, longitudinal direction
$F_{ty}(LT)$ = Tensile yield stress, long transverse direction
$F_{cy}(L)$ = Compressive yield stress, longitudinal direction
$F_{cy}(LT)$ = Compressive yield stress, long transverse direction
F_{su} = Shear ultimate stress
$F_{tu}(L)$ = Tensile ultimate stress, longitudinal direction
$F_{tu}(LT)$ = Tensile ultimate stress, long transverse direction.

9.8.4.6.3 Compression Tangent Modulus Curves — A mathematical procedure for construction of tangent modulus curves from compression stress-strain curves is given in Section 9.8.4.2. The compression stress-strain curve (up to the yield stress) may be constructed by adding the elastic strain component to the plastic strain component given in Equation 9.8.4.6(a). Calculation of the first derivative of stress with respect to strain gives tangent modulus values for specific values of total strain. Within MIL-HDBK-5 the tangent modulus curve is normally computed only up to the yield stress on the stress-strain curve. If tangent modulus values are desired at stress levels above the yield stress, a single function describing the relationship between stress and plastic strain over the range of interest should be used [rather than two separate functions as shown in Equations 9.8.4.6(a) and (b)].

9.8.5 ELEVATED TEMPERATURE GRAPHICAL MECHANICAL PROPERTIES — Effects of temperature and of thermal exposure on strength and certain other properties are presented graphically. Methods for determining these curves differ and are described below.

9.8.5.1 Strength Properties — Tensile ultimate and yield strengths, compressive yield strength, shear ultimate strength, and bearing ultimate and yield strengths at temperatures other than room temperature (80°F) are shown as percentages of room-temperature value for that property. Use of percentage curves allows a single curve to be used in place of multiple curves when more than one room-temperature value is presented for a property, as for example, differing A- and B-design values for each of several thickness ranges. In instances where related properties differ in their response to temperature, additional curves are provided and are labeled to indicate specific properties and forms to which they apply.

No significance level is attached to these curves. For practical purposes, however, the product of a room-temperature A or B design value and an appropriate percentage value from the curve may be regarded as an A or B design value at the indicated temperature.

9.8.5.1.1 Determination of Working Curves — Working curves for each product form, heat treat condition, property, and grain direction should be constructed. Separate curves should be examined to determine if certain data can be combined. For example, it may be possible to combine data for sheet and plate, T73 and T7351 tempers, tensile and compressive yield strengths, or longitudinal and long transverse grain directions.

The dimensional units of these working curves will be in terms of percentages of corresponding room-temperature value for the property. A percentage may be determined for each lot by dividing the average value of individual measurements (other than at room temperature) by the room-temperature average value for the same lot of material in the same testing direction (for isotropic materials, testing direction may be ignored), then multiplying by 100 to convert from a fraction to a percentage.

At each working temperature, the lower 95 percent confidence interval estimate (reduced ratio) of mean percentage will be determined from percentage values for each lot at that temperature. Letting r equal percentage values, $\bar{r}$ the average of these values, and n the number of such percentages, estimated standard deviation(s) and reduced ratio (R) will be determined from the equation:

$$s^2 = \Sigma(r - \bar{r})^2/(n - 1) \qquad [9.8.5.1.1(a)]$$

or

$$s^2 = [\Sigma(r^2) - (\Sigma\, r)^2/n]/(n - 1) \quad , \qquad [9.8.5.1.1(b)]$$

and

$$R = \bar{r} - t\, s/\sqrt{n} \qquad [9.8.5.1.1(c)]$$

where t is a 0.95 fractile of the t distribution corresponding to n-1 degrees of freedom (see Table 9.10.4).

The working curve will be a smooth curve drawn through 100 percent at room temperature and not higher than the computed values of R at each working temperature. When only room-temperature minima are applicable, no further adjustment of the working curve is required. However, when a secondary testing temperature is specified for the property, the working curve will be lowered, if required, so that the product of percentage from this curve and a room-temperature S-value will not exceed the S-value at the secondary testing temperature. In addition, if A-basis values have been established for this temperature, the working curve will be lowered, if required, so that the product of the percentage from this curve and room temperature A-value will not exceed the A-value at the secondary testing temperature.

Each working curve will be labeled appropriately, designating product, property, and testing direction(s) covered by it. In addition, individual percentages, including R values and (if applicable) secondary A or S-values reduced to percentages, will be plotted with the working curve. An example of a working curve is shown in Figure 9.8.5.1.1.

9.8.5.1.2 Preparation of Finished Curves — When two or more working curves are to be combined into a single curve, percentages shown in the finished curve will represent the separate bound of all individual working curves used in its preparation. When corresponding working curves differ substantially in shape or scaling, it may be appropriate to prepare more than one finished curve (for example, separate curves for longitudinal and transverse testing directions). Finished curves will not exhibit "humps", such as might appear with a temperature range where aging takes place. Where such humps appear in working curves, these will be leveled by means of horizontal line segments.

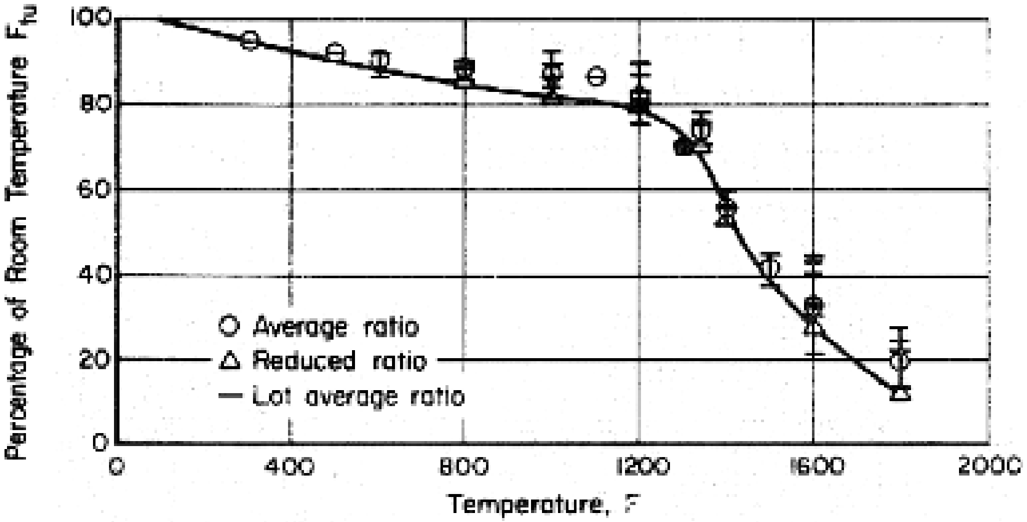


Figure 9.8.5.1.1. Working curve drawn through reduced ratios converted to percentages.

Finished curves will be drawn in reproducible form on grids of 10 lines to the inch, with each tenth line accented. The ordinate will normally be scaled in units of 20 percent per inch and will be labeled "Percentage of Room Temperature Strength". Abscissa will be scaled in units of 100, 200, or 400°F per inch, as appropriate, and will be labeled "Temperature, °F". Both axes will be annotated at intervals of 1 inch. Not more than two curves will be drawn in a single figure, and these should be labeled clearly to distinguish between them. In addition, each figure will carry a legend containing the words "strength at temperature", together with exposure limits and other information that would limit the applicability of the curve.

An example of the finished percentage curve is shown in Figure 9.8.5.1.2(a). When practical, single percentage curves, representing F_{tu} and F_{ty} may be located on a single illustration as shown in Figure 9.8.5.1.2(b). Likewise, single curves representative of F_{cy} and F_{su} may be located on one illustration and curves for F_{bru} and F_{bry} may also be placed on a single illustration.

9.8.5.2 ***Elongation and Reduction of Area*** — Elongation and reduction of area are presented as "typical" values at each temperature. If ductility values follow a log-normal distribution, they should be converted to logarithms before averaging. In most cases, the median (middle-most value) will be nearly identical to the average determined in this manner. Ductility values are not converted to percentages of the room-temperature value. Hence, a best smooth curve drawn through the typical values at each temperature is merely redrawn without data points for presentation in the document, as shown in Figure 9.8.5.2. Separate curves may be required for products differing in ductility.

As with strength data, care must be taken to avoid biasing the curve by the inclusion of large quantities of data from some lots and small quantities from others. Use of lot-average values in place of individual measurements is highly recommended.

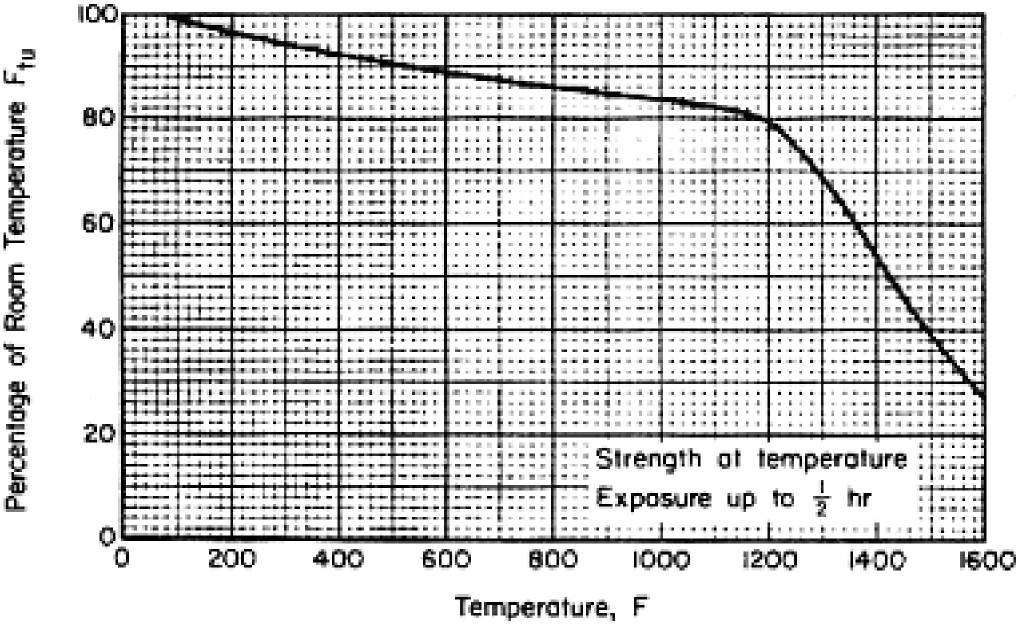


Figure 9.8.5.1.2(a). Working curve from Figure 9.8.5.1.1 redrawn as finished curve.

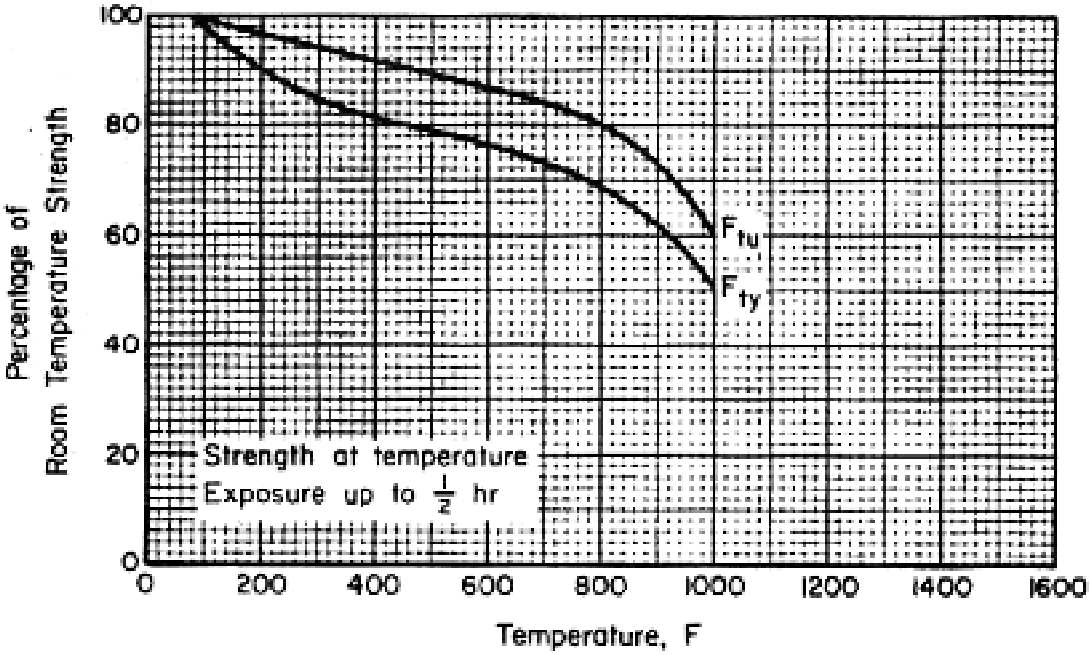


Figure 9.8.5.1.2(b). Multiple percentage curves drawn on a single illustration.

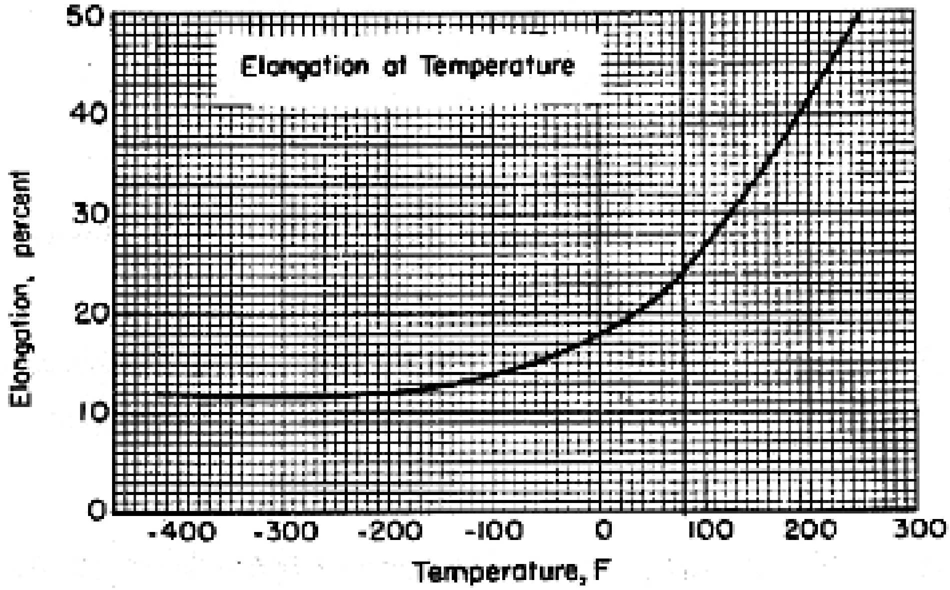


Figure 9.8.5.2. Typical curve for elongation.

9.8.5.3 ***Modulus of Elasticity*** — The elastic modulus may vary with test direction and product form. Data should be examined before plotting, and if differences are observed, separate working curves should be prepared for each variable. The percentage curve for modulus of elasticity is a best-fit smooth curve drawn through the average of all percentages at each temperature, where individual percentage values are obtained as described in Section 9.8.5.1.1. As with strength data, temperatures should be so selected that the shape of the curve is defined adequately. Figure 9.8.5.3 illustrates a finished percentage curve representing two moduli, E and E_c, for which working curves were similar enough to permit their combination into a single curve.

9.8.5.4 ***Physical Properties*** — When data are adequate to present curves showing specific heat,

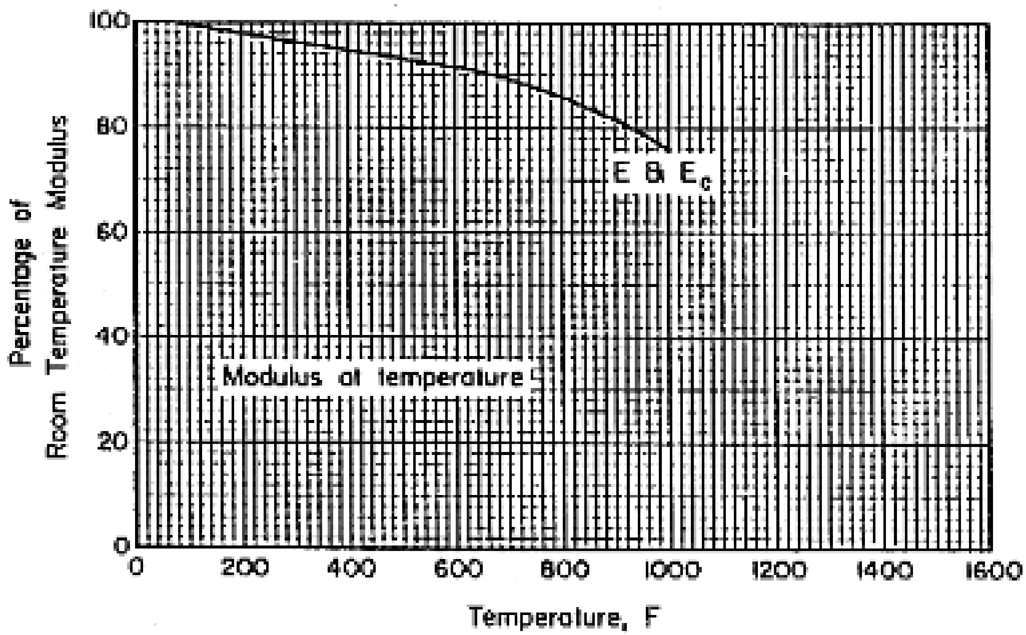


Figure 9.8.5.3. Percentage curve representing two elastic moduli.

thermal conductivity, and mean coefficient of thermal expansion over a range of temperatures, graphical presentation is used in place of tabular presentation described in Section 9.2.1.3. Working curves are first prepared for each property with the actual data plotted over the range of test temperatures.

Figure 9.8.5.4(a) shows a typical working curve. A best-fit smooth curve is drawn through the plotted points to depict the overall trend of data. The smooth curves from the specific heat, thermal conductivity, and thermal expansion working curves are then shown in a single figure as illustrated in Figure 9.8.5.4(b). The reference temperature for thermal expansion should be shown on the figure. In Figure 9.8.5.4(b) the reference temperature of 70°F indicates that the mean coefficient of expansion between 70°F and the indicated temperature is plotted.

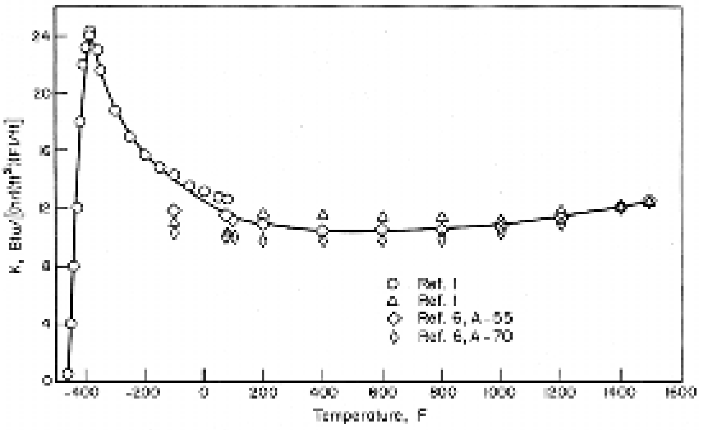


FIGURE 9.3.1.4(a). *Typical working curve for thermal conductivity.*

Figure 9.8.5.4(a). Typical working curve for thermal conductivity.

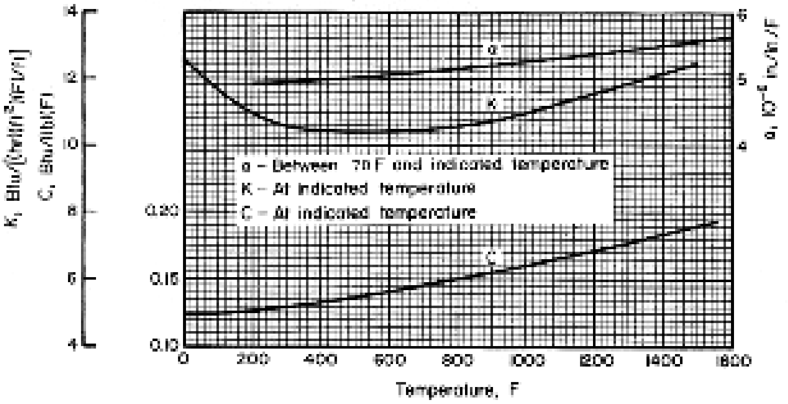


Figure 9.8.5.4(b). Typical curves for physical properties.

9.8.5.5 ***Effect of Thermal Exposure on Room Temperature Strength*** — Curves described in this section are presented (1) when the material exhibits a decrease in room-temperature strength as a result of unstressed exposure to elevated temperatures, and (2) when data are not presented in the form of parametric curves (see "Complex-Exposure" in Section 9.8.5.8). Supporting data expressed as percentages of the "no-exposure" strength are plotted with percent of room-temperature strength as the ordinate and exposure temperature as the abscissa. Separate plots are required for each exposure time. Typical exposure times are ½, 10, 100, and 1000 hours. Design curves are drawn in the same manner as for effect of temperature on strength; humps that may appear in the design curve should be leveled off in drawing the final curve.

The following restrictions are placed on effect-of-exposure curves for strength properties at room temperature:

(1) Percentage curves for a designated exposure temperature may not show increasing percentage values with increasing exposure time.

(2) Percentage curves for a designated exposure time may not show increasing percentage values with increasing exposure temperature.

A typical effect-of-exposure curve is illustrated in Figure 9.8.5.5.

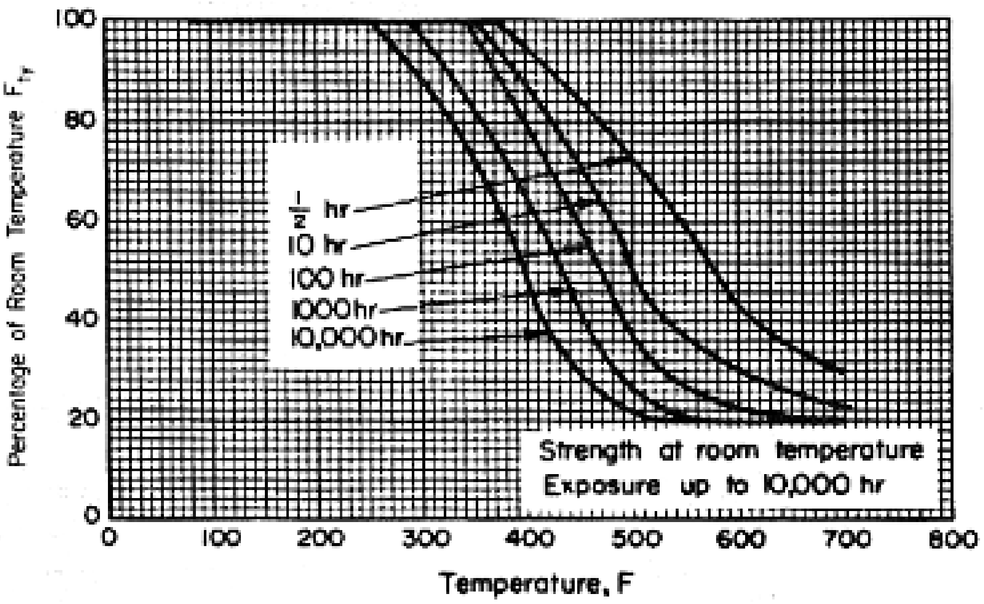


Figure 9.8.5.5. Effect of exposure at elevated temperatures on room-temperature properties.

9.8.5.6 ***Effect of Thermal Exposure on Elevated Temperature Strength*** — The effect of thermal exposure on elevated-temperature strength is presented in one of two manners, depending upon whether or not the exposure temperature equals the test temperature. In the case of simple exposure, exposure temperature and test temperature are assumed to be identical. For complex exposure, exposure temperature and test temperature need not be the same. When either of these curves is presented in MIL-HDBK-5, it includes all information normally presented in elevated temperature curves described in Section 9.8.5.1; thus, these curves replace the elevated temperature curves.

9.8.5.7 *Simple Exposure* — The curves are prepared in the same manner as basic elevated temperature curves described in Section 9.8.5.1. Separate design curves are prepared for each exposure time, and presented in a single figure. Typical exposure times for the curves are ½, 10, 100, and 1000 hours.

The following additional restrictions are placed on effect-of-exposure curves for strength properties at elevated temperatures:

(1) Percentage curves for a designated exposure (test) temperature may not show increasing percentage values with increasing exposure time.

(2) Percentage curves for a designated exposure time may not show increasing percentage values with increasing exposure (test) temperature.

A typical set of curves for exposure at test temperature is illustrated in Figure 9.8.5.7.

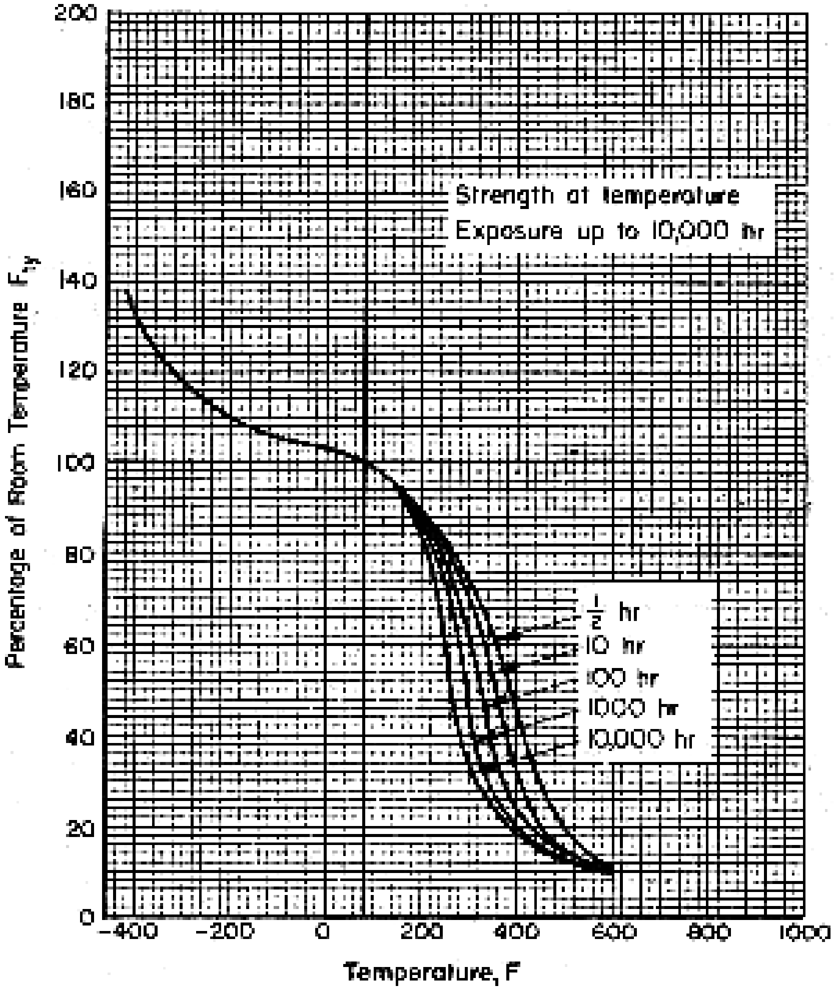


Figure 9.8.5.7. Simple-exposure curves.

9.8.5.8 *Complex Exposure* — In these curves, thermal-exposure variables, time, and temperature are combined into an exposure parameter, which is plotted as the abscissa. The ordinate is expressed in the same manner as in effect-of-temperature curves. Separate percentage curves are presented for each test temperature. In addition, each figure contains a nomograph for use in converting exposure time and temperature to the exposure parameter.

The exposure parameter may be of the form $P = (T_F + 460)(C + \log t)$, where T_F is exposure temperature in degrees F, C is a constant, and t is exposure time in hours. There are a number of ways to determine the values of C. The simplest method is to select (by interpolation of test data) two exposure conditions that produce the same strength at some designated test temperature, set two parameters equal to each other, and solve for C. For example, assume that the following data are obtained:

Exposure		
Time, hr	Temp, °F	TUS at 400 °F, ksi
1000	400	80.0
1	500	83.0
10	500	78.0

Plot 500°F data as stress versus log time; a straight line between (83, log 1) and (78, log 10) crosses 80 ksi at log 4 (hours). Thus, 4 hours' exposure at 500°F is equal to 1000 hours' exposure at 400°F:

$$(400 + 460)(C + 3) = (500 + 450)(C + 0.602),$$

$$C = 20.$$

This exercise should be repeated for several pairs of exposure conditions to obtain an average value for C.

Alternatively, several equivalent exposure conditions may be plotted as log exposure time (ordinate) versus $1/(T_F + 460)$ (abscissa). A best-fit straight line is drawn through the plotted points and its slope determined. C is then found from the relationship

$$C = m/(T_F + 460) - \log t,$$

where m is slope and $(1/T_F + 460)$ and log t are coordinates of any point on the line. This method is amenable to data-regression procedures described in Section 9.5.6, from which a least-squares estimate of C is obtained. Separate data plots are prepared for each test temperature, using percent of "no-exposure" room-temperature strength as the ordinate, and $P = (T_F + 460)(C + \text{lot } t)$ as the abscissa. Design curves are then drawn as described in Section 9.8.5.1.1.

A typical complex-exposure curve is illustrated in Figure 9.8.5.8. It should be noted that the abscissa scale is not shown in the figure since the time-temperature nomograph is used directly to locate the position on the abscissa.

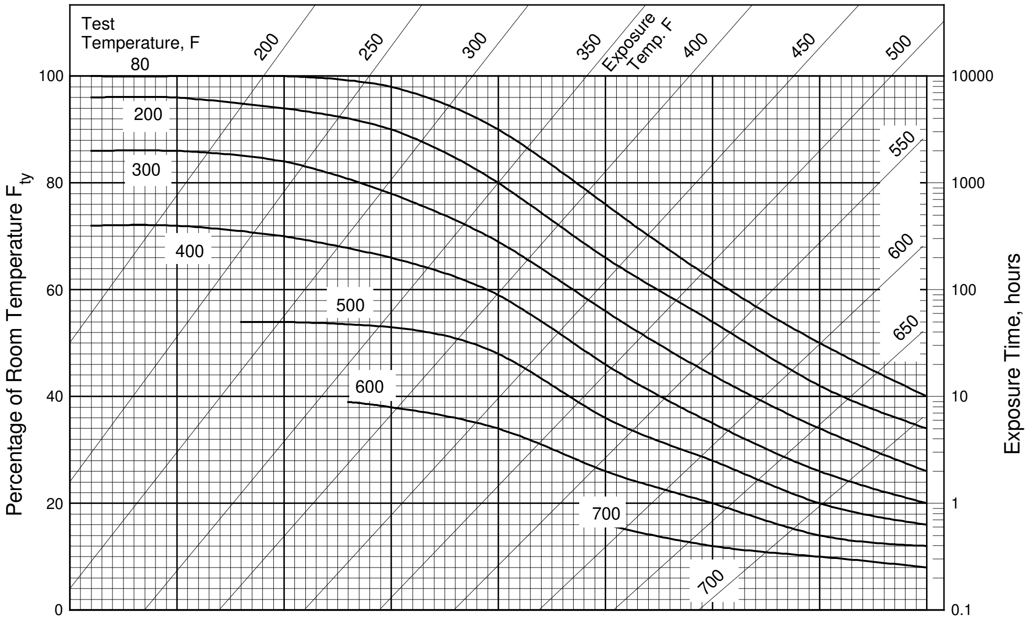


Figure 9.8.5.8. Complex-exposure curves.

9.9 EXAMPLES OF DATA FOR DYNAMIC AND TIME DEPENDANT PROPERTIES

9.9.1 FATIGUE — Separate data presentations are made for strain-controlled and load-controlled data. The only case where load-controlled data can be presented with strain-controlled data is when long-life tests have been switched from strain to load control in accordance with recommended procedures (see Section 9.2.5.1). Separate plots should be constructed for each material, notch concentration (in the case of load-controlled data), temperature, or other documented parameters that have been demonstrated to cause significant variations in fatigue behavior.

Load-controlled data presentations should consist of a family of at least three stress ratio or mean stress curves, with at least six data points per curve covering two orders of magnitude in life. (See exceptions noted in Section 9.2.3.5.1). The basic data should be included on each plot, with separate symbols used for each stress ratio or mean stress. Runouts should be identified with an arrow (→). The analytically defined mean S/N curves for each stress ratio or mean stress should also be included on each plot. These curves should not be extrapolated beyond existing data.

The fatigue curve for each stress ratio should be constructed based on the following criteria:

(1) The curve should start at the greatest maximum stress for that specific stress ratio. Unnotched fatigue curves should not extend above the average tensile ultimate strength of the material.

(2) The curve will terminate at the lowest maximum stress or longest life value, whichever is most limiting for that specific stress ratio.

In addition to the stress-life plot [such as shown in Figure 9.9.1.1(e)], a tabulation of test and material conditions should also be included. At a minimum the following information should be included with an S/N plot:

(1) Material
(2) Product Form, Grain Direction, Thickness, Processing History, Fabrication Sequence
(3) Test Parameters
  - Loading
  - Test Frequency
  - Temperature
  - Environment
(4) Average Tensile Properties
(5) Specimen Details
  - Notch Description
  - Specimen Dimensions
(6) Surface Condition/Surface Residual Stresses/Finish
  - Finish
  - Residual Stress Data
(7) Equivalent Stress Equation
  - Life Equation With Parameter Estimates
  - Standard Deviation of log(Life)
  - Adjusted R-Squared Statistic
  - Sample Size
(8) Reference Numbers
(9) No. of Heats/Lots

The following cautionary note should be included with each equivalent stress equation: [Caution: The equivalent stress model may provide unrealistic life predictions for maximum stresses and stress ratios beyond those represented above.] In calculating the "standard deviation of log(life)" and the adjusted R-squared statistic, all quantities should be computed using the final estimates of the fatigue model parameters and excluding runout observations.

The method for reporting the "standard deviation of log(life)" (SD) depends on whether there is evidence of nonuniform variance in the fatigue life data. If an unweighted fatigue model was fitted to the data, the single SD value from Equation 9.6.1.5(e) should be reported. If a weighted fatigue model was fitted to the data, SD should be reported as the linear function of the reciprocal of equivalent stress (strain) as calculated from Equation 9.6.1.5(g) or (h).

If an unweighted fatigue life model was fitted to the data, the adjusted R-squared statistic is

$$R^2 = 1 - (\mathrm{RMSE})^2/(\mathrm{RTE})^2 \qquad [9.9.1(a)]$$

where

$$\mathrm{RTE} = \sqrt{\sum_{i=1}^{n} D_i^2/(n-1)}$$

$$D_i = \log(N_i) - \overline{\log(N)}$$

$$\overline{\log(N)} = \frac{1}{n}\sum_{i=1}^{n}\log(N_i)$$

If a weighted fatigue life model was fitted to the data, the adjusted R-squared statistic may be calculated as

$$R^2 = 1 - (\mathrm{RMSE})^2/(\mathrm{RTE})^2 \qquad [9.9.1(b)]$$

where

$$\mathrm{RTE} = \sqrt{\sum_{i=1}^{n} WD_i^2 \,/\, (n-1)}$$

$$WD_i = \frac{\log(N_i) - \overline{\log(N)}}{g(S_{eq,i} \text{ or } \varepsilon_{eq,i})}$$

$$\overline{\log(N)} = \frac{\sum_{i=1}^{n}\log(N_i)\,/\,g(S_{eq,i} \text{ or } \varepsilon_{eq,i})}{\sum_{i=1}^{n}\left(1/g(S_{eq,i} \text{ or } \varepsilon_{eq,i})\right)}$$

and RMSE is as calculated in Equation 9.6.1.5(i).

Strain-controlled data presentations should consist of a plot of log(strain range) versus log(life) and a separate graph displaying the monotonic and cyclic stress-strain response for the material. Normally the fatigue curves should be based on at least six data points for each of three or more strain ratios, and the data should cover at least two orders of magnitude in life. As with the load-controlled data, the individual data points should be included on each plot, with separate symbols used for each strain ratio. If runouts are included in the data, they should be identified with an arrow (→). Data points that are based on tests that were switched from strain to load control should be identified clearly. The mean curves should extend from slightly above the greatest strain value to slightly below the least strain value.

Plotting the strain-life curves for different strain ratios is not as straightforward as plotting stress-life curves. The equivalent strain models cannot be written explicitly in terms of R_ε. Therefore, other information must be used to model the data trends for the various strain ratios. The mean-stress relaxation behavior for each strain ratio must be identified and mathematically defined. In general, the onset of mean stress relaxation occurs at smaller strain amplitudes for larger strain ratios. This behavior is shown in the mean stress relaxation plot of Figure 9.8.3(a). The elastic response (dashed lines) predicts much higher mean stresses than those actually observed, suggesting that mean stress relaxation has occurred. The regression line correlating the relaxed mean stresses with strain amplitude intersects the elastic response lines at larger strain amplitudes for smaller strain ratios. The elastic response line for the higher strain ratio ($R_\varepsilon = 0.6$) intersects the mean stress relaxation line at approximately $\Delta\varepsilon/2 = 0.0007$. The elastic response line for the lower strain ratio ($R_\varepsilon = 0.0$) intersects the mean stress relaxation at approximately $\Delta\varepsilon/2 = 0.002$. This information can be used to construct reasonable mean curves for each strain ratio for which fatigue data are available.

Considering the primary equivalent strain relation [Equation 9.6.1.4(c)]

$$\varepsilon_{eq} = (\Delta\varepsilon)^{A_3} \left(S_{max}/E\right)^{1 - A_3} \quad ,$$

S_{max} can be written as

$$S_{max} = S_m + S_a$$

where S_m is the relaxed mean stress and S_a is the stress amplitude found from the cyclic stress-strain curve. Given the mean stress relaxation data, both S_m and S_a can be estimated for a particular strain amplitude and strain ratio. Once S_{max} is defined, based on S_a and S_m, ε_{eq} can be calculated and a fatigue life can be determined. Through this procedure an approximate mean curve can be constructed for each strain ratio as shown in Figure 9.9.1(a).

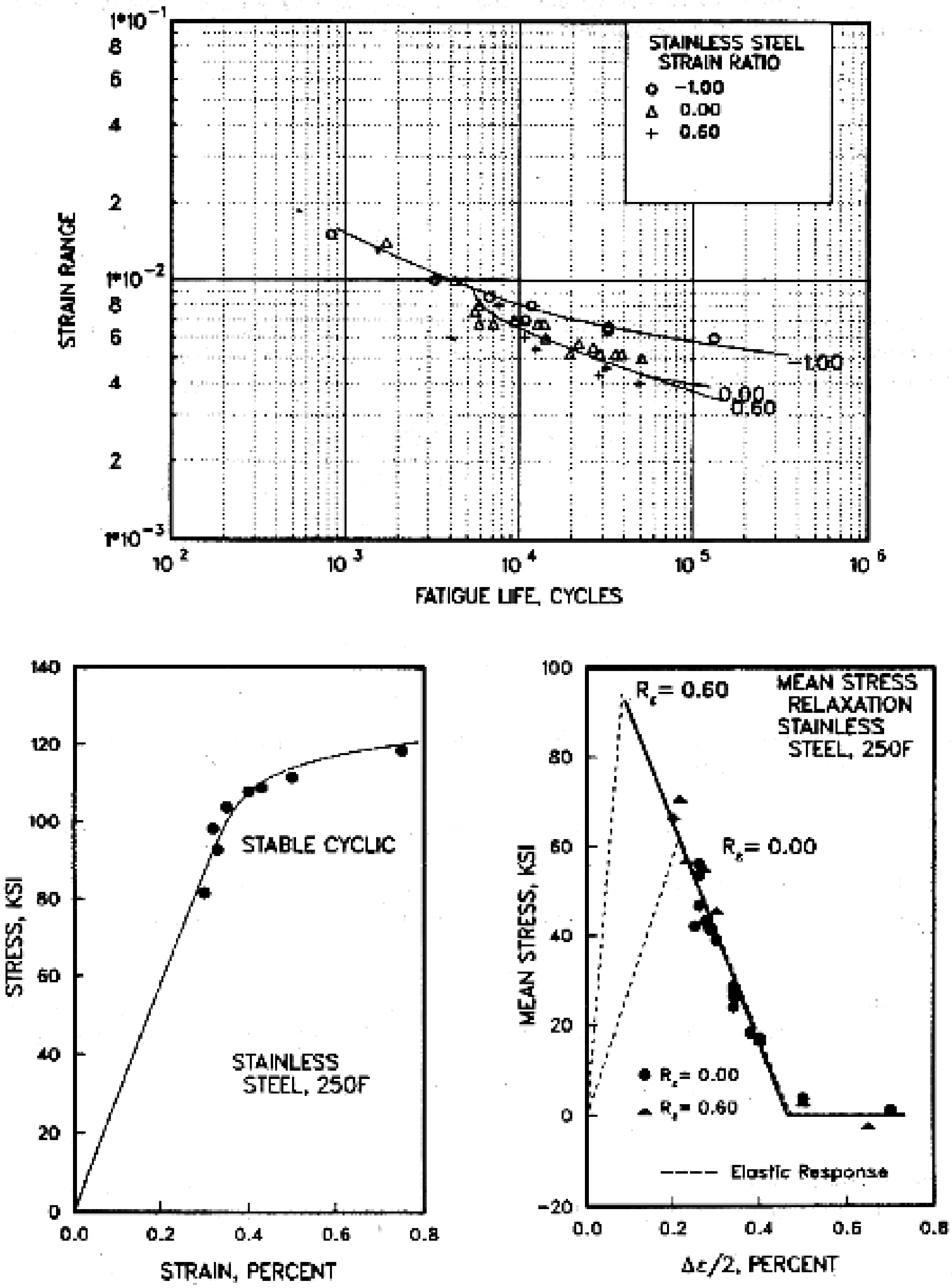


Figure 9.9.1(a). Example strain-life, cycle stress-strain, and mean stress relaxation curves.

If the stress amplitude (S_a) and the mean stress relaxation pattern can reasonably be assumed to be independent of strain ratio, the following procedure may be used to construct mean curves for each strain ratio by expressing S_a as a function of the strain range and S_m as a function of strain range and strain ratio. Using the data corresponding to a strain ratio of $R_\varepsilon = -1$ only, fit the regression equation

$$\log\left(S_{max}\right) = \alpha_1 + \beta_1 \log\left(\Delta\varepsilon/2 - S_{max}/E\right)$$

In some cases it may be necessary to exclude small plastic strain observations from the regression because of the scatter (and likely unreliability) in these values. In other words, it is recommenced that the cyclic stress-strain curve be defined, through at least squares regression treating stress as the dependent variable, with consideration given to a cutoff in cyclic plastic strain. A cutoff of approximately 0.0001 in plastic strain amplitude is often useful.

Assuming that stress amplitude is independent of strain ratio and provided that the estimate of the parameter β_1 is greater than zero, a mean value for stress amplitude can be determined as a function of strain range by solving the formula

$$S_a / \bar{E} + \left(S_a/k\right)^{\frac{1}{n}} = \Delta\varepsilon/2 \qquad [9.9.1(c)]$$

for S_a where $\bar{E}$ is the average elastic modulus for all specimens tested and

$$n = \beta_1 \text{ and } k = \text{Alog}\left(\alpha_1\right) \quad .$$

If the estimate of the parameter β_1 is less than or equal to zero, the data set should be examined further before proceeding with the analysis.

Using the data corresponding to all strain ratios other than $R_\varepsilon = -1$, fit the regression equation

$$S_m = \alpha_2 + \beta_2 \left(\Delta\varepsilon/2\right)$$

using weighed least squares to give higher weight to the observations which exhibit partial mean stress relaxation. If there is no way to directly calculate S_m from the data reported in the data set, an S_m value for use in fitting the above regression equation may be calculated by solving Equation 9.9.1(c) for S_a and subtracting this value from the reported S_{max} value. The weighting function

$$w = \left(|S_m|/S^*\right)\left(1 - S_m/S^*\right)^2$$

where

$$S^* = \left[\left(1 + R_\varepsilon\right) / \left(1 - R_\varepsilon\right)\right] E \left(\Delta\varepsilon/2\right)$$

appears to work well in general. Assuming that the mean stress relaxation pattern is independent of strain ratio and provided that the estimate of the parameter β_2 is less than zero, a mean value for S_m can be determined as a function of strain range and strain ratio according to the formula

$$S_m = \begin{cases} \beta_3(\Delta\varepsilon/2) & (\Delta\varepsilon/2) \leq \alpha_2/(\beta_3 - \beta_2) \\ \alpha_2 + \beta_2(\Delta\varepsilon/2) & \alpha_2/(\beta_3 - \beta_2) \leq \Delta\varepsilon/2 \leq -\alpha_2/\beta_2 \\ 0 & -\alpha_2/\beta_2 \leq (\Delta\varepsilon/2) \end{cases}$$

where

$$\beta_3 = \left[(1 + R_\varepsilon)/(1 - R_\varepsilon)\right] \overline{E} \quad .$$

If the estimate of parameter β_2 is greater than or equal to zero, the data set should be examined further before proceeding with the analysis.

Mean curves determined according to the above procedures exhibit the following characteristics:

(1) At large strain ranges, enough plastic strain is available to relax at the mean stress to zero, regardless of the strain ratio. Therefore, all strain ratios result in equivalent predicted fatigue lives.

(2) At strain ranges corresponding to mean stresses represented by the relaxation regression line, strain ratios other than $R_\varepsilon = -1$ (zero mean stress) result in equivalent predicted fatigue lives.

(3) At low strain ranges, the individual strain ratios assume their elastic mean stress response and diverge from each other.

The above procedure is used for plotting the strain-life curves in MIL-HDBK-5 when multiple strain ratios are involved.[1] The curves generally represent the mean data trends closely.

In addition to the strain-life plot, stress-strain curves and mean stress relaxation curves should be presented as shown in Figure 9.9.1(a). A tabulation of test and material conditions should also be included as shown in Figure 9.9.1(b). This information should include:

(1) Material
(2) Product Form, Grain Direction, Thickness, Processing History, Fabrication Sequence
(3) Test Parameters
  - Strain Rate and/or Frequency
  - Wave Form
  - Temperature
  - Environment
(4) Average Tensile Properties
(5) Stress-Strain Equation
  - Monotonic (if available and appropriate) - Cyclic
(6) Specimen Details

---

[1] In the general case, data generated at different strain ratios will not necessarily follow the same mean stress relaxation pattern. If different patterns for each strain ratio are evident in a particular case, it is suggested that a family of mean stress relaxation curves be constructed.

- Specimen Type
- Specimen Dimensions
- Fabrication Sequence

(7) Surface Condition/Surface Residual Stresses/Finish
  - Finish
  - Residual Stress Data

(8) Equivalent Strain Equation
  - Life Equation with Parameter Estimates
  - Standard Deviation of log(Life)
  - Adjusted R-Squared Statistic
  - Sample Size

(9) Reference Numbers

(10) No. of Heats/Lots.

The following cautionary note should be included with each equivalent strain equation: [Caution: The equivalent strain model may provide unrealistic life predictions for strain ratios and ranges beyond those represented above.]

Correlative Information for Figure 9.3.4.16(a)

Product Form: Die forging, 2 inch thick

Thermal Mechanical Processing History:
Annealed at 1800°F, water quench

Properties:

TUS, ksi	TYS, ksi	E, ksi	Temp., °F
155-160	135-140	29,000	250

Stress-Strain Equations:
Monotonic
Proportional Limit = 111 ksi
$\sigma = 289 (\varepsilon_p)^{0.138}$
Cyclic (Companion Specimens)
Proportional Limit = 92 ksi
$(\Delta\varepsilon/2) = 156 (\Delta\varepsilon_p/2)^{0.046}$
Mean Stress Relaxation
$\sigma_m = 114.0\text{-}24562(\Delta\varepsilon/2)$

Specimen Details:
Uniform gage test section
0.250 inch diameter
Polished with increasingly finer grits of emery paper to surface roughness of 10 RMS with polishing marks longitudinal.

Reference: 3.4.5.6.8(a)

Test Parameters:
Strain Rate/Frequency - 180 cpm
Wave Form - Sinusoidal
Temperature - 250°F
Atmosphere - Air

No. of Heats/Lots: 2

Equivalent Strain Equation:
$\text{Log } N_f = -6.56\text{-}4.20 \log (\varepsilon_{eq}\text{-}0.0022)$
$\varepsilon_{eq} = (\Delta\varepsilon)^{0.46} (S_{max}/E)^{0.54}$
Standard Error of Estimate, Log (Life) = 0.123
Standard Deviation, Log (Life) = 0.465
Adjusted R^2 Statistic = 93%

Sample Size = 33

[Caution: The equivalent strain model may provide unrealistic life predictions for strain ratios and ranges beyond those represented above.]

Figure 9.9.1(b). Example of correlative information and analysis results for a strain control fatigue data presentation.

9.9.1.1 *Load Control* — A large collection of 300M alloy die forging fatigue data is presented in Figure 9.9.1.1(a). The required steps for the analysis of the data set are presented below.

Data Requirements (See Section 9.2.4.8)—The data set consists of four stress ratios (R = -1.0, -0.33, 0.05, 0.2). Each stress ratio includes at least twenty-three nonrunout observations, easily satisfying the minimum sample size requirement of six tests per stress ratio.

Data Collection (See Section 9.6.1.1) — The data shown in Figure 9.9.1.1(a) were compiled from four sources. Each source reports the results of fatigue testing programs conducted within two years of each other (1968-1970).

The failure criteria for all tests is reported as complete separation of the specimen. Those tests which did not fail are identified on the S/N plot with an arrow (→). These runout observations are treated differently in the regression analysis which define the mean fatigue curves (see Section 9.6.1.9).

Evaluation of Mean Stress Effects (See Section 9.6.1.4)—The collection of data consists of four stress ratios, and therefore, an equivalent-stress formation was used to consolidate the data. Equation 9.6.1.4(a),

$$\log N_f = A_1 + A_2 \log \left(S_{eq} - A_4\right)$$

where

$$S_{eq} = S_{max}(1 - R)^{A_3} \quad ,$$

is the initial model attempted for fitting the data, and it proved adequate throughout the analysis.

Estimation of Fatigue Life Model Parameters — Least Squares (See Section 9.6.1.5) — The initial least-squares regression (runouts excluded) results in the following fatigue-life equation parameters:

A_1 = 23.7
A_2 = -8.41
A_3 = 0.366
A_4 = 0.0.

The fatigue-limit parameter (A_4) of zero seems somewhat inconsistent with the data shown in Figure 9.9.1.1(a). A visual examination of the S/N plot reveals a tendency for the data to asymptotically approach some limiting value. The zero fatigue limit term suggests that some problem may exist within the data collection. A plot of the residuals for the fatigue model using these parameters is shown in Figure 9.9.1.1(b).

The parameters obtained after the model is adjusted for nonconstant variance are:

A_1 = 23.4
A_2 = -8.38
A_3 = 0.40
A_4 = 13.5.

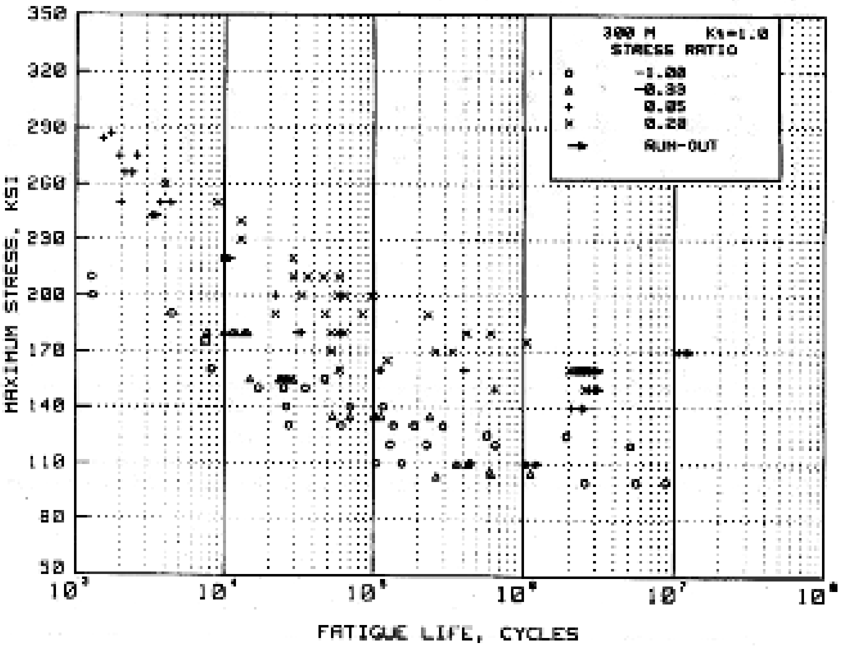


Figure 9.9.1.1(a). S/N plot of unnotched 300M die forging fatigue data, transverse orientation.

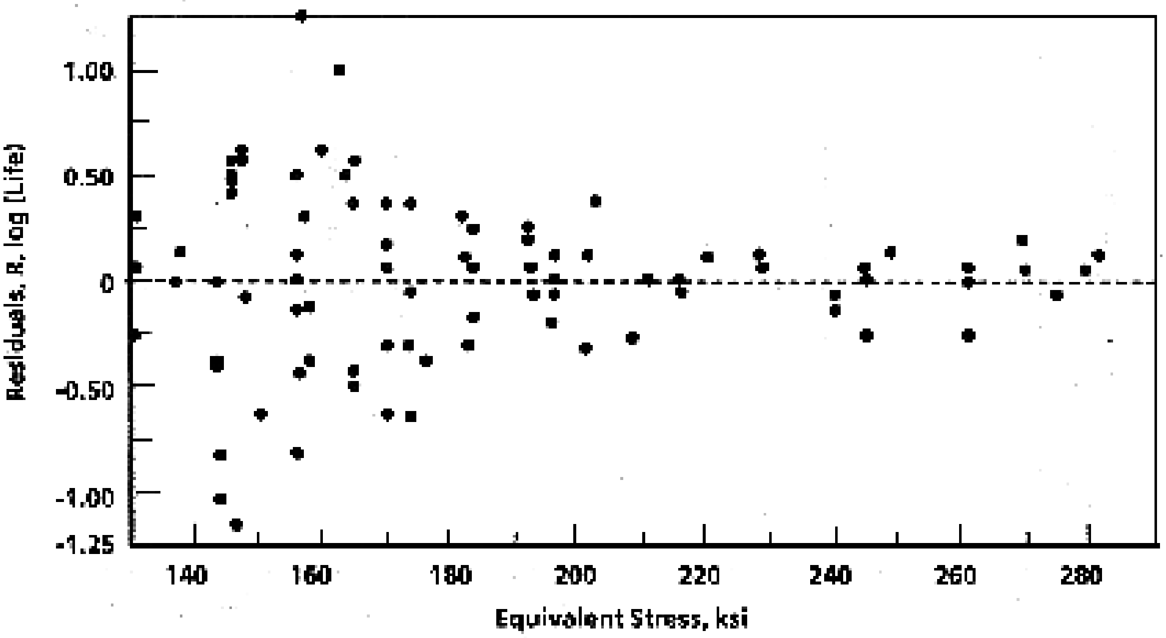


Figure 9.9.1.1(b). Residual plot before model has been adjusted for nonconstant variance.

Note that a fatigue limit term of 13 ksi has now been estimated. However, a check on the significance of the A_4 term revealed that it was clearly insignificant. All of the runouts in the data collection were above this equivalent stress level and, therefore, all runouts were used in the regression procedure. A plot of the residuals after the fatigue life model has been adjusted is shown in Figure 9.9.1.1(c). Note the relative shift in the magnitude of the residuals at the higher and lower S_{eq} values compared to Figure 9.9.1.1(b).

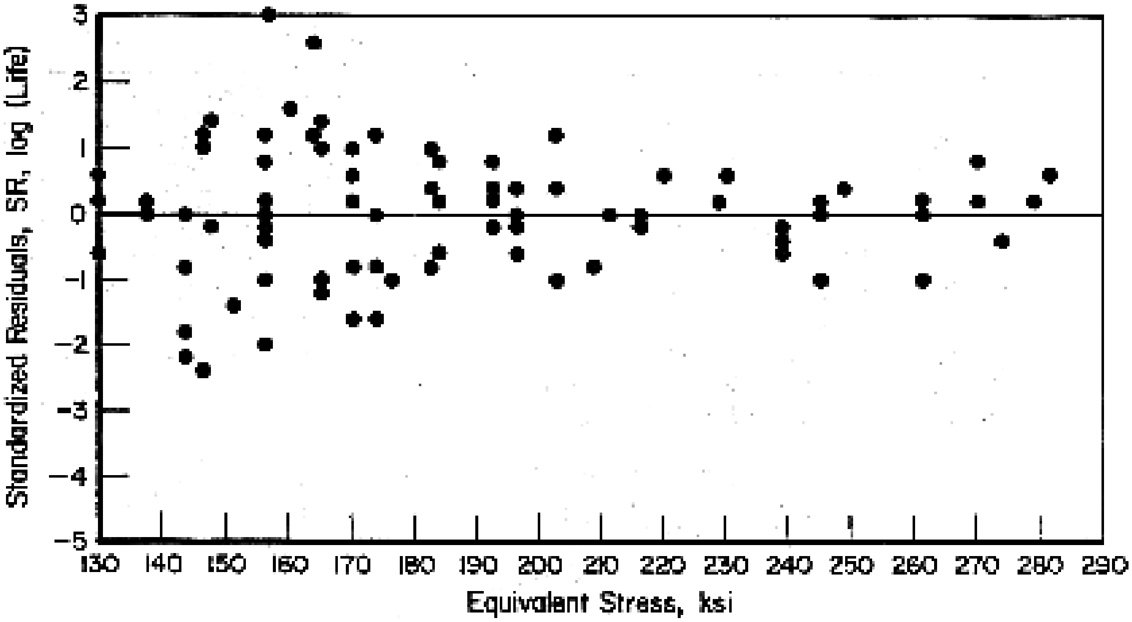


Figure 9.9.1.1(c). Standardized residual plot after model has adjusted for nonconstant variance.

Treatment of Outliers (See Section 9.6.1.6) — None of the observations were identified as outliers. The critical studentized residual at the 5 percent significance level for this data set of 114 observations is 3.63. The largest standardized residual was 3.23, resulting from a runout observation.

Assessment of the Fatigue Life Model (See Section 9.6.1.7) — The equivalent stress model is not able to consolidate the R = -0.33 stress ratio with the other stress ratios. The F-test performed on the residuals of the stress ratios proves significant at the 5 percent level for R = -0.33. This indicates that the mean of the residuals for R = -0.33 differs significantly from the mean of the residuals from the other ratios. The plot of stress ratios versus residuals, as shown in Figure 9.9.1.1(d), illustrates that the mean of the residuals for R = -0.33 is significantly different than those for the other stress ratios. A close examination of the original S/N plot shown in Figure 9.9.1.1(a) reveals that the R = -0.33 data tend to overlap the R = -1.0 data: at the lower maximum stress levels (about 100 ksi), the R = -1.00 data actually show longer average fatigue lives than do the R = -0.33 data, when the reverse would be expected. The Durbin-Watson D statistic for determining lack of fit is 1.61, indicating a poor fit of the model to the data. The critical value of D for a sample of 114 observations [Equation 9.6.1.7(a)] is 1.66.

This incompatibility among stress ratios indicates that either a problem exists with the data or with the assumed equivalent stress model. The data sources were re-examined to possibly determine if some difference in specimen preparation or testing procedure among the sources may have caused the inconsistencies. Unfortunately, no significant differences were discovered that would provide sufficient reason to exclude the suspect R = -0.33 data due to testing methods alone. The problem is confounded because all of the R = -0.33 data comes from a single source which does not include other stress ratios. This precludes examining source to source variability.

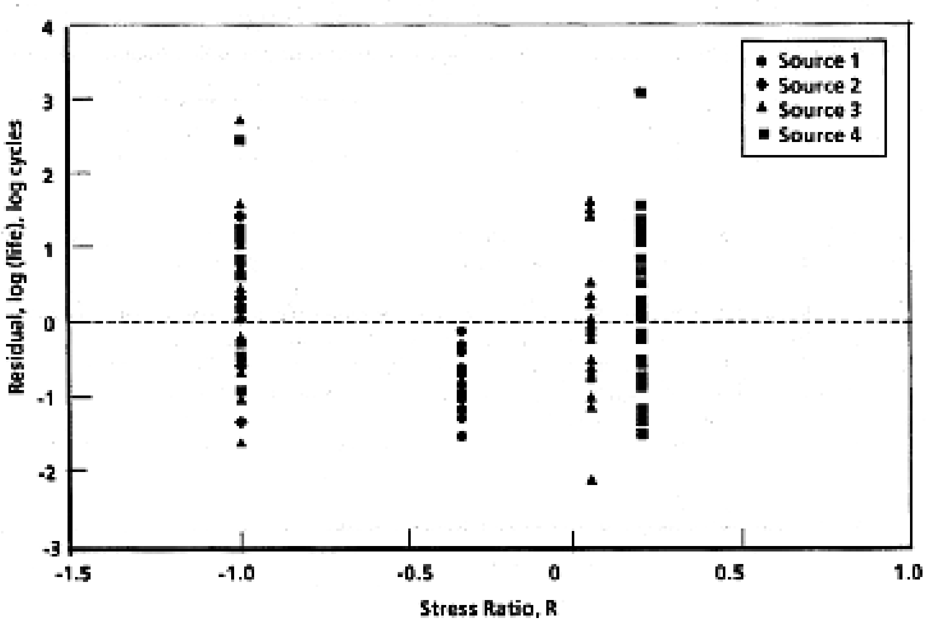


Figure 9.9.1.1(d). Residual plot of stress ratios. Note the low mean value of R = -0.33.

In situations such as this where a data set for a single source is determined to statistically deviate from the fatigue trends exhibited by the bulk of the data, it should be evaluated for exclusion. Engineering judgement suggests that the R = -0.33 data be excluded from the data collection based on the following:

(1) Unrealistic fatigue limit
(2) Lack of fit for fatigue life model based upon Durbin-Watson statistic
(3) Stress ratio incompatibility.

The modified data collection is now reanalyzed. For the sake of brevity, the details of the analysis procedure for Sections 9.2.4.8 (Data Requirements) and 9.6.1.3 (Fatigue Life Models) through 9.6.1.7 (Fatigue Life Models) will be omitted. It is interesting to note, however, that the fatigue limit term (A_4) resulting from the least squares regression with the R = -0.33 data excluded is 94.2 ksi. This result more realistically represents the longer life fatigue trends compared to the previous (insignificant) estimate of 13.5 ksi. With the suspect data removed, the equivalent stress model is determined to be acceptable at the 5 percent level. The Durbin-Watson D statistic also is increased to 2.18 indicating that the model now provides an adequate fit to the data.

Dataset Combination (See Section 9.6.1.8) — With the exclusion of the source containing the R = -0.33 data, the remaining data set combination is determined acceptable at the 5 percent level.

Treatment of Runouts (See Section 9.6.1.9) — The data collection includes seven runout observations. The maximum likelihood procedure has the effect of essentially shifting these runouts to the fatigue lives at which they most likely would have failed. The resulting fatigue life model parameters should reflect the slight increase in estimated fatigue life over the least squares parameters, particularly in the long life region. In general, the maximum likelihood regression will result in a higher intercept term (A_1) and a steeper (more negative) slope (A_2). The A_3 and A_4 terms are taken as constants to reduce the problem to a linear analysis.

The parameters resulting from the least squares regression are:

A_1 = 14.54

A_2 = -5.04

A_3 = 0.385

A_4 = 94.2.

The maximum likelihood parameters conform to the expected trends for A_1 and A_2:

A_1 = 14.79

A_2 = -5.16

A_3 = 0.385

A_4 = 94.2.

Note the increase in A_1 and the decrease (more negative slope) in A_2.

Presentation of Fatigue Analysis Results —The stress-life curve and correlative information shown in Figure 9.9.1.1(e) is typical of a MIL-HDBK-5 load-control fatigue data proposal.

9.9.1.2 *Strain Control* —A collection of iron alloy bar strain-controlled fatigue data at 70°F is given in Table 9.9.1.2. The required steps for the analysis of the data set are presented below. The guideline sections relating to each step in the analysis are noted.

Data Requirements (See Section 9.2.4.8) — The data set includes three strain ratios (R_ε = -1.0, 0.0, 0.6) each consisting of at least eight nonrunout data points. This satisfies the minimum recommended sample size for analysis. Two runouts ($N_f = 10^5$ and 10^6_ at R_ε = -1 are included in the data set.

Data Collection (See Section 9.6.1.1)—The specimen design for the test program is reported as uniform-gage section with a diameter of 0.20 inches. Failure is defined as complete separation. The tensile properties are presented in the correlative information. No information is available regarding the fabrication sequence for the specimens. Fabrication information is important, although in this case it is not considered sufficient cause to reject the data set for analysis. The test data at the R_ε = -1.0 strain ratio provide information regarding this material's cyclic stress-strain response. The cyclic stress-strain curve constructed from the data is shown in Figure 9.9.1.2(a). The monotonic curve (dashed) is estimated from the reported yield and ultimate strengths.

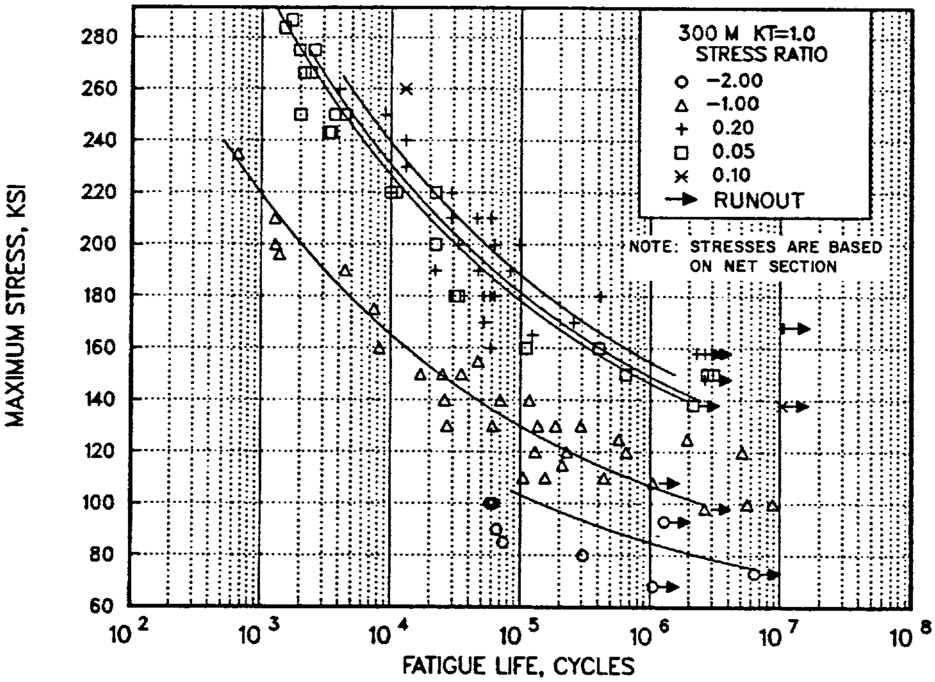


Figure X.X.X.X.X(a). Best-fit S/N curves for unnotched 300M alloy forging, F_{tu} = 280 ksi, longitudinal and transverse directions.

Correlative Information for Figure X.X.X.X.X

Product Forms: Die forging, 10 x 20 inches CEVM
Die forging, 6-1/2 x 20 inches CEVM
RCS billet, 6 inches CEVM
Forged Bar, 1.25 x 8 inches CEVM

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	274-294	227-247	RT

Specimen Details: Unnotched
0.200 - 0.250 inch diameter

Surface Condition: Heat treat and finish grind to a surface finish of RMS 63 or better with light grinding parallel to specimen length, stress relieve

References: 2.3.1.4.8(a), (c), (d), (e)

Test Parameters:
Loading - Axial
Frequency - 1800 to 2000 cpm
Temperature - RT
Atmosphere - Air

No. of Heat/Lots: 6

Equivalent Stress Equation:
Log N_f = 14.8-5.38 log (S_{eq}-63.8)
$S_{eq} = S_a + 0.48\ S_m$
Std. Error of Estimate, Log (Life) = 55.7 ($1/S_{eq}$)
Standard Deviation, Log (Life) = 1.037
R^2 = 82.0

Sample Size = 104

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

Figure 9.9.1.1(e). Example S/N curve and correlative information.

Table 9.9.1.2. Iron Alloy Strain-Controlled Fatigue Data at 70°F

Specimen Number	Δ_ε	S_{max} (ksi)	Cycles to Failure	Strain Ratio
1	0.600	71.1	10223	-1.00
2	0.600	77.8	10396	-1.00
3	0.600	79.2	8180	-1.00
4	0.970	117.2	605	-1.00
5	1.000	110.7	672	-1.00
6	1.000	112.8	642	-1.00
7	1.500	126.9	209	-1.00
8	1.500	127.1	340	-1.00
9	0.600	116.6	3958	0.0
10	0.600	124.2	3895	0.0
11	0.597	118.2	3919	0.0
12	0.600	128.3	4050	0.0
13	0.600	122.6	2470	0.0
14	0.400	106.4	16388	0.0
15	0.393	101.9	22896	0.0
16	0.400	102.1	15388	0.0
17	0.400	93.7	38648	0.0
18	0.400	101.2	11960	0.0
19	0.750	139.4	1099	0.60
20	0.750	137.3	1544	0.60
21	0.750	113.0	966	0.60
22	0.500	124.5	4665	0.60
23	0.500	140.6	4342	0.60
24	0.500	138.4	4240	0.60
25	0.400	158.0	7460	0.60
26	0.400	146.1	11134	0.60
27	0.400	119.1	10876	0.60
28	0.440	65.8	100000*	-1.00
29	0.330	50.0	1000000*	-1.00

* Did not fail.

Evaluation of Mean Stress and Strain Effects (See Section 9.6.1.4)—The data set consists of three strain ratios and therefore an equivalent-strain formulation is used to consolidate the data on the basis of equivalent strain. Equation 9.6.1.4(c),

$$\log N_f = A_1 + A_2 \log \left(\varepsilon_{eq} - A_4\right)$$

where

$$\varepsilon_{eq} = \left(\Delta\varepsilon\right)^{A_3} \left(S_{max}/E\right)^{1 - A_3} \quad ,$$

is the initial model attempted for fitting the data and proves to be adequate throughout the analysis.

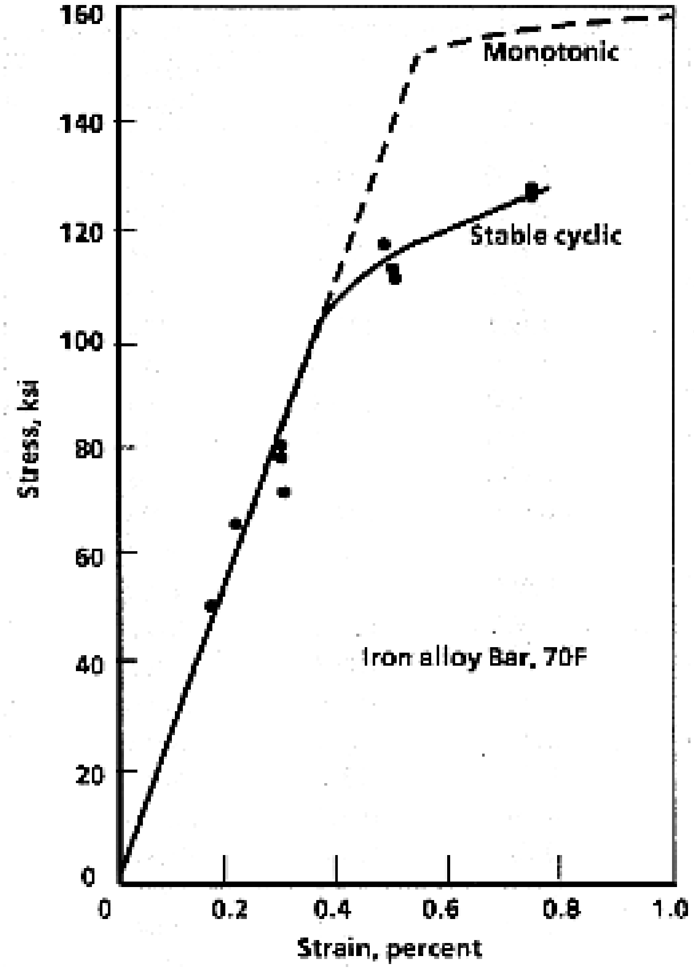


Figure 9.9.1.2(a). Stable cyclic and monotonic stress-strain curves for iron alloy at 70°F.

<u>Estimation of Fatigue Life Model Parameters - Least Squares</u> (See Section 9.6.1.5)—The initial least-squares regression results in the following fatigue-life equation parameters:

$$A_1 = -4.62$$

$$A_2 = -3.28$$

$$A_3 = 0.610$$

$$A_4 = 0.00198.$$

A plot of the residuals for the fatigue model using these parameters is shown in Figure 9.9.1.2(b). These residuals do not exhibit the characteristic pattern of increasing residual magnitudes with decreasing equivalent stress or strain levels shown in Figure 9.6.1.5(a). Rather, the variance appears to be relatively uniform. During Step 2 of the parameter estimation procedure, a negative, but insignificant, estimate of the residual model slope, σ_1, was obtained. This result indicates the residuals are already uniformly distributed and a constant variance model can be used. The constant variance model, in effect, does not weight the fatigue life model, so the initial parameter estimates are retained.

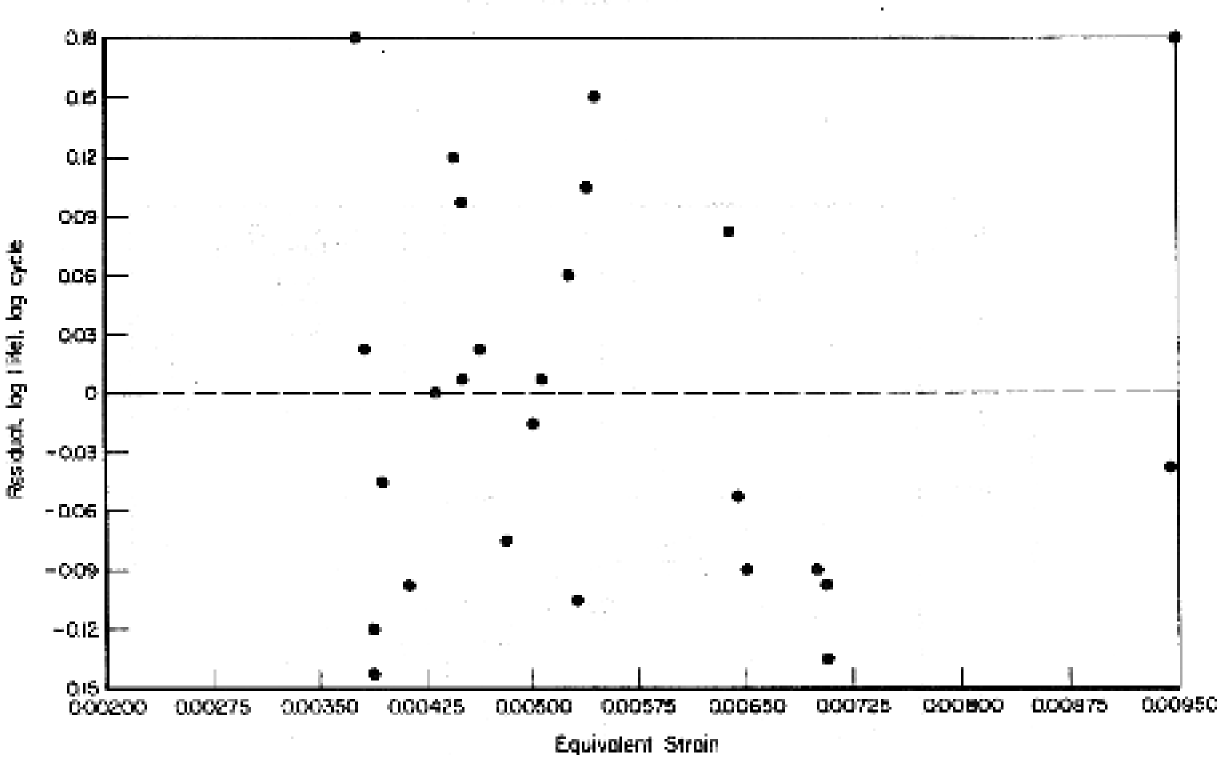


Figure 9.9.1.2(b). Residual plot of fatigue-life model for initial parameter estimates.

Treatment of Outliers (See Section 9.6.1.6) — After the data have been checked for uniformity of variance, they can be screened to determine if any outliers are present. The critical studentized residual at the 5 percent significance level for this sample of 27 observations is found to be 3.53. Any of the observations with the absolute value of the studentized residuals being greater than 3.53 would be considered outliers. The largest studentized residual from the data was 2.09; therefore, none of the observations are identified as statistically significant outliers.

Assessment of the Fatigue Life Model (See Section 9.6.1.7) — The equivalent strain formulation is marginally acceptable at the 5 percent level. The lack of fit test for the fatigue-life model results in a Durbin-Watson D statistic of 1.042. The critical value of D for a sample size of 27 is 1.241 [Equation 9.6.1.7(b)].

Since the Durbin-Watson statistic is less than the critical value, the equivalent strain model must be considered questionable in terms of its compensation for effects of strain ratio. However, no other model was found to perform better and a review of the plotted data revealed very low scatter compared to the predicted trends. Therefore, engineering judgement was used, and the proposed model was accepted.

Data Set Combination (See Section 9.6.1.8) — All of the data for this analysis came from a single source; therefore, this test is not applicable.

Treatment of Runouts (See Section 9.6.1.9) — The data set being considered includes two runout observations. The parameters A_1 and A_2 are therefore reestimated using the maximum likelihood regression to account for censored life values. The maximum likelihood estimates are:

A_1 = -5.07

A_2 = -3.47

A_3 = 0.610

A_4 = 0.00198.

The change in parameters A_1 and A_2 shift the predicted lives to greater values than the least squares parameter estimates.

Presentation of Fatigue Analysis Results — The presentation of the strain-life curve and correlative information shown in Figure 9.9.1.2(c) is typical of a MIL-HDBK-5 strain-control fatigue data proposal. Regarding the mean stress relaxation plot, note that a single regression has been performed to represent both the $R_\varepsilon = 0.6$ and $R_\varepsilon = 0.0$ strain ratios. Although it would be expected that higher strain ratios would result in higher stabilized mean stresses, the limited amount of data precludes performing separate regressions for each strain ratio. It can be seen from the strain-life plot that using the single regression does represent the mean fatigue trends fairly well.

9.9.2 FATIGUE CRACK GROWTH— When preparing fatigue crack growth data proposals for submittal to the MIL-HDBK-5 Coordination Group, several steps must be taken. First, various factors potentially influencing crack-propagation rates should be documented in a fatigue crack growth Data Proposal as shown in Table 9.9.2. Second, data for individual test conditions should be plotted and compared so that a determination can be made as to whether combinations of test conditions are appropriate. If data are available for a range of specimen thicknesses, it may be desirable to treat such data in separate plots, if fatigue crack growth rate behavior is influenced by thickness. Similarly, potential effects of environment, buckling restraints, specimen width, specimen type, crack orientation, temperature, and frequency should be evaluated; and, where visible differences in fatigue crack growth rate trends exist, separate plots must be developed. In some cases, it may be necessary (or helpful) to include working figures of trial combinations of fatigue crack growth data so that reviewers of the data proposal can more easily see reasons for particular data combinations. If a collection of fatigue crack growth data (involving one or more figures) is approved, working curves and background data sheet will be retained in MIL-HDBK-5 files and only the final data plot will be incorporated in the Handbook.

Fatigue crack growth data are presented in the Handbook on double logarithmic graphical displays of crack-growth rate, da/dN, μ-in./cycle, versus stress-intensity factor range, ΔK. Data points are presented along with a visually best-fit line judged to be most representative of the median behavior of those data. A sample display is presented in Figure 9.9.2.

Since data are not necessarily generated at predesignated stress ratio levels, stress ratio increments which are used on a given display are selected to present the most complete portrayal of available data. Data are summarized in graphical displays in the appropriate chapters of MIL-HDBK-5.

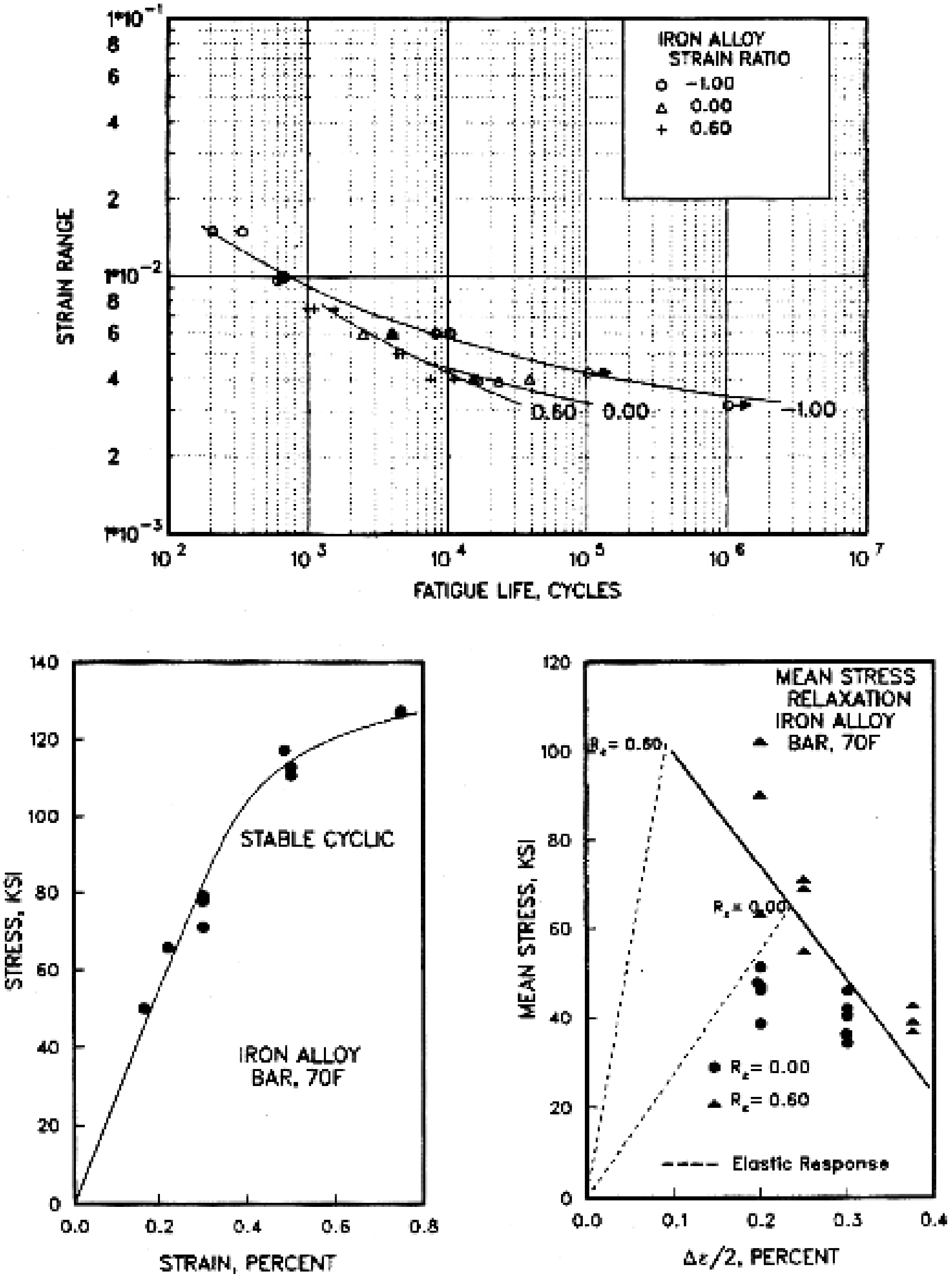


Figure 9.9.1.2(c). **ε/N curve and correlative information for iron alloy at 700°F.**

Correlative Information for Figure 9.3.4.17(c)

Product Form: Bar, 1 inch thick

Thermal Mechanical Processing History:
Not available

Properties:

TUS, ksi	TYS, ksi	E, ksi	Temp., °F
175-180	150-155	27,500	70

Stress-Strain Equations:
Monotonic
Proportional Limit = 150 ksi
$\sigma = 280\ (\varepsilon_p)^{0.12}$
Cyclic (Companion Specimens)
Proportional Limit = 105 ksi (est.)
$(\Delta\sigma/2) = 196\ (\Delta\varepsilon_p/2)^{0.076}$
Mean Stress Relaxation
$\sigma_m = 125.4\text{-}25666(\Delta\varepsilon/2)$

Specimen Details: Uniform gage test section
0.200 inch diameter

Reference: 3.4.5.6.8(a)

Test Parameters:
Strain Rate/Frequency - 180 cpm
Wave Form - Sinusoidal
Temperature - 70°F

No. of Heats/Lots: 4

Equivalent Strain Equation:
$\text{Log } N = -5.07\text{-}3.47 \log (\varepsilon_{eq}\text{-}0.00198)$
$\varepsilon_{eq} = (\Delta\varepsilon)^{0.61}\ (S_{max}/E)^{0.39}$
Standard Error of Estimate, Log(Life) = 0.111
Standard Deviation, Log (Life) = 0.555
Adjusted R^2 Statistic = 96%

Sample Size = 29

[Caution: The equivalent strain model may provide unrealistic life predictions for strain ratios and ranges beyond those represented above.]

Figure 9.9.1.2(c). ε/N curve and correlative information for iron alloy at 700°F — Continued.

9.9.3 FRACTURE TOUGHNESS (NEED SAMPLE PROBLEMS) — To assure proper evaluation of plane stress and traditional fracture toughness data, adequate documentation of test results must be included with any data submittals for MIL-HDBK-5. The minimum quantity of experimental information considered appropriate for data proposals on the subject is described in Section 9.2.4.10.

9.9.3.1 Plane Strain — (See Section 9.6.3.1) Room temperature values of K_{Ic} are tabulated in the introductory comments for each chapter. This table will include the range (minimum, average, and maximum) in K_{Ic} values, alloy, product form, heat treat condition, TYS range, product thickness, number of test specimens, number of lots, test specimen thickness range, and grain direction represented by data. Where data are available, effect of temperature on K_{Ic} is presented graphically in the appropriate alloy section. It is preferable that data incorporated in MIL-HDBK-5 represent a minimum of three specimens each from a minimum of five lots of material for each test direction.

9.9.3.2 Plane Stress — (See Section 9.6.3.2) Plane stress and transitional fracture toughness data and other crack damage information are presented in each alloy chapter. Data are categorized by product form, grain direction, thickness (or thickness range), temperature, and strain rate. The presentation format is dependent upon the flaw and structural configuration as described in the following paragraphs.

Table 9.9.2. Sample Listing of Fatigue-Crack-Growth Background Data

Materials: Ti-6Al-4V Titanium
Alloy Designation or Specification: MIL-T-9046, Type III, Composition C
Product Form: Plate
Heat Treatment: Mill Annealed
Heat Number(s): Ingot 295338

Chemistry (% by weight):

C	0.02
N	0.010
Fe	0.18
Al	6.4
V	4.2
O	0.127
H	81 (PPM)

Data Source(s): Feddersen, C. E., and Hyler, W. S., “Fracture and Fatigue-Crack Propagation Characteristics of 1/4 Inch Mill Annealed Ti-6Al-4V Titanium Alloy Plate”, Report No. G9706, Battelle (1971).

Specimen Description:
Type: M (T) Panel
Thickness: 0.250 inch
Width: 9, 16, 32 inches
Crack Orientation: L-T
Location w-r-t Product Thickness: Through-thickness specimen
Surface Finish: Not Indicated

Test Conditions:

No. of Specimens:	9	7	6
Maximum <u>Stress</u> or Load:	5, 10, 30 ksi	5, 10, 30, 50 ksi	10, 30, 50 ksi
Stress Ratio:	0.10	0.40	0.70
Cyclic Frequency:	1-25 Hz		
Environment:	50% relative humidity		
Temperature:	68 ± 2°F		
Buckling Restraints?:	Yes		
Crack Monitoring Technique:	Optical		

Additional Comments:

1. Frequency was varied from 1 to 25 Hz according to the magnitude of stress range, no frequency effects were noted in this environment.

2. From 20 to 70 crack readings were made on each specimen.

3. No panel width effects on FCG rates were evident.

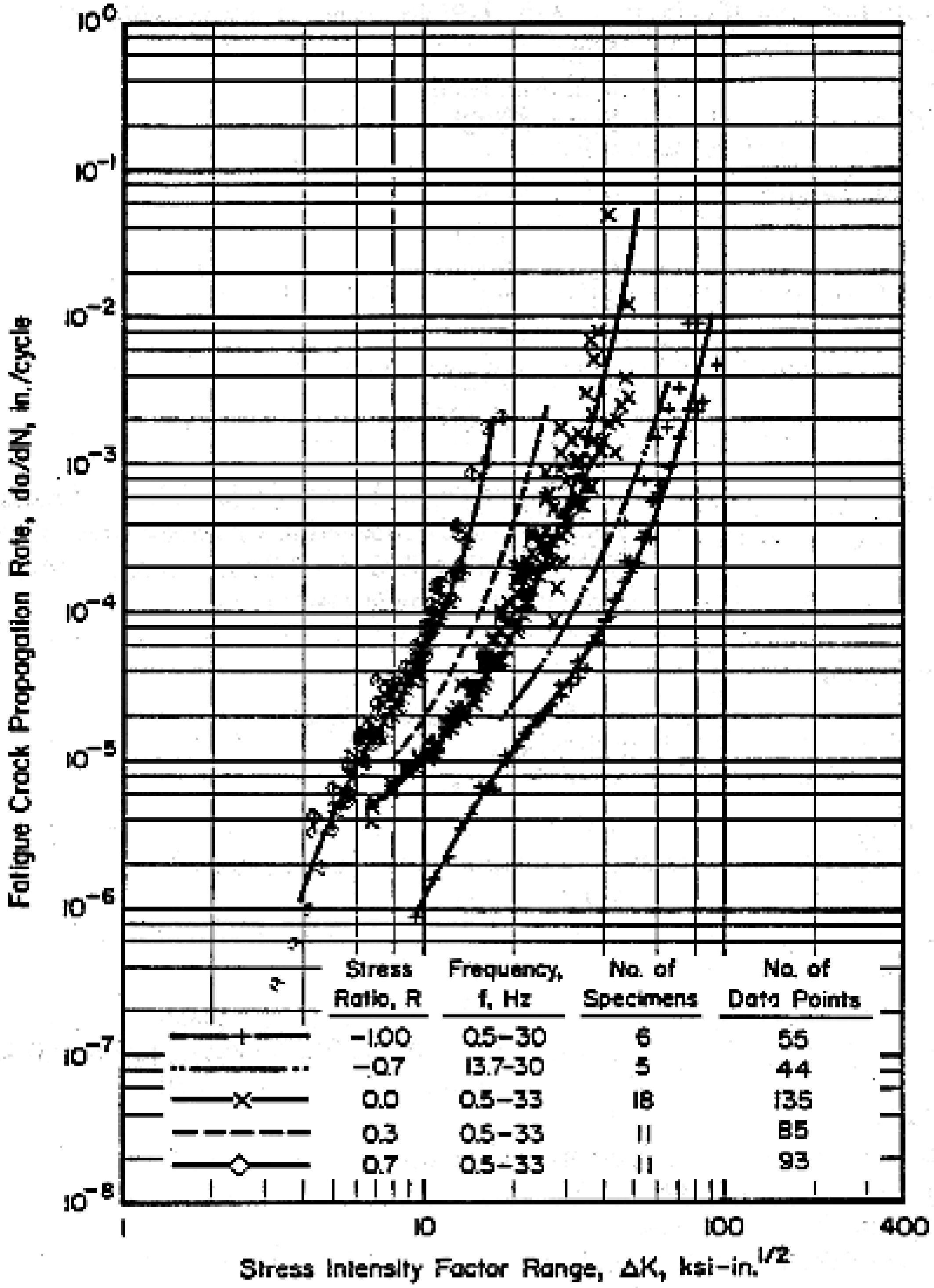


Figure X.X.X.X.X. Typical-crack-growth data for 0.090-inch-thick, 7075-T6 aluminum alloy sheet with buckling restraint. [References 3.7.4.1.9(a) through (e)].

Specimen Thickness:	*0.090 inch*	*Environment:*	*Lab Air*
Specimen Width:	*1-1/2 - 12 inches*	*Temperature:*	*RT*
Specimen Type:	*M (T)*	*Orientation:*	*L-T*

Figure 9.9.2. Sample display of fatigue-crack-growth-rate data.

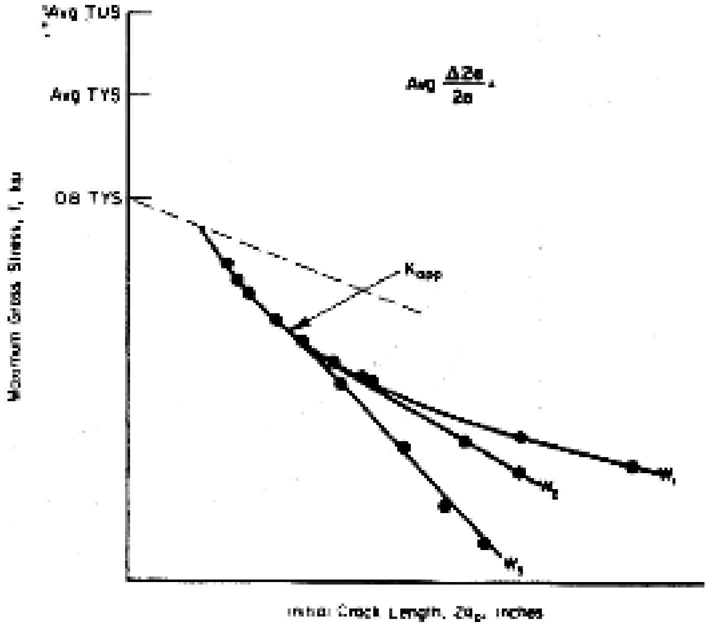


Figure 9.9.3.2. Format for the presentation of middle-tension panel data.

Middle-Tension Panel Data — Apparent fracture instability data for middle-tension panels are presented on the graphical format of maximum gross stress versus initial crack length as illustrated in Figure 9.9.3.2. These data plots are presented as information and not as design allowables; hence, additional testing is necessary to substantiate design allowables over the range of crack lengths of interest.

The data in such graphical display satisfy the screening criterion of Equation 9.6.3.2.

The apparent stability fracture toughness value K_{app} associated with each curve is a simple average of test values determined according to Equation 9.6.3.2.1

The average apparent toughness curve is presented over a range extending from the short crack length associated with a net section stress of 80 percent of tensile yield strength to either the largest crack length contained in the data, or one-third the panel width, whichever is greater.

Since slow, stable tear may occur during the loading of a cracked panel, an approximate measure of crack extension possible prior to fracture is useful to assess conditions of fracture instability. Where data are available, the average ratio, $\Delta(2a)/(2a_o)$, of crack extension prior to fracture to initial crack length is indicated in the field of the graphical display. This ratio is determined through

$$\frac{\Delta 2a}{2a_o} = \frac{2a_c - 2a_o}{2a_o} = \frac{a_c}{a_o} - 1 = \left(\frac{K_c^2}{K_{app}}\right) - 1 ,$$

where

$$K_c = f_c(\pi a_c \sec \pi a_c/W)^{1/2}$$

is the average stress intensity factor associated with critical fracture instability as determined by the reporting investigator.

Where data for a material include a thickness range from essentially plane stress to plane strain fracture toughness data will be summarized also as a display of thickness effect similar to Figure 9.9.3.2. From this figure, K values for the appropriate thickness, t, can be selected and residual strength curve similar to Figure 9.9.3.2 can be constructed.

At present, since these are not design allowable data, requirements on the quantity of information necessary will not be specified. Data displays will be prepared for those materials, product forms and thicknesses where a sufficient number of tests at various crack and specimen sizes are available to establish a distinct trend. Correlative information will be appended below such graphical displays to indicate range of test panel sizes, crack lengths, and number of heats or lots of the material from which determination of K_{app} was determined.

9.9.4 CREEP AND CREEP RUPTURE — Creep-rupture proposals developed for review and possible inclusion in MIL-HDBK-5 should contain the following information and meet associated criteria.

Data Reporting—The background information will meet the requirements of Section 9.2.4.11. Test results will be listed in a manner such that all data are identifiable in terms of material and test background information as well as test conditions used in generating data.

Analysis Reporting—The analysis report will display the following;

(a) Trials—Equations tried and reason for ejecting.

(b) Data rejected—Reason.

(c) Best-fit details—Listing of data, calculated values, and deviations. All data are to be clearly traceable in terms of data reporting requirements.

(d) Standard error or total variance and correlation coefficient.

(e) Subset variance—If random subsets are used, report both the pooled within-subset variance and the between-subset variances as well as the total variances.

(f) Constants—Report the average regression constant and regression constants for any subsets.(g) Coefficients—Report the numerical value of the coefficient of each regression variable and its standard error.

(h) Equation—Exhibit the equation used; with the coefficients, b_1, traceable to the numerical listing in above item (g).

(i) Deviation—Exhibit plots of deviations in life versus calculated life for each temperature and, as far as possible, identify according to subsets. It is also possible to provide a summary table of deviations. As an example of isostrain creep or rupture, divide the life range of data in five equal logarithmic increments and, for each temperature, give the algebraic sum of deviation with that increment. If random subsets are used, deviations summed are to be those from within the respective subsets.

(j) Data and Curve Comparison—Display data against the calculated average curve. Encode data with symbols as the deviation plots. Scale coordinates such that the curves have an apparent slope of about -1.0. Use scales appropriate for the most significant form of the regression variable, usually log(stress) versus log(life), with life (dependent variable) on the abscissa and stress on the ordinate.

(k) Curve Extrapolation Tests—Exhibit the average curve from one to 105 hours for corresponding temperature levels. Representative curves may be used including extreme values of independent variables represented in data. Further, calculation of desired tolerance limit (e.g., probability level) should be performed to assist in determining validity of the extrapolation.

The above recommendations apply to incorporation of new creep and/or stress-rupture curves in MIL-HDBK-5. The use of creep nomographs has been discontinued. Creep nomographs in MIL-HDBK-5 will be replaced as data are reanalyzed and new analytically defined creep and stress rupture curves are developed.

The presentation for MIL-HDBK-5 will include one or more pages of correlative information, equations, and curves as needed. Requirements on each will vary with the problem and should be reasonably obvious from data, background information, and analytical results.

An example of a typical data presentation is shown in Figure 9.9.4. Note that raw data are displayed along with mean trend lines, on a semi-logarithmic plot of stress versus time. Supportive data describing alloy, specimen details, and analysis results are also presented. Table 9.9.4 provides even more detailed, but necessary, information on such factors as heat treatment details and inverse matrix (which can be used in conjunction with other analysis results to compute lower level tolerance limits for the data).

Some creep data are still presented in creep nomographs. For these cases, the analysis and presentation were based primarily on Reference 1.4.8.2.1(b). The presentation of creep data in the form of a nomograph is not in compliance with the above guidelines.

9.9.4.1 *Creep-Rupture Example Problem* —By a slight chemical change and modification of heat, the former Alloy 325 is now believed to have an increased stress-rupture life of 20 percent to 30 percent. It is desired to fully characterize these properties over the 1600 to 1900°F range. Average creep life is to be from 10 hours to 1,000 hours.

Nineteen stress rupture tests from two heats of new alloy averaged 37.4 hours at 30 ksi/1800°F, s(log 10) = 0.150. Figure 9.9.4.1(a) is a log-log mean life plot of predicted stress rupture properties of modified Alloy 325 based on a predicted value. A 1750°F line has been added to the original plot. From this log-log plot, it can be seen that only three temperatures need to be tested because there are stress levels in common with the 1600°F line, and the same is true for the 1750°F and 1900°F lines.

Next, three temperature lines are bracketed with the 10-hours to 1000-hours life range. See Figure 9.9.4.1(b). Stress levels are then chosen to give the desired life. There are 25 tests required with this procedure. All 25 could be run, or 3 tests could be randomly eliminated from the center cells of the matrix (see circled cells). If 3 are deleted this would leave 22 tests, which are near the minimum of 20. These tests could be conducted and these data added to the 19 specific data points at 30 ksi/1800°F. This quantity would constitute the data set. Table 9.9.4.1 shows the results of a simulated sampling.

A Larson-Miller analysis of data produced the curves in Figures 9.9.4.1(c) and (d). Data plotted with the temperature lines of Figure 9.9.4.1(d) confirm a good fit over the range of data. The approach described in this example can be used for any creep or rupture experimental design.

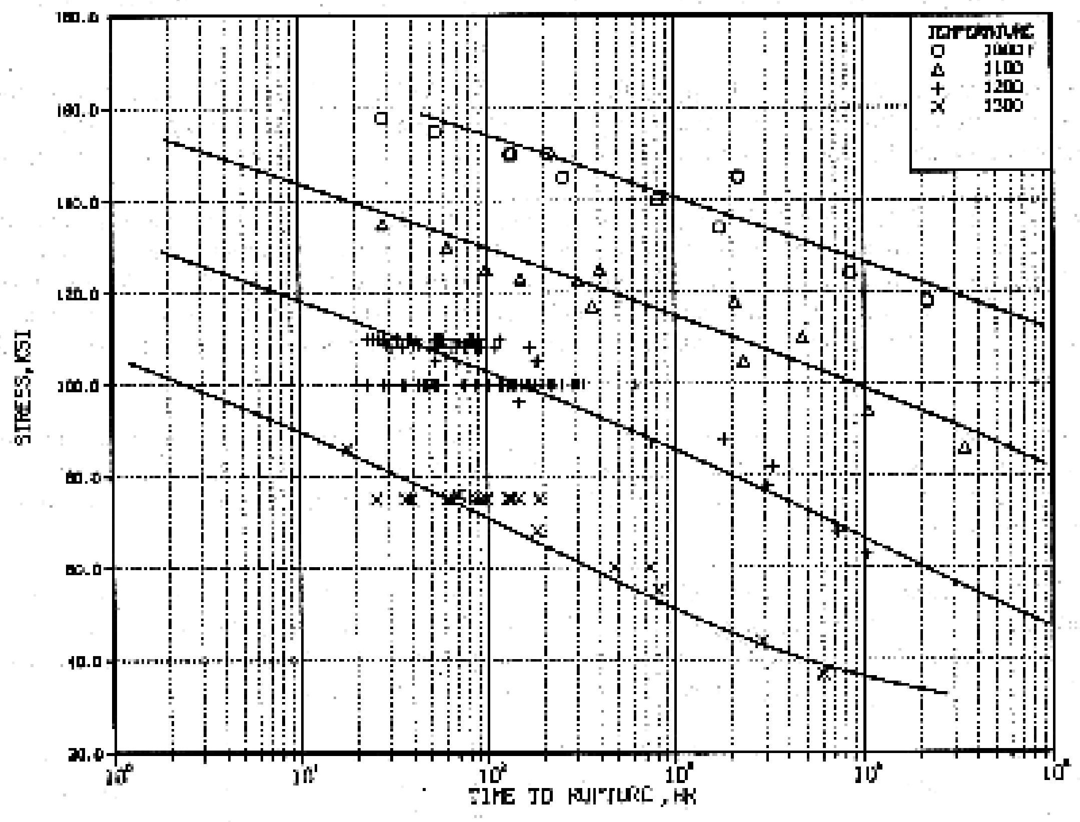


Figure 9.9.4. Average isothermal stress rupture curves for alloy XYZ forging.

Correlative Information for Figure 9.9.4

Makeup of Data Collection:
Public Specifications—AMS 5663
Heat Treatment—2, 21 [See Table 9.3.6.7(a)]
Number of Vendors—Not specified
Number of Heats—7
Number of Test Laboratories = 3
Number of Tests = 347

Specimen Description:
Type—Unnotched round bar
Gage Length—N.A.
Gage Thickness—1/4"—3/8"

Stress Rupture Equation:
$\text{Log } t = c + b_1 T + b_2 X + b_3 X^2 + b_4 X^3$
T = °R, X = log (stress, ksi)
c = 186.27
b_1 = -0.01778
b_2 = -255.25
b_3 = 146.28
b_4 = -28.65

Analysis Details:
Inverse Matrix—See Table 9.3.6.7(a)
Standard Deviation = 0.63
Standard Error of Estimate = 0.29
Within Heat Variance = 0.071
Ratio of Between to Within Heat
Variance = (at spec pt.) < 0.10

Table 9.9.4. Supplemental Data Pertaining to the Stress Rupture Behavior of Alloy XYZ Forging

Heat Treatment Details

Heat Treatment No.	Cycle No.	Temperature, °F	Time, Hours	Cool
2	1	1800	1	AC, WQ
	2	1325	8	FC (100 °F/hr)
	3	1150	8	AC
21	1	1700-1850	1	AC
	2	1325	8	FC (100°F/hr)
	3	1150	8	AC

Stress Rupture Equation and Inverse Matrix for the Creep Stress = 0.10, 0.20, 0.50, and 5.00% and Stress Rupture Conditions

$$\log t = c + b_1T + b_2X + b_3X^2 + b_4X^3 + b_5Y_1 + b_6Y_2 + b_7Y_3 + b_8Y_4 + b_9Y_5$$

where Y_1 = 1; Y_2, Y_3, Y_4, Y_5 = 0 for Creep Strain = 0.10% Data
Y_2 = 1; Y_1, Y_3, Y_4, Y_5 = 0 for Creep Strain = 0.20% Data
Y_3 = 1; Y_1, Y_2, Y_4, Y_5 = 0 for Creep Strain = 0.50% Data
Y_4 = 1; Y_1, Y_2, Y_3, Y_5 = 0 for Creep Strain = 5.00% Data
Y_1, Y_2, Y_3, Y_4, Y_5 = 0 for Stress Rupture Data

Column Row	1	2	3	4	5	6	7	8	9
1	1.809E+00	-1.108E-03	-1.978E+00	6.499E-01	-5.748E-02	-1.606E+00	-1.444E+00	-1.015E+00	-9.777E-01
2	-1.108E-03	6.834E-07	1.212E-03	-3.979E-04	3.517E-05	9.843E-04	8.852E-04	6.219E-04	5.993E-04
3	-1.978E+00	1.212E-03	3.482E+00	-1.657E+00	2.032E-01	1.634E+00	1.359E+00	6.886E-01	5.921E-01
4	6.499E-01	-3.979E-04	-1.657E+00	9.145E-01	-1.220E-01	-4.892E-01	-3.610E-01	-6.305E-02	3.594E-03
5	-5.748E-02	3.517E-05	2.032E-01	-1.220E-01	1.697E-02	3.801E-02	2.248E-02	-1.245E-02	-2.618E-02
6	-1.606E+00	9.843E-04	1.634E+00	-4.892E-01	3.801E-02	1.471E+00	1.303E+00	9.401E-01	9.124E-01
7	-1.444E+00	8.852E-04	1.359E+00	-3.610E-01	2.248E-02	1.303E+00	1.222E+00	8.806E-01	8.600E-01
8	-1.015E+00	6.219E-04	6.886E-01	-6.305E-02	-1.245E-02	9.401E-01	8.806E-01	7.491E-01	6.987E-01
9	-9.777E-01	5.993E-04	5.921E-01	3.594E-03	-2.618E-02	9.124E-01	8.600E-01	6.987E-01	1.195E+00

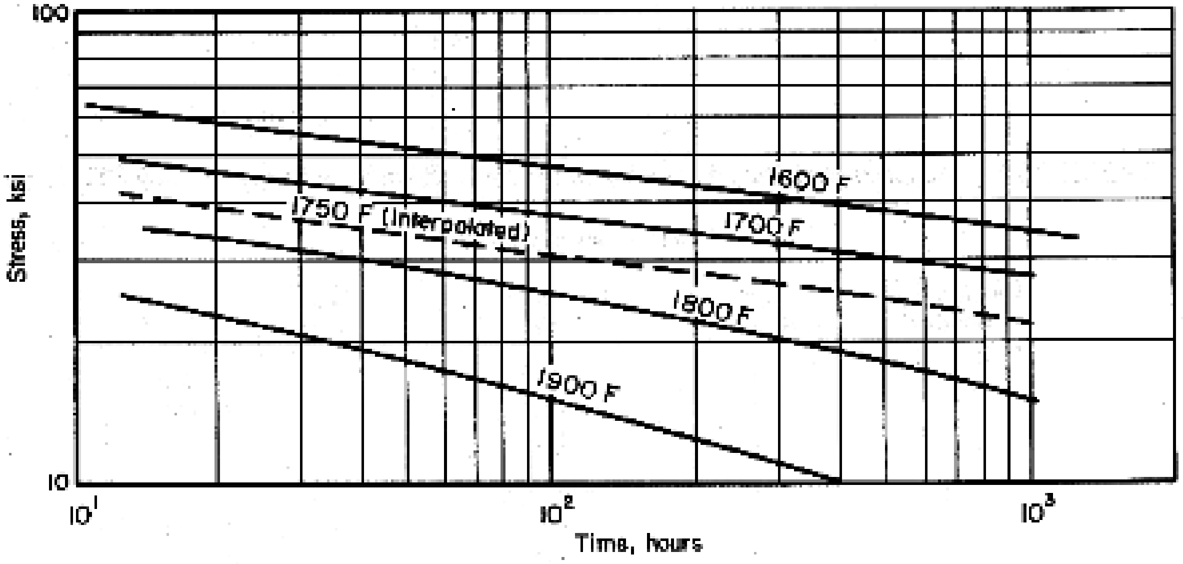
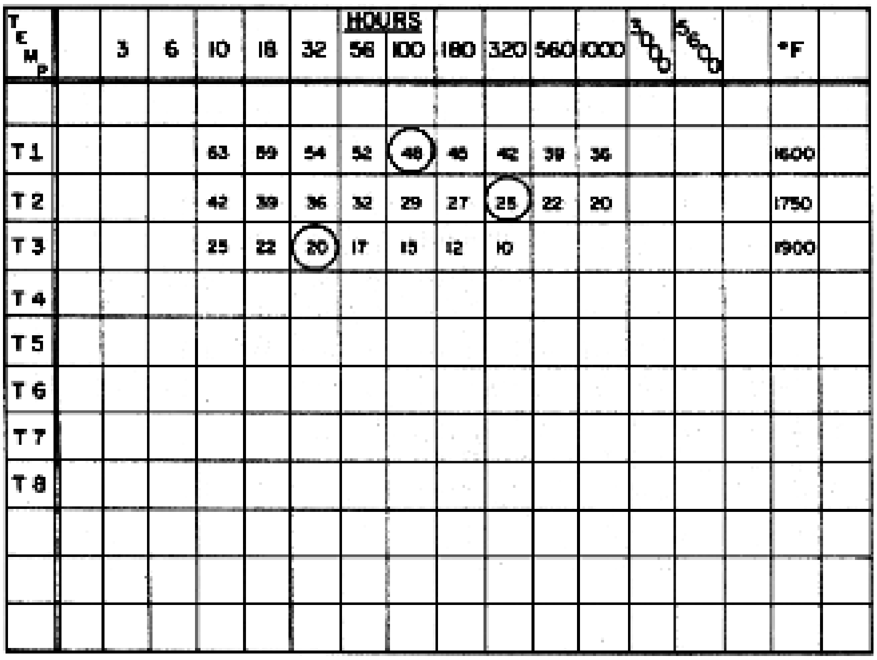


Figure 9.9.4.1(a). Estimated stress rupture curves for Alloy 325 (MOD).



TEMP							HOURS										
		3	6	10	18	32	56	100	180	320	560	1000	3000	5600		°F	
T 1				63	59	54	52	48	45	42	39	36				1600	
T 2				42	39	36	32	29	27	25	22	20				1750	
T 3				25	22	20	17	15	12	10						1900	
T 4																	
T 5																	
T 6																	
T 7																	
T 8																	

Figure 9.9.4.1(b). Experimental design matrix for creep rupture.

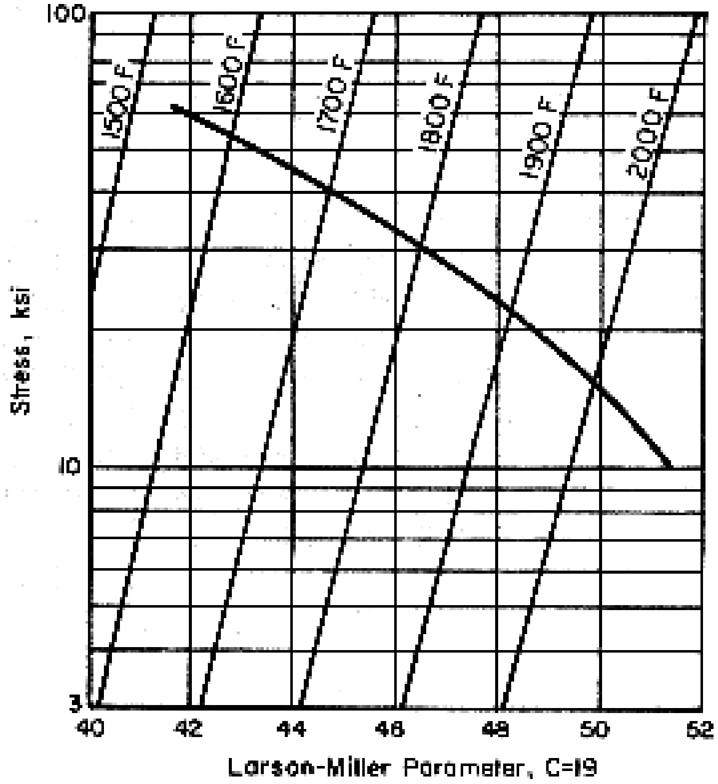


Figure 9.9.4.1(c). Alloy 325 (MOD) stress rupture typical life.

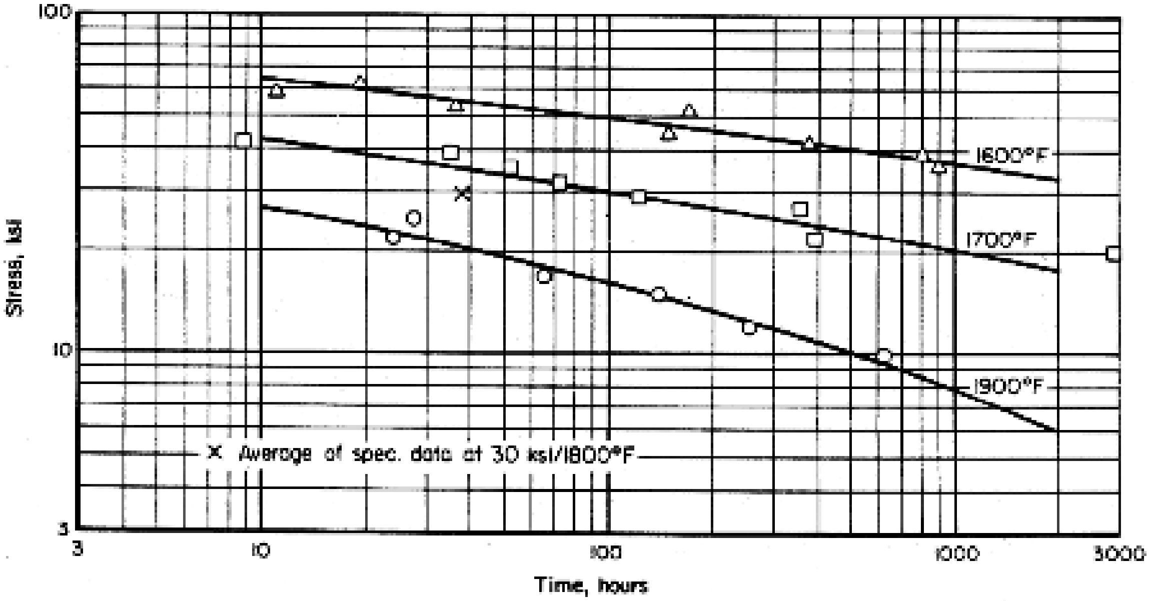


Figure 9.9.4.1(d). Alloy 325 (MOD) stress rupture typical life.

Table 9.9.4.1. Results of Simulated Sampling of Creep-Rupture Data

ksi	1600°F	ksi	1750°F	ksi	1900°F
63	19.0 hrs.	42	8.8 hrs.	25	27.6 hrs.
59	11.1 hrs.	39	35.5 hrs.	22	23.9 hrs.
54	36.3 hrs.	36	52.3 hrs.	17	65.4 hrs.
52	170.7 hrs.	32	71.8 hrs.	15	140.3 hrs.
45	148.0 hrs.	29	121.9 hrs.	12	257.5 hrs.
42	376.0 hrs.	27	355.9 hrs.	10	623.5 hrs.
39	806.9 hrs.	22	389.0 hrs.	*	
36	878.0 hrs.	20	2912.4 hrs.	*	

*No interest.

SPECIFICATION DATA
@ 30 KSI 1800°F

Hours

41.4	33.1	70.5	36.1
16.5	27.4	37.5	34.9
35.0	33.4	48.6	74.2
33.6	51.3	29.0	47.5
32.6	42.7	26.4	

(n = 19, $\overline{X}$ = 37.4, s(log 10) = 0.150)

9.9.5 Mechanically Fastened Joints — The final table of allowable loads must be presented in a format suitable for use in MIL-HDBK-5, as illustrated in Figures 9.9.5.1(a) and (b). Figure 9.9.5.1(a) is the approved format for fastener tables approved prior to December 31, 2002, while Figure 9.9.5.1(b) is the required format for fastener tables approved after December 31, 2002. The distinguishing factor between these two tables is the statistical basis associated with the ultimate and yield loads. Refer to Section 9.7 for a detailed discussion of the currently approved statistical analysis procedures for mechanical fasteners. The following notes apply to the circled numbers in Figures 9.9.5.1(a) and (b).

(1) Omit table number. (Secretariat will assign table number.)

(2) Head type: 100° Flush Head, 100° Flush Shear Head, Protruding Head, Protruding Shear Head, etc. The shear designation is applied to 100° or protruding head fasteners with heads similar in size to those on Hi-Shear rivets, shear-type lock-bolts, shear-head Hi-Lok, Taper-Lok, or similar fasteners.

(3) Fastener material: steel, aluminum alloy, Monel, A286, nickel alloy, etc.

(4) Type of fastener: blind rivet, rivet, bolt, blind bolt, screw, tapered fastener, etc.

(5) Type of hole: machine countersunk or dimpled. (Omit for protruding head fasteners.)

(6) Sheet material: consistent with other MIL-HDBK-5 tables.

(7) “Rivet” for blind or conventional rivets, “Fastener” for other type fasteners.

① ② ③ ④

Table XXXX(b). Static Joint Strength of Flush Head 6061-T8 Aluminum Alloy Rivets in Machine-⑤ Countersunk Clad Aluminum Alloy Sheet ⑥

Rivet Type ⑦	NASXXXX[a] (F_{su} = AAA ksi) ⑧				
Sheet Material	Clad 7075-T6 ⑨				
Rivet Diameter, in. (Nominal Hole Diameter, in.)[b]	3/32 ⑩ (0.096)	1/8 ⑩ (0.1285)	5/32 ⑩ (0.159)	3/16 ⑩ (0.191)	1/4 ⑩ (0.257)
	Ultimate Strength, lbs **(Estimated Lower Bound)**				
Sheet thickness:					
0.032	⑫ 182[c]	...	...	...	...
0.040	227	[d]⑫ 304	...	...	...
0.050	246	381	[d]⑫ 471	...	...
0.063	...	441	594	[d]⑫ 714	...
0.071 ⑪	...	...	670	805	[d] ...
0.080	...	...	675	907	... ⑯
0.090	...	...	...	974	⑫ 1375
0.100	...	...	...	...	1525 [d]
0.125	...	...	...	...	1765
Fastener shear strength[e] ⑬	246 ⑭	441 ⑭	675 ⑭	974 ⑭	1765 ⑭
	Yield Strength[f], lbs **(Conservatively Adjusted Average)**				
Sheet thickness, in.:					
0.032	119 ⑮	...	...	...	...
0.040	188	224 ⑮	...	...	...
0.050	246	307	349 ⑮	...	...
0.063	...	414	481	539 ⑮	...
0.071 ⑪	...	...	563	637	...
0.080	...	...	655	748	...
0.090	...	...	...	870	1060 ⑮
0.100	...	...	...	...	1230
0.125	...	...	...	...	1640
Fastener tensile strength[g], lbs ⑱	275	495	755	1090	1975
Head height (ref.), in. ⑲	0.039	0.049	0.059	0.070	0.091

a Data supplied by ABC Corporation and DEF Company, Confirmatory data provided by XYZ Company.
b Fasteners installed in clearance holes (.00XX-.00YY) (Ref. 8.1.X).
c Yield value is less than 2/3 of indicated ultimate strength value.
⑰ d Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.
e Rivet shear strength is documented in NAS XXZZ as AAA ksi.
f Permanent set at yield load: 4% of nominal diameter (Ref. 9.4.1.3.3).
g System maximum tensile strength as tested in steel fixture.

NOTE: See Section 9.4.1.6 for format recommendations indicated by circled numbers.

Figure 9.9.5.1(a). Sample format for MIL-HDBK-5 (non B-Basis) allowable joint strength tables published prior to December 31, 2002.

① ② ③ ④

Table XXXX(b). B-Basis Static Joint Strength of Flush Head 6061-T8 Aluminum Alloy Rivets in Machine-⑤ Countersunk Clad Aluminum Alloy Sheet ⑥

Rivet Type ⑦	NASXXXX[a] (F_{su} = AAA ksi) ⑧				
Sheet Material	Clad 7075-T6 ⑨				
Rivet Diameter, in. (Nominal Hole Diameter, in.)[b]	3/32 ⑩ (0.096)	1/8 ⑩ (0.1285)	5/32 ⑩ (0.159)	3/16 ⑩ (0.191)	1/4 ⑩ (0.257)
	Ultimate Strength, lbs **(B-Basis)**				
Sheet thickness:					
0.032	⑫ xxx[c]	...	...	...	...
0.040	xxx	d ⑫ xxx	...	...	...
0.050	xxx	xxx	d ⑫ xxx	...	...
0.063	...	xxx	xxx	d ⑫ xxx	...
0.071 ⑪	...	...	xxx	xxx	d ...
0.080	...	...	xxx	xxx	... ⑯
0.090	...	...	...	xxx	⑫ xxxx
0.100	...	...	...	...	xxxx d
0.125	...	...	...	...	xxxx
Fastener shear strength[e] ⑬	xxx ⑭	xxx ⑭	xxx ⑭	xxx ⑭	xxxx ⑭
	Yield Strength[f], lbs **(B-Basis)**				
Sheet thickness, in.:					
0.032	xxx ⑮	...	...	...	...
0.040	xxx	xxx ⑮	...	...	...
0.050	xxx	xxx	xxx ⑮	...	...
0.063	...	xxx	xxx	xxx ⑮	...
0.071 ⑪	...	...	xxx	xxx	...
0.080	...	...	xxx	xxx	...
0.090	...	...	...	xxx	xxxx ⑮
0.100	...	...	...	...	xxxx
0.125	...	...	...	...	xxxx
Fastener tensile strength[g], lbs ⑱	xxx	xxx	xxx	xxxx	xxxx
Head height (ref.), in. ⑲	x.xxx	x.xxx	x.xxx	x.xxx	x.xxx

a Data supplied by ABC Corporation and DEF Company, Confirmatory data provided by XYZ Company.
b Fasteners installed in clearance holes (.00XX-.00YY) (Ref. 8.1.X).
c Yield value is less than 2/3 of indicated ultimate strength value.
⑰ d Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.
e Rivet shear strength is documented in NAS XXZZ as AAA ksi.
f Permanent set at yield load: 4% of nominal diameter (Ref. 9.4.1.3.3).
g System maximum tensile strength as tested in steel fixture.

NOTE: See Section 9.4.1.6 for format recommendations indicated by circled numbers.

Figure 9.9.5.1(b). Sample format for MIL-HDBK-5 allowable joint strength tables published after December 31, 2002.

(8) Add footnote indicator to part numbers and indicate in a footnote the vendor(s) whose part number is shown if the fastener is not covered by an MS or NAS part number. Include fastener shear strength, material temper, and nut or collar identification.

(9) Sheet or plate material and heat treatment or condition.

(10) Nominal fastener diameter. For H-category fasteners, show nominal fractional hole size and, in parentheses, show actual nominal hole size in decimal equivalent. For S-category fasteners, show nominal fractional shank diameter and, in parentheses, show actual fastener shank diameter in decimals [i.e., a l/8-inch-diameter NAS1740 rivet would be listed as 1/8 (0.144)].

(11) Select standard sheet and plate thickness from the following:

0.008
0.010
0.012
0.016
0.020
0.025
0.032
0.040
0.050
0.063
0.071
0.080
0.090
0.100
0.125
0.160
0.190
0.250
0.312
0.375
0.500
0.625
0.750
0.875

(12) Present design allowable values starting at first sheet thickness below knife-edge condition and continuing through the first value equal to or greater than shear strength value. Allowable loads will not exceed shear strength. Add footnote indicator to ultimate strength values when yield is less than two-thirds of ultimate loads as indicated in Item (17).

(13) Use the words: "Rivet shear strength" or "Fastener shear strength" conforming to Item (7) nomenclature.

(14) Fastener single-shear allowable loads in pounds.

(15) Present yield strength values for the same thickness and diameters for which ultimate strength values are provided.

(16) For those countersunk head fasteners for which design values are applicable to thin sheet thicknesses, such that the countersink extends into the bottom sheet, a horizontal line will be drawn in each column of the joint allowables table above the first ultimate strength design value for which the countersink still is contained within the top sheet. For these cases, footnote (f) will be used, as indicated in Item (17).

(17) Add all applicable footnotes from the list of standard notes shown below. All footnotes will be designated by lower case letters.

(a) "Yield value is less than two-thirds of the indicated ultimate strength value." (Place footnote indicator next to applicable ultimate strength value.)

(b) "These allowables apply to double-dimpled sheets and to the upper sheet dimpled into a machine-countersunk sheet. The thickness of the machine-countersunk sheet must be at least one tabulated gage thicker than the upper dimpled sheet." (Place footnote indicator next to the words "Ultimate Strength, lbs" at the top of the table.)

(c) "Data supplied by ABC Corporation." When applicable add: "Confirmatory data provided by XYZ Company." (Place footnote indicator next to part number.)

(d) "Shear strength based on areas computed from nominal hole diameters or nominal shank diameters, as applicable (indicate Table 8.1.2(a), or list hole diameters), and F_{su} = (indicate shear strength)." Indicate the source of the shear strength (MIL or NAS specifications or data analysis). The footnote indicator is placed next to the words "Fastener shear strength" indicated by Item 13 above. The shear strength will not be greater than the strength required in the controlling specification or standard.

(e) "Allowables based on nominal hole diameters of (list hole diameters)." This footnote is used when shear strength is controlled by MIL or NAS specifications, and Table 8.1.2(a) hole diameters are not used.

(f) "Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency."

(g) "Permanent set at yield load: 4% of nominal diameter (see Section 9.7.1.1)."

(h) "Fasteners installed in clearance (or interference) holes." Indicate actual range of fastener-hole fits (interference-clearance) from test program.

(i) "System maximum tensile strength as tested in steel fixture." This footnote is used when table contains fastener tensile strength values. (Place footnote indicator next to the words "Fastener tensile strength, lbs".)

(18) When applicable, add line below yield strength section to present "Fastener tensile strength, lbs". List the appropriate value for each fastener diameter.

(19) For flush head fasteners, add line below yield strength section to present "Head height (ref.), in." List appropriate value for each fastener diameter.

9.9.6 Fusion-Welded Joints — The welding conditions of major significance to potential users of the data should be shown in the data presentation for each basic population of weldments considered. Among these variables, the following are the minimum that should be specified, where applicable:

(1) Alloys

(2) Weld-heat-treat conditions

(3) Filler materials

(4) Welding processes

(5) Weld repairs

(6) Joint thicknesses

(7) Joint types

(8) Weld quality levels

(9) Welding methods, i.e., manual or mechanized.

Since data presented are based on coupon-derived results, it is also necessary to provide comments on use of data in structural design.

9.9.6.1 ***Additional Information*** — When weldment data are presented, they should include comments to aid designers in selecting appropriate welding processes or conditions. In addition, comments alerting a designer to possible fabrication problems or environmental effects should be included. These may include:

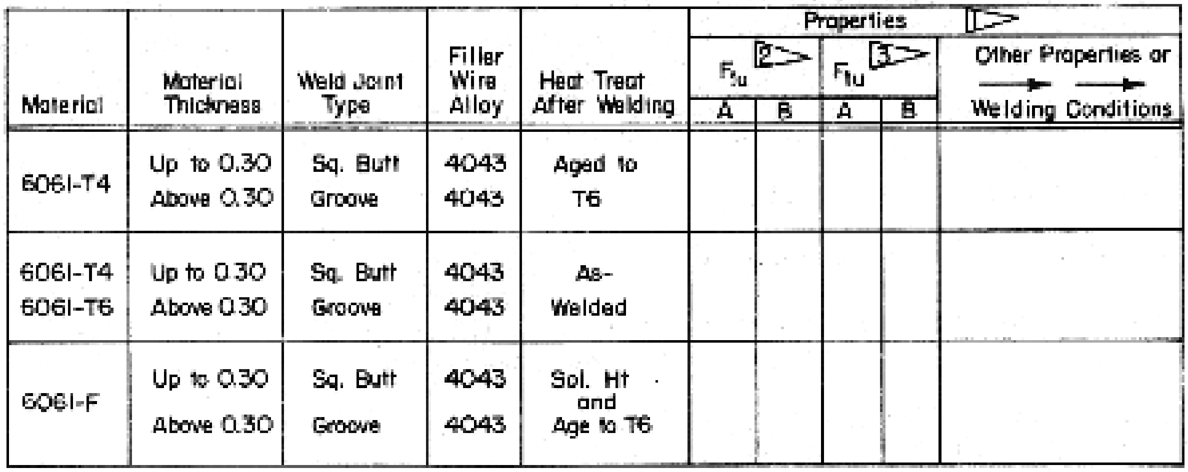
(1) Potential weld heat-treating sequences for the alloy

(2) Applicable welding methods

(3) Comments on weldment properties

(4) Discussion of pertinent welding process variables, such as heat input sensitivity or restrictions, preheat requirements, atmospheric contamination, and significant metallurgical phenomena.

9.9.6.2 ***Room-Temperature Properties*** — Data on room-temperature properties of weldments are presented in tabular form illustrated in Figure 9.9.6.2. The figure describes base material, welding variables, and weld character conditions that the data represent, as well as properties of interest. Precautionary notes for use of data in design are presented in footnotes and are discussed in Section 9.9.6.4.



Material	Material Thickness	Weld Joint Type	Filler Wire Alloy	Heat Treat After Welding	Properties [1]				
					F_{tu} [2]		F_{tu} [3]		Other Properties or → → Welding Conditions
					A	B	A	B	
6061-T4	Up to 0.30 Above 0.30	Sq. Butt Groove	4043 4043	Aged to T6					
6061-T4 6061-T6	Up to 0.30 Above 0.30	Sq. Butt Groove	4043 4043	As-Welded					
6061-F	Up to 0.30 Above 0.30	Sq. Butt Groove	4043 4043	Sol. Ht and Age to T6					

[1] These coupon-derived properties are subject to the usage limitations discussed under "Use of Design Data."

[2] For the following welding conditions ----------

[3] For the following welding conditions ---------

Figure 9.9.6.2. Typical format for presentation of room-temperature properties of weldments.

9.9.6.3 *Data on Effect of Temperature* — A typical effect-of-temperature curve of weldment properties is shown in Figure 9.9.6.3. This type of curve should be presented in conjunction with room-temperature properties, referencing welding conditions and precautionary notes of the room-temperature case.

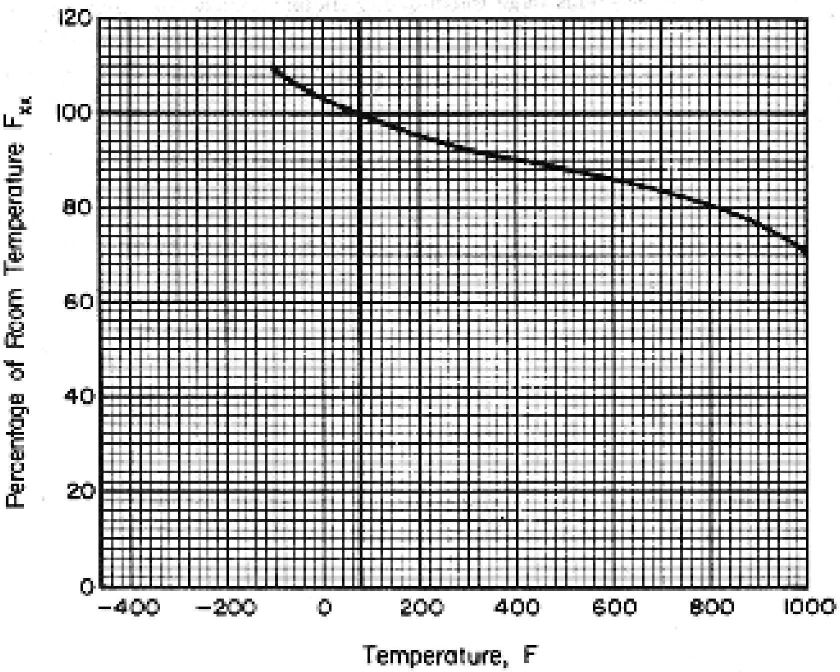


Figure 9.9.6.3. Typical effect of temperature presentation.

9.9.6.4 *Use of Design Data* — In footnotes to coupon-derived design data, it is necessary to present precautionary notes on the use of data in structural design. It is recognized that structures may not fail under load in the same manner as a coupon. This lack of one-to-one correlation may be due to differences either in weldment character resulting from potentially higher variability of production welding, or state of stress. Coupon-structure ratios are used to account for these differences.

The coupon-derived basic weld allowable accounts for a sizeable portion of the variability in welded joints; coupon-structure ratio accounts for the remainder. Since the state of stress (and to some extent, distribution of stress) is accounted for in the coupon-structure ratio, it is probable that each general structural configuration will have a unique coupon-structure ratio. For example, the coupon-structure ratio for a tank which must resist internal pressure would be different from the ratio for a welded joint in a sandwich panel.

9.10 STATISTICAL TABLES

A number of tables of statistical values that are required for analyses described in the MIL-HDBK-5 Guidelines are presented in this section. For tables containing various fractiles or confidence levels, only applicable portions are reproduced herein. Table 9.10.1 was reproduced by permission from Reference 9.10.1. Tables 9.10.2 through 9.10.6 were reproduced or adapted from tables in Reference 9.1.5, with the addition of a few individual values from various other sources. Tables 9.10.7 through 9.10.9 were created specifically for MIL-HDBK-5J.

Table 9.10.1. One-Sided Tolerance Limit Factors[a], k, for the Normal Distribution, 0.95 Confidence, and n-1 Degrees of Freedom

Note: These P values should only be used for substantiation of S-basis minimum properties (see Section 9.4). Weibull, Pearson, or nonparametric procedures should be used when calculating T_{90} and T_{99} values to determine A- and B-basis minimum static properties (see Section 9.5).

n	P = 0.99	n	P = 0.99	n	P = 0.99	n	P = 0.99
30	3.064						
31	3.048	61	2.802	91	2.704	121	2.648
32	3.034	62	2.798	92	2.701	122	2.646
33	3.020	63	2.793	93	2.699	123	2.645
34	3.007	64	2.789	94	2.697	124	2.643
35	2.995	65	2.785	95	2.695	125	2.642
36	2.983	66	2.781	96	2.692	126	2.640
37	2.972	67	2.777	97	2.690	127	2.639
38	2.961	68	2.773	98	2.688	128	2.638
39	2.951	69	2.769	99	2.686	129	2.636
40	2.941	70	2.765	100	2.684	130	2.635
41	2.932	71	2.762	101	2.682	131	2.634
42	2.923	72	2.758	102	2.680	132	2.632
43	2.914	73	2.755	103	2.678	133	2.631
44	2.906	74	2.751	104	2.676	134	2.630
45	2.898	75	2.748	105	2.674	135	2.628
46	2.890	76	2.745	106	2.672	136	2.627
47	2.883	77	2.742	107	2.671	137	2.626
48	2.876	78	2.739	108	2.669	138	2.625
49	2.869	79	2.736	109	2.667	139	2.624
50	2.862	80	2.733	110	2.665	140	2.622
51	2.856	81	2.730	111	2.663	141	2.621
52	2.850	82	2.727	112	2.662	142	2.620
53	2.844	83	2.724	113	2.660	143	2.619
54	2.838	84	2.721	114	2.658	144	2.618
55	2.833	85	2.719	115	2.657	145	2.617
56	2.827	86	2.716	116	2.655	146	2.616
57	2.822	87	2.714	117	2.654	147	2.615
58	2.817	88	2.711	118	2.652	148	2.613
59	2.812	89	2.709	119	2.651	149	2.612
60	2.807	90	2.706	120	2.649	150	2.611

Table 9.10.1. One-Sided Tolerance Limit Factors[a], k, for the Normal Distribution, 0.95 Confidence, and n-1 Degrees of Freedom (concluded)

Note: These P values should only be used for substantiation of S-basis minimum properties (see Section 9.4). Weibull, Pearson, or nonparametric procedures should be used when calculating T_{90} and T_{99} values to determine A- and B-basis minimum static properties (see Section 9.5).

n	P = 0.99	n	P = 0.99	n	P = 0.99	n	P = 0.99
151	2.610	176	2.587	205	2.566	330	2.512
152	2.609	177	2.587	210	2.563	340	2.509
153	2.608	178	2.586	215	2.560	350	2.506
154	2.607	179	2.585	220	2.557	360	2.504
155	2.606	180	2.584	225	2.555	370	2.501
156	2.605	181	2.583	230	2.552	390	2.496
157	2.604	182	2.583	235	2.549	400	2.494
158	2.603	183	2.583	240	2.547	425	2.489
159	2.602	184	2.581	245	2.544	450	2.484
160	2.601	185	2.580	250	2.542	475	2.480
161	2.600	186	2.580	255	2.540	500	2.475
162	2.600	187	2.579	260	2.537	525	2.472
163	2.599	188	2.578	265	2.535	550	2.468
164	2.598	189	2.577	270	2.533	575	2.465
165	2.597	190	2.577	275	2.531	600	2.462
166	2.596	191	2.576	280	2.529	625	2.459
167	2.595	192	2.575	285	2.527	650	2.456
168	2.594	193	2.575	290	2.525	675	2.454
169	2.593	194	2.574	295	2.524	700	2.451
170	2.592	195	2.573	300	2.522	750	2.447
171	2.592	196	2.572	305	2.520	800	2.443
172	2.591	197	2.572	310	2.518	850	2.439
173	2.590	198	2.571	315	2.517	900	2.436
174	2.589	199	2.570	320	2.515	1000	2.430
175	2.588	200	2.570	325	2.514	∞	2.326

[a] The following equations may be used to compute k factors in lieu of using table values:

$k_{99} = 2.326 + \exp[1.34 - 0.522 \ln(n) + 3.87/n]$

$k_{90} = 1.282 + \exp[0.958 - 0.520 \ln(n) + 3.19/n]$

These approximations are accurate to within 0.2% of the table values for n greater than or equal to 30.

Table 9.10.2. 0.950 Fractiles of the F Distribution Associated with n_1 and n_2 Degrees of Freedom

	n_1, degrees of freedom for numerator																		
n_2[a]	1	2	3	4	5	6	7	8	9	10	12	15	20	24	30	40	60	120	∞
1	161.4	199.5	215.7	224.6	230.2	234.0	236.8	238.9	240.5	241.9	243.9	245.9	248.0	249.0	250.1	251.1	252.2	253.2	254.3
2	18.51	19.00	19.16	19.25	19.30	19.33	19.35	19.37	19.38	19.40	19.41	19.43	19.45	19.45	19.46	19.47	19.48	19.49	19.51
3	10.13	9.55	9.28	9.12	9.01	8.94	8.89	8.85	8.81	8.79	8.74	8.70	8.66	8.64	8.62	8.59	8.57	8.55	8.53
4	7.71	6.94	6.59	6.39	6.26	6.16	6.09	6.04	6.00	5.96	5.91	5.86	5.80	5.77	5.75	5.72	5.69	5.66	5.63
5	6.61	5.79	5.41	5.19	5.05	4.95	4.88	4.82	4.77	4.74	4.68	4.62	4.56	4.53	4.50	4.46	4.43	4.40	4.37
6	5.99	5.14	4.76	4.53	4.39	4.28	4.21	4.15	4.10	4.06	4.00	3.94	3.87	3.84	3.81	3.77	3.74	3.70	3.67
7	5.59	4.74	4.35	4.12	3.97	3.87	3.79	3.73	3.68	3.64	3.57	3.51	3.44	3.41	3.38	3.34	3.30	3.27	3.23
8	5.32	4.46	4.07	3.84	3.69	3.58	3.50	3.44	3.39	3.35	3.28	3.22	2.15	3.12	3.08	3.04	3.01	2.97	2.93
9	5.12	4.26	3.86	3.63	3.48	3.37	3.29	3.23	3.18	3.14	3.07	3.01	2.94	2.90	2.86	2.83	2.79	2.75	2.71
10	4.96	4.10	3.71	3.48	3.33	3.22	3.14	3.07	3.02	2.98	2.91	2.85	2.77	2.74	2.70	2.66	2.62	2.58	2.54
11	4.84	3.98	3.59	3.36	3.20	3.09	3.01	2.95	2.90	2.85	2.79	2.72	2.65	2.61	2.57	2.53	2.49	2.45	2.40
12	4.75	3.89	3.49	3.26	3.11	3.00	2.91	2.85	2.80	2.75	2.69	2.62	2.54	2.51	2.47	2.43	2.38	2.34	2.30
13	4.67	3.81	3.41	3.18	3.03	2.92	2.83	2.77	2.71	2.67	2.60	2.53	2.46	2.42	2.38	2.34	2.30	2.25	2.21
14	4.60	3.74	3.34	3.11	2.96	2.85	2.76	2.70	2.65	2.60	2.53	2.46	2.39	2.35	2.31	2.27	2.22	2.18	2.13
15	4.54	3.68	3.29	3.06	2.90	2.79	2.71	2.64	2.59	2.54	2.48	2.40	2.33	2.29	2.25	2.20	2.16	2.11	2.07
16	4.49	3.63	3.24	3.01	2.85	2.74	2.66	2.59	2.54	2.49	2.42	2.35	2.28	2.24	2.19	2.15	2.11	2.06	2.01
17	4.45	3.59	3.20	2.96	2.81	2.70	2.61	2.55	2.49	2.45	2.38	2.31	2.23	2.19	2.15	2.10	2.06	2.01	1.96
18	4.41	3.55	3.16	2.93	2.77	2.66	2.58	2.51	2.46	2.41	2.34	2.27	2.19	2.15	2.11	2.06	2.02	1.97	1.92
19	4.38	3.52	3.13	2.90	2.74	2.63	2.54	2.48	2.42	2.38	2.31	2.23	2.16	2.11	2.07	2.03	1.98	1.93	1.88
20	4.35	3.49	3.10	2.87	2.71	2.60	2.51	2.45	2.39	2.35	2.28	2.20	2.12	2.08	2.04	1.99	1.95	1.90	1.84
21	4.32	3.47	3.07	2.84	2.68	2.57	2.49	2.42	2.37	2.32	2.25	2.18	2.10	2.05	2.01	1.96	1.92	1.87	1.81
22	4.30	3.44	3.05	2.82	2.66	2.55	2.46	2.40	2.34	2.30	2.23	2.15	2.07	2.03	1.98	1.94	1.89	1.84	1.78
23	4.28	3.42	3.03	2.80	2.64	2.53	2.44	2.37	2.32	2.27	2.20	2.13	2.05	2.01	1.96	1.91	1.86	1.81	1.76
24	4.26	3.40	3.01	2.78	2.62	2.51	2.42	2.36	2.30	2.25	2.18	2.11	2.03	1.98	1.94	1.89	1.84	1.79	1.73
25	4.24	3.39	2.99	2.76	2.60	2.49	2.40	2.34	2.28	2.24	2.16	2.09	2.01	1.96	1.92	1.87	1.82	1.77	1.71
26	4.23	3.37	2.98	2.74	2.59	2.47	2.39	2.32	2.27	2.22	2.15	2.07	1.99	1.95	1.90	1.85	1.80	1.75	1.69
27	4.21	3.35	2.96	2.73	2.57	2.46	2.37	2.31	2.25	2.20	2.13	2.06	1.97	1.93	1.88	1.84	1.79	1.73	1.67
28	4.20	3.34	2.95	2.71	2.56	2.45	2.36	2.29	2.24	2.19	2.12	2.04	1.96	1.91	1.87	1.82	1.77	1.71	1.65
29	4.18	3.33	2.93	2.70	2.55	2.43	2.35	2.28	2.22	2.18	2.10	2.03	1.94	1.90	1.85	1.81	1.75	1.70	1.64
30	4.17	3.32	2.92	2.69	2.53	2.42	2.33	2.27	2.21	2.16	2.09	2.01	1.93	1.89	1.84	1.79	1.74	1.68	1.62
40	4.08	3.23	2.84	2.61	2.45	2.34	2.25	2.18	2.12	2.08	2.00	1.92	1.84	1.79	1.74	1.69	1.64	1.58	1.51
60	4.00	3.15	2.76	2.53	2.37	2.25	2.17	2.10	2.04	1.99	1.92	1.84	1.75	1.70	1.65	1.59	1.53	1.47	1.39
120	3.92	3.07	2.68	2.45	2.29	2.18	2.09	2.02	1.96	1.91	1.83	1.75	1.66	1.61	1.55	1.50	1.43	1.35	1.25
∞	3.84	3.00	2.61	2.37	2.21	2.10	2.01	1.94	1.88	1.83	1.75	1.67	1.57	1.52	1.46	1.39	1.32	1.22	1.00

[a] n_2 = degrees of freedom for denominator.

Table 9.10.3. 0.975 Fractiles[a] of the F Distribution Associated with n_1 and n_2 Degrees of Freedom, $F_{.975}$ (n_1, n_2)

δ_2[b]	δ_1, degrees of freedom for numerator																		
	1	2	3	4	5	6	7	8	9	10	12	15	20	24	30	40	60	120	∞
1	647.8	799.5	864.2	899.6	921.8	937.1	948.2	956.7	963.3	968.6	976.7	984.9	993.1	997.2	1001	1006	1010	1014	1018
2	38.51	39.00	39.17	39.25	39.30	39.33	39.36	39.37	39.39	39.40	39.41	39.43	39.45	39.46	39.45	39.47	39.48	39.99	39.50
3	17.44	16.04	15.44	15.10	14.88	14.73	14.62	14.54	14.47	14.42	14.34	14.25	14.17	14.12	14.08	14.04	13.99	13.95	13.90
4	12.22	10.65	9.98	9.60	9.36	9.20	9.07	8.98	8.90	8.84	8.75	8.66	8.56	8.51	8.46	8.41	8.36	8.31	8.26
5	10.01	8.43	7.76	7.39	7.15	6.98	6.85	6.76	6.68	6.62	6.52	6.43	6.33	6.28	6.23	6.18	6.12	6.07	6.02
6	8.81	7.26	6.60	6.23	5.99	5.82	5.70	5.60	5.52	5.46	5.37	5.27	5.17	5.12	5.07	5.01	4.96	4.90	4.85
7	8.07	6.54	5.89	5.52	5.29	5.12	4.99	4.90	4.82	4.76	4.67	4.57	4.47	4.42	4.36	4.31	4.25	4.20	4.14
8	7.57	6.06	5.42	5.05	4.82	4.65	4.53	4.43	4.36	4.30	4.20	4.10	4.00	3.95	3.89	3.84	3.78	3.73	3.67
9	7.21	5.71	5.08	4.72	4.48	4.32	4.20	4.10	4.03	3.96	3.87	3.77	3.67	3.61	3.56	3.51	3.45	3.39	3.33
10	6.94	5.46	4.83	4.47	4.24	4.07	3.95	3.85	3.78	3.72	3.62	3.52	3.42	3.37	3.31	3.26	3.20	3.14	3.08
11	6.72	5.26	4.63	4.28	4.04	3.88	3.76	3.66	3.59	3.53	3.43	3.33	3.23	3.17	3.12	3.06	3.00	2.94	2.88
12	6.55	5.10	4.47	4.12	3.89	3.73	3.61	3.51	3.44	3.37	3.28	3.18	3.07	3.02	2.96	2.91	2.85	2.79	2.72
13	6.41	4.97	4.35	4.00	3.77	3.60	3.48	3.39	3.31	3.25	3.15	3.05	2.95	2.89	2.84	2.78	2.72	2.66	2.60
14	6.30	4.86	4.24	3.89	3.66	3.50	3.38	3.29	3.21	3.15	3.05	2.95	2.84	2.79	2.73	2.67	2.61	2.55	2.49
15	6.20	4.77	4.15	3.80	3.58	3.41	3.29	3.20	3.12	3.06	2.96	2.86	2.76	2.70	2.64	2.59	2.52	2.46	2.40
16	6.12	4.69	4.08	3.73	3.50	3.34	3.22	3.12	3.05	2.99	2.89	2.79	2.68	2.63	2.57	2.51	2.45	2.38	2.32
17	6.04	4.62	4.01	3.66	3.44	3.28	3.16	3.06	2.98	2.92	2.82	2.72	2.62	2.56	2.50	2.44	2.38	2.32	2.25
18	5.98	4.56	3.95	3.61	3.38	3.22	3.10	3.01	2.93	2.87	2.77	2.67	2.56	2.50	2.44	2.38	2.32	2.26	2.19
19	5.92	4.51	3.90	3.56	3.33	3.17	3.05	2.96	2.88	2.82	2.72	2.62	2.51	2.45	2.39	2.33	2.27	2.20	2.13
20	5.87	4.46	3.86	3.51	3.29	3.13	3.01	2.91	2.84	2.77	2.68	2.57	2.46	2.41	2.36	2.29	2.22	2.16	2.09
21	5.83	4.42	3.82	3.48	3.25	3.09	2.97	2.87	2.80	2.73	2.64	2.53	2.42	2.37	2.31	2.25	2.18	2.11	2.04
22	5.79	4.38	3.78	3.44	3.22	3.05	2.93	2.84	2.76	2.70	2.60	2.50	2.39	2.33	2.27	2.21	2.14	2.08	2.00
23	5.75	4.25	3.75	3.41	3.18	3.02	2.90	2.81	2.73	2.67	2.57	2.47	2.36	2.30	2.24	2.18	2.11	2.04	1.97
24	5.72	4.32	3.72	3.38	3.15	2.99	2.87	2.78	2.70	2.64	2.54	2.44	2.33	2.27	2.21	2.15	2.08	2.01	1.94
25	5.69	4.29	3.69	3.35	3.13	2.97	2.85	2.75	2.68	2.61	2.51	2.41	2.30	2.24	2.18	2.12	2.05	1.98	1.91
26	5.66	4.27	3.67	3.33	3.10	2.94	2.82	2.73	2.65	2.59	2.49	2.39	2.28	2.22	2.16	2.09	2.03	1.95	1.88
27	5.63	4.24	3.65	3.31	3.08	2.92	2.80	2.71	2.63	2.57	2.47	2.36	2.25	2.19	2.13	2.07	2.00	1.93	1.85
28	5.61	4.22	3.63	3.29	3.06	2.90	2.78	2.69	2.61	2.55	2.45	2.34	2.23	2.17	2.11	2.06	1.98	1.91	1.83
29	5.59	4.20	3.61	3.27	3.04	2.88	2.76	2.67	2.59	2.53	2.43	2.32	2.21	2.15	2.09	2.03	1.96	1.89	1.81
30	5.57	4.18	3.59	3.25	3.03	2.87	2.75	2.65	2.57	2.51	2.41	2.31	2.20	2.14	2.07	2.01	1.94	1.87	1.79
40	5.42	4.05	3.46	3.13	2.90	2.74	2.62	2.53	2.45	2.39	2.29	2.18	2.07	2.01	1.94	1.88	1.80	1.72	1.64
60	5.29	3.93	3.34	3.01	2.79	2.63	2.51	2.41	2.33	2.27	2.17	2.06	1.94	1.88	1.82	1.74	1.67	1.58	1.48
120	5.15	3.80	3.23	2.89	2.67	2.52	2.39	2.30	2.22	2.16	2.05	1.94	1.82	1.76	1.69	1.61	1.53	1.43	1.31
∞	5.02	3.69	3.12	2.79	2.57	2.41	2.29	2.19	2.11	2.05	1.94	1.83	1.71	1.64	1.57	1.48	1.39	1.27	1.00

a See following page for footnote.

b n_2 = degrees of freedom for denominator

Table 9.10.3. 0.975 Fractiles[a] of the F Distribution Associated with n_1 and n_2 degrees of Freedom $F_{.975}\,(n_1,n_2)$ (Continued)

a The following equation may be used to compute 0.975 fractiles of the F distribution in lieu of using table values:

$$F_{.975} \approx \exp\left[2\delta\left(1 + \frac{z^2 - 1}{3} - \frac{4\sigma^2}{3} \right) + 2\sigma z \left(1 + \frac{\sigma^2(z^2 - 3)}{6} \right)^{1/2} \right]$$

where

z = 1.96
δ = $0.5\,[1/(\gamma_2 - 1) - 1/(\gamma_1 - 1)]$
σ^2 = $0.5\,[(1/(\gamma_2 - 1) + 1(\gamma_1 - 1)]$
γ_1 = degrees of freedom for numerator
γ_2 = degrees of freedom for denominator.

This approximation is accurate to within 0.4% for $\gamma_1 \geq 10$ and $\gamma_2 \geq 16$. See Reference 9.10.3.

Table 9.10.4. 0.95 and 0.975 Fractiles[a] of the t Distribution Associated with df Degrees of Freedom

df	$t_{.95}$	$t_{.975}$	df	$t_{.95}$	$t_{.975}$
1	6.314	12.706	21	1.721	2.080
2	2.920	4.303	22	1.717	2.074
3	2.353	3.182	23	1.714	2.069
4	2.132	2.776	24	1.711	2.064
5	2.015	2.571	25	1.708	2.060
6	1.943	2.447	26	1.706	2.056
7	1.895	2.365	27	1.703	2.052
8	1.860	2.306	28	1.701	2.048
9	1.833	2.262	29	1.699	2.045
10	1.812	2.228	30	1.697	2.042
11	1.796	2.201	40	1.684	2.021
12	1.782	2.179	50	1.676	2.009
13	1.771	2.160	60	1.671	2.000
14	1.761	2.145	80	1.664	1.990
15	1.753	2.131	100	1.660	1.984
16	1.746	2.120	120	1.658	1.980
17	1.740	2.110	200	1.653	1.972
18	1.734	2.101	500	1.648	1.965
19	1.729	2.093	∞	1.645	1.960
20	1.725	2.086			

a The following equations may be used to compute 0.95 and 0.975 fractiles of the t distribution in lieu of using table values:

$$t_{.95} \approx 1.645 + \exp\,[0.377 - 0.990\,\ln(\gamma) + 1.15/\gamma]$$
$$t_{.975} \approx 1.96 + \exp\,[0.779 - 0.980\,\ln(\gamma) + 1.57/\gamma]$$

where γ is the degrees of freedom (df). These approximations are accurate to within 0.5% for $\gamma \geq 4$.

Table 9.10.5. Area Under the Normal Curve from -∞ to the Mean + Z_p Standard Deviations[a,b]

Z_p	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
.0	.5000	.5040	.5080	.5120	.5160	.5199	.5239	.5279	.5319	.5359
.1	.5398	.5438	.5478	.5517	.5557	.5596	.5636	.5675	.5714	.5753
.2	.5793	.5832	.5871	.5910	.5948	.5987	.6026	.6064	.6103	.6141
.3	.6179	.6217	.6255	.6293	.6331	.6368	.6406	.6443	.6480	.6517
.4	.6554	.6591	.6628	.6664	.6700	.6736	.6772	.6808	.6844	.6879
.5	.6915	.6950	.6985	.7019	.7054	.7088	.7123	.7157	.7190	.7224
.6	.7257	.7291	.7324	.7357	.7389	.7422	.7454	.7486	.7517	.7549
.7	.7580	.7611	.7642	.7673	.7704	.7734	.7764	.7794	.7823	.7852
.8	.7881	.7910	.7939	.7967	.7995	.8023	.8051	.8078	.8106	.8133
.9	.8159	.8186	.8212	.8238	.8264	.8289	.8315	.8340	.8365	.8389
1.0	.8413	.8438	.8461	.8485	.8508	.8531	.8554	.8577	.8599	.8621
1.1	.8643	.8665	.8686	.8708	.8729	.8749	.8770	.8790	.8810	.8820
1.2	.8849	.8869	.8888	.8907	.8925	.8944	.8962	.8980	.8997	.9015
1.3	.9032	.9049	.9066	.9082	.9099	.9115	.9131	.9147	.9162	.9177
1.4	.9192	.9207	.9222	.9236	.9251	.9265	.9279	.9292	.9306	.9319
1.5	.9332	.9345	.9357	.9370	.9382	.9394	.9406	.9418	.9429	.9441
1.6	.9452	.9463	.9474	.9484	.9495	.9505	.9515	.9525	.9535	.9545
1.7	.9554	.9564	.9573	.9582	.9591	.9599	.9608	.9616	.9625	.9633
1.8	.9641	.9649	.9656	.9664	.9671	.9678	.9686	.9693	.9699	.9706
1.9	.9713	.9719	.9726	.9732	.9738	.9744	.9750	.9756	.9761	.9767
2.0	.9772	.9778	.9783	.9788	.9793	.9798	.9803	.9808	.9812	.9817
2.1	.9821	.9826	.9830	.9834	.9838	.9842	.9846	.9850	.9854	.9857
2.2	.9861	.9864	.9868	.9871	.9875	.9878	.9881	.9884	.9887	.9890
2.3	.9893	.9896	.9898	.9901	.9904	.9906	.9909	.9911	.9913	.9916
2.4	.9918	.9920	.9922	.9925	.9927	.9929	.9931	.9932	.9934	.9936
2.5	.9938	.9940	.9941	.9943	.9945	.9946	.9948	.9949	.9951	.9952
2.6	.9953	.9955	.9956	.9957	.9959	.9960	.9961	.9962	.9963	.9964
2.7	.9965	.9966	.9967	.9968	.9969	.9970	.9971	.9972	.9973	.9974
2.8	.9974	.9975	.9976	.9977	.9977	.9978	.9979	.9979	.9980	.9981
2.9	.9981	.9982	.9982	.9983	.9984	.9984	.9985	.9985	.9986	.9986
3.0	.9987	.9987	.9987	.9988	.9988	.9989	.9989	.9989	.9990	.9990
3.1	.9990	.9991	.9991	.9991	.9992	.9992	.9992	.9992	.9993	.9993
3.2	.9993	.9993	.9994	.9994	.9994	.9994	.9994	.9995	.9995	.9995
3.3	.9995	.9995	.9995	.9996	.9996	.9996	.9996	.9996	.9996	.9997
3.4	.9997	.9997	.9997	.9997	.9997	.9997	.9997	.9997	.9997	.9998

a For negative values of Z_p, subtract the tabular value from unity.

b The following equation may be used to compute the probabilities in lieu of using table values:

$$p \approx 0.5\,\{1 - [1 + (A + BZ_p)^C]^D + [1 + (A - BZ_p)^C]^D\}$$

where

$A = 0.644693$
$B = 0.161984$
$C = 4.874$
$D = -6.158$

This approximation is accurate to within 0.07% of the true probabilities, see Reference 9.10.5.

Table 9.10.6. One-Sided Tolerance-Limit Factors for the Three-Parameter Weibull Acceptability Test with 95 Percent Confidence

Sample Size	V_{99}
10	-4.46
15	-4.77
20	-4.98
25	-5.12
30	-5.23
35	-5.32
40	-5.40
50	-5.51
75	-5.71
100	-5.82
150	-5.97
200	-6.05
300	-6.17
400	-6.23
500	-6.27
750	-6.29
1,000	-6.34
2,000	-6.39
5,000	-6.51
10,000	-6.55
∞	-6.65

Table 9.10.7 One-Sided Tolerance Factors for the Three-Parameter Weibull Distribution with 95 Percent Confidence

	V_{99} for T_{99}			V_{90} for T_{90}		
N	Uncensored	20% Censored	50% Censored	Uncensored	20% Censored	50% Censored
10	12.330	16.508	29.921	6.763	8.466	13.182
11	11.885	15.700	27.134	6.529	8.067	12.004
12	11.520	15.053	25.086	6.337	7.747	11.138
13	11.214	14.522	23.514	6.177	7.485	10.474
14	10.955	14.078	22.266	6.040	7.266	9.946
15	10.730	13.700	21.251	5.922	7.079	9.516
16	10.535	13.374	20.406	5.820	6.918	9.159
17	10.362	13.090	19.692	5.729	6.778	8.857
18	10.208	12.840	19.080	5.649	6.655	8.597
19	10.071	12.617	18.548	5.577	6.545	8.372
20	9.946	12.417	18.082	5.512	6.447	8.174
21	9.834	12.238	17.669	5.453	6.358	8.000
22	9.731	12.074	17.300	5.399	6.278	7.843
23	9.636	11.926	16.969	5.349	6.204	7.703
24	9.549	11.789	16.670	5.304	6.137	7.577
25	9.469	11.664	16.398	5.262	6.075	7.461
26	9.394	11.548	16.150	5.223	6.018	7.356
27	9.325	11.441	15.922	5.187	5.966	7.260
28	9.260	11.341	15.712	5.153	5.916	7.171
29	9.199	11.248	15.518	5.121	5.870	7.088
30	9.142	11.160	15.338	5.091	5.828	7.012
31	9.089	11.078	15.170	5.063	5.787	6.941
32	9.038	11.002	15.014	5.037	5.750	6.875
33	8.990	10.929	14.868	5.012	5.714	6.813
34	8.945	10.861	14.730	4.989	5.680	6.754
35	8.902	10.796	14.601	4.966	5.648	6.700
36	8.862	10.735	14.479	4.945	5.618	6.648
37	8.823	10.676	14.364	4.925	5.590	6.599
38	8.786	10.621	14.256	4.906	5.562	6.553
39	8.751	10.568	14.153	4.887	5.537	6.510
40	8.717	10.518	14.055	4.870	5.512	6.468
41	8.685	10.470	13.962	4.853	5.488	6.429
42	8.654	10.424	13.873	4.837	5.466	6.391
43	8.624	10.380	13.789	4.822	5.444	6.356
44	8.596	10.338	13.708	4.807	5.423	6.321
45	8.569	10.298	13.631	4.793	5.404	6.289
46	8.543	10.259	13.558	4.779	5.385	6.258
47	8.517	10.221	13.487	4.766	5.366	6.228
48	8.493	10.186	13.419	4.753	5.349	6.199

Table 9.10.7. One-Sided Tolerance Factors for the Three-Parameter Weibull Distribution with 95 Percent Confidence (Continued)

N	V_{99} for T_{99}			V_{90} for T_{90}		
	Uncensored	20% Censored	50% Censored	Uncensored	20% Censored	50% Censored
49	8.469	10.151	13.354	4.741	5.332	6.171
50	8.447	10.118	13.292	4.729	5.315	6.145
51	8.425	10.086	13.232	4.718	5.300	6.119
52	8.404	10.055	13.174	4.707	5.284	6.095
53	8.383	10.025	13.118	4.696	5.270	6.071
54	8.364	9.996	13.064	4.686	5.255	6.048
55	8.344	9.968	13.012	4.676	5.242	6.026
56	8.326	9.940	12.962	4.666	5.228	6.005
57	8.308	9.914	12.914	4.657	5.216	5.985
58	8.290	9.889	12.867	4.648	5.203	5.965
59	8.273	9.864	12.822	4.639	5.191	5.946
60	8.257	9.840	12.778	4.631	5.179	5.927
61	8.241	9.817	12.735	4.622	5.168	5.909
62	8.225	9.794	12.694	4.614	5.157	5.892
63	8.210	9.772	12.654	4.606	5.146	5.875
64	8.195	9.751	12.615	4.599	5.135	5.858
65	8.181	9.730	12.577	4.591	5.125	5.842
66	8.167	9.709	12.541	4.584	5.115	5.827
67	8.153	9.690	12.505	4.577	5.106	5.811
68	8.140	9.671	12.470	4.570	5.096	5.797
69	8.127	9.652	12.436	4.563	5.087	5.782
70	8.114	9.634	12.404	4.557	5.078	5.769
71	8.102	9.616	12.372	4.550	5.069	5.755
72	8.090	9.598	12.340	4.544	5.061	5.742
73	8.078	9.581	12.310	4.538	5.053	5.729
74	8.067	9.565	12.280	4.532	5.044	5.716
75	8.055	9.549	12.252	4.526	5.036	5.704
76	8.044	9.533	12.223	4.520	5.029	5.692
77	8.034	9.517	12.196	4.515	5.021	5.681
78	8.023	9.502	12.169	4.509	5.014	5.669
79	8.013	9.487	12.143	4.504	5.006	5.658
80	8.003	9.473	12.117	4.499	4.999	5.647
81	7.993	9.459	12.092	4.494	4.992	5.637
82	7.983	9.445	12.067	4.489	4.986	5.626
83	7.974	9.431	12.043	4.484	4.979	5.616
84	7.964	9.418	12.020	4.479	4.973	5.606
85	7.955	9.405	11.997	4.474	4.966	5.596
86	7.946	9.392	11.975	4.470	4.960	5.587
87	7.938	9.380	11.952	4.465	4.954	5.578
88	7.929	9.367	11.931	4.461	4.948	5.568
89	7.921	9.355	11.910	4.456	4.942	5.559

Table 9.10.7. One-Sided Tolerance Factors for the Three-Parameter Weibull Distribution with 95 Percent Confidence (Continued)

	V_{99} for T_{99}			V_{90} for T_{90}		
N	Uncensored	20% Censored	50% Censored	Uncensored	20% Censored	50% Censored
90	7.912	9.344	11.889	4.452	4.936	5.551
91	7.904	9.332	11.869	4.448	4.930	5.542
92	7.896	9.321	11.849	4.444	4.925	5.534
93	7.888	9.309	11.829	4.440	4.919	5.525
94	7.881	9.298	11.810	4.436	4.914	5.517
95	7.873	9.288	11.791	4.432	4.909	5.509
96	7.866	9.277	11.773	4.428	4.904	5.502
97	7.859	9.267	11.755	4.424	4.899	5.494
98	7.851	9.257	11.737	4.420	4.894	5.486
99	7.844	9.247	11.720	4.417	4.889	5.479
100	7.837	9.237	11.703	4.413	4.884	5.472
102	7.824	9.217	11.669	4.406	4.874	5.458
104	7.811	9.199	11.637	4.399	4.865	5.444
106	7.798	9.181	11.606	4.393	4.857	5.431
108	7.786	9.163	11.576	4.387	4.848	5.418
110	7.774	9.146	11.546	4.380	4.840	5.406
112	7.762	9.130	11.518	4.374	4.832	5.394
114	7.751	9.114	11.491	4.369	4.824	5.382
116	7.740	9.099	11.464	4.363	4.816	5.371
118	7.729	9.084	11.439	4.357	4.809	5.360
120	7.719	9.069	11.414	4.352	4.802	5.349
122	7.709	9.055	11.389	4.347	4.795	5.339
124	7.699	9.041	11.366	4.342	4.788	5.329
126	7.690	9.028	11.343	4.337	4.782	5.319
128	7.680	9.015	11.320	4.332	4.775	5.310
130	7.671	9.002	11.299	4.327	4.769	5.301
132	7.663	8.989	11.278	4.323	4.763	5.292
134	7.654	8.977	11.257	4.318	4.757	5.283
136	7.646	8.965	11.237	4.314	4.751	5.275
138	7.637	8.954	11.217	4.310	4.746	5.266
140	7.629	8.943	11.198	4.306	4.740	5.258
142	7.622	8.932	11.180	4.302	4.735	5.250
144	7.614	8.921	11.161	4.298	4.730	5.243
146	7.606	8.910	11.144	4.294	4.724	5.235
148	7.599	8.900	11.126	4.290	4.719	5.228
150	7.592	8.890	11.109	4.286	4.715	5.221
152	7.585	8.880	11.093	4.283	4.710	5.214
154	7.578	8.871	11.077	4.279	4.705	5.207
156	7.571	8.861	11.061	4.276	4.700	5.200
158	7.565	8.852	11.045	4.272	4.696	5.194
160	7.558	8.843	11.030	4.269	4.692	5.187

Table 9.10.7. One-Sided Tolerance Factors for the Three-Parameter Weibull Distribution with 95 Percent Confidence (Continued)

	V_{99} for T_{99}			V_{90} for T_{90}		
N	Uncensored	20% Censored	50% Censored	Uncensored	20% Censored	50% Censored
162	7.552	8.834	11.015	4.266	4.687	5.181
164	7.546	8.826	11.001	4.263	4.683	5.175
166	7.540	8.817	10.987	4.260	4.679	5.169
168	7.534	8.809	10.973	4.257	4.675	5.163
170	7.528	8.801	10.959	4.254	4.671	5.157
172	7.522	8.793	10.946	4.251	4.667	5.151
174	7.517	8.785	10.932	4.248	4.663	5.146
176	7.511	8.777	10.920	4.245	4.659	5.140
178	7.506	8.770	10.907	4.242	4.656	5.135
180	7.501	8.762	10.894	4.239	4.652	5.130
182	7.495	8.755	10.882	4.237	4.649	5.125
184	7.490	8.748	10.870	4.234	4.645	5.120
186	7.485	8.741	10.859	4.231	4.642	5.115
188	7.480	8.734	10.847	4.229	4.638	5.110
190	7.475	8.727	10.836	4.226	4.635	5.105
192	7.471	8.720	10.825	4.224	4.632	5.100
194	7.466	8.714	10.814	4.221	4.629	5.096
196	7.461	8.707	10.803	4.219	4.625	5.091
198	7.457	8.701	10.793	4.217	4.622	5.087
200	7.452	8.695	10.782	4.214	4.619	5.082
204	7.443	8.683	10.762	4.210	4.613	5.074
208	7.435	8.671	10.742	4.206	4.608	5.066
212	7.427	8.659	10.724	4.201	4.602	5.058
216	7.419	8.648	10.705	4.197	4.597	5.050
220	7.411	8.638	10.687	4.193	4.591	5.042
224	7.404	8.627	10.670	4.189	4.586	5.035
228	7.396	8.617	10.653	4.186	4.581	5.028
232	7.389	8.607	10.637	4.182	4.576	5.021
236	7.382	8.597	10.621	4.178	4.572	5.014
240	7.375	8.588	10.606	4.175	4.567	5.008
244	7.369	8.579	10.591	4.171	4.563	5.002
248	7.363	8.570	10.576	4.168	4.559	4.995
252	7.356	8.562	10.562	4.165	4.554	4.990
256	7.350	8.553	10.548	4.162	4.550	4.984
260	7.344	8.545	10.535	4.159	4.546	4.978
264	7.339	8.537	10.522	4.156	4.542	4.972
268	7.333	8.529	10.509	4.153	4.539	4.967
272	7.327	8.522	10.497	4.150	4.535	4.962
276	7.322	8.514	10.485	4.147	4.531	4.957
280	7.317	8.507	10.473	4.145	4.528	4.952
284	7.312	8.500	10.461	4.142	4.524	4.947

Table 9.10.7. One-Sided Tolerance Factors for the Three-Parameter Weibull Distribution with 95 Percent Confidence (Continued)

	V_{99} for T_{99}			V_{90} for T_{90}		
N	Uncensored	20% Censored	50% Censored	Uncensored	20% Censored	50% Censored
288	7.307	8.493	10.450	4.139	4.521	4.942
292	7.302	8.486	10.439	4.137	4.518	4.937
296	7.297	8.479	10.428	4.134	4.514	4.933
300	7.292	8.473	10.417	4.132	4.511	4.928
310	7.281	8.457	10.392	4.126	4.504	4.917
320	7.270	8.442	10.368	4.121	4.496	4.907
330	7.260	8.428	10.345	4.115	4.489	4.898
340	7.250	8.415	10.323	4.110	4.483	4.888
350	7.241	8.402	10.302	4.106	4.477	4.880
360	7.232	8.390	10.282	4.101	4.471	4.871
370	7.223	8.378	10.263	4.097	4.465	4.863
380	7.215	8.367	10.245	4.092	4.459	4.855
390	7.207	8.356	10.227	4.088	4.454	4.848
400	7.200	8.346	10.211	4.084	4.449	4.841
425	7.182	8.321	10.172	4.075	4.437	4.825
450	7.166	8.299	10.136	4.067	4.427	4.810
475	7.151	8.279	10.104	4.060	4.417	4.796
500	7.138	8.261	10.074	4.053	4.408	4.783
525	7.125	8.244	10.047	4.046	4.400	4.772
550	7.114	8.228	10.021	4.040	4.392	4.761
575	7.103	8.213	9.997	4.035	4.385	4.751
600	7.093	8.199	9.975	4.030	4.378	4.742
625	7.083	8.186	9.955	4.025	4.372	4.733
650	7.074	8.174	9.935	4.020	4.366	4.725
675	7.066	8.162	9.917	4.016	4.360	4.717
700	7.058	8.152	9.900	4.012	4.355	4.710
725	7.050	8.141	9.884	4.008	4.350	4.703
750	7.043	8.132	9.868	4.004	4.345	4.697
775	7.037	8.123	9.854	4.001	4.341	4.690
800	7.030	8.114	9.840	3.998	4.337	4.685
825	7.024	8.106	9.827	3.994	4.332	4.679
850	7.018	8.098	9.814	3.991	4.329	4.674
875	7.013	8.090	9.802	3.989	4.325	4.669
900	7.007	8.083	9.791	3.986	4.321	4.664
925	7.002	8.076	9.780	3.983	4.318	4.659
950	6.997	8.069	9.769	3.981	4.315	4.655
975	6.993	8.063	9.759	3.978	4.312	4.651
1000	6.988	8.057	9.750	3.976	4.309	4.646
1100	6.972	8.034	9.714	3.968	4.298	4.632
1200	6.957	8.015	9.684	3.960	4.288	4.619
1300	6.945	7.998	9.657	3.954	4.280	4.608

Table 9.10.7. One-Sided Tolerance Factors for the Three-Parameter Weibull Distribution with 95 Percent Confidence (Continued)

	V_{99} for T_{99}			V_{90} for T_{90}		
N	Uncensored	20% Censored	50% Censored	Uncensored	20% Censored	50% Censored
1400	6.934	7.983	9.633	3.948	4.273	4.597
1500	6.924	7.969	9.612	3.943	4.266	4.589
1600	6.914	7.957	9.593	3.938	4.260	4.580
1700	6.906	7.946	9.575	3.934	4.255	4.573
1800	6.899	7.936	9.560	3.930	4.250	4.567
1900	6.892	7.926	9.545	3.927	4.246	4.560
2000	6.886	7.918	9.532	3.923	4.241	4.555
3000	6.841	7.858	9.438	3.901	4.212	4.515
4000	6.815	7.822	9.383	3.887	4.195	4.492
5000	6.797	7.798	9.346	3.878	4.183	4.477
6000	6.784	7.781	9.319	3.871	4.175	4.465
7000	6.773	7.767	9.298	3.866	4.168	4.456
8000	6.765	7.756	9.281	3.862	4.163	4.449
9000	6.758	7.747	9.267	3.859	4.159	4.443
10000	6.753	7.739	9.255	3.856	4.155	4.438
15000	6.733	7.713	9.215	3.846	4.142	4.422
20000	6.722	7.698	9.192	3.840	4.135	4.412
25000	6.714	7.688	9.176	3.836	4.130	4.405
30000	6.708	7.680	9.164	3.833	4.126	4.400

The values provided in Table 9.10.7 are calculated by the following formula:

$$d^{-1}\left\{ ck_n \frac{\left(a_{11}+2a_{01}g(p)+a_{00}g(p)^2+c^2(a_{01}^2-a_{00}a_{11})/n\right)^{1/2}}{1-c^2a_{00}/n} + n^{1/2}\left[g(p)-k_n\frac{g(p)+c^2a_{01}/n}{1-c^2a_{00}/n}\right]\right\}$$

where $d=0.7796968$, $c=1.645$, $k_n=(n/(n-1))^{½}$, p is the percentile being estimated (T_{99}: $p=0.01$, T_{90}: $p=0.10$), and $g(p)=0.45 + 0.7797 \ln(-\ln(1-p))$. The constants a_{00}, a_{01}, and a_{11} depend on the level of censoring, and are given below. The statistical methodology employed here is discussed in detail in Reference 9.10.7.

Constant	Uncensored	20% Censored	50% Censored
a_{00}	0.6079	0.9282	1.7162
a_{01}	-0.4740	-0.4562	-0.0428
a_{11}	0.9775	0.9841	1.2169

Table 9.10.8. γ-values for Computing Threshold of Three-Parameter Weibull Distribution

n	Anderson-Darling Test		T_{90}			T_{99}		
	Uncensored or 20% Censored $\gamma_{50,0}$ or $\gamma_{50,20}$	50% Censored $\gamma_{50,50}$	Uncensored $\gamma_{90,0}$	20% Censored $\gamma_{90,20}$	50% Censored $\gamma_{90,50}$	Uncensored $\gamma_{99,0}$	20% Censored $\gamma_{99,20}$	50% Censored $\gamma_{99,50}$
10	0.50000	.	0.79644	0.85391	.	0.85162	0.86596	.
15	0.60692	0.50000	0.75277	0.78329	0.97146	0.81292	0.81934	0.86090
20	0.62147	0.57859	0.73316	0.75477	0.91726	0.79728	0.80072	0.83039
25	0.63033	0.60692	0.72186	0.73795	0.86979	0.78583	0.78741	0.80818
30	0.64057	0.62147	0.71316	0.72479	0.83400	0.77155	0.77185	0.79208
35	0.64379	0.62147	0.70831	0.71771	0.81708	0.76529	0.76477	0.78734
40	0.64630	0.63033	0.70472	0.71247	0.79441	0.76006	0.75893	0.77634
45	0.64997	0.63629	0.70113	0.70736	0.77717	0.75255	0.75101	0.76759
50	0.65135	0.64057	0.69900	0.70434	0.76374	0.74903	0.74714	0.76046
55	0.65252	0.64379	0.69724	0.70187	0.75306	0.74592	0.74376	0.75451
60	0.65440	0.64630	0.69522	0.69914	0.74440	0.74113	0.73882	0.74947
65	0.65516	0.64630	0.69401	0.69748	0.73985	0.73881	0.73632	0.74809
70	0.65583	0.64832	0.69296	0.69605	0.73347	0.73670	0.73406	0.74395
75	0.65697	0.64997	0.69163	0.69433	0.72810	0.73331	0.73062	0.74033
80	0.65745	0.65135	0.69084	0.69327	0.72352	0.73164	0.72885	0.73713
85	0.65789	0.65252	0.69013	0.69233	0.71959	0.73009	0.72721	0.73428
90	0.65865	0.65353	0.68917	0.69113	0.71618	0.72753	0.72464	0.73172
95	0.65898	0.65353	0.68860	0.69040	0.71433	0.72625	0.72330	0.73107
100	0.65929	0.65440	0.68808	0.68973	0.71157	0.72505	0.72206	0.72882
105	0.65983	0.65516	0.68735	0.68884	0.70912	0.72303	0.72004	0.72678
110	0.66007	0.65583	0.68692	0.68829	0.70694	0.72201	0.71899	0.72491
115	0.66030	0.65643	0.68652	0.68779	0.70499	0.72105	0.71799	0.72319
120	0.66071	0.65697	0.68593	0.68709	0.70323	0.71940	0.71636	0.72160
125	0.66090	0.65697	0.68559	0.68667	0.70229	0.71857	0.71551	0.72122
130	0.66107	0.65745	0.68528	0.68628	0.70079	0.71778	0.71469	0.71978
135	0.66139	0.65789	0.68479	0.68571	0.69942	0.71640	0.71334	0.71844
140	0.66154	0.65828	0.68452	0.68537	0.69817	0.71570	0.71263	0.71718
145	0.66167	0.65865	0.68425	0.68506	0.69702	0.71503	0.71195	0.71601
150	0.66193	0.65898	0.68385	0.68459	0.69597	0.71385	0.71080	0.71491
155	0.66205	0.65898	0.68361	0.68431	0.69541	0.71325	0.71019	0.71466
160	0.66216	0.65929	0.68339	0.68404	0.69448	0.71268	0.70961	0.71364
165	0.66237	0.65957	0.68304	0.68365	0.69361	0.71166	0.70862	0.71268
170	0.66247	0.65983	0.68284	0.68341	0.69281	0.71114	0.70810	0.71177
175	0.66256	0.66007	0.68266	0.68319	0.69206	0.71064	0.70760	0.71091
180	0.66273	0.66030	0.68235	0.68285	0.69135	0.70975	0.70673	0.71010
185	0.66282	0.66030	0.68218	0.68265	0.69100	0.70930	0.70628	0.70992
190	0.66289	0.66051	0.68201	0.68245	0.69036	0.70886	0.70584	0.70915
195	0.66304	0.66071	0.68174	0.68215	0.68977	0.70806	0.70507	0.70842
200	0.66311	0.66090	0.68159	0.68198	0.68921	0.70766	0.70467	0.70773
205	0.66318	0.66107	0.68145	0.68181	0.68868	0.70727	0.70428	0.70706
210	0.66331	0.66123	0.68121	0.68155	0.68818	0.70656	0.70360	0.70643
215	0.66337	0.66123	0.68108	0.68140	0.68793	0.70620	0.70324	0.70630
220	0.66342	0.66139	0.68095	0.68125	0.68747	0.70585	0.70289	0.70570
225	0.66353	0.66154	0.68073	0.68101	0.68704	0.70521	0.70228	0.70512
230	0.66358	0.66167	0.68061	0.68088	0.68663	0.70489	0.70196	0.70456

Table 9.10.8. γ-values for Computing Threshold of Three-Parameter Weibull Distribution (continued)

	Anderson-Darling Test		T_{90}			T_{99}		
n	Uncensored or 20% Censored $\gamma_{50,0}$ or $\gamma_{50,20}$	50% Censored $\gamma_{50,50}$	Uncensored $\gamma_{90,0}$	20% Censored $\gamma_{90,20}$	50% Censored $\gamma_{90,50}$	Uncensored $\gamma_{99,0}$	20% Censored $\gamma_{99,20}$	50% Censored $\gamma_{99,50}$
235	0.66364	0.66181	0.68049	0.68075	0.68623	0.70457	0.70165	0.70403
240	0.66373	0.66193	0.68030	0.68053	0.68586	0.70399	0.70109	0.70352
245	0.66378	0.66193	0.68019	0.68041	0.68568	0.70370	0.70080	0.70342
250	0.66382	0.66205	0.68009	0.68029	0.68533	0.70341	0.70052	0.70293
255	0.66391	0.66216	0.67991	0.68010	0.68500	0.70288	0.70002	0.70246
260	0.66395	0.66227	0.67981	0.67999	0.68468	0.70261	0.69975	0.70200
265	0.66399	0.66237	0.67971	0.67989	0.68438	0.70235	0.69949	0.70157
270	0.66406	0.66247	0.67955	0.67971	0.68409	0.70186	0.69903	0.70114
275	0.66410	0.66247	0.67946	0.67961	0.68396	0.70161	0.69879	0.70106
280	0.66413	0.66256	0.67937	0.67951	0.68368	0.70137	0.69855	0.70066
285	0.66420	0.66265	0.67922	0.67935	0.68342	0.70093	0.69813	0.70026
290	0.66423	0.66273	0.67914	0.67926	0.68317	0.70070	0.69790	0.69988
295	0.66426	0.66282	0.67906	0.67917	0.68293	0.70047	0.69768	0.69951
300	0.66433	0.66289	0.67892	0.67902	0.68269	0.70006	0.69729	0.69916
310	0.66438	0.66297	0.67877	0.67886	0.68237	0.69964	0.69688	0.69875
320	0.66446	0.66311	0.67857	0.67864	0.68195	0.69906	0.69633	0.69809
330	0.66454	0.66324	0.67838	0.67844	0.68156	0.69851	0.69580	0.69747
340	0.66459	0.66331	0.67825	0.67830	0.68130	0.69815	0.69545	0.69711
350	0.66466	0.66342	0.67807	0.67811	0.68095	0.69764	0.69497	0.69654
360	0.66472	0.66353	0.67790	0.67794	0.68063	0.69716	0.69451	0.69600
370	0.66476	0.66358	0.67779	0.67781	0.68041	0.69684	0.69420	0.69570
380	0.66482	0.66368	0.67764	0.67765	0.68012	0.69639	0.69378	0.69520
390	0.66487	0.66378	0.67749	0.67749	0.67984	0.69596	0.69337	0.69472
400	0.66490	0.66382	0.67739	0.67739	0.67965	0.69568	0.69310	0.69446
425	0.66501	0.66399	0.67707	0.67706	0.67912	0.69477	0.69224	0.69356
450	0.66511	0.66417	0.67678	0.67675	0.67858	0.69395	0.69146	0.69258
475	0.66519	0.66430	0.67655	0.67651	0.67816	0.69328	0.69083	0.69185
500	0.66526	0.66441	0.67631	0.67626	0.67778	0.69258	0.69017	0.69117
525	0.66534	0.66452	0.67608	0.67602	0.67743	0.69193	0.68955	0.69054
550	0.66539	0.66461	0.67589	0.67583	0.67711	0.69140	0.68906	0.68995
575	0.66545	0.66470	0.67569	0.67562	0.67682	0.69083	0.68852	0.68940
600	0.66550	0.66480	0.67551	0.67543	0.67652	0.69030	0.68802	0.68879
625	0.66554	0.66487	0.67536	0.67528	0.67627	0.68986	0.68762	0.68832
650	0.66559	0.66494	0.67519	0.67511	0.67604	0.68939	0.68718	0.68788
675	0.66563	0.66500	0.67503	0.67495	0.67583	0.68895	0.68676	0.68746
700	0.66567	0.66506	0.67490	0.67481	0.67563	0.68859	0.68642	0.68706
725	0.66570	0.66511	0.67476	0.67467	0.67545	0.68819	0.68605	0.68669
750	0.66574	0.66517	0.67463	0.67454	0.67524	0.68781	0.68570	0.68626
775	0.66576	0.66522	0.67452	0.67442	0.67508	0.68750	0.68541	0.68593
800	0.66579	0.66526	0.67440	0.67430	0.67493	0.68715	0.68509	0.68561
825	0.66582	0.66531	0.67428	0.67418	0.67478	0.68683	0.68479	0.68531
850	0.66584	0.66534	0.67419	0.67409	0.67464	0.68656	0.68454	0.68502
875	0.66587	0.66538	0.67408	0.67398	0.67451	0.68626	0.68426	0.68474
900	0.66589	0.66542	0.67398	0.67387	0.67437	0.68597	0.68400	0.68442
925	0.66591	0.66546	0.67389	0.67379	0.67425	0.68573	0.68377	0.68417
950	0.66593	0.66549	0.67380	0.67369	0.67414	0.68547	0.68353	0.68393

	Anderson-Darling Test		T_{90}			T_{99}		
n	Uncensored or 20% Censored $\gamma_{50,0}$ or $\gamma_{50,20}$	50% Censored $\gamma_{50,50}$	Uncensored $\gamma_{90,0}$	20% Censored $\gamma_{90,20}$	50% Censored $\gamma_{90,50}$	Uncensored $\gamma_{99,0}$	20% Censored $\gamma_{99,20}$	50% Censored $\gamma_{99,50}$
975	0.66595	0.66552	0.67371	0.67360	0.67403	0.68521	0.68330	0.68369
1000	0.66597	0.66554	0.67363	0.67353	0.67393	0.68500	0.68310	0.68347
1100	0.66603	0.66565	0.67332	0.67322	0.67354	0.68414	0.68231	0.68262
1200	0.66609	0.66574	0.67305	0.67295	0.67321	0.68339	0.68162	0.68188
1300	0.66613	0.66581	0.67282	0.67271	0.67294	0.68275	0.68103	0.68126
1400	0.66617	0.66587	0.67261	0.67250	0.67269	0.68216	0.68049	0.68069
1500	0.66620	0.66592	0.67241	0.67231	0.67246	0.68162	0.68000	0.68017
1600	0.66623	0.66597	0.67225	0.67214	0.67227	0.68116	0.67958	0.67973
1700	0.66626	0.66601	0.67209	0.67198	0.67209	0.68072	0.67918	0.67931
1800	0.66628	0.66605	0.67194	0.67184	0.67193	0.68032	0.67882	0.67893
1900	0.66630	0.66608	0.67181	0.67171	0.67179	0.67997	0.67849	0.67859
2000	0.66632	0.66611	0.67168	0.67158	0.67165	0.67963	0.67819	0.67827
3000	0.66643	0.66630	0.67080	0.67071	0.67072	0.67725	0.67604	0.67604
4000	0.66649	0.66639	0.67027	0.67019	0.67017	0.67584	0.67477	0.67474
5000	0.66653	0.66644	0.66990	0.66983	0.66981	0.67487	0.67390	0.67385
6000	0.66655	0.66648	0.66963	0.66956	0.66953	0.67415	0.67326	0.67321
7000	0.66657	0.66651	0.66942	0.66935	0.66933	0.67360	0.67277	0.67271
8000	0.66658	0.66653	0.66924	0.66919	0.66916	0.67315	0.67237	0.67230
9000	0.66659	0.66654	0.66910	0.66905	0.66902	0.67278	0.67204	0.67197
10000	0.66660	0.66656	0.66898	0.66893	0.66890	0.67247	0.67176	0.67169

The values of γ in Table 9.10.8 can be derived as percentiles of the beta distribution as follows. Let k be the greatest integer less than or equal to the minimum of 4n/15 and (1-p)n/3, where n represents the sample size and p represents the proportion of the sample being censored. When determining the γ value for an Anderson-Darling test (when calculating τ_{50}), let θ=0.50. When calculating τ_{90} or τ_{99} let

$$\theta = \frac{\exp(M)}{1 + \exp(M)}$$

where

$$M = \begin{cases} \dfrac{0.425384 - 0.74068p + 8.12668/n}{0.58478 - 0.97165p} & \text{for calculating } \tau_{90} \\[2ex] \dfrac{1.778 + 2.748/\sqrt{n} + p(7.051/\sqrt{n} - 1.253)}{0.959} & \text{for calculating } \tau_{99}. \end{cases}$$

The value of γ in Table 9.10.8 represents the θth percentile of the beta distribution with parameters 2k-2 and k.

Note: The sequential Weibull procedure which makes use of Table 9.10.8 has only been validated for sample sizes between 50 and 1000.

Table 9.10.9. Ranks, r, of Observations, n, for an Unknown Distribution Having the Probability and Confidence of T_{99} and T_{90} Values

T_{99} Value						T_{90} Value					
n	r_{99}	n	r_{99}	n	r_{99}	n	r_{90}	n	r_{90}	n	r_{90}
≤298	a	4635	36	8643	72	≤28	b	638	52	2693	340
299	1	4749	37	8753	73	29	1	660	54	3797	350
473	2	4862	38	8862	74	46	2	682	56	3901	360
628	3	4975	39	8972	75	61	3	704	58	4005	370
773	4	5088	40	9081	76	76	4	726	60	4109	380
913	5	5201	41	9190	77	89	5	781	65	4213	390
1049	6	5314	42	9300	78	103	6	836	70	4317	400
1182	7	5427	43	9409	79	116	7	890	75	4421	410
1312	8	5539	44	9518	80	129	8	945	80	4525	420
1441	9	5651	45	9627	81	142	9	999	85	4629	430
1568	10	5764	46	9736	82	154	10	1053	90	4733	440
1693	11	5876	47	9845	83	167	11	1107	95	4836	450
1818	12	5988	48	9954	84	179	12	1161	100	4940	460
1941	13	6099	49	10063	85	191	13	1269	110	5044	470
2064	14	6211	50	10172	86	203	14	1376	120	5147	480
2185	15	6323	51	10281	87	215	15	1483	130	5251	490
2305	15	6434	52	10390	88	227	16	1590	140	5354	500
2425	16	6545	53	10498	89	239	17	1696	150	5613	525
2546	18	6657	54	10607	90	251	18	1803	160	5871	550
2665	19	6768	55	10716	91	263	19	1909	170	6130	575
2784	20	6879	56	10824	92	275	20	2015	180	6388	600
2902	21	6990	57	10933	93	298	22	2120	190	6645	625
3020	22	7100	58	11041	94	321	24	2226	200	6903	650
3137	23	7211	59	11150	95	345	26	2331	210	7161	675
3254	24	7322	60	11258	96	368	28	2437	220	7418	700
3371	25	7432	61	11366	97	391	30	2542	230	7727	730
3487	26	7543	62	11475	98	413	32	2647	240	8036	760
3603	27	7653	63	11583	99	436	34	2752	250	8344	790
3719	28	7763	64	11691	100	459	36	2857	260	8652	820
3834	29	7874	65			481	38	2962	270	8960	850
3949	30	7984	66			504	40	3066	280	9268	880
4064	31	8094	67			526	42	3171	290	9576	910
4179	32	8204	68			549	44	3276	300	9884	940
4293	33	8314	69			571	46	3380	310	10191	970
4407	34	8423	70			593	48	3484	320	10499	1000
4521	35	8533	71			615	50	3589	330		

[a] T_{99} value is lower than value of lowest observation.
[b] T_{90} value is lower than value of lowest observation.

The following equations may be used to compute ranks in lieu of using table values or for n values greater than these presented in the table:

$$r_{99} = n/100 - 1.645\sqrt{99n/10000} + 0.29 + 19.1/n \text{ , for } n \geq 299$$

rounded to the nearest integer. For n less than 299, the T_{99} value does not exist. This approximation is exact for all but 23 values of n in the range of the table ($299 \leq n \leq 11691$), which is an error rate of about 0.2%. For this small percentage of n values, the approximation gives an r value 1 below the actual r, resulting in a conservative T_{99} value. For T_{90} values, the approximation is

$$r_{90} = n/10 - 1.645\sqrt{9n/100} + 0.23 \ , \ \text{for } n \geq 29$$

rounded to the nearest integer. For n less than 29, the T_{90} value does not exist. The approximation is exact for all but 12 values of n in the range of the table ($29 \leq n \leq 10499$), and errs conservatively by one rank for this small percentage (0.1%).

STANDARDS AND REFERENCES

STANDARDS

AMS 2355	Quality Assurance Sampling and Testing of Aluminum Alloys and Magnesium Alloys, Wrought Products, Except Forging Stock, and Rolled, Forged, or Flash Welded Rings
AMS 2370	Quality Assurance Sampling and Testing, Carbon and Low-Alloy Steel Wrought Products and Forging Stock
AMS 2371	Quality Assurance Sampling and Testing, Corrosion and Heat Resistant Steels and Alloys, Wrought Products and Forging Stock
ASTM B557	Method of Tension Testing Wrought and Cast Aluminum – and Magnesium-Alloy Products (vol. 02.02, 02.03, 03.01)
ASTM B769	Test Method for Shear Testing of Aluminum Alloys (vol. 02.02)
ASTM B831	Standard Test Method for Shear Testing of Thin Aluminum Alloy Products (vol. 02.02)
ASTM C693	Test Method for Density of Glass by Buoyancy (vol. 15.02)
ASTM C714	Test Method for Thermal Diffusivity of Carbon and Graphite by a Thermal Pulse Method (vol. 15.01)
ASTM D2766	Test Method for Specific Heat of Liquids and Solids (vol. 05.02)
ASTM E8	Test Methods of Tension Testing of Metallic Materials (vol. 01.02, 02.01, 02.03, 03.01)
ASTM E9	Compression Testing of Metallic Materials at Room Temperature (vol. 03.01)
ASTM E21	Recommended Practice for Elevated Temperature Tension Tests of Metallic Materials (vol. 03.01)
ASTM E29	Standard Practice for Using Significant Digits in Test Data to Determine Conformance with Specifications (vol. 14.02)
ASTM E83	Method of Verification and Classification of Extensometers (vol. 03.01)
ASTM E111	Test Method for Young’s Modulus, Tangent Modulus, and Chord Modulus (vol. 03.01)
ASTM E132	Test Method for Poisson’s Ratio at Room Temperature (vol. 03.01)
ASTM E139	Recommended Practice for Conducting Creep, Creep-Rupture, and Stress-Rupture Tests of Metallic Materials (vol. 03.01)
ASTM E143	Test Method for Shear Modulus at Room Temperature (vol. 03.01)

ASTM E228	Test Method for Linear Thermal Expansion of Solid Materials with a Vitreous Silica Delatometer (vol. 03.01, 14.02)
ASTM E238	Method for Pin-Type Bearing Test of Metallic Materials (vol. 03.01)
ASTM E399	Test Method for Plane-Strain Fracture Toughness of Metallic Materials (vol. 02.02, 03.01)
ASTM E466	Recommended Practice for Constant Amplitude Axial Fatigue Tests of Metallic Materials (vol. 03.01)
ASTM E561	Recommended Practice for R-Curve Determination (vol. 03.01)
ASTM E606	Recommended Practice for Constant-Amplitude Low-Cycle Fatigue Testing (vol. 03.01)
ASTM E647	Test Method for Measurement of Fatigue Crack Growth Rates (vol. 03.01)
ASTM E739	Practice for Statistical Analysis of Linear or Linearized Stress-Life (S-N) and Strain-Life (ε-N) Fatigue Data (vol. 03.01)
ASTM G34	Test Method for Exfoliation Corrosion Susceptibility in 2XXX and 7XXX Series Aluminum Alloys (EXCO Test) (vol. 03.02)
ASTM G47	Test Method for Determining Susceptibility to Stress-Corrosion Cracking of High-Strength Aluminum Alloy Products (vol. 02.02, 03.02)
NASM 1312-4	Fastener Test Methods- Method 4 Lap Joint Shear
NASM 1312-8	Fastener Test Methods- Method 8 Tensile Strength
NASM 1312-13	Fastener Test Methods- Method 13 Double Shear Test
NASM 1312-20	Fastener Test Methods- Method 20 Single Shear

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CHAPTER 10

NOTES

10.1 INTENDED USE – The intent of this handbook is to provide standardized design values and related design information for metallic materials and structural elements used in aerospace structures. The data contained herein, or from approved items in the minutes of MIL-HDBK-5 coordination meetings, are acceptable to the Air Force, the Navy, the Army, and the Federal Aviation Administration. Approval by the procuring or certificating agency must be obtained for the use of design values for products not contained herein.

10.2 SUBJECT TERM (KEY WORD) LISTING

alloy
aluminum
bearings
brazing
columns
compression
copper
creep
element
failure
fastener
fatigue
fracture
instability
joints
shear
steel
strain
stress
tensile
titanium
torsion
weld

10.3 CHANGES FROM PREVIOUS ISSUE – Marginal notations are not used in this revision to identify changes with respect to the previous issue due to the extent of changes.

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APPENDIX A

A.0 GLOSSARY

A.1 ABBREVIATIONS

a — Amplitude; crack or flaw dimension; measure of flaw size, inches.
a_c — Critical half crack length.
a_o — Initial half crack length.
A — Area of cross section, square inches; ratio of alternating stress to mean stress; subscript “axial”; A basis for mechanical-property values (see Section 1.4.1.1 or Section 9.1.6); “A” ratio, loading amplitude/mean load; or area.
A_ε — Strain “A” ratio, strain amplitude/mean strain.
A_i — Model parameter.
AD — Anderson-Darling test statistic, computed in goodness-of-fit tests for normality or Weibullness.
AISI — American Iron and Steel Institute.
AMS — Aerospace Materials Specification (published by Society of Automotive Engineers, Inc.).
Ann — Annealed.
AN — Air Force-Navy Aeronautical Standard.
ASTM — American Society for Testing and Materials.
b — Width of sections; subscript “bending”.
br — Subscript “bearing”.
B — Biaxial ratio (see Equation 1.3.2.(h)); B-basis for mechanical-property values (see Section 1.4.1.1 or Section 9.1.6).
Btu — British thermal unit(s).
BUS — Individual or typical bearing ultimate strength.
BYS — Individual or typical bearing yield strength.
c — Fixity coefficient for columns; subscript “compression”.
cpm — Cycles per minute.
C — Specific heat; Celsius; Constant.
CEM — Consumable electrode melted.
CRES — Corrosion resistant steel (stainless steel).
C(T) — Compact tension.
CYS — Individual or typical compressive yield strength.
d — Mathematical operator denoting differential.
D or d — Diameter, or Durbin Watson statistic; hole or fastener diameter; dimpled hole.
df — Degrees of freedom.
e — Elongation in percent, a measure of the ductility of a material based on a tension test; unit deformation or strain; subscript “fatigue or endurance”; the minimum distance from a hole, center to the edge of the sheet; Engineering strain.
e_e — Elastic strain.
e_p — Plastic strain.
e/D — Ratio of edge distance (center of the hole to edge of the sheet) to hole diameter (bearing strength).
E — Modulus of elasticity in tension or compression; average ratio of stress to strain for stress below proportional limit.

E_c — Modulus of elasticity in compression; average ratio of stress to strain below proportional limit.
E_s — Secant modulus of elasticity, Eq. 9.8.4.2(c).
E_t — Tangent modulus of elasticity.
ELI — Extra low interstitial (grade of titanium alloy).
ER — Equivalent round.
ESR — Electro-slag remelted.
f — Internal (or calculated) tension stress; stress applied to the gross flawed section; creep stress.
f_b — Internal (or calculated) primary bending stress.
f_c — Internal (or calculated) compressive stress; maximum stress at fracture: gross stress limit (for screening elastic fracture data).
f_{pl} — Proportional limit.
f_s — Internal (or calculated) shear stress.
f_t — Internal (or calculated) tensile stress.
ft — Foot: feet.
F — Design stress; Fahrenheit; Ratio of two sample variances.
F_A — Design axial stress.
F_b — Design bending stress; modulus of rupture in bending.
F_{bru} — Design ultimate bearing stress.
F_{bry} — Design bearing yield stress.
F_c — Design column stress.
F_{cc} — Design crushing or crippling stress (upper limit of column stress for local failure).
F_{cu} — Design ultimate compressive stress.
F_{cy} — Design compressive yield stress at which permanent strain equals 0.002.
F_H — Design hoop stress.
F_s — Design shear stress.
F_{sp} — Design proportional limit in shear.
F_{st} — Design modulus of rupture in torsion.
F_{su} — Design ultimate stress in pure shear (this value represents the average shear stress over the cross section).
F_{sy} — Design shear yield stress.
F_{tp} — Design proportional limit in tension.
F_{tu} — Design tensile ultimate stress.
F_{ty} — Design tensile yield stress at which permanent strain equals 0.002.
g — Gram(s).
G — Modulus of rigidity (shear modulus).
Gpa — Gigapascal(s).
hr — Hour(s).
H — Subscript “hoop”.
HIP — Hot isostatically pressed.
i — Slope (due to bending) of neutral plane of a beam, in radians (1 radian = 57.3 degrees).
in. — Inch(es).
I — Axial moment of inertia.
J — Torsion constant (= Ip for round tubes); Joule.
k — Tolerance limit factor for the normal distribution and the specified probability, confidence, and degrees of freedom; Strain at unit stress.
k_{99}, k_{90} — One-sided tolerance limit factor for T_{99} and T_{90}, respectively (see Section 9.10.1 and 9.10.7).
$k_{A,B}$ — k factor for A basis or B basis, respectively (see Section 9.10.1 and 9.10.7).
ksi — Kips (1,000 pounds) per square inch.

K — A constant, generally empirical; thermal conductivity; stress intensity; Kelvin; correction factor.
K_{app} — Apparent plane stress fracture toughness or residual strength.
K_c — Critical plane stress fracture toughness, a measure of fracture toughness at point of crack growth instability.
K_f — Fatigue notch factor, or fatigue strength reduction factor.
K_{Ic} — Plane strain fracture toughness.
K_N — Empirically calculated fatigue notch factor.
K_t — Theoretical stress concentration factor.
lb — Pound.
ln — Natural (base e) logarithm.
log — Base 10 logarithm.
L — Length; subscript "lateral"; longitudinal (grain direction).
LT — Long transverse (grain direction).
m — Subscript "mean"; metre; slope.
mm — Millimeter(s).
M — Applied moment or couple, usually a bending moment.
Mc — Machine countersunk.
Mg — Megagram(s).
MIG — Metal-inert-gas (welding).
MPa — Megapascal(s).
MS — Military Standard.
M.S. — Margin of safety.
M(T) — Middle tension.
n — Number of individual measurements or pairs of measurements; subscript "normal"; cycles applied to failure; shape parameter for the standard stress-strain curve (Ramberg-Osgood parameter); number of fatigue cycles endured.
N — Fatigue life, number of cycles to failure; Newton; normalized.
N_f — Fatigue life, cycles to failure.
N_i* — Fatigue life, cycles to initiation.
N_t* — Transition fatigue life where plastic and elastic strains are equal.
NAS — National Aerospace Standard.
p — Subscript "polar"; subscript "proportional limit".
psi — Pounds per square inch.
P — Load; applied load (total, not unit, load); exposure parameter; probability.
P_a — Load amplitude.
P_m — Mean load.
P_{max} — Maximum load.
P_{min} — Minimum load.
Pu — Test ultimate load, pounds per fastener.
Py — Test yield load, pounds per fastener.
q — Fatigue notch sensitivity.
Q — Static moment of a cross section.
Q&T — Quenched and tempered.

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* Different from ASTM.

r — Radius; root radius; reduced ratio (regression analysis); ratio of two pair measurements; rank of test point within a sample.
$\bar{r}$ — average ratio of paired measurements.
R — Load (stress) ratio, or residual (observed minus predicted value); stress ratio, ratio of minimum stress to maximum stress in a fatigue cycle; reduced ratio.
R_b — Stress ratio in bending.
R_c — Stress ratio in compression; Rockwell hardness - C scale.
R_ε — Strain ratio, $\varepsilon_{min}/\varepsilon_{max}$.
R_s — Stress ratio in shear or torsion; ratio of applied load to allowable shear load.
R_t — Ratio of applied load to allowable tension load.
RA — Reduction of area.
R.H. — Relative humidity.
RMS — Root-mean-square (surface finish).
RT — Room temperature.
s — Estimated population standard deviation; sample standard deviation; subscript “shear”.
s^2 — Sample variance.
S — Shear force; nominal engineering stress, fatigue; S-basis for mechanical-property values (see Section 1.4.1.1).
S_a — Stress amplitude, fatigue.
S_e — Fatigue limit.
S_{eq}* — Equivalent stress.
S_f — Fatigue limit.
s_m — Mean stress, fatigue.
S_{max} — Highest algebraic value of stress in the stress cycle.
S_{min} — Lowest algebraic value of stress in the stress cycle.
S_r — Algebraic difference between the maximum and minimum stresses in one cycle.
S_y — Root mean square error.
SAE — Society of Automotive Engineers.
SCC — Stress-corrosion cracking.
SEE — Estimate population standard error of estimate.
SR — Studentized residual.
ST — Short transverse (grain direction).
STA — Solution treated and aged.
SUS — Individual or typical shear ultimate strength.
SYS — Individual or typical shear yield strength.
t — Thickness; subscript “tension”; exposure time; elapsed time; tolerance factor for the “t” distribution with the specified probability and appropriate degrees of freedom.
T — Transverse direction; applied torsional moment; transverse (grain direction); subscript “transverse”.
T_F — Exposure temperature.
T_{90} — Statistically based lower tolerance bound for a mechanical property such that at least 90 percent of the population is expected to exceed T_{90} with 95 percent confidence.
T_{99} — Statistically based lower tolerance bound for a mechanical property such that at least 99 percent of the population is expected to exceed T_{99} with 95 percent confidence.
TIG — Tungsten-inert-gas (welding).
TUS — Individual or typical tensile ultimate strength.

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* Different from ASTM.

TUS (S_u)* — Tensile ultimate strength.
TYS — Individual or typical tensile yield strength.
u — Subscript “ultimate”.
U — Factor of utilization.
V_{99},V_{90} — The tolerance limit factor corresponding to T_{99}, T_{90} for the three-parameter Weibull distribution, based on a 95 percent confidence level and a sample of size n.
W — Width of center-through-cracked tension panel; Watt.
$\bar{x}$ — Distance along a coordinate axis.
x — Sample mean based upon n observations.
X — Value of an individual measurement; average value of individual measurements.
y — Deflection (due to bending) of elastic curve of a beam; distance from neutral axis to given fiber; subscript “yield”; distance along a coordinate axis.
Y — Nondimensional factor relating component geometry and flaw size. See Reference 1.4.12.2.1(a) for values.
z — Distance along a coordinate axis.
Z — Section modulus, I/y.

A.2 SYMBOLS

α — (1) Coefficient of thermal expansion, mean; constant. (2) Significance level; probability (risk of erroneously rejecting the null hypothesis (see Section 9.5.3)).
α_{99}, α_{90} — Shape parameter estimates for a T_{99} or T_{90} value based on an assumed three-parameter Weibull distribution.
α_{50} — Shape parameter estimate for the Anderson-Darling goodness-of-fit test based on an assumed three-parameter Weibull distribution.
β — Constant.
β_{99}, β_{90} — Scale parameter estimate for a T_{99} or T_{90} value based on an assumed three-parameter Weibull distribution.
β_{50} — Scale parameter estimate for the Anderson-Darling goodness-of-fit test based on an assumed three-parameter Weibull distribution.
$\Delta\varepsilon$ or ε_r* — strain range, ε_{max} - ε_{min}.
$\Delta\varepsilon_e$ — Elastic strain range.
$\Delta\varepsilon_p$ — Plastic strain range.
ΔS (S_r)* — Stress range.
$\Delta\sigma$ — True or local stress range.
ε — True or local strain.
ε_{eq}* — Equivalent strain.
ε_m — Mean strain, $(\varepsilon_{max} + \varepsilon_{min})/2$.
ε_{max} — Maximum strain.
ε_{min} — Minimum strain.
ε_t — Total (elastic plus plastic) strain at failure determined from tensile stress-strain curve.
δ — Deflection.
Φ — Angular deflection.
ρ — Radius of gyration; Neuber constant (block length).
μ — Poisson’s ratio.
σ — True or local stress; or population standard deviation.

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* Different from ASTM.

σ_x	—	Population standard deviation of x.
σ_x^2	—	Population variance of x.
τ_{99}, τ_{90}	—	Threshold estimates for a T_{99} or T_{90} value based on an assumed three-parameter Weibull distribution.
τ_{50}	—	Threshold estimate for the Anderson-Darling goodness-of-fit test based on an assumed three-parameter Weibull distribution.
ω	—	Density; flank angle.
∞	—	Infinity.
Σ	—	The sum of.
′	—	Superscript that denotes value determined by regression analysis.

A.3 DEFINITIONS

A-Basis.—The lower of either a statistically calculated number, or the specification minimum (S-basis). The statistically calculated number indicates that at least 99 percent of the population of values is expected to equal or exceed the A-basis mechanical design property, with a confidence of 95 percent.

Alternating Load.—See Loading Amplitude.

B-Basis.—At least 90 percent of the population of values is expected to equal or exceed the B-basis mechanical property allowable, with a confidence of 95 percent.

Cast.—Cast consists of the sequential ingots which are melted from a single furnace change and poured in one or more drops without changes in the processing parameters. (The cast number is for internal identification and is not reported.) (See Table 9.2.4.2).

Casting.—One or more parts which are melted from a single furnace change and poured in one or more molds without changes in the processing parameters. (The cast number is for internal identification and is not reported.) (See Table 9.2.4.2).

Confidence.—A specified degree of certainty that at least a given proportion of all future measurements can be expected to equal or exceed the lower tolerance limit. Degree of certainty is referred to as the confidence coefficient. For MIL-HDBK-5, the confidence coefficient is 95 percent which, as related to design properties, means that, in the long run over many future samples, 95 percent of conclusions regarding exceedance of A and B-values would be true.

Confidence Interval.—An interval estimate of a population parameter computed so that the statement "the population parameter lies in this interval" will be true, on the average, in a stated proportion of the times such statements are made.

Confidence Interval Estimate.—Range of values, computed with the sample that is expected to include the population variance or mean.

Confidence Level (or Coefficient).—The stated portion of the time the confidence interval is expected to include the population parameter.

*Confidence Limits**.—The two numeric values that define a confidence interval.

Constant-Amplitude Loading.—A loading in which all of the peak loads are equal and all of the valley loads are equal.

Constant-Life Fatigue Diagram.—A plot (usually on Cartesian coordinates) of a family of curves, each of which is for a single fatigue life, N—relating S, S_{max}, and/or S_{min} to the mean stress, S_m. Generally, the constant life fatigue diagram is derived from a family of S/N curves, each of which represents a different stress ratio (A or R) for a 50 percent probability of survival. NOTE—MIL-HDBK-5 no longer presents fatigue data in the form of constant-life diagrams.

Creep.—The time-dependent deformation of a solid resulting from force.

> Note 1—Creep tests are usually made at constant load and temperature. For tests on metals, initial loading strain, however defined, is not included.
>
> Note 2—This change in strain is sometimes referred to as creep strain.

Creep-Rupture Curve.—Results of material tests under constant load and temperature; usually plotted as strain versus time to rupture. A typical plot of creep-rupture data is shown below. The strain indicated in this curve includes both initial deformation due to loading and plastic strain due to creep.

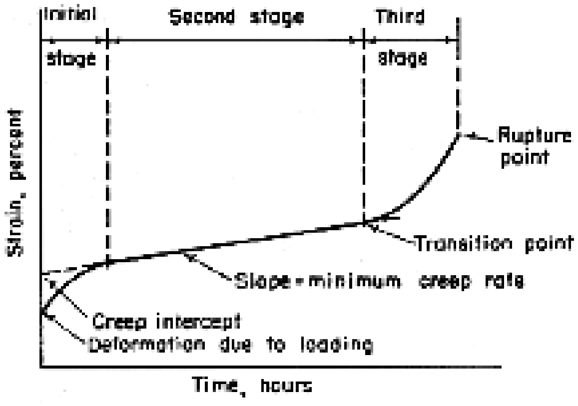

Figure A.1. Typical creep-rupture curve.

Creep-Rupture Strength.—Stress that will cause fracture in a creep test at a given time, in a specified constant environment. Note: This is sometimes referred to as the stress-rupture strength.

Creep-Rupture Test.—A creep-rupture test is one in which progressive specimen deformation and time for rupture are measured. In general, deformation is much larger than that developed during a creep test.

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* Different from ASTM.

Creep-Strain.—The time-dependent part of the strain resulting from stress, excluding initial loading strain and thermal expansion.

Creep Strength.—Stress that causes a given creep in a creep test at a given time in a specified constant environment.

Creep Stress.—The constant load divided by the original cross-sectional area of the specimen.

Creep Test.—A creep test has the objective of measuring deformation and deformation rates at stresses usually well below those which would result in fracture during the time of testing.

Critical Stress Intensity Factor.—A limiting value of the stress intensity factor beyond which continued flaw propagation and/or fracture may be expected. This value is dependent on material and may vary with type of loading and conditions of use.

Cycle.—Under constant-amplitude loading, the load varies from the minimum to the maximum and then to the minimum load. The symbol n or N (see definition of fatigue life) is used to indicate the number of cycles.

Deformable Shank Fasteners.—A fastener whose shank is deformed in the grip area during normal installation processes.

Degree of Freedom.—Number of degrees of freedom for n variables may be defined as number of variables minus number of constraints between them. Since the standard deviation calculation contains one fixed value (the mean) it has n - 1 degrees of freedom.

Degrees of Freedom.—Number of independent comparisons afforded by a sample.

Discontinued Test.—See Runout.

Elapsed Time.—The time interval from application of the creep stress to a specified observation.

Fatigue.—The process of progressive localized permanent structural change occurring in a material subjected to conditions that produce fluctuating stresses and strains at some point or points, and which may culminate in cracks or complete fracture after a sufficient number of fluctuations. NOTE—fluctuations in stress and in time (frequency), as in the case of “random vibration.”

Fatigue Life.—N—the number of cycles of stress or strain of a specified character that a given specimen sustains before failure of a specified nature occurs.

Fatigue Limit.—S_f—the limiting value of the median fatigue strength as N becomes very large. NOTE—-Certain materials and environments preclude the attainment of a fatigue limit. Values tabulated as “fatigue limits” in the literature are frequently (but not always) values of S_N for 50 percent survival at N cycles of stress in which $S_m = 0$.

Fatigue Loading.—Periodic or non-periodic fluctuating loading applied to a test specimen or experienced by a structure in service (also known as cyclic loading).

*Fatigue Notch Factor**.—The fatigue notch factor, K_f (also called fatigue strength reduction factor), is the ratio of the fatigue strength of a specimen with no stress concentration to the fatigue strength of a specimen

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* Different from ASTM.

with a stress concentration at the same number of cycles for the same conditions. NOTE—In specifying K_f, it is necessary to specify the geometry, mode of loading, and the values of S_{max}, S_m, and N for which it is computed.

Fatigue Notch Sensitivity.—The fatigue notch sensitivity, q, is a measure of the degree of agreement between K_f and K_t. NOTE—the definition of fatigue notch sensitivity is $q = (K_f - 1)/(K_t - 1)$.

Heat.—All material identifiable to a single molten metal source. (All material from a heat is considered to have the same composition. A heat may yield one or more ingots. A heat may be divided into several lots by subsequent processing.)

Heat.—Heat is material which, in the case of batch melting, is cast at the same time from the same furnace and is identified with the same heat number; or, in the case of continuous melting, is poured without interruption. (See Table 9.2.4.2)

Heat.—Heat is a consolidated (vacuum hot pressed) billet having a distinct chemical composition. (See Table 9.2.4.2)

Hysteresis Diagram.—The stress-strain path during a fatigue cycle.

Isostrain Lines.—Lines representing constant levels of creep.

Isothermal Lines.—Lines of uniform temperature on a creep or stress-rupture curve.

*Interrupted Test**.—Tests which have been stopped before failure because of some mechanical problem, e.g., power failure, load or temperature spikes.

Loading Amplitude.—The loading amplitude, P_a, S_a, or ε_a represents one-half of the range of a cycle. (Also known as alternating load, alternating stress, or alternating strain.)

Loading Strain.—Loading strain is the change in strain during the time interval from the start of loading to the instant of full-load application, sometimes called initial strain.

Loading (Unloading) Rate.—The time rate of change in the monotonically increasing (decreasing) portion of the load-time function.

Load Ratio.—The load ratio, R, A, or R_ε, A_ε, or R_σ, A_σ, is the algebraic ratio of the two loading parameters of a cycle; the two most widely used ratios are

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* Different from ASTM.

$$R = \frac{\text{minimum load}}{\text{maximum load}} = \frac{P_{min}}{P_{max}}$$

or

$$R_\sigma = \frac{S_{min}}{S_{max}}$$

or

$$R_\varepsilon = \varepsilon_{min}/\varepsilon_{max}$$

and

$$A = \frac{\text{loading amplitude}}{\text{mean load}} = \frac{P_a}{P_m} \text{ or } \frac{S_a}{S_M}$$

$$A_\varepsilon = \frac{\text{strain amplitude}}{\text{mean strain}} = \frac{\varepsilon_a}{\varepsilon_M} \text{ or } (\varepsilon_{max} - \varepsilon_{min})/(\varepsilon_{max} + \varepsilon_{min}) \quad .$$

NOTE—load ratios R or R_ε are generally used in MIL-HDBK-5.

Longitudinal Direction.—Parallel to the principal direction of flow in a worked metal. For die forgings this direction is within ±15° of the predominate grain flow.

Long-Transverse Direction.—The transverse direction having the largest dimension, often called the "width" direction. For die forgings this direction is within ±15° of the longitudinal (predominate) grain direction and parallel, within ±15°, to the parting plane. (Both conditions must be met.)

Lot.—All material from a heat or single molten metal source of the same product type having the same thickness or configuration, and fabricated as a unit under the same conditions. If the material is heat treated, a lot is the above material processed through the required heat-treating operations as a unit.

Master Creep Equation.—An equation expressing combinations of stress, temperature, time and creep, or a set of equations expressing combinations of stress, temperature and time for given levels of creep.

Master Rupture Equation.—An equation expressing combinations of stress, temperature, and time that cause complete separation (fracture or rupture) of the specimen.

Maximum Load.—The maximum load, P_{max}, S_{max}, ε_{max} is the load having the greatest algebraic value.

Mean Load.—The mean load, P_m, is the algebraic average of the maximum and minimum loads in constant-amplitude loading:

$$P_m = \frac{P_{max} + P_{min}}{2}, \text{ or}$$

$$S_m = \frac{S_{max} + S_{min}}{2}, \text{ or}$$

$$\varepsilon_m = \frac{\varepsilon_{max} + \varepsilon_{min}}{2} \quad ,$$

or the integral average of the instantaneous load values.

Median Fatigue Life.—The middlemost of the observed fatigue life values (arranged in order of magnitude) of the individual specimens in a group tested under identical conditions. In the case where an even number of specimens are tested, it is the average of the two middlemost values (based on log lives in MIL-HDBK-5). NOTE 1—The use of the sample median instead of the arithmetic mean (that is, the average) is usually preferred. NOTE 2—In the literature, the abbreviated term "fatigue life" usually has meant the median fatigue life of the group. However, when applied to a collection of data without further qualification, the term "fatigue life" is ambiguous.

Median Fatigue Strength at N Cycles.—An estimate of the stress level at which 50 percent of the population would survive N cycles. NOTE—The estimate of the median fatigue strength is derived from a particular point of the fatigue-life distribution, since there is no test procedure by which a frequency distribution of fatigue strengths at N cycles can be directly observed. That is, one can not perform constant-life tests.

Melt.—Melt is a single homogeneous batch of molten metal for which all processing has been completed and the temperature has been adjusted and made ready to pour castings. (For metal-matrix composites, the molten metal includes unmelted reinforcements such as particles, fibers, or whiskers.) (See Table 9.1.6.2)

Minimum Load.—The minimum load, P_{min}, S_{min}, or ε_{min}, is the load having the least algebraic value.

Nominal Hole Diameters.—Nominal hole diameters for deformable shank fasteners will be according to Table 9.4.1.2(a). When tests are made with hole diameters other than those tabulated, hole sizes used will be noted in the report and on the proposed joint allowables table.

Nominal Shank Diameter.—Nominal shank diameter of fasteners with shank diameters equal to those used for standard size bolts and screws (NAS 618 sizes) will be the decimal equivalents of stated fractional or numbered sizes. These diameters are those listed in the fourth column of Table 9.7.1.1. Nominal shank diameters for nondeformable shank blind fasteners are listed in the fifth column of Table 9.7.1.1. Nominal shank diameters for other fasteners will be the average of required maximum and minimum shank diameters.

Nondeformable Shank Fasteners.—A fastener whose shank does not deform in the grip area during normal installation processes.

*Outlier**—An experimental observation which deviates markedly from other observations in the sample. An outlier is often either an extreme value of the variability in the data, or the result of gross deviation in the material or experimental procedure.

Peak.—The point at which the first derivative of the load-time history changes from a positive to a negative sign; the point of maximum load in constant-amplitude loading.

Plane Strain.—The stress state in which all strains occur only in the principal loading plane. No strains occur out of the plane, i.e., $\varepsilon_z = 0$, and $\sigma_z \neq 0$.

Plane Stress.—The stress state in which all stresses occur only in the principal loading plane. No stresses occur out of the plane, i.e., $\sigma_z = 0$, and $\varepsilon_z \neq 0$.

Plastic Strain During Loading.—Plastic strain during loading is the portion of the strain during loading determined as the offset from the linear portion to the end of a stress-strain curve made during load application.

Plane-Strain Fracture Toughness.—A generic term now generally adopted for the critical plane-strain stress intensity factor characteristic of plane-strain fracture, symbolically denoted K_{Ic}. This is because in current fracture testing practices, specification of the slowly increasing load test of specimen materials in the plane-strain stress state and in opening mode (I) has been dominant.

Plane-Stress and Transitional Fracture Toughness.—A generic term denoting the critical stress intensity factor associated with fracture behavior under nonplane-strain conditions. Because of plasticity effects and stable crack growth which can be encountered prior to fracture under these conditions, designation of a specific value is dependent on the stage of crack growth detected during testing. Residual strength or apparent fracture toughness is a special case of plane-stress and transitional fracture toughness wherein the reference crack length is the initial pre-existing crack length and subsequent crack growth during the test is neglected.

Population.—All potential measurements having certain independent characteristics in common; i.e., “all possible TUS(L) measurements for 17-7PH stainless steel sheet in TH1050 condition”.

Precision.*—The degree of mutual agreement among individual measurements. Relative to a method of test, precision is the degree of mutual agreement among individual measurements made under prescribed like conditions. The lack of precision in a measurement may be characterized as the standard deviation of the errors in measurement.

Primary Creep.—Creep occurring at a diminishing rate, sometimes called initial stage of creep.

Probability.—Ratio of possible number of favorable events to total possible number of equally likely events. For example, if a coin is tossed, the probability of heads is one-half (or 50 percent) because heads can occur one way and the total possible events are two, either heads or tails. Similarly, the probability of

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* Different from ASTM.

throwing a three or greater on a die is 4/6 or 66.7 percent. Probability, as related to design allowables, means that chances of a material-property measurement equaling or exceeding a certain value (the one-sided lower tolerance limit) is 99 percent in the case of a A-basis value and 90 percent in the case of a B-basis value.

Range.—Range, ΔP, S_r, $\Delta\varepsilon$, ε_r, $\Delta\sigma$ is the algebraic difference between successive valley and peak loads (positive range or increasing load range) or between successive peak and valley loads (negative range or decreasing load range), see Figure 9.3.4.3. In constant-amplitude loading, for example, the range is given by $\Delta P = P_{max} - P_{min}$.

Rate of Creep.—The slope of the creep-time curve at a given time determined from a Cartesian plot.

Residual.*—The difference between the observed fatigue (log) life and the fatigue (log) life estimated from the fatigue model at a particular stress/strain level.

Runout.*—A test that has been terminated prior to failure. Runout tests are usually stopped at an arbitrary life value because of time and economic considerations. NOTE—Runout tests are useful for estimating a pseudo-fatigue-limit for a fatigue data sample.

Sample.—A finite number of observations drawn from the population.

Sample.—The number of specimens selected from a population for test purposes. NOTE—The method of selecting the sample determines the population about which statistical inferences or generalization can be made.

Sample Average (Arithmetic Mean).—The sum of all the observed values in a sample divided by the sample size (number). It is a point estimate of the population mean.

Sample Mean.—Average of all observed values in the sample. It is an estimate of population mean. A mean is indicated by a bar over the symbol for the value observed. Thus, the mean of n observations of TUS would be expressed as:

$$\overline{TUS} = \frac{TUS_1 + TUS_2 + \ldots + TUS_n}{n} = \frac{\sum_{i=1}^{n} (TUS_i)}{n}$$

Sample Median.—Value of the middle-most observation. If the sample is nearly normally distributed, the sample median is also an estimate of the population mean.

Sample Median.—The middle value when all observed values in a sample are arranged in order of magnitude if an odd number of samples are tested. If the sample size is even, it is the average of the two middlemost values. It is a point estimate of the population median, or 50 percentile point.

Sample Point Deviation.—The difference between an observed value and the sample mean.

Sample Standard Deviation.**—The standard deviation of the sample, s, is the square root of the sample variance. It is a point estimate of the standard deviation of a population, a measure of the "spread" of the

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* Different from ASTM.

** Different from ASTM.

frequency distribution of a population. NOTE—This value of s provides a statistic that is used in computing interval estimates and several test statistics.

Sample Variance.*—Sample variance, s^2, is the sum of the squares of the differences between each observed value and the sample average divided by the sample size minus one. It is a point estimate of the population variance. NOTE—This value of s^2 provides both an unbiased point estimate of the population variance and a statistic that is used on computing the interval estimates and several test statistics. Some texts define s^2 as "the sum of the squared differences between each observed value and the sample average divided by the sample size", however, this statistic underestimates the population variance, particularly for small sample sizes.

Sample Variance.—The sum of the squared deviations, divided by n - 1, and, based on n observations of TUS, expressed as

$$S_{TUS}^{2} = \frac{\sum_{i=1}^{n}\left(TUS_i - \overline{TUS}\right)^2}{n - 1} = \frac{n\sum_{i=1}^{n}(TUS_i)^2 - \left(\sum_{i=1}^{n} TUS_i\right)^2}{n(n - 1)}$$

S-Basis.—The S-value is the minimum property value specified by the governing industry specification (as issued by standardization groups such as SAE Aerospace Materials Division, ASTM, etc.) or federal or military standards for the material. (See MIL-STD-970 for order of preference for specifications.) For certain products heat treated by the user (for example, steels hardened and tempered to a designated F_{tu}), the S-value may reflect a specified quality-control requirement. Statistical assurance associated with this value is not known.

Secondary Creep.—Creep occurring at a constant rate, sometimes called second stage creep.

Short-Transverse Direction.—The transverse direction having the smallest dimension, often called the "thickness" direction. For die forgings this direction is within ±15° of the longitudinal (predominate) grain direction and perpendicular, within ±15°, to the parting plane. (Both conditions must be met.) When possible, short transverse specimens will be taken across the parting plane.

Significance Level (As Used Here).—Risk of concluding that two samples were drawn from different populations when, in fact, they were drawn from the same population. A significance level of $\alpha = 0.05$ is employed through these Guidelines.*

Significance Level.—The stated probability (risk) that a given test of significance will reject the hypothesis that a specified effect is absent when the hypothesis is true.

Significant (Statistically Significant).—An effect or difference between populations is said to be present if the value of a test statistic is significant, that is, lies outside of predetermined limits. NOTE—An effect that is statistically significant may not have engineering importance.

S/N Curve for 50 Percent Survival.**—A curve fitted to the median values of fatigue life at each of several stress levels. It is an estimate of the relationship between applied stress and the number of cycles-to-failure that 50 percent of the population would survive. NOTE 1—This is a special case of the more general

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* This is appropriate, since a confidence level of $1 - \alpha = 0.95$ is used in establishing A and B-values.

** Different from ASTM.

definition of S/N curve for P percent survival. NOTE 2—In the literature, the abbreviated term "S/N Curve" usually has meant either the S/N curve drawn through the mean (averages) or through the medians (50 percent values) for the fatigue life values. Since the term "S/N Curve" is ambiguous, it should be used only when described appropriately. NOTE 3—Mean S/N curves (based on log lives) are shown in MIL-HDBK-5.

S/N Diagram.—A plot of stress against the number of cycles to failure. The stress can be S_{max}, S_{min}, or S_a. The diagram indicates the S/N relationship for a specified value of S_m, A, or R and a specified probability of survival. Typically, for N, a log scale (base 10) is used. Generally, for S, a linear scale is used, but a log scale is used occasionally. NOTE—S_{max}-versus-log N diagrams are used commonly in MIL-HDBK-5.

Standard Deviation.—An estimate of the population standard deviation; the square root of the variance, or

$$S_{TUS} = \sqrt{\frac{\sum_{i=1}^{n}\left(TUS_i - \overline{TUS}\right)^2}{n - 1}} = \frac{\sqrt{n\sum_{i=1}^{n}\left(TUS_i\right)^2 - \sum_{i=1}^{n}\left(TUS_i\right)^2}}{n(n - 1)}$$

Stress Intensity Factor.—A physical quantity describing the severity of a flaw in the stress field of a loaded structural element. The gross stress in the material and flaw size are characterized parametrically by the stress intensity factor,

$$K = f\sqrt{a}\ Y,\ \text{ksi} - \text{in.}^{1/2}$$

Stress-Rupture Test—A stress-rupture test is one in which time for rupture is measured, no deformation measurement being made during the test.

Tertiary Creep.—Creep occurring at an accelerating rate, sometimes called third stage creep.

Theoretical Stress Concentration Factor (or Stress Concentration Factor).—This factor, K_t, is the ratio of the nominal stress to the greatest stress in the region of a notch (or other stress concentrator) as determined by the theory of elasticity (or by experimental procedures that give equivalent values). NOTE—The theory of plasticity should not be used to determine K_t.

Tolerance Interval.—An interval computed so that it will include at least a stated percentage of the population with a stated probability.

Tolerance Level.—The stated probability that the tolerance interval includes at least the stated percentage of the population. It is not the same as a confidence level, but the term confidence level is frequently associated with tolerance intervals.

Tolerance Limits.—The two statistics that define a tolerance interval. (One value may be "minus infinity" or "plus infinity".)

Total Plastic Strain.—Total plastic strain at a specified time is equal to the sum of plastic strain during loading plus creep.

Total Strain.—Total strain at any given time, including initial loading strain (which may include plastic strain in addition to elastic strain) and creep strain, but not including thermal expansion.

Transition Fatigue Life.*—The point on a strain-life diagram where the elastic and plastic strains are equal.

Transverse Direction.—Perpendicular to the principal direction of flow in a worked metal; may be defined as T, LT or ST.

Typical Basis.—A typical property value is an average value and has no statistical assurance associated with it.

Waveform.—The shape of the peak-to-peak variation of a controlled mechanical test variable (for example, load, strain, displacement) as a function of time.

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* Different from ASTM.

A.4 Conversion of U.S. Units of Measure Used in MIL-HDBK-5 to SI Units

Quantity or Property	To Convert From U. S. Unit	Multiply by[a]	SI Unit[b]
Area	in.^{2}	645.16[c]	Millimeter^2 (mm^2)
Force	lb	4.4482	Newton (N)
Length	in.	25.4[c]	Millimeter (mm)
Stress	ksi	6.895	Megapascal (MPa)[d]
Stress intensity factor	ksi $\sqrt{\text{in.}}$	1.0989	Megapascal $\sqrt{\text{meter}}$ (MPa · m^{½})[d]
Modulus	10^3 ksi	6.895	Gigapascal (GPa)[d]
Temperature	°F	$\frac{F + 459.67}{1.8}$	Kelvin (K)
Density (ω)	lb/in.^{3}	27.680	Megagram/meter^3 (Mg/m^3)
Specific heat (C)	Btu/lb·F (or Btu·lb^{-1}·F^{-1})	4.1868[c]	Joule/(gram·Kelvin) (J/g·K) or (J·g^{-1} ·K^{-1})
Thermal conductivity (K)	Btu/[(hr)(ft^2)(F)/ft] (or Btu·hr^{-1}·ft^{-2}·F^{-1}·ft)	1.7307	Watt/(meter·Kelvin) W/(m·K) or (W·m^{-1}·K^{-1})
Thermal expansion (α)	in./in./F (or in.·in.$^{-1}$·F^{-1})	1.8	Meter/meter/Kelvin m/(m·K) or (m·m^{-1}·K^{-1})

[a] Conversion factors to give significant figures are as specified in ASTM E 380, NASA SP-7012, second revision. NBS Special Publication 330, and *Metals Engineering Quarterly*. Note: Multiple conversions between U.S. and SI units should be avoided because significant round-off errors may result.

[b]

Prefix	Multiple	Prefix	Multiple
giga (G)	10^9	milli (m)	10^{-3}
mega (M)	10^6	micro (μ)	10^{-6}
kilo (k)	10^3		

[c] Conversion factor is exact.

[d] One Pascal (Pa) = one Newton/meter^2.

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APPENDIX B

B.0 Alloy Index

Alloy Name	Form	Specification	Section
250	Bar	AMS 6512	2.5.1
250	Sheet and Plate	AMS 6520	2.5.1
280	Sheet and Plate	AMS 6521	2.5.1
280	Bar	AMS 6514	2.5.1
354.0	Casting	AMS-A-21180	3.9.1
355.0	Permanent Mold Casting	AMS 4281	3.9.2
356.0	Sand Casting	AMS 4217	3.9.4
356.0	Investment Casting	AMS 4260	3.9.4
356.0	Permanent Mold Casting	AMS 4284	3.9.4
359.0	Casting	AMS-A-21180	3.9.8
2014	Bare Sheet and Plate	AMS 4028	3.2.1
2014	Bare Sheet and Plate	AMS 4029	3.2.1
2014	Bar and Rod, Rolled or Cold Finished	AMS 4121	3.2.1
2014	Forging	AMS 4133	3.2.1
2014	Extrusion	AMS 4153	3.2.1
2014	Forging	AMS-A-22771	3.2.1
2014	Extruded Bar, Rod and Shapes	AMS-QQ-A-200/2	3.2.1
2014	Rolled or Drawn Bar, Rod and Shapes	AMS-QQ-A-225/4	3.2.1
2014	Clad Sheet and Plate	AMS-QQ-A-250/3	3.2.1
2014	Forging	AMS-QQ-A-367	3.2.1
2017	Bar and Rod, Rolled or Cold-Finished	AMS 4118	3.2.2
2017	Rolled Bar and Rod	AMS-QQ-A-225/5	3.2.2
2024	Bare Sheet and Plate	AMS 4035	3.2.3
2024	Bare Sheet and Plate	AMS 4037	3.2.3
2024	Tubing, Hydraulic, Seamless, Drawn	AMS 4086	3.2.3
2024	Bar and Rod, Rolled or Cold-Finished	AMS 4120	3.2.3
2024	Extrusion	AMS 4152	3.2.3
2024	Extrusion	AMS 4164	3.2.3
2024	Extrusion	AMS 4165	3.2.3
2024	Extruded Bar, Rod and Shapes	AMS-QQ-A-200/3	3.2.3
2024	Rolled or Drawn Bar, Rod and Wire	AMS-QQ-A-225/6	3.2.3
2024	Bare Sheet and Plate	AMS-QQ-A-250/4	3.2.3
2024	Clad Sheet and Plate	AMS-QQ-A-250/5	3.2.3
2024	Tubing	AMS-WW-T-700/3	3.2.3
2025	Die Forging	AMS 4130	3.2.4
2026	Extruded Bars, Rods, and Profiles	AMS 4338	3.2.5
2090	Sheet	AMS 4251	3.2.6
2124	Plate	AMS 4101	3.2.7
2124	Plate	AMS-QQ-A-250/29	3.2.7
2219	Sheet and Plate	AMS 4031	3.2.8
2219	Hand Forging	AMS 4144	3.2.8
2219	Extrusion	AMS 4162	3.2.8
2219	Extrusion	AMS 4163	3.2.8
2219	Sheet and Plate	AMS-QQ-A-250/30	3.2.8
2297	Plate	AMS 4330	3.2.9

Key: Underline indicates inactive for new design.

Alloy Name	Form	Specification	Section
2424	Sheet (Clad)	AMS 4270	3.2.10
2424	Sheet (Bare)	AMS 4273	3.2.10
2519	Plate	MIL-DTL-46192	3.2.11
2524	Sheet and Plate	AMS 4296	3.2.12
2618	Die and Hand Forgings	AMS 4132	3.2.13
2618	Die Forging	AMS-A-22771	3.2.13
2618	Forging	AMS-QQ-A-367	3.2.13
4130	Bar and Forging	AMS 6348	2.3.1
4130	Sheet, Strip and Plate	AMS 6350	2.3.1
4130	Sheet, Strip and Plate	AMS 6351	2.3.1
4130	Tubing	AMS 6361	2.3.1
4130	Tubing	AMS 6362	2.3.1
4130	Bar and Forging	AMS 6370	2.3.1
4130	Tubing	AMS 6371	2.3.1
4130	Tubing	AMS 6373	2.3.1
4130	Tubing	AMS 6374	2.3.1
4130	Bar and Forging	AMS 6528	2.3.1
4130	Sheet, Strip and Plate	AMS-S-18729	2.3.1
4130	Bar and Forging	AMS-S-6758	2.3.1
4130	Tubing	AMS-T-6736	2.3.1
4135	Sheet, Strip and Plate	AMS 6352	2.3.1
4135	Tubing	AMS 6365	2.3.1
4135	Tubing	AMS 6372	2.3.1
4135	Tubing	AMS-T-6735	2.3.1
4140	Bar and Forging	AMS 6349	2.3.1
4140	Tubing	AMS 6381	2.3.1
4140	Bar and Forging	AMS 6382	2.3.1
4140	Sheet, Strip and Plate	AMS 6395	2.3.1
4140	Bar and Forging	AMS 6529	2.3.1
4140	Bar and Forging	AMS-S-5626	2.3.1
4340	Sheet, Strip and Plate	AMS 6359	2.3.1
4340	Bar and Forging	AMS 6414	2.3.1
4340	Tubing	AMS 6414	2.3.1
4340	Bar and Forging	AMS 6415	2.3.1
4340	Tubing	AMS 6415	2.3.1
4340	Sheet, Strip and Plate	AMS 6454	2.3.1
4340	Bar and Forging	AMS-S-5000	2.3.1
5052	Sheet and Plate	AMS 4015	3.5.1
5052	Sheet and Plate	AMS 4016	3.5.1
5052	Sheet and Plate	AMS 4017	3.5.1
5052	Sheet and Plate	AMS-QQ-A-250/8	3.5.1
5083	Bare Sheet and Plate	AMS 4056	3.5.2
5083	Extruded Bar, Rod and Shapes	AMS-QQ-A-200/4	3.5.2
5083	Bare Sheet and Plate	AMS-QQ-A-250/6	3.5.2
5086	Extruded Bar, Rod and Shapes	AMS-QQ-A-200/5	3.5.3
5086	Sheet and Plate	AMS-QQ-A-250/7	3.5.3
5454	Extruded Bar, Rod and Shapes	AMS-QQ-A-200/6	3.5.4
5454	Sheet and Plate	AMS-QQ-A-250/10	3.5.4
5456	Extruded Bar, Rod and Shapes	AMS-QQ-A-200/7	3.5.5
5456	Sheet and Plate	AMS-QQ-A-250/9	3.5.5
6013	Sheet (T4)	AMS 4347	3.6.1
6013	Sheet (T6)	AMS 4216	3.6.1
6061	Sheet and Plate	AMS 4025	3.6.2
6061	Sheet and Plate	AMS 4026	3.6.2

Key: Underline indicates inactive for new design.

Alloy Name	Form	Specification	Section
6061	Sheet and Plate	AMS 4027	3.6.2
6061	Tubing Seamless, Drawn	AMS 4080	3.6.2
6061	Tubing Seamless, Drawn	AMS 4082	3.6.2
6061	Bar and Rod, Rolled or Cold Finished	AMS 4115	3.6.2
6061	Bar and Rod, Cold Finished	AMS 4116	3.6.2
6061	Bar and Rod, Rolled or Cold Finished	AMS 4117	3.6.2
6061	Forging	AMS 4127	3.6.2
6061	Extrusion	AMS 4160	3.6.2
6061	Extrusion	AMS 4161	3.6.2
6061	Extrusion	AMS 4172	3.6.2
6061	Hand Forging	AMS 4248	3.6.2
6061	Forging	AMS-A-22771	3.6.2
6061	Extruded Rod, Bar Shapes and Tubing	AMS-QQ-A-200/8	3.6.2
6061	Rolled Bar, Rod and Shapes	AMS-QQ-A-225/8	3.6.2
6061	Extruded Rod, Bars and Shapes	AMS 4150	3.6.2
6061	Extruded Rod, Bars and Shapes	AMS 4173	3.6.2
6061	Sheet and Plate	AMS-QQ-A-250/11	3.6.2
6061	Forging	AMS-QQ-A-367	3.6.2
6061	Tubing Seamless, Drawn	AMS-WW-T-700/6	3.6.2
6151	Die Forging	AMS 4125	3.6.3
6151	Forging	AMS-A-22771	3.6.3
7010	Plate	AMS 4204	3.7.1
7010	Plate	AMS 4205	3.7.1
7040	Plate	AMS 4211	3.7.2
7049	Forging	AMS-QQ-A-367	3.7.3
7049	Forging	AMS 4111	3.7.3
7049	Extrusion	AMS 4157	3.7.3
7049	Forging	AMS-A-2271	3.7.3
7049	Plate	AMS 4200	3.7.3
7050	Bare Plate	AMS 4050	3.7.4
7050	Die Forging	AMS 4107	3.7.4
7050	Hand Forging	AMS 4108	3.7.4
7050	Bare Plate	AMS 4201	3.7.4
7050	Die Forging	AMS 4333	3.7.4
7050	Extruded Shape	AMS 4340	3.7.4
7050	Extruded Shape	AMS 4341	3.7.4
7050	Extruded Shape	AMS 4342	3.7.4
7050	Forging	AMS-A-22771	3.7.4
7055	Plate	AMS 4206	3.7.5
7055	Extrusion	AMS 4337	3.7.5
7055	Extrusion	AMS 4324	3.7.5
7055	Extrusion	AMS 4336	3.7.5
7075	Bare Sheet and Plate	AMS 4044	3.7.6
7075	Bare Sheet and Plate	AMS 4045	3.7.6
7075	Clad Sheet and Plate	AMS 4049	3.7.6
7075	Bare Plate	AMS 4078	3.7.6
7075	Bar and Rod, Rolled or Cold Finished	AMS 4122	3.7.6
7075	Bar and Rod, Rolled or Cold Finished	AMS 4123	3.7.6
7075	Bar and Rod, Rolled or Cold Finished	AMS 4124	3.7.6
7075	Forging	AMS 4126	3.7.6
7075	Die Forging	AMS 4141	3.7.6
7075	Forging	AMS 4147	3.7.6
7075	Bar and Rod, Rolled or Cold Finished	AMS 4186	3.7.6
7075	Bar and Rod, Rolled or Cold Finished	AMS 4187	3.7.6

Alloy Name	Form	Specification	Section
7075	Forging	AMS-A-22771	3.7.6
7075	Extruded Bar, Rod and Shapes	AMS-QQ-A-200/11, 15	3.7.6
7075	Rolled or Drawn Bar and Rod	AMS-QQ-A-225/9	3.7.6
7075	Bare Sheet and Plate	AMS-QQ-A-250/12, 24	3.7.6
7075	Clad Sheet and Plate	AMS-QQ-A-250/13, 25	3.7.6
7075	Forging	AMS-QQ-A-367	3.7.6
7149	Forging	AMS 4320	3.7.3
7149	Forging	AMS-A-2271	3.7.3
7149	Extrusion	ASM 4343	3.7.3
7150	Bare Plate	AMS 4252 (T7751)	3.7.7
7150	Bare Plate	AMS 4306 (T6151)	3.7.7
7150	Extrusion	AMS 4307 (T61511)	3.7.7
7150	Extrusion	AMS 4345 (T77511)	3.7.7
7175	Die Forging	AMS 4148 (T66)	3.7.8
7175	Die and Hand Forging	AMS 4149 (T74)	3.7.8
7175	Hand Forging	AMS 4179 (T7452)	3.7.8
7175	Extrusion	AMS 4344 (T73511)	3.7.8
7175	Forging	AMS-A-22771	3.7.8
7249	Hand Forging	AMS 4334	3.7.9
7475	Bare Sheet	AMS 4084 (T61)	3.7.10
7475	Bare Sheet	AMS 4085 (T761)	3.7.10
7475	Bare Plate	AMS 4089 (T7651)	3.7.10
7475	Bare Plate	AMS 4090 (T651)	3.7.10
7475	Clad Sheet	AMS 4100 (T761)	3.7.10
7475	Bare Plate	AMS 4202 (T7351)	3.7.10
7475	Clad Sheet	AMS 4207 (T61)	3.7.10
8630	Bar and Forging	AMS 6280	2.3.1
8630	Tubing	AMS 6281	2.3.1
8630	Sheet, Strip and Plate	AMS-S-18728	2.3.1
8630	Bar and Forging	AMS-S-6050	2.3.1
8630	Sheet, Strip and Plate	AMS 6350	2.3.1
8735	Tubing	AMS 6282	2.3.1
8735	Bar and Forging	AMS 6320	2.3.1
8735	Sheet, Strip and Plate	AMS 6357	2.3.1
8740	Bar and Forging	AMS 6322	2.3.1
8740	Tubing	AMS 6323	2.3.1
8740	Bar and Forging	AMS 6327	2.3.1
8740	Sheet, Strip and Plate	AMS 6358	2.3.1
8740	Bar and Forging	AMS-S-6049	2.3.1
15-5PH	Investment Casting	AMS 5400	2.6.7
15-5PH	Bar, Forging, Ring and Extrusion (CEVM)	AMS 5659	2.6.7
15-5PH	Sheet, Strip and Plate (CEVM)	AMS 5862	2.6.7
17-4PH	Investment Casting (H1100)	AMS 5342	2.6.9
17-4PH	Investment Casting (H1000)	AMS 5343	2.6.9
17-4PH	Investment Casting (H900)	AMS 5344	2.6.9
17-4PH	Sheet, Strip and Plate	AMS 5604	2.6.9
17-4PH	Bar, Forging and Ring	AMS 5643	2.6.9
17-7PH	Plate, Sheet and Strip	AMS 5528	2.6.10
2024-T3 ARAMID Fiber Reinforced	Sheet Laminate	AMS 4254	7.5.1
280 (300)	Bar	AMS 6514	2.5.1
280 (300)	Sheet and Plate	AMS 6521	2.5.1
300M (0.42C)	Bar and Forging	AMS 6257	2.3.1
300M (0.42C)	Tubing	AMS 6257	2.3.1
300M (0.42C)	Bar and Forging	AMS 6419	2.3.1

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Alloy Name	Form	Specification	Section
300M (0.42C)	Tubing	AMS 6419	2.3.1
300M (0.4C)	Bar and Forging	AMS 6417	2.3.1
300M (0.4C)	Tubing	AMS 6417	2.3.1
4130 - N	Tubing	AMS 6360	2.3.1
4330V	Bar and Forging	AMS 6411	2.3.1
4330V	Tubing	AMS 6411	2.3.1
4330V	Bar and Forging	AMS 6427	2.3.1
4330V	Tubing	AMS 6427	2.3.1
4335V	Bar and Forging	AMS 6429	2.3.1
4335V	Tubing	AMS 6429	2.3.1
4335V	Bar and Forging	AMS 6430	2.3.1
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4335V	Sheet, Strip and Plate	AMS 6435	2.3.1
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5Cr-Mo-V	Bar and Forging (CEVM)	AMS 6487	2.4.1
5Cr-Mo-V	Bar and Forging	AMS 6488	2.4.1
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9Ni-4Co-0.20C	Sheet, Strip and Plate	AMS 6523	2.4.2
9Ni-4Co-0.20C	Sheet, Strip and Plate	AMS 6524	2.4.3
9Ni-4Co-0.20C	Bar and Forging, Tubing	AMS 6526	2.4.3
A201.0	Casting (T7 Temper)	AMS-A-21180	3.8.1
A-286	Sheet, Strip and Plate	AMS 5525	6.2.1
A-286	Bar, Forging, Tubing and Ring	AMS 5731	6.2.1
A-286	Bar, Forging, Tubing and Ring	AMS 5732	6.2.1
A-286	Bar, Forging and Tubing	AMS 5734	6.2.1
A-286	Bar, Forging and Tubing	AMS 5737	6.2.1
A356.0	Casting	AMS 4218	3.9.5
A356.0	Casting	AMS-A-21180	3.9.5
A357.0	Casting	AMS-A-21180	3.9.6
AerMet 100	Bar and Forging	AMS 6478	2.5.3
AerMet 100	Bar and Forging	AMS 6532	2.5.3
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AISI 1025	Bar	ASTM A 108	2.2.1
AISI 1025	Sheet and Strip	AMS-S-7952	2.2.1
AISI 1025	Tubing	AMS 5077	2.2.1
AISI 1025 - N	Seamless Tubing	AMS 5075	2.2.1
AISI 1025 - N	Tubing	AMS 5077	2.2.1
AISI 1025 - N	Tubing	AMS-T-5066	2.2.1
AISI 301	Sheet and Strip	AMS 5517	2.7.1
AISI 301	Sheet and Strip	AMS 5518	2.7.1
AISI 301	Sheet and Strip	AMS 5519	2.7.1
AISI 301	Sheet, Strip and Plate	AMS 5901	2.7.1
AISI 301	Sheet and Strip (175 ksi)	AMS 5902	2.7.1
AISI 302	Sheet, Strip and Plate	AMS 5516	2.7.1
AISI 302	Sheet and Strip (125 ksi)	AMS 5903	2.7.1
AISI 302	Sheet and Strip (150 ksi)	AMS 5904	2.7.1
AISI 302	Sheet and Strip (175 ksi)	AMS 5905	2.7.1
AISI 302	Sheet and Strip (185 ksi)	AMS 5906	2.7.1
AISI 304	Sheet and Strip	AMS 5913	2.7.1
AISI 304	Sheet, Strip and Plate (125 ksi)	AMS 5910	2.7.1
AISI 304	Sheet and Strip (150 ksi)	AMS 5911	2.7.1
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AISI 304	Sheet and Strip (185 ksi)	AMS 5913	2.7.1
AISI 316	Sheet and Strip	AMS 5524	2.7.1
AISI 316	Sheet, Strip and Plate (125 ksi)	AMS 5907	2.7.1
AM100A	Investment Casting	AMS 4455	4.3.1
AM100A	Permanent Mold Casting	AMS 4483	4.3.1
AM-350	Sheet and Strip	AMS 5548	2.6.1
AM-355	Sheet and Strip	AMS 5547	2.6.2
AM-355	Plate	AMS 5549	2.6.2
AM-355	Bar, Forging and Forging Stock	AMS 5743	2.6.2
AZ31B	Sheet and Plate	AMS 4375	4.2.1
AZ31B	Plate	AMS 4376	4.2.1
AZ31B	Sheet and Plate	AMS 4377	4.2.1
AZ31B	Forging	ASTM B 91	4.2.1
AZ31B	Extrusion	ASTM B 107	4.2.1
AZ61A	Extrusion	AMS 4350	4.2.2
AZ61A	Forging	ASTM B 91	4.2.2
AZ91C/AZ91E	Sand Casting	AMS 4437	4.3.2
AZ91C/AZ91E	Sand Casting	AMS 4446	4.3.2
AZ91C/AZ91E	Investment Casting	AMS 4452	4.3.2
AZ92A	Sand Casting	AMS 4434	4.3.3
AZ92A	Permanent Mold Casting	AMS 4484	4.3.3
AZ92A	Investment Casting	AMS 4453	4.3.3
C355.0	Casting	AMS-A-21180	3.9.3
Copper Beryllium	Strip (TB00)	AMS 4530	7.3.2
Copper Beryllium	Strip (TD02)	AMS 4532	7.3.2
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Copper Beryllium	Bar and Rod (TH04)	AMS 4534	7.3.2
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Copper Beryllium	Bar, Rod, Shapes and Forging (TB00)	AMS 4650	7.3.2
Copper Beryllium	Bar and Rod (TD04)	AMS 4651	7.3.2
Copper Beryllium	Sheet (TB00, TD01, TD02, TD04)	ASTM B 194	7.3.2
CP Titanium	Sheet, Strip and Plate	AMS 4900	5.2.1
CP Titanium	Sheet, Strip and Plate	AMS 4901	5.2.1
CP Titanium	Sheet, Strip and Plate	AMS 4902	5.2.1
CP Titanium	Bar	AMS 4921	5.2.1
CP Titanium	Extruded Bars and Shapes	AMS-T-81556	5.2.1
CP Titanium	Sheet, Strip and Plate	AMS-T-9046	5.2.1
CP Titanium	Bar	MIL-T-9047	5.2.1
Custom 450	Bar, Forging, Tubing, Wire and Ring (air melted)	AMS 5763	2.6.3
Custom 450	Bar, Forging, Tubing, Wire and Ring (CEM)	AMS 5773	2.6.3
Custom 455	Tubing (welded)	AMS 5578	2.6.4
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D6AC	Tubing	AMS 6431	2.3.1
D6AC	Bar and Forging	AMS 6439	2.3.1
D6AC	Sheet, Strip and Plate	AMS 6439	2.3.1
EZ33A	Sand Casting	AMS 4442	4.3.4
Hastelloy X	Sheet and Plate	AMS 5536	6.3.1
Hastelloy X	Bar and Forging	AMS 5754	6.3.1
Haynes®230®	Plate, Sheet, and Strip	AMS 5878	6.3.9
Haynes®230®	Bar and Forging	AMS 5891	6.3.9
Haynes HR 120	Sheet, Strip and Plate	AMS 5916	6.3.10

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HS 188	Sheet and Plate	AMS 5608	6.4.2
HS 188	Bar and Forging	AMS 5772	6.4.2
Hy-Tuf	Bar and Forging	AMS 6425	2.3.1
Hy-Tuf	Tubing	AMS 6425	2.3.1
Inconel 718	Investment Casting	AMS 5383	6.3.5
Inconel 718	Tubing; Creep Rupture	AMS 5589	6.3.5
Inconel 718	Tubing; Short-Time	AMS 5590	6.3.5
Inconel 718	Sheet, Strip and Plate; Creep Rupture	AMS 5596	6.3.5
Inconel 718	Sheet, Strip and Plate; Short-Time	AMS 5597	6.3.5
Inconel 718	Bar and Forging; Creep Rupture	AMS 5662	6.3.5
Inconel 718	Bar and Forging; Creep Rupture	AMS 5663	6.3.5
Inconel 718	Bar and Forging; Short-Time	AMS 5664	6.3.5
Inconel Alloy 600	Plate, Sheet and Strip	AMS 5540	6.3.2
Inconel Alloy 600	Tubing, Seamless	AMS 5580	6.3.2
Inconel Alloy 600	Bar and Rod	ASTM B 166	6.3.2
Inconel Alloy 600	Forging	ASTM B 564	6.3.2
Inconel Alloy 625	Sheet, Strip and Plate	AMS 5599	6.3.3
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Inconel Alloy 706	Sheet, Strip and Plate	AMS 5605	6.3.4
Inconel Alloy 706	Sheet, Strip and Plate	AMS 5606	6.3.4
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Inconel Alloy 706	Bar, Forging and Ring	AMS 5702	6.3.4
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Inconel Alloy X-750	Bar and Forging; Equalized	AMS 5667	6.3.6
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L-605	Bar and Forging	AMS 5759	6.4.1
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Manganese Bronzes	Casting	AMS 4862	7.3.1
MP159 Alloy	Bar (solution treated and cold drawn)	AMS 5842	7.4.2
MP159 Alloy	Bar (solution treated, cold drawn and aged)	AMS 5843	7.4.2
MP35N Alloy	Bar (solution treated and cold drawn)	AMS 5844	7.4.1
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N-155	Bar and Forging	AMS 5769	6.2.2
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Ti-13V-11Cr-3Al	Sheet, Strip and Plate	AMS-T-9046	5.5.1
Ti-13V-11Cr-3Al	Bar	MIL-T-9047	5.5.1
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Alloy Name	Form	Specification	Section
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Ti-5Al-2.5Sn	Extruded Bar and Shapes	AMS-T-81556	5.3.1
Ti-5Al-2.5Sn	Sheet, Strip and Plate	AMS-T-9046	5.3.1
Ti-5Al-2.5Sn	Bar	MIL-T-9047	5.3.1
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Ti-6Al-2Sn-4Zr-2Mo	Bar	AMS 4975	5.3.3
Ti-6Al-2Sn-4Zr-2Mo	Forging	AMS 4976	5.3.3
Ti-6Al-2Sn-4Zr-2Mo	Sheet and Strip	AMS-T-9046	5.3.3
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Ti-6Al-4V	Extrusion	AMS 4935	5.4.1
Ti-6Al-4V	Casting	AMS 4962	5.4.1
Ti-6Al-4V	Bar	AMS 4967	5.4.1
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Ti-6Al-4V	Bar	AMS 4965	5.4.1
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Ti6Al-6V-2Sn	Bar and Forging	AMS 4971	5.4.2
Ti6Al-6V-2Sn	Bar and Forging	AMS 4978	5.4.2
Ti6Al-6V-2Sn	Bar and Forging	AMS 4979	5.4.2
Ti6Al-6V-2Sn	Extruded Bar and Shapes	AMS-T-81556	5.4.2
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Ti-8Al-1Mo-1V	Forging	AMS 4973	5.3.2
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APPENDIX C

C.0 Specification Index

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Specification	Alloy Name	Form/Application	Section
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AMS 4252 (T7751)	7150	Bare Plate	3.7.7
AMS 4254	2024-T3 ARAMID Fiber Reinforced	Sheet Laminate	7.5.1
AMS 4260	356.0	Investment Casting	3.9.4
AMS 4270	2424 (Clad)	Sheet	3.2.10
AMS 4273	2424 (Bare)	Sheet	3.2.10
AMS 4281	355.0	Permanent Mold Casting	3.9.2
AMS 4284	356.0	Permanent Mold Casting	3.9.4
AMS 4296	2524-T3	Sheet and Plate	3.2.12
AMS 4302	7475-T761 ARAMID Fiber Reinforced	Sheet Laminate	7.5.2
AMS 4306 (T6151)	7150	Bare Plate	3.7.7
AMS 4307 (T61511)	7150	Extrusion	3.7.7
AMS 4320	7149	Forging	3.7.3
AMS 4324	7055	Extrusion	3.7.5
AMS 4330	2297	Plate	3.2.9
AMS 4333	7050	Die Forging	3.7.4
AMS 4334	7249	Hand Forging	3.7.9
AMS 4336	7055	Extrusion	3.7.5
AMS 4337	7055	Extrusion	3.7.5
AMS 4338	2026	Bars, Rods, and Profiles	3.2.5
AMS 4340	7050	Extruded Shape	3.7.4
AMS 4341	7050	Extruded Shape	3.7.4
AMS 4342	7050	Extruded Shape	3.7.4

Key: Underline indicates inactive for new design.

Specification	Alloy Name	Form/Application	Section
AMS 4343	7149	Extrusion	3.7.3
AMS 4344 (T73511)	7175	Extrusion	3.7.8
AMS 4345 (T77511)	7150	Extrusion	3.7.7
AMS 4347	6013 (T6)	Sheet	3.6.1
AMS 4350	AZ61A	Extrusion	4.2.2
AMS 4352	ZK60A-T5	Extrusion	4.2.3
AMS 4362	ZK60A-T5	Die and Hand Forging	4.2.3
AMS 4375	AZ31B	Sheet and Plate	4.2.1
AMS 4376	AZ31B	Plate	4.2.1
AMS 4377	AZ31B	Sheet and Plate	4.2.1
AMS 4418	QE22A Magnesium	Sand Casting	4.3.5
AMS 4434	AZ92A	Sand Casting	4.3.3
AMS 4437	AZ91C/AZ91E	Sand Casting	4.3.2
AMS 4439	ZE41A Magnesium	Sand Casting	4.3.6
AMS 4442	EZ33A	Sand Casting	4.3.4
AMS 4446	AZ91C/AZ91E	Sand Casting	4.3.2
AMS 4452	AZ91C/AZ91E	Investment Casting	4.3.2
AMS 4453	AZ92A	Investment Casting	4.3.3
AMS 4455	AM100A	Investment Casting	4.3.1
AMS 4483	AM100A	Permanent Mold Casting	4.3.1
AMS 4484	AZ92A	Permanent Mold Casting	4.3.3
AMS 4530	Copper Beryllium	Strip (TB00)	7.3.2
AMS 4532	Copper Beryllium	Strip (TD02)	7.3.2
AMS 4533	Copper Beryllium	Bar and Rod (TF00)	7.3.2
AMS 4534	Copper Beryllium	Bar and Rod (TH04)	7.3.2
AMS 4535	Copper Beryllium	Mechanical tubing (TF00)	7.3.2
AMS 4650	Copper Beryllium	Bar, Rod, Shapes and Forging (TB00)	7.3.2
AMS 4651	Copper Beryllium	Bar and Rod (TD04)	7.3.2
AMS 4860	Manganese Bronzes	Casting	7.3.1
AMS 4862	Manganese Bronzes	Casting	7.3.1
AMS 4899	Ti-4.5Al-3V-2Fe-2Mo	Sheet	5.4.3
AMS 4900	CP Titanium	Sheet, Strip and Plate	5.2.1
AMS 4901	CP Titanium	Sheet, Strip and Plate	5.2.1
AMS 4902	CP Titanium	Sheet, Strip and Plate	5.2.1
AMS 4910	Ti-5Al-2.5Sn	Sheet, Strip and Plate	5.3.1
AMS 4911	Ti-6Al-4V	Sheet, Strip and Plate	5.4.1
AMS 4914	Ti-15V-3Cr-3Sn-3Al (Ti-15-3)-3-3	Sheet and Strip	5.5.2
AMS 4915	Ti-8Al-1Mo-1V	Sheet, Strip and Plate	5.3.2
AMS 4916	Ti-8Al-1Mo-1V	Sheet, Strip and Plate	5.3.2
AMS 4918	Ti6Al-6V-2Sn	Sheet, Strip and Plate	5.4.2
AMS 4919	Ti-6Al-2Sn-4Zr-2Mo	Sheet, Strip and Plate	5.3.3
AMS 4920	Ti-6Al-4V	Die Forging	5.4.1
AMS 4921	CP Titanium	Bar	5.2.1
AMS 4926	Ti-5Al-2.5Sn	Bar	5.3.1
AMS 4928	Ti-6Al-4V	Bar and Die Forging	5.4.1
AMS 4934	Ti-6Al-4V	Extrusion	5.4.1
AMS 4935	Ti-6Al-4V	Extrusion	5.4.1
AMS 4962	Ti-6Al-4V	Casting	5.4.1
AMS 4964	Ti-4.5Al-3V-2Fe-2Mo	Bars, Wires, Forgings and Rings	5.4.3
AMS 4965	Tii-6Al-4V	Bar	5.4.1
AMS 4966	Ti-5Al-2.5Sn	Forging	5.3.1
AMS 4967	Ti-6Al-4V	Bar	5.4.1
AMS 4971	Ti6Al-6V-2Sn	Bar and Forging	5.4.2
AMS 4973	Ti-8Al-1Mo-1V	Forging	5.3.2
AMS 4975	Ti-6Al-2Sn-4Zr-2Mo	Bar	5.3.3
AMS 4976	Ti-6Al-2Sn-4Zr-2Mo	Forging	5.3.3

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Specification	Alloy Name	Form/Application	Section
AMS 4978	Ti6Al-6V-2Sn	Bar and Forging	5.4.2
AMS 4979	Ti6Al-6V-2Sn	Bar and Forging	5.4.2
AMS 4983	Ti-10V-2Fe-3Al (Ti-10-2-3)	Forging	5.5.3
AMS 4984	Ti-10V-2Fe-3Al (Ti-10-2-3)	Forging	5.5.3
AMS 4986	Ti-10V-2Fe-3Al (Ti-10-2-3)	Forging	5.5.3
AMS 5046	AISI 1025	Sheet, Strip, and Plate	2.2.1
AMS 5075	AISI 1025 - N	Seamless Tubing	2.2.1
AMS 5077	AISI 1025 - N	Tubing	2.2.1
AMS 5342	17-4PH	Investment Casting (H1100)	2.6.9
AMS 5343	17-4PH	Investment Casting (H1000)	2.6.9
AMS 5344	17-4PH	Investment Casting (H900)	2.6.9
AMS 5383	Inconel 718	Investment Casting	6.3.5
AMS 5400	15-5PH	Investment Casting	2.6.7
AMS 5513	AISI 301	Sheet, Strip and Plate	2.7.1
AMS 5516	AISI 302	Sheet, Strip and Plate	2.7.1
AMS 5517	AISI 301	Sheet and Strip (125 ksi)	2.7.1
AMS 5518	AISI 301	Sheet and Strip (150 ksi)	2.7.1
AMS 5519	AISI 301	Sheet and Strip (185 ksi)	2.7.1
AMS 5520	PH15-7Mo	Plate, Sheet and Strip	2.6.8
AMS 5524	AISI 316	Sheet, Strip and Plate	2.7.1
AMS 5525	A-286	Sheet, Strip and Plate	6.2.1
AMS 5528	17-7PH	Plate, Sheet and Strip	2.6.10
AMS 5532	N-155	Sheet	6.2.2
AMS 5536	Hastelloy X	Sheet and Plate	6.3.1
AMS 5537	L-605	Sheet	6.4.1
AMS 5540	Inconel Alloy 600	Plate, Sheet and Strip	6.3.2
AMS 5542	Inconel Alloy X-750	Sheet, Strip and Plate; Annealed	6.3.6
AMS 5544	Waspaloy	Plate, Sheet and Strip	6.3.8
AMS 5545	René 41	Plate, Sheet and Strip	6.3.7
AMS 5547	AM-355	Sheet and Strip	2.6.2
AMS 5548	AM-350	Sheet and Strip	2.6.1
AMS 5549	AM-355	Plate	2.6.2
AMS 5578	Custom 455	Tubing (welded)	2.6.4
AMS 5580	Inconel Alloy 600	Tubing, Seamless	6.3.2
AMS 5585	N-155	Tubing (welded)	6.2.2
AMS 5589	Inconel 718	Tubing; Creep Rupture	6.3.5
AMS 5590	Inconel 718	Tubing; Short-Time	6.3.5
AMS 5596	Inconel 718	Sheet, Strip and Plate; Creep Rupture	6.3.5
AMS 5597	Inconel 718	Sheet, Strip and Plate; Short-Time	6.3.5
AMS 5599	Inconel Alloy 625	Sheet, Strip and Plate	6.3.3
AMS 5604	17-4PH	Sheet, Strip and Plate	2.6.9
AMS 5605	Inconel Alloy 706	Sheet, Strip and Plate	6.3.4
AMS 5606	Inconel Alloy 706	Sheet, Strip and Plate	6.3.4
AMS 5608	HS 188	Sheet and Plate	6.4.2
AMS 5617	Custom 455	Bar and Forging	2.6.4
AMS 5629	PH13-8Mo	Bar, Forging Ring and Extrusion (VIM+CEVM)	2.6.6
AMS 5643	17-4PH	Bar, Forging and Ring	2.6.9
AMS 5659	15-5PH	Bar, Forging, Ring and Extrusion (CEVM)	2.6.7
AMS 5662	Inconel 718	Bar and Forging; Creep Rupture	6.3.5
AMS 5663	Inconel 718	Bar and Forging; Creep Rupture	6.3.5
AMS 5664	Inconel 718	Bar and Forging; Short-Time	6.3.5
AMS 5666	Inconel Alloy 625	Bar, Forging and Ring	6.3.3
AMS 5667	Inconel Alloy X-750	Bar and Forging; Equalized	6.3.6
AMS 5701	Inconel Alloy 706	Bar, Forging and Ring	6.3.4
AMS 5702	Inconel Alloy 706	Bar, Forging and Ring	6.3.4
AMS 5703	Inconel Alloy 706	Bar, Forging and Ring	6.3.4

Key: Underline indicates inactive for new design.

Specification	Alloy Name	Form/Application	Section
AMS 5704	Waspaloy	Forging	6.3.8
AMS 5706	Waspaloy	Bar, Forgings and Ring	6.3.8
AMS 5707	Waspaloy	Bar, Forgings and Ring	6.3.8
AMS 5708	Waspaloy	Bar, Forgings and Ring	6.3.8
AMS 5709	Waspaloy	Bar, Forgings and Ring	6.3.8
AMS 5712	René 41 - STA	Bar and Forging	6.3.7
AMS 5713	René 41	Bar and Forging	6.3.7
AMS 5731	A-286	Bar, Forging, Tubing and Ring	6.2.1
AMS 5732	A-286	Bar, Forging, Tubing and Ring	6.2.1
AMS 5734	A-286	Bar, Forging and Tubing	6.2.1
AMS 5737	A-286	Bar, Forging and Tubing	6.2.1
AMS 5743	AM-355	Bar, Forging and Forging Stock	2.6.2
AMS 5754	Hastelloy X	Bar and Forging	6.3.1
AMS 5759	L-605	Bar and Forging	6.4.1
AMS 5763	Custom 450	Bar, Forging, Tubing, Wire and Ring (air melted)	2.6.3
AMS 5768	N-155	Bar and Forging	6.2.2
AMS 5769	N-155	Bar and Forging	6.2.2
AMS 5772	HS 188	Bar and Forging	6.4.2
AMS 5773	Custom 450	Bar, Forging, Tubing, Wire and Ring (CEM)	2.6.3
AMS 5842	MP159 Alloy	Bar (solution treated and cold drawn)	7.4.2
AMS 5843	MP159 Alloy	Bar (solution treated, cold drawn and aged)	7.4.2
AMS 5844	MP35N Alloy	Bar (solution treated and cold drawn)	7.4.1
AMS 5845	MP35N Alloy	Bar (solution treated, cold drawn and aged)	7.4.1
AMS 5862	15-5PH	Sheet, Strip and Plate (CEVM)	2.6.7
AMS 5878	Haynes®230®	Plate, Sheet and Strip	6.3.9
AMS 5891	Haynes®230®	Bar and Forging	6.3.9
AMS 5901	AISI 301	Plate, Sheet and Strip	2.7.1
AMS 5902	AISI 301	Sheet and Strip (175 ksi)	2.7.1
AMS 5903	AISI 302	Sheet and Strip (125 ksi)	2.7.1
AMS 5904	AISI 302	Sheet and Strip (150 ksi)	2.7.1
AMS 5905	AISI 302	Sheet and Strip (175 ksi)	2.7.1
AMS 5906	AISI 302	Sheet and Strip (185 ksi)	2.7.1
AMS 5907	AISI 316	Sheet, Strip and Plate (125 ksi)	2.7.1
AMS 5910	AISI 304	Sheet, Strip and Plate (125 ksi)	2.7.1
AMS 5911	AISI 304	Sheet and Strip (150 ksi)	2.7.1
AMS 5912	AISI 304	Sheet and Strip (175 ksi)	2.7.1
AMS 5913	AISI 304	Sheet and Strip (185 ksi)	2.7.1
AMS 5916	Haynes HR-120	Sheet, Strip and Plate	6.3.10
AMS 5936	Cutsom 465	Bar, Wires and Forgings	2.6.5
AMS 6257	300M (0.42C)	Bar and Forging	2.3.1
AMS 6257	300M (0.42C)	Tubing	2.3.1
AMS 6280	8630	Bar and Forging	2.3.1
AMS 6281	8630	Tubing	2.3.1
AMS 6282	8735	Tubing	2.3.1
AMS 6320	8735	Bar and Forging	2.3.1
AMS 6322	8740	Bar and Forging	2.3.1
AMS 6323	8740	Tubing	2.3.1
AMS 6327	8740	Bar and Forging	2.3.1
AMS 6348	4130	Bar and Forging	2.3.1
AMS 6349	4140	Bar and Forging	2.3.1
AMS 6350	4130	Sheet, Strip and Plate	2.3.1
AMS 6350	8630	Sheet, Strip and Plate	2.3.1
AMS 6351	4130	Sheet, Strip and Plate	2.3.1
AMS 6352	4135	Sheet, Strip and Plate	2.3.1
AMS 6355	8630	Tubing	2.3.1
AMS 6357	8735	Sheet, Strip and Plate	2.3.1

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Specification	Alloy Name	Form/Application	Section
AMS 6358	8740	Sheet, Strip and Plate	2.3.1
AMS 6359	4340	Sheet, Strip and Plate	2.3.1
AMS 6360	4130	Tubing (normalized)	2.3.1
AMS 6361	4130	Tubing	2.3.1
AMS 6362	4130	Tubing	2.3.1
AMS 6365	4135	Tubing	2.3.1
AMS 6370	4130	Bar and Forging	2.3.1
AMS 6371	4130	Tubing	2.3.1
AMS 6372	4135	Tubing	2.3.1
AMS 6373	4130	Tubing	2.3.1
AMS 6374	4130	Tubing	2.3.1
AMS 6381	4140	Tubing	2.3.1
AMS 6382	4140	Bar and Forging	2.3.1
AMS 6395	4140	Sheet, Strip and Plate	2.3.1
AMS 6411	4330V	Bar and Forging	2.3.1
AMS 6411	4330V	Tubing	2.3.1
AMS 6414	4340	Bar and Forging	2.3.1
AMS 6414	4340	Tubing	2.3.1
AMS 6415	4340	Bar and Forging	2.3.1
AMS 6415	4340	Tubing	2.3.1
AMS 6417	300M (0.4C)	Bar and Forging	2.3.1
AMS 6417	300M (0.4C)	Tubing	2.3.1
AMS 6419	300M (0.42C)	Bar and Forging	2.3.1
AMS 6419	300M (0.42C)	Tubing	2.3.1
AMS 6425	Hy-Tuf	Bar and Forging	2.3.1
AMS 6425	Hy-Tuf	Tubing	2.3.1
AMS 6427	4330V	Bar and Forging	2.3.1
AMS 6427	4330V	Tubing	2.3.1
AMS 6429	4335V	Bar and Forging	2.3.1
AMS 6429	4335V	Tubing	2.3.1
AMS 6430	4335V	Bar and Forging	2.3.1
AMS 6430	4335V	Tubing	2.3.1
AMS 6431	D6AC	Bar and Forging	2.3.1
AMS 6431	D6AC	Tubing	2.3.1
AMS 6433	4335V	Sheet, Strip and Plate	2.3.1
AMS 6435	4335V	Sheet, Strip and Plate	2.3.1
AMS 6437	5Cr-Mo-V	Sheet, Strip and Plate	2.4.1
AMS 6439	D6AC	Sheet, Strip and Plate	2.3.1
AMS 6439	D6AC	Bar and Forging	2.3.1
AMS 6454	4340	Sheet, Strip and Plate	2.3.1
AMS 6478	AerMet 100	Bar and Forging	2.5.3
AMS 6487	5Cr-Mo-V	Bar and Forging (CEVM)	2.4.1
AMS 6488	5Cr-Mo-V	Bar and Forging	2.4.1
AMS 6512	250	Bar	2.5.1
AMS 6514	280 (300)	Bar	2.5.1
AMS 6520	250	Sheet and Plate	2.5.1
AMS 6521	280 (300)	Sheet and Plate	2.5.1
AMS 6523	9Ni-4Co-0.20C	Sheet, Strip and Plate	2.4.2
AMS 6524	9Ni-4Co-0.20C	Sheet, Strip and Plate	2.4.3
AMS 6526	9Ni-4Co-0.20C	Bar and Forging, Tubing	2.4.3
AMS 6527	AF1410	Bar and Forging	2.5.2
AMS 6528	4130	Bar and Forging	2.3.1
AMS 6529	4140	Bar and Forging	2.3.1
AMS 6532	AerMet 100	Bar and Forging	2.5.3
AMS 7902	Standard Grade Beryllium	Sheet and Plate	7.2.1
AMS 7906	Standard Grade Beryllium	Bar, Rod, Tubing and Machined Shapes	7.2.1

Key: Underline indicates inactive for new design.

Specification	Alloy Name	Form/Application	Section
AMS-A-21180	A201.0	Casting (T7 Temper)	3.8.1
AMS-A-21180	354.0	Casting	3.9.1
AMS-A-21180	C355.0	Casting	3.9.3
AMS-A-21180	A356.0	Casting	3.9.5
AMS-A-21180	A357.0	Casting	3.9.6
AMS-A-21180	359.0	Casting	3.9.8
AMS-A-22771	2014	Forging	3.2.1
AMS-A-22771	2618	Die Forging	3.2.13
AMS-A-22771	6061	Forging	3.6.2
AMS-A-22771	6151	Forging	3.6.3
AMS-A-22771	7049/7149	Forging	3.7.3
AMS-A-22771	7050	Forging	3.7.4
AMS-A-22771	7075	Forging	3.7.6
AMS-A-22771	7175	Forging	3.7.8
AMS-QQ-A-367	2014	Forging	3.2.1
AMS-QQ-A-367	2618	Forging	3.2.13
AMS-QQ-A-367	6061	Forging	3.6.2
AMS-QQ-A-367	7049/7149	Forging	3.7.3
AMS-QQ-A-367	7075	Forging	3.7.6
AMS-QQ-A-200/2	2014	Extruded Bar, Rod and Shapes	3.2.1
AMS-QQ-A-200/3	2024	Extruded Bar, Rod and Shapes	3.2.3
AMS-QQ-A-200/4	5083	Extruded Bar, Rod and Shapes	3.5.2
AMS-QQ-A-200/5	5086	Extruded Bar, Rod and Shapes	3.5.3
AMS-QQ-A-200/6	5454	Extruded Bar, Rod and Shapes	3.5.4
AMS-QQ-A-200/7	5456	Extruded Bar, Rod and Shapes	3.5.5
AMS-QQ-A-200/8	6061	Extruded Rod, Bar Shapes and Tubing	3.6.2
AMS-QQ-A-200/11, 15	7075	Extruded Bar, Rod and Shapes	3.7.6
AMS-QQ-A-225/4	2014	Rolled or Drawn Bar, Rod and Shapes	3.2.1
AMS-QQ-A-225/5	2017	Rolled Bar and Rod	3.2.2
AMS-QQ-A-225/6	2024	Rolled or Drawn Bar, Rod and Wire	3.2.3
AMS-QQ-A-225/8	6061	Rolled Bar, Rod and Shapes	3.6.2
AMS-QQ-A-225/9	7075	Rolled or Drawn Bar and Rod	3.7.6
AMS-QQ-A-250/3	2014	Clad Sheet and Plate	3.2.1
AMS-QQ-A-250/4	2024	Bare Sheet and Plate	3.2.3
AMS-QQ-A-250/5	2024	Clad Sheet and Plate	3.2.3
AMS-QQ-A-250/6	5083	Bare Sheet and Plate	3.5.2
AMS-QQ-A-250/7	5086	Sheet and Plate	3.5.3
AMS-QQ-A-250/8	5052	Sheet and Plate	3.5.1
AMS-QQ-A-250/9	5456	Sheet and Plate	3.5.5
AMS-QQ-A-250/10	5454	Sheet and Plate	3.5.4
AMS-QQ-A-250/11	6061	Sheet and Plate	3.6.2
AMS-QQ-A-250/12, 24	7075	Bare Sheet and Plate	3.7.6
AMS-QQ-A-250/13, 25	7075	Clad Sheet and Plate	3.7.6
AMS-QQ-A-250/29	2124	Plate	3.2.7
AMS-QQ-A-250/30	2219	Sheet and Plate	3.2.8
AMS-QQ-A-367	7049	Forging	3.7.3
AMS-S-5000	4340	Bar and Forging	2.3.1
AMS-S-5626	4140	Bar and Forging	2.3.1
AMS-S-6049	8740	Bar and Forging	2.3.1
AMS-S-6050	8630	Bar and Forging	2.3.1
AMS-S-6758	4130	Bar and Forging	2.3.1
AMS-S-7952	AISI 1025	Sheet and Strip	2.2.1
AMS-S-18728	8630	Sheet, Strip and Plate	2.3.1
AMS-S-18729	4130	Sheet, Strip and Plate	2.3.1
AMS-T-5066	AISI 1025 - N	Tubing	2.2.1
AMS-T-6735	4135	Tubing	2.3.1

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Specification	Alloy Name	Form/Application	Section
AMS-T-6736	4130	Tubing	2.3.1
AMS-T-81556	CP Titanium	Extruded Bars and Shapes	5.2.1
AMS-T-81556	Ti-5Al-2.5Sn	Extruded Bar and Shapes	5.3.1
AMS-T-81556	Ti6Al-6V-2Sn	Extruded Bar and Shapes	5.4.2
AMS-T-9046	CP Titanium	Sheet, Strip and Plate	5.2.1
AMS-T-9046	Ti-5Al-2.5Sn	Sheet, Strip and Plate	5.3.1
AMS-T-9046	Ti-8Al-1Mo-1V	Sheet, Strip and Plate	5.3.2
AMS-T-9046	Ti-6Al-2Sn-4Zr-2Mo	Sheet and Strip	5.3.3
AMS-T-9046	Ti-6Al-4V	Sheet, Strip and Plate	5.4.1
AMS-T-9046	Ti6Al-6V-2Sn	Sheet, Strip and Plate	5.4.2
AMS-T-9046	Ti-13V-11Cr-3Al	Sheet, Strip and Plate	5.5.1
AMS-WW-T-700/3	2024	Tubing	3.2.3
AMS-WW-T-700/6	6061	Tubing Seamless, Drawn	3.6.2
ASTM A 108	AISI 1025	Bar	2.2.1
ASTM B 91	AZ31B	Forging	4.2.1
ASTM B 91	AZ61A	Forging	4.2.2
ASTM B 107	ZK60A-F	Extrusion	4.2.3
ASTM B 107	AZ31B	Extrusion	4.2.1
ASTM B 166	Inconel Alloy 600	Bar and Rod	6.3.2
ASTM B 194	Copper Beryllium	Sheet (TB00, TD01, TD02, TD04)	7.3.2
ASTM B 564	Inconel Alloy 600	Forging	6.3.2
MIL-DTL-46192	2519	Plate	3.2.11
MIL-T-9047	CP Titanium	Bar	5.2.1
MIL-T-9047	Ti-5Al-2.5Sn	Bar	5.3.1
MIL-T-9047	Ti-8Al-1Mo-1V	Bar	5.3.2
MIL-T-9047	Ti-6Al-4V	Bar	5.4.1
MIL-T-9047	Ti-13V-11Cr-3Al	Bar	5.5.1

APPENDIX D

D.0 Subject Index

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APPENDIX E

E.0 Figure Index

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1.4.11.3	Scanned
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1.4.12.4	Scanned
1.4.12.4.1	Scanned
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1.4.13.4	Scanned
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1.6.4.4(a)	Vector Graphic
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1.6.4.4(g)	Vector Graphic
1.6.4.4(h)	Vector Graphic
1.6.4.4(i)	Vector Graphic
2.2.1.0	Vector Graphic
2.3.0.2	Scanned
2.3.1.0	Vector Graphic
2.3.1.1.1	Vector Graphic
2.3.1.1.2	Vector Graphic
2.3.1.1.3	Vector Graphic
2.3.1.1.4	Vector Graphic
2.3.1.2.6(a)	Vector Graphic
2.3.1.2.6(b)	Vector Graphic
2.3.1.2.6(c)	Vector Graphic
2.3.1.2.8(a)	Vector Graphic
2.3.1.2.8(b)	Vector Graphic
2.3.1.2.8(c)	Vector Graphic
2.3.1.2.8(d)	Vector Graphic
2.3.1.2.8(e)	Vector Graphic
2.3.1.2.8(f)	Vector Graphic
2.3.1.2.8(g)	Vector Graphic
2.3.1.2.8(h)	Vector Graphic
2.3.1.3.6(a)	Vector Graphic
2.3.1.3.6(b)	Vector Graphic
2.3.1.3.6(c)	Vector Graphic
2.3.1.3.6(d)	Scanned
2.3.1.3.6(e)	Vector Graphic
2.3.1.3.6(f)	Vector Graphic
2.3.1.3.6(g)	Vector Graphic
2.3.1.3.8(a)	Vector Graphic
2.3.1.3.8(b)	Vector Graphic
2.3.1.3.8(c)	Vector Graphic
2.3.1.3.8(d)	Vector Graphic
2.3.1.3.8(e)	Vector Graphic
2.3.1.3.8(f)	Vector Graphic
2.3.1.3.8(g)	Vector Graphic
2.3.1.3.8(h)	Vector Graphic
2.3.1.3.8(i)	Vector Graphic
2.3.1.3.8(j)	Vector Graphic
2.3.1.3.8(k)	Vector Graphic
2.3.1.3.8(l)	Vector Graphic
2.3.1.3.8(m)	Vector Graphic
2.3.1.3.8(n)	Vector Graphic
2.3.1.3.8(o)	Vector Graphic
2.3.1.4.8(a)	Scanned
2.3.1.4.8(b)	Scanned
2.3.1.4.8(c)	Scanned
2.3.1.4.8(d)	Scanned
2.3.1.4.9	Scanned
2.3.1.5.9	Scanned
2.4.1.0	Vector Graphic
2.4.1.1.1(a)	Vector Graphic
2.4.1.1.1(b)	Vector Graphic
2.4.1.1.2(a)	Vector Graphic
2.4.1.1.2(b)	Vector Graphic
2.4.1.1.3(a)	Vector Graphic
2.4.1.1.3(b)	Vector Graphic
2.4.1.1.4	Vector Graphic
2.4.2.0	Vector Graphic
2.4.2.1.1	Vector Graphic
2.4.2.1.2	Vector Graphic
2.4.2.1.4	Vector Graphic
2.4.2.1.6(a)	Vector Graphic
2.4.2.1.6(b)	Vector Graphic
2.4.3.0	Vector Graphic
2.4.3.1.1	Vector Graphic
2.4.3.1.2	Vector Graphic

Figure No.	Current Form	Figure No.	Current Form
2.4.3.1.3	Vector Graphic	2.6.4.0	Vector Graphic
2.4.3.1.4	Vector Graphic	2.6.4.1.1	Vector Graphic
2.4.3.1.6(a)	Vector Graphic	2.6.4.1.2	Vector Graphic
2.4.3.1.6(b)	Vector Graphic	2.6.4.1.5	Vector Graphic
2.4.3.1.6(c)	Vector Graphic	2.6.4.1.6	Vector Graphic
2.4.3.1.6(d)	Vector Graphic	2.6.4.1.8(a)	Scanned
2.4.3.1.8	Scanned	2.6.4.1.8(b)	Scanned
2.5.0.2(a)	Vector Graphic	2.6.4.2.1	Vector Graphic
2.5.1.0	Vector Graphic	2.6.4.2.2	Vector Graphic
2.5.1.1.1	Vector Graphic	2.6.4.2.5	Scanned
2.5.1.1.2	Vector Graphic	2.6.4.2.6	Vector Graphic
2.5.1.1.3	Vector Graphic	2.6.4.2.8	Scanned
2.5.1.1.4	Vector Graphic	2.6.5.0(a)	Vector Graphic
2.5.1.1.6(a)	Vector Graphic	2.6.5.1(a)	Vector Graphic
2.5.1.1.6(b)	Vector Graphic	2.6.5.1(b)	Vector Graphic
2.5.1.1.6(c)	Vector Graphic	2.6.5.1(c)	Vector Graphic
2.5.1.1.6(d)	Vector Graphic	2.6.6.0	Vector Graphic
2.5.1.1.6(e)	Scanned	2.6.6.1.1	Vector Graphic
2.5.2.1.6(a)	Vector Graphic	2.6.6.1.6(a)	Vector Graphic
2.5.2.1.6(b)	Vector Graphic	2.6.6.1.6(b)	Vector Graphic
2.5.3.1.6(a)	Vector Graphic	2.6.6.1.6(c)	Vector Graphic
2.5.3.1.6(b)	Vector Graphic	2.6.6.1.8(a)	Vector Graphic
2.5.3.1.6(c)	Vector Graphic	2.6.6.1.8(b)	Vector Graphic
2.5.3.2.6(a)	Vector Graphic	2.6.6.1.8(c)	Vector Graphic
2.5.3.2.6(b)	Vector Graphic	2.6.7.0	Vector Graphic
2.5.3.2.6(c)	Vector Graphic	2.6.7.1.1	Vector Graphic
2.6.1.0	Vector Graphic	2.6.7.1.4	Vector Graphic
2.6.1.1.1	Vector Graphic	2.6.7.1.6(a)	Vector Graphic
2.6.1.1.2	Vector Graphic	2.6.7.1.6(b)	Scanned
2.6.1.1.3	Vector Graphic	2.6.7.1.6(c)	Vector Graphic
2.6.1.1.4	Vector Graphic	2.6.7.2.2	Vector Graphic
2.6.1.1.6(a)	Vector Graphic	2.6.7.2.6(a)	Scanned
2.6.1.1.6(b)	Vector Graphic	2.6.7.2.6(b)	Vector Graphic
2.6.2.0	Vector Graphic	2.6.7.2.8(a)	Vector Graphic
2.6.2.1.1	Scanned	2.6.7.2.8(b)	Vector Graphic
2.6.2.1.2	Vector Graphic	2.6.7.2.8(c)	Vector Graphic
2.6.2.1.3	Scanned	2.6.7.3.2	Scanned
2.6.2.1.4	Vector Graphic	2.6.7.3.6	Scanned
2.6.3.0	Vector Graphic	2.6.8.0	Vector Graphic
2.6.3.1.1	Vector Graphic	2.6.8.1.1	Scanned
2.6.3.1.2	Vector Graphic	2.6.8.1.4	Scanned
2.6.3.1.5	Vector Graphic	2.6.8.1.6(a)	Scanned
2.6.3.1.6	Vector Graphic	2.6.8.1.6(b)	Scanned
2.6.3.1.8	Scanned	2.6.8.1.6(c)	Scanned
2.6.3.2.1	Vector Graphic	2.6.8.1.8(a)	Scanned
2.6.3.2.2	Vector Graphic	2.6.8.1.8(b)	Scanned
2.6.3.2.5	Vector Graphic	2.6.8.1.8(c)	Scanned
2.6.3.2.6	Vector Graphic	2.6.8.1.8(d)	Scanned
2.6.3.2.8	Scanned	2.6.8.1.8(e)	Vector Graphic

Figure No.	Current Form	Figure No.	Current Form
2.6.8.1.8(f)	Scanned	2.8.3.2(b)	Vector Graphic
2.6.9.0	Vector Graphic	2.8.3.2(c)	Vector Graphic
2.6.9.1.2	Vector Graphic	2.8.3.2(d)	Scanned
2.6.9.1.3	Vector Graphic	2.8.3.2(e)	Scanned
2.6.9.1.4	Vector Graphic	2.8.3.2(f)	Vector Graphic
2.6.9.1.8(a)	Scanned	2.8.3.2(g)	Scanned
2.6.9.1.8(b)	Scanned	2.8.3.2(h)	Scanned
2.6.9.1.8(c)	Scanned	2.8.3.2(i)	Vector Graphic
2.6.9.2.1	Vector Graphic	2.8.3.2(j)	Scanned
2.6.9.2.6(a)	Vector Graphic	3.1.2.1.1(a)	Scanned
2.6.9.2.6(b)	Vector Graphic	3.1.2.1.1(b)	Scanned
2.6.9.3.6(a)	Vector Graphic	3.1.2.1.1(c)	Scanned
2.6.9.3.6(b)	Vector Graphic	3.2.1.0	Vector Graphic
2.6.9.4.8	Scanned	3.2.1.1.1(a)	Scanned
2.6.9.5.8	Scanned	3.2.1.1.1(b)	Vector Graphic
2.6.9.6.1	Vector Graphic	3.2.1.1.1(c)	Vector Graphic
2.6.10.0	Vector Graphic	3.2.1.1.1(d)	Vector Graphic
2.6.10.1.1	Vector Graphic	3.2.1.1.1(e)	Vector Graphic
2.6.10.1.2	Vector Graphic	3.2.1.1.1(f)	Vector Graphic
2.6.10.1.4(a)	Vector Graphic	3.2.1.1.2(a)	Vector Graphic
2.6.10.1.4(b)	Vector Graphic	3.2.1.1.2(b)	Vector Graphic
2.6.10.1.6(a)	Vector Graphic	3.2.1.1.3(a)	Vector Graphic
2.6.10.1.6(b)	Vector Graphic	3.2.1.1.3(b)	Vector Graphic
2.6.10.1.6(c)	Vector Graphic	3.2.1.1.4	Scanned
2.7.1.0	Vector Graphic	3.2.1.1.5(a)	Vector Graphic
2.7.1.1.1(a)	Vector Graphic	3.2.1.1.5(b)	Vector Graphic
2.7.1.1.1(b)	Vector Graphic	3.2.1.1.6(a)	Vector Graphic
2.7.1.2.6(a)	Vector Graphic	3.2.1.1.6(b)	Vector Graphic
2.7.1.2.6(b)	Vector Graphic	3.2.1.1.6(c)	Vector Graphic
2.7.1.3.1	Vector Graphic	3.2.1.1.6(d)	Vector Graphic
2.7.1.3.2	Vector Graphic	3.2.1.1.6(e)	Vector Graphic
2.7.1.3.3	Vector Graphic	3.2.1.1.6(f)	Vector Graphic
2.7.1.3.4	Vector Graphic	3.2.1.1.6(g)	Vector Graphic
2.7.1.3.6(a)	Vector Graphic	3.2.1.1.6(h)	Vector Graphic
2.7.1.3.6(b)	Vector Graphic	3.2.1.1.6(i)	Vector Graphic
2.7.1.4.6(a)	Vector Graphic	3.2.1.1.6(j)	Vector Graphic
2.7.1.4.6(b)	Vector Graphic	3.2.1.1.6(k)	Vector Graphic
2.7.1.5.1	Vector Graphic	3.2.1.1.6(l)	Vector Graphic
2.7.1.5.2(a)	Vector Graphic	3.2.1.1.6(m)	Vector Graphic
2.7.1.5.2(b)	Vector Graphic	3.2.1.1.6(n)	Vector Graphic
2.7.1.5.3	Vector Graphic	3.2.1.1.6(o)	Vector Graphic
2.7.1.5.4	Vector Graphic	3.2.1.1.6(p)	Vector Graphic
2.7.1.5.6(a)	Vector Graphic	3.2.1.1.6(q)	Vector Graphic
2.7.1.5.6(b)	Vector Graphic	3.2.1.1.6(r)	Vector Graphic
2.7.1.5.6(c)	Vector Graphic	3.2.1.1.6(s)	Vector Graphic
2.7.1.5.6(d)	Vector Graphic	3.2.1.1.6(t)	Vector Graphic
2.8.1.1(a)	Vector Graphic	3.2.1.1.6(u)	Vector Graphic
2.8.1.1(b)	Vector Graphic	3.2.1.1.6(v)	Vector Graphic
2.8.3.2(a)	Vector Graphic	3.2.1.1.8(a)	Scanned

Figure No.	Current Form	Figure No.	Current Form
3.2.1.1.8(b)	Vector Graphic	3.2.3.1.8(c)	Vector Graphic
3.2.1.1.8(c)	Vector Graphic	3.2.3.1.8(d)	Vector Graphic
3.2.1.1.8(d)	Vector Graphic	3.2.3.1.8(e)	Scanned
3.2.1.1.8(e)	Vector Graphic	3.2.3.1.8(f)	Vector Graphic
3.2.2.0	Vector Graphic	3.2.3.1.8(g)	Vector Graphic
3.2.2.1.4	Vector Graphic	3.2.3.1.8(h)	Vector Graphic
3.2.3.0	Vector Graphic	3.2.3.1.8(i)	Vector Graphic
3.2.3.1.1(a)	Vector Graphic	3.2.3.3.1(a)	Vector Graphic
3.2.3.1.1(b)	Vector Graphic	3.2.3.3.1(b)	Vector Graphic
3.2.3.1.1(c)	Vector Graphic	3.2.3.3.1(c)	Vector Graphic
3.2.3.1.1(d)	Vector Graphic	3.2.3.3.1(d)	Vector Graphic
3.2.3.1.1(e)	Vector Graphic	3.2.3.3.5(a)	Vector Graphic
3.2.3.1.1(f)	Vector Graphic	3.2.3.3.5(b)	Vector Graphic
3.2.3.1.2(a)	Vector Graphic	3.2.3.3.6(a)	Vector Graphic
3.2.3.1.2(b)	Vector Graphic	3.2.3.3.6(b)	Vector Graphic
3.2.3.1.3(a)	Vector Graphic	3.2.3.3.6(c)	Vector Graphic
3.2.3.1.3(b)	Vector Graphic	3.2.3.3.6(d)	Vector Graphic
3.2.3.1.4	Scanned	3.2.3.3.6(e)	Vector Graphic
3.2.3.1.5(a)	Vector Graphic	3.2.3.4.1(a)	Vector Graphic
3.2.3.1.5(b)	Vector Graphic	3.2.3.4.1(b)	Vector Graphic
3.2.3.1.6(a)	Vector Graphic	3.2.3.4.1(c)	Vector Graphic
3.2.3.1.6(b)	Vector Graphic	3.2.3.4.1(d)	Vector Graphic
3.2.3.1.6(c)	Vector Graphic	3.2.3.4.1(e)	Scanned
3.2.3.1.6(d)	Vector Graphic	3.2.3.4.1(f)	Scanned
3.2.3.1.6(e)	Vector Graphic	3.2.3.4.2(a)	Vector Graphic
3.2.3.1.6(f)	Vector Graphic	3.2.3.4.2(b)	Vector Graphic
3.2.3.1.6(g)	Vector Graphic	3.2.3.4.3(a)	Vector Graphic
3.2.3.1.6(h)	Vector Graphic	3.2.3.4.3(b)	Vector Graphic
3.2.3.1.6(i)	Vector Graphic	3.2.3.4.5(a)	Vector Graphic
3.2.3.1.6(j)	Vector Graphic	3.2.3.4.5(b)	Vector Graphic
3.2.3.1.6(k)	Vector Graphic	3.2.3.4.6(a)	Vector Graphic
3.2.3.1.6(l)	Vector Graphic	3.2.3.4.6(b)	Vector Graphic
3.2.3.1.6(m)	Vector Graphic	3.2.3.4.6(c)	Vector Graphic
3.2.3.1.6(n)	Vector Graphic	3.2.3.4.6(d)	Vector Graphic
3.2.3.1.6(o)	Vector Graphic	3.2.3.4.6(e)	Vector Graphic
3.2.3.1.6(p)	Vector Graphic	3.2.3.4.6(f)	Vector Graphic
3.2.3.1.6(q)	Vector Graphic	3.2.3.4.6(g)	Vector Graphic
3.2.3.1.6(r)	Vector Graphic	3.2.3.4.6(h)	Vector Graphic
3.2.3.1.6(s)	Vector Graphic	3.2.3.4.6(i)	Vector Graphic
3.2.3.1.6(t)	Vector Graphic	3.2.3.4.6(j)	Vector Graphic
3.2.3.1.6(u)	Vector Graphic	3.2.3.5.1(a)	Vector Graphic
3.2.3.1.6(v)	Vector Graphic	3.2.3.5.1(b)	Vector Graphic
3.2.3.1.6(w)	Vector Graphic	3.2.3.5.1(c)	Vector Graphic
3.2.3.1.6(x)	Vector Graphic	3.2.3.5.1(d)	Vector Graphic
3.2.3.1.6(y)	Vector Graphic	3.2.3.5.2(a)	Vector Graphic
3.2.3.1.6(z)	Vector Graphic	3.2.3.5.2(b)	Vector Graphic
3.2.3.1.6(aa)	Vector Graphic	3.2.3.5.3(a)	Vector Graphic
3.2.3.1.8(a)	Scanned	3.2.3.5.3(b)	Vector Graphic
3.2.3.1.8(b)	Vector Graphic	3.2.3.5.3(c)	Vector Graphic

Figure No.	Current Form
3.2.3.5.5(a)	Scanned
3.2.3.5.5(b)	Scanned
3.2.3.5.6(a)	Vector Graphic
3.2.3.5.6(b)	Vector Graphic
3.2.3.5.6(c)	Vector Graphic
3.2.3.5.6(d)	Vector Graphic
3.2.3.5.10(a)	Scanned
3.2.3.5.10(b)	Scanned
3.2.4.0	Vector Graphic
3.2.6.1.6(a)	Vector Graphic
3.2.6.1.6(b)	Vector Graphic
3.2.7.1.1(a)	Vector Graphic
3.2.7.1.1(b)	Vector Graphic
3.2.7.1.6(a)	Scanned
3.2.7.1.6(b)	Scanned
3.2.7.1.9(a)	Scanned
3.2.7.1.9(b)	Scanned
3.2.7.1.9(c)	Scanned
3.2.7.1.9(d)	Scanned
3.2.7.1.9(e)	Scanned
3.2.8.0	Vector Graphic
3.2.8.1.1(a)	Vector Graphic
3.2.8.1.1(b)	Vector Graphic
3.2.8.1.6(a)	Vector Graphic
3.2.8.1.6(b)	Vector Graphic
3.2.8.2.1(a)	Vector Graphic
3.2.8.2.1(b)	Vector Graphic
3.2.8.2.6(a)	Vector Graphic
3.2.8.2.6(b)	Vector Graphic
3.2.8.2.8(a)	Scanned
3.2.8.2.8(b)	Scanned
3.2.8.2.8(c)	Scanned
3.2.8.2.8(d)	Scanned
3.2.8.3.6(a)	Vector Graphic
3.2.8.3.6(b)	Vector Graphic
3.2.8.3.6(c)	Vector Graphic
3.2.8.3.6(d)	Vector Graphic
3.2.8.3.6(e)	Vector Graphic
3.2.8.4.1(a)	Vector Graphic
3.2.8.4.1(b)	Vector Graphic
3.2.8.4.6(a)	Vector Graphic
3.2.8.4.6(b)	Vector Graphic
3.2.8.4.6(c)	Vector Graphic
3.2.8.4.6(d)	Vector Graphic
3.2.8.4.6(e)	Vector Graphic
3.2.10.1.6(a)	Vector Graphic
3.2.10.1.6(b)	Vector Graphic
3.2.11.1.6(a)	Vector Graphic
3.2.11.1.6(b)	Vector Graphic
3.2.11.1.6(c)	Vector Graphic
3.2.12.0	Vector Graphic
3.2.12.1.1(a)	Vector Graphic
3.2.12.1.1(b)	Vector Graphic
3.2.12.1.1(c)	Vector Graphic
3.2.12.1.1(d)	Vector Graphic
3.2.12.1.2	Vector Graphic
3.2.12.1.3	Vector Graphic
3.2.12.1.4	Vector Graphic
3.2.12.1.5	Vector Graphic
3.2.12.1.6(a)	Vector Graphic
3.2.12.1.6(b)	Vector Graphic
3.5.1.0	Vector Graphic
3.5.1.1.1	Vector Graphic
3.5.1.1.4	Vector Graphic
3.5.1.1.5	Vector Graphic
3.5.1.3.1(a)	Vector Graphic
3.5.1.3.1(b)	Vector Graphic
3.5.1.3.1(c)	Vector Graphic
3.5.1.3.1(d)	Vector Graphic
3.5.1.3.5(a)	Vector Graphic
3.5.1.3.5(b)	Vector Graphic
3.5.1.5.1(a)	Vector Graphic
3.5.1.5.1(b)	Vector Graphic
3.5.1.5.1(c)	Vector Graphic
3.5.1.5.1(d)	Vector Graphic
3.5.1.5.5(a)	Vector Graphic
3.5.1.5.5(b)	Vector Graphic
3.5.2.0	Vector Graphic
3.5.2.1.6(a)	Vector Graphic
3.5.2.1.6(b)	Vector Graphic
3.5.2.1.6(c)	Vector Graphic
3.5.3.1.6(a)	Vector Graphic
3.5.3.1.6(b)	Vector Graphic
3.5.3.1.6(c)	Vector Graphic
3.5.3.2.6(a)	Vector Graphic
3.5.3.2.6(b)	Vector Graphic
3.5.3.2.6(c)	Vector Graphic
3.5.3.3.6(a)	Vector Graphic
3.5.3.3.6(b)	Vector Graphic
3.5.3.3.6(c)	Vector Graphic
3.5.3.4.6	Vector Graphic
3.5.3.7.6	Vector Graphic
3.5.4.1.6	Vector Graphic
3.5.4.2.6	Vector Graphic
3.5.4.3.6(a)	Vector Graphic
3.5.4.3.6(b)	Vector Graphic
3.5.5.0	Vector Graphic
3.5.5.1.6(a)	Vector Graphic

Figure No.	Current Form	Figure No.	Current Form
3.5.5.1.6(b)	Vector Graphic	3.7.3.1.8(b)	Scanned
3.5.5.2.6	Vector Graphic	3.7.3.1.8(c)	Scanned
3.5.5.4.6	Vector Graphic	3.7.3.1.8(d)	Scanned
3.6.1.1.6(a)	Vector Graphic	3.7.3.1.8(e)	Scanned
3.6.1.1.6(b)	Vector Graphic	3.7.3.1.8(f)	Scanned
3.6.2.0	Vector Graphic	3.7.3.1.8(g)	Scanned
3.6.2.2.1(a)	Vector Graphic	3.7.4.1.6(a)	Vector Graphic
3.6.2.2.1(b)	Vector Graphic	3.7.4.1.6(b)	Vector Graphic
3.6.2.2.1(c)	Vector Graphic	3.7.4.1.6(c)	Vector Graphic
3.6.2.2.1(d)	Vector Graphic	3.7.4.1.6(d)	Vector Graphic
3.6.2.2.4	Vector Graphic	3.7.4.1.8(a)	Scanned
3.6.2.2.5(a)	Vector Graphic	3.7.4.1.8(b)	Scanned
3.6.2.2.5(b)	Vector Graphic	3.7.4.2.1	Vector Graphic
3.6.2.2.6(a)	Vector Graphic	3.7.4.2.6(a)	Vector Graphic
3.6.2.2.6(b)	Vector Graphic	3.7.4.2.6(b)	Vector Graphic
3.6.2.2.6(c)	Vector Graphic	3.7.4.2.6(c)	Vector Graphic
3.6.2.2.6(d)	Vector Graphic	3.7.4.2.6(d)	Vector Graphic
3.6.2.2.6(e)	Vector Graphic	3.7.4.2.6(e)	Vector Graphic
3.6.2.2.6(f)	Vector Graphic	3.7.4.2.6(f)	Vector Graphic
3.6.2.2.6(g)	Vector Graphic	3.7.4.2.6(g)	Vector Graphic
3.6.2.2.6(h)	Vector Graphic	3.7.4.2.6(h)	Vector Graphic
3.6.2.2.6(i)	Vector Graphic	3.7.4.2.6(i)	Vector Graphic
3.6.2.2.6(j)	Vector Graphic	3.7.4.2.6(j)	Vector Graphic
3.6.2.2.6(k)	Vector Graphic	3.7.4.2.8(a)	Scanned
3.6.2.2.6(l)	Vector Graphic	3.7.4.2.8(b)	Vector Graphic
3.6.2.2.6(m)	Vector Graphic	3.7.4.2.8(c)	Vector Graphic
3.6.2.2.6(n)	Vector Graphic	3.7.4.2.8(d)	Vector Graphic
3.6.2.2.6(o)	Vector Graphic	3.7.4.2.8(e)	Scanned
3.6.2.2.8	Vector Graphic	3.7.4.2.8(f)	Scanned
3.6.3.0	Vector Graphic	3.7.4.2.8(g)	Scanned
3.7.1.1.1	Vector Graphic	3.7.4.2.8(h)	Scanned
3.7.1.1.6(a)	Vector Graphic	3.7.4.2.8(i)	Scanned
3.7.1.1.6(b)	Vector Graphic	3.7.4.2.8(j)	Scanned
3.7.1.1.6(c)	Vector Graphic	3.7.4.2.8(k)	Scanned
3.7.1.1.6(d)	Vector Graphic	3.7.4.2.8(l)	Scanned
3.7.1.2.6(a)	Vector Graphic	3.7.4.2.9(a)	Scanned
3.7.1.2.6(b)	Vector Graphic	3.7.4.2.9(b)	Scanned
3.7.1.2.6(c)	Vector Graphic	3.7.4.2.9(c)	Scanned
3.7.1.2.6(d)	Vector Graphic	3.7.4.3.6(a)	Vector Graphic
3.7.2.0	Vector Graphic	3.7.4.3.6(b)	Vector Graphic
3.7.3.1.1	Vector Graphic	3.7.4.3.6(c)	Vector Graphic
3.7.3.1.6(a)	Vector Graphic	3.7.4.3.6(d)	Vector Graphic
3.7.3.1.6(b)	Vector Graphic	3.7.4.3.6(e)	Vector Graphic
3.7.3.1.6(c)	Vector Graphic	3.7.4.3.6(f)	Vector Graphic
3.7.3.1.6(d)	Vector Graphic	3.7.4.3.8(a)	Scanned
3.7.3.1.6(e)	Vector Graphic	3.7.4.3.8(b)	Scanned
3.7.3.1.6(f)	Vector Graphic	3.7.6.0	Vector Graphic
3.7.3.1.6(g)	Vector Graphic	3.7.6.1.1(a)	Scanned
3.7.3.1.8(a)	Scanned	3.7.6.1.1(b)	Scanned

Figure No.	Current Form
3.7.6.1.1(c)	Vector Graphic
3.7.6.1.1(d)	Vector Graphic
3.7.6.1.2(a)	Vector Graphic
3.7.6.1.2(b)	Vector Graphic
3.7.6.1.3(a)	Vector Graphic
3.7.6.1.3(b)	Vector Graphic
3.7.6.1.4	Vector Graphic
3.7.6.1.5(a)	Vector Graphic
3.7.6.1.5(b)	Vector Graphic
3.7.6.1.6(a)	Vector Graphic
3.7.6.1.6(b)	Vector Graphic
3.7.6.1.6(c)	Vector Graphic
3.7.6.1.6(d)	Vector Graphic
3.7.6.1.6(e)	Vector Graphic
3.7.6.1.6(f)	Vector Graphic
3.7.6.1.6(g)	Vector Graphic
3.7.6.1.6(h)	Vector Graphic
3.7.6.1.6(i)	Vector Graphic
3.7.6.1.6(j)	Vector Graphic
3.7.6.1.6(k)	Vector Graphic
3.7.6.1.6(l)	Vector Graphic
3.7.6.1.6(m)	Vector Graphic
3.7.6.1.6(n)	Vector Graphic
3.7.6.1.6(o)	Vector Graphic
3.7.6.1.6(p)	Vector Graphic
3.7.6.1.6(q)	Vector Graphic
3.7.6.1.8(a)	Scanned
3.7.6.1.8(b)	Scanned
3.7.6.1.8(c)	Scanned
3.7.6.1.8(d)	Vector Graphic
3.7.6.1.8(e)	Scanned
3.7.6.1.8(f)	Vector Graphic
3.7.6.1.8(g)	Scanned
3.7.6.1.8(h)	Vector Graphic
3.7.6.1.9	Scanned
3.7.6.1.10(a)	Scanned
3.7.6.1.10(b)	Scanned
3.7.6.1.10(c)	Scanned
3.7.6.1.10(d)	Scanned
3.7.6.1.10(e)	Scanned
3.7.6.1.10(f)	Scanned
3.7.6.1.10(g)	Scanned
3.7.6.1.10(h)	Scanned
3.7.6.2.6(a)	Vector Graphic
3.7.6.2.6(b)	Vector Graphic
3.7.6.2.6(c)	Vector Graphic
3.7.6.2.6(d)	Vector Graphic
3.7.6.2.6(e)	Vector Graphic
3.7.6.2.6(f)	Vector Graphic
3.7.6.2.9(a)	Scanned
3.7.6.2.9(b)	Scanned
3.7.6.2.9(c)	Scanned
3.7.6.2.10(a)	Scanned
3.7.6.2.10(b)	Scanned
3.7.7.1.6(a)	Vector Graphic
3.7.7.1.6(b)	Vector Graphic
3.7.7.1.6(c)	Vector Graphic
3.7.7.1.6(d)	Vector Graphic
3.7.7.2.6(a)	Vector Graphic
3.7.7.2.6(b)	Vector Graphic
3.7.7.2.6(c)	Vector Graphic
3.7.7.2.6(d)	Vector Graphic
3.7.7.2.8(a)	Vector Graphic
3.7.7.2.8(b)	Vector Graphic
3.7.7.2.8(c)	Vector Graphic
3.7.8.1.6(a)	Vector Graphic
3.7.8.1.6(b)	Vector Graphic
3.7.8.1.8(a)	Vector Graphic
3.7.8.1.8(b)	Vector Graphic
3.7.8.1.8(c)	Vector Graphic
3.7.8.1.8(d)	Vector Graphic
3.7.8.2.6(a)	Vector Graphic
3.7.8.2.6(b)	Vector Graphic
3.7.8.2.6(c)	Vector Graphic
3.7.8.2.6(d)	Vector Graphic
3.7.8.2.6(e)	Vector Graphic
3.7.8.2.6(f)	Vector Graphic
3.7.8.2.8(a)	Scanned
3.7.8.2.8(b)	Scanned
3.7.9.1.6(a)	Vector Graphic
3.7.9.1.6(b)	Vector Graphic
3.7.9.1.6(c)	Vector Graphic
3.7.10.1.6(a)	Vector Graphic
3.7.10.1.6(b)	Vector Graphic
3.7.10.1.6(c)	Vector Graphic
3.7.10.1.6(d)	Vector Graphic
3.7.10.1.6(e)	Vector Graphic
3.7.10.1.6(f)	Vector Graphic
3.7.10.1.6(g)	Vector Graphic
3.7.10.1.8(a)	Scanned
3.7.10.1.8(b)	Vector Graphic
3.7.10.1.8(c)	Scanned
3.7.10.1.10(a)	Scanned
3.7.10.1.10(b)	Scanned
3.7.10.1.10(c)	Scanned
3.7.10.1.10(d)	Scanned
3.7.10.2.6(a)	Vector Graphic
3.7.10.2.6(b)	Vector Graphic

Figure No.	Current Form	Figure No.	Current Form
3.7.10.2.8(a)	Scanned	4.2.3.0	Vector Graphic
3.7.10.2.8(b)	Scanned	4.2.3.2.6(a)	Vector Graphic
3.7.10.2.9(a)	Scanned	4.2.3.2.6(b)	Scanned
3.7.10.2.9(b)	Scanned	4.2.3.2.8(a)	Scanned
3.7.10.3.6(a)	Vector Graphic	4.2.3.2.8(b)	Scanned
3.7.10.3.6(b)	Vector Graphic	4.2.3.2.8(c)	Scanned
3.7.10.3.6(c)	Vector Graphic	4.3.2.1.4	Vector Graphic
3.7.10.3.6(d)	Vector Graphic	4.3.2.1.6	Vector Graphic
3.7.10.3.6(e)	Vector Graphic	4.3.3.0	Vector Graphic
3.7.10.3.6(f)	Vector Graphic	4.3.3.1.1(a)	Vector Graphic
3.7.10.3.6(g)	Vector Graphic	4.3.3.1.1(b)	Vector Graphic
3.7.10.3.6(h)	Vector Graphic	4.3.3.1.1(c)	Vector Graphic
3.7.10.3.6(i)	Vector Graphic	4.3.3.1.4	Vector Graphic
3.7.10.3.6(j)	Vector Graphic	4.3.3.1.6(a)	Vector Graphic
3.7.10.3.6(k)	Vector Graphic	4.3.3.1.6(b)	Vector Graphic
3.7.10.3.6(l)	Vector Graphic	4.3.4.0	Vector Graphic
3.7.10.3.10(a)	Scanned	4.3.4.1.1(a)	Scanned
3.7.10.3.10(b)	Scanned	4.3.4.1.1(b)	Scanned
3.8.1.0	Vector Graphic	4.3.4.1.1(C)	Scanned
3.8.1.1.6	Vector Graphic	4.3.4.1.6	Vector Graphic
3.8.1.1.8(a)	Scanned	4.3.5.1.1	Scanned
3.8.1.1.8(b)	Scanned	4.3.5.1.4	Scanned
3.8.1.1.8(c)	Scanned	4.3.5.1.6	Vector Graphic
3.9.2.0	Vector Graphic	4.3.6.0	Scanned
3.9.4.0	Vector Graphic	4.3.6.1.1	Scanned
3.9.5.1.6(a)	Vector Graphic	4.3.6.1.4	Scanned
3.9.5.1.6(b)	Vector Graphic	4.3.6.1.6(a)	Scanned
3.9.6.1.6	Vector Graphic	4.3.6.1.6(b)	Vector Graphic
3.9.7.1.6	Vector Graphic	4.4.2.3(a)	Scanned
3.10.1.1.1	Vector Graphic	4.4.2.3(b)	Scanned
3.10.2.3(a)	Scanned	4.4.3.2	Scanned
3.10.2.3(b)	Scanned	5.2.1.0	Scanned
3.10.3.2(a)	Scanned	5.2.1.1.1(a)	Scanned
3.10.3.2(b)	Vector Graphic	5.2.1.1.1(b)	Scanned
3.10.3.2(c)	Scanned	5.2.1.1.2(a)	Scanned
3.10.3.2(d)	Scanned	5.2.1.1.2(b)	Scanned
3.10.3.2(e)	Vector Graphic	5.2.1.1.3(a)	Scanned
3.10.3.2(f)	Vector Graphic	5.2.1.1.3(b)	Scanned
3.10.3.2(g)	Vector Graphic	5.2.1.1.6(a)	Scanned
4.2.1.0	Vector Graphic	5.2.1.1.6(b)	Scanned
4.2.1.1.4	Scanned	5.3.1.0	Vector Graphic
4.2.1.1.6	Vector Graphic	5.3.1.1.1	Scanned
4.2.1.2.1	Scanned	5.3.1.1.2	Scanned
4.2.1.2.2	Scanned	5.3.1.1.3	Scanned
4.2.1.2.3	Scanned	5.3.1.1.4	Scanned
4.2.1.2.4	Scanned	5.3.1.1.5	Scanned
4.2.1.2.6	Vector Graphic	5.3.1.1.9(a)	Scanned
4.2.1.4.8(a)	Vector Graphic	5.3.1.1.9(b)	Scanned
4.2.1.4.8(b)	Scanned	5.3.1.1.9(c)	Scanned

Figure No.	Current Form
5.3.2.0	Scanned
5.3.2.1.1	Scanned
5.3.2.1.4	Scanned
5.3.2.1.6(a)	Vector Graphic
5.3.2.1.6(b)	Vector Graphic
5.3.2.2.1	Scanned
5.3.2.2.6(a)	Vector Graphic
5.3.2.2.6(b)	Vector Graphic
5.3.2.2.8(a)	Scanned
5.3.2.2.8(b)	Scanned
5.3.2.2.8(c)	Scanned
5.3.2.2.8(d)	Scanned
5.3.2.2.8(e)	Scanned
5.3.2.2.8(f)	Scanned
5.3.3.0	Scanned
5.3.3.1.1	Scanned
5.3.3.1.2	Scanned
5.3.3.1.4	Scanned
5.3.3.1.6(a)	Vector Graphic
5.3.3.1.6(b)	Vector Graphic
5.3.3.1.6(c)	Scanned
5.4.1.0	Vector Graphic
5.4.1.1.1	Vector Graphic
5.4.1.1.2	Scanned
5.4.1.1.3	Scanned
5.4.1.1.4	Scanned
5.4.1.1.5	Scanned
5.4.1.1.6(a)	Vector Graphic
5.4.1.1.6(b)	Vector Graphic
5.4.1.1.6(c)	Vector Graphic
5.4.1.1.6(d)	Scanned
5.4.1.1.8(a)	Scanned
5.4.1.1.8(b)	Scanned
5.4.1.1.8(c)	Scanned
5.4.1.1.8(d)	Scanned
5.4.1.1.8(e)	Scanned
5.4.1.1.8(f)	Scanned
5.4.1.1.8(g)	Scanned
5.4.1.1.9	Scanned
5.4.1.2.1	Scanned
5.4.1.2.2	Scanned
5.4.1.2.3	Scanned
5.4.1.2.4	Scanned
5.4.1.2.6(a)	Vector Graphic
5.4.1.2.6(b)	Vector Graphic
5.4.1.2.6(c)	Vector Graphic
5.4.1.2.6(d)	Vector Graphic
5.4.1.2.6(e)	Vector Graphic
5.4.1.2.6(f)	Vector Graphic

Figure No.	Current Form
5.4.1.2.6(g)	Vector Graphic
5.4.1.2.6(h)	Scanned
5.4.1.2.7	Scanned
5.4.1.2.8(a)	Scanned
5.4.1.2.8(b)	Scanned
5.4.1.2.8(c)	Scanned
5.4.1.2.8(d)	Scanned
5.4.1.2.8(e)	Scanned
5.4.1.2.8(f)	Scanned
5.4.1.2.8(g)	Scanned
5.4.1.2.8(h)	Scanned
5.4.1.2.8(i)	Scanned
5.4.2.0	Scanned
5.4.2.1.1(a)	Scanned
5.4.2.1.1(b)	Scanned
5.4.2.1.2(a)	Scanned
5.4.2.1.2(b)	Scanned
5.4.2.1.3(a)	Scanned
5.4.2.1.3(b)	Scanned
5.4.2.1.6(a)	Vector Graphic
5.4.2.1.6(b)	Vector Graphic
5.4.2.1.6(c)	Scanned
5.4.2.1.8(a)	Scanned
5.4.2.1.8(b)	Scanned
5.4.2.2.1	Scanned
5.4.2.2.2	Scanned
5.4.3.1(a)	Vector Graphic
5.4.3.1(b)	Vector Graphic
5.4.3.1(c)	Vector Graphic
5.4.3.2(a)	Scanned
5.4.3.2(b)	Scanned
5.4.3.3	Scanned
5.5.1.0	Scanned
5.5.1.1.1	Scanned
5.5.1.1.2	Scanned
5.5.1.1.3(a)	Scanned
5.5.1.1.3(b)	Scanned
5.5.1.1.4	Scanned
5.5.1.1.6	Vector Graphic
5.5.1.1.8(a)	Scanned
5.5.1.1.8(b)	Scanned
5.5.1.1.8(c)	Scanned
5.5.1.1.8(d)	Scanned
5.5.1.2.1	Scanned
5.5.1.2.2	Scanned
5.5.1.2.3	Scanned
5.5.1.2.4	Scanned
5.5.1.2.6	Vector Graphic
5.5.1.2.8(a)	Scanned

Figure No.	Current Form
5.5.1.2.8(b)	Scanned
5.5.1.2.8(c)	Scanned
5.5.2.0	Scanned
5.5.2.1.6(a)	Vector Graphic
5.5.2.1.6(b)	Vector Graphic
5.5.3.1.6	Vector Graphic
5.5.3.2.6	Vector Graphic
5.6.1.1.1	Scanned
6.2.1.0	Scanned
6.2.1.1.1	Scanned
6.2.1.1.3	Scanned
6.2.1.1.4(a)	Scanned
6.2.1.1.4(b)	Scanned
6.2.1.1.4(c)	Scanned
6.2.1.1.8(a)	Scanned
6.2.1.1.8(b)	Scanned
6.2.1.1.8(c)	Scanned
6.2.1.1.8(d)	Scanned
6.2.1.1.8(e)	Scanned
6.2.2.0	Scanned
6.2.2.1.1(a)	Scanned
6.2.2.1.1(b)	Scanned
6.2.2.1.4(a)	Scanned
6.2.2.1.4(b)	Scanned
6.3.1.0	Scanned
6.3.1.1.1	Scanned
6.3.1.1.4	Scanned
6.3.1.1.6(a)	Vector Graphic
6.3.1.1.6(b)	Vector Graphic
6.3.2.0	Scanned
6.3.2.1.1	Scanned
6.3.2.1.2	Scanned
6.3.2.1.3	Scanned
6.3.2.1.4	Scanned
6.3.3.0	Scanned
6.3.3.1.1(a)	Scanned
6.3.3.1.1(b)	Scanned
6.3.3.1.4(a)	Scanned
6.3.3.1.4(b)	Scanned
6.3.3.1.6(a)	Vector Graphic
6.3.3.1.6(b)	Vector Graphic
6.3.3.1.6(c)	Vector Graphic
6.3.3.1.6(d)	Vector Graphic
6.3.3.1.8(a)	Scanned
6.3.3.1.8(b)	Scanned
6.3.3.1.8(c)	Scanned
6.3.3.1.8(d)	Scanned
6.3.4.0	Vector Graphic
6.3.4.1.1	Vector Graphic
6.3.4.1.4	Vector Graphic
6.3.4.1.5	Vector Graphic
6.3.4.1.6(a)	Vector Graphic
6.3.4.1.6(b)	Vector Graphic
6.3.4.1.6(c)	Scanned
6.3.5.0	Vector Graphic
6.3.5.1.1	Scanned
6.3.5.1.4(a)	Scanned
6.3.5.1.4(b)	Scanned
6.3.5.1.4(c)	Scanned
6.3.5.1.6(a)	Vector Graphic
6.3.5.1.6(b)	Vector Graphic
6.3.5.1.6(c)	Vector Graphic
6.3.5.1.6(d)	Scanned
6.3.5.1.7(a)	Scanned
6.3.5.1.7(b)	Scanned
6.3.5.1.7(c)	Scanned
6.3.5.1.7(d)	Vector Graphic
6.3.5.1.7(e)	Vector Graphic
6.3.5.1.8(a)	Vector Graphic
6.3.5.1.8(b)	Vector Graphic
6.3.5.1.8(c)	Vector Graphic
6.3.5.1.8(d)	Vector Graphic
6.3.5.1.8(e)	Vector Graphic
6.3.5.1.8(f)	Vector Graphic
6.3.5.1.8(g)	Vector Graphic
6.3.5.1.9(a)	Vector Graphic
6.3.5.1.9(b)	Scanned
6.3.5.1.9(c)	Scanned
6.3.6.0	Scanned
6.3.6.1.1	Scanned
6.3.6.1.2	Scanned
6.3.6.1.3	Scanned
6.3.6.2.1(a)	Scanned
6.3.6.2.1(b)	Scanned
6.3.6.2.4(a)	Scanned
6.3.6.2.4(b)	Scanned
6.3.7.0	Scanned
6.3.7.1.1	Vector Graphic
6.3.7.1.2	Vector Graphic
6.3.7.1.3(a)	Scanned
6.3.7.1.3(b)	Scanned
6.3.7.1.4	Scanned
6.3.7.1.5	Scanned
6.3.7.1.7	Scanned
6.3.8.0	Scanned
6.3.8.1.1	Scanned
6.3.8.1.4	Scanned
6.3.8.1.5(a)	Scanned

Figure No.	Current Form	Figure No.	Current Form
6.3.8.1.5(b)	Scanned	7.2.1.1.1	Vector Graphic
6.3.8.1.6(a)	Scanned	7.2.1.1.4	Vector Graphic
6.3.8.1.6(b)	Scanned	7.3.2.0	Vector Graphic
6.3.9.0(a)	Vector Graphic	7.3.2.1.6(a)	Vector Graphic
6.3.9.0(b)	Vector Graphic	7.3.2.1.6(b)	Vector Graphic
6.3.9.0(c)	Vector Graphic	7.3.2.2.6	Vector Graphic
6.3.9.1.1(a)	Vector Graphic	7.4.1.0	Scanned
6.3.9.1.1(b)	Vector Graphic	7.4.1.1.1	Scanned
6.3.9.1.4	Vector Graphic	7.4.1.1.4(a)	Scanned
6.3.9.1.5	Vector Graphic	7.4.1.1.4(b)	Scanned
6.3.9.1.6(a)	Vector Graphic	7.4.1.1.5	Scanned
6.3.9.1.6(b)	Vector Graphic	7.4.1.1.6	Vector Graphic
6.3.9.1.6(c)	Vector Graphic	7.4.2.0	Scanned
6.3.9.1.6(d)	Vector Graphic	7.4.2.1.4	Scanned
6.3.9.1.6(e)	Vector Graphic	7.4.2.1.6	Vector Graphic
6.3.9.1.6(f)	Vector Graphic	7.5.1.1.6(a)	Vector Graphic
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DD Form 1426, FEB 1999 (EG) *PREVIOUS EDITION IS OBSOLETE* *WHS/DIOR, Feb 99*

MIL-HDBK-205A
15 JULY 1985
SUPERSEDING
MIL-HDBK-205
11 JUNE 1957

MILITARY HANDBOOK

PHOSPHATE AND BLACK OXIDE COATING OF FERROUS METALS

DEPARTMENT OF DEFENSE • UNITED STATES OF AMERICA

No deliverable data required by this document.

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DEPARTMENT OF DEFENSE
WASHINGTON, DC 20301

Phosphate and Black Oxide Coating
of Ferrous Metals

MIL-HDBK-205A

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FOREWORD

This handbook provides a working knowledge of phosphate and black oxide coatings of ferrous metals as used by the Department of Defense for equipment and ordnance. It is not intended to be an exhaustive treatise on the subject, but rather to furnish detailed information on phosphate and black oxide coatings that have proved satisfactory in service. It is intended to supplement, but not replace, various specifications and standards covering these coatings.

A survey of military users of phosphate and black oxide coatings was conducted. Consequently, the information contained in this handbook describes processing procedures, chemical control methods, cleaning operations and equipment used by the military.

GENERAL REFERENCES

Federal and Military specifications and standards are government publications and are available from the Naval Publication and Forms Center, 5801 Tabor Avenue, Philadelphia, PA 19120.

Aerospace Material Specifications are available from the Society of Automotive Engineers, Inc., 400 Commonwealth Drive, Warrendale, PA 15096.

ASTM specifications and standards may be obtained from the American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103.

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1. INTRODUCTION

1.1 General. Protective coatings composed of insoluble phosphate crystals or iron oxides are applied to ferrous metal parts by a number of component processes in which varying types of chemical solutions are used. (The iron oxide coatings are commonly known as black oxide coatings.) The following three stages are normally used to apply the coatings. These are:

Cleaning and pretreatment
Coating
Preservation Treatment

The objective of the coating process is to provide an economical base for subsequent treatment which will protect parts from corrosion resulting from abrasion or exposure to moisture and perspiration.

The zinc or manganese phosphate coatings are formed on the parts by dipping the iron or steel parts in a solution of zinc or manganese dihydrogen phosphate containing an oxidizing agent such as nitrate. The pH of the solution ranges from 2.0 to 2.5. As iron is dissolved from the part by the acidic solution, the pH of the solution adjacent to the part increases until the insoluble phosphate coating is deposited on the part. In the spray operation the reactions are similar and occur at the interface between the solution and the surface of the parts being treated.

The insoluble phosphates involved in the phosphate processes are of three types. An insoluble phosphate consisting of zinc, manganese or iron monohydrogen phosphate is precipitated at a pH of about 4. This material is found in the sludge in the bottom of the tanks and in the scale on heating surfaces and tank walls. The monohydrogen phosphate salts are soluble in an excess of phosphoric acid and serve as a buffer to prevent the accumulation of excess phosphoric acid in the processing bath. The phosphate coatings, normal phosphate salts, are formed at a PH of approximately 5.8 and are not easily dissolved in phosphoric acid even when exposed to an excess of that acid.

The zinc base phosphate coatings consist primarily of two crystals [$Zn_2Fe(PO_4)_2{:}4H_2O$ and $Zn_3(PO_4)_2{:}4H_2O$]. The proportions of the two crystals vary depending upon many factors. These factors include: The composition of the phosphating bath, the temperature of the phosphating bath, and the surface preparation which determines the number of sites on which the crystals form.

The manganese base phosphate coatings have not been as well characterized as the zinc base phosphate coatings but it is believed that the crystal composition is similar.

Water of Crystallization will be lost when the phosphate coating is exposed to elevated temperatures. This loss results in a non-adherent powdery coating and a subsequent decrease in corrosion resistance. Exposure of no more than 15 minutes to temperatures in air of 225°F (107°C) will not adversely affect a zinc phosphate coating Corresponding temperature for manganese phosphate coatings is 375°F (190°C). Exposure at these temperatures for longer times or for shorter times at higher temperatures will cause a decrease in corrosion resistance.

The black oxide coatings are formed by immersing the iron or steel parts in a solution where the iron or steel surface is converted to an oxide, generally believed to be Fe_3O_4. The bath for Class 1 treatments is a concentrated solution of sodium hydroxide and sodium nitrate. The bath for class 3 treatments is a molten dichromate salt, usually potassium dichromate. The bath for class 4 treatments is a concentrated solution of sodium hydroxide and proprietary sulfur compounds which form an oxide-sulfide coating.

The phosphate coatings are intended to provide supplementary resistance by holding a corrosion resistant finish such as an oil in the voids of the crystalline coating. Recent work has demonstrated that the phosphate coating itself provides some temporary corrosion resistance independent of the oil.

To obtain coatings (phosphate or black oxide) with the maximum corrosion resistance, it is necessary to remove all foreign matter from the part and process the part in a properly controlled chemical bath. On parts to be phosphated the surface must be conditioned to ensure that the crystalline coating has the desired structure. The preferred system is to remove all grease and oil, clean with abrasive blasting and process in a properly controlled bath.

Phosphate coatings meeting TT-C-490 are commonly suggested as the base for a paint specified by the procuring agency. The presence of the phosphate coating under the paint film aids in preventing underfilm corrosion and increases the durability of the paint film.

The black oxide coatings are commonly finished with a corrosion resistant oil. Both phosphate and black oxide coatings are used on a variety of military parts. Some examples of applications are listed in the Appendix.

Any of these protective coatings will be ineffective if their continuity is broken by surface defects that serve as points of entry for corrosive substances. Such imperfections are unavoidable unless the metal surface is completely free of dust, grit, oil, acid and alkaline residues, rust, and other contaminants before the protective coating is applied.

1.2 Cleaning. Thorough cleaning of the metal surface is of prime importance in the application of any of the coatings described in this handbook. With few exceptions, the methods followed for the removal of specific contaminants are similar in all systems. Thus, the cleaning methods described in this handbook apply to all the protective coatings described.

1.3 Conditioning. Some cleaning methods which are used to remove certain types of soil will cause the formation of coarse crystalline phosphate coatings which give inferior corrosion resistance. The use of these cleaners is required to remove the soil. The use of a grain refinement treatmemt chemical will change the surface and will result in a corrosion resistant crystalline structure. The material commonly used for this purpose ahead of zinc phosphate treatments is sodium monohydrogen phosphate containing titanium phosphate. The material commonly used prior to manganese phosphate treatments is a manganese phosphate. In order for these chemicals to have the desired affect on the coating formation, they are specially treated during manufacture. Conditioning salts increase the number of sites at which the phosphate coating is formed, thus producing a fine uniform coating rather than a coarse crystalline coating.

1.4 Phosphate coatings.

1.4.1 Manganese base phosphate coating, DOD-P-16232, type M. This phosphate protective coating, which ranges in color from gray to black depending upon the alloy being treated with high carbon alloys being darker, is used on iron and steel. The manganese base phosphate coating, although more resistant to heat than the zinc base phosphate coating, decomposes between 375°F (190°C) and 425°F (216°C). The coating may be applied to all clean ferrous metal parts with the exception of springs having a wire diameter less than one-eighth inch (3mm) and barrel bores, Patent No. 4194929, "Technique for Passivating Stainless Steel", describes a procedure for phosphating stainless steel. This phosphate coating is commonly used with a petroleum base, supplementary finish on articles or sections of articles not receiving paint. If the phosphate coated item is to be painted, no petroleum or wax based finish should be used prior to the application of the paint, as the petroleum or wax will interfere with the adhesion of the paint to the part. Manganese phosphate coatings are also used to improve the wear resistance of sliding surfaces which are under heavy load such as gear teeth. These coatings should not be used on roller or ball bearings.

1.4.2 Zinc base phosphate coating, DOD-P-16232, type Z. This phosphate protective coating, which ranges in color from gray to black depending upon the alloy, is used on iron and steel. It is suitable for application to parts where contact with alkaline materials or exposure to temperature in excess of 225°F (105°C) is not expected. The maintenance of the equipment is easier with the zinc based phosphate than with the manganese based phosphate. Also, zinc phosphate coatings normally provide greater corrosion resistance than manganese phosphate coatings, with or without supplemental coatings.

1.4.3 Phosphate coating for paint base, TT-C-490, type I. This coating process consists of a chemical treatment which produces a uniform, adherent, crystalline, phosphate coating on iron and steel surfaces. The color of the coating ranges from gray to black depending upon the alloy. The coating inhibits corrosion, retards the progress of filiform and underfilm corrosion, increases adhesion, and results in greater durability of applied paint finishes. The surface to be treated must be clean and free of rust, scale, dirt, paint or similar contaminant. The coatings used for TT-C-490, Type I normally are much lower in coating weight than those meeting DOD-P-16232.

1.5 Black Oxide Coatings.

1.5.1 Applications. These coatings are particularly suited for use on moving parts (sliding or bearing surfaces) which cannot tolerate the dimensional build-up of the more rust-resistant coatings. They are not recommended for weapons going into long-term storage because of their poor corrosion resistance.

1.5.2 Alkaline oxidizing process (for wrought iron, plain carbon, and low alloy steels), MIL-C-13924 class 1. This coating is applied by immersing the clean ferrous metal parts in an aqueous alkaline oxidizing bath at temperatures in the range of 285° to 290°F (140° to 143°C). The parts are then rinsed in water, dipped in a chromate rinse solution and dried. This coating is applicable to plain carbon steel, most low alloy steels cast and malleable irons.

1.5.3 Fused salt oxidizing process (for corrosion resistant steel alloys which are heated to 900°F (428°C) or higher MIL-C-13924, Class 3. This coating is applied by immersing the clean parts in molten dichromate salts at temperatures ranging from 825°F (440°C) to 850°F (455°C). Tempering can be done in conjunction with the blackening at temperatures up to 900°F (482°C) and is applicable to chromium stainless steels with draw temperatures above 900°F (482°C).

1.5.4 Alkaline oxidizing process (for 300 series corrosion resistant alloys), MIL-C-13924, Class 4. This coating is applied by immersing the clean parts in the aqueous alkaline oxidizing bath at temperatures in the 250° to 260°F (121° to 127°C) range.

2. CLEANING

2.1 Cleaning methods.

2.1.1 General. Surface preparation is one of the most important factors affecting the performance of the protective coating. The selection of an appropriate cleaning method for ferrous metals depends on three important factors:

The type and quantity of the grease, oil, and other soil
The equipment available, and
The residual effect of the cleaner on the coating produced

CAUTION: Protection from solvent splashing and projected particles is required. Goggles are the minimum protection and must be worn. Also, face shields, rubber aprons, rubber gloves, rubber boots, etc., must be used if needed.

Secondary, but very practical considerations include cost, quantities of parts involved, etc.

In general, there are three types of surface contaminants which must be removed to obtain adhesion of the protective coating. They are:

Grease, oil, drawing compounds, and dust from rolling, forming, extruding, machining, handling, etc.
Rust and mill scale, and
Salts or other chemicals which may or may not be visible but which serve as nuclei for rust formation.

No single cleaning process removes all of the surface contaminants encountered. Therefore, proper selection as well as the order of application of any combination of cleaning processes must be made. The best way to understand how a cleaning method or methods is selected is through knowledge of the properties and limitations of the various cleaning materials available commercially. Therefore, in this chapter the various mechanical and chemical surface cleaning methods and equipment presently in use will be outlined. It should be noted that abrasive blasting is recommended (and for some items required) as a final cleaning process prior to heavy phosphate coating (DOD-P-16232).

2.1.2 Solvent cleaning. Before adopting any solvent cleaning procedure, an investigation of the hazards involved and the regulations issued by the EPA and/or OSHA pertaining to the use of the solvents being considered should be completed.

Solvent cleaning is one of the oldest methods used for the removal of soil from a metal surface. The solvents employed cover a wide class of chemicals including mineral spirits, chlorinated hydrocarbons, etc. All solvents are potentially hazardous and should be used under such conditions that their concentration in the air being breathed by the workmen is within safe limits. Benzene, gasoline, and carbon tetrachloride should be avoided because of their toxicity or flammability. Solvents readily remove oils and greases, are easily applied, and the necessary equipment occupies a minimum of space. Unfortunately there are some serious disadvantages inherent in solvent cleaning which impose limitations on its use. These disadvantages include:

> Both solvent and applicator are soon contaminated and therefore instead of removing oil completely, only redistribute it.
>
> Solvent cleaning is expensive if carried out properly. Effective solvents have a high initial cost, distillation for re-use is expensive, and losses may be expected.
>
> Only oils and greases are removed. No rust or scale is removed. Rust stimulators, soaps, and salts may not be removed by some solvents in which case they must be removed or neutralized by other means.
>
> The fumes from some of the best solvents are toxic or represent long or short term health hazards in many instances. This includes most chlorinated solvents and aromatics.
>
> Some chlorinated solvents are decomposed by heat in contact with water and metal, forming hydrochloric acid which attacks the equipment and stimulates corrosion of clean parts.

The methods generally used in solvent cleaning are outlined in paragraphs 2.1.2.1 and 2.1.2.2.

2.1.2.1 Dipping. In dipping operations, parts are immersed in either cold or warm solvent. Usually two or more tanks are used for preliminary cleaning with the remainder used for rinsing. When the solvent in the first tank becomes contaminated, it should be discarded. The next tank should then be used for the preliminary cleaning and the clean solvent used for the final rinse.

2.1.2.2 Vapor degreasing. Cleaning materials by vapor degreasing consists of removing oils and greases from the part by suspending it in the vapor of chlorinated solvents. The vapors condense on the relatively cold metal surface and the condensate dissolves and rinses off the grease and other soils soluble in the solvent.

Equipment for vapor degreasing is specially engineered by the equipment manufacturers for proper heat input to control the solvent liquid and vapors. Machines are built with one or more compartments as required by the process. For continuous production, units are conveyorized and normally enclosed. Equipment for this type of cleaning is described briefly in section 2.2.2 and must be designed and assembled to enable the user to comply with all EPA and OSHA regulations. Vapor degreasing equipment is available meeting OSHA and EPA requirements.

2.1.3 Alkali cleaning. Alkali cleaning is usually more efficient, cheaper, and less hazardous than solvent cleaning. Alkaline cleaner chemicals, which are formulated to perform a variety of cleaning and pretreatment functions, are soluble in water and used at elevated temperatures. These formulations clean by saponifying certain oils and greases while their surface active additive components wash away other types of contaminants. Soil removal is accomplished through detergency or saponification, rather than solvency. Soil is removed mainly by displacement from the surface rather than by direct solution, as in solvent cleaning. One of the desirable characteristics of an alkaline cleaner is its ability to maintain reasonably high alkalinity despite the introduction of acidic soils or consumption of the alkali in the saponification of oils. Since no single alkaline salt has all the necessary properties (i.e., high pH, buffering action, rinsability, wetting and emulsifying action, detergent properties, etc.), blended alkaline cleaners are almost exclusively used today. These blends will differ depending on the cleaning problem of any given material, the kind of soil to be removed, and the equipment available.

Temperature is an important consideration in the application of any alkaline cleaner. Heat enhances the activity of the cleaner and improves the effectiveness of the alkaline cleaner components. Soaps formed by saponification of fatty acids are soluble in water and are readily removed by rinsing with water. Alkalies are less effective than solvents for removing heavy or carbonized oils, rust inhibitive oils, etc. Alkaline cleaners can be formulated to remove rust by immersion or electrolytic methods. (See MIL-C-14460.) Removal of heavy rust will require electrolytic action. The methods used in alkaline cleaning are outlined in paragraphs 2.1.3.1 to 2.1.3.3.

2.1.3.1 Dipping. In dipping operations, the contaminated parts are immersed in hot alkaline solutions contained in tanks. The use of two tanks is recommended. Some mechanical agitation is desirable to increase the effectiveness of this method of alkaline cleaning. One simple method of supplying this agitation is to maintain the cleaner at a rolling boil. Alkaline cleaners in a dip process are usually used at concentrations of 4 to 10 ounces per gallon (30 to 75 grams per liter), and at temperatures ranging from 180°F (82°C) to a rolling boil. Tanks should be equipped with an overflow weir so that oil and other floating contamination can be skimmed or overflowed periodically. See section 2.1.8.3 concerning disposal of the skimmings from the alkaline cleaner solutions.

2.1.3.2 Pressure spraying. In the spray process the contaminated parts are sprayed with the alkaline cleaning solution, usually in a mechanical system. The alkaline cleaning solution is pumped from a heated reservoir and applied to the metal under pressure through an array of nozzles. Alkaline spray cleaners are generally formulated with low foaming surface active agents to eliminate excessive foaming. Alkali concentrations used in power spraying are, in general, considerably lower than those used in other methods. One-quarter to 2 ounces per gallon (2 to 15 grams per liter) is the usual concentration range recommended. Recommended temperatures range from 160°F to 180°F (70° to 80°C), and cleaning time ranges from 30 to 75 seconds.

2.1.3.3 Electrolytic cleaning. Electrolytic cleaning is seldom used ahead of phosphate treatments due to the tendency for this type of cleaning to condition the metal surface such that non-uniform coatings are produced (phosphate coatings consisting of large crystals separated by uncoated areas). When electrolytic cleaning is used ahead of phosphate treatments, it is necessary to follow it with conditioning treatments as described in Section 3 which ensure the formation of the desired coating crystal structure. Electrolytic alkaline cleaning generates large quantities of gas close to the soil and is, consequently, very effective in providing a high level of mechanical agitation. The gas can be generated at the anode or cathode depending on the system employed. While a greater volume of gas is evolved at the cathode, there is a tendency to deposit small quantities of impurities. The trend has recently developed to combine cathodic and anodic cycles although straight anodic cleaning has been effectively used. High conductivity is important so electrolytic cleaners usually contain caustic soda. The electrolytic cleaners are used at higher concentrations than other alkaline cleaning methods. Recommended concentrations range from 6 to 14 ounces per gallon (45 to 105 grams per liter) and temperatures range from 180°F (82°C) to a rolling boil. In this method of cleaning, a reasonable amount of foam is desirable to hold down the mist that is generated by electrolysis.

2.1.4 Emulsion cleaning. Emulsion cleaning methods are designed to bring a soil into contact with both an organic solvent and water solution of surface active agents, so that the water and solvent soluble soils may be dissolved, and the soils dispersed in a water medium prior to being flushed away by a water rinse. In general, these cleaners leave a thin residue of an oily nature. When a protective coating is to be applied to the parts, this film must be removed by an additional cleaning operation. In other instances, it is desirable to have this light film of oily material to provide some rust protection during in-plant storage.

Because of the nature of the emulsions, there are no convenient methods for the control of the concentration of these cleaners other than performance checks.

While these cleaners are more effective in spray equipment, they have been used in dipping tanks. In dipping installations, the emulsion cleaners show some effectiveness at dilutions close to 1 to 10, and at temperatures of 160° to 200°F (71° to 93°C). In spray cleaning, the tank may be 140° to 180°F (60° to 83°C). Above these temperatures, solvent evaporation becomes a problem. A hot water rinse is recommended following emulsion cleaning.

In emulsion cleaners the solvent is present in the form of very fine droplets dispersed in the water solution and stabilized by surface active agents. In general, the solvents used are of the hydrocarbon type so that flammability becomes a problem but in emulsion cleaning the solvent is so well dispersed in water that a moderate flash point solvent can be used at temperatures as high as 180°F (83°C) without much danger. This cleaner concentrate consists of emulsifying agents, surface active agents, organic solvents, and, in some formulations, water. These formulations emulsify when mixed with water. Emulsion cleaners are used at concentrations ranging from 1 part of concentrate to 10 to 200 parts of water.

2.1.5 Steam cleaning. Steam cleaning is quite often used to remove soil when the parts to be cleaned do not lend themselves to soak or spray cleaning and the improved quality of cleaning over hand cleaning is desired. In steam cleaning, steam or hot water under pressure, along with detergents, is directed against the work to be cleaned through a hose fitted with an appropriate nozzle. The detergent used can be caustic enough to remove all oil paint as well as dirt, grease, smudge, soot, etc. The surface to be cleaned should be wetted to allow the cleaning compound to loosen foreign matter which is later removed by a cleaning pass. In applying the cleaning compound, the speed of spraying should be comparable to that used for spray painting. Several rapid passes are better than one very slow pass. Since large amounts of steam and chemicals are consumed in this type of cleaning, the cost may be several times that of immersion or spray cleaning.

CAUTION: The operators of steam cleaning equipment must wear protective clothing as well as face and eye protection to avoid burns from the steam, the hot equipment, and/or the caustic solutions.

2.1.6 Phosphoric Acid Cleaning.

2.1.6.1 Brush cleaning. The wash-off type material is commonly applied by hand using brushes or sponges when; production is small or infrequent, the area to be treated is large, and the most economical and practical application is by hand.

The use of the brush-on method requires cleaning of the metal before using the phosphoric acid if a heavy coating of grease or drawing compounds are present. For mild rust, a concentration of 1 volume of acid cleaner to 1 or 2 volumes of water should be used. Experience will indicate the most effective concentration to use. The diluted cleaner is applied with a brush or sponge and the surface thoroughly scrubbed. More than one application may be necessary. Before the cleaning solution dries, it is rinsed with clean water in a tank or with running water from a hose.

CAUTION: For safety reasons, the operators must use face shields, rubber gloves, rubber aprons, and rubber boots when using these materials. Care must be taken to protect adjacent equipment.

2.1.6.2 Spray application. The nonfoaming type solutions are applied by spraying a solution of the chemical on the parts. The operating solution is prepared by diluting the concentrate with water. The normal dilution is 1 volume of concentrate to 3 volumes of water. However, experience may indicate that greater or smaller dilutions should be used. The solution is applied at temperatures of about 150°F (65°C). This type of application is normally use in a spray tunnel in which the parts are transferred from stage to stage by a conveyor. These stages consist of a spray alkali cleaning, a water rinse, a phosphoric acid pickle, another water rinse, a conditioning compound treatment (Section III), a zinc phosphate treatment, another water rinse followed by a chromate rinse. After the chromate rinse the part is dried. It should be noted that some of these stages are omitted at times.

2.1.6.3 Immersion cleaning. Immersion tank type solutions are recommended for parts with medium to large production which can be conveniently treated in immersion tanks. The recommended dilution is three volumes of water per each volume of the concentrate. However, experience may indicate that greater or less dilution is preferred.

CAUTION: For safety reasons, the operators must wear face shields, rubber gloves, and rubber boots when using these chemicals.

2.1.7 Acid pickling. Acid cleaning is not recommended as a method of cleaning if any other method will remove the soils. When metal dissolves in acid, atomic hydrogen is released and a portion of this is absorbed or dissolved in the metal. Any resulting embrittlement of the metal, known as hydrogen embrittlement, can result in breakage of steel under stress unless the hydrogen is removed. Hydrogen removal is usually accomplished with heat. The temperature and times required to remove the hydrogen absorbed during pickling may also destroy the corrosion resistance of the phosphate coatings. For this reason, pickling should never be employed before a phosphating operation which is used to meet DOD-P-16232 without permission of the procuring agency. The higher temperatures used in the black oxide treatments will normally drive off the absorbed hydrogen from most hydrochloric acid pickles. This acid is frequently used prior to black oxide treatments to remove all traces of corrosion.

Special provisions shall be required to handle embrittlement when treating steel parts with an ultimate tensile strength of 200,000 psi (1379 MPa) or above. See 5.1.5.

In acid pickling, metals are immersed in acid solutions for the purpose of removing oxides and/or scale. The various acids used in commercial pickling are sulfuric, hydrochloric (muriatic), nitric, phosphoric, and mixtures of these acids. Sulfuric acid, because of its low cost, high boiling point, availability, and general suitability, is used widely in the pickling of mild and low carbon steels. Pickling is usually carried out by immersing the work in suitable pickle baths. However, the same factors apply if the pickling solution is sprayed or flowed over the work or if the work is pulled through baths of acid as in the continuous pickling of strip steel. Acids suitable for pickling not only remove scale from the base metal but also attack and pit it. When this occurs, metal and acid are wasted, and more smut develops which must be removed before subsequent coating treatment. To prevent the formation of smut, inhibitors, such as dibutylthiourea or proprietary materials are frequently recommended. When inhibitors are used, care must be taken to prevent the inhibitor from being carried into the coating treatment bath (phosphate or black oxide). Careful control of the amount of metal removed by controlling the acid concentration, time in the acid, and the temperature, is preferred as the means of avoiding excess pickling of the parts but when some areas are heavily rusted or scaled and other areas are not, the use of an inhibitor may be necessary.

Before pickling, oils, grease, and surface contaminants should be removed by solvent or alkali cleaning. After pickling, the work should be thoroughly rinsed. Then the metal should be treated to give a surface suitable for the treatments which are to follow.

When acid pickling is used, provision for safe handling of these hazardous materials must be provided. Workmen must wear eye protection, face shields, acid resistant clothing, gloves, and boots. Provision for the removal of the fumes released must be provided. Copies of the applicable EPA and OSHA regulations should be obtained and provision made to comply with them.

The rate at which acid solution approaches saturation with iron varies depending upon production conditions. Eventually it becomes necessary to discard the spent pickle solution. Local regulations vary as to the treatment required. Provision must be made to comply with these regulations.

2.1.8 Abrasive blasting. Blast cleaning consists of cutting, chipping, or abrading the surface through the high velocity impact of abrasive particles against the surface. Ordinarily, no other cleaning is necessary on pieces that have been blast cleaned. Rust, mill scale, and old paint, are removed. On parts which are contaminated with grease or oil, degreasing is required before blast cleaning.

There are three methods that can be used to accelerate and discharge the abrasive from the equipment:

Discharging the abrasive in a stream of high pressure gas such as air,

Discharging the abrasive in a stream of high pressure liquid such as water,

Discharging the abrasive centrifugally from the periphery of a rotating paddle wheel traveling at a high peripheral speed.

In blast cleaning operations, the impact velocity of the abrasive against the metal should correspond to its most effective abrasion level which depends upon the particle size, shape, hardness and its breakdown rate. The key to obtaining economical blast cleaning rates lies in the proper selection and use of the abrasive. The abrasive used may be metallic, siliceous (containing free silica), or nonmetallic synthetic (containing no free silica). When aluminum oxide abrasives are used, care must be taken to remove all abrasives and abrasive dusts from the parts before they are immersed in the phosphate solution. The aluminum can dissolve in the phosphate bath and inhibit the coating formation. Abrasives may be any one of three shapes (shot, grit, or semishape abrasive) or may consist of a mixture of shapes.

Some of the important factors which help to determine the abrasives to be used are:

Type of metal to be cleaned
Shape of the part
Kind of material to be removed
Loss of abrasive
Breakdown rate of the abrasive
Cost of reclaiming the abrasive
Hazards associated with use of the abrasive

> CAUTION: Any abrasive cleaning system should be designed to protect the workers from the dust. This is particularly important if silica containing abrasives are used.

All mill scale, rust, rust scale, paint or any other foreign matter should be removed and the surface appear as a grayish metallic white, very uniform in color and slightly roughened. Abrasive blasting is required as the final cleaning before heavy coatings (DOD-P-16232) are applied.

2.1.8.1 Nozzle blast cleaning. Nozzle blast cleaning utilizes a fluid medium to transport the abrasive. The fluid medium may be air or water. Three types of nozzle blast cleaning units are in general use.

2.1.8.1.1 Direct pressure type. A compartment or tank is held under constant pressure during the blasting operation. Abrasive is fed under pressure from the bottom outlet where the blasting stream of air meets the abrasive and carries it to the blast nozzle. This system offers many advantages over the gravity feed and suction feed units.

2.1.8.1.2 Suction Feed Type. The abrasive is drawn to the blast gun through an induction chamber. In the induction chamber the abrasive is fed to the blast gun by a small jet of compressed air. The expanded air and abrasive are passed through a large nozzle and directed at the work. This system is seldom employed in large applications.

2.1.8.1.3 Gravity Feed Type. The feed flows from a hopper at an elevation above the blast gun through the induction chamber behind the larger nozzle of the suction blast gun similar to the one described in 2.1.9.1.2.

2.1.8.2 Wheel Blast Cleaning. Lowest costs are achieved by use of a wheel blast cleaning system. The many advantages of wheel blast cleaning over air or nozzle blast cleaning are sufficiently great to warrant the installation of extensive wheel blast machines where feasible. One of the big advantages of using wheel blast cleaning equipment is the elimination of air compressors and pipelines and attendant labor. Other advantages are in the compactness and self-sufficiency of the unit as well as the ease of starting, the simplicity of the power supply, etc. The principle disadvantages of this type of equipment are the high initial cost, the high maintenance cost and shut down time for repair and maintenance. Where the equipment is used a high percentage of the time, it will furnish low cost cleaning.

Two types of wheels are used, the batter type and the slide type. In the batter type, the abrasive is propelled by impact when it comes in contact with the edge of the vanes. In the commonly used slide type, the abrasive is charged through the hub of the wheel and slides on the vanes to the edge of the wheel where it is projected at high velocity towards the work. The type of abrasive used with the wheel blast cleaning equipment is usually metallic.

2.1.8.3 Disposal of spent cleaning media. Consideration must be given to the proper disposal of spent cleaning media and the soil removed when selecting a cleaning method. Most cleaning procedures suspend the soils removed in the cleaning media and it is necessary to discard the mixture periodically in order to continue to remove soil. Selection of the disposal method will depend upon the local waste disposal regulations, the cleaning method used, and the soils being removed. Discussion of the disposal procedures and instructions is outside the scope of this handbook.

2.2 *Cleaning Equipment*

2.2.1 General. Only the major equipment required for each method of cleaning is outlined in this section. Further information concerning such equipment or any accessories needed may be obtained from current literature or from manufacturers. The necessity to comply with EPA and OSHA regulations and to allow for treatment of the spent cleaning media for proper disposal should be considered in the design and layout of any equipment.

2.2.2 Solvent Cleaning Equipment. Two or more solvent tanks are necessary for immersion solvent cleaning. For vapor degreasing, equipment which is specially engineered for proper heat input and control of solvent liquid and vapor is required. Machines are built with one to three or occasionally more compartments. Figure 1 illustrates a conventional degreaser with one compartment. For all solvent cleaning, equipment for reclaiming or recycling the solvent is needed, otherwise this method of cleaning is prohibitively expensive.

2.2.3 Alkali Cleaning Equipment. For immersion cleaning, tanks for the solution and equipment for heating the solution are required. Tanks equipped with electrodes or tumbling barrels with electrodes (very effective for small parts where electrolytic and mechanical action are combined) and accessories are required for electrolytic cleaning.

There are two general methods of applying cleaning solutions by spray. The most widely used method requires two banks of nozzles mounted on opposite sides of a conveyor. The nozzles may be mounted in vertical banks and directed at the work being conveyed between them with the solution returning to the heated reservoir. A variation of this system has the banks of nozzles mounted horizontally above and below a belt type conveyor. The second method is described in section 2.2.5 and, in this case, only one nozzle is used and the cleaner is not reused.

2.2.4 Emulsion Cleaning Equipment. Emulsion type cleaners are used by both immersion and by spray. The equipment used is similar to that used in alkali cleaning (Section 2.2.3).

2.2.5 Steam Cleaning Equipment. Equipment for steam cleaning usually consists of a small flash type boiler, a motor driven pump, and a water supply. The unit is normally mounted on wheels so that it can be easily moved to the part to be cleaned. Various types of nozzles are available depending on the type of cleaning problem.

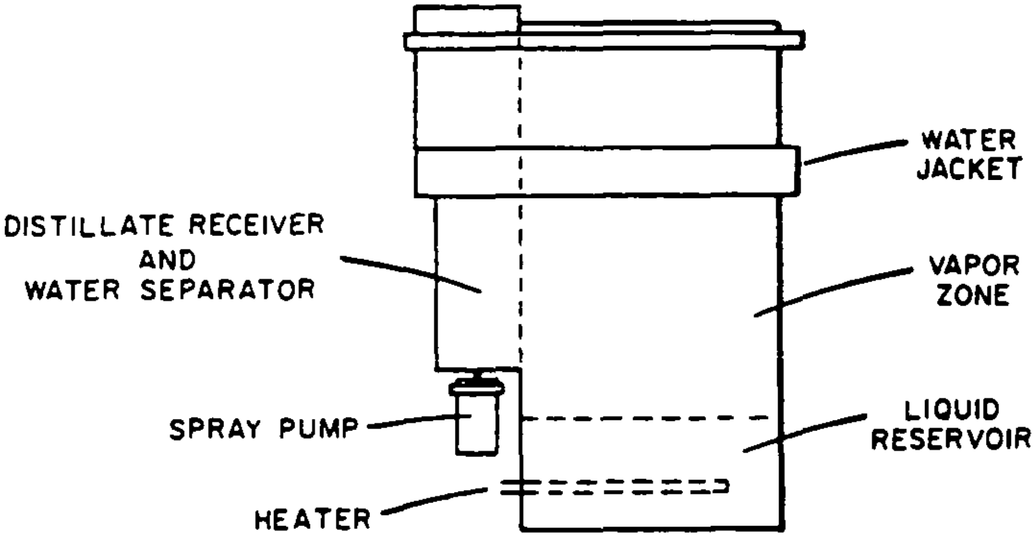


FIGURE 1: VAPOR DEGREASER

2.2.6 Acid-pickling Equipment. The materials of construction for the pickle tank, the rinse tank, and the heat exchanger must be resistant to the acid and temperature used.

2.2.7 Abrasive Blasting Equipment

2.2.7.1 Direct Pressure Type Equipment. In general, the equipment for direct pressure blast cleaning consists of a tank in which the abrasive is stored under pressure. The pressure on the abrasive forces it from the bottom of the tank into a mixing chamber. In the mixing chamber a stream of air picks up the abrasive and carries it to the nozzle. The design of direct pressure blast cleaning equipment is a specialized field. The services of manufacturers should be drawn upon for installation of this type of equipment. Their advice is particularly valuable in selecting abrasive lines, hoses, mixing chambers, valves, nozzles and reclamation, separation and ventilation equipment.

2.2.7.2 Suction Feed Type Equipment. The construction and design of suction feed type equipment is very simple. Operation of the equipment is based on a vacuum created by compressed air passing through a small jet. The vacuum draws the abrasive into an induction chamber where it is picked up by air from a larger nozzle. The mixture of air and abrasive is directed against the work through the blast gun.

2.2.7.3 Gravity Feed Type Equipment. Gravity feed equipment relies upon the flow of abrasive from a hopper to the nozzle by gravity alone. The conventional suction feed type equipment may be used for gravity feed abrasive blasting by raising the abrasive supply to a level above the gun. A feed control may be necessary to prevent blocking of the feed line because of the excessive amount of abrasive.

2.2.7.4 Wet Blast Cleaning Equipment. For some types of wet blast cleaning, special equipment must be used. For other types, standard dry blast units can be employed. Specially designed wet blast equipment is generally suitable for dry blasting. On the other hand, standard dry blasting equipment is usually not suitable for wet blasting.

2.2.7.5 Wheel Blast Equipment. The equipment for this type of cleaning consists of an abrasive feeding mechanism, a vaned wheel which supplies the final velocity of the abrasive, the drive assembly, and the wheel housing. Directional control of the stream is secured by varying the point at which the abrasive is fed to the vanes. Figure 2 illustrates an abrasive throwing wheel.

3. CONDITIONING PRIOR TO PHOSPHATE COATING

3.1 General. The phosphate coatings consist of many small crystals which are formed on and adhere firmly to the metal surface. Each crystal grows from a single point (a cathode) on the metal surface and continues to grow until it contacts a neighboring crystal. If there are few cathodes on the surface, few crystals will be formed. Thus, large crystals are formed which are easily broken and much of the surface is uncoated. If many cathodic sites are present when the parts are introduced into the phosphating bath many small crystals are formed. The coatings formed under these conditions are less easily broken (more resistant to abrasion). There is less uncoated surface, therefore, better corrosion resistance results.

3.2 Cleaning systems which leave many cathodic sites on the metal surface. Solvent cleaning, (with the exception of vapor degreasing), emulsion cleaning and abrasive blasting all appear to leave many cathodic sites on the surface. The phosphate coatings produced following these cleaning procedures consist of small dense crystals and are capable of meeting the required tests.

3.3 Cleaning systems which leave few cathodic sites on the metal surface. Strong caustic cleaners, electrolytic alkaline cleaners, pickles, and vapor degreasing appear to leave few cathodic sites on the metal surface. Phosphate coatings produced on these surfaces tend to be "sparse" in that there are uncoated areas between large crystals. These coatings frequently are not capable of meeting the required tests.

3.3.1 The use of conditioning agents. The surfaces referred to in Section 3.3 can be modified to produce the desired fine grain coatings by rubbing the surface with a damp rag or by the use of proprietary "conditioning" agents. A titanium-disodium phosphate complex (U.S. Patent 2,310,239-Jernstedt) is effective with zinc phosphate processes and can be obtained from many of the suppliers of phosphate coating chemicals. A proprietary chemical which produces a similar affect when used before manganese phosphate coating chemicals is also available.

4. PHOSPHATE COATINGS

4.1 Introduction

4.1.1 Characteristics. Phosphate coatings consist of crystalline, non-reflective, water insoluble metal phosphates which are very adherent to the base metal. The manganese and zinc phosphate coatings of DOD-P-16232 are impregnated with a rust-inhibiting oil, a solvent cut-back preservative, or other specified finish. The Type I phosphate coating of TT-C-490 is not oiled, since this coating is used as a base for paint.

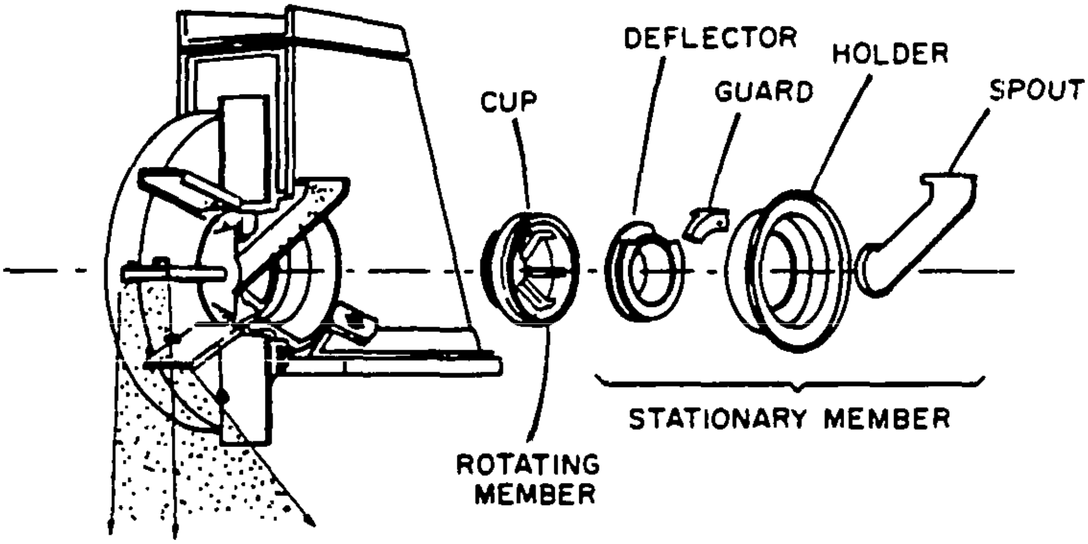


FIGURE 2: ABRASIVE THROWING WHEEL

The manganese based phosphate coatings are more resistant than the zinc based phosphate coatings to high temperatures but should not be exposed for long times to temperatures above 350°F (175°C). Zinc based phosphate coatings should not be exposed for long times to temperatures above 200°F (95°C). The maintenance of the heat exchangers is much easier with zinc based phosphate processes than with the manganese based phosphate processes.

The coatings meeting DOD-P-16232 are particularly effective in resisting corrosion between mating metal surfaces, such as encountered in fasteners and metallic belt links. These coatings reduce the tendency for parts to "freeze". Neither of these coatings is recommended for alkaline environments.

The color of the phosphate coatings ranges from gray to black depending upon the alloy and the dimensional buildup varies from 0.0001 to 0.0005 inch (0.0025 to 0.0125 millimeters). When the parts require close fit for proper functioning, no allowance should be made for this buildup as the crystals are easily broken and the parts quickly return to their original uncoated dimensions.

WARNING: When working with phosphating solutions and salts, goggles, face shields, impervous rubber aprons, boots and gloves must be worn.

4.1.2 Adaptability. Phosphate coatings may be applied to all ferrous metal parts used in military material by normal processing procedure with the exceptions noted in 4.1.2.1 through 4.1.2.6 below.

4.1.2.1 Springs. Springs, primarily those having a small diameter, are apt to become brittle during the phosphating process. This applies also to leaf springs and other parts of small cross section that take spring loads. Certain assemblies that contain springs which cannot be disassembled without damaging the parts may be phosphated without disassembling.

Any springs which are phosphatized should be relieved of hydrogen embrittlement by holding them at room temperature for 120 hours or heating them for eight hours at temperatures of 210° to 220°F (100° to 104°C).

4.1.2.2 Nonferrous Metals. The phosphate coatings described in this handbook cannot be applied to brass and copper. However, nonferrous metal parts such as brass bushings, which are permanently assembled to iron or steel components, will not normally be seriously damaged during processing. A small amount of copper will be dissolved in a normal operating phosphating bath and large amounts may be dissolved if the free acid is high. The dissolved copper will cause the coatings produced to be less resistant to corrosion than they would have been in the absence of copper in the bath. Brass, bronze, or other nonferrous metal holding fixtures or baskets should not be used to hold pieces of work while in the phosphating tank.

To remove copper from the phosphate bath, process batches of degreased steel wool or clean scrap iron for approximately 5 minutes. The steel wool or scrap iron should be removed as the copper plates out on the metal.

4.1.2.3 Stainless Steel. This material cannot be successfully treated with any known phosphate treatment. However, stainless steel is "activated" by blasting the metal surface with cast iron grit or cut steel blasting abrasive. Particles of ferrous metal abrasive are embedded in the corrosion resistant steel surface, causing a passive coating to form in a conventional phosphatng or oxalating solution. This may be desirable to make the stainless steel surface non-reflective and more corrosion resistant.

4.1.2.4 Gun Barrels. The barrels of all weapons must be plugged before phosphating. For this purpose, silicone plugs, tapered wooden plugs, rubber stoppers, or straight or tapered cork stoppers may be used. New corks should be soaked for 15 minutes at 200°F (95°C) in a dilute solution of soda ash and water to remove tannic acid, which may cause discoloration of the barrel.

4.1.2.5 Gas Ports. Gas ports on automatic rifles must be plugged before phosphating.

4.1.2.6 Reprocessing Phosphated Parts. Abrasive blasting is a process for cleaning and finishing of materials by propelling an abrasive media in a dry condition or suspended in a water slurry. As a cleaning tool it has the ability to remove phosphate coatings when required and will prepare that surface for additional treatment. It is highly recommended that abrassive blasting be used for these operations.

4.1.3 Cleaning of Phosphate Coatings. After this type of finish has been applied, it should be cleaned only with hot water and a surfactant or with solvent-type cleaners such as dry-cleaning solvent, mineral spirits, or degreasing solvent.

Phosphate coatings are soluble in alkali. Therefore, caustic soda, soda ash, trisodium phosphate, and all other strong alkali materials must be avoided, since they will destroy the phosphate finish.

4.1.4 Exercise of Assembled Weapons. Refinished weapons should be operated by hand until the moving parts work smoothly without binding or undue effort.

4.2 Processing Tanks and Equipment

4.2.1 General. The cleaning and other pretreatment operations preceeding the application of the phosphate coating have been described. This section covers the tanks and equipment used after the pretreatment operations are completed and includes those required for:

Phosphating,
Water rinsing,
Chromate rinsing, and
The application of the supplementary preservative coating

4.2.2 Phosphating Tank

4.2.2.1 Materials of Construction. Since the phosphating solution will corrode mild steel, the tank should be constructed of stainless steel (types 304, 316, 321, or 347), or plastic which is resistant to both the chemicals and the temperature used in the process. If plastic is used, the material should be checked to be sure that no plasticizers are present which can leach out and inhibit the phosphating reactions. A piece of the plastic, representative in composition, can be immersed in the phosphating solution at operating concentration and temperature for 48 hours. The volume of the phosphating solution and the size of the plastic part should be close to the relative volume and area that will exist in the operating tank. Test pieces should be run in this phosphate solution after it has been cooled, mixed thoroughly with the sludge formed, and reheated to be sure that the coatings produced are satisfactory. Mild steel may be used to construct the tank but the life of the tank will probably not exceed one year.

4.2.2.2 Construction. The tank should be double-wall construction with suitable insulation installed between the walls to conserve heat (Figure 3). The tank should be provided with a cover to conserve heat. Drains are not recommended in the phosphate processing tanks due to the tendency of the sludge to interfere with closing of the valves which leads to loss of solution.

The dimensions of the tank are governed by the number and size of the parts to be processed. Provisions should be made for at least 6 inches (15 centimeters) of sludge to accumulate on the bottom without contacting the work being processed. If a perforated processing barrel (Figures 4 and 5) is to be used in the processing system, the tank should be sized to accommodate the perforated barrel and its drive system.

4.2.2.3 Tank heating. Under no circumstances should any phosphating tank be heated from the bottom. If bottom heating is used, steam pockets will form under the sludge. These pockets can erupt violently, throwing hot solution on personnel in the vicinity.

Heating with entrance and exit pipes welded into the tank walls is objectionable for two reasons. The stresses due to temperature and differential expansion of the metal can cause leaks to develop. The removal of scale and sludge from the heating surfaces can be done only after the processing solution has been removed from the tank.

Excellent results have been obtained when the temperature differential between heating surface and the operating bath does not exceed 50°F (10°C). Higher temperature differentials have adverse affects on the phosphate bath and may cause distortion of portions of the tank and/or the heater.

Mixed results have been obtained when the heat is supplied through the tank walls by means of either a jacketed tank or by attaching electric strip heaters to the outside of the tank. The electric heaters produce local areas with a high temperature differential between the tank wall and the solution. Excellent results have been obtained when the heat is supplied by a heating medium circulating in a jacket around the tank as long as the temperature differential is less than 50°F (10°C). However, poor results have been obtained with higher heat differentials.

The use of electric immersion-type heaters should be avoided as the heating surfaces are normally at high temperatures and the high heat differential is harmful to the phosphating solution.

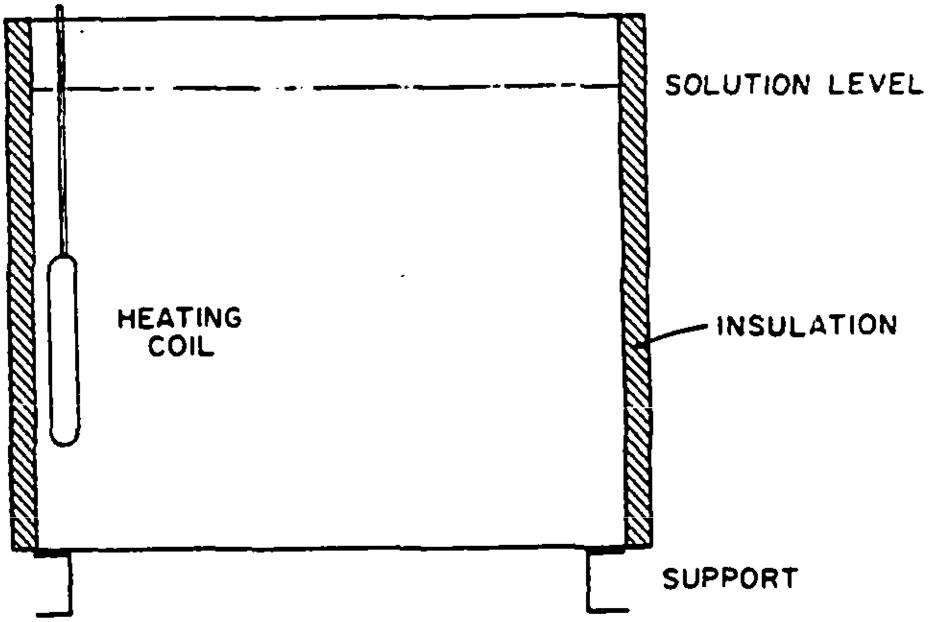


FIGURE 3 : PHOSPHATE TANK (CROSS SECTION)

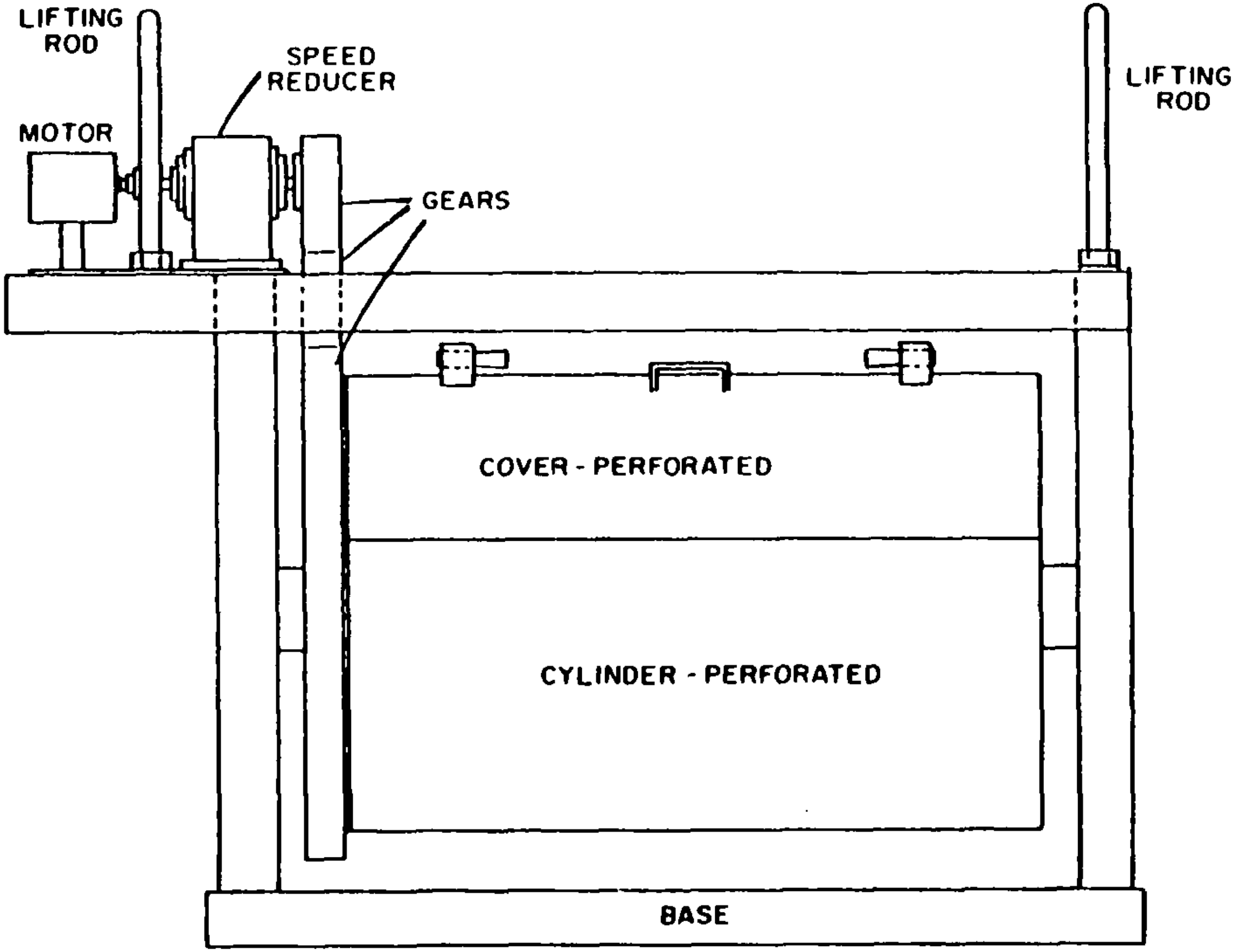


FIGURE 4: TUMBLING BARRELL (SIDE VIEW)

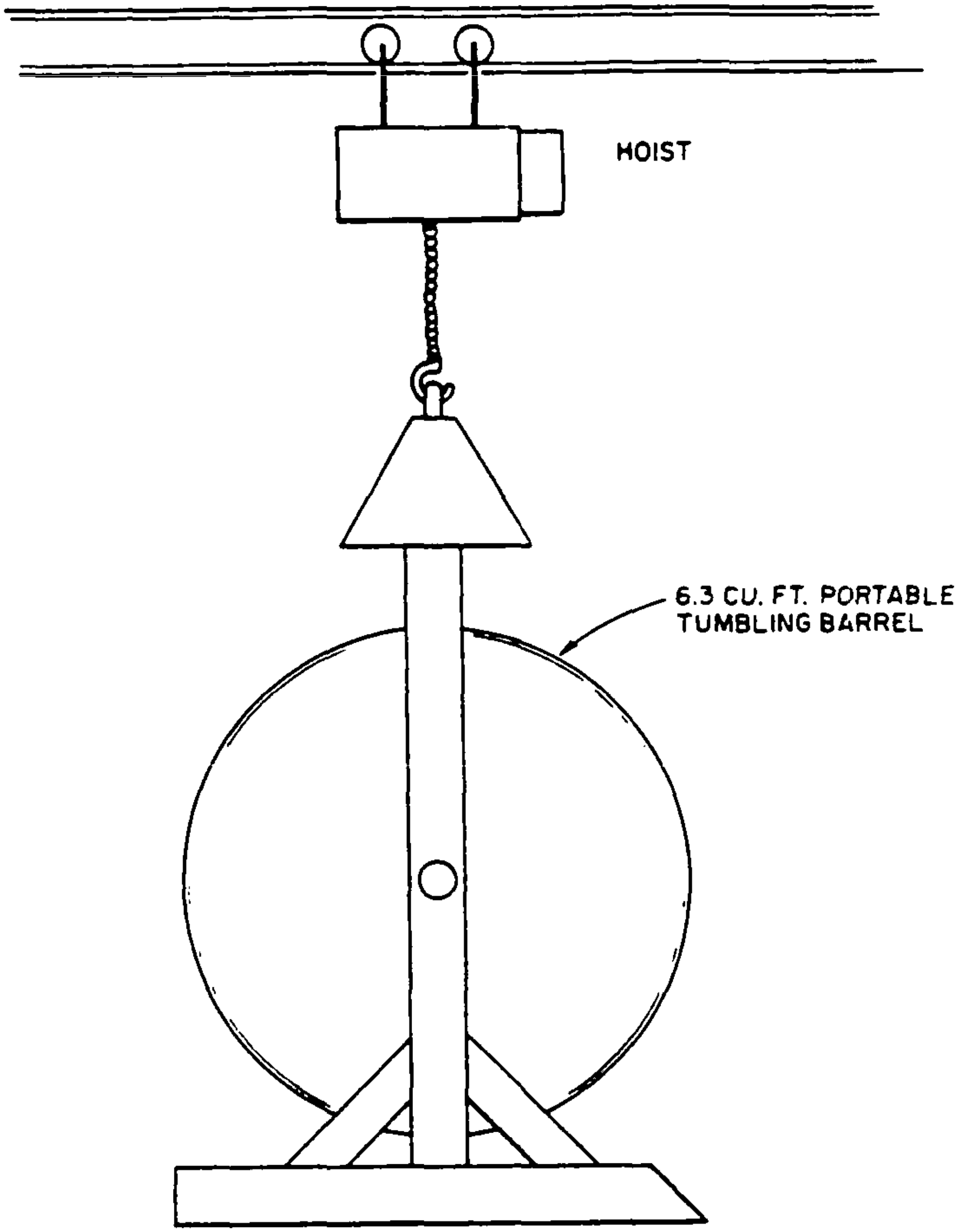


FIGURE 5 : TUMBLING BARRELL (END VIEW)

Steam at 30 psi (2.1 kg/sq cm) or less is the most desirable source of heat for a phosphating process. Downdraft gas heating units have been used successfully where steam was not available. Unfortunately, there is a high heat differential between the heating tube and the phosphate bath and adverse affects occur in the phosphate solution. In addition, the removal of scale and sludge is more difficult. Both the steam and the gas heating elements must be so installed that they can be easily removed from the tank for the removal of accumulated scale. The heating coil may be suspended on strap iron hangers hooked over the tank edge and equipped with a lifting lug to facilitate its removal from the solution. The coil should not be installed on the tank bottom nor should steam return nipples be cut through the tank wall. A steam trap should be placed in the return line at floor level to free the coil of water. At least two sets of coils should be provided for each phosphating tank to ensure continuous operation, and these should preferably be constructed of stainless steel to minimize scaling.

Effective steam heat exchangers are commercially available. These exchangers consist of steel plates welded together with passages between the plates through which the steam flows. These heat exchangers are light, easy to clean, and occupy less space than pipe coils. Heat exchangers of this type, constructed of mild steel or of stainless steel, are available. One type consists of two sheets embossed to form a tube similar to a pipe coil when the two sheets are joined. Another type is manufactured by welding the edges of the flat plates together, intermittently spot welding the two sheets, and inflating the sheets with hydraulic pressure to form "pillows" through which the steam flows. Both of these heat exchangers are light, easy to clean, and occupy less space than the pipe coils.

Immersion-type downdraft gas heating equipment can be used for heating the phosphatizing solution. The piping layout in this heating system is similar to that used for steam, but the ducts are much larger than the steam pipes. They are removable for removal of scale and sludge.

4.2.3 Processing Barrel. When the parts to be treated are small, it is frequently expensive to place them individually on racks. A common solution to this problem is to place the parts in a perforated barrel such as that shown in Figures 4 and 5. The parts are cleaned, rinsed, processed and, occasionally, finished without removal from the perforated barrel. The barrel is rotated while immersed in the cleaning and processing solutions. Rinsing is best accomplished by immersing the barrel in the rinse solution, and then removing it to allow the contaminated rinse solution to drain. This may be repeated 2 or 3 times for improved rinsing. To minimize abration of the coating during processing it is suggested that the barrel be filled completely.

The design shown in Figures 4 and 5 combines the rack to support the barrel and the mechanism to rotate the barrel in a single unit. An older design, still used in many places, uses a frame mounted in the tank. The shafts at each end of the barrel rest in bearings in the frame permitting the barrel to be rotated. A driving mechanism is mounted on the rear of the tank. The barrel is placed in the frame and the rotating mechanism engages the ratchet at the end of the barrel so the barrel can be rotated. This design requires that a frame and driving mechanism be present in each tank where the barrel is to be rotated. The speed of rotation is normally one revolution every 3-5 minutes in the phosphating baths used to produce coatings meeting DOD-P-16232.

4.2.4 Ventilating System. Steam and fumes rising from heated tanks containing corrosive liquids must be removed from the vicinity of operating personnel. The required ventilation is effectively accomplished with built-in exhaust equipment. The recommended type of exhaust system has a slot-type opening on the rear of the tanks, air is fed across the surface from the front and provision is made to scrub the fumes exhausted from the rear. The fan capacity for these units is based on 200 cubic feet of air per minute for each square foot of tank surface (18.6 cubic meters of air for each square meter of surface).

4.2.5 Cold Water Rinse Tank

4.2.5.1 Construction. The cold water rinse tank is constructed of mild steel, is provided with a bottom drain nipple, and has a weir type overflow with discharge nipple.

4.2.5.2 Location. The tank should be located as close as possible to the phosphatizing tank, thus reducing the time required to transfer the work from the phosphating solution to the rinse.

4.2.5.3 Water Supply. The water supply to the cold water rinse tank should enter the tank on the side of the tank opposite the overflow. The water should be delivered close to the bottom of the tank using a vacuum breaker or other means to prevent siphoning of water from the rinse tank into the water line. Heating coils need not be installed.

4.2.6 Chromate Rinse Tank. The chromate rinse tank is constructed of mild steel with double walls and insulated sides and ends. It has a heating coil mounted on one side of the tank and a bottom drain. A water inlet for replacement of water lost by evaporation is installed at the top of the tank. This tank should be located adjacent to the cold water rinse tank.

4.2.7 Compressed Air Outlet. It may be advisable to use compressed air to remove excess moisture from parts after the chromate rinse or to remove dust left on grit or sand blasted parts. If compressed air is to be used, an outlet should be provided near the area where the air will be used The air must be free of oil, moisture, and other contaminants. This can be accomplished by installing a moisture trap and particulate filter before the point of use.

4.2.8 Preservative Oil Tank. The tank holding the preservative oil can be constructed of mild steel. The oil being used may require specific features which would be unnecessary with other oils. When a water displacing oil is used, a bottom drain may be required to remove displaced water. Some oil in water emulsion type oils work best when recirculated continuously with the emulsion overflowing into a sump from where it is pumped back into the tank. Some oil in water emulsions are used at elevated temperatures to help dry the parts. In these cases heat must be supplied to the tank.

4.2.9 Automated Immersion Lines

4.2.9.1 General. The preceeding discussion has covered batch type operations in which the immersion of the parts to be cleaned, rinsed, or processed was controlled by an operator. In most cases he uses a hoist to handle the heavy loads but controls the treatment time and sequences. Many types of equipment are available in which the parts are transferred from operation to operation without operator dependence.

4.2.9.2 Types of Automated Equipment. There are many different designs for accomplishing the desired results. The most commonly used are of three general types.

Tumbling barrels automatically transferred from one station to the next station

Rotating or oscillating open perforated drums, automatically transferred from station to station

Horizontal rotating drum with an internal screw which advances the parts through the drum where they are immersed in the different solutions

4.2.9.2.1 Automated tumbling barrels. The tumbling barrels are basically the same as those described in Section 4.2.3. The barrel, loaded with parts, is placed on the automated system where it is transferred to the processing stages in the correct order and left in each stage for the proper time before transfer to the next stage. The results are comparable to a manually controlled system.

4.2.9.2.2 Open rotating or oscillating drums. These systems use drums which are open at the top making loading and unloading rapid and simple but the loosely loaded parts are subjected to more abrasion than when in a closed, completely filled barrel. Heavy parts with sharp edges may be severely abraded. To minimize abrasion, parts should be tumbled as little as possible when not immersed in liquid.

4.2.9.2.3 Horizontal drum with internal screw. An example of this type of unit is shown in Figures 6 and 7. Parts are fed into the rotating drum at the entrance and are moved forward as the drum rotates. The exterior shell of the drum is solid in the processing and rinse stages. Scoops on the drum pick up solution from the tank and transfer it to the drum where the parts are kept immersed for the designated time. The shell is perforated in the sections following the processing and rinse stages permitting the solution to return to the tank.

Parts are particularly subject to abrasion when being advanced by the screw in drain areas where no solution cushions the parts as they are tumbled. The weight and design of the parts contribute to the severity of the abrasion.

4.2.10 Spray Process Systems. The spray method for application of phosphate coatings may be used when applying coatings meeting TT-C-490 but never for coatings meeting DOD-P-16232. The spray method is normally used in a conveyorized system.

The construction of the equipment for this type of application is complex and expensive. It is recommended that an experienced equipment builder be consulted or contracted to build the equipment to avoid costly mistakes.

4.3 Phosphate Coating Process

4.3.1 Cleaning and Conditioning Before Phosphating. All parts must be completely free of oil, grease, rust, residues, and other contaminants before treatment with the phosphating solution. The methods used for the removal of such substances depend on the equipment and facilities available, the type of ferrous metal of which the parts are made, and their service application. See Section 2.

Each cleaning medium and each cleaning method, such as wiping, brushing, abrasive blasting, pickling, etc. have different and distinctive effects on the depth and design of the metal etching and the crystalline structure of the phosphate coating. This leads to the variations in the corrosion resistance of the phosphate coatings. Therefore, the conditioning procedures used for specific parts must be either based on experience or determined by trial. See Section 3. Several variations in the conditioning processes that can be used are illustrated in Figure 8. The conditioning procedure which includes a pickle shown in Figure 8 must not be used prior to heavy phosphate coatings (DOD-P-16232) without authorization from the purchasing facility.

The application of a phosphate finish with maximum corrosion resistant qualities depends not only on the accurate control of the phosphating solutions, but, particularly, on the cleaning and conditioning operations that precede the application of this coating. Therefore, the conditioning procedures described below must be observed if the desired results are to be obtained.

4.3.1.1 For phosphate coatings meeting the requirement of DOD-P-16232, abrasive blasting of all work is necessary to obtain the best results. Abrasive blasting provides the most satisfactory surface for receiving the phosphate coating and, if properly used, will not change the dimensions of most parts. Thin cross-sections and surface smoothness may require special consideration during processing.

4.3.1.1.1 Dust on abrasive blasted work should be removed with compressed air. It must not be removed by wiping with a cloth or by brushing.

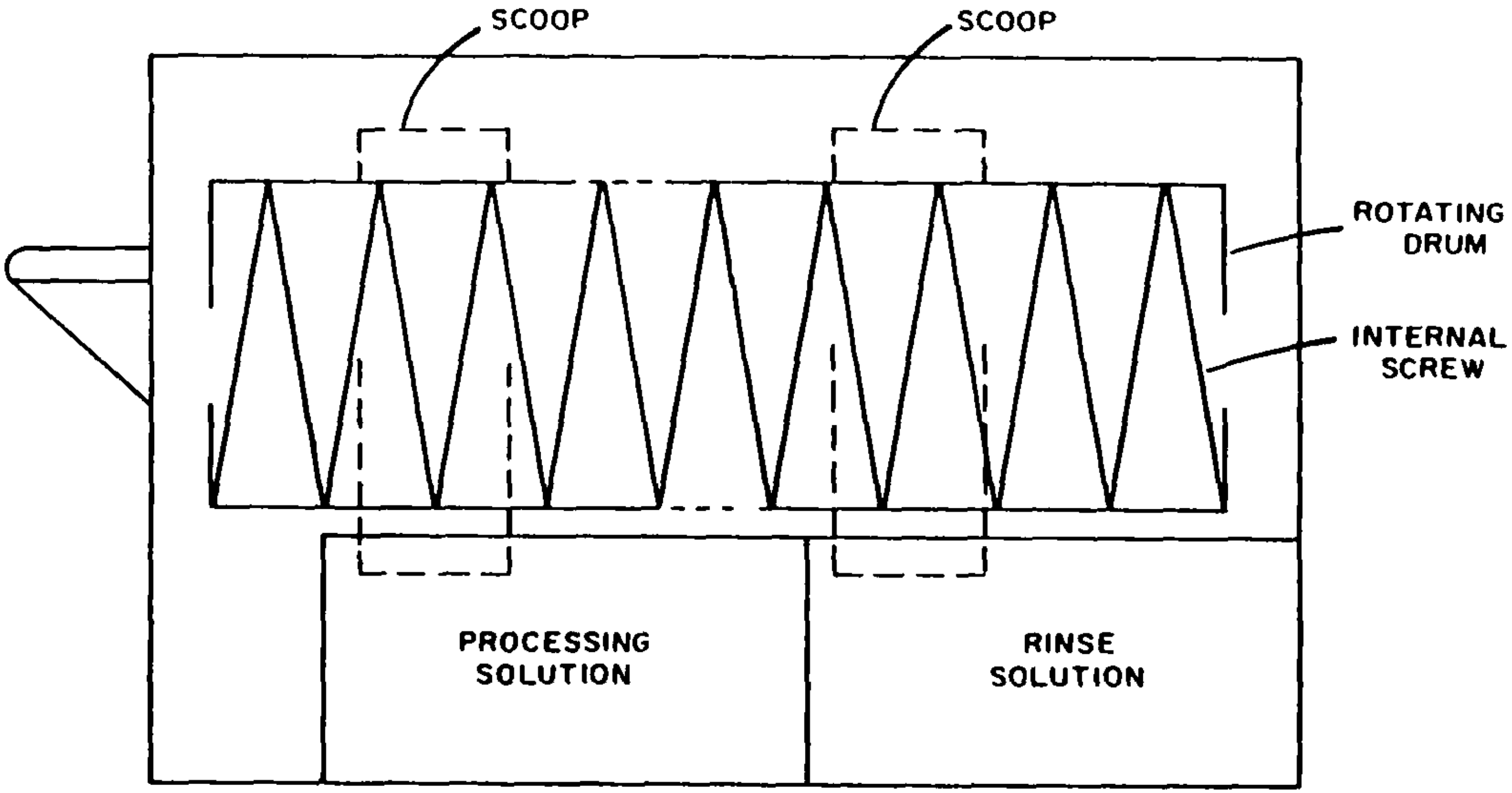


FIGURE 6: ROTATING DRUM WITH INTERNAL SCREW (SIDE VIEW)

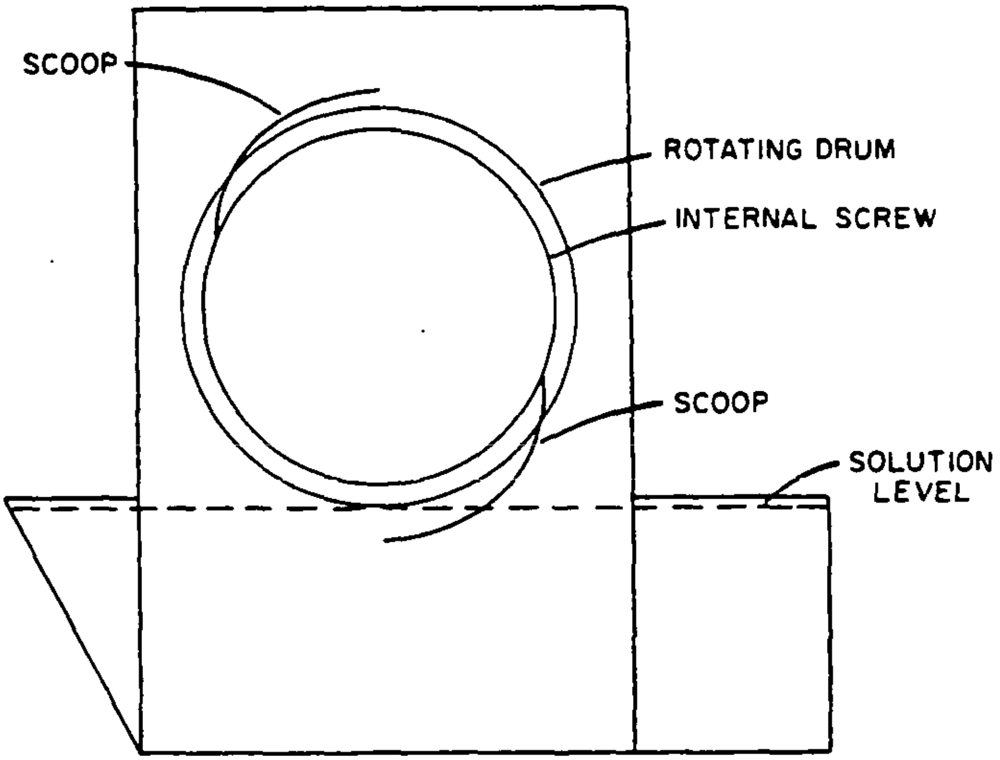


FIGURE 7 : ROTATING DRUM WITH INTERNAL SCREW (END VIEW)

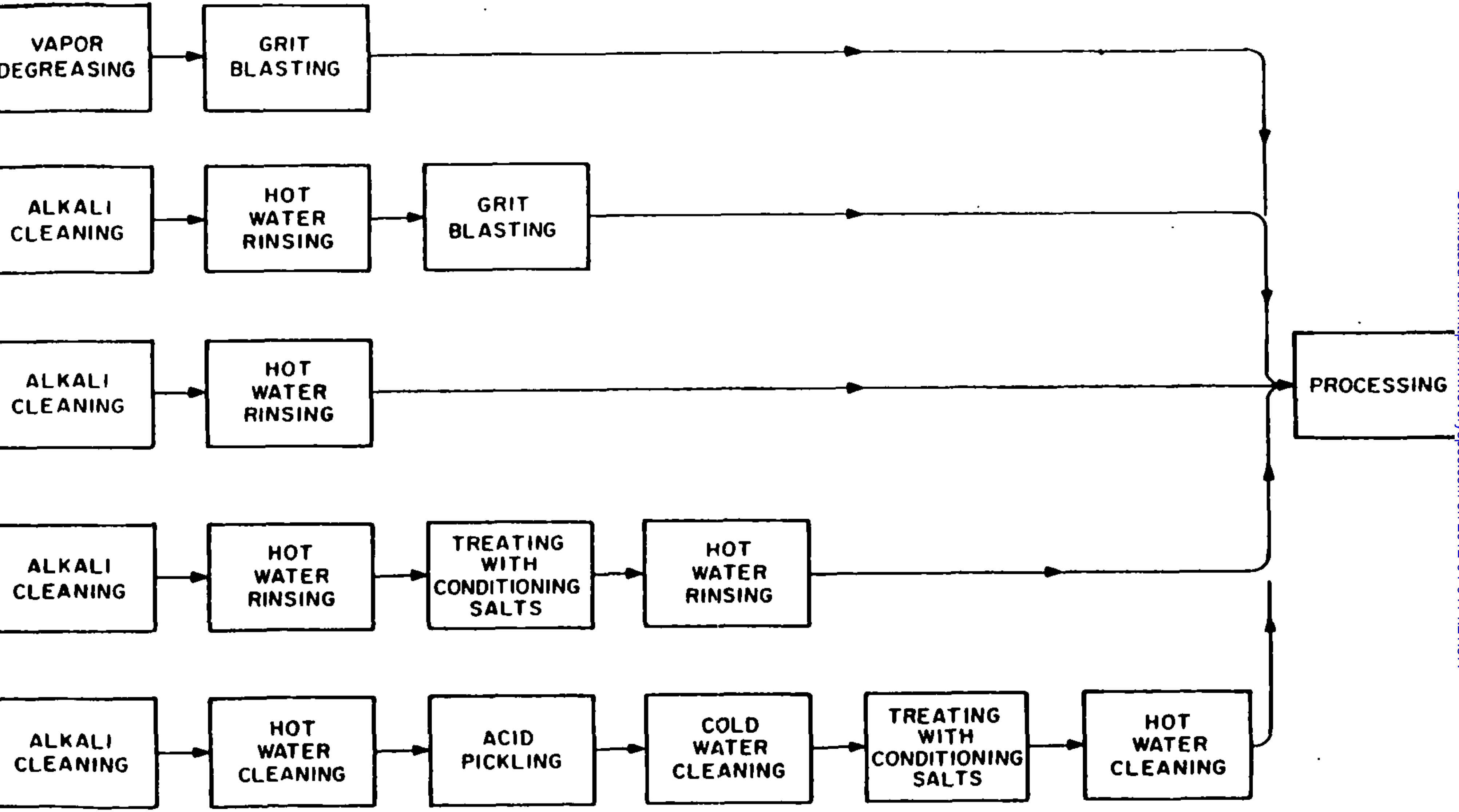


FIGURE 8 : PHOSPHATING UNIT CLEANING OPTIONS

4.3.1.1.2 Abrasive blasted work must not be touched by bare hands. Clean cotton or rubber gloves should be used when parts are turned on the blast table or placed in baskets or racks used for processing.

4.3.1.1.3 Abrasive blasted work must not be deburred or exposed in any manner to oil or any substance that will require removal by washing or rinsing before phosphating.

4.3.1.2 In most instances, oil and grease are removed from the work by vapor degreasing. However, some soaps with rust preventatives and greases contain substances that are insoluble in the solvents used. These substances are not removed by vapor degreasing. If these soils are present, other cleaning procedures have to be used. Vapor degreasing may still be included in the cleaning sequence to remove the oil and grease.

4.3.3 Processing Sequence. Cleaning materials, cleaning procedures, conditioning and cleaning equipment have been described in Sections 2 and 3. This section covers the operations that follow the cleaning and conditioning processes and includes phosphating, water rinsing, chromate rinsing, and the application of the supplementary preservative coating (Figure 9).

4.3.4 Phosphating Process

4.3.4.1 Materials. Phosphating materials may be either a manganese-base or a zinc-base phosphate chemical. The chemicals can be obtained by specifying the desired chemical meeting MIL-P-50002 or from commercial sources which supply chemicals capable of producing coatings meeting the requirements of the specification called for in the drawing.

4.3.4.2 Preparation of the Phosphating Solution

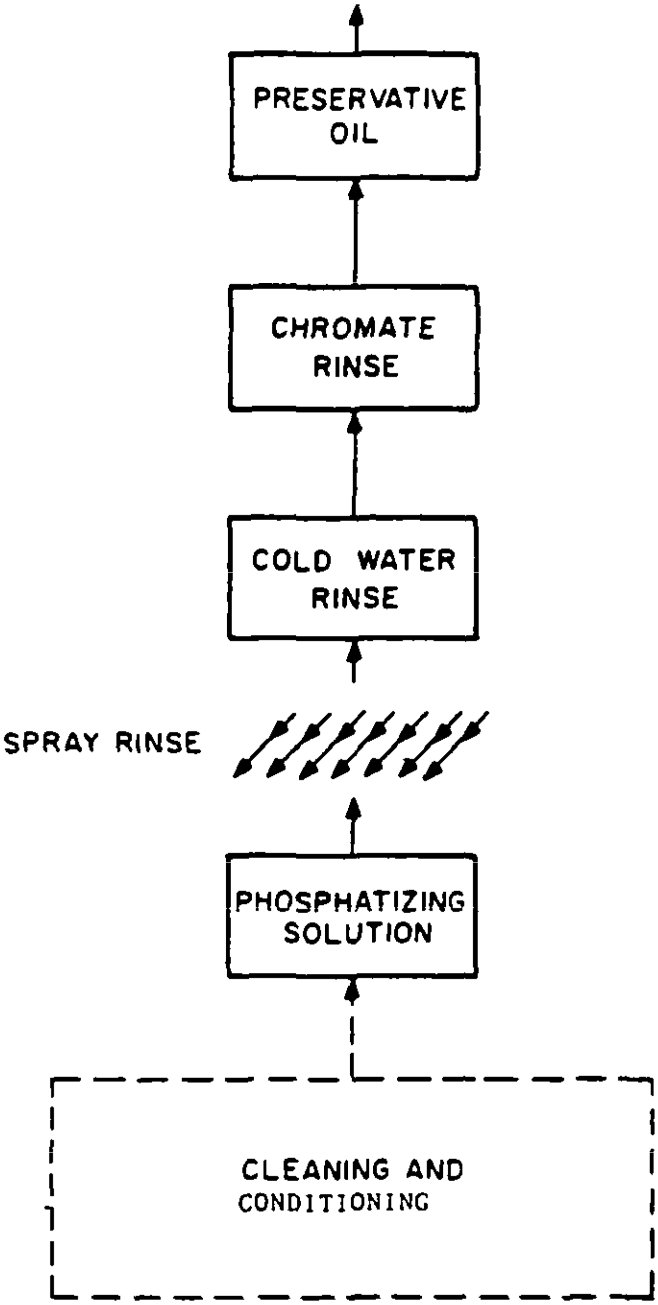
4.3.4.2.1 Type M and Z coatings (DOD-P-16232). Proper adherence to the procedures listed in (a) through (g), for preparation of the phosphating solution is necessary in order to prevent serious difficulty in the initial stages of use of the phosphating solution.

(a) Fill the tank with water to within 6 inches (15 centimeters) of the level at which it will ultimately be operated.

(b) Heat the water to 160°F (71°C). Do not exceed this temperature during the preparation of the solution. This is particularly important with the zinc-based chemicals as the nitrate content is higher in these chemicals than in the manganese-based chemicals. The nitrate may be reduced to nitrite while the ferrous iron content is low.

(c) Add the proper amount of phosphating chemical for the desired solution as shown in Table I or as recommended by the supplier of the chemical.

(d) Add the required amount of iron to the bath using any of the procedures given in 4.4.2.4.1.



NOTE: THE TYPE I TT-C-490 FINISH IS NOT TO BE OILED. THIS FINISH WILL BE THOROUGHLY DRIED AFTER THE CHROMIC ACID RINSE, AND THEN PAINTED OR COATED WITH THE REQUIRED FINISH.

FIGURE 9 : PHOSPHATING SEQUENCE

(e) Add water to the operating level, stir thoroughly, and remove a sample of the solution for analysis. See 4.4.2 for manganese-base and zinc-base baths.

(f) At this point, it is desirable to continue to use every means at hand to raise the iron content of the solution to within the range of 0.2 to 0.4% for the manganese-type solution and 0.2 to 0.45% for the zinc-type solution. When the iron content of the solution has reached the lower figure in the concentration range indicated above and the total acid has been adjusted as indicated in paragraph 4.4.2.1, the solution is ready for use.

(g) The thermostat may then be set between 190°F (88°C) and 210°F (99°C) and the phosphating process may begin.

(h) To maintain the concentration of iron in the solution within the designated percentage, the steam or other heat source should be shut off when the solution is not being used to process parts. In the hot solution ferrous iron is oxidized by air to the ferric form which forms insoluble ferric phosphate and drops out as sludge.

TABLE 1.

Coating Specification	Material Specification	Quantity Required*
Type M	Type M	62 (16.4)
DOD-P-16232	Composition B MIL-P-50002	
Type Z DOD-P-16232	Type Z MIL-P-50002	40 (4.8)

*in pounds per 100 gallons (kg per 100 liters)

The oxidation of the ferrous iron is accompanied by an increase in the free acid content of the bath because for every unit of iron oxidized, one unit of phosphoric acid is released into solution. When work is being processed, the free acid is normally consumed by the dissolving iron as rapidly as it is formed. Under these conditions, there is no significant change in the free acid content and the ferrous iron may tend to increase. If the solution is kept hot when no work is being processed, the ferrous iron may decrease and the free acid increase. When the use of the phosphating solution is to be discontinued, for overnight or a longer period, and the heat has been shut off, water should be added to the solution until the surface of the solution is 3 to 5 inches (7.5 to 12.5 centimeters) above normal. This reduces the rates of oxidation by cooling the solution and, at the same time, prevents excessive loss of water by evaporation which normally occurs during longer periods of cooling.

4.3.4.2.2 Type I coating (TT-C-490). Preparation of the phosphating bath is accomplished by following steps (a) through (g).

(a) Fill tank to within 6 inches (15 centimeters) of the operating level.

(b) Add the proper amount of phosphating material for the desired solution as recommended by the supplier of the chemical.

(c) Add water to the operating level.

(d) Add any additional chemicals according to the supplier's instructions.

(e) Heat the solution to operating temperature. The recommended temperature for immersion processing is 180°F to 190°F (82°C to 88°C) and for spray processing is 130°F to 175°F (55°C to 79°C).

(f) Stir thoroughly and take samples for analysis. See 4.4.3.

(g) Sodium nitrite accelerator. When specified in the operation of the bath, add one ounce per 100 gallons (7.5 grams per 100 liters) of sodium nitrite for immersion processing and two ounces per 100 gallons (15 grams per 100 liters) of sodium nitrite for spray processing immediately before processing work.

Some phosphating processes make use of accelerators other than sodium nitrite. The most commonly used of these is sodium chlorate. This material is stable in the concentrated phosphate chemical while sodium nitrite is not. The fact that no external accelerator is required simplifies the control of the bath but the coating weights tend to be below the weights required to meet TT-C-490.

4.3.4.3 Processing Procedures

4.3.4.3.1 Type M Coating (DOD-P-16232).

(a) The work should be completely immersed in the phosphatizing bath and should be kept between 200° and 210°F (93° to 99°C) for approximately 45 minutes. The chemical reactions involved in the formation of the coatings release hydrogen gas. The visible evolution of gas normally ceases within 15 minutes but the parts should be left in the processing solution for 45 minutes to produce coatings with the maximum corrosion resistance.

(b) Unless previous experience with parts of like composition and pretreatment indicate otherwise, a continuation of visible gassing beyond a period of 15 minutes may be an indication of high acidity, high iron content, or poor cleaning. In such cases, the parts should be removed from the bath, thoroughly rinsed, and prepared for reprocessing as outlined in paragraph 4.1.2.6.

(c) Work loads should be as large as possible and the interval between the removal of one load from the solution and the introduction of the next load should be as short as possible. It is much more advantageous, from the standpoint of solution control, to operate the solution steadily for one day, than to spread one day's work over two days.

(d) Evaporation losses should be replaced at least twice during the processing of each load of work if no provisions for automatic level control are available. The electronic level controller is superior to the mechanical float type in the phosphating solution, because layers of phosphate scale form on the floats and other mechanical parts of these devices. Water should be added in frequent small quantities rather than in infrequent large quantities.

(e) Shaking the work at intervals during processing minimizes contact marks. It also ensures the escape of gas, which might collect in blind holes or cavities and cause a poor or spotty finish.

4.3.4.3.2 Type Z coating (DOD-P-16232).

(a) The temperature of this solution should be maintained at 190° to 205°F (88° to 96°C). It is best to establish a temperature and maintain it so that less than a 5°F (3°C) variation will occur. The solution should not be allowed to boil.

(b) The clean work is completely immersed in the solution for approximately 30 minutes. Shorter immersion periods produce coatings with a suitable appearance but such coatings usually have substandard corrosion resistance. Longer immersion in the phosphating solution will not provide a significant improvement in corrosion resistance.

(c) The processing is continued as in paragraph 4.3.4.3.1 (c) through (e).

4.3.4.3.3 Type I coating (TT-C-490).

(a) Metals being prepared for this coating should be cleaned by vapor degreasing, emulsion cleaning, or alkaline cleaning. In some instances it may be desirable to clean with phosphoric acid in accordance with Method VI of TT-C-490, using phosphoric acid solution complying with MIL-M-10578. After cleaning, the metal must be rinsed with water to remove any solution on the surfaces. Carrying cleaning solution into the processing solution will destroy the chemical balance of the solution. This can result in excessive use of chemical and/or loss of the ability of the solution to produce a satisfactory coating. If a strong alkaline cleaner or phosphoric acid is used in the cleaning sequence, a conditioning agent (Section 3) should be used following the water rinse. It should be noted that baths have been developed that operate at relatively low temperatures, e.g. 100°F, for energy conservation.

(b) When treating parts by immersion, the properly cleaned parts should be immersed for a minimum of three minutes in the phosphating solution. The temperature at which the processing solution is operated should not be allowed to vary more than 5°F (3°C). This temperature is established for each installation and may vary from 130° to 165°F (55° to 75°C) in spray installations and from 180° to 190°F (82° to 88°C) in immersion installations. Fluctuations of more than 5°F (3°C) will tend to produce unsatisfactory results.

4.3.5 Water Rinsing

4.3.5.1 Immersion Water Rinsing. The water in the immersion rinse tank is unheated and immersion time should be about one minute. Agitation of the work in the rinse water is more effective than additional time for thorough rinsing. The most effective rinsing is obtained by raising the parts out of the rinse water and reimmersing them two or three times. The rinse water must overflow continuously while being used. The tank should be completely drained daily and filled with clean water. Use of double counter flow rinses should be considered for reduction of water consumption and more effective waste treatment of smaller volume rinse effluents.

4.3.5.2 Spray Water Rinsing on Immersion Processing Lines. The time lag in the transfer of work from the phosphating tank to the immersion rinse tank should be as short as possible to prevent the phosphating solution from drying and "setting up" on the surface of the work. This "setting up" is most effectively prevented if a cold water rinse is applied immediately after the work is lifted out of the phosphating solution by either of the methods described below:

(a) Install a system of spray nozzles positioned along the front and rear edges of the phosphating tank. These nozzles should be approximately two feet (60 centimeters) above the top of the tank and so directed that the cone of the spray will fall within the confines of the tank. The sprays should be controlled by a foot operated valve positioned such that it and the power hoist used to lift the work from the tank can be operated simultaneously by one man. After being phosphated for the required time, the work is slowly raised from the solution through the cold water spray and then transferred to the immersion rinse tank.

(b) If a permanently installed tank spray system is not avaialble, the work can be hand sprayed by means of a hose and attached nozzle.

(c) It is desirable to spray the parts until they are cool but the volume of water required may cause the phosphate solution to overflow. By using nozzles with the minimum flow rate which gives complete coverage, the phosphate solution on the parts can be removed so that no "setting up" of phosphating chemicals occurs even when the part is still hot when the sprays are shut off.

4.3.6 Chromate Rinse

4.3.6.1 Rinses Controlled by Free Acid. The chromate rinse plays a very important role in the corrosion resistance of the phosphate coatings. This rinse can be prepared by dissolving 8 ounces of chromic acid (CrO_3) or 4 ounces of chromic acid and 4 ounces (by weight) of 75% phosphoric acid (H_3PO_4) in 100 gallons (60 grams of chromic acid or 30 grams of chromic acid and 30 grams of 75% phosphoric acid per 100 liters) of water. These baths are normally controlled by titrating the free acid (see paragraph 4.6.2.3). A constant free acid concentration is maintained by additions of chromic acid or equal parts by weight of chromic acid and 75% phosphoric acid. The corrosion resistance offered by rinses prepared in this manner vary from plant to plant. Hexavalent chromium is the major contributor to the corrosion protection provided by the rinse which will vary with the amount of hexavalent chromium present in the rinse. The alkalinity of the water available varies widely. Larger amounts of acid, and thus the hexavalent chromium, are required where the alkalinity of the water is high in order to obtain the same free acid.

4.3.6.2 Rinses with Controlled Chromate. The problem of varying hexavalent chromium levels can be solved by the use of commercially available solutions. These are used to build up and maintain a constant chromate concentration in waters with varying alkalinities by means of two solutions. One is a solution of chromic acid and the other a solution of a dichromate salt (usually a calcium salt). The control procedures will be furnished by the supplier of the chemicals and should include a test for hexavalent chromium and pH or free acid.

4.3.6.3 Rinses Containing Trivalent Chromium. Rinses containing trivalent chromium (U.S. Patent Nos. 3,222,226 and 3,279,958) are available which may or may not contain hexavalent chromium. These rinses, when properly controlled, can be followed by a water rinse (deionized water is preferred) without reducing the benefits provided by the chromate rinse. This makes possible the removal of any soluble salts which can cause problems under paint. See 4.8.4.2. This type of rinse is normally used with processes meeting TT-C-490.

4.3.6.4 Chromium Free Rinses. Proprietary rinses which contain no chromate are available for use over phosphate coatings meeting TT-C-490. These are used where there are no provisions for disposing of the chromate salts and where anodic or cathodic paints, which can be harmed by the chromate salts, are being used.

4.3.6.5 Temperature. The temperature at which the chromate rinse is operated can vary widely and is frequently selected on the basis of what is needed to obtain dry parts. Many parts are sufficiently massive to retain enough heat from a hot chromate rinse to cause the parts to dry with no further treatment other than to remove any chromate solution from recessed areas. In these cases the chromate rinse is maintained at the temperature required to obtain dry parts. When the parts are made of thin sheet metal an additional drying stage may be required in which case the temperature of the chromate rinse is not important but temperatures below 130°F (55°C) are seldom used.

4.3.7 Drying. After the work is removed from the chromate rinse, it must be thoroughly dried before the final finish is applied unless a water displacing oil is used. Even when the latter type of oil is used, most of the moisture should be removed from the parts before they are placed in the oil. Parts being finished with a Type I finish (TT-C-490) must not be oiled. Heavy parts which retain heat will dry spontaneously when removed from a hot chromate rinse. Thinner metal parts may require a heated dry off. However, the temperature of the dry off should not exceed 225°F (107°C) with DOD-P-16232 Type Z coatings or 375°F (190°C) with DOD-P-16232 Type M coatings. Small parts phosphated in tumbling barrel units may be dried conveniently by centrifuge, preferably equipped with heated air circulation. The last traces of moisture can be removed from parts which are to be oiled by dipping them in a water displacing oil.

4.3.8 Preservative Oil Dip. The preservative oil dip is used only on parts coated to meet DOD-P-16232. The parts should be oiled as soon as possible after phosphating. The parts should be dried before oiling. However, the degree of dryness required varies with the type of oil used.

> Water displacing oils can be used on parts with damp areas where the dry-off has not removed all traces of moisture. For the best corrosion resistance the water displacing oil should be followed by a rust preventative oil.
>
> Other oils require that the parts be thoroughly dry before dipping in the oil.

4.3.9 Finish for TT-C-490 Type I Coatings. Parts given a Type I (TT-C-490) coating are to receive an organic coating and must not be oiled. Parts to be painted after assembly or to be held for a period of time should be given a prime coat of paint immediately after phosphating.

4.4 Maintenance of the Phosphating Tank and Chemical Control of the Phosphating Solution

4.4.1 Maintenance of the Phosphating Tank

4.4.1.1 Sludge Removal. In the normal operation of the phosphating process, a quantity of sludge is formed. This sludge consists primarily of ferric phosphate. However, in the operation of the process, partially soluble iron and zinc or manganese phosphates are also formed. These compounds act as buffers in stabilization of the iron, zinc, and free acid of the solution. Complete removal of these compounds from the solution permits large fluctuations in the concentration of the constituents of the solution. Therefore, sludge should not be completely removed from the tank. A satisfactory method consists of removing a small portion with a hoe each day. This prevents drastic changes in the solution and disturbance of work schedules. In addition, the sludge should be stirred into the cold solution before turning on the heat when starting production.

4.4.1.2 Level Control, Thermo-regulator Bulbs and Temperature Regulators. Level controls, thermo-regulator bulbs and temperature regulators must be removed periodically and all scale removed from the surfaces exposed to the solutions. In no instance should any regulator or other device constructed of lead, copper or its zinc and tin alloys be used in the phosphate solution. Only stainless steel or glass equipment should be used.

4.4.1.3 Coils. Scale on the coils may be removed by the use of a tool or with the aid of chemicals. Scale may be removed quickly by means of a tool shaped to the contour of the coil and a 5 pound air hammer.

CAUTION: Eye protection should be worn when removing scale in this manner.

The scale on coils can be removed more easily if the scale is heated before removal is attempted. A simple way of heating the scale is to run steam through the coil while it is not immersed in the solution. (If the tank is emptied, the coil can be heated in place.)

Heating coils for the zinc-base phosphating solutions may be cleaned chemically as indicated in (a) through (d) below:

(a) Remove the coil from the phosphating solution and place it in a narrow mild-steel tank just large enough to accommodate the coil with about three inches (7.6 cm) of clearance on all sides.

(b) Attach the coil to a steam line.

(c) Fill the tank with a solution of the following composition:

Rochelle Salts	15 pounds (6.82 K_g)
Caustic soda	150 pounds (68.18 K_g)
Water	100 pounds (45.45 K_g)

(d) The steam in the coil must be regulated so that the solution is maintained just below the boiling point. An automatic temperature control is required to avoid hazardous boiling of the highly caustic solution. The heat transfer efficiency of the coil increases as the scale is dissolved and adequate manual control is nearly impossible.

Immediately after being cleaned, the coils should be rinsed with a hose, followed by immersion in a water rinse tank. The cleaning solution will gradually lose its strength and a heavy sludge will accumulate on the bottom of the tank. When this interferes with the coil cleaning, the solution should be discarded. The cleaning solution, when ready for disposal, contains a large amount of caustic soda and phosphates of iron and zinc plus the Rochelle salts. The disposal of the solution must comply with all government, state and local regulations concerning waste disposal.

CAUTION: Protective clothing and face and eye protection must be used by operators working with this material.

4.4.2 Control of Phosphating Solutions. The manganese - base phosphate solution is used in producing heavy manganese phosphate coatings and the zinc-base phosphate solution is used in producing heavy zinc phosphate coatings. These coatings meet the requirements of DoD-P-16232, Type M and Type Z respectively. The phosphating baths should be operated in the concentration ranges recommended in Table 2. The control measure for adjusting the concentrations are given in the following paragraphs:

TABLE 2

Recommended Concentration Ranges

	Phosphating Solution	
	Manganese-Base	Zinc-Base
Free Acid, points[(a)], maximum	5.0	5.5
Total Acid, points[(a)]	26 to 30.0	26 to 30.0
Free Acid to Total Acid Ratio		
Minimum	1 to 5.5	1 to 5.5
Optimum	1 to 6.0	1 to 6.0
Iron (ferrous), percent	0.2 to 0.4	0.2 to 0.4

(a) One point equals 1 ml of 0.1 N NaOH per 10 ml sample.

4.4.2.1 Total Acid. The total acidity of the phosphating solution is maintained as follows:

Manganese - base phosphate solution - add a solution of manganese phosphate, manganese nitrate and phosphoric acid.

Zinc - base phosphate solution - add a solution of zinc phosphate, zinc nitrate and phosphoric acid.

The total acidity of these baths is maintained within the limits shown in Table 2. Small deviations are maintained by frequent small additions of the above solutions. The amount of chemical required to increase the total acid one point is 2.1 pounds per 100 gallons for the manganese - base phosphate solution when using the chemical conforming to MIL-P-50002 Type M, Composition B, and 1.5 pounds per 100 gallons for zinc - base phosphate solution when using the chenical meeting MIL-P-5002 Type Z. When material not covered by specification is used, this information may be obtained from the supplier. It is advisable to add the phosphating chemical in small frequent additions rather than larger infrequent additions. The bath should be stirred thorougly after the addition of chemical.

4.4.2.2. Free Acid. Maintenance of the free acidity of the solution is of great importance in the reactions involved in the coating formation. The free acidity which tends to rise due to dissociation of the dihydrogen phosphate salts in water, reaches a point where excessive etching of the work may occur. This condition is generally accompanied by inability to produce a complete coating within the normal processing period. Severe hydrogen embrittlement may be encountered as a result of the large amount of hydrogen formed when this condition arises. High free acidity is caused by the following:

(a) Prolonged idle periods during which the bath is heated but no work is processed.
(b) Overheating the solution.
(c) Processing small loads of work in a relatively large volume of solution.

Should the free acidity rise above the range designated, corrections should be made. The method used will depend upon the concentration of the ferrous iron as described in the two methods below.

4.4.2.2.1 If the iron content is near or approaching the upper limits, add 8 ounces per 100 gallons (60 grams per 100 liters) of manganese carbonate (manganese - base phosphate) or 8 ounces of zinc carbonate (zinc - base phosphate)for every point of free acid above the desired level. Manganese carbonate (for manganese-base phosphate solution) or zinc carbonate (for zinc-base phosphate solution) should be weighed, placed in a bucket, water added and mixed thoroughly. The resulting slurry should be stirred well and distributed over the solution surface. This treatment will reduce the free acidity but it may have to be repeated several times before the free acid remains within the desired range.

4.4.2.2.2 If the iron content of the solution is in the lower part of the recommended range or below, the free acid can be reduced by processing iron as described in 4.4.2.4.1.

4.4.2.3 Total Acid to Free Acid Ratio. The ratio of total acid to free acid should be maintained above the limit of 5.5 parts total acid (i.e., free acid plus combined acid) to one part free acid. The ratio, for most rapid coating action and best corrosion resistance, should be held at approximately 6 parts total acid to 1 part free acid. Should the free acidity tend to drop, the cause is usually contamination of the bath with alkaline cleaning salts. The source of the contamination must be located and eliminated. If the low free acid is causing poor coatings, it may be necessary to discard the contaminated phosphate bath and begin again with a new phosphate solution.

4.4.2.4 Ferrous Iron

4.4.2.4.1 Low ferrous iron. Ferrous iron can be introduced into the phosphating solution to build up a new solution or to raise the concentration in an existing bath by dissolving iron in the processing solution. The source of the iron is not important and the most readily available and cheapest source can be used providing it is clean or can be cleaned before it is immersed in the processing solution. Rusty metal should be pickled and thoroughly rinsed before being used. Steel wool, cast iron chips, scrap steel, and steel shavings can be placed in baskets and immersed until vigorous gassing ceases. No harm is done by leaving the iron in the phosphate solution after gassing ceases, but little iron will be dissolved after this point is reached. Iron powder and steel dust are best added by placing a cloth across the top of the tank so that it is 2 to 3 inches (5 to 7.5 centimeters) below the solution surface and scattering the powder or fine grit onto the solution surface. Additions should be at a rate which maintains vigorous gassing. When finished, remove the cloth and discard any material remaining on it. One pound of iron dissolved in 100 gallons (120 grams per 100 liters) will raise the ferrous iron content 0.12%. When introducing iron into a newly prepared phosphating solution, the instructions for temperature given in 4.3.4.2.1 should be observed.

4.4.2.4.2 High ferrous iron. While processing work, the iron which is dissolved during the coating action may cause the concentration of the ferrous iron to increase and eventually exceed the maximum level shown in Table 2. The concentration of the ferrous iron should be reduced before the maximum is reached. The ferrous iron content can be lowered by the addition of an oxidizing agent such as hydrogen peroxide. If the ferrous iron content is lowered in this manner it is essential that manganese carbonate (for manganese - base phosphate solution) or zinc carbonate (for zinc - base phosphate solution) be added to neutralize the phosphoric acid when ferrous phosphate is oxidized to form insoluble ferric phosphate. The addition of 0.5 pounds of 35% hydrogen peroxide to 100 gallons of processing solution (60 grams per 100 liters) will lower the ferrous iron 0.05%.

CAUTION: 35% hydrogen peroxide is a hazardous material and the precautions given by the supplier must be observed.

The hydrogen peroxide should be diluted with water before being added to the phosphating solution. For every added unit of weight of 35% hydrogen peroxide, two units by weight of manganese carbonate (for manganese - base phosphate solution) or two units by weight of zinc carbonate (for zinc - base phophate solution) should be added. The manganese carbonate or zinc carbonate should be separately mixed with water to form a slurry before addition to the phosphating solution. (Do not mix the hydrogen peroxide with either the manganese or the zinc carbonate.) No more than 0.05% ferrous iron should be removed at one time using this procedure.

An alternative method to lower the ferrous iron concentration consists of discarding a portion of the bath, and restoring the bath to the proper total acid following restoration of the level of the bath with water that has been thoroughly mixed into the bath. This method requires proper treatment of the discarded solution prior to disposal.

4.4.2.4.3 Ferrous iron vs. nitrite accelerator. If a bath which is thought to contain ferrous iron is milky in appearance or a sharp end point is not achieved when testing with potassium permanganate, the bath may contain nitrite instead of iron.

4.4.3 Control of Paint Base Zinc Phosphate Baths (TT-C-490 Type I). Zinc-based phosphate baths designed to produce coatings used as a base for paint (TT-C-490 Type I) are used in immersion applications and by spraying the solution on the work which is enclosed in a tunnel. With few exceptions these baths operate with nitrite as an accelerator and with no ferrous iron in the baths. The fact that the sodium nitrite is converted to volatile gasses in the phosphate solutions requires substantial differences in the control of immersion and spray processes and the instructions for their control will be given separately. See sections 4.4.4.1 and 4.4.4.2.

The zinc phosphate baths which do not use nitrite as the accelerator are seldom used on items being procured by the military and their control will not be covered in this manual. If these processes are being used, the control procedures will be furnished by the supplier.

4.4.3.1 Control of Immersion Type Processes. As work is processed in the solution, metallic acid phosphates, nitrates, and free phosphoric acid are consumed in the formation of the coatings. The bath must be replenished from time to time with the phosphating chemical. Frequent small additions of the phosphate chemical will produce more uniform work than occasional large additions. Not more than one point variance should be allowed. The processes are controlled by the operating temperature, the absence of any ferrous iron, the total acid, and the free acid (in decreasing order of importance).

4.4.3.1.1 Temperature. Operation of these baths below 170°F (76°C) greatly increases the risk of ferrous iron accumulation in the bath. Operation above 190°F (88°C) is not harmful but increases the cost of operation. The temperature should not be permitted to vary more than 5°F (3°C).

4.4.3.1.2 Absence of ferrous iron and presence of nitrite. For proper operation of these baths, some nitrite and no ferrous iron must be present.

4.4.3.1.3 Total acid. The total acidity of the bath should be maintained at 19 to 21 points. The amount of phosphating chemicals to increase the total acid 1 point can be obtained from the supplier of the chemical.

4.4.3.1.4 Free acid

4.4.3.1.4.1 High free acid. Free acid values above 5.0 in a 20 point bath may cause poor coatings. They are normally caused by excessive loss of processing solution due to leaks or drag-out of solution on the parts being processed. The loss of solution should be corrected and the free acid lowered by adding sodium hydroxide (or soda ash). The free acid will be reduced 1.0 points by the addition of 5.4 ounces of sodium hydroxide or 7.6 ounces of soda ash per 100 gallons of solution (40 grams of sodium hydroxide or 56 grams of soda ash per 100 liters). The sodium hydroxide or soda ash must first be dissolved in water to form a dilute solution before being added to the phosphate solution.

Another source of high free acid which is occasionally encountered occurs when pickling solution is carried into the phosphate solution. The source of the contamination should be determined and corrected and the free acid adjusted with sodium hydroxide (or soda ash) as in the previous paragraph.

4.4.3.1.4.2 Low free acid. If the free acid drops below 2.5 in a 20 point bath, the most frequent cause is contamination by alkaline cleaner salts. Any contamination should be eliminated. Normally, the bath will restore itself to a proper free acid level after a few hours of operation and no further adjustments should be necessary. If the free acid drops below 2 it may be necessary to discard the bath and prepare a new solution. If the bath is discarded, make sure that all waste disposal compliance requirements are met.

4.4.3.2 Control of Spray Type Processes. As work is processed in the solution, metallic acid phosphates and free acid are consumed in the formation of the coatings as in the immersion treatment. Control of the spray type processes differs from that for the immersion type due to the necessity of continuously adding sodium nitrite to replace the nitrite which is volatilized as the solution is sprayed. Unless corrective steps are taken, the sodium accumulates in the bath and the zinc decreases if the total acid is maintained at a constant value. A satisfactory bath can be maintained based on the total acid control if one nitrate ion is added (nitrate is contained in the zinc phosphate chemical) for each sodium ion added as sodium nitrite. (U.S. Patent, 2,351,605-R.C. Gibson.) For best results, both the phosphate chemical and a solution of sodium nitrite are added by means of small pumps capable of feeding small measured amounts of chemical.

The spray type processes are controlled by the total acid, nitrite, the free acid and the temperature (in decreasing order of importance).

4.4.3.2.2 Total acid. The total acidity of the bath should be maintained at 14 to 16 points. The supplier of the chemical will advise as to the amount of chemical required to increase the total acid one point.

4.4.3.2.3 Accelerator (nitrite). Sodium nitrite accelerator must be added continuously while processing parts in a spray process. (Avoid operating the sprays and adding sodium nitrite when no work is being processed.) The concentration of the accelerator should be maintained at the lowest level which will produce a satisfactory coating. This level is normally between 0.5 and 2.0. If it is determined that concentrations above 2.0 are required, refer to the discussion below under free acid (4.4.3.2.4). The problems due to improper free acid (high or low) are frequently counteracted by increased accelerator concentrations at the expense of using needlessly large amounts of chemical.

4.4.3.2.4 Free acid. The factors which affect the free acid in immersion type processes also affect the free acid in spray type processes. In addition, in spray type processes, the continuous additions of sodium nitrite can cause high or low free acid depending upon the composition of the phosphating chemical and ratio of phosphating chemical to sodium nitrite being used.

Frequently it is observed that satisfactory coatings can be obtained by operating with the accelerator at a higher level. While this produces satisfactory coatings, it does so at the cost of excessive usage of chemical.

4.4.3.2.4.1 Low free acid. Low free acid in the processing bath will develop if fewer ions of nitrate are furnished by the phosphating chemical than are necessary to compensate for the sodium ions being added as sodium nitrite. Low free acid values may also occur if excess nitrite is present in the phosphating chemical in the form of zinc nitrate.

The correction of low free acid due to either of these problems requires formulation of the phosphate chemical concentration by the supplier.

4.4.3.2.4.2 High free acid. If the free acid is high enough to give an acid ratio lower than 1 to 10 (i.e., 1 to 8) it may be difficult or impossible to obtain a satisfactory coating. The free acid can be lowered with sodium hydroxide as discussed in 4.4.3.1.4.1.

The high free acid values are normally the result of one of two conditions. If processing solution is lost due to leaks or is dragged out on the parts being processed, the problem of high free acid and high consumption can be corrected by eliminating the solution losses. If the phosphate chemical concentrate contains excess nitrate as nitric acid, the problem can be corrected by the supplier of your chemical by reformulating the material.

4.4.3.2.4.4 Temperature. The spray type process will operate satisfactorily at temperatures ranging from 130°F to 160°F (55°C to 70°C). The solution must be kept at the established temperature within 5°F (3°C) in order to produce consistent coatings.

4.5 Maintenance of the Chromate Rinse. During operation of the chromate rinse, evaporation causes the salts present in the water to become more concentrated. In addition, chemicals dissolved from the coatings accumulate in the chromate solution. These salts will be present in the solution and can dry on the work as it is removed from the chromate rinse. If present in sufficient quantities, failure in performance can result.

4.5.1 Control of the Chromate Rinse. The chromate solutions are controlled with a free acid test combined, in some cases, with a test for hexavalent chromium. A total acid test may be used as a guide for discarding the bath as discussed above and in section 4.5.2. The use of both a free acid test and a hexavalent chromium test permits excellent control and consistent results but requires the use of two chromate concentrates with different acidities. These are available from most suppliers of phosphate chemicals.

4.5.1.1 Free Acid. The free acid concentration is normally maintained at about 0.5 point with values as low as 0.2 and as high as 1.0 being used occasionally.

4.5.1.2 Hexavalent Chromium. The test and optimum concentration will be supplied by the supplier of the chemical.

4.5.1.3 Total acid. The acid is used as an indicator as to when to discard the bath. For further information see the first paragraph of this section (4.5) and paragraph 4.6.3.

4.5.2 Disposal of Chromate Solutions

4.5.2.1 These solutions, due to evaporation, accumulate salts present in the water and a small amount of the dissolved coating. When excessive amounts of these contaminants are present, they can cause failure of the finished parts. To prevent failures, all rinses must be discarded whenever they become contaminated. The final rinse shall be checked at least weekly and shall be discarded when the total acid reading rises to more than 7 times the free acid reading.

4.5.2.2 Common methods for determining when to discard the chromate solution are based on the free and/or total acid values. Discarding is recommended when the total acid exceeds an established value or divided by the free acid exceeds an established value.

These methods of determining when to discard the solutions frequently require discarding solutions which are capable of producing satisfactory results.

4.5.2.3 The cost of the chemicals is small and the cost of preparing new solutions is relatively minor. However, since the spent solutions usually must be treated to comply with waste disposal regulations (see paragraph 4.5.2.4), the cost to accomplish compliance requires that the baths not be discarded more often than necessary. The best procedure to use with a particular bath is to extend the time of use one shift at a time while testing all work processed. When it has been determined that process failures begin to occur after a given period of use, then set up a schedule for discarding the solution before this failure point is reached.

4.5.2.4 Waste Disposal. The method of disposal of chromate solutions depends on the local waste disposal regulations and is beyond the scope of this handbook. Generally it will be necessary to reduce the hexavalent chromium to trivalent chromium, precipitate the trivalent chromium, separate the precipitate from the liquid, and adjust the liquid to the proper pH.

The liquid can, in most cases, be discharged into the sewer but the precipitated trivalent chromium is normally shipped to a land fill site.

4.6 Chemical Analyses of Phosphating and Chromate Rinsing Solutions

4.6.1 Analytical Reagents. It is recommended that reagents required in the analysis of phosphating compounds be requisitioned if available from chemical supply houses. These are already made up to the proper strength. If local laboratory facilities are available, solutions may be made up as outlined in (a) through (j) below.

(a) Methyl orange-xylene cyanole indicator: Dissolve 1 gram methyl orange and 0.14 gram xylene cyanole in one liter of deionized water.

(b) One percent phenolphthalein indicator: Dissolve 1 gram phenolphthalein in 100 ml of alcohol.

(c) One percent bromcresol green indicator: Dissolve 1 gram bromcresol green in 100 ml of alcohol.

(d) 0.4% bromphenol blue indicator: Dissolve 0.4 gram of bromphenol blue in 6 ml of 0.1N sodium hydroxide diluted with 8 ml of deionized water. When completely dissolved, dilute to 1000 ml with deionized water.

(e) Sulfuric acid, H_2SO_4, 6 Normal: Sulfuric acid 6 N is made by adding 1 part by volume of concentrated sulfuric acid to 5 parts by volume of water.

CAUTION: Always add the acid to the water. Heat is generated when the acid mixes with water and protective clothing and eye and face protection should be worn when making this material.

(f) Sodium hydroxide, 0.1 Normal: Dissolve 4.0 grams of C.P. sodium hydroxide in deionized water and dilute to one liter. Standardize by titrating equal volumes of 0.1 N potassium acid phthalate, $KHC_8H_4O_4$, and the sodium hydroxide, using phenolphthalein indicator to a pink end point. The solution of sodium hydroxide must be diluted with deionized water or strengthened by adding a concentrated solution of sodium hydroxide, until the concentration is adjusted to 0.1 Normal.

(g) Potassium acid phthalate, 0.1 Normal: Weigh exactly 10.2 grams of carefully dried, chemically pure potassium acid phthalate (National Bureau of Standard Sample No. 84d) and transfer to a 500 milliliter volumetric flask. Dissolve the salt in the flask, dilute to 500 ml, and mix thoroughly. The resulting solution may be considered as being 0.1 Normal.

(h) Potassium permanganate solution, $KMnO_4$, 0.18 Normal: Weigh 5.66 grams potassium permanganate and dissolve in deionized water and dilute to a total volume of 1 liter. Mix well and allow to stand in a dark bottle for a week. Siphon off the clear solution (or filter through an asbestos filter) and standardize against known samples of pure iron wire, previously weighed and dissolved in sulfuric acid, in absence of air. Titrate the sample of iron solution with the $KMnO_4$ solution to a pink end point, and record the number of mls used. Calculate as follows:

$$\frac{\text{Grams of pure iron in sample} \times \text{purity of iron divided}}{\text{by Mls of } KMnO_4 \times 0.0558} = \text{Normality of } KMnO_4$$

Store in absence of light.

(i) Potassium permanganate solution, $KMnO_4$, 0.042 Normal: Prepare as above using 1.32 grams of potassium permanganate or dilute 233 ml of the 0.18 N $KMnO_4$ solution to 1 liter with deionized water and mix thoroughly. Store in the absence of light.

(j) 4,4' bipyridine paper: Dissolve 1 gram of 4,4' bipyridine in 100 ml of ethanol. Wet pieces of filter paper and allow the paper to dry. Cut the paper into convenient size strips and store in a closed glass jar.

4.6.2 Free Acid. The proper procedure for determining the free acid depends upon the solution being tested. Select the proper procedure as described below.

4.6.2.1 Free Acid in Phosphate Baths Containing Ferrous Iron. Using a 10 ml volumetric pipette, transfer a 10 ml sample of the solution to an Erlenmeyer flask or beaker. Add 3 drops of methyl orange-xylene cyanole indicator. Titrate with 0.1 N sodium hydroxide. The end point is a gray to greenish-gray color. Record the number of mls of 0.1 N sodium hydroxide used. This number is the number of points of free acid in the solution.

4.6.2.2 Free Acid in Phosphate Baths Containing Nitrite. Using a 10 ml volumetric pipette transfer a 10 ml sample of the solution to an Erlenmeyer flask or beaker. Add 5 drops of bromphenol blue indicator. Titrate with 0.1 N sodium hydroxide. The end point is reached when the yellow just changes to bluish-green by daylight or blue-violet by incandescent light. Record the number of mls of 0.1 N sodium hydroxide used. This number is the number of points of free acid in the solution.

4.6.2.3 Free Acid in Chromate Rinse Solutions. Using a 25 ml volumetric pipette transfer a 25 ml sample of the solution to an Erlenmeyer flask or beaker. Add 4 drops of bromcresol green indicator. The solution should remain yellow. If it turns green or blue there is no free acid present, and additional chemical is required. When the solution remains yellow, titrate with 0.1 N sodium hydroxide. The end point is the appearance of a permanent green color. Record the number of mls of 0.1 N sodium hydroxide used. This number is the number of free acid points in the solution.

4.6.3 Total acid. The procedure for determining the total acid depends upon the solution being tested. Select the proper procedure as described below.

4.6.3.1 Total Acid in Phosphate Baths. Using a 10 ml volumetric pipette transfer a 10 ml sample of the solution to an Erlenmeyer flask or beaker. Add 5 drops of phenolphthalein indicator. Titrate with 0.1 N sodium hydroxide. The end point is a permanent pink color. Record the number of mls of 0.1 N sodium hydroxide used. This number is the number of points of total acid in the solution.

4.6.3.2 Total Acid in Chromate Solutions. Using a 25 ml volumetric pipette transfer a 25 ml sample of the solution to an Erlenmeyer flask or beaker. Add 5 drops of phenolphthalein indicator. Titrate with 0.1 N sodium hydroxide. The end point is the appearance of a red or purple color. Record the number of mls of 0.1 N sodium hydroxide used. This number is the number of points of total acid in the solution.

4.6.4 Determination of Nitrite and Ferrous Iron. Both nitrite and ferrous iron react with potassium permanganate in an acidic solution and either may be present in a phosphate solution. This is seldom a problem in the manganese phosphate type baths as nitrite seldom develops in these baths. In the zinc phosphate type baths (and particularly those used to meet the requirements of TT-C-490), either material may be present and the potassium permanganate titration does not indicate which one is present. Therefore, a positive test for one or the other is desirable. The presence of ferrous iron can be determined by wetting a strip of paper impregnated with 4,4' bipyridine (see paragraph 4.6.1) with the phosphate solution. Ferrous iron is present if the paper turns pink or red. If the paper does not change color, and the acidified sample reacts with potassium permanganate, nitrite can be assumed to be present. There is no simple test for the positive identification of nitrite but under the above conditions, it can be assumed that it is present in a phosphate solution.

4.6.4.1 Ferrous Iron. Check for the presence of ferrous iron with paper immersed with 4,4' bipyridine. If the paper does not change color see paragraph 4.6.4.3. If the paper turns pink or red use a 10 ml volumetric pipette to transfer a 10 ml sample of the phosphate solution into an Erlenmeyer flask or beaker and add 10 ml of 6 N sulfuric acid. Titrate with 0.18 N potassium permanganate. The end point is a permanent pink color. Record the number of mls of 0.18 N potassium permanganate used. Divide this number by 10 to determine the percent of ferrous iron present.

4.6.4.2 Nitrite. Check for the presence of ferrous iron with paper impregnated with 4,4' bipyridine. If the paper turns pink or red, it indicates that ferrous iron is present and the ferrous iron must be removed in order to operate with nitrite present. See paragraph 4.6.4.4 for procedures for removing the ferrous iron. When the paper does not change color, use a 25 ml volumetric pipette to transfer a 25 ml sample of the phosphate solution into an Erlenmeyer flask or beaker and add 50 ml of 6 N sulfuric acid. Titrate with 0.042 N potassium permanganate. The end point occurs when one drop of potassium permanganate produces a pink color which persists for 10 seconds. Record the number of mls of 0.042 N potassium permanganate used. This number represents the concentration of the nitrite.

4.6.4.3 Destruction of Unwanted Nitrite. When iron is processed in a hot immersion type phosphate bath containing nitrite, the result is normally the generation of additional nitrite. To develop ferrous iron in the bath, allow the bath to cool below 160°F (70°C) and allow the nitrite to escape either by standing overnight or by bubbling air through the bath. Load the bath with iron as described in paragraph 4.4.2.4.1. When the minimum concentration of ferrous iron is present, the temperature can be increased to the proper operating level and production resumed.

4.6.4.4 To Destroy Ferrous Iron and Develop Nitrite. If the bath is designed to operate with nitrite present it is necessary to make sure that no ferrous iron is present. Wet a strip of paper impregnated with 4,4' bipyridine with the phosphate solution. If the paper turns pink or red, ferrous iron is present and must be removed.

If the paper turns pink, the ferrous iron can be oxidized to insoluble ferric phosphate with sodium nitrite. Add 2 ounces of sodium nitrite dissolved in water for each 100 gallons (15 grams per 100 liters) of phosphating solution. Repeat if necessary until no test for ferrous iron is obtained.

CAUTION: When adding sodium nitrite to a phosphate bath containing ferrous iron, make sure that the ventilating system is operating.

If the paper turns red, the above procedure may produce large amounts of a brown gas which consists of toxic oxides of nitrogen. In addition, a large volume of sludge will be produced.

The recommended procedure is to discard the solution observing local waste disposal regulations. Prepare a fresh phosphate solution.

4.6.5 Hexavalent Chromium. The procedure for controlling hexavalent chromium can be obtained from the supplier of the chromate rinse chemicals. The supplier will advise as to whether or not such a procedure is necessary.

4.7 Inspection of Phosphated Parts

4.7.1 Visual Inspection. To ensure work of acceptable quality, all work should be visually inspected before being oiled or painted. Good work may range in color from gray to black depending upon the alloy being treated but should be uniform in color except where a portion of the part has been subjected to localized heat treatment. These areas may be lighter or darker in color. There should be no contact marks which show uncoated metal. The phosphate coating should show no white or greenish-white stains. These streaks are normally indications of inadequate rinsing of the processing solution from the surface of the work.

4.7.2 Corrosion Resistance of the Phosphate Coating

4.7.2.1 Salt Spray Test for Heavy Phosphate Coatings, DOD-P-16232. The phosphated parts should be subjected to a 5% salt-spray (fog) test as described in ASTM B-117. The phosphate coatings should meet the salt-spray requirements of specifications. Parts intended for dry (i.e., unoiled) salt-spray corrosion tests should be placed directly in test without rinsing, degreasing, or any treatment other than that which constitutes a part of the process. Should the surface have been contaminated in handling, the parts should be thoroughly degreased, rinsed in the chromate solution, dried and placed directly in test.

4.7.2.2 Salt-Spray Test for Type I, TT-C-490. The phosphated parts to be tested should be coated with the coating to be used on the finished products. These parts should satisfactorily pass the 5% salt-spray requirement for the specification of the final coating used.

4.7.3 Determination of Phosphate Coating Weight Per Unit Area

4.7.3.1 Removal of Phosphate Coatings. Manganese based coatings (Type M, DOD-P-16232), zinc based coatings (Type Z, DOD-P-16232), and zinc based coatings (Type I, TT-C-490), can all be removed to determine the weight of the phosphate coating or to examine the base metal by following steps (a) through (f) below. Steps (a) and (f) can be omitted if the only concern is the appearance of the base metal.

(a) Weigh a suitable phosphated part which is clean and free from oil. Calculate the entire surface area.

(b) Immerse for 15 minutes at 165°F (74°C) in a 5% solution of chromic acid in water. The chromic acid solution should be used only once.

(c) Rinse thoroughly in two separate rinses of clear deionized water.

(d) Rinse in alcohol.

(e) Dry in an oven or with clean compressed air.

(f) Weigh the stripped part.

4.7.3.2 Phosphate Coating Weight. The weight of the phosphate coatings can be calculated from the above data as follows:

$$\text{Phosphate Coating (in mg per sq meter)} = \frac{\text{Weight Loss (in mg)}}{\text{Area of Part (in sq. meters)}}$$

4.8 Common Difficulties Encountered in Phosphate Coating Processes

4.8.1 General. In all protective coating processes, a certain amount of difficulty may be encountered, due to unobserved errors in carrying out one or more of the operations that directly influence the quality of the work. This section is devoted to brief descriptions of commonly encountered difficulties and the recommended corrective measures.

4.8.2 Visual Defects. The appearance of the phosphate coatings may vary. Some of these differences indicate a problem exists but other variations do not reflect a difference in quality.

4.8.2.1 Color. The color of the coatings can vary from gray to black. Variation in color is, by itself, not a cause for rejection and no attempt should be made to match the color of the coatings.

4.8.2.2 Rust Stained and Frozen Assemblies. Assemblies must not be phosphated as assemblies when the individual components can be treated separately. Where complete disassembly is impossible due to riveting or brazing, every precaution should be taken to prevent oil from remaining between the surfaces prior to phosphating. Special attention should be given to rinsing the solution from these areas. When treating parts to meet DOD-P-16232, a preservative compound of the water displacing type should be used after the phosphating.

4.8.2.3 Bare Areas on or Near Heated Areas (i.e. welds). These bare areas occur where oiled parts are subjected to enough heat to bake the oil but not enough to burn it off. This can be corrected by removing the oil before subjecting the part to heat or by removing the surface with the oil baked on by abrasive blasting.

4.8.2.4 Coarse Crystalline Coatings. Coarse crystalline coatings are not cause for rejection if the part meets all requirements of the specification. Unfortunately, these coatings frequently fail to give adequate corrosion protection and corrective steps are then necessary. These coatings are commonly the result of the cleaning procedure used. When alkaline cleaners are not thoroughly rinsed from the surface before phosphate treatment, a coarse crystalline coating may be produced, even when the alkaline cleaning stage is followed by abrasive blasting.

When parts are pickled prior to treatment with a phosphate process, coarse crystalline coatings may be produced even with good rinsing. (Acid pickling ahead of phosphate coating is not recommended and should never be used without the approval of the purchasing facility.)

Even with good rinsing, some cleaners result in the formation of phosphate coatings which are more crystalline than desired. There are proprietary pretreatments available which will help produce coatings with a fine crystal structure when such cleaners are used. These frequently are referred to as "conditioning salts".

4.8.2.5 White Powder on the Coating. This problem develops on parts processed by immersion but not on parts processed by spray. The phosphated work may have a white powder on the coating covering the upper surface of the work with the remaining surfaces of normal color and nature. This condition is the result of sludge from the bath depositing on the upper surfaces of the work during processing. While a light dusty deposit of sludge causes no serious difficulties, heavy deposits prevent adequate rinsing of the work surface. The most common causes for sludge depositing on the work are agitation of the sludge which has settled to the bottom of the tank due to boiling the solution or disturbing the sludge by movement of the work being processed. The first of these can be corrected with adequate temperature control and the second by removal of excess sludge (see paragraph 4.4.1.1.).

4.8.2.6 Streaks. The phosphated part may have streaks which appear to follow the flow of solution draining from the parts. These streaks may appear as rust streaks, as sandy material, or as green or gray-white material. This condition is generally the result of poor rinsing. If the water rinse following the phosphating bath is allowed to become contaminated with phosphating chemicals, streaks may occur. Streaks may also result if phosphating salts are trapped in recessed areas of the parts and allowed to drain out over the rinsed areas after removal from the rinse water.

This can be corrected in immersion processing by two methods or preferably by a combination of the two: namely, rotating the work in the rinse water to allow trapped solution to escape and/or removing the parts from the rinse water, rotating, and reimmersing. Streaks can also be formed when massive parts are being processed and the phosphate solution dries on the parts before they get into the rinse water. This can be corrected by the use of the spray rinse procedure described in paragraph 4.3.5.2.

When this problem occurs on parts processed by spray, the problem can be solved by adjusting the direction of the sprays in the water rinse and/or the use of a mist rinse of fresh water at the exit end of the spray zone.

4.8.2.7. Mottled Streaks. This problem develops on parts processed by immersion but not on parts processed by spray. The phosphated parts may have mottled streaks of extremely thin, light colored phosphate over part or all of the work surface. Streaks always are directed toward the uppermost portion of the piece as it is suspended in the phosphating solution. This difficulty is frequently encountered where alkaline cleaners are used and oil is allowed to collect on the surface of the cleaner. It is also encountered where heavy rust-preventive compounds are incompletely removed from recessed, blind or small holes, threaded parts, or between joining surfaces. The oil, grease, or rust-preventive compounds remain in these places through the abrasive blast treatment and flow out when the part is placed in the hot phosphating solution.

4.8.2.8 Scratches and Abrasions. This problem occurs primarily when treating parts to meet DOD-P-16232. When heavy parts are phosphated in a tumbling barrel or rotating screw unit, considerable battering, scratching, and abrading may occur. In such instances, every effort should be made to reduce the amount of tumbling but sufficient movement of the parts to avoid contact marks is essential. When closed tumbling barrels are used, the barrel should be filled as tightly as possible to reduce the movement of the parts during processing. It has been found that, regardless of how tightly the barrel is packed, enough movement of individual parts occurs to prevent the formation of harmful contact marks.

4.8.2.9 Fingerprints. This problem occurs primarily when treating parts to meet DOD-P-16232. Work that has been abrasive blasted in preparation for phosphating is very susceptible to fingerprints, which cause formation of very thin, light colored deposits. Even when clean cotton or rubber gloves are used, marks may be produced by the wiping action of sliding the fingers over the surface. This "wiping" action produces a thinner phosphate coating which will retain less preventive finish.

4.8.3 Failure to Meet Corrosion Resistance or Coating Weight Requirements of Specifications. When the coating appears to be uniform and shows none of the preceding faults, but fails to meet the specified requirements, the following possibilities should be investigated.

4.8.3.1 Is the bath being properly controlled as to temperature, total acid, ratio of free acid to total acid and ferrous iron (or nitrite accelerator)?

4.8.3.2 Has the bath been kept hot with little or no work being processed? If so, allow the bath to cool to below 110°F (44°C), stir thoroughly to mix the sludge with the solution, heat to operating temperature, and process freshly cleaned parts.

4.8.3.3 Has the chromate rinse been used too long a time? Prepare a fresh chromate rinse in a small container and compare the results obtained using the fresh rinse with those obtained using the production tank.

4.8.3.4 Is a silicate containing cleaner being used? Silicate containing alkaline cleaners are excellent in detergency, buffering, and ability to keep the removed solid in suspension. A problem can develop with these cleaners due to absorption of carbon dioxide from the air, burner exhausts, or acid introduced into the cleaner. A silicate containing cleaner contaminated in this manner may deposit a jell-like material which may not be visible on the surface of the parts, which is not removed in the rinse stage. The presence of this jell prevents the formation of a satisfactory phosphate coating. If this is suspected, it can be confirmed by taking a part which has been cleaned and rinsed, dipping the part in a solution containing approximately 5% by weight of sodium hydroxide in water for one minute, rinsing it in clean water, and finally processing it through the remainder of the phosphate system. If this corrects the problem, discard the cleaner solution (observing local waste disposal regulations) and prepare a fresh cleaner solution. Eliminate or reduce the input of carbon dioxide or other acidic material into the cleaner. If the problem continues, change to a silicate free cleaner.

4.8.3.5 Drawn or Pressed Parts. These parts, including metal stampings, are difficult to phosphate because of the nature of their surface. Such parts must be cleaned mechanically, preferably by abrasive blasting, in order to remove the surface stresses developed in their manufacture. Highly caustic alkaline cleaners and alkaline derusting must be followed by abrasive blasting, abrasive tumbling, treatment with a metal conditioner, or wiping to ensure a smooth phosphate coating.

4.8.3.6 Are the parts clean before entering the phosphating solution? A cleaning solution which has been satisfactorily removing the soil from the work may cease to do so. Two reasons for this are:

(a) A change in the soil present on the work and

(b) An accumulation of soil in the cleaner until it can no longer remove the soil from the work.

Try cleaning parts in a fresh cleaner solution. If this is successful, discard old solution. If the fresh solution does not remove the soil, other cleaning procedures should be investigated to find one which will remove the soil. The possibility of changing the soil to one which is more easily removed should also be investigated.

If it is necessary to discard a cleaner solution, make sure of compliance with all waste disposal regulations.

4.8.3.7 Low Coating Weights. Phosphate coating weights below the minimum specified can be caused by several conditions including those listed below:

(a) Excessive use of "conditioning salts" in or following the cleaner.

(b) Presence of surfactants or pickling inhibitors in the phosphating solution.

(c) When steam is used for heating, many plants use volatile inhibitors in the boiler water to protect the steam lines from corrosion. A loose connection or a leaking steam coil can allow these inhibitors to get into the cleaner, the water rinse (before the phosphate), or the phosphate solution. When present, the inhibitors can interfere with the formation of a satisfactory coating. The supplier of your boiler compound can provide chemicals which permit you to control the corrosion in the steam lines without the use of volatile inhibitors.

4.8.3.8 Determine if the poor corrosion resistance is due to poor corrosion resistance of the phosphate coating or poor corrosion resistance of the supplementary finish. Is the correct amount of finish being applied to the parts?

When treating parts to meet DOD-P-16232, the weight of the finish can be determined as follows: weigh a finished part, remove the finish with a solvent, dry, and reweigh the part. The difference in the two weights is the weight of the finish. If the specified amount of finish is present, compare parts finished with the material being used in production with parts finished with a freshly prepared finish. The finish may have been contaminated or may have lost some of its inhibitors.

When treating parts to meet TT-C-490, the paint should be checked for film thickness and the curing procedure should be checked. If the preceding appears to be correct, finish a part with a sample of paint known to give proper results.

4.8.3.9 Chromate Stains. Chromate stains have the general appearance of rust. These stains occur where the chromate solution is allowed to accumulate and dry on the part. They seldom cause any problem when the water used in the chromate rinse contains no dissolved salts. When the water does contain dissolved salts, these are also concentrated in the area of the chromate stain and can accelerate the formation of rust. This problem can be corrected by using deionized water to build up and replenish the chromate rinse solution or by removing any accumulation of the chromate rinse solution before it dries.

4.8.3.10 Effect of excessive heat on the corrosion resistance of the coating. This problem is related to coatings for DOD-P-16232. Zinc phosphate coatings should not be exposed to temperatures in exess of 225°F (105°C) for more than 15 minutes. Manganese phosphate coatings should not be exposed to temperatures in excess of 375°F (190°C) for more than 15 minutes. Longer exposures at these temperatures or shorter times at higher temperatures can lower the corrosion resistance of these coatings.

NOTE: DOD-P-16232F (7 November 1978) allows parts with a zinc phosphate coating to be heated 8 hours at 207-225°F (97-107°C) to relieve hydrogen embrittlement, but it will also reduce the corrosion resistance of the coating. The alternative method of holding the parts for 120 hours at room temperature is the preferred method of relieving hydrogen embrittlement in phosphated parts.

4.8.3.11 Contaminated Grit Used for Abrasive Blasting. If the grit being used for abrasive blasting becomes contaminated with grease or oil, the oil and grease will be driven into the surface during blasting and satisfactory coatings will not be produced. Oil and grease can get into the grit if oily or greasy parts are blasted or through leaking seals in the equipment. If the grit has become contaminated, the source of the contamination must be eliminated and the grit replaced with clean material.

4.8.3.12 Lime Drawn Wire. This problem occurs primarily on parts being treated to meet DOD-P-16232. Many nuts and bolts are made from heavy wire or rod which has been drawn using lime as a lubricant. When parts made from such wire are cleaned, it is usually necessary to include a pickle in the cleaning system. If sulfuric acid is used, insoluble calcium sulfate deposits on the work and interferes with subsequent phosphating. These parts can be successfully cleaned if a hydrochloric acid pickle is used. The calcium chloride which is formed is soluble and readily removed in the rinse stages.

4.8.3.13 Case Hardened Parts. This problem also is one encountered on parts being treated to meet DOD-P-16232. The problem generally occurs when phosphate coatings are used to replace plating. The tempering operation in the heat treat is frequently omitted when the parts are to be plated as it is necessary to bake the parts after plating to relieve hydrogen embrittlement. If the tempering operation is omitted prior to the phosphating operation, the coatings produced will not provide the expected corrosion resistance. The tempering operation is necessary to give the required physical properties as well as to permit proper formation of the phosphate coatings.

4.8.3.14 Cast Iron and Alloys Which Are Difficult to Treat. This is a problem when treating parts to meet DOD-P-16232. Cast parts such as malleable, pearlitic malleable, or cast iron, cast steel and some alloys which are difficult to treat may fail to meet corrosion resistance requirements. Cast iron, steel, or pearlitic malleable iron has a burned-in and sand-cast surface or high silicon alloy cast surface, which must be given a very thorough blasting treatment to permit the phosphate coating to be formed. In addition, these metals may not completely phosphate in the time normally required to phosphate steel. In the treatment of these materials, a low free acid phosphating solution gives a considerable advantage. Superior corrosion resistance can be obtained on cast parts as well as other steel parts by using either Procedure A or Procedure B.

Procedure A

(a) Abrasive blast all parts.

(b) Plan work schedules so parts made of malleable or cast iron will be treated immediately after a period during which the phosphate solution is idle and has been allowed to cool to room temperature.

(c) Add to the solution, prior to the shut down period, 0.5 pound per 100 gallons (75 grams per 100 liters) of either zinc carbonate (for zinc-base solutions) or manganese carbonate (for manganese-base solutions) and stir thoroughly.

(d) Turn on the heat to the tank. When the solution temperature reaches 170°F (75°C), place the work in the solution and raise the temperature to 205°F (95°C) as quickly as possible. Allow the work to remain in the solution after reaching the operating temperature for at least 45 minutes.

Procedure B

(e) Abrasive blast all parts.

(f) Use zinc or manganese carbonate to raise the ratio of total acid to free acid to 7.5 to 1 or higher.

(g) Process a large load of parts (a large surface area).

(h) Process the critical parts.

4.8.3.15 Heat Treated Parts. Satisfactory phosphate coatings may not form on parts if oil was present when the parts were subjected to heat during the heat treatment. If oil is present or suspected of being present on parts which are to be heat treated, try removing the oil from some parts, heat treat these parts and follow them through the phosphating operation to determine whether there is an improvement in the coatings produced.

4.8.4 Paint failures - blistering and/or spotting paint adhesion. The paint adhesion failure referred to here occurs when the adhesion is checked with tape and the paint pulls away in spots. This type of failure is normally the result of a blister having formed under the paint film destroying the adhesion of the paint to the metal. To prevent this type of paint failure, it is necessary to avoid those conditions which cause blisters to form.

Blisters form under paint when water soluble salts are trapped under the paint film and the paint is exposed to humid conditions. Water vapor can pass through the paint film and, if a water soluble salt is present, a solution is formed which lifts the paint and forms a blister. When checked for adhesion the paint is lifted from these areas even if the blister is no longer evident.

To prevent this type of failure, it is necessary to make sure that no water soluble salts are on the surface.

4.8.4.1 Salts Left by Poor Rinsing. If the rinse solutions are allowed to become contaminated or trapped solutions are not completely removed, the residue remaining on the surface may contain water soluble salts which can cause blistering. For corrective measures see 4.8.2.6.

4.8.4.2 Contaminated Chromate Solutions. The chromate solution is normally dried on the surface of the phosphate coated parts. If the chromate solution is prepared with water containing soluble salts, these salts will accumulate as water is added to replace that lost by evaporation. The amount of water soluble material left on the parts will increase as these salts accumulate. In areas of the parts where the chromate solution collects in streaks, puddles, or beads, this blistering problem can be of major importance. Corrective steps are of three types:

(a) Avoid allowing streaks, puddles, or beads of chromate solution to dry on the parts.

(b) Use deionized water to build up and replenish the chromate rinse.

(c) Follow the chromate rinse with a rinse of deionized water. If this is done, it is necessary to use specially formulated chromate rinses. See 4.3.6.3.

4.8.4.3 Handling. Soluble salts can also be left on the parts when they are handled with bare hands or dirty gloves.

5. BLACK OXIDE COATINGS

5.1 Introduction

5.1.1. General. This type of coating is produced by converting the surface of iron and steel parts to black iron oxide (Fe_3O_4) with a thickness of less than 0.0001 inch (0.00025 cm) according to MIL-C-13924. This coating affords very limited corrosion protection. The alloys that are given MIL-C-13924 Class 3 and 4 coatings have little need of added corrosion protection. The metals that are given a MIL-C-13924 Class 1 coating can have the corrosion resistance improved by the application of a rust-preventive oil.

Due to the fact that these coatings show only a slight build-up on the parts, they are suitable for moving parts that cannot tolerate a heavier coating.

5.1.2 Characteristics. The coatings produced by all three classes of MIL-C-13924 are similar in composition and appearance. The three classes use different chemicals to treat the alloys.

5.1.2.1 Class 1. Class 1 coatings are formed in an alkaline oxidizing bath on wrought iron, plain carbon, low alloy steels and cast and malleable irons.

5.1.2.2 Class 3. Class 3 coatings are formed in a fused salt bath on corrosion resistance steel alloys which are tempered at 900°F (482°C) or higher.

5.1.2.3 Class 4. Class 4 coatings are formed in an alkaline oxidizing bath on 300 series corrosion resistant steel alloys.

5.1.3 Safety Precautions. The safe handling of these chemicals requires caution due to different hazards at different phases in their operation.

5.1.3.1 The baths are operated at temperatures ranging from 250°F (121°C) in Class 4 baths to 850°F (455°C) in Class 3 baths. Contact with these baths can cause severe burns. Moisture on parts being introduced into the operating baths can turn to steam and cause the hot chemicals to splash or erupt and anyone nearby can be burned. Operators should wear protective clothing and no other personnel should be allowed in the vicinity of the operating bath.

5.1.3.2 The salts in the baths can cause chemical burns as well as thermal burns. In case the hot salts are splashed on anyone, the area contacted by the chemical should be flushed immediately with water to remove the salts and the affected area should be kept in water or kept covered with wet compresses which are constantly changed until medical attention can be obtained. If anyone should contact the unheated salts, the area of contact should be washed with water immediately. If there is evidence of skin irritation, medical help should be obtained.

5.1.3.3 The baths can solidify when allowed to cool. When heat is applied to a solidified bath there is danger of an eruption of molten salt through the solid crust. Class 1 and Class 4 baths will normally not solidify at room temperature but may solidify at lower temperatures or if allowed to become more concentrated than normal. Class 3 baths will solidify at room temperature and can be expected to erupt through the crust when being heated. This type of eruption may also occur with the other baths if they have cooled enough to cause solidification.

5.1.3.4 When cold, the Class 3 salts must be handled as toxic hexavalent chromium compounds. The Class 1 and 4 compounds are caustic with oxidizing agents and should be handled according to the instructions and cautions furnished by the supplier.

5.1.4 Disposal. The processing baths may have to be discarded for various reasons such as equipment repair or discontinued operations. The chemicals must be treated before disposal and the rinse waters may contain amounts of salts which will require that they be treated in order to meet the local waste disposal regulations.

5.1.4.1 Disposal of the Operating Baths. The Class 1 and 4 baths are normally "slushy" at room temperature and should be diluted with at least an equal volume, and preferably three or four volumes, of water before being treated for disposal. Class 3 baths are solid at room temperature. These baths are best handled by ladling them out, while hot, into shallow trays and allowed to cool in thin enough layers that they can be broken up without tools. THE SOLID SALT SHOULD NEVER BE STRUCK WITH A TOOL TO BREAK IT OR FOR ANY OTHER PURPOSE. The small pieces can then be dissolved in water and the solution treated for disposal.

5.1.4.2 Treatment for Disposal, Classes 1 and 4. The alkaline portion of these baths will have to be treated to lower the pH to an acceptable range in all locations. The oxidizing portion of the baths may require treatment depending upon the oxidizing chemical used and the local regulations.

5.1.4.3 Treatment for Disposal, Class 3. The waste disposal regulations will normally require that the hexavalent chromium be reduced to trivalent chromium and that the trivalent chromium be precipitated and removed before discharging the solution to the sewer.

5.1.5 Embrittlement. Embrittlement is seldom a problem with the black oxide treatments but can become a problem with high strength steels.

5.1.5.1 High strength steel (Rockwell C 40 or greater hardness) may fail due to "caustic embrittlement" if the part is processed in the black oxide bath under internal or applied stress.

5.1.5.2 Treatment of High Strength Steel. When specifying the treatment of steel parts having an ultimate tensile strength of 200,000 psi (1379MPa) or above, the procuring agency may require that the parts be baked at 375° ± 25°F (190° ± 14°C) for three hours or more or given an equivalent embrittlement relief treatment after the application of the oxide coating and/or specify that the parts be tested for embrittlement. If an embrittlement relief bake is required, it shall follow the chromate rinse and precede the supplementary preservative treatment.

5.2 Equipment

5.2.1 Processing Tanks. The tanks used to contain the black oxide chemicals are heated by gas or by immersion electric heaters. The high cost of heating these tanks makes the use of thorough insulation imperative. They should be installed on a concrete slab and surrounded by a curb (or installed in a non-combustible tray) providing adequate area to catch any drippings and deep enough to contain the chemicals if a tank should fail.

5.2.1.1 Gas Heated Tanks. Heat is supplied to gas heated tanks by burners mounted beneath the tank (Figure 10). Greater heat efficiency can be obtained by conducting the products of combustion around the sides of the tank using a second wall surrounding the tank. The products of combustion are then vented to the flue. The tank should be surrounded by insulation to minimize heat loss.

5.2.1.2 Electrically Heated Tanks. The immersion electric heaters must have adequate capacity to heat the baths to operating temperature in a reasonable time. What is reasonable will vary with the production requirements. The heaters should be protected from mechanical damage by a protective grating.

5.2.2 Water Diffuser. This applies to Class 1 and 4 only as water is not added to Class 3 baths. The addition of water to Class 1 and 4 baths can cause spattering due to the rapid conversion of the water into steam by the hot bath. Water can be safely added by adding it through a pipe with small holes in it. The pipe should be mounted along the back side of the tank with the holes directed toward the back wall. This allows a thin film of water to flow down the back wall into the bath away from the operator.

5.2.3 Rinse Tanks

5.2.3.1 Mist Rinse. If the use of a mist rinse is found to be necessary (5.3.2.3.3), it can be supplied either from a hand held nozzle or from nozzles mounted a short distance above the bath surface. The nozzles used must supply only a small amount of water and must break up the water into extremely small droplets to prevent spattering of the hot bath.

5.2.3.2 Warm Water Rinse Tanks. The first rinse following the black oxide treatment is overflowed at a rate which permits removal of the salts but may allow the water to be warmed by the hot parts. The tanks should be equipped with drains to permit emptying when they become excessively contaminated. Provision for heating the rinse used after the Class 3 treatment is essential as this rinse must be at about 190°F (88°C) for proper removal of the salt. (If necessary to obtain the required temperature, the overflow can be discontinued temporarily.)

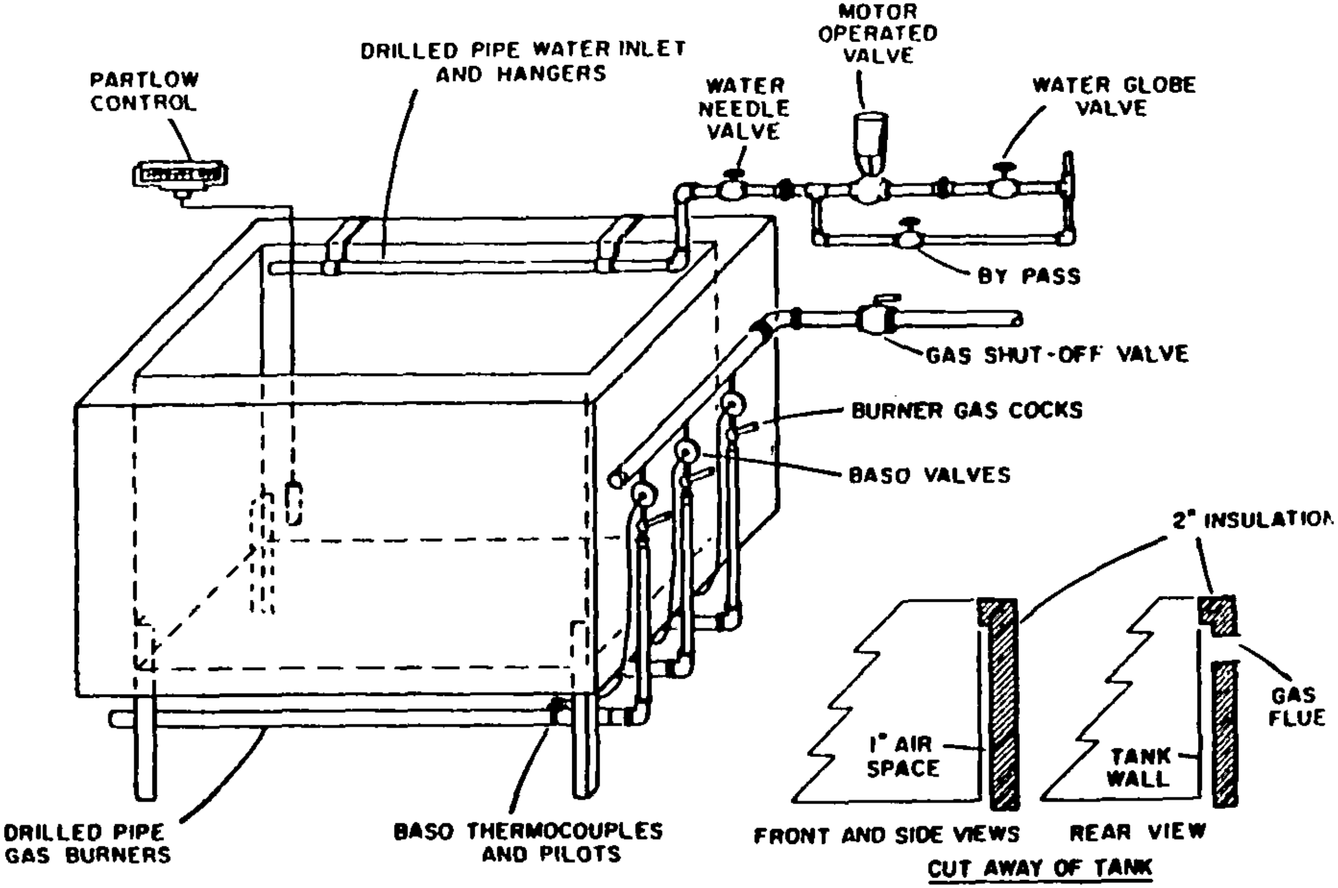


FIGURE 10: BLACK OXIDE TANK

5.2.3.3 Cold Overflowing Rinse Tanks. These tanks should be equipped with an overflow weir and a drain. The water supply to the tank should enter on the side opposite the overflow and should be delivered close to the bottom of the tank using a vacuum breaker or other means to prevent siphoning water from the rinse tank into the water line. Heating coils need not be installed in these tanks.

5.2.4 Chromate Rinse Tank. The chromate rinse tank is constructed of mild steel and can be heated by gas, electric heaters, or steam.

5.2.5 Thermometers and Thermocouples. The black oxide processing baths must be maintained at the specified temperature. It is recommended that a dial type thermometer be mounted where it can be readily seen and that the diameter be at least 5 inches (12.5 cm) for ease of reading. The thermocouple bulb should be mounted in a corner of the tank and kept away from the tank wall.

To relieve the operator, the thermocouple temperature control is connected to a motor-operated water valve which allows water to be fed automatically into the boiling solution whenever the control calls for it (i.e., whenever the temperature rises above the set operating temperature).

Because of the importance of close temperature control in the black oxide processes, particularly of Class 1, the accuracy of the indicating thermometer should be checked frequently. A reference thermometer should be available to check the indicating thermometers. A mercury thermometer can be used for this purpose in Class 1 and 4 baths but a thermocouple should be used in Class 3 baths.

5.2.6 Racks, Tumbling Barrels, and Baskets. The work being treated will usually be placed in a tumbling barrel, a rack, or an open mesh basket made of mild steel (do not use stainless steel). These should be constructed to allow good drainage. They must be welded, never soldered, and shall contain no tin, copper, zinc, lead or other non ferrous metals.

5.3 Processing

5.3.1 Processing Sequences. After the parts to be processed are cleaned of all soil, etc., rinsed and most or all water removed, they are immersed in the processing bath for the specified time. Following the blackening treatment they are given a warm or cool overflowing water rinse, except Class 3 which is given a hot water rinse prior to the cool rinse. The water rinse is followed by a chromate rinse and the parts are dried and, if specified, dipped in oil. See Figure 11.

5.3.2 Procedures for Class 1 and 4 Alkaline Oxidizing Processes

5.3.2.1 Preparation of the Solution. Determine the volume of solution necessary to fill the tank to the working level. This is normally about 6 inches (15 cm) below the top of the tank. More space may be required when processing long parts in a deep tank. Place one third of this volume of cold water in the tank. Slowly add about one third of the required amount (as recommended by the supplier of the chemical) of the black oxide chemical required for the volume at operating level while stirring vigorously to prevent caking.

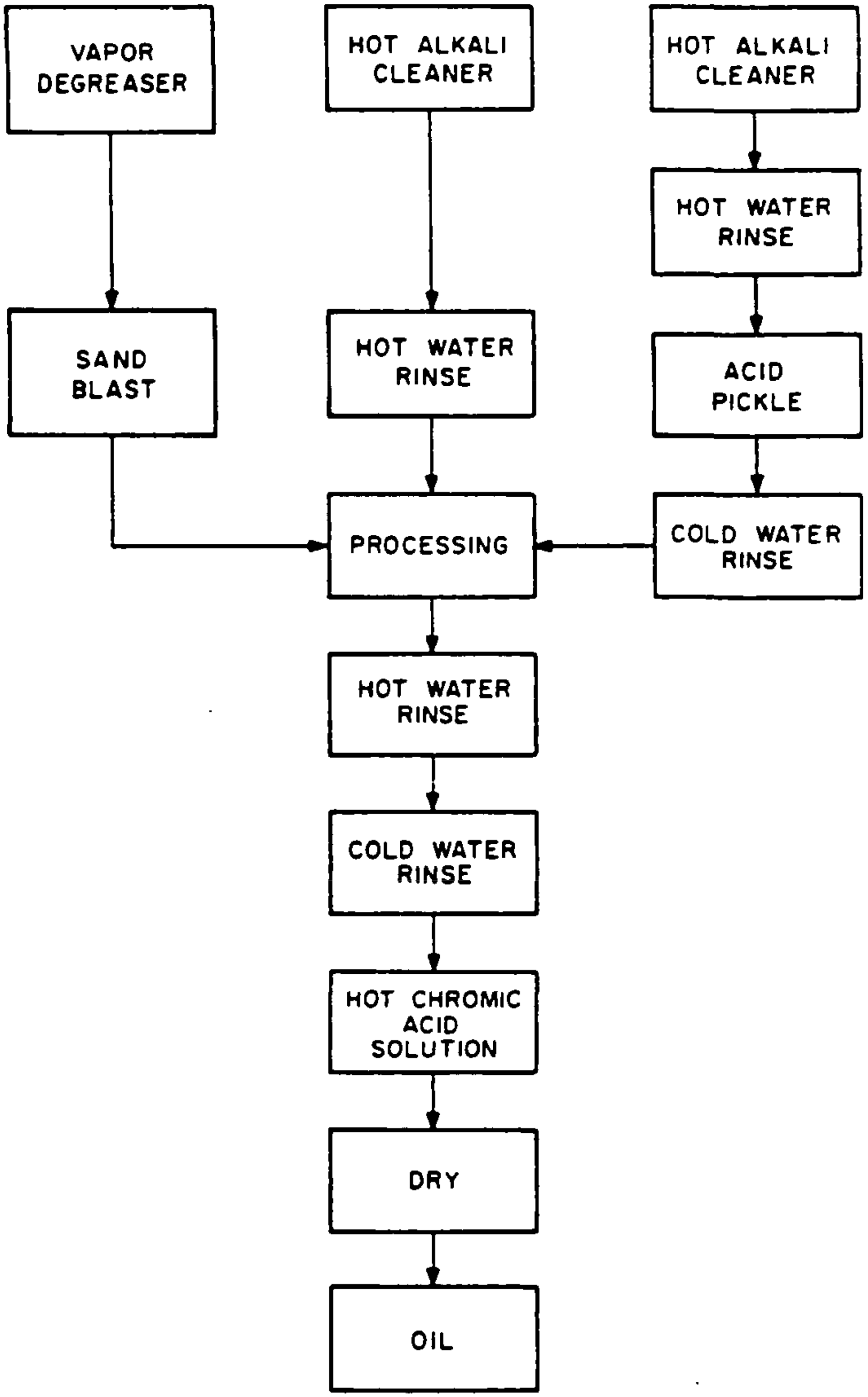


FIGURE 11 : BLACK OXIDE PROCESS

CAUTION: Wear goggles, rubber apron, rubber gloves and face shield. Avoid adding large amounts or lumps of chemical. Avoid causing the solution to splash or adding chemical rapidly enough to cause the temperature of the bath to exceed 200°F (93°C).

When the chemical is completely dissolved add an equivalent amount in the same water. Continue until the required amount has been added. Add cold water to bring the solution up to operating level. While stirring, heat the solution slowly to boiling and adjust to the specified operating temperature. See 5.3.2.2.1.

5.3.2.2 Processing. The clean work must be completely immersed for the specified time in the processing solution which is boiling at the correct temperature. The work should be lowered into the processed bath slowly to allow any water remaining on the parts to evaporate before contacting the hot bath. When processing in Class 3 baths, the parts must be completely dry. Any water contacting the hot bath will be transformed into steam and cause spattering of the hot chemical. While parts may be wet when introduced into Class 1 and 4 baths, special care must be used when immersing tubular parts so that the water inside the tubes does not erupt towards the operator.

5.3.2.2.1 Solution temperature control. The correct operating temperature may vary depending upon the chemical used and the metal being treated but Class 1 baths are normally operated at 285 to 290°F (140 to 143°C). Temperatures over 300°F (149°C) tend to build up red iron oxide in the bath and on the processed parts. To lower the boiling point, add water to the bath using a water diffuser such as that described in 5.2.2. To raise the boiling point, add more chemical by adding it slowly over the surface of the bath to avoid localized boiling and splattering of the solution.

CAUTION: Never dissolve the chemical in water to make additions. This will cause eruptions.

5.3.2.2.2 Ventilating system. A good system for removal of fumes is required with all three types of blackening baths. The recommended system for Class 1 and 4 baths is similar to that for phosphating baths (see 4.2.4). The Class 3 baths should be totally enclosed and good ventilation can be obtained with less air movement.

5.3.2.2.3 Excessive boiling and splashing. Excessive boiling and splattering may occur in a freshly prepared bath or when long parts are being processed in a deep tank. When the excessive boiling is caused by a newly prepared bath, the problem can be controlled by processing smaller loads less frequently until the boiling no longer is excessive. When the excessive boiling is caused by long parts in a deep tank, it will be necessary to allow more free board between the top of the tank and the solution level.

5.3.2.2.4 Sludge removal. Insoluble iron oxides will settle in the bottom of the processing tank as sludge. This sludge must not be allowed to accumulate. The common method for removing this sludge is to lift it out with a hoe or similar tool.

5.3.2.2.5 Smut on the work. The insoluble oxides will accumulate as a scum on the surface of the tank and if carried out on the work will appear as smut. This scum can be removed with a tool similar to a steel dust pan. Suspended sludge can also settle on the work and appear as smut. If this happens the sludge should be removed as described in 5.3.2.2.4.

5.3.2.2.6 Precautions. Non ferrous metals should not be introduced into these baths as they may contaminate the baths and interfere with the formation of the desired coating. Some metals will cause violent boiling of the processing solution which can result in injury to the operators and by-standers. If the baths become contaminated to a point where satisfactory coatings are not obtained, the chemical suppliers have proprietary chemicals which will restore the baths to operating condition in most cases.

5.3.2.3 Rinsing

5.3.2.3.1 Warm water rinsing. When the work is removed from the processing bath it should be transferred to the overflowing warm water rinse as quickly as possible and the parts should remain in the rinse long enough to lower their temperature sufficiently to prevent off-color (red) from developing. Rinsing is improved by agitation of the parts and/or the rinse water and raising the parts out of the water and reimmersing them.

5.3.2.3.2 Disposal of the warm water rinse. The warm water rinse must be discarded before it becomes too contaminated to adequately rinse the parts. The frequency of discarding will depend upon the amount of blackening salts carried into it. The contaminated rinse must be treated to meet the local waste disposal regulations before being discharged to the sewer. See 5.1.4.2 or 5.1.4.3.

5.3.2.3.3 Mist rinsing. If problems arise due to the processing solution drying on the parts before immersion in the warm water, the use of a fine mist of water sprayed on the parts can overcome this problem (see section 5.2.3.1). A very fine mist must be used to avoid drops of water causing steam eruptions at the bath surface and to avoid dilution of the bath which would lower the boiling point.

5.3.2.3.4 Cold water rinse. Following the warm water rinse the parts are rinsed in a cold, overflowing water rinse to remove the last traces of the blackening salts. Agitation of the part and/or the water and removal and reimmersion of the part will improve the rinsing.

5.3.2.4 Chromate Rinsing. After the cold water rinse the parts are immersed in a chromate rinse as described in section 4.5.

5.3.2.5 Drying. The chromate rinsed parts must be dried. The use of a hot chromate rinse makes it possible for many parts to dry spontaneously. If necessary the remaining beads of moisture can be removed with dry, clean compressed air, by heating in a air circulating oven or by dipping into a water-displacing oil.

5.3.3 Procedures for Class 3 Fused Salt Oxidizing Process

5.3.3.1 Preparation of the Bath. The required amount of salt will depend upon the size of the pot which should be no larger than necessary to hold the parts being treated and allow approximately 6 inches (15 cm) of free board between the bath surface and the top of the pot. The pot is initially charged by placing approximately one quarter of the required amount of potassium dichromate in the pot and heating it until it is liquid. Additions of similar amounts should be made until the desired operating level is reached by waiting until each addition has liquified before making the next addition.

The molten salt is then heated to the operating temperature of 825° to 850°F (440° to 455°C).

CAUTION: When reheating the solidified bath, the furnace door must remain closed until after the eruption of the liquid through the top crust of the bath. This will occur at approximately 450°F (232°C) The furnace door must not be opened except during the process of inserting or removing work. During these operations, an apron, long sleeved clothing, gloves, and a hood-type face shield must be worn. Every precaution should be taken to ensure that the work is dry before it is immersed in the molten salt.

5.3.3.2 Cleaning. All grease, oil, scale, and shop dirt must be removed before processing. The clean parts must be completely dry before introduction into the molten salt. The preferred method of ensuring a completely dry surface is to use abrasive blasting as the final cleaning step. Another method is to hold the parts near the pot for the time required to evaporate the last traces of moisture.

5.3.3.3 Processing. The clean dry parts are immersed in the molten salt bath for 30 minutes, removed from the pot, allowed to drain and air cool for 8 to 10 minutes.

CAUTION: Any moisture will create a hazardous spraying or splattering. Caution must be exercised to avoid the hazards of molten drippings when work is transferred from the furnace to the cooling fixture.

5.3.3.4 Hot Water Rinse. After cooling, the parts are rinsed in non-overflowing hot water at 190°F (88°C). Rinsing is improved by agitation of the parts and/or the water and by removal and reimmersion of the parts.

5.3.3.4.1 Disposal of the hot water. Potassium dichromate will accumulate in this rinse and eventually adequate removal of the salts will no longer be possible. The rinse should be discharged before this point is reached. Before discharging this solution to the sewer, it must be treated to meet the local waste disposal regulations. See 5.1.4.3.

5.3.3.5 Cold Water Rinse. To remove the final traces of the blackening salts, the parts are rinsed in a cold overflowing water rinse, after the hot water rinse. Rinsing is improved by agitation of the parts and/or the water and by raising the part out of the water and reimmersing it.

5.3.3.6 Chromate Rinse. After the cold water rinse the parts are immersed in a chromate rinse as described in 4.5.

5.3.3.7 Drying. See 5.3.2.5.

Custodians:

Army - MR
Navy - SH
Air Force - 20

Review activities:

Army - AR, AT, GL, ME,
Navy - AS, EC, OS, YD
Air Force - 99

Users:

Army - AR, AT
Navy -AS
Air Force - 12, 70, 82, 84

Preparing Activity:

Army - MR

Project No. MFFP-0010

WP ID #0637A/DISC 0028A (FOR AMMRC USE ONLY)

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Appendix

Examples of the use of Phosphate and Black Oxide Coatings on Military Parts.

Phophate Process:

M-16-A1	(Barrel Assembly, Trigger, Sear)
M-60	Machine Gun
M-203	Grenade Launcher
M-85	Machine Gun 50 Cal
M 2	Machine Gun 50 Cal
M-240	Machine Gun 7.62 MM
SAWS	Squad Automatic Weapons System
Navy standard missile motion chamber	
Mark 32 torpedo air flask	
Metallic belt links	
Grenades	42 MM
Hand Grenades	
Projectiles	

Black Oxide Process:

Cylinder, rifle, M-14
Spring, safety, M-14
Nut, cylinder, M-60
Extension, gas, M-60
Spring, catch, M-60
Shield, seed mechanism, M-60

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MIL-HDBK-694A(MR)
15 December 1966

MILITARY STANDARDIZATION HANDBOOK

ALUMINUM AND ALUMINUM ALLOYS

DEPARTMENT OF DEFENSE
UNITED STATES OF AMERICA

MISC

DEPARTMENT OF DEFENSE
WASHINGTON 25, D. C.

MIL-HDBK-694A(MR)
Aluminum and Aluminum Alloys
15 December 1966

1. This standardization handbook was developed by the Department of Defense in accordance with established procedure.

2. This publication was approved on 15 December 1966 for printing and inclusion in the military standardization handbook series.

3. This document provides basic and fundamental information on aluminum and aluminum alloys for the guidance of engineers and designers of military materiel. The handbook is not intended to be referenced in purchase specifications *except for informational purposes, nor shall it supersede any specification requirements.*

4. Every effort has been made to reflect the latest information on aluminum and aluminum alloys. It is the intent to review this handbook periodically to insure its completeness and currency. Users of this document are encouraged to report any errors discovered and any recommendations for changes or inclusions to the Commanding Officer, U. S. Army Materials Research Agency, Watertown, Mass., 02172. Attn: AMXMR-TMS.

Preface

This is one of a group of handbooks covering metallic and nonmetallic materials used in the design and construction of military equipment.

The purpose of this handbook is to provide, in condensed form, technical information and data of direct usefulness to design engineers. The data, especially selected from a very large number of industrial and government publications, have been checked for suitability for use in design. Wherever practicable the various types, classes, and grades of materials are identified with applicable government specifications. The corresponding technical society specifications and commercial designations are shown for information.

The numerical values for properties listed in this handbook, which duplicate specification requirements, are in agreement with the values in issues of the specifications in effect at the date of this handbook. Because of revisions or amendments to specifications taking place after publication, the values may, in some instances, differ from those shown in current specifications. In connection with procurement, it should be understood that the governing requirements are those of the specifications of the issue listed in the contract.

Wherever specifications are referred to in this handbook, the basic designation only is shown, omitting any revision or amendment symbols. This is done for purposes of simplification and to avoid the necessity for making numerous changes in the handbook whenever specifications are revised or amended.

Current issues of specifications should be determined by consulting the latest issue of the "Department of Defense Index of Specifications and Standards."

The material in the text is based on the literature listed in the bibliography. It is subdivided into four sections:

Section I - Aluminum in Engineering Design
Section II - Standardization Documents
Section III - Typical Properties of Aluminum and Aluminum Alloys
Section IV - Specification Requirements.

Comments on this handbook are invited. They should be addressed to Commanding Officer, U. S. Army Materials Research Agency, Watertown, Mass. 02172. Attn: AMXMR-TMS.

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Section I

Aluminum in Engineering Design

GENERAL

1. **Characteristics.** Aluminum alloys are used in engineering design chiefly for their light weight, high strength-to-weight ratio, corrosion resistance, and relatively low cost. They are also utilized for their high electrical and thermal conductivities, ease of fabrication, and ready availability. (Aluminum is the most widely distributed of the elements, except for oxygen, nitrogen, and silicon.)

Aluminum alloys weigh about 0.1 pound per cubic inch. This is about one-third the weight of iron at 0.28 pound and copper at 0.32, is slightly heavier than magnesium at 0.066, and somewhat lighter than titanium at 0.163.

In its commercially pure state, aluminum is a relatively weak metal, having a tensile strength of approximately 13,000 psi. However, with the addition of small amounts of such alloying elements as manganese, silicon, copper, magnesium, or zinc, and with the proper heat treatment and/or cold working, the tensile strength of aluminum can be made to approach 100,000 psi. Figure 1 shows some typical mechanical property values required by current Government specifications.

Corrosion resistance of aluminum may be attributed to its self-healing nature, in which a thin, invisible skin of aluminum oxide forms when the metal is exposed to the atmosphere. Pure aluminum will form a continuous protective oxide film – i.e., corrode uniformly – while high-strength alloyed aluminum will sometimes become pitted as a result of localized galvanic corrosion at sites of alloying-constituent concentration.

As a conductor of electricity, aluminum competes favorably with copper. Although the conductivity of the electric-conductor grade of aluminum is only 62 percent that of the International Annealed Copper Standard (IACS), on a pound-for-pound basis the power loss for aluminum is less that half that of copper – an advantage where weight and cost are the governing factors rather than space requirements.

As a heat conductor, aluminum ranks high among the metals. It is especially useful in heat exchangers and in other applications requiring rapid dissipation.

As a reflector of radiant energy, aluminum is excellent throughout the entire range of wavelengths, from the ultraviolet end of the spectrum through the visible and infrared bands to the electromagnetic wave frequencies of radio and radar. As an example, its reflectivity in the visible range is over 80 percent.

Aluminum is easily fabricated – one of its most important assets. It can be cast by any method known to the foundryman; it can be rolled to any thickness, stamped, hammered, forged, or extruded. Aluminum is readily turned, milled, bored, or machined at the maximum speeds of

Property	Cost	Wrought
Tensile Strength, min. psi	42,000	80,000
Yield Strength, min. psi	22,000	72,000
Endurance Limit, min. psi	13,500	24,000
Elongation, percent	6	varies markedly
Modulus of Elasticity	9.9 million to 11.4 million (usually taken as 10.3 million)	

FIGURE 1. Typical Mechanical Property Values

which most machines are capable, and is adaptable to automatic screw machine processing. Aluminum can be joined by almost any method – riveting; gas, arc, or resistance welding; brazing; and adhesive bonding.

Finally, aluminum can be coated with a wide variety of surface finishes for decorative as well as protective purposes. In addition to the more common chemical, electrochemical, and paint finishes, vitreous enamels – specially developed for aluminum – can be applied.

2. **Economic Considerations.** The cost of aluminum is relative, and should not be determined by the price of the base metal alone. Advantages in the processing of aluminum can materially contribute to the reduction of the cost of the end item. Therefore, the overall cost should be judged in relation to the finished product.

Many aluminum alloys have wide property ranges as a result of tempers attainable through treatment, both thermal and mechanical. With these wide ranges, much overlapping of properties exists among the various alloys thus making available a large number of compositions from which to choose. This increased selection provides for a greater latitude in the choice of fabricating techniques, and permits the selection of the most economical method.

In the fabrication of aluminum products, the economies effected may be more than enough to overcome other cost disparities. The ease with which the metal can be machined, finished, polished, and assembled permits a reduction of the time, material, labor, and equipment required for the product. Coupled with these assets are the advantages of light weight, which often can be of considerable importance in the cost of handling, shipping, storage, or assembly of the end item.

CLASSES OF ALUMINUM AND ALUMINUM ALLOY

3. **Types Available.** Aluminum is available in various compositions, including "pure" metal, alloys for casting, and alloys for the manufacture of wrought products. (Alloys for casting are normally different from those used for rolling, forging, and other working.) All types are produced in a wide variety of industrial shapes and forms.

4. **"Pure" Aluminum.** Pure aluminum is available both as a high-purity metal and as a commercially pure metal. Both have relatively low strength, and thus have limited utility in engineering design, except for applications where good electrical conductivity, ease of fabrication, or high resistance to corrosion are important. Pure aluminum is not heat treatable. However, its mechanical properties may be varied by strain hardening (cold work). Pure aluminum exhibits poor casting qualities; it is employed chiefly in wrought form. Commercially pure aluminum is available as foil, sheet and plate, wire, bar, rod, tube, and as extrusions and forgings.

5. **Casting Alloys.** The aluminum alloys specified for casting purposes contain one or more alloying elements, the maximum of any one element not exceeding 12 percent. Some alloys are designed for use in the as-cast condition; others are designed to be heat treated to improve their mechanical properties and dimensional stability. High strength, together with good ductility, can be obtained by selection of suitable composition and heat treatment.

Aluminum casting alloys are usually identified by arbitrarily selected, commercial designations of two- and three-digit numbers. These designations are sometimes preceded by a letter to indicate that the original alloy of the same number has been modified. (See table I.)

6. **Wrought Alloys.** Most aluminum alloys used for wrought products contain less than 7 percent of alloying elements. By the regulation of the amount and type of elements added, the properties of the aluminum can be enhanced and its working characteristics improved. Special compositions have been developed for particular fabrication processes such as forging and extrusion.

As with casting alloys, wrought alloys are produced in both heat-treatable and non-heat-treatable types. The mechanical properties of the non-heat-treatable type may be varied by strain-hardening, or by strain-hardening followed by partial annealing. The mechanical properties of the heat-treatable types may be improved by quenching from a suitable temperature and then aging. With the heat-treatable alloys, especially desirable properties may be obtained by a combination of heat treatment and strain hardening.

**ALUMINUM ASSOCIATION
DESIGNATIONS FOR ALLOY GROUPS**

		① AA No
Aluminum - 99.00% minimum and greater		1xxx
	Major Alloying Element	
Aluminum Alloys grouped by major Alloying Elements	Copper	2xxx
	Manganese	3xxx
	Silicon	4xxx
	Magnesium	5xxx
	Magnesium and Silicon	6xxx
	Zinc	7xxx
	Other Elements	8xxx
Unused Series		9xxx

① Only compositions conforming to those listed in the chemical composition of Table III or are registered with The Aluminum Association should bear the prefix "AA".

FIGURE 2. **Wrought Aluminum and Aluminum Alloy Designations**

The principal wrought forms of aluminum alloys are plate and sheet, foil, extruded shapes, tube, bar, rod, wire and forgings. (See table II.)

Wrought aluminum alloys are designated by four-digit numbers assigned by the Aluminum Association. The first digit indicates the alloy group; the second digit indicates modifications of the original alloy (or impurity limits); the last two digits identify the aluminum alloy or indicate the aluminum purity. The system of designating alloy groups is shown in figure 2. Experimental alloys are also designated in accordance with this system, but their numbers are prefixed by the letter X. This prefix is dropped when the alloy becomes standard. Chemical composition limits of wrought aluminum alloys are given in table III. Tables IV and V provide a cross reference between designations under Government and industrial standards.

PROPERTIES OF ALUMINUM

7. **Physical Properties.** The ranges of the physical properties of aluminum are shown in figure 3. Those properties which may assume importance in considering particular applications are indicated in tables VI and VII.

8. **Mechanical Properties.** The wide range of mechanical properties of aluminum alloys depends upon composition, heat treatment, cold working, and other factors. Some properties may also vary appreciably in identical compositions according to the type of product or processing history. It is, therefore, essential to define the form of material in addition to the alloy.

Aluminum alloys are restricted in use to only moderately elevated temperatures because of their relatively low melting point; 900°F (482°C) to 1200°F (649°C). Some aluminum alloys begin to soften and weaken appreciably at temperatures as low as 200°F (93°C); others maintain strength fairly well at temperatures up to 400°F (204°C). (See tables VIII, IX and X.)

The strength, hardness, and modulus of elasticity of aluminum alloys decrease with rising temperatures. Elongation increases with rising temperatures (until just below the melting point when it drops to zero). Some alloys have been developed especially for high-temperature service. These include alloys 2018, 2218, and 4032 in QQ-A-367 for forgings, alloy 142 in QQ-A-601 for sand castings, and classes 3, 9, and 10 in QQ-A-596 for permanent-mold castings.

PHYSICAL PROPERTIES

Property	Range		Notes	
	Cast Alloys	Wrought Alloys		
Specific Gravity	2.57 to 2.95	2.70 to 2.82	About 1/3 that of steel.	
Weight (pounds per cubic inch)	0.093 to 0.107	0.095 to 0.102	Approximately 173 pounds per cubic foot.	
Electrical Conductivity (International Annealed Copper Standard)	21% to 47%	30% to 60%	About 59% for 99.9% aluminum	Values for electrical and thermal conductivity depend upon the composition and condition of the alloys. Both are increased by annealing, and decreased by adding alloying elements to pure (99.0%) aluminum. Both are also decreased by heat treatment, cold work, and aging.
Thermal Conductivity (cgs units at 77 deg. F.)	0.21 to 0.40	0.29 to 0.56	About 0.53 for 99.0% aluminum	
Thermal Expansion (average coefficient between the range of 68 deg. and 212 deg. F.)	11.0 to 14.0	10.8 to 13.2	Roughly double that of ordinary steels and cast irons; substantially greater than copper-alloy materials. Alloying elements other than silicon have little effect on the expansion of aluminum. Considerable amounts of silicon (12%) appreciably decrease the dimensional changes induced by varying temperatures. Where a low coefficient of thermal expansion is desirable, as in engine pistons, an aluminum alloy containing a relatively high percentage of silicon may be specified.	
Reflectivity	–	–	Greater than any other metal. Suitably treated, aluminum sheet of high purity may yield a reflectivity for light greater than 80%. Used for shields, reflectors, and wave guides in radio and radar equipment.	

FIGURE 3. Physical Property Ranges

Creep and stress-rupture data, which are of interest when considering aluminum for some applications at elevated temperatures, are contained in References 16, 17, 44, and 46 of the Bibliography. From the design curves, which show stress versus time for total deformation in percent for various temperatures, minimum creep rates may be compared.

The mechanical properties of aluminum tend to improve as the temperature is lowered. Tests at temperatures down to -320°F (-196°C) show that with a decrease in temperature, there is a corresponding increase in strength and elongation. There is also an increase in modulus of elasticity (table XI) and in fatigue strength (table XII), and no evidence of low-temperature embrittlement.

Values for the various properties of aluminum alloys are given in Section II (typical values) and Section III (specification requirements). Unless otherwise stated, the tensile and compressive yield strengths correspond to 0.2 percent offset; elongation refers to gage length of 2 inches; Brinell hardness number is for a 500-kg load with a 10-mm ball; and endurance limit is based on 500 million cycles of completely reversed stress, using the R.R. Moore type of machine and specimen.

The following values generally apply to aluminum alloys:

Modulus of elasticity (tension and compression), psi	10.3×10^6
Modulus of rigidity, psi	3.9×10^6
Poisson's ratio	0.33
Torsional yield strength, percent of tensile yield strength	55
Ultimate torsional strength, percent of ultimate tensile strength	65

The mechanical properties of wrought alloys (table XIII) may be affected appreciably by the form, thickness, and direction of fabrication. Normally, tensile properties of commercial wrought materials are based on test data obtained on 1/2-inch diameter test specimens cut from production materials. Small sizes, such as wire, bar, and rod, as well as tube, are usually tested full size, The types of test specimens acceptable under Government specifications are illustrated in Fed. Test Method Std. No. 151.

The tensile properties of cast alloys (tables XIV, XV, and XVI), as ordinarily reported, are obtained from tests on 1/2-inch diameter test specimens separately cast under standard conditions of solidification. These specimens serve as controls of the metal quality, but their properties do not necessarily represent those of commercial castings. (The properties may be higher or lower depending on the factors that influence the rate of solidification in the mold.) Likewise, the properties of test specimens cut from a single casting may vary widely, depending on their location within the casting. Usually, the average strength of several test specimens taken from various locations in the casting – so that thick, thin, and intermediate sections are represented – will be at least 75 percent of the strength of the separately cast bars.

TEMPER DESIGNATION SYSTEM

9. **Temper Designations.** The following temper designations indicate mechanical or thermal treatment of the alloy. The temper designation shall follow the four-digit alloy designation and shall be separated from it by a dash, i.e., 2024-T4. Basic temper designations consist of letters. Subdivisions of the basic tempers, where required, are indicated by one or more digits following the letter. These designate specific sequences of basic treatments, but only operations recognized as significantly influencing the characteristics of the product are indicated. Should some other variation of the same sequence of basic operations be applied to the same alloy, resulting in different characteristics, then additional digits are added to the designation.

The basic temper designations and subdivisions are as follows:

-F As Fabricated. Applies to products which acquire some temper from shaping processes not having special control over the amount of strain-hardening or thermal treatment. For wrought products, there are no mechanical property limits.

-O Annealed, recrystallized (wrought products only). Applies to the softest temper of wrought products.

-H Strain-Hardened (Wrought Products Only). Applies to products which have their strength increased by strain-hardening with or without supplementary thermal treatments to produce partial softening. The -H is always followed by two or more digits. The first digit indicates the specific combination of basic operations as follows:

- -H1 Strain-Hardened Only. Applies to products which are strain-hardened to obtain the desired mechanical properties without supplementary thermal treatment. The number following the designation indicates the degree of strain-hardening.
- -H2 Strain-Hardened and then Partially Annealed. Applies to products which are strain-hardened more than the desired final amount and then reduced in strength to the desired level by partial annealing. For alloys that age-soften at room temperature, the -H2 tempers have approximately the same ultimate strength as the corresponding -H3 tempers. For other alloys, the -H2 tempers have approximately the same ultimate strength as the corresponding -H1 tempers and slightly higher elongations. The number following this designation indicates the degree of strain-hardening remaining after the product has been partially annealed.

-H3 Strain-Hardened and then Stabilized. Applies to products which are strain-hardened and then stabilized by low temperature heating to slightly lower their strength and increase ductility. The designation applies only to the magnesium-containing alloys which, unless stabilized, gradually age-soften at room temperature. The number following this designation indicates the degree of strain-hardening remaining after the product has been strain-hardened a specific amount and then stabilized.

The digit following the designations -H1, -H2, and -H3 indicates the final degree of strain-hardening. The hardest commercially practical temper is designated by the numeral 8 (full hard). Tempers between -0 (annealed) and 8 (full hard) are designated by numerals 1 through 7. Materials having an ultimate strength about midway between that of the -0 temper and that of and 8 temper is designated by the numeral 4 (half hard); between -0 and 4 by the numeral 2 (quarter hard); between 4 and 8 by the numeral 6 (three-quarter hard); etc. Numeral 9 designates extra hard tempers.

The third digit, when used, indicates that the degree of control of temper or the mechanical properties are different from, but within the range of, those for the two-digit -H temper designation to which it is added. Numerals 1 through 9 may be arbitrarily assigned and registered with The Aluminum Association for an alloy and product to indicate a specific degree of control of temper or specific mechanical property limits. Zero has been assigned to indicate degrees of control of temper, or mechanical property limits negotiated between the manufacturer and purchaser which are not used widely enough to justify registration with The Aluminum Association.

The following three-digit -H temper designations have been assigned for wrought products in all alloys:

-H111 Applies to products which are strain-hardened less than the amount required for a controlled H11 temper.

-H112 Applies to products which acquire some temper from shaping processes not having special control over the amount of strain-hardening or thermal treatment, but for which there are mechanical property limits or mechanical property testing is required.

-H311 Applies to products which are strain-hardened less than the amount required for a controlled H31 temper.

The following three-digit -H temper designations have been assigned for:

a. Patterned or Embossed Sheet	b. Fabricated From
-H114	-0 temper
-H134, -H234, -H334	-H12, -H22, -H32 temper, respect.
-H154, -H254, -H354	-H14, -H24, -H34 temper, respect.
-H174, -H274, -H374	-H16, -H26, -H36 temper, respect.
-H194, -H294, -H394	-H18, -H28, -H38 temper, respect.
-H195, -H395	-H19, -H39 temper, respect.

-W Solution Heat-Treated. An unstable temper applicable only to alloys which spontaneously age at a room temperature after solution heat-treatment. This designation is specific only when the period of natural aging is indicated; for example, -W 1/2 hour.

-T Thermally Treated to Produce Stable Tempers Other than -F, -O, or -H. Applies to products which are thermally treated, with or without supplementary strain-hardening to produce stable tempers. The -T is always followed by one or more digits. Numerals 2 through 10 have been assigned to indicate specific sequences of basic treatment, as follows:

-T2 Annealed (Cast Products Only). Designates a type of annealing treatment used to improve ductility and increase dimensional stability of castings.

-T3 Solution Heat-treated and then Cold Worked. This designation applies to products which are cold worked to improve strength, or in which the effect of cold work in flattening or straightening is recognized in applicable specifications.

-T4 Solution Heat-treated and Naturally Aged to a Substantially Stable Condition. Applies to products which are not cold worked after solution heat-treatment, but in which the effect of cold work in flattening or straightening may be recognized in applicable specifications.

-T5 Artificially Aged Only. Applies to products which are artificially aged after an elevated-temperature rapid-cool fabrication process, such as casting or extrusion, to improve mechanical properties and/or dimensional stability.

-T6 Solution Heat-Treated and then Artificially Aged. Applies to products which are not cold worked after solution heat treatment, but in which the effect of cold work in flattening or straightening may be recognized in applicable specifications.

-T7 Solution Heat-Treated and then Stabilized. Applies to products which are stabilized to carry them beyond the point of maximum hardness, providing control of growth and/or residual stress.

-T8 Solution Heat-Treated, Cold Worked, and then Artificially Aged. Applies to products which are cold worked to improve strength, or in which the effect of cold work in flattening or straightening is recognized in applicable specifications.

-T9 Solution Heat-Treated, Artificially Aged, and then Cold Worked. Applies to products which are cold worked to improve strength.

-T10 Artificially Aged and then Cold Worked. Applies to products which are artificially aged after an elevated-temperature rapid-cool fabrication process, such as casting or extrusion, and then cold worked to improve strength.

A period of natural aging at room temperature may occur between or after the operations listed for tempers -T3 through -T10. Control of this period is exercised when it is metallurgically important.

Additional digits may be added to designations -T2 through -T10 to indicate a variation in treatment which significantly alters the characteristics of the product. These may be arbitrarily assigned and registered with The Aluminum Association for an alloy and product to indicate a specific treatment or specific mechanical property limits.

The following additional digits have been assigned for wrought products in all alloys:

-TX51 Stress-Relieved by Stretching. Applies to products which are stress-relieved by stretching the following amounts after solution heat-treatment:

Plate – 1½ to 3% permanent set

Rod, Bar and Shapes – 1 to 3% permanent set

Applies directly to plate and rolled or cold-finished rod and bar. These products receive no further straightening after stretching. Applies to extruded rod, bar and shapes when designated as follows:

-TX510 Applies to extruded rod, bar and shapes which receive no further straightening after stretching.

-TX511 Applies to extruded rod, bar and shapes which receive minor straightening after stretching to comply with standard tolerances.

-TX52 Stress-Relieved by Compressing. Applies to products which are stress-relieved by compressing after solution heat-treatment.

-TX53 Stress-Relieved by Thermal Treatment.

The following two-digit -T temper designations have been assigned for wrought products in all alloys:

-T42 Applies to products solution heat-treated by the user which attain mechanical properties different from those of the -T4 temper.*

-T62 Applies to products solution heat-treated and artificially aged by the user which attain mechanical properties different from those of the -T6 temper.*

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*Exceptions not conforming to these definitions are 4032-T62, 6101-T62, 6061-T62, 6063-T42 and 6463-T42. The tempers are developed for special applications and are not normally considered for military applications.

HEAT TREATMENT

10. **Effects of Heat Treatment.** The heat treatment processes, commonly used to improve the properties of aluminum alloys, are: solution heat treatment, precipitation hardening (age hardening), and annealing.

Solution heat treatment is used to redistribute the alloying constituents that segregate from the aluminum during cooling from the molten state. It consists of heating the alloy to a temperature at which the soluble constituents will form a homogeneous mass by solid diffusion, holding the mass at that temperature until diffusion takes place, then quenching the alloy rapidly to retain the homogeneous condition.

In the quenched condition, heat-treated alloys are supersaturated solid solutions that are comparatively soft and workable, and unstable, depending on composition. At room temperature, the alloying constituents of some alloys (W temper) tend to precipitate from the solution spontaneously, causing the metal to harden in about four days. This is called natural aging. It can be retarded or even arrested to facilitate fabrication by holding the alloy at sub-zero temperatures until ready for forming. Other alloys age more slowly at room temperature, and take years to reach maximum strength and hardness. These alloys can be aged artificially to stabilize them and improve their properties by heating them to moderately elevated temperatures for specified lengths of time.

A small amount of cold working after solution heat treatment produces a substantial increase in yield strength, some increase in tensile strength, and some loss of ductility. The effect on the properties developed will vary with different compositions.

Annealing is used to effect recrystallization, essentially complete precipitation, or to remove internal stresses. (Annealing for obliterating the hardening effects of cold working, will also remove the effects of heat treatment.) For most alloys, annealing consists of heating to about 650°F (343°C) at a controlled rate. The rate is dependent upon such factors as thickness, type of anneal desired, and method employed. Cooling rate is not important, but drastic quenching is not recommended because of the strains produced.

11. **Effects of Quenching.** Quenching is the sudden chilling of the metal in oil or water. Quenching increases the strength and corrosion resistance of the alloy. The structure and the distribution of the alloying constituents that existed at the temperature just prior to cooling are *"frozen" into the metal by quenching.* The properties of the alloy are governed by the composition and characteristics of the alloy, the thickness of cross section, and the rate at which the metal is cooled. The rate is controlled by proper choice of both type and temperature of cooling medium.

Rapid quenching, as in cold water, will provide maximum corrosion resistance, and is used for items produced from sheet, tube, extrusions, and small forgings, and is preferred to a less drastic quench which would increase the mechanical properties. The slower quench, which is done in hot or boiling water, is used for heavy sections and large forgings; it tends to minimize distortion and cracking which result from uneven cooling. (The corrosion resistance of forging alloys is not affected by the temperature of the quench water; also the corrosion resistance of thicker sections is generally less critical than that of thinner ones.)

FORMABILITY

12. **Factors Affecting Formability.** Aluminum alloys can be formed hot or cold by common fabricating processes. In general, pure aluminum is more easily worked than the alloys, and annealed tempers are more easily worked than the hard tempers. Also, the naturally aged tempers afford better formability than the artificially aged tempers. For example, the 99-percent metal (alloy 1100, QQ-A-250/1) in the annealed temper, "-O", has the best forming characteristics; alloy 7075 (QQ-A-250/12) in the full heat-treated temper, "-T6", is the most difficult to form because of its hardness.

In the process of forming, the metal hardens and strengthens by reason of the working effect. In cold drawing, the changes in tensile strength and other properties can become quite large, depending upon the amount of work and on the alloy composition used. In bending, which is another form of cold working, the bend radius and the thickness of the metal are also factors that must be considered. (Refer to table XVII which gives the permissible bend radii for 90-degree bends in terms of sheet thickness.)

Most forming of aluminum is done cold. The temper chosen usually permits the completion of the fabrication without the necessity of any intermediate annealing. In some difficult drawing operations, however, intermediate annealing may be required between successive draws.

Hot forming of aluminum is usually done at temperatures of 300°F (149°C) to 400°F (204°C). At these temperatures the metal is readily worked, and its strength is not reduced appreciably, provided the heating periods are no more than 15 to 30 minutes. In general, a combination of the shortest possible time with the lowest temperature which will give the desired results in forming is the best.

Forming is also done in the as-quenched condition on those alloys that age spontaneously at room temperature after solution heat treatment ("-W" temper). In these instances the quenched metal is refrigerated to retard hardening until forming is complete.

The selection of the proper temper is important when specifying aluminum for forming operations. When non-heat-treatable alloys are to be formed, the temper chosen should be just sufficiently soft to permit the required bend radius or draw depth. In more difficult forming operations material in the annealed temper "-O" should be used; for less severe forming requirements, material in one of the harder tempers, such as "-H14", may be handled satisfactorily.

When heat-treatable alloys are to be used for forming, the shape should govern the selection of the alloy and its temper. Maximum formability of the heat-treatable alloys is attained in the annealed temper. However, limited formability can be effected in the fully heat-treated temper, provided the bend radii are large enough.

A clue to the formability of an alloy may be found in the percent of elongation, and in the difference between the yield strength and the ultimate tensile strength. As a rule, the higher the elongation value or the wider the range between the yield and tensile strengths, the better the forming characteristics.

MACHINABILITY

13. Factors Affecting Machinability. Machinability is the ease with which a material can be finished by cutting. Good machinability is characterized by a fast cutting speed, small chip size, smoothness of surface produced, and good tool life. Some aluminum alloys are excellent for machining; others are more troublesome. The troublesome ones are soft and "gummy", producing chips that are long and stringy, and the cutting rates are slow. The harder alloys and the harder tempers afford better machinability. The machinability of forging alloys are rated in table XVIII.

In general, alloys containing copper, zinc, or magnesium as the principal added constituents are the most readily machined. Other compositions (such as alloy 2011, QQ-A-225/3), containing bismuth and lead, are also unusually machinable, being specially designed for high-speed screw-machine work. Compositions containing more than 10 percent silicon are ordinarily the most difficult to machine. (Even alloys containing 5 percent silicon do not machine to a bright, lustrous finish, but exhibit a gray surface.)

Wrought alloys that have been heat treated have fair to good machining characteristics. These are easier to machine to a good finish in the full-hard temper than when annealed. Wrought alloys that are not heat treated, regardless of temper, tend to be gummy. Also, wrought compositions that contain copper as the principal alloying element are more easily machined than those that have been hardened mainly by magnesium silicide.

JOINING

14. Joining Methods. Aluminum and its alloys may be joined by a number of processes. The choice of method depends on the design, the material to be joined, the strength requirements, and the service conditions to be encountered. The methods available include riveting, welding, brazing, soldering, and adhesive bonding.

15. Riveting. Riveting is a commonly used method of joining aluminum. When done properly, riveting can produce extremely dependable and consistently uniform joints without affecting the strength or other characteristics of the metal. However, it is more time consuming and creates bulkier joints than those made by other methods. Also, riveting requires care in the formation of the rivet holes, in the selection of the size and length of rivets, and in the choice of the rivet alloy and temper.

The selection of the size of rivet is not governed by hard-and-fast rules. However, the diameter and the length of the rivet should be such that the sheet is not damaged during driving, and the joint does not fail in service. In general, the diameter should not be less than the thickness of the thickest part through which the rivet is driven nor greater than three times the thinnest outside part. The length (which should be determined by experimentation) should be sufficient to fill the rivet hole after driving.

The holes should be large enough to accept the rivet without forcing but not so large that the rivet will be bent or upset eccentrically, or that the sheets will bulge or separate. Also, the holes should be small enough so that the rivets will fill them without excessive cold working. The spacing of the holes should be such that the sheets are not weakened by the holes, and that the sheet does not buckle. According to general recommendations, the spacing (center-to-center) should be not less than three times the hole diameter nor more than 24 times the thickness of the sheet.

Holes for riveting may be formed by punching, by drilling, or by subpunching and reaming. Drilling is preferred to punching because it does not produce rough edges which might cause cracks to propagate radially from the hole. However, subpunching or subdrilling, followed by reaming is preferred to either because reaming produces a smooth edge, permits exact aligning of holes, and forestalls uneven loading on the rivets.

The choice of rivet alloy is influenced by several considerations, including corrosion problems, property requirements, and fabricating costs. From a strength standpoint, it is generally advantageous to use a rivet alloy having the same properties as the material into which it is driven. However, from a fabrication standpoint, it is often necessary to have a somewhat softer rivet to permit driving. A list of combinations of the structural metals and rivet alloys that have proved satisfactory is shown in figure 4.

Most aluminum alloy rivets are driven cold in the as-received temper, others are heat treated

Structural Metal			Rivet Metal Temper	
Alloy	Temper	Alloy	Before Driving	After Driving
1100	Any	1100	H14	F
2014	T6	2017 2024 2117 7277	T4 T4 T4 T4	T31 T31 T3 T41
3003	0 H12*	1100 6053	H14 T61	F T61
5052	H12*	6053	T61	T61
6053	T4	6053 6061 7277	T61 T6 T4	T61 T6 T41
6061	T4 or T6	6053 6061 7277	T61 T6 T4	T61 T6 T41

*Or harder.

Note: Rivet alloys 1100, 2017, 2024, 2117, and 5056 are specified in QQ-A-430; 3003, 6053, and 6061 in MIL-R-1150; and 7277 in MIL-R-12221. These meet the majority of riveting needs. Alloys 6053 and 6061 are recommended for clad sheet because of their high resistance to corrosion and their similarities in solution potential to the cladding material of the sheet.

FIGURE 4. Suggested Combinations of Rivet Alloy and Structural Metal

Rivet Condition Before Driving			Shear Strength* Developed, ksi
Rivet Alloy	Rivet Temper	Condition When Inserted	
1100	H14	As received	11
2017	T4	Immediately after quenching	34
2024	T4	Immediately after quenching	42
2117	T4	As received	33
6053	T61	As received	23
6061	T6	As received	30
7277	T4	Hot (850° to 975°F)	38

*Cone-point heads. (Slightly higher for heads requiring more pressure.)

FIGURE 5. Rivet Condition at Driving

just before being driven, while rivets of alloy 7277 are driven hot. Figure 5 indicates the condition of the various rivet alloys at insertion, and the shear strengths developed after driving.

16. Welding. The welding of aluminum is common practice in industry because it is fast, easy, and relatively inexpensive. It is especially useful in making leakproof joints in thick or thin metal, and can be employed with either wrought or cast aluminum, or a combination of both.

The nominal strengths of welds in some specified aluminum alloys are given in tables XIX, XX, and XXI. If greater strengths are required, and if increased weight and bulk are not objectionable, a mechanical joint should be substituted for welding.

Not all compositions of aluminum alloy are suitable for welding, and not all methods of welding can be used with them. The suitability for welding and the relative weldability of some aluminum alloys are given in table XXII.

The welding of aluminum consists of fusing the molten parent metal together (with or without the use of filler metal), or of upsetting by pressure (with or without heat generated by the electrical resistance of the metal).

A wide variety of welding methods are employed in the welding of aluminum. These include torch (gas), metal-arc, carbon-arc, tungsten-arc, atomic-hydrogen, and electric-resistance welding. The equipment used is the same, except that it must be modified in some instances to permit slight changes in welding practices.

The corrosion-resistant oxide film that protects aluminum, deters the "wetting" action required for coalescence of the metals during welding. To effect a successful weld, this tough coating must be removed (and prevented from reforming) either mechanically, chemically, or electrically. Mechanical removal consists of abrading with a sander, stainless-steel wool, or some such means. Such a method is fast, but it is a manual operation, and should be reserved for comparatively small amounts of work. Chemical removal is accomplished with fluxes that dissolve and float the oxides away. It is the most practical means of penetrating the glass-like oxide coating, and is well suited to the production of larger amounts of work. Its drawbacks include the danger of leaving voids or blow holes as a result of entrapment of slag, and the need for cleaning operations to remove any remaining corrosive flux. Electrical removal, used in some forms of arc welding, consists of the application of a reverse polarity (work negative) of welding current which loosens the oxide by electron emission. The reforming of oxides is prevented during welding and cooling of the weld by the cover of flux or by the use of inert gases to blanket the weld area.

The good thermal conductivity of aluminum allows the heat of welding to spread rapidly from the weld zone; this can result in a loss in strength in work-hardened or heat-treated alloys through annealing. It can also cause buckling or total collapse of the parent metal if the metal is not supported properly during welding. The good electrical conductivity necessitates the use of higher currents in resistance welding.

The low melting point of aluminum, in the range of 900°F (482°C) to 1216°F (658°C), increases the need for care in preventing the melting away of the metal parts that are to be welded. Since aluminum gives no visual indication of having attained welding temperature (that is, it does not become red, as does steel), the temperature has to be measured by the physical condition of the aluminum instead of its appearance.

In welding applications where a considerable amount of general heating can be tolerated and where an easily finished bead is desired, gas welding is preferred. However, where minimum general heating, absence of flux, and very good properties are requirements, one of the types of inert-gas-shielded arc-welding method should be selected.

Gas welding is commonly done with oxyhydrogen or oxyacetylene mixtures. The oxyacetylene flame is used most widely because of its availability for welding other metals. Butt, lap, and fillet welds are made in thickness of metal from 0.040 up to 1 inch.

Metal-arc welding is especially suitable for heavy material. Welds in plate 2½ inches thick are made satisfactorily by this method. Unsound joints are likely to appear in metal-arc-welded material which is less than 5/64 inch thick. Weld soundness and smoothness of the surface are not as good as other arc-welding methods. The latter factors, and the necessity to use a welding flux, have been responsible for the decrease in popularity of this process.

Carbon-arc welding is an alternative method for joining material about 1/16 to 1/2 inch thick. The carbon arc affords a more concentrated heat source than a gas torch flame. Hence, it permits faster welding with less distortion. Soundness of welds is excellent and is comparable to that of good gas welding.

Tungsten-arc welding has two distinct advantages over other forms of fusion welding; no flux is needed, and welds can be made with almost equal facility in the flat, vertical, or overhead positions. The advantages are the result of the ability to concentrate the heat, and the blanketing of the area with inert gas (argon or helium). The process can be used for either manual or automatic welding on metals 0.05 inch thick or thicker.

Resistance welding is especially useful for joining high-strength aluminum alloy sheet with practically no loss of strength. It includes three main types of processes; spot welding, seam or line welding, and butt or flash welding. The type adopted for assembly operations depends mainly on the form of material to be joined. Spot welding is widely used to replace riveting; it joins sheet structures at intervals as required. Seam welding is merely spot welding with the spots spaced so closely that they overlap to produce a gas-tight joint. Flash welding, sometimes classified as a resistance welding process, differs from spot welding in that it is used only for butt joints; the metal is heated for welding by establishing an arc between the ends of the two pieces to be joined.

17. **Brazing.** Brazing differs from welding, in that filler metal is melted and flowed into the joint with little or no melting of the parent metal. (The brazing alloy melts at about 100°F (38°C) below that of the parent metal.) As a result, brazing is ideally suited to the joining of thinner material. It is also lower in cost than welding, has neater appearance, requires little finishing, and is suited to mass production methods. In addition, the corrosion resistance of brazed aluminum joints compares favorably, in general, to welded joints in the same alloy because, unlike solder, the filler metal is an aluminum alloy.

The strength of a brazed joint is equivalent to that of the metal in the annealed condition. However, in some instances where an age-hardening alloy is used, the mechanical properties of the metal can be enhanced by treatment. For example, alloy 6061 (61S), when quenched from the brazing operation and then artificially aged, will exhibit a tensile strength of approximately 45,000 psi, a yield strength of 40,000 psi, and an elongation in two inches of 9 percent.

Brazeable alloys are available in plate, sheet, tube, rod, bar, wire, and shapes. They are generally confined to alloys 1100, 3003, and 6061.

18. **Soldering.** Aluminum can be joined to aluminum and to other solderable metals by means

of a soldering iron or torch, and an alloy of approximately 60 percent tin and 40 percent zinc. (Solders for aluminum are specified in MIL-S-12204.) This method of joining is satisfactory for such applications as indoor electrical joints; it is not recommended for joining structural members or for use in moist or corrosive atmospheres because of the low mechanical properties of the solder and the difference in electrical potential between the solder and the aluminum.

The soldering of aluminum is similar to other forms of soldering, but it is somewhat more difficult to perform because of the high thermal conductivity of the aluminum and the presence of a tough oxide film. The thermal conductivity increases the problem of maintaining sufficient heat at the working area to melt the solder. (Aluminum solder melts at 550°F (288°C) to 700°F (371°C) as compared with 375°F (190°C) to 400°F (204°C) for most other solders.) Thus only small parts (20 square inches or less) which can be preheated, are suitable for soldering with an iron; larger parts require the use of a torch to concentrate sufficient heat.

The tough oxide film may be removed by dissolving it with a flux or by abrading it with a soldering iron or other mechanical means. In each instance, the working area must be kept covered with fluid flux or molten solder to exclude oxygen from the surface and to prevent the formation of a new oxide coating. However, after the surfaces are tinned, they may be joined in the usual manner.

19. **Adhesive Bonding.** Adhesive bonding of aluminum, either metal-to-metal or metal-to-nonmetal, may be effected with thermosetting or thermoplastic resins, or with one of the elastomeric compounds. These adhesives can provide tensile strengths up to 7000 psi and shear strengths of approximately 5000 psi, depending on the type of adhesive used and the conditions under which it is used. Their peel strengths vary from 10 to 65 pounds per linear inch. (The peel strength of solder is about 60 pounds per inch.) The reliability of the joint will depend upon several factors, including the type of joint, thickness of adherents, cleanliness of surfaces, method and care in fabrication, and the service conditions. For further information on adhesive bonding, refer to MIL-HDBK-691(MR), "ADHESIVES".

CORROSION RESISTANCE

20. **Factors Affecting Corrosion Resistance.** Aluminum and its alloys are inherently corrosion resistant as a result of the oxide film that forms on the surface upon exposure to oxygen. This coating prevents further oxidation of the aluminum beneath the surface. In many instances, this film is sufficient. However, in some environments, supplementary protection is required.

The degree of inherent corrosion resistance of the aluminum alloy depends on the composition and on the thermal history of the metal. Compositions containing magnesium, silicon, or magnesium silicide (relatively close to aluminum in the electromotive series) exhibit the greatest resistance to corrosive attack. On the other hand, alloys containing copper have relatively poor corrosion resistance. (Copper behaves cathodicly with respect to aluminum – in a galvanic couple, the anode corrodes.) The relative corrosion resistance of aluminum casting alloys is given in table XXIII.

The potential differences between aluminum and its alloying elements become important when the alloy has not been properly heat treated; that is, when there has been a lag between the solution heat treating and quenching. This lag permits excessive precipitation of the alloying elements to the grain boundaries. As a result, the alloy is subject to intergranular corrosion through galvanic action.

21. **Protective Finishes.** Supplementary protection of aluminum can be accomplished by cladding, chemical treatment, electrolytic oxide finishing, electroplating, and application of organic or inorganic coatings. (These processes are covered briefly in the following paragraphs.) For additional information on protective finishes, the reader should consult MIL-HDBK-132, Military Handbook Protective Finishes. This publication includes finishes for aluminum and aluminum alloys.

Cladding is probably the most effective means of corrosion protection for aluminum. The process consists of applying layers (approximately 2 to 15 percent of the total thickness) of pure aluminum or a corrosion-resistant aluminum alloy to the surface of the ingot, and hot working the ingot to cause the cladding metal to weld to the core. In subsequent hot working and fabricating, the cladding becomes alloyed with the core and is reduced in thickness proportionately.

The cladding serves as a protective coating for the core metal; it also affords protection by electrolytic action because the cladding is anodic to the base metal and, hence, corrodes sacrificially. (This protection remains even when the metal is sheared or scratched so that the core metal is exposed.) Clad sheet and plate are specified in QQ-A-250/3, QQ-A-250/5, and QQ-A-250/13, QQ-A-250/15, and QQ-A-250/18.

Some chemical treatments result in the formation of oxide films; others etch the metal and lower the corrosion resistance by removing the oxide film. Chemical finishes, though widely used, are not as satisfactory as those produced by electrolytic means. They are, however, well suited as bases for paint because they are slightly porous. Requirements for chemical finishes are specified in MIL-C-5541A.

Electrolytic oxide finishing is perhaps the most widely used method for protecting aluminum. It consists of treating the metal in an electrolyte capable of giving off oxygen, using the metal as an anode. The film thus formed is an aluminum oxide which is thin, hard, inert, and minutely porous. It can be used as is, painted, or dyed.

The electroplating process is similar to that used on other metals. Preparation of the surface however, requires greater care to ensure proper adhesion. The surface must be buffed to remove any scratches and defects; it must be cleaned thoroughly to remove all grease, dirt, or other foreign matter; and it must be given a coating of pure zinc (by immersion in a zincate solution) as a base for the plating metal. After plating, the surface is buffed and finished like other metals.

Organic and inorganic coatings range from paints and lacquers to vitreous enamels. Although paint for decorative purposes may be applied to the metal after removal of surface contaminants, paint used for protective purposes requires more elaborate surface preparation. Usually, an etching type cleaner such as one containing phosphoric acid is used to remove surface contaminants and deposit a thin phosphate film. Then a prime coat such as zinc chromate, with good corrosion-inhibiting properties, good adhesion, and good flexibility is applied. This is followed by the paint, varnish, or lacquer.

Vitreous enamels are essentially lead borosilicates, which are complex glasses. These are applied as frit and fired at about 920°F (493°C). The resulting glaze is hard and heat resistant.

SELECTING ALUMINUM ALLOY

22. Choice of Alloys. With few exceptions, aluminum alloys are designed either for casting or for use in wrought products, but not for both. Some general purpose alloys are available, but on the whole, compositions are formulated to satisfy specific requirements. The more widely used and readily available compositions are covered by Government specifications; most are adaptable to a variety of applications.

In the selection of aluminum, as in the selection of any material used in engineering design, many factors must be taken into account to obtain maximum value and optimum performance. Among these factors are the service conditions to be satisfied, the number of items to be produced, and the relative costs of suitable fabricating processes. These factors dictate the mechanical and physical properties required and the methods of fabrication to be used; and these in turn dictate the requirements for composition, thermal and mechanical treatment, and finishing.

Within certain limits, the selection of a specific composition for a particular use may be much simplified. Having determined the requirements for mechanical or physical properties, determine which alloys will satisfactorily meet the requirements. From these, select all those alloys that are suitable for use with the proposed method and alternate methods of fabrication. Then weigh the costs of the various methods of production.

23. Casting Alloys. The choice of an alloy for casting is governed to a great extent by the type of mold to be employed. The type of mold (sand, permanent, or die) to be used is determined by such factors as intricacy of design, size, cross section, tolerance, surface finish, and number of castings to be produced.

Sand molds are particularly suited to large castings, wide tolerances, and small runs. They are not suitable for the production of thin (less than 3/16 inch) sections or smooth finishes.

Permanent molds, which are generally of cast iron, yield castings with better surface finishes and closer tolerances than those from sand molds, but the minimum thicknesses which can be produced are about the same. Permanent molds are also better suited to larger runs because they do not require the pattern equipment or molding operations needed in sand casting.

Dies are especially suited to long-run production. Although they are relatively expensive, their initial cost can be justified by the savings in machining and finishing costs, and in high production rate. Other advantages include ability to produce thinner cross sections, closer tolerances, smoother surfaces, and intricate designs.

Alloys for use with the various types of molds are listed in table XXIV, together with their characteristics and their recommended uses. In all casting processes, alloys with a high silicon content are useful in the production of parts with thin walls and intricate design.

24. **Wrought Alloys.** The choice of an alloy for a wrought product is influenced almost as much by the proposed method of fabrication, as by the design requirements for the part to be fabricated. Although a variety of compositions and tempers will generally produce the desired mechanical and physical properties, the number of compositions and tempers amenable to the various fabrication techniques in some instances is limited. On the other hand, the fabrication technique that will provide the greatest economy is governed to some extent by the quantity to be produced. It is therefore necessary in the selection of an appropriate alloy to compare the costs of the various methods, taking into account all the processes and tooling that must be employed for each method, such as forming, joining, hardening, and finishing, and such items as designing and manufacturing an extrusion die.

Aluminum can be formed by any of the conventional methods, but is especially suited to extrusion, drawing, and forging. The principal characteristics and uses of wrought aluminum alloys that are covered by Government specifications are summarized in table XXV.

When choosing an aluminum alloy for any wrought product, keep in mind that for corresponding tempers, the ease of fabricating decreases as the strength increases; also, that as the strength increases, the price increases. Hence, economy will indicate the use of alloys with lower strength when their properties are adequate for the intended service conditions. Also, to ensure that the finished part will have the maximum strength and stiffness, the material should be chosen in the hardest temper that will withstand the necessary fabricating operations.

Aluminum extrusions have numerous applications, and are especially useful for producing shapes for architectural assemblies. This method of fabrication makes possible the economical manufacture of more efficient shapes that can withstand relatively higher stresses. It is cheaper than roll-forming, but it cannot produce as thin sections. In addition, the dies used are not expensive, but their design requires care to ensure uniform metal flow from both thick and thin sections. Finally, extruded shapes are ready for use after little more than heat treating and straightening.

Alloys for extrusion are specially designed for the intended use. Alloy 7075-T6 is often used when high strength is desired. Alloy 2014-T6 may also be used, but it is not as strong as the 7075. Alloy 2024-T6 is useful for thinner sections, while alloy 6061 has good forming qualities, resistance to corrosion, and high yield strength. Alloy 6063, either in the as-extruded (-T42) or the artificially aged (-T5) temper, provides adequate strength for some purposes and does not discolor when given an anodic oxide finish. When high resistance to corrosion is required, extruded shapes of alloy 1100 and 3003 are often used.

Drawing is much the same as that for other metals. It is a more expensive operation than extrusion, but it yields products with much closer tolerances. In drawing aluminum, tool radii are important for proper results; a thickness of 4 to 8 times that of the metal thickness is usually satisfactory. Too small a radius may cause tensile fracture; too large a radius may result in wrinkling. Alloys of the non-heat-treatable variety, such as 1100, 3003, 5050, and 5052, are commonly used because they can be deformed to a greater extent before they rupture.

Forgings are used where higher strength is required, or where the forging process is especially adapted for manufacturing the part. Aluminum may be either press forged or drop forged, using special forging stock produced in the form of an extruded bar or shape. Press forging, though slower than drop forging, affords greater flexibility in design, higher accuracy, and lower die cost. Aluminum alloy for forgings is specified in QQ-A-367.

Section II

Standardization Documents

25. **General.** Both the Government and non-government technical societies issue standardization documents dealing with aluminum and aluminum alloy materials and processes. This section covers the current specifications and standards prepared by the Government, the American Society for Testing and Materials (ASTM), and the Aerospace Materials Specifications (AMS) issued by the Society of Automotive Engineers (SAE).

26. **Government Documents.** Following is a list of Government documents dealing with aluminum and aluminum alloy materials processes and items.

MILITARY SPECIFICATIONS

Specification No.	Title	Date
MIL-A-148D #1#	Aluminum Foil	February 1964
JAN-M-454 #1#	Magnesium-Aluminum Alloy, Powdered	February 1952
MIL-A-512A	Aluminum, Powdered, Flaked, Grained and Atomized	22 May 1961
MIL-R-1150A #1#	Rivets, Solid (Aluminum Alloy), and Aluminum Alloy Rivet Wire and Rod	June 1952
MIL-P-1747C INT AMD 2 #GL#	Pan, Baking and Roasting, Aluminum with Cover for Range, Field	March 1962
MIL -A-2877B INT AMD 1 #SH#	Aluminum and Aluminum Alloy Tape, Gray	May 1962
MIL-C-3554	Candler, Egg (Aluminum) 110 Volts AC-DC	August 1951
MIL-D-4303A	Drum Aluminum, 55-Gallon	January 1953
MIL-A-4864A	Aluminum Wool	February 1960
MIL-C-5410B #3#	Cleaning Compound, Aluminum Surface, Non-Flame-Sustaining	September 1965
MIL-R-5674C	Rivet, Aluminum and Aluminum Alloy	January 1966
MIL-H-6088D	Heat Treatment of Aluminum Alloys	March 1965
MIL-W-6858C #INT AMD 1#	Welding, Resistance, Aluminum, Magnesium, Non-Hardening Steels or Alloys, Nickel Alloys, Heat-Resisting Alloys, and Titanium Alloys, Spot and Seam	October 1964
MIL-T-6869B #2#	Impregnants for Aluminum Alloy and Magnesium Alloy Castings	January 1963
MIL-P-6888B	Polish, Metal, Aluminum, Aircraft, (ASG)	March 1963
MIL-W-7072B	Wire, 600-Volt, Aluminum Aircraft, General Specification for (ASG)	September 1962

Specification No.	Title	Date
MIL-T-7081D #1#	Tube, Aluminum Alloy, Seamless, Round 6061, Aircraft Hydraulic Quality	February 1966
MIL-C-7438C #2#	Core Material, Aluminum, for Sandwich Construction	March 1961
MIL-S-7811	Sandwich Construction, Aluminum Alloy Faces, Aluminum Foil Honeycomb Core	August 1952
MIL-R-7885B	Rivets, Blind, Structural, Pull-Stem, and Chemically Expanded	June 1963
MIL-I-8474B	Inspection of Aluminum Alloy Parts, Anodizing Process For	May 1965
MIL-W-8604 #1#	Welding of Aluminum Alloys, Process For	October 1959
MIL-A-8625B	Anodic Coatings, for Aluminum and Aluminum Alloys	June 1965
MIL-A-882A #1#	Aluminum Alloy Plate and Sheet, 2020 (ASG)	February 1964
MIL-A-8920A	Aluminum Alloy Plate and Sheet, 2219 (ASG)	May 1963
MIL-A-8923	Aluminum Alloy Sheet, Alclad 7079 (ASG)	December 1962
MIL-T-10086D	Tanks Liquid Storage, Metal, Vertical Bolted (Steel and Aluminum)	
MIL-S-10133B #1#	Seat, Outlet-Valve, Aluminum-Base-Alloy Die Casting for Outlet Valve-C15	August 1957
MIL-T-10794D #1#	Tubes, Aluminum-Alloy, Extruded Pipeline Sect With Grooved Nipple Welded on Each End	August 1965
MIL-C-11080	Coating, Corrosion-Resistant (For Aluminum Gas Mask Canisters)	April 1951
MIL-A-11267B	Aluminum Sheet, X8280 (For Recoil Mechanism Cup Rings)	June 1963
MIL-B-11353B #1#	Bridge, Floating, Aluminum, Foot Type, Packaging of	September 1958
MIL-S-12204B #1#	Solder, Aluminum Alloy	December 1957
MIL-R-12216B	Reflector, Light, Aluminum and Shield Telescoping Lamp, Aluminum	June 1960
MIL-R-12221B	Rivet, Solid Aluminum Alloy, Grade 7277, Tempered	April 1962
MIL-A-12545B	Aluminum Alloy Impacts	June 1966
MIL-A-12608	Aluminum Chips for Hydrogen Generation (Aluminum Charge ML-389/UM)	April 1953
MIL-B-13141	Boat, Skiff Type, Outboard Motor or Oar Propelled Aluminum, 18 Ft., Design 6002, With Ice Runners	December 1953
MIL-B-13157A	Bridge, Fixed Panel, Single Lane, Aluminum	May 1965
MIL-I-13857	Impregnation of Metal Castings (including Al)	December 1954
MIL-P-14462	Protractor, Fan, Range Deflection Aluminum, Graduated In Mils and Meters	March 1961
MIL-T-15089B	Tubing, Aluminum Alloy, Round, Seamless (For Rocket Motors)	April 1959
MIL-E-16053K AMEND 1	Electrodes, Welding, Bare, Aluminum Alloys	June 1964

Specification No.	Title	Date
MIL-L-17067B	Ladder, Berth, Adjustable (Aluminum) MS&S (Passenger Ships)	September 1952
MIL-F-17132B	Floor Plate, Aluminum Alloy (6061) Rolled	February 1961
MIL-S-17917 #1#	Sandwich Construction, Aluminum Alloy Facings Balsa Wood Core	August 1956
MIL-M-17999B	Metal, Expanded, Aluminum	October 1965
MIL-B-19942	Box, Food Handling, Aluminum	June 1957
MIL-B-20148A	Brazing Alloys Aluminum, and Aluminum Alloy Sheets and Plates, Aluminum Brazing Alloy Clad	August 1955
MIL-A-21180C #1#	Aluminum Alloy Castings - High Strength	February 1965
MIL-T-21494A	Tube, Aluminum Alloy 5086, Round Seamless (Extruded or Drawn)	April 1961
MIL-A-22152 AMEND 1	Aluminum Alloy Sand Castings, Heat Treatment Processes For	November 1959
MIL-W-22248	Weldments, Aluminum and Aluminum Alloy	November 1959
MIL-B-22342A	Brows, Aluminum, Beam and Truss	August 1965
MIL-A-22771B	Aluminum Alloy Forgings, Heat Treated	February 1966
MIL-C-23217A	Coating, Aluminum, Vacuum Deposited (ASG)	September 1963
MIL-C-23396	Chair, Stacking, Aluminum Frame, Upholstered	June 1962
MIL-B-23362 CHANGE 1	Brazing of Aluminum and Aluminum Alloys	February 1964
MIL-S-24149/5	Studs, Aluminum Alloy, for Stored Energy (Capacitor Discharge) Arc Welding	June 1965
MIL-S-24149/2	Studs, Aluminum Alloy for Direct Energy Arc Welding and Arc Shields (Ferrules)	June 1965
MIL-A-25994	Aluminum Alloy Angles, Channels, I and Z Beams, Extruded or Rolled, Structural Shapes	June 1959
MIL-P-25995	Pipe, Aluminum Alloy, Drawn or Extruded	June 1959
MIL-C-26094	Can, Hermetic Sealing, Aluminum, Two-Piece	November 1965
MIL-S-36079	Sterilizer, Surgical Instrument Boiling Type, Electrically and Fuel Heated, Aluminum	June 1961
MIL-B-36195A	Bowl, Gauze Pad, Aluminum, Nesting	November 1964
MIL-S-36315	Splint, Hand, Mason-Allen, Aluminum	October 1964
MIL-C-36465	Cot, Folding, Hospital, Aluminum	January 1966
MIL-T-40057A	Table, Wrapping, Plywood, Aluminum Top	November 1964
MIL-P-40130B	Paddle, Parachute Packing, Aluminum	December 1965
MIL-A-40147 #1#	Aluminum Coating (Hot Dip) For Ferrous Parts	March 1963
MIL-P-40618A	Pan, Pie, Aluminum, Disposable	November 1965
MIL-T-43124	Trucks, Hand, Platform, 4 wheel, Caster Steer Magnesium or Aluminum	December 1962

Specification No.	Title	Date
MIL-B-43341	Breadbox, Delivery, Aluminum	June 1965
MIL-W-45205 #1#	Welding, Inert-Gas, Metal Arc, Aluminum Alloys Readily Weldable for Structures Excluding Armor	May 1962
MIL-W-45206 #1#	Welding, Aluminum Alloy Armor	November 1960
MIL-W-45210A	Welding, Resistance, Spot, Weldable Aluminum Alloys	January 1965
MIL-W-45211A	Welding, Stud, Aluminum	November 1964
MIL-A-45225B	Aluminum Alloy Armor - Forged	December 1965
MIL-R-45774 #1#	Radiographic Inspection, Soundness Requirements for Fusion Welds in Aluminum and Magnesium Missile Components	October 1963
MIL-A-46027C AMEND 1	Aluminum Alloy Armor Plate; Weldable 5083 and 5456	June 1966
MIL-A-46063B AMEND 2	Aluminum Alloy Armor Plate, Heat Treatable, Weldable	August 1966
MIL-A-46083 AMEND 1	Aluminum Alloy Armor, Extruded Weldable	June 1966
MIL-A-46104	Aluminum Alloy Bar, Rod, Shapes and Tube, Extruded, 6070	October 1965
MIL-C-52084 #1#	Curb Assemblies, Bridge, Floating, Aluminum, Light-Tactical	March 1962
MIL-A-52174A #1#	Aluminum Alloy Duct Sheet	November 1963
MIL-A-52242	Aluminum Alloy Extruded Rod, Bar and Shapes, 7001	August 1962
MIL-C-52269	Clamp, Hinge, Bridge, Steel, Treadway Bridge, Floating, Foot, Aluminum	February 1963
MIL-L-54002	Ladders, Aluminum, Three-Way Combination, Step, Straight, Extension	July 1962

FEDERAL SPECIFICATIONS

Specification No.	Title	Date
L-T-80A	Tape, Pressure Sensitive Adhesive, Aluminum Backed	September 1965
L-T-775	Tray, Service, Aluminum and Plastic	May 1956
QQ-A-200B	Aluminum Alloy Bar, Rod, Shapes and Tube, Extruded, General Specification For Parts 1 - 13	August 1964
QQ-A-200/1A	3003	December 1963
QQ-A-200/2B	2014	August 1964
QQ-A-200/3B	2024	August 1964
QQ-A-200/4A	5083	December 1963
QQ-A-200/5A	5086	December 1963

Specification No.	Title	Date
QQ-A-200/6B	5454	June 1964
QQ-A-200/7B	5456	June 1964
QQ-A-200/8B	6061	August 1964
QQ-A-200/9A	6063	December 1963
QQ-A-200/10B	6066	August 1964
QQ-A-200/11B	7075	August 1964
QQ-A-200/12B	7079	August 1964
QQ-A-200/13	7178	August 1964
QQ-A-225B	Aluminum Alloy Bar, Rod, Wire or Special Shapes Rolled, Drawn, or Cold Finished, General Specification For Parts 1 - 9	August 1964
QQ-A-225/1B	1100	August 1964
QQ-A-225/2B	3003	August 1964
QQ-A-225/3B	2011	August 1964
QQ-A-225/4B	2014	August 1964
QQ-A-225/5B	2017	August 1964
QQ-A-225/6B	2024	August 1964
QQ-A-225/7A	5052	December 1963
QQ-A-225/8B #1#	6061	December 1964
QQ-A-225/9B	7075	August 1964
QQ-A-250C	Al Alloy Plate and Sheet General Specification For Parts 1 - 18	September 1964
QQ-A-250/1C	1100	September 1964
QQ-A-250/2B	3003	December 1963
QQ-A-250/3C	ALCLAD 2014	September 1964
QQ-A-250/4C	2024	September 1964
QQ-A-250/5D	ALCLAD 2024	April 1965
QQ-A-250/6D	5083	September 1964
QQ-A-250/7C	5086	May 1964
QQ-A-250/8C	5052	September 1964
QQ-A-250/9D	5456	September 1964
QQ-A-250/10B	5454	December 1963
QQ-A-250/11C	6061	September 1964
QQ-A-250/12C	7075	September 1964
QQ-A-250/13C	ALCLAD 7075	September 1964
QQ-A-250/14C	7178	
QQ-A-250/15C	ALCLAD 7178	September 1964
QQ-A-250/16C	2020	April 1964

Specification No.	Title	Date
QQ-A-250/17C	7079	September 1964
QQ-A-250/18C	ALCLAD One Side 7075	September 1964
QQ-A-367G	Aluminum Alloy Forgings	June 1966
QQ-A-371E	Aluminum Alloy Ingot (For Remelting)	August 1965
QQ-A-430 #1#	Aluminum Alloy Rod and Wire, for Rivets and Cold Heading	April 1962
QQ-A-00435	Aluminum Alloy Sheet, Painted (For Exterior Use)	May 1964
QQ-A-591D	Aluminum Alloy Die Castings	January 1963
QQ-A-596D	Aluminum Alloy Permanent and Semi-permanent Mold Castings	May 1966
QQ-A-601C #2# INT AMD 3 #SH#	Aluminum Alloy Sand Castings	October 1965
QQ-A-00640	Aluminum Foil (Insulation Reflective Building)	October 1964
QQ-A-825	Bus Bar, Copper Aluminum or Aluminum Alloy	May 1965
QQ-B-655B	Brazing Alloys, Aluminum and Magnesium, Filler Metal	September 1959
QQ-N-286A #1#	Nickel-Copper - Aluminum Alloy, *K-Monel	August 1956
QQ-R-566A	Rods, Welding, Aluminum and Aluminum Alloys	March 1964
RR-K-00190	Kettles, Steam-Jacketed (Aluminum)	December 1957
RR-P-54	Pan, Aluminum	January 1965
RR-P-0090	Pan, Pie (Aluminum Foil)	August 1964
RR-B-500	Boiler, Kettle and Pot (Aluminum)	January 1965
TT-P-320	Pigment, Aluminum, Powder and Paste, for Paint	August 1961
WW-C-540A	Conduit, Metal, Rigid, (Electrical Aluminum)	November 1960
WW-P-402A	Pipe, Corrugated (Aluminum Alloy)	December 1964
WW-P-471A	Pipe Fittings, Bushings, Locknuts and Plugs, Brass or Bronze, Iron or Steel, and Aluminum (Screwed) 125-150 pounds	March 1964
WW-T-700C	Tube, Aluminum Alloy, Drawn, Seamless, General Specification For Parts 1 - 6	August 1964
WW-T-700/1C	Tube 1100	August 1964
WW-T-700/2C	Tube 3003	August 1964
WW-T-700/3C	Tube 2024	August 1964
WW-T-700/4C	Tube 5052	August 1964
WW-T-700/5C	Tube 5086	August 1962
WW-T-700/6C	Tube 6061, 6062	August 1962
WW-T-816 AMEND 2	Tubing, Flexible, Aluminum Alloy (Number Was Formerly RR-T-791) Supersedes ANT 13	January 1961

MILITARY STANDARDS

Standard No.	Title	Date
MS-9095	Nipple, Tube, AMS 4120 Boss A1	April 1960
MS-9096A	Elbow, Tube, AMS 4135 Boss 90 A1	May 1962
MS-9097A	Elbow, Tube, AMS 4135 Boss 45 A1	May 1962
MS-9098A	Tee, Tube - AMS 4135, Boss A1	May 1962
MS-9099	Nut-Hex, Boss Connection, Aluminum	
MS-9199	Nut, Tube Coupling - Aluminum, AMS 4121 ASG	March 1962
MS-9200	Nut-Plain, Hex, Boss Connection, Aluminum ASG	
MS-16206	Bolt, Machine, Hexagon Head, Regular Semi-Finished, Aluminum Alloy, UNC-2A, Non-Magnetic	May 1957
MS-16593A	Rivet Solid, 78 Degree, Flat Head, Aluminum	2 February 1956
MS-17354	Nut Plain, Hex, Boss Connection, Aluminum #MIL-S-8879 Thread#	March 1962
MS-20426D	Rivet, Solid, Countersunk 100 Deg., Precision Head Aluminum and Aluminum Alloy	July 1964
MS-20470B	Rivet, Solid-Universal Head, Aluminum and Aluminum Alloy	September 1960
MS-25191B	Wire, Electric, 600-Volt, Aluminum, Aircraft #ASG#	October 1962
MS-27088A	Nipple, Brazed, Aluminum Alloy	2 July 1963
MS-27957	Hinge, Butt Narrow and Broad, Template; Hardware, Builders, Commercial, Aluminum	February 1961
MS-27959	Hinge, Butt- Narrow and Broad, Without Holes, Hardware, Builders, Commercial, Aluminum	February 1961
MS-35202B	Screw, Machine, Flat Countersunk Head, Cross-Recessed, Aluminum Alloy Anodize Finish Nc2A-UNC-2 A	May 1965
MS-35516	Corrosion Resistant Coating Chemically Treated Aluminum	March 1956
MS-35965	Dish, Moisture Determination, Aluminum	September 1959
MS-36163	Rack, Test Tube, Laboratory Folding, Aluminum	December 1960
MIL-STD-437A	X-Ray Standard for Bare Aluminum Alloy Electrode Welds	December 1958
MIL-STD-645A	Dip Brazing of Aluminum Alloys	December 1965
MIL-STD-649	Aluminum and Magnesium Products Preparation For Shipment and Storage	July 1963

QUALIFIED PRODUCTS LISTS

Number	Title	Date
QPL-6888-14	Polish, Metal, Aluminum Aircraft	October 1963
QPL-6939-4	Flux, Aluminum and Aluminum Alloy Gas Welding	February 1960

Number	Title	Date
QPL-14276-7	Paint, Heat Resisting Silicone, Aluminum	March 1963
QPL-15599-44	Electrode, Welding, Covered, Aluminum and Aluminum Alloy	March 1965
QPL-27347-1	Cloth, Coated Glass, Aluminum Face Silicone Rubber Back	June 1960

OTHER STANDARDIZATION DOCUMENTS

Number	Title	Date
AN 123020 thru 123150	Gasket, Aluminum-Asbestos, Annular (Reactivated for Design)	
AND 10106 Rev 3	Tubing-Standard Sizes for Aluminum Alloy Round (5250)	April 1948
AND 10107 Rev 3	Tubing - Standard Sizes for Aluminum Alloy (24ST) Round	October 1942
AND 10125	Aluminum Wire-Standard Alloys, Tempers and Sizes of Round and Hexagon (For Welding Rod and General Use)	October 1945
AND 10126 Rev 1	Aluminum Wire-Standard Conditions and Sizes for Sheet, Strip	February 1943
AND 10130 Rev 1	Aluminum Rod and Bar - Standard Alloys Tempers and Sizes of Round and Hexagon	July 1943
AND 10131	Aluminum Bar - Standard Alloys, Temper and Sizes of Square	October 1942
AND 10132	Aluminum Bar - Standard Alloy and Temper (24st) and Sizes of Rectangular	October 1942
USAF Spec X-40911 (1) Change 2 1 Aug 1958	Rivets, Blind, Aluminum Alloy (Reinstated) For Requirements of Type B, Class 1 Rivets Only	July 1948
AIA-NAS 1516 - 1522	Pin, Swage Locking, Aluminum Alloy 100 Deg. Head (AN509) Tension Pull Type, Close Tol.	October 1963
AIA-NAS NAS 1525 - 1532	Pin, Swage Locking, Aluminum Alloy Protruding Head, Tension, Pull Type, Close Tol.	
AIA-NAS 1535 - 1542	Pin, Swage Locking, Aluminum Alloy 100 Deg. Head (MS20426), Tension, Pull Type Close Tol.	
AIA-NAS 1546 - 1552	Pin, Swage Locking, Aluminum Alloy, 100 Deg., Head (AN509), Tension, Stump Type, Close Tol.	October 1963
AIA-NAS 1556-1562	Pin, Swage Locking, A1 Alloy Protruding Head Tension, Stump Type, Close Tol.	October 1963

Number	Title	Date
Fed. Std. 184	Identification Marking of Aluminum Magnesium and Titanium	August 1959
Fed. Std. 245B	Tolerances for Aluminum Alloy and Magnesium Alloy Wrought Products	December 1963

CANCELLED AND SUPERSEDED STANDARDIZATION DOCUMENTS

The following listed standardization documents have been cancelled or superseded since the compilation that appeared in the previous issue of this handbook.

Number	Title
QQ-A-411	Aluminum Alloy Bars, Rods, and Wire; Rolled Drawn or Cold Finished, 1100. Superseded by Federal Specification QQ-A-225/1a, December 16, 1963.
MIL-A-799	Aluminum High Purity, Wrought. Cancelled without replacement, 15 October 1965.
MIL-A-8097	Aluminum Alloy Forgings, 76S for Aircraft Applications.
MIL-A-8705	Aluminum Alloy, Bare and Alclad 2024 (24S), Artificial Aging of.
MIL-A-8825	Aluminum Bars and Shapes, Extruded 7079. See QQ-A-200/12b.
MIL-A-8877	Aluminum Alloy Sheet and Plate 7079. See QQ-A-250/17c.
MIL-A.8902	Aluminum Alloy Plate and Sheet Alclad One Side 7075. See QQ-A-250/18c.
MIL-A-9180	Aluminum Alloy Plate and Sheet 7178. See QQ-A-250/14c.
MIL-A-9183	Aluminum Plate and Sheet Clad 7178. See QQ-A-250/15c.
MIL-A-9186	Aluminum Alloy Bars, Rods and Shapes Extruded, 7178. See QQ-A-200/13.
MIL-A-17358	Aluminum Alloy Plate and Sheets, 5083 (X-183). See QQ-A-250/6d.
MIL-A-19842	Aluminum Alloy Plates and Sheets, 5456. See QQ-A-250/9.
MIL-A-20695	Aluminum Products, Preparation for Storage and Shipment of. See MIL-STD-649.
MIL-A-21170	Aluminum Alloy Bar, Rod, and Structural Shaped Sections Rolled or Extruded, 5456. See QQ-A-200/7b.
MIL-T-21494A	Tube, Aluminum Alloy 5086, Round, Seamless (Extruded or Drawn). See WW-T-700/5.
MIL-A-21579	Aluminum Alloy Bars, Rods and Structural Shapes, Rolled or Extruded 5086. See QQ-A-200/5a.
MIL-A-25493	Aluminum Alloy Bars, Rods, and Shapes, Extruded, 6066. See QQ-A-200/10b.
MIL-STD-192A	Alloy and Temper Designation System for Wrought-Aluminum. See ASA - H-35.1 - 1962.

27. **Society of Automotive Engineers Specifications.** Following is a list of Aerospace Materials Specifications Dealing with Aluminum and Aluminum Alloys.

AMS Number	Title
4000C	Sheet and Plate - 99.7 Aluminum (Annealed)
4001C	Sheet and Plate - 99.0 Aluminum

AMS Number	Title
4003C	Sheet and Plate - 99.0 Aluminum
4006C	Sheet and Plate - 1.25 Manganese
4008C	Sheet and Plate - 1.25Mn
4010	Foil - 1.2 Manganese
4012A	Sheet - Laminated, Edge Bonded
4013A	Sheet - Laminated, Surface Bonded
4014	Plate - 4.5Cu, 0.8Si, 0.80Mn, 0.5Mg
4015E	Sheet and Plate - 2.5Mg, 0.25Cr
4016E	Sheet and Plate - 2.5Mg, 0.25Cr
4017E	Sheet and Plate - 2.5Mg, 0.25Cr
4018A	Sheet and Plate - 3.5Mg, 0.25Cr
4019	Sheet and Plate - 3.5Mg, 0.25Cr
4020	Plate, Alclad - 1.0Mg, 0.6Si, 0.25Cu, 0.25Cr
4021B	Sheet and Plate, Alclad - 1Mg, 0.6Si, 0.25Cu, 0.25Cr
4022C	Sheet and Plate, Alclad - 1.0Mg, 0.60Si, 0.25Cu, 0.25Cr
4023C	Sheet and Plate, Alclad - 1.0Mg, 0.60Si, 0.25Cu, 0.25Cr
4024A	Sheet and Plate - 4.3Zn, 3.3Mg, 0.60Cu, 0.20Mn, 0.17Cr
4025D	Sheet and Plate - 1.0Mg, 0.60Si, 0.25Cu, 0.25Cr
4026D	Sheet and Plate - 1.0Mg, 0.60Si, 0.25Cu, 0.25Cr
4027E	Sheet and Plate - 1.0Mg, 0.60Si, 0.25Cu, 0.25Cr
4028B	Sheet and Plate - 4.5Cu, 0.85Si, 0.80Mn, 0.50Mg
4029B	Sheet and Plate - 4.5Cu, 0.85Si, 0.80Mn, 0.50Mg
4031A	Sheet and Plate - 6.3Cu, 0.30Mn, 0.18Zr, 0.10V, 0.06Ti
4033A	Plate - 4.5Cu, 1.5Mg, 0.6Mn, Stress Relief Stretched
4034A	Plate, Alclad - 4.5Cu, 1.5Mg, 0.6Mn, Stress-Relief Stretched
4035E	Sheet and Plate - 4.5Cu, 1.5Mg, 0.6Mn
4036A	Sheet and Plate, Alclad One Side - 4.5Cu, 1.5Mg, 0.60Mn
4037F	Sheet and Plate - 4.5Cu, 1.5Mg, 0.6Mn
4038A	Plate - 5.6Zn, 2.5Mg, 1.6Cu, 0.30Cr, Stress-Relief Stretched
4039A	Plate - 5.6Zn, 2.5Mg, 1.6Cu, 0.30Cr, Stress-Relief Stretched
4040F	Sheet and Plate, Alclad - 4.5Cu, 1.5Mg, 0.6Mn
4041G	Sheet and Plate, Alclad - 4.5Cu, 1.5Mg, 0.6Mn
4042F	Sheet and Plate, Alclad - 4.5Cu, 1.5Mg, 0.60Mn, Width 48 in. and under
4043	Plate - 1.0Mg, 0.60Si, 0.25Cu, 0.25Cr, Stress-Relief Stretched
4044C	Sheet and Plate - 5.6Zn, 2.5Mg, 1.6Cu, 0.25Cr
4045C	Sheet and Plate - 5.6Zn, 2.5Mg, 1.6Cu, 0.25Cr
4046A	Sheet and Plate, Alclad One Side - 5.6Zn, 2.5Mg, 1.6Cu, 0.25Cr
4047B	Sheet & Pl. Alclad, Roll Tapered - 5.6Zn, 2.5Mg, 1.6Cu, 0.25Cr
4048D	Sheet and Plate, Alclad - 5.6Zn, 2.5Mg, 1.6Cu, 0.25Cr
4049D	Sheet and Plate, Alclad - 5.6Zn, 2.5Mg, 1.6Cu, 0.25Cr
4051B	Sheet and Plate, Alclad - 6.8Zn, 2.75Mg, 2.0Cu, 0.30Cr
4052A	Sheet and Plate, Alclad - 6.8Zn, 2.7Mg, 2Cu, 0.3Cr
4053	Plate - 1.0Mg, 0.60Si, 0.25Cu, 0.25Cr, Stress-Relief Stretched
4054A	Sheet, Clad One Side - 0.60Mg, 0.35Si, 0.30Cu
4055A	Sheet, Clad Two Sides - 0.60Mg, 0.35Si, 0.30Cu
4056B	Sheet and Plate - 4.5Mg, 0.65Mn, 0.15Cr
4057B	Sheet and Plate - 4.5Mg, 0.65Mn, 0.15Cr
4058B	Sheet and Plate - 4.5Mg, 0.65Mn, 0.15Cr
4059C	Sheet and Plate - 4.5Mg, 0.65Mn, 0.15Cr

AMS Number	Title
4060	Sheet and Plate, Alclad - 4.5Cu, 1.5Mg, 0.60Mn, Width Over 48-60 in., Incl.
4061	Sheet and Plate, Alclad - 4.5Cu, 1.5Mg, 0.60Mn, Width Over 60 in.
4062D	Tubing, Seamless, Round, Drawn - 99.0 Aluminum
4065C	Tubing, Seamless, Drawn - 1.25Mn
4067C	Tubing, Seamless, Round, Drawn - 1.25Mn
4069	Tubing, Seamless, Drawn-Close Tolerance, 2.5Mg, 0.25Cr
4070F	Tubing, Seamless, Drawn, Round - 2.5Mg, 0.25Cr
4071F	Tubing, Hydr., Seamless, Drawn, Round - 2.5Mg, 0.25Cr
4072	Sheet and Plate, Alclad - 4.5Cu, 1.5Mg, 0.60Mn, Width 30 in. and Under
4073	Sheet and Plate, Alclad - 4.5Cu, 1.5Mg, 0.60Mn, Width Over 30 to 48 in., Incl.
4074	Sheet and Plate, Alclad - 4.5Cu, 1.5Mg, 0.60Mn, Width Over 48 to 60 in., Incl.
4075	Sheet and Plate, Alclad - 4.5Cu, 1.5Mg, 0.60Mn, Width Over 60 Inches
4079	Tubing, Seamless, Drawn - Close Tolerance, 1Mg, 0.6Si, 0.25Cu, 0.25Cr
4080G	Tubing, Seamless, Drawn - 1.0Mg, 0.60Si, 0.30Cu, 0.20Cr
4081A	Tubing, Hydr., Seamless, Drawn - 1.0Mg, 0.6Si, 0.25Cu, 0.25Cr
4082F	Tubing, Seamless, Drawn - 1.0Mg, 0.60Si, 0.30Cu, 0.20Cr
4083D	Tubing, Hydr., Seamless, Drawn - 1.0Mg, 0.6Si, 0.25Cu, 0.25Cr
4086F	Tubing, Hydr., Seamless, Drawn - 4.5Cu, 1.5Mg, 0.6Mn
4087C	Tubing, Seamless, Drawn - 4.5Cu, 1.5Mg, 0.60Mn
4088E	Tubing, Seamless, Drawn - 4.5Cu, 1.5Mg, 0.6Mn
4091A	Tubing, Hydraulic
4092A	Tubing Seamless, Drawn
4093A	Tubing, Hydraulic
4097	Sheet and Plate - 4.5Cu, 1.5Mg, 0.60Mn, Width 48 in. and Under
4098	Sheet and Plate - 4.5Cu, 1.5Mg, 0.60Mn, Width Over 48 to 60 in., Incl.
4099	Sheet and Plate - 4.5Cu, 1.5Mg, 0.60Mn, Width Over 60 Inches
4102B	Bars and Rods, Rolled or Cold Finished - 99.0 Aluminum
4103	Sheet and Plate - 4.5Cu, 1.5Mg, 0.60Mn, Width 30 in. and Under
4104	Sheet and Plate - 4.5Cu, 1.5Mg, 0.60Mn, Width Over 30 to 48 in., Incl.
4105	Sheet and Plate - 4.5Cu, 1.5Mg, 0.60Mn, Width Over 48 to 60 in., Incl.
4106	Sheet and Plate - 4.5Cu, 1.5Mg, 0.60Mn, Width Over 60 Inches
4110A	Bars and Rods, Rolled or Cold Finished - 4.0Cu, 0.70Mn, 0.50Mg, Stress-Relief Stretched
4112	Bars, Rods, and Wire, Rolled, Drawn, or Cold Finished - 4.5Cu, 1.5Mg, 0.60Mn
4114C	Bars, Rolled, Drawn, or Cold Finished - 2.5Mg, 0.25Cr
4115A	Bars, Rolled, Drawn, or Cold Finished - 1.0Mg, 0.60Si, 0.30Cu, 0.20Cr
4116B	Bars, Rolled, Drawn, or Cold Finished - 1.0Mg, 0.60Si, 0.30Cu, 0.20Cr
4117B	Bars, Rolled, Drawn, or Cold Finished - 1.0Mg, 0.60Si, 0.30Cu, 0.20Cr
4118D	Bars, Rods, and Wire, Rolled, Drawn, or Cold Finished - 4.0Cu, 0.7Mn, 0.50Mg
4119C	Bars and Rods, Rolled or Cold Finished - 4.5Cu, 1.5Mg, 0.60Mn, Stress-Relief Stretched
4120F	Bars, Rods, Wire, Rolled - 4.5Cu, 1.5Mg, 0.60Mn
4121C	Bars, Rods, Wire, Rolled - 4.5Cu, 0.90Si, 0.80Mn, 0.50Mg
4122D	Bars, Rods, Wire, Rolled, Drawn, or Cold Finished - 5.6Zn, 2.5Mg, 1.6Cu, 0.30Cr
4123C	Bars and Rods, Rolled or Cold Finished - 5.6Zn, 2.5Mg, 1.6Cu, 0.30Cr, Stress-Relief Stretched
4125E	Forgings - 1Si, 0.6Mg, 0.25Cr
4127C	Forgings - 1.0Mg, 0.60Si, 0.30Cu, 0.20Cr
4130G	Forgings - 4.5Cu, 0.85Si, 0.80Mn
4132A	Forgings - 2.3Cu, 1.6Mg, 1.1Fe, 1.1Ni, 0.07Ti
4134A	Forgings - 4.4Cu, 0.8Si, 0.8Mn, 0.4Mg
4135J	Forgings - 4.5Cu, 0.9Si, 0.8Mn, 0.5Mg

AMS Number	Title
4136	Forgings - 4.3Zn, 3.3Mg, 0.6Cu, 0.2Mn, 0.2Cr, Sol. and Precip. Ht. Treated, Low Residual Stresses
4137A	Forgings - 7.5Zn, 1.6Mg, 0.7Cu, 0.55Mn
4138	Forgings - 4.3Zn, 3.3Mg, 0.6Cu, 0.2Mn, 0.2Cr
4139F	Forgings - 5.6Zn, 2.5Mg, 1.6Cu, 0.25Cr
4140D	Forgings - 4.0Cu, 2.0Ni, 0.7Mg
4141	Forgings - 5.6Zn, 2.5Mg, 1.6Cu, 0.25Cr
4142B	Forgings - 4Cu, 2Ni, 1.5Mg, 0.7Si
4143	Forgings - 6.3Cu, 0.3Mn, 0.2Zr, 0.1Ti, 0.1V, Solution and Precip. Heat Treated
4144	Hand Forgings and Rings - 6.3Cu, 0.3Mn, 0.2Zr, 0.1V, 0.1Ti, Stress-Relief Compressed
4145E	Forgings - 12.2Si, 1.1Mg, 0.9Cu, 0.9Ni
4146A	Forgings - 1.0Mg, 0.60Si, 0.30Cu, 0.20Cr
4150D	Extrusions - 1.0Mg, 0.60Si, 0.30Cu, 0.20Cr
4152G	Extrusions - 4.5Cu, 1.5Mg, 0.60Mn
4153C	Extrusions - 4.5Cu, 0.85Si, 0.80Mn, 0.50Mg
4154F	Extrusions - 5.6Zn, 2.5Mg, 1.6Cu, 0.3Cr
4155B	Extrusions
4156D	Extrusions - 0.65Mg, 0.40Si
4158A	Extrusions - 6.8Zn, 2.75Mg, 2.0Cu, 0.3Cr
4160A	Extrusions - 1.0Mg, 0.60Si, 0.30Cu, 0.20Cr
4161A	Extrusions - 1.0Mg, 0.60Si, 0.30Cu, 0.20Cr
4164C	Extrusions - 4.4Cu, 1.5Mg, 0.60Mn, Stress-Relief Stretched, Unstraightened
4165C	Extrusions - 4.4Cu, 1.5Mg, 0.60Mn, Stress-Relief Stretched and Straightened
4168A	Extrusions - 5.6Zn, 2.5Mg, 1.6Cu, 0.3Cr, Stress-Relief Stretched, Unstraightened
4169B	Extrusions - 5.6Zn, 2.5Mg, 1.6Cu, 0.3Cr, Stress-Relief Stretched and Straightened
4170	Extrusions, Impact - 5.6Zn, 2.5Mg, 1.6Cu, 0.25Cr
4171A	Extrusions - 4.3Zn, 3.3Mg, 0.6Cu, 0.2Mn, 0.17Cr
4180B	Wire, Spray-Aluminum, 99.0 Min
4182A	Wire - 5Mg, 0.12Mn, 0.12Cr
4184B	Wire, Brazing - 10Si, 4Cu
4185A	Wire, Brazing - 12Si
4190A	Rod and Wire, Welding - 5Si
4191A	Rod and Wire, Welding - 6.3Cu, 0.3Mn, 0.18Zr, 0.15Ti, 0.10V
4210F	Castings, Sand - 5Si, 1.2Cu, 1.5Mg
4212E	Castings, Sand - 5Si, 1.2Cu, 0.5Mg
4214D	Castings, Sand - 5Si, 1.2Cu, 0.5Mg
4215B	Castings, Premium Grade - 5Si, 1.2Cu, 0.5Mg
4217D	Castings, Sand - 7Si, 0.3Mg
4218B	Castings, Premium Grade - 7Si, 0.3Mg
4219	Castings, High Strength, Premium Quality - 7.0Si, 0.60Mg
4220D	Castings, Sand - 4Cu, 2Ni, 1.5Mg, 0.2Cr, Sol Tr. & Overaged
4222D	Castings, Sand - 4Cu, 2Ni, 1.5Mg, Sol. Tr. & Overaged
4224	Castings, Sand - 4Cu, 2Ni, 2Mg, 0.3Cr, 0.3Mn, 0.1Ti, 0.1V, Stabilized
4227A	Castings, Sand - 8Cu, 6Mg, 0.5Mn, 0.5Ni
4230C	Castings, Sand - 4.5Cu, Sol. Treated
4231C	Castings, Sand - 4.5Cu, Sol. & Precip, Treated
4238A	Castings, Sand - 6.8Mg, 0.2Ti, 0.2Mn, As Cast
4239	Castings, Sand - 6.8Mg, 0.2Ti, 0.2Mn, Stabilized
4240C	Castings, Sand - 10Mg, Solution Treated

Number	Title
4260A	Castings, Investment - 7Si, 0.3Mg, Sol. & Precip. Treated
4261	Castings, Investment - 7.0Si, 0.3Mg, Precipitation Heat Treated
4275B	Castings, Permanent Mold - 6Sn, 1Cu, 1Ni, Stress Relieved
4280E	Castings, Permanent Mold - 5Si, 1.2Cu, 0.5Mg, Sol. Tr. & Overaged
4281C	Castings, Permanent Mold - 5Si, 1.2Cu, 0.5Mg, Sol. & Precip. Treated
4282E	Castings, Permanent Mold - 4.5Cu, 2.5Si, Sol. & Precip. Treated
4283D	Castings, Permanent Mold - 4.5Cu, 2.5Si, Solution Treated
4284D	Castings, Permanent Mold - 7Si, 0.3Mg, Sol. & Precip. Treated
4285	Castings, Centrifugal - 7Si, 0.3Mg, Sol. & Precip. Treated
4286A	Castings, Permanent Mold - 7Si, 0.3Mg
4290F	Castings, Die - 9.5Si, 0.5Mg, As Cast
4291B	Castings, Die - (5Si or 8.5Si) 3.5Cu, As Cast
2201G	Tolerances - Aluminum & Alum. Alloy Bar, Rod, Wire & Forging Stock - Rolled or Drawn
2202F	Tolerances - Aluminum and Magnesium Alloy Sheet and Plate
2203F	Tolerances - Aluminum Alloy Drawn Tubing
2204C	Tolerances - Aluminum Rolled or Extruded Standard Structural Shapes
2205J	Tolerances - Aluminum and Magnesium Alloy Extrusions
2355	Tensile Testing of Wrought Alum. & Magnesium Prods., Except Forgings
2420	Plating - Aluminum for Solderability (Zincate Process)
2450C	Sprayed Metal Finish - Aluminum
2468A	Hard Coating Treatment - Aluminum Alloys
2469B	Hard Coating Treatment - Process and Performance Requirements of Aluminum Alloys
2470F	Anodic Treatment - Aluminum Base Alloys (Chromic Acid Process)
2471B	Anodic Treatment - Aluminum Base Alloys, Sulfuric Acid Process, Undyed Coating
2472A	Anodic Treatment - Aluminum Base Alloys, Dyed Coating (Sulfuric Acid Process)
2473B	Chemical Treatment - Aluminum Base Alloys (General Purpose Coating)
2474A	Chemical Treatment - Aluminum Base Alloys (Low Electrical Resistance Coating)
2672B	Brazing - Aluminum
2673	Brazing - Aluminum Molten Flux (Dip)
3412A	Flux - Brazing, Aluminum
3414A	Flux - Welding, Aluminum
3415	Flux - Aluminum Dip Brazing, 1030F Fusion Point
3416	Flux - Aluminum Dip Brazing, 1090F Fusion Point

28. **American Society for Testing and Materials Specifications.** Following is a list of ASTM Specifications.

Number	Title
B26-65	Sand Castings, Aluminum Alloy
B85-60	Die Castings, Aluminum Alloy
B108-65	Permanent Mold Castings, Aluminum Alloy
B209-65	Sheet and Plate, Aluminum Alloy
B210-65	Drawn Seamless Tubes, Aluminum Alloy
B211-65	Bars, Rods, and Wire, Aluminum Alloy
B221-65	Extruded Bars, Rods, Shapes and Tubes, Aluminum Alloy
B234-65	Drawn Seamless Tubes for Condensers and Heat Exchangers - Aluminum Alloy

AMS Number	Title
B241-65	Seamless Pipe Aluminum Alloy
B307-64	Drawn Seamless Coiled Tubes for Special Purpose Applications, Aluminum Alloy
B313-65	Round Welded Tubes, Aluminum Alloy
B345-65	Seamless Pipe for Gas and Oil Transmission and Distribution Piping Systems, Aluminum Alloy
B361-64	Welding Fittings, Factory Made Wrought, Aluminum and Aluminum Alloy
B404-65T	Seamless Condenser and Heat Exchanger Tubes with Integral Fins, Aluminum Alloy
B429-65T	Extruded Structural Pipe and Tube, Aluminum Alloy

Aluminum Wrought Products for Electrical Purposes

AMS Number	Title
B230-60	Wire for Electrical Purposes, Aluminum, EC-H19
B231-64	Concentric-Lay-Stranded Aluminum Conductors
B232-64T	Concentric-Lay-Stranded Aluminum Conductors, Steel-Reinforced (ACSR)
B233-64	Rods for Electrical Purposes, Rolled Aluminum
B236-64	Bars for Electrical Purposes (Bus Bars), Aluminum
B245-63	Steel Core Wire for Aluminum Conductors, Standard Weight Zinc-Coated (Galvanized), Steel-Reinforced (ACSR)
B258-65	Standard Nominal Diameters and Cross-Sectional Areas of Awg Sizes of Solid Round Wires Used as Electrical Conductors
B261-63	Steel Core Wire (With Coatings Heavier Than Standard Weight) for Aluminum Conductors, Zinc-Coated (Galvanized), Steel-Reinforced (ACSR)
B262-61	Wire for Electrical Purposes, Aluminum, EC-H16 or -H26
B314-60	Wire for Communication Cable, Aluminum
B317-64	Bar, Rod, Pipe, and Structural Shapes for Electrical Purposes (Bus Conductors), Aluminum-Alloy Extruded
B323-61	Wire for Electrical Purposes, Aluminum, EC-H14 or -H24
B324-60	Wire for Electrical Purposes, Rectangular and Square Aluminum
B341-63T	Steel Core Wire for Aluminum Conductors, Aluminum-Coated (Aluminized), Steel-Reinforced (ACSR)
B373-65	Aluminum Foil for Capacitors
B396-63T	Wire for Electrical Purposes, 5005-H19 Aluminum-Alloy
B397-63T	Concentric-Lay-Stranded Conductors, 5005-H19 Aluminum-Alloy
B398-63T	Wire for Electrical Purposes, 6201-T81 Aluminum-Alloy
B399-63T	Concentric-Lay-Stranded Conductors, 6201-T81 Aluminum-Alloy
B400-63T	Concentric-Lay-Stranded Aluminum EC Grade Conductors, Hard-Drawn Compact Round
B401-63T	Concentric-Lay-Stranded Aluminum Conductors, Steel-Reinforced (ACSR) Compact Round
B415-64T	Steel Wire, Hard-Drawn Aluminum-Clad
B416-64T	Concentric-Lay-Stranded Steel Conductors, Aluminum-Clad

Section III

Typical Properties and Characteristics

The properties cited in this Section are average for various forms, sizes, and methods of manufacture, and may not exactly describe any one particular product.

The abbreviations used in this section and in Section III are defined as follows:

A1 - Aluminum
BHN - Brinell Hardness Number
Cr - Chromium
Cu - Copper
D - Die cast
EL - Permanent extension in gage length measured after rupture and stated as a percent of the original gage length
End - Endurance
Fe - Iron
Ksi - Thousand pounds per square inch
Mg - Magnesium
Mn - Manganese
Ni - Nickel
PM - Permanent-mold cast
S - Sand cast
Si - Silicon
Sn - Tin
SS - Shear strength
Ti - Titanium
TS - Tensile strength
YS - Yield strength (0.2% offset)
Zn - Zinc

TABLE 1. CASTING ALLOYS - CROSS REFERENCE

		SAND CASTINGS			PERMANENT AND SEMI-PERMANENT MOLD CASTINGS			DIE CASTINGS			
Commercial Designation	SAE	QQ-A-601d	ASTM B-26-65	AMS	QQ-A-596d	ASTM B108-65	AMS	QQ-A-591d	ASTM B-85-60	AMS	MIL-A-21180C
13								13	S12B		
A13	305							A13	S12A		
40E	310	40E	ZG61A								
43	35, 304	43	S5A		43			43	SC5		
108		108	CS43A								
A108					A108						
113	33	113	CS72A		113						
122	34	122	CG100A		122						
A132	321				A132	SN122A					
B132	328										
E132	334										
F132	332				F132	SC103A					
142	39	142	CN42A	4220, 4221	142	CN42A					
152	300										
195	38	195	G4A	4230, 4231							
B195	380				B195		4282, 4288				
214	320	214									
A214					A214	CZ428					
B214		B214									
218								218			
220	324	220	G10A	4240							
319	326, 329	Allcast	SC64D		319	SC64D					
333					333	SC94A					
354											354
355	322	355	SC51A	4210, 4212, 4214		SC51A	4281, 4282				
C355	335				C355	SC51B					C355
356	323	356	SG70A	4217		SG70A	4260, 4261 4284, 4285 4286				
A356	336				A356	SG70B					A356
357		357			357						357
360								360	SG100B	4290	359
A360	309							A360			
380	308							380	SC84B		
A380	306							A380	SC84A	4291	
384	303										
A612	313	A612	ZG61A								
C612	314										
750		750			750		4275				
A750		A750			A750						
B750		B750			B750						
Almag 35		Almag 35	GM70B								
Precedent 71A		Precedent 71A									
Red X-8	327	Red X-8	SC82A								
T-1		T-1									
Tenzaloy	315	Tenzaloy	ZC81A		Tenzaloy (613)	ZC81B					
Ternalloy 5	311	Ternalloy 5	ZG32A		Ternalloy 5 (603)	ZG32A					
Ternalloy 7	312	Ternalloy 7	ZG42A		Ternalloy 7 (607)	ZG42A					
SC114A								SC114A	SC114A		

TABLE II. CHEMICAL COMPOSITION LIMITS OF CAST ALUMINUM ALLOYS

Alloy Number	Copper	Iron	Silicon	Magnesium	Manganese	Nickel	Zinc	Titanium	Chromium	Tin	Other Elements		Remainder
											Each	Total	
13	0.6	2.0	11.0-13.0	0.10	0.35	0.50	0.50	-	-	0.15	-	0.25	
A13	0.6	1.3	11.0-13.0	0.10	0.35	0.50	0.50	-	-	0.15	-	0.25	
40E	0.25	0.50	0.30	0.50-0.65	0.10	-	5.0-7.0	0.15-0.25	0.40-0.60	-	0.05	0.20	
43 (1)	0.15	0.80	4.5-6.0	0.05	0.35	-	0.35	0.25	-	-	0.05	0.15	
108	3.5-4.5	1.2	2.5-3.5	0.10	0.50	0.35	1.0	0.25	-	-	-	0.50	
A108	4.0-5.0	1.0	5.0-6.0	0.10	0.50	-	1.0	0.25	-	-	-	0.50	
113	6.0-8.0	1.4	1.0-4.0	0.10	0.60	0.35	2.5	0.25	-	-	-	0.50	
SC114A	3.0-4.5	1.3	10.5-12.0	0.10	0.50	0.50	1.0	-	-	0.35	-	0.50	
122	9.2-10.8	1.5	2.0	0.15-0.35	0.50	0.50	0.8	0.25	-	-	-	0.35	
A132	0.50-1.5	1.3	11.0-13.0	0.70-1.3	0.35	2.0-3.0	0.35	0.25	-	-	0.05	-	
F132	2.0-4.0	1.2	8.5-10.5	0.50-1.5	0.50	0.50	1.0	0.25	-	-	-	0.50	
142	3.5-4.5	1.0	0.70	1.2-1.8	0.35	1.7-2.3	0.35	0.25	0.25	-	0.05	0.15	
195	4.0-5.0	1.0	1.5	0.03	0.35	-	0.35	0.25	-	-	0.05	0.15	
B195	4.0-5.0	1.2	2.0-3.0	0.05	0.35	0.35	0.50	0.25	-	-	-	0.35	
214	0.15	0.50	0.35	3.5-4.5	0.35	-	0.15	0.25	-	-	0.05	0.15	
A214	0.10	0.40	0.30	3.5-4.5	0.30	-	1.4-2.2	0.20	-	-	0.05	0.15	
B214	0.35	0.60(2)	1.4-2.2	3.5-4.5	0.80(2)	-	0.35	0.25	0.25	-	0.05	0.15	
218	0.25	1.8	0.35	7.5-8.5	0.35	0.15	0.15	-	-	0.15	-	0.25	
220	0.25	0.30	0.25	9.5-10.6	0.15	-	0.15	0.25	-	-	0.05	0.15	
319	3.0-4.5	1.20	5.5-7.0	0.50	0.80	0.50	1.0	0.25	-	-	-	0.50	
333	3.0-4.0	1.0	8.0-10.0	0.05-0.50	0.50	0.50	1.0	0.25	-	-	-	0.50	
355	1.0-1.5	0.80(3)	4.5-5.5	0.40-0.60	0.50(3)	-	0.35	0.25	0.25	-	0.05	0.15	
C355	1.0-1.5	0.20	4.5-5.5	0.40-0.60	0.10	-	0.10	0.20	-	-	0.05	0.15	
356	0.25	0.60	6.5-7.5	0.20-0.40	0.35	-	0.35	0.25	-	-	0.05	0.15	
A356	0.20	0.20	6.5-7.5	0.20-0.40	0.10	-	0.10	0.20	-	-	0.05	0.15	
357	0.05	0.15	6.5-7.5	0.45-0.60	0.03	-	0.05	0.20	-	-	0.05	0.15	
360	0.60	2.0	9.0-10.0	0.40-0.60	0.35	0.50	0.50	-	-	0.15	-	0.25	
A360	0.60	1.3	9.0-10.0	0.40-0.60	0.35	0.50	0.50	-	-	0.15	-	0.25	
380	3.0-4.0	1.3	7.5-9.5	0.10	0.50	3.0	0.50	-	-	0.35	-	0.50	
A380	3.0-4.0	2.0	7.5-9.5	0.10	0.50	3.0	0.50	-	-	0.35	-	0.50	
A612	0.35-0.65	0.50	0.15	0.60-0.80	0.05	-	6.0-7.0	0.25	-	-	0.05	0.15	
750	0.70-1.30	0.70	0.70	-	0.10	0.70-1.30	-	0.20	-	5.5-7.0	-	0.30	
A750	0.70-1.30	0.70	2.0-3.0	-	0.10	0.30-0.70	-	0.20	-	5.5-7.0	-	0.30	
B750	1.7-2.3	0.70	0.40	0.60-0.90	0.10	0.90-1.50	-	0.20	-	5.5-7.0	-	0.30	
Almag 35	0.10	0.25(4)	0.20(4)	6.2-7.5	0.10-0.25	-	-	0.10-0.25	-	-	0.05	0.15	
Allcast	3.3-4.3	1.0	5.5-7.0	0.10	0.50	0.35	1.0	0.25	-	-	-	0.50	
Precedent 71A	0.10	0.15	0.15	0.75-0.92	0.10	0.05	6.5-7.5	0.08-0.20	0.06-0.20	0.03	0.03	0.10	
Red X-8	1.0-2.0	1.0	7.0-8.6	0.20-0.60	0.20-0.60	0.25	1.5	0.25	0.35	-	-	0.50	
TI	1.5-2.5	0.80	0.25	0.50-1.10	0.30	-	0.50-1.25	0.10-0.25	0.15-0.30	1.25-2.50	-	-	
Tenzaloy	0.40-1.0	1.3	0.25	0.20-0.50	0.60	0.15	7.0-8.0	0.25	0.35	-	0.10	0.25	
Ternalloy 5	0.20	0.80	0.20	1.4-1.8	0.40-0.60	-	2.7-3.3	0.25	0.20-0.40	-	0.05	0.15	
Ternalloy 7	0.20	0.80	0.20	1.8-2.40	0.40-0.60	-	4.0-4.5	0.25	0.20-0.40	-	0.05	-	

(1) Values given are taken from QQ-A-596 and QQ-A-601. QQ-A-591 differs in that it requires; 0.60 Copper, 2.0 Iron, 0.10 Magnesium, 0.50 Nickel, 0.50 Zinc, NO Titanium and 0.15 Tin.

(2) If Copper plus Iron exceeds 0.50 percent, a Manganese content of at least 0.35 percent is desirable.

(3) If the Iron content exceeds 0.45 percent, it is desirable to have the Manganese content equal to one-half the Iron.

(4) Iron plus Silicon not to exceed 0.40 percent.

TABLE III. CHEMICAL COMPOSITION LIMITS OF WROUGHT ALUMINUM ALLOYS

Designation	Silicon	Iron	Copper	Manganese	Magnesium	Chromium	Nickel	Zinc	Titanium	Others (3) Each	Others (3) Total	Aluminum(4) Min.
EC(6)	-	-	-	-	-	-	-	-	-	-	-	99.45
1100	1.0 Si + Fe		0.20	0.05	-	-	-	0.10	-	0.05(18)	0.15	99.00
1130(7)	0.7 Si + Fe		0.20	-	-	-	-	-	-	0.05	-	99.30
1230(8)	0.7 Si + Fe		0.10	0.05	-	-	-	0.10	-	0.05	-	99.30
1235	0.65 Si + Fe		0.05	-	-	-	-	-	-	0.05	-	99.35
1145(9)	0.55 Si + Fe		0.05	0.05	-	-	-	-	-	0.03	-	99.45
1345	0.30	0.40	0.10	-	-	-	-	-	-	0.05	-	99.45
1060	0.25	0.35	0.05	0.03	0.03	-	-	0.05	0.03	0.03(18)	-	99.60
1175(10)	0.15 Si + Fe		0.10	-	-	-	-	-	-	0.02	-	99.75
2011	0.40	0.7	5.0-6.0	-	-	-	-	0.30	-	0.05(11)	0.15	Remainder
2014	0.50-1.2	1.0	3.9-5.0	0.40-1.2	0.20-0.8	0.10	-	0.25	0.15	0.05(18)	0.15	Remainder
2017	0.8	1.0	3.5-4.5	0.40-1.0	0.20-0.8	0.10	-	0.25	-	0.05	0.15	Remainder
2117	0.8	1.0	2.2-3.0	0.20	0.20-0.50	0.10	-	0.25	-	0.05	0.15	Remainder
2018	0.9	1.0	3.5-4.5	0.20	0.45-0.9	0.10	1.7-2.3	0.25	-	0.05	0.15	Remainder
2218	0.9	1.0	3.5-4.5	0.20	1.2-1.8	0.10	1.7-2.3	0.25	-	0.05	0.15	Remainder
2618	0.25	0.9-1.3	1.9-2.7	-	1.3-1.8	-	0.9-1.2	-	0.04-0.10	0.05	0.15	Remainder
2219	0.20	0.30	5.8-6.8	0.20-0.40	0.02	-	-	0.10	0.02-0.10	0.05(20)	0.15	Remainder
2024	0.50	0.50	3.8-4.9	0.30-0.9	1.2-1.8	0.10	-	0.25	-	0.05	0.15	Remainder
2025	0.50-1.2	1.0	3.9-5.0	0.40-1.2	0.05	0.10	-	0.25	0.15	0.05	0.15	Remainder
3003	0.6	0.7	0.20	1.0-1.5	-	-	-	0.10	-	0.05(18)	0.15	Remainder
3004	0.30	0.7	0.25	1.0-1.5	0.8-1.3	-	-	0.25	-	0.05(18)	0.15	Remainder
4032	11.0-13.5	1.0	0.50-1.3	-	0.8-1.3	0.10	0.50-1.3	0.25	-	0.05	0.15	Remainder
4043	4.5-6.0	0.8	0.30	0.05	0.05	-	-	0.10	0.20	0.05(18)	0.15	Remainddr
4343(12)	6.8-8.2	0.8	0.25	0.10	-	-	-	0.20	-	0.05	0.15	Remainder
5005	0.40	0.7	0.20	0.20	0.50-1.1	0.10	-	0.25	-	0.05	0.15	Remainder
5050	0.40	0.7	0.20	0.10	1.0-1.8	0.10	-	0.25	-	0.05(18)	0.15	Remainder
5052	0.45 Si + Fe		0.10	0.10	2.2-2.8	0.15-0.35	-	0.10	-	0.05(18)	0.15	Remainder
5252	0.08	0.10	0.10	0.10	2.2-2.8	-	-	-	-	0.03	0.10	Remainder
5652	0.40 Si + Fe		0.04	0.01	2.2-2.8	0.15-0.35	-	0.10	-	0.05(18)	0.15	Remainder
5154	0.45 Si + Fe		0.10	0.10	3.1-3.9	0.15-0.35	-	0.20	0.20	0.05(18)	0.15	Remainder
5254	0.45 Si + Fe		0.05	0.01	3.1-3.9	0.15-0.35	-	0.20	0.05	0.05(18)	0.15	Remainder
5454	0.40 Si + Fe		0.10	0.50-1.0	2.4-3.0	0.05-0.20	-	0.25	0.20	0.05	0.15	Remainder
5155	0.30	0.7	0.25	0.20-0.6	3.5-5.0	0.05-0.25	-	0.25	0.15	0.05	0.15	Remainder
5056	0.30	0.40	0.10	0.05-0.20	4.5-5.6	0.05-0.20	-	0.10	-	0.05(18)	0.15	Remainder
5356	0.50 Si + Fe		0.10	0.05-0.20	4.5-5.5	0.05-0.20	-	0.10	0.06-0.20	0.05(18)	0.15	Remainder
5456	0.40 Si + Fe		0.10	0.50-1.0	4.7-5.5	0.05-0.20	-	0.25	0.20	0.05	0.15	Remainder
5257	0.08	0.10	0.10	0.03	0.20-0.6	-	-	0.03	-	0.02	0.05	Remainder
5457	0.08	0.10	0.20	0.15-0.45	0.8-1.2	-	-	-	-	0.03	0.10	Remainder
5557	0.10	0.12	0.15	0.10-0.40	0.40-0.8	-	-	-	-	0.03	0.10	Remainder
5657	0.08	0.10	0.10	0.03	0.6-1.0	-	-	0.03	-	0.02	0.05	Remainder
5083	0.40	0.40	0.10	0.30-1.0	4.0-4.9	0.05-0.25	-	0.25	0.15	0.05	0.15	Remainder
5086	0.40	0.50	0.10	0.20-0.7	3.5-4.5	0.05-0.25	-	0.25	0.15	0.05	0.15	Remainder
6101(13)	0.30-0.7	0.50	0.10	0.03	0.35-0.8	0.03	-	0.10	-	0.03(19)	0.10	Remainder
6201	0.50-0.9	0.50	0.10	0.03	0.6-0.9	0.03	-	0.10	-	0.03(19)	0.10	Remainder
6003(14)	0.35-1.0	0.6	0.10	0.8	0.8-1.5	0.35	-	0.20	0.10	0.05	0.15	Remainder

TABLE III (Continued). CHEMICAL COMPOSITION LIMITS OF WROUGHT ALUMINUM ALLOYS

Designation	Silicon	Iron	Copper	Manganese	Magnesium	Chromium	Nickel	Zinc	Titanium	Others(3)		Aluminum(4) Min.
										Each	Total	
6011	0.6-1.2	1.0	0.40-0.9	0.8	0.6-1.2	0.30	0.20	1.5	0.20	0.05	0.15	Remainder
6151	0.6-1.2	1.0	0.35	0.20	0.45-0.8	0.15-0.35	-	0.25	0.15	0.05	0.15	Remainder
6951	0.20-0.50	0.8	0.15-0.40	0.10	0.40-0.08	-	-	0.20	-	0.05	0.15	Remainder
6053	(17)	0.35	0.10	-	1.1-1.4	0.15-0.35	-	0.10	-	0.05	0.15	Remainder
6253(15)	(17)	0.50	0.10	-	1.0-1.5	0.15-0.35	-	1.6-2.4	-	0.05	0.15	Remainder
6061	0.40-0.8	0.7	0.15-0.40	0.15	0.8-1.2	0.15-0.35	-	0.25	0.15	0.05	0.15	Remainder
6262	0.40-0.8	0.7	0.15-0.40	0.15	0.8-1.2	0.04-0.14	-	0.25	0.15	0.05(5)	0.15	Remainder
6063	0.20-0.6	0.35	0.10	0.10	0.45-0.9	0.10	-	0.10	0.10	0.05	0.15	Remainder
6463	0.20-0.6	0.15	0.20	0.05	0.45-0.9	-	-	-	-	0.05	0.15	Remainder
6066	0.9-1.8	0.50	0.7-1.2	0.6-1.1	0.8-1.4	0.40	-	0.25	0.20	0.05	0.15	Remainder
7001	0.35	0.40	1.6-2.6	0.20	2.6-3.4	0.18-0.40	-	6.8-8.0	0.20	0.05	0.15	Remainder
7039	0.30	0.40	0.10	0.10-0.40	2.3-3.3	0.15-0.25	-	3.5-4.5	0.10	0.05	0.15	Remainder
7072(16)	0.7 Si + Fe		0.10	0.10	0.10	-	-	0.8-1.3	-	0.05	0.15	Remainder
7075	0.50	0.7	1.2-2.0	0.30	2.1-2.9	0.18-0.40	-	5.1-6.1	0.20	0.05	0.15	Remainder
7076	0.40	0.6	0.30-1.0	0.30-0.8	1.2-2.0	-	-	7.0-8.0	0.20	0.05	0.15	Remainder
7277	0.50	0.7	0.8-1.7	-	1.7-2.3	0.18-0.35	-	3.7-4.3	0.10	0.05	0.15	Remainder
7178	0.50	0.7	1.6-2.4	0.30	2.4-3.1	0.18-0.40	-	6.3-7.3	0.20	0.05	0.15	Remainder
7079	0.30	0.40	0.40-0.8	0.10-0.30	2.9-3.7	0.10-0.25	-	3.8-4.8	0.10	0.05	0.15	Remainder
Al Zn Mg. MIL-A-45225B	0.30	0.40	0.10	0.10-0.70	2.0-3.8	0.25	-	3.5-5.0	0.10	0.05	0.15	Remainder + 0.20 Zirconium

NOTES:

(1) Composition in percent maximum unless shown as a range.

(2) For purposes of determining conformance to these limits, an observed value or a calculated value obtained from analysis is rounded off to the nearest unit in the last right-hand place of figures used in expressing the specified limit.

(3) Analysis is regularly made only for the elements for which specific limits are shown, except for unalloyed aluminum. If, however, the presence of other elements is suspected, or indicated in the course of routine analysis, further analysis is made to determine that these other elements are not in excess of the amount specified.

(4) The aluminum content for unalloyed aluminum not made by a refining process is the difference between 100.000 percent and the sum of all other metallic elements present in amounts of 0.010 percent or more each, expressed to the second decimal.

(5) Also contains 0.40-0.7 percent each of lead and bismuth.

(6) Electric conductor.

(7) Reflector sheet.

(8) Cladding on alclad 2024.

(9) Foil.

(10) Cladding on clad 1100 and clad 3003 reflector sheet.

(11) Also contains 0.20-0.6 percent each of lead and bismuth.

(12) Brazing alloy

(13) Bus conductor

(14) Cladding on alclad 2014.

(15) Cladding on alclad 5056.

(16) Cladding on alclad 2219, 3003, 3004, 5050, 5155, 6061, 7075, 7178 and 7079.

(17) Silicon 45 to 65 percent of magnesium content.

(18) Beryllium 0.0008 maximum for welding electrode and filler wire only.

(19) Boron, 0.06 percent maximum.

(20) Vanadium 0.05-0.15; zirconium 0.10-0.25.

TABLE IV. WROUGHT ALLOYS - CROSS REFERENCE (ALLOY TO FORM)

Commercial Alloy Designation	Plate Sheet	Bar, Rod Shapes and Tube Extruded	Bar, Rod, Wire or Special Shapes Rolled, Drawn or Cold Finished	Drawn Seamless Tube	Forgings	Impact Extrusions	Rivet Heading Wire
1100(1)	QQ-A-250/1		QQ-A-225/1	WW-T-700/1		MIL-A-12545	QQ-A-430
2011			QQ-A-225/3				
2014		QQ-A-200/2	QQ-A-225/4		QQ-A-367	MIL-A-12545	
Alclad 2014	QQ-A-250/3						
2017			QQ-A-225/5		QQ-A-367		QQ-A-430
2018					QQ-A-367		
2020	QQ-A-250/16						
2024	QQ-A-250/4	QQ-A-200/3	QQ-A-225/6	WW-T-700/3			QQ-A-430
Alclad 2024	QQ-A-250/5						
2025					QQ-A-367		
2117							QQ-A-430
2218					QQ-A-367		
2219					QQ-A-367		
2618					QQ-A-367		
3003	QQ-A-250/2	QQ-A-200/1	QQ-A-225/2	WW-T-700/2			QQ-A-430
4032					QQ-A-367		
5052	QQ-A-250/8		QQ-A-225/7	WW-T-700/4			QQ-A-430
5056							QQ-A-430
5083	QQ-A-250/6	QQ-A-200/4			QQ-A-367		
5086	QQ-A-250/7	QQ-A-200/5		WW-T-700/5			
5454	QQ-A-250/10	QQ-A-200/6					
5456	QQ-A-250/9	QQ-A-200/7					
6011						MIL-A-12545	
6053							QQ-A-430
6061	QQ-A-250/11	QQ-A-200/8	QQ-A-225/8	WW-T-700/6	QQ-A-367		QQ-A-430
6063		QQ-A-200/9					
6066		QQ-A-200/10			QQ-A-367		
6151					QQ-A-367	MIL-A-12545	
7075	QQ-A-250/12	QQ-A-200/11	QQ-A-225/9		QQ-A-367	MIL-A-12545	QQ-A-430
Alclad 7075	QQ-A-250/13						
Alclad one side 7075	QQ-A-250/18						
7076					QQ-A-367		
7079	QQ-A-250/17	QQ-A-200/12			QQ-A-367		
7178	QQ-A-250/14						
Alclad 7178	QQ-A-250/15						
7277							MIL-R-12221
X8280	MIL-A-11267						

NOTE:

(1) MIL-A-148 — Aluminum Foil

TABLE V. WROUGHT ALLOYS - CROSS REFERENCE (ALLOY TO SPECIFICATION)

Alloy	Government	ASTM	SAE	AMS
1060		B209, B211, B221, B245, B210, B234	AA1060	4000B
1100	QQ-A-225/1	B211	AA1100	4102, 4180
	QQ-A-250/1	B209	AA1100	4001, 4003
	QQ-A-430	B316	AA1100	7220
	QQ-A-00435	B209	AA1100	4001, 4003
	WW-T-700/1	B234, B210	AA1100	4062
	MIL-A-148	-	-	-
	MIL-A-12545	-	-	-
	MIL-R-5674	B316	AA1100	-
2011	QQ-A-225/3	B211	AA2011	-
2014	QQ-A-200/2	B221	AA2014	4153
	QQ-A-225/4	B211	AA2014	4121
	QQ-A-367	B247	AA2014	4134, 4135
	MIL-A-12545	-	-	-
	MIL-T-15089	B221	AA2014	-
	MIL-A-22771	B247	AA2014	-
	MIL-A-25994	B221	AA2014	4028, 4029, 4014
Alclad 2014	QQ-A-250/3	B209	AA2014	-
2017	QQ-A-225/5	B211	AA2017	4110, 4118
	QQ-A-430	B316	AA2017	-
2018	QQ-A-367	B247	AA2018	4146
2020	QQ-A-250/16	-	AA2020	-
	MIL-A-8882	-	-	-
2024	QQ-A-200/3	B221	AA2024	4152, 4164, 4165
	QQ-A-225/6	B211	AA2024	4112, 4119, 4120
	QQ-A-250/4	B209	AA2024	4033, 4035, 4037
	QQ-A-430	B316	AA2024	-
	WW-T-700/3	B210, B234	AA2024	4086, 4087, 4088, 4097, 4098, 4099, 4103, 4104, 4105, 4106
	MIL-R-5674	B316	AA2024	-
	MIL-R-7885	B316	AA2024	-
	MIL-T-15089	B234, B221	AA2024	-
Alclad 2029	QQ-A-250/5	B209	AA2024	4034, 4036, 4040, 4041, 4042, 4060, 4061, 4072, 4073, 4074, 4075
	MIL-S-7811	-	-	-
2025	QQ-A-367	B247	-	4130
2117	QQ-A-430	B316	AA2117	-
	MIL-R-5674	B316	AA2117	-
2218	QQ-A-367	B247	AA2218	4142
2219	MIL-A-8920	B209	AA2219	4031
2618	QQ-A-367	-	-	4132
3003	QQ-A-200/1	B221	AA3003	-
	QQ-A-225/2	B211	AA3003	
	QQ-A-250/2	B209	AA3003	4006, 4008
	QQ-A-430	-	-	-
	QQ-A-00434	-	-	-
	WW-T-700/2	B210, B234	AA3003	4065, 4067
	MIL-R-1150	316	AA3003	-
	MIL-M-17999	-	-	-
	MIL-P-25995	B241, B345	AA3003	-
3004	WW-P-402	-	AA3004	-
4032	QQ-A-36	B247	AA4032	4145
5052	QQ-A-225/7	B211	AA5052	4114
	QQ-A-250/8	B209	AA5052	4015, 4016, 4017
	QQ-A-430	B316	AA5052	-
	QQ-A-00435	-	AA5052	-
	WW-T-700/4	B210, B234, B307	AA5052	4069, 4070, 4071
	MIL-M-17999	-	AA5052	-

TABLE V (Continued). WROUGHT ALLOYS - CROSS REFERENCE (ALLOY TO SPECIFICATION)

Alloy	Government	ASTM	SAE	AMS
5056	QQ-A-430	B316	-	4182
	MIL-R-5674C	B316	-	-
5083	QQ-A-200/4	B221, 345	AA5083	-
	QQ-A-250/6	B209	AA5083	4056, 4057, 4058, 4059
	MIL-A-45225	-	AA5083	-
	MIL-A-46027	-	AA5083	-
	MIL-A-46083	-	AA5083	-
5086	QQ-A-200/5	B221	AA5086	-
	QQ-A-250/7	B209	AA5086	-
	WW-T-700/5	B210	AA5086	-
	MIL-A-21579	-	AA5086	-
5154	MIL-P-25995	B241, B234	AA5154	-
5254	MIL-P-25993	B241	-	-
5454	QQ-A-200/6	B221	AA5454	-
	QQ-A-250/10	B209	AA5454	-
	MIL-P-25995	B241	AA5454	-
5456	QQ-A-250/9	B209	AA5456	-
	MIL-A-25994	-	AA5456	-
	MIL-A-25995	B241, B345	AA5456	-
	MIL-A-45225	B209	AA5456	-
	MIL-A-46027	-	AA5456	-
	MIL-A-46083	-	AA5456	-
6053	WW-P-402	-		-
	QQ-A-430	B316	-	-
	MIL-P-1150	B316	-	-
6061	QQ-A-200/8	B221	AA6061	4150, 4160, 4161
	QQ-A-225/8	B211	AA6061	4115, 4116, 4117
	QQ-A-250/11	B209	AA6061	4025, 4026, 4027, 4053
	QQ-A-367	B247	AA6061	4127, 4146
	WW-P-402	-	AA6061	-
	QQ-A-430	B316	AA6061	-
	WW-T-700/6	B210, B234	AA6061	4079, 4080, 4081, 4082, 4083
	MIL-R-1150	B316	AA6061	-
	MIL-T-7081	B345	AA6061	-
	MIL-T-10794	B345	AA6061	-
	MIL-A-12545	-	AA6061	-
	MIL-F-17132	B209	AA6061	-
	MIL-M-17999	-	AA6061	-
	MIL-A-22771	B247	AA6061	-
	MIL-A-25994	B221	AA6061	-
	MIL-A-25995	B241, B345	AA6061	-
6063	QQ-A-200/9	B221	AA6063	4156
	MIL-P-25995	B241, B345	AA6063	-
6066	QQ-A-200/10	-	-	-
	QQ-A-367	-	-	-
	MIL-A-25994	-	-	-
6070	MIL-A-12545	-	-	-
	MIL-A-46104	-	-	-
6151	QQ-A-367	B247	AA6151	4125
	MIL-A-12545	-	AA6151	-
7001	MIL-A-52242	-	-	-
7075	QQ-A-200/11	B221	AA7075	4154, 4168, 4169, 4170
	QQ-A-225/9	B211	AA7075	4122, 4123
	QQ-A-250/12	B209	AA7075	4038
	QQ-A-367	B247	AA7075	4139, 4141, 4044, 4045
	QQ-A-430	B316	AA7075	-
	MIL-A-18545	-	AA7075	4170
	MIL-A-22771	B247	AA7075	-
Alclad 7075	QQ-A-250/13	B209	AA7075	4039, 4047, 4048, 4049
	MIL-S-7811	-	AA7075	-
Alclad 7075 One Side	QQ-A-250/18	B204	-	4046

TABLE V (Continued). WROUGHT ALLOYS - CROSS REFERENCE (ALLOY TO SPECIFICATION)

Alloy	Government	ASTM	SAE	AMS
7076	QQ-A-367	-	-	4137
7079	QQ-A-200/12	B221	AA7079	4171
	QQ-A-250/17	B209	AA7079	4024
	QQ-A-367	-	AA7079	4138, 4136
	MIL-A-22771	-	AA7079	-
Alclad 7079	MIL-A-8923	B209	AA7079	-
7178	QQ-A-200/13	B221	AA7178	4158
	QQ-A-350/14	B209	AA7178	-
Alclad 7178	QQ-A-250/15	B209	-	4051, 4052
7277	MIL-R-12221	B316	AA7277	-
X8280	MIL-A-11267	-	-	-
Al, Zn, Mg	MIL-A-45225	-	-	-
	MIL-A-46063	-	-	-
	MIL-A-46083	-	-	-

TABLE VI. TYPICAL PHYSICAL PROPERTIES OF ALUMINUM ALLOYS

Alloy			Density, lb per cu in.	Thermal Conductivity,		Electrical Resistivity		Coef. Linear Therm. Expan. 10^{-6}in./in. (5)	Melting Point, °F	
Type	Designation	Temper		CGS (1)	Eng. (2)	% IACS (3)	µΩcm (4)		Solidus	Liquidus
Sand Cast (QQ-A-601)	43	-F	0.097	0.34	990	37	4.660	12.3	1065	1170
	356		0.097					11.9	1035	1135
		-T51		0.40	1160	43	4.010			
		-T6		0.36	1045	39	4.421			
		-T7		0.37	1070	40	4.310			
	195	-T4	0.102	0.33	960	35	4.926	12.7	970	1190
	214		0.096	0.33	960	35	4.926	13.4	1110	1185
	142		0.102					12.6	990	1175
		-T21		0.40	1160	44	3.9			
		-T571		0.32	930	34	5.1			
	122		0.107					12.4	965	1155
		-T61		0.31	900	33	5.225			
	108		0.101					12.4	970	1160
		-F		0.29	840	31	5.562			
	113		0.106					12.3	965	1160
		-F		0.29	840	30	5.747			
	355		0.098					12.4	1015	1170
		-T51		0.40	1160	43	4.010			
		-T6		0.34	990	36	4.789			
	220		0.093					13.7	840	1120
		-T4		0.21	610	21	8.210			
	40E		0.100					13.7	1105	1195
		-T5		0.33	960	35	4.926			
	Allcast		0.101					11.9	960	1120
		-F		0.26	750	27	6.4			
	Red X-8		0.096					11.9	960	1135
		-F		0.24	695	26	6.6			
	Tenzaloy		0.100							
	A612		0.102					13.1	1105	1195
		-F		0.33	960	35	4.9			
	Ternalloy 5								1030	1175
	Ternalloy 7		0.100						1020	1170
	Almag 35		0.095					13.0	1020	1165
		-F				23	7.5			
	B214		0.096					12.7	1090	1170
		-F		0.35	1015	38	4.5			

TABLE VI (Continued). TYPICAL PHYSICAL PROPERTIES OF ALUMINUM ALLOYS

Alloy			Density, lb per cu in.	Thermal Conductivity,		Electrical Resistivity		Coef. Linear Therm. Expan. 10^{-6} in./in. (5)	Melting Point, °F	
Type	Designation	Temper		CGS (1)	Eng. (2)	% IACS (3)	μΩcm (4)		Solidus	Liquidus
Permanent Mold Cast (QQ-A-596)	113		0.106					12.3	965	1160
		-F		0.29	840	30	5.747			
	122		0.107					12.4	965	1155
		-F		0.32	930	34	5.071			
	142		0.102					12.6	990	1175
		-T571		0.32	930	34	5.071			
		-T61		0.31	900	33	5.224			
	B195		0.101					12.4	970	1170
		-T4		0.31	900	33	5.224			
		-T6		0.31	900	33	5.224			
	A108		0.101						970	1135
		-F		0.34	990	37	4.660	11.9		
	355		0.098					12.4	1015	1150
		-T51		0.40	1160	43	4.010			
		-T6		0.34	990	36	4.789			
	43		0.097					12.3	1065	1170
		-F		0.34	990	37	4.660			
	356		0.097					11.9	1035	1135
		-T6		0.36	1045	39	4.421			
		-T7		0.37	1070	40	4.310			
			0.098					11.0	1000	1050
		-T551		0.28	810	29	5.945			
	319		0.101					11.9	960	1120
		-F		0.26	750	27	6.386			
	Tenzaloy 613								1100	1185
	Ternalloy 5 603								1105	1180
	Ternalloy 7 607								1085	1165
	750		0.104					13.0	435	1200
		-T5		0.44	1275	47	3.668			
MIL-A-10935			0.095			23	7.496	13.0	1020	1165
Die Cast (QQ-A-591)	13		0.096	0.29	841	31	5.561	11.5	1065	1080
	A13		0.096							
	43		0.096	0.34	990	37	4.660	12.3	1065	1170
	218		0.093	0.23	670	24	7.184	13.3	995	1150
	B214		0.096	0.35	1015	38	4.537	12.7		
	A380		0.098	0.24	695	25	6.896	11.7	1000	1100
	380		0.098	0.23	670	23	7.496	11.6	1000	1100
	360		0.095	0.27	785	28	6.158	11.6	1035	1105
	A360		0.095	0.29	841	30	5.747	11.8	1035	1105
	384		0.098	0.23	670	23	7.496	11.3	960	1080
Wrought	1060	-O	0.098	0.56	1625	62	2.8	13.1	1195	1215
		-H18		0.53	1540	61	2.8			
	1100		0.098					13.1	1190	1215
		-O		0.53	1540	59	2.9			
		-H18		0.52	1510	57	3.0			
	2011		0.102					12.7	995	1190
		-T3		0.34	990	36	4.8			
	2014		0.101					12.8	950	1180
		-O		0.46	1340	50	3.4			
		-T4		0.29	840	30	5.7			
		-T6		0.37	1070	40	4.3			
	2017		0.099					13.2	950	1200
		-O		0.41	1190	45	3.8			
		-T4		0.29	840	30	5.7			

TABLE VI (Continued). TYPICAL PHYSICAL PROPERTIES OF ALUMINUM ALLOYS

Alloy			Density, lb per cu in.	Thermal Conductivity,		Electrical Resistivity		Coef. Linear Therm. Expan. 10^{-6} in./in. (5)	Melting Point, °F	
Type	Designation	Temper		CGS (1)	Eng. (2)	% IACS (3)	μΩcm (4)		Solidus	Liquidus
Wrought (Cont.)	2018		0.101					12.4	948	1180
		-T61		0.37	1070	40	4.3			
	2024		0.100					12.9	935	1180
		-O		0.45	1310	50	3.4			
		-T4		0.29	840	30	5.7			
	2025		0.101					12.6	970	1185
		-T6		0.37	1070	40	4.3			
	2117		0.099					13.2	950	1200
		-T4		0.37	1070	40	4.3			
	2218		0.102					12.4	940	1175
		-T72		0.37	1070	40	4.3			
	2219		0.103					12.4	1010	1190
		-O		0.41	1190	44	4.3			
		-T31,T37		0.27	780	28	3.4			
		-T62,T81,T87		0.30	870	30	5.1			
	3003		0.099					12.9	1190	1210
		-O		0.46	1340	50	3.4			
		-H12		0.39	1130	42	4.1			
		-H18		0.37	1070	40	4.3			
	3004	All	0.098	0.39	1130	42	4.1	13.3	1165	1205
	4032		0.097					10.8	990	1160
		-T6		0.33	960	35	4.9			
	4043	-O	0.097	0.39	1130	42	4.1	-	1065	1170
	5005	All	0.098	0.48	1390	52	3.3	13.2	1170	1205
	5050	All	0.097	0.46	1340	50	3.4	13.2	1160	1205
	5052		0.097					13.2	1100	1200
		All		0.33	960	35	4.9			
	5056		0.095					13.4	1055	1180
		-O		0.28	810	29	5.9			
		-H38		0.26	750	27	6.4			
	5083	-O	0.096	0.28	810	29	5.9	13.2	1060	1180
	5086	All	0.096	0.30	870	31	5.5	13.2	1084	1184
	5154	All	0.096	0.30	870	32	5.3	13.3	1100	1190
	5252	All	0.097	0.33	960	35	4.9	13.2	1100	1200
	5254	All	0.096	0.30	870	32	5.3	13.3	1100	1190
	5357	All	0.098	0.40	1160	43	3.9	13.2	1165	1210
	5454		0.097					13.1	1115	1195
		-O		0.32	930	34	5.1			
		-H38		0.32	930	34	5.1			
	5456	-O	0.096	0.28	810	29	5.9	13.3	1060	1180
	5557	All	0.098	0.45	1310	49	3.5	13.1	1180	1215
	5657	All	0.098	0.33	960	35	4.9	13.1	1180	1215
	6053		0.097					12.8	1070	1205
		-T6		0.37	1070	40	4.3			
	6061		0.098					13.1	1080	1200
		-O		0.41	1190	45	3.8			
		-T4		0.37	1070	40	4.3			

TABLE VI (Continued). TYPICAL PHYSICAL PROPERTIES OF ALUMINUM ALLOYS

Alloy			Density, lb per cu.in.	Thermal Conductivity,		Electrical Resistivity		Coef. Linear Therm. Expan. 10^{-6}in./in. (5)	Melting Point, °F	
Type	Designation	Temper		CGS (1)	Eng. (2)	% IACS (3)	µΩcm (4)		Solidus	Liquidus
	6063		0.098					13.0	1140	1205
		-T6		0.48	1390	53	3.3			
		-T42		0.46	1340	50	3.4			
	6066		0.098					12.9	1050	1200
		-O		0.37	1070	40	4.3			
		-T6		0.35	1010	37	4.7			
	6101		0.098					13.0	1140	1205
		-T6		0.52	1510	57	3.0			
		-T61		0.53	1540	59	2.9			
		-T62		0.52	1510	58	3.0			
		-T64		0.54	1570	60	2.9			
	6151		0.098					13.0	1140	1205
		-O		0.49	1420	54	3.2			
		-T4		0.39	1130	42	4.1			
		-T6		0.41	1190	45	3.8			
	6262	-T9	0.098	0.41	1190	44	3.9	13.0	1100	1205
	7001	-T6	0.102	0.29	840	31	5.5	13.0	890	1160
	7072	-O	0.098	0.53	1540	59	2.9	13.1	1195	1215
	7075		0.101					13.1	890	1180
		-T6		0.29	840	30	5.7			
	7178	-T6	0.102	0.30	870	31	5.6	13.0	890	1165
	7079		0.099					13.1	900	1180
		-T6		0.29	840	31	5.5			

NOTES :

(1) CGS - cal/cm/cm^2/°C/sec at 77°F

(2) English units - btu/in./ft^2/°F/hour at 77°F

(3) IACS - International Annealed Copper Standard - equal volume

(4) uocm - microhm - centimeter at 68°F

(5) Average Change in length per °F from 68°F to 212°F

TABLE VII. EFFECT OF TEMPERATURE ON THERMAL COEFFICIENT OF LINEAR EXPANSION

Alloy		Average Coefficient, 10^{-6} in./in./°F			
		Temperature Range, °F			
Type	Designation	-58 to +68	68 to 212	68 to 392	68 to 572
Sand Cast (QQ-A-601)	43	11.4	12.3	12.9	13.4
	356	11.0	11.9	12.5	12.9
	195	11.7	12.7	13.2	13.8
	214	12.3	13.4	13.9	14.5
	142	11.6	12.6	13.1	13.6
	122	11.5	12.4	12.9	13.4
	108	11.5	12.4	13.0	13.4
	113	11.3	12.3	12.9	13.3
	355	11.5	12.4	13.0	13.7
	220	12.6	13.7	14.2	14.8
	40E		13.7		
	Allcast	11.0	11.9	12.4	12.7
	Red X-8		11.9		
	A612	12.1	13.1	13.6	14.2
	Ternalloy 7		13.3		14.4
	Almag 35	12.0	13.0	14.2	14.8
	B214	11.8	12.7	13.3	13.8
Permanent Mold Cast (QQ-A-596)	113	11.3	12.3	12.9	13.3
	122	11.5	12.4	12.9	13.4
	142	11.6	12.6	13.1	13.6
	B195	11.4	12.4	13.0	13.4
	A108	11.1	11.9	12.5	12.9
	355	11.5	12.4	13.0	13.7
	43	11.4	12.3	12.9	13.4
	356	11.0	11.9	12.5	12.9
	A132	10.3	11.0	11.5	12.0
	319	11.0	11.9	12.4	12.7
	750	12.0	13.0	13.5	
Die Cast (QQ-A-591)	13	10.7	11.5	12.0	12.6
	43	11.4	12.3	12.9	13.4
	218	12.4	13.3	14.0	14.3
	B214	11.8	12.7	13.3	13.8
	A380	10.8	11.7	12.2	12.6
	380	10.7	11.6	12.1	12.5
	360	10.8	11.6	12.2	12.7
	A360	10.9	11.8	12.4	12.8
	384	10.5	11.3	11.8	12.3
Wrought	1100	12.2	13.1	13.7	14.2
	2011	11.9	12.8	13.4	13.9
	2014	12.0	12.3	13.1	13.6
	2017	12.1	12.7	13.3	13.9
	2018	11.7	12.4	12.9	13.4
	2024	11.9	12.6	13.2	13.7
	2025	12.1	12.6	13.1	13.6
	2117	12.1	13.0	13.6	14.0
	2218	11.7	12.4	13.0	13.5
	3003	12.0	12.9	13.5	13.9
	4032	10.3	10.8	11.3	11.7
	5052	12.3	13.2	13.8	14.3
	5056	12.5	13.4	14.0	14.5
	6053	12.1	12.8	13.4	14.0
	6061	12.1	13.0	13.5	14.1
	6063	12.1	13.0	13.6	14.2
	6151	12.1	12.8	13.4	13.9
	7075	12.1	12.9	13.5	14.4

TABLE VIII. TYPICAL EFFECT OF TEMPERATURE ON ULTIMATE TENSILE STRENGTH

Alloy			Percent of Ultimate Strength at 75°F									
Type	Designation	Temper	-320F	-110F	-20F	+75F	+212F	+300F	+400F	+500F	+600F	+700F
Sand Cast (QQ-A-601)	356	-T51	126	108	104	100	92	83	48	30	16	8
		-T6					90	70	36	23	12	6
	195	-T4					95	86	46	28	12	8
		-T6					94	78	42	25	11	7
	214	-F					94	88	72	52	36	20
	142	-T21						85	67	44	28	
		-T571					100	94	81	41	25	16
	122	-T61					90	80	55	37	18	11
	355	-T51	118	105	101		100	86	50	34	21	12
		-T6					100	94	49	27	17	10
		-T7	116	106	103		97	55	34	20	12	8
		-T71					97	86	49	27	17	10
Permanent Mold Cast (QQ-A-596)	122	-T551					92	81	68	49	24	14
	142	-T571					99	92	70	33	20	12
	B195	-T6					88	72	42	18	9	6
	355	-T51					93	77	50	32	20	12
		-T6					95	76	30	17	10	7
		-T71					92	80	53	26	17	10
	356	-T6					79	55	32	20	10	7
		-T7	133	107	103		84	66	38	22	12	8
	A132	-T551					97	86	72	50	28	14
Die Cast (QQ-A-591)	13						86	74	56	30	16	10
	43						85	67	48	27	15	11
	218						89	71	47	29	19	11
	360						94	74	47	26	15	10
	A360						93	74	46	24	14	9
	380						94	71	50	27	15	8
	A380						94	70	49	26	13	8
	384						98	81	55	30	15	10
Wrought	1100	-O	189	115	104		77	65	46	31	19	16
		-H18	144	109	104		92	75	25	17	10	8
	3003	-O	206	122	107		81	69	53	38	25	19
		-H14	164	109	103		95	82	64	34	18	14
		-H18	143	110	104		90	79	48	26	14	10
	5052	-O	158	106	101		100	86	64	43	27	18
		-H34	144	106	101		100	82	60	32	20	13
		-H38	141	105	101		98	81	55	29	18	12
	5083	-O	141	105	101		100	68	52	36	25	14

TABLE VIII (Continued). TYPICAL EFFECT OF TEMPERATURE ON ULTIMATE TENSILE STRENGTH

Alloy			Percent of Ultimate Strength at 75°F									
Type	Designation	Temper	-320F	-110F	-20F	+75F	+212F	+300F	+400F	+500F	+600F	+700F
Wrought (Cont.)	2011	-T3					85	51	29	12	6	4
	2014	-T6	120	104	103		89	57	23	13	9	6
	2017	-T4	128	104	103		90	64	36	19	10	7
	2018	-T61	118	104	103		92	74	31	16	9	7
	2024	-T3					94	79	41	17	11	8
		-T4	127	106	104		94	66	40	18	12	8
		-T81					94	79	41	17	11	8
		-T86					93	73	27	16	11	7
	2117	-T4					84	70	37	17	10	7
	2218	-T61					95	70	37	17	9	7
	4032	-T6	119	105	102		91	67	24	14	9	6
	6053	-T6					86	68	35	15	11	8
	6061	-T6	133	110	105		93	76	42	17	10	7
	6063	-T42	153	120	108		100	95	41	20	14	11
		-T5	138	108	105		89	74	33	17	11	9
		-T6	135	109	103		89	60	26	13	9	7
	6151	-T6	125	107	104		88	56	25	14	10	8
	7075	-T6	123	105	103		80	30	17	13	10	8
	7079	-T6					86	44	20	14	10	6

TABLE IX. TYPICAL EFFECT OF TEMPERATURE ON YIELD STRENGTH

Alloy			Percent of Yield Strength at 75°F									
Type	Designation	Temper	-320F	-110F	-20F	+75F	+212F	+300F	+400F	+500F	+600F	+700F
Sand Cast (QQ-A-601)	356	-T51	108	102	100	100	98	84	48	25	12	8
		-T6					96	79	37	21	12	8
	195	-T4					95	86	46	28	12	8
		-T6					96	83	37	25	12	6
	214	-F					100	100	100	67	33	17
	142	-T21						83	61	28	17	
		-T571					100	93	70	27	13	10
	122	-T61					95	88	42	23	12	6
	355	-T51	122	109	104		96	83	43	22	13	9
		-T6					100	100	38	20	12	8
		-T7	107	100	100		93	81	26	14	8	6
		-T71					96	90	45	17	10	7
Permanent Mold Cast (QQ-A-596)	122	-T551					93	78	57	34	15	7
	142	-T571					99	97	65	24	12	9
	B195	-T6					88	87	42	15	10	6
	355	-T51					100	83	42	21	12	8
		-T6					100	93	35	19	11	7
		-T71					94	84	42	16	10	6
	356	-T6					93	63	31	18	11	7
		-T7	119	107	103		96	71	35	19	12	8
	A132	-T551					89	78	54	36	14	11
Die Cast (QQ-A-591)	13						95	90	71	43	21	12
	43						100	94	75	38	22	16
	218						92	78	56	33	17	9
	360						100	96	56	30	18	12
	A360						100	96	54	27	17	10
	380						100	92	67	33	17	10
	A380						100	91	65	30	17	11
	384						100	96	72	36	16	10
Wrought	1100	-O	123	107	103		100	90	70	40	30	20
		-H18					82	64	18	9	7	4
	3003	-O	145	116	105		92	83	75	58	42	33
		-H14	120	104	101		90	76	43	19	12	10
		-H18	122	107	103		78	59	33	15	9	7

TABLE IX (Continued). TYPICAL EFFECT OF TEMPERATURE ON YIELD STRENGTH

Alloy			Percent of Yield Strength at 75°F									
Type	Designation	Temper	-320F	-110F	-20F	+75F	+212F	+300F	+400F	+500F	+600F	+700F
Wrought (Cont.)	5052	-O	121	100	100		100	100	85	62	38	23
		-H34	118	103	100		97	87	48	26	16	10
		-H38	116	101	100		100	78	40	22	14	8
	5083	-O					100	82	77	50	34	20
	2011	-T3					79	44	26	9	5	4
	2014	-T6	113	103	102		93	58	22	12	8	6
	2017	-T4	132	104	101		92	75	42	24	12	9
	2018	-T61	110	103	101		94	87	28	14	6	5
	2024	-T3	133	106	101		96	92	44	18	12	8
		-T4					96	77	43	19	13	8
		-T81					95	78	34	14	9	6
		-T86					94	73	23	13	9	6
	2117	-T4					88	71	50	23	15	8
	2218	-T61					95	80	36	14	7	6
	4032	-T6	103	100	100		96	72	20	12	6	4
	6053	-T6					88	75	38	12	8	6
	6061	-T6	116	105	103		95	78	38	12	6	5
	6063	-T42	126	119	110		108	115	50	26	19	16
		-T5	116	105	104		95	86	31	17	12	10
		-T6	116	106	102		90	64	21	11	8	6
	6151	-T6	115	106	104		91	58	22	13	10	8
	7075	-T6	124	105	102		85	29	16	12	9	6
	7079	-T6					88	44	19	12	9	6

TABLE X. TYPICAL EFFECT OF TEMPERATURE ON ELONGATION

Alloy			Percent Elongation									
Type	Designation	Temper	-320F	-110F	-20F	+75F	+212F	+300F	+400F	+500F	+600F	+700F
Sand Cast (QQ-A-601)	356	-T51										
		-T6				3.5	4	5	15	30	60	75
	195	-T4				8.5		9	20	25	80	
		-T6				5	5	5	15	25	75	100
	214	-F				9	9	7	9	12	17	35
	142	-T21				1	1	1	3	8	20	
		-T571				0.5	0.5	0.5	1	8	20	40
	122	-T61				0.5	0.5	1	2	6	14	30
	355	-T51	1.2	1.5	1.5	1.5	2	3	8	16	36	50
		-T6				3	2	1.5	8	16	36	50
		-T7										
		-T71				1.5	2	3	8	16	36	50
Permanent Mold Cast (QQ-A-596)	122	-T551				0.5	0.5	0.5	1	3	10	25
	142	-T571				1	1	1	2	15	35	60
	B195	-T6				5	5	5	15	25	75	100
	355	-T51				2	3	4	19	33	38	60
		-T6				4	5	10	20	40	50	60
		-T71				3	4	8	20	40	50	60
	356	-T6				5	6	10	30	55	70	80
		-T7				6	10	20	40	55	70	80
	A132	-T551				0.5	1	1	2	5	10	45
Die Cast (QQ-A-591)	13					2.5	5	8	15	30	35	40
	43					9	9	10	25	30	35	35
	218					8	8	25	40	45	45	45
	360					3	2	4	8	20	35	40
	A360					5	3	5	14	30	45	45
	380					3	4	5	8	20	30	35
	A380					4	5	10	15	30	45	45
	384					1	1	2	6	25	45	45
Wrought	1100	-O				45	45	55	65	75	80	85
		-H18				15	15	20	65	75	80	85
	3003	-O	49	45	44	43	40	47	60	65	70	70
		-H14	32	18	16	16	16	16	20	60	70	70
		-H18				10	10	11	18	60	70	70

TABLE X (Continued). TYPICAL EFFECT OF TEMPERATURE ON ELONGATION

Alloy			Percent Elongation									
Type	Designation	Temper	-320F	-110F	-20F	+75F	+212F	+300F	+400F	+500F	+600F	+700F
Wrought (Cont.)	5052	-O				30	35	45	65	80	100	120
		-H32	30	21	18	14	16	25	40	80	100	120
		-H38				8	9	20	40	80	100	120
	5083	-O				25	35	45	60	70	95	120
	2011	-T3				15	16	25	35	45	90	125
	2014	-T6				13	14	15	35	45	65	70
	2017	-T4				22	18	16	28	45	95	100
	2018	-T61				12	12	12	25	40	60	100
	2024	-T3				17	16	11	23	55	75	100
		-T4				19	19	17	27	55	75	100
		-T81				7	8	11	23	55	75	100
		-T86				5	6	11	28	55	75	100
	2117	-T4				27	16	20	35	55	80	110
	2218	-T61				13	14	17	30	70	85	100
	4032	-T6				9	9	9	30	50	70	90
	6053	-T6				13	13	13	25	70	80	90
	6061	-T6	25	20	19	17	18	20	28	60	85	90
	6063	-T42				33	18	20	40	75	80	105
		-T5				22	18	20	40	75	80	105
		-T6				18	15	20	40	75	80	105
	6151	-T6				17	19	22	40	50	50	50
	7075	-T6				11	15	30	60	65	80	65
	7079	-T6				13	18	37	60	100	175	175

TABLE XI. TYPICAL MODULII OF ELASTICITY (TENSILE) AT 75° F

Designation		Modulus 10^6 psi
Type	Alloy	
Sand Cast (QQ-A-601	43	10.3
	356	10.5
	195	10.0
	214	10.3
	142	10.3
	122	10.7
	355	10.2
	220	9.5
	40E	10.3
	Allcast	10.7
	A612	9.7
	Ternalloy 5	10.3
	Ternalloy 7	10.3
Permanent Mold Cast (QQ-A-596)	All	10.3
Die Cast (QQ-A-591)	All	10.3
Wrought	1100	10.0
	2011	10.2
	2014	10.6
	Alclad 2014	10.5

Designation		Modulus 10^6 psi
Type	Alloy	
Wrought	2017	10.5
	2018	10.8
	2024	10.6
	Alclad 2024	10.6
	2025	10.4
	2117	10.3
	2218	10.8
	3003	10.0
	4032	10.3
	5052	10.2
	5056	10.3
	5083	10.3
	6053	10.0
	6061	10.0
	6063	10.0
	6066	10.0
	6151	10.2
	7075	10.4
	7079	10.4

NOTE :
(1) For temperatures other than 75° F refer to the following table:

MULTIPLIERS FOR
OTHER TEMPERATURES

Temperature °F	Percent of Modulus at 75°F
-320	112
-112	107
-18	102
+75	100
+212	98
+300	95
+400	90
+500	80

TABLE XII. TYPICAL FATIGUE STRENGTHS – WROUGHT PRODUCTS

Designation		Repeated Flexure Fatigue Strength⁽¹⁾, ksi				
		Million Cycles to Failure				
Alloy	Temper	0.1	1.0	10	100	500
1100	-O		6.5	5.5	5	5
	-H16	14	11.5	10	9	8
3003	-O	10.5	9	8	7.5	7
	-H14	17	12	10	9	9
	-H18	19	14	11.5	10.5	10
5052	-O	23.5	19.5	17.5	16.5	16
	-H34	26	20.5	19	18	18
	-H38	29.5	24	22.5	21	20
2011	-T3	35	26.5	22.5	19.5	18
2014	-T6	39	30	24	19	18
2017	-T4	42	34	27	22	20
2018	-T61	42	29	23	19.5	17
2024	-T4	43	31	24	21	20
4032	-T6	37	30	23.5	18	16
6061	-T6	31	23	17	14.5	13.5
6063	-T42	19.5	16	13.5	11	9.5
	-T5	20.5	15.5	12	10.5	9.5
	-T6	23.5	16.5	13.5	11	9.5
6151	-T6	30	22	17	13	12
7075	-T6	40	29	24	22	22

Designation		Fatigue Strength⁽¹⁾, ksi			
Alloy	Temper	75°F	300°F	400°F	500°F
3003	-H18	10	7.5	5	3.5
2014	-T6	18	12	8	5
2024	-T4	20	14	9	6
5052	-H36	18.5	12.5	9.5	6
6061	-T6	16	11	7.5	4.5
7075	-T6	22	12	8.5	7

NOTE :

(1) Reversed Flexural Stress (R. R. Moore Rotating Beam Test)

TABLE XIII. TYPICAL MECHANICAL PROPERTIES OF WROUGHT ALLOYS

Alloy	Temper	Ult. TS ksi	Ten. YS ksi	Ult. EL %		Hard-ness BHN	Shear Str ksi	Fatigue End. Limit ksi
				1/16-in. thick	1/2-in. dia.			
1100	-O	13	5	35	45	23	9	5
	-H12	16	15	12	25	28	10	6
	-H14	18	17	9	20	32	11	7
	-H16	21	20	6	17	38	12	9
	-H18	24	22	5	15	44	13	9
2011	-T3	55	43	-	15	95	32	18
	-T8	59	45	-	12	100	35	18
2014	-O	27	14	-	18	45	18	13
	-T4, -T451	62	42	-	20	105	38	20
	-T6, -T651	70	60	-	13	135	42	18
Clad 2014	-O	25	10	21	-	-	18	-
	-T3	63	40	20	-	-	37	-
	-T4, -T451	61	37	22	-	-	37	-
	-T6, -T651	68	60	10	-	-	41	-
2017	-O	26	10	-	22	45	18	13
	-T4, -T451	62	40	-	22	105	38	18
2018	-T61	61	46	-	12	120	39	17
2020	-O	35	-	10	-	-	-	-
	-T6	75	70	2	-	-	-	-
	-T651	67	59	6	-	-	-	-
	-F	No Requirements						
2024	-O	27	11	20	22	47	18	13
	-T3	70	50	18	-	120	41	20
	-T4, -T351	68	47	20	19	120	41	20
	-T36	72	57	13	-	130	42	18
Clad 2024	-O	26	11	20	-	-	18	-
	-T3	65	45	18	-	-	40	-
	-T4, -T351	64	42	19	-	-	40	-
	-T36	67	53	11	-	-	41	-
	-T81, -T851	65	60	6	-	-	40	-
	-T86	70	66	6	-	-	42	-
2025	-T6	58	37	-	19	110	35	18
2117	-T4	43	24	-	27	70	28	14
2218	-T72	48	37	-	11	95	30	-
2219	-T6	58	38	8	-	-	-	-

TABLE XIII (Continued). TYPICAL MECHANICAL PROPERTIES OF WROUGHT ALLOYS

Alloy	Temper	Ult. TS ksi	Ten. YS ksi	Ult. EL %		Hard-ness BHN	Shear Str ksi	Fatigue End. Limit ksi
				1/16-in. thick	1/2-in. dia.			
2616	-T61	58	48	4	-	-	-	-
3003	-O	16	6	30	40	28	11	7
	-H12	19	18	10	20	35	12	8
	-H14	22	21	8	16	40	14	9
	-H16	26	25	5	14	47	15	10
	-H18	29	27	4	10	55	16	10
4032	-T6	55	46	-	9	120	38	16
5052	-O	28	13	25	30	47	18	16
	-H32	33	28	12	18	60	20	17
	-H34	38	31	10	14	68	21	18
	-H36	40	35	8	10	73	23	19
	-H38	42	37	7	8	77	24	20
5056	-O	42	22	-	35	65	26	20
	-H18	63	59	-	10	105	34	22
	-H38	60	50	-	15	100	32	22
5083	-O	42	21	22	-	-	25	-
	-H113	46	33	16	-	-	-	23
5086	-O	35	14	14	-	-	-	-
	-H111	36	21	12	-	-	-	-
5454	-O	41	19	14	-	-	-	-
	-H111	42	26	12	-	-	-	-
	-H112	41	19	12	-	-	-	-
5456	-O	45	23	24	-	-	-	-
	-H112	45	24	22	-	-	-	-
	-H311	47	33	18	-	-	-	-
6011	-F	35	32	-	3	70	-	-
	-T6	50	42	-	7	95	-	-
6053	-O	16	8	-	35	26	11	8
	-T6	37	32	-	13	80	23	13
6061	-O	18	8	25	30	30	12	9
6063	-O	13	7	-	-	25	10	8
	-T4	25	13	22	-	-	-	-
	-T5	27	21	12	-	60	17	10
	-T6	35	31	12	-	73	22	10
	-T42	22	13	20	-	42	14	9
	-T83	37	35	9	-	82	22	-
	-T831	30	27	10	-	70	18	-
	-T832	42	39	12	-	95	27	-

TABLE XIII (Continued). TYPICAL MECHANICAL PROPERTIES OF WROUGHT ALLOYS

Alloy	Temper	Ult. TS ksi	Ten. YS ksi	Ult. EL %		Hard-ness BHN	Shear Str ksi	Fatigue End. Limit ksi
				1/16-in. thick	1/2-in. dia.			
6066	-O	22	12	-	18	43	14	-
	-T4, -T451	52	30	-	18	90	30	-
	-T6, -T651	57	52	-	12	120	34	16
6151	-T6	48	43	-	17	100	32	11
7075	-O	40(1)	24(1)	-	10	-	-	-
	-T6 -T6510 -T6511	78	70	7	-	-	-	-
		81	73	-	7	-	-	-
Alclad 7075	-O	36(1)	20(1)	10	-	-	-	-
		40(1)	-	-	10	-	-	-
	-T6	72	62	8	-	-	-	-
		77	66	-	6	-	-	-
	-T651	77	66	-	6	-	-	-
	-F	No Requirements						
Alclad one side 7075	-O	22(1)	21(1)	10	-	-	-	-
		40(1)	-	-	10	-	-	-
	-T6	74	64	8	-	-	-	-
		77	66	-	6	-	-	-
	-T651	77	66	-	6	-	-	-
	-F	No Requirements						
7076	-T61	70	60	-	-	-	-	-
7079	-T6, -T651	78	68	-	14	145	45	23
7178	-O	40(1)	21(1)	10	-	-	-	-
		40(1)	-	-	10	-	-	-
	-T6	84	73	8	-	-	-	-
		84	73	-	6	-	-	-
	-T651	84	73	-	6	-	-	-
	-F	No Requirements						
Alclad 7178	-O	36(1)	20(1)	10	-	-	-	-
		40(1)	-	-	10	-	-	-
	-T6	78	68	8	-	-	-	-
		84	73	-	6	-	-	-
	-T651	84	73	-	6	-	-	-
	-F	No Requirements						
7277	-T4	60	-	-	-	-	35	-
X8280	-H12	18	15	4	-	-	-	-

NOTE : (1) Specification maximum requirement

TABLE XIV. TYPICAL MECHANICAL PROPERTIES OF SAND CAST ALLOYS

QQ-A-601		Ult. TS ksi	Ten. YS ksi	Ult. El. %	Hardness BHN	Comp. YS ksi	Shear Str ksi	Fatigue End. Limit ksi
Alloy	Temper							
43	-F	19	8	8	40	9	14	8
356	-T4	25(1)	16	3(1)	65			
	-T51	25	20	2	60	21	20	8
	-T6	33	24	3.5	70	25	26	8.5
195	-T4	32	16	8.5	60	17	26	7
	-T6	36	24	5	75	25	30	7.5
	-T62	41	32	2	90	34	33	8
	-T7	29(1)	19	3(1)	70			
214	-F	25	12	9	50	12	20	7
142	-T21	27	18	1	70	18	21	8
	-T571	32	30	0.5	85	34	26	11
122	-T2	27	20	1	80			
	-T61	41	40	(2)	115	43	32	8.5
108	-F	21	14	2.5	55	15	17	11
	-T55	21(1)			75			
113	-F	24	15	1.5	70	16	20	9
355	-T51	28	23	1.5	65	24	22	8
	-T6	35	25	3	80	26	28	9
	-T7	38	36	0.5	85	38	28	10
	-T71	35	29	1.5	75	30	26	10
220	-T4	48	26	16	75	27	34	8
40E	-T5	35	26	5	75	14	28	9
Allcast	-F	27	18	2	70	19	22	10
	-T6	36	24	2	80	25	29	11
Red X-8	-F	30	21	1.5	60			
	-T6	39	30	1.5	85			
T1	-T5	30(1)	22	4(1)	65			
Tenzaloy	-T5	34	25	4.5	75			
A612	-T5	35	25	5	75	25	26	8
Ternalloy 5	-T5	30(1)	19	5(1)	65			
Ternalloy 7	-T5	37	27	1.5	85			
Almag 35	-F	40	21	13	70			10
	-T4	35(1)	18(1)	9(1)				
B214	-F	20	13	2	50	14	17	8.5

NOTES :

(1) Specification minimum requirement

(2) Less than 0.5 percent

TABLE XV. TYPICAL MECHANICAL PROPERTIES OF PERMANENT AND SEMI-PERMANENT MOLD CASTING ALLOYS

QQ-A-596		Ult. TS ksi	Ten. YS ksi	Ult. EL %	Hardness BHN	Comp. YS ksi	Shear Str ksi	Fatigue End Limit ksi
Class	Temper							
113	-F	28	19	2	70	20	22	9.5
122	-T551	37	35	0.5	115	40	30	8.5
	-T65	48	36	0.5	140	36	36	9
142	-T571	40	34	1	105	34	30	10.5
	-T61	47	42	0.5	110	44	35	9.5
B195	-T4	37	19	9	75	20	30	9.5
	-T6	40	26	5	90	26	32	10
	-T7	39	20	4.5	80	20	30	9
A108	-F	28	16	2	70	17	22	13
355	-T51	30	24	2	75	24	24	
	-T6	42	27	4	90	27	34	10
	-T62	45	40	1.5	105	40	36	10
	-T71	36	31	3	85	31	27	10
43	-F	23	9	10	45	9	16	8
356	-T6	38	27	5	80	27	30	13
	-T7	32	24	6	70	24	25	11
A132	-T551	36	28	0.5	105	28	28	13.5
	-T65	47	43	0.5	125	43	36	
319	-F	34	19	2.5	85	19	24	10
	-T6	40	27	3	95			
Tenzaloy (613)	-T5	33	22	4				
Ternalloy 5 (603)	-T5	37	21	10	70			
Ternalloy 7 (607)	-T5	47	29	4	95			
	-T7	53	43	3	95			
750	-T5	23	10	12	45	11	15	9
A214	-F	22		2.5				
333	-F	28		-				
	-T5	30		-				
	-T6	35		-				
	-T7	31		-				
357	-T6	45		3.0				
A750	-T5	18		6.0				
B750	-T5	27		3.0				
F132	-T5	31		-				
C355	-T61	40		3.0				
A356	-T61	37		5.0				

TABLE XVI. TYPICAL MECHANICAL PROPERTIES OF DIE CASTING ALLOYS

QQ-A-591 Alloy No.	Tensile Strength ksi	Yield strength at 0.2% offset ksi	Elongation in 2 inches %	Shear Str ksi	Fatigue End. Limit ksi
13	43	21	2.5	25	19
A13	42	19	3.5	25	19
43	33	14	9.0	19	17
218	45	27	8.0	29	20
A360	46	24	3.5	26	18
360	44	25	2.5	28	20
A380	47	23	3.5	27	20
380	46	23	2.5	28	20
SC114A	48	24	2.5	-	-

TABLE XVII. APPROXIMATE RADII FOR 90-DEGREE COLD BEND OF WROUGHT ALLOYS

Designation		Radius Required (in terms of sheet thickness, t)							
Alloy	Temper	t=1/64	t=1/32	t=1/16	t=1/8	t=3/16	t=1/4	t=3/8	t=1/2
1100	-O	0	0	0	0	0	0	0	1 - 2
	-H14	0	0	0	0	0 - 1	0 - 1	0 - 1	2 - 3
	-H18	0 - 1	0.5 - 1.5	1 - 2	1.5 - 3	2 - 4	2 - 4	3 - 5	3 - 6
3003	-O	0	0	0	0	0	0	0	1 - 2
	-H14	0	0	0	0 - 1	0 - 1	1 - 1.5	1 - 2.5	1.5 - 3
	-H18	0.5 - 1.5	1 - 2	1.5 - 3	2 - 4	3 - 5	4 - 6	4 - 7	5 - 8
5052	-O	0	0	0	0	0 - 1	0 - 1	0.5 - 1.5	1 - 2
	-H34	0	0	0 - 1	0.5 - 1.5	1 - 2	1.5 - 3	2 - 3	2.5 - 3.5
	-H38	0.5 - 1.5	1 - 2	1.5 - 3	2 - 4	3 - 5	4 - 6	4 - 7	5 - 8
5083	-O	-	-	0 - 0.5	0 - 1	0 - 1	0.5 - 1.5	1.5 - 2	1.5 - 2.5
2014 Clad	-O	0	0	0	0	0 - 1	0 - 1	1.5 - 3	3 - 5
	-T3	1 - 2	1.5 - 3	2 - 4	3 - 5	4 - 6	4 - 6	5 - 7	5.5 - 8
	-T4	1 - 2	1.5 - 3	2 - 4	3 - 5	4 - 6	4 - 6	5 - 7	5.5 - 8
	-T6	2 - 4	3 - 5	3 - 5	4 - 6	5 - 7	6 - 10	7 - 10	8 - 11
2024	-O	0	0	0	0	0 - 1	0 - 1	1.5 - 3	3 - 5
	-T3	1.5 - 3	2 - 4	3 - 5	4 - 6	4 - 6	5 - 7	6 - 8	6 - 9
	-T4	1.5 - 3	2 - 4	3 - 5	4 - 6	4 - 6	5 - 7	6 - 8	6 - 9
	-T81	3.5 - 5	4.5 - 6	5 - 7	6.5 - 8	7 - 9	8 - 10	9 - 11	9 - 12
5456	-O	-	-	-	0 - 1	0.5 - 1	0.5 - 1	0.5 - 1.5	0.5 - 2
	-H321	-	-	-	2 - 3	2 - 3	3 - 4	3 - 4	3 - 4
6061	-O	0	0	0	0	0 - 1	0 - 1	0.5 - 2	1 - 2.5
	-T4	0 - 1	0 - 1	0.5 - 1.5	1 - 2	1.5 - 3	2 - 4	2.5 - 4	3 - 5
	-T6	0 - 1	0.5 - 1.5	1 - 2	1.5 - 3	2 - 4	3 - 4	3.5 - 5.5	4 - 6
7075	-O	0	0	0 - 1	0.5 - 1.5	1 - 2	1.5 - 3	2.5 - 4	3 - 5
	-T6	2 - 4	3 - 5	4 - 6	5 - 7	5 - 7	6 - 10	7 - 11	7 - 12

TABLE XVIII. FORGING ALLOYS - RELATIVE RATING BY CHARACTERISTICS

Alloy	Strength	Cold Workability	Corrosion Resist.	Machinability	Electric Conductance	Hardness	Forgability
1100	4 - 3	1 - 3	1	4 - 3	2	4 - 3	1
2011	2	3 - 4	3 - 4	1	3	2	-
2014	1	3 - 4	3 - 4	2	3	1 - 2	3
2014-Clad	1	3 - 4	1	2	3	-	-
2017	1	3	3 - 4	2	4	2	-
2018	1	-	3	2	3	2	3
2024	1	3 - 4	3 - 4	2	4	1	-
2024-Clad	1	4	1	2	4	-	-
2117	3	2	3	3	-	-	-
2218	2	-	3	2	3	2	4
3003	4 - 3	1 - 3	1	4 - 3	3	4 - 3	1
4032	2	-	3	3	4	2	3
5052	3	1 - 3	1	4 - 3	4	3 - 2	-
5056	2	1 - 3	1 - 3	4 - 3	4	-	-
5083	2	3	1	4 - 3	4	2	-
5456	2	3	1 - 2	4 - 3	4	2	-
6061	3 - 2	3 - 4	1	3	3	3 - 2	-
6063	3 - 2	2 - 3	1	3	2	3 - 2	-
6151	2	-	2	3	3	2	1
7075	1	4	3	2	4	1	4
7075-Clad	1	4	1	2	4	-	-
7079	1	4	3	2	4	1	3

NOTES:

(1) — Relative ratings are in decreasing order of merit.

(2) — First number in numbered pairs is rating for softest temper; second number is for hardest.

TABLE XIX. TYPICAL TENSILE STRENGTHS OF GAS-WELDED JOINTS

Alloy			Thickness, inch	Tensile Strength ksi
Type	Designation	Temper		
Sand Cast (QQ-A-601)	43	-F	0.500	12
	214	-F	0.500	12
Wrought	1100	-H14	0.249	11
	3003	-H14	0.249	14
	5052	-H34	0.249	27

TABLE XX. TYPICAL TENSILE STRENGTHS OF BUTT WELDED JOINTS

Designation			Tensile Strength Across Weld, ksi	
Base Metal		Filler Metal Alloy	As Welded	After Heat Treatment and Aging
Alloy	Temper			
1100		1100	13.5	-
3003		1100	16	-
5052		5052	28	-
2014	-T6	4043	34	51
6061	-T6	4043	27	43
6063	-T5, T6	4043	20	-

NOTE :

(1) Using Argon - shielded tungsten arc or Argon - shielded consumable electrode.

TABLE XXI. TYPICAL SHEAR STRENGTHS OF SPOT WELDS

Combination		Shear Strength (minimum), pounds per spot									
Alloy	Temper	Thinnest Sheet in Joint, inch									
		0.016	0.020	0.025	0.032	0.040	0.051	0.064	0.081	0.102	0.125
1100	-H14) to -H18)	40	55	70	110	150	205	280	420	520	590
3003 3003 5052	-H12) or -H18) to -O)	70	100	145	210	300	410	565	775	950	1000
5052 6061	-H32) or -H38) to -T4) or -T6)	98	132	175	235	310	442	625	865	1200	1625
2024 Clad 2024 7075 Clad 7075	-T3) to) -T3) or -T6) or) -T6)	108	140	185	260	345	480	690	1050	1535	2120

TABLE XXII. WELDABILITY RATINGS FOR CAST AND WROUGHT PRODUCTS

Government Designation		Relative Suitability for Welding, Brazing, and Soldering						
			Arc Weld					
Spec.	Alloy	Gas Weld	with flux	with inert gas	Resistance Weld	Pressure Weld	Soldering	Brazing
QQ-A-601 (Sand-cast)	43	A	A	A	A	D	D	C
	356	B	B	B	B	D	D	C
	195	C	C	C	C	D	D	D
	214	C	C	C	C	D	D	D
	142	C	C	C	C	D	D	D
	122	C	C	C	C	D	D	D
	108	B	B	B	B	D	D	D
	113	C	C	C	C	D	C	D
	355	B	B	B	B	D	D	C
	220	D	D	D	D	D	D	D
	Allcast	B	B	B	B	D	D	D
	A612	C	C	C	C	D	C	A
	B214	C	B	B	C	D	D	D
Spec.	Class							
QQ-A-596 (Permanent and semi-permanent Mold Cast)	1	C	C	C	C	D	C	D
	2	C	C	C	C	D	D	D
	3	C	C	C	C	D	D	D
	4	C	C	C	C	D	D	D
	5	B	B	B	B	D	D	D
	6	B	B	B	B	D	D	C
	7	A	A	A	A	D	D	C
	8	B	B	B	B	D	D	C
	9	B	B	B	B	D	D	D
	15	D	D	D	B	D	D	D
Spec.	Alloy							
(Wrought) (See table V for corresponding spec. nos)	1100	A	A	A	B	A	A	A
	2011	D	D	D	D	D	D	D
	2014	D	B	B	B	D	D	D
	2014-Clad	D	B	B	A	C	D	D
	2017	D	B	B	B	D	D	D
	2018	D	B	B	B	D	D	D
	2024	D	B	B	B	C	D	D
	2024-Clad	D	B	B	A	C	D	D
	3003	A	A	A	A-B	A	A	A
	4032	D	B	B	C	C	D	D
	5052	A	A	A	A-B	A-B	C	C
	6061	A	A	A	A	C	B	A
	6151	A	A	A	A	C	B	B
	7075	D	D	D	B	D	D	D

NOTES:

(1) - Ratings are defined as follows:

A - Generally weldable by all commercial procedures and methods.

B - Weldable by special technique.

C - Weldability limited because of crack sensitivity or loss of properties.

D - No common methods have been developed.

TABLE XXIII. CASTING ALLOYS – RELATIVE RATING BY CHARACTERISTICS

Designation			Foundry Characteristics				
Sand QQ-A-601 Alloy	P&SP Mold QQ-A-596 Class	Die QQ-A-591 Alloy	Pattern Shrinkage Allowance (2)	Resistance to Hot Cracking (3)	Pressure Tightness	Fluidity (4)	Solidification Shrinkage Tendancy (5)
43		43	5/32	1	1	1	1
	7		-	1	1	1	2
356			5/32	1	1	1	1
	8		-	1	1	2	1
195			5/32	4	4	3	3
214			5/32	4	5	5	5
142			5/32	4	3	3	4
	3		-	4	4	3	4
122			5/32	3	3	3	3
	2		-	4	4	3	4
108			-	2	2	2	2
113			5/32	3	3	2	3
	1		-	3	3	2	3
355			5/32	1	1	1	1
	6		-	1	1	2	2
220			1/10	2	5	4	5
40E			3/16	5	3	4	4
Allcast			5/32	2	2	2	2
319			5/32	2	2	2	2
	11		-	2	2	2	3
Red X-8			5/32	1	1	1	1
T1			-	-	-	3	-
Tenzaloy			3/16	5	3	4	4
	12		-	5	4	4	5
A612			3/16	5	3	4	4
Ternalloy 5			3/16	5	3	4	4
	13		-	5	4	4	5
Ternalloy 7			3/16	5	3	4	4
	14		-	5	4	4	5
Almag 35	MIL-A-10935		-	3	5	5	5
B214		B214	-	3	4	3	4
	4		-	4	3	3	3
	5		-	1	2	2	3
	9		-	1	2	1	3
	10		-	1	2	1	3
	15		-	-	4	4	-
		13	-	1	2	1	-
		A13	-	1	2	1	-
		43	-	2	3	3	-
		A380	-	2	2	2	-
		380	-	2	2	2	-
		360	-	1	1	1	-
		A360	-	1	1	1	-
		218	-	5	5	5	-
		SC114A	-	2	2	1	-

Notes:

(1) Rating: 1 through 5 are relative ratings with 1 indicating the highest and 5 the lowest in each type of casting.

(2) Not applicable to permanent mold and die castings. Allowances are for average sand castings. Shrinkage requirements will vary with intricacy of design and dimensions.

(3) Ability of alloy to withstand contraction stresses while cooling through hot-short or brittle temperature range.

(4) Ability of liquid alloy to flow readily in mold and fill thin sections.

(5) Decrease in volume accompanying freezing of alloy and measure of amount of compensating feed metal required in form of risers.

(6) Based on alloy resistance in 5% salt spray test (ASTM B117).

(7) Composite rating based on ease of cutting, chip characteristics, quality of finishing, and tool life. Ratings, in the case of heat treatable alloys, based on T6 temper. Other tempers, particularly the annealed temper, may have lower rating.

(8) Composite rating based on ease and speed of polishing and quality of finish provided by typical polishing procedure.

(9) Ability of casting to take and hold an electroplate applied by present standard methods.

(10) Rated on lightness of color, brightness, and uniformity of clear anodized coating applied in sulfuric acid electrolyte.

(11) Rated on combined resistance of coating and base alloy to corrosion.

(12) Rating based on tensile and yield strengths at temperature up to 500 F. after prolonged heating at testing temperatures.

(13) Based on ability of material to be fusion welded with filler rod of same alloy.

(14) Refers to suitability of alloy to withstand brazing temperatures without excessive distortion or melting.

(15) Not recommended for service at temperatures exceeding 200 F.

(16) Stress relief anneal at 250 F or less.

TABLE XXIII (Continued). CASTING ALLOYS – RELATIVE RATING BY CHARACTERISTICS

Designation			Other Characteristics									
Sand QQ-A-601 Alloy	P&SP Mold QQ-A-596 Class	Die QQ-A-591 Alloy	Normally Heat Treated	Resistance to Corrosion (6)	Machining (7)	Polishing (8)	Electroplating (9)	Anodize Appearance (10)	Chemical Oxide Coating Protection (11)	Strength at Elevated Temperatures (12)	Welding Suitability (13)	Brazing Suitability (14)
43		43	no	3	5	5	2	5	2	4	1	limited
	7		no	3	5	4	2	4	2	4	1	limited
356			yes	2	4	5	2	4	2	3	2	no
	8		yes	2	3	3	1	4	2	3	2	no
195			yes	3	2	2	1	2	3	3	3	no
214			no	1	1	1	5	1	1	2	4	no
142			yes	4	2	2	1	3	4	1	4	no
	3		yes	4	2	2	1	2	3	1	4	no
122			yes	4	1	2	1	3	4	1	4	no
	2		yes	5	1	2	1	3	4	1	4	no
108			no	4	3	3	2	3	3	3	2	no
113			no	5	2	2	2	3	4	3	3	no
	1		no	6	2	2	2	3	4	3	4	no
355			yes	3	3	3	1	4	2	2	2	no
	6		yes	3	3	3	2	4	2	2	2	no
220			yes	1	1	1	4	1	1	(15)	5	no
40E			aged only	2	1	1	2	2	3	5	4	yes
Allcast			yes	3	3	4	2	4	3	3	2	no
319			yes	3	3	4	2	4	3	3	2	no
	11		yes	3	3	3	2	4	3	3	2	no
Red X-8			yes	3	4	5	2	4	2	2	2	no
Tl			aged only	-	1	-	-	-	-	-	-	-
Tenzaloy			aged only	2	1	1	2	2	3	5	4	yes
	12		aged only	2	1	1	2	1	2	5	4	yes
A612			aged only	2	1	1	2	2	3	5	4	yes
Ternalloy 5			aged only	2	1	1	3	2	2	5	4	yes
	13		aged only	2	1	1	3	1	2	5	4	yes
Ternalloy 7			yes	2	1	1	3	2	2	5	4	yes
	14		yes	2	1	1	3	1	2	5	4	yes
Almag 35	MIL-A-10935		(16)	1	1	1	5	1	1	3	4	no
B214		B214	no	1	2	2	4	2	1	3	4	no
	4		yes	4	3	2	1	3	2	2	4	no
	5		no	4	3	3	2	4	3	3	2	no
	9		yes	3	4	5	4	5	2	2	2	no
	10		yes	3	4	5	3	5	2	2	2	no
	15		aged only	3	1	-	-	-	-	-	4	-
		13	no	3	3	5	3	5	3	3	no	no
		A13	no	3	4	5	3	5	3	3	no	ro
		43	no	2	5	4	2	4	3	5	no	no
		A380	no	5	3	3	1	3	5	2	no	no
		380	no	5	3	3	1	3	5	2	no	no
		360	no	3	3	3	1	3	3	2	no	no
		A360	no	3	3	3	1	3	3	2	no	no
		218	no	1	1	1	5	1	1	4	no	no
		SC114A	no	5	3	3	2	4	4	2	no	no

TABLE XXIV. TYPICAL APPLICATIONS FOR CASTING ALLOYS

Type of Casting	General Purpose	Pressure Tight	Corrosion Resistance	High Temp. Strength	Architectural and Decorative	Special Purpose
Sand (QQ-A-601)(1)	43, 195, 108, 40E Allcast T1, 356 355, Red X-8 Tenzaloy A612 Ternalloy 5, Ternalloy 7, Precedent 71A	43, 356 195, 113, 355, Precedent 71A	43, 356, 214, 355, 220, Almag 35, B214	142, 122, 355,	43, 356, 214, 40E Tenzaloy, A612, Ternalloy 5, Almag 35, B214	142-pistons 122-pistons 750-bearings A750-bearings B750-bearings
Permanent & Semi-Permanent Mold (QQ-A-596)(2)	1, 4, 5, 6, 7, 8, 11, 12, 13, 14, 16, 17, 18	5, 6, 7, 8, 9, 10, 11, 13, 14	7, 8, 12, 13, 14, 18 Almag 35 MIL-A-10935	2, 3, 6, 9 10	12, 13, 14, Almag 35 MIL-A-10935	2-pistons 3-pistons 9-pistons 10-pistons 15-bearings 19-bearings 20-bearings
Die (QQ-A-591)(1)	13, A13, 43, 380, A380	360, A360 384	13, A13, 43, B214 218, 360 A360	A380, 380, A360, 360 384	13, A13, B214, 218	

NOTES:

(1) Alloy designation

(2) Class designation

TABLE XXV. PRINCIPAL CHARACTERISTICS AND USES OF WROUGHT ALUMINUM ALLOYS

Alloy	Outstanding Characteristics	Recommended Use
	Non-heat-treatable Alloys	
1100	Very good formability, weldability, and resistance to corrosion. Relatively low strength but high ductility.	General purpose material for drawing and stamping, and for a miscellany of parts where high strength is not required.
3003	Good formability and weldability, very good resistance to corrosion. Appreciably higher strength than 1100.	General purpose material for drawing and stamping. Miscellaneous parts where higher strength is needed than that provided by 1100.
5052	Moderate mechanical properties, stronger and harder than 1100 and 3003. Fairly good formability. Readily weldable. Excellent resistance to corrosion by salt water.	General purpose alloy where fairly high strength is required. For marine and outside applications, fuel and hydraulic lines, and tanks.
	Heat-treatable Alloys	
2011	Excellent free-machining qualities. Fairly high mechanical properties.	Stock for screw-machine products. Bolts, nuts, screws, and a great diversity of parts made on automatic screw machines.
2014	High mechanical properties including yield and tensile strength, fatigue, and hardness. Fair formability and forging qualities. Readily machinable.	Most commonly used alloy where high strength is required. General structural applications, heavy duty forgings, and strong fittings.
Clad 2014	A sheet product which combines the high mechanical properties of 2014 with the good corrosion resistance of 6053.	For structures requiring high unit strength together with good resistance to various corrosive environments.
2017	A bar, rod, and wire alloy having relatively high strength, and good machining qualities.	Screw-machine products, fittings, and structural applications where relatively high strength is required. Now largely superseded by newer alloys
2018 2218	Both retain strength well at elevated temperatures.	Forged pistons and cylinder head for internal-combustion engines. Suitable for various types of high temperature services. Forged cylinder heads and pistons.
2024	A high strength alloy with mechanical properties intermediate between 2014 and 6061.	General purpose material for various structural applications where good strength is required. Fittings and screw-machine products.

TABLE XXV (Continued). PRINCIPAL CHARACTERISTICS AND USES OF WROUGHT ALUMINUM ALLOYS

Alloy	Outstanding Characteristics	Recommended Use
	Heat-treatable Alloys	
Clad 2024	A sheet product which combines the mechanical properties of 2024 with the corrosion resistance of 1230 aluminum alloy.	For structural applications requiring good strength together with resistance to corrosion.
2025	Fairly high mechanical properties. Good forging qualities.	Specialty forging alloy. Applications mostly confined to propellers for superchargers and engines.
4032	Retains strength well at elevated temperatures	Forged pistons for internal-combustion engines.
6151	Fairly good mechanical properties. Excellent forging qualities. Good resistance to corrosion.	General purpose material for ordinary forgings. Small press forgings and intricate pieces that are difficult to forge in the harder alloys.
6061	Good mechanical properties. Superior brazing and welding qualities. Good forging characteristics, workability, and resistance to corrosion.	General structural purposes. Marine and outside work. Transportation equipment. Many small forged parts. Various extrusion applications.
7075	Affords maximum strength and endurance limit. Not readily formed. Poorest forging qualities.	Structual applications requiring maximum yield and tensile strength. Section thickness limited to 3 inches.
Clad 7075	A sheet product which combines the mechanical properties of 7075 with improved corrosion resistance.	Structural applications where the highest strength together with maximum corrosion resistance is necessary.

Section IV

Specification Requirements

This section contains tabulations of the chemical composition and mechanical property requirements for wrought aluminum alloys used by the Government. The data are arranged according to the numerical commercial designations of the alloys.

Each tabulation of chemical composition shows the maximum allowable percentage of the alloying element, or if a range is indicated, the minimum and the maximum allowable percentages of the element. The mechanical property tabulation, when given, indicates the minimum values that can be expected unless otherwise noted.

In the tables, reference is made to explanatory footnotes (numerals in parentheses). Since these footnotes are repeated in many of the tables, they are omitted from the tabulations and are included in the following listing.

(1) Analysis shall regularly be made only for the elements listed. If, however, the presence of other elements is indicated in the course of routine analysis, further analysis shall be made to determine conformance with the limits specified for other elements.

(2) Not required for wire of less than 0.125 inch diameter.

(3) For rounds (rod) maximum diameter is 8.000 inches; for square, rectangular, hexagonal, or octagonal bar maximum thickness is 4.000 inches, and maximum cross-sectional area is 36 inches.

(4) Direction of specimen:
P - Parallel to forging flow lines
NP - Not parallel to forging flow lines
L - Longitudinal
LT - Long Transverse
ST - Short Transverse

(5) Maximum heat treat section thickness.

(6) Test coupon.

(7) Identification classification number.

(8) Applicable to flat sheet only.

(9) Applicable to plate and coiled sheet and to flat sheet heat treated by the user.

(10) Applicable to plate heat treated by user.

(11) These properties are those of the core alloy since the tests are made on a round specimen machined from the plate.

(12) For bar, maximum cross-sectional area is 50 square inches.

(13) Applicable to plate and coiled sheet only.

(14) Applicable to flat sheet and plate only.

(15) Applicable to sheet and plate heat treated by user.

(16) Not required for material ½ inch or less in width.

(17) For rounds (rods) maximum diameter is 6.500 inches - see note (3) for other requirements.

(18) Cutout specimen.

(19) Tensile and yield strength test requirements may be waived for material in any direction in which the dimension is less than 2 inches because of the difficulty to obtain a tension test specimen suitable for routine control.

(20) For cross sectional areas greater than 144 square inches, or thickness greater than 4 inches at the time of heat treatment, the properties shall be as specified in the contract or purchase order.

(21) Non-heat treatable alloys.

(22) For cross-sectional areas greater than 72 square inches, or thicknesses greater than 6 inches at the time of heat treatment, the properties shall be as specified in the contract or purchase order.

1100

CHEMICAL COMPOSITION - percent

Specification	Cu	Si & Fe	Mg	Zn	Mn	Ti	Cr	Sn	Ni	Al	Other (1)
All (a) - see below	0.20	1.0 max	-	0.10	0.05	-	-	-	-	99.0 min	0.05 each 0.15 total

(a) - Aluminum foil (Spec. MIL-A-148) shall contain less than 0.01 percent each of arsenic, cadmium or lead.

MECHANICAL PROPERTIES - minimum

Designation Specification	Designation Temper	Thickness inch	Area Sq. in.	Tensile Str ksi	Yield Str ksi	EL %	Mullen Bursting Strength - psi min	Mullen Bursting Strength - psi max
MIL-A-148 Foil	Annealed	0.0008					8	23
		0.0010					11	31
		0.0015					22	55
		0.0020					40	90
		0.0030					75	150
		0.0040					110	220
		0.0050					140	280
QQ-A-250/1 Plate and Sheet	-O	0.006-0.019		11	-	15		
		0.020-0.031		11	-	20		
		0.032-0.050		11	-	25		
		0.051-0.249		11	3.5	30		
		0.250-3.000		11	3.5	28		
	-H12 and -H22	0.017-0.019		14	-	3		
		0.020-0.031		14	-	4		
		0.032-0.050		14	-	6		
		0.051-0.113		14	11	8		
		0.114-0.499		14	11	9		
		0.500-2.000		14	11	12		
	-H14 and -H24	0.009-0.012		16	-	1		
		0.013-0.019		16	-	2		
		0.020-0.031		16	-	3		
		0.032-0.050		16	-	4		
		0.051-0.113		16	14	5		
		0.114-0.499		16	14	6		
		0.500-1.000		16	14	10		
	-H16 and -H26	0.006-0.019		19		1		
		0.020-0.031		19		2		
		0.032-0.050		19		3		
		0.051-0.162		19		4		

1100 (Cont.)

MECHANICAL PROPERTIES - minimum (Cont).

Designation Specification	Temper	Thickness inch	Area Sq. in.	Tensile Str ksi	Yield Str ksi	EL %	Mullen Bursting Strength - psi min	max
QQ-A-250/1 Plate and Sheet (Cont.)	-H18 and -H28	0.006-0.019		22		1		
		0.020-0.031		22		2		
		0.032-0.050		22		3		
		0.051-0.128		22		4		
	-H112	0.250-0.499		13		9		
		0.500-2.000		12		14		
		2.001-3.000		11.5		20		
	-F	2.250-6.000		- No requirement -				
QQ-A-225/1 Bar, Rod, and Wire, Rolled, Drawn, or Cold Finished	-O	All		15.5 max		25(2)		
	-H12	Up to 0.374		14		-		
	-H14	Up to 0.374		16		-		
	-H16	Up to 0.374		19		-		
	-H18	Up to 0.374		22		-		
	-F	0.375 and over		- No requirement -				
	-H12	All		11		-		
WW-T-700/1 Tube, Seamless, Round, Square, Rectangular, and Other Shapes	-O	All		15.5 max				
	-H12	All		14				
	-H14	All		16				
	-H16	All		19				
	-H18	All		22				
	-F	-		- No requirement -				
MIL-A-12545 Impact Extrusion	-F	-		-	-	-		
		-diameter-						
QQ-A-430 Rod and Wire for Rivets and Cold Heading	-O	0.501 and over		15.5 max	-	-		
	-H14	0.501 and over		16	-	-		

2011 Free-machining

CHEMICAL COMPOSITION - percent

Specification	Cu	Si	Fe	Mg	Zn	Mn	Cr	Sn	Ni	Bi	Pb	Al	Other(1)
QQ-A-225/3	5.0-6.0	0.40	0.7	-	0.30	-	-	-	-	0.20-0.6	0.20-0.6	Balance	0.05 each 0.15 total

MECHANICAL PROPERTIES - minimum

Designation Specification	Temper	Thickness inch	Area Sq. in.	Tensile Str ksi	Yield Str ksi	EL %
QQ-A-225/3 Bar, Rod, and Wire	-T3	0.125 to 1.500	-	45	38	10
		1.501 to 2.000	-	43	34	12
		2.001 to 3.000	-	42	30	14
	-T8	0.125 to 3.250	-	52	40	10

2014

CHEMICAL COMPOSITION - percent										
Specification	Cu	Si	Fe	Mg	Zn	Mn	Ti	Cr	Al	Other(1)
All-see below	3.9- 5.0	0.50- 1.2	1.0	0.20- 0.8	0.25	0.40- 1.2	0.15	0.10	Bal- ance	0.05 each 0.15 total

MECHANICAL PROPERTIES - minimum							
Designation		Thickness inch	Area Sq. in.	Tensile Str ksi	Yield Str ksi	EL %	BHN
Specification	Temper						
QQ-A-200/2 Bar, Rod, Shapes, and Tube, Extruded	-O	All	All	30 max	18 max	12	
	-T4, -T4510, -T4511	All	All	50	35	12	
	-T42	All	All	50	29	12	
	-T6, -T6510, -T6511	Up to 0.499	All	60	53	7	
		0.500-0.749	All	64	58	7	
		0.750 & over	Up thru 25	68	60	7	
		0.750 & over	Over 25 thru 32	68	58	6	
	-T62	Up to 0.749	All	60	53	7	
		0.750 & over	Up thru 25	60	53	7	
		0.750 & over	Over 25 thru 32	60	53	6	
QQ-A-225/4 Bar, Rod, Wire and Special Shapes; Rolled, Drawn, or Cold Finished	-O	Up to 8.000	-	35 max	-	12(3)	
	-T4	Up to 8.000(3)	-	55	32	16	
	-T451	0.500-8.000(3)	-	55	32	16	
	-T6	Up to 8.000(3)	-	65	55	8	
	-T651	0.500-8.000(3)	-	65	55	8	
		(5)		(4)	(19)-(4)	(6)	
QQ-A-367 Die Forgings, Heat Treated	-T4	4 max		55(P)	30(P)	16	100
	-T6	4 max		65(P)	55(P)	10	125
	-T6	4 max		64(NP)	56(P)	3	125
	-T6(I)(7)	6	Up to 16. Lengths up to 3 X the width	65(L) 63(LT) 60(ST)	55(L) 55(LT) 55(ST)	10 6 3	
	-T6(II)(7)	6	Up to 16. Lengths up to 3X the width	65(L) 63(LT) 60(ST)	55(L) 55(LT) 55(ST)	10 4 2	
	-T6(III)(7)	6	Over 16 to 36. Lengths up to 3 X the width	65(L) 63(LT) 60(ST)	53(L) 53(LT) 53(ST)	9 5 2	
	-T6(IV)(7)	6	Over 16 to 36. Lengths up to 3X the width	65(L) 63(LT) 60(ST)	53(L) 53(LT) 53(ST)	9 3 2	

2014 (Cont.)

MECHANICAL PROPERTIES - minimum (Cont).

Designation Specification	Temper	Thickness inch (5)	Area Sq. in.	Tensile Str ksi (4)	Yield Str ksi (19) - (4)	EL % (6)	BHN
QQ-A-367 Die Forgings, Heat Treated (Cont.)	-T6(V)(7)	6	Over 36 to 144 Lengths up to 3X the width	62(L) 59(LT) 56(ST)	53(L) 52(LT) 52(ST)	7 3 1	
	-T6(VI)(7)	6	Over 36 to 144 Lengths up to 3X the width	62(L) 59(LT) 56(ST)	53(L) 52(LT) 52(ST)	7 2.5 1	
	-T6(VII)(7)	6	Over 144	60(L) 58(LT) 55(ST)	52(L) 50(LT) 50(ST)	5 2 1	
MIL-A-12545 Impact Extrusions	-F	-	-	-	-	-	-
	-O	-	-	30 max	-	-	-
	-T4	-	-	55	32	10	100
	-T6	-	-	65	55	6	125

2014 Alclad

CHEMICAL COMPOSITION - percent

Specification	Cu	Si	Fe	Mg	Zn	Mn	Ti	Cr	Other[a] (1)
QQ-A-250/3 Core 2014	3.9-5.0	0.5-1.2	1.0 max	0.20-0.8	0.25 max	0.40-1.2	0.15 max	0.10 max	0.05 each, 0.15 total
Cladding 6003	0.10 max	0.35-1.0	0.6 max	0.8-1.5	0.20 max	0.8 max	0.10 max	0.35 max	0.05 each, 0.15 total

a - Remainder Al

MECHANICAL PROPERTIES - minimum

Designation Specification	Temper	Thickness inch	Area Sq. in.	Tensile Str ksi	Yield Str ksi	EL %
QQ-A-250/3 Plate and Sheet	-O	0.020-0.499	-	30 max	14 max	16
		0.500-1.000(11)	-	-	-	10
	-T3(8)	0.020-0.039	-	55	35	14
		0.040-0.249	-	57	36	15
	-T4(9)	0.020-0.039	-	55	32	14
		0.040-0.249	-	57	34	15
		0.250-0.499	-	57	36	15
		0.500-1.000(11)	-	58	36	15
	-T451	0.250-0.499	-	57	36	15
		0.500-1.000(11)	-	58	36	15
	-T42(10)	0.250-0.499	-	57	34	15
		0.500-1.000(11)	-	58	34	15
	-T6	0.020-0.039	-	63	55	7
		0.040-0.499	-	64	57	8
		0.500-1.000	-	67	59	6
		1.001-1.500(11)	-	67	59	4
		1.501-2.000	-	65	59	3
		2.001-3.000	-	63	57	2
	-T651	0.250-0.499	-	64	57	8
		0.500-1.000	-	67	59	6
		1.001-1.500(11)	-	67	59	4
		1.501-2.000	-	65	59	3
		2.001-3.000	-	63	57	2
	-F	All	- No requirements -			

2017

CHEMICAL COMPOSITION - percent									
Specification	Cu	Mg	Mn	Si	Fe	Zn	Cr	Other(1)	Al
All - see below	3.5-4.5	0.20-0.8	0.40-1.0	0.8	1.0	0.25	0.10	0.05 each, 0.15 total	Balance

MECHANICAL PROPERTIES - minimum									
Designation Specification	Temper	Thickness inch	Area Sq. in.	Tensile Str ksi	Yield Str ksi	EL %	Shear Str ksi	BHN
QQ-A-225/5 Bar, Rod, and Wire (Rolled or Drawn)	-O	Up to 8.000	-	35 max	-	16		
	-T4	Up to 8.000(12)	-	55	32	12		
	-T451	Up to 8.000(12)	-	55	32	12		
QQ-A-367 Forgings, Heat Treated	-T4	4 max(5)		55(P)(4)	30(19)	16(6)		100
QQ-A-430 Rod and Wire for Rivets and Cold Heading	-O	- diameter - 0.501 and over	-	35 max	-	-		
	-H13	Up thru 0.500	-	30	-	-		
	-T4	0.063-0.615		55	32(19)	16	33	

2018

CHEMICAL COMPOSITION - percent										
Specification	Cu	Si	Fe	Mn	Mg	Zn	Cr	Ni	Other(1)	Al
QQ-A-367	3.5-4.5	0.9	1.0	0.20	0.45-0.9	0.25	0.10	1.7-2.3	0.05 each, 0.15 total	Balance

MECHANICAL PROPERTIES - minimum							
Designation Specification	Temper	Thickness inch	Area Sq. in.	Tensile Str ksi	Yield Str ksi(19)	EL %	BHN
QQ-A-367 Forgings, Heat Treated	-T61	4 max(5)	-	55(P)(4)	40(P)(4)	10(6)	100

2020

CHEMICAL COMPOSITION - percent											
Specification	Li	Cd	Mn	Cu	Fe	Si	Mg	Zn	Ti	Other(1)	Al
QQ-A-250/16	0.9-1.7	0.10-0.35	0.30-0.8	4.0-5.0	0.40	0.40	0.03	0.25	0.10	0.05 each 0.15 total	Balance

MECHANICAL PROPERTIES - minimum						
Designation Specification	Temper	Thickness inch	Area Sq. in.	Tensile Str ksi	Yield Str ksi	EL %
QQ-A-250/16 Plate and Sheet	-O	0.040-2.000	-	35 max	-	10
	-T6	0.040-0.249	-	76	70	4
		0.250-0.499	-	76	70	3
		0.500-1.000	-	75	70	2
		1.001-2.000	-	75	70	1.5
	-T651	0.250-0.499	-	64	57	8
		0.500-1.000	-	67	59	6
		1.001-1.500	-	67	59	4
		1.501-2.000	-	65	59	3
		2.001-3.000	-	63	57	2
	-F	All	-	- No requirements -		

2024

	CHEMICAL COMPOSITION - percent								
Specification	Cu	Mg	Mn	Fe	Si	Zn	Cr	Other[1]	Al
All - see below	3.8-4.9	1.2-1.8	0.30-0.9	0.50	0.50	0.25	0.10	0.05 each 0.15 total	Balance

MECHANICAL PROPERTIES - minimum						
Designation						
Specification	Temper	Thickness inch	Area Sq. in.	Tensile Str ksi	Yield Str ksi	EL % (16)
QQ-A-250/4 Plate and Sheet	-O	0.010-0.499	All	32 max	14 max	12
		0.500-1.750	All	32 max	-	-
	-T3(8)	0.008-0.009	All	63	42	10
		0.010-0.020	All	64	42	12
		0.021-0.249	All	64	42	15
	-T4(13)	0.010-0.020	All	62	40	12
		0.021-0.249	All	62	40	15
		0.250-0.499	All	64	40	12
		0.500-1.000	All	62	40	8
		1.001-1.500	All	60	40	7
		1.501-2.000	All	60	40	6
		2.001-3.000	All	56	40	4
			- width -			
	-T36(14)	0.020-0.062	30 & under	69	52	8
		0.063-0.499	30 & under	69	52	9
		0.500	30 & under	69	52	10
		0.020-0.062	over 30 thru 48	69	52	8
		0.063-0.249	over 30 thru 48	69	52	9
		0.250-0.500	over 30 thru 48	69	52	10
		0.020-0.062	over 48 thru 60	67	50	8
		0.063-0.249	over 48 thru 60	68	51	9
		0.250-0.500	over 48 thru 60	67	50	10
		0.063-0.249	over 60	67	50	8
		0.250-0.499	over 60	66	49	9
		0.500	over 60	66	49	10
	-T42(15)	0.010-0.020	All	62	38	12
		0.021-0.249	All	62	38	15
		0.250-0.499	All	64	38	12
		0.500-1.000	All	62	38	8
		1.001-1.500	All	60	38	7
		1.501-2.000	All	60	38	6
		2.001-3.000	All	56	38	4
	-T351	0.250-0.499	All	64	40	12
		0.500-1.000	All	62	40	8
		1.001-1.500	All	60	40	7
		1.501-2.000	All	60	40	6
		2.001-3.000	All	56	40	4
	-T6(15)	0.012-0.499	All	64	50	5
		0.500 & over	All	63	50	5
	-T81(14)	0.010-0.499	All	67	58	5
		0.500-1.000	All	66	58	5
			- width -			
	-T86(14)	0.020-0.062	30 & under	72	66	3
		0.063-0.249	30 & under	72	68	4
		0.250-0.500	30 & under	72	67	4
		0.020-0.062	over 30 thru 48	72	66	3
		0.063-0.249	over 30 thru 48	72	67	4
		0.250-0.500	over 30 thru 48	71	66	4
		0.020-0.062	over 48 thru 60	70	62	3
		0.063-0.249	over 48 thru 60	71	67	4
		0.250-0.500	over 48 thru 60	70	65	4
		0.063-0.249	over 60	71	66	4
		0.250-0.500	over 60	70	64	4
	-T851	0.250-0.499	All	67	58	5
		0.500-1.000	All	66	58	5
	-F	All	All	- No requirements -		

2024 (Cont.)

MECHANICAL PROPERTIES - minimum (Cont.)

Designation Specification	Temper	Thickness inch	Area Sq. in.	Tensile Str ksi	Yield Str ksi	EL %
QQ-A-200/3 Bar, Rod, Shapes, and Tube, Extruded	-O	All	All	35 max	10max	12
	-T4, -T3510, -T3511	Up to 0.249 incl	All	57	42	12(10 for tube)
		0.250-0.749	All	60	44	12(10 for tube)
		0.750-1.499	All	65	46	10
		1.500 & over	Up thru 25	70	52 (48 for tube)	10
		1.500 & over	Over 25 thru 32	68	48(46 for tube)	8
	-T42	Up to 0.749	All	57	38	12
		0.750-1.499	All	57	38	10
		1.500 & over	Up thru 25	57	38	10
		1.500 & over	Over 25 thru 32	57	38	8
	-T81, -T8510, -T8511	0.050-0.249	All	64	56	4
		0.250-1.499	All	66	58	5
		1.500 & over	Up thru 32	66	58	5
QQ-A-225/6 Bar, Rod, and Wire, Rolled, Drawn, or Cold Finished	-O	Up to 8.000 incl	-	35 max	-	(2) 16
	-T351	0.500 to 6.500(17)	-	62	40	10
	-T4	Up to 6.500(17)	-	62	40	10
	-T6	Up to 6.500(17)	-	62	50	5
	-T851	0.500 to 6.500(17)	-	66	58	5
WW-T-700/3 Tube, Round, Square, Rectangular, and Other Shapes, Drawn, Seamless		- wall thickness -				
	-O	All	-	32 max	15 max	-
	-T3	0.018-0.024	-	64	42	-
		0.025-0.049	-	64	42	10(18)
		0.050-0.259	-	64	42	10(18)
		0.260-0.500	-	64	42	12(18)
	-T4	0.018-0.024	-	64	40	-
		0.025-0.049	-	64	40	10(18)
		0.050-0.259	-	64	40	10(18)
		0.250-0.500	-	64	40	12(18)
QQ-A-430 Rod and Wire; For Rivets and Cold Heading		- diameter -				
	-O	0.501 & over	-	35 max	-	-
	-H13	Up thru 0.500	-	32	-	-

2024 Alclad

CHEMICAL COMPOSITION - percent

Specification	Cu	Mg	Mn	Fe	Si	Cr	Zn	Others(1)	Al
QQ-A-250/5 Core 2024	3.8-4.9	1.2-1.8	0.30-0.9	0.5	0.50	0.10	0.25	0.05 each 0.15 total	Balance
Cladding 1230	0.10	-	0.05	Fe&Si 0.7		-	0.10	0.05 each	99.3 min

MECHANICAL PROPERTIES - minimum

Designation Specification	Temper	Thickness inch width	Area Sq. in.	Tensile Str ksi	Yield Str ksi	EL %
QQ-A-250/5 Plate and Sheet	-O	0.008-0.009	All	30 max	14 max	10
		0.010-0.062	All	30 max	14 max	12
		0.063-0.499	All	32 max	14 max	12
		0.500-1.750	All	32 max		12
	-T3(8)	0.008-0.009	All	58	39	10
		0.010-0.020	All	59	39	12
		0.021-0.062	All	59	39	15
		0.063-0.249	All	62	40	15

2024 Alclad (Cont.)

MECHANICAL PROPERTIES - minimum (Cont.)

Designation		Thickness	Area	Tensile Str	Yield Str	EL
Specification	Temper	inch	Sq. in.	ksi	ksi	%
QQ-A-250/5 Plate and Sheet (Cont)	-T4(13)	0.010-0.020	All	58	37	12
		0.021-0.062	All	58	37	15
		0.063-0.128	All	61	38	15
		0.250-0.499	All	62	40	12
		0.500-1.000(11)	All	62	40	8
		1.001-1.500(11)	All	60	40	7
		1.501-2.000(11)	All	60	40	6
		2.001-3.000(11)	All	56	40	4
	-T36(14)	0.020-0.062	48 and under	62	48	8
		0.063-0.499	48 and under	66	50	9
		0.500(11)	48 and under	69	52	10
		0.020-0.062	over 48 thru 60	61	47	8
		0.063-0.499	over 48 thru 60	65	49	9
		0.500(11)	over 48 thru 60	67	50	10
		0.063-0.499	over 60	64	48	9
		0.500(11)	over 60	66	49	10
	-T42(15)	0.008-0.009	All	55	34	10
		0.010-0.020	All	56	34	12
		0.021-0.062	All	56	34	15
		0.063-0.249	All	59	36	15
		0.250-0.499	All	62	38	12
		0.500-1.000(11)	All	62	38	8
		1.001-1.500(11)	All	60	38	7
		1.501-2.000(11)	All	60	38	6
		2.001-3.000(11)	All	56	38	4
	-T351	0.250-0.499	All	62	40	12
		0.500-1.000(11)	All	62	40	8
		1.001-1.500(11)	All	60	40	7
		1.501-2.000(11)	All	60	40	6
		2.001-3.000(11)	All	56	40	4
	-T6(15)	0.010-0.062	All	60	47	5
		0.063-0.499	All	62	49	5
	-T81(14)	0.010-0.062	All	62	54	5
		0.063-0.499	All	65	56	5
		0.500-1.000(11)	All	66	58	5
	-T86(14)	0.020-0.062	30 and under	66	62	3
		0.063-0.249	30 and under	70	66	4
		0.250-0.499	30 and under	70	65	4
		0.500(11)	30 and under	72	67	4
		0.020-0.062	over 30 thru 48	66	62	3
		0.063-0.249	over 30 thru 48	70	65	4
		0.250-0.499	over 30 thru 48	69	64	4
		0.500(11)	over 30 thru 48	71	66	4
		0.020-0.062	over 48 thru 60	64	58	3
		0.063-0.249	over 48 thru 60	69	65	4
		0.250-0.499	over 48 thru 60	68	63	4
		0.500(11)	over 48 thru 60	70	65	4
		0.063-0.249	over 60	69	64	4
		0.250-0.499	over 60	68	62	4
		0.500(11)	over 60	70	64	4
	-T851	0.250-0.499	All	65	56	5
		0.500-1.000(11)	All	66	58	5
	-F	All	All	- No requirements -		

2025

CHEMICAL COMPOSITION - percent

Specification	Cu	Si	Fe	Mn	Mg	Zn	Cr	Ti	Other(1)	Al
QQ-A-367	3.9-5.0	0.50-1.2	1.0	0.40-1.2	0.05	0.25	0.10	0.15	0.05 each 0.15 total	Balance

MECHANICAL PROPERTIES - minimum

Designation Specification	Designation Temper	Thickness inch	Area Sq. in.	Tensile Str ksi	Yield Str(19) ksi	EL %
QQ-A-367 Forgings, Heat Treated	-T6	4(5)	-	55(P)(4)	33(P)(4)	16(6)

2117

CHEMICAL COMPOSITION - percent

Specification	Cu	Mn	Mg	Si	Fe	Cr	Zn	Others(1)	Al
QQ-A-430	2.2-3.0	0.20	0.20-0.50	0.8	1.0	0.10	0.25	0.05 each 0.15 total	Balance

MECHANICAL PROPERTIES - minimum

Designation Specification	Designation Temper	Diameter	Area Sq. in.	Tensile Str ksi	Yield Str ksi	EL %	Shear Str ksi
QQ-A-430 Rod and Wire; for Rivets and Cold Heading	-O	0.501 and over	-	25 max	-	-	-
	-H15	Up thru 0.500	-	28	-	-	-
	-T4	0.063-0.615	-	38	18	18	26

2218

CHEMICAL COMPOSITION - percent

Specification	Cu	Si	Fe	Mn	Mg	Zn	Cr	Ti	Ni	Other(1)	Al
QQ-A-367	3.5-4.5	0.9	1.0	0.20	1.2-1.8	0.25	0.10	-	1.7-2.3	0.05 each 0.15 total	Balance

MECHANICAL PROPERTIES - minimum

Designation Specification	Designation Temper	Thickness inch	Area Sq. in.	Tensile Str ksi	Yield Str(19) ksi	EL %	BHN
QQ-A-367 Forgings, Heat Treated	-T61	4(5)	-	55(P)(4)	40(P)(4)	10(6)	100

2219

CHEMICAL COMPOSITION - percent

Specification	Cu	Si	Fe	Mn	Mg	Zn	Cr	Ti	Ni	Other(1)a	Al
QQ-A-367	5.8-6.8	0.20	0.30	0.20-0.40	0.02	0.10	-	0.02-0.10	-	0.05 each 0.15 total	Balance

a - Vanadium 0.05-0.15 and Zirconium 0.10-0.25

MECHANICAL PROPERTIES - minimum

Designation Specification	Temper	Thickness inch	Area Sq. in.	Tensile Str(4,19) ksi	Yield Str(4,19) ksi	EL %
QQ-A-367 Forgings, Heat Treated	-T6	4(5)	-	58(P)	38(P)	8(6)
	-T6	4(5)	-	58(NP)	38(NP)	8(6)
	-T6	4(5,20)	-	58(L) 55(LT) 53(ST)	40(L) 37(LT) 35(ST)	6 4 2
	-T852	4(5,20)	-	61(L) 58(LT) 56(ST)	43(L) 40(LT) 38(ST)	6 4 2
	-T87	4(5,20)	-	65(L) 62(LT) 58(ST)	47(L) 44(LT) 40(ST)	6 4 2

2618

CHEMICAL COMPOSITION - percent

Specification	Cu	Si	Fe	Mn	Mg	Zn	Cr	Ti	Ni	Other(1)	Al
QQ-A-367	1.9-2.7	0.25	0.9-1.3	-	1.3-1.8	-	-	0.04-0.10	0.9-1.2	0.05 each 0.15 total	Balance

MECHANICAL PROPERTIES - minimum

Designation Specification	Temper	Thickness inch	Area Sq. in.	Tensile Str(4,19) ksi	Yield Str(4,19) ksi	EL %	BHN
QQ-A-367 Forgings, Heat Treated	-T61	4(5)		58(P)	48(P)	6(6)	115
	-T61	4(5)		55(NP)	45(NP)	4(6)	
	-T61 (Class I)	4(5,20)	16 and under	58(L) 55(LT) 52(ST)	48(L) 45(LT) 42(ST)	7 5 4	
	-T61 (Class II)	4(5,20)	Over 16 to 36	57(L) 55(LT) 52(ST)	47(L) 45(LT) 42(ST)	7 5 4	
	-T61 (Class III)	4(5,20)	Over 36 to 144	56(L) 53(LT) 51(ST)	46(L) 40(LT) 39(ST)	7 4 4	

3003

CHEMICAL COMPOSITION - percent							
Specification	Mn	Fe	Si	Cu	Zn	Other(1)	Al
All - see below	1.0-1.5	0.7	0.6	0.20	0.10	0.05 each 0.15 total	Balance

MECHANICAL PROPERTIES - minimum						
Designation		Thickness inch	Area Sq. in.	Tensile Str ksi	Yield Str ksi	EL %
Specification	Temper					
						(16)
QQ-A-250/2 Plate and Sheet	-O	0.006-0.007	-	14	-	14
		0.008-0.012	-	14	-	18
		0.013-0.031	-	14	-	20
		0.032-0.050	-	14	-	23
		0.051-0.249	-	14	-	25
		0.250-3.000	-	14	-	23
	-H12 or -H22	0.017-0.019	-	17	-	3
		0.020-0.031	-	17	-	4
		0.032-0.050	-	17	-	5
		0.051-0.113	-	17	-	6
		0.114-0.161	-	17	-	7
		0.162-0.249	-	17	-	8
		0.250-0.499	-	17	-	9
		0.500-2.000	-	17	-	10
	-H14 or -H24	0.009-0.012	-	20	-	1
		0.013-0.019	-	20	-	2
		0.020-0.031	-	20	-	3
		0.032-0.050	-	20	-	4
		0.051-0.113	-	20	-	5
		0.114-0.161	-	20	-	6
		0.162-0.249	-	20	-	7
		0.250-0.499	-	20	-	8
		0.500-1.000	-	20	-	10
	-H16 or -H26	0.006-0.019	-	24	-	1
		0.020-0.031	-	24	-	2
		0.032-0.050	-	24	-	3
		0.051-0.162	-	24	-	4
	-H18 or -H28	0.006-0.019	-	27	-	1
		0.020-0.031	-	27	-	2
		0.032-0.050	-	27	-	3
		0.051-0.128	-	27	-	4
	-H112	0.250-0.499	-	17	-	8
		0.500-2.000	-	15	-	12
		2.001-3.000	-	14	-	18
	-F	0.250-6.000	-	- No requirements -		
QQ-A-200/1 Bar, Rod, Shapes, and Tube Extruded	-O	All	-	19 max	-	25
	-H112	All	-	14	-	-
	-F	All	-	- No requirements -		
QQ-A-225/2		- diameter -				
	-O	All sizes	-	15 max	-	25
	-H12	Up to 0.374	-	14	-	-
	-H14	Up to 0.374	-	16	-	-
	-H16	Up to 0.374	-	19	-	-
	-H18	Up to 0.374	-	22	-	-
	-H112	All sizes	-	11	-	-

3003 (Cont.)

MECHANICAL PROPERTIES - minimum (Cont.)

Designation Specification	Temper	Thickness inch	Area Sq. in.	Tensile Str ksi	Yield Str ksi	EL %
WW-T-700/2 Tube, Round, Square, Rectangular, and Other Shapes, Drawn, Seamless		- wall thickness -				
	-O	All	-	19 max	-	-
	-H12	All	-	17	-	-
	-H14	All	-	20	-	-
	-H16	All	-	24	-	-
	-H18	All	-	27	-	-
	-F	-	-	- No requirements -		
QQ-A-430 Rod and Wire; for Rivets and Cold Heading		- diameter -				
	-O	0.501 and over	-	19 max		
	-H14	Up thru 0.500	-	20		

4032

CHEMICAL COMPOSITION - percent

Specification	Cu	Si	Fe	Mn	Mg	Zn	Cr	Ti	Ni	Other$^{(1)}$	Al
QQ-A-367	0.50-1.3	11.0-13.5	1.0	-	0.8-1.3	0.25	0.10	-	0.50-1.3	0.05 each 0.15 total	Balance

MECHANICAL PROPERTIES - minimum

Designation Specification	Temper	Thickness inch	Area Sq. in.	Tensile Str ksi	Yield Str$^{(19)}$ ksi	EL %	BHN
QQ-A-367 Forgings, Heat Treated	-T6	$4^{(5)}$	-	52(P)$^{(4)}$	42(P)$^{(4)}$	$5^{(6)}$	115

5052

CHEMICAL COMPOSITION - percent

Specification	Mg	Fe & Si	Cr	Cu	Mn	Zn	Others	Al
All-see below	2.2-2.8	0.45	0.15-0.35	0.10	0.10	0.10	0.05 each 0.15 total	Balance

MECHANICAL PROPERTIES - minimum

Designation Specification	Temper	Thickness inch	Area Sq. in.	Tensile Str ksi	Yield Str ksi	EL %
						(16)
QQ-A-250/8 Plate and Sheet	-O	0.006-0.007	-	25	-	--
		0.008-0.019	-	25	-	15
		0.020-0.031	-	25	-	18
		0.032-0.249	-	25	-	20
		0.250-3.000	-	25	-	18
	-H32 or -H22	0.017-0.019	-	31	-	4
		0.020-0.050	-	31	-	5
		0.051-0.113	-	31	-	7
		0.114-0.249	-	31	-	9
		0.250-0.499	-	31	-	11
		0.500-2.000	-	31	-	12
	-H34 or -H24	0.009-0.019	-	34	-	3
		0.020-0.050	-	34	-	4
		0.051-0.113	-	34	-	6
		0.114-0.249	-	34	-	7
		0.250-1.000	-	34	-	10
	-H36 or -H26	0.006-0.007	-	37	-	--
		0.008-0.031	-	37	-	3
		0.032-0.162	-	37	-	4

5052 (Cont.)

MECHANICAL PROPERTIES - minimum (Cont.)

Designation Specification	Temper	Thickness inch	Area Sq. in.	Tensile Str ksi	Yield Str ksi	EL %
QQ-A-250/8 Plate and Sheet (Cont)	-H38 or	0.006-0.007	-	39	-	--
	-H28	0.008-0.031	-	39	-	3
		0.032-0.128	-	39	-	4
	-H112	0.250-0.499	-	28	-	7
		0.500-2.000	-	25	-	12
		2.001-3.000	-	25	-	16
	-F	0.250-6.000	-	- No requirements -		
		- diameter -				(2)
QQ-A-225/7 Bar, Rod, and Wire; Rolled, Drawn, or Cold Finished	-O	All sizes	-	32 max	-	25
	-H32	Up to 0.374	-	31	-	--
	-H34	Up to 0.374	-	34	-	--
	-H36	Up to 0.374	-	37	-	--
	-H38	Up to 0.374	-	39	-	--
		- wall thickness -				
WW-T-700/4 Tube, Round, Square, Rectangular, and Other Shapes, Drawn, Seamless	-O	All	-	35 max	-	-
	-H32	All	-	31	-	-
	-H34	All	-	34	-	-
	-H36	All	-	37	-	-
	-H38	All	-	39	-	-
	-F	All	-	- No requirements -		
		- diameter -				
QQ-A-430 Rod and Wire; For Rivets and Cold Heading	-O	0.501 and over	-	32 max	-	
	-H32	Up thru 0.500	-	31	-	

5056

CHEMICAL COMPOSITION - percent

Specification	Mg	Mn	Cr	Cu	Si	Fe	Zn	Ti	Others[1]	Al
QQ-A-430	4.5-5.6	0.05-0.20	0.05-0.20	0.10	0.30	0.40	0.10	-	0.05 each 0.15 total	Balance

MECHANICAL PROPERTIES - minimum

Designation Specification	Temper	Thickness inch	Area Sq. in.	Tensile Str ksi	Yield Str ksi	EL %
		- diameter -				
QQ-A-430 Rod and Wire; For Rivets and Cold Heading	-O	0.501 and over	-	46 max		
	-H32	Up thru 0.500	-	44		

5083

CHEMICAL COMPOSITION - percent											
Specification	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Ni	Other(1)	Al
QQ-A-250/6 and QQ-A-200/4	0.40	0.40	0.10	0.30-1.0	4.0-4.9	0.05-0.25	0.25	0.15	-	0.05 each 0.15 total	Balance
QQ-A-367	0.40	0.40	0.10	0.30-1.0	4.0-4.9	-	0.25	-	-	0.05 each 0.15 total	Balance

MECHANICAL PROPERTIES - minimum						
Designation						
Specification	Temper	Thickness inch	Area Sq. in.	Tensile Str ksi	Yield Str ksi	EL %
						(16)
QQ-A-250/6 Plate and Sheet	-O	0.051-1.500	-	40	18	16
		1.501-3.000	-	39	17	16
	-H32	0.051-0.125	-	45	34	8
		0.126-0.249	-	45	34	10
	-H34	0.051-0.125	-	50	39	6
		0.126-0.249	-	50	39	8
	-H113	0.188-2.000	-	44	31	12
QQ-A-200/4 Bar, Rod, Shapes; and Tube, Extruded	-O	Up thru 5.000	Up thru 32	39	16	14
	-H111	Up thru 5.000	Up thru 32	40	24	12
				(4-19)	(4-19)	
QQ-A-367 Forgings, Heat Treated	-H111	5(5)	-	42(P)	22(P)	16(6)
	-H112	5(5)	-	40(P)	18(P)	16(6)
	-H111	4(5)(21)	-	42(NP)	22(NP)	14(6)
	-H112	4(5)(21)	-	40(NP)	18(NP)	16(6)
	-H111		-	42(L)	22(L)	16
			-	39(LT)	20(LT)	14
	-H112		-	40(L)	18(L)	16
			-	39(LT)	16(LT)	14

5086

CHEMICAL COMPOSITION - percent										
Specification	Si	Fe	Cu	Mn	Mg	Cr	Ti	Zn	Others(1)	Al
All - see below	0.40	0.50	0.10	0.7	3.5-4.5	0.05-0.25	0.15	0.25	0.05 each 0.15 total	Balance

MECHANICAL PROPERTIES - minimum						
Designation						
Specification	Temper	Thickness inch	Area Sq. in.	Tensile Str ksi	Yield Str ksi	EL %
						(16)
QQ-A-250/7 Plate and Sheet	-O	0.020-0.050	-	35	14	15
		0.051-0.249	-	35	14	18
		0.250-2.000	-	35	14	14
	-H32	0.020-0.050	-	40	28	6
		0.051-0.249	-	40	28	8
		0.250-2.000	-	40	28	12
	-H34	0.020-0.050	-	44	34	5
		0.051-0.249	-	44	34	6
		0.250-2.000	-	44	34	10
	-H36	0.020-0.050	-	47	38	4
		0.051-0.162	-	47	38	6
	-H112	0.188-0.499	-	36	18	8
		0.500-1.000	-	35	16	10
		1.001-2.000	-	35	14	14
		2.001-3.000	-	34	14	14

5086 (Cont.)

MECHANICAL PROPERTIES - minimum (Cont.)

Designation		Thickness	Area	Tensile Str	Yield Str	EL
Specification	Temper	inch	Sq. in.	ksi	ksi	%
QQ-A-200/5 Bar, Rods, Shapes, and Tube Extruded	-O	Up thru 5.000	Up thru 32	35 max	14	14
	-H111	Up thru 5.000	Up thru 32	36	21	12
WW-T-700/5 Tube, Round, Square, Rectangular, and Other Shapes, Drawn, Seamless	-O	-wall thickness- All sizes	-	35	14	14
	-H32	0.010-0.050	-	40	28	6
		0.051-0.450	-	40	28	8
	-H34	0.010-0.050	-	44	34	5
		0.051-0.450	-	44	34	6
	-H36	0.010-0.050	-	47	38	4
		0.051-0.450	-	47	38	5
	-F	- No requirements -				

5454

CHEMICAL COMPOSITION - percent

Specification	Mg	Cr	Mn	Ti	Cu	Zn	Fe & Si	Other(1)	Al
All - see below	2.4-3.0	0.05-0.20	0.50-1.0	0.20	0.10	0.25	0.50	0.05 each 0.15 total	Balance

MECHANICAL PROPERTIES - minimum

Designation		Thickness	Area	Tensile Str	Yield Str	EL
Specification	Temper	inch	Sq. in.	ksi	ksi	%
						(16)
QQ-A-250/10 Plate and Sheet	-O	0.020-0.031	-	31	12	12
		0.032-0.050	-	31	12	14
		0.051-0.113	-	31	12	16
		0.114-3.000	-	31	12	18
	-H32	0.020-0.050	-	36	26	5
		0.051-0.249	-	36	26	8
		0.250-2.000	-	36	26	12
	-H34	0.020-0.050	-	39	29	4
		0.051-0.161	-	39	29	6
		0.162-0.249	-	39	29	7
		0.250-1.000	-	39	29	10
	-H112	0.250-0.499	-	32	18	8
		0.500-2.000	31	12	11	11
		2.001-3.000	-	31	12	15
QQ-A-200/6 Bar, Rod, Shapes, and Tube, Extruded	-O	Up thru 5.000	Up thru 32	41	19	14
	-H111	Up thru 5.000	Up thru 32	42	26	12
	-H112	Up thru 5.000	Up thru 32	41	19	12

5456

CHEMICAL COMPOSITION - percent

Specification	Mg	Cr	Mn	Ti	Cu	Zn	Fe & Si	Others(1)	Al
All - see below	4.7-5.5	0.05-0.20	0.50-1.0	0.20	0.10	0.25	0.40	0.05 each 0.15 total	Balance

MECHANICAL PROPERTIES - minimum

Designation Specification	Temper	Thickness inch	Area Sq. in.	Tensile Str ksi	Yield Str ksi	EL %
QQ-A-250/9 Plate and Sheet	-O	0.051-1.500	-	42	19	(16) 16
		1.501-3.000	-	41	18	16
		3.001-5.000	-	40	17	14
		5.001-7.000	-	39	16	14
		7.001-8.000	-	38	15	12
	-H24	0.051-0.249	-	51	39	9
	-H112	0.250-1.500	-	42	19	12
		1.501-3.000	-	41	18	12
	-H321	0.051-0.624	-	46	33	12
		0.625-1.250	-	46	33	12
		1.251-1.500	-	44	31	12
		1.501-3.000	-	41	29	12
	-H323	0.051-0.125	-	48	36	6
		0.126-0.249	-	48	36	8
	-H343	0.051-0.125	-	53	41	6
		0.126-0.249	-	53	41	8
QQ-A-200/7 Bar, Rod, Shapes, and Tube, Extruded	-O	Up thru 5.000	Up thru 32	31	12	14
	-H111	Up thru 5.000	Up thru 32	33	19	12
	-H112	Up thru 5.000	Up thru 32	31	12	12

6011

CHEMICAL COMPOSITION - percent

Specification	Cu	Mg	Si	Mn	Zn	Fe	Ti	Cr	Ni	Others(1)	Al
MIL-A-12545	0.40-0.9	0.6-1.2	0.6-1.2	0.8	1.5	1.0	0.20	0.30	0.20	0.05 each 0.15 total	Balance

MECHANICAL PROPERTIES - minimum

Designation Specification	Temper	Thickness inch	Area Sq. in.	Tensile Str ksi	Yield Str ksi	EL %	BHN
MIL-A-12545	-F	-	-	35	32	3	70
Impact Extrusions	-T6	-	-	50	42	7	95

6053

CHEMICAL COMPOSITION - percent

Specification	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Others(1)	Al
QQ-A-430	-a-	0.35	0.10	-	1.1-1.4	0.15-0.35	0.10	-	0.05 each 0.15 total	Balance

a - 45 to 65 percent of magnesium content.

MECHANICAL PROPERTIES - minimum

Designation Specification	Temper	Thickness inch	Area Sq. in.	Tensile Str ksi	Yield Str ksi	EL %	Shear Str ksi
QQ-A-430 Rod and Wire; For Rivets and Cold Heading	-O	- diameter - 0.501 and over	-	19 max	-	-	-
	-H13	Up thru 0.500	-	19	-	-	-
	-T61	0.063-0.615	-	30	20	14	20

6061

CHEMICAL COMPOSITION - percent										
Specification	Mg	Si	Cr	Fe	Cu	Ti	Mn	Zn	Others(1)	Al
All - see below	0.8-1.2	0.40-0.8	0.15-0.35	0.7	0.15-0.40	0.15	0.15	0.25	0.05 each 0.15 total	Balance

MECHANICAL PROPERTIES - minimum

Designation Specification	Temper	Thickness inch	Area Sq. in.	Tensile Str ksi (19)	Yield Str ksi	EL %	BHN	Shear Str ksi
QQ-A-250/11 Plate and Sheet	-O	0.010-0.020	-	22 max	12 max	(16) 14		
		0.021-0.128	-	22 max	12 max	16		
		0.129-0.499	-	22 max	12 max	18		
		0.500-1.000	-	22 max	--	18		
		1.001-3.000	-	22 max	--	16		
	-T4	0.010-0.020	-	30	16	14		
		0.021-0.249	-	30	16	16		
		0.250-1.000	-	30	16	18		
		1.001-3.000	-	30	16	16		
	-T451	0.250-1.000	-	30	16	18		
		1.001-3.000	-	30	16	16		
	-T6	0.010-0.020	-	42	35	8		
		0.021-0.499	-	42	35	10		
		0.500-1.000	-	42	35	9		
		1.001-2.000	-	42	35	8		
		2.001-3.000	-	42	35	6		
		3.001-4.000	-	42	35	6		
		4.001-5.000	-	40	35	6		
	-T651	0.250-0.499	-	42	35	10		
		0.500-1.000	-	42	35	9		
		1.001-2.000	-	42	35	8		
		2.001-3.000	-	42	35	6		
		3.001-4.000	-	42	35	6		
		4.001-5.000	-	40	35	6		
	-F	0.250-6.000	- No requirements -					
QQ-A-200/8 Bar, Rod, Shapes, and Tube, Extruded	-O	-	-	22 max	16 max	16		
	-T4, -T4510, -T4511	-	-	26	16	16		
	-T6, -T6510, -T6511	-	-	38	35	10		
QQ-A-225/8 Bar, Rod, Wire and Special Shapes; Rolled, Drawn or Cold Finished	-O	(12) Up to 8.000	-	22 max	(2) --	18		
	-T4	Up to 8.000	-	30	16	18		
	-T451	0.500 to 8.000	-	30	16	18		
	-T6	Up to 8.000	-	42	35	10		
	-T651	0.500 to 8.000	-	42	35	10		
WW-T-700/6 Tube, Round, Square, Rectangular, and Other Shapes, Drawn, Seamless	-O	-wall thickness- All sizes	-	22 max	14 max	(18) 15		
	-T4	0.025 to 0.049	-	30	16	14		
		0.050 to 0.259	-	30	16	16		
		0.260 to 0.500	-	30	16	18		
	-T6	0.025 to 0.049	-	42	35	8		
		0.050 to 0.259	-	42	35	10		
		0.260 to 0.500	-	42	35	12		

6061 (Cont.)

MECHANICAL PROPERTIES - minimum (Cont.)

Designation		Thickness inch	Area Sq. in.	Tensile Str ksi	Yield Str ksi	EL %	BHN	Shear Str ksi
Specification	Temper							
				(4)	(4)			
QQ-A-367 Forgings, Heat Treated	-T6	4(5)	-	38(P)	35(P)	10(6)	80	
	-T6	4(5)	-	38(NP)	35(NP)	5(6)	80	
	-T6	Up to 4	Up to 144	38(L)	35(L)	10		
				38(LT)	35(LT)	8		
				37(ST)	33(ST)	5		
		Over 4 to 8	Up to 256	37(L)	34(L)	8		
				37(LT)	34(LT)	6		
				35(ST)	32(ST)	4		
		- diameter -						
QQ-A-430 Rod and Wire; For Rivets and Cold Heading	-O	0.501 and over	-	22 max	-	-		
	-H13	Up thru 0.500	-	22	-	-		
	-T6	0.063-0.615	-	42	35	10		25

6063

CHEMICAL COMPOSITION - percent

Specification	Mg	Si	Fe	Cu	Ti	Mn	Zn	Cr	Others(1)	Al
QQ-A-200/9	0.45-0.9	0.20-0.6	0.35	0.10	0.10	0.10	0.10	0.10	0.05 each 0.15 total	Balance

MECHANICAL PROPERTIES - minimum

Designation Specification	Temper	Thickness inch	Area Sq. in.	Tensile Str ksi	Yield Str ksi	EL %
QQ-A-200/9 Bar, Rod, Shapes, and Tube, Extruded	-O	All	-	19 max	-	18
	-T4	Up thru 0.500	-	19	10	14
		0.501-1.000	-	18	9	14
	-T42	Up thru 0.500	-	17	9	12
		0.501-1.000	-	16	8	12
	-T5	Up thru 0.500	-	22	16	8
		0.501-1.000	-	21	15	8
	-T6	Up ~~thru~~ 0.124	-	30	25	8
		0.125-1.000	-	30	26	10

6066

CHEMICAL COMPOSITION - percent

Specification	Mg	Si	Cu	Mn	Cr	Fe	Zn	Ti	Others	Al
All - see below	0.8-1.4	0.9-1.8	0.7-1.2	0.6-1.1	0.40	0.50	0.25	0.20	0.05 each 0.15 total	Balance

MECHANICAL PROPERTIES - minimum

Designation Specification	Temper	Thickness inch	Area Sq. in.	Tensile Str ksi	Yield Str ksi	EL %	BHN
QQ-A-200/10 Bar, Rod, Shapes, and Tube Extruded	-O	-	-	29 max	18 max	16	
	-T4, -T4510, -T4511	-	-	40	25	14	
	-T42	-	-	40	24	14	
	-T6, -T6510, -T6511	-	-	50	45	8	
	-T62	-	-	50	42	8	
QQ-A-367 Forgings, Heat Treated	-T6	4(5)	-	50(P)(4)	45(P)(4)	12(6)	100

6151

CHEMICAL COMPOSITION - percent

Specification	Cu	Si	Fe	Mn	Mg	Zn	Cr	Ti	Others	Al
All - see below	0.35	0.6-1.2	1.0	0.20	0.45-0.8	0.25	0.15-0.35	0.15	0.05 each 0.15 total	Balance

MECHANICAL PROPERTIES - minimum

Designation Specification	Temper	Thickness inch	Area Sq. in.	Tensile Str ksi	Yield Str ksi	EL %	BHN
QQ-A-367 Forgings, Heat Treated	-T6	(5) 4	-	(4) 44(P)	(4) 37(P)	(6) 14	90
	-T6	4	-	44(NP)	37(NP)	6	90
MIL-A-12545 Impact Extrusions	-T6	-	-	44	37	10	90

7075

CHEMICAL COMPOSITION - percent										
Specification	Zn	Mg	Cu	Cr	Mn	Fe	Si	Ti	Others(1)	Al
All - see below	5.1-6.1	2.1-2.9	1.2-2.0	0.18-0.40	0.30	0.7	0.50	0.20	0.05 each 0.15 total	Balance

MECHANICAL PROPERTIES - minimum								
Designation		Thickness inch	Area Sq. in.	Tensile Str ksi	Yield Str ksi	EL %	BHN	Shear Str ksi
Specification	Temper							
QQ-A-250/12 Plate and Sheet	-O	0.015-0.499	-	40 max	21 max	(16) 10		
		0.500-2.000	-	40 max	-	10		
	-T6	0.015-0.039	-	76	65	7		
		0.040-0.499	-	77	66	8		
		0.500-1.000	-	77	66	6		
		1.001-2.000	-	77	66	4		
		2.001-2.500	-	73	62	3		
		2.501-3.000	-	70	60	3		
		3.001-3.500	-	70	57	3		
		3.501-4.000	-	67	53	2		
	-T651	0.250-0.499	-	77	66	8		
		0.500-1.000	-	77	66	6		
		1.001-2.000	-	77	66	4		
		2.001-2.500	-	73	62	3		
		2.501-3.000	-	70	60	3		
		3.001-3.500	-	70	57	3		
		3.501-4.000	-	67	53	2		
	-F	All		- No requirements -				
QQ-A-200/11 Bar, Rod, Shapes, and Tube, Extruded	-O	All sizes	-	40 max	24 max	10		
	-T6, -T6510, -T6511	Up to 0.249	-	78	70	7		
		0.250 to 0.499	-	81	73	7		
		0.500 to 2.999	-	81	72	7		
		3.000 to 4.499	-					
		Up to 20 sq. in.	-	81	71	7		
		Over 20 to 32 sq. in.	-	78	70	6		
		4.500 to 5.000	-					
		Up to 32 sq. in.	-	78	68	6		
QQ-A-225/9 Bar, Rod, Wire, and Special Shapes; Rolled Drawn, or Cold Finished	-O	Up to 8.000	-	40 max	(2) -	(2) 10		
	-T6	Up to 4.000	-	77	66	7		
	-T651	0.500 to 4.000	-	77	66	7		
QQ-A-367 Forgings, Heat Treated	-T6	(5) 3	-	(19, 4) 75(P)	(19, 4) 65(P)	10(6)	135	
	-T6	3	-	71(NP)	62(NP)	3(7)	135	
	-T6 (Class I)	3	Up to 16 Lengths up to 3 times the width	75(L) 75(LT) 72(ST)	64(L) 63(LT) 63(ST)	9 4 2		
	-T6 (Class II)	3	Up to 16 Lengths over 3 times the width	75(L) 73(LT) 70(ST)	63(L) 61(LT) 61(ST)	9 4 2		
	-T6 (Class III)	3	Over 16 to 36 Lengths over 3 times the width	73(L) 71(LT) 68(ST)	61(L) 60(LT) 60(ST)	7 3 2		
	-T6 (Class IV)	3	Over 16 to 36 Lengths over 3 times the width	73(L) 71(LT) 68(ST)	60(L) 59(LT) 59(ST)	7 3 2		

7075 (Cont.)

MECHANICAL PROPERTIES - minimum (Cont).

Designation Specification	Temper	Thickness inch	Area Sq. in.	Tensile Str ksi	Yield Str ksi	EL %	BHN	Shear Str ksi
QQ-A-367 Forgings, Heat Treated (Cont)	-T6 (Class V)	3	Over 36 to 144 Lengths up to 3 times the width	71(L) 69(LT) 66(ST)	60(L) 58(LT) 58(ST)	4 2 1		
	-T6 (Class VI)	3	Over 36 to 144 Lengths up to 3 times the width	71(L) 69(LT) 66(ST)	59(L) 57(LT) 57(ST)	4 2 1		
	-T6 (Class VII)	3	Over 144 to 256	70(L) 67(LT) 64(ST)	58(L) 56(LT) 56(ST)	4 2 1		
MIL-A-12545 Impact Extrusions	-F	-	-	-	-	-		
	-O	-	-	40 max	-	-		
	-T6	-	-	75	65	5	135	
QQ-A-430 Rod and Wire; For Rivets and Cold Heading	-O	-diameter- 0.501 and over	-	40 max				
	-H13	Up thru 0.500	-	36				
	-T6	0.063-0.615	-	77	66	7		42

7075 Alclad

CHEMICAL COMPOSITION - percent

Specification	Zn	Mg	Cu	Cr	Mn	Fe	Si	Ti	Others(1)	Al
QQ-A-250/13 Core (7075)	5.1-6.1	2.1-2.9	1.2-2.0	0.18-0.40	0.30	0.7	0.50	0.20	0.05 each 0.15 total	Balance
Cladding (7072)	0.8-1.3	0.10	0.10	-	0.10	Fe & Si/0.7		-	0.05 each 0.15 total	Balance

MECHANICAL PROPERTIES - minimum

Designation Specification	Temper	Thickness inch	Area Sq. in.	Tensile Str ksi	Yield Str ksi	EL(16) %
QQ-A-250/13 Plate and Sheet	-O	0.008-0.014	-	36 max	20 max	9
		0.015-0.062	-	36 max	20 max	10
		0.063-0.087	-	38 max	20 max	10
		0.188-0.499	-	39 max	21 max	10
		0.500-1.000	-	40 max(11)	-	10
	-T6	0.008-0.011	-	68	58	5
		0.012-0.039	-	70	60	7
		0.040-0.062	-	72	62	8
		0.063-0.187	-	73	63	8
		0.188-0.499	-	75	64	8
		0.500-1.000	-	77	66	6
		1.001-2.000	-	77	66	4
		2.001-2.500	-	73(11)	62(11)	3
		2.501-3.000	-	70	60	3
		3.001-3.500	-	70	57	3
		3.501-4.000	-	67	53	2
	-T651	0.250-0.499	-	75	64	8
		0.500-1.000	-	77	66	6
		1.001-2.000	-	77	66	4
		2.001-2.500	-	73	62	3
		2.501-3.000	-	70(11)	60(11)	3
		3.001-3.500	-	70	57	3
		3.501-4.000	-	67	53	2
	-F	0.250-6.000	-	- No requirements -		

7075 Alclad one side

CHEMICAL COMPOSITION - percent

Specification	Zn	Mg	Cu	Cr	Mn	Fe	Si	Ti	Others(1)	Al
QQ-A-250/18 Core (7075)	5.1-6.1	2.1-2.9	1.2-2.0	0.18-0.40	0.30	0.7	0.50	0.20	0.05 each 0.15 total	Balance
Cladding (7072)	0.8-1.3	0.10	0.10		0.10	Fe & Si/0.7		-	0.05 each 0.15 total	Balance

MECHANICAL PROPERTIES - minimum

Designation		Thickness inch	Area Sq. in.	Tensile Str ksi	Yield Str ksi	EL %
Specification	Temper					
QQ-A-250/18 Plate and Sheet	-O	0.015-0.062	-	38 max	21 max	10
		0.063-0.187	-	39 max	21 max	10
		0.188-0.499	-	39 max	21 max	10
		0.500-1.000	-	40 max	-	10
	-T6	0.015-0.039	-	73	62	7
		0.040-0.062	-	74	64	8
		0.063-0.187	-	75	64	8
		0.188-0.499	-	76	65	8
		0.500-1.000	-	77(11)	66(11)	6
		1.001-2.000	-	77(11)	66(11)	4
	-T651	0.250-0.499	-	76	65	8
		0.500-1.000	-	77(11)	66(11)	6
		1.001-2.000	-	77(11)	66(11)	4
	-F	All	-	- No requirements -		

7076

CHEMICAL COMPOSITION - percent

Specification	Cu	Si	Fe	Mn	Mg	Zn	Cr	Ti	Ni	Others(1)	Al
QQ-A-367	0.30-1.0	0.40	0.6	0.30-0.8	1.2-2.0	7.0-8.0	-	0.20	-	0.05 each 0.15 total	Balance

MECHANICAL PROPERTIES - minimum

Designation		Thickness inch	Area Sq. in.	Tensile Str(4) ksi	Yield Str(4) ksi	EL(6) %	BHN
Specification	Temper						
QQ-A-367 Forgings, Heat Treated	-T61	4(5)	-	70(P)	60(P)	14	140
			-	67(NP)	58(NP)	3	140

7079

CHEMICAL COMPOSITION - percent

Specification	Zn	Mg	Cu	Cr	Mn	Fe	Si	Ti	Others(1)	Al
All - see below	3.8-4.8	2.9-3.7	0.40-0.8	0.10-0.25	0.10-0.30	0.40	0.30	0.10	0.05 each 0.15 total	Balance

MECHANICAL PROPERTIES - minimum

Designation		Thickness inch	Area Sq. in.	Tensile Str ksi	Yield Str ksi	EL %	BHN
Specification	Temper						
		(Long traverse mechanical properties)				(16)	
QQ-A-250/17 Plate	-T6	0.040-0.249	-	72	62	8	
	-T6 and -T651	0.250-1.000	-	73	63	8	
		1.001-1.500	-	73	63	8	
		1.501-2.000	-	73	63	7	
		2.001-2.500	-	73	63	6	
		2.501-3.000	-	71	62	6	
		3.001-4.000	-	70	60	5	
		4.001-4.500	-	68	58	5	
		4.501-5.000	-	68	58	5	
		5.001-5.500	-	67	57	4	
		5.501-6.000	-	66	56	4	
	-F	0.250-6.000	-	- No requirements -			
		(Mechanical capabilities properties)					
	-T6 and -T651	3.001-4.000	-	70	60	6	
			-	65	56	2	
		4.001-4.500	-	68	58	6	
			-	63	54	2	
		4.501-5.000	-	68	58	5	
			-	63	54	2	
		5.001-5.500	-	67	57	4	
			-	62	53	2	
		5.501-6.000	-	66	56	4	
			-	61	52	2	
QQ-A-250/12 Plate and Sheet	-O	All	All	42 max	24 max	10	
	-T6	Up thru 0.249	Up thru 20	75	67	7	
	-T6510	0.250-0.499	Up thru 20	77	68	7	
	-T6511	0.500-1.499	Up thru 20	78	70	7	
		1.500-2.999	Up thru 20	79	70	7	
		3.000-4.499	Up thru 20	79	70	7	
			Over 20 thru 32	77	70	7	
			Over 32 thru 50	76	68	7	
		4.500-5.000	Up thru 38	78	68	6	
			Over 38 thru 60	76	68	6	
		5.001-5.999	Up thru 38	78	68	6	
			Over 38 thru 60	76	68	6	
		6.000-6.999	Up thru 50	76	66	6	
			Over 50 thru 60	74	64	4	
QQ-A-367 Forgings, Heat Treated	-T6	6(5)		(22, 4) 72(P)	(19, 4) 62(P)	10(6)	135
	-T6	6(5) Up to 6	Up to 72(22)	70(NP) 71(L) 69(LT) 65(ST)	60(NP) 62(L) 58(LT) 54(ST)	3(6) 9 6 4	135

7178

CHEMICAL COMPOSITION - percent

Specification	Zn	Mg	Cu	Cr	Mn	Fe	Si	Ti	Others(1)	Al
QQ-A-250/14	6.3-7.3	2.4-3.1	1.6-2.4	0.18-0.40	0.30	0.7	0.50	0.20	0.05 each 0.15 total	Balance

MECHANICAL PROPERTIES - minimum

Designation		Thickness	Area	Tensile Str	Yield Str	EL
Specification	Temper	inch	Sq. in.	ksi	ksi	% (16)
QQ-A-250/14 Plate and Sheet	-O	0.015-0.499	-	40 max	21 max	10
		0.500	-	40 max	--	10
	-T6	0.015-0.044	-	83	72	7
		0.045-0.499	-	84	73	8
		0.500-1.000	-	84	73	6
		1.001-1.500	-	84	73	4
		1.501-2.000	-	80	70	3
	-T651	0.250-0.499	-	84	73	8
		0.500-1.000	-	84	73	6
		1.001-1.500	-	84	73	4
		1.501-2.000	-	80	70	3
	-F	All	-	- No requirements -		

7178 Alclad

CHEMICAL COMPOSITION - percent

Specification	Zn	Mg	Cu	Cr	Mn	Fe	Si	Ti	Others(1)	Al
QQ-A-250/15 Core (7178)	6.3-7.3	2.4-3.1	1.6-2.4	0.18-0.40	0.30	0.7	0.50	0.20	0.05 each 0.15 total	Balance
Cladding (7072)	0.8-1.3	0.10	0.10	-	0.10	Fe & Si/0.7		-	0.05 each 0.15 total	Balance

MECHANICAL PROPERTIES - minimum

Designation		Thickness	Area	Tensile Str	Yield Str	EL
Specification	Temper	inch	Sq. in.	ksi	ksi	% (16)
QQ-A-250/15	-O	0.015-0.499	-	36 max	20 max	10
		0.500(11)	-	40 max	--	10
	-T6	0.015-0.044	-	76	66	7
		0.045-0.499	-	78	68	8
		0.500-1.000(11)	-	84	73	6
		1.001-1.500(11)	-	84	73	4
		1.501-2.000(11)	-	80	70	3
	-T651	0.250-0.499	-	78	68	8
		0.500-1.000(11)	-	84	73	6
		1.001-1.500(11)	-	84	73	4
		1.501-2.000(11)	-	80	70	3
	-F	All	-	- No requirements -		

7277

CHEMICAL COMPOSITION - percent										
Specification	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Others[(1)]	Al
MIL-R-12221	0.50	0.7	0.8-1.7	-	1.7-2.3	0.18-0.35	-	3.7-4.3	0.10	0.05 each 0.15 total	Balance

MECHANICAL PROPERTIES - minimum						
Designation Specification	Temper	Thickness inch	Area Sq. in.	Tensile Str ksi	Yield Str ksi	EL %
MIL-R-12221 Rivet, Solid, Tempered	-	-	-	-	-	-

X8280

CHEMICAL COMPOSITION - percent									
Specification	Sn	Cu	Ni	Si	Fe	Mn	Ti	Others[(1)]	Al
MIL-A-11267	5.5-7.0	0.7-1.3	0.20-0.7	1.0-2.0	0.7	0.10	0.10	0.05 each 0.15 total	Balance

MECHANICAL PROPERTIES - minimum						
Designation Specification	Temper	Thickness inch	Area Sq. in.	Tensile Str ksi	Yield Str ksi	EL %
MIL-A-11267 Sheet (For Recoil Mechanism Cup Rings)	-H12	-	-	18	15	4

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MILITARY HANDBOOK

TITANIUM AND TITANIUM ALLOYS

DEPARTMENT OF DEFENSE
UNITED STATES OF AMERICA

FSC 95GP

DEPARTMENT OF DEFENSE
WASHINGTON, D. C.

MIL-HDBK-697A
Titanium and Titanium Alloys
1 June 1974

1. This standardization handbook was developed for the Department of Defense in accordance with established procedure.

2. This publication was approved on 1 June 1974 for printing and inclusion in the military standardization handbook series.

3. This handbook provides basic and fundamental information on titanium and titanium alloys for the guidance of engineers and designers of military materiel. This handbook is not intended to be referenced in purchase specifications except for informational purposes, nor shall it supersede any specification requirements.

4. Every effort has been made to reflect the latest information on titanium and titanium alloys. It is the intent to review this document periodically to insure its completeness and currency. Users of this document are encouraged to report any errors discovered and recommendations for changes or inclusions to the Director, US Army Materials and Mechanics Research Center, Watertown, Massachusetts 02172, ATTN: AMXMR-MS.

PREFACE

This is one of a group of handbooks covering metallic and nonmetallic materials used in the design and construction of military equipment.

The purpose of this handbook is to provide, in condensed form, technical information and data of direct usefulness to design engineers. The data, especially selected from a number of government and industrial publications, have been checked for suitability for use in design. Wherever practicable, the various types, classes, and grades of materials are identified with applicable government specifications. The corresponding technical society specifications and commercial designations are shown for information.

The numerical values for properties listed in this handbook, which duplicate specification requirements, are in agreement with the values in issues of the specifications in effect at the date of this handbook. Because of revisions or amendments to specifications taking place after publication, the values may, in some instances, differ from those shown in current specifications. In connection with procurement, it should be understood that the governing requirements are those of the specifications of the issue listed in the contract.

This revision of the handbook was prepared by the Metals and Ceramics Information Center of Battelle Columbus Laboratories and the Army Materials and Mechanics Research Center. Comments on this handbook are invited. They should be addressed to Director, US Army Materials and Mechanics Research Center, Watertown, Massachusetts 02172, ATTN: AMXMR-MS.

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SECTION I

GENERAL INFORMATION

Titanium in Engineering Design

1. General Characteristics. Titanium and titanium alloys are used in engineering design chiefly for their excellent combination of mechanical properties coupled with low density and their corrosion resistance. Other advantages of titanium for specific applications include: low coefficient of thermal expansion, good oxidation resistance at intermediate temperatures, low magnetic permeability, high toughness, and low heat-treating temperature during hardening. Alloying may be used to enhance selected properties of titanium and many alloys can be strengthened by processing and heat treatment. Although about 40 percent lighter than steel, certain titanium alloys can be equated on a strength-to-weight basis to steels having yield strength levels of about 300 ksi. Compared to aluminum, titanium alloys (60 percent heavier than aluminum) are much stronger, are useful to much higher temperatures and show higher fatigue resistance and greater hardness. A wide range of physical and mechanical properties are available from titanium and its alloys.

Table I compares some of the physical properties of titanium with those of other pure metals. As mentioned above, a low density, intermediate to aluminum and steel, and a low coefficient of thermal expansion are properties of titanium that can be used to afford unique advantages for some applications. The elastic modulus of titanium, also intermediate to aluminum and steel, can be used to advantage in certain applications (e.g. torsion bars and springs). Another physical characteristic of titanium is its transformation from one crystal morphology, body-centered-cubic to another hexagonal-close-packed (hcp) at about 1625 F (885 C). The transformation is reversible. The hcp form is the stable structure at room temperature although the bcc form can be stabilized by alloying. The processing and heat treatment of titanium alloys are inevitably involved with the transition behavior and the two basic structures or phases, hcp (alpha) and bcc (beta).

The secondary processing of titanium or alloys that might be required by the fabricator of end-use items usually may be accomplished without difficulty by the experienced shop. There are of course certain precautions to be observed which are described in more detail in later sections. For example, the preservation of properties imparted by primary processing (at the titanium producers shop) must be a consideration during any secondary fabrication, heat treatment, and finishing operations. Forming, joining (titanium can be welded or joined by several other methods), heat treatment, and machining operations must follow procedures which allow for the physical characteristics common to the metal.

Titanium is strain-rate sensitive. For example, mechanical properties may vary greatly with different speeds of testing. Strain-rate sensitivity also must be given consideration in part-forming operations. For example some complex parts can be formed at a low strain rate which would be impossible to form at a high strain rate. A strain rate of 0.005 in./in./min. is generally accepted as standard for tensile testing.

TABLE I. PHYSICAL PROPERTIES OF TITANIUM AND OTHER PURE METALS

Properties	Titanium (99.9%)	Iron (99.9+%)	Aluminum (99.996%)	Magnesium (99.98%)	Copper (99.95%)
Atomic Number	22	26	13	12	29
Atomic Weight (based on Carbon = 12)	47.90	55.85	26.98	24.312	63.54
Density (lb/cu. in) at 68°F (20°C)	0.163	0.284	0.098	0.063	0.323
Liquidus Temperature, °F	3035±18	2797.7±1.8	1220.4	1202	1981.4±0.2
Liquidus Temperature, °C	1668±10	1536.5±1	660.2	650	1083.0±0.1
Transformation Temperature, °F	1625(a)	1670(b)	None	None	None
Magnetic Susceptibility(c)	Para(d)	Ferro	Para	Para	Dia
Tensile Modulus, psi x 10^6	14.7	29.7	10.0	6.25	16.0
Shear Modulus, psi x 10^6	5.0	10.0	3.8	2.4	6.0
Thermal Expansion (10^{-6} in./in./°F at 68°F)	4.67	6.8	13.1	14.0	9.4
Thermal Conductivity (Btu/Hr/ft^2/°F/ft)	9	46	117	56	226
Specific Heat (Btu/lb/°F) at RT	0.126	0.107	0.215	0.246	0.092
Electric Resistivity (microhm–cm at RT)	47.8	10.0	2.824	4.6	1.724
% IACS(e)	3.6	17.2	61.1	38.7	100

Note:

(a) Titanium is hcp at <1625 F and bcc at >1625 F.

(b) Iron is bcc at <1670 F and fcc between 1670 and 2535 F.

(c) Paramagnetic = slightly more permeable than a vacuum and independent of magnetizing force.
Diamagnetic = less permeable than a vacuum and *weakly repelled* by magnetic force.
Ferromagnetic = strongly magnetic and dependent of magnetizing force.

(d) Susceptibility of titanium is 3.17 x 10^{-6} emu/g. Permeability is 1.00005 at 20 oersteds.

(e) Percent International Annealed Copper Standard at 20°C. (Measure of electrical conductivity)

The high friction characteristics of titanium and associated wear can present somewhat of a problem in certain applications. However, specialized coatings and lubricants have been developed to greatly alleviate galling and other difficulties in selected applications. Each application, where titanium would be subject to friction wear, should be analyzed to determine the optimum system to be used.

Normally, protective coatings to eliminate corrosion effects are not required for titanium. The ever present oxide surface affords ample protection in most ambient environments and in a wide range of corrosive media. In cases where coatings are needed, such as for protection against friction wear, erosion, and elevated temperature corrosion, specific materials and techniques have been employed for specific applications. Decorative or other nonservice required coatings can also be applied.

The relative price of titanium and its alloys is an important consideration in design applications. Although the initial unit price of titanium may be considered high, weight savings, superior corrosion resistance, and other design factors may warrant its selection over other structural materials for a given job. Indeed, for certain applications, weight savings resulting in increased payload can more than offset initial costs and perhaps in the long run prove less costly than lower priced materials.

2. Titanium Alloy Availability – Designations. The titanium industry of the United States did not achieve significant size until the late 1950's. However, it was an important industry from the viewpoint of its military potential and received considerable industrial and governmental research and development funding. This support stimulated steady growth and generated an advanced titanium technology. During the course of its existence, the industry has developed about 50 different grades and compositions which have been described as commercial. Approximately 30 alloy compositions and unalloyed grades of titanium are currently commercially viable. These are listed in Table II. Table III gives typical producer company designations for these alloys.

As shown in Table II, the major types of titanium alloys are: alpha, alpha-beta, and beta. Other types are known as near-alpha, near-beta, and alpha-dispersoid types. As the type names suggest, the classification is based on the dominant microstructural features of the alloys. For example, unalloyed titanium grades are predominantly of hcp (alpha phase) structure, beta alloys are bcc (beta phase), and a host of compositions are of mixed hcp and bcc structure (alpha plus beta phases). Alpha-dispersoid types have intermetallic compound phase interspersed with the alpha matrix phase. Several other alloys (notably those containing silicon) also can exhibit intermetallic phase in the microstructure.

Aluminum and oxygen are the alloy additions capable of stabilizing the alpha phase in titanium and in general increasing amounts of these elements result in the stabilization of increasing amounts of the alpha phase. Beta stabilizing additions such as vanadium, molybdenum, manganese, iron and chromium, cause the stabilization of the beta phase generally proportional to the amount of beta addition used but subject to modification by the amount of alpha stabilizers combined in the alloy. Most of the commercial alloys have combinations of alpha stabilizing and beta stabilizing additions to impart the characteristics desired.

The many alloys available collectively provide a very wide range of mechanical and physical properties suitable for many applications. Some alloys, for example 5621S, were formulated specifically to have good elevated temperature characteristics (e.g. creep strength). Others for example Beta III and Ti-8Mo-8V-2Fe-3Al, were designed for improved combinations of formability, deep hardenability, and high strength. Some alloys, for example Ti-6Al-4V, are very versatile,

TABLE II. TITANIUM ALLOYS OF CURRENT GENERAL INTEREST

Nominal Composition, wt %	Alloy Type	Common Name(a)
Unalloyed Ti, ~99.5(b)	Alpha	CP
Unalloyed Ti, ~99.2(b)	Alpha	CP
Unalloyed Ti, ~99.01(b)	Alpha	CP
Ti-0.15 to 0.20 Pd	Alpha	Pd alloy
Ti-5A1-2.5Sn(c)	Alpha	A-110
Ti-1 to 2Ni	Alpha-dispersoid	––
Ti-2Cu	Alpha-dispersoid	––
Ti-2.25A1-11Sn-5Zr-1Mo-0.2Si	Near-alpha	679
Ti-5A1-6Sn-2Zr-1Mo-0.25Si(d)	Near-alpha	5621S
Ti-6A1-2Sn-1.5Zr-1Mo-0.35Bi-0.1Si	Near-alpha	Ti-11
Ti-6A1-2Cb-1Ta-0.8Mo	Near-alpha	6-2-1-1
Ti-8A1-1Mo-1V	Near-alpha	8-1-1
Ti-8Mn	Alpha-beta	8Mn
Ti-3A1-2.5V	Alpha-beta	3-2.5
Ti-4A1-3Mo-1V	Alpha-beta	4-3-1
Ti-5A1-2Sn-2Zr-4Mo-4Cr	Alpha-beta	Ti-17
Ti-6A1-4V(c)	Alpha-beta	6-4
Ti-6A1-6V-2Sn	Alpha-beta	6-6-2
Ti-6A1-2Sn-4Zr-2Mo(e)	Alpha-beta	6-2-4-2
Ti-6A1-2Sn-4Zr-6Mo	Alpha-beta	6-2-4-6
Ti-6A1-2Sn-2Zr-2Mo-2Cr-0.2Si	Alpha-beta	6-2-2-2-2
Ti-7A1-4Mo	Alpha-beta	7-4
Ti-1A1-8V-5Fe	Near-beta	185
Ti-2A1-11V-2Sn-11Zr	Beta	Transage 129
Ti-3A1-8V-6Cr-4Mo-4Zr	Beta	Beta C
Ti-4.5Sn-6Zr-11.5Mo	Beta	Beta III
Ti-8Mo-8V-2Fe-3A1	Beta	8-8-2-3
Ti-13V-11Cr-3A1	Beta	13-11-3

Note:

(a) Producer nomenclature varies since some companies use a code for designating products while others use logical symbols such as the company name followed by the composition in alphanumeric form. See Table 3 for guidance.
(b) Several grades of unalloyed titanium are produced which differ in impurity level, hence strength and ductility.
(c) High-purity grades of these alloys are available and are designated with the suffix ELI, meaning Extra Low Interstitials.
(d) A modification of this alloy, Ti-5A1-5Sn-2Zr-2Mo-0.25Si, may become commercial.
(e) A silicon-containing grade of 6-2-4-2 is also available.

TABLE III. TYPICAL DESIGNATIONS FOR TITANIUM ALLOYS OF COMMERCIAL INTEREST

Nominal Composition, wt %	Crucible(a)	Martin(b)	RMI(c)	TIMET(d)	Other
Unalloyed Ti, ~99.5	A-40	MMA-1940	RMI 40	Ti-35A	Armco Ti-40(e)
Unalloyed Ti, ~99.2	A-55	MMA-1950	RMI 55	Ti-65A	--
Unalloyed Ti, ~99.0	A-70	MMA-1970	RMI 70	Ti-75A	--
Ti-0.15 to 0.20 Pd	--	MMA-1942	RMI 0.2 Pd	Ti-0.20 Pd	TiTech 0.2 Pd(f)
Ti-5Al-2.5Sn	A-110AT	MMA-5137	RMI 5Al-2.5Sn	Ti-5Al-2.5Sn	--
Ti-1 to 2 Ni	--	--	--	Ti-2Ni	Company name preceding alloy composition or Company name symbol preceding alloy composition
Ti-2Cu	--	--	RMI 2Cu	--	
Ti-2.25Al-11Sn-5Zr-1Mo-0.2Si	--	--	--	Ti-679	
Ti-5Al-6Sn-2Zr-1Mo-0.25Si	--	--	RMI 5Al-6Sn-2Zr-1Mo-Si	--	
Ti-6Al-2Sn-1.5Zr-1Mo-0.35Bi-0.1Si	--	--	--	Ti-11	
Ti-6Al-2Cb-1Ta-0.8Mo	--	--	RMI 6Al-2Cb-1Ta-1Mo	--	
Ti-8Al-1Mo-1V	8Al-1Mo-1V	MMA-8116	RMI 8Al-1Mo-1V	Ti-8Al-1Mo-1V	
Ti-8Mn	C-110M	--	RMI 8 Mn	Ti-8Mn	
Ti-3Al-2.5V	3Al-2.5V	MMA-3138	RMI 3Al-2.5V	Ti-3Al-2.5V	
Ti-4Al-3Mo-1V	--	--	RMI 4Al-3Mo-1V	--	
Ti-5Al-2Sn-2Zr-4Mo-4Cr	--	--	--	Ti-17	--
Ti-6Al-4V	C-120AV	MMA-6510	RMI 6Al-4V	Ti-6Al-4V	Tel-Ti-6Al-4V(g)
Ti-6Al-6V-2Sn	C-125AVT	MMA-5158	RMI 6Al-6V-2Sn	Ti-6Al-6V-2Sn	--
Ti-6Al-2Sn-4Zr-2Mo	6Al-2Sn-4Zr-2Mo	MMA-9744	RMI 6Al-2Sn-4Zr-2Mo	Ti-6Al-2Sn-4Zr-2Mo	Sometimes alloy designation is entirely in symbols
Ti-6Al-2Sn-4Zr-6Mo	--	MMA-6246	RMI 6Al-2Sn-4Zr-6Mo	Ti-6Al-2Sn-4Zr-6Mo	
Ti-6Al-2Sn-2Zr-2Mo-2Cr-0.2Si	--	--	RMI 62222S	--	
Ti-7Al-4 Mo	--	MMA-7146	RMI 7Al-4Mo	Ti-7Al-4Mo	
Ti-1Al-8V-5Fe	--	--	RMI 1Al-8V-5Fe	--	
Ti-2Al-11V-2Sn-11Zr	--	--	--	--	Transage 129, Experimental
Ti-3Al-8V-6Cr-4Mo-4Zr	--	--	RMI 38-6-44	--	Allvac Ti-3-8-6-4-4(h)
Ti-4.5Sn-6Zr-11.5Mo	Beta III	--	--	--	--
Ti-8Mo-8V-2Fe-3Al	--	--	--	Ti-8Mo-8V-2Fe-3Al	--
Ti-13V-11Cr-3Al	B-120VCA	--	RMI 13V-11Cr-3Al	Ti-13V-11Cr-3Al	OMC-VCA(i)

Note:

(a) Crucible, Inc., subsidiary of Colt Industries.
(b) Martin Marietta Aluminum, Titanium Division.
(c) RMI Company (formerly Reactive Metals, Inc.).
(d) TIMET Division, Titanium Metals Corporation of America (TMCA).
(e) Armco Steel Corporation, Advanced Materials Division (Armco).
(f) TiTech International, Inc. (TiTech).
(g) Teledyne Titanium, Inc. (Teledyne Ti).
(h) Teledyne Allvac (Allvac).
(i) Oregon Metallurgical Corporation (Oremet).
(j) The companies providing the high-purity grades of Ti-5Al-2.5Sn and Ti-6Al-4V alloys (and sometimes others) designate such grades with the suffix ELI, meaning Extra Low Interstitials.

having properties intermediate to some of the specialty alloys but having broad utility in part due to the intermediacy. The Ti-6Al-4V alloy is in fact the most widely used titanium alloy (>50%) with the next most used titanium materials being the unalloyed grades (~20%). The next most used materials are the Ti-5Al-2.5Sn and Ti-6Al-6V-2Sn alloys (~7% each) and all other alloys are used to a lesser extent. In selecting an alloy for a particular application, it is good practice to not only examine and match the properties available for a material with the requirements but to discuss the selection with producers.

3. Availability of Titanium-Forms and Sizes. A wide range of unalloyed and alloyed titanium mill products, castings, and powder-metallurgy products are produced by the industry. However, not all forms and sizes of products are available for each alloy or grade of titanium available and no single company produces a full range of products. On the other hand, individual product forms are usually available from a number of sources. Thus this section is offered to afford the titanium user guidance in determining certain limitations and restrictions concerning product availability.

The basic titanium product is called sponge titanium because lumps of metal extracted from the primary titanium ore (rutile, TiO_2) have the porosity of sponges. (Other ores such as ilmenite, are used in addition to rutile by foreign sponge producers.) The Kroll Process (named for Dr. Wilhelm Kroll) is used by the commercial producers to win titanium from rutile. This process is a batch operation requiring stringent control in order to maintain purity. Titanium sponge is subject to atmospheric contamination unless suitably protected. Sponge is subsequently purified and compacted into electrodes for melting and remelting in the production of ingot (or casting). Titanium metal production, from ore to final ingot, usually follows the basic steps outlined below and is shown schematically in the illustration of Figure 1.

<u>Chlorination</u>—Rutile ore is reacted with chlorine gas and carbon at elevated temperatures to yield titanium tetrachloride ($TiCl_4$), a colorless liquid, and the carbon gases (CO, CO_2) according to the following reactions:

$$TiO_2 + 2Cl_2 + C \qquad TiCl_4 + CO_2 + \text{heat}$$

$$TiO_2 + 2Cl_2 + 2C \qquad TiCl_4 + 2CO + \text{heat}$$

As indicated, these reactions are exothermic and are carefully conducted in large reaction vessels to produce as pure an intermediate product ($TiCl_4$, sometimes called "tickle") as possible. Additional purification of "tickle" in distillation towers is usually necessary.

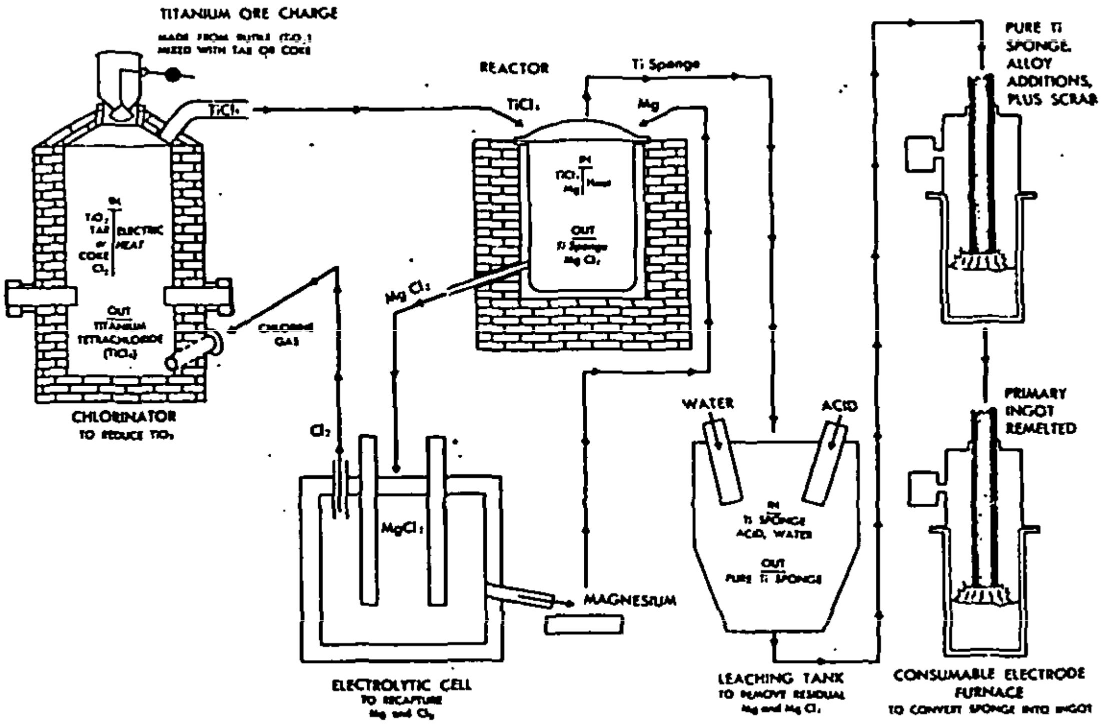
<u>Magnesium Reduction</u>—The $TiCl_4$ is combined with molten magnesium metal in a steel reactor under a controlled atmosphere to yield titanium metal in sponge form. Magnesium chloride ($MgCl_2$) is a byproduct. (The $MgCl_2$ is electrolyzed to recapture chlorine gas and magnesium metal, both of which are recycled through the process). The reactions are:

$$TiCl_4 + 2Mg \qquad Ti + 2MgCl_2$$

$$MgCl_2 \text{ (by electrolysis)} \qquad Mg + Cl_2$$

Sodium instead of magnesium is used in the same type of reactions by some producers of titanium.

<u>Purification</u>. Titanium sponge is placed in leaching tanks where acid and water remove trace quantities of magnesium chloride and residual magnesium. Another method of removing these impurities from sponge is vacuum distillation. Producers of titanium sponge in the Soviet Union



Courtesy of Titanium Metals Corporation of America

FIGURE 1. Titanium Processing from Ore to Ingot

and Japan make a very high quality product by this method. Considerable quantities of foreign produced sponge titanium are imported by the United States.

Melting. — Sponge titanium may be compacted as the only constituent to make electrodes for producing ingots, or, if an alloy is desired, sponge is mixed with other metallic ingredients before compacting electrodes for the melting operation. An electric arc-melting process converts the compacted electrode (consumable electrode) into a primary ingot which, in turn, is remelted into a final ingot (triple melting may be used to produce a premium quality ingot). Another method of making primary ingot, that of melting sponge, alloy additions, or scrap, by continuously feeding small uncompacted particles of the charge into the molten pool of metal created by the arc, is used by some ingot producers. In either method, melting is accomplished in vacuum furnaces which removes volatile impurities such as hydrogen and residual $MgCl_2$.

The typical titanium product forms manufactured from domestic and foreign sponge by the U. S. industry are listed in Table IV. It is to be noted that this is a typical listing and does not include all products that can be made, for example, on special order. To illustrate some exceptions, wire of Ti-5Al-2.5Sn and Ti-8Al-1Mo-1V alloys, extrusions of Ti-4Al-3Mo-1V alloy, and castings of Ti-11.5Mo-6Zr-4.5Sn alloy can and have been produced. Inquiries to producers should be made to determine current availability of unlisted products for any desired material.

TABLE IV. TYPICAL TITANIUM PRODUCT FORMS

Nominal Composition, wt %	Typical Product Forms(a)
Unalloyed Ti, ~99.5(b)	All forms are available
Unalloyed Ti, ~99.2(b)	in unalloyed
Unalloyed Ti, ~99.0(b)	grades
Ti-0.15 to 0.20 Pd	All forms
Ti-5Al-2.5Sn(c)	I, B, b, P, S, E, C
Ti-1 to 2 Ni	B, b, P, S
Ti-2Cu	B, b, P, S
Ti-2.25 Al-11Sn-5Zr-1Mo-0.2Si	I, B, b, P, S
Ti-5Al-6Sn-2Z4-1Mo-0.25Si	I, B, b, P, S
Ti-6Al-2Sn-1.5Zr-1Mo-0.35Bi-0.1Si	I, B, b
Ti-6Al-2Cb-1Ta-0.8Mo	I, B, b, P
Ti-8Al-1Mo-1V	I, B, b, P, S, E
Ti-8Mn	I, S, s
Ti-3Al-2.5V	S, s, f, T
Ti-4Al-3Mo-1V	P, S, s
Ti-5Al-2Sn-2Zr-4Mo-4Cr	I, B, b
Ti-6Al-4V(c)	All forms
Ti-6Al-6V-2Sn	I, B, b, P, S, E
Ti-6Al-2Sn-4Zr-2Mo	I, B, b, P, S, E
Ti-6Al-2Sn-4Zr-6Mo	I, B, b, P, S
Ti-6Al-2Sn-2Zr-2Mo-2Cr-0.2Si	B, b, P
Ti-7Al-4Mo	I, B, b, P
Ti-1Al-8V-5Fe	I, B, b, w
Ti-2Al-11V-2Sn-11Zr	B, b, P
Ti-3Al-8V-6Cr-4Mo-4Zr	B, b, w, P, S, s, f, T
Ti-4.5Sn-6Zr-11.5Mo	B, b, w, P, S, s, f, T
Ti-8Mo-8V-2Fe-3Al	I, B, b, w, P, S, s, f, T
Ti-13V-11Cr-3Al	I, B,b, w, P, S, s, f, T

Note:

(a) I = ingot bloom, B = billet, b = bar, w = wire,
P = plate, S = sheet, s = strip, f = foil,
E = extrusion, T = tubing, C = casting.

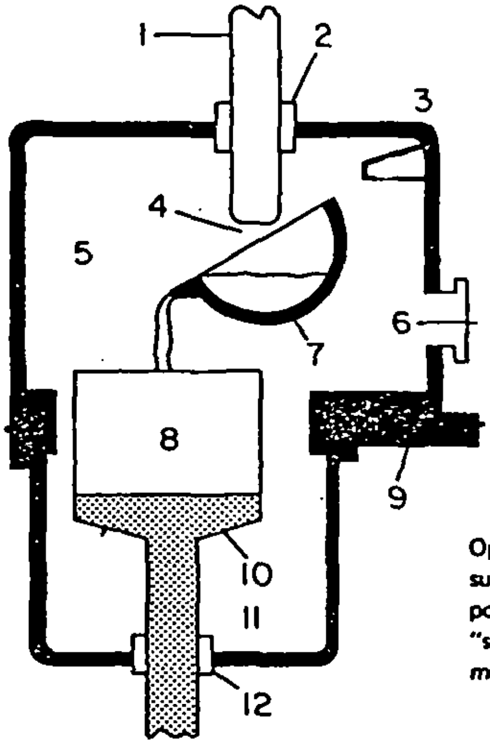
(b) There are several unalloyed titanium grades available.

(c) High purity grades of these alloys are available and are designated with the suffix ELI, meaning Extra Low Interstitials.

Ingots. – The largest titanium ingot produced to date was about 40 inches in diameter and weighed about 11 tons (Krupp, West Germany in 1966). However, more commonly, ingots of ~30 inches in diameter x ~10,000 pounds and ~15,000 pounds are produced domestically. Smaller ingots are also produced. Ingots are usually converted into castings or mill product forms prior to sale to the major users of titanium.

Castings. – Titanium castings are produced by remelting ingot or billet (used as electrode) in so-called skull-type vacuum furnaces having the general arrangement shown in Figure 2. The casting producing companies differ in their operations and capabilities due to types of molds used and equipment size. They may be considered in two categories: (1) those that use investment molds, and (2) those that use rammed graphite molds. Investment casting techniques can potentially produce more intricate parts, closer tolerances, and better as-cast surface finishes. The rammed graphite process, because of greater flexibility in gating and risering, is potentially capable of producing castings having better internal quality, higher mechanical properties, larger cast configurations, and lower costs. However, no one process is superior to the other; both have their place and both fill specific needs.

Rammed-graphite-mold castings can and have been made in quite large sizes. A 2400-pound pour can be made to yield castings of up to 2000 pounds (balance of metal in gates and risers). Large castings have a maximum dimension of 100 inches. The more common size limitations of rammed-graphite-mold castings are 400 pounds with dimensions fitting within a 52-inch diameter x 32 inch high envelope. Intricate shapes as well as preform shapes for forgings (e.g., engine rings) are made in this type mold.



1. Consumable or nonconsumable electrode
2. Vacuum seal
3. Material feed
4. Arc
5. Furnace chamber
6. Vacuum
7. Tiltable melting crucible
8. Mold
9. Valve body
10. Mold table
11. Mold chamber
12. Vacuum seal

Operation. Electrode is rapidly melted into 7. to obtain a superheated titanium or alloy pool which is then immediately poured. About one-quarter of the melt is retained as a "skull", lining the interior of 7. Hence the name, "skull melting".

FIGURE. 2. General Arrangement and Operation of Melting Furnace and Casting Apparatus Used by Titanium Casting Foundries

Investment-mold castings have been produced in much smaller sizes than rammed-graphite-mold castings. Maximum weights of about 50 pounds and maximum envelopes of about 2 x 2 x 2 feet are offered. Wall thickness limitations of investment-mold castings are about half of rammed-graphite-mold castings (0.050-inch compared with 0.10 inch) and surface finish potential is better for investment-mold castings. Intricate shapes with good dimensional tolerances are possible with investment-mold castings. The mechanical properties of castings produced by either of the available techniques are not quite as good as those of most wrought mill products.

Forgings, Billets. — Ingots are converted to ingot-bloom, billet, or bar, and these are offered by the primary titanium producers (the melters) for secondary processing. While each of the major titanium producers has forging capability, most of the forgings produced are made by companies specializing in this aspect of the titanium business (e.g., Wyman-Gordon Company). Forged billets generally have a cross-sectional area of 16 square inches or more and are available in rounds, squares, rectangles, and octagons. Forged shapes may be produced by hammer, press, or ring-roll type operations and are usually classified into four dimensional tolerance groups. (1) blocker, (2) conventional, (3) close, and (4) precision. Table V gives examples of the types of forging shapes commonly produced and the availability of such shapes in the various tolerance categories. Forgings as large as 4000 pounds and 22 feet long or as small as under one pound have been made. Details for determining shape, size, and tolerance limitations can be obtained from numerous forging companies experienced in working with titanium.

TABLE V. AVAILABILITY OF TITANIUM ALLOYS IN FORGINGS BY SHAPE AND TOLERANCES

[Forgings classified by dimensional tolerance]

Forged Shape	Availability[(a)]			
	Blocker-Type Tolerances	Conventional Tolerances	Close Tolerances	Precision Tolerances
Disks	A	A	L	LS
Cones	A	A	L	U
Hemispheres	A	A	L	U
Cylinders	A	A	L	U
Blades	A	A	A	A
Airframe (fittings)	A	A	A	LS
Airframe (rib and web)	A	A	L	LS
Rings	A	A	L	U

Note:

(a) Code:
A = Readily available
L = Limited availability
LS = Limited availability = small parts only
U = Virtually unavailable

Bar, Rod and Wire. — Bar and rod are available in rounds, hexagonals, squares, and rectangles. Rolled bar, which has a cross-sectional area ranging from 16 square inches down to about 1.4 square inches, has a length restriction because of annealing-furnace limitations. Lengths up to 90 feet are possible, but the usual lengths produced are 16 to 25 feet. Round bars having diameters less than 0.3125 inch are priced as wire: coil lengths in the smaller diameters range between 300 and 500 feet.

Rods and bars are frequently converted to end-use items by forging and machining or simply by machining. Wire is produced for use as weld-filler and for such end-use items as springs and fasteners. Most alloys are available in bar and rod form but several alloys are not routinely available in wire form.

Plate, Sheet, Strip and Foil. — Plate, sheet, and strip are flat-rolled products available in many alloy grades and from several producers. Foil is a specialty product available in just a few alloys and unalloyed titanium. Plate is generally defined as 0.1875 inch or more in thickness and commonly in sizes listed below.

Thickness, inch	Width x Length, inches
0.1875-0.249	100 x 420
0.250-0.374	110 x 420
0.375-0.499	120 x 450
0.500-0.749	130 x 480
0.750-0.999	140 x (a)
1.0 and up	145 x (a)

(a) Any practical length within ingot size limitations.

The thickness and flatness tolerances of alloy plate are given in Table VI.

Flat-rolled titanium products are priced as sheet if width is 24 inches or greater and thickness is less than 0.1875 inch. The product is priced as strip when it is less than 24 inches in width. The availability of sheet and strip with regard to size and some alloy limitations is indicated by the data of Table VII. Note that in the thinner gages, and this is especially true for foil gages (<0.008 inch thickness), only unalloyed titanium and a few of the alloys are available in this form.

Extruded Shapes. — Extruded shapes are currently supplied in a wide variety of configurations, although most of these are basic angle, tee, or channel shapes. Section thicknesses generally vary from 0.125 to 1.25 inches within circumscribing circles of 1.50 to 11.0 inches in diameter. Most shapes, however, fit within a 3- to 5-inch-diameter circle. Lengths usually supplied in the annealed condition vary between 20 and 75 feet. Lengths up to 40 feet can be supplied in the solution-treated-and-aged (STA) condition. In the present state of development, as-extruded titanium alloys are not of requisite quality for direct use because of surface roughness or surface contamination. Thus, extruders supply product in an oversize condition to allow a suitable envelope for machining to final size and acceptable surface finish. Minimum envelope requirements vary with users. Some allow as little as 0.020 inch excess per surface while others require as much as 0.125 inch excess per surface. Part design and application influence these requirements. Research and development efforts are continuing towards the goal of supplying net extrusions of acceptable surface finish and precision dimensional tolerances. Redrawing, straightening, and heat treatment techniques are a part of this development effort.

TABLE VI. TYPICAL THICKNESS AND FLATNESS TOLERANCES OF CURRENT TITANIUM PLATE

	Thickness Tolerance, in.		Variation from Flat Surface, in.[a]	
Plate Thickness, in.	Width	Thickness Overage	Width	Variation in 15 feet
0.1875 to 0.375	Max available	0.050	Up to 48	0.75
0.375 to 1.00	Max available	0.060	Up to 48 48 to 76	0.50 0.62
1.00 to 2.00	Max available	0.070	Up to 48 48 to 76	0.5 to 0.2[b] 0.6 to 0.3[b]

Note:

(a) Plate of special flatness (0.060 inch measured anywhere) is available by the Vacuum Creep Flattening (VCF) process.

(b) Flatness increases with increasing thickness and decreases with increasing plate size.

TABLE VII. AVAILABILITY OF TITANIUM-ALLOY SHEET AND STRIP[a,b]

Thickness, in.	Maximum Width, in.	Maximum Length, in.
0.008-0.012	26	Coil[c]
0.012-0.016	30	Coil[c]
0.016-0.020	36	Coil[c]
0.020-0.032	44	Coil[c]
	48	120-144
0.032-0.060	44	Coil[c]
	48	144
0.060.-0.187	48	144

Note:

(a) Unalloyed grades are generally available in greater widths at thinner gages than alloy grades.

(b) Tolerances for all gages meet AMS 2242 specifications.

(c) Coil only available in select grades, i.e., unalloyed Ti, Ti–5Al–2.5Sn, Ti–6Al–4V, and beta alloys.

Tubing. – Seamless tubing is produced in unalloyed titanium, Ti-3Al-2.5V and Ti-6Al-4V (in some sizes) commercially, and in such beta alloys as Ti-11.5Mo-6Zr-4.5Sn and Ti-3Al-8V-6Cr-4Mo-4Zr on a developmental basis. Seamless tubing is produced from extruded tube hollows and is sized to finish dimensions by drawing or tube reducing operations (usually cold worked with intermediate annealing).

Unalloyed titanium seamless tubing is available in diameters ranging from 0.062 inch to several inches (>8<36) with wall thickness as low as 0.004 inch in the smaller diameters (large diameter tubes can only be supplied in thick wall sizes). Diameters of 0.75 to 1.00 inch with wall thicknesses ranging from 0.03 to 0.04 inch are the most used. Seamless alloy tubing is supplied in a more restricted size range: the Ti-3Al-2.5V alloy, for example, is available in tube form in diameters of 0.25 inch to 1.75 inch with wall thicknesses between 0.012 to 0.030 inch. Lengths up to 34 feet as vacuum annealed are available. The Ti-3Al-2.5V alloy is available in quality sufficient to meet aircraft hydraulic tubing specifications.

In addition to seamless tubing, an important supply of rolled and welded tube (with longitudinal seam weld) is available. Suppliers can provide both unalloyed and alloyed (Ti-6Al-4V is common) rolled and welded tubing in sizes ranging from 1 to 10 inches diameter with wall thicknesses between 0.012 to 0.168 inch. Generally only the most weldable and stable-after-welding titanium alloys are available such as Ti-6Al-4V, Ti-3Al-2.5V, Ti-5Al-2.5Sn, Ti-8Al-1Mo-1V, and Ti-6Al-2Sn-4Zr-2Mo compositions. Structural members and corrosion resistant piping commonly utilize roll and weld tubing.

Powder Metallurgy Products. – Unalloyed and alloy titanium powders are made by several different processes including mechanical attrition, gas attrition, chemical reduction, hydride-dehydride, and comminution from the molten state – e.g., powder-size droplets from a rotating electrode. Alloy powders also may be obtained by blending unalloyed titanium powder with powders of the desired elements. End-use products are made by die pressing the powders to shape and subsequently sintering such compacts or by simultaneously hot pressing and sintering the powders. Research also has been conducted in producing forged products from pressed and sintered powder preforms. The latter products approach full theoretical density and have mechanical properties equivalent to wrought metal properties provided the powder used is of highest quality (oxygen as a contaminant is one of the problems with powders). The principal reason for the quest for product via powder metallurgy is cost reduction since net shapes can be produced without high associated scrap losses and machining time. However, except for some specialized purposes and parts such as porous titanium filtering elements, titanium hardware via powder metallurgy techniques has never materialized as a major segment of the titanium industry. Currently, quality titanium end-use items can be made at reasonable costs but the method is not popular for producing hardware.

SECTION II

SPECIFICATIONS AND PROPERTIES

Titanium Materials Specifications

4. General. Both the Government and nongovernment technical societies issue specifications for titanium and titanium alloys. This section covers the current specifications for titanium materials prepared by the Government (MIL specifications), by the American Society for Testing and Materials (ASTM specifications), the Aerospace Materials Specifications (AMS) issued by the Society of Automotive Engineers (SAE) and by the American Welding Society (AWS specifications).

5. Military Specifications. Specifications prepared by the Government on titanium materials are listed in Table VIII, and are described in the following paragraphs. It should be noted that military specifications currently in force have different preparation and coordination dates, include limited coordination specifications as well as fully coordinated specifications, and are inconsistent one from another in alloy coverage and composition designations. Further, some of the titanium materials currently being produced are not included in any military specification. Additionally, specifications include alloys not now being produced or much used. Therefore, in an effort to relate currently available titanium materials with the descriptions and designations offered in some of the important military specifications, the correlation tabulation of Table IX is given. This table does not include composition designations from MIL-T-46035 and MIL-T-46038 because no specific compositions are described therein. Similarly, titanium materials (sponge and powder) are described generally in MIL-T-13405C. The table also does not include designations from MIL-T-46077 since it refers specifically to the Ti-6Al-4V alloy which is not otherwise designated. Specifications, standards, etc., required by suppliers in connection with specific procurement functions should be obtained from the procuring activity or as directed by the contracting officer.

a. MIL-R-81588 (22 July 1970). — Rods and Wire, Welding, Titanium and Titanium Alloys. This specification covers the requirements for bare titanium and titanium alloy filler rods and wire suitable for use with gas-tungsten arc (GTA) or gas-metal-arc (GMA) welding processes. Alloy types and compositions are given in Table IX. Chemical composition requirements and form, size and weight requirements are given.

b. MIL-T-13405C (27 May 1966) — Titanium Powder. This specification covers one type and one grade of titanium powder which is intended for use in pyrotechnic mixtures. This grade of titanium powder is not intended for use in manufacturing structural titanium parts by powder metallurgy techniques.

c. MIL-T-009047F (25 March 1971) and Amendment No. 1 (19 September 1972) — Titanium and Titanium Alloy Bars and Forging Stock. This specification has not been approved for promulgation as a coordinated revision of MIL-T-9047E (i.e., it is subject to modification). However it may be used in procurement of aircraft quality wrought titanium and titanium alloy bars, billets, slabs and forging stock in lieu of MIL-T-9047E since it describes the same materials under identical designations (see Table IX). MIL-T-009047F was prepared to specifically cover macrostructural and microstructural aspects of the titanium materials included in MIL-T-9047E.

TABLE VIII. MILITARY SPECIFICATIONS – TITANIUM AND TITANIUM ALLOYS

Specification No.	Date	Title
MIL-R-81588	22 July 1970	Rods and Wire, Titanium and Titanium Alloys
MIL-T-13405C	27 May 1965	Titanium Powder
MIL-T-009047F Amendment No. 1	25 March 1971 19 September 1972	Titanium and Titanium Alloy Bars and Forging Stock
MIL-T-9047E	15 June 1970	Titanium and Titanium Alloy Bars and Forging Stock
MIL-F-83142A	1 December 1969	Forging, Titanium Alloys, Premium Quality
MIL-T-46038A Amendment No. 1 Amendment No. 2	28 October 1966 14 March 1967 5 October 1972	Titanium Alloy, Wrought, Rods, Bars and Billets (for Critical Applications)
MIL-T-81556	20 March 1968	Titanium and Titanium Alloys, Bars, Rods, and Special Shaped Sections, Extruded
MIL-T-9046H	14 March 1974	Titanium and Titanium Alloy, Sheet, Strip and Plate
MIL-T-46035A Amendment No. 1	28 October 1966 5 October 1972	Titanium Alloy, High Strength, Wrought, (for Critical Applications)
MIL-T-46077A	28 June 1968	Titanium Alloy Armor Plate, Weldable
MIL-H-81200A Amendment No. 1	12 September 1968 24 March 1969	Heat Treatment of Titanium and Titanium Alloys
MIL-W-6858C Amendment No. 1	20 October 1964 28 June 1965	Welding, Resistance: Aluminum, Magnesium, Nonhardening Steels or Alloys, Nickel Alloys, Heat Resisting Alloys and Titanium Alloys; Spot and Seam

d. MIL-T-9047E (15 June 1970) – Titanium and Titanium Alloy Bars and Forging Stock. This specification covers bars, billets, and blooms of several of the materials included in superseded MIL-T-9047D, less four compositions which are no longer much used, plus three new alloys currently being produced. Table X gives the correlation of MIL-T-9047C, MIL-T-9047D and MIL-T-9047E (same as MIL-T-009047F) designations. The specification gives the composition

TABLE IX. MILITARY SPECIFICATION CORRELATION

Nominal Composition, wt %	MIL-T-9047E	MIL-T-009047F[a]	MIL-F-83142A	MIL-T-9046H	MIL-T-81556	MIL-R-81588
Unalloyed Ti, ~99.5	Composition 1 (All unalloyed grades are in this category)	Composition 1 (All unalloyed grades are in this category)	Composition 1 (All unalloyed grades are in this category)	Type I, Composition A Unalloyed (40KSI-Y.S.)	Type I, Composition B[a]	--
Unalloyed Ti, ~99.2				Type I, Composition C Unalloyed (55KSI-Y.S.)	Type I, Composition C	--
Unalloyed Ti, ~99.0				Type I, Composition B Unalloyed (70KSI-Y.S.)	Type I, Composition D	
Ti-0.15 to 0.20Pd	--	--	--	--	--	--
Ti-5Al-2.5Sn	*Composition 2*	*Composition 2*	Composition 2	Type II, Composition A	Type II, Composition A	--
Ti-5Al-2.5Sn ELI	Composition 3	Composition 3	Composition 3	Type II, Composition B	Type II, Composition B	--
Ti-1 to 2 Ni	--	--	--	--	--	--
Ti-2Cu	--	--	--	--	--	--
Ti-2.15Al-11Sn-5Zr-1Mo-0.2Si	Composition 10	Composition 10	Composition 10	--	--	--
Ti-2.25Al-6Sn-2Zr-1Mo-0.25Si	--	--	--	--	--	--
Ti-6Al-2Sn-1.5Zr-1Mo-0.35Bi-0.1Si	--	--	--	--	--	--
Ti-6Al-2Cb-1Ta-0.8Mo	--	--	--	Type II, Composition G	--	Type II, Composition D
Ti-8Al-1Mo-1V	Composition 5	Composition 5	Composition 5	Type II, Composition F	Type II, Composition C	Type II, Composition C
Ti-8Mn	--	--	--	Type III, Composition A	--	--
Ti-3Al-2.5V	--	--	--	--	--	- --
Ti-4Al-3Mo-1V	--	--	--	Type III, Composition B	--	--
Ti-5Al-2Sn-2Zr-4Mo-4Cr	--	--	--	--	--	--
Ti-6Al-4V	*Composition 6*	*Composition 6*	Composition 6	Type III, Composition C	Type III, Composition A	Type III, Composition A
Ti-6Al-4V ELI	Composition 7	Composition 7	Composition 7	Type III, Composition D	Type III, Composition B	Type III, Composition B
Ti-6Al-4V SPL	--	--	--	Type III, Composition H	--	--
Ti-6Al-6V-2Sn	Composition 8	Composition 8	Composition 8	Type III, Composition E	Type III, Composition C	
Ti-6Al-2Sn-4Zr-2Mo	Composition 11	Composition 11	Composition 11	Type III, Composition G	--	--
Ti-6Al-2Sn-4Zr-6Mo	Composition 14	*Composition 14*	--	--	--	--
Ti-6Al-2Sn-2Zr-2Mo-2Cr-0.2Si	--	--	--	--	--	--
Ti-7Al-4Mo	Composition 9	Composition 9	Composition 9	--	Type III, Composition D	
Ti-1Al-9V-5Fe	--	--	--	--	--	--
Ti-2Al-11V-2Sn-11Zr	--	--	--	--	--	--
Ti-3Al-8V-6Cr-4Mo-4Zr	--	--	--	--	--	--
Ti-4.5Sn-6Zr-11.5Mo	Composition 13	Composition 13	Composition 13	--	--	--
Ti-8Mo-8V-2Fe-3Al	--	--	--	--	--	--
Ti-13V-11Cr-3Al	Composition 12	Composition 12	Composition 12	Type IV, Composition A	--	Type IV, Composition A
Ti-11.5Mo-6Zr-4.5Sn	--	--	--	Type IV, Composition B	--	--
Ti-3Al-8V-6Cr-4Mo-4Zr	--	--	--	Type IV, Composition C	--	--
Ti-8Mo-8V-2Fe-3Al	--	--	--	Type IV, Composition D	--	--
Ti-5Al-5Zr-5Sn[c]	--	--	Composition 4	--	--	--

Note:

(a) Type I, Composition A, is a high-purity unalloyed titanium grade.

(b) The following alloys have limited current use and are described in the heat treatment specification MIL-H-81200A:

Ti-7Al-12Zr[c]
Ti-7Al-2Cb-1Ta[c]
Ti-4Al-4V[c]
Ti-5Al-1.5Cr-1.5Fe-1Mo[c]
Ti-2Fe-2Cr-2Mo[c]

} *These alloys are not described in current specifications except for the Heat Treatment Specification MIL-H-81200A*

MIL-R-81588

Type I – Commercial pure titanium
Composition A - unalloyed
Composition B – unalloyed

Type II – Alpha titanium alloy
Composition A – 5 Al – 2.5 Sn
Composition B – 5 Al – 2.5Sn ELI
Composition C – 8 Al – 1 Mo – 1 V
Composition D – 6 Al – 2 Cb - 1 Ta – 0.8 Mo

Type III – Alpha-beta titanium alloy
Composition A – 6 Al – 4 V
Composition B – 6 Al – 4 V ELI

Type IV – Beta titanium alloy
Composition A-13 V-11 Cr-3 Al

TABLE X. CORRELATION TABLE: MIL-T-9047

MIL-T-9047E	MIL-T-9047D	MIL-T-9047C(a)
Alpha Alloys	Type I—Commercially pure titanium	
Composition 1 - unalloyed	Composition A — unalloyed	Class 1
	Type II—Alpha titanium alloys	
Composition 2 - 5Al-2.5Sn	Composition A (5Al-2.5Sn)	Class 2
Composition 3 - 5Al-2.5Sn ELI	Composition B (5Al-2.5Sn ELI)	—
	Composition C (5Al-5Zr-5Sn)(b)	—
Composition 5 - 8Al-1Mo-1V	Composition D (8Al-1Mo-1V)	—
Alpha beta alloys	Type III-Alpha beta titanium alloys	
Composition 6 - 6Al-4V	Composition A (6Al-4V)	Class 5
Composition 7 - 6Al-4V ELI	Composition B (6Al-4V ELI)	—
Composition 8 - 6Al-6V-2Sn	Composition C (6Al-6V-2Sn)	—
Composition 9 - 7Al-4Mo	Composition D (7Al-4Mo)	—
	Composition E (4Al-4Mn)(b)	Class 6
	Composition F (5Al-1.5Fe-1.5Cr-1.5Mo)(b)	Class 7
Composition 10 - 11Sn-5Zr-2Al-1Mo	Composition G (11Sn-5Zr-2Al-1Mo)	—
	Composition H (4Al-3Mo-1V)(b)	—
Composition 11 - 6Al-2Sn-4Zr-2Mo	Composition I (6Al-2Sn-4Zr-2Mo)	—
Composition 14 - 6Al-2Sn-4Zr-6Mo		
Beta Alloys	Type IV—Beta titanium alloys	
Composition 12 - 13V-11Cr-3Al	Composition A (13V-11Cr-3Al)	—
Composition 13 - 11.5Mo-6Zr-4.5Sn		

Note:

(a) Class 3, 3Al-5Cr and Class 4, 2Fe-2Cr-2Mo, of MIL-T-9047C were deleted in the "D" revision.

(b) Commercially unavilable.

limits and mechanical property requirements (minimums) for all materials covered in the annealed condition per various thickness ranges where that is applicable. In addition, the solution-treated and aged (STA) mechanical properties of compositions 6 through 13 are given for the thickness ranges applicable to the specific alloys.

e. MIL-F-83142A (1 December 1969) – Forging, Titanium Alloys, Premium Quality. This specification covers unalloyed titanium and titanium alloy forgings suitable for aircraft and aerospace components and supersedes MIL-F-83142. Table XI gives the correlation of MIL-F-83142 and -83142A designations. It is to be noted that the alloy lists reflect alloy availability at the time of specification preparation and that composition categories were changed (Type I, II, III, and IV category nomenclature dropped). Composition designation correlation between MIL-F-83142A and MIL-T-9047E is given in Table IX. Specification MIL-F-83142A gives the composition limits and mechanical property requirements (minimums) for all materials covered in the annealed condition per various thickness ranges where that is applicable and also the solution-treated and aged (STA) mechanical properties of compositions 6 through 13 for the thickness ranges applicable to these alloys. In addition, mechanical property requirements for various conditions of the alpha alloys, Ti-5Al-2.5Sn and Ti-5Al-5Zr-5Sn, are given.

f. MIL-T-46038A (28 October 1966), Amendment No. 1 (14 March 1967) and Amendment No. 2 (5 October 1972) – Titanium Alloy, Wrought, Rods, Bars and Billets (for Critical Applications). This specification covers wrought-titanium alloy rods, bars, and billets which are suitable for processing by hot forming and heat treatment or by heat treatment only, or for direct application to highly stressed critical components, and it is required for use with Specification MIL-T-46035A. Specification MIL-T-46038A describes mechanical property ranges for bars and billets of various section sizes. MIL-T-46035A covers high strength wrought titanium alloys, in annealed or heat-treated shapes, having a critical section thickness of one-quarter to two and one-half inches, for critical components other than armor, such as tubes, chambers, and nozzles.

g. MIL-T-81556 (20 March 1968) – Titanium and Titanium Alloys, Bars, Rods and Special Shaped Sections, Extruded. This specification covers extruded titanium and titanium alloy bars, rods, and special shaped sections. The compositions covered by MIL-T-81556 have the designations given in Table IX. The composition requirements and the mechanical property requirements in the mill annealed condition per various thickness ranges where that is applicable are given. The mechanical property requirements for various section thicknesses of Ti-6Al-4V, Ti-6Al-6V-2Sn, and Ti-7Al-4Mo alloys, are given also for the solution treated and aged (STA) condition. Dimensional tolerance requirements also are given.

h. MIL-T-9046H (14 March 1974) – Titanium and Titanium Alloy, Sheet, Strip and Plate. This specification gives composition (see Table IX), mechanical property (see Table XIX), and dimensional tolerance requirements for the compositions covered in the appropriate section size and heat treatment condition. The materials procurable under the specification are intended for structural and engineering applications in airborne vehicles and equipment based upon the combination of excellent mechanical properties coupled with low density and corrosion resistance. Table XII gives the correlation of the "D", "E", "F", "G", and "H" versions.

i. MIL-T-46035A (28 October 1966) and Amendment No. 1 (5 October 1972) – Titanium Alloy, High-Strength, Wrought (for Critical Components). This specification covers high strength wrought titanium alloys, in annealed or heat-treated shapes, having a critical section thickness of ¼ to 2-½ inches, for critical components other than armor, such as tubes, chambers and nozzles. Mechanical property requirements are given.

TABLE XI. CORRELATION TABLE: MIL-F-83142

MIL-F-83142	MIL-F-83142A
Type I — Commercially pure	**Alpha Alloys**
Composition 1 — unalloyed	Composition 1 — unalloyed
Type II — Alpha alloys	
Composition 2 - 5Al-2.5Sn	Composition 2 — 5Al-2.5Sn
Composition 3 — 5Al-2.5Sn ELI	Composition 3 — 5Al-2.5Sn ELI
Composition 4 — 5Al-5Zr-5Sn(a)	Composition 4 — 5Al-5Zr-5Sn
Composition 5 — 8Al-1Mo-1V	Composition 5 — 8Al-1Mo-1V
Type III — Alpha beta alloys	**Alpha beta alloys**
Composition 6 — 6Al-4V	Composition 6 — 6Al-4V
Composition 7 — 6Al-4V- ELI	Composition 7 — 6Al-4V ELI
Composition 8 — 6Al-6V-2Sn	Composition 8 — 6Al-6V-2Sn
Composition 9 — 7Al-4Mo	Composition 9 — 7Al-4Mo
Composition 10 — 5Al-1.5Fe-1.5Cr-1.5Mo(a)	
Composition 11 — 11Sn-5Zr-2Al-1Mo	Composition 10 — 11Sn-5Zr-2Al-1Mo
Composition 12 — 4Al-3Mo-1V(a)	
Composition 13 — 6Al-2Sn-4Zr-2Mo	Composition 11 — 6Al-2Sn-4Zr-2Mo
Type IV — Beta alloys	**Beta alloys**
Composition 14 — 13V-11Cr-3Al	Composition 12 — 13V-11Cr-2Al
	Composition 13 — 11.5Mo-6Zr-4.5Sn

Note:

(a) Commercially unavailable or not much used.

TABLE XII. CORRELATION TABLE: MIL-T-9046

Type	Comp.	MIL-T-9046D	MIL-T-9046E	MIL-T-9046F	MIL-T-009046G	MIL-T-9046H
		17 June 1964	29 Sep 1965	3 April 1967	12 Oct 1970	14 March 1974
I	A	Unalloyed	Unalloyed	Unalloyed	----	Unalloyed (40 KSI-YS)
	B	Unalloyed	Unalloyed	Unalloyed	----	Unalloyed (40 KSI-YS)
	C	Unalloyed	Unalloyed	Unalloyed	----	Unalloyed (55 KSI-YS)
II	A	5Al-2.5Sn	5Al-2.5Sn	5Al-2.5Sn	----	5Al-2.5Sn
	B	5Al-2.5Sn ELI	5Al-2.5Sn ELI	5Al-2.5Sn ELI	----	5Al-2.5Sn ELI
	C	5Al-5Zr-5Sn	5Al-5Zr-5Sn	----	----	----
	D	7Al-12Zr	7Al-12Zr	----	----	----
	E	7Al-2Cb-1Ta	7Al-2Cb-1Ta	----	----	----
	F	8Al-1Mo-1V	8Al-1Mo-1V	8Al-1Mo-1V	----	8Al-1Mo-1V
	G	----	----	6Al-2Cb-1Ta-0.8Mo	-----	6Al-2Cb-1Ta-0.8Mo
III	A	8Mn	8Mn	8Mn	----	----
	B	4Al-3Mo-1V	4Al-3Mo-1V	4Al-3Mo-1V	----	----
	C	6Al-4V	6Al-4V	6Al-4V	6Al-4V (No. 6)	6Al-4V
	D	6Al-4V ELI	6Al-4V ELI	6Al-4V ELI	6Al-4V ELI (No. 7)	6Al-4V ELI
	E	6Al-6V-2Sn	6Al-6V-2Sn	6Al-6V-2Sn	6Al-6V-2Sn (No. 8)	6Al-6V-2Sn
	F	7Al-4Mo	7Al-4Mo	----	----	----
	G	----	----	6Al-2Sn-4Zr-2Mo	6Al-2Sn-4Zr-2Mo (No. 11)	6Al-2Sn-4Zr-2Mo
	H	----	----	----	----	6Al-4V SPL (Special Low, .005 H)
IV	A	13V-11Cr-3Al	13V-11Cr-3Al	13V-11Cr-3Al	----	13V-11Cr-3Al
	B	----	----	----	----	11.5Mo-6Zr-4.5Sn
	C	----	----	----	----	3Al-8V-6Cr-4Mo-4Zr
	D	----	----	----	----	8Mo-8V-2Fe-3Al

j. MIL-T-46077A (28 June 1968) – Titanium Alloy Armor Plate, Weldable. This specification covers a weldable wrought-titanium alloy 6Al-4V ELI, armor plate in the mill-annealed condition with composition ranges or maximum values as shown below (values in weight percent):

Al	V	C	O*	N	H	Fe	Ti
5.5-6.5	3.5-4.5	.04	.14	.02	.0125	.25	Remainder

The nominal thicknesses of armor plate covered by this specification are ¼ to 2-¼ inches, inclusive. Mechanical properties and ballistic requirements are given. Ballistic properties are contained in the Supplement which has a security classification of confidential.

k. MIL-H-81200A (12 September 1968) and Amendment No. 1 (24 March 1969) – Heat Treatment of Titanium and Titanium Alloys. This specification covers furnace equipment requirements and test procedures, heat treating procedures, heat treating temperatures, and general information for the heat treatment of titanium and titanium alloy items used in the construction of military equipment. It also describes procedures which, when followed, have produced the desired properties within the limitation of the respective alloys. Several compositions included in this specification are not now in production. Therefore, representative alloys listed in Table III are the compositions described in the Heat Treatment section of this handbook.

l. MIL-W-6858C (20 October 1964) and Amendment No. 1 (28 June 1965) – Welding, Resistance, Aluminum, Magnesium, Non-hardening Steels or Alloys, Nickel Alloys, Heat Resisting Alloys, and Titanium Alloys, (Spot and Seam). This specification covers requirements for resistance spot and seam welding of the following nonhardening materials:

(a) Aluminum, aluminum alloys, magnesium alloys
(b) Steels, heat resisting alloys, nickel and cobalt alloys
(c) Titanium and titanium alloys.

MIL-W-6858C covers welding machine qualification, and certification of the welding process or schedule. Radiographic, shear strength and metallurgical test requirements are given.

6. AMS Specifications. The Aerospace Materials Specifications (AMS) for titanium materials issued by the Society for Automotive Engineers (SAE) are listed in Table XIII. Since the AMS titles accurately describe the titanium materials covered, no individual descriptions are necessary. However, as an aid in relating AMS specifications with the alloy coverage and material forms described in this handbook, Table XIV is offered. This table includes alloys which are too new to be covered by specifications and alloys that are no longer much used or produced as well as those covered by Current AMS specifications.

7. ASTM Specifications. The American Society for Testing and Materials (ASTM) specifications for titanium materials are listed in Table XV. The Standards are issued under fixed designations, for example B299 in Table XV and the year of last revision or year of adoption, whichever is most recent, is given as a suffix, for example, B299-69. The ASTM Specification titles are descriptive with regard to product form but do not describe material coverage except in general terms. Therefore Table XVI is offered to show more specifically the compositions and their ASTM designations included in individual specifications. As is the usual practice in

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*Other military and nonmilitary specifications for ELI (extra low interstitial content) grade Ti-6Al-4V call out lower maximum oxygen contents.

TABLE XIII. AEROSPACE MATERIALS SPECIFICATIONS FOR TITANIUM MATERIALS

AMS No.	Title of Specification
4900D	Plate, Sheet and Strip-Annealed-55,000 psi Yield (Unalloyed Ti)
4901E	Sheet, Strip and Plate-Annealed-70,000 psi Yield "
4902B	Plate, Sheet and Strip-Annealed-40,000 psi Yield "
4906	Sheet and Strip-6Al 4V, Continuously Rolled, Annealed
4907B	*Plate, Sheet, and Strip--6Al 4V, Extra Low Interstitial, Annealed*
4908B	Sheet and Strip--8Mn, Annealed--110,000 psi Yield
4909B	Plate, Sheet, and Strip--5Al 2.5Sn, Extra Low Interstatial, Annealed
4910F	Plate, Sheet, and Strip--5Al 2.5Sn, Annealed
4911C	Plate, Sheet, and Strip--6Al 4V, Annealed
4912A	Sheet and Strip--4Al 3Mo 1V Solution Heat Treated
4913A	Sheet and Strip--4Al 3Mo 1V Solution and Prec. Tr.
4915B	Plate, Sheet and Strip--8Al 1Mo 1V, Single Annealed
4916B	*Plate, Sheet and Strip--8Al 1Mo 1V, Duplex Annealed*
4917B	Plate, Sheet and Strip--13.5V 11Cr 3Al, Solution Treated
4918C	Plate, Sheet and Strip--6Al 6V 2Sn, Annealed
4921B	Bars, Forgings and Rings--Annealed--70,000 psi Yield (Unalloyed Ti)
*---4923A	Bars and Forgings--2Cr 2Fe 2Mo, Annealed--120,000 psi Yield
4924B	Bars, Forgings, and Rings, 5Al 2.5 Sn, Extra Low Interstitial Annealed, 90,000 psi Yield
*---4925B	Bars and Forgings--4Al 4Mn, Annealed--130,000 psi Yield
4926D	Bars and Rings--5Al 2.5Sn, Annealed--110,000 psi Yield
*---4927	Bars and Forgings--5Cr 3Al
4928G	Bars and Forgings--6Al 4V, Annealed--120,000 psi Yield
*---4929	Bars--5.4Al 1.4Cr 1.3Fe 1.15Mo, Annealed--135,000 psi Yield
4930A	Bars, Forgings and Rings--6Al 4V, Extra Low Interstitial, Annealed
4935B	Extrusions--6Al 4V Annealed
4936	Extrusions--6Al 6V 2Sn
4941	Tubing, Welded-Annealed--40,000 psi Yield (Unalloyed Ti)
4942	Tubing, Seamless-Annealed--40,000 psi Yield (Unalloyed Ti)
4943	Tubing Seamless-Annealed, 3.0Al 2.5V
4951C	Wire, Welding (Unalloyed Ti)
4953	Wire, Welding--5Al 2.5Sn, Annealed
4954B	Wire, Welding--6Al 4V
4955	Wire, Welding, 8Al 1Mo 1V
4956	Wire, Welding--6Al 4V, Extra Low Interstitial, Environment Controlled
4965B	Bars, Forgings, and Rings--6Al 4V, Sol. & Precip. Heat Treated
4966D	Forgings--5Al 2.5Sn, Annealed--110,000 psi Yield
4967D	Bars and Forgings--6Al 4V, Annealed, Heat Treatable
*---4968A	Bars and Forgings--5Zr 5Al 5Sn, Annealed
*---4969	*Forgings--5.4Al 1.4Cr 1.3Fe 1.2Mo, Annealed 135,000 psi Yield*
4970C	Bars and Forgings, 7Al 4Mo, Sol. & Precip. Treated
4971A	Bars, Forgings, and Rings--6Al 6V 2Sn, Annealed, Heat Treatable
4972A	Bars and Rings--8Al 1Mo 1V, Solution Treated and Stabilized
4973A	Forgings--8Al 1Mo 1V, Solution Treated and Stabilized
4974	Bars and Forgings--11Sn 5.0Zr 2.3Al 1.0Mo 0.21Si, Sol. and Precip. Treated
4975B	Bars and Rings--6Al 2Sn 4Zr 2Mo, Solution and Precipitation Heat Treated
4976	Forgings--6Al 2Sn 4Zr 2Mo, Solution and Precipitation Heat Treated
4977A	Bars and Wire--11.5Mo 6.0Zr 4.5Sn, Solution Heat Treated
4978A	Bars, Forgings and Rings--6Al 6V 2Sn, Annealed, 140,000 Yield
4979	Bars, Forgings and Rings--6Al 6V 2Sn, Sol. and Precip. Heat Treated
4980A	Bars and Wire--11.5Mo 6.0Zr 4.5Sn, 1375F Solution Heat Treated
4981	Bars and Forgings--6Al 2Sn 4Zr 6Mo, Sol. & Precip. Heat Treated

Note: *--- Not current. Materials which have been widely used in the past but which are not now generally recommended for use in new designs.

TABLE XIV. AMS MATERIALS AND PRODUCT FORM CORRELATION

Composition, wt %	Forgings	Bars	Rings	Wire	Plate	Sheet	Strip	Tubing	Extrusions
Unalloyed Ti, ~99.5, Ann. 40 ksi YS	--	--	--	4951C (welding)	4902B	4902B	4902B	4941 (welded)	--
Unalloyed Ti, ~99.5, Ann. 40 ksi YS	--	--	--	--	--	--	--	4942 (seamless)	--
Unalloyed Ti, ~99.2, Ann. 55 ksi YS	--	--	--	--	4900D	4900D	4900D	--	--
Unalloyed Ti, ~99.0, Ann. 70 ksi YS	4921B	4921B	4921B	--	4901E	4901E	4901E	--	--
Ti-0.15 to 0.20 Pd	--	--	--	--	--	--	--	--	--
Ti-5Al-2.5Sn, Ann. 110 ksi YS	4966D	4926D	4926D	4953 (welding)	4910F	4910F	4910F	--	--
Ti-5Al-2.5Sn ELI, Ann. 90 ksi YS	4924B	4924B	4924B	--	4909B	4909B	4909B	--	--
Ti-1 to 2Ni	--	--	--	--	--	--	--	--	--
Ti-2Cu	--	--	--	--	--	--	--	--	--
Ti-2.25Al-11Sn-5Zr-1Mo-0.2Si, STA	4974	4974	--	--	--	--	--	--	--
Ti-5Al-6Sn-2Zr-1Mo-0.25Si	--	--	--	--	--	--	--	--	--
Ti-6Al-2Sn-1.5Zr-1Mo-0.35Bi-0.1Si	--	--	--	--	--	--	--	--	--
Ti-6Al-2Cb-1Ta-0.8Mo	--	--	--	--	--	--	--	--	--
Ti-8Al-1Mo-1V, Single Ann.	--	--	--	4955 (welding)	4915B	4915B	4915B	--	--
Ti-8Al-1Mo-1V, Duplex Ann.	--	--	--	--	4916B	4916B	4916B	--	--
Ti-8Al-1Mo-1V, Sol. Treated & Stabilized	4973A	4972A	4972A	--	--	--	--	--	--
Ti-8Mn, Ann. 110 ksi YS	--	--	--	--	--	4908B	4908B	--	--
Ti-3Al-2.5V, Ann.	--	--	--	--	--	--	--	4943 (seamless)	--
Ti-4Al-3Mo-1V, Sol. Treated	--	--	--	--	--	4912A	4912A	--	--
Ti-4Al-3Mo-1V, STA	--	--	--	--	--	4913A	4913A	--	--
Ti-5Al-2Sn-2Zr-4Mo-4Cr	--	--	--	--	--	--	--	--	--
Ti-6Al-4V, Ann. 120 ksi YS	4928G	4928G	--	4954B (welding)	4911C	4911B	4911B	--	4935B
Ti-6Al-4V, Continuously Rolled, Ann.	--	--	--	--	--	4906	4906	--	--
Ti-6Al-4V, Ann. Heat Treatable	4967D	4967D	--	--	--	--	--	--	--
Ti-6Al-4V, STA	4965B	4965B	4965B	--	--	--	--	--	--
Ti-6Al-4V ELI, Ann.	4930A	4930A	4930A	4956 (welding)	4907B	4907B	4907B	--	--
Ti-6Al-6V-2Sn, Ann. 140 ksi YS	4978A	4978A	4978A	--	4918C	4918C	4918C	--	4936
Ti-6Al-6V-2Sn, Ann. Heat Treatable	4971A	4971A	4971A	--	--	--	--	--	--
Ti-6Al-6V-2Sn, STA	4979	4979	4979	--	--	--	--	--	--
Ti-6Al-2Sn-4Zr-2Mo, STA	4976	4975B	4975B	--	--	--	--	--	--
Ti-6Al-2Sn-4Zr-6Mo, STA	4981	4981	--	--	--	--	--	--	--
Ti-6Al-2Sn-2Zr-2Mo-2Cr-0.2Si	--	--	--	--	--	--	--	--	--
Ti-7Al-4Mo, STA	4970C	4970C	--	--	--	--	--	--	--
Ti-1Al-8V-5Fe	--	--	--	--	--	--	--	--	--
Ti-2Al-11V-2Sn-11Zr	--	--	--	--	--	--	--	--	--
Ti--3Al-8V-6Cr-4Mo-4Zr	--	--	--	--	--	--	--	--	--
Ti-11.5Mo.6Zr-4.5Sn, Sol. Treated	--	4977A	--	4977A	--	--	--	---	--
Ti-11.5Mo-6Zr-4.5Sn, 1375F Sol. Treated	--	4980A	--	4980A	--	--	--	--	--
Ti-8Mo-8V-2Fe-3Al	--	--	--	--	--	--	--	--	--
Ti-13V-11Cr-3Al, Sol. Treated	--	--	--	--	4917B	4917B	4917B	--	--
Ti-5Al-5Sn-5Zr, Not current	4968A	4968A	--	--	--	--	--	--	--
Ti-2Cr-2Fe-2Mo, Not Current	4923A	4923A	--	--	--	--	--	--	--
Ti-4Al-4Mn, Not Current	4925B	4925B	--	--	--	--	--	--	--
Ti-3Al-5Cr, Not Current	4927	4927	--	--	--	--	--	--	--
Ti-5.4Al-1.4Cr-1.3Fe-1.25Mo, Not Current	4969	4929	--	--	--	--	--	--	--

Note: Ann. = annealed, YS = yield strength, STA = solution and precipitation heat treated (i.e., aged), Sol. = solution.

TABLE XV. AMERICAN SOCIETY FOR TESTING AND MATERIALS SPECIFICATIONS – TITANIUM AND TITANIUM ALLOYS

ASTM No.	Specification Title
B299-69	Titanium Sponge
B348-72	Titanium and Titanium Alloy Bars and Billets
B381-69	Titanium and Titanium Alloy Forgings
B265-72	Titanium and Titanium Alloy Strip, Sheet, and Plate
B337-73	Seamless and Welded Titanium Pipe
B338-73	Seamless and Welded Titanium and Titanium Alloy Tubes for Condensers and Heat Exchangers
B363-71	Seamless and Welded Unalloyed Titanium Welding Fittings
B367-69	Titanium and Titanium Alloy Castings
F67-66	Titanium for Surgical Implants
F136-70	Specification for Titanium 6Al-4V ELI Alloy for Use in Clinical Evaluations as a Surgical Implant Material

specifications, the ASTM Standards include requirements for composition, mechanical properties, dimensions of product, testing, and marking.

The ASTM Specification B382-64 entitled "Titanium and Titanium Alloy Bare Welding Rods and Electrodes" was discontinued in 1969.and replaced by the American Welding Society (AWS) Specification AWSA5.16–70. The AWS Classification designations and impurity composition limitations are given for such materials in Table XVII.

8. Specification and Designation Correlation. The proliferation of unalloyed titanium grades and titanium alloys by modification with interstitial and solid solution alloying additions has led to a bewildering array of nomenclature for these materials. The producers have their trade names, there are common names, and each military and society specification has its code for describing particular titanium materials. As an example for one material, several of the designations for various forms and grades of the Ti-6Al-4V alloy are shown below.

Armco Ti-6Al-4V
C-120AV
MMA-6510
RMI-6Al-4V
Tel-Ti6Al-4V
Ti Tech 6Al-4V

AMS-4906
AMS-4907B
AMS-4911B
AMS-4928G
AMS-4935B
AMS-4965B

TABLE XVI: ASTM SPECIFICATION COMPOSITION AND DESIGNATION CORRELATIONS

Nominal Composition wt %	B348-72 Bars and Billets	B381-69 Forgings	B265-72 Strip, Sheet and Plate	B337-73 Pipe	B338-73 Tubing	B363-71 Welding Fittings	B367-69 Castings	F67-66 Wrought Forms	F136-70 Wrought Forms
Unalloyed Titanium (Low iron, low interstitials)	Grade 1	Grade F-1	Grade 1	Grade 1	Grade 1	WPT1[a]	Grade C-1	--	--
Unalloyed Titanium (Intermediate iron and interstitials)	Grade 2	Grade F-2	Grade 2	Grade 2	Grade 2	WPT2[a]	Grade C-2	--	--
Unalloyed Titanium (Intermediate iron, high interstitials)	Grade 3	Grade F-3	Grade 3	Grade 3	Grade 3	WPT3[a]	Grade C-3	Grade 3[b]	--
Unalloyed Titanium (High iron and intersitials)	Grade 4	Grade F-4	Grade 4	Grade 4	Grade 4	--	Grade C-4	Grade 4[c]	--
Ti-6Al-4V	Grade 5	Grade F-5	Grade 5	--	--	--	Grade C-5	--	--
Ti-6Al-4V ELI (High Purity)	--	--	--	--	--	--	--	--	Ti-6Al-4V ELI
Ti-5Al-2.5Sn	Grade 6	Grade F-6	Grade 6	--	--	--	Grade C-6	--	--
Ti-0.12 to 0.25 Pd (Low iron, low interstitials)	--	--	--	--	--	--	Grade C-7A	--	--
Ti-0.12 to 0.25 Pd (Intermediate iron and interstitials)	Grade 7	Grade F-7	Grade 7	Grade 7	Grade 7	--	Grade C-7B	--	--
Ti-0.12 to 0.25 Pd (Intermediate iron, high interstitials)	--	--	--	Grade 8	Grade 8	--	Grade C-8A	--	--
Ti-0.12 to 0.25 Pd (High iron and interstitials)	--	--	--	--	--	--	Grade C-8B	--	--
Ti-11.5Mo-6Zr-4.5Sn	Grade 10	--	Grade 10	--	--	--	--	--	--

Note:

(a) When fittings are of welded construction, the symbol shown shall be supplemented by the letter "W". The designated grades correspond to Grades 1, 2, and 3 of B348, B265, B337, B338, and Grades C-1, C-2 and C-3 of B367.

(b) Corresponds to Grade 3 of B348, B381, and B265.

(c) Corresponds to Grade 4 of B381 and B265.

TABLE XVII. COMPOSITIONS AND DESIGNATIONS OF MATERIALS DESCRIBED IN AWS A5.16-70, SPECIFICATION FOR TITANIUM AND TITANIUM ALLOY BARE WELDING RODS AND ELECTRODES

Nominal Composition, wt.%	AWS Classification	Interstitial and Iron Contents, weight percent[a]				
		C	O	H	N	Fe
Unalloyed Titanium[b]	ERTi-1	0.03	0.10	0.005	0.012	0.10
Unalloyed Titanium	ERTi-2	0.05	0.10	0.008	0.020	0.20
Unalloyed Titanium	ERTi-3	0.05	0.10-0.15	0.008	0.020	0.20
Unalloyed Titanium	ERTi-4	0.05	0.15-0.25	0.008	0.020	0.30
Ti-0.15 to 0.25 Pd	ERTi-0.2 Pd	0.05	0.15	0.008	0.020	0.25
Ti-3Al-2.5V	ERTi-3Al-2.5V	0.05	0.12	0.008	0.020	0.25
Ti-3Al-2.5V[b]	ERTi-3Al-2.5V-1	0.04	0.10	0.005	0.012	0.25
Ti-5Al-2.5Sn	ERTi-5Al-2.5Sn	0.05	0.12	0.008	0.030	0.40
Ti-5Al-2.5Sn[b]	ERTi-5Al-2.5Sn-1	0.04	0.10	0.005	0.012	0.25
Ti-6Al-2Cb-1Ta-0.8Mo	ERTi-6Al-2Cb-1Ta-1Mo	0.04	0.10	0.005	0.012	0.15
Ti-6Al-4V	ERTi-6Al-4V	0.05	0.15	0.008	0.020	0.25
Ti-6Al-4V[b]	ERTi-6Al-4V-1	0.04	0.10	0.005	0.012	0.15
Ti-8Al-1Mo-1V	ERTi-8Al-1Mo-1V	0.05	0.12	0.008	0.03	0.25
Ti-13V-11Cr-3Al	ERTi-13V-11Cr-3Al	0.05	0.12	0.008	0.03	0.25

Note:

(a) Analyses to meet interstitial content requirements are made after the welding rod or electrode is reduced to the final diameter. Single values are maximum values allowed.

(b) Very high purity compositions.

MIL-T-9046H, Type III, Composition C	AMS-4967D
MIL-T-9047E, Composition 6	B348-72, Grade 5
MIL-T-81556, Type III, Composition A	B381-69, Grade F-5
MIL-F-83142A, Composition 7	B265-72, Grade 5
MIL-T-009047F, Composition 7	B367-69, Grade C-5
MIL-T-46077A	AWS A5.16-70 ERTi-6Al-4V-1

A number of titanium users and producers, government agencies and metals-oriented societies have recognized that the nomenclature problem is not unique for titanium. Personnel from these groups have met to sponsor a Unified Numbering System (UNS) for all metals and alloys produced and used in North America. The UNS effort has become a joint activity of the SAE and ASTM where the purpose of the activity is to develop and promulgate for adoption a unified system for the identification of metals and alloys. A proposed SAE/ASTM Standard entitled, "Recommended Practice for Numbering Metals and Alloys", has emerged as a result of this activity. In part, the scope of this Standard reads:

"The UNS provides a means of correlating many nationally used numbering systems currently administered by societies, trade associations, and individual users and producers of metals and alloys, thereby avoiding confusion caused by use of more than one identification number for the same material — and by the opposite situation of having the same number assigned to two or more entirely different materials. It provides, also, the uniformity necessary for efficient indexing, record keeping, data storage and retrieval, and cross referencing."

Part A of the Specification describes the alpha-numeric numbers (or codes) established for each family of metals and alloys. The code consists of a letter (which identifies a metal family) followed by five numerals (which identify compositions). For example, nickel and nickel alloys are the N-series (Nxxxxx), rare earth metals are in the E-series (Exxxxx), and reactive and refractory metals are in the R-series. Within the R series titanium materials are assigned the Numeral 5 (R5xxxx) and the various grades of titanium are identified by the remaining numerals of the six-place code. The numbers R50001—R59999 have been reserved for titanium and titanium alloys.

Considerable effort will be required to complete the details of this activity and finally to promote it and to achieve its adoption by the metals community. However, since it appears as the logical activity to achieve an ultimate correlation of metals nomenclature, the UNS assigned to titanium and its alloys is presented in this handbook with the expectation that it will eventually be adopted.

9. General Specification Requirements. Specifications prepared by the Government or metals-oriented societies have the basic aim of establishing uniformity in prescribed materials under selected conditions. Such parameters as metal composition, manufacturing technique, thermal processing, mechanical properties, product sampling and testing, dimensional tolerances, workmanship, and finishes, marking, packaging, and certification are identified and described in terms of restrictions and limitations designed to standardize product. As shown in previous sections, all commercial titanium-base materials are not covered by specifications but most are included in at least one specification and some products are covered by several. In the case of such multiple coverage, the specifications while using different language, basically define the same limitations for the product, usually concerning the parameters of prime interest to users. The parameters are those of interest to titanium producers as well since specification requirements may serve as the authority to limit responsibility for product improperly utilized. Most specifications call out material composition ranges or maximums and tensile property limitations in the descriptions of the

TABLE XVIII. TYPICAL MINIMUM MECHANICAL PROPERTY REQUIREMENTS – MIL-T-9047E SPECIFICATION

Nominal Composition, wt %	Designation	Thickness, in.	Tensile Strength, ksi	Yield Strength(a), ksi	Elongation(b) %	Red. in Area(c), %	Charpy Impact(d), ft-lb
Annealed Bars and Forging Stock(e)							
Unalloyed titanium	Composition 1	—	80	70	15	30	20
Ti-5Al-2.5Sn	Composition 2	—	115	110	10	25	10
Ti-5Al-2.5Sn ELI	Composition 3	≤2.0	100	90	10	20	—
		2.0-4.0	100	90	10	15	—
Ti-8Al-1Mo-1V	Composition 5	≤2.5	130	120	10	20	15
		2.5-4.0	120	110	10	20	—
Ti-6Al-4V	Composition 6(f)	—	130	120	10	25	10
Ti-6Al-4V ELI	Composition 7	≤1.5	120	110	10	20	—
		1.5-2.0	125	115	10	25	15
Ti-6Al-6V-2Sn	Composition 8(f)	≤1.5	150	140	8	—	—
		1.5-3.0	145	135	8	15	—
		3.0-4.0	140	130	8	20	—
Ti-7Al-4Mo	Composition 9(f)	≤2.0	145	135	10	20	10
		2.0-3.0	140	130	10	20	—
Ti-2.25Al-11Sn-5Zr-1Mo-0.2Si	Composition 10(g)	—	140	130	10	20	—
Ti-6Al-2Sn-4Zr-2Mo	Composition 11	—	130	120	10	25	—
Ti-13V-11Cr-3Al	Composition 12(f)	—	125	120	10	25	15
Ti-11.5Mo-6Zr-4.5Sn	Composition 13	≤1.675	100	90	15	50	—
		1.68-3.0	100	90	15	50	—
Heat Treated (STA) Bars and Forging Stock							
Ti-6Al-4V (≤ 8 in. width)	Composition 6	≤0.5	160	150	10	15	—
(≤ 4 in. width)		0.5-1.0	155	145	10	15	—
(4-8 in. width)		0.5-1.0	150	140	10	15	—
(≤ 4 in. width)		1.0-1.5	150	140	10	15	—
(4-8 in. width)		1.0-1.5	145	135	10	15	—
(≤ 4 in. width)		1.5-2.0	145	135	10	15	—
(4-8 in. width)		1.5-2.0	140	130	10	15	—
(≤ 8 in. width)		2.0-3.0	135	125	8	15	—
(≤ 8 in. width)		3.0-4.0	130	120	6	15	—
Ti-6Al-4V ELI (≤ 8 in. width)	Composition 7	≤0.5	150	140	12	20	—
(≤ 4 in. width)		0.5-1.0	145	135	12	20	—
(4-8 in. width)		0.5-1.0	140	130	12	20	—
(≤ 4 in. width)		1.0-1.5	140	130	12	20	—
(4-8 in. width)		1.0-1.5	135	125	12	20	—
(≤ 4 in. width)		1.5-2.0	135	125	12	20	—
(4-8 in. width)		1.5-2.0	130	120	12	20	—
(≤ 8 in. width)		2.0-3.0	125	115	10	20	—
(≤ 8 in. width)		3.0-4.0	120	110	8	20	—
Ti-6Al-6V-2Sn	Composition 8	≤1.0	175	160	6	15	—
		1.0-2.0	170	155	6	15	—
		2.0-3.0	155	145	6	15	—
		3.0-4.0	150	140	6	15	—
Ti-7Al-4Mo	Composition 9	≤1.0	170	160	8	15	—
		1.0-2.0	160	150	8	15	—
		2.0-4.0	160	140	8	15	—
Ti-2.25Al-11Sn-5Zr-1Mo-0.2Si	Composition 10	≤1.0	145	135	12	25	—
		1.0-2.0	145	130	12	25	—
		2.0-3.0	140	125	12	25	—
Ti-6Al-2Sn-4Zr-2Mo	Composition 11	≤1.0	150	138	10	25	—
Ti-13V-11Cr-3Al	Composition 12	≤2.0	170	160	4	10	—
		2.0-7.0	170	160	2	10	—
Ti-11.5Mo-6Zr-4.5Sn	Composition 13	≤1.625	180	175	8	22	—
		1.62-3.0	180	170	4	10	—

Note:

(a) 0.2% offset yield strength.
(b) Elongation in 4D.
(c) Transverse reduction in area minimums.
(d) Room temperature, transverse, V-notch values are shown. Longitudinal values shall be 20 percent higher.
(e) Properties apply to sections up to 3 inches thick with a maximum of 10 square inches.
(f) Materials shall be capable of meeting the mechanical property requirements after being heated to any temperature up to 1200 F for approximately 30 minutes in air and then cooled in air.
(g) Properties are for section sizes up to 2.25 inches in thickness or 5 square inches.

materials covered. Several specifications have been prepared for specific products, for example, Ti-6Al-4V ELI material for medical implants or unalloyed titanium tubing for heat exchanger utilization, and such specifications describe specific requirements for these materials.

10. Properties Specification Requirements. Tables XVIII, XIX, XX, and XXI summarize the typical mechanical property requirements specified for the various titanium materials by Government, ASTM, and SAE (AMS) specifications. The tensile and impact toughness minimums for bars and forging stock described in MIL-T-9047E for ranges of thicknesses in either the annealed or heat treated (STA) conditions are given in Table XVIII. Note that as thickness of stock increases, strength and ductility requirements generally decrease. Table XIX, typical minimum tensile and bend properties as described in MIL-T-9046H for plate, sheet, and strip, reflects the same stipulations regarding flat-rolled product thickness. Typically, tensile property requirements are described in ASTM and AMS specifications, Tables XX and XXI respectively, without reference to product thickness. The ASTM specification for castings, B367-69, includes reference hardness values. The total requirements for any alloy, form, thickness, and heat treated condition are described in the particular specifications of interest. Tables XVIII through XXI merely present the salient features of the total requirements.

Nonspecification Mechanical Properties

11. General. There are many important properties and characteristics of titanium and its alloys that are not described in specifications. Tensile requirements appear to be the properties emphasized in government, public, and private specifications, which when met, afford a reasonably good description of the material for intended applications. However, there are a host of other properties which are not usually described in specifications but which are important for design considerations. These include such properties as elevated temperature strength, compressive strength, modulus of elasticity, creep and stress-rupture, fracture toughness, fatigue, and stability characteristics such as the behavior of a material after exposures at various temperatures and for various times. The intent of this section is to briefly present some of the typical properties and characteristics of selected alloys which might serve to describe various titanium materials somewhat beyond the descriptions afforded by specifications. Obviously complete descriptions require a separate handbook for each material, and often such handbooks for a material are available from producers. Typical nonspecification properties and characteristics for the major types of titanium alloys, alpha, alpha-beta, and beta, are described in the following paragraphs.

12. Tension and Compression Properties—Temperature Effects. The high elevated-temperature strength of titanium alloys has been one of the attractive features of these materials from the time of their first utilization. More recently, their high low-temperature strength also has been exploited. Figure 3 shows the tensile yield strength range of the alpha-beta Ti-6Al-4V alloy at the low to high temperatures commonly encountered in various devices. It is quite apparent that the higher temperature usefulness for Ti-6Al-4V is limited by a rapid decrease in tensile yield strength above about 800 F. This is representative of the behavior of titanium alloys although several compositions have higher strength than Ti-6Al-4V at high temperatures. In general, the upper service temperature limit for titanium alloys is 1000 F. However, the limit for any one alloy depends largely on composition, mill product form, heat treatment condition, and the time, temperature, and stress combinations of the application.

TABLE XIX. TYPICAL MINIMUM MECHANICAL PROPERTY REQUIREMENTS – MIL-T-9046 SPECIFICATION

MATERIAL	DESIGNATION	THICKNESS INCH	THERMAL CONDITION A – *Annealed* ST – *Solution Treated* STA – *Solution Treated and Aged* DA – *Duplex Annealed*	TENSILE STRENGTH KSI	YIELD STRENGTH ¹ (0.2% Offset, KSI, Min. *Unless Range Indicated*)	ELONGATION % in 2 in. ²	MINIMUM BEND RADIUS XT ≤0.07 in.	MINIMUM BEND RADIUS XT >0.07 in. to 0.1875
			SHEET AND STRIP (≤0.1875 inch)				(Annealed or ST)	
TYPE I	COMMERCIALLY PURE TITANIUM							
	Composition A–Unalloyed (40 KSI Y.S.)	–	A	60	40-65	20	2.0	2.5
	Composition B–Unalloyed (70 KSI Y.S.)	–	A	80	70-95	15	2.5	3.0
	Composition C–Unalloyed (55 KSI Y.S.)	–	A	65	55-80	18	2.0	2.5
TYPE II	ALPHA TITANIUM ALLOY							
	Composition A–5Al-2.5Sn	–	A	120	113	10	4.0	4.5
	Composition B–5Al-2.5Sn (ELI)	–	A	100	95	10③	4.0	4.5
	Composition F–8Al-1Mo-1V	–	A	145③	135③	10③⑤	5.4 ⑤	5.0 ⑤
	Composition G–6Al-2Cb-1Ta-0.8Mo	–	–	—	—	—	—	—
TYPE III	ALPHA–BETA–TITANIUM ALLOY							
	Composition C–6Al-4V	–	A/ST	134/③	126/150	8④/10.0④	4.5	5.0
		–	STA	160	145	6.0⑤		
	Composition D–6Al-4V ELI	–	A/ST	130/	120/	10 ²	4.5	5.0
		–	STA					
	Composition E–6Al-6V-2Sn	–	A/ST	155/③	145/180	10③/10.0	4.0	4.5
		–	STA	170	160	8③		
	Composition G–6Al-2Sn-4Zr-2Mo	–	A/ST	135③	135③/–	8④⑤	4.5	6.0
		–	STA					
	Composition H–6Al-4V SPL	–	A/ST	130/–	120/–	10③	4.5	5.0
		–	STA					
TYPE IV	BETA TITANIUM ALLOY							
	Composition A–13V-11Cr-3Al⑥	–	ST	125 ⑤	120 ⑤ ⑥	10 ⑤	3.0	3.5
		–	STA	170	160	4 ⑤	3.0	3.5
	Composition B–11.5Mo-6Zr-4.5Sn⑥	–	ST	100	90 ⑥	12 ⑤	3.0	3.0
		–	STA	180	170	6 ⑤		
	Composition C–3Al-8V-6Cr-4Mo-4Zr⑦	–	ST	125	120	6 ⑦	3.5	4.0
		–	STA	180	170	6		
	Composition D–8Mo-8V-2Fe-3Al⑥	–	ST	125	120	8	3.5	3.5
		–	STA	175	155	10 ⑤		
			PLATE (>0.1875 inch)					
TYPE I	COMMERCIALLY PURE TITANIUM							
	Composition A–Unalloyed (40 KSI Y.S.)	0.1875–1.0	A	60	40-65	20		
	Composition B–Unalloyed (70 KSI Y.S.)	0.1875–1.0	A	80	70-95	15		
	Composition C–Unalloyed (55 KSI)	0.1875–1.0	A	65	55-80	18		
TYPE II	ALPHA TITANIUM ALLOY							
	Composition A–5Al-2.5Sn	–	A	120⑤	113⑤	10		
	Composition B–5Al-2.5Sn ELI	0.1875–10	A	100	95	10		
	Composition F–8Al-1Mo-1V	3/16–1/4	A	145	135	10		
		3/16–1/4	DA	130	120	10		
		>1/4–1/2	A	145	135	10		
		>1/4–1/2	DA	130	120	10		
		>1/2–3/4	A	140	130	10		
		>1/2–3/4	DA	130	120	10		
		>3/4–1	A	140	130	10		
		>3/4–1	DA	130	120	10		
		>1–1-1/2	A	130	120	10		
		>1–1-1/2	DA	125	115	10		
		>1-1/2–2	A	130	120	10		
		>1-1/2–2	DA	125	115	10		
		>2–2-1/2	A	130	120	10		
		>2–2-1/2	DA	120	110	8		
		>2-1/2–4	A	120	110	8		
		>2-1/2–4	DA	120	110	8		
	Composition G–6Al-2Cb-1Ta-0.8Mo	0.1875–2.750	A	103	95	10		
TYPE III	ALPHA BETA TITANIUM ALLOY							
	Composition C–6Al-4V	0.1875–4.0	A	130	120	10		
		3/16–1/4	STA	160	145	8		
		>1/4–1/2	STA	160	145	8		
		>1/2–3/4	STA	160	145	8		
		>3/4–1.0	STA	150	140	6		
		>1.0–1-1/2	STA	145	135	6		
		>1-1/2–2.0	STA	145	135	6		
		>2.0–2-1/2	STA	130	120	6		
		>2-1/2–4.0	STA	130	120	6		
	Composition D–6Al-4V ELI	1.0–3.0	A	130⑤	120⑤	10		

	Composition E–6Al-6V-2Sn		A	150 [illegible]	140 [illegible]	10 [illegible] [illegible]
		3/16–1/4	STA	170	160	8
		>1/4–1/2	STA	170	160	8
		>1/2–3/4	STA	170	160	8
		>3/4–1.0	STA	170	160	8
		>1.0–1-1/2	STA	170	160	8
		>1-1/2–2.0	STA	160	150	6
		>2.0–2-1/2	STA	160	150	6
		>2-1/2–4.0	STA	150	140	6
	Composition H–6Al-4V-SPL			130 [illegible]	120 [illegible]	10
TYPE IV	BETA TITANIUM ALLOY Composition A–13V-11Cr-3Al [illegible]	0.1875–4.0	A	125	120	10
		3/16–1/4	STA	170	160	4
		>1/4–1/2	STA	170	160	4
		>1/2–3/4	STA	170	160	4
		>3/4–1.0	STA	170	160	4
		>1.0–1-1/2	STA	170	160	4
		>1-1/2–2.0	STA	170	160	4
		>2.0–2-1/2	STA	170	160	4
		>2-1/2–4.0	STA	170	160	4
	Composition B–11.5Mo-6Zr-4.5Sn [illegible]	0.1875–4.0	A	100	90	10
		3/16–1/4	STA	180	170	6
		>1/4–1/2	STA	180	170	6
		>1/2–3/4	STA	180	170	6
		>3/4–1.0	STA	180	170	6
		>1.0–1-1/2	STA	180	170	6
		>1-1/2–2.0	STA	180	170	6
		>2.0–2-1/2	STA	180	170	8
		>2-1/2–4.0	STA	180	170	6
	Composition C–3Al-8V-6Cr-4Mo-4Zr [illegible]		A	125 [illegible]	120 [illegible]	10 [illegible]
		3/16–1/4	STA	180	170	8
		>1/4–1/2	STA	180	170	8
		>1/2–3/4	STA	180	170	8
		>3/4–1.0	STA	180	170	8
		>1.0–1-1/2	STA	180	170	8
		>1-1/2–2.0	STA	180	170	8
		>2.0–2-1/2	STA	180	170	6
		>2-1/2–4.0	STA	180	170	6
	Composition D-8Mo-8V-2Fe-3Al		A	125 [illegible]	120 [illegible]	10 [illegible]
		3/16–1/4	STA	170	160	8
		>1/4–1/2	STA	170	160	8
		>1/2–3/4	STA	170	160	8
		>3/4–1.0	STA	170	160	8
		>1.0–1-1/2	STA	170	160	8
		>1-1/2–2.0	STA	170	160	8
		>2.0–2-1/2	STA	170	160	6
		>2-1/2–4.0	STA	170	160	6

Notes:

1. The rate of strain shall be 0.003 to 0.007 inch per minute through the yield strength, and then is increased so as to product failure in approximately one additional minute. In case of dispute, a strain rate of 0.005 shall be used to the yield point and from yield to fracture a minimum crosshead speed of 0.10 inch per minute shall be used.
2. For 0.025 inch and heavier. For 0.008 inch and up to 0.014 inch, a minimum of 6 percent elongation is required. For 0.015 inch and up to 0.024 inch, a minimum of 8 percent elongation is required.
3. For Duplex annealed, a minimum of 135 ksi for ultimate tensile strength, a minimum of 120 ksi for yield strength, and a minimum of 10 percent elongation is required.
4. For 0.063 inch and heavier, a minimum of 10 percent elongation is required.
5. Spread between ultimate tensile strength and yield strength shall be 15 ksi minimum.
6. For 0.033 inch and heavier, a minimum of 8 percent elongation is required.
7. For elongation in longitudinal direction. Elongation in the transverse direction shall require a minimum of 8 percent. For less than 0.025 inch, a minimum of 6 percent elongation in longitudinal direction and 6 percent elongation in transverse direction is required.
8. For duplex annealed, a minimum of 8 percent elongation is required for less than 0.020 inch and a minimum of 10 percent elongation for 0.020 inch and greater. For triplex annealed, a minimum of 145 ksi for ultimate tensile strength, a minimum of 135 ksi for yield strength, a minimum of 8 percent elongation for less than 0.020 inch and a minimum of 10 percent elongation for 0.020 inch and greater is required.
9. For this all–beta alloy, solution heat treated condition properties are synonymous with annealed.
10. For material less than 0.050 inch, a minimum of 132 ksi for ultimate tensile strength, a minimum of 126 ksi for yield strength, and a minimum of 8 percent elongation is required.
11. For this material, the value for yield strength is minimum.
12. For material less than 0.025 inch, a minimum of 10 percent elongation is required.
13. ~~For material less than 0.030 inch, a minimum of 6 percent elongation is required.~~
14. For 0.050 inch and over, 4 percent for 0.033 inch to 0.049 inch and 3 percent for 0.032 inch and below.
15. For elongation in longitudinal direction. Elongation in transverse direction shall require a minimum of 6 percent.
16. For 0.025 inch and over, 3 percent below 0.025 inch.
17. When specified, the following shall be required:
    (a) For aging at 1000°F, a minimum of 165 ksi for ultimate tensile strength, a minimum of 155 ksi for yield strength, and a minimum of 8 percent elongation. a minimum of 125 ksi for yield strength, and a minimum of 8 percent elongation
    (b) For aging at 1100°F of material 0.012 inch and greater, a minimum of 130 ksi for ultimate tensile strength, a minimum of 140 ksi for yield strength and a minimum of 15 percent elongation.
18. When specified, the following shall be required for aging at 1100°F, a minimum of 150 ksi for ultimate tensile strength, a minimum of 140 ksi for yield strength and a minimum of 15 percent elongation.
19. Requirement for mill–annealed. For Duplex annealed, a minimum of 4.0T for nominal thickness of 0.070 inch and under, and a minimum of 4.5T for nominal thickness of over 0.070 to 0.1875 inch.
20. For sections from 1.500 to 4.000 inches, a minimum of 115 ksi for ultimate tensile strength and a minimum of 110 ksi for yield strength is required.
21. For section from 1.000 to 3.000 inches, a minimum of 125 ksi for ultimate tensile strength and a minimum of 115 ski for yield strength is required.
22. For sections from 0.1875 to 2.000 inches. For sections 2.001 to 4.000 inches, a minimum of 145 ksi for ultimate tensile strength, a minimum of 135 ksi for yield strength, and a minimum of 8 percent elongation in longitudinal direction, 6 percent elongation in transverse direction is required.
23. For elongation in longitudinal direction. Elongation in the transverse direction shall require a minimum of 8 percent.
24. For sections from 0.1875 to 2.000 inches. For sections 2.001 to 4.000 inches a minimum of 120 ksi for ultimate tensile strength, a minimum of 115 ksi for yield strength and a minimum of 8 percent elongation in the longitudinal direction, 6 percent elongation in the transverse direction and 3 percent elongation in the short transverse direction is required.

TABLE XX. TYPICAL TENSILE PROPERTY REQUIREMENTS – ASTM SPECIFICATIONS

Nominal Composition, wt %	Grade	Tensile Strength, ksi(a) Min.	Yield Strength, ksi(a) Min.	Yield Strength, ksi(a) Max.	Min. Elongation, % in 2 inches(b)	Min. Red in Area, %	Min. Bend Radius, T(c) ≤0.07 in.	Min. Bend Radius, T(c) >0.07 in.
			Strip, Sheet, and Plate (B265 - 72)(d)					
Unalloyed Titanium (Low iron and interstitials)	1	35	25	45	24	--	3	4
Unalloyed Titanium (Intermediate iron and interstitials)	1	50	40	65	20	--	4	5
Unalloyed Titanium (Intermediate Iron, high interstitials)	3	65	55	80	18	--	4	5
Unalloyed Titanium (High iron and interstitials)	4	80	70	95	15	--	4	6
Ti-6Al-4V	5(e)	130	120	--	10	--	9	10
Ti-5Al-2.5Sn	6(e)	120	115	--	10	--	8	9
Ti-0.12 to 0.25 Pd (Intermediate iron and interstitials)	7	50	40	65	20	--	4	5
Ti-11.5Mo-6Zr-4.5Sn	10(d,e)	100	90	--	10	--	6	6
		Seamless and Welded Tube For Condensers and Heat Exchangers (B338 - 65) and Seamless and Welded Titanium Pipe (B337 - 65)						
Unalloyed Titanium (Low iron and interstitials)	1	35	25	45	24	--	--	--
Unalloyed Titanium (Intermediate iron and interstitials)	2	50	40	60	20	--	--	--
Unalloyed Titanium (Intermediate iron, high interstitials)	3	65	55	75	18	--	--	--
Unalloyed Titanium (High iron and interstitials)	4	80	70	90	15	--	--	--
Ti-0.12 to 0.25 Pd (Intermediate iron and interstitials)	7	50	40	60	20	--	--	--
Ti-0.12 to 0.25 Pd (Intermediate iron, high interstitials)	8	65	55	75	18	--	--	--
			Bars and Billets (B348 - 72)(f)					
Unalloyed Titanium (Low Iron and Interstitials)	1	35	25	--	24	30	--	--
Unalloyed Titanium (Intermediate iron and interstitials)	2	50	40	--	20	30	--	--
Unalloyed Titanium (Intermediate iron, high interstitials)	3	65	55	--	18	30	--	--
Unalloyed Titanium (High iron and interstitials)	4	80	70	--	15	25	--	--
Ti-6Al-4V	5	130	120	--	10	25	--	--
Ti-5Al-2.5Sn	6	120	115	--	10	25	--	--
Ti-0.12 to 0.25 Pd (Intermediate iron and interstitials)	7	50	40	--	20	25	--	--
Ti-11.5Mo-6Zr-4.5Sn	10(e)	100	90	--	15	50	--	--
			Forgings (B381 - 69)(g)					
Unalloyed Titanium (Low iron and interstitials)	F-1	35	25	--	24	30	--	--
Unalloyed Titanium (Intermediate iron and interstitials)	F-2	50	40	--	20	30	--	--
Unalloyed Titanium (Intermediate iron, high interstitials)	F-3	65	55	--	18	30	--	--
Unalloyed Titanium (High iron and interstitials)	F-4	80	70	--	15	25	--	--
Ti-6Al-4V	F-5	130	120	--	10	25	--	--
Ti-5Al-2.5Sn	F-6	120	115	--	10	25	--	--
Ti-0.12 to 0.25 Pd (Intermediate iron and interstitials)	F-7	50	40	--	20	30	--	--
			Castings (B367 - 69)(i)					
Unalloyed Titanium (Low iron and interstitials)	C-1	35	25	(190 HB)(j)	24	--	--	--
Unalloyed Titanium (Intermediate iron and interstitials)	C-2	50	40	(210 HB)	20	--	--	--
Unalloyed Titanium (Intermediate iron, high interstitials)	C-3	65	55	(235 HB)	15	--	--	--
Unalloyed Titanium (High iron and interstitials)	C-4	80	70	(245 HB)	12	--	--	--
Ti-6Al-4V	C-5	130	120	(365 HB)	6	--	--	--
Ti-5Al-2.5Sn	C-6	115	105	(335 HB)	8	--	--	--
Ti-0.12 to 0.25 Pd (Low iron and interstitials)	C-7A	35	25	(190 HB)	24	--	--	--
Ti-0.12 to 0.25 Pd (Intermediate iron and interstitials)	C-7B	50	40	(210 HB)	20	--	--	--
Ti-0.12 to 0.25 Pd (Intermediate iron, high interstitials)	C-8A	65	55	(235 HB)	15	--	--	--
Ti-0.12 to 0.25 Pd (High iron and interstitials)	C-8B	80	70	(245 HB)	12	--	--	--

Note:

(a) Limits apply to both longitudinal and transverse sample directions where applicable. Yield strength limits are 0.2% offset values.
(b) Elongation minimums are percent in 4D for Billets, Bars, and Forgings.
(c) T value equals bend radius divided by sheet thickness.
(d) Limits specified for annealed of 1 inch thickness or less. Bend minimums are not applicable to material over 0.187 inch in thickness.
(e) Elongation minimum on sheet and strip of less than 0.025 inch thickness may be negotiated.
(f) Material in the solution treated condition.
(g) Limits apply to longitudinal sections up to 3 inches in thickness with a section maximum of 10 square inches.
(h) Limits apply to forgings having a maximum cross section not greater than 3 square inches.
(i) Maximum hardness values (11B) are specified in lieu of maximum yield strength values. Elongation values are for 1 inch gage length.
(j) Hardness values.

TABLE XXI. TYPICAL TENSILE REQUIREMENTS – AMS SPECIFICATIONS

Nominal Composition, wt%	AMS No.	*Tensile* Strength, ksi	Yield Strength, ksi	Elongation %	Red. in Area %
Forgings, Bars, and Rings					
Unalloyed Ti, ~99.0	4921B	80	70	15	30
Ti-5Al-2.5Sn	4926D	115	110	10	25
	4966D	115	110	10	25
Ti-5Al-2.5Sn ELI	4924B	100	90	10	20
Ti-2.5Al-11Sn-5Zr-1Mo-0.2Si	4974	145	130	10	20
Ti-8Al-1Mo-1V	4972A	130	120	10	20
	4973A	130	120	10	20
Ti-6Al-4V	4928G	130	120	10	25
	4965B	150	140	10	20
	4967D	150	140	10	20
Ti-6Al-4V ELI	4930A	120	110	10	20
Ti-6Al-6V-1Sn	4971A	170	160	8	20
	4978A	150	140	10	20
	4979	170	155	8	20
Ti-6Al-2Sn-4Zr-2Mo	4975B	130	120	10	25
	4976	130	120	10	25
Ti-6Al-2Sn-4Zr-6Mo	4981	170	160	10	20
Ti-7Al-4Mo	4970C	160	150	8	15
Ti-11.5Mo-6Zr-4.5Sn	4977A	110	90	15	50
	4980A	110	90	15	50
Extrusions					
Ti-6Al-4V	4935B	130	120	10	20
Ti-6Al-6V-2Sn	4936	145	135	8	15
Plate, Sheet, and Strip					
Unalloyed Ti, ~99.5	4902B	50	40	20	--
Unalloyed Ti, ~99.2	4900D	65	55	18	--
Unalloyed Ti, ~99.0	4901E	80	70	15	--
Ti-5Al-2.5Sn	4910F	120	113	10	--
Ti-5Al-2.5Sn ELI	4909B	100	95	10	--
Ti-8Al-1Mo-1V	4915B	145	135	10	--
	4916B	135	120	10	--
Ti-8Mn	4908B	125	110	10	--
Ti-4Al-3Mo-1V	4912A	150	135	10	--
	4913A	180	155	4	--
Ti-6Al-4V	4906	140	126	10	--
	4911C	134	126	8	--
Ti-6Al-4V ELI	4907B	130	120	10	--
Ti-6Al-6V-2Sn	4918C	150	145	8	--
Ti-13V-11Cr-3Al	4917B	130	120	10	--
Tubing					
Unalloyed Ti, ~99.5	4941	50	40	20	--
	4942	50	40	20	--
Ti-3Al-2.5V	4943	90-115	75	15	--
Wire					
Unalloyed Ti, ~99.5	4951C	50-80	--	--	--
Ti-5Al-2.5Sn	4953	115-150	--	--	--
Ti-8Al-1Mo-1V	4955		No tensile requirements		
Ti-6Al-4V	4954B		No tensile requirements		
Ti-6Al-4V ELI	4956		No tensile requirements		
Ti-11.5Mo-6Zr-4.5Sn	4977A	110	90	15	50
	4980A	110	90	15	50

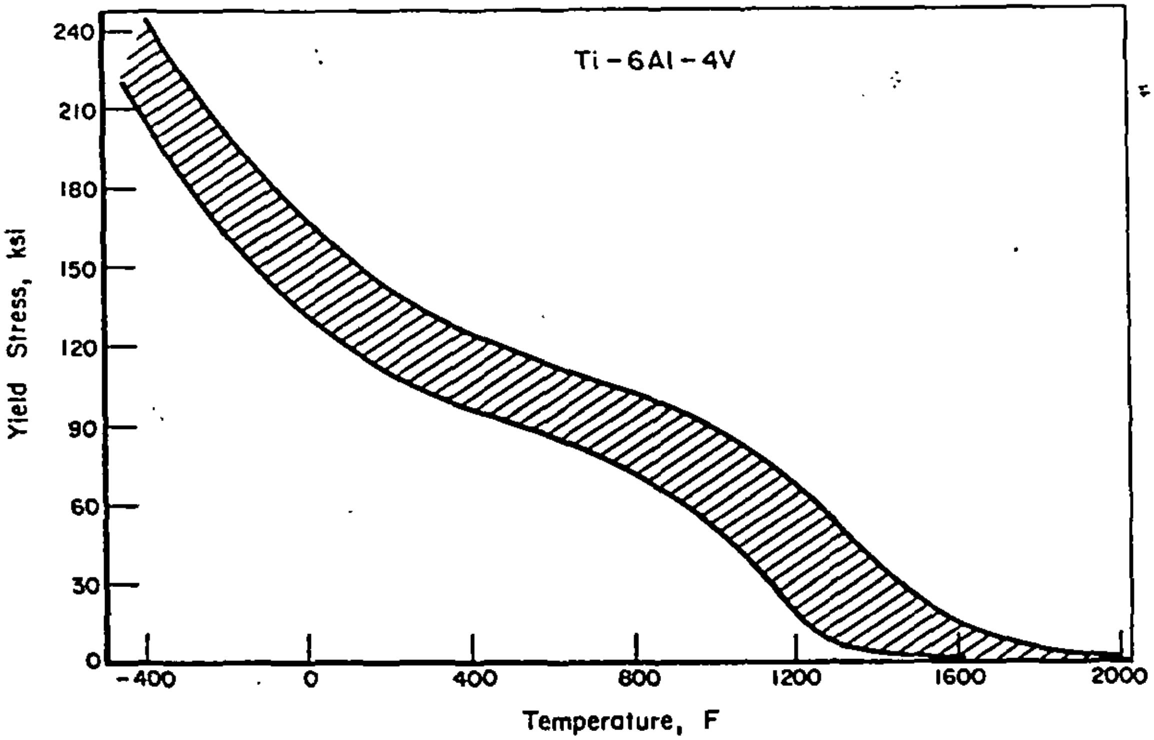


Figure 3. Typical Range in Tensile Yield Strength Found for Ti-6Al-4V Alloy Due to Variation in Chemistry, Structure, Mill Product Form, Heat Treatment, and Test Conditions

At cryogenic temperatures, titanium alloys are not so much service limited by strength as by ductility and toughness limitations. Nevertheless, several alloys are quite ductile at low temperature and Ti-6Al-4V and Ti-5Al-2.5Sn alloys (ELI grades), as well as unalloyed titanium, can be used to the low temperature of liquid helium (-453 F).

The rather broad range of yield strengths depicted in Figure 3 for the Ti-6Al-4V alloy at any particular temperature is a result of differences in material chemistry, structure, and test conditions. Major differences in yield strength can be observed for low to high alloy content (high aluminum structures have lower strength than structures altered by a precipitate phase, e.g. as-aged structures), and variations in the strain rate of the tensile test (high strain rates result in high yield strengths). These are not the only variables contributing to the variations in properties found for a given titanium composition, but they are major variables.

The typical tensile properties of unalloyed titanium and four common alloys over a broad use-temperature range are shown in Figure 4. The yield strength, ultimate strength separation shown for Ti-6Al-4V alloy is typical for the other materials shown. Note that tensile ductility generally decreases with decreasing temperature and is generally highest for the lowest strength materials. Note too, the very large difference in yield strength between unalloyed titanium (annealed) and that shown for one of the high strength beta titanium alloys, Ti-13V-11Cr-3Al (in the solution treated plus aged condition).

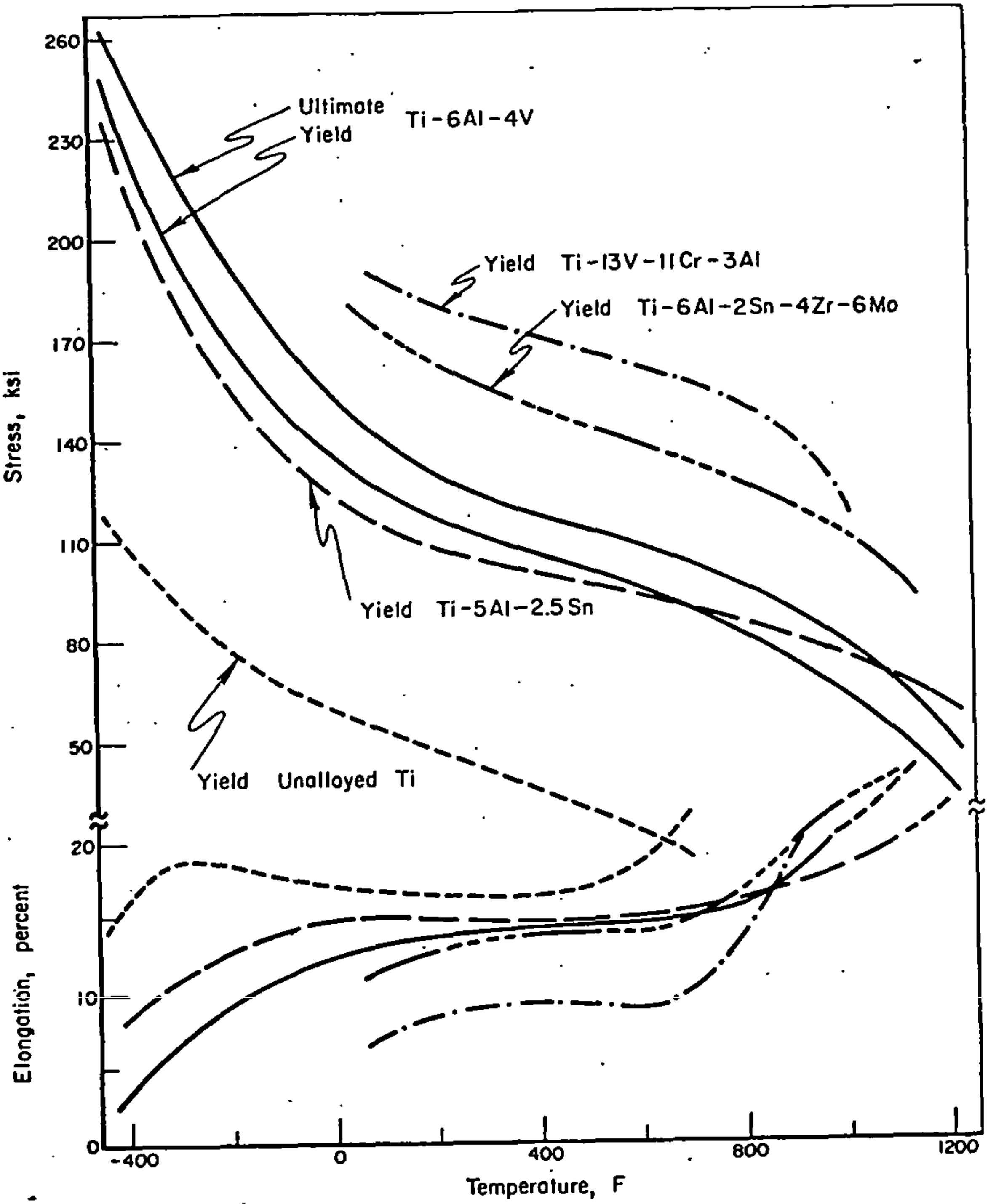
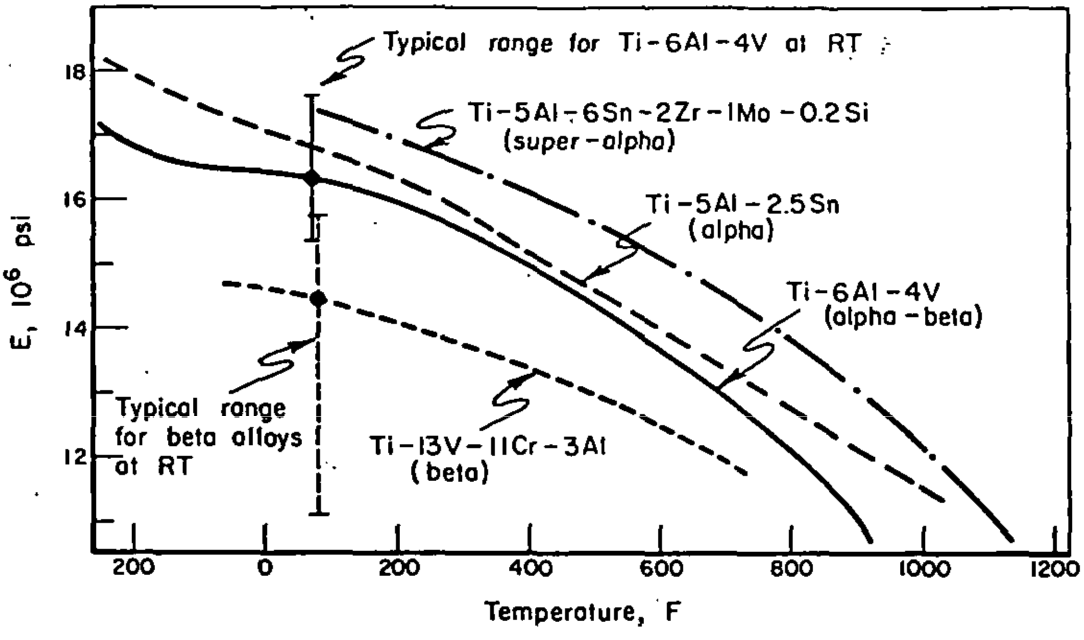
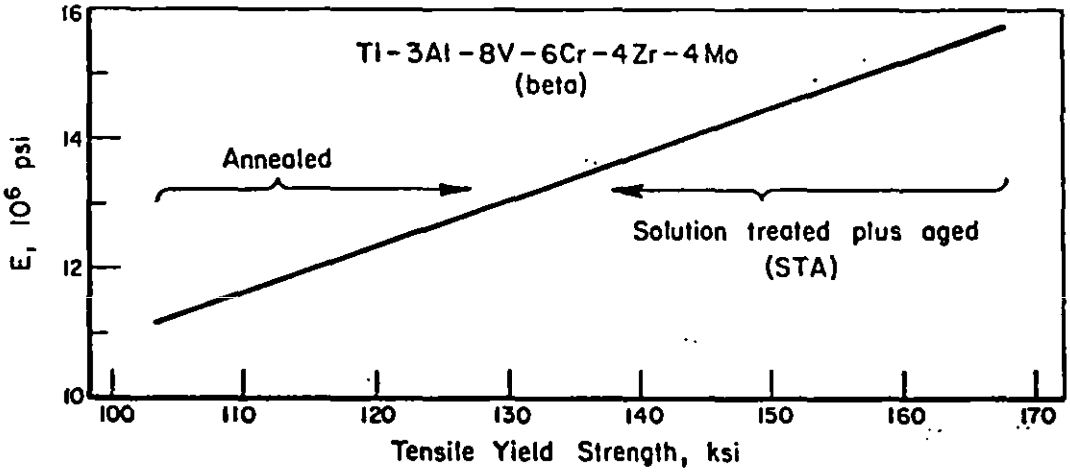


Figure 4. Effect of Temperature on the Typical Tensile Properties of Titanium Materials



a.



b.

Figure 5. Typical Variation in Elastic Modulus Values for Selected Titanium Alloys Due to (a) *Test Temperature, and* (b) *Heat Treatment Condition and Strength Level*

The effect of temperature on the tensile modulus of elasticity for selected titanium alloys is shown in Figure 5a. The rather large variation in modulus values that can be observed for many titanium materials at any given temperature is depicted for the Ti-6Al-4V and beta titanium alloys by the vertical lines drawn at room temperature. As is the case for tensile yield strength, modulus may vary due to chemistry, structure, texture, heat treatment, and test conditions and techniques. The variation of modulus with one of these variables, heat treatment (and the resulting strength variation), is illustrated in Figure 5b. The data for the Ti-3Al-8V-6Cr-4Zr-4Mo beta alloy reveal

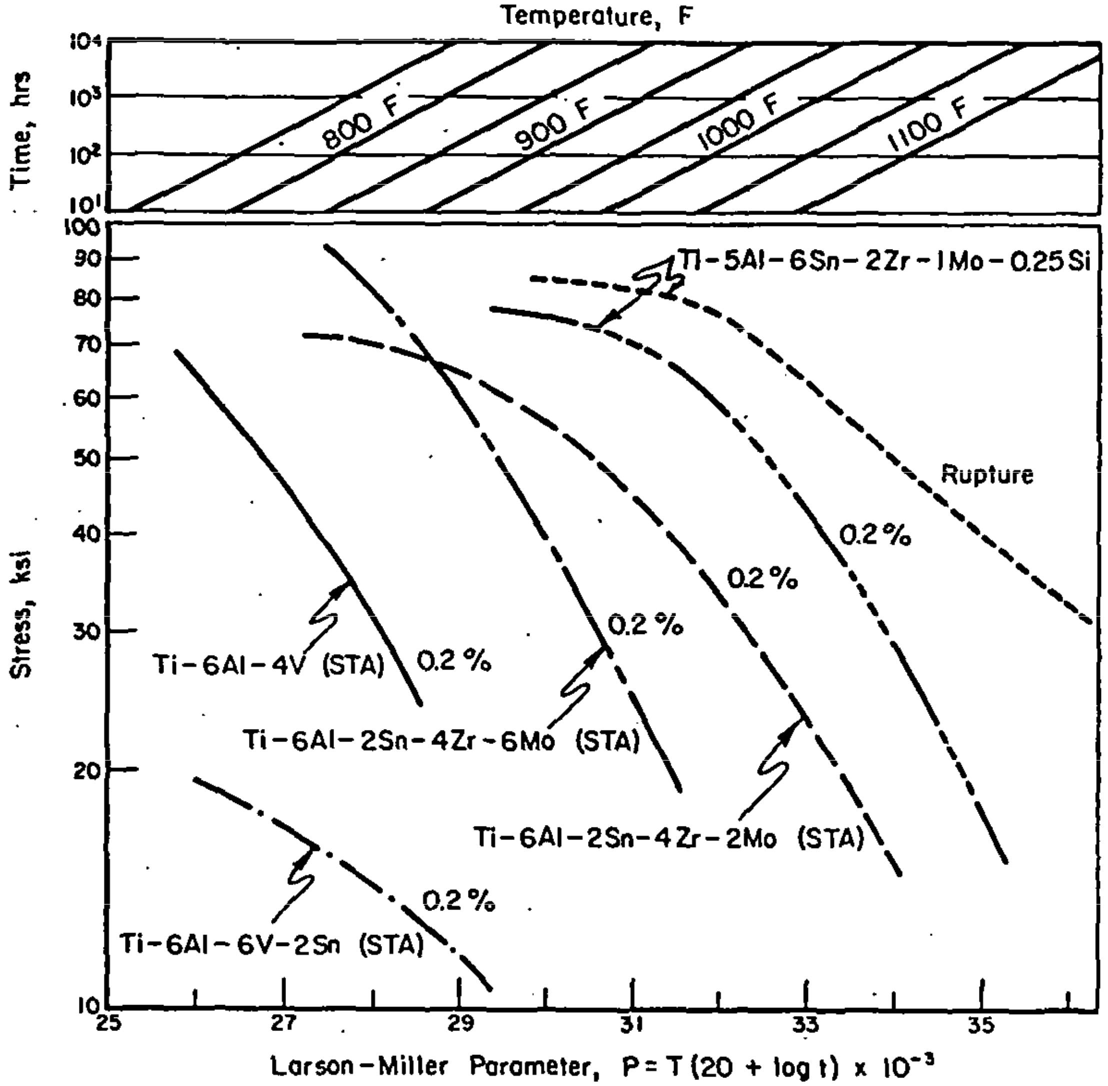


Figure 6. Typical Creep and Stress Rupture Behavior for Selected Titanium Alloys

that the trend is for higher modulus values to be found for higher strength material, in this case for beta microstructures that have been modified by alpha phase precipitate (STA treatments).

The compression properties of many materials are on a 1 to 1 equivalency with the measured tensile properties. Several titanium alloys have shown higher strengths in compression tests however, as for example, Ti-6Al-4V, Ti-6Al-2Cb-1Ta-0.8Mo, and Ti-8Al-1Mo-1V alloys. The Ti-8Al-1Mo-1V alloy has been shown to have 127 ksi F_{cy} versus 120 ksi F_{ty} *in appropriate tests on* material from a single heat. Typically, the Ti-6Al-4V alloy has higher compression strength than tensile strength as shown below:

	F_{cy}, ksi	F_{ty}, ksi
Annealed plate, sheet, strip	132	126
Annealed bar and forgings	126	120
Heat treated (STA) plate and sheet	154	145

Modulus values (and Poissons ratio) for Ti-6Al-4V have been reported as: E_c, 16.4; E_t. 16.0; G, 6.2; (and μ, 0.31). On the other hand, some titanium alloys have been shown to behave opposite to the above. For example, the F_{cy} for one heat of Ti-6Al-2Sn-4Zr-6Mo alloy was measured as 157 ksi versus an F_{ty} of 170 ksi. Thus, it would appear appropriate to study reliable data to determine the relationship between compression and tensile properties for any titanium material of interest with respect to use under compression conditions.

13. Typical Creep and Stress-Rupture Behavior. The elevated-temperature utility of titanium alloys under creep conditions is of great importance in such applications as jet engine compressor components. The excellent creep properties of titanium alloys in the intermediate temperature range of about 350 to 1000 F have enabled them to become prime materials for this and other elevated temperature applications. The Ti-6Al-4V alloy has been used extensively in engines where creep was an important consideration, but the history of the titanium industry reveals the continuous development of alloys having improved creep strengths. Figure 6 shows three such materials compared on the basis of creep stress versus the Larson-Miller parameter where time and temperature (for elevated-temperature exposure) are combined. As shown in this plot, the Ti-6Al-6V-2Sn alloy is not as creep resistant as Ti-6Al-4V alloy which in turn is not as resistant as any of the alloys whose curves (depicting the creep conditions of time, temperature, and stress to result in 0.2 percent plastic strain) plot to the right of the curve for Ti-6Al-4V. These are typical curves for the alloys illustrated, and, like tensile and other properties, variations can occur with chemistry, microstructural, heat treatment, and testing technique variables. The rupture curve shown in Figure 6 for the Ti-5Al-6Sn-2Zr-1Mo-0.25Si alloy is displaced to the right of the 0.2 percent plastic creep curve since obviously, longer times, higher temperatures, or higher stress levels are required to produce the rupture end point of the deformation process defined as creep. Some additional alloys notable for their excellent creep resistance are the Ti-8Al-1Mo-1V, Ti-2.5Al-11Sn-5Zr-1Mo-0.2Si, and Ti-6Al-2Sn-1.5Zr-1Mo-0.35Bi-0.1Si compositions.

14. Stability Characteristics. The elevated-temperature tensile, creep, and other mechanical properties of titanium alloys are important items for consideration regarding a materials service limitations. Related to such limitations and of equal importance is the stability of properties during and/or after exposure to service conditions. The stability of properties for titanium alloys is quite good if exposures are confined within the limits determined for given compositions. The limits generally relate to conditions that promote oxidation, corrosion, stress-corrosion, metallurgical changes, and simple overstressing, and may be approached or exceeded to various degrees. In some cases, the degree of property change after a particular exposure may be so small that stability is unquestioned. In other cases, large property changes might occur so that an instability is not in doubt. However, arbitrary amounts of property change are typically assigned to define stability or instability and are often determined on the basis of what minimum properties can be tolerated during or after a service exposure.

Tensile yield strength and tensile ductility are the properties frequently used as guides in evaluating the stability of titanium alloys. For example, a 50 percent decrease in the tensile ductility of a titanium alloy due to an elevated temperature exposure may be used as the arbitrary stability-instability demarcation point. In other cases, a large change in yield strength, in either the positive or negative direction, resulting from an exposure, may be used to define the stability-instability limit. Others have cited stability as the ability to retain an adequate (some tolerable value) low temperature toughness after long-time thermal exposure. Whatever the stability criterion might be, it is important to understand that exposure conditions should be selected so that they do not promote property changes in excess of tolerable amounts. Generally speaking, the severity of exposures can be reduced by reducing either time, temperature, or stress, or combinations of these variables.

The data of Table XXII show typical stability data for selected alloys. Tensile properties before and after thermal or thermal-stress (creep) exposures show relative stability (e.g. Ti-6Al-4V alloy) or instability (e.g. Ti-5Al-6Sn-2Zr-1Mo-0.25Si alloy) for particular exposure conditions. While not illustrated by the data of this table, it is well known that some titanium alloys are more stable than others for a given exposure condition, and for particular alloys, some material conditions are more stable than others. For example, as shown in Figure 7, the Ti-13V-11Cr-3Al beta alloy is more stable in 600 F thermal exposure in the cold worked condition than as annealed. Similarly, as illustrated in Figure 8, the Ti-5Al-6Sn-2Zr-1Mo-0.25Si super-alpha alloy is more stable under conditions where surface embrittlement caused by oxidation is not a problem. The case shown eliminates the surface oxidation effects by metal removal but the same degree of stability might be obtained by eliminating oxygen during exposure, as for example, during exposure in vacuum or by use of protective coatings. The decrease in ductility of the surface machined samples with increasing exposure temperature, as shown in Figure 8, is undoubtedly due to metallurgical changes such as precipitation or ordering of structural phases. It is apparent that these changes become more pronounced with increasing exposure temperature. The degree of change might be reduced with a change in alloy processing, heat treatment, or perhaps with slight composition modification. Thus it may be readily seen that many variables enter a stability-instability consideration and that control over this characteristic may be exercised by proper selection of alloy and condition as well as by matching exposure conditions to the limitations of the material.

15. Toughness Parameters. There are several methods used to take the measure of toughness of titanium materials including impact toughness, notched and unnotched impact tensile, notched low strain rate tensile, dynamic tear, and static crack propagation tests. The various methods yield data indicating the relative resistance to cracking and fracture under overload conditions. Notched tensile testing (notched/unnotched strength ratio) and impact testing are methods that have long been used to afford a measure of toughness. Tough materials have a high impact energy absorption characteristic and are less sensitive to notches as in notch tensile testing. For example, notch insensitive materials commonly show a notch/unnotch tensile strength ration of > 1 whereas notch sensitive materials have ratios < 1. Sensitivity of a material to environmental (e.g. low temperatures) or to metallurgical (e.g. heat treatment or interstitial contamination) conditions can be determined using notch to unnotch tensile data comparisons.

Commonly the Charpy V-notch impact test is employed to afford a quick and inexpensive toughness determination. Specimens are used either at room or sub-room temperatures to determine the amount of energy absorbed at fracture. Typical Charpy impact data are shown in Figure 9 for unalloyed titanium and three alloys, all in the annealed condition. As might be expected, low strength unalloyed titanium is very tough to very low temperatures. The Ti-5Al-2.5Sn alpha alloy and the Ti-6Al-4V alpha-beta alloy also are quite tough whereas the Ti-8Mn alloy, being a richly beta stabilized alpha-beta alloy, does not show exceptional toughness at low temperatures. Its ductile to brittle transition temperature is somewhat higher than for the other alloys shown. Generally, titanium alloys that are richly beta stabilized, have moderately high ductile to brittle transition temperatures and are not noted for good toughness characteristics at low temperature.

As with many other properties of titanium, toughness is highly dependent upon a large number of variables which include alloy chemistry, structure, texture, and testing conditions.

TABLE XXII. TYPICAL TENSILE PROPERTY STABILITY OF SELECTED ALLOYS AFTER ELEVATED TEMPERATURE EXPOSURE

Exposure Conditions			RT Tensile Properties			
Time, hours	Temp. F	Stress, ksi	Ultimate Strength, ksi	Yield Strength, ksi	Elongation %	Red. in Area, %
			Ti-5Al-2.5Sn			
	No exposure data		138	132	8	40
500	700	None	138	131	10	40
			Ti-6Al-4V (Case A, Sheet annealed 2 hours at 1300F)			
	No exposure data		145	137	13	38
7000	550	None	143	135	14	41
			Ti-6Al-4V (Case B, Bar Annealed 15 hours at 1290 F)			
	No exposure data		123	117	14	43
100	750	50	133	124	14	40
100	750	70	133	122	11	37
			Ti-6Al-2Sn-4Zr-2Mo			
	No exposure data		153	140	20	41
3000	825	48	156	145	14	23
150	1000	25	146	136	15	42
			Ti-6Al-2Sn-4Zr-6Mo			
	No exposure data		186	174	10	35
150	900	45	185	164	7	21
			Ti-8Mo-8V-2Fe-3Al			
	No exposure data		149	139	14	32
500	600	94	156	144	16	29
			Ti-11.5Mo-6Zr-4.5Sn			
	No exposure data		147	141	25	66
2000	550	70	148	146	24	70
			Ti-5Al-6Sn-2Zr-1Mo-0.25Si			
	No exposure data		146	131	10	23
181	1000	35	144	134	5	9
376	1000	45	155	147	2	5

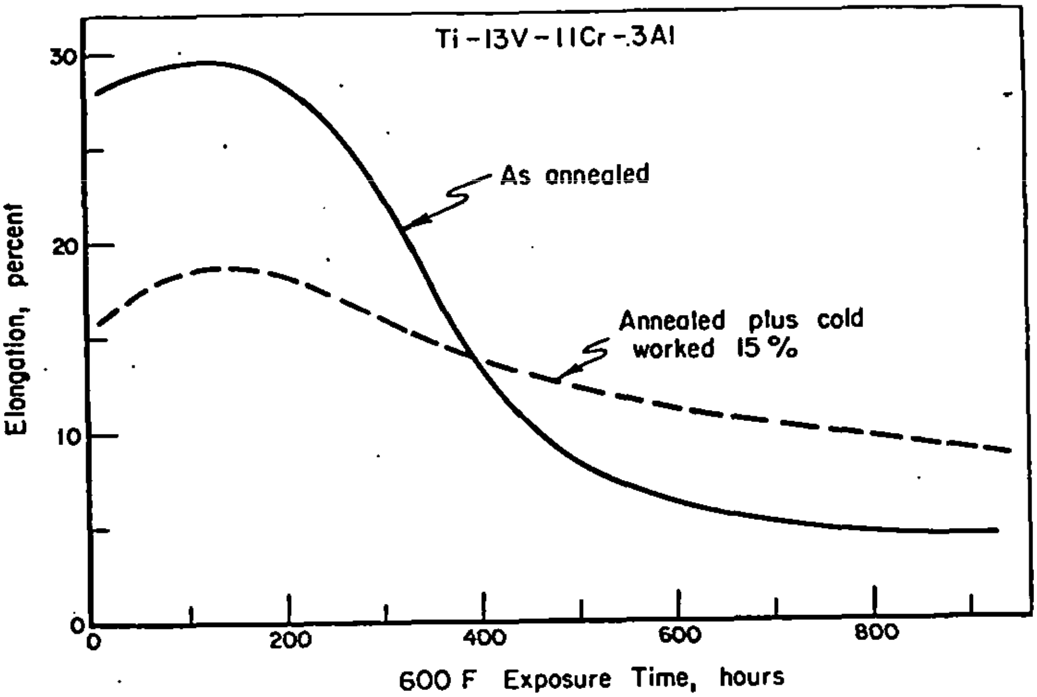


Figure 7. Effect of Thermal Exposure on the Post-Exposure Tensile Ductility of a Beta Titanium Alloy in Two Conditions

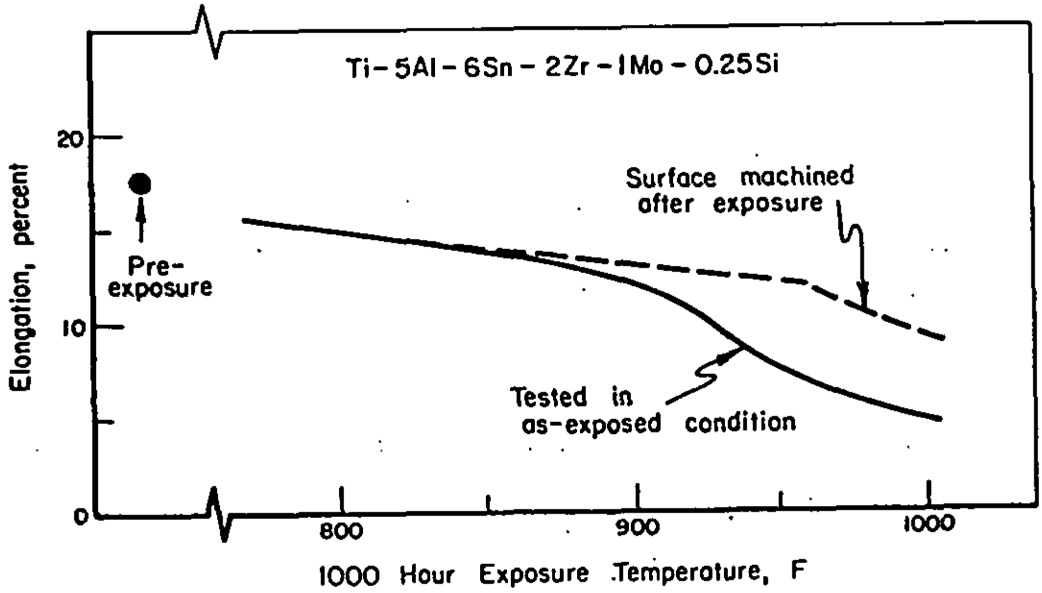


Figure 8. Effect of Creep Exposure on the Post-Exposure Tensile Ductility of a Super-Alpha Titanium Alloy with and without the Exposed and Oxidized Surface Layer Removed

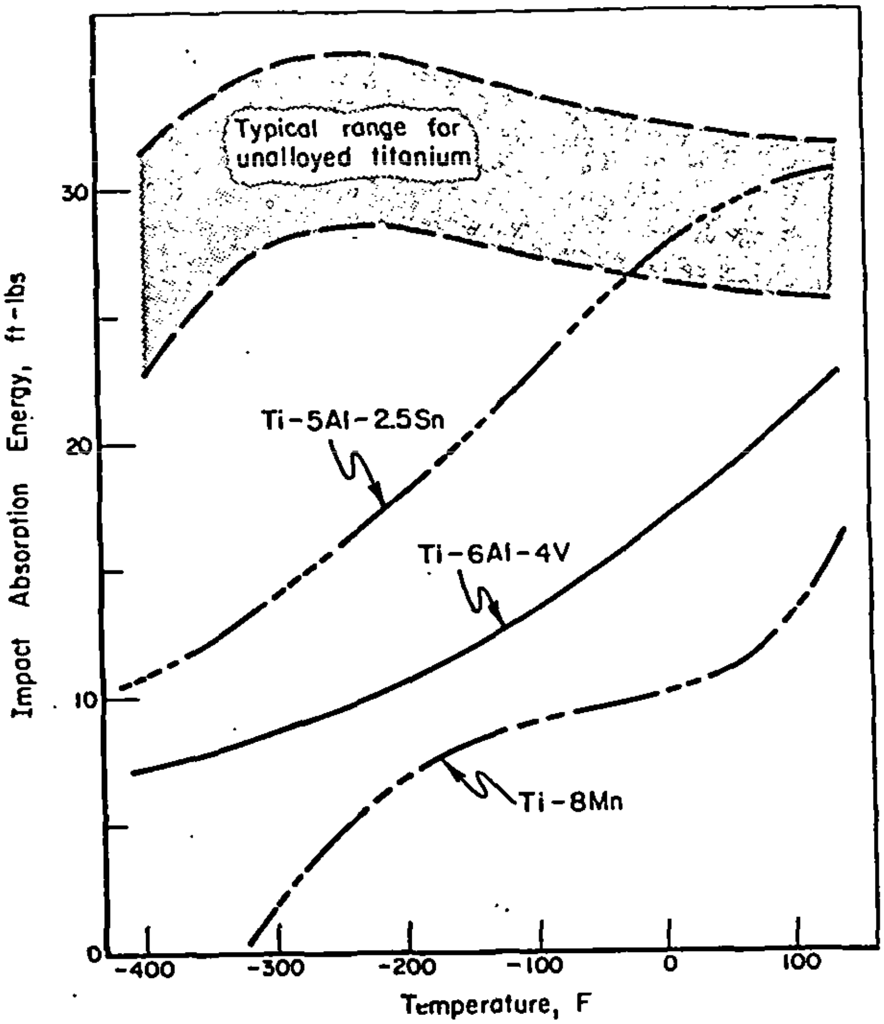


Figure 9. Effect of temperature on the Charpy V–Notch Toughness of Unalloyed Titanium (Various Grades) and Three Alloys in the Annealed Condition

not been possible to control all the variables to obtain entirely consistent results with some of the more sophisticated static crack propagation type fracture toughness tests. For example, a large number of specimens taken from numerous heats of annealed bars, plates, and forgings of Ti-6Al-4V alloy gave the fracture toughness-tensile yield strength data of Figure 10. Compact tension and four point bending tests were used in generating these data. The large spread in toughness at a single strength level and the range of strength levels measured for the annealed condition are both possible as a result of the aforementioned material variables which may exist within the confines of specification limitations. Generally, low alloy chemistry tends to result in low strength-high toughness combinations, acicular microstructures tend to give the same result, and anisotropic textured materials yield results directly related to test specimen orientation. The overriding generalization that has been observed most consistently is that toughness tends to be inversely related to strength as illustrated by the scatter band trend lines of Figure 10.

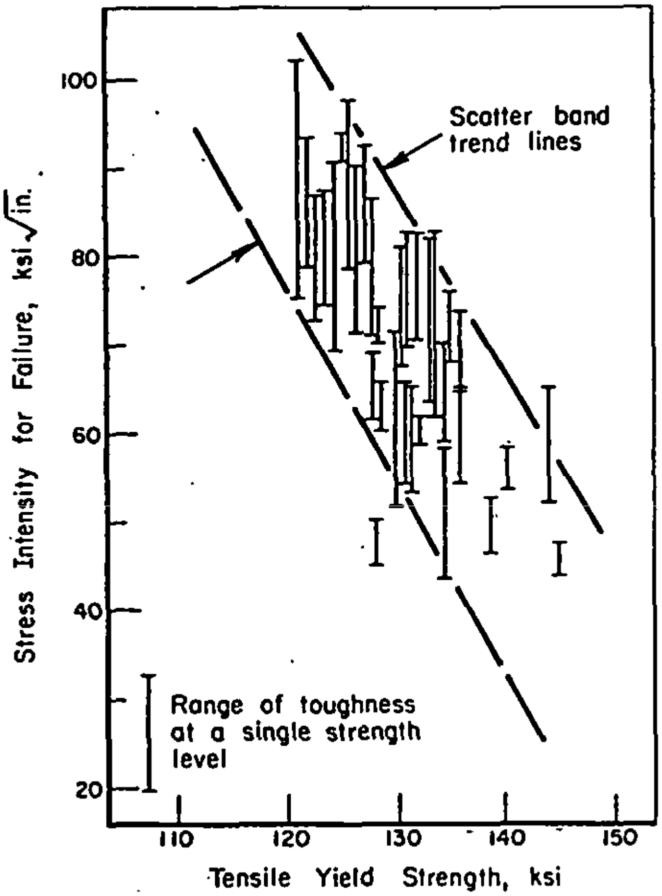


Figure 10. Fracture Toughness—Tensile Yield Strength Relationship Observed for Annealed Ti-6Al-4V Bars, Plates, and Forgings (within Specifications Limitations)

The typical fracture toughness-tensile yield strength trend lines for several alloys are shown in Figure 11. The data are for annealed Ti-5Al-2.5Sn, Ti-8Al-1Mo-1V, and Ti-5Al-6Sn-2Zr-1Mo-0.2Si, alloys and solution heat treated plus aged (STA) Ti-6Al-2Sn-4Zr-6Mo, Ti-6Al-6V-2Sn, and the beta alloys. Both annealed and STA conditions are included in the trend line shown for the Ti-6Al-4V alloy. The excellent fracture toughness characteristics of the annealed materials at low to moderately high strength levels are a feature of titanium alloys generally. The toughness advantage of the beta alloys in the range of high strengths commonly obtained in the STA condition is not a feature of all beta titanium alloys (the Ti-13V-11Cr-3Al alloy has low fracture toughness in the STA condition), but is a feature for some of the newer beta alloys including the indicated compositions and the Ti-3Al-8V-6Cr-4Mo-4Zr alloy. The trend for decreasing toughness with increasing strength is again apparent in the data of Figure 11.

16. Fatigue Characteristics. The fatigue properties of titanium and its alloys, while being of the most importance in many applications, are seldom if ever described in specifications. Possibly this is because there are so many variables associated with the fatigue performance of a material that it is difficult to predict the behavior except within rather broad limits. The material variables affecting fatigue performance include chemistry, microstructure, and texture, and of

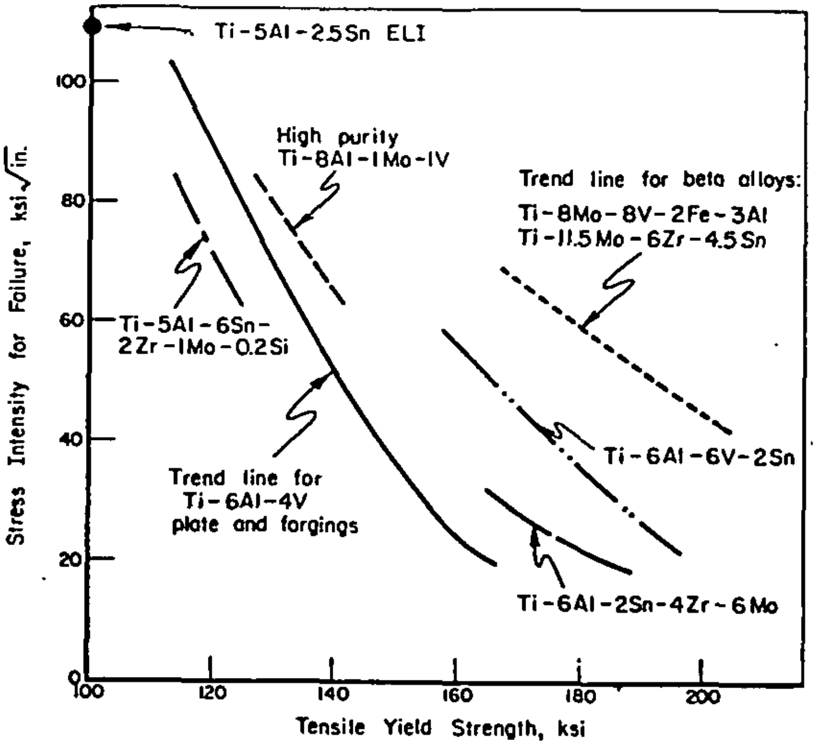


Figure 11. *Fracture Toughness—Tensile Yield Strength Trend Lines for Selected Titanium Alloys in the Annealed and Heat Treated (STA) Conditions.*

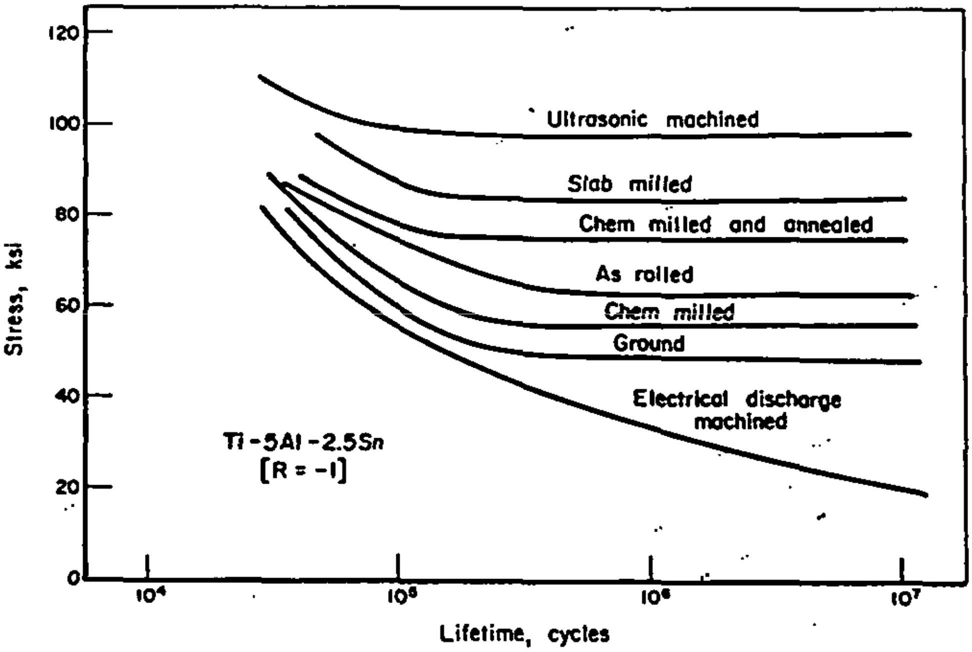


Figure 12. Effect of Surface Finish on the Room Temperature Rotating Beam Fatigue Behavior of Ti-5Al-2.5Sn Alloy

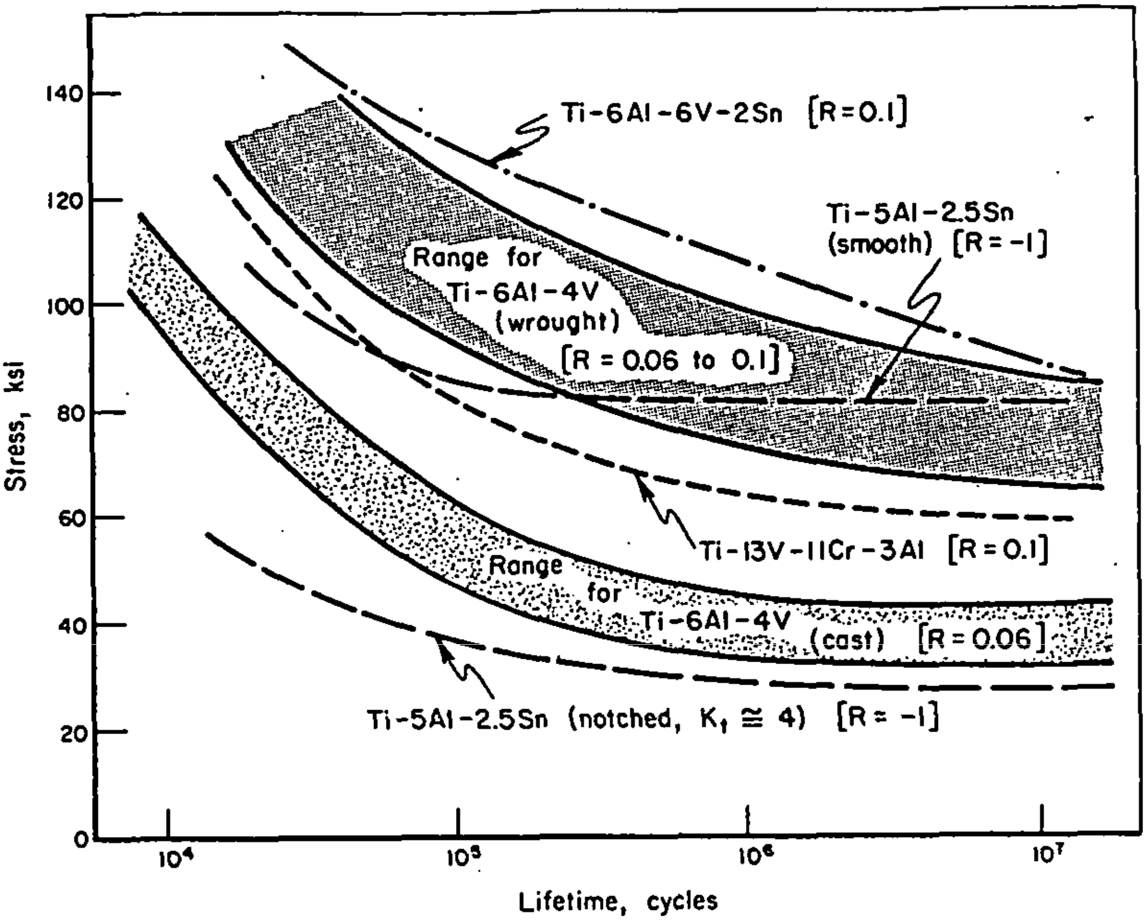


Figure 13. Typical Room Temperature Fatigue Characteristics of Selected Titanium Alloys

course, these are controlled during the make-up and processing of titanium alloys. In addition to the material factors, fatigue performance is determined by surface conditions of the material, environmental factors, and of course specimen geometry and the test variables. To afford some idea of the influence these factors bring to bear, the range in fatigue strength observed for Ti-5Al-2.5Sn alloy surface finished in a variety of ways is depicted in Figure 12. Shop peening or glass-bead peening to optimum surface conditions can be used to alleviate the bad effects induced by some of the surface conditions illustrated.

The typical fatigue behavior observed in tension-tension and rotating beam tests for selected titanium alloys is shown in Figure 13. Some of the stress-lifetime cycle curves are comparable (same kind of tests) and indicate relationships between alloys, notch-unnotch (smooth) test geometries, and product forms. For example, the superior fatigue strength of Ti-6Al-6V-2Sn and Ti-6Al-4V alloys over the Ti-13V-11Cr-3Al beta alloy is indicated. Note the range depicted for various mill product forms and annealed microstructures of Ti-6Al-4V alloy. The effect of a moderately sharp notch on reducing the fatigue strength of Ti-5Al-2.5Sn illustrates generally the degradation in strength induced by stress risers. The large difference between the fatigue strength of wrought forms and cast forms of Ti-6Al-4V alloy, both in the smooth condition, is readily apparent. The notched geometry for both wrought and cast forms of Ti-6Al-4V alloy result in

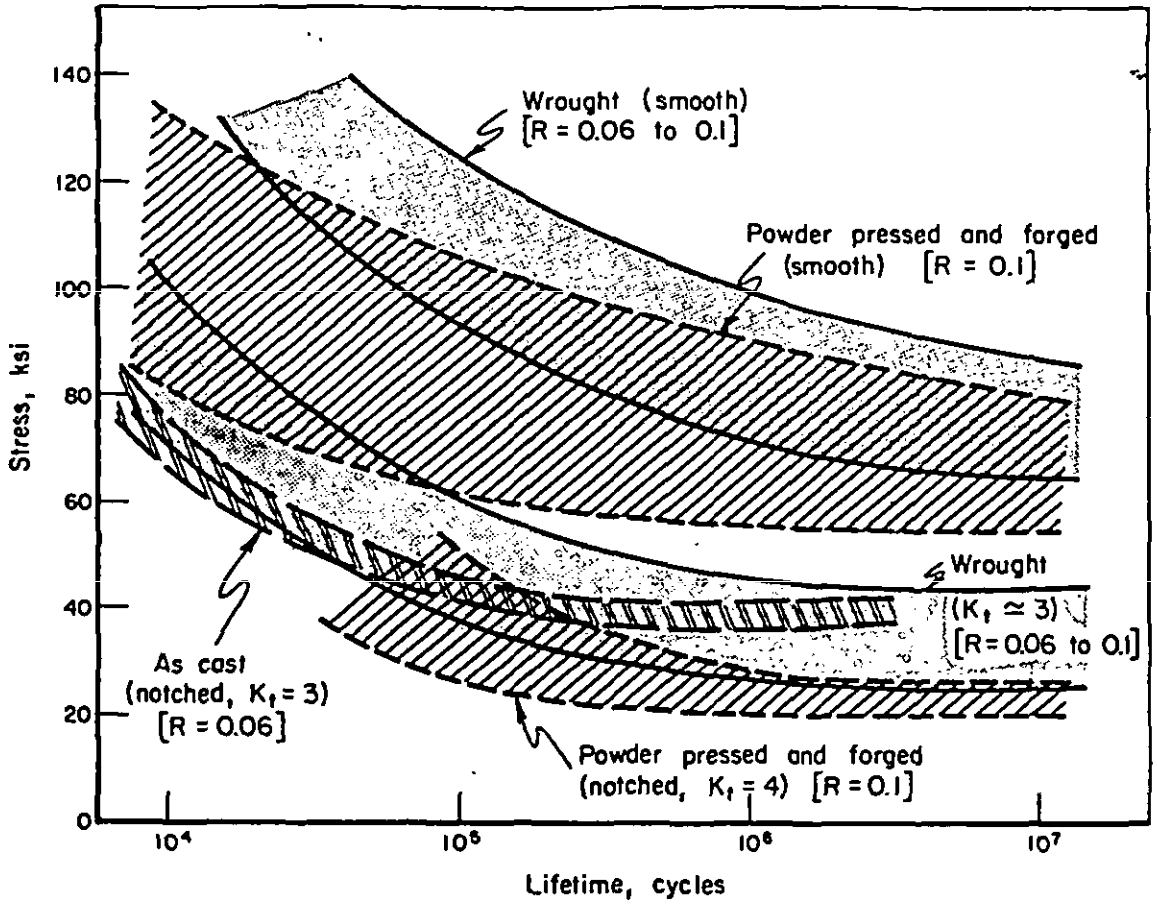


Figure 14. Ranges in Fatigue Behavior Observed for Various Forms of Ti-6Al-4V Alloy

essentially the same strength range as shown by the curves of Figure 14. In this figure, the notched and smooth fatigue strength ranges for alloy produced by powder metallurgy techniques are also shown. The range for the notched condition is basically comparable with the ranges for notched wrought and notched cast materials (the powder product specimens have a somewhat sharper notch to result in slightly lower fatigue strength). The range for smooth specimens produced by powder metallurgy is somewhat inferior to the range for wrought products although superior to the range for cast Ti-6Al-4V alloy. It should be understood that the data summarized are those for a powder metallurgy product that has been additionally forged to further densify and optimize the microstructure. Powder metallurgy products that are not densified by forging (or other metalworking techniques) do not have as good fatigue strength as the consolidated products.

17. Comparison of Properties of Various Products. The room temperature tensile properties and the —40 F Charpy impact properties of selected titanium alloys are given in Table XXIII. Typical data are given for wrought, cast, and powder metallurgy bars. As might be expected, the properties of the wrought material are superior to those of cast or powder forms in any of the alloys compared. Unalloyed titanium product prepared by any one of the techniques has quite good properties. The development of improved cast and powder metallurgy products and properties continues, so that the inferiority of such materials compared with wrought product becomes less pronounced. In many cases, the cost advantages available with cast or powder

TABLE XXIII. COMPARISON OF PROPERTIES REPORTED FOR POPULAR ALLOYS FROM WROUGHT, CAST, AND POWDER FORMS

Nominal Composition wt %	Product Type	Remarks	Room Temperature Tensile Data: Ultimate Tensile Strength, ksi	Room Temperature Tensile Data: Yield Strength, ksi	Room Temperature Tensile Data: Elongation, %	Room Temperature Tensile Data: Red. in Area, %	Charpy –40 F Impact Toughness, ft–lb
Unalloyed Ti	Wrought bar	Annealed	80	70	18	33	26
	Cast bar	As cast	92	74	20	31	19
	Pressed powder	Annealed(a)	70	54	18	22	––
Ti-5Al-2.5Sn ELI	Wrought bar	Annealed	118	103	19	34	––
	Cast bar	As cast	115	105	10	17	––
	Pressed powder	Anneal and forge(b)	115	104	16	27	––
Ti-6Al-4V	Wrought bar	Annealed	145	134	16	34	16
	Cast bar	As cast	149	128	12	19	14
		Annealed	147	129	10	16	––
		STA(c)	171	157	6	11	––
	Pressed powder	Annealed(c)	120–127	107–114	5–8	8–14	––
		Anneal and forge(b)	134	122	12	27	––
		STA(c)	140	130	4	6	––
Ti-6Al-6V-2Sn	Wrought bar	Annealed	163	153	16	38	15
	Cast Bar	As cast	160	140	6	11	10
	Pressed powder	Annealed(a)	140	122	5	5	––

Note:
(a) About 94 percent dense.
(b) Almost 100 percent dense.
(c) Aging treatment not specified

TABLE XXIV. COMPARISON OF ROOM TEMPERATURE PROPERTIES REPORTED FOR SEVERAL FORMS OF Ti-11.5Mo-6Zr-4.5Sn ALLOY AS SOLUTION TREATED PLUS AGED
(8 Hour Aging at 950 F)

Product Form	Thickness, inches	Ultimate Tensile Strength, ksi	Tensile Yield Strength, ksi	Tensile Elongation %	Fracture Toughness K_{Ic} ksi$\sqrt{in.}$	10^7–Cycle Fatigue Strength, ksi
Forging	4.0	182	172	4	61	—
	<1.0	193	185	5	—	—
Plate	2.0	186	182	4	57	—
	0.5	204	194	4	60	140
Sheet	0.063	205	195	5	—	82
	0.020	196	186	4	—	120
	0.010	201	192	3	—	—
Foil	0.002	227	213	2	—	—
Extrusion	0.27	186	169	—	48	—
Tubing	0.120 (wall)	185	176	8	—	—
	0.050 (wall)	180	169	6	—	—
Bar	1.188	210	201	8	—	—
	0.500	180	172	10	—	150
	0.196	185	170	18	—	—
Wire	0.063	195	184	15	—	150
Casting	<1.0	173	160	7	—	—
	<1.0	182	164	7	—	—

products are considerable so that potential applications should be carefully examined to determine if the slightly lower properties of these products might be profitably utilized.

The data of Table XXIV are for numerous wrought and cast forms of the Ti-11.5Mo-6Zr-4.5Sn (Beta III) alloy in the solution treated and aged condition. Tensile, fracture toughness, and fatigue data are given. Properties also are given for various product thicknesses where available. While the general uniformity of properties for various section sizes of any of the wrought products is apparent, the total range in properties for all wrought products is quite large as shown below.

180-227 ksi UTS, 169-213 ksi YS, 2-18% EL.

The range is broadened if the data for the cast products are included. A range in properties for various product forms is quite a common occurence for metals but is typically the case for titanium alloys. Thus, the user of titanium materials should be fully aware of the variations in properties that can pertain between product forms and examine the available data carefully prior to a material commitment.

TABLE XXV. DENSITY AND STRENGTH/DENSITY RATIOS TYPICALLY AVAILABLE IN TITANIUM ALLOYS

Nominal Composition, wt %	Density lb/in.^{3}	Typical Annealed/STA Yield Strengths, ksi	Typical Yield Strength to Density Ratios, inch x 10^6
Unalloyed Ti (Medium Strength)	0.163–0.164	60/—	0.367/—
Ti-0.15 to 0.25Pd	0.163	46/—	0.282/—
Ti-2Cu	0.165	90/115	0.545/0.697
Ti-5Al-2.5Sn (also ELI)	0.161	117/—	0.726/—
Ti-2.25Al-11Sn-5Zr-1Mo-0.25Si	0.174	—/135	—/0.776
Ti-5Al-6Sn-2Zr-1Mo-0.25Si	0.163	135/—	0.828/—
Ti-6Al-2Sn-1.5Zr-1Mo-0.35Bi-0.1Si	0.162	137/—	0.846/—
Ti-6Al-2Cb-1Ta-0.8Mo	0.162	120/—	0.741/—
Ti-8Al-1Mo-1V	0.159	142/—	0.893/—
Ti-8Mn	0.171	125/—	0.731/—
Ti-3Al-2.5V	0.162	85/110	0.525/0.679
Ti-4Al-3Mo-1V	0.163	120/167	0.736/1.024
Ti-5Al-2Sn-2Zr-4Mo-4Cr	0.168	—/160	—/0.952
Ti-6Al-4V (also ELI)	0.161	130/155	0.807/0.963
Ti-6Al-6V-2Sn	0.164	150/180	0.915/1.098
Ti-6Al-2Sn-4Zr-2Mo	0.164	135/—	0.823/—
Ti-6Al-2Sn-4Zr-6Mo	0.169	165/—	0.976/—
Ti-6Al-2Sn-2Zr-2Mo-2Cr-0.2Si	0.162	—/160	—/0.988
Ti-7Al-4Mo	0.162	150/175	0.926/1.080
Ti-1Al-8V-5Fe	0.168	165/215	0.982/1.280
Ti-2Al-11V-2Sn-11Zr	0.174	—/180	—/1.034
Ti-3Al-8V-6Cr-4Mo-4Zr	0.174	125/170	0.718/0.977
Ti-11.5Mo-6Zr-4.5Sn	0.183	115/185	0.628/1.011
Ti-8Mo-8V-2Fe-3Al	0.175	125/180	0.714/1.028
Ti-13V-11Cr-3Al	0.175	130/175	0.743/1.000

The density and strength-to-density ratio data presented in Table XXV represent an additional consideration when comparing the properties of titanium alloys. While densities for individual materials can vary slightly, for example with compositional differences from heat to heat, the values tabulated are the generally accepted values. The tensile yield strength values given (annealed and solution treated plus aged values) are representative for the materials and conditions shown and as previously described, can vary markedly due to a number of factors. Thus, the strength/density ratios given in Table XXV are merely representative. Nevertheless, the strength/density ratio affords a useful parameter for comparison purposes and in such terms density should always be one of the factors considered in selecting a titanium material for an application.

SECTION III

METALLURGY AND PROCESSING

Metallurgical Information

18. Titanium Production Variables. The production of the basic titanium sponge metal from its primary ore (rutile) and the basic processing of sponge to finished mill products and castings was described earlier in Section I, Paragraph 3. While the previous description described the production of ingot and subsequent products in terms of the forms and dimensions available, it is appropriate at this point to describe in more detail the alloys available and the metallurgical factors of importance.

The alloys of titanium which are now commonly available to users are listed in Table II and additional tables. The compositions listed are nominal compositions and the actual compositions can vary over the ranges or below the maximum amounts of components given in specifications. Since titanium producers are subject to the external pressures of numerous company and public specifications, they find it frequently necessary to make several grades of some alloys to meet the many requirements of users including cost requirements. Thus, for many of the nominal compositions, several grades of the alloy are available, and in at least one case, that for the Ti-6Al-4V alloy, more than a dozen different grades can be found.

There are two primary factors controlling grades: ingot quality and alloy chemistry. Ingot quality has to do with such variables as input raw material and additional variables as described below.

- Input raw material (virgin sponge metal versus scrap)
- Kinds of scrap (laboratory control revert, massive scrap, turnings, etc).
- Ratio of scrap to virgin metal (in mixed material electrodes)
- Methods of making electrodes (pressed virgin metal versus welded scrap—welding of components in or out of vacuum)
- Melting controls (degree of vacuum, abnormalities in the melt cycle if any, double or triple melting of ingots)
- Degree of ingot testing (macro- and micrometallographic and chemical analyses from prescribed locations).

Surprisingly, there are only a few classifications for ingot quality resulting from all these variables. Those of interest to this description are: (1) Premium Grade, and (2) Standard Grade. As might be expected, both reliability and cost are higher with the premium grade of ingot. The ingot grades in turn may be subclassified in grade according to alloy chemistry.

Alloy chemistry is basic to grade control. In the case of the Ti-6Al-4V alloy where numerous grades are available, the variation of oxygen content is used as the primary control. For example, the ELI (for extra low interstitial content) grade of Ti-6Al-4V alloy has been mentioned. (ELI grades of alloy usually contain less than 0.13 percent oxygen). Other grades might have more oxygen (e.g. a standard grade or a high oxygen grade). Within the primary grades controlled by interstitial content, there are subgrades which differ from one another due to the control of the aluminum, vanadium, and iron contents. For example, Ti-6Al-4V alloy with high aluminum content (within specification range) might be prepared for thick section product or product to be solution treated plus aged to a high strength level. Thus by simply multiplying the variables of ingot quality and alloy chemistry, the availability of a large number of alloy grades for a given composition is apparent. The grade of an alloy is important with respect to particular properties and property combinations and these are further controlled by the mill processing and product form as well as by heat treatment procedures. It is therefore recommended, due to the foregoing, that users of titanium products should communicate with the producers to insure that the product supplied will meet the intended requirements.

19. Effects of Alloying Elements — Metallurgy and Microstructure.

a. General. An alloying element added to titanium has important effects upon the physical and mechanical characteristics of this metal. Each element that might be combined with titanium either intentionally or unintentionally, and in either small or large amounts, results in some degree of strengthening and in some change in the basic crystal structure. In this sense, even the commercial unalloyed grades of titanium are alloys, since each of the grades contain various quantities of the interstitial elements (carbon, oxygen, nitrogen, and hydrogen) and iron plus other metallic elements in measurable amounts. The iron and other metallic additions result in the solid solution strengthening of titanium. In addition, iron and selected other metallics can combine with titanium to form intermetallic compounds under thermal and saturation conditions when solid solution conditions are exceeded.

Another important alloying effect apart from the strengthening effect of additions to titanium, is the change induced in the polymorphous transformation temperature of the crystal structure. The transformation temperature from the hexagonal-close-packed form (hcp or alpha phase) to the body-centered-cubic form (bcc or beta phase) in pure titanium, occurs at about 1625 F (885C). The effect of alloying elements on titanium is to raise or lower the transformation temperature dependent upon the kind of alloying elements in solution. The amount of the element affects the degree of change. The interstitial soluble elements, carbon, oxygen, and nitrogen, and the metal aluminum, are examples of elements that raise the hcp to bcc transformation temperature. Iron, vanadium, chromium, molybdenum, and manganese, are examples of elements that markedly lower the transformation temperature. Tin and zirconium tend to lower the transformation temperature only slightly (e.g. tin lowers the hcp to bcc transus temperature 1F/1%) and such elements are often referred to as neutral stabilizers.

The ability of elements to distort the crystal structure of titanium to cause strengthening or to cause changes in the polymorphous behavior varies from element to element and is the basis of titanium alloy metallurgy. Metallurgists are continually experimenting with alloying elements to obtain improved titanium alloys with consistent and predictable properties. Elements that raise the hcp-bcc transus (alpha stabilizers), or those that lower the transus (beta stabilizers), and combinations of such elements have been used to develop alpha, beta, and alpha-beta alloys — so-called because their microstructures are predominantly of these phases at room temperature.

b. Alpha Alloys. The commercial unalloyed grades of titanium are technically alpha alloys as is the alloy of titanium containing small amounts of palladium added to improve corrosion resistance. The Ti-5Al-2.5Sn alloy is the best example of a high strength alpha alloy that has commercial status. The amount of tin included in the make-up of Ti-5Al-2.5Sn, as well as the small amounts of iron and other beta stabilizers that might be present as impurities, is insufficient to override the dominant effect of the aluminum alpha stabilizer alloyed at the 5 percent level. This alloy may be characterized as having a hcp alpha microstructure at ambient temperature and of course due to the alloying additions, moderately high strength compared to unalloyed titanium.

Two notable features of alpha alloys are: a good retention of strength at elevated temperature under low strain rate conditions, and good weldability. Also, alpha alloys show little strain rate sensitivity. There are numerous applications where these attributes are of great importance. The high strength at elevated temperature feature of the more highly aluminum alloyed alpha compositions can be somewhat disadvantageous from the viewpoint of a more limited fabricability compared with mixed two-phase alpha-beta alloys and beta compositions. This difficulty can be alleviated by additions of neutral stabilizers and small amounts of beta stabilizers to afford extremely useful compositions.

c. Near-Alpha Alloys. As previously mentioned, the commercial alpha titanium alloys contain some beta-stabilizing elements although these are frequently in alpha soluble quantities. The microstructures of such materials may or may not include small observable quantities of the beta phase. Additional but still small quantities of beta stabilizers to an alpha stabilized base result in the presence of larger quantities of the beta phase in the predominant alpha structure. Such additions not only promote a small amount of beta phase retention but alter the mechanical characteristics of the alloy as well. Depending upon the amount and kind of beta stabilizers used, strength, stability, and fabricability may be improved in comparison with all alpha compositions of the same alpha stabilized base. Alpha alloys modified with relatively small amounts of beta stabilizers are frequently referred to as near-alpha alloys.

A small but critical amount of an intermetallic-compound-forming addition to molybdenum-containing near-alpha alloys has been found to have a synergistic effect on creep strength. Boron, germanium, bismuth, and silicon behave similarly as the compound forming element in such alloys but the latter has been used most extensively in near-alpha compositions (also called super-alpha alloys). Since an intermetallic compound such as Ti_5Si_3, complex intermetallics, can form in these materials and can be observed in the microstructures as a dispersed precipitate phase, the term alpha-dispersoid alloy is also sometimes applied. Alloys of this class are almost exclusively for service in gas turbine engines having as their principal attribute significantly higher creep strength than an all-alpha or a near-alpha alloy of the same base composition. The alloys of this class also have been developed to maintain other useful features including high short-time elevated temperature strength, adequate ductility, and stability during and after thermal excursions.

The Ti-1 to 2 Ni and Ti-2Cu alloys are the commercial representatives of yet another type of alpha-dispersoid composition. The intermetallic compound forming elements, nickel and copper, are used in a titanium base that is not fortified with additions of aluminum, tin, or zirconium. The titanium-nickel alloy is made exclusively for its good corrosion resistance. The titanium copper alloy is made for uses requiring the formability and weldability of unalloyed titanium combined with an improved elevated-temperature strength requirement. The intermetallic compounds, Ti_2Ni and Ti_2Cu, are usually observed as a fine precipitate phase randomly dispersed in an alpha microstructure. This is generally the form of occurrence of the intermetallic compounds that can precipitate under certain thermal conditions when the so-called beta-eutectoid stabilizers are alloyed with titanium. Elements of this type include bismuth, silicon, iron, manganese, and chromium, as well as nickel and copper. The alloying characteristics of these elements in titanium is the lowering of the hcp-bcc transformation temperature (called the beta transus temperature), limited solubility in the alpha phase, and propensity to form intermetallic compounds.

d. *Alpha-Beta Alloys.* As mentioned previously, one type of beta stabilizer is called beta-eutectoid stabilizers because they have eutectoid behavior when alloyed with titanium and are compound formers. Another type of beta stabilizers is called beta-isomorphous stabilizers because they are soluble in beta titanium over the full range of the alloy system. Elements of this type do not form compounds and include molybdenum, vanadium, columbium, and tantalum. Alpha-beta titanium alloys result when sufficient beta-stabilizers of either type are added to a base composition to cause quantities of the beta phase to persist to room temperature. The base composition may or may not contain alpha stabilizers although the commercial alpha-beta titanium alloys usually do—an exception is the Ti-8Mn composition. A two phase alpha plus beta microstructure is characteristic, although a large variation in the appearance of the structure, due to various deformation and thermal processing techniques, can make the interpretation of microstructures difficult.

The mechanical characteristics of alpha-beta titanium alloys are highly dependent upon the combination of alpha-stabilizers and beta stabilizers used in their make-up as well as upon processing history. Aluminum is frequently used as the alpha stabilizer which among other features contributes to the strength of the alloy over the full service temperature range. Commercial alpha-beta alloys usually contain considerable quantities of the beta isomorphous elements, molybdenum or vanadium, which impart stability as well as strength at high temperatures. The addition of beta-eutectoid stabilizers also imparts strength although their use in large quantities can result in instability due to the inappropriate precipitation of compound.

In general terms, the amount of alloy addition in alpha-beta alloys is relatable to strength level. For example, the Ti-6Al-4V alloy is considerably stronger than the Ti-3Al-2.5V alloy. Similarly, alpha-beta alloys with increasing amounts of beta stabilizing addition are inherently stronger in short-time tensile testing and due to the larger beta content, are heat treatable to higher strengths. For example, the short-time strength and the heat treatability of the Ti-6Al-6V-2Sn alloy is greater than Ti-6Al-4V. Also, Ti-6Al-2Sn-4Zr-6Mo is stronger and more responsive to heat treatment than Ti-6Al-2Sn-4Zr-2Mo. (The latter alloy is also frequently considered a near-alpha alloy and serves to show the relationship between near-alphas and weakly beta stabilized alpha-beta alloys.) However, if the low strain rate performances of these materials are compared, as in creep for example, the Ti-6Al-4V alloy is shown to be better than Ti-6Al-6V-2Sn and the Ti-6Al-2Sn-4Zr-2Mo outperforms Ti-6Al-2Sn-4Zr-6Mo.

In addition to the strength and heat treatability features characteristic of alpha-beta alloys, this class can be characterized as having good fabricability, good ductility and stability commensurate with preferred strength levels and exposure conditions, and marginal weldability except when the beta stabilizing content is low. For example, Ti-3Al-2.5V, Ti-6Al-4V, and Ti-6Al-2Sn-4Zr-2Mo alloys are weldable whereas weldability is not recommended for the Ti-6Al-6V-2Sn, Ti-6Al-2Sn-4Zr-6Mo, Ti-4Al-3Mo-1V, and Ti-8Mn alloys. The heat treatment of alpha-beta alloys is discussed further in a subsequent section.

e. Beta Alloys. Increasing quantities of the beta stabilizing elements added to a titanium base have been described to result in increasing amounts of the beta phase in the micro-structure and to afford alloys of the classes: alpha (trace to small amounts of beta stabilizers), near-alpha (small amounts of beta), and alpha-beta (weakly beta stabilized to strongly beta stabilized compositions). Larger amounts of beta stabilizing additions result in up to 100 percent beta phase retention to room temperature and the alloy class—beta. The commercial beta titanium alloys are so-called metastable beta compositions since the partial transformation of the beta phase to alpha phase, to an intermediate phase (omega), or to intermetallic compound phase, can occur during thermal exposure. In fact, the precipitation of these phases during the heat treatment of the betas is the reaction relied upon to result in the high strengths characteristic of metastable beta alloys. Metastable beta titanium alloys have been used in airframes (e.g. Ti-13V-11Cr-2Al sheet and forgings in the SR-71) and for such specialty items as springs and fasteners. Titanium alloys with larger amounts of beta stabilizers to result in stable beta microstructures are possible but are not currently utilized as commercial materials.

In addition to the heat treated high strength characteristic of beta alloys, the excellent ductility of the nonheat-treated beta phase is a notable feature. The highly ductile beta phase has great cold workability which permits excellent room temperature formability. The alloys also can be formed at elevated temperatures where their deformation resistance is very low when the strain rate is low but high when strain rate is high. In short, the beta alloys are strain rate sensitive. Thus, as with richly beta stabilized alpha-beta alloys, short-time elevated temperature strengths of betas are high, whereas creep strengths are low compared with alpha or near-alpha alloys.

The weldability of beta titanium alloys is not considered outstanding. The betas are quite weldable from the annealed condition and are very ductile as welded. However, the annealed condition is a low strength condition and attempts to strengthen welded material by heat treatment usually result in very low ductility of weldments. Combinations of post-weld heat treatment and deformation, if amenable to the welded part, can improve the weld ductility although it is not a commonly used procedure.

f. Synopsis. There are basically two classifications of the alloying elements that might be combined with titanium: (1) alpha stabilizing additions, and (2) beta stabilizing additions. The alpha stabilizing elements which promote the alpha phase are principally represented by aluminum and by the interstitially soluble elements, carbon, oxygen, and nitrogen. The beta stabilizing elements which promote retention of the beta phase are represented by the so-called beta isomorphous elements such as molybdenum and vanadium by the beta-eutectoid stabilizers (intermetallic compound formers) such as iron, manganese, chromium, and silicon, and the so-called neutral stabilizers, tin and zirconium that tend to lower the beta transus temperature only slightly. Singly or in any combination, these additions tend to strengthen titanium, to promote other mechanical, physical, and metallurgical characteristics, as well as to control basic microstructures. These effects are summarized in Figure 15 where the highly schematized microstructures of the various alloy classes are approximately correlated with exemplary commercial compositions and trend lines of major significance.

20. Effects of Processing and Heat Treatment Variables. Mill products of many types are produced by the hot fabrication of ingots or cast preforms using a wide variety of reduction schedules and methods. The variations in the reduction schedules and associated processing variables (e.g. cooling rate from processing temperatures and post-fabrication heat treatment) result in a wide variety of microstructural conditions which, as might be expected, are characterized by different mechanical properties. Processing variables are interrelated with alloy composition variables in determining microstructure and property differences.

To illustrate the typical fabrication schedules for titanium alloys in terms of thermal history and to show their correlation with resulting microstructures and properties, the case for the Ti-6Al-4V alloy is described. It should be understood that an idealized and highly simplified case

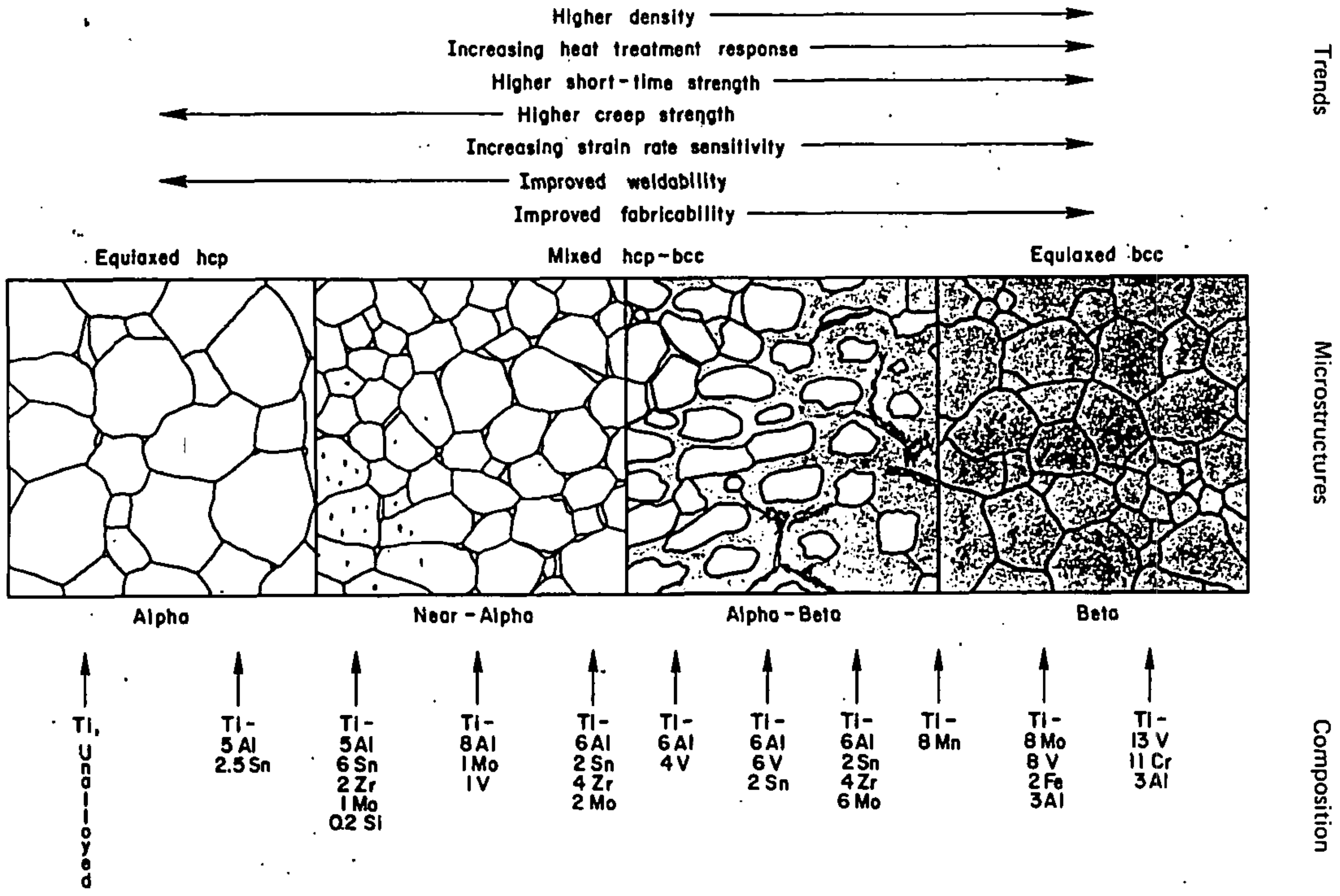


Figure 15. Correlation of Titanium Alloy Class with Schematic Equilibrium Microstructures, Major Property Trends and Compositions

is presented since it is impossible in a short space to depict all the variables and variations which actually occur. Also, the alloy variable should be apparent—the Ti-6Al-4V alloy would be processed differently and behave differently than dissimilar compositions.

The case for the Ti-6Al-4V alloy is shown schematically in Figure 16. The line drawing of this figure is a partial phase diagram of the Ti-6Al-V system wherein the points on the vertical through the 4 percent vanadium composition represent significant temperatures of processing and heat treatment. Representative microstructures are depicted from selected temperatures.

Normal breakdown fabrication operations for Ti-6Al-4V alloy usually are performed above the beta transus temperatures (e.g. point A in Figure 16) whereas finishing fabrication temperatures can be high in the alpha-beta field (point B) to low in the alpha-beta field (point C). Subsequent mill annealing (and sometimes fabrication) may be carried out at still lower temperatures (point D). Solution heat treatment of Ti-6Al-4V alloy may be accomplished in the alpha-beta field (ranging between points B and C) whereas subsequent aging is done at a much lower temperature (point E). The microstructures shown for various temperatures and cooling rates of processing are generalized and in practice can vary considerable from those depicted (e.g. variation with degree of deformation at the indicated temperature and/or prior processing history). Nevertheless, the illustrations show the major differences in structure resulting from beta processing versus alpha-beta processing versus alpha-beta processing and such differences in the alpha to beta phase ratio that might be obtained by fabrication at different temperatures within the alpha-beta field. Processing at increasing temperatures within the alpha-beta field gives rise to decreasing amounts of primary equiaxed alpha in the microstructures. Extensive processing moderately low in the alpha-beta field followed by simple annealing at still lower temperatures results in an equiaxed alpha plus grain-boundary beta microstructure as illustrated. The alpha phase is the continuous phase under these conditions. Heat treatments at still lower temperatures; that is at aging or overaging temperatures, result in microstructural transformations that may vary in extent with the thermal exposure conditions and are sometimes difficult to detect visually. Profound changes of a microscopic and sub-microscopic nature do not occur however, that can be observed with magnification, and generally consist of precipitate phases emanating from preexisting phases. Classically, alpha phase precipitates from the metastable beta phase.

The acicularity of the transformed beta microstructure is an important feature of many titanium alloys and processing procedures. The platelets or needles of the alpha phase occur as the beta phase transforms to alpha with the lowering of temperature and the resulting acicularized structure may have quite different properties than equiaxed structures. Note in Figure 16 that in structures emanating from high in the alpha-beta field, a mixture of equiaxed alpha (called primary alpha) and acicular alpha (called alpha prime, α') is observed. The acicular alpha is also referred to as martensitic alpha and is the transformation product from the beta phase which existed at the solution temperature (point B of Figure 16).

The coarseness of acicular alpha that forms from either beta processing or alpha-beta processing is related to cooling rate. Decreased cooling rates result in coarse acicular structures. If the processing of Ti-6Al-4V and other similar alpha-beta alloys has included relatively little or no work in the alpha-beta field, and if it is subsequently annealed low in the two-phase region, the structure reflects the prior beta and transformed beta structures developed during the processing above, passing through, and just below the beta transus temperature. If extensive working of the alloy occurs in the alpha-beta field, the structure is altered from the predominant transformed beta structure to one consisting of a mixture of equiaxed primary alpha and either a transformed beta (working high in the alpha-beta field) or a metastable beta (working low in the alpha-beta field) microstructure.

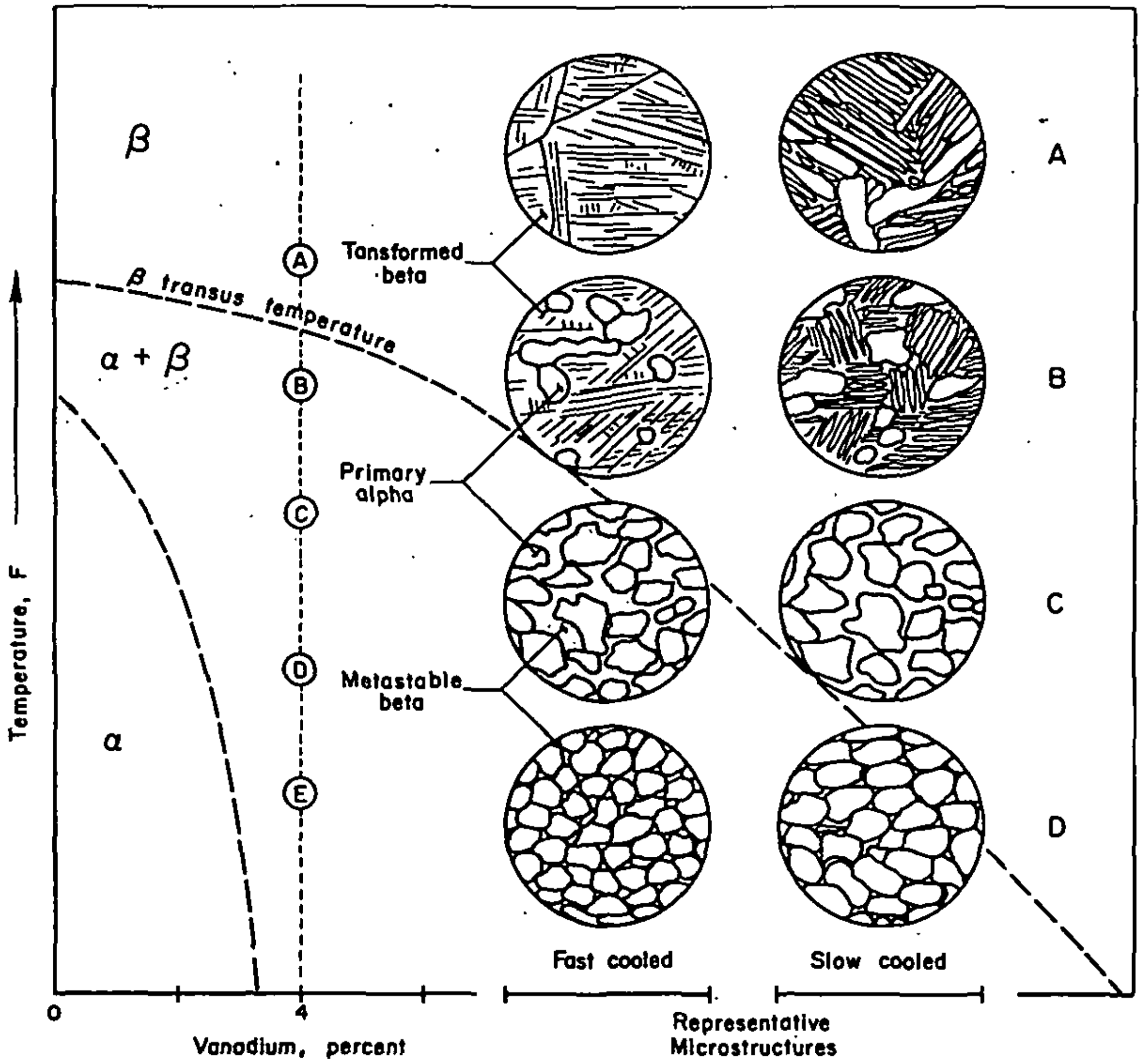


Figure 16. Partial Phase Diagram of the Ti-6Al-V System and the Schematic Representation of Microstructures Resulting from the Fabrication of Ti-6Al-4V Alloy at Various Temperatures

Currently, the fabrication of many alloys, principally near-alpha and alpha-beta types, is accomplished using either alpha-beta fabrication or beta fabrication schedules. As the names imply, the schedules differ principally in the fabrication temperatures used. Alpha-beta processing, while usually including beta temperatures for breakdown fabrication, features finish fabrication (preferably at least 50 percent reduction) in the alpha-beta field. Beta processing features extensive work in the beta field, resulting in a predominantly acicularized microstructure, with some limited fabrication at temperatures below the beta acicularized microstructure, with some limited fabrication at temperatures below the beta transus which is insufficient to cause the formation of much equiaxed primary alpha. The two main advantages of alpha-beta processing are: (1) oxidation rates are lower at alpha-beta temperatures than at beta temperatures, and (2) alpha-beta microstructures have long been equated with maximum tensile yield strength and ductility. The advantages of correct beta processing *(incorrect beta processing can be deleterious to properties)* include: (1) lower fabrication energy requirements for a given part size or production of larger part size with the same fabrication energy and equipment, (2) closer part dimension tolerances which may be related to substantial material savings, and (3) improvement of important mechanical properties. A summary of the properties observed for the Ti-6Al-4V alloy as beta processed (relative to alpha-beta processing) are shown below.

Property	Beta Processing Effect
Tensile yield strength	Slightly lower
Ultimate tensile strength	Same
Tensile elongation	Slightly lower
Tensile reduction in area	Reduced
Notched tensile strength ($K_t = 10$)	Improved
Notched-time-fracture strength ($K_t = 3.8$)	Improved
Creep strength	Improved
Creep stability	Same
Fatigue strength (at 10^7 cycles)	Same
Fracture toughness	Improved

The amount of reduction during metalworking, the reduction temperatures, the temperature holding time, and the cooling rates are the important variables that control microstructures and subsequently mechanical properties. The processing steps may be distinctly categorized for the various mill product forms, i.e., forgings, bar, plate, sheet, strip, or extrustions. However, there are variables within these variables, such as: initial ingot size (relative to reductions achievable for a specific end-item thickness), planned or unplanned beta processing versus alpha-beta processing, final end-item section size, and variations in microstructure and texture associated with each processing history. The directionality effects stemming from various degrees of texturing are well known to be different in continuously rolled strip than in forgings, for example, and to be somewhat controllable through control of processing variables. The morphology of microstructure, beta grain size, and primary alpha grain size and shape (important with regard to fracture toughness and saltwater stress-corrosion susceptibility), are similarly controllable to a large extent through process control. Each variable, interacting with possibly one or more additional variables, can give rise to rather wide differences in mechanical properties. In addition to the above variables, the variables of secondary processing mill products to finished parts via bending, stretching, twisting, machining, and pickling operations must be considered with regard to their possible influence on final properties.

The variables of final heat treatment are imposed on the processing variables introduced earlier. Heat treatment procedures are the "last chance" for the titanium user to control mechanical properties and of course the extent of heat treatment property control is somewhat limited by the prior processing. While heat treatments have been developed to somewhat neutralize the effects of earlier occurring variables, some are more difficult to neutralize than others. Further, the variables of the various heat treatment techniques and schedules are influential in themselves toward effecting property variation. Thus, relative to the mechanical properties available for Ti-6Al-4V alloy as obtained in a specific condition of heat treatment, the entire gamut of possible variables may have influenced the properties observed (and in addition, the testing variables). Therefore, consideration for all variables and their effects should be given in the review and study of properties obtainable with selected heat treatments. A review of the heat treatments being used for Ti-6Al-4V alloy follows:

- Stress relief annealing
  (2 to 4 hours at 1100 F, air cool to room temperature)

- Full annealing (or mill annealing)
  (2 hours, 1350 ±25 F, air cool to room temperature)

- Annealing for continuously rolled sheet
  (5 minutes, 1600 F, Rapid furnace cool, plus 5 minutes
  1100 F, air cool to room temperature)

- Recrystallization annealing
  [4 or more hours, 1700 F, furnace cool to 1400 F at
  100 F/hour (no faster), cool to 900 F at 670 F/hour
  (no slower), air cool to room temperature]

- Duplex annealing
  (10 minutes 1725 F, air cool, plus 4 hours, 1250 F,
  air cool to room temperature)

- Beta annealing [or beta conditioning followed by other heat treatments]
  (30 minutes, 1900 F, air cool, plus 2 hours, 1350 F, air
  cool to room temperature)
  [30 minutes, 1900 F, air cool, followed by solution
  treating and overaging.]

- Solution heat treatment
  (10 minutes, 1725 F, water quench)

- Solution heat treatment and overaging
  (10 minutes, 1725 F, water quench, plus 4 hours,
  1250 F, air cool to room temperature)

- Solution heat treatment and aging
  (10 minutes, 1725 F, water quench, plus 4 hours, 950-1000 F,
  air cool to room temperature)

The general effects of the various heat treatments are as follows: annealing heat treatments result in moderately low strength but ductile material; the specialized annealing heat treatments—i.e., recrystallization annealing, duplex annealing, and beta annealing—result in nearly the same strength and ductility combinations as from annealing but with improved fracture toughness characteristics; and the solution heat treatment plus aging heat treatments result in improved strength with some sacrifice in ductility and toughness. Overaging heat treatments result in less strength but in more ductility and toughness than aging heat treatments. The difference between overaging and aging heat treatments on the hardness of Ti-6Al-4V alloy (directly relatable to tensile strength) is illustrated in Figure 17. (Overaging treatments tend to produce more precipitate than aging treatments, and in different form and distribution, to account for differences in properties.) Beta heat treatments given as preliminary treatments tend to lower strength and ductility but to improve toughness. Solution heat treatment, per se, results in a ductile condition suitable for forming and/or subsequent aging but is usually not used as a final heat treatment for a serviceable part.

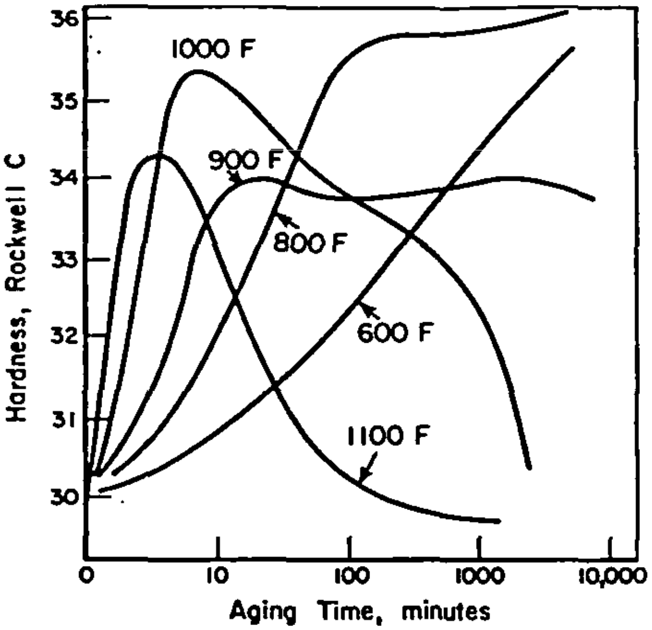


Figure 17. Effect of Aging Time and Temperature on the Hardness of Ti-6Al-4V Alloy Solution Annealed at 1562 F and Water Quenched

While it is not possible to describe the fabrication and heat treatment variables that exist for all commercial alloys, it is hoped that the features detailed for the Ti-6Al-4V alloy can be viewed as an exemplary case. Many of the principles described pertain to numerous other materials and can be directly applied. On the other hand, sufficient differences exist between Ti-6Al-4V alloy and alpha alloys (e.g. alpha alloys are not heat treatable) or beta alloys (e.g. beta alloys are routinely beta fabricated and seldom show primary alpha in structures) so that the careful review of the metallurgy of each grade to be used should be undertaken prior to using them.

Heat Treatment Processes

21. Heat Treatment Requirements. Generally, heat treating procedures are used to obtain desired properties within the limitations of the respective titanium alloys, mill product forms, sizes, and prior metallurgical conditions imposed by prior processing. The requirements for control of heat treating processes, as applied to titanium and titanium alloys in manufacturing and maintenance facilities, are covered by Specification MIL-H-81200A, "Heat Treatment of Titanium and Titanium Alloys". This specification is currently being studied to determine the extent of revisions to be made, since it currently does not contain information on all titanium alloys listed in major materials specifications such as MIL-T-9046 and MIL-T-9047 and others such as some newer AMS specifications. In addition, MIL-H-81200A presently describes heat treatments for quite a few alloys that are no longer in production and/or used. Nevertheless, this specification describes the minimums acceptable for such items as temperature measuring equipment, furnaces, heating media, fixtures and racks, and heat treatment operations and procedures (time-temperature-and cooling details) as well as sampling, inspection, and testing procedures. As

described in previous subsections, temperatures and times for heat treatment are merely two of the variables that can influence final properties; other variables relate to alloy chemistry, fabricating schedules, part thickness, etc. For this reason, the temperature and time ranges recommended for heat treatment are adjustable to develop the desired properties for titanium alloys which are specified in the related procurement documents, or detailed in applicable drawings and purchase orders. Mandatory temperatures and soaking times specified for the various heat treatments (solution, aging, annealing, and stress-relief annealing) to cover all the variables for titanium materials as previously described, cannot be stated. On the other hand, the recommendations of specifications such as those in MIL-H-81200A, establish a minimum acceptance level for procedures and properties, and deviation from them must be substantiated by actual tests to prove that the deviation produces an equivalent or superior product.

22. Furnaces. Since titanium is such a reactive metal at elevated temperatures, vacuum furnaces are ideal for its heat treatment, However, while vacuum furnaces are commonly used to heat treat titanium and its alloys, the expense of vacuum heat treatment is not practical for many procedures and parts. Therefore, furnaces having inert gas, air, or combusted gases as the atmospheres are used more commonly. In all cases, the furnace should be of a suitable design and construction to permit the easy handling of the part, the uniform heating of the part, and any desired preferential cooling of the part.

In the case of inert atmosphere furnaces, the inert gas such as argon or helium, should be used at a dew point of -65 F or lower to prevent contamination of the titanium parts being heat treated. The inert gas should be circulated to insure the protection of all surfaces of the part(s). In the case of fuel-fired furnaces, where combusted gas is the atmosphere, the most important precaution to be observed is that the titanium work piece should not be exposed directly to the flame. The furnace atmosphere should be as free from water vapor as possible and should be slightly oxidizing. Both water vapor and incompletely burned fuel vapors can react with titanium to form atomic hydrogen which is readily absorbed by titanium. The only practical method for removing hydrogen from titanium is by vacuum annealing. The other contaminating interstitial elements, carbon, oxygen, and nitrogen, cannot be removed from titanium although contaminated outer metal layers can be removed from work pieces.

Air chamber furnaces are very flexible and economical for handling large volumes of titanium parts being heat treated, especially for moderately low-temperature heat treatments. On the other hand, at high temperatures, where surface oxidation becomes significant, a muffle furnace design using external heating offers more protection, particularly if the furnace is gas fired. Electric furnaces for small lots or special heat treatments are preferred, since heating can be accomplished either internally or externally with a minimum of contamination. Resistance and induction types of electric furnaces also have been used to minimize contamination through reduced heating times. Salt bath type furnaces have been used for the heat treatment of titanium also, although furnaces of this type do not appear to be preferred, probably due to the intergranular attack of titanium by certain salts, notably chlorides, which necessitate removal of the outer metal layers of work pieces so contaminated.

The effectiveness of certain heat treatments, notably solution heat treatment is largely dependent upon the effectiveness of the cold quenching termination of the thermal exposure. Quench delay time is critical with regard to obtaining optimum properties. For this reason, furnaces for solution heat treatment, for example, should be located in close proximity to the quenching equipment. In many cases, furnaces and quenching equipment are built together in such a way that the titanium part can be dropped or rolled from the hot zone into the quenching media in a very short time. Water is the most widely used quenching medium, although low-viscosity oils and water containing wetting agents (e.g. 3 percent NaOH) have been used also.

23. Stress-Relief Annealing Treatments. The manipulation of titanium during fabrication and/or welding operations in making end-use items can result in the build-up of residual stresses. Since the part may be in a penultimate finished condition when the stresses are built up, a final full annealing operation may not be feasible due to surface oxidation, fixturing to hold dimensions, or mechanical property considerations (e.g. if the penultimate finished part is in the aged condition). For the allevaition of such residual stress, the stress relief annealing of the part may be considered. This is generally a moderately low temperature, short-time thermal exposure designed to relieve the stresses by thermal activation but to not degrade properties by oxidation or undesirable phase transformations. As indicated in Table XXVI, temperatures in the range of 700 to 1450 F can be used (varies with alloy composition) although commonly temperatures around 1000 F are popular. To minimize oxidation, the time and temperature of the stress relief anneal should be kept low. Frequently only portions of the residual stresses are removed, but to a level not likely to be troublesome. A common practice in the stress relief of weldments in aged structures is to perform part of the aging heat treatment prior to welding and to complete the aging after welding, simultaneously relieving residual stresses. Aging heat treatment temperatures also can be used to relieve the stresses in nonwelded structures to be finished in the aged condition. Higher temperature, longer time, stress relief annealing treatments result in conditioning the metal to approach the full annealed state.

24. Annealing Treatments. A stress-free, equilibrium crystal structure in titanium materials achieved by full annealing is generally the most ductile and stable condition. The annealed structure varies with alloy type as might be expected; alpha alloys ideally are annealed to an "all-alpha" (trace of beta phase possible) equiaxed microstructure, near-alpha and alpha-beta alloys are annealed to equiaxed alpha plus residual beta phase microstructures (alpha/beta ratio depends on composition and annealing temperature), and beta alloys are annealed to an equiaxed beta microstructure. Since annealing temperatures for beta titanium alloys may be the same as solution heat treatment temperatures and beta phase may be retained with either slow or fast cooling from temperature, annealing and solution treatments for beta alloys are synonomous.

As described in Section III, Paragraph 20., there are several kinds of annealing variations for the Ti-6Al-4V alloy. The various thermal exposures are designed to promote modifications of microstructures, commensurate with various mill product forms, which yield somewhat different combinations of strength, ductility, and toughness, but characteristically the moderately strong and stable condition is promoted—not the highest strength condition. Typically the more highly alloyed near-alpha compositions and the alpha-beta alloys may be annealed in more than one manner. One of the common aims of all such heat treatments is to achieve a reproducible structure capable of resisting further change by phase transformation when exposed to the elevated temperatures of a service exposure. In general, the high temperature exposure in a modified annealing heat treatment fixes or determines the phase morphology and alpha/beta ratio (subject to a preferred prior fabrication schedule) and the final low temperature part of the treatment stabilizes the composition of the beta phase to resist transformation. In many ways, the low temperature exposure of modified annealing heat treatments are like overaging heat treatments which are discussed in Paragraph 26. The modified special purpose annealing treatments also are further discussed in a subsequent paragraph (Paragraph 27). The frequently used full annealing time and temperature ranges for titanium alloys are given in Table XXVII. These annealing treatments result in the moderately strong, ductile and tough properties commonly sought for structural materials.

25. Solution Heat Treatments. Thermal exposures that are designed to develop a preferred metastable composition of the beta phase in two-phase (alpha plus beta) or all-beta alloys are

TABLE XXVI. STRESS–RELIEF ANNEALING SCHEDULES

Nominal Composition, wt %	Stress-Relief Temperature, F	Stress-Relief Time, hours
Unalloyed Ti grades and Ti-0.15 to 0.20 Pd alloys	780 to 825	7 to 8
	880 to 925	2 to 4
	975 to 1000	1/2 to 1
	1000 to 1100	1/4 to 2/3
Ti-5Al-2.5Sn (and ELI)	990 to 1200	1/4 to 6
Ti-1 to 2 Ni	Not reported	
Ti-2Cu	1075 to 1125	1
Ti-2.25Al-11Sn-5Zr-1Mo-0.2Si	Not reported	
Ti-5Al-6Sn-2Zr-1Mo-0.25Si	Not reported	
Ti-6Al-2Sn-1.5Zr-1Mo-0.35Bi-0.1Si	Not reported	
Ti-6Al-2Cb-1Ta-0.8Mo	1000 to 1200	1/4 to 1
Ti-8Al-1Mo-1V	1075 to 1125	2
	1450	1/6 to 1/3 (a)
Ti-8Mn	900 to 1100	1/2 to 2
Ti-3Al-2.5V	700 to 1200	1/2 to 3
Ti-4Al-3Mo-1V	900 to 1100	1/2 to 8
Ti-5Al-2Sn-2Zr-4Mo-4Cr	Not reported	
Ti-6Al-4V (and ELI)	900 to 1200	1/2 to 50(b)
	1000 to 1100	2 to 4(c)
Ti-6Al-6V-2Sn	1000 to 1200	1/2 to 4
Ti-6Al-2Sn-4Zr-2Mo	900 to 1200	1 to 4
Ti-6Al-2Sn-4Zr-6Mo	Not reported	
Ti-6Al-2Sn-2Zr-2Mo-2Cr-0.2Si	Not reported	
Ti-7Al-4Mo	900 to 1300	1/2 to 8
Ti-1Al-8V-5Fe	1000 to 1300	1/2 to 4
Ti-2Al-11V-2Sn-11Zr	Not reported	
Ti-3Al-8V-6Cr-4Mo-4Zr	Not reported(d)	
Ti-11.5Mo-6Zr-4.5Sn	900 to 1100	8(e)
	1325 to 1350	[1 to 5 minutes](f)
Ti-8Mo-8V-2Fe-3Al	950 to 1100	1 to 4(e)
Ti-13V-11Cr-3Al	900 to 1000	1/2 to 60(e)
	1400 to 1450	1/4 (f)

Notes:

(a) A short exposure at full annealing temperature may be used. Air cooling from this exposure results in stimulating the duplex annealed condition; slow cooling; stimulates the mill annealed condition.

(b) For 100 percent relief; 50 hr – 1000 F or 5 hr – 1200 F. For 50 percent relief; 5 hr – 1000 F or 1/2 hr – 1100 F.

(c) Commonly used ranges.

(d) Full annealing or above the beta transus temperature (~ 1460 F) may be used to relieve residual stresses or stress relief may be achieved simultaneously with aging heat treatment.

(e) Stress relief may be achieved simultaneously with aging heat treatment.

(f) Stress relief may be achieved using short-time exposure at the solution annealing temperature.

TABLE XXVII. ANNEALING SCHEDULES

Nominal Composition, wt %	Annealing Temperature, F	Annealing Time, hours[a]	
Unalloyed Ti grades	1300	2[b]	(AC)
and Ti-0.15 to 0.20 Pd alloys	1000 to 1500	1/4 to 4	(AC)
Ti-5Al-2.5Sn (And ELI)	1300 to 1675	1/4 to 4	(AC)
Ti-1 to 2Ni		Not reported	
Ti-2Cu	1250 to 1450	1/2 to 2	(AC)
Ti-2.25Al-11Sn-5Zr-1Mo-0.2Si	1650 +	1	(AC)
Duplex (2 step) anneal[c]	930	24	(AC)
Ti-5Al-6Sn-2Zr-1Mo-0.25Si	1800 +	1/2	(AC)
Duplex (2 step) anneal[c]	1100	2	(AC)
Ti-6Al-2Sn-1.5Zr-1Mo-0.35Bi-0.1Si	1300	1	(AC)
Duplex (2 step) anneal[c]	1950 +	1/4	(AC)
	1300	1	(AC)
Ti-6Al-2Cb-1Ta-0.8Mo	1300 to 1700	1/4 to 2	(AC)
Ti-8Al-1Mo-1V	1400 to 1450	1/4 to 8	(AC)(FC)[d]
Duplex (2 step) anneal[c]	1650 to 1850 +	1/3 to 1	(AC)
	1100 to 1375	8	(AC)
Ti-8Mn	1250 to 1350	1/2 to 1-1/2	(FC)[e]
Ti-3Al-2.5V	1200 to 1400	1 to 3	(AC)
Ti-4Al-3Mo-1V	1225 to 1350	1 to 4	(FC)[e]
Ti-5Al-2Sn-2Zr-4Mo-4Cr		Not reported	
Ti-6Al-4V (And ELI)	1275 to 1600	1/4 to 8	(AC)
	1350 to 1400	2[b]	(AC)
Ti-6Al-6V-2Sn	1300 to 1500.	1 to 8	(AC)(FC)[f]
Ti-6Al-2Sn-4Zr-2Mo	1300 to 1550	1 to 8	(FC)[e]
Duplex (2 step) anneal[c]	1650 to 1750 +	1/2 to 1	(AC)
	1100 to 1450	1/4 to 8	(AC)
Triplex (3 step) anneal[c]	1650 +	1/2	(AC)
	1450 +	1/4	(AC)
	1100	2	(AC)
Ti-6Al-2Sn-4Zr-6Mo	1500 to 1600 +	1/2 to 1	(AC)
Duplex (2 step) anneal[c]	1100 to 1300	1/4 to 8	(AC)[g]
Ti-6Al-2Sn-2Zr-2Mo-2Cr-0.2Si		Not reported	
Ti-7Al-4Mo	1425 to 1475	1 to 8	(FC)[e]
Ti-1Al-8V-5Fe	1250 to 1400	1 to 4	(AC)(FC)[f]
Ti-2Al-11V-2Sn-11Zr	1400 to 1600	1/2 to 1	(AC)(FC)[h]
Ti-3Al-8V-6Cr-4Mo-4Zr	1500 to 1700	1/4 to 1/2	(AC)(WQ)[i]
Ti-11.5Mo-6Zr-4.5Sn	1275 to 1600	1/10 to 2/3	(AC)(WQ)[i]
Ti-8Mo-8V-2Fe-3Al	1450	1/10 to 1/4	(AC)(WQ)[i]
Ti-13V-11Cr-3Al	1400 to 1500	1/10 to 1	(AC)(WQ)[i]

Notes:

(a) Cooling rates in parentheses: AC=air cooling, FC=furnace cooling, WQ=water quench.

(b) Commonly used annealing treatment.

(c) Both the high and the low temperature steps are required. Three steps are required in triplex annealing.

(d) Slow cooling results in the mill annealed condition. Air cooling results in the duplex annealed condition.

(e) Slow cooling to 1000-1050 F, not exceeding 300 F/hour, improves stability.

(f) Either air cooling or slow cooling as in (e).

(g) Short-time, high temperature second step for sheet and up to 8 hours at 1100 F for thick-section products.

(h) Either air cooling or slow cooling to 1000 F, followed by WQ.

(i) Either air cooling or water quenching from solution annealing temperature.

designated solution heat treatments. A feature of solution heat treatment technique is to rapidly cool from the elevated temperature to ambient temperature to retain the composition of the beta phase as it existed at temperature. This beta phase may retain a metastability or it may transform to various degrees upon cooling, depending upon its composition, but in either case it is cooled to a condition which will transform upon subsequent aging heat treatment. The transformation of the phases fixed during solution heat treatment by subsequent aging heat treatments is the mechanism responsible for the high strength in heat treatable titanium alloys. Table XXVIII gives the commonly used time and temperature solution heat treatment schedules for titanium compositions amenable to strengthening by solution heat treatment and aging (STA) procedures.

The solution temperature required to bring about a preferred solid solution depends upon alloy composition and degree of heat treatment response desired. Generally, for alpha-beta alloys, temperatures high in the two-phase field promote a high aging (strengthening) response and vice versa. Soaking times at temperature relate to temperature uniformity within sections of various thickness and solid solubility equilibrium conditions. Soaking time requirements increase with increasing section thickness. The minimum soaking period may be determined by testing samples to make sure that the required mechanical properties can be developed from the solution treatment used. Minimum soaking times are sought for production reasons and in order to minimize the contamination that can occur at solution temperatures. The oxygen surface contamination which commonly occurs during solution treatment in air is frequently removed prior to further processing such as by forming or aging treatments.

A rapid cooling (e.g. water quenching) from the solution temperature is necessary to obtain the maximum heat treatment response (strengthening or hardenability) in alpha-beta alloys. Quick cooling also aids in avoiding the formation of grain boundary alpha (which can occur upon slow cooling) that can result in poor ductility. Richly beta stabilized alloys such as beta alloys can be cooled less quickly (e.g. air cooling) from solution temperatures and still retain a good aging response because the beta phase, being more highly alloyed than in alpha-beta alloys, is more sluggish. For the above reasons, beta alloys have deeper hardenability than alpha-beta alloys. That is, thicker sections may be strengthened more uniformly through the thickness than comparable thicknesses of alpha-beta alloys. In thick sections of weakly beta stabilized alpha-beta alloys, center sections cannot be cooled rapidly enough to promote much subsequent aging response and for such alloys, their depth of hardenability is limited. Alloys that are strongly beta stabilized have a deep hardenability which is generally proportional to the degree of beta stabilization. The following tabulation shows the relationship between compositions in terms of beta stabilization and depth of hardenability (section thickness that can be strengthened by STA treatment although not necessarily to a uniform strength level throughout the thickness.)

Ti-6Al-4V, weakly beta stabilized : up to 1 inch
Ti-6Al-6V-2Sn, greater beta stabilization : up to 2 inches
Ti-6Al-2Zr-2Sn-2Mo-2Cr-0.25Si and
 Ti-6Al-2Sn-4Zr-6Mo, richly beta stabilized : up to 6 inches
Ti-8Mo-8V-2Fe-3Al and
 Ti-13V-11Cr-3Al, beta alloys : up to 8 inches

Relative to rapid cooling and the attainment of acceptable STA mechanical properties in alpha-beta alloys, is the quench delay time—the time delay between solution temperature and the actual start of the quenching operation. Obviously, if the delay time is long, the part will be essentially slow cooled between the solution temperature and whatever temperature the part reaches just prior to quenching. That situation can lead to poor heat treatment response and therefore quench delay time should be minimized especially for the weakly beta stabilized alpha-beta alloys.

TABLE XXVIII. SOLUTION HEAT TREATING SCHEDULES(a)

Nominal Composition, wt %	Solution Temperature, F Flat-Rolled Products	Solution Temperature, F Bars and Forgings	Soaking Time, hours Flat-Rolled Products	Soaking Time, hours Bars and Forgings
Ti-3Al-2.5V	1600 to 1700	1600 to 1700	1/4 to 1/3	1/4 to 1/3
Ti-4Al-3Mo-1V	1620 to 1700	1700 to 1775	1/10 to 1/2	1/6 to 2
Ti-5Al-2Sn-2Zr-4Mo-4Cr	—	1475(b)	—	4(b)
Duplex solution treatment (d)	—	1500 to 1575 +	—	4(c)
	—	1475	—	4
Ti-6Al-4V	1650 to 1775	1650 to 1775	1/10 to 1	1/6 to 1
Ti-6Al-6V-2Sn	1550 to 1650	1550 to 1650	1/6 to 1/2	1/6 to 1
Ti-6Al-2Sn-4Zr-6Mo	1550 to 1700	1550 to 1700	1/6 to 1/2	1/4 to 1
Ti-6Al-2Sn-2Zr-2Mo-2Cr-0.2Si	1725 to 1750	1725 to 1750	1/4 to 1(e)	1/2 to 1(e)
Ti-7Al-4Mo	1675 to 1775	1675 to 1775	1/6 to 1-1/2	1/6 to 2
Ti-1Al-8V-5Fe	—	1350 to 1450	—	1/6 to 2
Ti-2Al-11V-2Sn-11Zr(f)	1350 to 1450	1400 to 1700	1/6 to 1/2(e)	1/3 to 1(e)
Ti-3Al-8V-6Cr-4Mo-4Zr(g)	1500 to 1700	1500 to 1700	1/10 to 1/2(e)	1/4 to 1(e)
Ti-11.5Mo-6Zr-4.5Sn(g)	1275 to 1500	1275 to 1600	1/10 to 1/2(e)	1/10 to 1(e)
Ti-8Mo-8V-2Fe-3Al(g)	1450 to 1475	1450 to 1475	1/10 to 1/3(e)	1/4 to 1(e)
Ti-13V-11Cr-3Al	1400 to 1500	1400 to 1500	1/6 to 1/2(e)	1/6 to 1(e)

Notes:

(a) Only alloys recommended for use in the solution treated plus aged condition are tabulated. Solution treatments terminated by water quenching (WQ) unless otherwise indicated.
(b) Solution treatment for beta fabricated material.
(c) Air cooled from high solution temperature to low solution temperature.
(d) Solution treatment for alpha-beta fabricated material.
(e) Solution treatments terminated by either water quenching (WQ) or air cooling (AC).
(f) Typical solution treatments indicated.
(g) The longer-time, higher temperature solution treatments are favored for thick-section products (e.g., plate and forgings) while short-time, lower temperature treatments are used for items such as sheet and wire.

TABLE XXIX. MAXIMUM QUENCH DELAY, WROUGHT ALLOYS

(For Immersion—Type Quenching)(a)

Nominal Thickness, inches	Maximum Time, seconds (b)
Up to 0.091 incl	4
Over 0.91	7

Notes:

(a) Quench delay time should begin when the furnace door begins to open, and end when the last corner of the load is immersed in the water quench tank. The maximum quench delay time may be exceeded, with extremely large loads or long length, if performance tests indicate that all parts comply with all other requirements.
(b) Shorter times than those shown may be necessary to ensure that the minimum requirements are complied with when quenched

The maximum quench delay times suggested for various product thicknesses are given in Table XXIX.

26. Aging Heat Treatments. The heat treatments recommended to achieve the commonly expected high strength levels for titanium alloys are given in Table XXX. Aging heat treatments cause the transformation of the metastable phases produced by the solution heat treatment to other phases. Classically, alpha phase precipitates from the beta phase during aging resulting in a residual enriched beta phase and alpha precipitate.

$$\text{Metastable } \beta \rightarrow \alpha \text{ ppt.} + \text{enriched } \beta .$$

However, other reactions are commonplace. For example, the omega phase also may precipitate from the beta phase and intermetallic compounds can form upon aging. Further, in the case of certain alloys, the beta phase existing at the solution temperature transforms upon quenching to an alpha form that is supersaturated with beta stabilizer (alpha prime). During subsequent aging, the supersaturated alpha transforms to beta and alpha phases.

$$\text{Supersaturated } \alpha' \rightarrow \beta + \alpha \text{ ppt.}$$

It is not unusual for several of these reactions to occur simultaneously during the aging heat treatment to contribute to the total strengthening process.

As indicated by the curves of Figure 17, the time and temperature of the aging exposure has much to do with the strength level achieved. Classically, the low aging temperatures result in the formation of much omega phase which characteristically imparts high strength and low ductility to the material being aged. Higher aging temperatures tend to precipitate alpha from the beta phase by a nucleation and growth process, and with longer aging times, alpha particle size may become large, the residual beta phase may be softened, and a net reduction in strength may occur. This condition is called the overaged condition. It is characterized as a moderately high strength condition combined with better ductility and toughness than an aged condition for the same alloy with the same prior processing history. Overaging may be carried out to an extreme degree to render the properties of a material similar to the properties of a fully annealed structure.

27. Special Purpose Heat Treatments. The demand for higher strength and better ductility in titanium materials which existed since their first use has recently been accompanied by a demand for additional characteristics such as improved toughness, improved thermal stability, and improved resistance to stress-corrosion. To meet this demand, the development of new titanium alloys has been pursued, and in addition, heat treatment techniques have been modified to afford property improvements. For example, several of the annealing heat treatments described for the Ti-6Al-4V alloy in Section III, Paragraph 20, are relatively new and have led to the availability of mechanical property combinations that were not available with simple mill annealing or with the solution treating plus aging procedures.

Recrystallization Annealing, for example, affords a maximum toughness and resistance to stress-corrosion cracking at an annealed strength level. The recrystallization anneal is achieved by furnace cooling from a moderately high solution temperature in the alpha-beta field. Such a treatment tends to enrich the residual beta phase at a low volume percent of the structure and to otherwise produce an equilibrium microstructure composed of equiaxed alpha and residual beta phases—very stable and tough.

Duplex annealing is similar to solution treating plus overaging for Ti-6Al-4V alloy with the important difference of a low cooling rate from the solution temperature. Due to the difference

TABLE XXX. AGING HEAT TREATMENT SCHEDULES[a]

Nominal Composition, wt %	Aging Temperature, F	Aging Time, hours[b]
Ti-3Al-2.5V	900 to 950	2 to 8
Ti-4Al-3Mo-1V	900 to 975	2 to 12
	1050 to 1150[c]	1/6 to 6
Ti-5Al-2Sn-2Zr-4Mo-4Cr	1100 to 1200	8
Ti-6Al-4V	900 to 1050	4 to 12
	1050 to 1300[c]	2 to 4
Ti-6Al-6V-2Sn	875 to 1150	2 to 8
	1100 to 1200[c]	2 to 8
Ti-6Al-2Sn-4Zr-6Mo	1050 to 1150	2 to 8
	1200 to 1300[c]	1 to 4
Ti-6Al-2Sn-2Zr-2Mo-2Cr-0.2Si	1000	4
Ti-7Al-4Mo	950 to 1200[d]	4 to 24
Ti-1Al-8V-5Fe	900 to 1100	2 to 4
Ti-2Al-11V-2Sn-11Zr[e]	850 to 1250	1 to 48
Ti-3Al-8V-6Cr-4Mo-4Zr	800 to 1050	6 to 24
	1050 to 1250[c]	6 to 12
Ti-11.5Mo-6Zr-4.5Sn	900	8
	1100[c]	8
Ti-8Mo-8V-2Fe-3Al	900 to 950	8
	1100 to 1200[c]	8 to 16
Ti-13V-11Cr-3Al	825 to 1000	2 to 60

Notes:
(a) Only alloys recommended for use in the solution treated plus aged condition are tabulated.
(b) Aging and overaging treatments are terminated by air cooling.
(c) Overaging heat treatment schedules.
(d) The overaged condition may be achieved with the higher temperatures of the range indicated.
(e) Aging treatments, including double aging treatments within the time and temperature ranges shown have been evaluated. A standard aging treatment has not been selected.

in cooling rate, the beta phase residual from the solution treatment is not subject to profound transformation since it is already partially stabilized during slow cooling. The subsequent overaging treatment further stabilizes the two-phase microstructure and affords a material with moderately high strength (intermediate to annealed and STA strengths) and good ductility and toughness. Also, the elimination of the quenching operation offers a production advantage for this heat treatment.

Beta annealing of alpha-beta alloys as the name implies, is accomplished using an annealing temperature above the beta transus temperature and relatively slow cooling from this high temperature, followed by an overaging treatment. The high solution annealing temperature results in a 100 percent beta microstructure (at temperature) which transforms to an acicular alpha structure upon cooling (see Structure A of Figure 16). Transformed beta microstructures are associated with excellent toughness and desirable combinations of other properties as described previously.

While the above special heat treatments have been described using the case for Ti-6Al-4V alloy, other alpha-beta compositions can be similarly heat treated with similar results. In addition to these treatments, some compositions have preferred heat treatment schedules that were developed along with the development of the alloy or of a particular alloy form, to optimize properties. For example, continuously rolled Ti-6Al-4V strip is annealed according to a special schedule. Further, the Ti-8Al-1Mo-1V alloy has simple and duplex annealing treatments applicable to various product forms and to the degree of stability and other properties desired. The Ti-6Al-2Sn-4Zr-2Mo alloy has duplex and triplex annealing treatments, and variations in the heat treatment schedules appropriate to various product forms. Thus it becomes apparent that while broad descriptions of the various heat treatments for titanium can be summarized, it is recommended that users of any particular titanium material should seek detailed heat treatment instructions for the development of combinations of properties desired.

28. Heat Treatment Precautions. There are two fundamental requirements for successful titanium heat treatment: (1) minimizing contamination, and (2) maximizing the accuracy of the time, temperature, and cooling rate prescribed for heat treating a given material. The importance of the latter point and the related metallurgical effects have been reviewed in the foregoing sections. Additional points related to precautions in avoiding contamination are summarized.

The oxidation of titanium at elevated temperatures can occur in air at quite low temperatures including aging temperatures and can lead to the degradation of properties if aging times are prolonged or if aging temperatures are high. The actual scaling of titanium can occur at about 1100 F, and above this temperature, scaling and contamination of subscale metal layers increases with increasing temperature and time of exposure. Oxygen diffusion results in a hard, brittle surface (subscale) layer. This layer should be removed by mechanical or chemical means prior to forming parts, further heat treatment steps, or application in components.

In addition to oxygen contamination (and to a small extent nitrogen) precautions that should be observed during heat treatment, hydrogen contamination precautions should be followed. Hydrogen may be readily absorbed from uncontrolled atmospheres of heat treating furnaces (e.g. high dew point in inert gas atmospheres, fuel vapors in fuel-fired furnaces, or atmospheric water vapor), and from pickling and scale removal baths. Absorbed hydrogen can be embrittling in titanium under various conditions related to alloy type. Therefore if a hydrogen contamination is suspected, it should be eliminated by vacuum annealing.

The above interstitial contamination problems are not the only ones of concern. For example, iron oxide in contact with very high temperature titanium can result in a thermite type reaction. In addition, the presence of chlorides during heat treatment (even from finger prints) can lead to a stress-corrosion problem. Other metals can react vigorously with titanium at elevated temperatures, and so can ceramic, other inorganic and organic materials. The necessity for the cleanliness of the heat treatment operation becomes apparent when the reactivity of titanium with practically everything it is in contact with is fully realized.

Distortion due to heat treatment has been a problem among some titanium users. Generally no problem exists if the work piece being heat treated is not finished to final dimensions, since a final dimensional control can be imposed on a heat distorted part. However, the heat treatment of dimensionally finished parts can be a problem due to distortion and should be avoided. In some cases, fixturing can be quite helpful in avoiding gross distortion, and in fact is frequently used even on undimensioned work pieces. However fixturing cannot be relied upon to prevent distortion and warpage completely, so the preferred technique is to perform heat treatment prior to dimensional finishing.

Forming Processes

29. General. Titanium is more difficult to form than the more familiar steels and aluminum alloys. Titanium alloys generally have less predictable forming characteristics, and being quite strong materials, require higher forming pressures which must be controlled over a smaller workability range. That is, the spread between yield and ultimate strength, expressed as a percentage of the ultimate strength, is smaller. Other characteristics adversely affecting titanium formability include tendencies toward nonuniformities in sheet, notch sensitivity, galling sensitivity, low shrink capabilities, and potential embrittlement by interstitial contamination (as in hot forming). Substantial improvements have been made in forming machines, dies and techniques during the last several years that have led to practices for forming titanium that have had a high degree of success. Nevertheless, the successful forming of titanium still relies on a good deal of experience.

Some companies prefer hot forming to improve the formability and dimensional tolerance control of titanium. Others use the cold forming, hot-sizing approach to accomplish the fabrication of parts having close tolerances and acceptable mechanical properties.

When formed at room temperature, unalloyed titanium and its alloys behave like cold-rolled stainless steel. For example, in stretch forming, titanium seems to behave like full-hard stainless steel, while in press forming, unalloyed titanium can be produced to shapes achieved in one-quarter-hard stainless. Further, the formability of most titanium alloys at 1200 F is comparable to that of annealed stainless steel at room temperature. The commercial unalloyed titanium grades, being more ductile than the titanium alloys (generally), present fewer problems and can be fabricated to simple shapes at room temperature.

Springback in titanium is often unpredictable but always to a degree that can be a problem if not taken into forming considerations. Springback angles commonly range between 20 and 40 degrees for sheets of Ti-6Al-4V alloy formed in bending at room temperature. The wide variations in yield strength among different heats, magnified by a low modulus of elasticity, can give a wide spread in springback angle, especially if the bend angle of the part is fixed by the forming tool and the bend radius to thickness ratio is large. Of course, springback and springback nonuniformity, tend to diminish with increasing forming temperature.

All titanium alloys resist sudden movement; hence, stretching and pressing operations are usually recommended where a controlled rate of load application can be maintained. The slower the forming speed, the better the formability at room temperature. At elevated temperatures, some titanium alloys, like Ti-6Al-4V, have better formabilities at higher forming temperatures. Faster speeds may be necessary from an economic viewpoint, and can be tolerated if large radii can be accommodated in the part design. The formability of titanium is poor in operations characterized by shrink flanges such as found in rubber press forming. Consequently areas that require gathering of material should be minimized when designing parts.

Hot forming improves the forming characteristics of titanium mainly by increasing its ductility; major improvements normally occur above 1000 F for most titanium alloys. The yield strength normally starts to decrease significantly at about the same temperature and this leads to lower forming pressure requirements. Parts formed at elevated temperatures exhibit greater contour uniformity since smaller property variations exist between various lots of material at the higher temperatures.

It is apparent from the foregoing discussion that titanium and its alloys may be formed both at room temperature and at elevated temperatures with formability being improved using the higher

TABLE XXXI. RELATIVE FORMABILITY OF ANNEALED TITANIUM ALLOYS FOR SIX SHEET–FORMING OPERATIONS AT ROOM AND ELEVATED TEMPERATURES(a)

Brake Press (Minimum Bend Radius) at Room Temperature	Drop Hammer (Maximum Stretch) at 850 to 950 F	Hydropress (Trapped Rubber)		Joggle (Runout Joggle-Depth Ratio)		Stretch Wrap (Maximum) at Room Temperature	Skin Stretch (Maximum at 850 to 950 F
		Stretch (Maximum) at 600 to 700 F	Shrink (Maximum) at 600 to 700 F	At Room Temperature	At 600 to 700 F		
13V-11Cr-3Al(b) (1.5T)	13V-11Cr-3Al(b) (16%)	13V-11Cr-3Al(b) (10%)	13V-11Cr-3Al(b) (6%)	13V-11Cr-3Al(b) (1.25)	13V-11Cr-3Al(b) (1)	8Mn (8%)	8Mn (18%)
8Mn (3T)	8Mn (16%)	8Mn (7.5%)	8Mn (5%)	8Mn (4)	8Mn (3)	5Al-2.5Sn (8%)	6Al-4V (17%)
5Al-2.5Sn (3.5T)	5Al-2.5Sn (13%)	6Al-4V (5%)	6Al-1V (4%)	5Al-2.5Sn (4)	6Al-4V (3)	13V-11Cr-3Al(b) (5.5%)	13V-11Cr-3Al(b) (13.5%)
6Al-4V (4.5T)	6Al-4V(13%)	5Al-2.5Sn (5%)	5Al-2.5Sn (3%)	6Al-4V (4.5)	5Al-2.5Sn (4.5)	6Al-4V (3.5%)	5Al-2.5Sn (12.5%)

Notes:

(a) Alloys are listed in order of forming ease, the most formable alloy being at the top of the list.
Numbers in parentheses following alloy designations are laboratory test values for the indexes of formability shown in parentheses at the top of each list.
Laboratory index values shown should be related at least 25 percent when designing for production.

(b) Solution-treated condition.

temperatures. The disadvantages of hot forming, the possibility of work-piece contamination and the requirement for heated tooling, are not formidable and hot forming is today more widely used than cold forming. Table XXXI gives a comparison of the relative formability of representative titanium alloys in various hot and cold forming operations.

30. Material Preparation. Conventional cleaning, etching, and descaling procedures can be used to remove dirt, surface oxidized layers, and/or scales from titanium materials before forming. Scales and surface oxides can increase the notch sensitivity during forming. Grease, oil, and all residues from solvents or fingerprinting that might be a source of chlorides must be removed before any heating operation associated with forming to avoid a possible stress-corrosion reaction. Parts requiring removal of oxides by etching or pickling operations must be of sufficient gage to allow for this metal removal treatment. The pickling operation must be carefully controlled to minimize local attack and undue dimensional changes.

Blanks and parts prepared for forming by one or more of several possible cutting operations such as sawing, nibbling, or shearing should have the worked edges deburred. The scratches resulting from the deburring operation should be parallel to the material surface. The edges of shrink and stretch flanges should be polished prior to forming. Sharp edges should be removed and chamferred edges should be avoided. Cracks in sheared edges are undesirable, but may be tolerated if they are in an area that can be removed by trimming after forming. Scratches on the surface of a blank to be formed are detrimental to the formability of titanium. Consequently, all necessary steps should be taken to reduce the occurrence of scratches before or between forming operations. Interleafing with paper is often used as an aid in minimizing surface scratching.

When titanium is to be heated in air for a long period of time, scale-inhibiting coatings may be used to minimize surface contamination. The application of such coatings are usually covered by company specifications and should be carefully followed. Inspection procedures, both on incoming material and on material processed for forming, cannot be overemphasized.

31. Tooling. The choice of tooling materials for titanium forming depends on the forming operation, the forming temperature, the number of parts to be produced, and cost considerations. Cold forming operations, which stress the tooling in compression, can be conducted with tools made from epoxy-faced aluminum or zinc alloys. The latter can be cast close to the desired dimensions and are easy and cheap to machine. Because machining is expensive, the cost of tool materials is usually a small part of the total tooling costs.

The ability of tooling to withstand wear and distortion at the forming temperature controls the number of parts that can be made on a set of hot-forming dies. The selection of tooling materials for hot forming is often a compromise based on expectations of tool performance and the number of parts to be produced before changes in design or order completion occur. Ceramic materials, cast iron, die steels, nickel-base alloys, and stainless steels have been used successfully for hot-forming tools. Good tooling is expensive and is only justified when close tolerances or large production quantities of parts are required. The following materials are examples of some used for hot-forming operations.

Operation	Materials
Stretch forming	Cast ceramic (Glasrock), H-11, H-15, Hi Si cast iron, AISI 4130, and type 310 stainless steel
Brake forming	H-11, H-13, and Incoloy 802.
Yoder roll forming	H-11, H-13 tool steels

Draw forming	High Si cast iron and Incoloy 802.
Hammer and hydropress forming	High Si cast iron, RA330 stainless steel, Inconel X, and Incoloy 802.
Hot sizing operations	Mild steel, High Si cast iron, High Si nodular cast iron, H-13, Types 310 and RA330 stainless steels, Inconel X, Hastelloy X, and Incoloy 802.

Hot forming may be accomplished using heating of the blank alone or combined blank-die heating. The latter, of course, is preferred. Integral heating of tooling for hot forming is common since temperature control is easier and more precise. Die temperatures of 400 to 1500 F have been used and depend on the titanium alloy to be formed, the shape of the part, and the forming method. Dies and platens are frequently heated with electricity because of its flexibility, ease of control, and cleanliness. Insulating blankets of various types are frequently used in conjunction with hot-forming operations.

32. Lubricants. Lubricants perform three main functions in titanium forming operations: (1) they minimize the energy of pressure required to overcome friction between the blank and the tooling, (2) they reduce galling and seizing between blank and tooling, and (3) they control the rate of heat transfer between blank and tooling as in hot forming. Friction is generally undesirable since it accentuates the difficulty of securing uniform blank movement over the tooling.

Organic, nonchlorinated oils, greases, and waxes may be used in cold forming operations as well as the solid dry film lubricants such as the graphites and molybdenum disulfide types. Colloidal graphite is commonly used in both hot and cold forming operations. At elevated temperatures, boundary type lubrication seems to be best. Consequently it is common practice to use the solid dry film lubricants in conjunction with oils and greases for hot forming. Many satisfactory lubricants have been used in forming titanium that typically result in reducing the coefficient of friction to 0.20 or less and in turn this results in low tool wear.

33. Forming Methods. The many kinds of forming operations commonly used in making end items from the better known metals of commerce, are also used in making parts from titanium and its alloys. Basically each of the operations involves deformation by bending or stretching or combinations of these and as earlier described might be done hot or cold. Hot forming generally affords greater ductility and therefore greater formability. The operations include: brake forming, stretch forming, deep draw forming, trapped rubber and drop hammer forging, spinning and shear forming, dimpling, joggling, roll bending and roll forming, tube bulging, and tube bending. As mentioned previously, titanium work pieces under deformation in these various operations behave much like the various grades of stainless steel. Generally, the titanium alloys have a more limited formability than the steels so that while all of the various forming methods can be used in making titanium parts, cautious approaches to the forming method selected should be employed.

34. Forming Process Precautions. There are several specific precautions to be observed in forming titanium and its alloys. These relate to contamination, notch sensitivity, anisotropy, strain rate sensitivity, the Bauschinger effect, and simple overstraining.

The contamination of titanium during forming may be avoided or eliminated as a problem quite easily when it is realized how readily it can occur. In the handling of as-received titanium stock, for example, the mere act of fingerprinting to any extent is considered poor form since the chlorides of the prints might lead to a stress-corrosion problem in some further processing step. Similarly the ink printing on some stock and any accumulation of layout marking, dirt, grease, etc., should be eliminated early in the processing sequence. Cleaning procedures, the use of solvents and pickling operations for example, should be controlled so as not to introduce further contamination. These precautions are especially important when hot forming is planned. During hot forming, the oxidation of titanium surfaces is certain to occur to some degree, depending on any coatings used, and severity of the exposure—temperature and dwell time. Thus, the elimination of contamination picked up during the hot-forming operation must be carefully controlled too, by descaling, pickling, or machining operations. To insure the attainment of desired mechanical properties, contamination should be minimized throughout the entire sequence of forming operations.

Titanium alloys are perhaps as sensitive to surface defects as any of the high strength materials with respect to effects on formability. The scratch marks on surfaces that can appear during handling and the tool marks on cut surfaces, edges in particular, can be the stress risers that result in poor formability. Such notches must be minimized or eliminated to achieve a good formability, and in critical operations, such as stretch forming, the polishing of edges is not a too extreme precautionary measure. Generally, scratches, notches, or defects oriented parallel to the major strain axis of the workpiece are less a problem than those otherwise oriented.

Because titanium mill products are often anisotropic, sections that are to be formed should be oriented in such a way that the major deformation occurs in a direction of maximum ductility. For example, in stretch forming, blank layout should be performed so that maximum stretch will be accomplished in the rolling or longitudinal direction—parallel to the grain. In bending, the bend axis would preferable be perpendicular to the grain to take advantage of the maximum tensile elongation in the longitudinal direction. While it is realized that preferred material orientations cannot be achieved in some forming operations or in some parts, the limitations of ductility in anisotropic products should be understood and accommodated. Similarly, the strain rate sensitivity and the variation of this sensitivity among various titanium alloys should be understood in selecting a forming process that is the most closely matched to the materials capability.

Cold forming can result in a loss of compressive yield strength via the Bauschinger effect. This is a phenomenon wherein the compressive yield strength can be appreciably lowered upon plastically deforming a metal in tension. (Tensile yield strength also may be decreased by plastically deforming in compression.) Titanium alloys are subject to this phenomenon to various degrees and serious degradation of properties can be experienced in cold formed parts where the problem has not been anticipated. Figure 18 shows the decreases in compressive yield strengths for representative alloys deformed by various amounts in tension. In spite of the extent of these strength decreases under certain conditions, the yield strengths may be restored by stress relief annealing or, of course, by full annealing or solution treating and aging if those are steps in part making subsequent to forming. Stress relief annealing, a hot sizing operation, or a full heat treatment of some type following a cold forming operation not only eliminates the problem of the Bauschinger effect but minimizes or eliminates problems of delayed cracking and stress corrosion. Thus where cold forming is selected in lieu of a hot forming operation, it is well to consider an appropriate thermal exposure to recondition the workpiece to insure optimum properties.

Machining Processes

35. General. Several years ago, titanium had the reputation of being very difficult to machine compared with common construction materials. However, years of experience and research on various problems have progressively improved the situation. Today, tools and techniques are available for machining titanium efficiently. In fact, some machining operations give more consistent results on titanium than they do for some steels. A bonus factor is the ease of attaining good surface finishes. Roughness values as low as 20 to 30 microinches can be obtained on some parts.

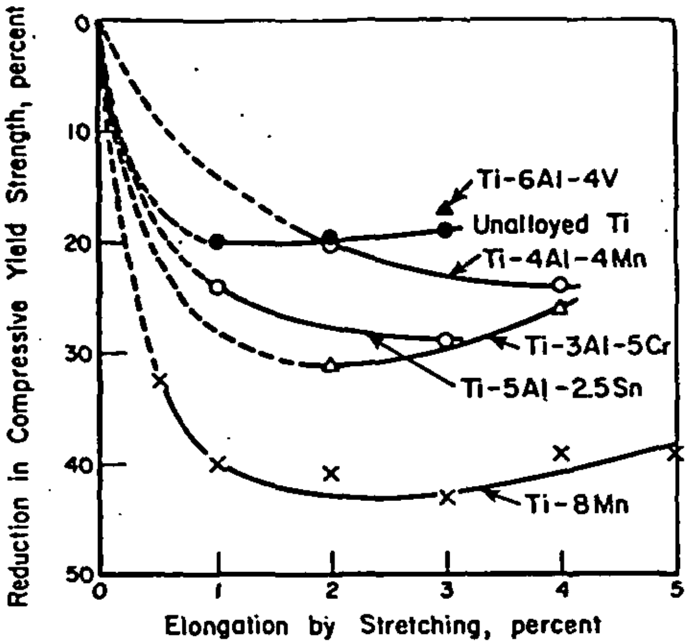


Figure 18. Effect of Cold Stretch Forming on the Compressive Yield Strengths of Various Titanium Alloys

Generally, machining problems for titanium can originate from four sources: high cutting temperatures, chemical reactivity and abrasiveness with tools, and a relatively low modulus of elasticity. A built-up edge, however, does not form on tools used to machine titanium. Although this phenomenon accounts for the characteristically good finish on machined surfaces, it also leaves the cutting edge naked to the abrading action of the chip peeling off the work. In addition, titanium produces a thin chip, which flows at high velocity over the tool face on a small tool-chip contact area. This, plus the high strength of titanium produces high contact pressures at the tool-chip interface. This combination of events and the poor heat conductivity of titanium results in unusually high tool-tip temperatures.

The cutting temperature achieved at the tool point depends partly on the rate at which heat is generated, from the tool forces involved, and partly on the rate at which it is removed by the chip, the cutting fluid, and by conduction through the tool. The heat-transfer characteristics of the chip and work material depend on thermal diffusivity, which is a function of density, specific heat, and thermal conductivity. Since titanium exhibits poor thermal diffusivity, tool-chip interface temperatures are higher than they would be when machining other metals at equal tool stresses. The higher temperatures in the cutting zone lead to rapid tool failure unless efficient cooling is provided by suitable cutting fluids.

The strong chemical reactivity of titanium with tool materials at high cutting temperatures and pressures induces galling, welding, and smearing, since an alloy is continuously formed between the titanium chip and the tool material. This alloy passes off with the chip, producing tool wear. Titanium reactivity also shows up when the tool dwells in the cut, even momentarily as in drilling.

The surface of titanium usually contains a high content of oxygen, especially if it has been exposed to air at high temperatures. This oxygen-enriched layer is hard and abrasive, and can cause dulling of tools. Therefore, it is often desirable to clean the surface, prior to machining, by sand blasting or by chemical descaling. When this is not possible, the first cut taken is usually a heavy one, to cause the tool to penetrate under the hard "skin" of oxygen-enriched titanium. Abrasion by surface contamination or scale can notch cutting tools at the depth-of-cut line. Consequently, this is another reason to remove oxygen enriched surface layers, if possible, prior to machining operations.

The stiffness of a part, determined by the shape and the elastic modulus of the alloy workpiece is an important consideration in designing fixtures and selecting machining conditions for titanium. Since the elastic modulus for titanium is only about half that of steel, a titanium part may deflect several times as much as a similar steel part during machining, creating tolerance, tool rubbing and other tool miscutting problems.

36. Machining Requirements. Successful machining of titanium and its alloys requires the use of high-quality machine tools and cutting tools; an absolute minimum of vibration; rigid setups; and observance of recommended machining practices.

Machine tool selection is a primary factor; just any machine will not do. In fact, machine tools used for machining titanium must be in excellent condition and possess certain basic attributes that insure vibration-free operations. These include dynamic balance of rotating elements; true running spindles; snug bearings, slides, and screws; sturdy frames; wide speed/feed ranges; and ample power to maintain speed throughout cutting. Undersized or under-powered machines should be avoided. Certain locations of machines near or adjacent to heavy traffic also can induce unwanted vibration and chatter during machining.

Rigidity of operation is a very important consideration. Generally, it is obtained through the use of adequate clamping and by minimizing deflection of work and tool during machining. In milling, this means strong, short tools, machining close to the table, rigid fixturing, frequent clamping of long parts, and the use of backup support for thin walls and delicate workpieces. Rigidity in turning is achieved by machining close to the spindle, gripping the work firmly in the collet, and providing steady or follow rests for slender parts. Drilling requires short drills, positive clamping of sheet, and backup plates on through holes.

Cutting speed is important in all machining operations and is a very critical variable for titanium. Cutting speed has a pronounced effect on tool-chip temperature: excessive speeds can cause overheating and short tool life. Consequently, speeds are limited to relatively low values, unless adequate cooling can be supplied at the cutting site. However, all machining variables should be carefully selected to effect optimum machining rates.

All machining operations require a positive uniform feed achieved mechanically. The cutting tool should never dwell or ride in the cut without removing metal. As an added precaution, all cutters should be retracted when they are returned across the work. The cutter should be up to speed and should maintain this speed as the cutter takes the load.

In summary, correct machining setups for titanium require strong, sharp cutting tools; positive feeds; relatively low cutting speeds; and certain types of cutting fluids. Improper cutter rigidity and/or geometry can contribute to vibration. Spindle speeds and feeds should be verified on each machine to ensure correct cutting conditions, since small changes in cutting conditions can produce large changes in tool life. All machining variables should be carefully selected to effect optimum machining rates.

37. Tooling. When machining titanium, it is necessary to select a tool that retains its hardness at high temperatures. Sintered-carbide tools are a good choice because of their "red hardness". Excellent results are usually obtained with these but, because of their brittleness, carbide tools may chip and spall when titanium chips weld to them. Machining of titanium with carbide tools requires rigid machines and a rigid setup. "Throwaway" carbide inserts are the most economical cutters because of their high productivity. With the use of inserts, higher-rotational speeds and heavier feeds can be used, and no time is lost picking up cuts. Another reason why the "throwaway" inserts are more economical than cemented types, is that the cost of new or multi-point inserts is lower than the cost of retipping or regrinding. Grade 883 or equivalent carbide tips have performed best on titanium alloys, both for roughing cuts and finishing operations. Cast-alloy steels, which fill the gap between carbides and high-speed steels, are used when conditions do not permit the use of carbides.

Titanium can be cut using high-speed steel tools; however, production rate is lowered. Nevertheless, for interrupted cuts, high-speed tools may be the best choice. Live centers are always used to support the work because of seizing when fixed centers are employed.

38. Coolants. Titanium can be machined dry with good results; however, much better results will be obtained when proper coolants are used. The coolant should be directed as close as possible to the point of tool contact. Mist coolant or "through-the-wheel" coolant has proven excellent for grinding or drilling titanium.

Cutting fluids are used on titanium to increase tool life, to improve surface finish, to minimize welding, and to reduce residual stresses in the part. Soluble oil-water emulsions, water-soluble waxes, and chemical coolants are usually used at the higher cutting speeds (75 to 100 fpm and up). Low-viscosity sulfurized oils, chlorinated oils, and sulfochlorinated oils are used at lower cutting speeds to reduce tool-chip friction and to minimize welding of chip to tool. Cutting oils may have either mineral oil or mineral oil-lard oil bases. Many fluids that improve machinability are complex, often proprietary, and sometimes contain unidentified active compounds. (Chlorinated oil cutting fluids pose a danger of stress corrosion from chlorine residues. These residues should be promptly removed with a nonchlorinated degreaser.) Machining handbooks frequently identify specific coolants for use in specific titanium machining operations.

39. *Metal Removal Techniques.* Both conventional and unconventional metal removal techniques can be used in machining titanium. Conventional methods including milling, turning, boring, drilling, tapping, reaming, sawing, broaching, and various abrasive cutting operations have been developed for titanium. Unconventional methods such as electrochemical machining and grinding, chemical milling, and electric-discharge machining have been advanced to a high state of efficiency in working titanium. Each method has connected with it a multitude of procedural details which should be followed to obtain the best results. Due to the large number of instructions and recommendations for each process it is impossible to cover them thoroughly in this handbook. However, highlights concerning several of the commonly used metal removal techniques are cited.

a. Milling. Breaking or chipping of milling cutters remains a problem. A partial solution is to use "climb milling", rigid machines, and a rigid setup. Progressive tool chipping and wear produces a surface-finish deterioration and loss of tolerance. Other problems found in milling include heat, deflection, and abrasion. In addition to using "climb milling" and rigid setups, milling may be done more successfully when cutting speed is low, tool angles promote unhampered chip flow, and tools are used that are of relatively small diameter but with the largest number of teeth.

b. Drilling. Success in drilling titanium is obtained by adopting a "keep drilling" concept, using mechanical feeds. The drill should not be allowed to ride, and low speeds and heavy feeds should be maintained. The drill should be sharp and as short as possible. When feeding the work by hand, galling and seizing will occur if the rate of feed is not constant. The coolant should consist of a sulfurized- or chlorinated-type mixed with mineral oils, or soluble oils and water and should be supplied to the cutting zone in a positive manner. The galling action of titanium during drilling, which may be accentuated by high cutting temperatures and pressures, results in rapid tool wear, out-of-round holes, tapered holes, or smeared holes, with tap breakage a likely consequence if the holes are to be threaded.

c. Tapping. Tapping screw-holes can be troublesome, particularly in tapping blind-holes where chips can build up. The largest possible tap drill should be used; those with spiral points are the best. A rigid power setup is better than hand tapping. Very slow tapping speeds with highly active cutting fluids are most effective.

d. Sawing. Titanium can be sawed by using a coarse pitch blade having two to six teeth per inch. Blades whose analysis is high in molybdenum content outperform general-purpose blades. Blade tension should be high. Heavy feeds and slow speeds are best, and a coolant should be used. Some difficulty is encountered in sawing large billets. Due to the relatively heavy feed pressures required to keep the blade cutting the material, and because the blade is subject to wear, it is difficult to maintain a straight cut. In cutting billet diameters over 8 inches, grooving the material 1/8-inch wide to a 1-inch depth on the circumference helps to alleviate this problem, as this reduces the diameter and helps to guide the saw blade. Maximum rigidity is needed when sawing titanium and is favored by using the widest and thickest cutting band permitted by the band wheel and any radii of cut that might be desired.

e. Turning and Boring. These operations and facing are essentially the same and offer no unusual difficulties: They give less trouble than milling, especially when cutting is continuous rather than intermittent. However, the problems of high tool-tip temperatures, galling and abrasive reaction with tool materials, and lack of set-up rigidity can be serious if the general rules for titanium machining are not followed. Low cutting speeds, feeds to result in constant metal removal, and adequate coolant directed positively to the work zone are recommended for best results.

f. Abrasive Cutting. Another means of cutting titanium is to use abrasive cutting belts, discs, or cutoff wheels. Overheating and contamination of the work is prevented by generous use of coolants. Titanium and its alloys can be cut abrasively at about the same rate as hardened high-speed steels. Moderately light cuts are recommended. Smearing of ground titanium surfaces can result from abrasive tool loading, and inadequacies of the set-up rigidity, cutting speed inadequacies and poor tool characteristics. These problems can be minimized by choosing the right abrasive tool and conditions. Aluminum oxide and silicon carbide abrasive tools are available in a variety of grit sizes, hardnesses and bond materials. Optimum speeds and feeds (generally light) are recommended for each type. As in other machining operations, cutting fluids and their proper application to the workpiece are very important for the successful abrasive cutting of titanium.

g. Chemical Milling. This unconventional method for metal removal refers to shaping, fabricating, machining, or blanking of metal parts to specific configurations by controlled chemical dissolution with suitable etchants or reagents. Chemical milling is particularly useful for removing metal from the surface of formed or complex-shaped parts, or from thin sections. The method provides an increased capability and flexibility in the fabrication of parts and offers savings in labor time, and materials. The chief drawback is the very careful control required in maintaining the desired dimensional tolerances and the composition of the acid etchant to prevent excessive hydrogen pickup.

The acid etchants used for the chemical milling of titanium are proprietary aqueous solutions containing hydrofluoric acid (HF) plus other oxidizing acids and additives to inhibit hydrogen pickup and to enhance etching characteristics. Etch rates range from about 0.5 to 5.0 mils per minute (1 to 1.5 usually). Time of immersion in the acid solution of course determines the depth of cut. Depth of cut limitations are about 0.5 inch for titanium and minimum widths of cuts that can be machined are about three times the etch depths (due to the sideways etching at about the same rate as down). Dimensional tolerances can be held to about ±2 mils and typical surface-roughness values produced range between 15 to 50 microinches. Etchants are usually circulated in the etch tanks and parts are moved and turned to promote uniform metal removal. Etchants also may be sprayed against the work piece where, for example, the piercing of thin parts is desired.

Metal can be removed from an entire part with chemical milling or else selective machining can be accomplished by using masking. Simultaneous etching of a part from both sides is possible. No elaborate holding fixtures are required. Many parts can be machined at the same time with of course tank size and solution volume limitations. Masking materials such as vinyl polymers and neoprene elastomers are often applied in multiple coats and baked on (200 to 300 F) and patterns desired may be subsequently scribed. The manual peeling of the mask to expose the area to be etched follows. Patterns also may be developed by silk screen and photographic techniques. After machining, the maskants can be easily removed by manual peeling or by immersion in solvents.

Joining Technology

40. General. Many individual joining processes may be used in assembling a titanium structure. The processes include welding of several types, brazing, soldering (rarely), solid state adhesive bonding, and mechanical fastening. Of these joining types, only welding is markedly sensitive to the choice of titanium alloy. The remaining processes can be applied to any of the alloys with about the same degree of success. There are many factors affecting the choice of a joining process and these include consideration of the metallurgical compatibility, strength requirements, cost requirements, and permanency of the joint. Each process has its advantages and disadvantages and few fixed rules are applicable in selecting a joining method. Since joint requirements are quite varied, this handbook does not attempt to compare advantages associated with the various methods. Instead, brief descriptions of the processes are offered which emphasize the major requirements and precautions.

Before discussing the several individual methods for joining titanium, some of the various characteristics of titanium, which strongly affect joining techniques are reviewed.

a. Titanium and its alloys have a high affinity for oxygen, hydrogen and nitrogen at elevated temperatures, and can become severely embrittled by them at relatively low levels of concentration. There are several possible sources for the contaminants.

b. Titanium alloys are susceptible to stress corrosion by sodium chloride (e.g., from fingerprints) at temperatures above 600 F.

c. Molten titanium is highly reactive with most materials, including all the common refractories.

d. Excessive alloying with other structural metals (e.g., steel and aluminum) greatly reduces the impact strength of titanium due to the formation of brittle intermetallic compounds and excessive solid-solution hardening.

e. Titanium exhibits a high coefficient of friction, and has poor wear and galling characteristics.

f. Titanium is noble in most galvanic couples.

41. Welding Technology. Important factors for welding titanium concern material and process suitabilities. Titanium materials suitability involves two distinct criteria: (1) The ability to physically produce a welded joint, and (2) satisfactory performance of the joint in service. Very few titanium alloys fail to meet the first while the second may be satisfied by proper alloy selection. Commercially-pure titanium and the alpha-type alloys do not respond to heat treatment, and their mechanical properties are affected only slightly by variations in microstructure. These alloys are readily adapted to all types of welding operations. Depending on alloy content, the mechanical properties of alpha-beta alloys may be greatly affected by heat treatment and variations in microstructure. Special consideration is required in selecting alpha-beta alloys for welding applications, because some alloys are embrittled by welding operations. Generally, increased beta stabilizer content in alpha-beta type alloys decreases the suitability of the alloy for welding. Welded joints in beta alloys are ductile in the as-welded condition, but their strengths are low. When heat-treated to increase strength, weld ductility decreases. Thus, where a choice is available, alpha titanium alloys are preferred for welded assemblies, with alpha-beta and beta alloys being less desirable depending upon the ultimate properties required in the joint.

Titanium welding process suitability is related to cost, requirements for joint strength and leaktightness, and considerations for mill product form, component configuration, and joint design and location. The welding processes that may be used on titanium assemblies include fusion welding, resistance welding and explosive welding, though less popular than these other methods is used in the clodding of sheet and plate and the interior or exterior of cylinders. In the first category, the processes of inter-gas-shielded tungsten arc (GTA for gas-tungsten-arc), inert gas-shielded metal arc (GMA), inter-gas-shielded arc spot (arc-spot), and electron beam (EB) welding are popular. Laser welding is being developed. In the second category, spot, roll-spot, and seam welding are the classic processes. In addition, upset-welding processes may be used to assemble special configurations. For example, flash welding, a form of resistance welding, is used to produce joints in bars, forgings, rolled rings, and tubing. Induction pressure welding, gas pressure welding, and high frequency (ultrasonic) welding also are common processes.

42. Fusion Welding. This is a general term often used to categorize welding processes in which joining is accomplished by heating to the melting point using an external heat source. Titanium fusion welding is accomplished using an electric arc, plasma arc, or an electron beam to melt the metal. GTA, GMA, Arc-Spot, and EB fusion welding processes for titanium have much in common and the points discussed in this section relate to all of them. Factors to be considered in fusion welding include: composition of base metal, cleaning of the parts to be joined, joint design, filler wire, inert gas and its application, tooling, heat input, distortion (shrinkage and residual stress), residual stress (property values), weld defects, inspection, and subsequent joint performance. Obviously a welding handbook would be required to describe all these variables and their interrelationships. Here, only the highlights are mentioned.

a. Base metal composition and condition. Alloy selection for titanium welding has been previously discussed. Points to be added include concerns regarding compatibility with the heat-treated condition of the base metal before and after welding and contamination that might be incorporated in the base metal prior to welding. Since any fusion-welding cycle results in a weld zone of as-cast metal, any preexisting microstructural condition in the joint area will be changed during welding. In addition to the weld zone, the heat-affected zone of the weld area goes through a cycle of heating high into the solid solution phase range. While this heating cycle has no harmful effect on the mechanical properties of unalloyed titanium, it can adversely affect the properties of highly heat-treatable titanium alloys to the extent that they become unsuitable for many applications. Heat treatment subsequent to welding must be designed for compatibility to the modified structures of the joint. Contamination of the base metal surface layers in operations preceding welding should be removed prior to welding because this source of contamination is sure to result in nonoptimum weld joints.

Since excessive alloying of titanium with other common structural metals has a deleterious effect, titanium has never been satisfactorily directly welded to other metals. However, methods have been advanced which use compatible metals (e.g., silver and vanadium) as an interlayer between steel and titanium to afford serviceable joints between these dissimilar metals.

b. Cleaning. Careful preweld cleaning is essential to successful fusion welding of titanium. Poor cleaning can result in weld contamination and defects, particularly porosity. Edges to be joined are often etched*, draw filed, wire brushed, or abraded and wiped with acetone or alcohol just prior to welding. One commonly followed rule is: if the areas to be welded cannot be cleaned, do not try to make the weld.

c. Joint Design. Square abutting edges of titanium parts to be joined are satisfactory for the thinner sections. Thick sections may require a machined bevel or some other contour on the abutting edges. Designs are usually based on geometries that are suitable from the viewpoints of amenability to proper shielding and of allowing sufficient clearance for filling with molten metal. The fusion welding process to be used is also a factor. For example, EB weld joint configuration has a much narrower gap than GTA or GMA configurations. Close dimensional tolerances are always preferred with any of the welding processes.

d. Filler Wire. Some fusion welding processes involve the addition of metal from sources other than the base metal. Wire is most commonly used, since it is easy to add at a controlled rate. Wire added during GTA (formerly referred to as TIG) welding is called "cold wire". Wire used in GMA (formerly referred to as MIG) welding may be called "electrode wire". Filler wire is the common term and is available in both unalloyed and alloy grades. Titanium wire for welding must meet stringent quality standards since the high surface-area-to-volume ratios of common wire sizes used in welding represent a sizeable contamination source for weldments. Wire defects, such as seams, laps, cracks, or center bursts, are strictly undesirable for filler wire since the defect areas are a possible repository for contaminants.

e. Inert Gas. Special procedures have been developed to ensure against weld contamination in adopting fusion-welding processes to titanium assemblies. Only high purity welding grade gases should be used. The special procedures include the use of large gas nozzles and trailing shields to protect the face of the welds from air, and backing bars that provide means for introducing inert gas to shield the back of the welds from air. Also, inert-gas-filled welding chambers are often used

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* Recommended etchant is a 30% HNO_3—3% HF—balance H_2O solution, used with caution to avoid hydrogen pickup.

with these processes. The dew point of the shielding gas serves as a measure of the gas purity with respect to water vapor. Argon and helium are used for shielding with all fusion welding processes except EB (EB welding in vacuum). In addition to making sure of the purity of the basic gas, another concern is that the inert gas is not degraded during flow through the welding equipment due to leaky joints, etc.

f. Tooling. Conventional GTA and GMA welding power supplies, torches, and control systems are used effectively in welding titanium. Of course, the conventional welding equipment selected for use must be supplemented with auxiliary shielding tooling for welding to be done outside of chambers. Shielding devices are available that provide an adequate inert gas flow at the fusion zone, behind the fusion zone (trailing shield) and on the side opposite the fusion zone (backup shielding). Hold down tooling is commonly of the "chill" type (e.g. copper) to afford rapid cooling of the heated metal and may in fact be designed integrally with the shielding arrangement.

g. Heat Input. With titanium fusion welding, it is the preferred practice to use heat inputs that are just above the minimum energy required to melt sufficient metal to form a weld. High level heat inputs contribute to various bad effects. The lowest heat inputs are obtained with EB welding.

h. Distortion. Fusion welding processes are characterized by thermal cycles that cause localized shrinkage. Shrinkage must be planned for—it cannot be avoided. Shrinkage, in turn, can result in part distortion. Shrinkage can be controlled to some extent by tooling restraints and both shrinkage and distortion are minimized by low heat inputs. The residual stresses in fusion weldments caused by shrinkage and other aspects of the thermal cycle are often high when distortion is low and vice versa. Such locked-in stresses are best alleviated by stress-relief annealing or full heat treatment cycles if those are appropriate after welding. If the residual stresses are not relieved, it is quite possible that in addition to distortion problems, the stresses can contribute to general mechanical property degradation.

i. Defects. Fusion weldments can exhibit defects related to irregularities of the weld zone geometry such as underfilling, overlaps, undercuts, porosity, lack of fusion (e.g. at abutting surfaces), inclusions, and cracks. The production of defect-free welds is highly dependent on the quality requirements of applicable specifications and inspection methods used. For example, cracks are easily inspected for visually and are cause for weld rejection. Similarly, underfill, undercuts, and overlaps, are easily detected and such defects may be alleviated by weld repairing (rewelding). Inclusions, internal cracks, and porosity are much more difficult to detect however, requiring, for example, radiography for identification. Some factors suspected of causing porosity in titanium welds are: high hydrogen content, oxygen, nitrogen, and carbon contamination (joint area improperly cleaned or dirty filler wire), and insufficiencies in technique related to improper heat input, welding speed, gas flow, and cooling rate. Thorough inspection techniques are capable of detecting most of the defects that are known to result in degradation of weld properties.

j. Joint Performance. The only reliable way to determine what weld features are truly defects is to evaluate the effects of such features in a test program. Evaluations must include tests that are representative of the service conditions expected. Many defect-like weld anomolies have no effect on the static-tension properties although these same features may be found to degrade performance in a fatigue test. Thus, under the best of circumstances regarding both weld preparation, inspection, and evaluation short of actual service, a conservative engineering approach is called for in the use of weldments. Under these conditions, fusion welding can be an extremely advantageous technique for assembling components.

43. Electron Beam Welding. Because EB welding is quite a different form of fusion welding than GTA or GMA processes, a general description of some of the features of EB welding is offered. The EB welding process is carried out in a high vacuum – at, or less than, 0.1 micron of mercury pressure – and uses a stream of electrons accelerated from a cathode by a high electrical potential to produce the required heat. The electrons give up their energy as heat upon striking the material to be welded. Two types of equipment are generally available: low voltage, rated up to 60 kilivolts accelerating potention, and high voltage, rated at 60 to 150 kilovolts. With either type, the low-vacuum system assures that contamination of the weld and heat-affected zone is less than that caused by any other welding technique. The lower-voltage equipment gives a weld fusion zone with a width-to-penetration ratio of from two-to-one (2:1) to unity; the high-voltage equipment gives a ratio of one-to-five (1:5) or greater. This penetration is often quite large because the electron beam drills a fine hole through the work which is then filled in by capillary action. The main disadvantages of the high-voltage equipment are the generation of X-rays, which require lead shielding, and the excessive drop-through and spatter at the root of the weld. The disadvantages can be managed quite efficiently however so that EB welding has become a highly valued process for the joining of titanium.

44. Resistance Welding. This category of joining technology is characterized by methods wherein the metals to be joined are heated to the melting point or very close to it, using heat generated by the resistance of the parts to the flow of electric current. Titanium and all ofiits weldable grades can be successfully resistance-welded with techniques similar to those used for ferrous alloys; these techniques are somewhat simpler than those often used for aluminum alloys. The most pertinent processes of this type are spot, roll-spot, and seam welding. As mentioned previously, flash welding is sometimes considered a resistance welding method although it also can be classified along with pressure welding.

In the most common form of spot and seam welding, electric current is passed through a localized area of overlapping sheets until sufficient heat is generated to melt a portion of the interfacing metals to form a weld nugget. The nugget is entirely contained within the remaining solid portions of the sheet. Joints can also be made in which no melting is involved. These have been called diffusion bonded or solid-state bonded joints. They are similar to conventional resistance welds except that no molten nugget area is formed. Both kinds of joints have heat affected zones in the joint area. As might be expected, the weld nugget and the heat affected zones can be controlled by selection of current size and application time which in turn controls the elevated temperature cycle experienced at the joint. Electrode tool size and pressure applied through the electrodes as well as the composition and geometry of the parts being joined are also factors in determining the size and quality of the joint.

As in fusion welding, titanium alloy composition, condition, and cleanliness contribute to the success or failure of resistance welds. Thus, these factors of pertinency to fusion welding as previously discussed apply to resistance welding. Joint design is of course different; resistance welding involves joining of overlapping material layers. Such factors as edge distance and interspot spacing are of importance. Access to both sides of the joint is mandatory. There are further differences. For example, filler wire is never used in spot or seam welding. Also, some of the defects found in resistance welds, e.g. insufficient penetration, excessive sheet separation or surface indentation, are of a different character than defects in fusion welds. On the other hand, some of the problems encountered are common to both forms of welding, e.g. porosity, inclusions, contamination, cracks, distortion, requirements for stress relief annealing, inspection, and post-weld joint performance. Some of the features of spot and seam welding are as follows:

a. Spot Welding. Titanium is spot welded in much the same manner as other metals. Special shielding (i.e., inert-gas shielding), such as used for fusion welding, is not necessary because of the close proximity of the adjacent surfaces at the weld zone, and the very short duration of the weld cycle. Titanium is often considered to be more readily spot welded than aluminum and many of the carbon and low alloy steels, because of its relatively low electrical and thermal conductivity. Also, since titanium and stainless steels are similar in electrical and thermal conductivity, and strength at elevated temperatures, it is convenient and simple to adapt stainless steel spot-welding techniques for use with titanium. Therefore, a titanium alloy of a given thickness can be spot welded with the same welding machine settings that are satisfactory for a similar gage stainless steel. The recommended machine settings developed for titanium by various investigators substantiate this to a degree, and is generally considered as accurate as the ability to incorporate any recommended data into the settings from one production machine to another. Various auxiliary controls, such as up-slope or down-slope or post-weld heat controls, do not seem to offer any exceptional advantages when used in welding titanium. Roll-spot welding is the same as spot welding except that a wheel-shaped electrode is used instead of the cylindrical type. Rotation of the wheel is intermittent with the wheel electrodes in a fixed position during the actual weld cycle. The apparatus is indexed to provide programmed spacing between the parts joined.

b. Seam Welding. Since seam welding is essentially a series of overlapping spot welds made progressively along a joint by rotating the electrodes, the same criteria for the spot welding of titanium would apply to seam welding techniques for titanium.

45. Upset Welding Processes. This method of making joints not only involves the generation of heat within the parts to be joined but in addition features sufficient pressures to upset the heated metal, bringing the surfaces to be joined in intimate contact. Further, there may be an actual extrusion of the metal which formed the original contact surface to a position removed from the axis of the ultimate joint. Thus, a feature of some pressure weldments is that original surfaces which may become contaminated during heating, are removed from the critical portion of the final joint. In this kind of joint, heat generation may be from gas torches, induction coils, electric resistance between parts to be joined (flash welding), or high frequency generators (ultrasonic welding). Contamination from the heat source is relatively unimportant due to the above described upset feature in making the joint. Other methods are used too. For example, entire parts may be heated in vacuum or inert gas and pressure joined with a minimum of localized upset at the joint. Such methods are akin to diffusion bonding as well as to upset welding.

Conventional pressure welding equipment is satisfactory for upset welding titanium and its alloys. The welds are made in the same manner as for steel using similar upset pressures of about 2500 psi. The pressure may be applied throughout the heating cycle which, as previously mentioned, may be generated using gas torch welding equipment, induction heating, or resistance heating techniques. The pieces to be joined are machined so that they are in a good fit up in the welding machine prior to the application of heat. Butt joints are satisfactory for thin sections whereas beveled edges are sometimes used on thicker sections. For joints with solid cross sections, inert-gas shielding is not required but may be used. Enclosures can be placed around the joints and in the case of hollow cross sections, inert gas can be introduced inside of the assembly so that all surfaces are protected from contamination.

Upset welding is better adapted to the high-strength heat treatable titanium alloys than fusion welding in two respects. (1) molten metal is not retained in the joint, so cast structures are not present and (2) the hot metal of the ultimate joint is worked in the joining process which tends to improve ductility. Upset welds that have mechanical properties approaching those of the base metals can be made on conventional machines.

While ultrasonic welding is not truly an upset welding technique, it is described within this category as a convenience and due to the fact that small amounts of metal can be displaced in producing the joint. Ultrasonic welding may be considered a form of pressure welding in which two sheet surfaces to be joined are brought together and clamped between two electrodes. One electrode oscillates at ultrasonic frequency with respect to the other, parallel to the plane of the interface. This causes the faying surfaces to rub across each other to form a solid-phase weld where a galling action takes place. The vibrational energy not only causes relative motion of the two surfaces, but generates some heat in the joint area which softens the metal and promotes welding. As in other upset welding processes, the mechanical properties of the joint can be nearly equivalent to those of the base metal under optimum welding conditions.

46. Quality Assurance for Weldments. Quality control for welding should start with incoming material. Weld tests made on material to be used in welded assemblies will ensure that the base metal and filler rods are satisfactory for the intended application.

One of the better and quicker means of evaluating weldments is visual appearance. Generally, welds with dull white, gray, or yellow scale are excessively contaminated. With more adequate shielding, the weld surface may have a bright metallic blue or gold appearance or a combination thereof. Colors such as these indicate surface contamination only, and the welds generally are satisfactory. If the welds have the appearance of newly polished silver, this is an indication of nearly perfect shielding. However, contaminated welds with this appearance can be produced if the shielding around the molten puddle is insufficient, but shielding over the solidified weld is good. Also, good weld surface appearance does not provide an indication that the base or filler metals were not excessively contaminated before the welding operation began. Even slight surface contamination should be removed from titanium weldments if post weld heat treatment is to be used. If not removed it can diffuse into the material during the heat treatment causing property deterioration. Of course, before surface appearance is used to evaluate weld contamination, welds with varying surface appearances should be made under routine welding conditions, and then should be tested for ductility.

Other quality-control procedures used for titanium weldments include dye penetrant, ultrasonics and radiography for locating cracks, porosity, and other defects such as incomplete weld penetration, tungsten inclusions, visual examination for undercut, penetration, and weld reinforcement. Metallographic examination, mechanical tests, and hardness measurements are also usual specification requirements.

47. Diffusion and Deformation Bonding. These techniques for joining metals including titanium are important subcategories of the technique referred to as solid state bonding. Within this class, joints are produced with all components of the joining system being maintained as solids. Roll bonding, gas-pressure bonding, and solid-state welding are other names used for the general technique. Properly prepared—metallurgically clean—surfaces are essential for achieving a successful joint using this joining method.

In diffusion bonding, deformation is limited to that amount required to bring the surfaces to be joined into intimate contact. Once the surfaces are in contact, a joint is formed by diffusion of some element or elements across the previously existing interface. Diffusion bonding is primarily a time- and temperature-controlled process. The steps involved in diffusion bonding are:

(1) Preparation of the surfaces to be bonded by cleaning or other special treatments

(2) Assembly of the components to be bonded

(3) Application of the required bonding pressure and temperature in the selected bonding environment

(4) Holding under the conditions prescribed in Step 3 for the required bonding time

(5) Removal from the bonding equipment for inspection and/or test.

Diffusion-bonded joints have been made in titanium and several of its alloys at selected conditions encompassing the following ranges:

Temperature	1500 to 1900 F
Time	30 minutes to 6 hours
Pressure	5 to 10 ksi.

The methods used to apply pressure include simple presses containing a fixed and movable die, evacuation of sealed assemblies so that the pressure differential applies a given load, and placing the assembly in autoclaves so that high gas pressures can be applied. A variety of heating methods also can be used in diffusion bonding, but generally the temperature is raised by heating with some type of radiation heater. With titanium, a vacuum environment is most practical, although it is possible to bond in an inert gas.

Deformation bonding differs from diffusion bonding primarily in that a measurable reduction in the thickness of the parts being joined occurs with deformation bonding. The large amount of deformation involved makes it possible to produce a bond in much shorter times and frequently at lower temperatures than with diffusion bonding. The desired pressure in deformation bonding may be applied by suitable mechanical devices such as presses, as in the joining of built-up structures from layered components, or rolling mills, as in roll-welded sandwich structures. Considerable effort has been expended in the development of these processes since the joint mechanical properties that are attainable are the same as base metal properties. Correctly produced, a bonded joint may be indistinguishable from the base metal.

48. Brazing. This method of joining titanium can be used to advantage in many applications where welded joints are undesirable or difficult to achieve such as in the joining of dissimilar metals to titanium or of sandwich structures. Most of the common brazing techniques are used including induction, furnace, resistance, torch; and dip brazing. Most of the problems encountered in brazing titanium are related to titanium's high affinity for other elements. That is, contamination problems, as described in previous sections, and compatibility problems related to the difficulty in finding braze filler metals that do not react disadvantageously with the base metal (i.e. producing embrittlement or erosion problems). Another problem area has been one of finding braze filler metals suitable for use in the thermal cycles that are compatible with the heat treatments used for titanium alloys. Since the preparation of surfaces to be brazed involves the same general precautions as are applicable to other joining processes for titanium, discussion will be confined to the topics of filler metals, fluxes and atmospheres, and brazing methods.

a. Filler Metals. To be useful as a brazing filler metal for titanium, an alloy must melt within a desired temperature range which is generally between a temperature much above the use temperature (on the low side) and below the beta transus temperature of the titanium alloy (on the high side). Also, a brazing filler metal should readily wet but not alloy with titanium at brazing temperatures to prevent degradation of the joint by formation of brittle intermetallic compounds.

Practically all metals readily wet titanium but because of titanium's high reactivity, they also readily alloy with titanium. Because titanium-silver compounds are relatively ductile, silver and silver-base alloys are used as brazing filler metals to produce brazed joints. Although alloying and consequent formation of brittle intermetallics are not eliminated, ductile joints are possible when the copper content of the silver is low. Silver and silver-base brazing filler metals form strong joints with usable strengths up to 600-800 F. The most useful alloys are silver-lithium, silver-aluminum-manganese, and silver-copper-lithium. The silver-lithium alloys are used in a composition range of 0.5 to 3.0 percent lithium. The typical composition for the silver-aluminum-manganese alloy is Ag-5Al-1Mn. The brazing temperature for this alloy is between 1450 and 1650 F.

Among other brazing alloys of interest are the silver-cadmium-zinc filler metals developed for oxyacetylene torch-brazing applications (Ag-5Cd-25Zn is typical), palladium-base alloys which are quite strong and are resistent to nitric acid (also impermeable to helium leakage), aluminum base alloys such as 3003 alloy, and a family of titanium-zirconium-beryllium alloys. A preferred palladium-base alloy is Pd-15.4 Ag-3.5 Si with a liquidus temperature of 1280 F. Titanium-zirconium-base filler metal alloys include: Ti-43Zr-12Ni-2Be, Ti-48Zr-5Be, and Ti-45Zr-5Al-5Be. The latter alloys have improved crevice corrosion resistance, good strength and peel characteristics and flow at temperatures below the beta transus temperatures of the titanium foil alloys.

b. Fluxes and Atmospheres. Special fluxes, either in combination with, or without, inert-gas atmospheres or vacuums, may be used for successful brazing of titanium. However it is not a common practice to use fluxes in brazing titanium. All fluxes for titanium contain chloride compounds. Thus there is a strong possibility that stress-corrosion cracking as a result of flux entrapment may occur when brazing with these compounds. Consequently, tests should be made with brazed joints, prior to use of these materials, to determine adequacy and acceptability.

Vacuums of from 10^{-5} to 10^{-6} Torr are often used to prevent contamination of titanium by oxygen and nitrogen from the air during furnace and induction brazing. Inert-gas atmospheres of helium or argon are also employed. The argon gas technique, however, is more commonly used than either the helium-gas or vacuum techniques. Some fluxes have been developed for use where the titanium member(s) of the joint is protected against high-temperature oxidation by first electrochemically depositing a metal-protecting film on the titanium. However, as previously stated, fluxes are not commonly used in conjunction with any of the brazing methods.

c. Brazing Methods. The effect of the brazing thermal cycle on base-metal properties is important in selecting brazing method and filler metal for any particular application. The brazing temperature may affect the ultimate and yield strengths of heat-treatable alloys unless it is possible to fully heat treat the assembly after brazing. If the brazing operation is part of the heat treatment schedule, it must be at the solution temperature since brazing alloys are not available that melt and flow at aging temperatures. Some overaging heat treatments are compatible with brazing temperatures however if the lower strengths of an overaged condition are satisfactory. If the brazing is to be done at the solution temperature, cooling rate from the thermal exposure must be compatible with the recommended cooling rate for the alloy being brazed in order to develop the preferred properties. Of course, if the material to be brazed is intended for use in the annealed condition, the brazing cycle can usually be adjusted to conform with a preferred annealing heat treatment schedule.

The various brazing techniques used for titanium and its alloys, together with their relative advantages and disadvantages, are as follows:

Induction brazing technique is used when the filler metals being used alloy readily with titanium; the object of this technique is to obtain the shortest brazing time to minimize alloying in the joints. The assembly to be brazed or the assembly and induction coil, together with filler metal preplaced, are enclosed in a nonmetallic container filled with an inert gas; then, they are brazed using a predetermined heating cycle. Design of both joint and induction coil are important. Some drawbacks to this technique are the type and size of joint that can be heated by an induction coil, and the need for protection against atmospheric contamination.

Furnace brazing is more easily adapted to various joint configurations and larger-sized assemblies than the induction brazing method. However, filler metals are usually held in the molten state for longer periods of time than in the induction method, which can result in excessive alloying. To minimize brittle intermetallics formation, filler metals that do not alloy readily with titanium should be used. The joints produced by this method are usually of lower strengths than those from either induction or torch-brazed techniques. Also, preplaced filler metal and protective-atmosphere or vacuum techniques are required.

Torch brazing uses a standard oxyacetylene torch. Short brazing times, with consequent minimizing of alloying, are possible. A slightly reducing flame is used. The equipment cost is low when using this technique. The flux is preplaced in the joint, and the filler metal either preplaced or fed into the joint. This method generally requires special fluxes and skilled operators. Also, the removal of fluxes, contaminated surfaces after brazing, and possibility of stress-corrosion from entrapped flux pose certain problems.

The resistance brazing technique uses spot-welding equipment to make lap joints. Filler metal in the form of foil, is placed between the sheets with or without flux. Protection against atmospheric contamination is not generally required.

Chemical-bath dip brazing can be used, but this method is not generally recommended because the titanium surface can be contaminated rather easily by the salt bath.

49. *Soldering.* Solder joining of titanium can be accomplished by first depositing a thin film of silver, copper, or tin on titanium using a metal plating technique applicable to titanium. These films can be wetted by 60Sn-40Pb or 50Sn-50Pb solder-alloys heated with a soldering iron using commercial soldering flux. The deposited films are thin and soluble in the liquid solders. If the soldering temperatures become too high or soldering time too long, the film will completely dissolve in the liquid solder. The soldering of titanium is not a much used joining process.

50. Adhesive Bonding. This method of joining titanium shares many factors in common with other joining techniques. Reproduction of good adhesive-bonded joints requires consideration of the materials, processing conditions, equipment, and subsequent service conditions. The principal material involved in adhesive bonding is the adhesive itself—the titanium composition being bonded is of little importance. A wide variety of chemical compounds have been used for adhesives. They may be classified as thermoplastic, thermosetting, elastomeric, ceramic, and blends of the first three types. Suitable adhesives for a given application must fulfill the requirements of being amenable to a reliable processing technique that will insure reproducible joint properties, and of performing satisfactorily under service exposures particularly if elevated temperature exposures are involved.

Equipment for adhesive bonding of titanium is of the same general types used in bonding other materials. A major factor in the bonding process is the surface preparation. Books have been written on the subject. Significant differences in joint properties may occur because of surface preparation variations. Degreasing and acid etching or alkaline cleaning as well as abrasive cleaning (e.g. grit blasting) have been used. The chief aim is to remove foreign matter from the surface and to activate it to receive the adhesive. Chlorinated solvents are avoided as are pickling solutions which promote hydrogen pickup. Activation films typically used for titanium can be complex mixtures of phosphates, fluorides, chromates, sulfates, and nitrates. Film thickness as well as composition is important and prepared adherend surfaces should be bonded no later than 8 hours after preparation.

Assembly of an adhesive-bonded joint after surface preparation involves applying the adhesive, positioning and holding the adherends in the desired relationship, and curing. Adhesive application depends on the type of adhesive used and can involve roller coating, brushing, troweling, dipping, spraying, or laying on since thick or thin liquids, viscous plastics, tapes or sheets may be the adhesive form used. Positioning and holding pressures and devices are quite variable depending upon the configuration being assembled and other factors. For example, dead-weight loading may be satisfactory for simple shapes whereas elaborate vacuum chucking arrangements might be required in the assembly of complex parts. Riveting has been used to hold assemblies together too. Up to several hundred psi pressures are required for some adhesives. Curing may be possible at room temperature but the higher strength adhesives are cured at elevated temperatures. Curing time is quite important and joints properly processed and cured can be very satisfactory from a mechanical properties viewpoint.

51. Mechanical Fastening. There are many methods available to produce a mechanically fastened joint including shrink fitting, keys, spring retainers, nails, screws, rivets, and bolts. The type of fastening used is determined on the basis of expected loads and type of loading to be encountered in service. Titanium and its alloys may be joined by any of the mechanical fastening methods. Further, titanium fastening devices such as rivets and bolts are manufactured to be used in the joining of titanium and other materials. Mechanically fastened joints differ so widely from each other in joint design, type fastener, and means of assembly, that it is impossible in a short space to fully describe any of the variables involved. Instead, this section limits discussion to a few features of the mechanical fastening of and with titanium.

Titanium and its alloys are mechanically joined with the same kind of fasteners used for more conventional structural metals. Fasteners are available in a large number of sizes and shapes. Fastener types for both shear and tension loading are available and may be made of titanium (and alloys), aluminum, Monel, H11 or SAE 4340 steels, or A286 high temperature alloy. Almost any fastener design can be applied to titanium so long as the factors of cost, application equipment, fastener availability, shop experience, and joint performance are considered. Two compatibility considerations also should be given attention: coefficient of thermal expansion and galvanic corrosion potential. For example, in high temperature service, mechanically fastened joints between titanium and other metals can be subject to loosening and tightening of the fastener due to thermal expansion differences. Fastening with dissimilar metals also raises the possibility of galvanic corrosion in the presence of aqueous electrolytes unless the fasteners are electrically isolated as with sealants.

Fastening devices have been manufactured from a wide variety of titanium materials including unalloyed grades (principally rivets), Ti-8Al-1Mo-1V, the beta alloys, Ti-6Al-6V-2Sn, but chiefly the Ti-6Al-4V alloy. Galling and seizing are problems encountered with fasteners made of titanium-between fastener and hole in interference fit joints and between screw and thread in threaded type fasteners. To ameliorate these difficulties, various coatings have been used, some of which (e.g. cadmium) have led to fastener failure problems. Coatings on titanium fasteners also have been used to alleviate galvanic corrosion problems, for example on titanium fasteners used to join aluminum components. As more and more experience is gained, solutions to the problems are more readily available and an increased use of titanium fasteners has been observed. They offer a reliable high strength means of securing a joint with a considerable weight saving potential.

Coatings and Surface Treatments

52. General. Surface preparations of numerous types may be applied to titanium and its alloys for a variety of protection, property improvement, and decoration purposes. The preparations include metallic and nonmetallic coatings of numerous types and chemical and mechanical treatments. These may be categorized in several different ways, the usual method being classification by type of processing. However, since only a brief presentation of the subject will be included in this handbook, the various surface treatments available for titanium are included under the categories of protective coatings, coatings for property improvement, and surface treatments other than coatings.

Surface treatments for titanium may be applied to improve the oxidation and/or the corrosion resistance, the erosion and the wear and galling characteristics, the dynamic mechanical properties, other physical properties such as radiation characteristics, and the cosmetics. Some surface treatments require an elaborate process for application while others may be quite simply applied. Most surface treatments require precleaning of the titanium surface. The usefulness of surface treatments strongly depends upon the type and severity of service requirements. For example, service requirements range from the simple need to color-code equipment, achievable by painting, to the complex needs of wear resistant gear teeth, obtainable for lightly loaded gears by combinations of electrochemical metal plating, shot blasting, and lubricants. Generally, surface treatments for titanium are quite useful and serviceable in the less severe applications whereas some of the more severe potential applications cannot be satisfied with existing surface treatments.

53. Protective Coatings. The reactivity of titanium increases markedly with increasing temperature which results in scaling and surface contamination. At temperatures of about 1200 F and above, oxygen contamination can be a problem if workpieces are not in some way protected (e.g. by inert atmosphere, vacuum, or coatings). At 1500 F and above, scale formation on titanium can be quite rapid and metal loss to the scale can be significant. Further, the metal layers beneath the scale can be severely contaminated. Thus, the need for protective coatings in such operations as the primary fabrication of mill products and heat treatment is apparent. The titanium producers use protective coatings to minimize the problem. Ceramic coatings of several types are used which are generally composition controlled for selected temperature usage. Compositions are usually proprietary but products are readily available with full instructions for application and use temperature limits. A principal feature of these coatings is that they inhibit hydrogen pickup as well as oxygen pickup. Both nonfusing nonself-descaling and fusable self-descaling types are available and coatings of both types may be used in certain heat treatment processes as well as in metalworking operations.

Titanium and its alloys are quite resistant to many corrosive media and conditions but the useful range of alloys may be extended in certain environments by the use of coatings. For example, the degradation of titanium (by cracking) by the so-called hot-salt-stress-corrosion reaction (in chloride containing environments at temperatures of 450 F and higher) may be alleviated by anodized coatings or by metallic coatings. Since anodized coatings vary in hardness, density, crystallinity, and thickness depending upon anodizing conditions and electrolytes, different results have been reported. Generally however, thin, dense anodized coatings formed in NaOh, H_2SO_4 or $NaNH_4HPO_4$, afford some protection from hot-salt stress-corrosion and such coatings have been found to minimally degrade conjunctive properties such as post-creep tensile ductility and fatigue. Aluminum coatings applied by hot dipping or flame spraying to thicknesses of about 1 mil and electroplated nickel coatings also have been found to afford some protection against the hot-salt stress-corrosion reaction. Aluminum coatings also are useful for the protection against oxidation and contamination of titanium in elevated-temperature exposures. Incorrectly applied coatings, or coatings which can interact with the basis metal in the service environment, are likely to have deleterious effects to the basis metal. It is highly improbable that coatings which are classified as protective for titanium apply optimally for all conditions of use designated for the protective coating. On the other hand, judicial selection of coating systems will do much to enhance protection of titanium in many specific and unique applications.

54. Coatings for Property Improvement. The most widely researched type of coating for titanium is one for the improvement of titanium's wear and galling resistance. The relative softness of titanium even in heat treated hardened conditions, combined with its high reactivity with other materials, leads to the wear and galling problem. The hard oxides and the oxygen enriched surface layers that form on titanium are of no help in alleviating galling and wear since they tend to be brittle as well as hard and readily spall. Therefore, in service conditions where a rubbing together of surfaces is likely to be encountered, the necessity exists for coatings which can improve upon the galling and wear characteristics of titanium.

Metallic and nonmetallic coatings of many types have been used to improve wear properties. Metallic coatings can be applied by dipping, electroplating, flame spraying, plasma-spraying, vapor deposition, painting and baking, and other methods. Numerous metals can be used, including aluminum, nickel, chromium, molybdenum, and others. Nonmetallic coatings can be applied by a number of methods also, including gaseous diffusion, salt bath reaction, painting, electrochemical reaction, flame spraying, and chemical conversion reactions. The nonmetallics researched have included nitrogen, oxygen, carbon, metal oxides, ceramics, and complex organic and inorganic compounds. Each coating appears to have advantages, such as relative ease of application and improved wear characteristics, and disadvantages, such as degradation of fatigue properties, associated with it. There is no such thing as the best coating for the improvement of wear and galling: each need for coating must be carefully studied to determine the best coating for a particular application. The following descriptions are for typical coatings which have been found to be beneficial in the prior experience.

a. Aluminum. This metal has been applied by painting, flame spraying, roll cladding, and hot dipping methods for example, wherein various thicknesses of coatings can be built up. Although aluminum has no better galling and wear resistance than titanium, it can be anodized by conventional means. The anodized aluminum coating in combination with a lubricant, organics or resin bonded dry-film lubricants for example, offer some improvement in the wear of titanium. As previously mentioned, aluminum coatings are more commonly applied to afford some protection against oxidation.

b. Nickel. Both electroless nickel plating and electroplating from conventional baths have been used to apply nickel to titanium surfaces. Nickel plating has been used by itself in conjunction with lubricants and as a primary undercoating for overplates with chromium, iron, and other metals, to achieve improvements in wear and galling properties. The metal can be used as plated, or as plated plus diffusion heat treated to achieve better adherency. Titanium-nickel intermetallic compound can form at elevated temperatures and this compound has been shown to be deleterious to mechanical properties as well as to contribute to surface spalling. Nevertheless, nickel plates can be used advantageously to improve the surface properties of titanium in some applications.

c. Chromium. Electroplating of chromium on titanium, with or without an underplate of nickel or copper, has been examined extensively with the purpose of improving wear and galling properties. Various electroplating procedures have given different degrees of adherency which is one of the problems in using electroplate for this purpose. Diffusion heat treatments can be used to improve adherency but this can lead to the formation of titanium-chromium intermetallic compound and problems of surface embrittlement. Lubricants used in conjunction with electroplates afford meaningful benefits in titanium applications where the wear problem does not involve heavy contact stresses.

d. Molybdenum. This metal is usually flame-sprayed onto the titanium substrate and can be built up to desirable thicknesses. Since titanium and molybdenum do not form intermetallic compounds, surface embrittlement is not a problem. However, oxygen enriched molybdenum coatings and thick coatings are inherently brittle. Used with organic or inorganic lubricants, molybdenum is used satisfactorily in applications involving sliding contact (e.g. shafts), whereas it is unsuitable for resisting severe abrasion and high-shock loads.

e. Nitrogen. The surface of titanium may be hardened significantly with nitrogen via a gas diffusion reaction or from cyanide salt baths. Carbonitriding also may be accomplished from cyanide type baths. Quite high reaction temperatures are involved in nitriding titanium which may be undesirable from a substrate properties viewpoint. However, the high hardness of nitrided surfaces may be successfully used in conjunction with lubricants to resist wear.

f. Oxygen. Titanium surfaces may be hardened by simply exposing work pieces to air or oxygen at elevated temperatures. However, a more satisfactory coating from the viewpoint of coating durability is obtained by using one of the numerous anodizing procedures. Titanium can be anodized in nearly any electrolyte to give coatings ranging between hard, thin, crystalline coats and soft, thick, amorphous coats depending on electrolyte and electrical conditions. Direct current exposure of the work piece in the anodizing solution should only be attempted after thorough precleaning and exposures should be carefully controlled to yield the coating characteristics desired. Anodized coatings used in conjunction with either wet or dry-film lubricants are widely used to improve the wear and galling resistance of titanium.

g. Ceramics. As an example of this type coating for titanium, flame sprayed aluminum oxide may be considered. The Al_2O_3 coatings, applied either on the bare titanium or with a nickel-chromium intermediate coating, can be used effectively in conjunction with lubricants to provide hard coatings that are resistant to abrasion and wear. Ceramic coatings also may be used to improve erosion resistance.

h. Chemical Conversion Coatings. Coatings of this type act as a base for lubricants promoting their retention and thereby aiding the lack of lubricity and associated wear problems. Conversion coatings may be applied by spraying, brushing, or immersion in salt baths, the latter being the commonly used method. Sodium and potassium salts of phosphates and fluorides in carefully controlled acidic solutions give a useful coating in from 2 to 10 minute exposure. The resultant coatings are comprisedoof titanium-potassium-phosphate-fluoride compounds which are quite stable and hold lubricants well. The conversion coatings can be used to facilitate metalworking as well as to improve wear in service exposures.

i. Lubricants. The list of lubricants that have been applied to titanium is seemingly without end. Liquid and solid lubricants used on bare titanium afford some improvement for the wear problem but are much more effective when used with a hard coating of some type, e.g. anodized coatings. Synthetic long-chain compounds, halogenated hydrocarbons, reactive inorganic solutions (e.g. iodine in alcohol or hydrogen sulfide in water), colloidal graphite, and molybdenum disulfide in either resin or lacquer have been used with variable results. When used on bare titanium, no strong natural bonding takes place between lubricant and titanium. Lubricants alone may perform satisfactorily at low loads but heavy loads quickly cause a breakthrough and metal to metal contact. The liquid lubricants which have shown a great deal of promise on bare titanium are methylene iodide and polyethylene glycol. Molybdenum disulfide in a heat cured resin base appears to be one of the most beneficial dry-film lubricants. It cannot be overemphasized, however, that lubricants alone do not offer much improvement in the wear and galling of titanium and are better used in conjunction with one of the coatings for titanium such as a metal electroplate or anodized coating.

In addition to the coatings applied to titanium for the improvement of the wear problem, coatings of various kinds can be used to improve other surface properties. For example, metallic plating (thin) followed by diffusion annealing was found to alter surface stress relaxation characteristics and thereby improve creep and fatigue properties of the basis metal. Aluminum, copper, and chromium were effective in this regard. Aluminum coatings and gold castings, the latter painted on and subsequently fired (at 950 to 1400 F) have been used to improve the heat-reflection characteristics of titanium. High emissivity paints for titanium also have been developed although paints are usually used more for appearance and identification purposes than for such functional purposes as an aid to thermal radiation. Anodized titanium has relatively low reflectance at short wave-lengths and high reflectance at longer wavelengths to afford improved solar energy collecting surfaces. The corrosion resistance coatings and the oxidation resistant coatings were previously described and are rementioned here to point out the fact that there are coatings for titanium of many types, apparently a coating for nearly every need.

55. Surface Treatments Other Than Coatings. Both mechanical and chemical surface treatments are available for titanium that can impart desirable surface characteristics. Processes such as shot peening, vapor blasting, grit blasting, surface rolling, or barrel tumbling can be used, for example, to introduce surface residual stress for the purpose of improving fatigue properties or reducing stress-corrosion sensitivity. Such treatments work harden the surface and alter surface roughness, both factors that can affect bulk mechanical properties. For example, a fatigue life improvement may be obtained in properly glass-bead peened surfaces (glass shot preferred to steel shot to avoid iron contamination of surfaces in certain corrosive or reactive environments). Glass bead peening of the interior surfaces of titanium spacecraft tankage also was used to reduce stress-corrosion susceptibility. Peening intensity is quite an important factor in achieving a beneficial result. In addition to the mechanical working of surfaces, mechanical finishing of titanium surfaces achieved by machining, grinding, or polishing operations, is equally important in affecting such properties as fatigue life. Smooth finishes also can be important where reflectivity, fluid flow resistance, corrosion, coating adherency, friction, or appearance might be the property of interest.

Electrochemical and chemical polishing of titanium surfaces are important processes for some applications. A jewelry finish can be obtained on titanium in an alcohol-chloride electrolyte using titanium as anode and 30- to 60-volt direct current. A current of 1 to 5 amp/sq. in. is maintained in the room temperature solution for 1 to 6 minutes to achieve a polished surface quite pleasing in appearance and beneficial to such surface sensitive properties as fatigue life and bend ductility. Chemical polishing also is possible, usually in aqueous solutions containing the fluoride ion (e.g. NH_4FHF to H_2SiF_6 solutions) and an oxidizing acid (e.g. HNO_3). The rate of chemical dissolution and the degree of polishing are related to the solution temperature, the titanium alloy, and the condition of the initial surface. Polished surfaces can be beneficial in many applications.

Corrosion Characteristics

56. General. Titanium is inherently a reactive metal, so that whenever it is exposed to air or other environments containing available oxygen a thin surface film of oxide is formed. It is to

this film that titanium owes its excellent corrosion resistance. Titanium is equal to, or better than, most metals in resistance to direct chemical corrosion by a wide variety of chemicals and is generally resistant to stress corrosion, erosion-corrosion, galvanic corrosion, and oxidation. Compared to many other structural metals, titanium generally is more resistant to corrosion in a wide variety of chemical environments, and generally is less prone to failure from stress-, erosion-, and galvanic-corrosion, and from oxidation.

The most protective films on titanium are usually developed when water, even in trace amounts, is present in the environment. For example, if titanium and its alloys are exposed to some strongly oxidizing environments in the absence of moisture, the film that is formed is not protective, and rapid oxidation, often pyrophoric in nature, may take place. Examples of such reactions that may be initiated at room temperature or slightly above are (1) titanium and dry chlorine and (2) titanium and dry fuming nitric acid.

The corrosion resistance of the various titanium alloys has not been investigated as extensively as that of the commercially pure grades; however, available data indicates that the general corrosion-resistance characteristics of titanium are not impaired by alloying. In fact, some of the beta alloys are highly resistant to some very hostile environments (e.g. H_2SO_4). When exposed to various types of atmospheres for extended periods, commercially pure alloy titanium retains the luster obtained in the finishing operation.

57. Chemical Environments. Titanium and its alloys corrode rapidly in environments that cause breakdown of the protective films. Of most importance are such reagents as hydrofluoric, hydrochloric, sulfuric, phosphoric, oxalic, and formic acids. However, attack by all these media except hydrofluoric acid can be reduced in many instances by the addition of acid salts, oxidizing acids, and other suitable inhibitors. Dry chlorine also attacks titanium, but it is quite resistant in wet chlorine (1% moisture) and other oxidizing gases, such as SO_2 and CO_2.

Titanium has excellent corrosion resistance to all concentrations of nitric acid up to 350 F. However in nitric acid above 20 percent concentration and at 375 F, the corrosion rate may be as high as 100 mils/year. Even at 550 F the rate of attack in 20% HNO_3 is only 12 mils/year. An anomaly exists, however, at 375 F, in that corrosion rates as high as 100 mils/year are reported at concentrations above 20 percent HNO_3. Caution should be exercised, however, when titanium alloys are used in anhydrous fuming HNO_3 because the reaction can by pyrophoric. The resistance of titanium to chromic acid is good, as is its resistance to aqua regia ($3HCl$-$1HNO_3$). For mixtures of sulfuric and nitric acids, corrosion rates increase with increasing H_2SO_4 concentration.

Titanium, like many other metals, has good resistance to dilute solutions of alkali. Hot, strong, caustic solutions will attack unalloyed titanium and titanium alloys. On the other hand, there is no evidence to suggest that titanium alloys are susceptible to caustic embrittlement as are carbon steels and stainless steels.

Titanium is superior to stainless steels in its resistance to corrosion and pitting in most neutral chloride solutions. The main exceptions are boiling solutions of aluminum chloride, stannic chloride, cupric chloride, zinc chloride, magnesium chloride, and calcium chloride, which all will cause pitting of titanium alloys. In addition, at temperatures above about 200 F, titanium may evince crevice corrosion in seawater or in promine. On the other hand, titanium is not attacked by the highly corrosive ferric chloride and sodium hypochlorite solutions, which are corrosive to stainless steel.

Long-term studies indicate that titanium in seawater and marine environments is resistant to pitting, stress corrosion, galvanic corrosion, crevice corrosion (below about 200 F), erosion-corrosion, and corrosion fatigue. Titanium tested for effect of flowing seawater showed a thinning rate corresponding to 0.00003 inch per year. No thinning could be detected in similar tests conducted in slowly moving seawater. Even after severe testing for 60 days in rapidly moving seawater, titanium showed negligible attack. Conditions which usually accelerate attack (stagnation in crevices; under fouling organisms; under moist salt crystals) failed to damage the metal. In salt spray tests, titanium alloys were not attacked after exposure for 1000 hours.

The tensile properties of titanium alloys are generally unaffected by prolonged exposure to a marine environment. Tensile test specimens with yield strengths of 105 ksi have withstood static loads of up to 80 ksi in sea air for over four years without sign of failure. Specimens tested in seawater and in marine air maintained a fatigue endurance limit of 60 ksi.

Pure hydrocarbons are not considered corrosive to most metals, including titanium. In addition, titanium exhibits good corrosion behavior in most chlorinated and fluorinated hydrocarbons, and other similar compounds used as hydraulic and/or heat-exchange fluids. It should be pointed out, however, that such materials may hydrolyze in the presence of water, forming HF or HCl, which in turn may attack titanium. In addition, at elevated temperatures, these hydrocarbons may decompose, liberating hydrogen, a portion of which may be absorbed by the titanium, resulting in loss of ductility, or chlorides may be released that can initiate elevated-temperature stress-corrosion cracking.

Titanium is not recommended for use in gaseous or liquid oxygen since a violent reaction can occur. When a fresh titanium surface such as a crack or fracture is exposed to gaseous oxygen, even at -250 F and at a pressure of about 50 to 100 psi, burning can begin. Once the reaction starts, the oxide formed is not protective, as it is, for example, with stainless steel. In liquid oxygen, titanium is impact sensitive at levels below those of many organics. Titanium and its alloys also exhibit pyrophoric reactions under impact in chlorine trifluoride, liquid fluorine, and nitrogen tetroxide. However, only in the case of liquid and gaseous oxygen has the reaction been found to propagate once it was initiated.

58. Stress-Corrosion. "Stress-corrosion is a form of localized corrosion which results in cracking from the simultaneous action of a corrosive environment and sustained tensile stress on a metal." It is characterized by a brittle-type fracture occurring in an otherwise ductile material. The surface direction of the cracks is perpendicular to the direction of the stress load. Cracking may be either intergranular or transgranular, depending on the alloy, the structure, and the environment. In general, stress-corrosion cracking of titanium alloys is intergranular.

Commercially pure titanium has not been found to fail by stress-corrosion cracking in any media except fuming HNO_3 or methanol containing HCl, H_2SO_4, or Br_2. However, under "plane strain" conditions, in the presence of a preexisting crack, unalloyed titanium containing high oxygen levels will exhibit rapid crack propagation in seawater at low stress levels. This phenomenon is thought by many to be akin to stress corrosion cracking. The common aqueous stress-corrosion test solutions do not have any effect on titanium alloys under normal conditions. However recent tests have disclosed that titanium alloys under exposure conditions of ambient temperature, aqueous media, and in a state of stress that produces a virgin metal surface (a fresh crack) will undergo stress corrosion. In particular, it has been found that some common aqueous stress-corrosion solutions (distilled water, tap water, 3.5% NaCl solution) affect the fatigue life of sharp-notch test specimens at high stress levels. Figure 19 illustrates the increased fatigue crack growth rate in water and salt water compared with cracking in air. Such environments cause reduced stress

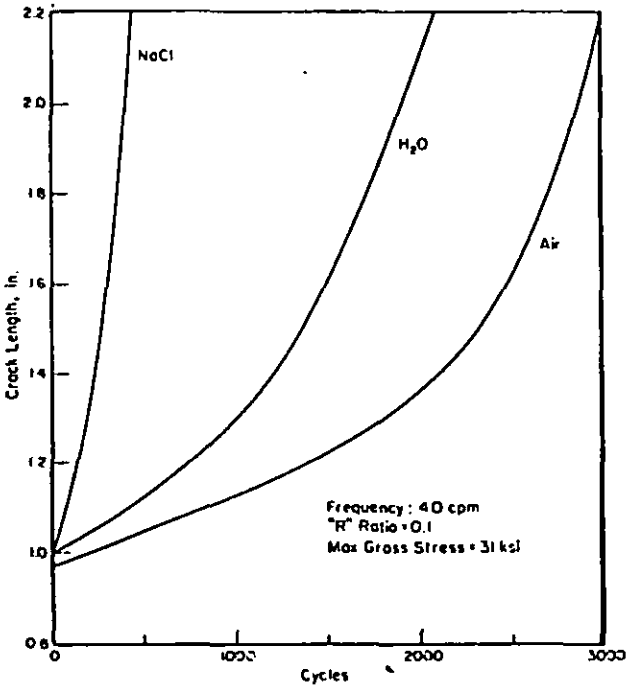

Figure 19. Crack Length Increase As a Function of Fatigue Cycles in Duplex Annealed Ti-8Al-1V Sheet in Various Environments

rupture life in fatigue-cracked tension and bend specimens. In the latter case, cracking propagates very rapidly from the infinitely sharp fatigue-induced notch in a direction normal to the direction of the tension stress. A fresh titanium surface is continually being exposed to the test medium in this type of test. Under these conditions, it appears that the titanium materials, as well as some other structural materials tested, undergo a stress-corrosion type of deterioration. The same effect was observed in steels and was commonly used to speed up crack development in the preparation of fatigue-precracked fracture-toughness specimens. While the practical limitations imposed by this ambient-temperature reaction are presently unknown, it is entirely clear that titanium alloys are not immune from such reactions, as was previously believed.

The susceptibility of precracked titanium alloys to stress corrosion cracking in salt water appears to be affected by the aluminum, oxygen, and tin content and isomorphous beta stabilizers. The data indicate that the susceptibility occurs with higher oxygen, aluminum, or aluminum-tin contents. Figure 20 shows the effect of increasing aluminum content on the environmental toughness of a Ti-Al-Mo-V alloy series. Tensile yield strength and air toughness are not much affected by a high aluminum content whereas the high aluminum content alloys have a degraded toughness in salt water. The presence of isomorphous beta-stabilizers—molybdenum, vanadium, and columbium—tends to reduce sensitivity of titanium alloys. The addition of molybdenum to Ti-7Al-2Cb-1Ta or Ti-7Al-3Cb tended to reduce their susceptibility to cracking, and the addition

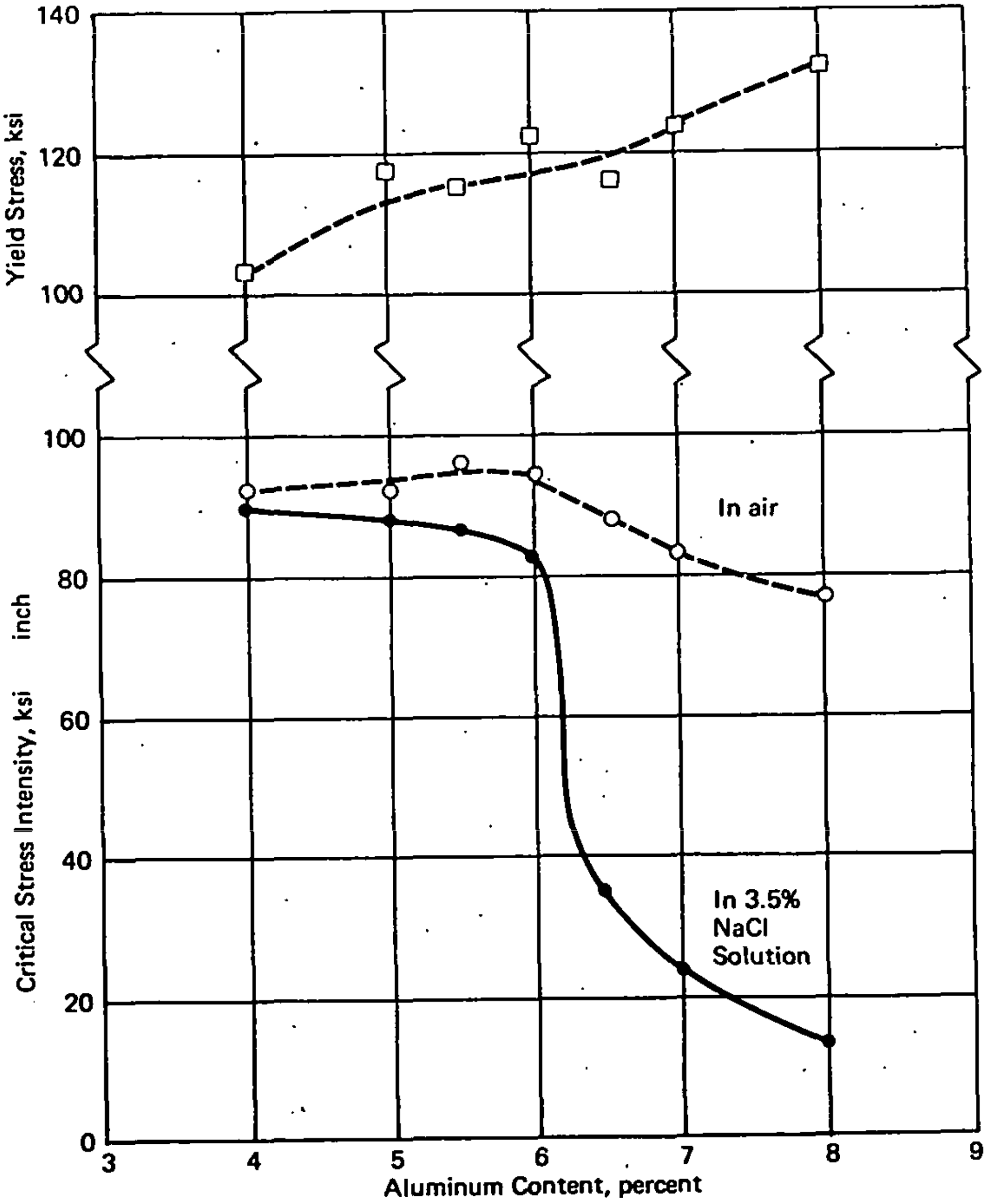

Figure 20. Effect of Aluminum Content on the Strength, Toughness, and Stress-Corrosion Susceptibility of Ti-1.5Mo-0.5V—Base Alloys (Nominally 1000 PPM Oxygen)

of molybdenum is currently being considered as a compositional improvement for certain alloys in order to reduce their cracking potential in salt water. The Ti-6Al-2Cb-1Ta-0.8Mo alloy was developed on this basis.

Alloys that have shown some degree of susceptibility to rapid crack propagation in salt water are listed below, but not necessarily in order of susceptibility:

Unalloyed Ti with 0.32 percent oxygen content
Ti-5Al-2.5Sn
Ti-6Al-4V
Ti-6Al-6V-2Sn
Ti-7Al-3Mo
Ti-8Al-1Mo-1V
Ti-8Mn
Ti-13V-11Cr-3Al

There probably is no such thing as a titanium alloy which is completely immune to the salt-water stress-corrosion reaction although some materials are highly resistant to it. These include:

Unalloyed Ti with low oxygen content
Ti-4Al-3Mo-1V
Ti-6Al-2Mo
Ti-6Al-2Cb-1Ta-0.8Mo
Ti-2Al-4Mo-4Zr (experimental)
Ti-5Al-2Sn-2Mo-2V (experimental)
Ti-11.5Mo-6Zr-4.5Sn (as solution treated)

The degree of susceptibility of some titanium alloys to stress-corrosion cracking in salt water can be changed by the heat treatment given the material. In general, rapid quenching from temperatures above the beta transus tends to improve resistance, while aging in the 900 to 1300 F range tends to decrease resistance to accelerated cracking.

Alloys of titanium can also suffer stress-corrosion cracking at ambient temperatures under certain other specific conditions. Failures have been encountered in red fuming HNO_3 (as mentioned above), in N_2O_4, and in HCl. In addition, certain alloys have shown susceptibility to stress-corrosion cracking in chlorinated-hydrocarbon solvents. Cracks will initiate and propagate only if the right combination of stress, metallurgical history, and environmental factors is present.

In the case of red fuming HNO_3, cracking is limited to environments containing less than 1.5% water or more than 6% NO_2. The cracking is thought to be related to the selective attack of small amounts of beta-phase and/or an enriched-alloy zone along the grain boundaries. In addition, this attack leaves finely divided, highly reactive particles of titanium which will detonate under slight shock. Adding water above 1.5% to the anhydrous acid greatly reduces the chance for stress-corrosion cracking and pyrophoric reactions.

Failure of the Ti-6Al-4V alloy in tankage applications has occured in N_2O_4 containing oxygen and chlorides as impurities. With the oxygen replaced by greater than 0.06 percent NO as an inhibitor, failures are prevented. This attack may be the result of incomplete oxide formation at the metal-surface slip planes, or by preferential absorption of the chloride ion. Current specifications for propellant-grade N_2O_4 require the NO content to be between 0.4 and 0.8 percent.

Methyl alcohol is another medium that initiates stress-corrosion cracking of titanium and its alloys. With small additions of bromine, HCl, or H_2SO_4 to methanol, even unalloyed titanium can be made to crack. With chemically pure methanol, the susceptibility of titanium alloys varies, depending on alloy, heat treatment, and stress level. For example, solution-treated-and-aged

Ti-6Al-4V evinces some failures at about 70 percent of its yield strength, while annealed Ti-6Al-4V cracks only on stressing near its yield point. The Ti-6Al-1Mo-1V alloy appears more susceptible.

Stress-corrosion cracking also occurs at elevated temperatures. Late in 1955, surface cracking was observed on Ti-6Al-4V alloys undergoing creep testing at 700 F. The cracking was attributed at that time to surface embrittlement induced by oxidation. Later, it was established that cracks were often associated with fingerprints. Follow-up testing of specimens under stress in contact with pure NaCl produced cracking at elevated temperatures. This phenomenon has become known as hot-salt stress-corrosion cracking.

While cracking of titanium alloys in contact with hot sodium chloride has been obtained in laboratory studies at temperatures as low as 450 F, this phenomenon has not been officially reported as the cause of failure of a titanium part in service. It should be pointed out, however, that, with the possible exception of jet-engine components, titanium parts in service are not usually subjected to combinations of stress and temperature in the range found to induce cracking in the laboratory.

Studies to date have indicated that several types of chloride salts will initiate failure. However, NaCl now appears to be most reactive. Oxygen or a reducible oxide (TiO_2) must also apparently be present for cracking to occur, although the critical concentration of oxygen is low (1 to 10 microns Hg pressure). Water may also enter into the reaction and appears to be necessary, although its critical concentration is low (on the order of 10 ppm).

Recent studies on the mechanism have shown that a gas-phase reaction can occur, whereas previously a liquid-phase reaction seemed to be required. The mechanism apparently involves NaCl, O_2, H_2O, and reaction products of $TiCl_2$, NaOH and TiO_2. A more recent theory proposes that NaCl and water react to form NaOH and HCl. The HCl.reacts with the protective oxides on the surface, forming unprotective chlorides. The hydrogen released by the attack of the exposed titanium is then believed to diffuse into the metal to cause subsequent hydrogen embrittlement.

It appears that most titanium alloys are susceptible to some degree to hot-salt stress-corrosion cracking. The alpha-phase alloys, such as Ti-5Al-2.5Sn, are apparently most susceptible to attack. The alpha-beta alloys are less susceptible but the degree of susceptibility may increase with increases in aluminum content. For example, the Ti-8Al-1Mo-1V alloy (both as mill annealed and duplex annealed) is very susceptible. However, the Ti-8Mn alloy, which contains no aluminum, is also susceptible.

Alloys with intermediate resistance are Ti-6Al-4V, Ti-6Al-6V-2Sn, and Ti-3Al-11Cr-13V. Among the most resistant alloys are Ti-4Al-3Mo-1V, Ti-2.5Al-11Sn-5Zr-1Mo-9.2Si, and an experimental Ti-2Al-4Mo-4Zr alloy. Variations in heat treatment have been found to affect the reactivity of many alloys also. Table XXXII lists approximate stress-temperature thresholds for several titanium alloys.

The use of certain coatings on a titanium surface shows promise of protection. Surface coatings of nickel plate, aluminum plate, and zinc plate show promise of delaying attack when the coating is nonporous. In one study, flame-sprayed aluminum and nickel and electroless nickel were porous and not very effective, while hot-dipped aluminum gave good protection. In other work, promising results were obtained with a duplex nickel coating. In view of the role of oxygen (even as TiO_2) on the hot-salt cracking, it is not believed that anodized films will offer satisfactory protection.

TABLE XXXII. APPROXIMATE THRESHOLDS FOR STRESS–CORROSION CRACKING OF TITANIUM ALLOYS IN HOT SALT

Nominal Composition, wt %	Condition	100–Hr Threshold Stress, ksi								
		550	600	650	700	750	800	850	900	950
Ti-5Al-2.5Sn	Annealed	28	30	—	15	—	10-20	—	—	—
Ti-8Al-1Mo-1V	Aged	—	—	—	—	25	—	20	—	15
	Annealed	25	55	—	23	—	18	—	—	—
Ti-2.5Al-1Mo-10Sn-5Zr	Aged	—	—	—	70	—	40	—	35	—
Ti-4Al-3Mo-1V	Aged	—	95	—	25	—	25	—	—	—
	Annealed	84	78	—	28	—	15-49	—	—	—
Ti-6Al-4V	Aged	—	95	65	25	30	12	15	—	—
	Annealed	50	50	—	22	—	18-24	—	—	—

Another phenomenon that is closely related to stress-corrosion cracking is that of liquid-metal embrittlement. Many alloy systems, including titanium, have been found to exhibit brittle failure when in contact with specific low-melting-point metals. In the case of titanium alloys, molten cadmium will cause cracking (e.g. when used as a coating on titanium fasteners). Mercury and mercury amalgams also initiate cracking. However, in this case, plastic rather than elastic deformation is required to induce cracking. Further, it has been found that silver will cause cracking of stressed Ti-7Al-4Mo and Ti-5Al-2.5Sn alloys at temperatures of 650 F and above.

59. Crevice Corrosion. Crevice corrosion of titanium and its alloys has been shown to occur in chloride-salt solutions at elevated temperature. This attack occurs above 200 F, with increasing frequency from 300 to 400 F. Acid and neutral solutions cause the greatest susceptibility, whereas no attack has been observed at pH of 9 or more. Crevice attack occurs with about the same frequency among unalloyed titanium and the common titanium alloys. The titanium alloy with about 0.2 percent palladium provides increased resistance to crevice attack, but it too is attacked after long-term exposure at elevated temperature. A comparatively new alloy, Ti-(1-2) Ni, also is resistant to crevice corrosion. While the mechanism is not completely understood, microcrevices, lack of oxygen, and hydride formation may be involved.

60. Galvanic Corrosion. In most environments, the electromotive potential of passive titanium is quite similar to that for Monel and stainless steels. Therefore, galvanic effects are not likely to occur when titanium alloys are coupled to these materials. On the other hand, less noble materials, such as aluminum alloys, carbon steels, and magnesium alloys, may suffer accelerated attack when coupled with titanium. The extent and degree of galvanic attack of a dissimilar metal couple depends on the environment to which the couple is exposed, and on the respective areas of each metal involved, e.g., if titanium is the cathodic member of a couple, and if the area of the anodic member is smaller in relation to the titanium, then in a corrosive environment severe corrosion of the anodic member could be expected. On the other hand, less attack will be evident if the areas of the two metals are reversed. Such attack can be prevented or minimized in most cases by protective paints and other treatments, which include modifying the environment or insulating the dissimilar metals from direct contact with each other.

SECTION IV

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Pertinent references to the various subjects described in this handbook are listed according to the topical paragraph numbering system used. The Table of Contents may be used as a guide to the subjects covered. Insofar as possible, the readily available references are listed, although in several cases, references that fully describe the subjects of interest are difficult to obtain. Governmental libraries and the various information services may be of assistance in locating some of the references cited.

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Custodians:
Army - MR
Navy - AS
Air Force - 84

Preparing activity:
Army-MR

Project No. 95GP-0046

Review Activities:
Army - MR, EL, MI, ES, Mu, WC, GL
Navy - AS
Air Force - 84
DSA - IS

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MIL-HDBK-723A
30 NOVEMBER 1970

MILITARY HANDBOOK

STEEL AND IRON WROUGHT PRODUCTS

DEPARTMENT OF DEFENSE
UNITED STATES OF AMERICA

FSC 95GP

DEPARTMENT OF DEFENSE
WASHINGTON, D.C.

MIL-HDBK-723A
Steel and Iron Wrought Products

1. This standardization handbook was developed for the Department of Defense in accordance with established procedure.

2. This publication was approved on 30 November 1970 for printing and inclusion in the military standardization handbook series.

3. This handbook provides basic and fundamental information on steel and iron wrought products for the guidance of engineers and designers of military materiel. The handbook is not intended to be referenced in purchase specifications except for informational purposes, nor shall it supersede any specification requirements.

4. Every effort has been made to reflect the latest information on steel and iron wrought products. It is the intent to review this document periodically to insure its completeness and currency. Users of this document are encouraged to report any errors discovered and recommendations for changes or inclusions to The Director, Army Materials and Mechanics Research Center, Watertown, Massachusetts 02172, ATTN: AMXMR-MS .

Preface

This is one of a group of handbooks covering metallic and nonmetallic materials used in the design and construction of military equipment.

The purpose of the handbook is to provide technical information and data about steel and iron wrought products for use in achieving the objectives of the Defense Standardization Program. The handbook is intended for use, as applicable, in engineering design, development, inspection, procurement, maintenance, supply, and disposal of equipment and materials. Whenever practicable, the various types, classes, and grades of materials are identified with applicable government specifications. Corresponding technical society specifications and commercial designations are listed for reference.

The numerical values for properties listed in this handbook are in agreement with values listed in the issues of specification in effect on the issue date of the handbook. The handbook values may, in some instances, differ from those listed in current specifications because of revisions or amendments made to specifications after publication of the handbook. In connection with procurement, it should be understood that the issue of specifications listed in the contract govern requirements.

Whenever specifications are referred to in this handbook, only the basic designation is given, all revision and amendment symbols are omitted. This is done for simplification and also to avoid the necessity of correcting the handbook whenever specifications are revised or amended. Current issues of specifications should be determined by consulting the latest issue of the "Department of Defense Index of Specifications and Standards".

The basic handbook was prepared by the Materials Engineering Section of the Denver Division of Martin-Marietta Corporation and the Army Materials and Mechanics Research Center, Watertown, Mass. Comments on the handbook are invited and should be addressed to:

The Director
Army Materials and Mechanics Research Center
Watertown, Massachusetts 02172
ATTN: AMXMR-MS

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Chapter 1

Introduction

PURPOSE

MIL-HDBK-723A was developed for the Department of Defense (DOD) in accordance with standard procedure and in compliance with policies and requirements of the Defense Standardization Program (DSP).

DOD Directive 4120.3-M establishes and, together with Defense Standardization Manual 4120.3-M, "Standardization Policies, Procedures and Instructions", implements the DSP. Because of the comprehensive description of the DSP provided in these documents a detailed discussion is not presented here. However, the following definition of standardization, taken from DOD Directive 4120.3-M, in effect summarizes the DSP.

"Standardization is the adoption and use (by consensus or decision) of engineering criteria to achieve the objectives of the DSP. These criteria are applied, as appropriate, in design, development, procurement, production, inspection, supply, maintenance, and disposal of equipment and supplies".

As implied in the preceding definition, the mission of the DOD with respect to standardization is to develop, establish, and maintain a comprehensive and integrated system of technical documentation in support of design, development, engineering, procurement, inspection, maintenance, and supply management.

MIL-HDBK-723A is one of a group of standardization handbooks covering the metallic and non-metallic materials used in the construction of military equipment. These handbooks are part of the previously referenced integrated system of technical documentation developed, established, and maintained by the DOD in support of the DSP.

The basis for the development of MIL-HDBK-723A then is the DSP. The specific purpose of MIL-HDBK-723A is to provide technical information and data on steel and iron wrought products for use in achieving the objectives of the DSP. The provisions of DOD Directive 4120.3 apply to all departments and agencies of the DOD, consequently, the data provided by the handbook are intended for application, as appropriate, in design, development, procurement, production, inspection, maintenance, supply, and disposal of military equipment and supplies.

SCOPE

1. **General.** MIL-HDBK-723A contains technical information and data pertaining to the wrought products of three ferrous materials; wrought iron, carbon steels, and low alloy steels

2. Definitions.

a. General. The terms carbon steel and low-alloy steel apply to a large number of ferrous alloys. Various designations, such as, trade names, specification numbers, and descriptive phrases, are commonly used to identify the various alloys; a practice that quite often leads to misunderstanding and confusion. To avoid that problem, the following definitions of the handbook subjects are provided.

b. Wrought iron. (American Society for Testing and Materials - ASTM definition.) A ferrous material, aggregated from a solidifying mass of pasty particles of highly refined metallic iron, with which, without subsequent fusion, is incorporated a minutely and uniformly distributed amount of slag.

c. ***Carbon steel.*** (The American Iron and Steel Institute - AISI Definition.) Carbon steel is classed as such when no minimum content is specified or guaranteed for aluminum, chromium, columbium, molybdenum, nickel, titanium, tungsten, vanadium, or zirconium; when the minimum for copper does not exceed 0.40 percent; or when the maximum content specified or guaranteed for any of the following elements does not exceed the percentages noted; manganese, 1.65; silicon, 0.60; copper, 0.60.

d. ***Alloy steel (low alloy steel).*** (The AISI Definition.) By common custom, steel is considered to be alloy steel when the maximum range given for the content of alloying elements exceeds one or more of the following limits: manganese, 1.65 percent; silicon, 0.60 percent; copper, 0.60 percent; or in which a definite range or a definite minimum quantity of any of the following elements is specified or required within the limits of the recognized field of constructional alloy steels; aluminum, boron, chromium up to 3.99 percent, cobalt, columbium, molybdenum, nickel, titanium, tungsten, vanadium, zirconium, or any other alloying element added to obtain a desired alloying effect. Small quantities of certain elements are present in alloy steels which are not specified or required. These elements are considered as incidental and may be present to the following maximum amounts: copper, 0.35 percent; nickel, 0.25 percent, chromium, 0.20 percent, molybdenum, 0.06 percent.

3. Contents.

a. ***General.*** It is anticipated that this handbook will be used by personnel engaged in any of a variety of occupations including engineering design, development, procurement, inspection, manufacturing, supply, maintenance, and disposal of military equipment and materials. To satisfy the wide range of interest of this audience the subject of steel and iron wrought products is covered from the smelting of iron ores through to the production and ultimate use of the wrought products.

Unlike other handbooks of the series, MIL-HDBK-723A does not contain a complete listing or tabulation of minimum physical and mechanical properties values for the various alloys included in the subject categories. Properties of this type, commonly referred to as design allowables, are available in other publications, for example, MIL-HDBK-5, industrial handbooks, and material specifications. Repetition of these data is unwarranted and beyond the scope of the handbook. As indicated in the following chapter summaries, the handbook is intended to provide practical information about the production, availability, working, and use of steel and iron wrought products.

b. ***Chapter 1.*** Chapter 1 is a short introductory chapter in which the purpose and scope of the handbook are defined. In addition, applications for the data presented in the handbook are identified, and a brief review of iron and steel wrought product development and use is presented.

c. ***Chapter 2.*** Chapter 2 deals with fundamental concepts and principles of iron and steel production and technology. First, the production of pig iron by the reduction smelting of iron ores in a blast furnace is described. Then, by explaining the use of this basic material, the methods currently used to produce wrought iron and steels are introduced. In the discourse on steel production, the difference between carbon and alloy steels is explained by describing how the properties and characteristics of steel are affected by carbon and other common alloying elements. The chapter concludes with a brief treatise of the basic principles of ferrous metallurgy which discusses: the structure of metals; the iron-carbon system; the theory of heat treatment; isothermal transformation diagrams; and hardenability.

d. ***Chapter 3.*** In Chapter 3, the wrought product forms in which wrought iron, carbon steels, and alloy steels may be obtained are identified. Pertinent information is given about each of the various forms, including, how each is made, and size limits. The remainder of the chapter deals with how the wrought product forms of the subject materials are worked. The main topics covered are: heat treatment, machining, forming, and joining.

e. ***Chapter 4.*** Chapter 4 is concerned with the identification and definition of selection criteria, that is, those factors upon which, in keeping with good practice, the selection of materials of construction should be based. The most common uses found for iron and steel wrought products are structural applications where the primary purpose of the material is to sustain some applied load. Therefore, the mechanical properties of these materials are usually of singular importance. For this reason, the subjects of mechanical properties, mechanical testing, elastic analysis, and brittle fracture have been treated in considerable detail in Chapter 4. Not only have the various mechanical properties been identified, but associated test methods are described, and the significance and use of the properties in selecting materials is explained.

In the final section of the chapter the general problem of material selection is considered. The importance of identifying and considering all requirements in searching for a solution to a material selection problem is developed by examining the relationship to intelligent material selection of topics such as: essential design requirements; material properties and characteristics, manufacturing and producibility factors; material availability; and total project costs.

Selecting a material for a particular application can be a simple or very difficult task depending upon the limiting factors involved. In some cases, previous experience is directly applicable to the problem and the proper material is selected almost automatically. At other times, the material may be selected on the basis of availability and cost alone. However, selecting the proper material is usually not such a simple task. Design requirements, functional requirements, environmental requirements, the size of the structure and its elements, the limitations of manufacturing facilities and equipment, producibility features of the material, total cost of the program, and many other factors which directly influence material selection must be accorded due consideration.

To determine the most suitable material for an application it is necessary to first identify all of the pertinent requirements and factors with which the material must be compatible. Next, candidate materials are selected and evaluated with respect to these requirements, and, on the basis of comparison, the proper material can be selected. This seems to be a simple and straightforward procedure; however, in practice, due primarily to the nature of structural metals, more often than not one or more compromises must be made in choosing the material. In other words, it is usually impossible to find a material that totally meets all of the essential requirements.

f. ***Chapter 5.*** Quality assurance, which is the title and subject of the fifth and final chapter of the handbook, is obviously an ambiguous phrase which, to be meaningful, must be identified with a particular subject. Since iron and steel wrought products are raw materials, the meaning of "quality assurance" derived in Chapter 5 is based on application of the term to the purchase of raw materials. It is defined as: a general descriptive phrase that serves to identify any, and all, of the means available and used by a purchaser of raw materials to assure himself that the materials he orders and receives are of acceptable quality.

To assure that the quality of purchased material meets the required or desired level, the purchaser must assume a number of responsibilities. He must define the exact requirements to which the material must conform; communicate these requirements, completely and explicitly, to the material producer; obtain confirmation from the producer that the requirements are realistic and that the producer is willing to supply material to them; contract for purchase of the material; and inspect the material to confirm that it meets the requirements.

The use of material specifications and associated standards simplifies this system. Specifications and standards have been developed and issued by government agencies, industrial societies and organizations, private companies, and others. The use of these specifications serves to simplify and standardize communications between the buyer and producer of raw materials. Since this is a MIL-HDBK, the use of government specifications and standards is emphasized in Chapter 5, although industrial specifications, such as ASTM, AISI, SAE (Society of Automotive Engineers), ASM (American Society for Metals), are examined and compared to government specifications on the basis of purpose and scope.

In addition to the explanation of the purpose and use of material specifications and standards, Chapter 5 deals with the inspection of iron and steel wrought products. To confirm that a material meets specification requirements, it is necessary to perform examinations and tests. Depending upon the material and specification involved the inspection may be cursory or extensive. The tests and methods normally used to inspect ferrous wrought products are identified and their purposes explained together with the significance of the results obtained.

Chapter 5 also contains a cross index tabulation of government and industrial specifications and standards applicable to the handbook subjects.

APPLICATIONS

4. Objectives. This handbook is intended to be used in achieving the objectives of the Defense Standardization Program, established in DOD Directive 4120.3. Essentially, it serves as a means of disseminating technical data and information about ferrous wrought products to cognizant and interested personnel of the Department of Defense and associated government and industrial organizations. The use of the handbook in fields of interest such as; design and development engineering, procurement, inspection, manufacturing, maintenance, and supply of military equipment and materials certainly does not require explanation or elaboration. Rather, it is the limitations of the handbook which should be identified.

5. Limitations. First, this handbook does not contain design allowables, that is, a listing of mechanical and physical properties values for the various alloys covered by the handbook. Design allowables for these alloys are published in various documents, such as; MIL-HDBK-5; appropriate Military, Federal, American Society for Metals (ASM), ASTM, Society of Automotive Engineers (SAE), and AISI material specifications; Metals Handbook (published by ASM); the Aerospace Structural Metals Handbook; to name but a few. These and other appropriate references should be consulted for design allowable properties values. Also, consultation with Materials Engineering organizations to confirm design values, regardless of the source, is recommended.

Second, this handbook, although it contains considerable data relative to material specifications and standards, is neither, and should not be referenced in a purchase order or contract. Materials specifications have been developed specifically to communicate material requirements from the buyer to the material producer. Standards contain supplementary data and are used to augment the scope of specifications. These documents are designed for use in the purchase of materials and should be specified in the contract or purchase order. The handbook only explains the use of specifications and standards and has no function in the procurement of materials.

BACKGROUND

Even before the time of recorded history man knew how to reduce iron-rich ores to make a usable form of iron. From this modest beginning, the current technology of iron and steel production evolved. Numerous ferrous alloys and products are marketed today; allowing the consumer to choose the alloy with the combination of properties and characteristics that best suit his needs. However, even the wide variety of steels currently available does not satisfy all of the demands of industry. The demand for new alloys to satisfy more stringent environmental and functional requirements stimulates research and development efforts, with the result that the technology continues to expand.

The use of ferrous materials in military equipment undoubtedly dates back to the initial discovery of crude wrought iron. In more recent eras, carbon and alloy steels have been, and are being, used extensively in military equipment and structures. Aside from the fact that these materials are ideally suited to the application, they are also inexpensive, relatively easy to fabricate, and readily available in large or small quantities. To illustrate the versatility of these materials and their importance to defense and military efforts it is necessary only to recount a few familiar applications. For example, various carbon and alloy steels are used in tanks, jeeps, trucks, ships, and earth moving equipment. Some of the higher strength alloy steels have been used in airborne structures of both aircraft and missiles. These examples are cited to demonstrate the versatility of the ferrous wrought products, which derives from the wide range of properties and characteristics developed, collectively, by the various alloys. Therefore, even in the space age, carbon and alloy steels continue to play a vital role in military and defense efforts.

Chapter 2

Iron and Steel

PIG IRON PRODUCTION

Iron and steel production begins with the mining of iron-rich mineral deposits known as iron ores. Iron is present in the ores in the form of chemical compounds, not as free iron, because the element iron is so active chemically that it does not exist in nature in the free state. The important iron compounds, as related to iron and steel production, are the oxides of iron. In the United States the important ores are, hematite, magnetite, and limonite, which contain ferric oxide (Fe_2O_3), ferrosoferric oxide (Fe_3O_4), and hydrated ferric oxide ($2Fe_2O_3 \cdot 3H_2O$), respectively,

Iron is extracted from iron ore in a blast furnace. A blast furnace, shown in vertical cross-section in Figure 1, is essentially a tall steel shell erected on a concrete base. The inner surfaces of the furnace, lined with refractory materials, form three distinct sections: the cylindrical hearth at the bottom; the upward and outward sloping bosh located directly above the hearth; and the stack.

The blast furnace process of extracting iron from ore is a reduction smelting process. Free iron is obtained by developing conditions in the furnace whereby the iron oxides in the ore are converted, through a series of oxidation - reduction reactions, to free iron and carbon compounds. In operation, ore and other solids are fed into the furnace through the top and the iron and waste materials are drawn off at the bottom of the furnace. Ordinarily, once a blast furnace is started up it is operated continuously until it must be shut down for repair or for some other reason.

The solids are fed into a blast furnace through a two-hopper, two-bell system, incorporated in the conical cover on the stack. The solids, consisting chiefly of iron ore, coke, and limestone, are conveyed to the top of the furnace in open-end cars called skips. The solids are discharged into the small hopper and collect on the small bell forming the bottom of the hopper. The small bell is lowered and the solids drop onto the bell shaped bottom of the large hopper. When the proper charge has collected on the large bell it is lowered and the charge is deposited on top of the material in the stack. The two bells operate independently, and at least one is closed at all times to prevent the escape of gases and flames through the top of the furnace.

Pre-heated air is blown into the furnace through nozzles, called tuyeres, located at the top of the hearth. The tuyeres, usually about 20 in number, are equally spaced around the circumference of the hearth. In the vicinity of the tuyeres, the oxygen in the air reacts with the carbon in the coke to form carbon dioxide (CO_2), which, at the prevailing elevated temperature, reacts with the excess carbon present to form carbon monoxide (CO). As the carbon monoxide travels upward through the charge of solid materials it contacts and reacts with the iron oxides in the ore. The oxides are converted, through a series of oxidation-reduction reactions, to free iron, carbon dioxide and carbon monoxide. Reaction of the oxides with carbon monoxide accounts for a majority of the iron reduced in a blast furnace, although approximately 20 percent is produced by direct reduction of the oxides reacting with carbon.

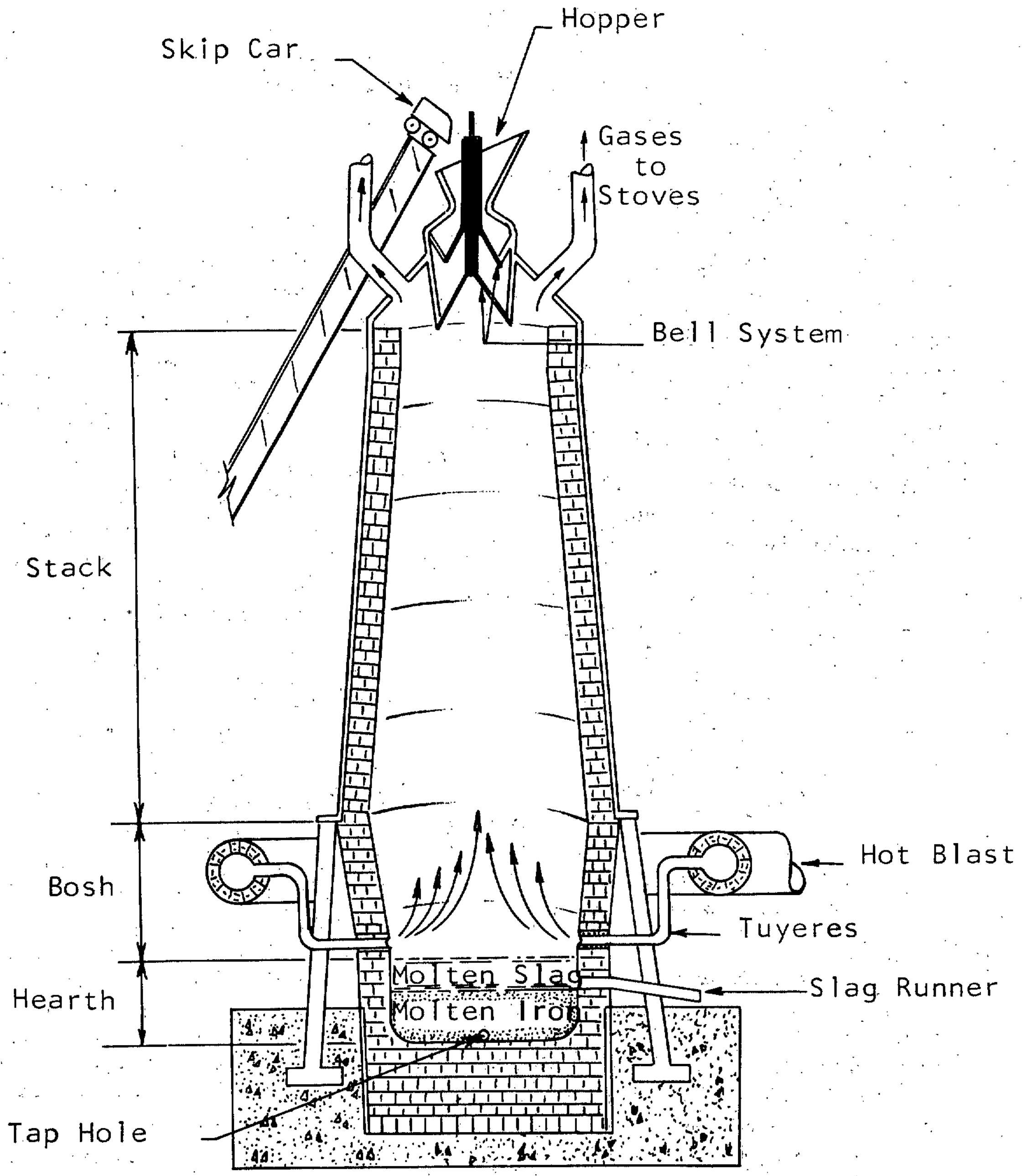


FIGURE 1. Vertical Section Through a Blast Furnace

The reducing reactions begin in the charge near the top of the furnace where the prevailing temperature is 300 to 400°F. As the charge descends in the stack, the concentration of CO increases, and the temperature becomes progressively higher; in the vicinity of the tuyeres the temperature exceeds 3000°F. The higher temperatures and increased quantity of CO combine to accelerate the reactions as the charge descends into the furnace.

The limestone in the charge also reacts to the increasing temperature as the charge descends. Limestone is essentially calcium carbonate ($CaCO_3$), which decomposes at temperatures above 1500°F to form lime (CaO), and carbon dioxide (CO_2). The lime reacts with the gangue (waste materials in the ore), and with the ash that is produced by combustion of the coke near the tuyeres. The product of these reactions is a nonmetallic material known as slag.

In the stack the charge is a mixture of the various solid materials and hot gases. As the solid charge descends and passes through the bosh, it is converted first into a pasty mass and finally, in the lower portion of the bosh, into molten iron and molten slag. The molten materials collect in the hearth and, since they are immiscible, the less dense slag floats on the iron. The molten slag and molten iron are drawn off periodically through ports provided in the hearth. Because the two materials collect at different levels they are drawn off through separate ports. The slag, when it is drawn off, is either discarded or processed for sale as ballast, aggregate, or insulation material.

The third product of the blast furnace process, hot gases, are exhausted through offtakes in the conical cover on the stack. After a number of cleaning operations they are passed into a stove and burned. The heat produced by their combustion is used to pre-heat the air that is forced into the furnace through the tuyeres.

When the molten iron is drawn off, it is passed through troughs and collected in refractory-lined ladles. As it passes through the troughs any slag flowing with it is skimmed off and disposed of. The molten iron in the ladles is used either as a molten charge in steel making furnaces or it is taken to a pig casting machine and cast into small blocks, called pigs, weighing approximately 100 pounds each. It is from the latter form that the material derives the name pig iron.

The pig iron produced in a blast furnace is not pure iron. During the smelting process the iron dissolves impurities such as sulphur, phosphorus, manganese, silicon, and other elements that are contained in the coke, ore and other materials in the furnace charge. Pig iron is produced in different grades, for example: open hearth basic, foundry, malleable, bessemer, which vary in chemical composition to meet use requirements.

WROUGHT IRON PRODUCTION

The methods now used to produce wrought iron differ considerably from the primitive methods employed thousands of years ago. The ancients undoubtedly discovered iron by accidentally reducing it from a surface deposit of iron rich ore. From that time on wrought iron has been produced directly from iron ore. The practice probably persists in less advanced areas of the world even today, although the production of wrought iron directly from ore disappeared from commercial practice in the United States around 1900. Wrought iron is now produced by indirect processes, that is, by remelting and refining pig iron.

In 1875, Henry Cort introduced a process for making wrought iron in which pig iron and scrap iron could be used as well as ore. An improved version of this process known as the "Puddling Process", was used successfully for many years in the United States, retaining commercial significance until the Aston process was introduced, about 1930.

The "Puddling Process" was carried out in a reverberatory furnace. Pig iron was melted in the hearth of the furnace, the bottom of which was formed of iron oxide, while the sides were lined with hematite ore. Iron oxide was added to the molten metal and the mixture was stirred manually to accelerate the oxidation reactions by which carbon and other impurities in the iron were eliminated. During this refining process an iron-silicate slag was formed. Since pure metals have higher melting points than alloyed or impure metals, as the contaminants were eliminated from the pig iron, the melting point of the iron gradually, but continuously, increased. Refining continued until the temperature of the furnace (about 2600°F) was not sufficient to keep the metal in the molten condition. The slag, with a lower melting temperature than the refined iron, remained molten. As manual stirring was continued a pasty mass of plastic refined iron, impregnated with molten slag, was produced. The material was then divided into ball shaped portions, weighing 200 to 500 lbs. each, which were taken from the furnace while still at welding temperature and subjected to a squeezing or pressing operation to eliminate excess slag. The resultant blooms were immediately rolled flat to form bars which were then cut into short lengths. These were then assembled into a pile, reheated to welding temperature, and rolled to eliminate more slag and simultaneously weld the individual bars together to form a single bar.

The skill of the operator directly affected the quality of individual heats of wrought iron produced by the hand-puddling process. Consequently, there was considerable variance in the composition and quality of the material produced by this process. Also the manual nature of the operation limited the amount of material that could be produced in one heat. These process limitations prompted the development of various machines which were intended to improve the quality and quantity of the wrought iron produced. Although these efforts met with varying degrees of success, none of the devices or processes developed were completely satisfactory. Generally, the various machines were designed to eliminate the manual stirring operations. The melting and refining of the pig iron and subsequent operations were still carried out in one furnace. While some of the machines did produce larger heats than were possible by hand puddling, the production of material of consistent quality continued to be a problem.

The Aston process, which was first used on a commercial production basis in 1930, proved to be a practical solution to the problem. Wrought iron can be produced in large quantity by this process and the quality of the material can be consistently maintained at a high level. This process differs considerably from either the hand puddling or mechanical puddling processes that preceded it. The various operations, such as, melting of the pig iron, refinement of the pig iron, preparation of the slag, and mixing of the constituents, are each carried out separately in equipment provided for that specific purpose.

In brief, the pig iron is melted in a cupola, tapped into a ladle where it is desulfurized, and then poured into a Bessemer converter where it is further refined. The refined iron is then tapped into a ladle for transportation to the processing area where it is poured at a controlled rate into the ladle of a processing machine which contains a specially prepared iron-silicate slag. As the iron is poured, the ladle containing the slag is moved back and forth to assure proper mixing of the iron and slag. When the iron is poured into the ladle the temperature of the slag is several hundred degrees below the freezing point of the molten refined iron. Consequently, the iron solidifies rapidly and the dissolved gases in the iron are entrapped. The resulting small explosions, by which the entrapped gases are liberated, shatter the metal into small fragments which collect at the bottom of the ladle. At the prevailing temperature the small pieces of iron weld together to form a ball of refined iron impregnated with molten slag. When the reactions stop, the excess slag is poured off and the spongy ball, which weighs 6000 to 8000 pounds, is dumped on the platform of a large press. The excess slag is squeezed out of the ball which is reduced to a solid bloom. The bloom is then reduced to any of a number of wrought forms through a series of rolling operations.

In finished form, wrought iron produced by the Aston Process contains about 2 percent slag, by weight. The slag is distributed throughout the iron matrix in the form of minute fibers which may number more than 250,000 per square inch of cross sectional area. The multitude of slag inclusions are responsible for the excellent resistance of wrought iron to progressive corrosion, since they serve as natural barriers that confine the corrosion to the surface of the material.

STEEL PRODUCTION

6. General. Before delving into the intricacies of steel production the two classes or types of steels covered by this handbook, carbon steels and low alloy steels, will be briefly examined. Definitions of these steels were given in Chapter I, however, for convenience they are repeated here.

a. ***Carbon steel.*** (The AISI Definition). Steel is classed as carbon steel when no minimum content is specified or guaranteed for aluminum, chromium, columbium, molybdenum, nickel, titanium, tungsten, vanadium, or zirconium; when the minimum for copper does not exceed 0.40 percent; or when the maximum content specified or guaranteed for any of the following elements does not exceed the percentages noted: manganese, 1.65; silicon, 0.60; copper, 0.60.

b. ***Alloy steel.*** (The AISI Definition). By common custom, steel is considered to be alloy steel when the maximum range given for the content of alloying elements exceeds one or more of the following limits: manganese, 1.65 percent; silicon, 0.60 percent; copper, 0.60 percent; or in which a definite range or a definite minimum quantity of any of the following elements is specified or required within the limits of the recognized field of constructional alloy steels; aluminum, boron, chromium up to 3.99 percent, cobalt, columbium, molybdenum, nickel, titanium, tungsten, vanadium, zirconium, or any other alloying element added to obtain a desired alloying effect. Small quantities of certain elements are present in alloy steels which are not specified or required. These elements are considered as incidental and may be present to the following maximum amounts; copper, 0.35 percent, nickel, 0.25 percent; chromium, 0.20 percent; molybdenum, 0.06 percent.

c. ***Low-alloy steel.*** Since this handbook covers only carbon and low-alloy steels it is necessary to qualify the preceding definition. Low alloy steels, for this handbook, are defined as steels with a total alloy content of five percent or less. This figure includes the constructional high strength low-alloy steels, and the AISI-SAE steels defined in Chapter 5.

7. Effects of Alloying Elements

a. ***General.*** Steel, in the generic sense, defines a family of iron-carbon alloys which, collectively, develop a vast range of physical, mechanical and chemical properties. There are many different types and alloys of steel, each capable of developing a particular combination of properties and characteristics that make it uniquely suitable for one or more applications. The versatility of steel is derived from two factors:

(1) Properties can be changed by thermal treatment; and

(2) The addition of one or more alloying elements, in proper amounts and proportions, can effect further changes in properties and characteristics.

The combined effect of these factors is demonstrated by the widespread application of the various steels produced today. Carbon steels, corrosion resisting steels, tool steels, high-hardenability alloy steels, low-alloy high-strength structural steels, spring steels, maraging steels, and others are produced in many alloys and forms each with a distinctive combination of properties and characteristics. A user may choose the alloy and form that best meets his requirements. The tremendous versatility of steel accounts for the fact that it is the most important metal produced today.

The heat treatment of steels will be covered later in this chapter. In this section the effects of various common alloying elements on the properties of steel will be discussed.

Even the carbon steels are not pure iron-carbon alloys. The previously listed definition of carbon steel indicates that elements other than carbon are present in these steels. Some of these are intentionally included in the composition of the steel, while others are present as impurities. Actually, all of the commercial plain carbon steels contain limited amounts of manganese, sulfur, phosphorus and usually some silicon. In addition they may contain, normally in trace amounts only, one or more of the other common alloying elements.

The carbon steels are produced in two grades, the plain carbon steels, and the free cutting or free machining grade. These steels conform with the composition limits of the AISI-SAE designations. Further composition restrictions are provided by applicable specifications, which usually limit the amounts of carbon, manganese, sulfur and phosphorus permitted in the steel. In the plain carbon steels, sulfur and phosphorus are considered as impurities and maximum limits are specified. Carbon and manganese are purposely included in the composition of these steels and permissible ranges are specified for both elements.

In the free machining alloys, sulfur, and in some alloys, phosphorus and lead, are also controlled within specified limits as well as carbon and manganese.

Despite the fact that other elements are purposely included in the composition of plain carbon steels, carbon is the principal alloying element, and the properties of a steel are primarily dependent upon the amount of carbon alloyed with the iron. For practical purposes, therefore, a plain carbon steel may be considered as one in which only carbon is added to the iron for the singular purpose of controlling the properties of the steel. Manganese and silicon, which are intentional additions to the compositions of plain carbon steels, do affect the properties of the steel, but they are not added specifically for that purpose. The effect on properties is a secondary function of these elements; silicon is added as a deoxidizing agent, while manganese, also a strong deoxidizer, in addition combines with the sulfur to form manganese sulfide, thereby restricting the formation of a less desirable compound, iron sulfide. The free machining alloys retain the carbon steel classification because the extraneous elements are added to the iron-carbon alloy in small amounts well within the composition limits of the AISI designation for carbon steels. The principal effect of the additions is to achieve improved machining characteristics, as compared with a comparable plain carbon alloy.

By contrast with the carbon steels, an alloy steel is one to which one or more elements, in addition to carbon, are added to the iron specificially to effect a change or changes in properties. These elements impart special properties to steel that cannot be obtained in a plain carbon steel. Some of the common alloying elements of steel are discussed briefly in the succeeding paragraphs.

b. **Carbon.** The principal alloying element in carbon steels is carbon. Theoretically, the carbon content range for steels extends from approximately 1.7 percent carbon (by weight) to 0.001 or less. In actual practice, commercial carbon steels are produced with carbon content ranging, in nominal figures, from about 1.0 percent to approximately 0.05 percent.

The properties of a carbon steel are dependent upon the amount of carbon in the steel. Hardness, toughness, strength, ductility, and weldability are all directly affected by carbon. The hardness and strength of carbon steels in the as-rolled condition increase with increasing carbon content up to approximately 0.85 percent carbon. The maximum hardness that can be achieved by proper heat treatment of carbon steels also increases with increasing carbon content up to 0.60 percent carbon. Ductility, toughness, and weldability generally decrease as carbon content increases.

c. **Manganese.** Manganese is an active deoxidizer and, in addition, combines with the sulfur to form manganese sulfide. This constituent enhances the machining characteristics of the free machining carbon steels. When sulfur is present as an impurity, the formation of manganese sulfide restricts the formation of iron sulfide. Iron sulfide is detrimental to the hot rolling and forging characteristics of steel, producing a condition known as "red shortness" or "hot shortness", that is, the material is susceptible to tearing or cracking at rolling or forging temperatures. Manganese enhances the hardenability of the steel because it decreases the critical, or minimum, cooling rate necessary for hardening a steel.

d. **Silicon.** Silicon in the form of ferrosilicon is used as a deoxidizer and hardener in both alloy and carbon steels.

e. ***Nickel.*** Nickel increases impact resistance and toughness, particularly at low temperatures. It lowers the critical temperatures of steel for heat treatment and enhances hardenability. In the high strength low-alloy structural steels which receive no more than an air-quench, nickel is used to obtain given strength levels at lower carbon content than would otherwise be required. As a result the ductility, toughness, and fatigue resistance of the steels are improved.

f. ***Chromium.*** Chromium enhances hardenability, improves wear and abrasion resistance, and promotes carburization.

g. ***Molybdenum.*** Molybdenum enhances hardenability, and widens the temperature range for effective heat treatment.

h. ***Vanadium.*** Vanadium is a strong deoxidizer and also inhibits grain growth.

i. ***Aluminum.*** Aluminum is a strong deoxidizer and, like vanadium, inhibits grain growth. Aluminum improves the nitriding characteristics of steel when present in amounts of approximately 1 percent.

j. ***Boron.*** Boron serves one purpose in steel; it increases hardenability.

k. ***Multiple alloying elements.*** A combination of two or more of the above alloying elements usually imparts some of the characteristic properties of each. Constructional chromium-nickel-alloy steels, for example, develop good hardening properties, with excellent ductility, while chromium-molybdenum combinations develop excellent hardenability with satisfactory ductility and a certain amount of heat resistance. The combined effect of two or more alloying elements on the hardenability of a steel is considerably greater than the sum of the effects of the same alloying elements used separately. The general effectiveness of the nickel-chromium-molybdenum steels, both with and without boron, is accounted for in this way.

Various combinations of alloying elements are employed by the different producers of high strength low alloy steels to achieve the mechanical properties, resistance to atmospheric corrosion, and other properties that characterize those steels. Carbon is generally maintained at a level that will insure freedom from excessive hardening after welding and will retain ductility. Manganese is used principally as a strengthening element. Phosphorus is sometimes employed as a strengthening element and to enhance resistance to atmospheric corrosion. Copper is used to enhance resistance to atmospheric corrosion and as a strengthening element. Silicon, nickel, chromium, molybdenum, vanadium, aluminum, titanium, zirconium, and other elements sometimes are used, singly or in combination, for their beneficial effects on strength, toughness, corrosion resistance, and other desirable properties.

8. Steelmaking Processes

a. ***General.*** Various processes have been developed to produce carbon and low-alloy steels from pig iron and scrap steel. In the United States the processes of the greatest commercial significance are: the basic open-hearth process; the acid Bessemer process; the basic-oxygen process; and the electric arc process. Each process is distinctive, with inherent advantages and disadvantages, but, there are marked similarities in the fundamental elements of these processes.

In each process, refining of the raw materials is an essential operation. The raw materials used to make the steel contain various metallic and non-metallic elements as impurities. To make steel, many of these impurities must be removed or reduced in amount to a level that can be tolerated in steel. In all of the previously listed steel-making processes, refining is accomplished by promoting chemical reactions, principally, but not exclusively, oxidation reactions. Carbon, manganese, iron, silicon and other elements are oxidized during the refining period. Many of the oxides evolve as gases or enter the slag thus reducing the amounts of the extraneous elements in the iron.

During the refining process elements that are needed in the steel, such as, carbon and manganese, are removed from the iron along with the impurities. Consequently, each process is designed to permit the addition of selected materials to the molten metal so that the amounts of carbon, manganese and other desirable alloying elements in the steel can be adjusted, within limits, to produce a steel of the desired composition.

As steel is refined during the course of these processes, its oxygen content is increased. Various means are employed to deoxidize steels. Deoxidizing and ingot practices are discussed after each of the processes are described.

As a final prelude to the process description, it should be noted that steel making processes are classed as either basic or acid processes. Classification depends upon the type of furnace lining used, which can be either an acid or a basic refractory material. The slag that forms during the process must be compatible with the lining, that is, a basic slag for a basic lining, and an acid slag for an acid lining. Silica (SiO_2) is a common acid furnace lining, while magnesite ($MgCO_3$) and dolomite (Magnesite + $CaCO_3$) are basic linings. The open-hearth, Bessemer, and electric arc processes may be operated as basic or as acid processes. In the United States the basic open-hearth process is the predominant process, accounting for more than 80 percent of the steel produced.

*b. **The basic open-hearth process.*** The open-hearth process is a regenerative process that employs a furnace with the following features: the hearth is shallow, usually elliptically shaped, and lined with basic refractory materials; the hearth combines with the front and back walls and the roof to form the combustion chamber; and the combustion chamber is closed at each end by similar structures that include the burners and also the air-gas passageways that are part of the regenerative system.

During operation of the furnace, the burners are fired alternately. One burner fires for approximately 20 minutes, it is then shut-off and the other burner is fired for a like period of time. Pre-heated air and gases enter the furnace through the regenerative system passageways at the end of the combustion chamber where the burner is firing. The gases and combustion products travel the length of the furnace, being exhausted through the regenerative passageways at the opposite end of the chamber from which the air and gases entered. When the burners are alternated, the flow of air and gases is reversed.

The hot exhaust gases enter the regenerative system through the passageways at the end of the combustion chamber. They are passed through a regenerative chamber at the exhaust end of the furnace and from there to the exhaust stack.

Regenerative chambers are located at each end of the furnace. They are large brick chambers in which firebricks are arranged in a criss-cross pattern to form vertical and horizontal passages for the air and gases to pass through. The firebricks are arranged so that as much of their surface area as possible is exposed to the gases flowing through the passages. As the hot exhaust gases from the furnace pass through a regenerative chamber heat is transferred to the firebricks. When the burners are alternated the air and gas flow through the furnace is reversed. Air and gases now pass through the heated chamber, absorbing heat as they do so, and then enter the combustion chamber. In this manner, the regenerative chamber at one end of the furnace is being heated by exhaust gases while the chamber at the other end of the furnace is preheating the air and gases entering the combustion chamber. The function of the chambers are interchanged whenever the burners are alternated.

An open-hearth furnace is charged through water-cooled, hydraulically operated doors in the front wall of the furnace. Solids are charged first. Usually the solid charge includes solid pig iron, scrap steel, iron ore and limestone. The charge is melted by heat from the long sweeping flame of the operating burner. When the solids have nearly melted, molten pig iron is added to the charge and the refining period begins. The first phase of the refining period is known as the ore boil. A slag forms on the molten metal and the silicon, manganese and phosphorus in the pig iron are oxidized and enter the slag. Carbon is also oxidized, forming carbon monoxide gas which, as it boils off, agitates the bath causing the slag to foam and increase in volume. When the volume of the slag is sufficient, it is drawn off or flushed out through a door at the rear of the furnace. The slag contains silicon, phosphorus, and manganese, so the flush serves as a means of reducing the quantity of these elements in the heat. The flush is continued for as long as necessary to assure a thorough flushing of the heat, which may be for two hours or more.

The ore boil continues until the carbon content in the melt diminishes and the temperature of the bath rises. With increasing temperatures the limestone begins to decompose forming carbon dioxide and calcium oxide (lime). This phase of the operation is known as the lime boil because of the vigorous reaction caused by the release of the carbon dioxide. The lime rises to the surface and a strong basic and reducing slag is formed which is capable of retaining phosphorus and sulfur.

The lime boil subsides due to depletion of the limestone and when most of the lime has risen to the surface the working period begins. Almost all of the impurities have been eliminated by this time, except for carbon, of which there is usually a slight excess. Any alloy additions are made during this period, and oxidation is continued to reduce the amount of carbon and any other elements in the steel to the proper and desired levels. When a suitable composition is achieved, as determined by analysis of samples from the heat, the heat is tapped.

The molten steel and slag are drawn-off through the tap hole, which in stationary furnaces is located at the center and near the back of the hearth. The tap hole which is sealed with dolomite and clay, is opened when the heat is ready to tap. The steel flows out of the furnace and into a refractory lined spout or runner that directs the steel into a large ladle. The slag follows the steel out of the furnace and into the ladle where some is retained as an insulating cover for the steel. The excess slag overflows into a slag pot.

c. *The Acid-Bessemer process.* Although the Bessemer process may be operated as either an acid or basic process, only the acid process is of commercial significance in the United States, consequently, this discussion is restricted to the acid process only.

The furnace in which the Bessemer process is carried out is known as a converter. The converter is a large, open topped, pear shaped, steel shell vessel, the inside surfaces of which are lined with acid refractory materials, predominately silica. The bottom surface of the refractory lined chamber is pierced with numerous small holes, or tuyeres, which lead from the chamber into the windbox below the chamber. The converter is trunion mounted so that it can be tipped to the horizontal position for charging and pouring. One of the trunions is hollow and compressed air is piped through it to the windbox. From the windbox the air passes through the tuyeres into the refractory lined chamber.

The converter is tipped to a horizontal position for charging. Molten pig iron is a common charge, although solids, such as roll scale, scrap and solid pig iron can be added to the molten charge. After the converter is charged the compressed air is turned on and the vessel is slowly rotated to a vertical position. The air, under 15 to 30 psi pressure, passes through the tuyeres and is blown through the charge. The silicon, manganese and carbon in the pig iron are oxidized rapidly, in the order mentioned, by the oxygen in the air passing through the charge. The progress of the blow can be determined by changes in the flame coming from the open end of the converter. When the blow is completed the air is shut off and the converter is tilted to pour the steel into a large ladle. Ferromanganese is added as the steel is poured into the ladle. The purpose of this addition is to convert the iron oxide and iron sulfide in the steel to MnO and MnS. The carbon in the ferromanganese also reacts with oxygen in the steel to form carbon monoxide, which as it boils off agitates the bath and helps to distribute the manganese more uniformly.

d. The basic-oxygen process. This process was developed in Linz, Austria and is sometimes referred to as the LD process (Linz-Dorowitz). Other names by which it is known are the direct oxygen process and the oxygen converter process.

The process is carried out in a converter somewhat similar in shape and construction to the Bessemer converter. However, in this process the inside surfaces of the vessel are lined with basic refractory materials and the bottom surface is solid and does not contain tuyeres.

The basic oxygen converter is tilted to a horizontal position for charging. Solid scrap is usually charged first and makes up about 25 to 30 percent of the charge. Molten pig iron is added after the scrap, along with some roll scale and lime. After charging the converter is rotated to a vertical position and a water-cooled oxygen lance is lowered into position above the charge. High purity oxygen (98%) under 100 to 150 psi pressure is blown onto the surface of the charge. The charge is refined by the resulting oxidation reactions. The difference in density of refined and unrefined metal, and the evolution and boiling off of carbon monoxide gas, produce a violent agitation and circulation of the bath which brings fresh metal into contact with the oxygen, thereby accelerating the refining process.

Completion of the process is indicated by a change in the flame at the mouth of the converter. When the process is completed the oxygen lance is withdrawn and the converter is rotated to a horizontal position where the slag is skimmed off. The converter is then rotated in the opposite direction and the steel is poured into a large ladle.

e. ***Electric arc processes.*** Steel can be made in electric arc furnaces by either acid or basic processes. However, the basic process is generally used to produce electric arc steels that are converted into wrought products. Therefore, this discussion is restricted to the basic electric arc processes.

Two types of electric arc furnaces have been developed, the direct-arc type and the indirect arc type. Of the two, the direct-arc furnace is the more common.

The carbon or graphite electrodes of the indirect-arc furnace are located above the charge and are positioned in-line with a gap between them. The arc is struck between the electrodes and the charge is heated by radiation.

The modern direct-arc furnace employs a different principle. Three electrodes are used, each connected to a single phase of a three phase current. The electrodes are held in the vertical position by external supporting structure and pass through openings in the furnace roof. Heat is generated by arcs that are struck between the electrodes and the charge.

Direct arc furnaces are versatile units with definite advantages as compared to the other types of furnaces discussed previously. The advantages include:

(1) Fuel burning furnaces require an oxidizing atmosphere to support combustion of the fuel, but in an electric arc furnace a neutral or reducing atmosphere can be developed and maintained.

(2) The heat generated by the electric arc is pure heat. Neither liquid nor gaseous fuels are burned in the furnace, consequently, the hazard of contaminating the bath with impurities normally contained in a liquid or gaseous fuel is eliminated.

(3) Very high temperatures can be attained in electric arc furnaces and temperatures can be accurately controlled.

(4) Refining and alloying can be controlled to meet exacting requirements. By comparison with other processes the operating costs of electric arc furnaces are relatively high. In the strict sense, the electric arc processes do not compete with other processes, being used primarily to produce clean, high quality steels, generally, tool steels, stainless steels, and the like.

A direct arc furnace is usually charged with carefully selected steel scrap of known composition. To assure an excess of carbon in the charge, coke, anthracite coal, broken electrodes or other forms of carbon are usually added to the scrap. Ore, limestone, and alloying elements may be included in the initial charge or they can be added later after the metal charge has melted.

After the charge is laid in the hearth the electrodes are lowered into position and arcs are struck between the electrodes and the charge. As melting progresses silicon, manganese, and phosphorus begin to oxidize and, with the lime, form a slag. As the oxidation reactions continue the temperature of the bath is increased to about 2900°F to promote oxidation of the carbon and also to increase the fluidity of the bath. With increased fluidity, solid inclusions rise to the slag and are retained there.

The initial oxidizing slag is made up of lime, silica and iron oxides. When the bath is sufficiently refined by the oxidation reactions, the oxidizing slag is removed and a reducing slag is built by adding fluorspar, lime and carbon to form calcium carbide. The carbide slag reacts with the oxides of iron, manganese, vanadium, chromium, and tungsten, that are in the slag, reducing them, thus returning the metals to the steel. The basic slag also reduces oxides in the steel, and converts sulfur to calcium sulfide (CaS) which is retained in the slag. During this period, any necessary alloy additions are made and when analyses indicate that the desired composition has been achieved a final deoxidizer is added, the temperature is raised to about 3000°F, and the steel is tapped into a ladle.

Vacuum arc melting is a process for refining and improving steel. In this process, the steel is first melted in an electric arc furnace to produce a special ingot suitable for remelting. This ingot, when properly processed, then serves as an electrode in a vacuum arc furnace. The furnace is placed under a vacuum, an electric current is applied, and the electrode melts under heat of the electric arc into a copper crucible. Metal turbulence caused by the electric arc, and the high rate of heat transfer through the water cooled walls of the copper crucible, make possible a sound ingot structure.

Vacuum arc melting effectively lowers oxygen, nitrogen, and hydrogen, and nonmetallic inclusions carried over from the first melting can be significantly reduced in the vacuum remelt. Steels produced by this method are generally more uniform and finer grained in structure and have better mechanical, chemical, and physical properties than those obtained by conventional air melt processes. Equipment, processing, and process controls are, however, generally more complex, stringent, and costly than conventional steel making processes. Vacuum arc process steels are premium quality grades used for specialized applications such as for aircraft applications.

9. Ingot and Deoxidizing Practices. The preceding process descriptions stopped at the point where the steel was tapped into a ladle. At this point the steel is ready to be poured into ingot molds. Ingot and deoxidizing practices are the next subjects discussed.

a. Ingots. Ingots are produced in a variety of types, sizes, and shapes depending upon the wrought product to be manufactured. The cross sectional shape of an ingot may be square, rectangular, slab, round or polygonal, any functional shape that fits the ingot to the final wrought product and provides for economical processing. Ingot mold cavities are usually tapered from one end to the other so that the ingot is either smaller or larger at the top than at the bottom. The taper, or draft, allows the mold to be stripped from the casting. Depending upon the direction of the taper, molds are classed as either big-end-up or big-end-down type molds.

Like most metals, steel contracts during solidification, thus, the volume of the solid is less than that of the liquid from which it forms. When molten steel is poured into an ingot mold the metal in contact with the mold surface freezes almost immediately, establishing the outside surface of the ingot. With the extremeties of the casting established by the solidified skin, it is apparent, since solidification progresses from the outside surfaces inward, that the difference in volume between the liquid and solid steel must produce some effect. If the difference in volume is not compensated for in some other way, a cavity forms in the section of the casting that freezes last. The last portion to solidify is usually the upper central portion of the ingot and the cavity that forms there is called a pipe. This effect is shown schematically in Figure 2. The only way to eliminate the pipe is to crop (cut off) the end of the ingot.

The pipe can be confined or concentrated at the top of the ingot by regulating the solidification of the casting. Big-end-up molds promote progressive solidification of the casting from the bottom upward. When a refractory lined collar, or hot top, is added to the mold a portion of the molten steel is insulated and a reservoir of molten metal is provided to feed the ingot as it solidifies, thus compensating for the contraction that occurs. In this manner the pipe can be confined to the hot top portion of the ingot.

Hot tops can, and are, used effectively both with big-end-up and with big-end-down type molds to minimize the portion of each ingot that must be cropped.

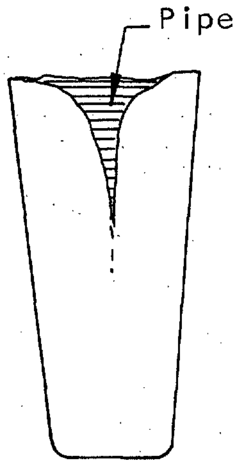


FIGURE 2. Pipe in an Ingot

b. Deoxidation practices

(1) General. Molten steel usually contains oxygen in the form of iron oxide, and as a dissolved gas. If the steel is not deoxidized before it is cast, the oxygen reacts with carbon to form a gas (CO) which evolves during solidification of the steel. The amount of gas evolved during solidification can be controlled effectively by various deoxidation practices. Deoxidizers can be added to the steel in the furnace, in the ladle, in the mold, or by a combination of these methods, to effect complete or partial deoxidation of the steel, as desired. Common deoxidizers are ferromanganese, ferrosilicon and aluminum.

Three types of steel, classified according to deoxidation, are: killed steel, semikilled steel, and rimmed steel.

(2) Killed Steel. Killed steels are those that have been so thoroughly deoxidized that they lie quietly in the mold because little or no gas is evolved. Killed steels are usually cast in big-end-up hot top molds. Generally killed steels are used when a sound, homogeneous structure is required. Alloy steels, carburizing steels, steels for forgings, are typical applications for killed steel.

(3) Semikilled Steel. Semikilled steel is not as thoroughly deoxidized as killed steel. Some oxygen is present to react with the carbon to form CO when the steel is poured into the ingot molds. Steel of this type generally contains more blow-holes and inclusions than killed steel. Semikilled steel is used extensively for heavy structural shapes and plate.

(4) Rimmed Steel. A relatively small amount of deoxidant is added to rimmed steel and a considerable amount of gas evolves and rises to the surface as the steel solidifies. An ingot of rimmed steel has an outside skin of low carbon content steel, an intermediate zone which contains blow-holes of various sizes, and a core of metal rich in carbon, sulfur and phosphorus. Rimmed steel has a good surface finish and a high degree of ductility which makes it useful for thin sheet, wire, tinplate and similar products.

(5) Capped Steel. Capped steel practice is a variation of rimmed practice. The steel is poured into big-end-down molds with a constricted top (bottle top) to facilitate capping. The rimming action is allowed to begin but is terminated after a short time by sealing the mold with a steel or cast iron cap. An addition of aluminum or ferrosilicon to the top of the top surface of the molten steel has the same effect as capping and is sometimes used in place of a cap. The product is an ingot with a thin skin or rim which is relatively free of blow-holes and with less segregation than rimmed steels. Steel of this type is used to make sheet, strip, tin plate and bars.

FERROUS METALLURGY

10. The Structure of Metals. Metallic materials, together with the other substances in our world, can be divided into three basic classifications: elements, compounds, and mixtures.

a. Elements. Elements are substances that cannot be broken down into simpler substances by ordinary chemical methods. For example, iron, carbon, manganese, sulfur and phosphorus are included among the more than 100 elements discovered to date.

b. ***Compound.*** A compound is a substance produced by a chemical reaction between two or more elements. The constituents of a compound unite in definite fixed proportion by weight. The properties of a compound differ from those of its component elements. Compounds, unlike elements, can be decomposed by chemical reactions into simpler substances, that is, into elements, and/or other compounds. Iron carbide (Fe_3C), also known as cementite, is a compound.

c. ***Mixtures.*** Mixtures are produced by the intermingling of elements, compounds, or both. The composition of a mixture is not governed by the law of definite proportions, as are compounds, and the components of a mixture may be intermingled in various proportions. The constituents of a mixture can be separated by purely physical means and each component in a mixture retains its own properties. An often cited example, air, is a gaseous mixture of nitrogen, oxygen, argon, carbon dioxide, water vapor and other gases.

d. ***Solutions.*** Solutions are a specific kind of mixture in which the components are so completely miscible as to be indistinguishable under the optical microscope.

Elements, the fundamental substances from which other substances are made, are, in turn, composed of atoms. It is convenient to visualize an atom as a miniature solar system composed of a nucleus surrounded by electrons which revolve in what may be considered as concentric orbital shells located at discrete distances from the nucleus. The electrons are small particles of unit negative charge. The nucleus is composed of protons and neutrons. Protons are small particles with an equal but opposite charge to that of an electron, that is, they bear a unit positive charge. Neutrons are small electrically neutral particles. The mass of a proton is 1836 times that of an electron, while the mass of a neutron is 1839 times that of an electron.

Atoms are essentially electrically neutral, possessing equal numbers of protons and electrons. The number of protons in the nucleus of an atom is unique for each element and is called the atomic number of the element. Of course the number of electrons possessed by an atom is also equal to the atomic number.

The electrons surrounding the nucleus of an atom are grouped in specific and distinct energy levels commonly described as orbital shells. Progressing away from the nucleus, each additional shell may contain successively more electrons. The first shell may contain two electrons: the second, eight electrons; the third, eighteen electrons; and so forth. The outermost shell of electrons is known as the valency group. The properties of the elements are strongly related to electrons in this group, which are known as valence electrons. When the outer shell is completely filled the atom is very stable and does not combine with other atoms. Some of the inert gases are examples; helium, atomic number 2, has one electron shell filled with two electrons, and neon, atomic number 10, has two complete shells of two and eight electrons respectively. Provisional stability is achieved when the third and higher shells contain eight electrons. For example, argon, atomic number 18, has three electron shells, the first two are complete with two and eight electrons respectively, while the third shell, although incomplete, contains the stable number of eight electrons. Argon is also included among the inert gases.

The ability of atoms to combine with like atoms to form crystals or with other atoms to conform compounds is governed by the valence electrons. Metals typically have positive valence, that is, their atoms tend to give up electrons in chemical reactions leaving them with more protons than electrons. In this state, the atoms possess a positive charge and are called positive ions. Non-metals tend to accept electrons and form negative ions.

Ionic compounds are formed between strongly metallic and strongly non-metallic elements. Electrons are transferred from the metal atoms to the non-metal atoms, forming positively and negatively charged ions. The electrostatic forces acting between the oppositely charged ions bond the ions together as a molecule of the new compound.

Solid metals, under ordinary circumstances, are crystalline materials. By definition, a crystal consists of atoms arranged in a pattern that

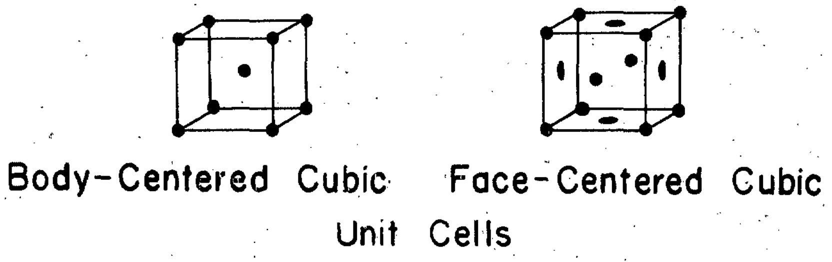


FIGURE 3. Unit Cells of the Body-Centered Cubic and the Face-Centered Cubic Crystal Structures

repeats periodically in three dimensions. The space-lattice is a useful and convenient concept for describing the geometric arrangement of atoms within a crystal. A space-lattice is a geometric construction depicting the three dimensional arrangement of atoms in space for a specific crystal structure. Therefore, a space-lattice consists of points in space, not lines or planes, and the lattice is understood to extend indefinitely in space in a regular arrangement within which each point has identical surroundings. In practice it is often inconvenient to use a point lattice, consequently it is common practice to connect the points by straight lines to form an equivalent line lattice. Also, it is often more convenient to describe a space-lattice in terms of a unit cell, which is the smallest group of points which, when repeated in all directions, will develop the space-lattice.

Most metals solidify in one of three crystal structures; the body-centered cubic; the face-centered cubic, or the close-packed hexagonal. The crystal structure of iron is body-centered cubic at temperature below 1697°F. Between 1697°F and 2535°F it is face-centered cubic and from 2535°F to the melting point, 2795°F, it is body-centered cubic again. The ability of a substance to exist in more than one crystal structure is known as polymorphism and the change from one structure to another is referred to as a polymorphic transformation. The unit cells of the body-centered cubic and the face-centered cubic structures are illustrated in Figure 3.

When a solid metal is heated sufficiently it melts and becomes liquid. If heating is continued the liquid metal eventually boils and is transformed to a vapor. To effect these changes in physical state a considerable amount of thermal energy must be supplied to the metal, which in turn, manifests itself as increased potential and kinetic energy of the metallic atoms. The vapor state is the highest energy state of the three states in which a metal can exist. In the vapor state, the kinetic energy of individual atoms is so great that their gravitational and chemical attraction for each other is overcome. Their movement is a rapid, random, independent vibration, restricted only by the container and collisions with other atoms. Obviously. the arrangement of atoms in a gas is unordered and continuously changing.

As a gas is cooled it loses thermal energy and the average kinetic energy of the metal atoms diminishes. As cooling continues the vapor condenses into a liquid. In the liquid phase the atoms are still capable of a relatively free and independent motion, although such motion is much more restricted than in the vapor phase. Continued cooling of the liquid, of course, further reduces the kinetic energy of the atoms. At the freezing point, the mutual attraction of some neighboring atoms prevails over their kinetic energies and small groups of atoms form at random within the mass of liquid. The atoms in these groups align in the definite ordered geometrical arrangement characteristic of the metal's crystal structure. Some of these groups become relatively stable and serve as crystal nuclei to which other atoms are attracted and become attached. The atoms continue to align in the definite geometric arrangement of the metal's crystal structure as the nuclei grow in three crystallographic directions. Because of the random orientation and distribution of the nuclei the crystals develop rather freely in the liquid during the initial phase of solidification. Inevitably, however, individual adjacent crystals approach each other and further growth is impaired by mutual interference. As a result of the mutual interference on every side, the crystals form geometrically irregular external surfaces. The irregularly shaped crystals thus formed are commonly referred to as grains. Because the crystals nucleate and grow in different orientation, the surface atoms of adjacent grains are mismatched and grain boundaries are formed by the distorted layers of atoms between normal grains. Each grain boundary atom, as a result of the distortion, exists in a higher-energy state than that which is typical for the atoms within the grains. Grain boundaries then, are regions of abnormally high free energy, a condition that significantly affects the mechanical, physical, and chemical characteristics of a metal. First, the less densely packed arrangement along the grain boundaries furnishes a path for more rapid transfer of atoms than do the aligned atoms within the grains. Second, because they exist at higher energy levels, grain boundary atoms tend to react more readily with corrosive media than the normal atom within the grains. Third, foreign or impurity atoms tend to concentrate at grain boundaries where they can be fitted in more readily. Fourth, nucleation, for precipitation and eutectoid reactions involving the formation of one or more new phases, occurs at grain boundaries. Fifth, below the recrystallization temperature grain boundaries are stronger than the matrix crystals, while above the recrystallization temperature the relative strengths of the grain boundaries and the matrix crystals are reversed.

The metals are elements that possess, to some degree, particular properties that are referred to as metallic properties. One particular characteristic of metals, already discussed, is the type of atomic bond which they form. The bond of course is the metallic bond in which the atoms in the metal share electrons. The electrons are relatively free to move from atom to atom and form what is commonly referred to as an electron cloud or gas. Metals also possess metallic luster. They are opaque, generally are good conductors of heat and electricity, and are, to some extent, malleable and ductile.

While metals are elements possessed of metallic properties, there are other substances that also possess metallic properties. These substances, which are combinations of two or more elements, are called metallic alloys, or more commonly, alloys. At least one of the components of any alloy is a metal. The importance of alloys is indicated by the fact that the majority of the metallic materials used in structural applications today are alloys rather than metals.

Elements can combine either as compounds, or as mixtures. Compounds, as previously discussed, are formed when atoms of the reacting elements unite in a definite ratio by weight. Compounds are identified by chemical formulas, for example: water, H_2O; iron-carbide, Fe_3C. Mixtures, however, are combinations of elements that are not governed by the law of fixed proportions. In mixtures the component elements may be intermingled in any desired proportion. It was previously noted that solutions are mixtures. Liquid solutions are commonplace and everyone is quite familiar with them. Brine, a solution of salt in water is a common example. In true solutions, single atoms or molecules of one substance are uniformly dispersed throughout another in such a manner that the identity of the dispersed substance is lost. Sugar, for example, will dissolve in water, but the solution will remain clear. The combination of sugar and water becomes a single-phase liquid which is homogeneous within the limits of observation. A true solution is a uniform mixture of a solute (the dissolved substance) and a solvent (the substance in which the solute dissolves).

Solutions are not restricted to liquids; solid solutions form in a manner similar to liquid solutions. Brass, for example is a solid solution of zinc atoms dissolved in copper. When zinc is added to copper to form brass, zinc atoms substitute for some of the copper atoms in the crystal structure. This type of solid solution is called a substitutional solid solution.

Another form of solid solution is the interstitial solid solution. In this type of solution the solute atoms do not replace the solvent atoms but rather occupy positions between the normal positions of the solvent atoms, that is, at the interstices. The solution of carbon in iron is an example of this type of solution.

In any alloy, when the components are completely soluble in the liquid state, the solubility

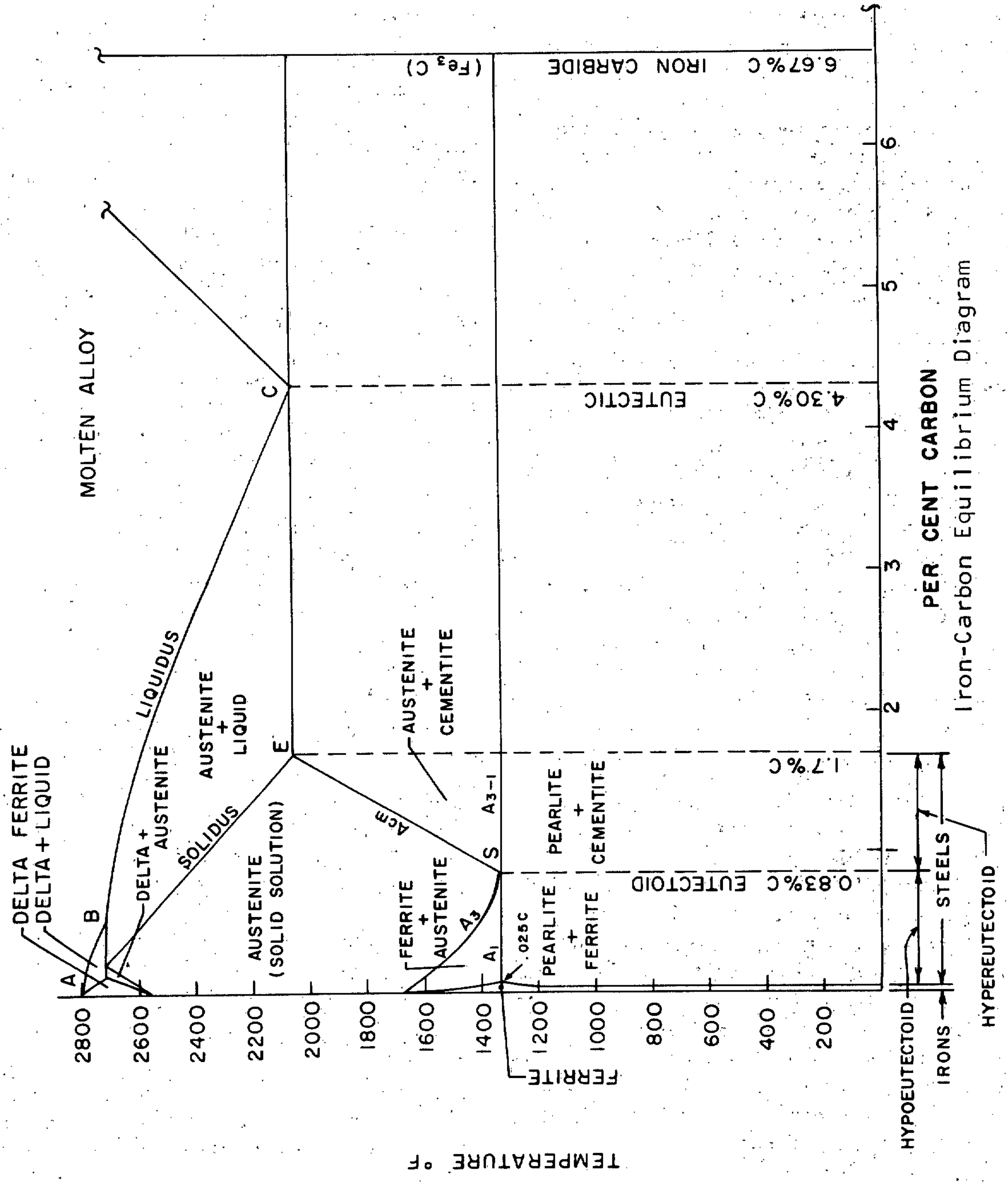


FIGURE 4. Equilibrium Diagram-Iron-Carbon System

may or may not change upon solidification. When complete solubility persists in the solid state, the alloy will consist of one phase, a solid solution. If, however, the solubility of the components in the solid state is negligible, they may form more than one phase upon solidification. A phase is generally defined as a microscopically homogeneous body of matter; as related to alloys, a phase may be considered as a structurally homogeneous and physically distinct portion of the alloy system. For example, when an alloy solidifies, or freezes, the phases formed may be a chemical compound and a solid solution, or two solid solutions. Before the alloy solidifies completely, a solid solution may exist in equilibrium with a liquid. In each of these examples, two phases of the alloy are involved.

II. The Iron-Carbon System. Equilibrium diagrams are graphs or maps of the temperature and composition boundaries of the phase fields that exist in an alloy system under conditions of complete equilibrium.

The equilibrium diagram of the iron-carbon system, from 0 percent to 7 percent carbon by weight, is shown in Figure 4. This is the only portion of the system pertinent to steels. Extensive reference will be made to the diagram in the following discussion.

Pure iron is polymorphic, that is, it exists in more than one crystal structure. In the case of pure iron the crystal structure changes with temperature. The crystal structure of pure iron is body-centered cubic up to 1670°F. This polymorphic form of iron is called alpha-iron. From 1670°F to 2535°F, the stable crystal structure of pure iron is face-centered cubic, designated as gamma-iron. Above 2535°F iron again has a body-centered cubic crystal structure and is known as delta-iron. This form is stable up to the melting temperature 2795°F. These points are identified on the equilibrium diagram along the zero percent carbon ordinate.

The polymorphic transformations of iron account for the very great importance of steel as a structural material. Gamma-iron is capable of dissolving, in solid solution, approximately forty times more carbon than alpha-iron. This fact, as will be developed later, is of considerable industrial importance.

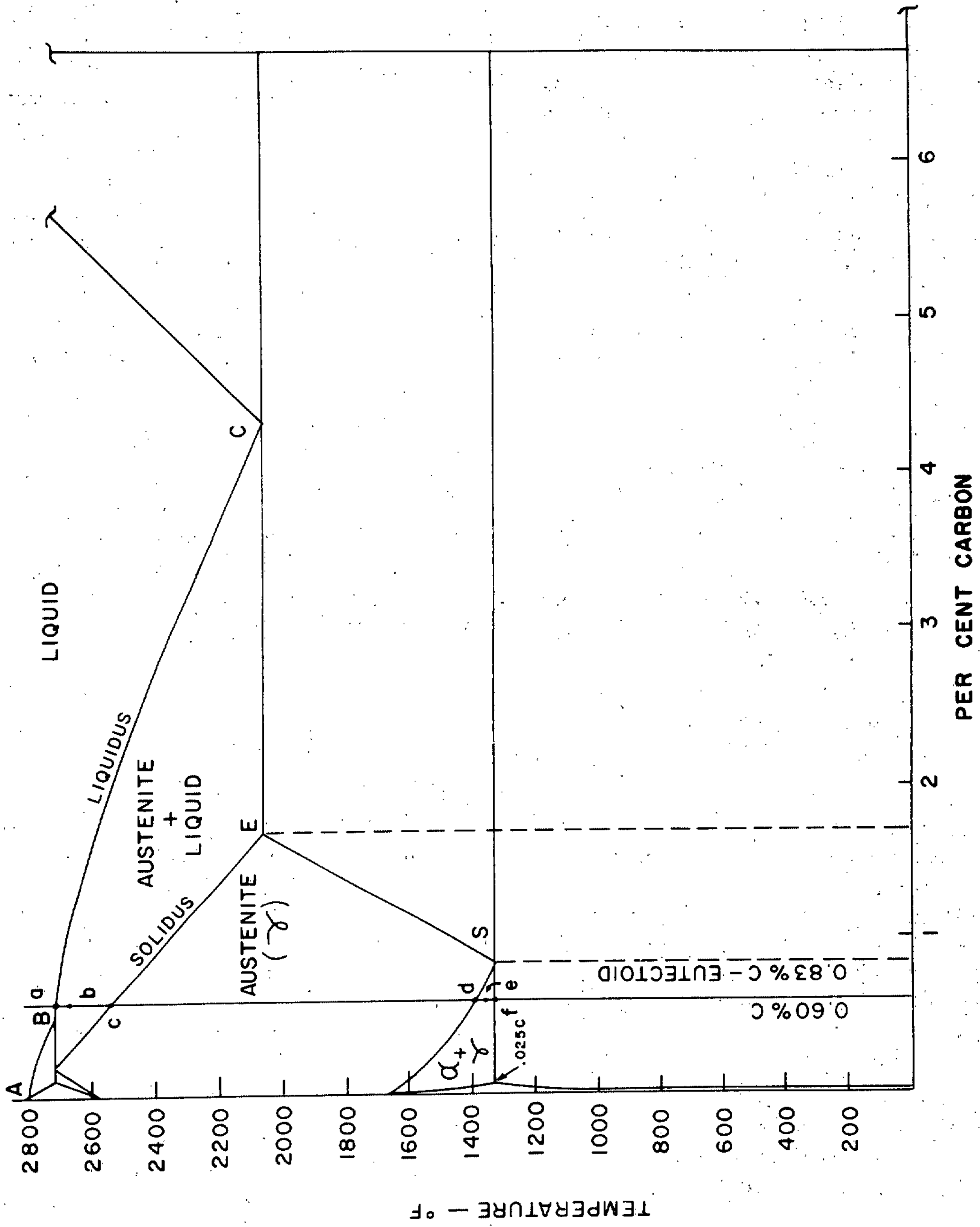
Carbon is soluble, to some extent, in all three of the polymorphic forms of iron. The extent of these solid solution phase fields are indicated in Figure 4. The solid solution of carbon in alpha-iron is known as ferrite or alpha-ferrite. The maximum solubility of carbon in alpha-iron is 0.025 percent by weight at 1333 °F.

Austenite is the name applied to the solid solution of carbon in gamma-iron. Gamma-iron can dissolve a maximum of 2.0 percent carbon, and this at a temperature of 2065°F. The solid solution of carbon in delta-iron is called delta-ferrite or delta solid solution (ΔSS). The maximum solubility of carbon in delta-iron is 0.10 percent at 2715°F.

In addition to the solid solutions just described, carbon and iron form a hard, brittle intermetallic compound, iron carbide (Fe_3C), which is commonly referred to as cementite. In steels, under equilibrium conditions, carbon occurs as iron carbide rather than as free carbon. For that reason the equilibrium diagram of the iron-rich portions of the iron-carbon system is often called the iron-iron carbide equilibrium diagram.

Two points of particular interest and importance in equilibrium diagrams are points C and S, Figure 4. C is the eutectic point and S is the euctectoid point. The eutectic reaction is an isothermal reaction in which a liquid solution is converted into two or more intimately mixed solids on cooling. The number of solids formed is the same as the number of components in the solution. A eutectic is defined as an intimate mechanical mixture of two or more phases having a definite melting point and a definite composition.

A eutectoid reaction is an isothermal reversible reaction in which a solid solution is converted into two or more intimately mixed solids on cooling. The number of solids formed is the same as the number of components in the solution. Therefore, a eutectoid is a mechanical mixture of two or more phases having a definite composition and a definite temperature of transformation within the solid state.



Iron-Carbon Equilibrium Diagram

FIGURE 5. Equilibrium Diagram-Iron-Carbon System

In the iron-carbon system the eutectic is a mixture of austenite and iron carbide. The iron-carbon eutectic contains 4.3 percent carbon by weight and forms at 2065°F when the liquid solution is cooled under equilibrium conditions. It should be noted that the eutectic composition has the lowest melting temperature of any alloy in the iron-iron carbide system. As carbon content is decreased in the system, the melting point increases along line C-B-A, Figure 4.

The eutectoid of the iron-carbon system contains 0.83 percent carbon by weight. The eutectoid, which forms at 1333 °F is a mixture of ferrite and cementite, called pearlite. As indicated in Figure 4, steels containing more than 0.83 percent carbon are hypereutectoid steels, and steels with less than 0.83 percent carbon are hypoeutectoid steels.

The temperatures at which the solid state transformations take place are called critical temperatures or critical points. The loci of these critical points, which establish the boundaries of the phase fields, are identified at A_1, A_3, A_{cm}, and A_{3-1}, in Figure 4. Note that the 1333°F isotherm located at the left of the eutectoid point is designated as A_1, while to the right of the eutectoid point it is identified as A_{3-1}.

Another interesting reaction is indicated on the equilibrium diagram at 2700°F to 2800°F and from 0 to 0.5 percent carbon. The reaction is a peritectic reaction, which is essentially an inversion of a eutectic reaction. In the latter, there is a transformation of one phase to two on cooling. In a pertectic reaction two phases convert to one on cooling.

The iron-carbon equilibrium diagram and other two-component system diagrams are called binary diagrams. Interpretation of these diagrams is not difficult, as shown by the following example.

The first step in using a binary diagram is to identify the alloy of interest. For this example consider an alloy containing 0.60 percent carbon and 99.40 percent iron. After the alloy has been selected a vertical line is drawn through the diagram at the selected composition. In this example the line starts at the 0.60 percent carbon point on the abscissa, as shown in Figure 4. Now, assume that the alloy is heated to 2800°F and held at that temperature until the system is in equilibrium. From this temperature the alloy will be slowly cooled, under equilibrium conditions, to room temperature.

At 2800°F the alloy is a liquid solution of 0.60 percent carbon and 99.40 percent iron. Crystals of austenite begin to form in the liquid when the temperature of the alloy reaches the point where the constant composition line intersects the liquidus curve, A-B-C, at point "a", Figure 5. By drawing an isotherm through point "a" and noting where it intersects the solidus curve, the composition of the first austenite crystals to form can be determined. In this instance the first austenite crystals will contain about 0.20 percent carbon. Now, assume that the alloy has cooled to the temperature at point "b", 2650°F. Another isotherm drawn through point "b" intersects the solidus at the 0.30 percent carbon ordinate, which indicates that the austenite formed at 2650°F will contain 0.30 percent carbon. The isotherm through "b" intersects the liquidus at the 1.20 percent carbon ordinate, so that liquid at 2650°F contains 1.20 percent carbon. Next consider the isotherm between the 0.30 carbon ordinate and the 1.20 carbon ordinate to be a lever with its fulcrum at the 0.60 carbon ordinate. For simplification the fulcrum and terminal points of the lever will be identified as x, y and z, as shown in Figure 6.

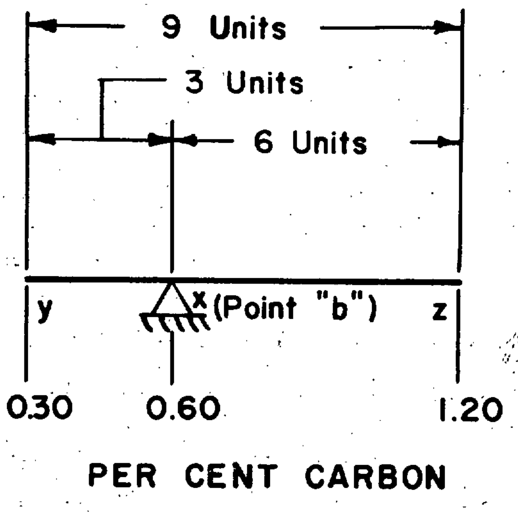


FIGURE 6. Lever Diagram

At 2650°F the fraction of the total mass of the alloy that, under equilibrium conditions, is solid austenite is given by the relation $\frac{xz}{yx}=\frac{6}{9}=\frac{2}{3}$. The fraction of the total mass that is liquid is given by $\frac{xy}{yz}=\frac{3}{9}=\frac{1}{3}$. These fractions can be converted to percentages by multiplying them by 100. The rule employed to find the relative amounts of the two phases present at a temperature of interest is known as the lever principle. The lever principle can be applied anywhere in the equilibrium diagram where two phases exist.

When the alloy has cooled to point "c", Figure 5, the entire mass is solid austenite crystals. Figure 5 shows that this phase exists, for the composition under study, from the temperature at point "c" to the temperature at point "d". Austenite, it will be recalled, is a solid solution of carbon in gamma-iron. For the composition under study, the austenite contains 0.60 percent carbon.

When the alloy is cooled to point "d", ferrite begins to form. By drawing an isotherm through point "d" and noting where it intersects the boundary line at the left side of the phase field, the composition of the ferrite can be determined. In this case it consists of 0.02 percent carbon and 99.98 percent iron.

When the alloy has cooled to point "e" (1350°F), Figure 5, by applying the lever principle, the relative amounts of each phase that exist at 1350°F can be determined as follows: The isotherm is drawn and the fulcrum and terminal points are labeled as shown in Figure 7. Then the left-hand end point, "m", is on the 0.02 percent carbon ordinate: the fulcrum, "n" is on the 0.6 percent carbon ordinate: and the right-hand end point "q" is on the 0.70 percent carbon ordinate.

The percentage of ferrite in the total mass is $\frac{nq}{mq}=\frac{0.10}{0.68}$ x 100 = 14.7 percent. The percentage of austenite in the total mass is $\frac{mn}{mq}=\frac{0.58}{0.68}$ x 100=85.3 percent. The austenite contains 0.70 percent carbon and the ferrite 0.02 percent carbon.

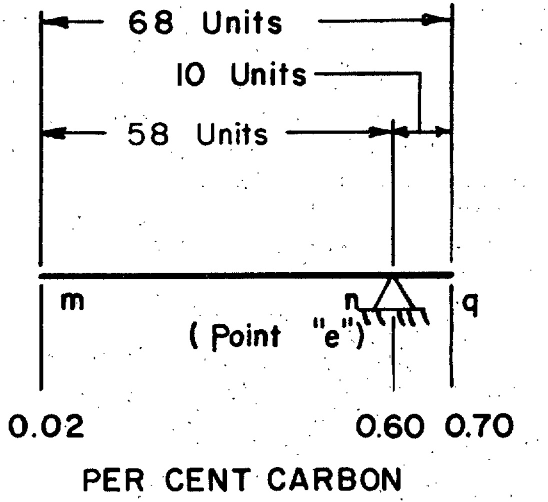


FIGURE 7. Lever Diagram

The composition of the alloy as it reaches point "f" is:

$$\text{Percent austenite} = \frac{0.60 - 0.025}{0.83 - 0.025} \times 100$$

$$= \frac{0.575}{0.805} \times 100 = 71.4 \text{ percent}$$

$$\text{Percent ferrite} = \frac{0.83 - 0.60}{0.83 - 0.025} \times 100$$

$$= \frac{0.23}{0.805} = 28.6 \text{ percent}$$

When the alloy reaches point "f" the remaining austenite (71.4 percent of the total mass) contains 0.83 percent carbon, the eutectoid composition. This austenite then transforms, isothermally, to the eutectoid, pearlite.

The ferrite that forms before the eutectoid reaction is called proeutectoid ferrite. As computed above, 28.6 percent of the total mass is proeutectoid ferrite. The remainder of the mass is now pearlite, which is a mixture of ferrite and cementite (iron carbide). The ferrite formed during the eutectoid reaction is known as eutectoid ferrite, and the cementite formed is called eutectoid cementite.

The percentages of eutectoid ferrite, and eutectoid cementite in the total mass can be found by applying the lever principle. Figure 8 illustrates the lever relationships of this calculation.

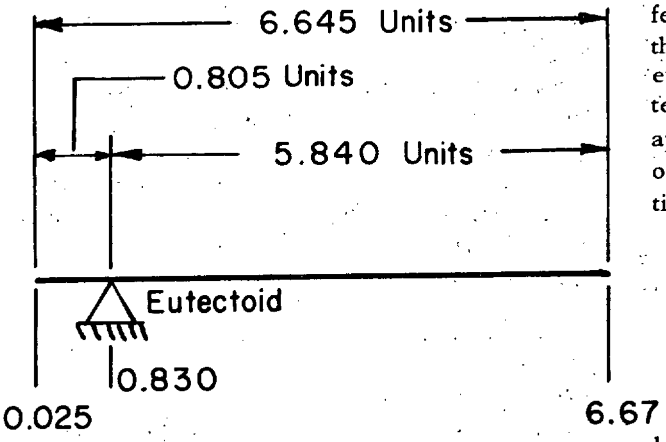


FIGURE 8. Lever Diagram

The lever for this reaction has its fulcrum on the 0.83 carbon ordinate and its terminal points on the 0.025 and 6.67 percent carbon ordinates. Then, the percentages of ferrite and cementite in the pearlite are:

$$\text{Percent ferrite} = \frac{5.84}{6.645} \times 100 = 87.9 \text{ percent}$$

$$\text{Percent cementite} = \frac{.805}{6.645} \times 100$$

$$= 12.1 \text{ percent}$$

Since 71.4 percent of the total mass is pearlite, the percent of eutectoid ferrite in the total mass is: 71.4 x .879 = 62.8 percent. The percent of eutectoid cementite in the total mass is: 71.4 x .121 = 8.6 percent. As shown by the foregoing calculations, the total amount of ferrite in the solidified steel is 28.6 percent + 62.8 percent = 91.4 percent. The total amount of cementite in the steel is 8.6 percent.

The preceding example demonstrates the reactions involved when a hypoeutectoid steel is cooled from above its melting point to below the A_1 temperature under equilibrium conditions. At room temperature the 0.60 percent carbon steel was found to consist of two phases, cementite (iron carbide, Fe_3C) and ferrite. The ferrite was observed to exist in two forms: as proeutectoid ferrite, which formed as the steel was cooled from the A_3 temperature to the A_1 temperature; and as eutectoid ferrite which combined with the eutectoid cementite to form eutectoid pearlite. By applying the lever principle, the relative amounts of the two phases in the solid steel were estimated to be:

Total ferrite = 91.4% (28.6% proeutectoid ferrite + 62.8% eutectoid ferrite).

Total cementite = 8.6%

Any alloy of the iron-iron carbide system can be analyzed in a similar manner. Actually, the lever diagram shown in Figure 8 and the associated calculations are the relationships and calculations which would be developed for the final transformation of an alloy of eutectoid composition (0.83 %C). As indicated, the eutectoid alloy would, after the final transformation, be composed entirely of the eutectoid, pearlite, consisting of 87.9 percent eutectoid ferrite and 12.1 percent eutectoid cementite.

Inspection of the equilibrium diagram Figure 4 indicates that any hypoeutectoid alloy will transform, under equilibrium cooling, in the same manner as the 0.60 percent carbon steel cited in the sample analysis. When these steels cool to the A_3 temperature ferrite begins to form from the austenite; as cooling continues, more ferrite forms and the austenite becomes increasingly rich in carbon. The composition of the austenite of course follows the A_3 curve so that when the temperature reaches 1333 °F the remaining austenite contains 0.83 percent carbon, the eutectoid composition. This austenite then transforms to the eutectoid, pearlite. Hypoeutectoid alloys, when solidified under equilibrium conditions, are composed of proeutectoid ferrite and the eutectoid, pearlite. The relative amount of each constituent in an alloy is determined by the amount of carbon in the alloy. It is evident from the equilibrium diagram that as the carbon content decreases the proeutectoid ferrite content of hypoeutectoid alloys increases, and the pearlite content decreases proportionately.

The hypereutectoid steels contain carbon in excess of 0.83 percent to 1.7 percent. These alloys, when cooled under equilibrium conditions, transform into proeutectoid cementite and pearlite. The proeutectoid cementite begins to form when the alloys are cooled to the A_{cm} temperature, which, as shown, varies with carbon content. With continued cooling the austenite rejects more and more carbon in the form of cementite so that as the temperature decreases the amount of proeutectoid cementite increases. The change in composition of the austenite with decreasing temperatures is indicated by the A_{cm} curve. When the temperature reaches 1333 °F the remaining austenite contains 0.83 percent carbon, the eutectoid composition, which transforms to the eutectoid, pearlite. As indicated in Figure 4, the proeutectoid cementite content of hypereutectoid alloys increases with increasing carbon content and the pearlite content decreases proportionately.

Equilibrium diagrams are maps of the transformations that occur in alloy systems under equilibrium conditions. As previously mentioned, the temperatures shown on an equilibrium diagram at which some transformation takes place are called critical temperatures or critical points. The loci of these critical temperatures are identified as the A_1, A_3, A_{3-1} and A_{cm} lines or curves. The letter A derives from the word arrest, since at these temperatures an arrest occurs in the heating or cooling curve. The temperature interval between the A_1 and A_3 critical points for a particular alloy is designated as the critical range. The A_3 is called the upper critical temperature and the A_1 is the lower critical temperature.

The rate at which an iron-carbon alloy is heated or cooled affects the critical temperature of the alloy. In practice, strict equilibrium conditions are not maintained during heating or cooling because equilibrium could be achieved only if the heating or cooling rate was extremely slow, or more accurately, infinitely slow. In commercial enterprises equilibrium rates are not practical. Heating at nonequilibrium rates tends to raise the critical temperatures, while cooling at nonequilibrium rates lowers the critical temperatures from the equilibrium critical temperatures. Generally the greater the rate of heating or cooling the greater is the deviation from the equilibrium critical temperatures. The critical points on heating are identified by the symbol Ac, for example, A_{c1}, A_{c3}, A_{c1-3}. The letter "c" derives from the French word for heating, "chauffage". The symbol A_r denotes critical points on cooling. Again the "r" derives from a French word, this time, "refroidissement" for cooling. When it is necessary to identify the critical points for equilibrium (e) conditions, the symbol Ae is occasionally used, as A_{e1}, A_{e3}, etc.

12. The Theory of Heat Treatment. The heat-treatment of steels is essentially a process of controlled departure from equilibrium heating and cooling. When a steel is cooled, under equilibrium cooling conditions, from above the A_3 critical temperature, the austenite remaining when the A_1 temperature is reached transforms to pearlite. With more rapid cooling, the faster the cooling rate the farther the transformation temperature (A_{r1}) is depressed below the A_{e1} temperature.

The eutectoid, pearlite, that forms when austenite is cooled below the A_{r1} temperature is a lamellar product made up of alternate plates of ferrite and cementite. The pearlite formed under equilibrium cooling is a coarse lamellar product. The process of transformation of pearlite from austenite involves diffusion of carbon and since the diffusion rate is a function of temperature, faster cooling rates with attendant lower transformation temperatures produces pearlite with a finer lamellar structure. A finer dispersion of phases tends to promote greater strength and hardness and to reduce the ductility of the steel. With very rapid cooling the austenite transformation occurs at a low temperature and the resulting structure is not pearlite but a structure known as martensite. Therefore, by controlling the cooling rate, the temperature of the austenite transformation, and hence, the structure and properties of the steel are controlled.

Isothermal Transformation Diagrams: The time-temperature relationships for austenite transformations are graphically presented in isothermal transformation diagrams, commonly referred to as

T-T-T curves, or more precisely, Time-Temperature-Transformation diagrams. T-T-T diagrams have been developed for various plain carbon and alloy steels. These diagrams are a plot of the times of the beginning and end of austenite transformations as a function of temperature.

The data that are required to plot a T-T-T diagram are developed through a series of isothermal transformation studies. The purpose of an isothermal transformation study is to determine the austenite transformation(s) that occur in a steel held at a constant temperature for increasing periods of time. To accomplish this objective small thin pieces of the steel under study are heated above the upper critical temperature and held at temperature long enough for homogeneous austenite for form. Each specimen, in turn is removed and quenched into a lead or salt bath which is held at the desired study temperature. Thin specimens are used so that cooling to the bath temperature can be assumed to be instantaneous. Each specimen is held in the isothermal bath for a different period of time, which may be seconds, minutes, or hours, and then quenched in brine or water to transform any remaining austenite to martensite. After the brine quench, the structure of each specimen is examined to determine what transformation product or products, if any, had formed during the isothermal cycle, and what percentage of the total structure had transformed into each product. A plot of these data is called an isothermal transformation curve. The data obtained from a series of isothermal studies are used to develop T-T-T diagrams in which the time for the beginning and ending of transformations are plotted as functions of temperature. The basic method is illustrated in Figure 9.

Isothermal transformation studies provide information on the transformation rates encountered at various temperatures and also the transformation products that form at the various temperatures. Depending upon the transformation temperatures, and the composition of the steel, austenite will transform into one or more of the following constituents: proeutectoid ferrite; proeutectoid cementite; pearlite; upper bainite; lower bainite; and martensite.

Figures 10 and 11 are the isothermal transformation diagrams for eutectoid steel and a hypoeutectoid steel, respectively. Generally, for carbon and low alloy steels, the temperature ranges over which austenite transforms into the various constituents, under isothermal cooling, are as indicated in Figure 10.

Referring to Figure 10, pearlitic microstructures are formed from about 1300°F to 1000°F. Pearlite, as previously discussed, is a constituent with a lamellar structure of alternating plates of ferrite and cementite. The lamellar structure formed at the higher transformation temperatures is relatively coarse but as the transformation temperatures decrease the lamellae become more closely spaced. When the transformation occurs at about 1000°F the lamellar structure is very fine and difficult to resolve with an optical microscope.

The transformation of austenite to pearlite is a process of nucleation and growth. In homogeneous austenite nucleation apparently occurs almost exclusively at the grain boundaries. When the austenite is not of uniform composition, but contains residual iron carbide particles and carbon concentration gradients, pearlite can nucleate within the grains as well as at the grain boundaries.

The generally accepted theory is that the pearlite nucleus is a small lamella of cementite which, assuming the austenite is homogeneous, forms at an austenite grain boundary. As the nucleus grows into the grain it absorbs carbon atoms from the surrounding austenite. When the carbon concentration of the surrounding austenite has been sufficiently reduced, ferrite nucleates and grows along the surface of the cementite plate. Because ferrite can dissolve only about 0.02 percent carbon, carbon atoms are rejected by the ferrite as it forms. As a result there is a build-up of carbon at the ferrite-austenite interface. The carbon-concentration continues to increase until the concentration level is sufficiently high and a new cementite nucleus forms. The sideways nucleation is repeated while, simultaneously, growth occurs at the edges of the ferrite and cementite plates. The alternating lamellae of cementite and ferrite originating from a single cementite nucleus is called a pearlite colony.

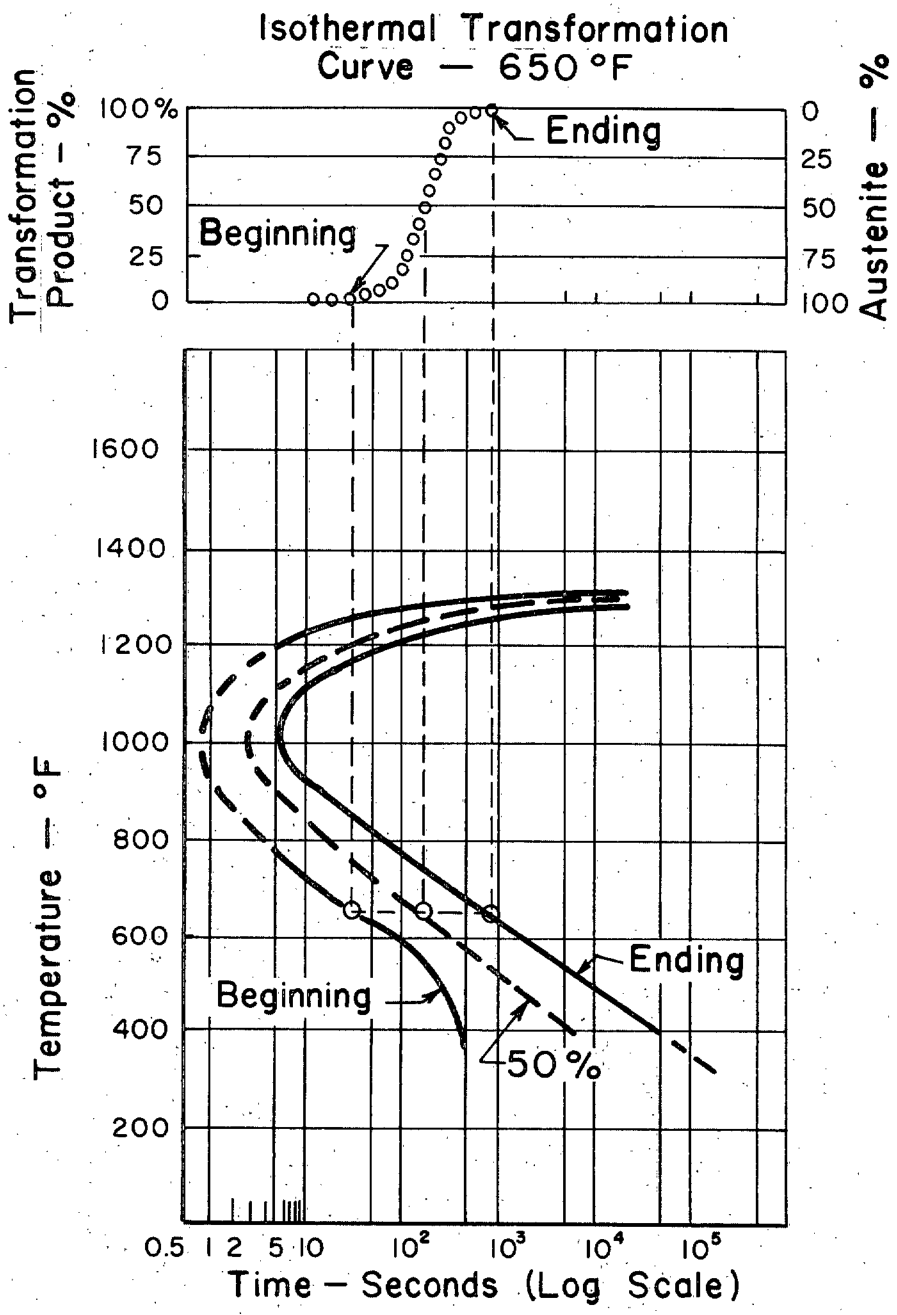


FIGURE 9. The Use of Transformation Curves to Develop Isothermal Transformation Diagrams

A = Austenite
F = Ferrite
C = Carbide (Fe_3C)
M_s = Martensite Start

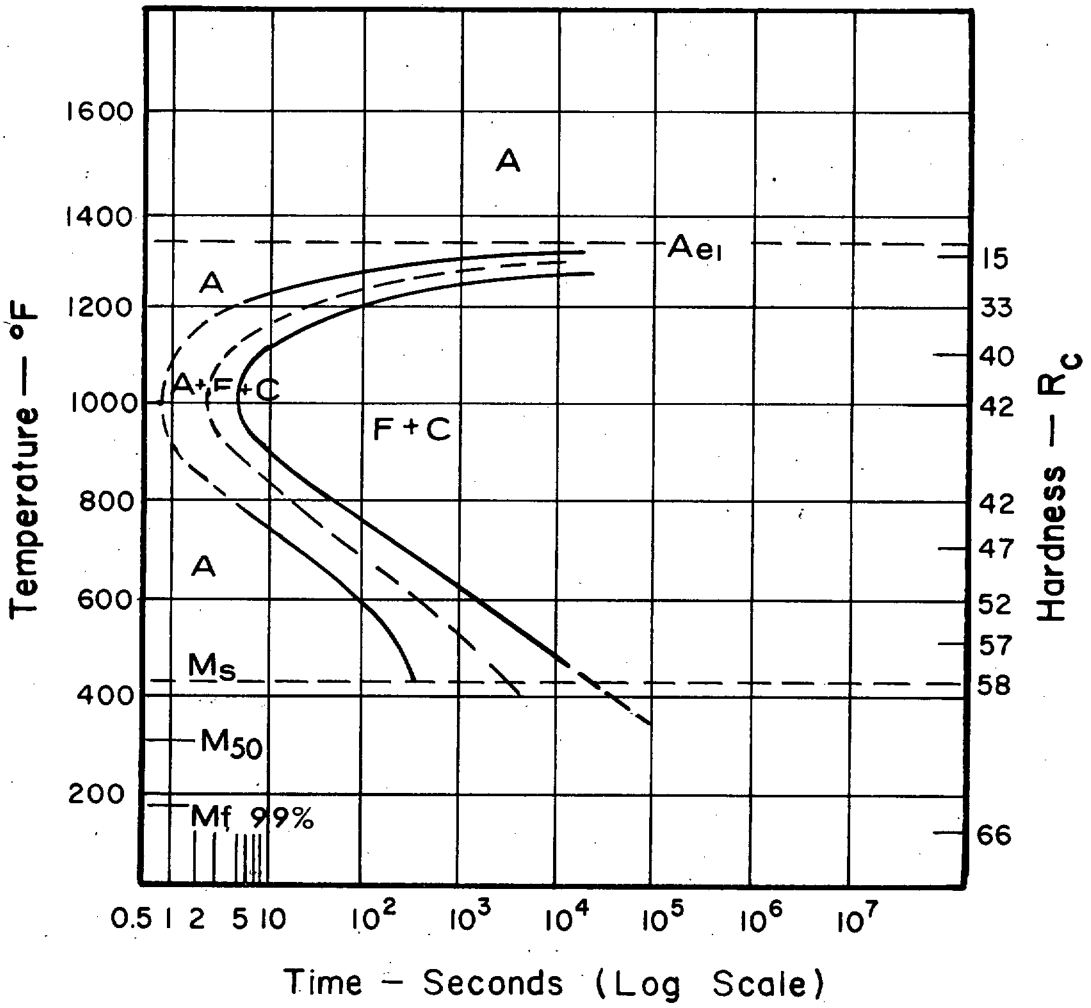


FIGURE 10. The Isothermal Transformation Diagram of an Eutectoid Carbon Steel

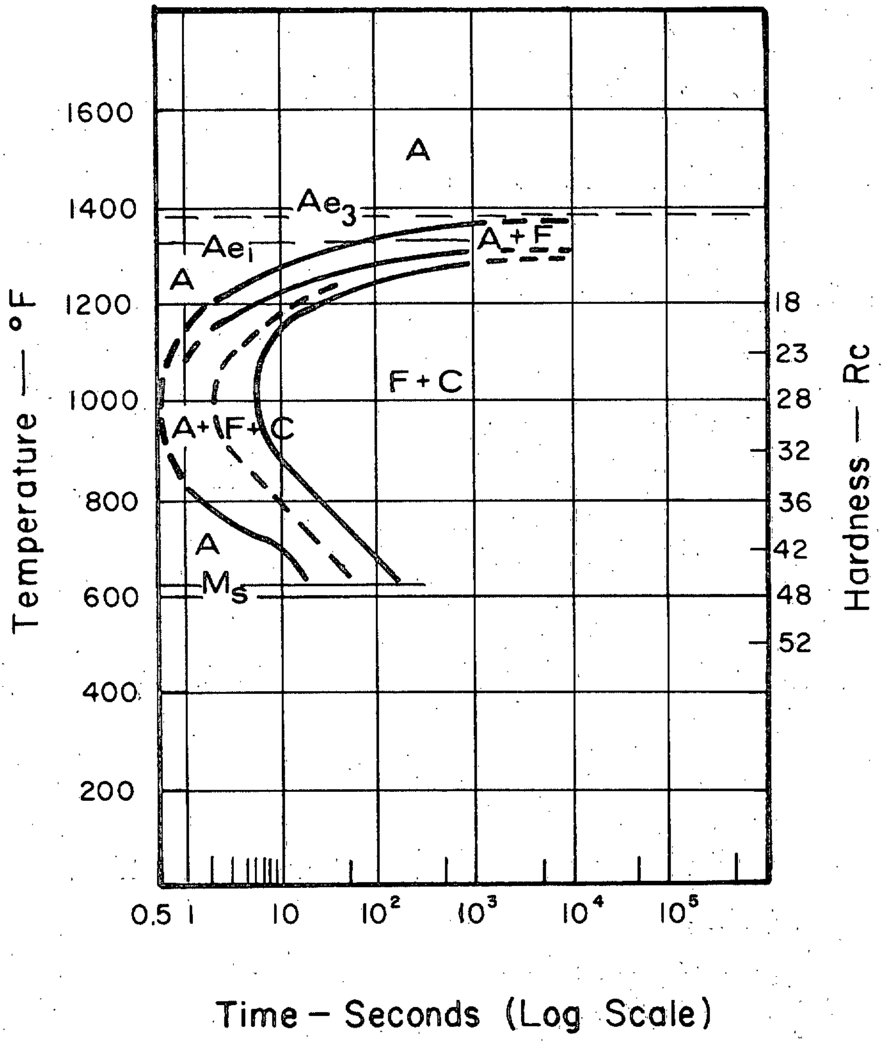


FIGURE 11. The Isothermal Transformation Diagram of a Hypoeutectoid Carbon Steel

With decreasing temperatures, from A_{e1} down to about 1100°F the rate of nucleation and the rate of growth of pearlite colonies both increase. As a result, at lower transformation temperatures the spacing the pearlite lamellae becomes smaller and the metal becomes harder. Pearlite formed just below the Ae_1 temperature, at about 1300° F, is coarse pearlite with a lamellar spacing in the order of 10^{-3} mm and a hardness of about Rockwell C-15. The pearlite formed at about 1100°F is fine pearlite with a spacing in the order of 10^{-4} mm and a hardness of about Rockwell C-40. The fine pearlites formed at the lower transformation temperatures besides being harder than the coarse pearlites formed at higher temperatures are tougher and more ductile.

At temperatures near the low end of the pearlite transformation range another constituent forms from austenite. In plain carbon steels this constituent is formed only by isothermal transformation treatments and does not form when the steel is cooled continuously from above the critical temperature. The new constituent, known as bainite, forms from about 1050°F down to about 400°F. Steels transformed in the range where the bainite and pearlite transformation temperatures overlap have structures containing both pearlite and bainite. As the isothermal transformation temperatures are lowered, bainite becomes the predominant constituent and pearlite disappears. Like pearlite, bainite is a mixture of ferrite and cementite but the two phases are not arranged in lamellar form as in a pearlitic structure. The transformation of austenite to bainite is also considered to involve a process of nucleation and growth accompanied by carbon diffusion. Bainite apparently grows from a ferrite nucleus into a plate-like structure with each plate composed of a ferrite matrix in which carbide particles are embedded. Bainite, when viewed as a metallographic section, has a characteristic acicular (needlelike) appearance. Bainite formed at the higher temperatures in the transformation range has a feathery appearance and is commonly referred to as upper-bainite. The bainite that forms at lower temperatures assumes a more pronounced acicular structure identified as lower bainite.

As with pearlite, the hardness and toughness of bainite both increase as the temperature of transformation is lowered. Pearlite is usually tougher than upper-bainite of similar hardness, while lower bainite will compare favorably with tempered martensite on the basis of toughness.

The transformations of austenite to pearlite or bainite are time and temperature dependent. By contrast the transformation of austenite to martensite is an athermal transformation, which means that the reaction is dependent primarily upon temperature and is essentially independent of time. The martensite transformation then is considerably different than the pearlite and bainite transformations. In the latter transformations, as indicated in Figure 10, neither pearlite nor bainite forms immediately upon reaching an isothermal reaction temperature. An incubation period is required before the transformation begins and the steel must be held at temperature for a sufficient period of time for the reaction to be completed. By contrast, when austenite reaches the M_s (martensite start) temperature the austenite begins to transform to martensite instantly. Further, if the steel is held at that temperature the small amount of martensite that is formed instantly is all that will form. Until the steel is cooled to a still lower temperature, the transformation is arrested.

At some temperature below the M_s temperature the transformation of austenite to martensite will be essentially completed. This temperature is identified as the M_f (martensite finish) temperature. At temperatures between M_s and M_f fractional transformation will occur. It is possible to quench a steel to, say, the temperature at which 50 percent of the austenite will transform to martensite and then isothermally transform the remaining austenite to lower bainite.

The transformation of austenite to martensite does not involve the diffusion of carbon. The instantaneous transformation of a small volume of austenite to form a martensite needle involves a shear displacement of the iron atoms in the austenite crystal lattice. The martensite thus formed has a body-centered tetragonal crystal structure. In this form it is identified as alpha martensite. Alpha martensite consists of ferrite and carbon (C) or finely divided iron-carbide (Fe_3C) in a metastable (unstable) structure which is considered to be a transitional structure between the face-centered cubic structure of austenite and the body-centered cubic structure of ferrite. The instantaneous athermal transformation of austenite to martensite at relatively low temperature does not allow the carbon atoms to diffuse out of the lattice and they remain in solution in the highly stressed transition lattice. The tetragonal crystal structure of alpha martensite transforms to the body-centered cubic structure, beta martensite, upon slight heating or long standing. Essentially the trapped carbon escapes or is thrown out of the crystal lattice allowing the stressed lattice to shrink down to the body-centered cubic structure.

Alpha martensite has an acicular structure similar to lower bainite. It is the hardest and most brittle of the microstructures that can be obtained in a given steel. The hardness of alpha martensite is a function of carbon content, ranging from a theoretical maximum of Rc 65 in eutectoid alloys to Rc 40 or less in low carbon steels.

Alpha martensite is usually tempered to increase its ductility and toughness although these changes are usually accomplished at the expense of hardness and strength. In tempering, the steel is heated to some temperature below the critical temperatures and cooled at a suitable rate. The microstructure and mechanical properties of tempered steel depend upon the temperature and duration of the tempering cycle. The carbide particles agglomerate, become progressively larger, as the tempering temperature and time at temperature are increased. Usually an increase in temperature and/or the time at temperature results in a lowering of the hardness and strength of a steel while its ductility and toughness are increased.

To develop a martensitic structure a steel must be austenitized and then cooled at a rate sufficient to prevent the formation of ferrite, pearlite or bainite. Most steels must be cooled very rapidly if the formation of pearlite is to be avoided. This fact is illustrated in Figure 9 which indicates that the transformation of austenite to pearlite begins in one second or less between the temperatures of 1100°F and 950°F. In this range, often referred to as the pearlite nose of the curve, the transformation is complete in less than ten seconds.

An isothermal transformation diagram shows the changes in microstructure that occur when a steel is cooled instantly to some reaction temperature and held at that temperature long enough for the reactions to go to completion. The diagram for a given steel shows what structure or structures are formed by isothermal transformation at any selected temperature, the time that the material must be at temperature before a reaction starts, and the time required to complete the reaction.

Fine grained austenite transforms to pearlite more rapidly than does coarser grained austenite. This is explained by the fact that as grain size decreases the proportion of grain boundary material to the total mass increases. As previously discussed, pearlite nucleates at the grain boundaries in homogeneous austenite. Consequently, transformation to pearlite begins more quickly and progresses faster in fine grained austenite than in coarse grained austenite.

Figures 10 and 11 illustrate the effect of carbon on the isothermal transformation reactions in plain carbon steels. For the steel with the higher carbon content (Figure 10) the transformations are shown to start later and to progress more slowly than do comparable reactions in the lower carbon steel (Figure 11). In effect, higher carbon content shifts the isothermal transformation curves to the right, that is, transformations start later and proceed more slowly as carbon content is increased.

Most of the common metallic alloying elements also tend to retard the start of isothermal transformations and to increase the length of time required to complete them.

Compared to isothermal transformations, transformations under continuous cooling take longer to start and begin at lower temperature. In effect, the isothermal transformation curve is shifted downward and to the right. This is illustrated by the reactions of a plain carbon steel of eutectoid composition. In actual practice, the steel can be fully hardened by cooling at a rate of 250°F per second. However, the isothermal diagrams for such steel, Figure 12, indicates that a cooling rate of at least 400°F per second is required to prevent the cooling rate curve from intersecting

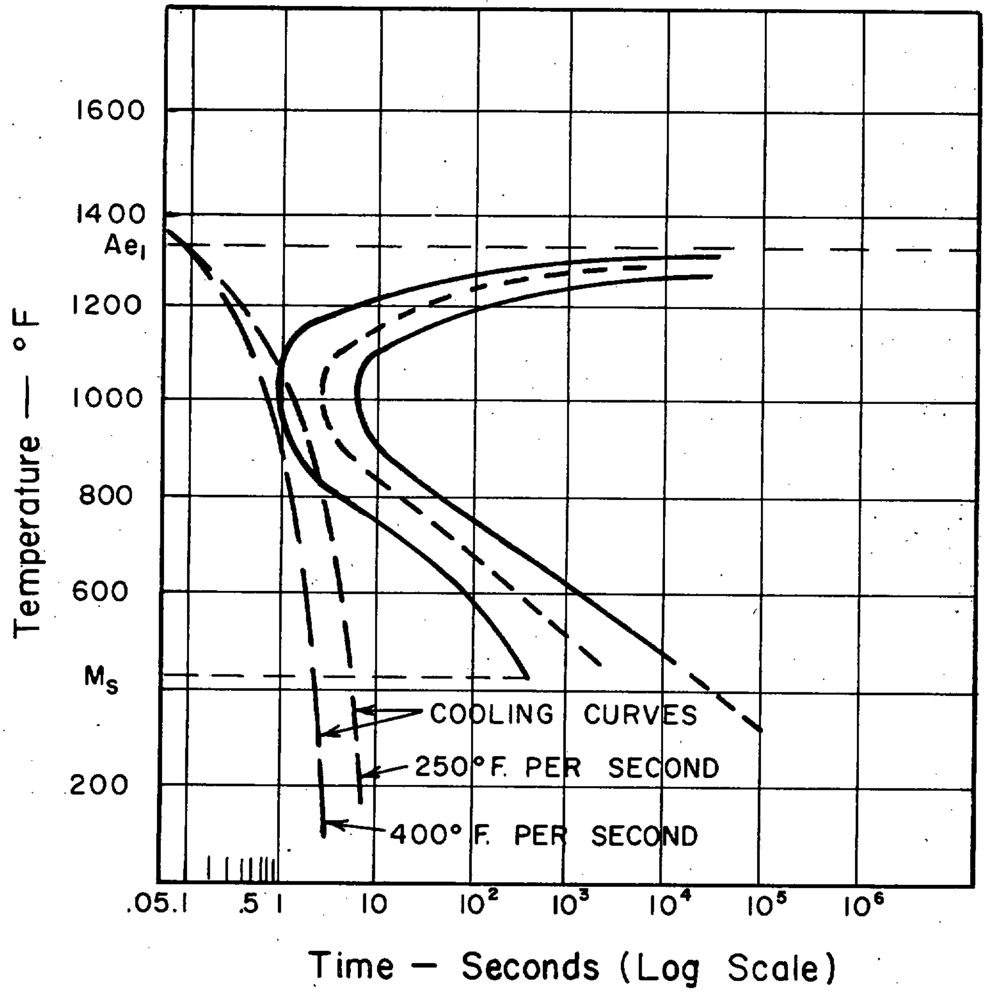


FIGURE 12. The Isothermal Transformation Diagram of an Eutectoid Carbon Steel with Cooling Curves Shown

the transformation start curve at the pearlite knee. Theoretically, when the two curves intersect transformation to pearlite should begin and should continue until the cooling curve passes out of the pearlite field.

13. **Hardenability.** If a steel is to be hardened to a martensitic structure it must be austenitized and then cooled at a rate that is fast enough to prevent the formation of any of the other transformation products, such as, pearlite. ferrite or bainite. The slowest rate that avoids all other transformations is called the critical cooling rate for martensite. As would be expected, different steels have different critical cooling rates, in fact there is considerable variation in this respect.

Steel with relatively slow critical cooling rates are high hardenability steels, conversely, steels that must be cooled rapidly to obtain a martensitic structure are low-hardenability steels. Hardenability, then, is actually a measure of the capacity of a steel to transform to martensite, that is, to harden. Hardenability is also a measure of the depth to which a steel will transform to martensite, or harden, under given cooling conditions. Low hardenability steels respond to only a limited depth, and are called shallow hardening steels. With steels of high hardenability it is possible to harden thicker sections to greater depths.

The most common method of cooling a steel to obtain a martensitic structure is by quenching, that is, rapidly cooling the steel from above the critical temperature by immersion in some medium that is capable of cooling it at the required rate. The cooling rate is determined by the hardenability of the steel and the size of the piece being quenched. Brine, water, and oils are the most common quenching media, listed in the order of decreasing severity of quench.

In a piece of steel of any appreciable size the cooling rates at the surface and at the center are different. The difference in these rates increases with the severity of the quench. Low hardenability steels, because of this difference in cooling rates, respond, or harden, to only a limited depth when quenched. High hardenability steels harden to greater depths.

The most widely used hardenability test is the Jominy end-quench test. The popularity of this test is attributed to its convenience; only a single specimen is required and in one operation it is exposed to a range of cooling rates that vary from a rapid water quench at one end of the specimen to a slow air quench at the other end. The test specimen is a bar, four inches long and one-inch in diameter. It is heated to an austenitizing temperature and held at temperature long enough to develop a uniform austenite structure and then placed in a fixture and quenched. Quenching is accomplished by a gentle stream of water that is directed at and allowed to impinge on only one flat end of the specimen. The test bar is thereby subjected to a series of cooling rates which vary continuously from a rapid water quench at one end to a slow air cool at the other end. After quenching two flat surfaces are ground on the specimen. These are located 180° apart, run the full length of the specimen and the depth of grind is at least 0.015 inch. Starting at the quenched end, Rockwell C hardness measurements are taken at 1/16 inch intervals along the length of the bar for at least 2 1/2 inches. The results are plotted to show hardness versus distance from the quenched end.

The procedures for conducting the Jominy end-quench test are established in Federal Test Method Standard 151, Method 711. The Jominy end-quench hardenability test is the most generally accepted and widely used hardenability test yet developed. Its popularity led to the development of the "H" grade steels. These alloy steels are distinguished from the usual AISI-SAE grade designation by the suffix "H" to denote steels produced to a hardenability specification. For example, 4340 is the standard AISI-SAE grade designation for a nickel-chromium-molybdenum steel, while 4340H identifies the same steel produced to a hardenability specification.

Minimum and maximum end quench hardenability curves have been established for the "H" steels. The establishment of these curves, known as hardenability bands, permits the use of steel specifications in which hardenability tolerances are specified directly. In this type of steel specification, hardenability is established as the primary requirement, and chemical composition, grain size, etc., assume less importance and are not as stringently controlled as for standard steels.

The practical application of hardenability data to procurement specifications is of vital interest to the buyer of alloy steels. Federal Standard No. 66, "Steels: Chemical Composition and Hardenability" gives the hardenability bands for the standard "H" steels and explains how these data can be used. ASTM specification A304, the SAE Handbook, and the ASM Metals Handbook, Volume 1, also present and explain the use of hardenability bands and other types of hardenability data.

Chapter 3

Wrought Products

WROUGHT PRODUCTS

14. General. Steel making, from the reduction of iron-rich ores in a blast furnace to the casting of ingots, was discussed in Chapter 2. Steel in ingot form is usually a coarse-grained, heterogeneous, brittle material, and is in some cases quite porous. To convert the relatively brittle cast ingot material into a tougher, more ductile, wrought product the steel must be plastically deformed, or worked.

The production of finished wrought steel forms usually involves a sequence of operations that gradually convert the ingot into finished form, Figure 13. The working of metals is divided into two basic classifications, hot working, and cold working. Hot working is the plastic deformation of a metal at a temperature above the recrystallization temperature of the metal. Cold working is the plastic deformation of a metal at a temperature lower than the recrystallization temperature of the metal.

15. Hot Working. During hot working the individual grains in a piece of steel deform in much the same manner as the whole piece. That is, the grains tend to elongate in the same direction as the piece of steel elongates. At hot working temperatures, however, the deformed grains tend to break-up and re-form into new grains, a process known as recrystallization. The size of the new grains depends upon the temperature at which the steel is worked, with grain size increasing as temperature increases. Hot working also closes blow holes (porosity) and, if the surfaces are not oxidized, the pores will weld shut. Inclusions, such as oxides, sulfides, and other compounds are drawn out by hot working to form stringers which align in the direction of principal deformation.

16. Cold Working. Cold working, as related to the production of wrought forms is usually accomplished by cold rolling or cold drawing. Cold rolling which results in only a slight reduction in the thickness of the steel, say 1 to 2 percent, is called temper rolling. With greater reductions, the operation is known as cold rolling or cold reduction. Cold working produces two effects; the surface of the steel is improved by comparison to hot worked material, and the ultimate and yield strengths of the steel are increased while ductility and toughness decrease. In effect the material strain hardens. Both effects are dependent upon the magnitude of the reduction during the cold working operation.

17. Wrought Forms.

a. General. The conversion of an ingot into a wrought form usually involves a series of operations. Because of the physical characteristics of ingot material the first operations are usually hot working operations conducted at relatively high temperatures, about 2200°F to 2350°F. For standard wrought forms, such as, plate, sheet, strip, structural shapes, bar, etc., the ingot is usually first rolled on a primary mill to convert it to a bloom, billet or slab. Rolling is a process of shaping materials by passing it between two rolls that are revolving in opposite directions at the same peripheral speed, Figure 14. The rolls are spaced so that the distance between them is less than the thickness of the material being worked, thus, in passing through the rolls the thickness of the

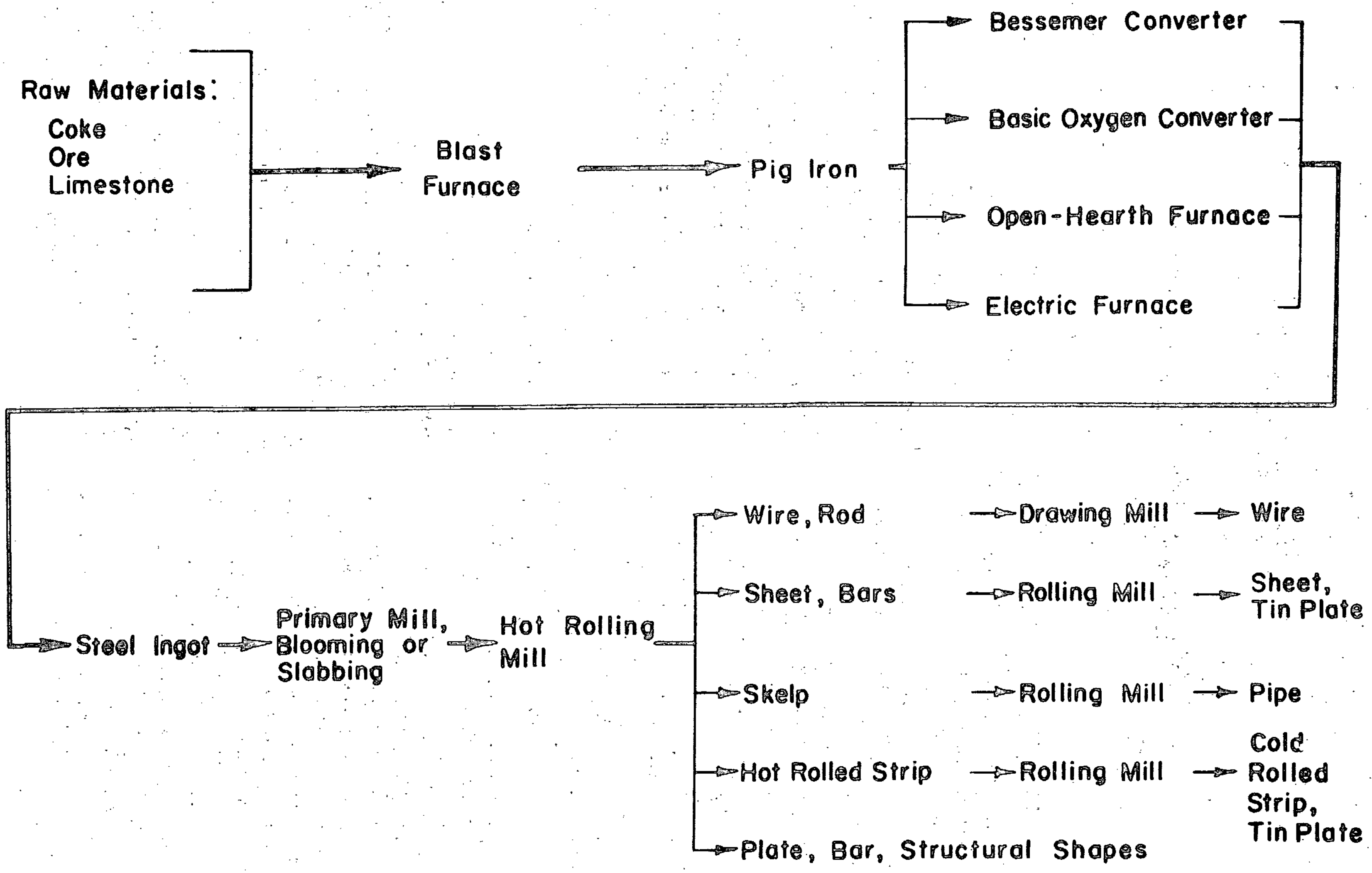


FIGURE 13. Flow Chart - Steel Wrought Products

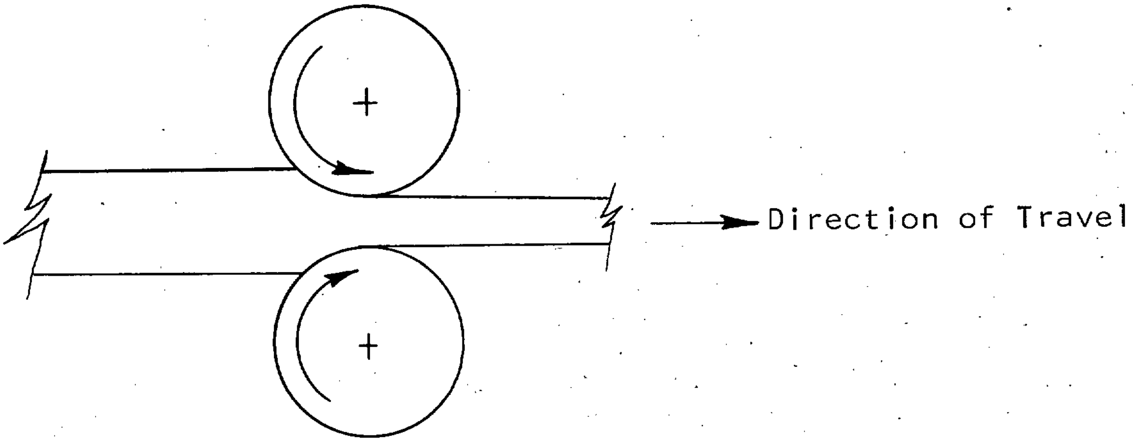


FIGURE 14. Principle of Rolling Operations

material is reduced. The ingot is gradually converted to a bloom, billet or slab by a series of operations or passes through the rolls. If necessary the ingot is turned between passes to develop the proper shape. The shapes produced on the primary mills are identified by size and geometry as follows:

(1) Billets are generally round or square with a minimum diameter or thickness of 1-1/2 inches. The cross sectional area of billets range from 2-1/4 sq. inches to 36 sq inches.

(2) Blooms usually have a square or rectangular cross-section. If rectangular, the width is limited to no greater than twice the thickness. The cross-sectional area is usually 36 sq inches or greater.

(3) Slabs have a rectangular cross-section with a width greater than twice the thickness. The minimum thickness of slabs is 2 inches and the minimum cross-sectional area is 16 sq inches.

It is possible to roll ingots directly through the bloom, slab, or billet stage into finished steel products in one continuous operation. Usually, however, the blooms, billets, or slabs are cooled, and stored for some period of time between the primary and subsequent operations. During this period the products are inspected and surface defects are removed by machining or other methods to condition the material for further processing.

Ingots may be converted directly to wrought products by forging. Forging is discussed later in the chapter and the present discussion will be limited to wrought forms produced by rolling.

Finished rolled wrought forms can be classed as flat rolled products and shapes. Flat rolled products are formed between smooth rolls. Rolls with grooved surfaces are used to produce shapes. Flat rolled products include plate, sheet, strip, and bar. These products characteristically have a high width to thickness ratio.

Finished flat rolled steel products are divided into two major categories, hot rolled products and cold rolled products. Hot rolled products are rolled to final thickness at elevated temperatures, usually above 1300°F. Cold rolled products are actually only cold finished since the ingot is reduced to nearly the final thickness by hot rolling and only the final reduction or reductions are accomplished by cold rolling.

b. Available forms.

(1) General. Following are brief descriptions of the basic wrought forms in which carbon and alloy steels are available. When applicable, general size ranges are listed but there is no attempt to define standard sizes, conditions, and tolerances for the various forms. This information was deliberately omitted because:

(a) When standard sizes are listed the erroneous inference is often drawn that all alloys are available in all sizes at all times and in limitless quantity. Because such conditions do not exist standard size data are actually of academic interest rather than of practical value.

(b) Standard sizes, tolerances, and other related information are included in available publications, including but not limited to the following: Bulletin R22-46, National Bureau of Standards; Steel Products Manual, American Iron and Steel Institute; Federal Standard 48; SAE Handbook; and the specifications and standards listed in Chapter 5.

(c) The producers and suppliers of steel products should be consulted regarding the availability of wrought products. They are the most valid source of information regarding wrought products and the sizes, finishes, and compositions in which each is available. The sizes of the various commodities that are produced and stocked vary with demand and the stock lists and data sheets provided by the producers and suppliers are periodically revised to reflect the ever changing conditions.

(2) Plate. Plates are hot rolled, flat finished steel products that are rolled either directly from ingots or from reheated slabs. In terms of thickness and width, carbon and alloy steel plate is defined as follows:

Width (inches)	Thickness (inch)
Over 8 to 48 inclusive	0.2300 and thicker
48 and over	0.1800 and thicker

(3) Hot Rolled Bars. Hot rolled carbon and alloy steel bars are rolled in a variety of sections such as rounds, squares, round cornered squares, flats, spring flats, hexagons, octagons, and special bar shapes (angles, channels, tees, zees, with a maximum sectional diameter of 3 inches or less).

The general size limits for hot rolled carbon and alloy steel bar are as follows:

Rounds, 1/4" to 8-1/2", inclusive;

Squares, 1/4" to 5-1/2", inclusive;

Round cornered squares, 3/8" to 8", inclusive;

Hexagons, 1/4" to 4-1/16", inclusive;

Flats, 13/64" and over in specified thickness, and up to 6", inclusive, in specified width;

Flats, 0.230" and over in specified thickness, over 6" to 8", inclusive, in specified width;

Bar size shapes, including angles, channels, tees and zees when their greatest sectional diameter is less than 3";

Ovals, half-ovals and half-rounds;

Special bar sections.

(4) Cold Finished Bars. Cold finished carbon and alloy steel bars are produced from hot rolled steel by several cold finishing processes. Cold finishing improves the surface finish, dimensional accuracy and alignment of the bars. Cold finishing processes, which can be used singly or in combination, include cold drawing, cold rolling, turning, grinding, straightening and polishing. Bars produced by cold finishing are generally restricted to rounds, squares, flats, and hexagons.

Cold rolling was discussed previously but cold drawing was not. Cold drawing is a process that consists essentially of pulling a hot rolled bar through an opening in a die. The die opening is similar in shape to the cross-section of the bar but of smaller size, thus the section size of the hot rolled bar is reduced by the drawing operation. Before drawing the bars are descaled, washed in clear water, and dipped in a hot lime solution which retards rusting and aids lubrication.

Turning and polishing is a cold finishing operation by which hot rolled round bars are reduced to the desired size by turning in a lathe, or a special purpose turning machine, and finished by polishing. The rough surface metal is removed and a bright, smooth, surface is produced by the polishing operation. The sizes of bars made by this operation generally range from 3/4 inch to 9 inches.

Other processes used on hot rolled rounds are turning, grinding, and polishing. Except that the bar is ground before it is polished there is little difference between this operation and the turning and polishing operation. Bars made by turning, grinding, and polishing range from 3/4 inch to 9 inches.

For small diameter bars a high quality surface is produced by a combination of cold drawing, centerless grinding and polishing operations performed in the sequence indicated. Bars up to 1-15/16 inch diameter can be made in this manner.

(5) Hot Rolled and Cold Rolled Sheet and Strip. The distinction between hot rolled and cold rolled sheet and strip lies in the methods used to attain the finished thickness. The cold rolled commodities develop superior surface finishes. Size ranges are indicated in the following tables:

Hot Rolled Carbon Steel Sheets

Thickness (inch)	Width (inches)
0.2299 to 0.1800	12 to 48 inclusive
0.1799 to 0.0449	over 12

Cold Rolled Carbon Steel Sheets

Thickness (inch)	Width (inches)
0.0142 and up	over 12
0.0142 to 0.0821 incl.	over 2

Hot Roller High Strength Low Alloy Steel Sheets

Thickness (inch)	Width (inches)
0.2299 to 0.1800 incl.	12 to 48 inclusive
0.1799 to 0.0710 incl.	over 12

Cold Rolled High Strength Low Alloy Steel Sheets

Thickness (inch)	Width (inches)
0.0142 to 0.0821 incl.	2 to 12 inclusive
0.0142 and thicker	over 2

Hot and Cold Rolled Alloy Sheets

Thickness (inch)	Width (inches)
0.2299 and thinner	24 to 48 inclusive
0.1799 and thinner	over 48

Hot Rolled Carbon Steel Strip

Thickness (inch)	Width (inches)
0.0255 to 0.2030 incl.	to 3-1/2 incl.
0.0344 to 0.2030 incl.	over 3-1/2 to 6 incl.
0.0449 to 0.2299 incl.	over 6 to 12 incl.

Cold Rolled Carbon Steel Strip
(0.75% carbon maximum)

Thickness (inch)	Width (inches)
0.2499 and thinner	over 1/2 to 23-15/16 incl.

Hot Rolled High Strength Low Alloy Steel Strip

Thickness (inch)	Width (inches)
0.0255 to 0.2030 incl.	to 3-1/2 incl.
0.0344 to 0.2030 incl.	over 3-1/2 to 6 incl.
0.0499 to 0.2299 incl.	over 6 to 12 incl.

Cold Rolled High Strength Low Alloy Steel Strip

Thickness (inch)	Width (inches)
0.2499 and thinner	1/2 to 12
0.2499 and thinner	12 to 23-15/16 when a special edge or special finish is specified

Hot Rolled Alloy Steel Strip

Thickness (inch)	Width (inches)
0.2030 and thinner	to 6 incl.
0.2299 and thinner	over 6 to 23-15/16 incl.

Cold Rolled Alloy Steel Strip

Thickness (inch)	Width (inches)
0.2499 and under	to 23-15/16 incl.

(6) Structural Shapes. Structural shapes is the general term applied to rolled flanged sections used in the construction of bridges, buildings, ships, railroad rolling stock, and for numerous other constructional purposes. They are designated as wide flange sections, beams, channels, angles, tees, zees, and include center sills, bulb angles and miscellaneous sections for carbuilding.

Angles, channels, tees and zees are classified as structural shapes only when their greatest sectional dimension is 3 inches or more. Smaller sizes are classified as bar shapes.

The method of designating the size of structural sections is as follows:

Wide-flange sections: by depth, width across flange, and weight per foot, in that order.

Beams and Channels: by depth of section and weight per foot.

Angles: by length of legs and thickness in fractions of an inch; or by length of legs and weight per foot. The longer leg of an unequal angle is commonly stated first.

Tees: by width of flange, overall depth of stem, and weight per foot, in that order.

Zees: by depth, width of flanges and thickness in fractions of an inch; or by depth, flange width and weight per foot.

Size designations have been listed by the U. S. Department of Commerce Simplified Practice Recommendation R216-46 covering Hot Rolled Carbon Steel Structural Shapes. Another excellent reference is the Steel Construction Manual of the American Institute of Steel Construction.

(7) Miscellaneous Flat Forms. Carbon steel is also available in flat rolled form with various coatings, for example; galvanized sheet and strip (zinc coated); tin plate (tin coated); and long terne and short terne sheets and plate (coated with a lead-tin alloy).

(8) Wire. Carbon and alloy steels are, in some compositions, available in the form of wire. Wire is not restricted to a round cross section, it is in addition produced in many common shapes, such as, square, hexagon, octagon, oval, half-oval, triangular, and flat. Wire is drawn from hot rolled rod. The size limits for wire range from 0.001 inch to 4 inches diameter for round wire and from a few thousandths of an inch of thickness to 3-1/2 inches for square, hexagonal, and octagonal wire.

(9) Tubular Products. Steel is also available in a wide variety of tubular forms, such as, standard pipe, aircraft quality tubes, conduit pipe, and tubular poles, to name a few classifications. Tubular products are classified as welded and seamless, according to the methods of manufacture.

HEAT TREATMENT OF STEEL

18. General. The predictable changes to the microstructure that can be effected by heating and cooling solid steel at selected rates under controlled conditions is the basis for the heat treatment of steel. In Chapter 2 the theory of heat treatment was introduced during the study of equilibrium and isothermal transformation diagrams. Some of the practical aspects of steel heat treatment are introduced in the following discussions of annealing, normalizing, quench and tempering, martempering, and austempering.

19. Annealing.

a. General. Steel is annealed for various reasons, i.e., to reduce the hardness, to relieve stresses, to develop a particular microstructure and associated physical and mechanical properties, and to improve machinability and formability. To accomplish these purposes various procedures are used, each of which is identified by a descriptive term, such as, full annealing, isothermal annealing, and process annealing. Unless the term is qualified, annealing when applied to steel implies full annealing.

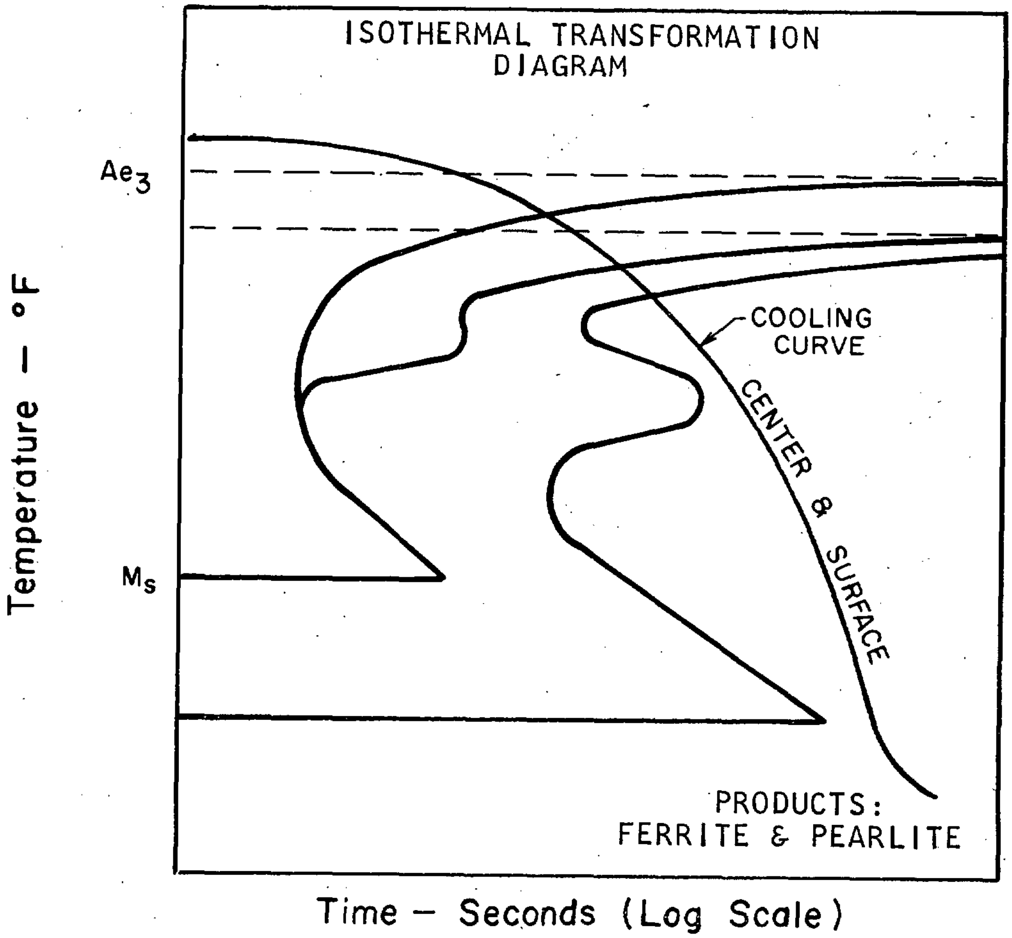


FIGURE 15. Schematic Representation of the Full Annealing Cycle

b. Full annealing. Full annealing is a relatively simple heat treatment. The steel is heated to a temperature above the A_{c3} critical temperature and held at temperature long enough to allow the solution of carbon and other alloying elements in the austenite. The steel is cooled from the annealing temperature at a slow rate so that the transformation is completed in the high temperature region of the pearlite range. This process is shown schematically in Figure 15. Full annealing produces a structure of relatively soft coarse pearlite. Depending upon the composition of the steel, ferrite or carbide may also be present.

Full annealing is a simple process but it is also a slow process. The steel must be cooled very slowly from the annealing (austenitizing) temperature to a temperature below that at which the transformation is completed.

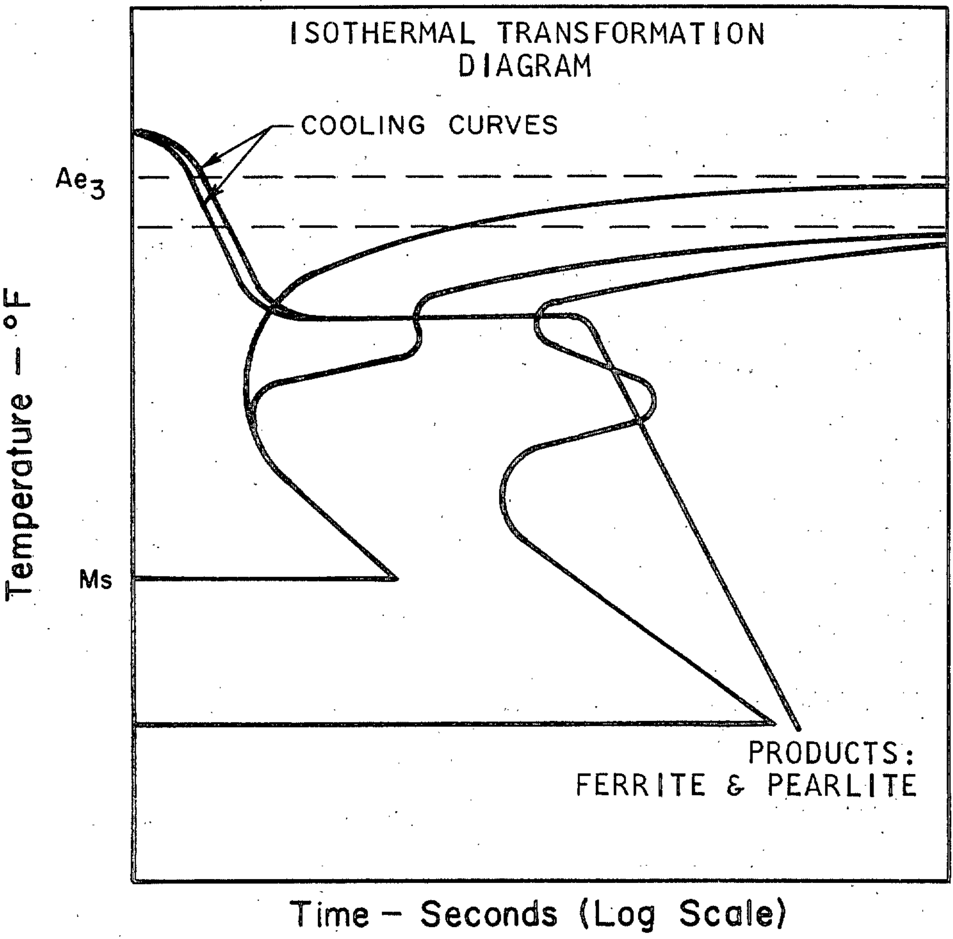


FIGURE 16. Schematic Representation of the Isothermal Annealing Cycle

c. *Isothermal annealing.* Annealing to a coarse pearlitic microstructure can be accomplished by cooling steel from the austenitizing temperature to the proper temperature for the transformation to occur. It is held at that temperature until the transformation is completed. This process is depicted in Figure 16.

d. *Spheroidize annealing.* Steels may be heated and cooled to produce a structure of globular carbides in a ferrite matrix (a spheroidized structure) by various procedures. One such method consists of holding the steel at a temperature just below the Ae1 (holding between Ac1 and Ac3 for at least part of the time is generally involved). To achieve full spheroidization of the carbides by this method the steel usually must be held at temperature for long periods of time. Heating and cooling the steel alternately to temperatures slightly above and slightly below the Ae1 temperature will also produce a spheroidized structure. Also, if the carbide is not completely dissolved during austenitizing and the steel is slowly cooled in a manner similar to full annealing, or if it is isothermally treated as in isothermal annealing, a spheroidized structure can be developed. A spheroidized structure is sometimes desirable to develop minimum hardness and maximum ductility to facilitate forming, or, in high carbon steels, to improve the machining characteristics of the steel.

e. ***Process annealing.*** The annealing of cold worked steel to restore its ductility and to reduce its hardness by recrystallization at subcritical (below A_{c1}) temperatures is called process annealing. Process annealing consists of heating steel to some temperature below, and usually near, A_{c1}, holding it at temperature for an appropriate time after which it is slowly cooled, usually in air.

20. Normalizing. Normalizing is that process of heat treatment which consists of reheating steel above its critical temperature and then cooling it in air. Steels are normalized for two basic purposes, to refine the grain, and to develop a more uniform microstructure. It is used as a preliminary treatment to quenching and tempering to develop a more uniform microstructure and facilitate the solution of carbides and alloying elements. Normalizing is also used when the as-normalized properties are those desired in the finished part, in which case normalizing is the final treatment. When necessary, normalizing can be followed by tempering, usually at 1000°F to 1300°F, to reduce hardness and to improve toughness.

21. Hardening by Quenching and Tempering.

a. ***General.*** Hardening by quenching and tempering is the heat treatment commonly used to develop martensitic structures with the desired combination of toughness and strength. The process is divided into three separate operations; heating, quenching, and tempering.

b. ***Austenitizing.*** The first step in the hardening process is to austenitize the steel by heating it to a temperature above the critical range. The material should be held at temperature long enough for the carbon and other alloying elements to dissolve but not long enough for excessive grain growth to occur.

c. ***Quenching.*** Quenching is the rapid cooling of the steel from the austenitizing temperature to a temperature below the Ms (Martensite start) temperature. The cooling rate must be rapid enough to prevent the formation of other transformation products such as pearlite, bainite, ferrite or cementite. Common quenching media include oils, water, brine, and forced air. The choice of cooling medium is dependent upon the desired cooling rate which is determined by the composition (hardenability) of the steel, and the size and shape of the section being quenched. Quenching sets up high thermal and transformation stresses which may cause distortion and cracking of the part. Consequently it is usually desirable to keep these stresses at a minimum by cooling at a rate that is just slightly faster than the critical cooling rate as determined by the hardenability of the steel and the size and shape of the piece being quenched.

Brine quenching is the most severe, followed in order by water and oil quenching. Agitation of the quenching medium is important because it produces more uniform cooling and accelerates the rate of cooling.

d. ***Tempering.*** Tempering is the name applied to the process of heating quench hardened or normalized steel to a temperature below the transformation range, holding it at temperature for a suitable time and cooling it at an appropriate rate. The martensite formed on quenching is very hard, brittle and highly stressed. Tempering is employed to relieve these stresses and to improve the ductility of the steel, usually at the expense of strength and hardness. The stress relief, and the recovery of ductility are brought about by the precipitation of carbide from the supersaturated unstable alpha martensite and through diffusion and coalescense of the carbide as tempering proceeds.

Tempering is usually carried out at temperature between 350°F and 1300°F and the usual time at temperature ranges from 30 minutes to 4 hours. For many carbon and low alloy steels ductility and toughness increases upon tempering at temperatures up to 400°F. In the approximate temperature range of 450°F to 700°F notch toughness decreases as tempering temperatures are increased, consequently quench hardened steels are rarely tempered in that temperature range. Tempering in the range of 200°F to 400°F is used when it is important to retain

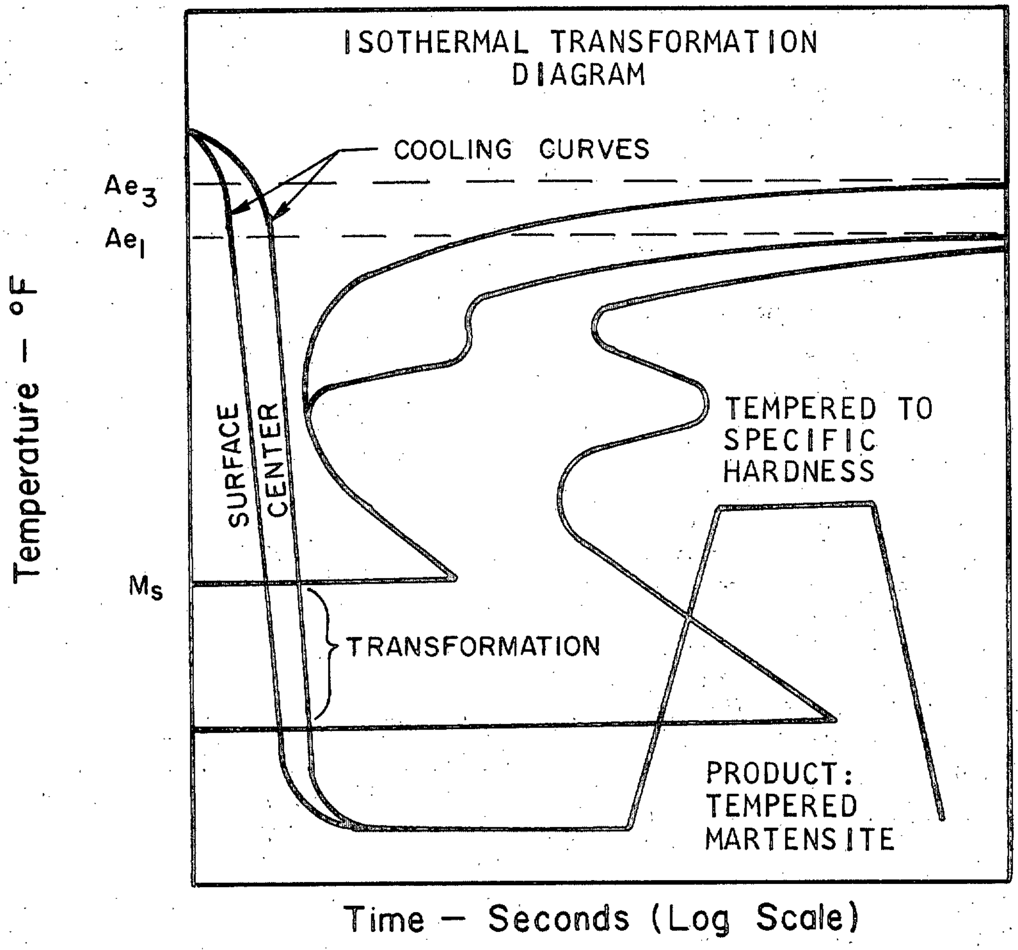


FIGURE 17. Schematic Representation of the Quench and Temper Cycle

hardness and strength and effect a modest improvement in toughness. In the higher temperature range of 700°F to 1250°F tempering causes an appreciable increase in toughness and ductility of the steel and a simultaneous decrease in hardness and strength.

As discussed in Chapter 2, the maximum as-quenched hardness of a steel is primarily dependent upon carbon content regardless of what other alloying elements are included in the composition. Steels with the same carbon content but with otherwise different compositions temper at different rates and the tempering cycles must be adjusted accordingly. The tempering procedure for a fully hardened steel can be varied, within limits, to develop different combinations of hardness and toughness.

22. Heat Treatment of Selected Steels. The conventional quench and tempering process is shown schematically in Figure 17. Military Specification Mil-H-6875, "Heat Treatment of Steels (Aircraft Practice, Process for)" establishes heat treating practices for selected steels commonly used in construction of aircraft and missiles. The processes covered by this specification are: normalizing, annealing (full), process annealing (stress-relieving), hardening by quenching, and tempering. In addition to specifying temperatures or temperature ranges for the various heat treatments for each alloy, the specification establishes requirements for equipment, operating and test procedures, and certification of equipment.

ASM Metals Handbook, Volume II, "Heat Treating, Cleaning, and Finishing" gives particulars for the heat treatment of many carbon and low alloy steels. In addition to temperature data the Metals Handbook provides comprehensive coverage of the practical aspects of heat treating steels. The SAE Handbook and other sources listed in the bibliography also provide specific information regarding the heat treatment of the various carbon and low alloy steels.

Tables I through V, give representative heat treatment temperatures for selected steels. The data presented in these tables are for general cases and the temperatures and times listed can, and should be adjusted to compensate for differences in equipment, chemical composition, the size and shape of the parts being treated, and other variables. The data presented in these tables are intended only as examples of the heat treatments applicable to the selected steels. These tables should not be used to establish heat treatment processes for the steels listed. Specification Mil-H-6875 and other approved references, or preferably, a Materials Engineering organization should be consulted for that purpose.

TABLE I. STRESS RELIEF TEMPERATURES

Material	Stress Relief Temperature (°F)	Soak Time at Temperature
Low-Alloy Steels (after heat treat at 150 to 180,000 psi)	700 ± 25	1 hr*

*Allow 1 hr per in. of cross section for heatup time.

TABLE II. ANNEALING CYCLE FOR LOW-CARBON AND LOW-ALLOY STEELS

Material	Alloy	Annealing Temperature (°F)	Furnace Cooling Cycle at 50°F/hr* From (°F)	To	Soak Time (hr)	Heatup Time
Low-Carbon	1018	1575 to 1650	1575	1300	1 hr for sections to 1 in. thick. Add 1/2 hr for each additional 1 in. of thickness.	1 hr per in. of material thickness.
	1020	1575 to 1650	1575	1290		
	1025	1575 to 1650	1575	1290		
	1030	1550 to 1625	1550	1200		
	1035	1550 to 1625	1550	1200		
Low-Alloy	4130	1450 to 1550	1450	900		
	4140	1450 to 1550	1450	900		
	4340	1450 to 1550	1450	900		
	5150	1500 to 1600	1500	900		
	6150	1550 to 1650	1550	1000		

*After reaching the lower temperature, the rate of cooling is unimportant.

TABLE III. NORMALIZING CYCLE FOR LOW-CARBON AND LOW-ALLOY STEELS

Material	Alloy	Normalizing Temperature (°F)	Soak Time (hr)	Heatup Time
Low-Carbon	1015	1650 to 1700	1 hr for sections to 1 in. thick. Add 1/2 hr for each additional 1 in. of thickness.	1 hr per in. of material thickness.
	1020	1650 to 1700		
	1025	1625 to 1675		
	1030	1625 to 1675		
	1035	1600 to 1650		
Low-Alloy	4130	1600 to 1750		
	4140	1550 to 1700		
	4340	1550 to 1700		
	5150	1550 to 1700		
	6150	1600 to 1750		

TABLE IV. AUSTENITIZING CYCLE FOR LOW-CARBON AND LOW-ALLOY STEELS

Material	Alloy	Austenitizing Temperature (°F)	Soak Time		Heatup Time
			Thickness (in.)	Time (hr)	
Low-Carbon*	1025	1575 to 1650	1/2 or less	1/4	1 hr per in. of material thickness.
	1030	1550 to 1600	1	1/3	
	1035	1525 to 1575	2	1/2	
Low-Alloy	4130	1500 to 1600	3	3/4	
	4140	1550 to 1600	4	1-1/4	
	4340	1500 to 1550	5	1-1/2	
	5150	1475 to 1550			
	6150	1550 to 1625			

*The amount of strengthening by austenitizing and quenching is insignificant.

TABLE V. TEMPERING CYCLE FOR LOW-ALLOY STEELS

Alloy	Tempering Temperature (°F)				
	125,000 psi	150,000 psi	180,000 psi	Soak Time	Heatup Time
4130	950 to 1150	800 to 1000	700 to 900	1 hr per in. of material thickness	1 hr per in. of material thickness
4140	1050 to 1250	950 to 1150	800 to 1000		
4340	1075 to 1225	975 to 1075	850 to 975		

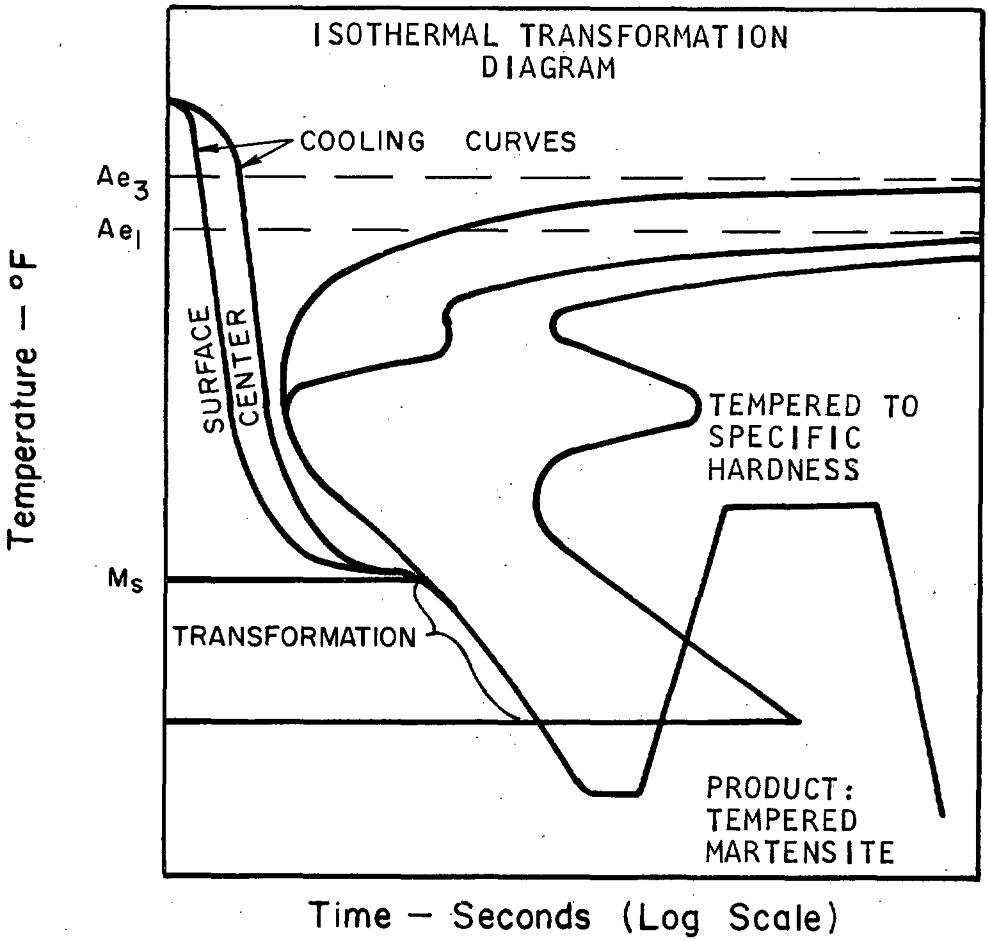


FIGURE 18. Schematic Representation of the Martempering Cycle

23. Controlled Atmospheres. Controlled atmospheres are often used to protect the surfaces of steel parts during heat treatment. Unless such precautions are taken, scaling, carburization, or decarburization may result. Scaling, or oxidization, mars the surface, represents a loss of metal, and may affect the cooling rate when the part is quenched. Carburization is the addition of carbon to the surface material by heating it in contact with a carbonaceous material. Decarburization is the loss of carbon from the surface of the part as a result of heating the part in contact with some medium that reacts with carbon. Decarburization results in a soft surface and can seriously affect the fatigue life of a steel part.

Controlled atmospheres are generally used when temperatures exceed 1200°F. The temperature, time at temperature, and the carbon content of the steel are important factors which must be considered in selecting an atmosphere for a given application. Various atmospheres are used depending upon the material, the treatment, available equipment, and the disposition of the parts after heat treatment. Parts that are machined after heat treatment to a depth sufficient to remove the affected material usually do not need to be heat treated in a controlled atmosphere.

24. Martempering. The transformation of austenite to martensite during rapid cooling of a steel through the martensite transformation range produces high stresses and can cause distortion and cracking. Martempering is a process that is useful in reducing these high stresses. It is an interrupted quenching process in which a steel is quenched from the austenitizing temperature into hot oil or a molten salt bath at a temperature near, but slightly above, the Ms temperature of the alloy, Figure 18. The steel is held in the quenching medium long enough for its temperature to stabilize, after which time it is removed and allowed to cool slowly in air.

The transformation of austenite to martensite occurs during the period when the steel is cooling slowly in air. Because of the slow cooling rate a relatively uniform temperature is maintained throughout the mass of the steel, and the severe thermal gradients that are characteristic of conventional quenching are not developed. Consequently, martensite forms at a uniform rate throughout the piece and the stresses developed during transformation are much lower than for conventional quenching. The lower stresses developed by martempering in turn lessen the distortion of the treated part.

Martempering is usually reserved for steels of medium hardenability such as those that are conventionally hardened by oil quenching. A modified martempering process can also be used to advantage. It consists of quenching from the austenitizing temperature to a temperature slightly below the Ms. The higher cooling rates obtained by the lower temperature quench in effect allows the treatment of steels of lower hardenability than can be treated by the standard martempering process.

25. Austempering. Austempering is the name applied to the heat treatment whereby austenite is transformed isothermally to lower bainite, Figure 19. Lower bainite, as mentioned in Chapter 2, compares favorably to tempered martensite with respect to strength and hardness, and for a comparable hardness, exhibits superior ductility. Austempering is an alternate method of heat treating steels to develop high strength and hardness in combination with good ductility and toughness.

The austempering process consists of:

a. Heating the steel to a temperature within its austenitizing range.

b. Quenching the steel in a constant temperature bath at the desired transformation temperature in the lower bainite region.

c. Holding the steel in the bath for a sufficient period of time to allow the austenite to transform isothermally to bainite.

d. Cooling the steel to room temperature in still air.

Austempering is an isothermal transformation process carried out at relatively high temperatures so that, compared to conventional quenching, transformation stresses are reduced, and distortion is minimized. Austempering is usually substituted for conventional quenching and tempering to obtain higher ductility or notch toughness at a given hardness, and/or to decrease the distortion and cracking associated with normal quenching.

26. Surface Hardening of Steel.

a. General. In many industrial applications it is necessary to develop a high surface hardness on a steel part so that it can resist wear and abrasion. This can be done by hardening a high carbon steel; however, the high hardness is then accompanied by low ductility and toughness. In many applications the poor ductility and toughness cannot be tolerated throughout the entire part and another solution to the problem must be found.

Low carbon steels can be treated to develop a hard surface or case while the interior of the steel, or core, is unaffected and retains its normal ductility and toughness. Surface hardening or case hardening processes for steels may

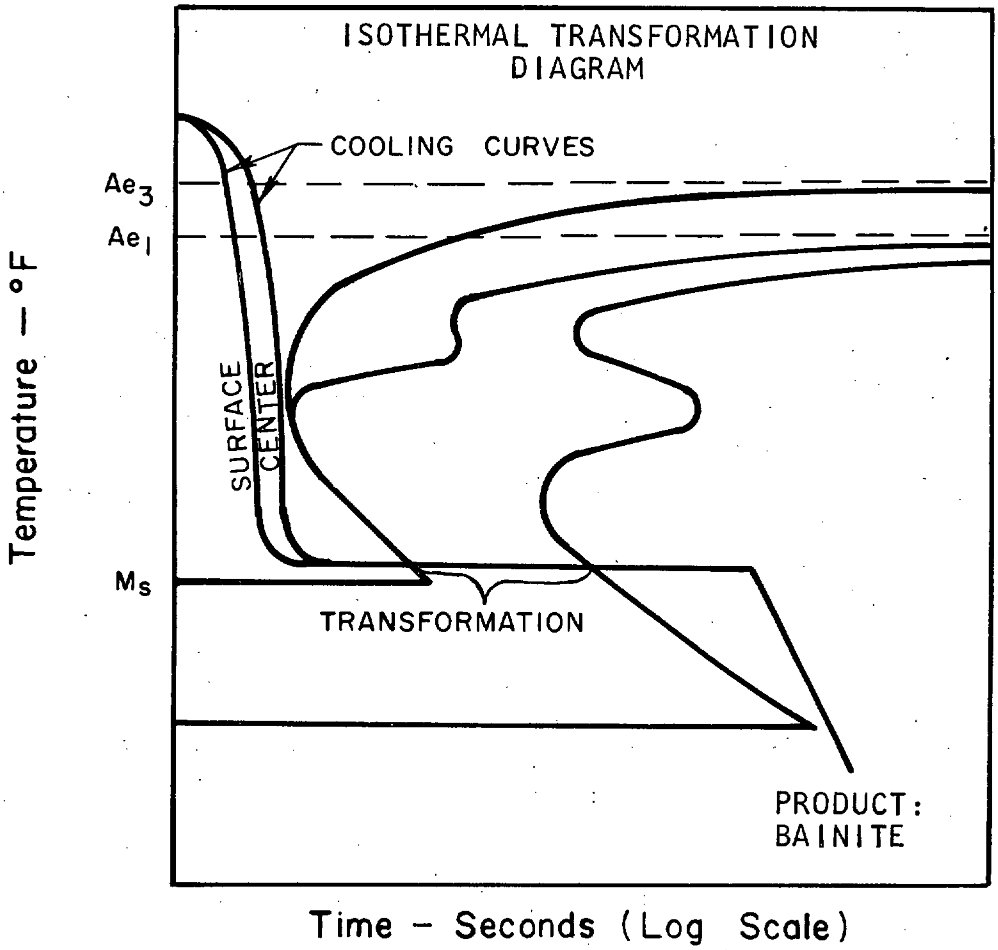


FIGURE 19. Schematic Representation of the Austempering Cycle

be divided into two broad classifications: (1) those in which the composition of the surface material is changed; and (2) those in which the composition of the surface material is not changed. Carburizing, nitriding, carbonitriding, and cyaniding are processes that fit into the first classification. Flame hardening and induction hardening are included in the second classification.

b. ***Carburizing.*** Carburizing is usually applied to plain carbon or low-alloy steels with less than 0.20% carbon. The low carbon steel is heated in contact with a carbonaceous material to develop a case or surface layer on the steel that has a high carbon content. Upon quenching, the high carbon case becomes very hard while the low-carbon core remains relatively soft. This process produces parts with hard, wear-resistant exterior surfaces, and soft, tough cores. Three methods of carburizing steel are:

(1) Pack Carburizing - in which the steel parts are placed in containers and carbonaceous solids are packed around them. The carbonaceous material is usually charcoal, or coke mixed with a suitable energizer such as barium

or sodium carbonate. The carbon monoxide gas which forms is actually the carburizing medium. The chemical reaction is:

$$3Fe + 2CO \longrightarrow Fe_3C + CO_2$$

The carbon atoms diffuse into the steel, which for carburizing is heated above the critical range, hence the carbon goes into solid solution in the austenite. The temperature range for pack carburizing is from 1500°F to 1750°F; the temperature selected is usually about 100°F above the A_{c3} point of the alloy being treated. The depth of core and the carbon concentration gradient of carburized parts are governed by the carburizing temperature, time, the carbon potential of the pack, and the original composition of the steel.

(2) Gas Carburizing - in which the steel parts are exposed to carburizing gases. This process is more controllable than pack carburizing and generally more versatile and efficient. The usual operating temperature range for gas carburizing is from 1550°F to 1750°F.

(3) Liquid Carburizing - in which the steel parts are immersed in a molten salt bath containing sodium cyanide. Low temperature salt baths, 1550°F to 1650°F, are best suited for cases 0.003 to 0.030 inches deep. High temperature baths are used to produce deeper cases, 0.020 to 0.120 inches deep, and in some instances cases up to 0.250 may be produced.

Many carbon and low-alloy steels are used for carburizing, although the general practice is to use steels containing about 0.15 or 0.20 percent carbon.

The heat treatment of a carburized steel will depend upon the carburizing temperature, the composition of the core and the case, and the properties that must be obtained. In some instances the steel may be quenched directly from the carburizing temperature and then tempered. Another method is to slowly cool the steel from the carburizing temperature, reheat it to a temperature slightly above the A_{3-1} temperature, quench, and temper. Double reheat and quench operations are also employed with some steels.

In some instances it is necessary to develop a case in only local areas and not over the entire surface of a part. Carburization can be prevented in local surface areas by protecting those areas by copper plating them or covering them with a copper bearing lacquer. Another effective method is to machine the part after carburizing to remove the case from those areas where a soft surface is desired.

c. ***Nitriding.*** Nitriding is a nitrogen case-hardening process. For successful nitriding it is necessary to use alloy steels containing aluminum, chromium and molybdenum which combine with the nitrogen to form hard nitrides. The nitriding medium is commonly ammonia gas and the operating temperature is in the vicinity of 950°F. Core depths are usually 0.015 to 0.020 inch. It is unnecessary to quench or temper the steel after nitriding; consequently, parts are usually fully machined and hardened before nitriding.

d. ***Carbonitriding.*** Carbonitriding is a case hardening process in which carbon and alloy steels are exposed to a gaseous atmosphere from which they absorb carbon and nitrogen simultaneously. The process is a modified gas carburizing process in which ammonia is introduced into the gas carburizing atmosphere. Operating temperatures range from 1300°F to 1650°F. Case depths of 0.003 to 0.030 inch are developed. Many carbon and alloy steels with carbon contents up to 0.25 percent are carbonitrided. Nitrogen increases the hardenability of the case. Thus full hardness can be achieved by less severe quenching, and distortion is minimized.

e. ***Cyaniding (liquid carbonitriding).*** This process is similar to liquid carburizing except that the molten salt bath contains higher percentages of sodium cyanide, ranging from 30 percent to 97 percent. The steel absorbs both carbon and nitrogen from the molten bath and by selection of bath composition and operating temperature it is possible to regulate, within limits, the relative amounts of carbon and nitrogen in the case. Operating temperatures range from 1400°F to 1600°F. Usually, thin cases, less than 0.010 inch deep, are produced by this process.

f. Flame hardening. Flame hardening is a surface hardening process that consists of heating the surface area to be hardened to a temperature above the upper critical temperature of the alloy with a high temperature flame. The heated surface is then quenched in a suitable manner. The process produces a hard surface with a soft tough core.

g. Induction hardening. In this process the surface of the steel is heated by induced current to a temperature above the upper critical temperature. The part to be hardened is placed in coil, usually of water cooled copper tube, that does not contact the steel. A high frequency current is passed through the coil and the surface of the steel is heated by induced current. The current is shut off and the steel is immediately quenched. The heating time is fast, from 1 to 5 seconds, and there is no time for serious oxidization, decarburization or grain growth to occur. This process also develops a hard surface over a soft tough core.

Steels used for flame and induction hardening must have a carbon content of 0.40 percent or greater.

THE FORMING OF STEEL

27. General. Carbon and low-alloy steels in the form of ingots, billets, blooms, bar, sheet, strip, plate and rod are formed to desired shapes by various hot and cold forming methods. Some of the more common methods are discussed briefly in this section.

28. Forging.

a. General. Modern forging methods encompass the various hot working operations by which metals and alloys are hammered or pressed to the desired shape. The material is shaped by impact or pressure either on anvils, in open dies or in closed dies. Large forgings are often made directly from the ingot, smaller forgings are made from billets, blooms, bar, and rod.

b. Hammer or smith forging. Hammer or smith forging consists of hammering the heated metal with hand tools (blacksmithing) or between flat dies on a steam hammer. Hand forging, as practiced by blacksmiths, is the oldest forging process, and is still in use today. Hand forgings are necessarily limited in size, complexity of shape, and dimensional accuracy. The skill of the blacksmith is the all important factor in the process. Currently the process is generally restricted to repair work and to the production of limited quantities of small parts. Larger forgings are hand shaped with open dies on steam hammers and pneumatic hammers. Although the use of the steam or pneumatic hammers permits the forging of larger parts, the process, smith forging, is dependent upon operator skill and is limited as to the shape and accuracy of the forgings produced.

c. Drop forging (impact die forging). Drop forging or impact die forging differs from smith forging in the type of dies used. Open faced dies are used to produce smith forgings while closed impression dies are used in drop forging. Closed impression dies consist of two die blocks in which cavities or impressions of the required configurations are machined. One die block is mounted to the anvil of the forging machine, the other attaches to the ram. The heated metal is placed between the die blocks and is caused to flow and conform to the shape of the cavities by the impact of repeated blows on the metal. Proper flow and shaping of the metal is controlled by a gradual change of shape through a succession of forming steps. Each step is carried out in a different die cavity. The cavities are designed to be used in succession so that forming of the part is a progressive operation. The number of steps and the number of different die cavities, or impressions, required of course vary according to the size and shape of the final forging. For small forgings a set of die blocks may contain all of the different impressions required to produce the part. For larger parts more than one set of dies may be required. Drop forgings are produced on steam drop hammers.

d. Press forging. Press forging consists of a slow squeezing of the metal between dies as opposed to the rapid impact blows of hammer forging. Press forging is used for all types of forging operations, from open to closed die. Hydraulic and mechanical presses are used in press forging.

e. *Upset forging.* Upset forging machines are designed to operate horizontally with a vertical die parting plane as opposed to the vertical operation and horizontal die parting of hammer and press forgings. The operation consists of gripping a bar of uniform section between gripper dies. The gripper dies form a cavity into which the free end of the bar protrudes. Pressure is applied to the free end of the bar by a ram which upsets the bar until it conforms to the shape of the die cavity. For some products the upsetting operation may be completed in one die cavity. For most shapes the forming is accomplished in successive operations in a series of cavities. Upset forging is a versatile hot forming method by which a wide variety of parts are produced. In addition to upsetting, the upset forging machines may be used for piercing, trimming or punching.

29. Hot Extrusion. In this process, hot plastic metal is forced through an orifice in a die. Since the extruded metal assumes the shape of the orifice, some shapes that cannot be produced by rolling can be made as an extrusion. Squeezing toothpaste from a tube is analogous to the extrusion of metal. The advantages of the hot extrusion process, as related to steel, are: shapes can be produced by extrusion that are not possible by rolling; and the directionality of mechanical properties is minimized. Die wear is a problem and affects the tolerances of steel extrusions.

30. Hot Drawing or Cupping. Hot drawing is the operation in which heated steel is pushed through a die to change its cross section or shape. One common hot drawing process is cupping. A round disk, cut out of a steel plate of suitable thickness, is heated to forging temperature and placed on a ring die. A plunger forces the metal down through the die to form a cup shaped part. The operation may be repeated using dies of reduced diameter until the desired cup shape is obtained.

Drawing may also be performed on a hot draw bench. In this horizontal operation a tubular part, closed on one end, is forced through a series of dies of continually decreasing diameter. Cylinders are often formed by cupping followed by hot drawing.

31. Hot Spinning. Hot spinning is an operation by which plate in the form of a circular blank is formed to a dish shape on special spinning machines or on lathes adapted to the process. The flat blank is held or attached to a mandrel so that the blank and mandrel can be rotated as a unit. A roller is brought to bear against the rotating blank. The steel is formed to the shape of the mandrel by adjusting the pressure on the roller and manipulating its position.

32. Hot Pressing. Hot pressing is also used to produce large dish shaped heads of various sizes and designs from steel plate. Other shapes are also produced by this method in which a plate blank is formed to the desired shape by squeezing it between forming dies in a large press. Again successive operations may be required to produce the final shape.

33. Cold Heading. Nails, rivets, and small bolts are made by this method. Coiled bar or rod is automatically fed into the machine which upsets it to the desired shape.

34. Press Work. The forming operations performed on presses range from simple bends produced on a press brake to the complex compound-curvature-forming involved in the production of automotive parts. Many different types and sizes of presses are used, most of which may be adapted to different operations, depending upon the types of dies used. The tools most used in press operations come under the general heading of punches and dies. The punch refers to that part of the assembly which is attached to the ram of the press while the die is usually stationary and rests on the bed of the press. The die usually has an opening or is shaped to mate with the punch and the two must be aligned for proper operation. The material is worked between the punch and the die. Common press operations include: shearing - blanking, notching, perforating, etc; bending - forming, angle bending, folding, etc; drawing - tubes, cupping, forming flanges, embossing, etc; and squeezing - coining, upsetting, cold forging, hot pressing, etc.

35. Explosive Forming. Explosive forming is a high energy rate forming method which is rapidly gaining prominence. It is a versatile method that can be adapted to large or small parts and can be used effectively when production quantities are limited. The energy released by detonating an explosive charge is transferred through some suitable medium, such as water, to the workpiece. The very fast rates at which metal is deformed by explosive forming methods often permits more severe forming between process anneals than can be accomplished by standard methods.

36. Roll Forming. Coiled strip is formed into tubular and various other shapes by passing it through a series of mating rolls which progressively form it to the desired shape.

37. Other Forming Processes. Carbon and low-alloy steels may be hot worked and cold worked by other processes too numerous to list here. Forming characteristics vary with composition, condition, and the severity of the forming. The ASM Metals Handbook, Volume 1, 8th Edition, presents a comprehensive discussion of metal forming and the selection of steels for forming.

MACHINING OF STEEL.

38. General. The methods used to machine carbon and low-alloy steels include all of the common operations such as turning on lathes, milling, drilling, sawing, grinding, broaching, shaping, planing, etc. The machinability of steel varies with composition and condition or temper. The Machining Data Handbook compiled by Metcut Research Associates, Inc., Cincinnati, Ohio, for Rock Island Arsenal, Rock Island, Illinois, (Contract DA-11-070-AMC-224(w)) is an excellent source of detailed information for various machining operations as applied to steels and many other materials.

39. Machinability. Machinability has been defined as "a complex property of a material that controls the facility with which it can be cut to the size, shape and surface finish required commercially". The predominant factor governing the machinability of carbon steels, as would be expected, is carbon content. Low carbon steels, 0.15 percent carbon or less, have low tensile and shear strengths in the annealed condition. As a result they are soft and gummy and machine poorly. Cold drawing increases strength and hardness and serves to improve the machining characteristics of these steels.

Steels containing from 0.15 to 0.30 percent carbon usually machine satisfactorily in the as-forged, as-rolled, normalized, or annealed condition.

The medium-carbon steels, containing up to 0.55 percent carbon, usually machine best if they have been annealed to produce a microstructure that is a mixture of pearlite (lamellar) and spheroidite. If the material is not partially spheroidized its hardness will be too high for optimum machinability. Steels containing 0.55 to 0.60 percent carbon should be completely spheroidized to develop the best machining characteristics.

Selection of the 1000 series carbon steels is seldom based on machinability alone, although relative machinability may be a consideration. For example 1022 may be preferred to 1020 because of better machinability in those applications where either alloy is otherwise satisfactory.

The 1100 and 1200 series free machining carbon steels have improved machining characteristics as compared to equivalent 1000 series steels. The resulfurized carbon steels (1100 series) may contain up to 0.33 percent sulfur, although for most of the compositions the sulfur is held to within 0.08 to 0.13 percent. The sulfur combines with manganese to form MnS. The sulfides promote favorable machining conditions by causing the chips to break up and also serve as a built in lubricant that prevents the chips from sticking to the tool.

The series 1200 steels are resulfurized and rephosphorized. Sulfur serves the purposes noted above and phosphorus tends to increase the strength and hardness of the ferrite which also promotes chip breakage.

The machinability of the alloy steels varies with composition and temper. Generally alloy steels are more difficult to machine than carbon steels of equal carbon content. In addition, the machining and heat treatment of alloy steels must be coordinated for efficient production. The effects of heat treatment on surface finish, size, the distortion from quenching, etc., must be considered in scheduling the operations.

JOINING OF STEEL AND WROUGHT IRON

40. General. In general, wrought iron, carbon, and low alloy steels can be readily and effectively joined by the various methods commonly used in the metal fabricating industry. The various joining methods may be grouped as follows:

a. High temperature methods; various fusion welding and resistance welding processes.

b. Intermediate temperature methods; brazing and soldering processes.

c. Room temperature methods; mechanical fastening.

The welding methods commonly used to join wrought iron, carbon and low alloy steels include oxyacetylene welding, shielded metal-arc welding, gas shielded-arc welding, submerged-arc welding, forge welding, flash welding, induction welding, electroslag welding, friction welding, stud welding, spot, seam and projection welding.

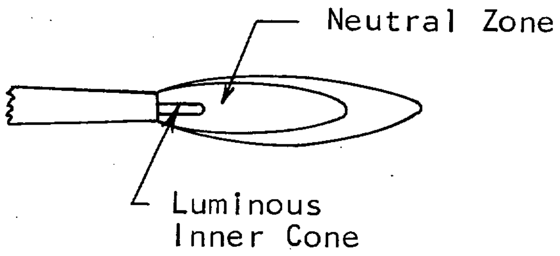
Intermediate temperature methods include torch brazing, furnace brazing and induction brazing as well as the various soldering methods.

Room temperature mechanical methods include lock seaming, riveting and fastening with screws, nuts and bolts.

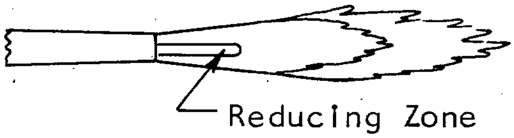
41. Oxyacetylene Welding. Oxyacetylene welding is a welding process in which coalescence is produced by heating a metal with an oxyacetylene gas flame or flames, with or without the application of pressure, and with or without the addition of filler metal. The acetylene gas and oxygen are mixed in the proper proportion in a mixing chamber which is generally a part of the welding tip assembly. The torch is designed so that the operator has complete control of the flame.

Oxyacetylene welding involves the melting of the base metal and also the filler metal, if any is used, with the heat produced by the burning of the gases at the tip of the welding torch. The molten metal, which includes base metal and any filler metal, intermix in a common molten pool and upon cooling coalesce to form one continuous mass. Properly adjusted the flame can also provide a protective atmosphere to cover the pool of molten metal. A mixture of one part oxygen to one part acetylene provides flame temperatures up to 5600°F, approximately twice the melting temperature of steel, and produces the high localized heating necessary for welding.

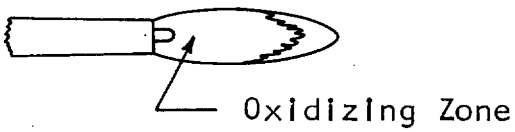
A range of welding tip sizes are available so that welding flames of various sizes can be produced, with selection dependent upon the specific application. Flame sizes range up to 3/16 inch or more in diameter and 2 inches or more in length. The inner core or blue flame is called the working flame. The closer the working flame is to the surface of the metal being welded, the more efficient is the transfer of heat from the flame to the metal. Changing the ratio of the volume of oxygen to acetylene alters the chemical action of the flame on the molten weld puddle. Generally, wrought iron and steels are welded with a neutral flame having approximately a 1:1 gas ratio. Increasing the oxygen flow produces an oxidizing action; conversely, increasing the acetylene flow produces a carburizing action on the molten pool. Three types of flame adjustment are shown in Figure 20.



Neutral Flame
Clear, sharp luminous inner cone with quiet flame



Carburizing or Reducing Flame
Long inner cone coupled with feathery edges on flame



Oxidizing Flame
Short inner cone with smaller overall flame

FIGURE 20. Characteristics of Neutral, Carburizing and Oxidizing Flames

The cleanliness of the base metal at the weld joint is of utmost importance. Oil, dirt or oxides may cause blowholes, lack of fusion, slag inclusions or porosity.

The configuration of the edges of the material to be welded is determined by its thickness. Thin sheet (up to 3/16 inch thick) can be completely melted by the flame without edge preparation. Material from 3/16 to 1/4 inch thick requires a slight root opening for complete penetration; however, filler metal must be added to compensate for the root opening. The joint edges of material 1/4 inch or greater in thickness should be beveled. The angle of bevel for the oxyactylene welding of wrought iron and steel varies from 35 to 45 degrees, which is equivalent to an included angle of from 70 to 90 degrees. A root face of 1/16 inch is recommended, however, thinner edges are occasionally used. Material 3/4 inch and greater in thickness should be double beveled when it is possible to weld from both sides of the joint. The root face can vary from 0 to 1/8 inches. See Figure 21.

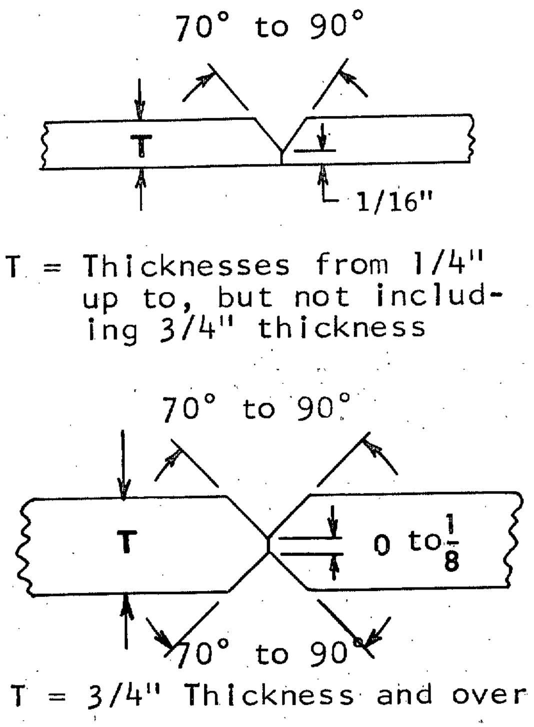


FIGURE 21. Edge Configurations for Oxyacetylene Welding

A bad characteristic of oxyacetylene welding is the steep temperature gradient that is produced across the weld joint and in the surrounding base metal. This temperature gradient often results in distortion unless precautions are taken to minimize its effect. The problem can often be minimized by first tack welding the assembly and then starting the final weld at that section of the assembly that is least subject to distortion. Peening, the proper use of braces, welding alternately on both sides of the joint, and the use of a backstep sequence in welding are all methods which may be used to control or minimize distortion. However, the most effective deterrent of all is to design weldments properly.

During welding, the temperature of the base metal ranges from the melting temperature and above in the weld puddle, to room temperature in areas remote from the heat source. Because the material adjacent to and in the weld is heated to a temperature considerably above the transformation temperature of the steel a coarse grain structure develops in the weld metal and adjacent base material. This condition can be corrected by a grain refining heat treatment after welding.

If a steel contains sufficient carbon, and if the rate of cooling after welding is rapid enough, the weld metal and material in the heat affected zone will harden. Hardening should be avoided because the affected material will lack ductility and will be susceptible to cracking. Hardening can be avoided in most hardenable steels by playing the torch over the weld and the adjacent heat affected zone for a short period of time after welding is completed, or by preheating the material before it is welded. Air hardening steels may require a post heat treatment, such as a stress relief treatment or an annealing treatment, to eliminate the hardened zone.

A variety of equipment is available for both manual and automatic oxyacetylene welding. Most oxyacetylene welding is performed manually. However, when production rates warrant, automatic or semi-automatic equipment can be used to great advantage. Figure 22 shows schematically the relationship of the basic tools required in manual oxyacetylene welding. Automatic

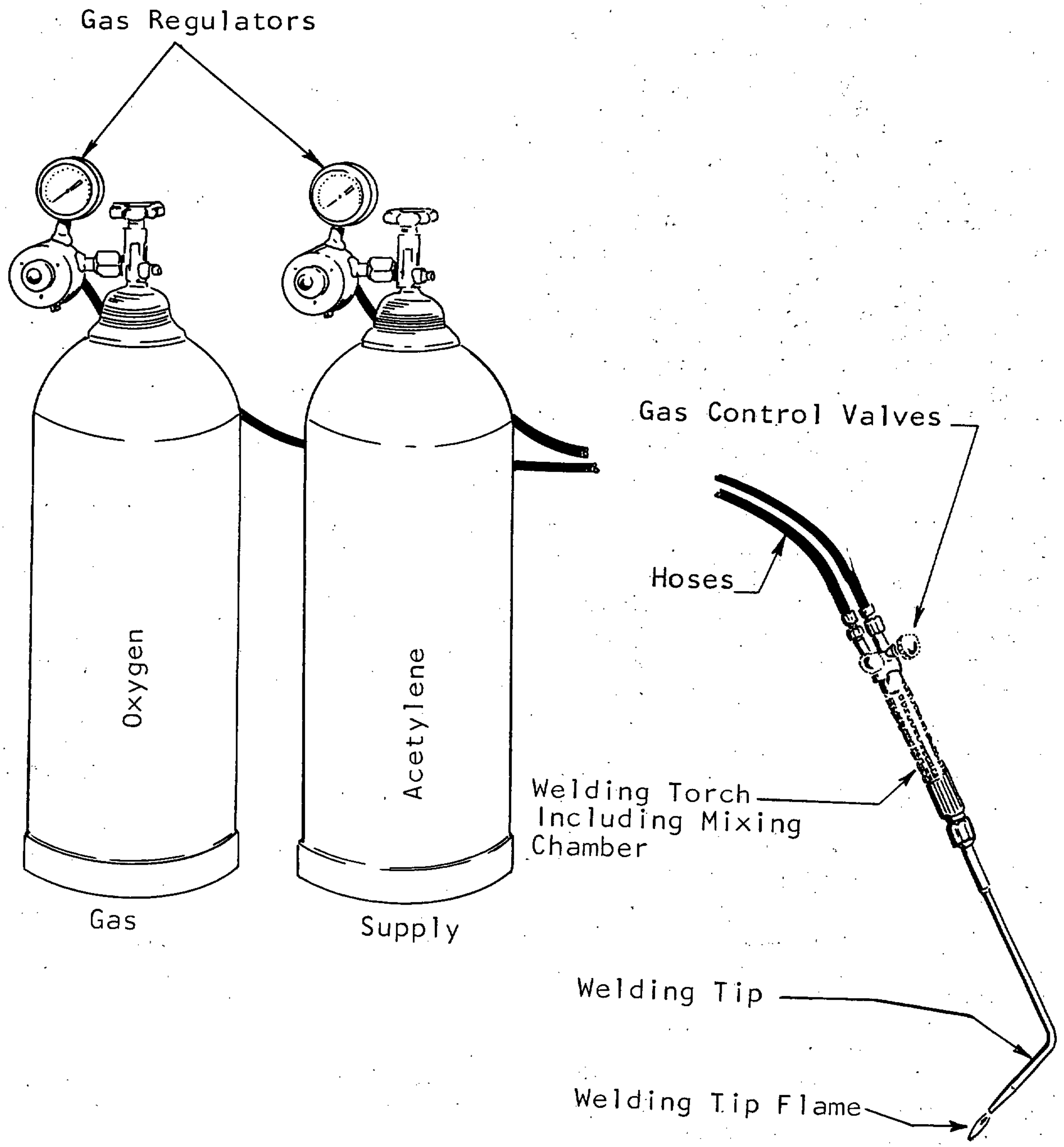


FIGURE 22. Oxyacetylene Welding Equipment

systems employ special welding heads, regulators, valves and other accessories designed for automatic operation.

Low carbon, low alloy steels, and wrought iron are readily welded by the oxyacetylene process. For welding, carbon steels having more than 0.35% carbon are generally considered high carbon steels and require special care to preserve their particular properties. Low alloy steels with air hardening tendencies also require special attention during welding, even those with a carbon content less than 0.35%. For these steels the material in the joint area is usually preheated to a temperature of 300°F to 750°F to retard the rate of cooling in the weld zone. Retarding the cooling rate minimizes the possibility of hardening the weld metal and the material in the heat affected zone. It is also important to maintain a uniform temperature in the weld area when these steels are welded.

Multi-pass welding is used when it is desirable to obtain maximum ductility of a steel weld in the as-welded or stress-relieved condition. Improved ductility in the weld deposit results from grain refinement in the underlying weld beads when they are reheated during subsequent passes. The final deposit will not be refined unless an extra deposit is added and subsequently removed, or unless the last deposit is subsequently torch heated to a normalizing temperature.

Generally, the composition of the weld deposit should approach that of the base metal. This is particularly true when the weldment will be heat treated after welding to develop mechanical properties that are not possible in the as-welded condition. Steel rods and wire for oxyacetylene welding are designed to deposit metal of a desired composition. Allowances are usually made in the composition of the rod to allow for the recovery of certain elements in the weld deposit. Filler metal conforming to Type A, Mil-R-908 "Rods, Welding; Steel and Cast Iron"; Class 1 Mil-R-5632 "Rods and Wire, Steel, Welding"; and GA60 or GB60 of the AWS-ASTM Specifications for Iron and Steel Gas Welding Rods are suitable for welding wrought iron and low carbon steels. Filler metals conforming to Type B or Type C, Mil-R-908; and Class 2, Mil-R-5632 are suitable for welding low alloy steels.

42. Shielded Metal-Arc Welding Process. Shielded metal-arc welding is a welding process in which coalescence is produced by heating the material with an electric arc which is struck between a coated metal electrode and the work. Shielding is obtained from the decomposition of the electrode coating. Pressure is not used and filler metal is obtained from the electrode. The shielded metal-arc process is primarily a manual process although automatic procedures have been developed.

Basically, the process consists of establishing an electric arc between a coated metallic electrode and the metal to be welded. Current flows through two leads and arcs across the gap between the end of a consumable electrode and the metal being welded. Transformation of electrical energy into heat energy at the gap provides the necessary heat. Figure 23 illustrates the metallic arc welding circuit.

During welding, the materials in the electrode coating are decomposed by the heat of the arc and perform a number of functions, namely: (a) they promote and help stabilize conduction across the arc; (b) they produce an envelope of gas which excludes oxygen and nitrogen in the air from contacting the molten weld puddle; (c) they add fluxing ingredients to the molten puddle for refining purposes; (d) In certain electrode designs, they add alloying elements to the weld deposit; and (e) they provide materials that help to control the bead shape. Figure 24 is a schematic presentation of the shielded metal arc process.

Actual welding consists of striking an arc by touching the work piece with the electrode and quickly withdrawing it to normal arc length, then guiding the electrode to produce simultaneous fusion to the electrode tip and base metal to form a solid bond on cooling. Intermixing of the deposited filler metal with melted base metal occurs to a greater or lesser degree depending on the techniques used.

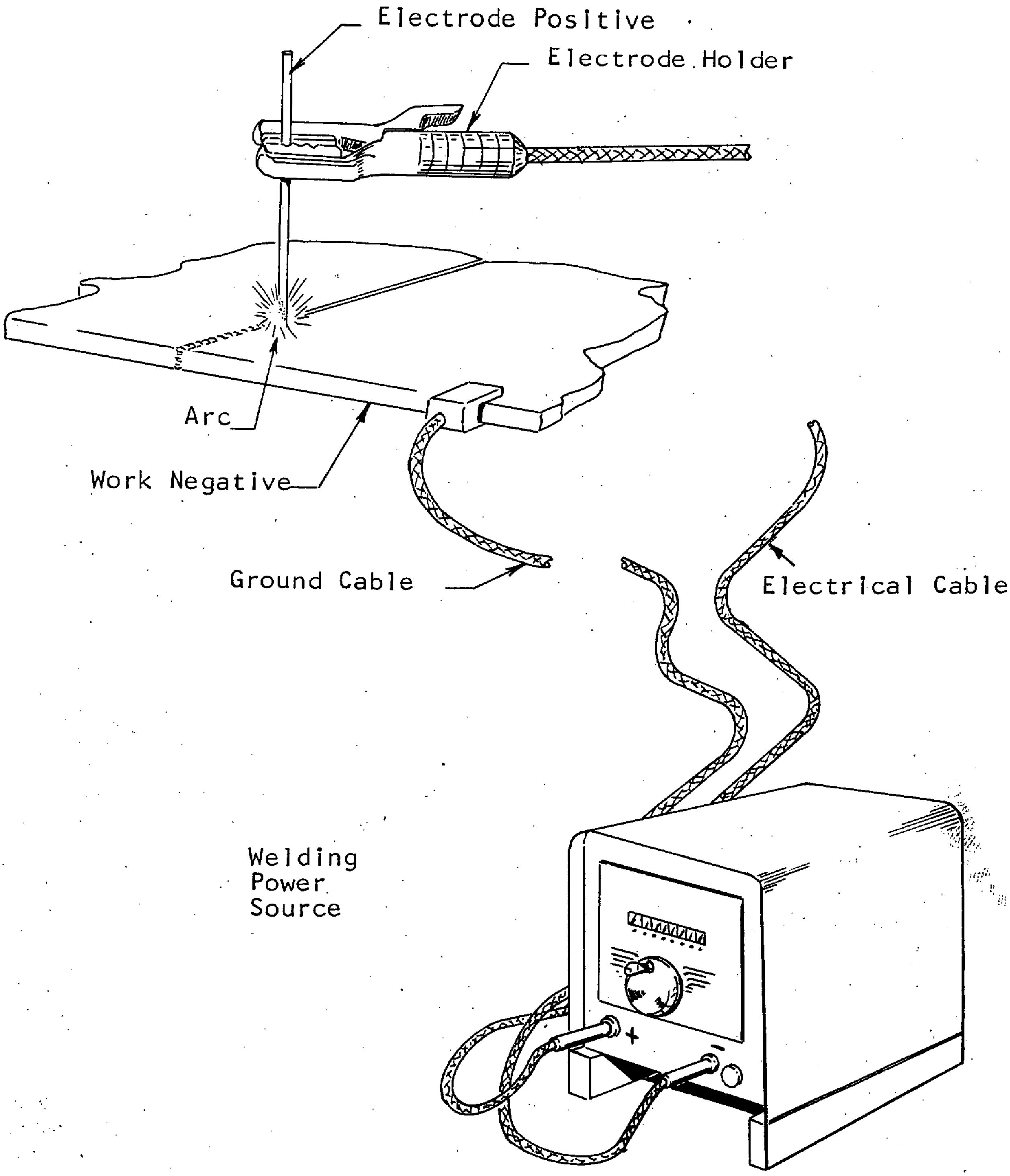


FIGURE 23. The Shielded Metal-Arc Welding Circuit (Reverse Polarity Operation)

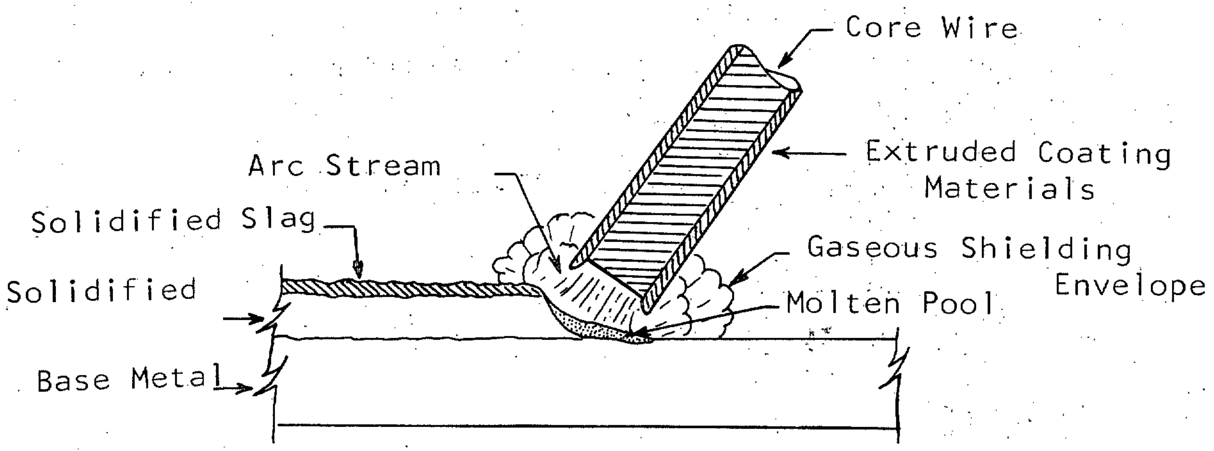


FIGURE 24. A Schematic Diagram of the Shielded Metal-Arc Welding Process

Manual welding equipment includes a power source (as transformer, dc generator, ac generator or dc rectifier), electrode holders, cables, cable connectors, ground connectors, chipping hammers, wire brushes, helmets and weld gages. Automatic shielded metal-arc welding equipment, in addition to a welding head, consists of such items as work positioners, head travel carriages, turning rolls, work skids with hold-downs, and portable power units.

Joint design is very important particularly in heavy sections and in the case of higher carbon and low alloy steels. In general, joint design should be in accordance with the latest practices for shielded metal arc welding as recommended by the American Welding Society.

Dirt, greases, oil, paint, and oxide should be removed from joint areas to prevent porosity and inclusions in the weld deposit.

In shielded metal-arc welding of wrought iron the best results are obtained when the welding speed and current are slightly below those used for mild steel of the same thickness. The slower speed permits the molten metal immediately behind the arc to remain molten longer, thereby allowing entrapped slag and gases to float out of the weld puddle. The use of a lower current also minimizes the possibility of burning through thinner sections. In practice, as little base metal as possible is melted to minimize the accumulation of slag in the weld. In multi-pass operations each weld bead should be thoroughly cleaned of oxide before subsequent beads are deposited.

Electrodes selected for welding wrought iron should meet the requirements of Mil-E-15599, or the requirements of the E60XX series of classifications of the AWS-ASTM Specifications for Mild Steel Arc Welding Electrodes.

Low carbon steels up to 0.30 percent carbon content are readily welded by the shielded metal-arc process. These steels are normally welded without preheat, post-heat or special electrodes. Special precautions such as preheating to 200°F, maintaining a minimum interpass temperature of 200°F, and postweld stress relief are advisable when section thickness exceeds one inch.

When the carbon content is over 0.30% special precautions are necessary to avoid cracking in the weld deposit or in the adjacent heat affected zone. Preheating to, and maintaining a minimum interpass temperature of 300°F to 400°F is advisable for all thicknesses of material. A stress relief treatment should follow welding.

Carbon steels having a carbon content over 0.50% are seldom welded. However, satisfactory welds may be obtained if special precautions are taken to avoid cracking.

The selection of electrode type and the size of electrode to use in welding carbon steels depends upon the weld strength requirements, the composition of the steel being welded, the thickness of the steel, the joint configuration, and the welding position. Electrodes of the Mil-60XX series of Mil-E-15599 or the E60XX series of AWS-ASTM Specification for Mild Steel Arc Welding Electrodes are suitable for welding the low carbon steels. For welding the medium and higher carbon steels, low hydrogen type electrodes of the Mil-70XX series, meeting Mil-E-18038 and Mil-E-22200, and electrodes of the AWS-ASTM E70XX series are recommended.

It is usually advisable to preheat the low alloy steels prior to welding in order to avoid cracking. Preheating in the order of 400°F to 750°F is recommended depending upon hardenability. The areas to be welded should be preheated to the temperature noted in Table VI.

TABLE VI. PREHEAT TEMPERATURES FOR LOW-ALLOY STEELS

Carbon Content (%)	Hardenability Equivalency	Preheat and Interpass Temp. (°F Min.)
0.16 through 0.35	AISI-4130 and steels of equal or equivalent hardenability	400
0.34 through 0.43	Steels with hardenability higher than above	500 to 750

Exceptions to the preheating rule are a group of high-strength low-alloy steels such as HY80, HY100 and similar steels marketed by the steel industry. These steels are supplied in the quenched and tempered condition and combine high yield strength and good notch toughness with good weldability. To obtain 100% joint efficiency when welding these steels it is necessary to use the proper electrode and to cool the weld zone as rapidly as possible. Interpass temperatures must also be held to certain minimums if 100% joint efficiency is to be attained. As a result reheat treatment after welding is not necessary. Moderate preheating may be advisable when the thickness of the steel section exceeds one inch.

Preheating of face hardened armor steels is neither recommended nor desirable for the obvious reason that heat input should be held as low as practical to avoid tempering and softening wide areas of the hardened surface adjacent to the weld deposit.

For low alloy steels electrodes conforming to Mil-70XX, Mil-80XX, Mil-90XX and Mil-100XX of Mil-E-6843, Mil-E-15716, Mil-E-18038, and Mil-E-22200 are generally used when the weldment will remain in the as-welded condition or when the weldment will be stress relieved after welding. The type of electrode selected for use depends upon the steel being welded and strength requirements. Electrodes meeting the requirements for the E70XX, E80XX, E90XX and E100XX classifications of the AWS-ASTM Specifications are also widely used by industry.

When heat treatment after welding is required to develop mechanical properties higher than those attainable in the as-welded condition, specially designed electrodes with chemical compositions capable of responding to heat treatment must be used. Electrodes in this category are obtainable to Mil-E-8697 requirements. The selection of a particular electrode is based upon the alloy being welded and strength level required after heat treatment.

Electrodes used for welding the high-strength low-alloy structural steels include the Mil-110XX series, and Mil-120XX series of Mil-E-18038 and Mil-E-22200. When lower-than-base-metal strength can be tolerated, electrodes of the Mil-90XX series, Mil-E-18038 and Mil-E-22200, may be used. Corresponding electrodes of the AWS-ASTM classification are widely used by industry to weld these steels.

Because of its importance, reference should be made to the care of low hydrogen type electrodes. Low hydrogen type electrodes generally have less than 0.2 percent moisture in the coating to avoid introducing hydrogen to the weld zone. Usually, these electrodes are packed in hermetically sealed containers which should not be opened until the time of use. After opening the container, storing the electrodes in a holding oven at the temperature recommended by the manufacturer is advisable. Electrodes that have been exposed to moisture should be reconditioned according to the manufacturer's instructions or discarded.

It is generally advantageous to stress relieve the low alloy steels after welding. In addition to relieving residual stresses in the welded structure, the temperatures involved in stress relieving are such that any hardened material adjacent to the weld will be tempered, with a corresponding improvement in ductility.

43. Gas-Shielded Arc Welding Process.

a. General. The gas-shielded arc welding process is a process in which coalescence is produced by heating the metal with an electric arc which is struck and maintained between the end of a metal electrode and the part being welded. The arc and weld region are shielded by a protective gas. The shielding gas may or may not be inert; pressure may or may not be applied; and filler metal may or may not be added to the joint.

Gas-shielded arc welding is divided into two variations which may be classified as follows:

(1) Procedures using non-consumable electrodes, including both manual and mechanized operation, termed the gas tungsten-arc process.

(2) Procedures using consumable electrodes, also including both manual and mechanized operation, termed the gas metal-arc process.

b. The gas tungsten-arc welding process. This process, often referred to as the TIG process, uses a tungsten or tungsten alloy electrode as the source of welding heat. The heat for welding is produced by an electric arc maintained between the electrode tip and the metal being welded. Basic features of the process are illustrated in Figure 25. In manual welding, the filler metal, if required, is fed into the molten puddle in the vicinity of the arc in a manner similar to oxyacetylene welding. The molten metal, the adjacent base metal, and the electrode are protected from the atmosphere by an envelope of inert gas fed through the electrode holder. Generally, argon, helium, or mixtures of the two gases are used for shielding purposes; argon is most frequently used. The process utilizes both direct current reverse polarity (DCRP) and direct current straight polarity (DCSP), however, direct current straight polarity is preferred for welding steels.

The basic components for manual welding include a power unit, an electrode holder (commonly called a torch) with gas passages and a nozzle for directing the flow of shielding gas, tungsten or tungsten alloy electrodes, gas flow regulating equipment, and usually a foot control for on-off switching purposes. Mechanized welding equipment may include electronic devices for checking and adjusting the welding torch level, work handling equipment, provisions for initiating the arc and controlling gas flow, and filler metal feed mechanisms.

c. The gas metal-arc welding process. This process, commonly referred to as the MIG process, uses a consumable electrode which is deposited as filler metal in the weld joint. The arc and weld puddle are shielded from the atmosphere by a gas, gas mixture or gas-flux mixture. In welding the carbon and low alloy steels, shielding is usually accomplished with mixtures of argon plus 2 percent oxygen; argon and carbon dioxide (CO_2); or CO_2 with flux additions. Direct current reverse polarity (DCRP) is used for welding steels.

The basic equipment required for semi-automatic MIG welding is shown in Figure 26. The equipment permits automatic feeding of the filler metal, and manual control of the welding gun. The process has been adapted to fully automatic operation with electronic devices controlling the equipment.

d. Process considerations.

(1) Carbon Steels. Both the gas tungsten-arc and gas metal-arc processes are used to weld carbon steels. The gas tungsten-arc process is usually limited to the welding of thinner sections with or without the addition of filler metal. The gas metal-arc process, because of its high deposition rate, is generally used to weld heavier section thicknesses. Quite often the root pass of a multi-pass weld is made with the gas tungsten-arc process, while the remaining passes are made with some other welding process, such as the shielded metal-arc process. This procedure assures a clean, sound root bead.

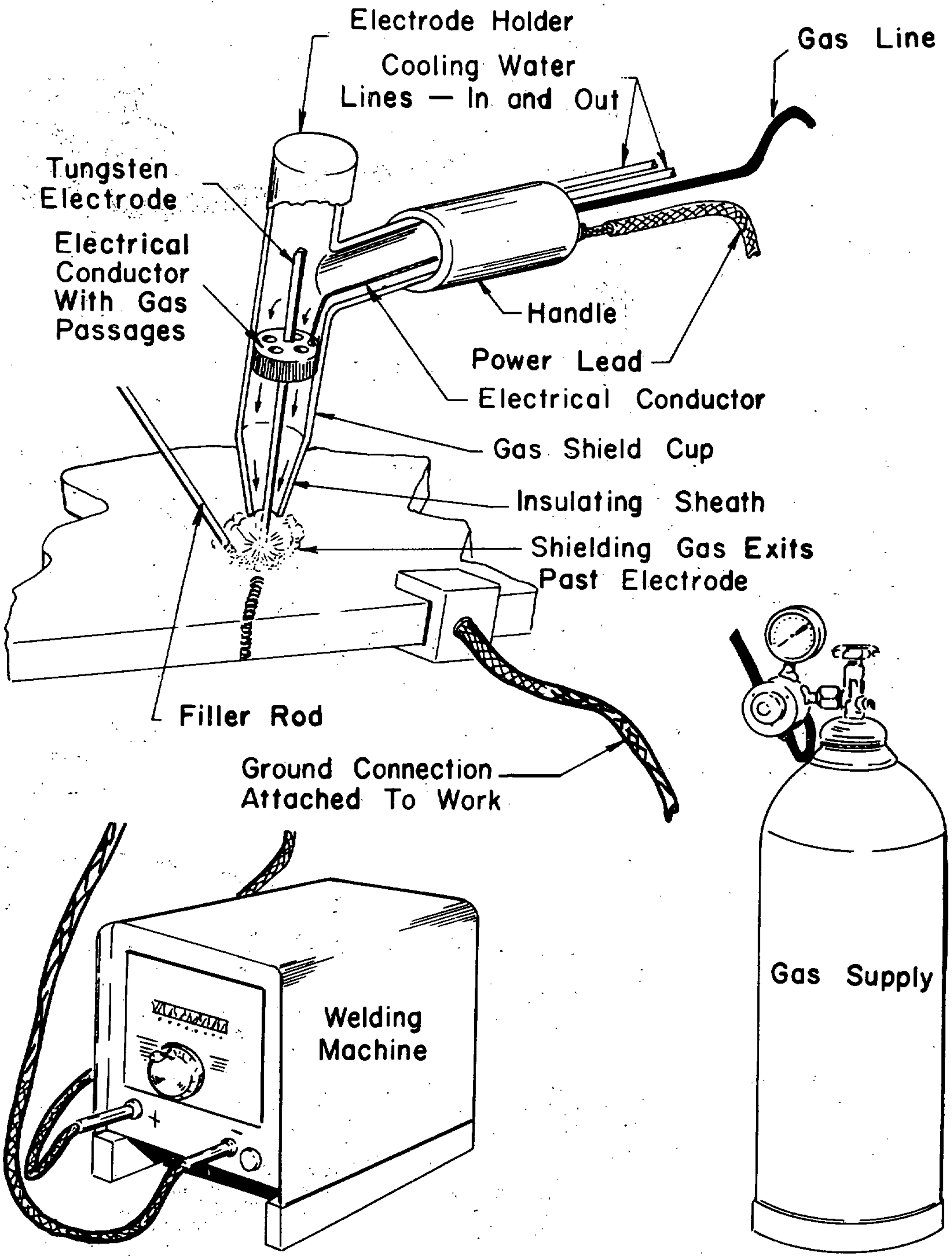


FIGURE 25. The Gas Tungsten-Arc (TIG) Welding Process

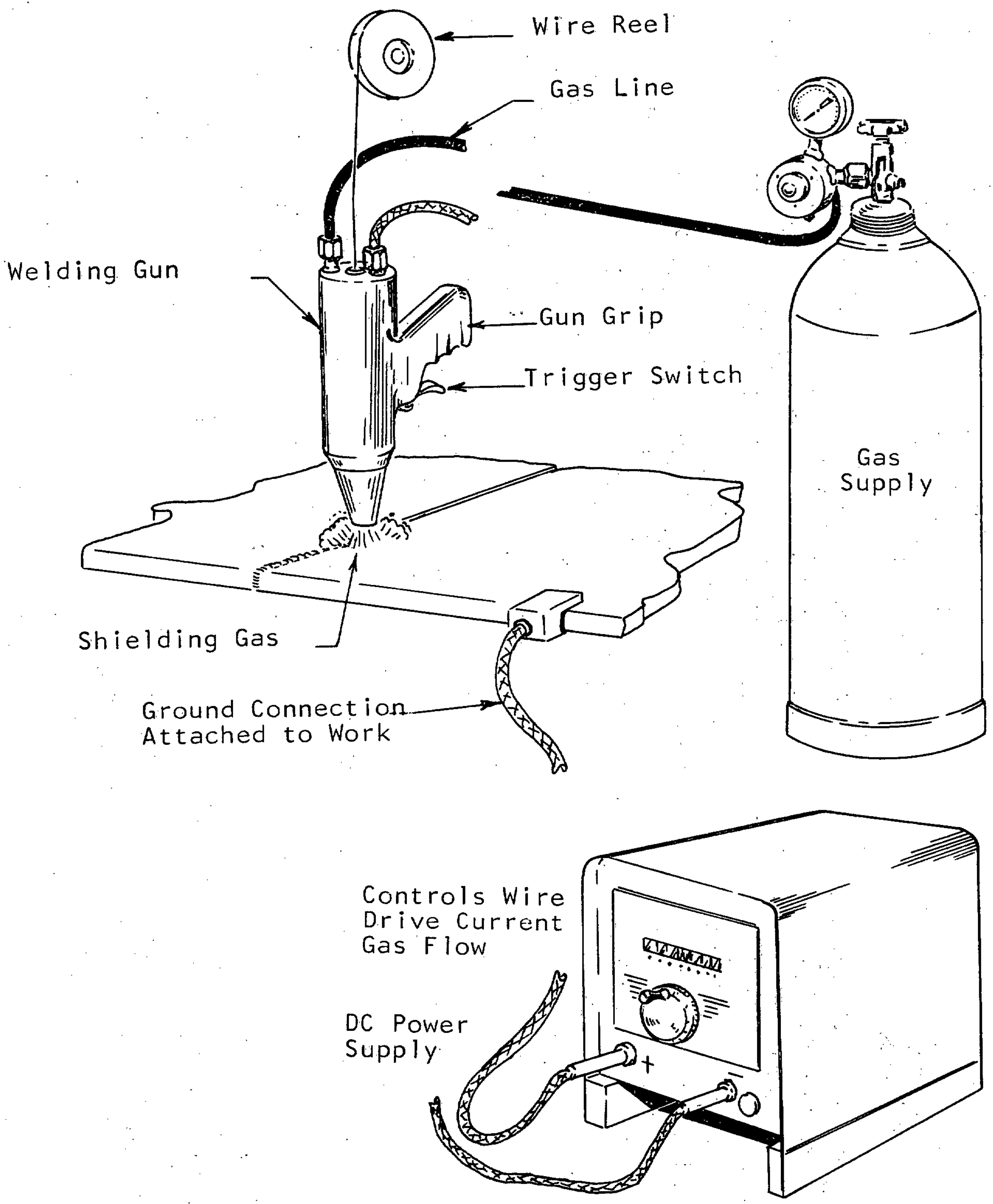


FIGURE 26. The Gas Metal-Arc (MIG) Welding Process

Joint design and preparation should be in accordance with the best practices recommended by the American Welding Society. Cleanliness of areas to be welded is very important in gas shielded-arc welding. All greases, dirt, paint and oxides should be removed from joint areas to prevent excessive porosity and inclusions in the weld deposit.

In general, preheating practices applicable to shielded metal-arc welding of carbon steels also apply to gas shielded-arc welding.

Filler rods meeting Class 1 requirements of Mil-R-5632 are used with the gas tungsten-arc process in the welding of low and medium carbon steels. A number of welding wires are available which are designed specifically for gas metal-arc welding of the low and medium carbon steels. These wires usually contain deoxidizers or other scavenging agents to prevent porosity or other damage to the weld metal from the oxygen, nitrogen or hydrogen that may be in the shielding gas or which may reach the weld from the surrounding atmosphere. Deoxidizing agents are essential in welding wires that are used *with shielding gases containing oxygen.* The deoxidizing elements generally used are manganese, silicon and aluminum.

(2) Low Alloy Steels. The gas tungsten-arc and gas metal-arc processes are both used for welding the low alloy steels; however, the gas tungsten-arc process is generally selected when optimum mechanical properties are required for highly stressed parts. Joint design and preparation are similar to that used in shielded metal-arc welding.

Preheating practices generally parallel those used for shielded metal-arc welding.

Several compositions of filler wire have been developed for use in gas metal-arc welding the low-alloy steels. Selection is usually based on composition of the steel to be welded and weld strength requirements. Generally the composition of the wire is similar to the base metal to be welded except that, in some cases, the carbon content is lowered in order to obtain improved ductility in the weld. Usually the lower carbon content is compensated for by increasing the alloy content of the wire. This often improves weld ductility and notch toughness without sacrificing tensile strength. Filler metal meeting Class 2 requirements of Mil-R-5632 may be used to weld low alloy steel structures which will be heat treated after welding to develop high mechanical properties.

44. **Submerged Arc Welding.** Submerged arc welding may be defined as a process in which the heat for coalescence is produced by an electric arc or arcs struck and maintained between a bare metal electrode, or electrodes, and the work under a shielding blanket of granular, fusible material. Pressure is not used and filler metal is obtained either from the electrode or from supplementary welding rod. *The basic feature of the submerged arc welding* process is the flux, a finely crushed mineral composition, which makes possible the special operating conditions involved in this process. In submerged arc welding the electrode is not in contact with the material being welded; the current is carried across the gap by the flux. The flux, when cold, is a nonconductor of electricity, but in the molten state it becomes a highly conductive medium. The flux is laid either manually or automatically ahead of the weld zone. It serves as a shield to protect the material from the atmosphere, and also as the conducting medium. The insulating effect of the molten flux blanket enables intense heat to be generated in the weld zone where the electrode and base metal are rapidly fused. Since the atmosphere is excluded, bare welding wire can be fed directly into the weld zone. The fused flux cracks off or can be readily removed upon cooling. Figure 27 shows the essential elements of the submerged arc process.

Alternating current transformers are the most widely used sources of power because of the high welding current required for submerged arc welding. However, standard motor-generator or rectifier-type dc welding power supplies can be used. Remote control adjusters, actuated by controls on the operator's panel, are generally part of the equipment. Both automatic and semi-automatic equipment can be obtained.

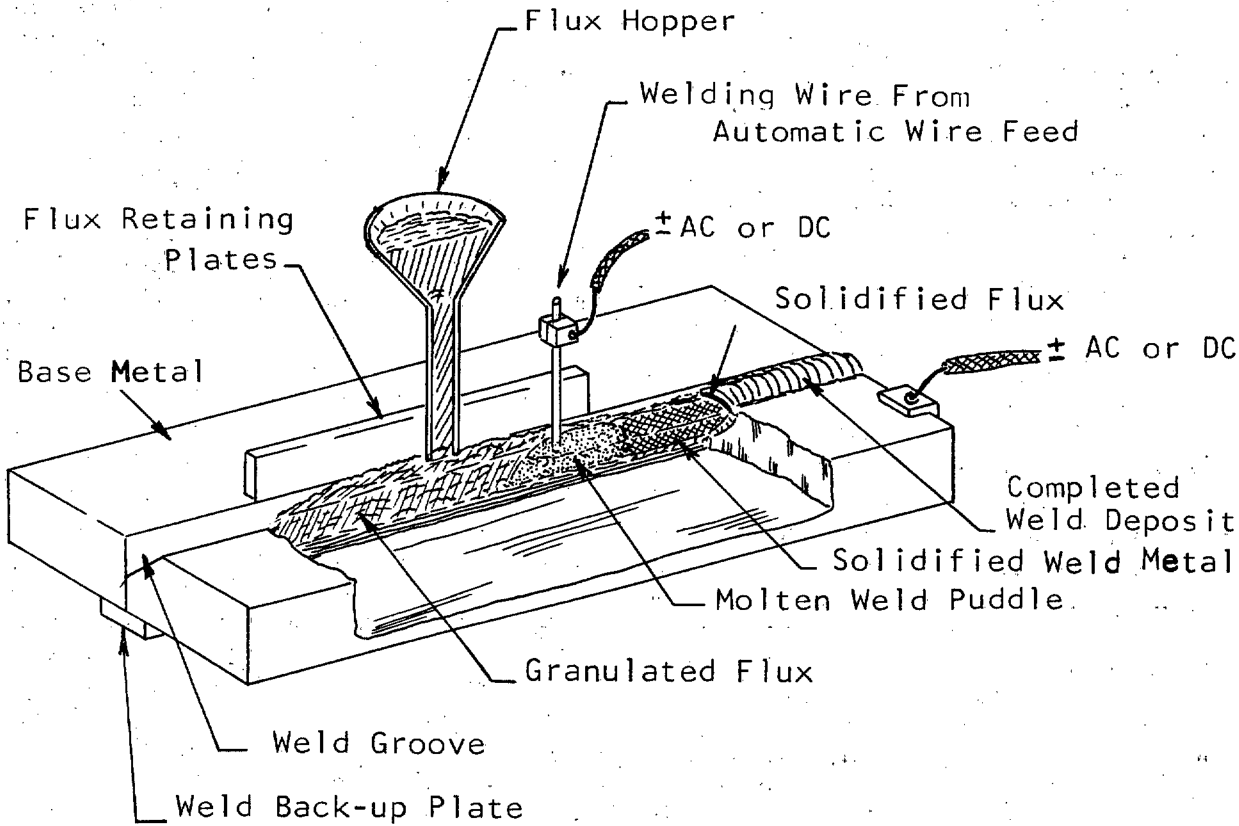


FIGURE 27. The Submerged Arc Welding Process

Electrodes are normally coiled, although straight lengths are sometimes used. Steel rods and wire supplied for carbon and low alloy steel welding are generally lightly coated with copper to improve the contact surfaces and to prevent rusting.

Alloy weld deposits are produced by (a) the use of an alloy steel wire or rod, (b) the use of a composite electrode, as a sheath enclosing a core of alloying elements, and (c) the use of a flux containing the alloying elements in conjunction with a low carbon steel electrode. Bare welding electrodes conforming with requirement of Mil-E-18193 may be used in conjunction with certain fluxes for welding many low carbon and low alloy steels.

The fluxes used in submerged arc welding are granulated. fusible, mineral materials of various compositions and particle sizes. Alloying elements may be included in their composition to be introduced into the molten weld metal during welding. The choice of flux depends upon several factors: (a) the welding procedure employed (b) the joint configuration, and (c) the composition of the base metal to be welded. Fluxes conforming with requirements of Mil-F-18251 and Mil-F-19922 are intended for use in conjunction with Mil-E-18193 electrodes.

The deep penetrating effect of the concentrated heat generated during submerged arc welding permits the use of small welding grooves. Consequently a smaller amount of filler metal is used in making a joint. Generally, the fused metal consists of about two parts of base metal to one part of filler metal. Joints should be designed in accordance with the recommendations of the American Welding Society.

Since the submerged arc process creates a large volume of molten metal which remains fluid for an appreciable time, some means must be employed to support and contain it until solidification takes place. This is accomplished by the use of temporary or permanent weld backing, Figure 27. As with other welding processes it is important that all paint, rust or scale, grease and dirt be removed from the areas to be welded.

Wrought iron can be readily welded using the same fluxes and electrodes that are used to weld low carbon steels. Slower welding speeds than those used in welding carbon steels are recommended to allow the greater volume of gases generated during welding to escape before the molten metal solidifies. Since the weld deposit is more like a low carbon steel than wrought iron, the second and subsequent passes, if required, can be made at normal speeds.

The submerged arc welding process is one of the leading welding processes used for joining low and medium-carbon steels. Moderately thick sections with a carbon content ranging up to 0.35 percent can be welded without precautionary measures such as preheating and postweld heat treatment. Preheating is generally necessary when the carbon content is over 0.35 percent.

The low alloy steels are easily welded using the submerged arc process. Precautions are usually necessary, however, to avoid cracking in the weld and heat affected zone. The heat treatable low alloy steels may be welded provided the weld area is preheated and the rate of cooling is slow. One important factor in welding these steels is the proper selection of filler metals and fluxes which will deposit weld metal capable of response to heat treatment after welding. Since some of the fluxes contain alloying elements, it is advisable to follow the manufacturer's recommendations in the choice of fluxes and wire.

In welding certain quenched and tempered structural steels, the heat input must be closely controlled to assure the retention of strength and notch toughness in the heat affected zone. Retention of a high level of strength and notch toughness in the heat affected zone of these steels depends on the rapid dissipation of heat to permit formation of desirable microstructures. Any practice that will retard cooling, such as preheating or high welding heat inputs, should be avoided whenever possible.

45. Forge Welding. The term "forge welding" encompasses a group of welding processes in which coalescence is produced by heating the material to be welded in a forge or other furnace after which welding is accomplished by applying pressure or by hammering. Forge welding processes include roll welding, hammer welding and die welding.

a. In hammer welding, the sections to be joined are heated in a forge or furnace until the surfaces to be joined are in a plastic condition. The surfaces are placed together and pressure is applied by means of hammer blows. The hammer blows may be applied manually with a sledge hammer or by more modern means such as with semi-automatic or automatic hammer welding equipment powered by hydraulic, steam or pneumatic equipment.

b. In die welding, the heated material is welded by pressing it between dies which are mounted in a suitable press.

c. Roll welding is used mainly to manufacture clad steel plates. After the material is heated it is passed through a set of rolls which apply the pressure to make the bond.

Several joint designs commonly used in manual and automatic forge welding operations are shown in Figure 28.

Wrought iron and low carbon steels are the materials most commonly forge welded. Temperatures somewhat higher than those required for steels are used in forge welding wrought iron. Since wrought iron is easily deformed at these temperatures the pressure applied must be carefully controlled to avoid excessive upsetting in the joint areas. The ductility of forge welded joints is notoriously low in the as-welded condition. Annealing after welding will refine the grain structure and improve ductility in the joint area.

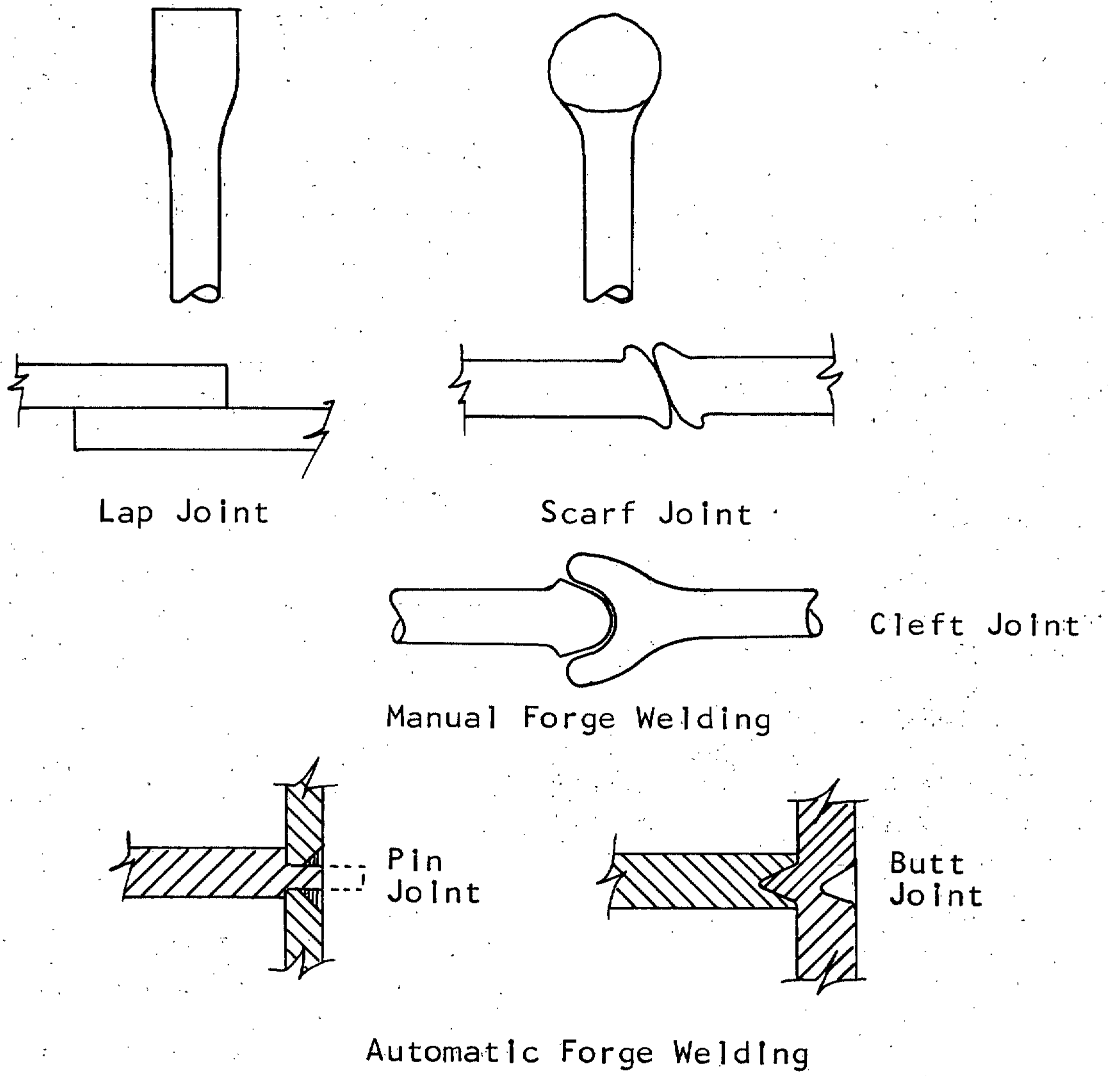


FIGURE 28. Joint Designs for Forge Welding

46. **Flash Welding.** Flash welding is a method of resistance welding in which heat is developed by the resistance to the flow of electric current across a gap between two surfaces to be joined. The two surfaces are positioned sufficiently close together to allow the flow of an electric current across the gap. When the two surfaces are heated to the fusion point they are brought into tight contact under sufficient pressure to cause upsetting to effect a joint. At this point the current is shut-off and the joint is allowed to cool. Figure 29 shows the flash welding sequence.

Most equipment in use today is either semi-automatic or fully automatic with controls which start and stop the current supply, sequence the motion of the movable platen, and in some instances, apply preheat and postheat to the joint area.

Flash welding heats the abutting surfaces to a plastic temperature. At these temperatures low alloy steels and carbon steels with moderate or high carbon content will tend to harden upon cooling unless the cooling rate is retarded. This may be done by including a postheating

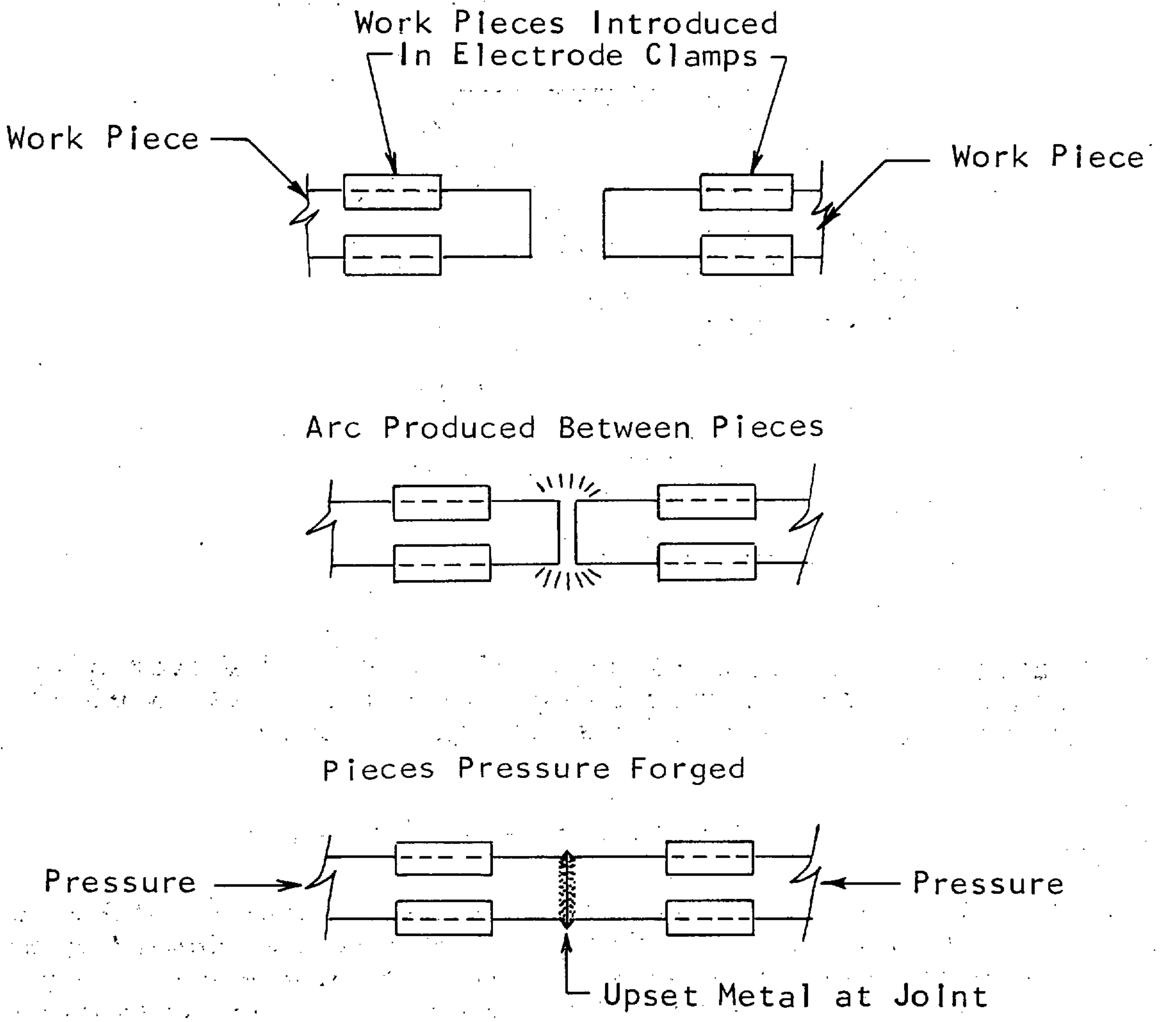


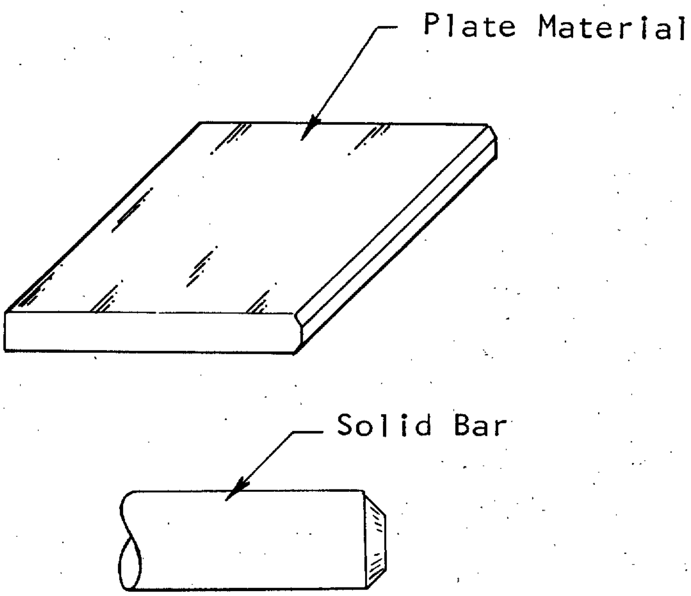
FIGURE 29. The Flash Welding Sequence

operation in the welding cycle. In some cases it is necessary to heat treat the entire welded assembly to obtain a uniform structure and hardness.

Most specifications governing the flash welding of steels, such as Mil-W-6873, require the establishment of flash welding schedules for each setup. This involves the preparation and testing of specimens to develop the proper equipment setup before production welding. All data necessary to insure satisfactory production parts are recorded on the weld schedule which governs production operations.

Probably the most important reason why flash welding finds limited application is the expensive testing requirements imposed on the process. Usually it is required that moderately or highly stressed parts be subjected to proof testing after welding (and heat treatment if required) to ensure joint integrity. This requirement together with the testing necessary to establish weld schedules greatly increases the cost of the process.

At times it is necessary to bevel one or both pieces of the joint, as shown in Figure 30, to facilitate flashing and obtain uniform heating



Size of chamfer depends upon thickness or diameter of material, capacity of welding machine, and upon whether one or both mating surfaces are chambered.

FIGURE 30. Joint Designs for Flash Welding

of both faces of the joint. This is particularly true with thicker materials. The surfaces of the parts contacting the electrodes and the surfaces to be joined should be free of dirt, grease, and oxides.

It is frequently necessary to remove all or part of the extruded or upset material after welding. They may be necessary in some cases only from the standpoint of appearance. Usually removal of internal flash from the joints of hollow shapes is not necessary.

47. Induction Welding. Induction welding is a welding process in which the heat for welding is produced by the resistance of the material to the flow of an induced electric current. Fusion may be accomplished with or without the application of pressure. The equipment for induction welding includes: (a) a source of alternating or pulsating current, (b) a device for transferring energy to the work piece, and (c) precise methods of controlling the energy input, the duration of input, and the rate of cooling. The available sources for alternating current are high frequency motor generator sets, vacuum-tube oscillators and spark-gap oscillators. Heating for welding occurs very rapidly, in the order of a few hundredths of a second, requiring the use of precise control devices. Inductor coils of copper tubing or bar, are generally used to transfer the energy to the work piece. The coil is usually formed to the geometry of the piece being heated and may be of single or multiple turn design. When the configuration of the work piece precludes using a surrounding coil, other shapes are formed and placed adjacent to the work piece.

The process is well adapted to the joining of thin sheet where a very localized heat affected zone adjacent to the weld is desired. Induction welding is used extensively in the continuous forming of tube and pipe from strip steel.

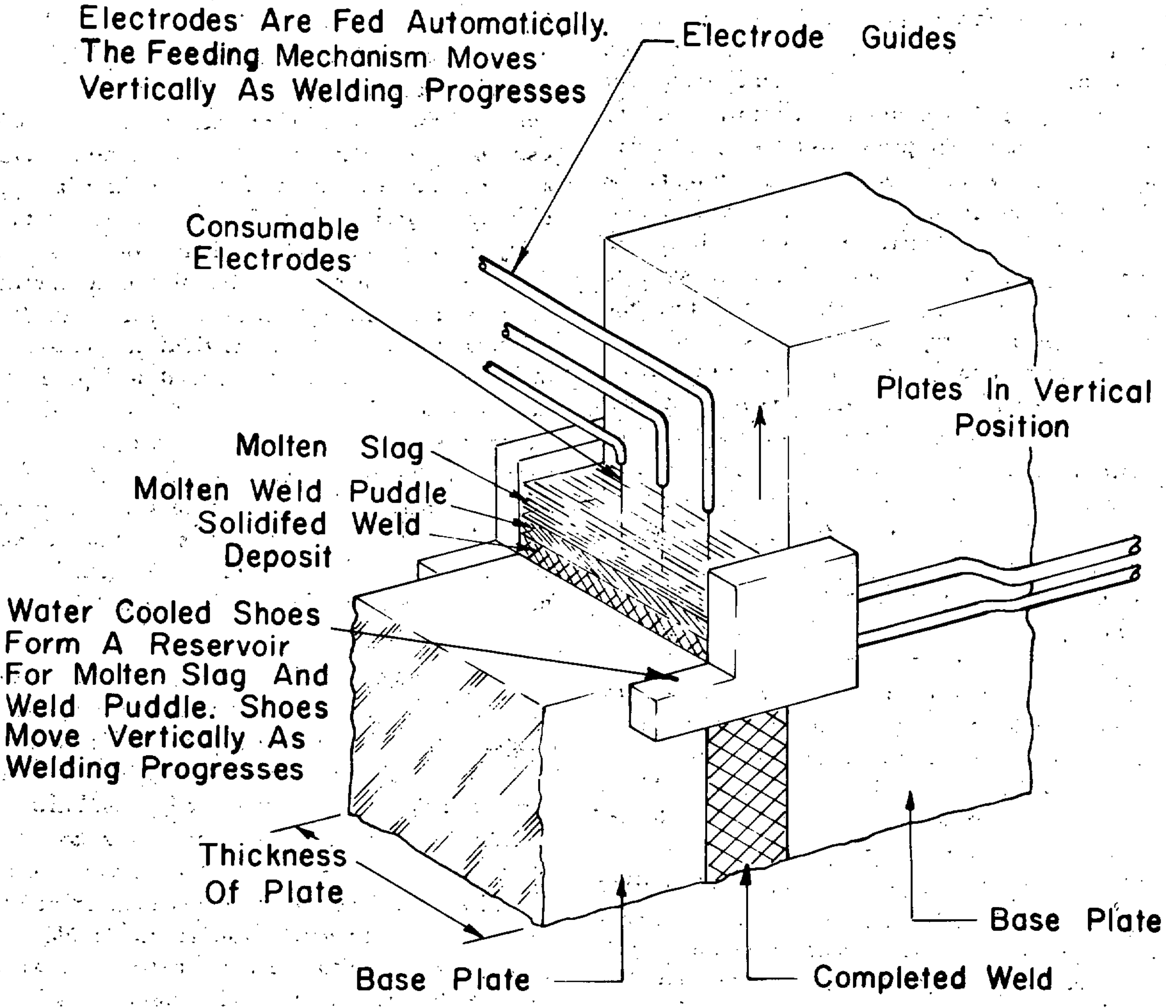


FIGURE 31. The Electroslag Welding Process

Postweld heat treatment may be performed by the welding equipment in cases where undesirable as-welded structures exist in the weld zone.

48. **Electroslag Welding.** Electroslag welding is a welding process which relies on molten slag to melt the filler metal and the base material to be welded. The weld pool is also shielded by the molten slag. The electrically conductive slag is maintained in a molten condition by its resistance to the current which flows between the electrode and the work. The electroslag process has unique features which set it apart from other forms of electric welding. The principle involves the fusion of parent metal and continuously fed filler metal under a layer of high temperature electrically conductive molten slag. Figure 31 is a schematic diagram of the electroslag process.

The electroslag process is applied mainly to the vertical welding of medium and heavy plate. Parts are assembled with a joint gap of approximately 1 to 1-1/2 inches. Joint edges need not be beveled. Square edges, either flame cut or machined, are satisfactory. A starting tab is necessary to build the proper depth of conductive slag before welding reaches the joint to be welded. A run-off tab is also required as a dam at the end of the seam. The arc is initiated, much like the submerged arc process, by starting an arc beneath granular flux dropped into the cavity. Arc energy, however, is used only initially to reduce the granular slag to a molten state. The molten slag then serves as a conductor through which current passes from the electrode to the work piece. Heat generated by the resistance to the flow of current through the molten slag and the weld puddle is sufficient to melt the edges of the base metal and the welding electrode into a pool beneath the slag. To obtain consistent energy dissipation a transverse motion, backwards and forwards, can be automatically imparted to the electrode wire as it is fed into the slag. For very heavy thicknesses, with suitable equipment, two or three wires may be fed into the same pool simultaneously. Water cooled copper shoes are used on each side of the joint to retain the molten metal and slag pool. As the pool of weld metal builds up the lower portion is continuously cooling to form a homogeneous weld with effective penetration of the base plates. Fresh flux must be added to the slag pool during welding to replace slag that solidifies into a thin layer on the surface of the weld as it cools. The thin layer on the surface can be easily removed.

Equipment for electroslag welding is usually designed and built to meet the special requirements of the user. The design generally depends on the range of thicknesses to be welded and degree of portability desired. The welding power is usually supplied by alternating current transformers, although direct current power sources may also be used.

The large quantity of heat generated during the electroslag welding operation preheats the base metal ahead of the actual welding zone. This is beneficial in two respects: (a) preheating is not required, and (b) the heat as it dissipates in the adjacent base metal tends to minimize residual stress in the weld area. Because of the thermal characteristics of the process, the welds have a coarse dendritic structure and a wide heat affected zone exhibiting considerable grain growth. By using suitably alloyed electrodes, mechanical properties equal to or better than the base metal can be obtained in the weld, notch impact energy excepted. Heat treating above the lower critical temperature of the base metal is recommended if high notch-impact properties are required. Austenitizing treatments such as normalizing, and, quench and tempering, refine the grain structure of the weld and heat affected zone with resultant improvement in mechanical properties. Also, a subcritical stress relieving has been found to be beneficial in improving weld ductility.

Experience has shown that it is good practice to use electrode wire with a lower carbon content than the base metal when medium carbon and low alloy steels are welded with the electroslag process. Usually additional alloying in the electrode wire is relied upon to obtain strength in the weld deposit equivalent to the parent metal. When heat treatment after welding is required, electrode composition should compare favorably with the base metal composition in order to achieve the desired properties in the weld deposit. Three types of wire that have been used with the electroslag process include: solid wires; flux cored wires; and braided wires.

Materials that have been successfully welded by the electroslag process include the low tensile strength structural steels (45,000 - 72,000 psi), the medium tensile strength structural steels (65,000 - 85,000 psi), and high tensile strength structural steels (75,000 - 100,000 psi). These include both carbon steels and low alloy steels. Several high strength heat treatable low alloy steels such as HY80, AISI 41XX and AISI 43XX have been successfully welded.

49. Friction Welding. Friction welding is a process in which mechanical energy is converted to thermal energy through friction. The most common method for friction welding is illustrated in Figure 32. Two cylindrical bars are aligned, one is rotated while the other is held stationary. The process is controlled by regulating the speed of the rotating member and the force at the rubbing surfaces to develop sufficient heat and metal displacement for welding.

Although the principles of friction welding are not new, application on a production basis is quite recent. However, the process has found wide acceptance and a number of friction welding machines have been developed with several speeds and adjustments to provide the necessary versatility.

The carbon steels and low alloy steels are readily welded by the friction welding process. The higher carbon steels and certain low alloy steels may require a postheat treatment depending upon the welding cycle employed and the intended service conditions. In general, the heat treatment of friction welded parts is much the same as flash welded parts.

50. Stud Welding. Stud welding is an arc welding process in which an electric arc is struck between a metal stud and another piece of metal. When the surfaces to be joined are properly heated they are brought together under pressure. Partial shielding may be obtained by the use of a ceramic ferrule surrounding the stud.

In stud welding, a stud welding gun is used to properly position the stud on the work piece. Manual pressure holds the stud on contact with the work piece so that the welding circuit is completed. After the circuit is completed the gun automatically withdraws the stud a short distance to create a gap and an electric arc. Then, simultaneously, the flow of electric current is stopped and the stud is plunged into the puddle of molten metal which has formed on the surface of the work piece. The process is similar to conventional arc welding because, in effect, the stud serves as a consumable electrode while the current is flowing. Figure 33 is a schematic diagram of the stud welding process.

The equipment used in stud welding consists of a source of dc welding current, a stud welding gun, ferrules for shielding the arc, and controls, including timing devices. The equipment is usually designed with portability in mind, although stationary equipment for large scale operations are in wide use today.

Welding studs are usually supplied with a quantity of welding flux either recessed within or permanently attached to the welding end of the stud. Generally, welding studs are made from low carbon steels with a carbon content ranging from 0.15 to 0.23 percent. Minimum tensile properties in the order of 60,000 psi ultimate strength, 50,000 psi yield strength, and 20 percent elongation in 2 inches are often specified.

In practice the same restrictions that apply to the metal-arc welding of carbon steels apply to stud welding. Carbon steels with a carbon content up to 0.30 percent may be welded without preheating. When the carbon content exceeds 0.30 percent, particularly in heavy sections, preheating is advisable in order to prevent cracking in the heat affected zone. In some cases, a combination of preheating and postheating has proven beneficial.

Low alloy steels may be satisfactorily stud welded without preheating provided the carbon content is held to 0.12 percent maximum. Preheating is necessary when the carbon content exceeds 0.12 percent to avoid cracking in the heat affected zone.

The heat treatable high-strength low-alloy structural steels require more attention since these steels usually are sufficiently hardenable to form martensite in the heat affected zone. These steels are quite sensitive to underbead cracking and usually the weld area is low in ductility. Preheating to about 700 °F is recommended when steels of this category are stud welded.

51. Spot Welding. Spot welding is a resistance welding process. Lapped work pieces are positioned between two electrodes to which pressure is applied to hold the work pieces together. Resistance to the electric current passed through the material between the electrodes produces sufficient heat to effect local

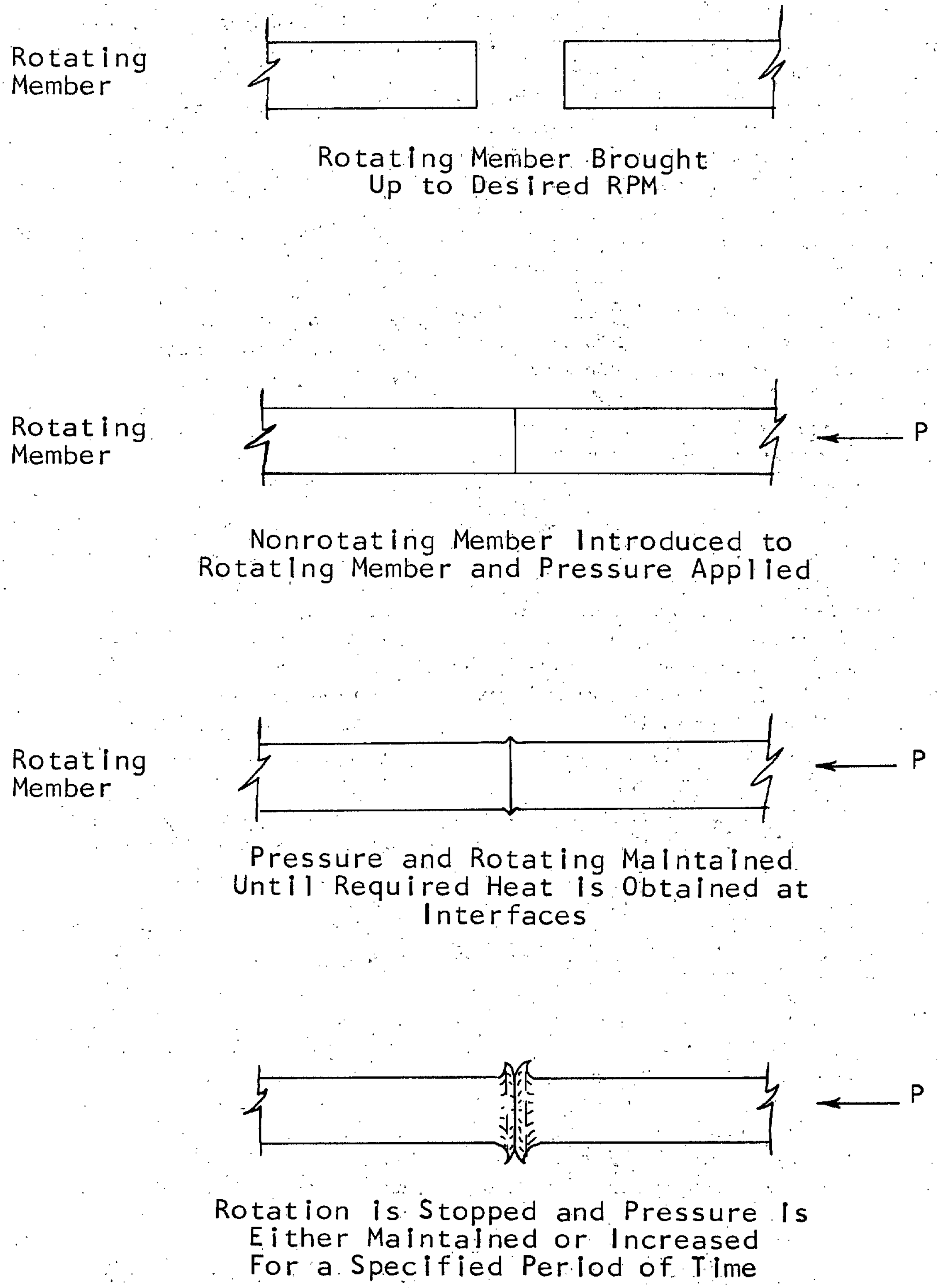


FIGURE 32. The Friction Welding Process

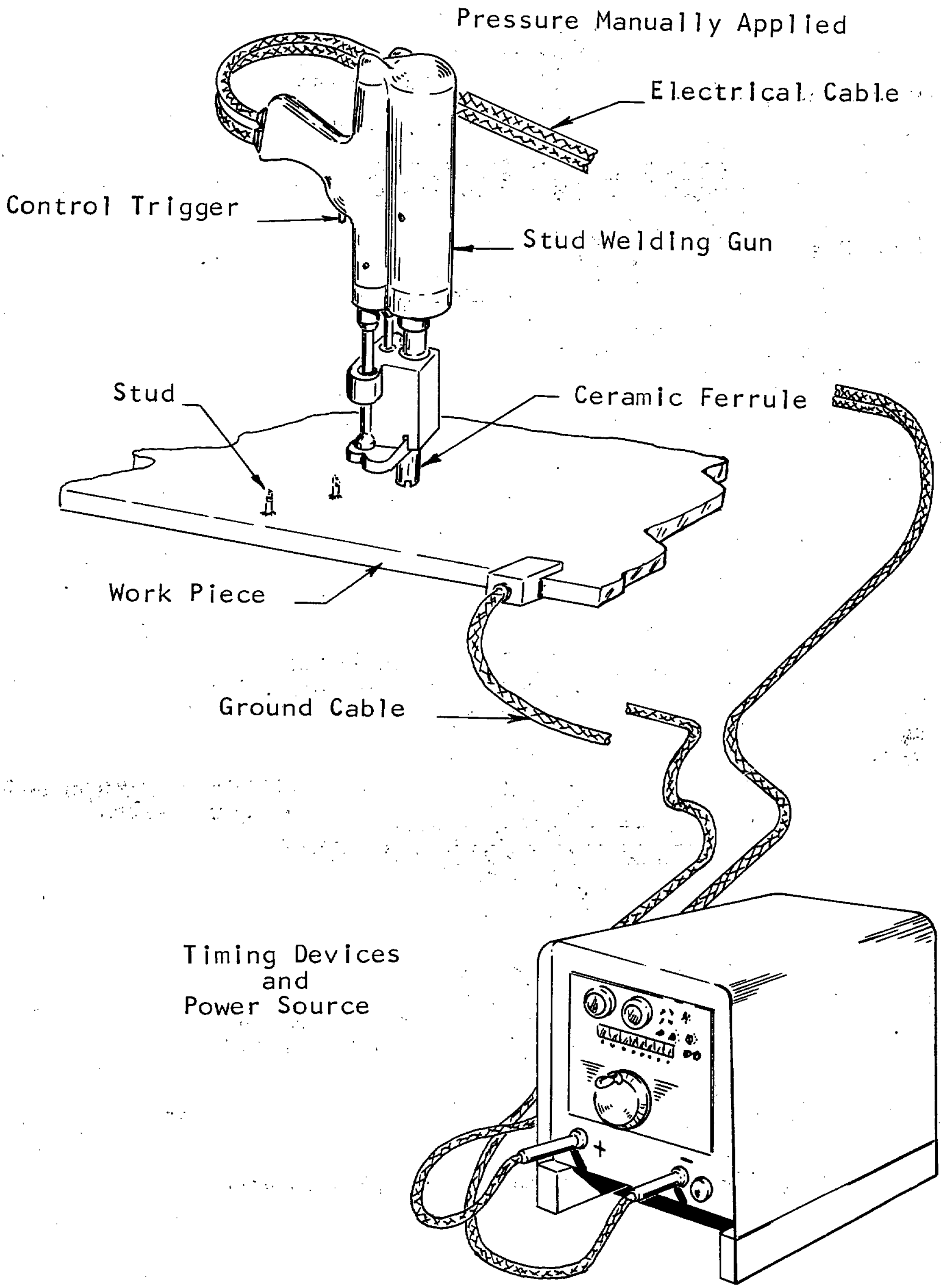


FIGURE 33. The Stud Welding Process

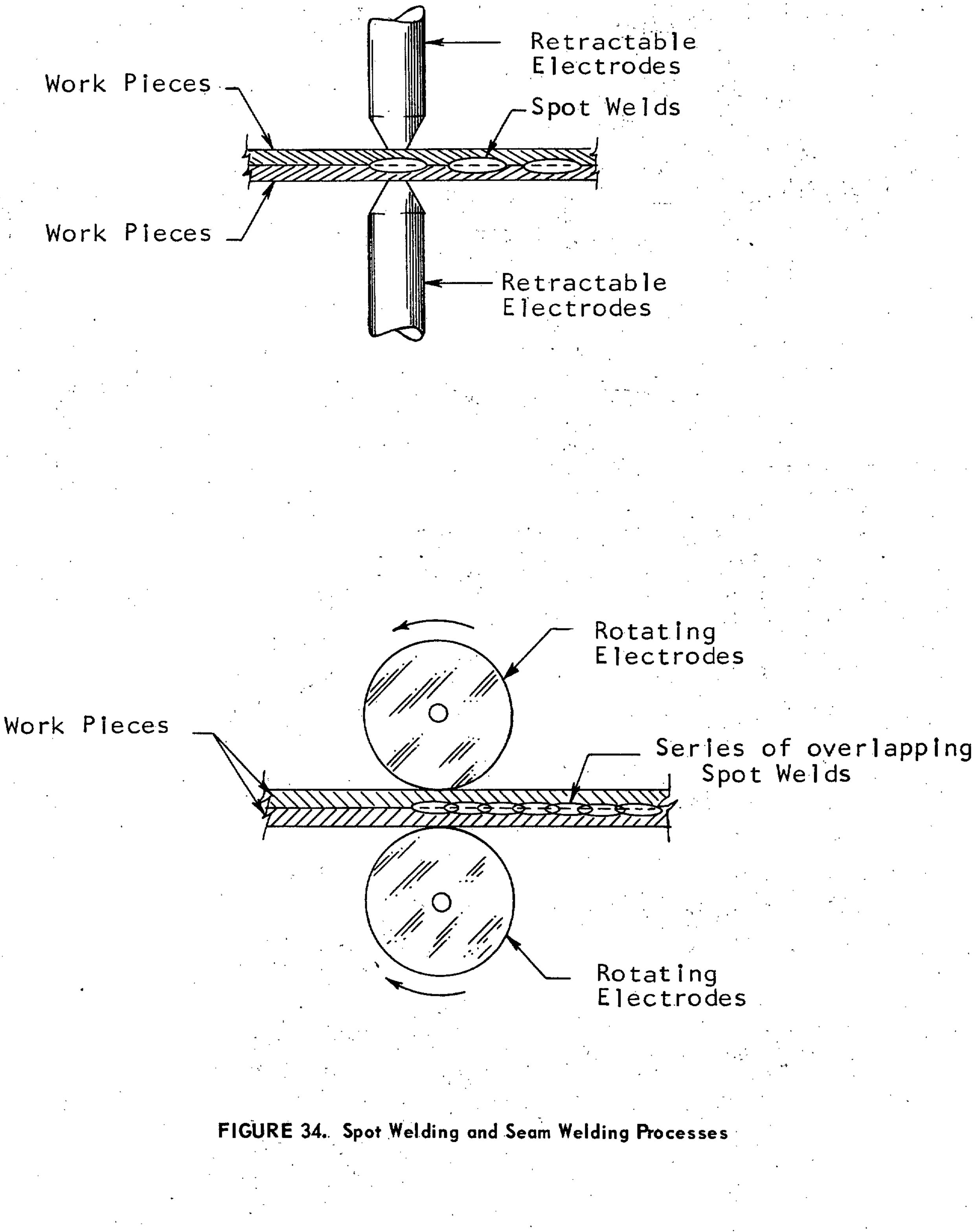


FIGURE 34. Spot Welding and Seam Welding Processes

fusion of the work pieces. The size and shape of the individually formed welds are limited by the size and shape of the electrodes.

a. Roll-spot welding. A spot welding process in which circular, rotating electrodes are used to produce a series of aligned, spaced, spot welds.

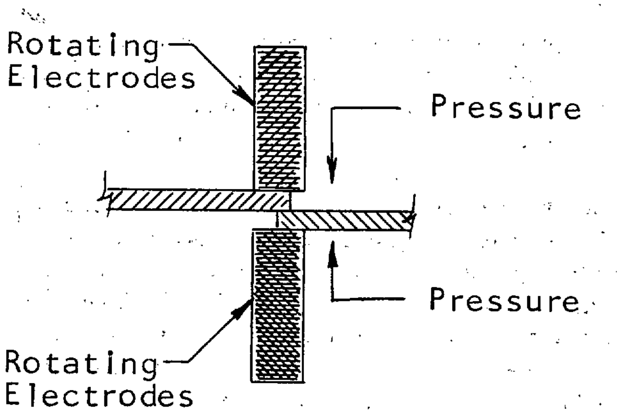
b. Seam welding. A spot welding process in which circular, rotating, electrodes are used to produce a series of aligned, overlapping spot welds.

Figure 34 shows the characteristic differences between spot and seam welding. The important difference between spot and seam welding is that in spot welding the electrodes are withdrawn out of contact with the weld area after each individual weld or simultaneously made group of welds, whereas in seam welding at least one rotating electrode maintains continuous pressure on the weld area.

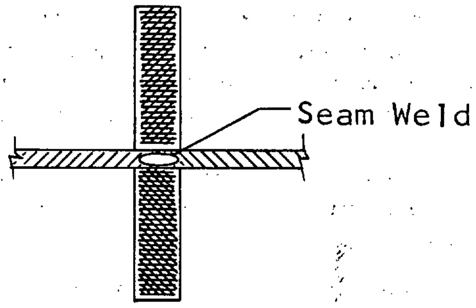
One widely used modification of the seam welding process is known as "mash welding". This produces a weld in which the overlap of the mating pieces comprising the joint is much less than for the conventional seam welded joint. High quality joints can be produced by mashing down the double thickness of an overlap to approximately the thickness of one member of the assembly. Figure 35 shows a mash seam weld set up. Low carbon steel sheet up to 1/16 inch thick can be successfully mash welded if the overlap distance is held to 1-1/2 times the stock thickness. Tack welding or clamping to maintain the overlap ahead of the electrodes is advisable.

Basically, a spot or seam welding machine consists of three principal elements:

(1) The electrical circuit including the welding transformer, and a secondary circuit including electrodes, which conducts the welding current through the work pieces.



Before Welding



Completed Joint

FIGURE 35. Mash Seam Welding

(2) A mechanical system consisting of the frame and apparatus for holding the work and applying the necessary welding force or pressure.

(3) Equipment for controlling various functions of the process such as current initiation and duration, current magnitude and other process sequences.

The surfaces of the parts to be welded should be free from dirt, grease, paint, oxides or other films since these foreign substances tend to increase surface resistance, with resultant variation in the amount of heat generated at the weld area. Consequently, weld quality and consistency suffer. There are numerous methods of cleaning used in preparing steels for spot and seam welding. The most widely used include vapor degreasing, chemical cleaning, wire brushing and scraping.

Most specifications that govern the production of high quality spot and seam welds require the development of welding schedules which establish specific values for all of the welding variables before production welding is permitted to start. The suitability of the schedule is usually determined by the preparation and testing of a specified number of samples. A weld schedule is required for each material, or combination of materials and each combination of thicknesses that will be welded in production. The weld schedule should be strictly adhered to in production welding to maintain a high level of weld quality.

High quality spot or seam welds are dependent upon good design, the use of proper welding procedures and effective in-process controls. In designing the weld joint, consideration must be given to the spacing of spot welds with respect to one another to avoid shunting losses through prior welds. Minimum edge distances (location of weld with respect to sheet edge) must be established to prevent weld metal expulsion from between the joint members.

In high quality welding, representative samples from each welding machine are tested periodically to ensure that a high level of weld quality is being maintained during production. The usual practice for high quality spot and seam weld production is to compare samples with established quality standards on the basis of a number of factors which affect weld quality. These factors, in general, are related to the weld structure and include the following:

(1) Penetration Requirements: Penetration into the base metal is ordinarily permitted to vary from 20 to 90 percent of the thickness of the member.

(2) Weld Symmetry: Welds should be symmetrical around the plane of the faying surfaces.

(3) Weld Diameter: Minimum weld nugget diameters are generally related to minimum shear strengths required.

(4) Interface Expulsion: Generally caused by excessive current and results in internal cavitation that usually reduces weld strength.

(5) Cracks and Porosity: Cracks and porosity within the weld nugget are caused primarily by excessive current and insufficient electrode force.

(6) Lack of Fusion: Lack of fusion at the weld interface may be due to insufficient current or weld time.

(7) Surface Appearance and Electrode Pick-Up: Electrode pick-up usually results from improperly cleaned electrode tips (or faces in seam welding). Excessive current may be a contributing factor.

(8) Surface Indentation: Excessive surface indentation results from the use of excessive heat or weld time, excessive electrode force or improperly contoured electrodes.

(9) Sheet Separation: Excessive sheet separation results from the same causes as excessive surface indentation. Sometimes edge cracks accompany excessive sheet separation.

Spot or seam welding of carbon steels is usually limited to low carbon steels with a maximum of 0.15 percent carbon content. Higher carbon contents require the use of special welding techniques involving a machine postheating cycle to avoid undesirable weld structures, cracking and extremely low ductility in the weld region.

Welding of low-alloy and high-strength low-alloy structural steels requires special welding techniques to reduce the hardness and avoid excessive brittleness in the weld area. Means can be provided in the machine for preheating and/or tempering the weld zone to improve ductility.

Some of the low-alloy high-strength structural steels may be welded without the benefit of preheating in the machine. In such cases welding is followed by tempering in a furnace at about 1100°F to eliminate any undesirable weld zone microstructures and to improve weld ductility.

52. Projection Welding. Projection welding is a resistance welding process wherein coalescence is produced by the heat obtained from resistance to the flow of electric current through the work pieces held together by electrode pressure. The resultant welds are localized at predetermined points by the design of the parts to be welded. The localization is usually accomplished by projections, bosses or intersections.

Projection welding is a modification of the spot welding process. Machines and process controls similar to those employed in spot welding are used. One big difference in equipment is the electrode employed in projection welding. The pointed or domed electrodes used in spot welding are replaced by electrodes with flat or recessed faces as shown in Figure 36. Projection welding electrodes are often designed to maintain alignment of the parts during welding and to act as work locators.

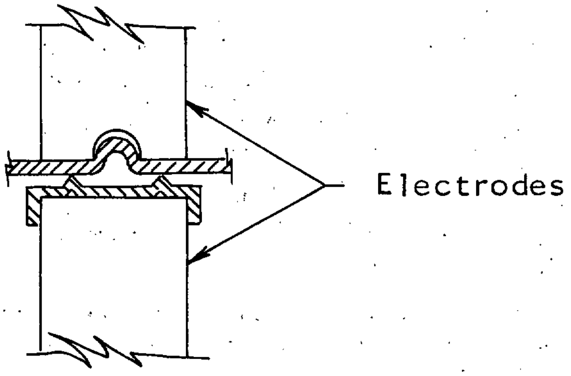


FIGURE 36. Projection Welding

Projections are formed in various ways such as by forming in a punch press or by machining. They may be of circular cross section or they may be square, oval or elongated depending upon the configuration of the parts to be welded. Parts with typical welding projections are shown in Figure 37. When the parts to be welded are of differing thickness, the projections are usually mounted on the thicker material, in order to maintain heat balance on both sides of the weld.

Projection welding lends itself well to the joining of relatively small parts that can be assembled in holding jigs prior to introduction into the welding machine. Examples include many types of studs, nuts, screws and stampings. Projection welding of steels is generally confined to the low carbon variety with less than 0.20 percent carbon content.

53. Residual Stresses.

a. General. When two pieces of steel are joined by welding, the weld metal and adjacent heat-affected base metal undergo considerable expansion on heating, and contract upon cooling to room temperature. If the two pieces are free to move they will be drawn closer together during contraction of the weld metal. If conditions are such that the pieces cannot move freely toward each other during contraction, then the weld area is said to be "under restraint". The forces set up by the restraining action create residual or "locked-in" stresses in the weld region. Generally the stresses are the highest in the metal near the center of the weld, which is the last to cool.

b. Stress relief. Although not always the case, residual stresses in welded structures are considered to be detrimental. There are two practical methods of reducing or eliminating residual stresses in welded structures: (a) thermally (stress relief heat treatment), (b) peening (hammer blows on the weld deposit).

Peening is frequently used to relieve residual stresses but its effectiveness is questionable because the method is difficult to control. Stress relief by thermal means is the more effective of the two. This is usually accomplished by heating the entire welded structure in a furnace or by local heating with a gas torch.

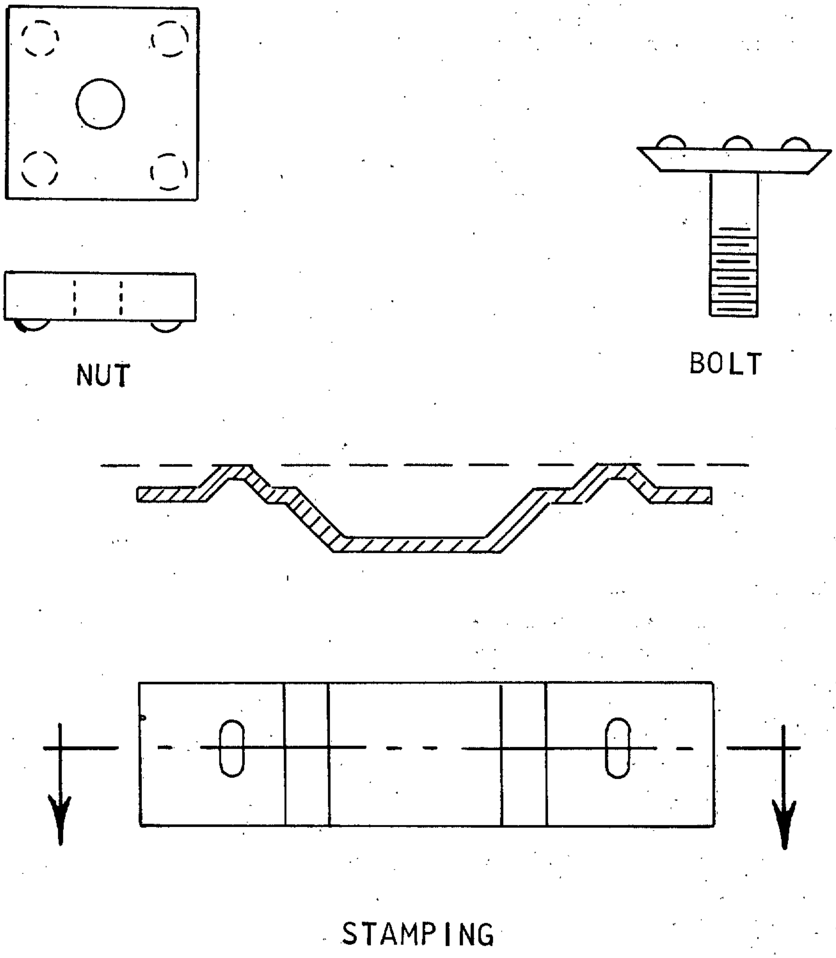


FIGURE 37. Examples of Fasteners and Clips Designed for Projection Welding

In general, the stress relief of low carbon and low alloy steel welded structures is accomplished at temperatures ranging from 1100°F to 1200°F. Usual soaking time at temperature is one hour for each inch of thickness, with a one hour minimum. Cooling should be as gradual as possible.

c. ***Control of residual stresses.*** Much can be done to control residual stresses during the fabrication of welded structures, for example:

(1) The assembly and welding sequences should permit movement of the detail parts during welding. Joints of maximum fixity should be welded first.

(2) An intermittent sequence of welding such as "skip" or "backstep" welding is often advantageous.

(3) The introduction of bending stresses during welding should be avoided.

(4) Avoid overwelding, i.e., excessively large welds.

(5) Peening of all weld beads, except root and last bead, in multiple weld bead joints may be helpful.

d. ***Cracking.*** While the cracking conditions described below may occur in many of the low carbon and medium carbon steels, low alloy

Cracking of welded joints results from the presence of localized stress which at some point exceeds the ultimate strength of the material. When cracks occur during welding, usually little or no deformation is apparent.

Probably the most troublesome form of cracking that occurs in the weld deposit is termed "hot cracking". Factors that lead to the formation of "hot cracks" in the weld deposit are high joint rigidity, the contour of the weld bead, a high carbon content and a high sulphur or silicon content. This type of cracking usually occurs in the last metal to freeze and is intergranular in nature. A convex bead is less susceptible to cracking than a concave bead. A stress concentration is developed at the thinnest and hottest part of a concave bead during cooling from the welding temperature, and a convex bead, because of its thicker center section, is less likely to crack.

Small star-shaped cracks are one type of hot crack associated with weld craters. Unless special care is exercised, there is usually a tendency to form a weld crater when the welding operation is interrupted. Crater cracks may be starting points for longitudinal weld cracks, particularly when they form in a crater at the end of a weld bead. To avoid crater cracks it is necessary to fill the crater with additional metal before breaking off the welding operation. Preheating usually minimizes any tendency toward hot cracking by reducing stresses in the area.

A basic problem encountered in welding many of the low alloy steels is a type of cracking termed "underbead cracking". When underbead cracking occurs it is invariably located under the fusion zone in the heat affected zone of alloy steels. Figure 38 illustrates underbead cracking. Underbead cracking is attributed to the affect of dissolved hydrogen released from the austenite as it transforms. This type of cracking in alloy steels can be virtually eliminated by preheating and the use of a low hydrogen welding process. There is no tendency toward underbead cracking in low carbon steels.

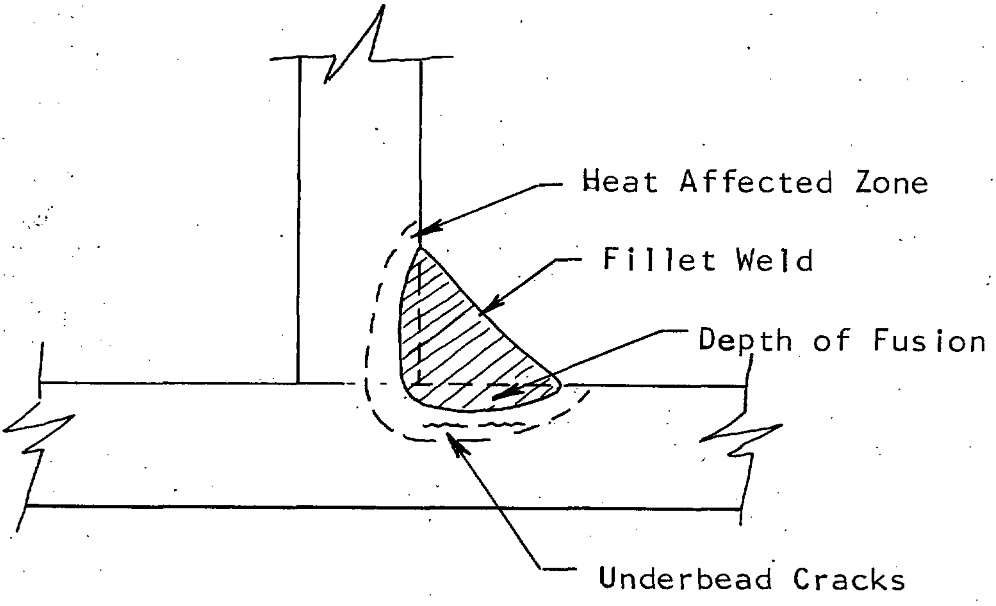


FIGURE 38. Underbead Cracking in a Fillet Weld

Sometimes cracks occur within the heat-affected zone of the base metal. These cracks are usually longitudinal in nature and almost always associated with the hardened zone developed in hardenable steels, such as the medium carbon and low alloy steels. Hardness and brittleness in the heat-affected zone of the base metal are metallurgical effects produced by the heat of welding and are the chief factors which tend to cause cracking during welding. When base metal cracking is encountered with hardenable steels, improvement can be obtained by (a) using a suitable preheat, (b) increasing heat input which will tend to retard the cooling rate, and (c) selecting the most suitable electrode for the steel being welded.

54. Brazing. Brazing is a term used to describe a group of welding processes wherein coalescence is produced by heating to suitable temperatures above 800°F and by using a nonferrous filler metal having a melting point below that of the base metal. The filler metal is distributed between the closely fitted surfaces of the joint by capillary attraction. In the brazing process there is no melting of the metals that are being joined. The molten brazing alloy flows between the heated surfaces of the joint members by capillary action, or it is melted in place between the surfaces to be joined. The bond between the brazing alloy and base metal is obtained by slight diffusion of the brazing alloy into the heated base metal, by surface alloying of base metal with the brazing alloy, or by a combination of both.

Brazing processes have been classified according to the heating method used. Heating methods commonly employed in brazing carbon and alloy steels include the following:

a. Torch brazing - the most commonly used method. Gas mixtures may be air-gas, air-acetylene, oxyacetylene, or other oxy-fuel gases.

b. Furnace brazing - used extensively when parts can be preassembled or jigged and when atmosphere control is required. The atmosphere may be one of a number of types, combusted fuel gas, dissociated ammonia, high purity hydrogen, purified inert gases or vacuum atmospheres.

c. Induction brazing - used when parts are self jigging or can be fixtured easily, and when rapid, economic heating is required, as with large production runs of single items.

The brazing alloy classifications used for brazing carbon and low alloy steels include the

TABLE VII. BRAZING ALLOYS FOR CARBON AND LOW ALLOY STEELS

Brazing Alloy	Brazing Temperature Range (°F)	Remarks
BCu (Copper)	200 to 2100	Lap and butt joints commonly used.
RBCu-Zn-A (Copper-Zinc)	1670 to 1750	Overheating should be avoided because voids may form in joints as a result of entrapped zinc vapors.
BAg-1 (Silver Base)	1145 to 1440	Flows freely into capillary joints.
BAg-1A (Silver Base)	1175 to 1400	Low temperature applications. Free flowing.
BAg-2 (Silver Base)	1295 to 1550	Good "bridging" characteristics. Forms fillets readily.
BAg-5 (Silver Base)	1370 to 1550	Cadmium free. Applications involving "step" brazing.
BAg-18 (Silver Base)	1325 to 1550	Good "wetting" in controlled atmosphere or vacuum brazing without flux.

copper and copper-zinc alloys and the silver base alloys. It should be noted that the copper-phosphorus brazing alloys should not be used for joining ferrous alloys because the phosphorous content may cause the formation of brittle phosphides at the interfaces of the joint and brazing alloy. Cracking will occur through the brittle phosphide if the joint is stressed after brazing. Characteristics and usability of the filler alloys for brazing carbon and low alloy steels are presented in Table VII.

Brazing alloys can be obtained in strip, wire and powder form. Department of Defense and industry specifications governing the procurement of brazing alloys include QQ-S-561, Mil-B-15395 and AWS A5.8.

A variety of brazing fluxes are available. Selection is usually based on the temperature range to be used in brazing. Fluxes are specially compounded mixtures of fluorides, borides and wetting agents which melt below the melting temperature of the brazing alloy, clean the surface prior to alloy flow, prevent oxidation of the brazing alloy and base metal surface during brazing, promote flowing of the brazing alloy, and cause it to wet the surfaces being brazed. Fluxes should be removed as soon as possible after brazing is completed. Many fluxes are corrosive and may cause corrosion in the joint.

Basically there are two types of joints used in brazing; they are the lap joint and the butt joint. The lap joint provides the strongest joint of the two, since the overlap can be adjusted to develop strengths in the joint equal to or better than the parent metal despite the lower unit strength of the brazing alloy. Joint design and joint clearance should be selected in accordance with practices recommended by the American Welding Society. Figure 39 shows several typical brazed joint designs. Cleanliness of the surfaces to be joined is of prime importance in brazing, particularly when brazing will be accomplished by the controlled atmosphere furnace method without the application of fluxes.

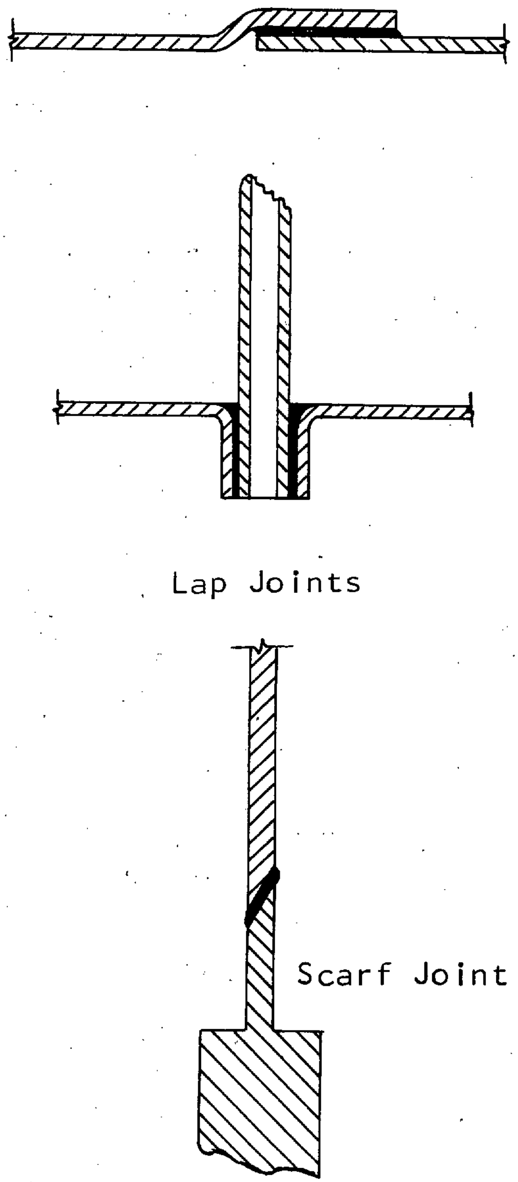


FIGURE 39. **Examples of Brazed Joints**

When brazing the carbon and low alloy steels with copper or copper-zinc alloys there is some grain growth in the base metal because of the high brazing temperatures involved. The accompanying decrease in mechanical properties may not be objectionable for some applications. When necessary, the grain structure and mechanical properties of the material can be improved by reheating the brazed assembly above the critical range of the steel, provided the brazing alloy used has a melting temperature above the austenitizing temperature of the steel.

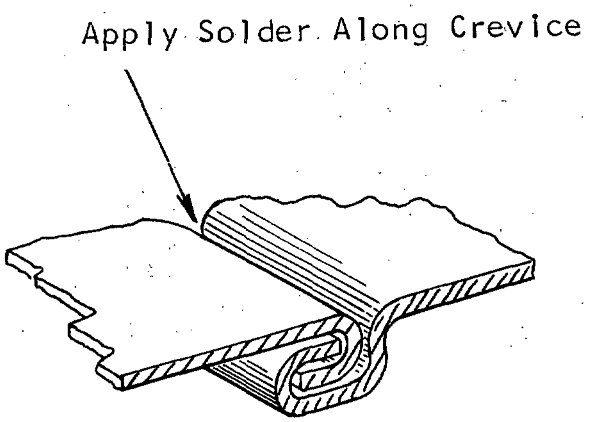
55. Soldering. Soldering is defined as a joining process wherein coalescence between metal parts is produced by heating to suitable temperatures generally below 800°F and by using nonferrous filler metals (solder) having melting temperatures below those of the base metals. The solder is usually distributed between the properly fitted surfaces of the joint by capillary attraction.

The more common heating methods employed in soldering include the soldering iron, or soldering copper as it is sometimes called, torch, oven or furnace, and induction coil.

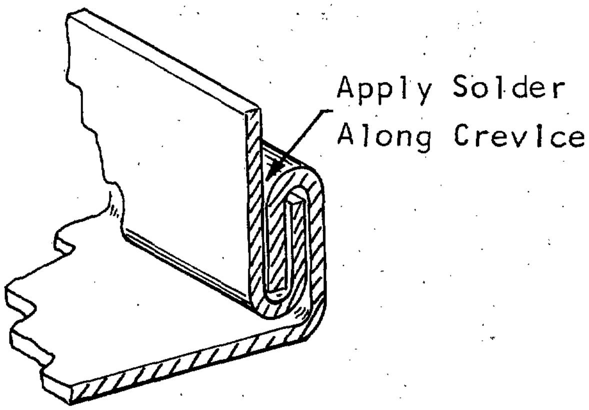
The two basic types of joints used in soldering are the conventional lap joint and butt joint. Joint clearances of .002 to .005 inch are recommended, however, clearances ranging to .010 inch have been used. Higher strengths can be obtained with the lap joint. Joint strengths considerably higher than attainable with the conventional lap joint are possible by interlocking the parts to be joined and employing the solder only to seal the joint. Figure 40 shows typical interlock joint designs. In order to obtain maximum bond strength, the surfaces to be joined must be thoroughly cleaned. Foreign materials such as grease, oil, dirt, scale and finger marks should be eliminated to insure uniform and continuous contact between the solder and the base metal. Cleaning may be accomplished by degreasing, acid cleaning, or by wire brushing, shot blasting, filing, or grinding. Mechanical cleaning has the advantage over the other methods in that the surface is roughened thus creating little irregularities against which the solder can solidify. This results in increased gripping power.

The most common solders are composed of tin and lead in varying amounts. Solders with special properties may also contain antimony, silver, bismuth or indium. Most of the common solders are included in Federal Specification QQ-S-571 and industry specifications ASTM B-32 and ASTM B284.

The main function of a flux is to promote good wetting action between the solder and the base metal. Fluxes may be highly corrosive, mildly corrosive, or noncorrosive depending on the ingredients. They are available in either liquid or paste form. Fluxes, both liquid and paste, can be procured to Federal Specification O-F-506.



Interlock Butt Type Joint



Interlock Corner Joint

FIGURE 40. Interlock Solder Joints

Flux residues that might corrode the base metal or prove harmful to the soldered joint must be removed or neutralized after the soldering operation is completed. This is particularly important in cases where the service environment might be humid. A noncorrosive type flux should be used in cases where, for reasons of joint design, all surfaces are not accessible to removal of flux residues after soldering.

56. Inspection of Welds, and Brazed or Soldered joints. Weldment defects may be classified as being in three general categories: dimensional defects, structural discontinuities, and those associated with the properties of the weld or welded joint. The purpose of this section is to briefly describe some of the defects encountered in welding practice and the inspection methods used to establish the soundness and integrity of a weld or weldment. For a more complete treatment of the subject reference should be made to the Inspection Handbook for Metal-Arc Welding published by the American Welding Society.

The acceptance of weldments depends upon, among other things, the maintenance of specified dimensions whether it be the size and shape of welds or dimensions of a completed assembly. Any departure from the specified requirements should be regarded as a dimensional defect subject to correction before final acceptance of the weldment.

Welding involves the application of heat to local sections of the material. Expansion and contraction of the heated metal creates stresses of varying magnitude which persist after cooling. These stresses cause warpage and distortion in welded assemblies. Warpage or distortion is controllable, to a large degree, by the judicious use of peening, clamps, jigs, or fixtures and by proper welding sequence. Warpage or distortion is often corrected by a straightening operation which may involve the application of heat.

The size of a fillet weld is based on the length of the shortest leg in its triangular cross section. The effective throat thickness of a fillet weld is the shortest distance from the root to the face of the diagrammatic weld. For example, the effective throat thickness of an equal leg 45 degree fillet weld is 0.707 multiplied by the normal leg size of the weld, as shown in Figure 41. The size of a butt weld is based on the joint penetration plus the root penetration when so specified. The profile of a weld may have considerable effect upon its performance in service. Excess convexity tends to produce notches, while excess concavity may actually reduce the strength of a weld. Figure 42 illustrates acceptable and defective weld profiles. Weld size deficiencies may be detected visually and with the aid of suitable weld gauges. Weld size deficiencies can be corrected by selecting the proper size filler metal, and employing the proper welding technique. Undercut and overlap are the result of improper welding technique. These defects can be detected visually and are illustrated in Figure 43. Incomplete penetration of butt welds welded from one side may be detected visually provided the side opposite to the welding side is accessible for viewing. Incomplete root penetration in fillet welds and butt welds welded from both sides cannot be detected visually.

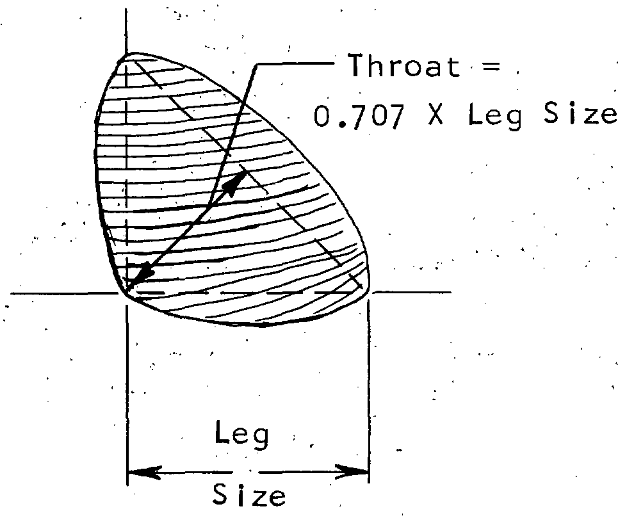


FIGURE 41. Effective Throat Thickness of an Equal Leg 45 Degree Fillet Weld

Cracks may occur in the weld deposit, adjacent parent metal, or both. Cracking in weld joints results from the presence of localized stress which at some point exceeds the ultimate strength of the material. Cracks open to the surface can be detected visually.

Low power magnifying glasses, magnetic particle inspection and penetrant inspection are methods used to detect external discontinuities.

Internal discontinuities that may be present in the weld zone include porosity, non-metallic inclusions, incomplete fusion and cracks. Inspection and test methods employed to detect

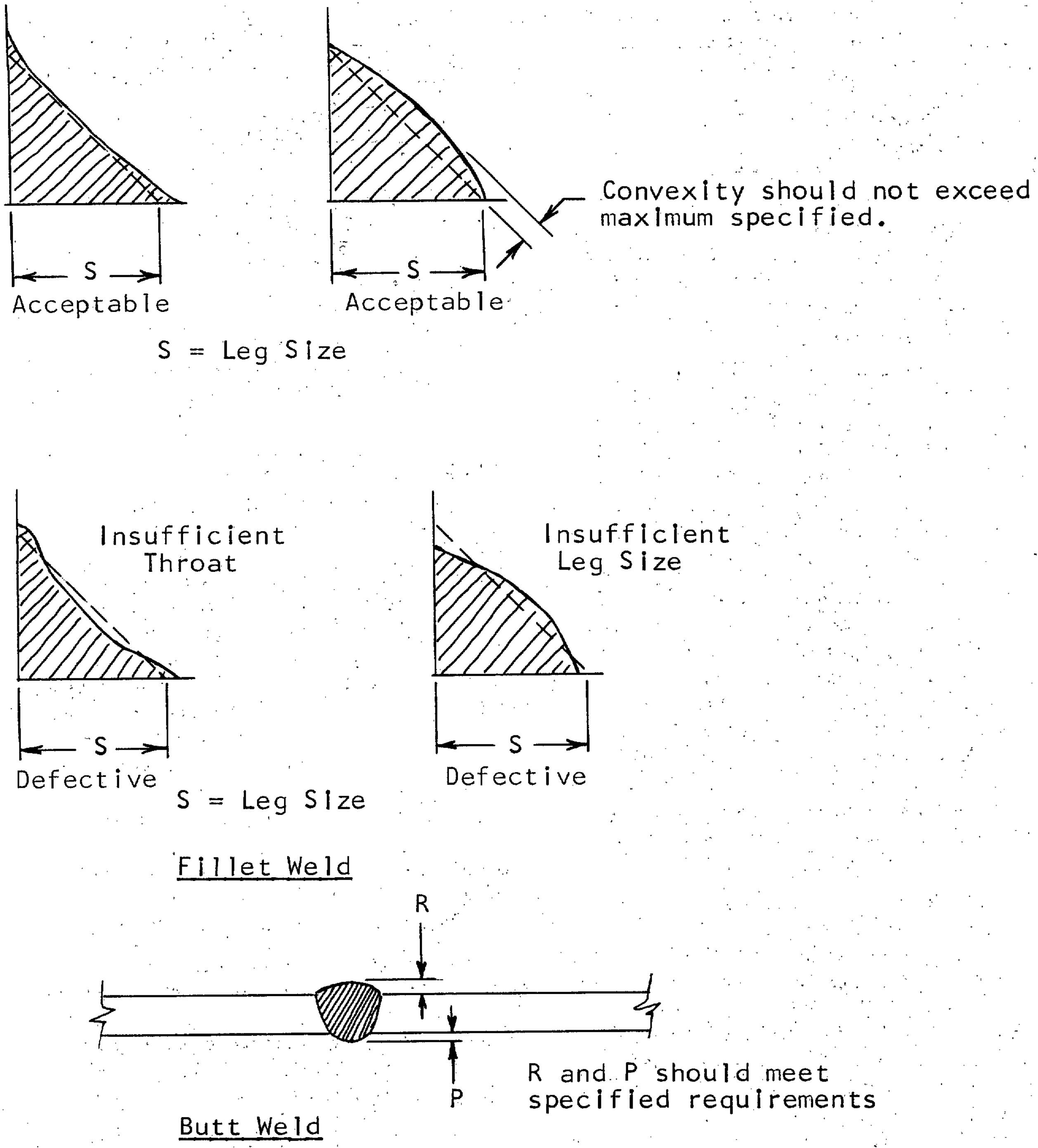


FIGURE 42. Acceptable and Defective Weld Bead Profiles

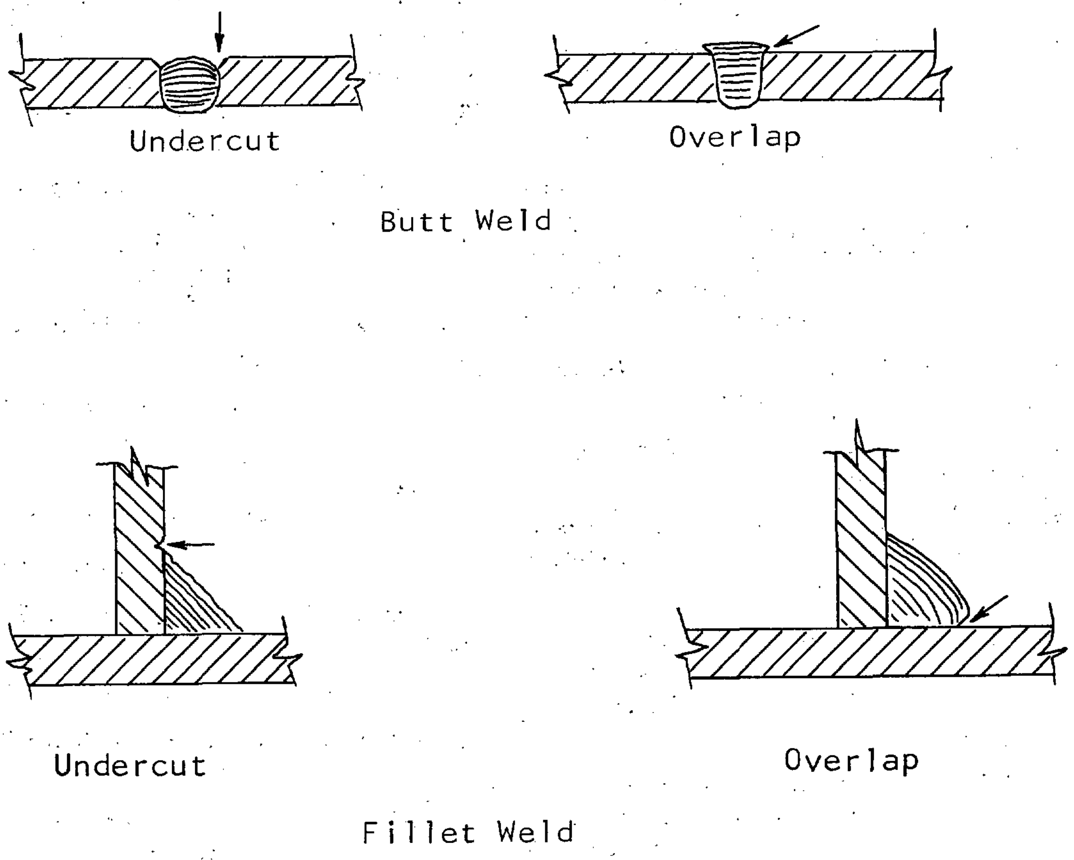


FIGURE 43. Undercut and Overlap in Fillet and Butt Welds

internal defects include radiographic examination, ultrasonic inspection, magnetic particle inspection, fraction test, bend test, and microscopic or macroscopic examination. Porosity and inclusions are usually the result of improper precleaning or poor gas coverage. Incomplete fusion can usually be traced to improper welding procedures.

Specific mechanical and chemical properties are required of all weld joints in any given weldment. The requirements depend on the specifications involved and any departure from the specified requirements should be judged as a defect. These properties may be determined by testing pre-fabrication or in-process test plates, although in many cases sample weldments taken from production are tested.

Resistance welds (spot, seam and projection) and brazed or soldered joints generally must meet the standards required by the contract or design drawings. Methods of inspection are usually dictated by the requirements.

The criteria for acceptance of carbon and low alloy steel weldments are generally a part of, or referenced in, most specifications, codes, standards and regulations controlling welding practices today. Some specifications contain two or more levels of acceptance based upon known service requirements or the intended function of the welded part. The following specifications, codes and standards largely control welding practices today. Included are specifications related to brazing and soldering practices.

DEPARTMENT OF DEFENSE

Mil-W-41	Welding of Armor, Metal-Arc, Manual with Austenitic Electrodes, for Aircraft.
Mil-W-6858	Welding, Resistance, Aluminum, Magnesium, Non-Hardening Steels or Alloys, Nickel Alloys, Heat Resisting Alloys, and Titanium Alloys, Spot and Seam.
Mil-S-6872	Soldering Process, General Specification for.
Mil-W-6873	Welding, Flash, Carbon and Alloy Steel.
Mil-B-7883	Brazing of Steels, Copper, Copper Alloys, and Nickel Alloys.
Mil-W-8611	Welding, Metal-Arc and Gas, Steels, and Corrosion and Heat Resistant Alloys, Process for.
Mil-W-12332	Welding, Resistance, Spot and Projection, for Fabricating Assemblies of Low Carbon Steel.
Mil-B-12672	Braze-Welding, Oxyacetylene, of Built-Up Metal Structures.
Mil-B-12673	Brazing, Oxyacetylene of Built-Up Metal Structures.
Mil-W-21157	Weldment, Steel, Carbon and Low Alloy (Yield Strength 30,000 - 60,000 psi).
Mil-W-45223	Welding, Spot, Hardenable Steels.
Mil-W-46086	Welding, Homogeneous Armor, Metal Arc, Manual.
MIL-STD-278	Welding and Inspection of Machinery, Piping and Pressure Vessels for Ships of the United States Navy.
MIL-STD-1261	Welding Procedures for Constructional Steels.
NAVSHIPS 0900-000-1000	Fabrication, Welding and Inspection of Ship Hulls.
NAVSHIPS 0900-006-9010	Fabrication, Welding and Inspection of HY-80 Submarine Hulls.
MIL-HDBK-721(MR)	Corrosion and Corrosion Protection of Metals
H-56	Arc Welding

INDUSTRY

ASME	Boiler and Pressure Vessel Code.
AWS D1.0	Code for Welding in Building Construction.
AWS D2.0	Specifications for Welded Highway and Railroad Bridges.
ASA B31	Code for Pressure Piping.
API Standard 1104	Field Welding of Pipelines.
SAE AMS 2665	Silver Brazing.
SAE AMS 2666	Silver Brazing (High Temperature)
SAE AMS 2667	Silver Brazing (For Flexible Metal Hose)
SAE AMS 2668	Silver Brazing (Flexible Metal Hose - 400°F Max Operating Temperature)
SAE AMS 2669	Silver Brazing (Flexible Metal Hose - 800°F Max Operating Temperature)
SAE AMS 2670	Copper Furnace Brazing (Carbon and Low Alloy Steels)

57. Mechanical Fastening. The number of mechanical fasteners and fastening methods other than those briefly described herein is almost infinite. The most common mechanical fastening methods employed include lock seaming, rivets, screws, nuts and bolts.

Low carbon steel sheet and strip in thicknesses of 1/16 inch and less lend themselves well to joining by lock seaming. Figure 44 shows a typical lock joint design. The open seam may be soldered if a leak tight joint is desired (Figure 40).

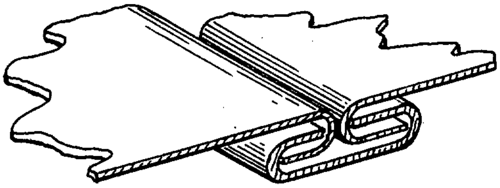


FIGURE 44. Lock Joint Design

Riveting is a common method used to join low carbon and low alloy structural steels. Its use, however, has been overshadowed somewhat by the higher joint efficiencies obtainable with joints of welded design. Rivet types and sizes in use are multitudinous. Rivet designs include universal heads, flat heads, and countersunk heads with solid or tubular shanks. Riveting may be accomplished either hot or cold depending upon the application. The chief advantages of riveting are that it affords a quick method of joining and, as practiced cold, it avoids the hazards of heating (warping and distortion) that are encountered in welding.

A wide variety of screws are used in joining steel components. Screws are available in numerous sizes and designs including flat fillister heads, drilled fillister heads, oval fillister heads, slotted hex heads, hexagon socket heads, slotted hexagon shaped heads and slotted flat countersunk heads with either solid or drilled out shanks. Screws may be either carbon or low alloy steel and may be obtained with a cadmium, zinc or phosphate protective coating.

Nuts and bolts are commercially available in a wide assortment of sizes and types including round heads, square heads, hexagon heads, drilled heads, square and hexagon socket type heads with solid or drilled out shanks. They may be obtained with cadmium, zinc, black oxide or phosphate coating for added corrosion resistance.

Chapter 4

Selection Criteria

INTRODUCTION

This chapter is concerned with the identification and application of selection criteria that are the basis for determining the suitability of an alloy for a particular application. Iron and wrought steel products are used primarily as structural members which must carry an applied load. Therefore the mechanical properties of these materials are of special interest. For this reason, tensile properties and related mechanical properties, elastic and plastic behavior, brittle fracture, and fatigue are discussed in detail.

In addition to these mechanical properties, certain pertinent physical properties, corrosion, stress corrosion, propellant compatibility, thermal conductivity and expansion, and density are discussed.

In the final section of the chapter the problem of materials selection as related to design requirements, material availability, costs, materials properties, and manufacturing considerations, is discussed.

MECHANICAL PROPERTIES

58. Elasticity. Consider a rod being acted upon by external forces, Figure 45. The intensity of load is called the stress in the rod. Stress is defined as the magnitude of the load divided by the area over which it acts.

$$f = \frac{P}{A_o} \qquad (1)$$

where:

f = stress

P = applied load

A_o = the original cross-sectional area

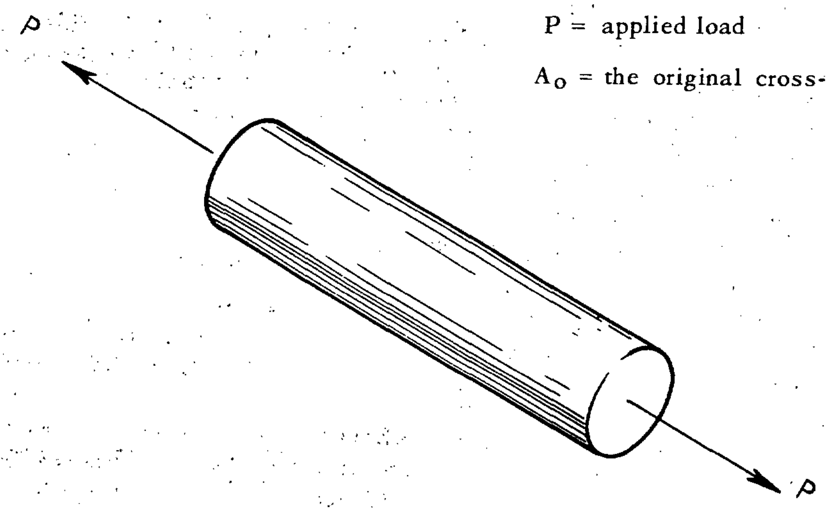


FIGURE 45. A Rod Subjected to Tensile Loading

Stresses may be either tensile or compressive and are usually expressed in units of pounds per square inch (psi) or a similar load per unit of area term. A tensile stress is one which would tend to make the bar shown in Figure 45 longer, a compressive stress would make it shorter.

If a force acts normal to a given cross section, the resultant stress is a normal stress. If the force acts parallel to a cross section the resultant stress is a shear stress, and the magnitude of this shear stress is obtained by dividing the force by the area of the face.

$$f_s = \frac{P}{A} \tag{2}$$

where f_s = shear stress

P = applied force acting parallel to the cross section

A = cross-sectional area

An example of shear stress is given by a pin joining two plates, as shown in Figure 46. The shear stress in the pin is:

$$f_s = \frac{P}{A}$$

where A = cross sectional area of the pin parallel to the applied load.

Every stress is accompanied by a corresponding deflection, or change in dimension, in the stressed member. For the tensile loading shown in Figure 47 the rod will increase in length an amount δ. If the loading direction was reversed and the bar was put in compression, it would increase in length an amount δ, providing that the magnitude of load remained the same. When the deflection δ, is divided by the original length, L_o, a value defined as normal conventional strain is obtained. $e = \frac{\delta}{L_o}$, e = strain in units of inches per inch (in/in).

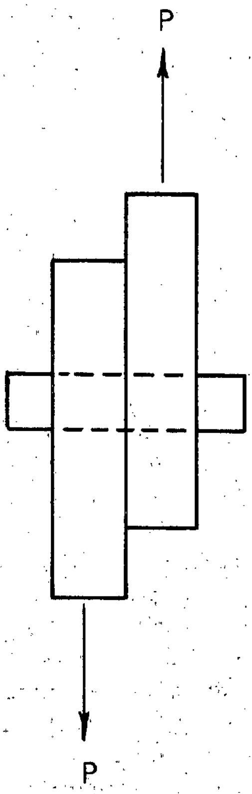


FIGURE 46. Shear Loading

Stress and strain are related by a constant, Young's Modulus, which is commonly called the Modulus of Elasticity, E, usually expressed in pounds per square inch.

$$E = \frac{f}{e} \tag{3}$$

where f = stress

e = strain

E = modulus of elasticity (about 30,000,000 psi for steel)

Knowing this relationship, based on Hooke's Law, if either f or e is known the other can be calculated.

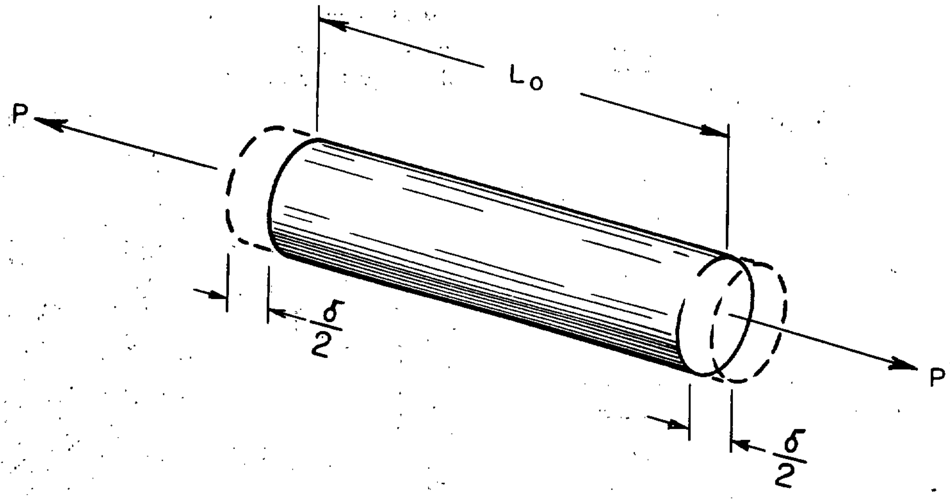


FIGURE 47. Deflection in a Rod Subjected to a Tensile Load

Shear strain, which is more complex in definition, can be described by considering Figure 48. If the rectangle is displaced by a force so that it assumes the configuration described by the dotted lines, the shear strain (e_s) is defined as:

$$e_s = \frac{\delta}{d_o}$$

Shear stress and shear strain are related in the same manner as are normal stress and strain.

$$f_s = G e_s \tag{4}$$

where G = shear modulus, $G = \frac{E}{2\,(1 + \mu)}$

E = modulus of elasticity

μ = Poisson' ratio (about 0.3 for steel)

The tensile properties of a material are determined by subjecting a specimen to an increasing tensile load until failure of the specimen occurs. Depending upon the instrumentation of the test, a load-deflection or a load-strain curve is usually obtained.

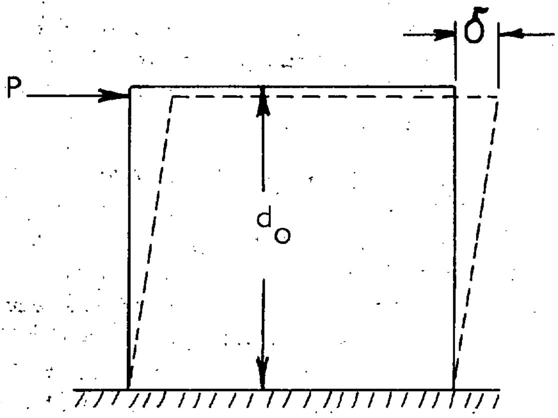


FIGURE 48. Shear Deflection

The curve in Figure 49 represents either of these curves. For engineering applications this curve is converted to a stress-strain curve, Figure 50. This curve has the same shape as the load-strain curve and is obtained by converting the load to stress by dividing the load by the cross sectional area of the specimen.

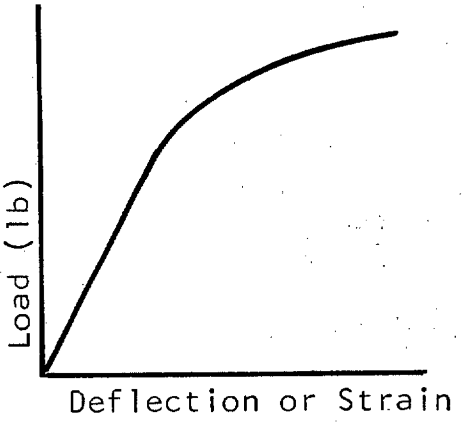


FIGURE 49. A Load-Deflection Curve

The stress-strain curve can be divided into two regions; the elastic region and the plastic region, as indicated in Figure 50. The initial straight line portion of the stress-strain (or load-deflection) curve is the elastic region. Here stress and strain are related by f = Ee, where E is the elastic modulus and is the slope of the stress-strain curve.

If a material is loaded to a stress, f_1, in the elastic region a corresponding strain e_1, will occur, Figure 51. When the load is removed the total elastic strain will be recovered. If the total load is not removed but is instead reduced to f_2, then the total existing strain will be e_2, and the amount of strain recovered will be $e = e_1 - e_2$. This strain can be calculated by using the formula f = Ee.

$$f_1 = e_1 E \text{ or } e_1 = \frac{f_1}{E}$$

$$f_2 = e_2 E \text{ or } e_2 = \frac{f_2}{E} \qquad (5)$$

so,

$$e_1 - e_2 = \frac{f_1}{E} - \frac{f_2}{E}$$

$$\Delta e = \frac{f_1 - f_2}{E}$$

No permanent deflection or strain will result if a material is stressed in the elastic region and the load is later released.

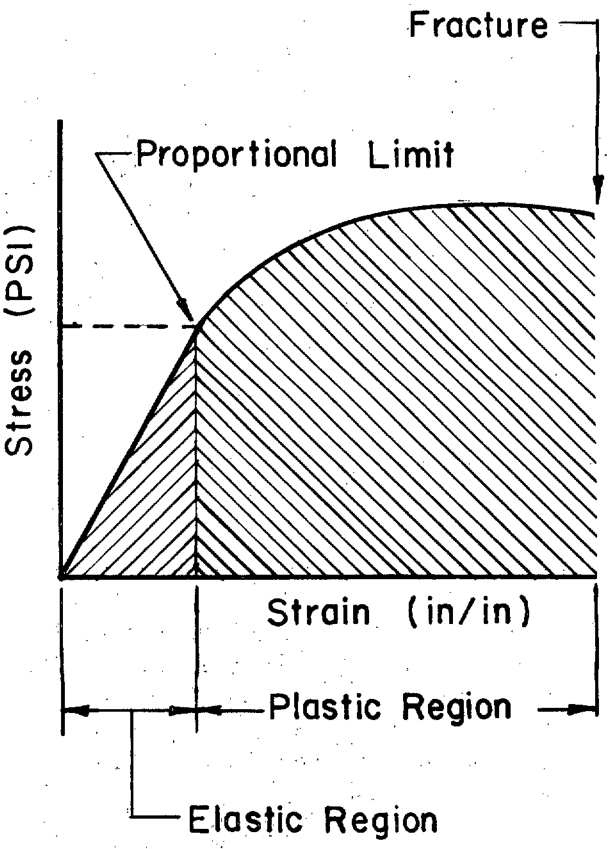


FIGURE 50. A Stress-Strain Curve

A tensile force acting along the x-axis in Figure 52 will produce a strain e_x. This force will also produce transverse strains e_y and e_z in the y and z directions respectively. As discussed previously $e_x = \frac{f}{E}$. e_y and e_z will not be as large as e_x and will be negative as the bar will contract in these two directions. The ratio of e_y and e_z to e_x is Poisson's ratio, μ, a non-dimensional term.

$$\mu = \frac{e_y}{e_x} = \frac{e_z}{e_x} \text{ or } e_y = e_z = \mu e_x \qquad (6)$$

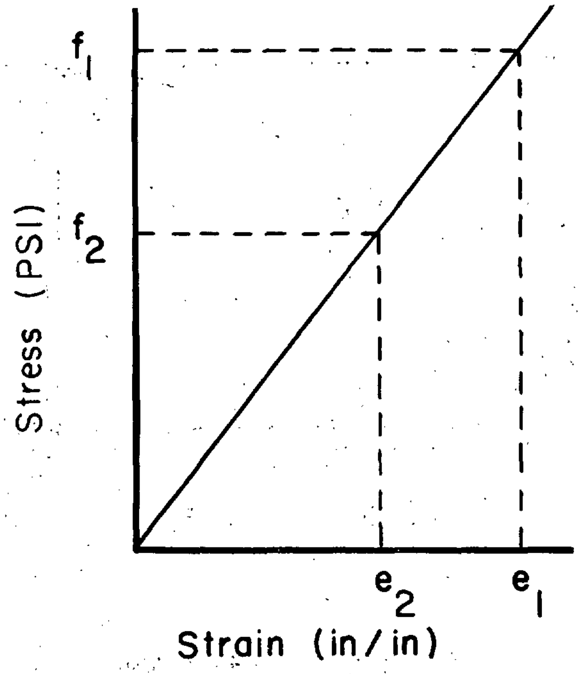


FIGURE 51. The Elastic Portion of a Stress Strain Curve

When a body is acted on by a stress or a system of stresses the total strain in a direction is determined by algebraically adding the direct $\frac{f}{E}$ strains and the Poisson's ratio strains, μe.

A material will behave elastically only until a characteristic stress is reached. At this stress the straight line portion of the stress-strain curve ends, Figure 53. This stress is the proportional or elastic limit stress. Beyond this limit the standard value of E cannot be accurately applied. The proportional limit, as defined in MIL-HDBK-5, is the stress at which the stress-strain diagram departs from a straight line by a strain of 0.0001 inch per inch.

After the proportional limit has been exceeded, stress and strain are no longer related by Hooke's Law. In this plastic region the total strain is composed of elastic strain + plastic strain. Plastic strain is permanent strain that is not recovered after the load has been removed. It is important to note that although plastic strain is occurring, elastic strain is also occurring, Figure 54. The magnitude of this elastic strain is still given by Hooke's Law as $e = \frac{f}{E}$. If a material is loaded to f_1 it will follow the stress strain curve OAB and the total strain will be e_2. When unloaded it will unload along BC which is parallel to the original elastic line OA. The remaining plastic strain at $f = 0$ will be e_1. The recovered elastic strain will be $e_2 - e_1$.

59. **Strain Hardening.** When a metal is deformed past its proportional limit, the magnitude of the stress required for further deformation increases. This increase is caused by strain

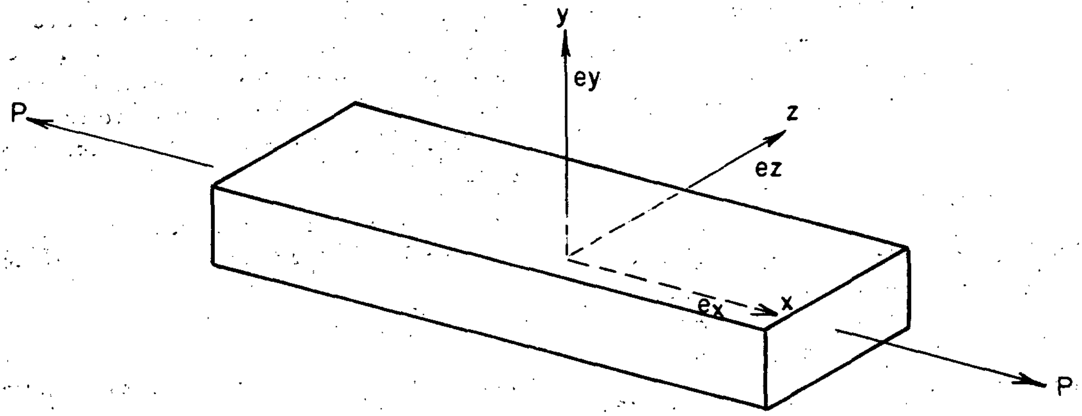


FIGURE 52. Three Dimensional Strain

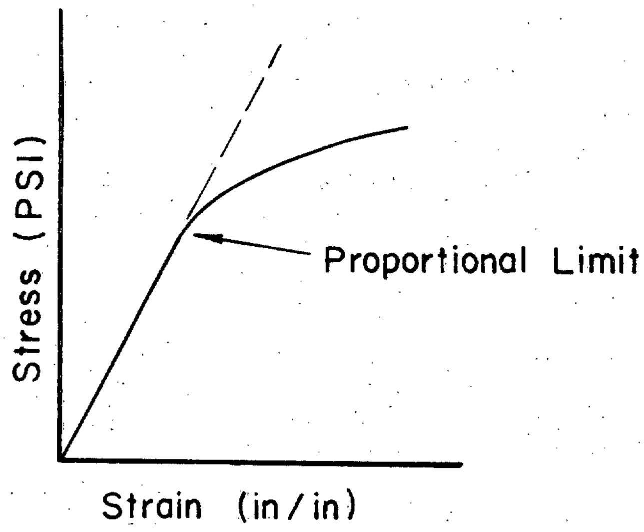


FIGURE 53. The Proportional Limit

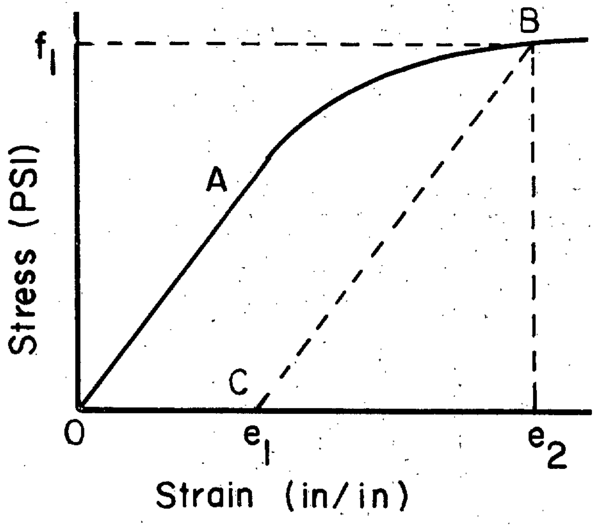


FIGURE 54. Plastic Behavior

hardening and the rate of increase is determined by the strain hardening exponent, m. For analysis the plastic portion of the stress-strain curve is often closely approximated by an equation of the form $S'_o = B\,\epsilon_o^m$, where B is a constant, and S'_o = true stress and is obtained by dividing the load by the actual instantaneous cross-sectional area of the bar. As previously defined the engineering stress f, is obtained by dividing the load by the original cross-sectional area (f = P/A). Since the area decreases, under tensile loading, with increasing plastic strain, the actual true stress is always greater than the engineering stress. ϵ_o is the logarithmic plastic strain and is related to conventional plastic strain e by:

$$\epsilon_o = \ln(1 + e). \tag{7}$$

In addition to describing the stress-strain behavior in the plastic region, the strain hardening exponent, m, is a measure of the uniform elongation an alloy may undergo before necking.

During a tensile test, as a tensile specimen elongates the load will increase due to strain hardening. At the same time the cross-sectional area of the specimen decreases. During the first part of the test, strain hardening predominates and the load increases. During the later stages of the test strain hardening becomes less pronounced and the load reaches a maximum and then progressively decreases until fracture occurs. Strain will be uniform along the entire test section until the maximum load is reached. At this load some cross-section of the bar that is infinitesimally weaker than the rest of the specimen will stretch under the constant load, while other portions of the specimen will not. Because of this, localized strain will occur and the specimen will get thinner or "neck" at this particular location. Then the load will begin to decrease, the neck will continue to stretch and get thinner, and fracture will eventually occur at the neck.

The strain at which necking begins is directly related to the strain hardening exponent.

$$\epsilon\ \text{necking} = m = \ln(1 + e) \tag{8}$$

where ϵ necking = logarithmic plastic strain

e = conventional plastic strain

m = strain hardening exponent

60. The Tension Test. There are two standard tensile specimens used for tensile testing. As shown in Figure 55 the specimens have either a rectangular or circular cross-section. The grips can be of any configuration that allows tensile loads to be applied axially through the specimens. The common grip configurations are shown. The general requirements for both specimens are as follows:

a. The gage section should be of uniform cross section along its length, it may taper slightly so that at the center of the gage length the width of flat specimens may be reduced to a width that is 0.010" less than the width of the specimen at the ends of the gage length. For round specimens the permissible reduction is limited to 1 percent of the diameter of the specimen at the center of the gage length.

b. The gage section should be free from burrs, scratches, pits or other surface defects.

c. The ratio of gage section length to specimen width or diameter should be at least 4:1.

d. The radius of the shoulder fillets should be large enough to preclude failures in this area.

e. The grip length should be long enough to prevent slipping or fracture in the grips.

The properties most frequently obtained from a tension test are yield strength, ultimate strength, percent elongation and reduction of area. Other properties, less frequently measured, are the elastic modulus, Poisson's ratio, and the strain hardening exponent. A typical sequence of events in tension testing is as follows:

a. The cross-sectional area of the gage section is measured.

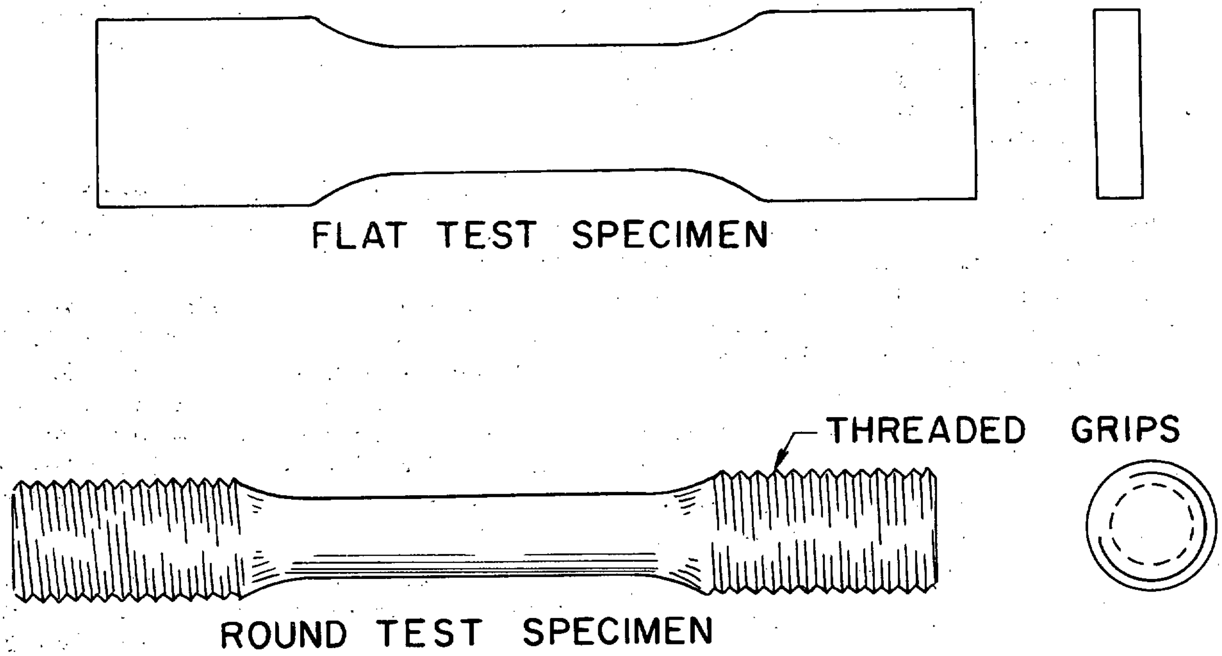


FIGURE 55. Flat and Round Tensile Specimens

b. The specimen is marked with standard gage lengths for subsequent elongation measurements.

c. The specimen is placed into a tensile machine and a suitable strain measuring device is attached.

d. The specimen is loaded to fracture.

Depending on the type of data readout used, a load-strain, stress-strain, or load-deflection curve is obtained.

For those alloys having a distinct yield point, the stress at which the yield point occurs is the yield strength, Figure 56. For those alloys that don't have a distinct yield point, the yield strength is commonly designated as the stress at which 0.20 percent plastic strain has occurred. This stress is determined by the method illustrated in Figure 57.

A distance corresponding to 0.002 in./in. strain is measured along the x-axis. From this point, line BC is drawn parallel to OA. The intersection of this line with the curve gives the yield load, read from the y-axis. This yield load is converted to yield stress by dividing by the original cross-sectional area of the specimen.

The ultimate strength is obtained by dividing the maximum load that the specimen carried by the original cross-sectional area. This load can be obtained from the load-strain curve, Figure 57, but it is usually read directly from a dial on the tensile machine.

Percent elongation is the ratio of the increase in length of the gage section of the specimen to its original length expressed as a percent. It is measured by indexing a gage length (1" or 2" long usually) on the specimen section and then measuring this length after fracture. In Figure 58 the percent elongation (%el) would be:

$$\%el = \frac{\Delta L}{2''} \times 100 \qquad (9)$$

Elongation measurements made in this manner are only an approximation of the true uniform strain that an alloy can undergo before necking. The measurement is made across the fracture, introducing an error, and localized strain occurring in the necked portion introduces additional error. The true uniform elongation that can be expected can be determined by measuring the strain hardening exponent (m = slope of Log S^1 - log ϵ curve). Then:

$$m = \epsilon = \ln(1 + e),$$

where

e = conventional plastic strain at necking.

Reduction of area is the ratio of the decrease in area at the fracture cross-section (the neck) to the original area, then:

$$\% \text{R.A.} = \frac{A_o - A_f}{A_o} \times 100 \qquad (10)$$

where

A_o = original or initial cross section area

A_f = final cross section area

The tensile test is covered in good detail in Federal Test Method Standard 151, and ASTM Standard A370.

The application of tensile properties to design is straightforward. The yield and ultimate strengths designate how much load a structure can carry under ideal conditions. However, in many applications some other criteria such as fatigue characteristics, defect tolerance or shear stresses will determine the actual working stress of a structure.

Elongation and reduction of area are measurements of ductility and have primary application in fabrication and forming work. Elongation values are the main consideration in stretching or drawing operations, while the reduction of area is important in roll forming.

Elongation is also used as a qualitative indication of brittleness of an alloy or temper. This is reasonable because in every structure

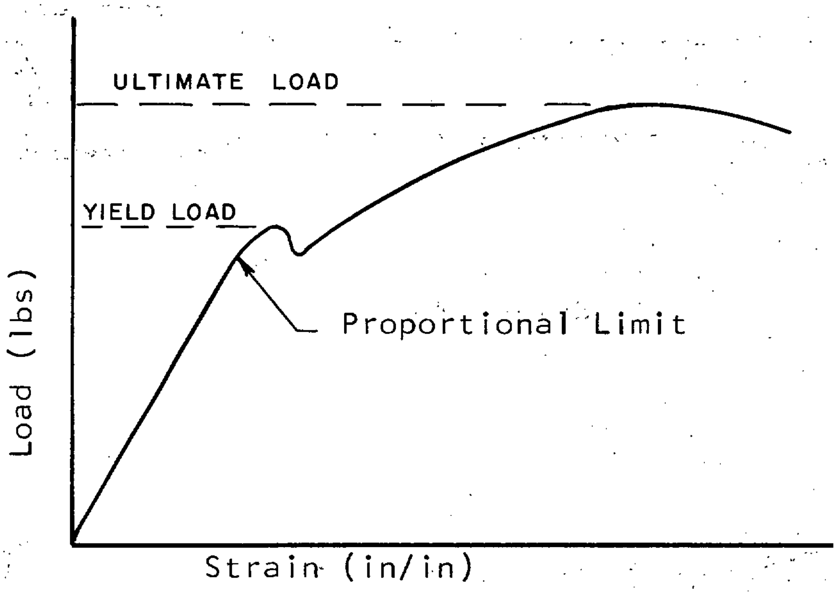


FIGURE 56. A Load-Strain Diagram for a Material With a Definite Yield Point

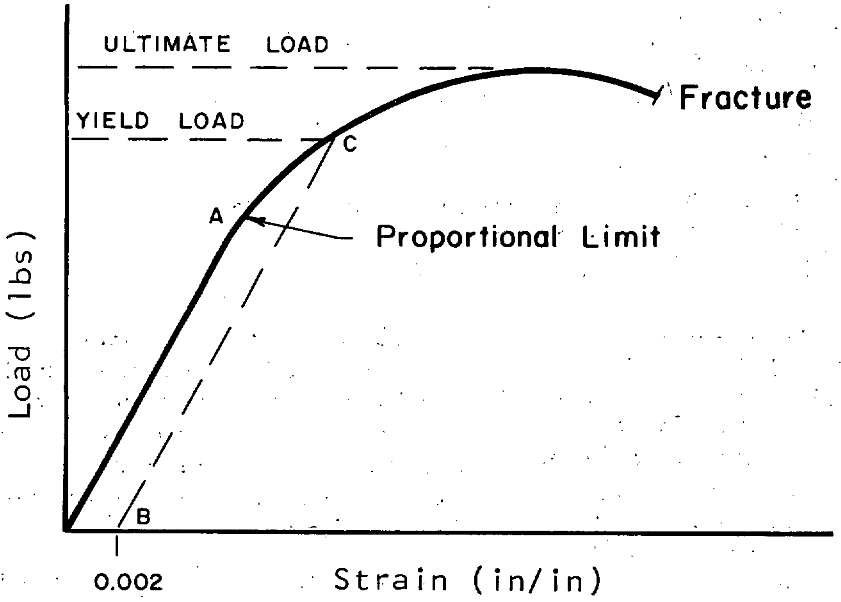


FIGURE 57. A Load-Strain Diagram for a Material Without a Definite Yield Point

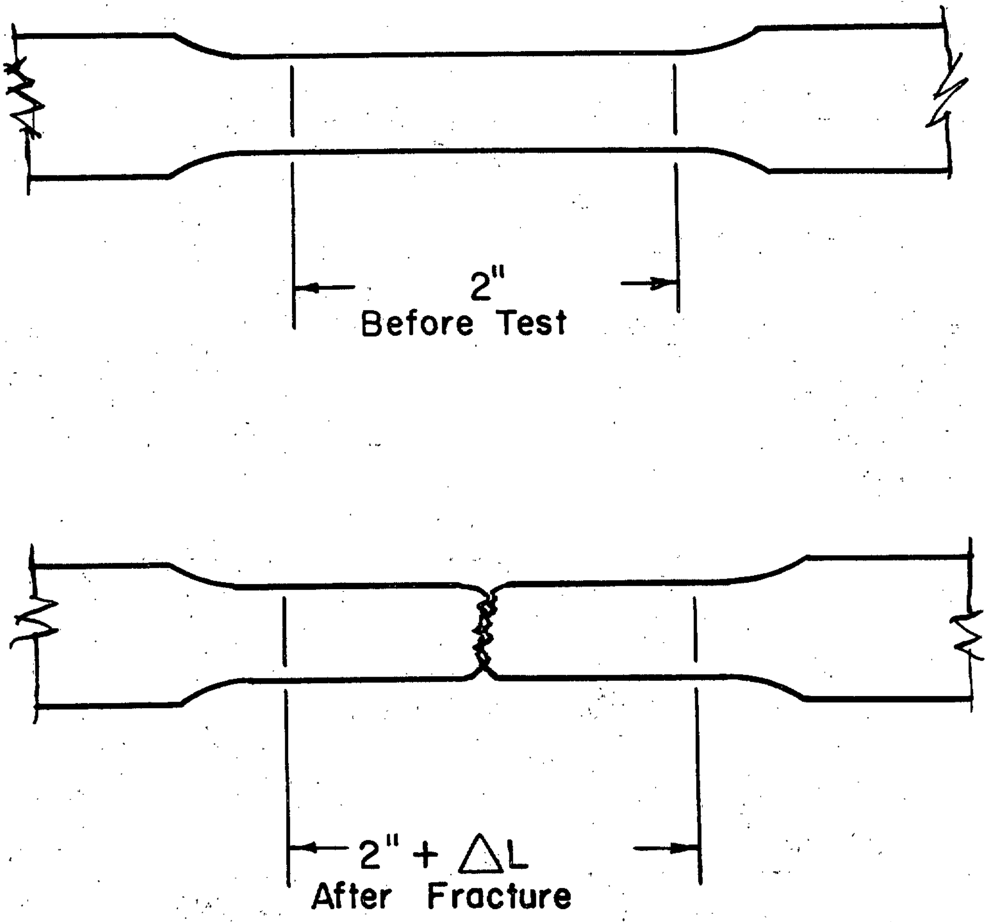


FIGURE 58. Measurement of the Elongation of a Tensile Specimen

there is likely to be some localized plastic flow, even though it was designed to behave elastically. Of course if the particular temper or alloy cannot be subjected to some plastic strain without failure, the entire structure may be endangered. For a quantitative measure of brittleness the methods described in the section on Brittle Fracture should be used.

61. Compression Properties. Compression properties are determined by subjecting a specimen to an increasing compressive load until general yielding has occurred. Only the compressive yield strength and compressive elastic modulus are measured. This is done in a manner similar to the methods of the tensile test. Theoretically these values should be the same as the tensile yield and modulus values. In reality there is usually some small difference. Generally no significant data are obtained from a compression test that are not obtained from a tension test.

A material fails by crack formation and propagation. Since a crack cannot form under compressive loading conditions a true compression failure will never occur. Failures under compressive loading can be attributed to buckling instability and in some cases shear or bending stresses.

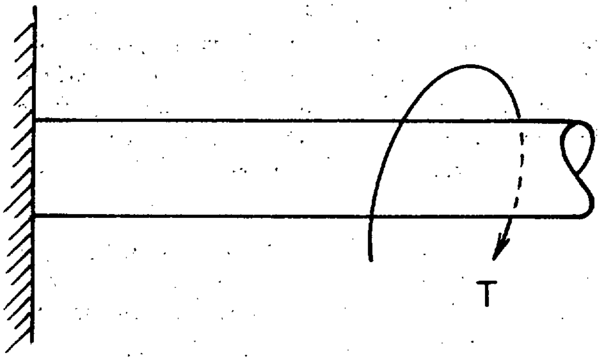


FIGURE 59. Torsion Loading

62. Shear Properties. Shear properties are usually determined in a torsion test. In the torsion test shear modulus, shear yield strength, shear ultimate strength (modulus of rupture) and the shear modulus are measured. The torsion tests are made by restraining a cylindrical specimen at one end and subjecting it to a twisting moment at the other, Figure 59. For accurate yield strength measurements a thin-walled cylindrical tube is used as the specimen. The shear stress is given by:

$$f_s = \frac{T}{2 r^2 t} \qquad (11)$$

where

r = outer radius of tube

t = tube wall thickness

T = torque

A torque-angle of twist curve is obtained and the shear yield strength is determined at the proportional limit or at a specified permanent twist such as 0.001 radian per inch.

The shear ultimate, or modulus of rupture, is obtained by substituting the maximum moment into equation (11). The shear ultimate strength is usually in the range of 55% to 65% of the tensile strength of a material.

In actuality the shear stress at a point is one-half the algebraic difference between the maximum and minimum stresses at the point, equation

$$f_s = 1/2\,(S_1 - S_3) \qquad (12)$$

where

S_1 = maximum principal stress

S_3 = minimum principal stress

Furthermore, the shear stress law of yielding states that the uniaxial stress ($S_o^{\prime}$) in a tensile test is related to the stress under multiaxial loading by

$$S_o^{\prime} = S_1^{\prime} - S_3^{\prime} \qquad (13)$$

Combining 12 and 13

$$S_o^{\prime} = 2f_s \qquad (14)$$

$$f_s = \frac{S_o^{\prime}}{2}$$

If $S_o^{\prime}$ is the ultimate stress (true) then the actual shear ultimate strength is 1/2 the tensile ultimate. For thin walled tubes in torsion, equation (11) is slightly in error. Experimentally determined values of the shear ultimate strength indicate the error to be about 10%. So the actual shear ultimate strength is about 10% higher than those predicted by equation (14).

63. Hardness Tests.

a. General. There are three basic types of hardness tests: (a) indentation hardness, (b) scratch hardness and (c) rebound hardness. Only indentation hardness, which is of primary importance to metals, will be discussed.

As the name implies, indentation hardness is measured by indenting the metal with a suitable load and indenter. The hardness obtained in this way is actually a measure of the resistance of the metal to plastic deformation, but through empirical correlations, hardness gives the designer an indication of the strength of the alloy or metal being tested.

The advantages of indentation hardness testing are that it is fast, inexpensive, and essentially non-destructive. In the majority of cases the small indentation (usually less than 1/16" in diameter) will not cause any structural damage to the part being tested.

b. Brinell hardness. The Brinell hardness is measured by indenting the surface of the metal with a 10mm diameter ball under a static load of 3000 Kg. The Brinell hardness number (BHN) is then calculated by dividing the load, P, by the surface area of the indentation.

$$\text{BHN} = \frac{P}{(\pi D/2)\,(D - \sqrt{D^2 - d^2})} \qquad (15)$$

where

P = applied load = (3000 Kg)

D = diameter of ball = (10mm)

d = diameter of indentation (mm)

It is usually unnecessary to calculate the BHN since tables are available for converting the impression diameter directly to hardness. The diameter of the impression is measured with a microscope having an ocular scale with 0.1 mm graduations. The diameter is measured to the nearest 0.05mm.

c. Vickers hardness. A square base diamond pyramid is used as the indenter for the Vickers hardness test. The static load used for testing varies from 1 to 120 K_g depending on the hardness of the material being tested. A diamond pyramid hardness (DPH) or Vickers hardness number (VHN) obtained in this way is defined as the load divided by the area of indentation. The hardness is calculated by using the following equation.

$$\text{DPH} = \frac{1.854\,P}{L^2} \qquad (16)$$

P = indenter load (Kg)

L = average length of the diagonals of the indentation (mm)

d. Rockwell hardness. The most widely used hardness test is the Rockwell hardness test. It is fast, easy, requires very little surface preparation, and is sensitive to small variation in hardness. The depth of penetration under load is the measure of hardness.

A minor load of 10 Kg is first applied to stabilize the indenter and specimen. The major load is then applied and the depth of penetration is read directly from a dial gage as arbitrary hardness numbers. The hardness number read from the gage varies directly with the actual material hardness, and inversely with depth of penetration. A hard material will not allow as deep a penetration of the indenter as will a softer material. The dial gage contains 100 divisions, each of which corresponds to a penetration of 0.00008".

A single combination of indenter and load is not satisfactory for determining hardness for materials having a wide range of hardness. Therefore, several combinations of indenters and loads are used. A 120° diamond cone (Brale indenter) and a 1/16" or a 1/8" diameter ball are generally used. Major loads of 60, 100 and 150 Kg are used. The hardness reading obtained depends on which combination of load and indenter is used; so the combination must be specified. This is done by adding a suffix to the letter R. The suffix corresponds to a particular scale which is determined by the load and indenter used. Thus if a reading of 40 is determined on the C scale, (Brale indenter and 150 Kg load) this hardness would be reported as Rockwell C 40 or R_C40.

e. Microhardness tests. It is sometimes necessary to perform hardness tests on smaller samples and areas than is possible with the hardness tests previously discussed. For example the variation of hardness through the thickness of a carburized case may be desired. For this type of application a microhardness tester is used.

A microhardness test is analagous to the ordinary indentation hardness tests; the only difference being that a smaller indenter and much lighter loads are used. The Knoop indenter and Tukon tester are used for microhardness testing. The Knoop indenter is a pyramidal shaped diamond. The impression of the Knoop indenter, viewed normal to the specimen surface, is rhombic in shape with the long diagonal perpendicular to and seven times the length of the shorter diagonal. The loads applied by the Tukon tester are from 25g to 1000 g. The length of the long diagonal of the impression is measured precisely with a microscope and a filar eyepiece calibrated in millimeters. The Knoop hardness number (KHN) is calculated as follows:

$$KHN = \frac{P}{L^2 C} \qquad (17)$$

P = applied load (Kg)

L = length of longest diagonal (mm)

C = constant, characteristic of indenter

Knoop hardness numbers can be converted to more conventional scales with suitable conversion tables.

f. Hardness testing precautions. When a hardness test is made the following precautions should be observed:

(1) The indenter should be clean and in good condition.

(2) The test surface should be clean and free from scale or oxides. For the Vickers and the microhardness tests a metallurgically polished surface is required. A rough ground surface will usually suffice for Brinell and Rockwell tests.

(3) The specimen surface should be flat and perpendicular to the indenter. Tests may be made on cylindrical or spherical surfaces, but low readings are obtained and must be empirically corrected.

(4) The specimen should be thick enough so that the indenter does not produce a bulge on the surface opposite the test surface.

(5) Indentations should not be closer than 5 times the longest indentation dimension.

g. Hardness - tensile strength correlation. The hardness of a steel can be closely correlated to the ultimate tensile strength of the steel:

$$f_{tu} = 500 \times BHN \qquad (18)$$

f_{tu} = ultimate tensile strength

BHN = Brinell hardness number

For example, a hardness reading of 200 BHN would correspond to a tensile strength of 100,000 psi. Conversion tables are available for converting hardness values obtained from one type of test to equivalent hardness values for other tests. These tables also list the approximate tensile strength, for steel, corresponding to a given hardness value.

BRITTLE FRACTURE

64. General. The catastrophic failures of welded ships and tankers during World War II brought to the attention of engineers the fact that structural steels could fail at very low stress levels in some environments. These failures occurred at low ambient temperatures and there was generally a notch, crack or other defect present at the failure origin. This type of failure has been appropriately termed brittle fracture, because the failure is preceded by little or no plastic strain. However, it is not the brittleness of the fracture that is important. The important consideration is that the failure stress may be considerably less than the yield strength of the material. The engineering methods used to prevent such low strength failures are discussed in this section.

65. Quantitative Approaches. The basic methods used to design against the occurrence of brittle fracture may be divided into two broad categories, quantitative methods and qualitative methods. The quantitative methods are the more powerful since they give the designer some limiting parameter, such as: a minimum operating temperature; a maximum permissible defect size; or a maximum safe operating stress for a particular alloy in a given application. Quantitative methods include the Transition Temperature Method and the Fracture Mechanics Method.

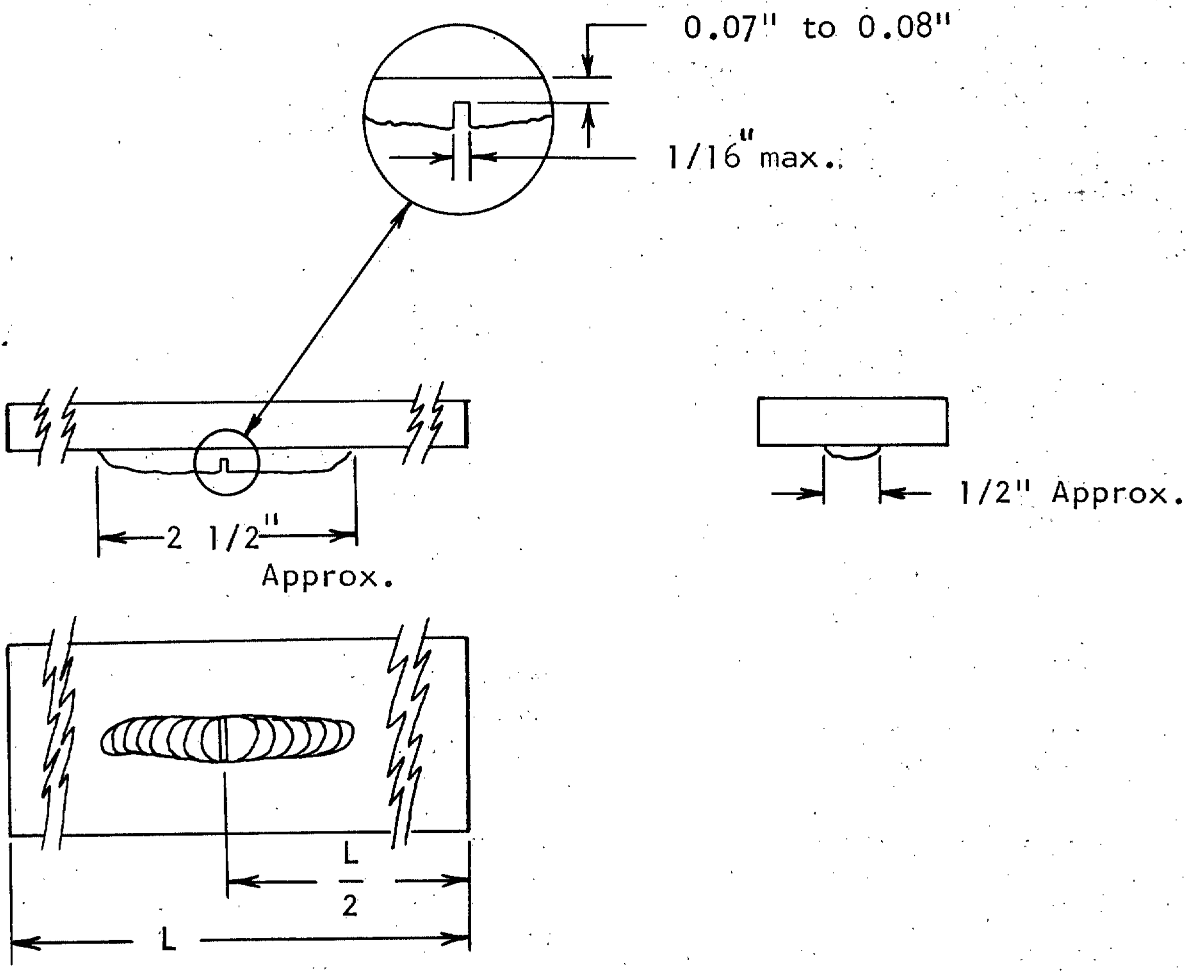


FIGURE 60. The Drop-Weight Test Specimen

a. Transition temperature method. The drop-weight test described in ASTM Standard E208-63T is a test method which was developed to determine the nil-ductility transition temperature of ferritic steels. This test is based on the concept that ferritic steels used in the notched condition are markedly affected by temperature so that there is a characteristic temperature below which a given steel will fail in a brittle manner and above which brittle fracture will not occur. The nil-ductility transition temperature determined by the drop-weight test is defined as the temperature at which, in a series of tests conducted under specific conditions, specimens break; while at a temperature 10°F higher, under duplicate test conditions, no-break performance is obtained from similar specimens.

The drop-weight test is a simple and inexpensive test to conduct. ASTM E208 gives the particulars for several different sized specimens. The significant feature of all sizes of specimens is the weld bead deposited on the tension side of the specimen along its longitudinal centerline, as shown in Figure 60. The drop test is conducted by positioning a specimen in a fixture, as indicated in Figure 61; the specimen is then struck by a 60 or 100 lb.

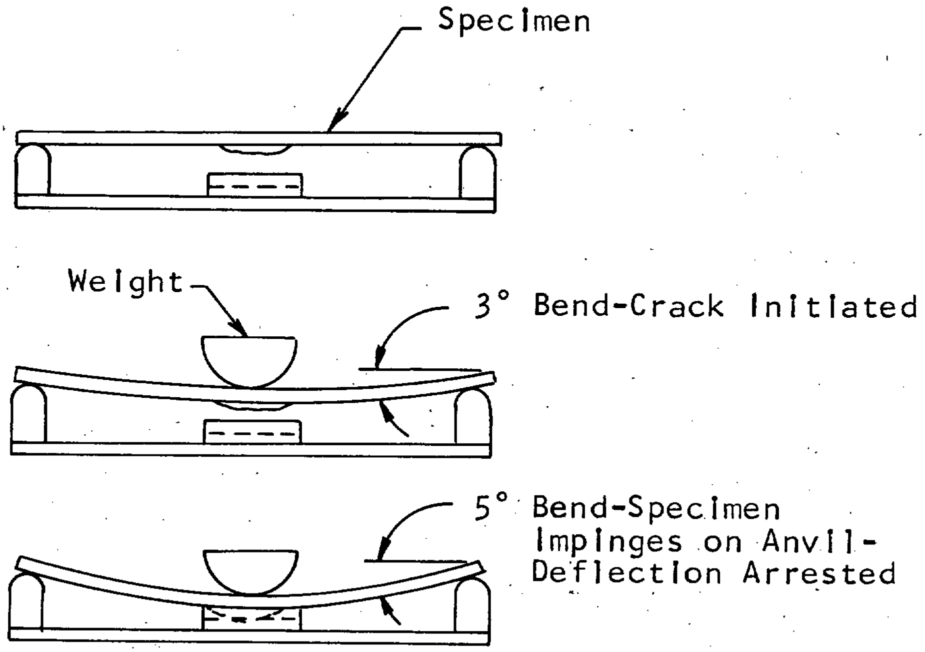


FIGURE 61. The Drop-Weight Test

weight which is dropped from a predetermined height, sufficient to develop the necessary impact energy to deflect the specimen until it impinges on the anvil, about 5°. A cleavage crack forms in the weld bead as soon as incipient yield occurs, at about 3° deflection. A series of specimens are tested over a range of temperatures. From these tests the nil-ductility transition temperature is determined. It is the temperature at which the steel, in the presence of a cleavage crack, will not deform plastically before fracturing, but will fracture at the moment of yielding. A specimen is considered broken if it fractures to one or both edges of the tensile surfaces. Complete separation at the compression side is not required. When a specimen develops a crack which does not extend to either edge of the tensile surface, it is considered a no-break performance.

After the nil-ductility transition temperature of an alloy has been determined, brittle fracture is prevented by using the alloy at temperatures above the transition temperature. Or, if the operating temperature is fixed, an alloy is selected that has a transition temperature below the lowest operating temperature. A complete discussion of nil-ductility transition temperature determination and application is contained in ASTM Test Method E308-63T.

There are two major disadvantages of the transition temperature approach to designing against brittle fracture. It is often necessary to use an alloy at a temperature below its transition temperature, and it would be desirable to know what stress level is safe. Secondly, the higher strength steel alloys do not have definite transition temperatures. The fracture mechanics methods, does, however satisfy both of these requirements.

b. Fracture mechanics method.

(1) General. The fracture mechanics approach to brittle fracture analysis is to determine the fracture strength of an alloy in the presence of a defect of known geometry. The fracture mechanics method was developed

originally from Griffith's elastic analysis of the fracture of brittle materials.

The Griffith theory of the fracture of elastic materials is based on the concept that small elliptical cracks in a material act as local stress risers that cause stresses to exceed the strength of the material, even though the nominal (P/A) stress across the section may be quite low. A crack will begin to propagate when the elastic energy released by propagation is equal to, or greater than, the energy of formation of the two new surfaces. Since the elastic energy increases with increasing stress, it is apparent that, at some value of stress, the strain energy released by the crack will be greater than the energy of formation of the surfaces, and the crack will become self-propagating under its own stress concentration.

Griffith's theory was developed for a completely brittle material and so it does not strictly apply to metals, which always undergo some localized plastic strain before a brittle fracture occurs.

To account for plastic flow, Irwin has modified the Griffith theory, with the result that the fracture stress of an alloy containing a crack of known size can be accurately predicted. The fracture stress is characterized by the strain energy release rate, G, an experimentally determined parameter. G increases with crack length, and at the stress at which a crack of known dimensions becomes self-propagating it is called the critical strain energy rate and is denoted by the subscript "c", e.g., G_c, G_{Ic}. G_c denotes the critical G determined under plane stress conditions, and G_{Ic} denotes the critical G determined under plane strain conditions. G can also be expressed in terms of the stress intensity factor K,

$$K_c = \sqrt{G_c E} \qquad (19)$$

and

$$K_{Ic} = \sqrt{\frac{G_{Ic} E}{(1 - \mu^2)}}$$

where E = modulus of elasticity
μ = Poisson's Ratio

G and K are both referred to as fracture toughness values. Since these values vary considerably from each other it is important to specify which is being discussed.

(2) Plane Stress and Plane Strain. By definition a plane stress condition is one in which the stress in at least one direction is zero. This is illustrated by a thin-walled pressure vessel or a thin sheet loaded in tension. In each instance the stress through the thickness is zero. As applied to fracture mechanics, plane stress actually describes the stress state or restraint at the leading crack edge. In view of this a through crack in thin material is in plane stress conditions because the stress in the thickness direction at the crack tip is zero or very small. For thicker material the restraint at the crack front increases until full restraint exists and the stress in the thickness direction is quite high. This fully restrained condition is the plane strain condition. The thickness at which full restraint is reached differs for different materials, but it is in the neighborhood of 1/4" to 1/2".

The significance of the plane stress to plane strain transition is that a much lower fracture stress is required for a given defect size when plane strain conditions exist. This is apparent from the difference in magnitude between K_c and K_{Ic}, Figure 62. It can be seen from Figure 62 that as the thickness increases, the fracture toughness in the plane stress region (K_c) decreases to a constant value of K_{Ic}, corresponding to plane strain or full restraint.

Three types of cracks are likely to be encountered, Figure 63. A fracture initiated by a through crack may occur under either plane stress or plane strain conditions, depending on the material thickness. The initial propagation of the surface and the embedded crack is always under plane strain conditions. However, when the crack pops through the thickness it will be identical to a through crack and may be in either the plane stress or plane strain stress state. Again this depends on the thickness.

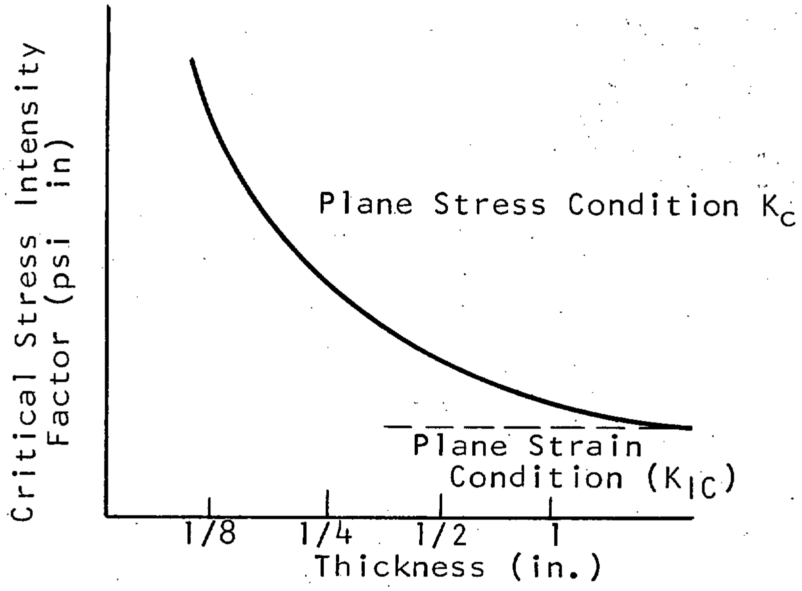


FIGURE 62. Effect of Thickness on Fracture Toughness

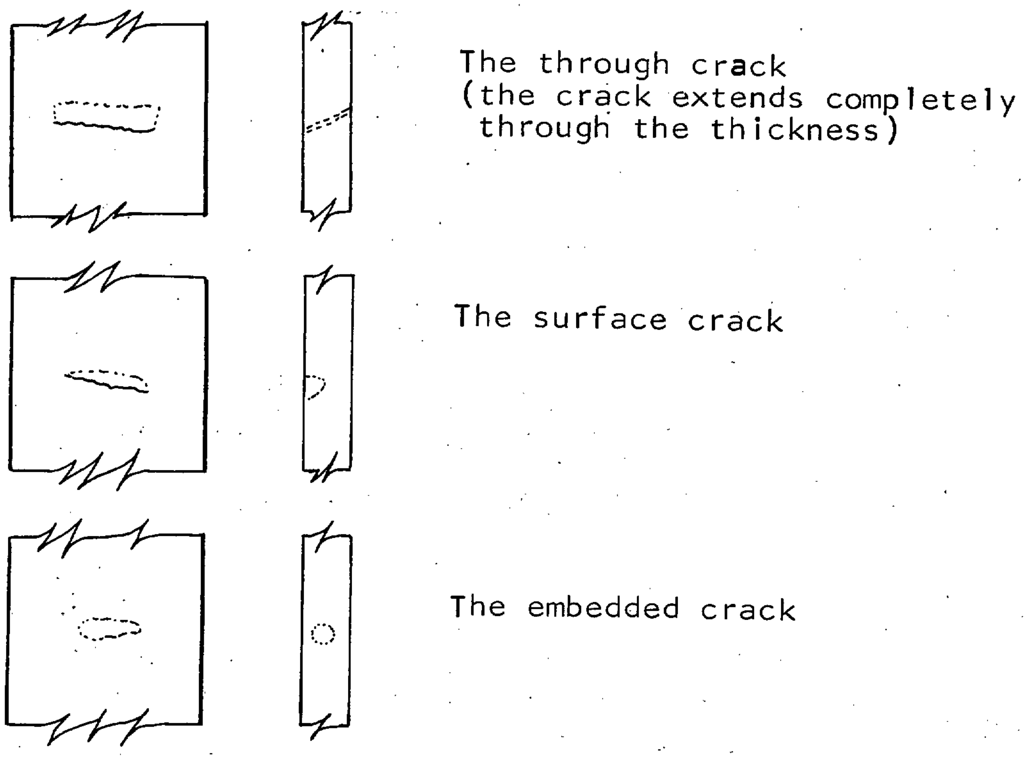


FIGURE 63. Types of Cracks

The stress at which a tension member fails in the presence of a crack is dependent on the fracture toughness of the material, and the defect size. The relationship, sometimes called the inverse square root law, is the basis of fracture mechanics and is expressed by:

$$S_f = \frac{A}{\sqrt{2c}} \qquad (20)$$

where

S_f = fracture stress

A = a constant which expresses the fracture toughness

$2c$ = crack length

For example, using this expression, if a stress of 100,000 psi will cause failure in a material in which a .25" long crack is present, then 50,000 psi would cause failure if the crack were 1" long.

$$S_{f1} = \frac{A}{\sqrt{2c\,1}} = 100{,}000 = \frac{A}{\sqrt{0.25}}$$

$$A = 100{,}000\sqrt{0.25}$$

So,

$$S_{f2} = \frac{100{,}000\sqrt{0.25}}{\sqrt{1}} = 100{,}000 \times 0.5$$

$$S_{f2} = 50{,}000 \text{ psi}$$

For the case of a crack in an infinitely wide solid, such as a small crack in a pressure vessel, this equation takes the form:

$$S_f = \frac{K_c}{\sqrt{\pi c}} \qquad (21)$$

for plane stress, where

K = fracture toughness, and

c = 1/2 the crack length, or

$$S_f = \frac{K_{Ic}}{\sqrt{\pi c\,(1 - u^2)}} \qquad (22)$$

for plane strain.

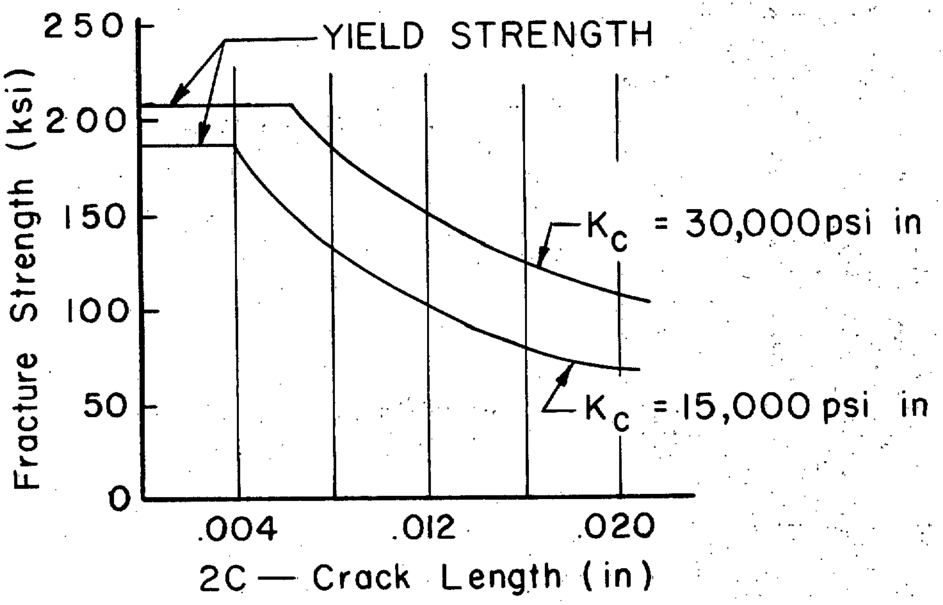


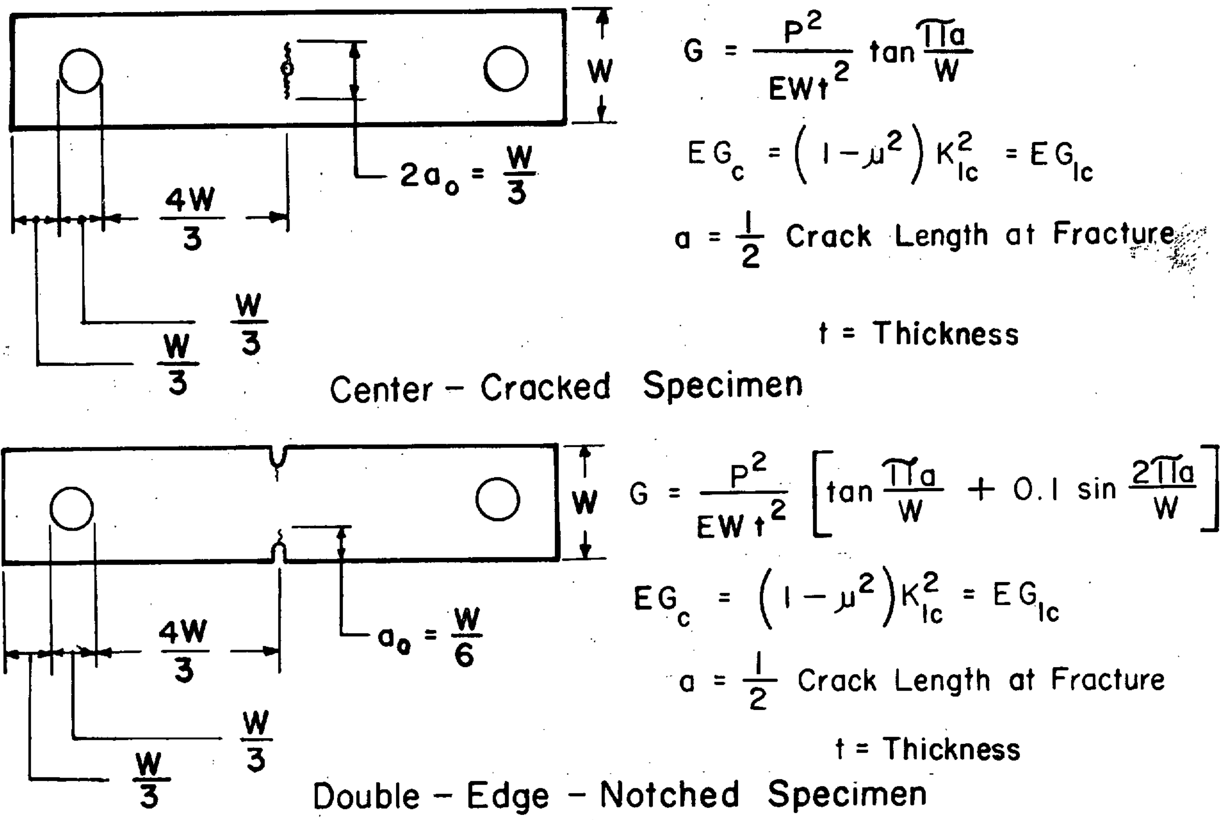
FIGURE 64. Effect of Crack Length on Fracture Strength

Equation 22, as plotted in Figure 64, is one of the standard ways of presenting fracture strength as a function of defect size. As discussed previously, the K_c values for thin material are considerably higher than K_{Ic} values. Plotting the lower K_{Ic} values in place of the K_c values would have the effect of shifting the curves in Figure 64 to the left, indicating that it takes a considerably longer crack to cause failure under plane stress conditions, than it does under plane strain conditions at a given stress level.

(3) Fracture Toughness Testing. The fracture toughness of a material is determined by loading a fatigue cracked specimen in tension and recording the load at which the crack begins to propagate, and also the failure load. The test methods employed to determine fracture toughness and the restrictions on them are numerous and sometimes complex. For a complete description of testing methods, the many publications covering the subject, especially the ASTM publication "Fracture Toughness Testing and Its Applications", should be consulted.

The specimens most often used are shown in Figure 65. The specimens widths are usually in the range of 1" to 4". The thickness is usually the same as that of the part that is to be made from the given material. The major restriction on testing is that fracture toughness data may only be obtained in the elastic region of the tensile curve. If yielding of the specimen occurs, then the equations that are used to determine K are no longer valid, since they are based on the elastic theory of stress analysis.

The equations attendant the specimens shown in Figure 65 are those used to calculate K or G. K_{Ic} or G_{Ic} values are obtained by using the load at which the crack first begins to propagate ("pop-in values"). K_c and G_c are determined by using the load at fast fracture.



$$G = \frac{P^2}{EWt^2} \tan \frac{\pi a}{W}$$

$$EG_c = \left(1-\mu^2\right) K_{Ic}^2 = EG_{Ic}$$

$a = \frac{1}{2}$ Crack Length at Fracture

t = Thickness

Center - Cracked Specimen

$$G = \frac{P^2}{EWt^2} \left[\tan \frac{\pi a}{W} + 0.1 \sin \frac{2\pi a}{W}\right]$$

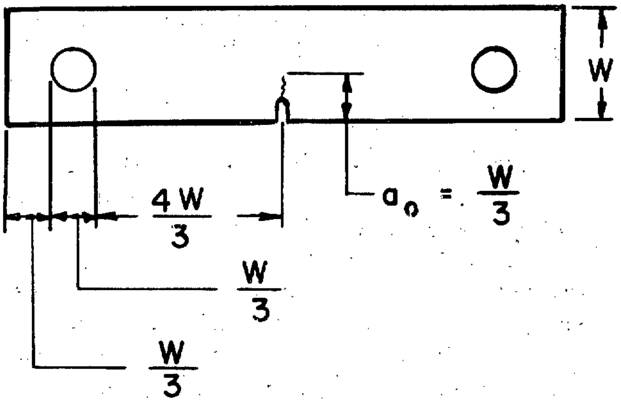
$$EG_c = \left(1-\mu^2\right) K_{Ic}^2 = EG_{Ic}$$

$a = \frac{1}{2}$ Crack Length at Fracture

t = Thickness

Double - Edge - Notched Specimen

FIGURE 65. Common Fracture Toughness Test Specimens



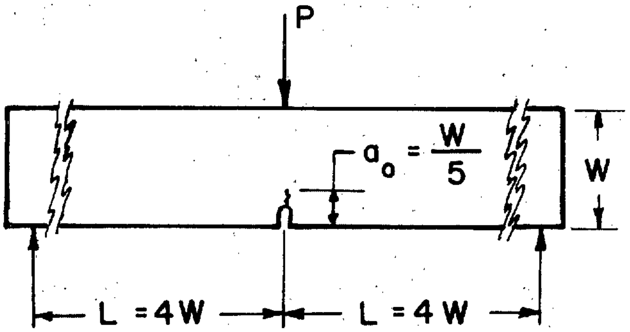
$$G_{Ic} = \frac{P^2}{EWt^2}\left[7.59\frac{a}{W} - 32\left(\frac{a}{W}\right)^2 + 117\left(\frac{a}{W}\right)^3\right]$$

$$EG_c = \left(1-\mu^2\right)K_{Ic}^2 = EG_{Ic}$$

$a = \frac{1}{2}$ Crack Length at Fracture

t = Thickness

Single – Edge – Notched Specimen



$$G_{Ic} = \frac{P^2L^2}{Et^2W^3}\left[31.7\frac{a}{W} - 64.8\left(\frac{a}{W}\right)^2 + 211\left(\frac{a}{W}\right)^3\right]$$

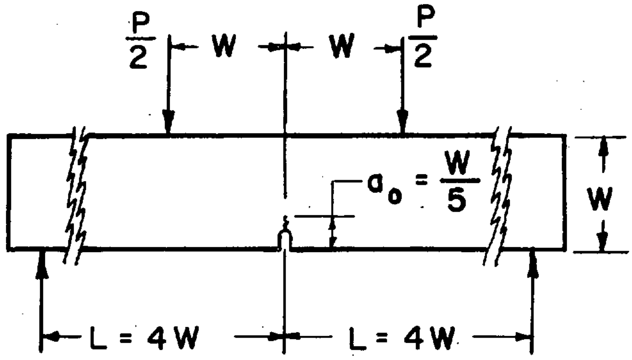
$$EG_c = \left(1-\mu^2\right)K_{Ic}^2 = EG_{Ic}$$

$a = \frac{1}{2}$ Crack Length at Fracture

t = Thickness

Three Point Bend Specimen

FIGURE 65. Common Fracture Toughness Test Specimens (continued)



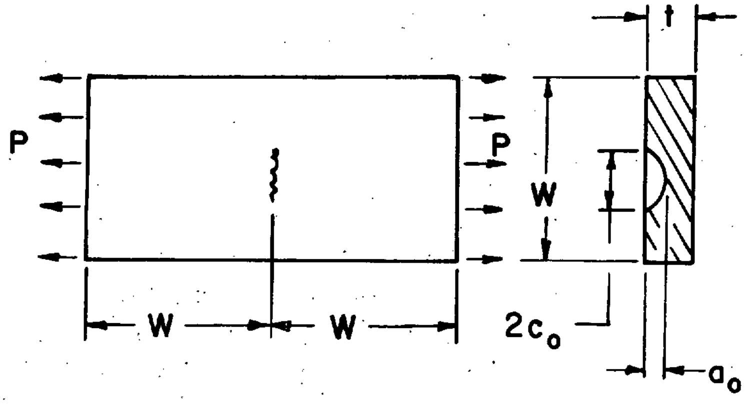
$$G_{Ic} = \frac{P^2 L^2}{E t^2 W^3}\left[34.7\,\frac{a}{W} - 55.2\left(\frac{a}{W}\right)^2 + 196\left(\frac{a}{W}\right)^3\right]$$

$$EG_c = \left(1-\mu^2\right)K_{Ic}^2 = EG_{Ic}$$

$a = \frac{1}{2}$ Crack Length at Fracture

Four Point Bend Specimen

t = Thickness



$$2c_o \leq \frac{W}{3} \qquad a_o < \frac{t}{2}$$

$$\Phi = \int_0^{\frac{\pi}{2}} \sqrt{1 - \frac{c_o^2 - a_o^2}{c_o^2}\sin^2\theta}\; d\theta$$

$$G_{Ic} = \frac{1.2\,\pi\, P^2 a_o \left(1-\mu^2\right)}{W^2 t^2\, E}\left[\frac{1}{\Phi^2 - 0.2\left(\frac{P^2}{W^2 t^2 \sigma_{ys}^2}\right)}\right]$$

Surface Cracked Specimen

FIGURE 65. Common Fracture Toughness Test Specimens (continued)

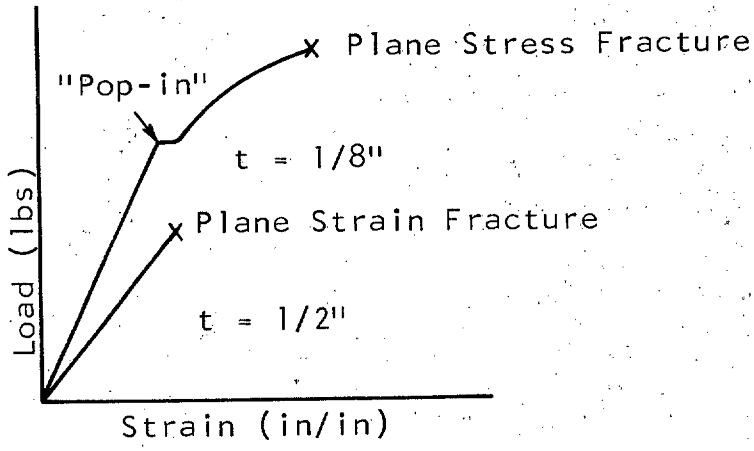


FIGURE 66. **Fracture Toughness Load Curves**

The load at pop-in is measured by recording the strain occurring across the crack, in much the same way as in the tensile test. A load-strain curve, Figure 66 is attained. The deviation from linearity is the pop-in load. Two types of behavior are shown. In the first, pop-in occurs and then the load increases to failure under plane stress condition. In the second case, failure occurs immediately as pop-in initiates, indicating that at the 1/2" thickness full restraint exists and the plane strain conditions prevail.

(4) Designing Against Low Strength Failures. There are three basic fracture mechanics philosophies to designing against low strength failures. These are: proof testing; leak before failure criteria; and stress analysis method.

(a) Proof Testing. If a structure contains a crack and it is loaded to a particular stress and the crack does not propagate, then it may be safely used at a slightly lower static operating stress. This is the basis of implementing fracture toughness through proof testing.

If a material has a characteristic fracture stress-flaw size curve like that in Figure 67, and it is proof tested at Sp, then the largest flaw that can possibly be present is slightly smaller than c_1. The static operating stress in this case is So. For a failure to occur at So, a crack of size c_2 must be present. However, it has already been shown that the largest possible flaw that can exist is c_1. Since c_2 is larger than c_1, the structure can safely operate at So.

(b) Leak Before Failure. This method has primary application in pressure vessel design. The success of this method is dependent on the plane strain-plane stress transition. A surface or embedded flaw in a pressure vessel

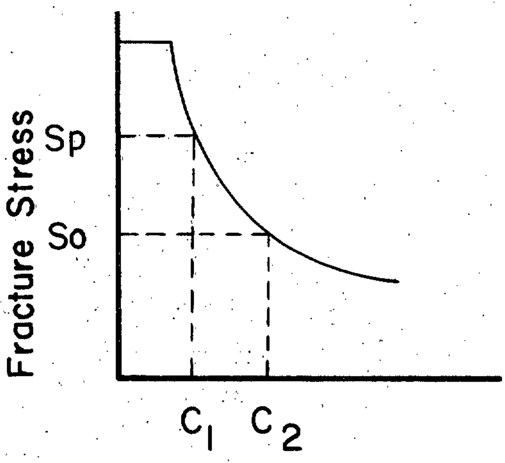


FIGURE 67. **Fracture Stress Flaw Size Curve**

may propagate at the proof or operating pressure of the vessel. As previously discussed these flaws will initially propagate under plane strain conditions. The material used is selected on the basis that it will be able to tolerate a crack having a length of at least twice the wall thickness of the vessel, at the required stress level, under plane strain conditions. Then, if a surface or embedded crack exists, it may propagate at the operating stress. If it does, it will pop through the thickness when its length is approximately twice the wall thickness. At this time, providing the wall is thin enough, the crack is under plane stress conditions and additional load or stress is required for further crack propagation. Therefore, the vessel will leak and the defect can be easily detected before brittle failure can occur.

(c) Stress Analysis. In the stress analysis method the fracture toughness of the material and the defect size that can be detected by nondestructive inspection limit the working stress of a part. The defect shape and size are both considered, and are expressed in terms of the defect size parameter a/Q. This parameter is the ratio of a, the crack depth, to Q, the flaw shape parameter. Q is in turn a function of the ratio of crack depth to crack length, that is, $Q = f\frac{a}{2c}$ where 2c = crack length. This function is plotted in Figure 68. To determine the fracture strength of a part having a known defect size, the value of Q is found from Figure 68. The fracture stress is then determined from equation 23.

$$S = \frac{K_{Ic}}{\sqrt{1.21\left(\frac{a}{Q}\right)Cr}} \qquad (23)$$

where

S = applied stress

K_{Ic} = plane strain fracture toughness

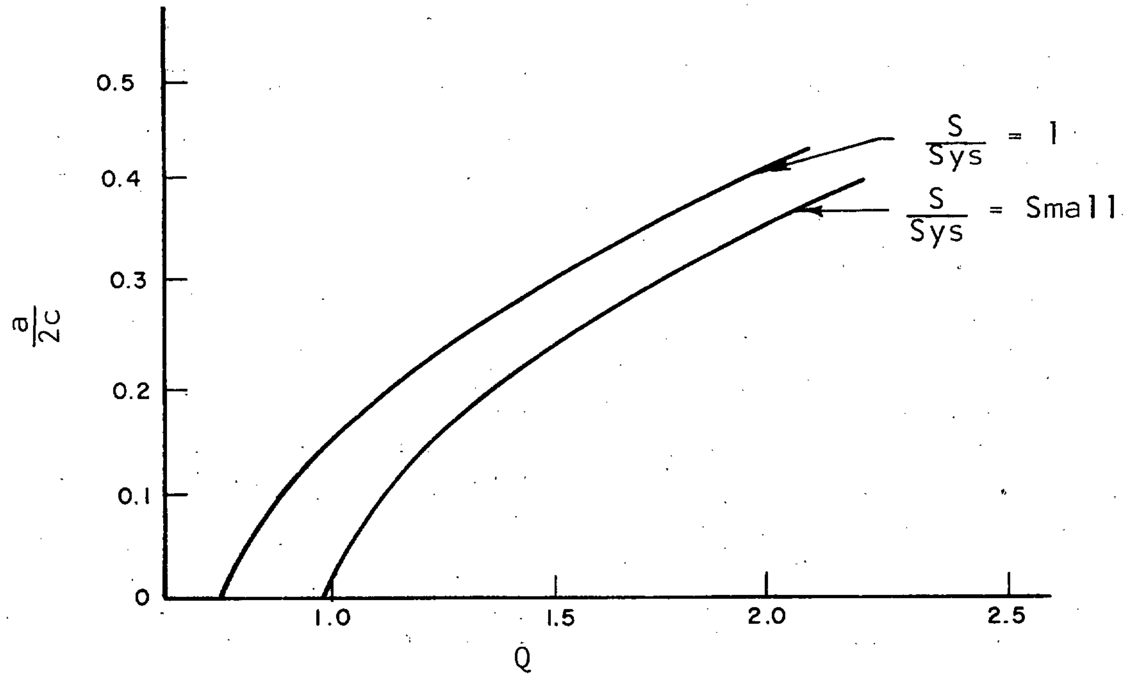


FIGURE 68. Flaw Shape Parameter Curve

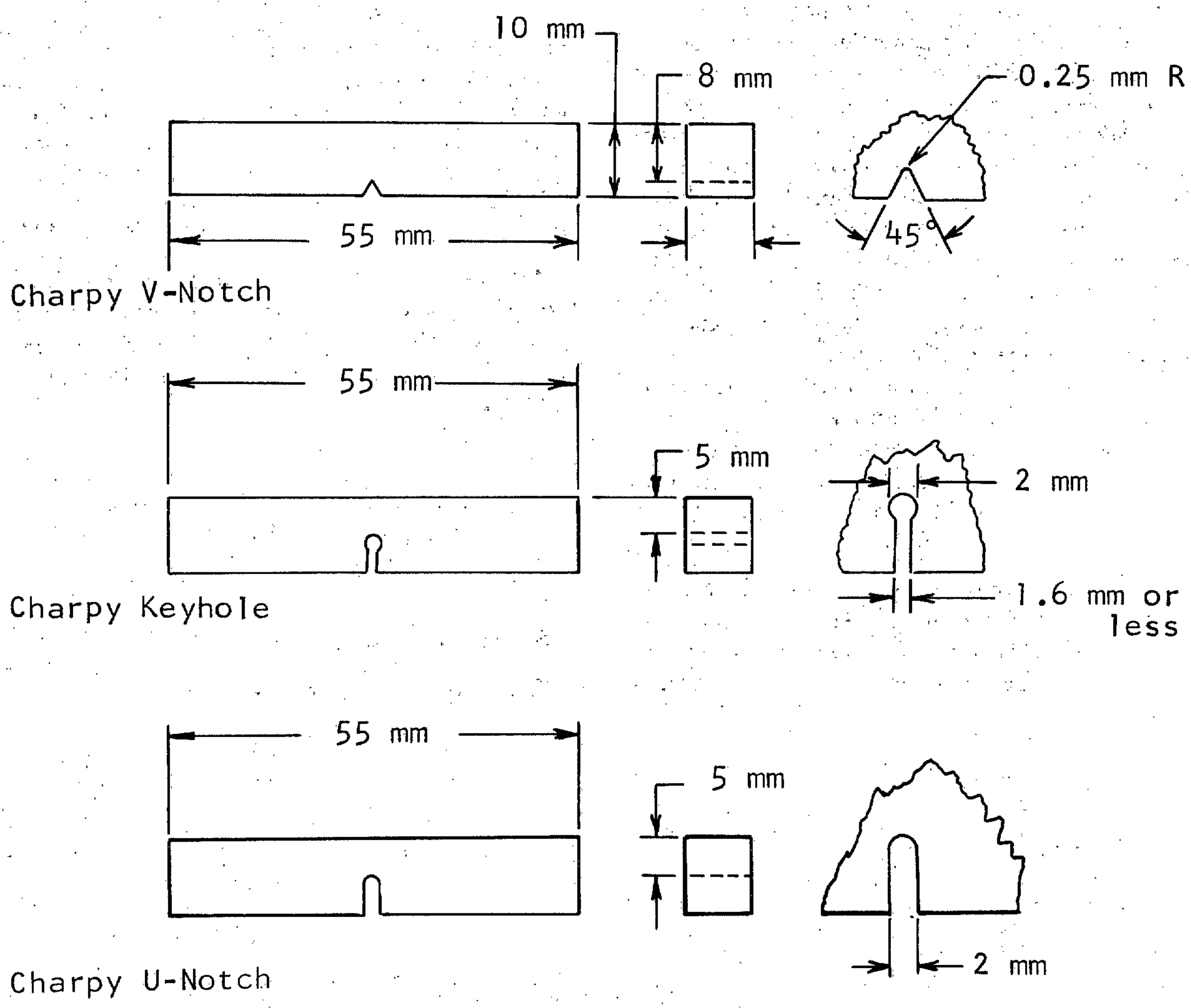


FIGURE 69. Charpy Impact Test Specimens

66. Qualitative Approaches.

a. General. The Charpy impact test, and notched tensile tests, are classified as qualitative brittle fracture tests*, because the test data are not readily converted to design data.

b. The Charpy impact test. Numerous tests have been devised to evaluate the transition from brittle to ductile fracture in steels. One such test, the Charpy impact test, has gained wide recognition and acceptance because it is a simple and rapid test to conduct. The reliability of the Charpy impact test, and the reproducibility of results obtained from Charpy tests, were confirmed through an experiment conducted at the Army Materials and Mechanics Research Center, Watertown, Massachusetts.(1)

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*Notched tensile test may be quantitative and provide fracture toughness values if the proper testing requirements are satisfied.

(1) D.E. Driscoll, "Reproducibility of Charpy Impact Tests", Symposium on Impact Testing ASTM STP No. 176, American Society for Testing and Materials, p. 170 (1955).

The Charpy test is a swinging pendulum type of impact test. A pendulum is released from a known height to strike a specially prepared notched specimen (Figure 69) positioned in the anvil of the impact machine. The pendulum's knife edged striker contacts the specimen at the bottom of the swing, at which point the kinetic energy of the pendulum reaches a maximum value, Figure 70. After breaking the specimen, the pendulum continues in its swing to a height which is measured. Since the pendulum is released from a known height the kinetic energy of the pendulum at the time of impact is also a known quantity. The energy expended in breaking the specimen may be expressed as a function of the difference in the release height of the pendulum and the height it attains after the specimen is broken, so that:

$$E_a = W(h_o - h_f). \qquad (24)$$

where:

W = weight of the pendulum in pounds

h_o = release height in feet

h_f = final height in feet

E_a = energy absorbed by the specimen in foot-pounds

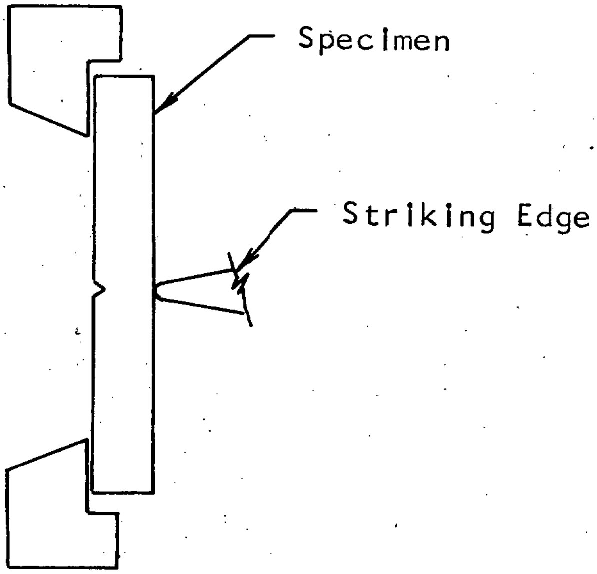


FIGURE 70. Charpy Impact Test

Normally, swinging pendulum impact machines are equipped with scales from which the energy absorbed by the specimen is read directly in foot-pounds.

The Charpy test is a convenient test method for determining the change in the fracture mode of a steel as a function of temperature. A series of specimens can be tested over a range of temperatures and the data thus obtained can be plotted to develop a brittle to ductile transition curve, such as that shown in Figure 71. As indicated in Figure 71, the transition from a brittle to a ductile fracture usually occurs over a range of temperatures. Likewise the fracture of the specimen changes from 100% cleavage (a bright, faceted appearance) to 100% shear (a silky, fiberous appearance). The temperature at which specimens show a fracture of 50% shear and 50% cleavage is frequently defined as the transition temperature. Fracture appearance data can be plotted as a function of temperature as shown in Figure 72.

The Charpy test is often used as an acceptance test for incoming material. In such cases the material is usually required to meet or exceed a specified impact energy level at a given testing temperature, for example, 15 foot-pounds at -40°F.

The Charpy test is also a convenient method for comparing the notch toughness characteristics of various materials.

The methods and procedures of conducting the Charpy Impact Test are specified in ASTM Standard E23, "Notched Bar Impact Testing of Metallic Materials". The test is also discussed in ASTM Standard A370, "Mechanical Testing of Steel Products". Detailed discussions of the Charpy test are contained in References 2, 8, 18 and 19 of the bibliography.

The Charpy test has been accepted as the standard impact test for steel for guns by the NATO Nations, as described in the following:

(1) NATO Standardization Agreement, STANAG 4020, Edition No. 2, 10 May 1966, "Impact Tests at Low Temperature for Steel for Guns".

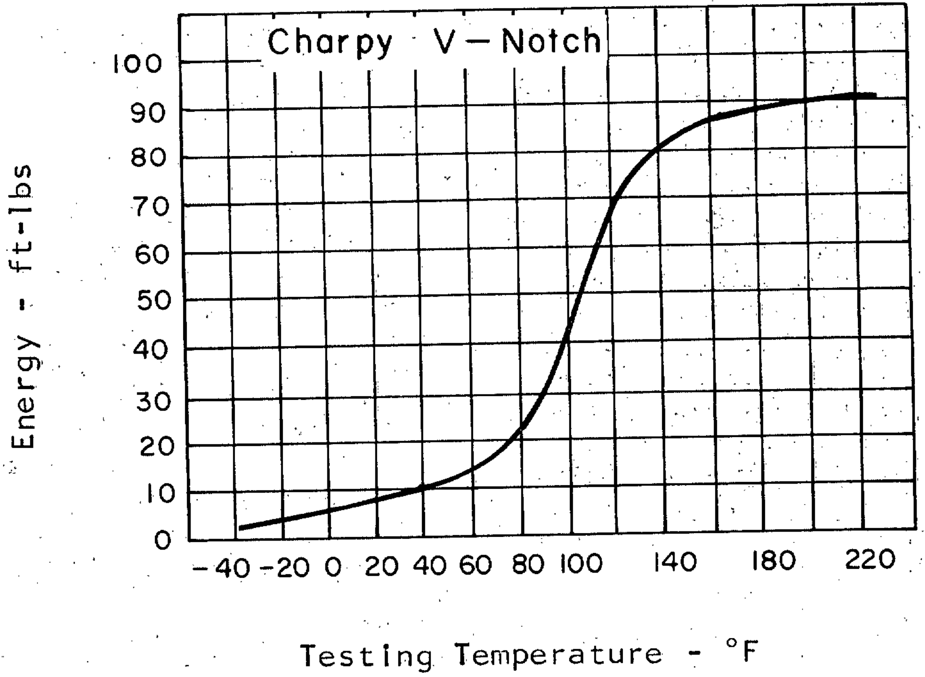


FIGURE 71. Brittle to Ductile Transition Curve

(2) Department of the Army Technical Bulletin, TB-34-9-90, 15 August 1966, "Impact Tests at Low Temperatures for Steel for Guns".

c. ***Notched tensile tests.*** Notch tensile tests are performed on cylindrical specimens having an annular notch, or on flat specimens having double edge notches, Figure 73. These notches act as stress concentrators and affect the load carrying capabilities of the specimens. The stress concentration due to a notch or an abrupt change of section is described in terms of K_t, the theoretical stress concentration factor. K_t is defined as the ratio of the maximum stress, due to the notch, to the nominal stress across the area under the notch. K_t should not be confused with K_c or K_{Ic} which are fracture toughness values. Values of K_t have been determined for various geometries and the values for the geometries of major importance in notch testing are shown in Figure 73. K_t depends on both the specimen size and the notch radius, and is often approximated by the formula $K_t \doteq \sqrt{a/R}$.

In the most commonly used notch tests a round specimen with a 50% notch depth is used. The restraint caused by the notch sets up a state of triaxial tension near the notch root. This stress state increases the flow resistance of the metal and thus decreases the ductility at failure, but it may increase the fracture strength. The notch strength ratio, NSR, (ratio of notched strength to unnotched strength), has been shown to increase with increasing notch sharpness, at a constant notch depth, to a maximum value at which the triaxiality becomes constant. Increasing the sharpness beyond this point causes a reduction in the NSR for notch sensitive materials. Increasing the notch depth will increase the triaxiality, and will increase the notch strength of the specimen. Notched tensile tests are used primarily as material screening tests.

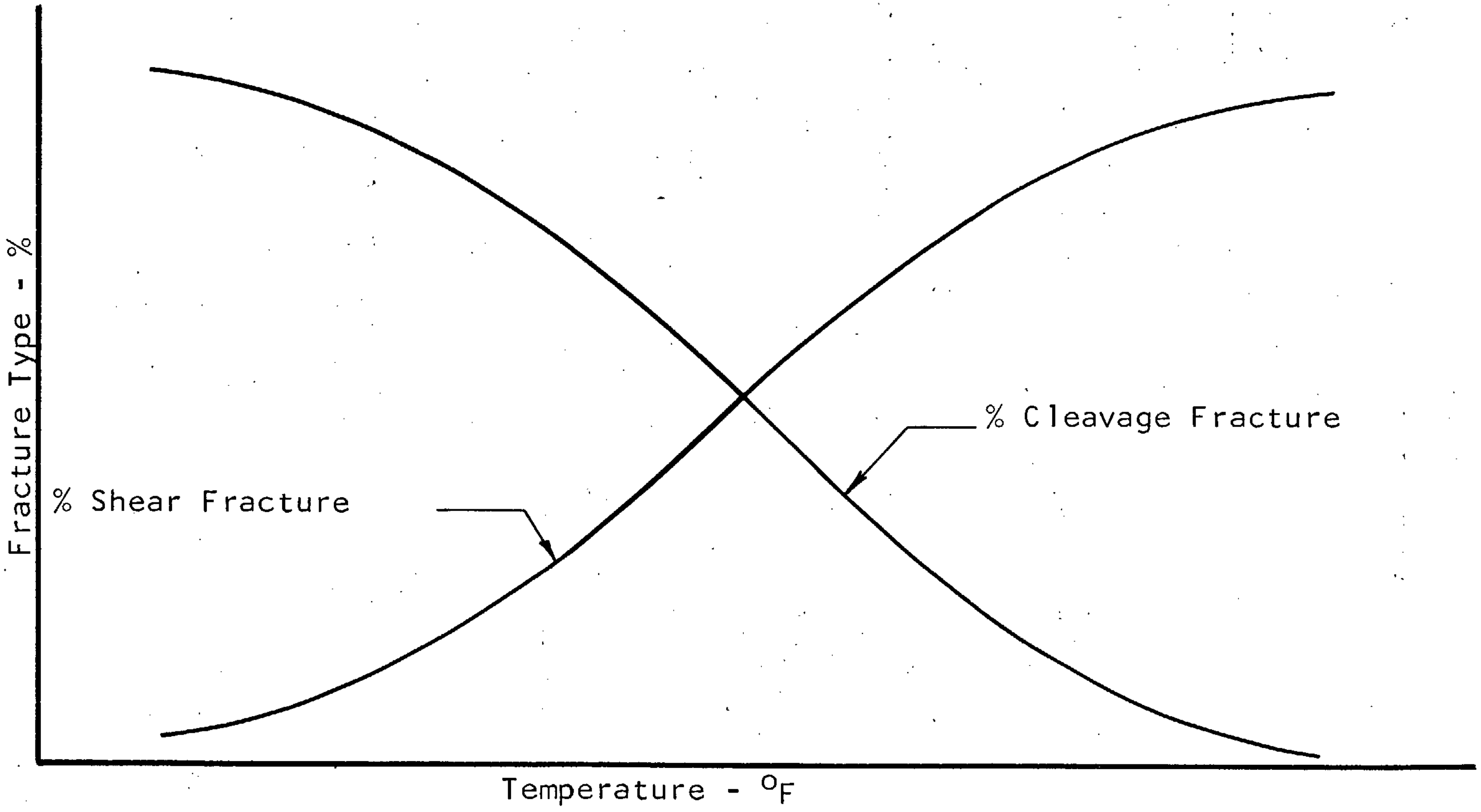


FIGURE 72. Transition of Fracture Appearance with Temperature

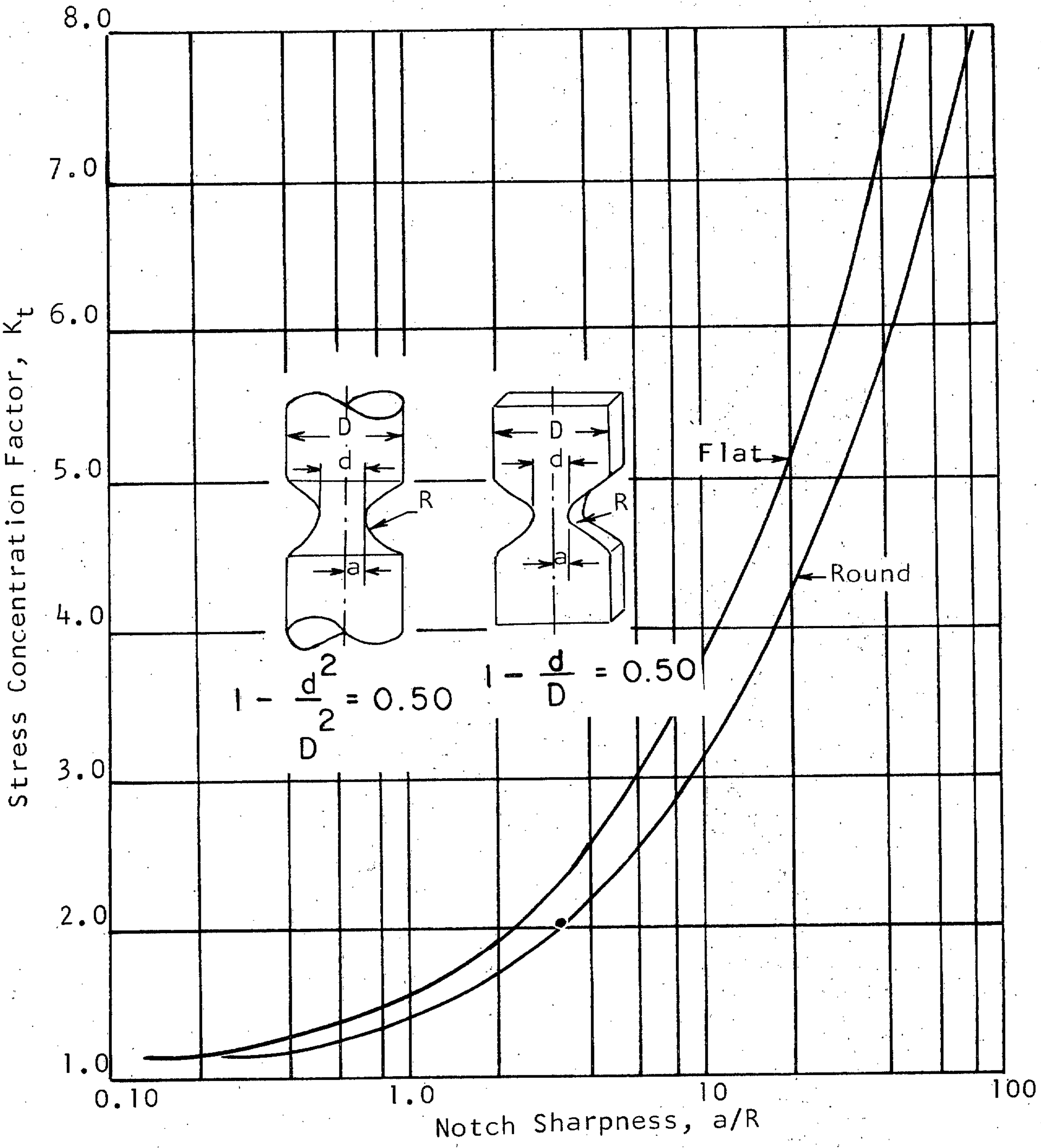


FIGURE 73. Effect of Notch Sharpness on the Stress Concentration Factor

FATIGUE

67. General. A material subjected to repeated tensile loading may fail even though the stresses are below yield strength. Failure may occur after a few load applications or after a few million applications. This phenomenon is known as fatigue. The fatigue life is dependent upon many variables, the most important of which are, maximum stress, average stress, alternating stress, the ratio of alternating to average stress, yield strength, surface condition, and environment. To determine the fatigue life of a material for a given application these factors must be considered.

68. Fatigue Tests. Fatigue tests are made by subjecting a specimen to repeated cyclic loading until failure occurs, or until the test is discontinued. The typical types of load-cycling are shown in Figure 74. The loading cycles are either tension-compression, tension-tension, or zero stress-tension.

The maximum stress, S max, is the highest tension stress in the cycle. The minimum stress, S min, is the largest compressive stress for compression-tension cycling, or the minimum tensile stress for tension-tension cycling. Sm is the average or mean stress of the cycle and is given by equation 25.

$$Sm = \frac{S\ max + S\ min}{2} \qquad (25)$$

Sa is the alternating stress and is equal to the difference between S max and Sm.

$$Sa = S\ max - Sm \qquad (26)$$

Another quantity useful in fatigue analysis is the stress ratio R.

$$R = \frac{S\ min}{S\ max} \qquad (27)$$

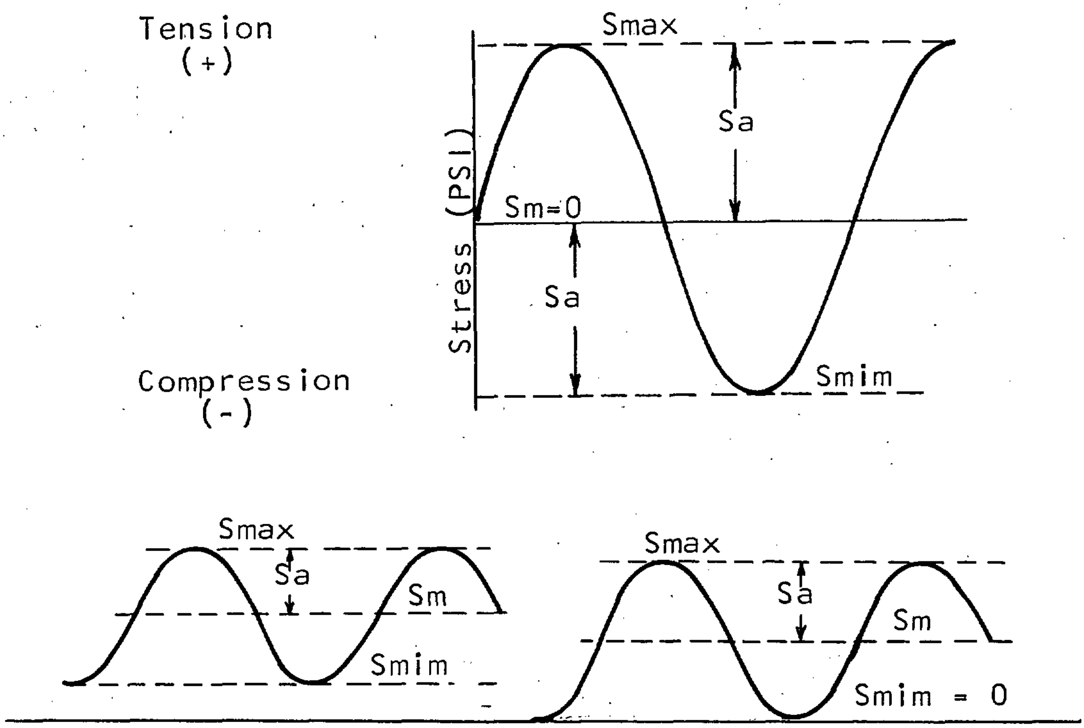


FIGURE 74. Fatigue Loading Cycles

For reversed bending where S min = – S max

$$R = \frac{S\ \text{min}}{S\ \text{max}} = \frac{-S\ \text{max}}{S\ \text{max}}$$

$$R = -1$$

Another very similar quantity is the A ratio.

$$A = \frac{Sa}{Sm} \qquad (28)$$

For reversed bending, Sm = 0 and $A = \frac{Sa}{0} = \infty$

69. Presentation of Fatigue Data.

a. ***The S-N curve.*** The basic method of presenting fatigue data is the S-N curve. The maximum stress is plotted as a function of the number of cycles to failure, Figure 75. When data are presented on an S-N curve it is necessary to identify the A ratio or the stress ratio, R, because the fatigue life of a material is dependent upon the maximum stress and mean stress of the applied cyclic load. At a specified maximum stress, the fatigue life of a material is the lowest under reversed bending, when $S_m = 0$, and $A = \infty$. For a given maximum stress, the fatigue life increases as S_m increases and A decreases. The horizontal lines labeled "Endurance Limit" in Figure 75 are the stresses below which a steel will not fail by fatigue, under the indicated conditions.

b. ***The Soderberg diagram.*** A more useful method of presenting fatigue data is the Soderberg diagram or modified Goodman diagram. In the Soderberg diagram the alternating stress is plotted against the mean stress, Figure 76. The diagram shows the dependence of fatigue life on the alternating and mean stress, as well as on the A ratio. If the fatigue life is to be determined under the conditions of Sa = Sm (A = 1), at a given maximum stress, and if Sa = S max – Sm = Sa_1, then the stress Sa_1 is read off the proper axis, and the fatigue life at the proper A ratio is read from the diagram, in this case 10^4 cycles. Notice that at an A ratio of 5, the alternating stress that could be endured would be Sa_2, and the mean stress would be Sm_2 for 10^4 cycles.

Ideally the Soderberg diagram should be constructed by determining the S-N curve for several A ratios and then plotting these data. The diagram can, however, be determined by testing with only one A ratio. To do this the S-N curve is established and the points are plotted on the appropriate A ratio line. As an example, data might be obtained for an A ratio of 1. These data are plotted on the 45° (A = 1) line, Figure 77. A straight line is then drawn connecting these points and the material ultimate strength value that has been plotted on the Sm axis. This gives a Soderberg diagram that is conservative, and accurate enough for many engineering applications. This method is of considerable utility because most of the fatigue data found in the literature is in the form of

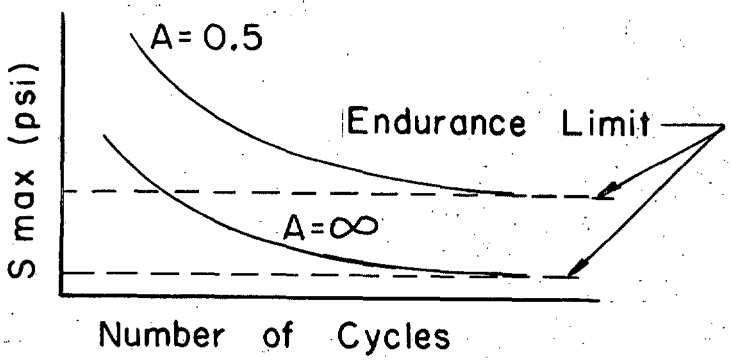


FIGURE 75. S-N Curve

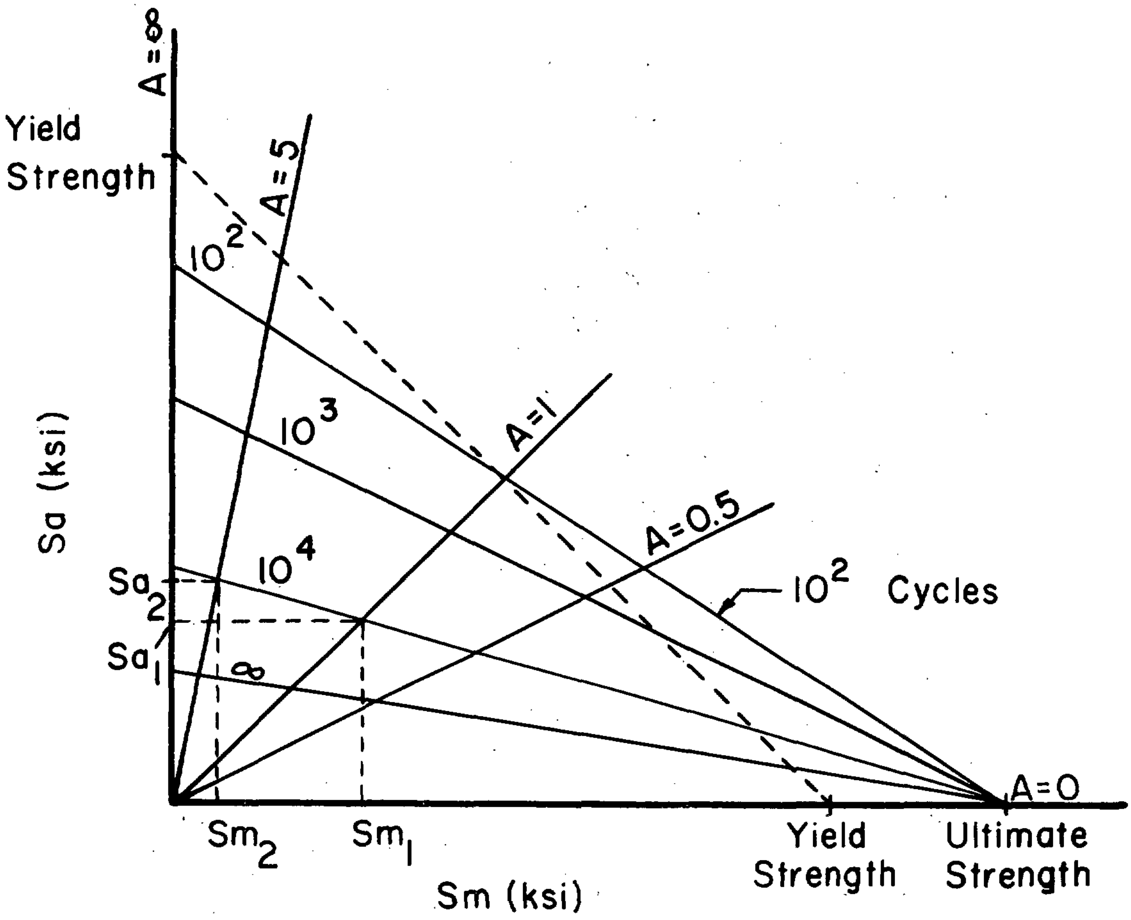


FIGURE 76. Soderberg Diagram

S-N curves for reversed bending (A ratio = ∞). This method of determining the Soderberg diagram makes it possible to use such data for applications in which the A ratio is other than ∞.

The dashed line connecting the yield strengths plotted on each axis in Figures 76 and 77 limits the range over which the Soderberg diagram is used. If values beyond this line are picked the yield strength of the material is exceeded. General yielding is usually a criteria for failure, so fatigue tests in which the maximum stress is greater than yield are seldom needed.

70. Factors Affecting Fatigue Life. The presence of a notch or any other defect that causes a stress concentration seriously reduces the fatigue strength of a metal. The reduction in fatigue strength is dependent on the stress concentration factor K_t. For a K_t of 2, the expected fatigue strength would be 1/2 of the unnotched fatigue strength for a given number of cycles. The actual amount that the fatigue strength is reduced is expressed by fatigue notch factor K_f.

K_f is simply the ratio of the unnotched strength to the notched strength for a given number of cycles.

$$K_f = \frac{Su}{Sn} \qquad (29)$$

Su = unnotched fatigue strength

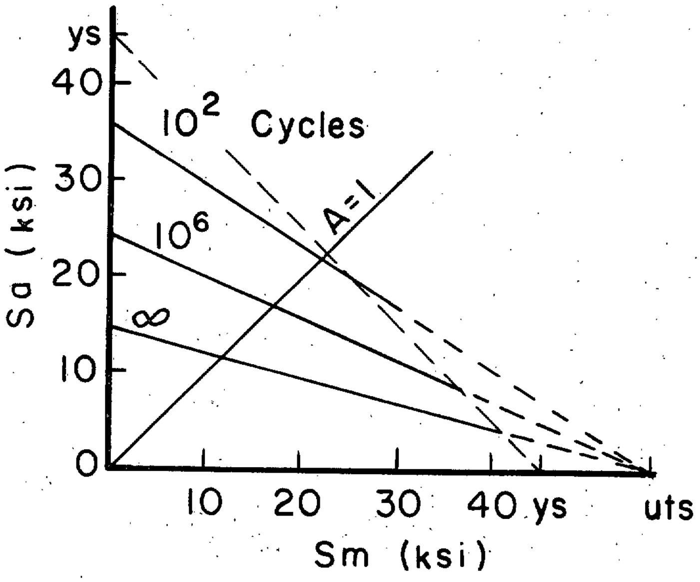


FIGURE 77. Method of Constructing the Soderberg Diagram

Sn = notched fatigue strength

K_f is equal to K_t for small values of K_t, but as K_t increases the ratio $\left(\frac{K_f}{K_t}\right)$ decreases. K_f is determined by obtaining S-N curves for unnotched specimens, and for notched specimens of the same material, Figure 78. Then for a given number of cycles the ratio of $\frac{Su}{Sn}$ is determined from these curves. K_f is dependent on the notch radius and sharpness, and may have different values for the same K_t, when K_t is developed from two different geometries.

For applications where the cyclic loading does not vary, i.e., Sa and Sm remain constant, the fatigue life can be read directly from the S-N curve or the Soderberg diagram. When the loading cycle varies (Sa and Sm vary) a method such as the linear damage principal is used. This principal can be stated as follows: The total fatigue life is the sum of the number of cycles experienced at a given stress, divided by the fatigue life at that stress. In equation form this would be:

$$\frac{M_1}{N_1} + \frac{M_2}{N_2} + \frac{M_3}{N_3} + \frac{Mi}{Ni} = 1 \qquad (30)$$

where:

M = cycles at a given strees

N = fatigue life at that stress

As an example; if a material having the fatigue characteristics shown in Table VIII had been subjected to 20,000,000 cycles at 20,000 psi, how many additional cycles could it withstand at 50,000 psi before it would fail?

TABLE VIII. FATIGUE CHARACTERISTICS

S Max	Cycles to Failure
10,000 psi	∞
20,000	70,000,000
30,000	20,000,000
50,000	6,000,000

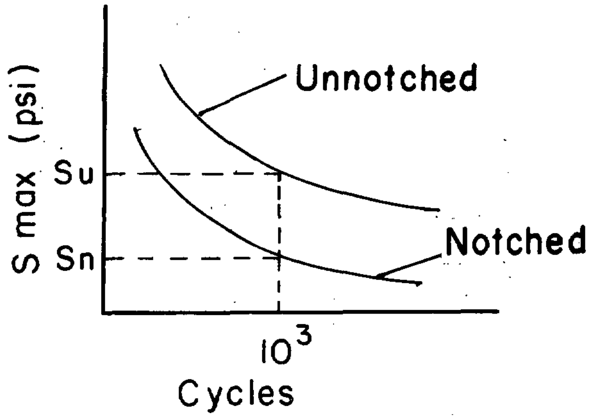


FIGURE 78. S-N Curves of Notched and Unnotched Specimens

In this case, $M_1 = 20{,}000{,}000$ for $S = 20{,}000$ psi and $N_1 = 70{,}000{,}000$ from Table I

M_2 = unknown for $S = 50{,}000$ psi

$N_2 = 6{,}000{,}000$

$$\frac{M_1}{N_1} + \frac{M_2}{N_2} = 1$$

$$\frac{20{,}000{,}000}{70{,}000{,}000} + \frac{M_2}{6{,}000{,}000} = 1$$

and $M_2 = 6{,}000{,}000 \times 1 - \frac{20{,}000{,}000}{70{,}000{,}000}$

$$M_2 = 6{,}000{,}000 \times \frac{5}{7} = 4{,}280{,}000$$

Therefore the part could be expected to withstand an additional 4,280,000 cycles at 50,000 psi.

It is good design practice to eliminate stress concentrations. This applies not only to stress concentrations designed into a part, but also to those resulting from surface roughness and defects in the material. The effect of surface finish on fatigue life is indicated in Table IX.

TABLE IX. *FATIGUE LIFE OF 3130 STEEL SPECIMENS TESTED UNDER COMPLETELY REVERSED STRESS AT 95,000 PSI

	Surface Roughness, Min.	Average Fatigue Life (Cycles)
Lathe-formed	105	24,000
Partly hand-polished	6	91,000
Hand-polished	5	137,000
Ground	7	217,000
Ground & polished	2	234,000
Superfinished	7	212,000

*G. Dieter, Jr., Mechanical Metallurgy, McGraw-Hill, Inc., 1961

Other surface properties can be adjusted to improve fatigue life. Carburizing, nitriding and cold working, which increase the surface hardness, will increase the fatigue life. On the other hand, decarburization of the surface is particularly damaging to fatigue properties. Shot-peening introduces compressive residual stresses into the surface, as well as increasing the strength through cold work. Both of these factors increase the fatigue life. However, shot-peening also increases the surface roughness and this of course decreases fatigue life.

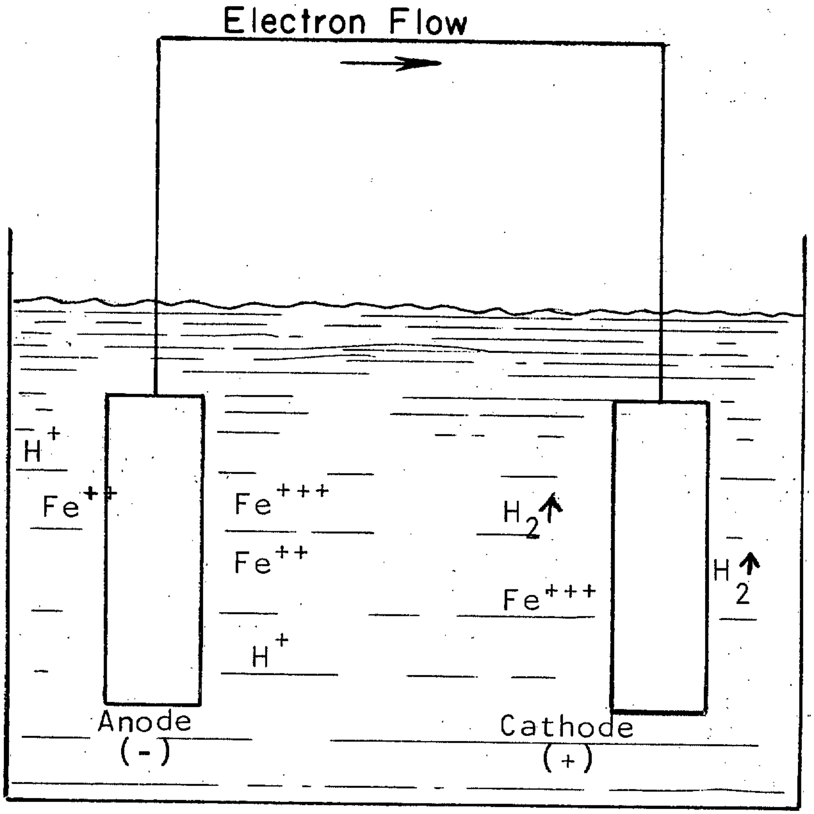
CORROSION

71. General. Corrosion is the deterioration of a metal due to chemical or electrochemical action. Because corrosion is so prevalent, corrosion losses are one of the most expensive problems that are faced in the application of metals.

72. GALVANIC CORROSION.

a. **General.** In its simplest form, the galvanic cell consists of two electrodes immersed in a conducting solution (the electrolyte). The electrodes may be two dissimilar metals, a metal and a conducting nonmetal (e.g., carbon), or a metal and an oxide. In each case, an electrical potential is induced between the electrodes. This potential may produce current when the electrodes are joined by a suitable conductor. When current is flowing, reactions take place at each electrode, the reactions for one combination of electrodes and solutions are shown in Figure 79.

In a cell, dissolution of the metal occurs at the negative electrode (the anode), while hydrogen is evolved at the positive electrode (cathode). The anodic metal is corroded and the cathode is protected. The rate of corrosion of the anodic metal depends on the degree of separation of the two metals concerned in the practical galvanic series, Table X. The corrosion rate is also dependent on the conductivity and composition of the electrolyte and the relative areas of the two metals. Galvanic corrosion in service applications occurs through the formation of composition cells or concentration cells.



Anode Reaction: $Fe \longrightarrow Fe^{++} + 2e^- \longrightarrow Fe^{+++} + 3e^-$

Cathode Reaction: $2H^+ + 2e^- \longrightarrow H_2$ (gas)

FIGURE 79. Galvanic Cell

TABLE X - GALVANIC SERIES OF METALS AND ALLOYS

Anodic End	Magnesium
	Magnesium Alloys
	Zinc
	Alclad
	Aluminum 6053
	Cadmium
	Aluminum 2024
	Cast Iron
	Wrought Iron
	Mild Steel
	13% Chromium Steel Type 410 (Active)
	18-8-3 Chromium Nickel Stainless Steel Type 316 (Active)
	18-8 Chromium Nickel Stainless Steel Type 304 (Active)
	Tin
	Lead
	Lead Tin Solders
	Naval Brass
	Manganese Bronze
	Muntz Metal
	76 Ni-16 Cr-7 Fe Alloy (Active)
	Nickel (Active)
	Silicon Bronze
	Copper
	Red Brass
	Aluminum Brass
	Admiralty Brass
	Yellow Brass
	76 Ni-16 Cr-7 Fe Alloy (Passive)
	Nickel (Passive)
	Silver Solder
	70-30 Cupro-Nickel
	Monel
	Titanium
	13% Chromium Steel Type 410 (Passive)
	18-8-3 Chromium Nickel Stainless Steel Type 316 (Passive)
	18-8 Chromium Nickel Stainless Steel Type 304 (Passive)
	Silver
	Graphite
	Gold
Cathodic End	Platinum

b. ***Composition cells.*** A composition cell may occur between dissimilar metals or in a single metal that has areas of differing electrode potential. An illustration of the dissimilar metal cell is galvanized (Zn coated) steel. The Zn coating is anodic to the steel base metal. Therefore when an electrolyte, such as water is present between the Fe and Zn a galvanic cell is produced. Since Zn is anodic to steel, it is preferentially attacked, protecting the steel.

A composition cell may be set up in a single metal because of differences in electrode potential between various phases, or between the grain boundaries and the matrix. An example of this is intergranular corrosion. This type of attack occurs when the grain boundaries are anodic to the matrix. The occurrence of intergranular corrosion is strongly dependent on the thermal and mechanical treatment given the metal. Generally speaking, the stronger the alloy is made through heat treat or coldwork, the less corrosion resistant it becomes.

c. ***Concentration cells.*** Concentration cells are formed when there is a difference in the concentration of the electrolyte between the areas in contact. The area that has the weakest concentration of electrolyte is attacked. The same type of cell, but of considerably more importance is the oxygen concentration cell. This cell is characterized by areas that have different oxygen concentrations. The area having the lowest oxygen concentration is anodic and attacked. Corrosion caused by an oxygen concentration cell can be expected to be found under surface dirt, mill scale or other areas that may be oxygen deficient.

73. Stress Corrosion.

a. General. Stress corrosion may occur in a susceptible material when it is subjected to residual or applied surface tensile stresses while exposed to a corrosive environment. Stress corrosion cracks initiate and propagate transverse to the loading direction, and a low strength failure results. The time required for stress corrosion to occur is dependent on several variables.

b. Strength level. As is the case with general corrosion, the higher the strength level obtained through the heat treatment or cold working of a given alloy, the lower will be its resistance to stress corrosion.

c. Grain orientation. The direction of the applied stress with reference to the grain orientation is of prime importance. The stress corrosion resistance is lowest in the short transverse grain direction and highest in the longitudinal direction, with the long transverse being intermediate. The stress corrosion resistance of a material in the short transverse may be only 10% as good as that in the longitudinal. The resistance in the long transverse direction is dependent on the grain geometry. A material with narrow elongated grains would have a long transverse susceptibility to stress corrosion nearly as poor as that in the short transverse direction. For equiaxed grains, such as found in cross-rolled material, there is no difference between the longitudinal and the long transverse direction.

Concentration of Corrosive Environment: The effect of varying the concentration of the corrosive environment on stress corrosion cannot always be predicted. In dilute solutions the stress corrosion rate is generally increased as the concentration of corrodents increases. However, it is often found that a concentrated solution is not as severe an environment as is a dilute one.

d. Stress level. At a high stress level a susceptible alloy, when exposed to a corrosive medium, may fail in a matter of minutes. As the stress is decreased, the time to failure increases. This is the basis for the threshold stress concept, which postulates, that for stress corrosion susceptible materials there is a stress value, the threshold stress, below which stress corrosion cracking will not occur, while at higher stress levels, stress corrosion cracking should be expected to occur.

74. Corrosion Protection. There are two basic methods of corrosion protection, surface protection and galvanic protection. Surface protection simply involves keeping the corrosive environment away from the part. This is commonly achieved through plating, cladding or painting. Galvanic protection is achieved by electrically connecting the metal with a sacrificial anode. This is illustrated by Zn coating of steels and by magnesium bars buried in contact with underground pipelines.

Stress corrosion is not usually a problem with carbon steel and wrought iron, but the higher strength low alloy steels may be susceptible to stress corrosion. Stress corrosion is prevented primarily by surface protection, proper grain direction exposure and by control of the magnitude of applied stresses.

75. Rocket and Missile Propellant Compatibility. Although the low alloy and carbon steel are compatible (not attacked) by many of the common rocket and missile propellants, if no water is present, their use is usually not recommended in applications where propellant contact is likely. The combination of propellants with atmospheric humidity presents a corrosive environment that is too severe for this class of steel. When they are used, protection methods such as plating or painting are recommended, but even this may not be sufficient, and failures will only be delayed.

PHYSICAL PROPERTIES.

76. Thermal Conductivity. Thermal conductivity is the measure of the ability of a material to carry or conduct heat. It is analagous to electrical conductivity. The thermal conductivity is designated by the symbol K and has the units of Btu/(hr)(ft^2)(°F)/ft. Thermal conductivity is used in the analysis of heat transfer problems.

77. Thermal Expansion. The change in dimension a solid experiences, when it is subjected to a change in temperature, is described by the coefficient of linear expansion, α. The coefficient of linear expansion can be expressed as:

$$\alpha = \frac{\Delta L}{L_o} \times \frac{1}{{}^\circ F} \tag{31}$$

where:

L_o = original dimension

ΔL = change in dimension with temperature

°F = degrees Fahrenheit

The units of α are in/in/°F. It is apparent from these units that is actually the strain in the solid due to a temperature change of 1°F. The coefficient of expansion depends on the temperature at which it is measured, so the range of temperatures over which α is valid is always specified. α is used to calculate volume changes and to determine stresses in restrained members that are subjected to temperature changes. As an example of stresses induced by temperature changes consider Figure 80. If the rigidly restrained steel rod is heated until a temperature rise of 200°F is obtained, the amount it would increase in length is

$$\Delta L = L_o \, \alpha \, \Delta T$$

or,

$$\frac{\Delta L}{L_o} = \alpha \Delta T = e \tag{32}$$

where

T = temperature change

e = strain

L_o = original length

Since the rod is restrained it cannot increase in length and a compressive stress is induced in the rod.

By definition,

$$S = Ee \tag{33}$$

Combining equations 32 and 33,

$$S = Ee = E\alpha\Delta T \tag{34}$$

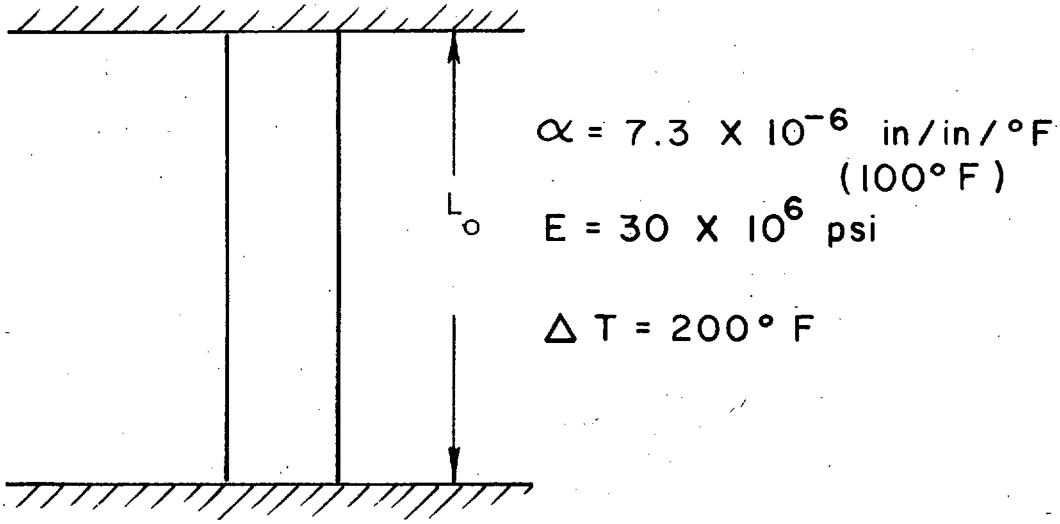


FIGURE 80. Restrained Rod

Substituting the proper values into equation 34

$$S = (30 \times 10^6 \text{ psi})(7.3 \times 10^{-6} \text{ in/in}^\circ\text{F}) \times (200^\circ\text{F})$$

$$S = 43{,}800 \text{ psi}$$

A compressive stress of 43,800 psi would be induced in the rod by a temperature change of +200°F.

78. Density. Density is defined as the mass per unit volume of a solid, but it is common engineering practice to express density as weight per unit volume, either in lb/in.^{3} or lb/ft^3.

Density is a design consideration when the weight of a structure must be controlled. The selection of an alloy is then often made on the basis of a high yield strength to density ratio, or as sometimes expressed, the "strength to weight ratio".

MATERIALS SELECTION

Choosing the correct material for use in a particular application can be a simple task or a complex one, depending upon the requirements which the material must satisfy. Generally a material is selected for use in a particular application because:

(1) The part or structure made from it will satisfy, as completely as possible, all of the essential requirements of the application.

(2) The part or structure can be produced and maintained for a lower total cost than is possible with any other material.

This doesn't, and isn't intended to imply that material should be selected on the basis of initial or raw material cost alone. Raw material cost is an important factor; however, the choice of material, encompassing alloy, form, temper and surface condition, can significantly affect manufacturing costs, maintenance costs, inspection costs, repair costs, handling costs, etc. The effect on these costs should be carefully analyzed before a material is actually selected for a particular application. Consideration of raw material costs alone very often does not reveal the true total cost situation.

Carbon and low-alloy steels are available in many different combinations of composition, form, temper and surface condition. As discussed in earlier chapters, different alloys possess different combinations of properties and characteristics. Many of the plain carbon steels and the high strength low alloy steels, for example, are most often used in the as-rolled condition, in applications where the moderate strength they develop in this condition is adequate for the purpose. When higher strengths are required, an alloy steel that can be heat treated to the required strength level is ordinarily used. Naturally, alloy steels are more expensive than plain carbon steels and in addition, the heat treatment increases the fabrication costs. An alloy can be selected on the basis of mechanical properties, machining characteristics, welding characteristics, forming characteristics, heat treat response, the capability of being case hardened, or any combination of properties and characteristics. Considering only carbon and alloy steels, a user may choose from a wide variety of alloys, each offering a particular combination of properties and characteristics. To further complicate the situation, other materials are competitive with steels in some applications; as for example, the high strength aluminum alloys and titanium alloys.

The functional requirements of some applications can be satisfied by any one of a number of different materials. Choosing the best material under such conditions can be a difficult decision and the choice of material can significantly affect the total cost of the project. Many variables can be involved and each should be accorded due consideration. In other cases requirements are so stringent or so unique that it is necessary to conduct a test program to evaluate various materials for the particular application. Often it is impossible to find any material that completely satisfies all of the essential requirements of a given application and some compromise must be effected. In any event, careful analysis of all pertinent factors is essential to arrive at a satisfactory solution.

As with other engineering problems, a logical, orderly approach is beneficial in solving materials selection problems. The Value

Engineering technique first identifies essential functional requirements such as the type and magnitude of the loads which the part or structure must sustain, the operating environment, service life, surface finish requirements, surface hardness requirements, size, shape, and weight limits, and so forth. When all of the requirements are identified, candidate materials can be selected on the basis of the appropriate selection criteria, for example, tensile strength, endurance limit, hardenability, corrosion resistance, fracture toughness, etc. Then by comparative analysis, on the basis of satisfying the essential functional requirements and considering total cost, the most suitable material can be selected.

Again it must be emphasized that the materials should be compared on the basis of total cost, not initial raw material cost alone. Also, it is essential that the end product must be capable of satisfying, as completely as possible, all of the essential functional requirements of the application. Further, before a particular material, that is, alloy, form, temper, and surface condition is specified on a drawing, its current availability and cost should be confirmed.

Careful attention to materials selection can help to keep the total cost of producing and maintaining an item at a minimum, whether it is a simple part or a complex structure. Some material selections are easily made, others require extensive analysis, In either case consultation with a qualified Materials Engineering organization is recommended.

Chapter 5

Quality Assurance

GENERAL

When the term "quality assurance" is applied to the purchase of raw materials, such as iron or steel wrought products, it may be considered as a general definition of the various responsibilities which are incumbent upon the purchaser (purchasing agency) to assure that the material ordered and accepted for use in a particular application is of suitable quality. It is the responsibility of the purchaser to:

a. Determine the exact requirements the materials must meet;

b. Communicate these requirements, completely, concisely, and explicitly, to the material producer(s);

c. Obtain confirmation from the producer that the requirements are realistic and that the producer is willing to supply material to these requirements;

d. Verify that the incoming material satisfies the established requirements.

MATERIALS DESIGNATIONS

The American Iron and Steel Institute and the Society of Automotive Engineers, Inc., have developed similar numerical designation systems by which steels are identified by chemical composition. The basics of these systems are presented in Table XI, which was taken from Federal Standard No. 66 (Steel: Chemical Composition and Hardenability). The standard also contains a listing of the chemical composition limits for carbon and alloy steels, including the hardenability steels (H-steels). The AISI designations are given for the various compositions, and, when there is no difference, the SAE designation is also listed. The data in Federal Standard No. 66 are directly applicable to the procurement of carbon and alloy steel wrought products and the Standard is referenced in, and forms a part of, many Federal and Military materials specifications.

SPECIFICATIONS

79. General. Material specifications are also used extensively in the procurement of steel and iron wrought products. Among the various specifications series available for use are the Military Specifications and Standards, the Federal Specifications and Standards, the AMS Specifications (Aerospace Material Specifications issued by the Society of Automotive Engineers, Inc.), and the ASTM Standards (issued by the American Society for Testing and Materials). The cross index at the end of this chapter lists the Federal, Military, AMS, and ASTM specifications which apply to the same composition and form of carbon or low alloy steel. When applicable the AISI-SAE standard composition designation number is also listed.

The different specifications that are shown to apply to steel of the same composition and form are not necessarily equivalent specifications. There are often slight differences between specifications issued by the various organizations; any two specifications should be carefully reviewed before they are used as equivalents.

Also, the cross index is not a complete listing

TABLE XI. NUMERICAL DESIGNATION OF STEELS BY COMPOSITION

Classification	Groupings	Series Designation		Explanation
		AISI	SAE	
Carbon Steels	Plain (nonresul.)			Each of the standard carbon and alloy steels is identified by a four-digit AISI or SAE number. The majority of AISI and SAE steels are identical. The first two digits of the number indicate the type of steel; i.e., for carbon steels 10xx indicates the non-resulphurized carbon steels, 11xx indicates the rephosphorized and re-sulphurized carbon steels. Similarly, for alloy steels, the first two digits indicate the grouping based on the significant alloying element or elements; i.e., 13xx for manganese steels. The last two digits of the number generally indicate the approximate middle of the carbon percentage range for the particular steel. For example in the composition identified as 1035, the 35 in the designation indicates that the steel has a carbon content range with a midpoint at 0.35 percent. In addition, prefix letters are used (primarily in AISI designations) to indicate the steelmaking process employed or the special end-use of the steel; i.e., B indicates acid bessemer steel. For alloy steels suffix letters indicate modifications or special types.
	Low carbon	Up to 1013	Up to 1013	
	Med. low carbon	1031 to 1022 incl	1013 to 1022 incl	
	Med. high carbon	Over 1022 to 1041 incl	Over 1022 to 1041 incl	
	High carbon	Over 1041	Over 1041	
	Free-cutting (Free-machining)			
	Resulphurized	11xx	11xx	
	Rephosphorized and resulphurized	12xx	11xx	
	Acid bessemer	B11xx	11xx	
Alloy Steels	Manganese	13xx	13xx	
	Boron	14xx	14xx	
	Nickel-chromium	31xx	31xx	
		33xx	33xx	
	Molybdenum	40xx	40xx	
		44xx	44xx	
		45xx	45xx	
	Chromium-molybdenum	41xx	41xx	
	Nickel-chromium-molybdenum	43xx	43xx	
		47xx	47xx	
		81xx	81xx	
		86xx	86xx	
		87xx	87xx	
		88xx	88xx	
		93xx	93xx	
		98xx	98xx	
	Nickel-molybdenum	46xx	46xx	
		48xx	48xx	
	Chromium			
	Low	50xx	40xx	
		51xx	51xx	
	Low (bearing)	50xxx	501xx	
	Medium (bearing)	51xxx	511xx	
	High (bearing)	52xxx	521xx	
	Chromium-vanadium	61xx	61xx	
	Silicon-manganese	92xx	92xx	
	Boron-intensified	xxBxx	xxBxx	
	Leaded	xxLxx	xxLxx	

of all of the specifications covering steel wrought products. Only the more common compositions and forms, to which more than one specification applies, are listed. For a complete listing of specifications and standards the following should be consulted.

a. The Department of Defense Index of Specifications and Standards. This is a two part index, numeric and alphabetical, listing all of the Military and Federal Specifications and Standards.

b. The Index of Aerospace Materials Specifications.

c. The Index to ASTM Standards.

80. Use of Specifications. The use of Military, Federal, AMS, and ASTM specifications greatly simplifies the communication of requirements from the purchaser to the supplier or producer. The specifications in these four series are generally recognized and accepted by the steel producers and are widely used throughout the industry. By using specifications from these series the purchaser communicates his requirements to the producer or supplier in a familiar standard form and minimizes the possibility of a misunderstanding.

The specifications are generally designed to fit the composition and form of steel to which they apply. Consequently, the requirements established by different specifications vary considerably. For example, many of the specifications for carbon steels establish requirements for chemical composition, temper, surface condition, form, and dimensional tolerances, but mechanical properties are often omitted. When these specifications are used it is necessary for the procuring agency to specify the mechanical properties requirements in the purchase order or contract, whenever the control of these properties is considered to be necessary.

The requirements which a material must satisfy are established by the purchaser on the basis of meeting the functional and processing requirements demanded by a particular application. A material specification should be selected which establishes requirements for a material that are consistent with the requirements of the application. Because of the wide difference in specifications it is advisable to select specifications on the basis of careful comparison with application requirements.

The material specifications establish pertinent requirements for a specific composition and form of steel. Examples are, chemical composition, mechanical properties, hardness, dimensional tolerances, austenite grain size, decarburization limits, and the like. As noted, the requirements established by the different specification vary greatly. The tests and examinations which must be conducted to verify that a material satisfies established requirements necessarily vary with the requirements. It is the responsibility of the purchaser to determine what tests must be conducted to verify the quality of a lot of material. Many specifications require the performance of certain tests by the producer and require the producer to submit certified reports of the test results along with the material. In addition the purchaser is permitted to duplicate these tests and to perform any other appropriate tests that are deemed necessary. A wide variety of tests can be conducted on steel and iron wrought products and the purchaser must select those that are necessary and appropriate depending upon the composition, form, and requirements imposed upon the material.

STANDARDS

Federal and Military Specifications reference various Military and Federal Standards which are considered to form a part of the specifications. One such standard has already been noted, FED STD No. 66, "Steels - Chemical Composition and Hardenability", which provides the composition and hardenability requirements for various carbon and alloy steels. Federal Test Method Standard No. 151, "Metals, Test Methods" is another often referenced standard. Others are: MIL-STD 430, "Macrograph Standards for Steel Bars, Billets, and Blooms"; FED STD No. 48, "Tolerances for Steel and Iron Wrought Products"; FED STD No. 123, "Marking for Domestic Shipment (Civilian Agencies)"; FED STD No. 102, "Preservation, Packaging and Packing Levels"; MIL STD No. 163, "Steel Mill Products, Preparation for Shipment and Storage;" MIL-STD 271, "Nondestructive Testing Requirements for Metals"; MIL-STD 410, "Qualification of Inspection Personnel (Magnetic Particle and Penetrant)"; MIL-STD 453, "Inspection Radiographic"; FED STD No. 183, "Continuous Identification Marking of Iron and Steel Products."

The ASM and ASTM specification systems have the equivalent of the Federal and Military Standards. These documents provide supplementary data which are applicable to many specifications.

Federal Test Method Standard No. 151, for example, establishes the procedures and methods for testing metals when Military and Federal specifications are used. There are various tests which may be used depending upon the properties and characteristics to be checked. Many are specifically called for in the various specifications, for example, tensile tests, analysis of chemical composition, austenite grain size determination, inclusion content, magnetic particle inspection, ultrasonic inspection, radiographic tests, etc. The purchaser should verify by appropriate tests that the incoming material satisfies the requirements established by the specification and by the contract with the producer. It is the responsibility of the purchasing agency to decide what tests will be conducted and by whom.

Special skills are required for many of the tests specified in Federal Standard Test Method 151. Care should be exercised to assure that competent operators and equipment are used in performing the specified tests.

Many of the tests applicable to the inspection of raw materials are also useful as process control inspection tests. Careful selection and inspection of the raw materials used to produce a part or structure does not insure the quality of the final article. Steel wrought products can be severely damaged during fabrication unless the processes are effectively controlled. The hardness test, tensile test, X-ray examination, ultrasonic inspection, and many of the other tests described in Federal Test Method Standard 151 are applicable not only to the inspection of raw materials but are equally useful as in-process inspection tests.

TABLE XII. SPECIFICATION CROSS INDEX

AISI-SAE Designation	Specification Numbers			
	Federal	Military	AMS	ASTM
BAR - WROUGHT CARBON STEEL				
	QQ-S-630			
	QQ-S-631			
	QQ-S-631			A31
	QQ-S-631			A283, A306
	QQ-S-631			A306
	QQ-S-631			A113
	QQ-S-634			A108
	QQ-S-637			A108
	QQ-S-632			A615
	QQ-S-632			A616
	QQ-S-632			A617
	QQ-S-632			A615, A616, A617
	QQ-S-632			A615
	QQ-S-632			A615
	QQ-S-632			A615
1015	QQ-S-631		5060	
1018	QQ-S-631		5069	
1022	QQ-S-631	Mil-S-16974	5070	
1035	QQ-S-631		5080	
1095	QQ-S-631	Mil-S-8559	5132	
1117	QQ-S-637	Mil-S-3917	5022	A108
1137	QQ-S-637	Mil-S-3917	5024	A108
B1112	QQ-S-637	Mil-S-3917	5010	A108
	QQ-S-741			A283, A306
	QQ-S-741			A36
	QQ-S-741			A36

TABLE XII. SPECIFICATION CROSS INDEX (Cont.)

AISI-SAE Designation	Specification Numbers			
	Federal	Military	AMS	ASTM
SHEET AND STRIP - WROUGHT CARBON STEEL				
1010	QO-S-636(Cond. 2)		5044	
	QQ-S-698 (HRCQ)			A415
	QQ-S-698 (HR Strip)			A425
	QQ-S-698 (CRCQ)			A109
	QQ-S-698 (Drawing Quality)			A365, A316, A320
	QQ-S-699 (Classes 1, 2 & 3)			A245 (Grade A, B & C)
	QQ-S-699 (Classes 1, 2 & 3)			A303
1050	QQ-S-700 (1050)		5085	
1074	QQ-S-700 (1074)		5120	
1095	QQ-S-700 (1095)	Mil-S-7947	5121, 5122	
1095	QQ-S-777 (1095)	Mil-S-7947	5121, 5122	
PLATE - WROUGHT CARBON STEEL				
	QQ-S-741			
	QQ-S-741			A36
	QQ-S-741			A36
	QQ-S-691 (Class A & B)			A201 (Grade A & B)
				A515, A516
	QQ-S-691 (Class C)			A212 (Grade B)
				A515, A516
1009	QQ-S-635			A283
1020	QQ-S-635			A283
1035	QQ-S-635			A283
1040	QQ-S-635			A283
1045	QQ-S-635			A283
1050	QQ-S-635			A283
TUBING AND PIPE - WROUGHT CARBON STEEL				
		Mil-T-20157 (Pipe)		A53 (Type S Grades A & B)
1010	QQ-T-830	Mil-T-20162		A513, A512, A519
1015	QQ-T-830			A513, A512, A519
1020	QQ-T-830			A513, A512, A519
1022	QQ-T-830			A513, A512, A519
1025	QQ-T-830	Mil-T-5066		A513, A512, A519
1026	QQ-T-830			A513, A512, A519
1030	QQ-T-830			A513, A512, A519
1035	QQ-T-830		5082	A513, A519
1040	QQ-T-830			A519
1045	QQ-T-830			A519
1050	QQ-T-830			A519
1118	QQ-T-830			
1137	QQ-T-830			
		Mil-T-17188		A178
		Mil-T-16286		A1292
		Mil-T-16343 (Pipe)		A53
		Mil-T-16343 (Pipe)		A135
		Mil-T-16343 (Pipe)		A139
		Mil-T-16343 (Tube)	5075, 5077	A344 (Grades 1 & 6)

TABLE XII. SPECIFICATION CROSS INDEX (Cont.)

AISI-SAE Designation	Specification Numbers			
	Federal	Military	AMS	ASTM
STRUCTURAL SHAPES - WROUGHT CARBON STEEL				
	QQ-S-741			
	QQ-S-741			A36
	QQ-S-741			A36
FORGINGS - WROUGHT CARBON STEEL				
		Mil-S-24093		
		(Class IV, V)		A235
		Mil-S-23194		
		(Comp 2-Type		
		C)		A235
		Mil-S-890		
		Classes Ac,		
		B-S Special,		
		B and C)		A235
		Mil-F-7190		A235
WIRE - WROUGHT CARBON STEEL				
1020	QQ-W-461		5032	A228
1090	QQ-W-470		5112	
BAR - WROUGHT LOW ALLOY STEELS				
3135	QQ-S-624		6330	A304, A331, A322
3140	QQ-S-624			A304, A331, A322
3310	QQ-S-624	Mil-S-7393		A304, A331, A322
	QQ-S-624	(Comp. 1)	6250	A304, A331, A322
3316		Mil-S-7393		
		(Comp. II)		
4037	QQ-S-624		6300	A304, A331, A322
4130	QQ-S-624	Mil-S-6758	6370	A304, A331, A322
4140	QQ-S-624	Mil-S-5626	6382	A304, A331, A322
4150	QQ-S-624			A304, A331, A322
4320	QQ-S-624		6299	A304, A331, A322
4340	QQ-S-624	Mil-S-5000	6415	A304, A331, A322
4615	QQ-S-624	Mil-S-866		
4615	QQ-S-624	Mil-S-7493	6290	A331, A322
4617	QQ-S-624	Mil-S-7493	6292	
4620	QQ-S-624	Mil-S-7493	6294	A304, A331, A322
4640	QQ-S-624		6312	A331, A322
6150	QQ-S-624	Mil-S-8503	6448	A304, A331, A322
8615	QQ-S-624	Mil-S-866	6270	A331, A322
8620	QQ-S-624	Mil-S-8690	6274	A304, A331, A322
8630	QQ-S-624	Mil-S-6050	6280	A304, A331, A322
8640	QQ-S-624			A304, A331, A322
8650	QQ-S-624			A304, A322
8735	QQ-S-624	Mil-S-6098	6320	
		(Cond. C)		
8740	QQ-S-624	Mil-S-6049	6322	A304, A331, A322
		Cond. C)		
9310	QQ-S-624	Mil-S-7393	6260, 6267	A304, A331, A322
		(Comp. III)		
945		Mil-S-7809		
950		Mil-S-7809		
9840	QQ-S-624		6342	A304, A322
		Mil-S-6709	6470	
		Mil-S-6709		
		(Cond. F)	6472	
52100		Mil-S-7420	6440, 6447	
		Mil-S-18410		A182(GR. F-11)
		(CL. a)		
		Mil-S-18410		A336(CL. F-22)
		(CL. b)		
SHEET AND STRIP - WROUGHT LOW ALLOY STEEL				
4130	QQ-S-627	Mil-S-18729	6350, 6351	A505
4135	QQ-S-627	Mil-S-18733	6352	A505
4140	QQ-S-627		6395	A505
4142	QQ-S-627			A505
4145	QQ-S-627			A505
4150	QQ-S-627			A505
4340	QQ-S-627		6359	A505
5140	QQ-S-627			A505

TABLE XII. SPECIFICATION CROSS INDEX (Cont.)

AISI-SAE Designation	Specification Numbers			
	Federal	Military	AMS	ASTM
SHEET AND STRIP - WROUGHT LOW ALLOY STEEL (Continued)				
5150	QQ-S-627			A505
6150	QQ-S-627	Mil-S-18731	6455	A505
8615	QQ-S-627			A505
8617	QQ-S-627			A505
8620	QQ-S-627			A505
8630	QQ-S-627	Mil-S-18728	6355	A505
8640	QQ-S-627			A505
8645	QQ-S-627			A505
8735	QQ-S-627		6357	A505
9262	QQ-S-627			A505
945		Mil-S-7809		
950		Mil-S-7809		
PLATE - WROUGHT LOW ALLOY STEEL				
4130	QQ-S-626			6350, 6351
4135		Mil-S-18733		
4140	QQ-S-626	Mil-S-18729	6395	
4340	QQ-S-626		6359	
4620	QQ-S-626			
6150	QQ-S-626			
8620	QQ-S-626			
8630		Mil-S-18728	6355	
945		Mil-S-7809		
950		Mil-S-7809		A514
		Mil-S-16216		A302(GR B)
		Mil-S-871 (CL. 2)		
TUBING - WROUGHT LOW ALLOY STEEL				
4130	QQ-T-00825	Mil-T-6736	6360, 6371	A513, A519
4135	QQ-T-00825	Mil-T-6735	6365, 6372	A519
4140	QQ-T-00825		6381, 6390	A519
6150	QQ-T-00825			A519
8630	QQ-T-00825	Mil-T-6734	6281	
	QQ-T-00825	Mil-T-6732	6530, 6550	A513, A519
8640	QQ-T-00825			A519
8720	QQ-T-00825			
8740	QQ-T-00825		6323	
8735		Mil-T-6733	6282, 6535	A519
9310			6260	
STRUCTURAL SHAPES - WROUGHT LOW ALLOY STEEL				
		Mil-S-12505		A440
945		Mil-S-7809		
950		Mil-S-7809		
FORGINGS - WROUGHT LOW ALLOY STEELS				
		Mil-S-23194		A237
		Mil-S-24093		A237
4130		Mil-F-7190		A237
4135		Mil-F-7190	6370	
4140		Mil-F-7190	6382	A237
4320		Mil-S-23194		
4340		Mil-F-7190	6415	A237
8630		Mil-F-7190	6280	A237
8735		Mil-F-7190	6320	A237
8740		Mil-F-7190	6322, 6325, 6327	A237
8750		Mil-F-7190	6328	A237
9840		Mil-F-7190	6342	A237
		Mil-S-18410 (CL. 2)		A182(GR. F-11)
		Mil-S-18410 (CL. b)		A336(CL. F-22)
WIRE - WROUGHT LOW ALLOY STEELS				
	QQ-W-412			A231
-	QQ-W-412	Mil-W-16632		A401
6150		Mil-W-22826	6450	A232

Appendix A

Glossary

alloy steel: (The American Iron and Steel Institute Definition). By common custom, steel is considered to be alloy steel when the maximum range given for the content of alloying elements exceeds one or more of the following limits: manganese, 1.65 percent; silicone, 0.60 percent; copper, 0.60 percent; or in which a definite range or a definite minimum quantity of any of the following elements is specified or required within the limits of the recognized field of constructional alloy steels; aluminum, boron, chromium up to 3.99 percent, cobalt, columbium, molybdenum, nickel, titanium, tungsten, vanadium, zirconium, or any other alloying element added to obtain a desired alloying effect. Small quantities of certain elements are present in alloy steels which are not specified or required. These elements are considered as incidental and may be present to the following maximum amounts; copper, 0.35 percent; nickel, 0.25 percent; chromium, 0.20 percent; molybdenum, 0.06 percent.

alpha iron: The body-centered cubic form of pure iron, stable below 1670°F.

annealing: A heat treat process; heating a metal to and holding it at a particular temperature and then cooling it at a suitable rate to achieve a desired result, such as, reducing hardness, grain refinement, developing a particular microstructure, stress relieving, etc.

austempering: A heat treat process which consists of quenching a ferrous alloy from a temperature above its transformation range in a medium having a sufficiently high rate of heat abstraction to prevent the formation of high temperature transformation products. The alloy is held at a temperature below that of pearlite formation and above that of martensite formation until transformation is complete.

austenite: The solid solution of one or more elements in gamma-iron (face-centered cubic). The solute is assumed to be carbon, unless otherwise designated, e.g., nickel austenite.

austenitizing: The process of forming austenite in a ferrous alloy by heating it to a temperature within the transformation range (partial austenitizing), or to a temperature above the critical range (complete austenitizing).

bainite: A transformation product of austenite. Bainite is formed by isothermal transformation of austenite at temperatures lower than that for the fine pearlite and above the M_S temperature. Bainite is an aggregate of ferrite and cementite, when formed at temperatures in the upper portion of the transformation range it has a feathery appearance (upper bainite), while that formed at lower temperatures has an acicular or needlelike structure (lower bainite).

basic-oxygen process: A process of steelmaking in which molten pig iron and scrap are refined in a converter by blowing high purity oxygen onto the surface of the charge.

Bessemer process: A process of steelmaking in which air is blown through the charge of molten pig iron contained in a bessemer converter.

billet: A semifinished hot rolled, forged, or extruded product, generally with a round or square cross-section. For ferrous materials the minimum diameter or thickness for a billet is 1 1/2 inches, and the cross-sectional area may range from 2 1/4 to 36 square inches.

blast furnace: A shaft furnace in which solid fuel is burned with an air blast to smelt ore in a continuous operation. The molten metal and molten slag are collected at the bottom of the furnace and are drawn off periodically.

bloom: A semifinished hot rolled product, usually with a square or rectangular cross section. If rectangular the width is no greater than twice the thickness. The cross-sectional area of a bloom usually exceeds 36 square inches.

carbon steel: (The American Iron and Steel Institute Definition). Carbon steel is classed as such when no minimum content is specified or guaranteed for aluminum, chromium, columbium, molybdenum, nickel, titanium, tungsten, vanadium, or zirconium; when the minimum for copper does not exceed 0.40 percent; or when the maximum content specified or guaranteed for any of the following elements does not exceed the percentages noted; manganese, 1.65; silicon, 0.60; copper, 0.60.

cementite: Iron carbide a hard brittle compound of iron and carbon, Fe_3C.

cold working: Plastic deformation of a metal at a temperature below its recrystallization temperature.

critical cooling rate: The slowest rate at which steel can be cooled from above the upper critical temperature to prevent the transformation of austenite at any temperature above the M_s.

critical point: In an equilibrium diagram, the specific combination of composition, temperature, and pressure at which the phases of a heterogeneous system are in equilibrium.

critical range: In ferrous alloys, the temperature ranges within which austenite forms on heating and transforms on cooling. The heating and cooling ranges may overlap but they never coincide.

critical temperature: Synonymous with critical point when pressure is constant.

crystal: A solid in which the atoms, ions, or molecules are arranged in a definite pattern which is repetitive in three directions.

decarburization: The loss of carbon from the surface of a ferrous alloy as the result of heating in a medium that reacts with the carbon at the surface of the material.

delta iron: The body-centered cubic crystalline form of pure iron, stable in the temperature range of 2535°F to the melting termperature, 2795°F.

delta solid solution: The solid solution of carbon in delta iron.

deoxidizer: A substance that can be added to molten metal to react with free or combined oxygen to facilitate its removal.

elastic deformation: The change in dimensions accompanying stress in the elastic region, the original dimensions are restored upon release of stress.

elastic limit: The greatest stress that a material can withstand without any permanent strain remaining upon complete release of the stress.

elastic modulus: See modulus of elasticity.

element: A substance that cannot be decomposed by ordinary chemical reactions.

endothermic: A reaction attended by the absorption of heat.

equilibrium: A dynamic condition of balance between atomic movements where the resultant change is zero and the condition appears to be static rather than dynamic.

equilibrium diagram: A graph of the composition, temperature, and pressure limits of the phase fields in an alloy system under equilibrium conditions. In metal systems pressure is usually considered to be constant.

eutectic: An intimate mechanical mixture of two or more phases having a definite composition and a definite melting point.

eutectic reaction: An isothermal reaction in which a liquid solution is converted into two or more intimately mixed solids on cooling. The number of solids formed is the same as the number of components in the system.

eutectoid: A mechanical mixture of two or more phases having a definite composition and a definite temperature of transformation within the solid state.

eutectoid reaction: An isothermal reversible reaction in which a solid solution is converted into two or more intimately mixed solids on cooling. The number of solids formed is the same as the number of components in the solution.

exothermic: A reaction attended by the liberation of heat.

fatigue: The phenomenon which results in the fracture of materials under repeated cyclic stresses having a maximum value lower than the tensile yield strength of the material.

fatigue limit: The maximum or limit stress value below which a material can presumably endure an infinite number of stress cycles.

fatigue strength: The maximum stress that can be sustained by a material for a specified number of cycles without failure. Completely reversed loading is implied unless otherwise qualified.

ferrite: The solid solution of carbon in alpha iron, body-centered cubic structure.

ferroalloy: An alloy of iron that contains a sufficient amount of some other element(s) to be useful as an agent for introducing the other element(s) into molten metal.

gamma iron: The face-centered cubic form of pure iron, stable from 1670°F to 2535°F.

gangue: The worthless portion of ore.

grain: An individual crystal in a polycrystalline metal or alloy.

hardenability: The property of a ferrous alloy which determines the depth and distribution of hardness that may be induced by quenching.

heat treatment: The operation or series of operations of heating and cooling a metal or alloy in the solid state to develop specific desired properties or characteristics.

Hooke's Law: Stress is proportional to strain. This law is valid only up to the elastic limit.

hot shortness: Brittleness in metal when hot.

hypereutectoid steel: Steel containing more than the eutectoid amount of carbon.

hypoeutectoid steel: Steel containing less than the eutectoid amount of carbon.

ingot: A special kind of casting (in steelmaking) intended for rolling or forging to wrought form.

iron carbide: A binary compound of iron and carbon, Fe_3C, see also cementite.

iron-carbon diagram: The equilibrium diagram for the iron-carbon binary system.

isothermal transformations: A phase change which is made to occur at a constant temperature within the transformation range.

killed steel: Steel that has been deoxidized with a strong deoxidizer such as aluminum so that little or no reaction occurs between carbon and oxygen during solidification.

low-alloy steel: Alloy steels with a total alloy content of five percent or less.

martempering: A heat treat process that consists of quenching a ferrous alloy from an austenitizing temperature to a temperature slightly above or within the martensite transformation range, holding the the material in the quench medium until the temperature throughout the mass is essentially uniform, after which the material is removed from the quench medium and cooled slowly in air.

martensite: A transformation product of austenite that forms below the M_s temperature. Is a metastable phase; as formed, alpha-martensite is a supersaturated interstitial solid solution of iron carbide in ferrite having a body-centered tetragonal crystal structure, characterized by an acicular or needlelike microstructural appearance. Aging or tempering alpha-martensite converts the tetragonal crystal structure to the body-centered cubic structure, in which form it is called beta-martensite.

modulus of elasticity: Within the proportional limit, the ratio of stress to corresponding strain. A measure of the rigidity of a metal; in tension or compression, Young's modulus; in torsion or shear, the modulus of rigidity, or modulus of torsion, or the modulus of shear.

normalizing: A heat treat process for ferrous materials that consists of cooling the material in air from a temperature slightly above the transformation range to room temperature.

open-hearth process: A steelmaking process in which pig iron and scrap are refined in a reverbatory furnace having a shallow hearth and low roof. The charge is heated by a long sweeping flame that passes over it.

ore: A natural mineral that may be mined and treated to extract any of its components.

pearlite: The lamellar aggregate of ferrite and iron-carbide that results from the transformation of austenite at the lower critical point on cooling.

permanent set: Plastic deformation that remains after the release of the stress that produced the deformation.

plastic deformation: Deformation that will or does remain permanent after the load that caused it is removed.

Poisson's *ratio*: The ratio of the transverse strain to the corresponding axial strain in a body subjected to uniaxial stress; usually applied to elastic conditions.

proportional limit: The maximum stress at which strain remains directly proportional to stress.

quench hardening: Hardening a ferrous alloy by austenitizing and then cooling rapidly enough so that all or some of the austenite transforms to martensite. Austenitizing temperatures for the hypoeutectoid steels are usually above the A_3, for the hypereutectoid steels austenitizing temperatures are usually between the A_1 and the A_{cm}.

red shortness: See hot shortness.

rimmed steel: A low carbon steel containing sufficient iron oxide to promote a continuous evolution of carbon monoxide during solidification of the ingot.

semikilled steel: Steel that is incompletely deoxidized so that sufficient oxygen remains to react with carbon to form carbon monoxide to offset solidification shrinkage.

shear modulus: See modulus of elasticity.

slab: A semifinished hot rolled product of rectangular cross section with a width greater than twice the thickness.

stress relieving: A heat treatment which consists of heating a metal to a suitable temperature and holding it at the temperature long enough to reduce residual stresses and then cooling it slowly to minimize the possibility of developing new residual stresses.

tempering: Reheating a quench-hardened or normalized ferrous alloy to a temperature below the transformation range and then cooling at any suitable rate.

transformation temperature: The temperature at which a phase change occurs. Often used to denote the limiting temperature of a transformation range. Standard identification symbols for iron and steel are as follows:

Ac_{cm}	For hypereutectoid steel, the temperature at which the solution of cementite in austenite is completed on heating.
A_{c1}	The temperature at which austenite begins to form on heating.
A_{c3}	The temperature at which the transformation of ferrite to austenite is completed on heating.
A_{c4}	The temperature at which austenite transforms to delta ferrite on heating.
Ar_{cm}	For hypereutectoid steels, the temperature at which cementite begins to precipitate from austenite on cooling.
Ar_1	The temperature at which the transformation of austenite to ferrite, or to ferrite plus cementite is completed on cooling.
Ar_3	The temperature at which austenite begins to transform to ferrite on cooling.
Ar_4	The temperature at which delta ferrite transforms to austenite on cooling.
Ae_1, Ae_3, A_{e4} or A_{cm}, A_1, A_3, A_4	Transformation temperatures under equilibrium conditions.
M_s	(Martensite Start) The temperature at which austenite starts to transform to martensite.
M_f	(Martensite Finish) The temperature at which the formation of martensite is completed.

welding: (American Welding Society Definition) "A localized coalescence of metal wherein coalescence is produced by heating to suitable temperatures, with or without the application of pressure, and with or without the use of filler metal. The filler metal either has a melting point approximately the same as the base metals or has a melting point below that of the base metals but above 800°F.

wrought iron: (ASTM definition) A ferrous material, aggregated from a solidifying mass of pasty particles of highly refined metallic iron, with which, without subsequent fusion, is incorporated a minutely and uniformly distributed amount of slag.

Young's modulus: See modulus of elasticity.

Appendix B

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Department of Defense
Washington, DC 20301

MIL-HDBK-728
Military Handbook of Nondestructive Testing
16 December 1985

1. This Military Handbook is approved for use by all Departments and Agencies of the Department of Defense.

2. This publication was approved on 21 October 1985 for printing and inclusion in the military standardization handbook series.

3. This document provides basic and fundamental information on nondestructive testing, inspection and evaluation useful during all phases of the DoD hardware's life cycle.

4. Every effort has been made to reflect the latest information on nondestructive examination. It is the intent to review this handbook periodically to insure its completeness and currency. Beneficial comments (recommendations, additions, deletions) and any pertinent data which may be of use in improving this document should be addressed to: Director, U.S. Army Materials Technology Laboratory, ATTN: SLCMT-MSR-ES, Watertown, MA 02172-0001 by using the self-addressed Standardization Document Improvement Proposal (DD Form 1426) at the end of this document or by letter.

FOREWORD

This handbook provides to all Department of Defense (DoD) personnel information, facts, and principles on the science of nondestructive testing, inspection, and evaluation. By proper use of this science, the safety, the reliability, and the efficiency of the procurement and use of all DoD material and hardware will be increased. This handbook information should be useful during all phases of the DoD hardware's life cycle including production, maintenance, and repair of the hardware.

This handbook, by combining the existing nondestructive testing handbooks and related materials from all DoD agencies into one document, should help to establish unity in the nondestructive testing area within and between all the agencies of the DoD. The organization and loose-leaf format will make it easy to correct, update, and tailor to fit individual needs within the DoD.

Since the handbook's effectiveness depends upon continuous feedback from its users, individuals are encouraged to contribute comments and suggestions by filling in and mailing Form DD 1426 provided at the end of this document.

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1.0 SCOPE

1.1 Scope. Although this handbook is provided as a guide to all those employed in nondestructive testing (NDT), it will be of specific interest to administrators, designers, production engineers, quality assurance personnel, and nondestructive test engineers and technicians. It has been formulated to cover both broad and specific applications of NDT, so as to satisfy individuality, as well as conformity, of interests and knowledge among the divisions of reponsibility in NDT. Not everyone will be interested in all of the specially identified sections. However, to obtain optimum benefits, it is recommended that users of this document review it in its entirety, while paying particular attention to those sections, often identified by a heading or subnote, which may be of specific concern to them.

The handbook, which currently incorporates general principles and procedures (as well as safety items) of eddy current, liquid penetrant, magnetic particle, radiographic and ultrasonic testing, will be updated to include chapters on other NDT methods as they become appropriate.

It must be emphasised that this handbook is not a training manual. Nor can it replace other written directives, procedures or specifications. However, it can serve as a ready reference to the important principles and facts relating to the employment of nondestructive testing, inspection and evaluation. It can be used to refresh one's memory of a particular NDT principle or relationship, to double check or establish a particular fact, or to review the main ideas, concepts or completeness of a particular approach.

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1.2 USERS GUIDE

1.2.1 HANDBOOK ORGANIZATION

This handbook, which is intended to make changes, additions and tailoring easy, uses chapters as independent organizational elements. Each chapter is reasonably complete and self-contained with respect to each specific topic presented and is divided into numbered sections and subsections for ease of reference and use.

Pages are numbered consecutively within each section; sections are numbered consecutively within each chapter; and chapters are numbered consecutively within the handbook. The publication or revision date of each page is located at the bottom inner edge of the page.

Tables, monographs, drawings, and other illustrative material are normally presented within the text. They are identified by the number of the section in which they first are referenced, followed by a sequence number in parentheses: e.g., the first Table in section 5.2 is designated as Table 5.2 (1), the second Table in the same section is designated Table 5.2(2), etc.

The general Table of Contents listing all chapters in the handbook is found on page iv. A Table of Contents listing all sections in a chapter is located at the beginning of each chapter.

1.2.2 REFERENCES

There are two types of references used in this handbook: (1) cross-references to paragraphs in the handbook, and (2) references to other publications which are the sources of specific material. Cross-references are used within this handbook wherever possible to avoid duplication of information.

1.2.3 INDEX

A detailed index of subject matter, keyed to section numbers, is provided at the end of each chapter.

1.2.4 FORMAT FOR DEFINITIONS

Terms which apply to a specialized area and are not defined in standard publications are usually explained in this handbook. If a term is used only once or infrequently, it is explained in the text where it occurs. If it is used frequently throughout a chapter, it will appear in the glossary at the end of the chapter. Common terms, or those whose definitions appear in standard glossaries or dictionaries, are not normally included in this handbook.

1.2.5 HANDBOOK REVISIONS

Every effort has been made to reflect the latest information on eddy current, liquid penetrant, magnetic particle, radiographic, and ultrasonic testing. It is the intent to review this handbook periodically to ensure its completeness and currency. Each revision will include a revised List of Current Pages which will show the latest issue of each page of the handbook.

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1.3 DEFINITIONS FOR NDT, NDI, AND NDE

Although extensive definitions are included in each chapter, several basic terms -- Nondestructive Testing (NDT), Nondestructive Inspection (NDI), and Nondestructive Evaluation (NDE) -- are worthy of special discussion.

Any testing, inspection, or evaluation that does not cause harm to or impair the usefullness of an object satisfies the meaning of the word "nondestructive." In common usage, testing often refers just to test methods and test equipment with only a general reference to materials and/or parts. Inspection relates to specific written requirements, procedures, personnel, standards, and controls for the testing of a particular material or a specific part. Evaluation is concerned with the decision-making process, the determination of the meaning of the results, or the final acceptance or rejection of the material or part and may be qualitative or quantitative. When only qualitative or relative values are required, the use of reference standards is minimized. For quantitative evaluations, however, extensive use of reference standards and controls is often involved.

Although these distinctions between NDT, NDI, and NDE can be (and often are) made, the terms are also often interchanged. In order to evaluate, the results of an inspection must be available. In order to have the results of an inspection, a test must be conducted. And no test or inspection is really complete without an evaluation. As a result of these interdependancies, no strict differentiations between these terms are made in this handbook.

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1.4 GENERAL PRINCIPLES AND GUIDELINES

The following section presents principles and guidelines for the general employment of NDT, as well as for specific NDT disciplines. In some cases, the material is repetitive, since several disciplines are involved in similar activities. It is important, however, to understand differences, as well as similarities, between the disciplines, and to recognize how cooperation between these disparate disciplines is vital to the overall success of NDT.

Guides for applying specific NDT methods are contained in the chapters for those specific methods. The principles and guides covered in this section are all summarized in tables at the end of each subsection, and can be used as handy reference guidelines.

1.4.1 GENERAL PRINCIPLES AND GUIDELINES FOR USING NDT

Before specifing the use of NDT in any program, several things should be considered. First, determine exactly why, or if, NDT is required. There are many reasons why NDT may be desired or necessary: to increase the production rate (by assuring a higher success rate), to increase reliability, to improve or maintain safety, to meet legal requirements, to differentiate or identify improved processing methods, or to detect changes in the product before they become a problem.

There is a danger that specifying NDT has become routine practice rather than the result of a real need: i.e., it was done this way last time; it is always done this way; they did it, we have to do it; everyone else is doing it; or let's do it just to be safe. Sometimes NDT is specified just for administrative reasons: the contract requires it.

Often, although the use of NDT is specified to satisfy a legitimate requirement, it may actually be inappropriate. For example, the ultimate purpose of a test may be to ensure that a part has its required designed strength. NDT tests are often used to accomplish this determination, even though they do not directly measure the strength of a part: its strength can only be inferred by the absence of certain detectable flaws. A simple proof test, which does not require any assumptions, standards, correlations, or other inferred relationships, would have been much more appropriate. The principle here being that an effort should always be made to determine the critical properties directly. Inferring the results by secondary means should only be considered when specific circumstances warrant. Since almost all NDT methods are indirect or "secondary" types of measurements, they are often best replaced by more direct methods. Direct methods are not relevant to nondestructive test methods deployed in end items where destructive tests are not feasible, i.e. thermal damage to aircraft structure.

Whatever the reasons given for specifying NDT, it is important that everyone involved in NDT recognizes and evaluates those reasons realistically so that those responsible/for implementation are able to provide logical and effective responses. Certainly, all programs should consider specifying the use of NDT; however, its automatic use should be avoided. NDT should always have an identifiable purpose that justifies its expense. The reasons for the requirement of NDT will often affect all other decisions.

Once the reasons for the requirement of NDT have been established, it is always wise to determine if the requirement can be eliminated or reduced through the use of better materials, or better processing controls, or a better design. Nondestructive testing has no intrinsic value. Specimens do not last longer simply because they have been ultrasonically inspected. Specimens are not made stronger simply because they have been X-rayed. (If they were, we would inspect and X-ray every part ten times over.) The removing of the justification for any NDT is therefore desirable. The requirement for NDT, however, cannot always be removed. Therefore, although alternatives should ideally be considered first, NDT will often be specified.

It is the designer who has the largest responsibility in this area. (See section 1.4.3 for information on the subject as it relates to the designer.) Once it becomes clear that NDT is appropriate or otherwise required, the designer must consider other important aspects of the situation, including whether the design can be inspected and whether it can be improved to make the inspection more reliable or efficient.

Since NDT can be (and is) used for a multitude of reasons, it is important that all needs be correlated. The production engineer may want to inspect the raw material as soon as possible, even before it arrives on site. NDT engineers, if given a choice, would prefer to inspect material after it has been machined to a simple shape with smooth surfaces. Reliability and safety engineers would prefer that the NDT test be performed after all major operations have been completed. Many times, all of these tests are not affordable. Therefore, it is important to decide exactly when and where in the manufacturing process NDT should and will be specified.

For every place NDT is specified in the manufacturing process, one of the most important factors to be stipulated is the critical flaw limitations that must be detectable. Almost all materials, and all items made of materials, have imperfections of one size or another. These imperfections can be defined as flaws. However, the very small imperfections or flaws do not always impair the usefulness of an item. When this is the situation, it would be inefficient to inspect for these non-critical flaws. Therefore, the specifying of this critical size where the usefulness becomes potentially impaired is important. Those imperfections or flaws that are critical, or larger than that acceptable, are called defects. It is impossible to determine the flaw limitations required for an inspection without knowing the purposes of the inspection, as well as the complete design requirements of the finished parts.

The determination of this limitation in flaw size is not always easy. One very common limitation specified in the use of NDT is "no flaws are allowed." Certainly such an achievement would be desirable. However, no test or inspection with that kind of limitation can be expected to succeed. Often, when this impossibility is eventually understood, the next requirement specified is "find the smallest flaws possible." Again, although the desirability of this type of requirement is apparent, testing to this degree is generally not affordable.

Ultimately, the decision on the proper limitation for allowable flaw size must be made by the designer working in cooperation with production, stress, and material engineers. They must determine the types of flaws expected and the maximum allowable flaw limits required to achieve or maintain design goals.

Only after this groundwork has been completed, can the proper decisions for the requirements for NDT be made. Depending upon the NDT capabilities that exist, trade-off studies may be necessary to ensure that the critical flaws, at their specified limits, can be effectively and reliably detected. Although trade-off studies and decisions should be accomplished at the design level, they often are not because of insufficient information. When not made at the design level, choices become more limited, often resulting in either a reduction of the original design goals or the acceptance of unreliable products.

Once these flaws and flaw limitations have been determined, then NDT engineers must respond by finding answers to more questions -- What NDT method must be used? What equipment, personnel, and controls are necessary? Many times, one method alone may not be adequate.

No test or inspection is complete without the proper and adequate evaluation of the data. If a permanent test record is required, the documentation must be considered in the NDT test itself. Since some methods of NDT do not provide results in terms of a permanent record, specifying permanent records or documented proof of the passing of a test does limit the choices available. This limitation of test methods should be considered before such requests are made.

Principles and guidelines for specific disciplines are given in the paragraphs that follow. The assignment of principles and guidelines to specific disciplines clarifies who is responsible for implementing the concepts of NDT and how each discipline must support the other if success is to be achieved.

Table 1.4(1). General principles and guidelines for NDT.

1. Determine exactly why NDT is required.
2. If unreasonable, to remove the NDT requirement or minimize it.
3. If the need for NDT cannot be denied, design for inspection.
4. Determine the proper place(s) in the life cycle for performing NDT.
5. Establish critical flaw limitations in quantitive items. These limitations cannot be: "No flaws allowed" or "Find the smallest possible flaws." They should be in terms such as "No cracks shall exceed a length of 4 mm in any direction or "any pores or combination of contiguous pores that equal or exceed the volume of a 3 mm sphere shall be rejected".
6. Determine the appropriate method(s), equipment, personnel, standards, and controls. Remember, most NDT methods do not reveal flaws directly and interpretation is often possible only through the use of proper standards. NDT methods usually only find indications or differences. These indications are significant only to the degree that they can be interpreted correctly. Also remember that complete answers (positive answers) cannot always be obtained by a single inspection method. Two or more methods may be required for a complete analysis.
7. Establish the means for complete, proper, or adequate evaluations (to include reports and documentation).

1.4.2 PRINCIPLES AND GUIDELINES FOR ADMINISTRATORS

The success for any NDT program will always rest upon managers. It is the manager who must decide the overall goals, the proper division of the available funds, and the coordination that must be maintained. It is the manager who determines the degree to which the total life cycle of a component is considered -- including the production of raw stock to the final salvage of worn-out parts. The manager must often accept the responsibility if proper funds have not been set aside for adequate NDT, if designers did not properly coordinate with production and NDT engineers to design a system that could be efficiently inspected and built, and if completed parts cannot be properly inspected in the field. Because the manager plays such an important role, special administrative directives have been published by DoD. The guidelines and principles given in DAP 11-25, should receive serious attention.

Managers must recognize and maintain consistent control over the integrity of the total inspection system by separating quality inspection command from the production group, while simultaneously encouraging communication and coordination between the two areas. The manager must determine the relative degree of this separation, effectively balancing the pressure of meeting production rates with the necessity for successful inspection by using independent managers.

Keeping communications active between functional groups is important, especially during the design phase. Communication, which can be either formal or informal, often takes the form of written release statements required on all design drawings by Quality Assurance (QA) and NDT engineers. Since the effectiveness of communications depends on the time, money and personnel available to make analyses, it is up to the manager to determine the degree of effort to devote to specific communications actions.

Communication during the production phase is especially required if there are incomplete design decisions, since QA and NDT engineers cannot do their jobs effectively until designers have established specific flaw limitation requirements and allowable trade-offs. Although it is true that many testing decisions cannot be made during the design phase, until the flaw limitations are established, the designer must remain on the project and in communicaton with QA personnel.

The manager must employ sound management practices to encourage quality results by fostering high morale and positive motivation among his subordinates. Most importantly he must be provided with the means to establish accountability and given the power and the authority to take definitive action when necessary.

Table 1.4(2). Guidelines for administration of NDT (managers).

1. Maintain integrity (clear separation of responsibilities) between:
    - o Rate of production (Production Engineering).
    - o Quality of production (Inspection, QA, etc.).
2. Ensure adequate communications (before, during, and after) between:
    - o Designer.
    - o QA.
    - o Production Engineer.
    - o NDT Engineer.
    - o Materials Engineer.
3. Provide adequate personnel, facilities and avenues for implementation.
4. Employ sound management practices.

1.4.3 PRINCIPLES AND GUIDELINES FOR DESIGNERS

To achieve a successful design, a designer has to deal with several constraints, such as size, weight, weight distribution, dimensional tolerances and fits, material compatabilities, production capabilities, cost limitations, strength, fatigue life, appearance, surface finish, etc. Although a designer should be careful about adopting unnecessary constraints, he should be aware of the inspectability of his design and whether it will require NDT or whether choices exist that could render NDT nonessential. A designer who has a background in NDT can more readily reach this determination (taking into account cost-effectiveness, safety, and legal obligations associated with safety and reliability) and can make decisions, when required, that favor a successful NDT program.

One of the most important obligations of the designer, when NDT is determined to be necessary, is to establish the requirements for the inspection, with the help of stress, material, and test engineers. If these limits are not reasonable relative to the NDT methods available, then trade-offs must be considered.

One area that is seldom considered by designers is the use of internal standards. For example, almost all ultrasonic inspections require a special setup with comparisons to reference standards. Ideally, there must be a like correspondence between significant factors within the comparison. Reference standards should perfectly match the test article in the type of material, the hardness, the thickness, the surface finish, etc. Test setups should produce equal indications for equivalent flaws. With very little extra cost, components can be developed that have their own internal standards designed into them as an alternative. When standards are designed into the component, all the correlations required for surface finish, for type of material, hardness, etc., are all automatically achieved and the inspection is greatly improved in terms of time and reliability. The arrangement of having the designer create the NDT standard saves time and provides the designer with important NDT knowledge.

Almost all NDT tests, including radiographic, eddy current, and ultrasonics, can be improved by similar considerations. Designers should exercise a direct effort to improve the inspectability of the parts they design, not just in the development and construction phase, but also in terms of inspection required during the service and repair phases of the component's life. Only a designer can accomplish this desirable total life cycle approach.

Table 1.4(3). Guidelines for designers.

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1. Determine if NDT is really required.

2. Determine if the need for NDT can be removed by:

   Improving the design.

   Using an over-design approach.

   Using redundancy.

   Using better materials.

   Selecting better production methods.

   Establishing better production controls.

   Accepting more risks.

   Substituting proof tests.

3. If NDT requirements cannot be removed:

   Does the design allow NDT?

   Will trade-offs be necessary, or can trade-offs be found, to make possible and/or improve the NDT inspection?

   Will internal standards be necessary and/or practical?

NOTE: Sometimes NDT will be required by contract. Therefore, if NDT must be done, use it to your advantage. The use of cheaper material may be feasible, etc.

1.4.4 PRINCIPLES AND GUIDELINES FOR PRODUCTION ENGINEERS

Production engineers also work under constraints. They must produce acceptable products within an assigned time schedule and fixed budget. Their success depends upon the employment of both basic and technical knowledge, of which optimal use of NDT is an important part.

Production engineers must constantly assess the amount of NDT required and determine exactly where it is to be accomplished. For example, expensive machine time cannot be spent cutting raw material into a finished product only to find, at the last cut, an internal flaw that requires rejection of the part. Such flaws should be found before such operations are initiated.

Production engineers normally desire to perform NDT at the earliest possible point in time, usually at receipt of raw stock. The NDT engineers, however, usually want to do NDT when the parts have the simplest shape with the most uniformly prepared surfaces. Reliability engineers often want to do the NDT after all possible disturbing operations are completed. Usually, there is not sufficient time or money to do all these inspections. The final decisions often rest with the project engineer who must meet overall budget and time constraints.

Production engineers should also be aware that production methods and controls, many times, establish the need for NDT. Although selection of production methods and controls that prevent flaws from occuring would, of course, be ideal, trade-offs between the costs of using a more expensive but less flaw-inducing method, versus the cost of testing and possible rejection, must be a consideration for every choice being made.

One of the most productive uses of NDT is the direct employment of inspection during the actual manufacturing process. For example, a method that completely changes the approach to the manufacturing process and greatly increases the reliability of the finished product is the use of ultrasonically controlled cutting machines which determine material thickness as each cut is made. Automatic NDT controls such as these provide great opportunities for increased productivity and reliability.

Table 1.4(4). Principles and guidelines for production engineers.

1. Determine the earliest point in time when NDT is desired.
2. Ensure that the rate of inspection is adequate or initiated early enough to maintain adequate stock levels.
3. Know the material, the reputation of the sources of the material, and the characteristics of the production operations as affected by the material.
4. Select production operations and controls that minimize material problems.
5. Coordinate the NDT tasks with requirements from QA and Design.
6. Use the science of NDT as a direct production control method where developed and appropriate

1.4.5 PRINCIPLES AND GUIDELINES FOR QUALITY ASSURANCE PERSONNEL

The information given herein should be taken only as general guidelines for Quality Assurance (QA) personnel. Specific detailed instructions are provided by each of the separate branches of the DoD. All QA personnel should refer to their respective manuals for specific instructions.

Quality Assurance (QA) responsibilities extend over the full NDT spectrum. The total magnitude of administrative and technical responsibilities depends upon the size of the operation involved. However, whether only one individual or many individuals are involved in the QA task, the following areas must be considered as part of the QA responsibilities:

1. Train, test, and classify inspection personnel and maintain their records.
2. Know the availability, effectiveness, and costs of NDT facilities and operations.
3. Maintain test records and reports.
4. Establish and maintain communications with design, production, and program managers.
5. Maintain a "corrective action" system.
6. Maintain an advanced technological improvement program.

Administration of the QA task includes control over personnel, NDT facilities and data records. Personnel rosters, showing NDT related education, training, tests, test scores, qualifications, classifications, and appropriate medical records should be maintained on all individuals responsible for NDT (including those outside of QA who are involved in NDT). Comments on their abilities and limitations should also be included. These records should be continually checked and updated. In addition, QA administration should provide a formal training, testing, scoring, and classification program utilizing assigned instructors and personnel to administer these areas. Retesting and reclassification of personnel should be done periodically on a continuous basis with maximum time periods specified for retesting each time a classification is assigned.

QA should maintain a current inventory of all NDT equipment with ready references to the accuracy, resolution, reliability, maintenance schedule, average downtime, and inspection rate of each item. In addition, records should be kept on all other factors that might impact on time, money, and personnel. Cost of labor, maintenance, electricity, and other power sources must all be monitored and kept current. All of this information is vital for making the decisions that must be made by QA.

One of the major administrative duties performed by QA includes maintaining inspection records and reports. As a result, the following questions should be considered by QA:

1. What records are to be kept?
2. How long should they be kept?
3. How shall they be maintained?
4. How should they be purged or corrected?
5. Who shall have access?

Many of these records must be maintained for the life of the program or the parts involved.

Communication is another large area of administration for QA. Communication with upper management, project engineers, designers, production and material engineers, facilities, and laboratory standards personnel should be established and maintained by QA.

In the technical area, QA should provide predesign support to help the designers develop parts that are inspectable to the degree necessary to assure the required reliability. QA should also be able to check the completeness of the designers' approach to NDT.

Quality assurance must support the setup, or initiation, of production runs. This support requires an understanding of exactly what is required, why it is required, and all appropriate trade-offs that may be present. Decisions on exact methods to be used must be made, whether those methods are NDT or others, and the standards or verifications required must be established. It then becomes necessary for QA to monitor the existing production runs to ensure that all original assumptions are still valid, that all procedures are being followed, and that proper records, reports, and interpretations are being developed.

It is essential that QA maintain systems for detecting potential or actual problems and expeditiously solving those problems. These "corrective action" systems may consist of several items, including formal report procedures, review boards, and rejection tags for defective parts.

In addition, for any QA department to be successful over a long period of time, it must recognize that changes must be made as technology is improved. QA should have a formal interest and obligation to stay up-to-date with the state-of-the-art of NDT, thus allowing personnel to become knowledgeable and experienced, so they can periodically improve NDT capabilities as new developments occur. Although funding for this area of effort is not always available, it is essential to effective preplanning activities that personnel have access to current technology.

It does not have to be assumed that QA accomplishes all the details of every assigned task in all these areas, either administratively or technically. But it is QA's responsibility to see that, overall, these details are accounted for or that reports to the contrary are made. Much of QA's success will depend upon the quality of communications established with all the involved areas and the formulation of decisions based upon their combined inputs.

Table 1.4(5). Guidelines for quality assurance personnel.

A. Administrative Areas:

1. Administer Personnel Training and Classification (including rosters, NDT education, training, tests, test scores, qualification ratings, work classifications, medical histories, NDT work experiences, and evaluations by supervisors).

2. Maintain Current Inventories of NDT Facilities to include specified accuracy, resolution, reliability, maintenance schedule, average down-times, inspection rates, availability of operators, operator costs, depreciation rates, maintenance costs, availability of power, operating costs, etc.

3. Maintain Inspection Data Records - What records, how maintained, how long, how purged and/or corrected, who has access.

4. Establish Communications (Policies, Planning, Scheduling, Coordination, Proposals, etc.) with and between administrators, project engineers, designers, production, material, and facilities.

B. Technical Areas

1. Support Design Drawing Reviews - Assist in checking and approving completeness of designers approach, trade offs, and decisions.

2. Support the Program - Determine exactly what is required, why it is required, and what methods are to be used. Establish procedures for chosen method, standards, reports, and data controls.

3. Detect and Solve Problems (Corrective Action) - Establish corrective action review boards, and rejection tags.

4. Encourage Research and Development (R & D) - Staying up with the state-of-the-art.

1.4.6 PRINCIPLES AND GUIDELINES FOR NDT ENGINEERS

Some NDT engineers may be directly involved with receiving and inspection, quality assurance, or production activities, while other NDT engineers are associated with research and development efforts. Different qualifications are often required in each of these areas. Basically, however, it is the NDT engineer who must understand the principles of each type of nondestructive test and the specific limitations of those tests. He must be able to recognize which inspection procedures are proper or adequate for the desired results and he must understand the results and their interpretation.

In order for the NDT engineer to perform his duties to the fullest, he must have certain specific information. He must know the materials involved and how the part was fabricated. He must know what defects and/or properties are to be detected and/or measured. He must be able to identify the kinds of false indications that may be encountered so that they may be properly considered. It is the NDT engineer who must often communicate and explain the differences and difficulties when what is requested differs from what can actually be obtained.

Because the NDT engineer knows the equipment and personnel available, he can provide a significant amount of data necessary for scheduling nondestructive tests. Sometimes an NDT engineer receives complete instructions from QA where test plans, procedures, and standards have all been predetermined. It is a requirement that the NDT engineer double check these procedures and standards, and essentially, reverify their effectiveness.

The NDT engineer will normally have NDT technicians under his direction, and the training and instruction of these technicians will be one of his primary concerns. He must understand each technician's ability to handle complicated tasks and the limits or the "confusion" level with which an individual technician can adequately cope. These factors will greatly influence the assignment of tasks and the degree of independence that can be given to each technician.

All of the preceding factors will affect the type of inspection routine that an NDT engineer will institute. The NDT engineer should also be cognizant of the sorting routines and scanning methods that have proven to be the most reliable for his personnel to follow in any particular situation. When a variety of flaws are to be detected, the approach, sorting routines, order of the search, number of repeats in the search operation, direction of scanning, scanning rate, and type of data comparisons (digital or analog) that must be observed will affect the reliability of the results. Often, a search for one kind of flaw at a time, on one type of part, will serve to remove some of the complexities which exist for multiple parts and flaws, as well as to establish reliability.

One parameter beyond the control of the NDT engineer is the rate at which the presence of flaws is indicated. When parts are relatively "clean" and free of indications, or alternately, when there are a great many indications, the percentage of flaw indications missed usually increases for most inspectors. NDT engineers should be aware of the frequency of occurence of the flaws to be detected and adjust the inspection routine as necessary to maintain the required reliability.

Table 1.4(6). Guidelines for NDT engineers.

---

*1. Know exactly what is wanted and why.

*2. Know the part and/or material to be inspected.

*3. Know the defect and/or property to be detected and/or measured.

4. Know limitations of equipment and personnel.

5. Establish time requirements and schedule.

6. Double check exact procedures and standards required.

7. Provide the technician with adequate material, facilities, and working conditions.

8. Ensure that an honest and complete report is made (that both assumptions and limitations are known to those receiving the report). Provide information and training to technicians, and guidance and suggestions to QA, designers, and managers. This is done both formally and informally. These lines of communications should be established and well used.

---

* Information that should be provided to the NDT engineer by QA or project engineer.

1.4.7 PRINCIPLES AND GUIDELINES FOR NDT TECHNICIANS

Technicians are the final key to successful NDT. The personal efforts of knowledgeable and experienced technicians can often save a program otherwise doomed to failure. Likewise, a seemingly successful program can fail if proper responses to indications are not maintained by the technicians.

Even though a technician's task -- to note all exceptions to that which is normal -- appears fairly simple, it can often become complicated. In NDT, meaningful observations may consist of only slight changes or fleeting signals that can easily go undetected -- particularly if they randomly occur between extensive amounts of unimportant data. Sometimes, the problem can develop from too much information. If a technician is being presented with a multitude of nonrelevant or false indications that must be continuously rejected, valid indications can sometimes be automatically rejected as well, through force of habit. A good technician will be aware of these problems and their impact on NDT and will consciously guard against them.

The danger of fatigue and hypnotic effects on the technician must also be consciously fought against, and the technician should not hesitate to ask for a break or change in routine that might prevent these kinds of difficulties from developing. Present efforts to automate all inspections exist mainly because of these human weaknesses.

However, since automatic inspection systems are incapable of noticing all the various types of exceptions that a technician can, technicians will still be needed and valued for their technical knowledge and attentiveness to detail.

General guides for technicians include: 1) Not hesitating to ask questions or double-checking procedures relating to the NDT work; 2) Recording all NDT tasks and results; 3) Always checking all dial settings each time an instrument is used for a new setup; 4) Knowing the capabilities and limitations of the equipment is essential.

Table 1.4(7). Guidelines for NDT technicians.

1. Be aware of the dangers of fatigue and hypnotic effects (Know how to fight these effects. Do not hesitate to ask for a break when any sign of these effects are present).
2. Always note all exceptions to that which is normal - they may be important.
3. If you are not sure if you should ask about something, you probably should.
4. Always record everything done in NDT.
5. Always check all dial settings each time an instrument is used for a new setup.
6. Know your equipment and your own limitations.

1.5 CHOOSING TEST METHODS

Choosing a proper NDT method requires a knowledge of the types of flaws that must be found, their maximum acceptable limits in size and distribution, and their possible locations and orientations. Also the presence of all other possible variables that may affect the inspection must be known. This might include the orientation and accessibility of the part, the part geometry and size, internal variables in densities, etc. This knowledge must then be coupled with knowledge of the basic principles and limitations of all NDT methods, their availability, and costs. One must also be familiar with the requirements and availability of standards to employ these methods and the type of records required. (See Table 1.5(1) at end of this section.)

The appropriate method may consist of several separate inspections. One inspection by itself may indicate the presence of a possible flaw and other inspections may be required to confirm or verify the original indication.

When the choosing of NDT methods is done routinely, then it is important that a list of average basic costs of each available method is formulated. An example would be as follows:

LIST OF AVAILABLE METHODS	PRELIMINARY SET UP REQUIREMENTS		ACTUAL TEST COSTS		
	LABOR	STANDARDS	LABOR MH/Part	ADDITIONAL COSTS	AVAILABILITY
Liquid Penetrant	Minor	Minor	0.8	Minor	Good
Mag Particle	Minor	Minor	1.1	Minor	In heavy use
Eddy Current	Possibly extensive	Yes	1.2	None	Good
Ultrasonic (C-scan)	Possibly extensive	Normally extensive	2.0	Paper	Not working until next month
X rays	Minor	Routine	2.0	Film and development	Good

With such a chart, one can start with the cheapest method available and then progress through the list to the first available method that will meet acceptable detection limits. These lists must be individualized for each operation, taking into consideration how modern the available equipment and facilities are and the level of personnel staffing. Although these lists can provide some broad guidance, they should not be used as a definitive standard. Costs for each test vary and the maximum or minimum of one test method may, in some cases, overlap the costs for another test method.

The choice of a proper NDT method requires an understanding of the basic principles, and advantages and disadvantages of all available NDT test methods. Detailed knowledge of their comparative effectiveness, availability, and costs are all critical in making the correct decisions. Tables 1.5(2) through 1.5(6) (at the end of this section) list some of the general advantages and disadvantages of a number of general NDT methods. All NDT users should maintain similar lists, based upon experience with their particular equipment.

There are times when the choice of methods is very clear. When small delaminations between layers deep within a flat composite panel must be detected, an ultrasonic test of some type will almost always be chosen. If surface cracks on an iron part were to be detected, liquid penetrant, magnetic particle, ultrasonic, eddy current and X-ray tests could all be individually considered. If porosity were to be found, a quick ultrasonic C-scan might be used to locate potential areas, followed by X rays concentrated in those areas identified by the C-scan, to confirm if porosity is really involved and, if so, to what extent.

Since the difference between success or failure depends on knowing the details of the specimen and/or material being inspected, many NDT courses properly begin with a study of raw material manufacturing processes to indicate the origin and causes of flaws in castings, ingots, and forgings. The reshaping and redistribution of the flaws in subsequent manufacturing processes must be understood.

Although a study of these flaws and processes will not be given in this handbook, the importance of this area should not be minimized. All NDT personnel should be familiar with: porosity, nonmetallic inclusions, pipe, macrosegregation, cold shots, cold shuts, hot tears, shrinkage cracks, blowholes, misruns, forging laps, stress cracks, grinding cracks, fatigue cracks, galling, and scale. They should know where they occur or can be expected to exist, and what impact they may have in each of the test methods. The comprehension that flaws are to be expected does not always exist with those who are inexperienced. Yet it is the first step in choosing a proper NDT method. Knowing what the flaws might be and where to look for them is the next step. Therefore, a study of materials, as well as the relevant production and manufacturing processes, is vital to the choice and administration of an NDT program.

Lastly, the most critical (and often the most unavailable) data for determining an appropriate method involves what the acceptable limits on the size of the defect are. Those limits determine whether the method would be feasible and how expensive an effort would be required. Figure 1.5(1) expresses the importance of this size tolerance. References to sections 1.4.3 (Designers), 1.4.4 (QA) and 1.4.1 (General Principles) all discuss the importance of defining this limit.

Table 1.5(1). Choosing proper NDT methods.

1. Determine the material to be inspected and the type of flaws or difficulties common to that material.
2. Determine the material manufacturing processes and the type of flaws or inconsistancies associated with those processes.
3. Know the part to be inspected and determine its design requirements so that critical flaw limits can be established.
4. Know the basic principles and limitations of all NDT methods.
5. Know costs and availability of NDT personnel and facilities.
6. Determine what standards are required and their availability.
7. Determine what records and controls are required.

Table 1.5(2). Advantages and disadvantages of liquid penetrant.

Advantages:

1. Usually very cheap (often is the cheapest method).
2. Usually quick, even for large parts.
3. Can be portable (taken to test site).
4. Reasonably easy to interpret.

Disadvantages:

1. Can only detect defects opened to the surface.
2. No automatic or permanent records.
3. Often requires a pre-cleaning step.
4. Use of fluorescence required for maximum sensitivity.
5. Not good for rough or porous surfaces.
6. Penetrants chemically attack some rubbers and plastics, and should have a low sulfur and/or chlorine content when used with certain stainless steel, nickel, or titanium materials.

Table 1.5(3). Advantages and disadvantages of magnetic particle.

Advantages:

1. Surface or near surface flaws can be detected.
2. Reasonably cheap and quick.

Disadvantages:

1. Magnetic type materials only.
2. No permanent records.
3. Must often demagnetize parts following test.
4. Surfaces can be marred where contact probes are used.

Table 1.5(4). Advantages and disadvantages of eddy current.

Advantages:

1. Surface or near surface flaws can be detected.
2. Very sensitive to many variables such as:
    - geometry (thickness, stand-off).
    - surface roughness.
    - frequency.
    - electrical conductivity.
    - magnetic properties.
    - cracks.
3. Direct go/no-go type answers can be obtained quickly.
4. Portable.
5. No physical contact required (can be accomplished in a vacuum).
6. Not too expensive.
7. Easily adaptable to production line situations (electrical signals for electrical controls).

Disadvantages:

1. Must involve one or more layers and/or surfaces that are electrically conductive or magnetic in nature.
2. Requires skill when many variables are involved.
3. Adequate separation of variables cannot always be achieved.

Table 1.5(5). Advantages and disadvantages of ultrasonics.

Advantages:

1. Internal inspection method (the deepest penetrating method).
2. Can be adapted for thick or thin panels.
3. Extremely sensitive to many specimen variables:
    - porosity.
    - delaminations.
    - micro cracks.
    - geometry
    - density changes.
    - grain or fiber size.
    - orientations.
4. Many test control variables:
    - transducer frequency.
    - transducer size.
    - transducer type.
    - transducer focal length.
    - type of test (immersed, contact, or jet).

Disadvantages:

1. Non-linear responses (variable relationship between flaw size and indication size).
2. Sometimes too sensitive (impossible to separate out desired parameter).
3. Often limited by geometry and surface roughness.
4. Often must have special standards (especially when details are as small or smaller than the width of the inspection beam).

Table 1.5(6). Advantages and disadvantages of X-rays (radiography).

Advantages:

1. Good internal inspection method.
2. Excellent geometric representations.
3. Good sensitivity, 2% is reasonable.
4. Small details are visible (the limit is often the size of the grains on the film being used).

Disadvantages:

1. The image is a shadow only (The shadow varies only as the amount or density of the material varies. Therefore, it can "see" missing material, but if a delamination exists perpendicular to the X-ray beam with material pulled apart but not missing, an X ray will not detect it).
2. Sometimes expensive in time, labor, and facilities.
3. Personnel safety requirements.
4. Sensitive to orientation of cracks.

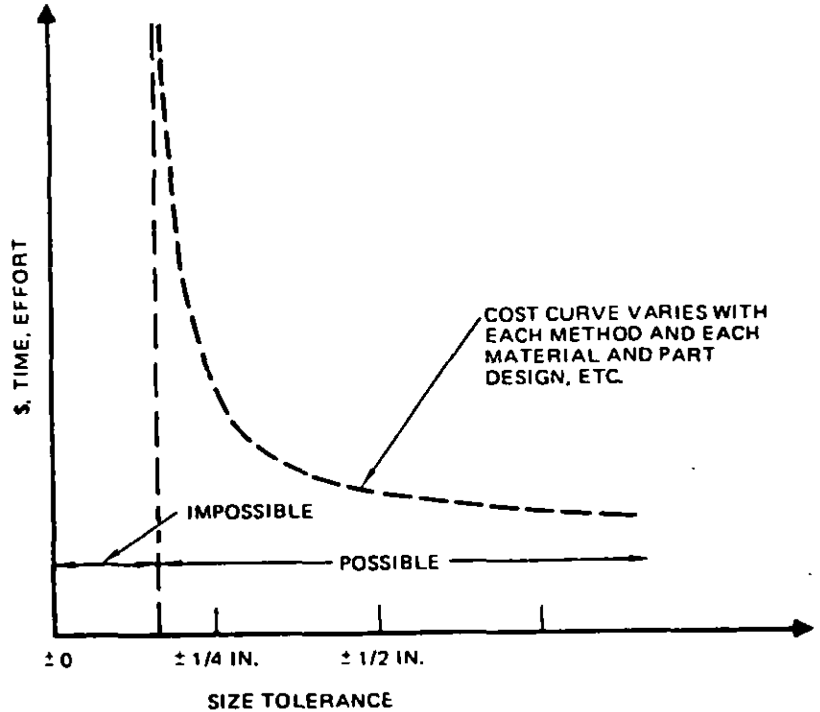

Figure 1.5(1). Cost curve.

1.6 GLOSSARY

Classifications (for NDT personnel). Personnel classifications can be made by nondestructive test methods, by specific equipment, or by specific product lines in which qualifications have been obtained.

Corrective Action. Action taken (or plans for actions to be taken) for solving problems that occur during production.

Correlations. Establishing relationships between facts or events.

Critical Flaw Size. The minimum extent of a flaw (e.g., minimum depth, length, etc.) that prevents achievement of the designed goals for a particular part.

Defect. Any condition of a part that prevents achievement of a designed goal is a defect. A flaw that is of critical size or larger is a defect.

Delamination. A delamination is a partial or complete separation between two layers of a material which should be bonded together.

Discipline. A specialty of profession or training.

Documentation. Written or recorded proof, usually includes a "picture" or other data recording made in a controlled test. Documentation should include names, date, equipment, and all other vital information necessary to confirm the status of a part or the results of a test.

Fatigue Life. The expected number of load cycles that a part can withstand and still perform adequately.

Flaw. Any imperfection in a part can be considered to be a flaw. By this definition, all parts have flaws. Many flaws are too small to be of concern. Some flaws may be large enough to cause a part to fail. When flaws are large enough to cause failure, they can be called "defects."

Flaw Size Limitation (see critical flaw size).

Indications. Any signal or markings obtained in a test is an indication. Indications must be interpreted. There can be false indications (not due to the material variable of concern) and valid indications. There can be acceptable indications and rejectable indications.

Integrity. Integrity is a measure of the completeness of a part, or the property of being solid or continuous, with no break in the uniformity of the part.

Life-Cycle. The complete history or activities associated with a part, from its manufacturing, to its ultimate utility as a waste product.

Nondestructive Evaluation. (See Section 1.3).

GLOSSARY (CONTINUED)

Nondestructive Inspection. (See Section 1.3).

Nondestructive Testing. (See Section 1.3).

Permanent Record. Any automatically produced "picture" or recording of data (e.g., X-ray negatives, C-Scans) obtained from a test which is permanent and can be used at any time to confirm the results of a test. It forms part of the Documentation that might be specified for particular inspections.

Qualifications (for NDT personnel). The minimum education, knowledge and experience required of an individual to use a particular NDT method. ASNT qualifications include three levels: I, II and III. All inspection supervisors should be level II or higher.

Quality Assurance (QA). Quality Assurance can be the organization, the control, or the actions taken to ensure that parts will meet all design goals. A particular group is often assigned responsibility to ensure that parts are correctly built, inspected and tested to confirm their quality and reliability.

Reliability. Confidence in the achievement of specific goals, often expressed in statistical terms.

Reference Standards. Any part or image that is used to judge the status or acceptability of another part or image can be called a reference standard.

Standards. The base upon which or by which other variables are judged or measured.

Tailoring. The act of changing something from one state or condition to another state or condition to better fit or apply to particular circumstances.

Trade-off. Mutually exclusive events or conditions often require a choice between them. A trade-off is exchanging one state or condition for another, with subsequent gains and losses.

1.7 BIBLIOGRAPHY

The following lists of Specifications, Standards, Handbooks and other publications are provided as additional sources of information to aid in any particular NDT problems that may arise.

1.7.1 GOVERNMENT DOCUMENTS

TECHNICAL ORDERS

Air Force	TO 00-25-224	Welding High Pressure & Cryogenic Systems (Section 4 - Nondestructive Inspection by Ultrasonic and Eddy Current Methods)
Air Force Navy Army	TO 33B-1-1 NAVAIR 01-1A-16 TM 43-0103	Nondestructive Testing Methods (Chapter 1 - General, Chapter 2 - Magnetic Partical Method, Chapter 3 - Eddy Current Method, Chapter 4, Ultrasonic Inspection Method, Chapter 5, Radiographic Inspection Method, Chapter 6, Flourescent and Dye Penetrant Method).

MILITARY STANDARDS AND SPECIFICATIONS

MIL-STD-271	Nondestructive Testing Requirements for Metals (Radiography, Magnetic Particle, Liquid Penetrant, Leak Testing, Ultrasonics).
MIL-STD-798	Nondestructive Testing, Welding Quality Control, Material Control & Identification & Hi-Shock Test Requirements for Piping System Components for Naval Shipboard Use (Radiography, Magnetic Particle, Penetrant).
MIL-I-6870	Inspection Requirements, Nondestructive for Aircraft Materials & Parts (Magnetic Particle, Penetrant, Radiographic, Ultrasonic, Eddy Current).
MIL-STD-410	Qualification of Personnel.
MIL-STD-721	Definition of Terms for Reliability, Maintainability, Human Factors, and Safety.

MILITARY QUALITY ASSURANCE PAMPHLETS

AMCP 702-3	Reliability Handbook (Army Material Command)
DAP 11-25	Life Cycle Management Model for Army Systems (Department of the Army)

NASA PUBLICATIONS

NASA SP-3079, Nondestructive Evaluation Technique Guide, A. Vary (U. S. Government Printing Office, Washington, DC) 1973

NASA SP-5113, Nondestructive Testing - A survey, (U. S. Government Printing Office, Washington, DC) 1973

NBS PUBLICATIONS

NBS Handbook 14, General safety standard for installations using non-material x-ray and sealed gamma ray sources, energies up to 10 Me V (U. S. Government Printing Office, Washington, D.C.)

NBS Handbook 50, X-ray protection design (U. S. Government Printing Office, Washington, D.C.)

NBS Handbook 57, Photographic dosimetry of X and gamma rays (U. S. Government Printing Office, Washington D.C.)

NBS Handbook 66, Safety design and use of industrial beta ray sources (U. S. Government Printing Office, Washington, D.C.)

NBS Handbook 114, General safety standards for installation using non-medical x-ray and sealed gamma ray sources, energies up to 10 Me V (U. S. Government Printing Office, Washington, D.C.) 1975

1.7.2 OTHER PUBLICATIONS

ASME	Boiler and Pressure Vessel Code (Section I, Section III, Section IV, Section V, Section VIII, Section IX, Division 2, and Section IV)
ASNT-TC-1A	Recommended Practice Nondestructive Testing Personnel Qualification and Certification (Supplement A, Radiographic Testing; Supplement B, Magnetic Particle; Supplement C, Ultrasonic Testing; Supplement D, Liquid Penetrant; and Supplement E, Eddy Current)
AWS-A2.4	Nondestructive Testing Symbols

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1.7.2 WHERE TO OBTAIN SPECIFICATIONS AND STANDARDS

All U.S. Department of Commerce, National Bureau of Standards Handbooks are available from the Superintendent of Documents, Government Printing Office, Washington, D.C. 20402.

All other government agency specifications or standards are under the control of the Department of Defense.

All requests for copies of specifications, standards, and qualified products lists should state the title and identifying number and should be submitted to Commanding Officer, Naval Supply Depot, 5801 Tabor Ave., Philadelphia, PA 19120, Attn. - Code CDS, except:

a. Copies of specifications, standards and qualified products lists required by contractors in connection with specific procurement functions should be obtained from the procuring agency awarding the contract or as directed by the contracting officer.

b. Federal Specifications and Standards and Military Book Form Standards will not generally be furnished by the Naval Supply Depot to commercial concerns unless required in conjunction with a bid or contract, or for sufficient other justification. Copies of federal documents may be purchased from the Business Service Center, General Service Administration, Washington, D.C. 20405. Most book-form Military Standards may be purchased from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.

c. Only current, "in effect" issues of standardization documents will be available from the Naval Supply Depot. Copies of canceled or superseded documents required for contractural purposes will have to be obtained from the contracting office of the concerned service.

d. Information regarding obtaining DoE standards relative to the Division of Reactor Development and Technology may be obtained from Oak Ridge National Laboratory, P.O. Box X, Oak Ridge, TN 37830.

All specifications or standards as issued by the organizations listed below are available directly from the organization at the address given.

ABS
American Bureau of Shipping
45 Broad Street
New York, NY 10004

AIA
Aerospace Industries Association of America
1725 De Sales St., NW
Washington, DC 20036

AISI
American Iron and Steel Institute
1000 16th St., NW
Washington, D.C. 20036

Al. Assoc.
The Aluminum Association
420 Lexington Avenue
New York, NY 10017

ANS
American Nuclear Society
555 N. Kensington Avenue
La Grange Park, IL 60525

ANSI
American National Standards Institute, Inc.
1430 Broadway
New York, NY 10018

API	American Petroleum Institute 50 West 50th Street New York, NY 10019
ASME	American Society of Mechanical Engineers 345 East 47th Street New York, NY 10017
ASNT	American Society for Nondestructive Testing, Inc. 4153 Arlingate Plaza Caller 28518 Columbus, OH 43228
ASTM	American Society for Testing and Materials 1916 Race Street Philadelphia, PA 19103
AVS	American Vacuum Society 335 East 45th Street New York, NY 10017
AWS	American Welding Society 2501 N.W. 7th Street Miami, FL 33125
ICRU	International Commission on Radiation Units 7910 Woodmont Avenue, Suite 1016 Washington, D.C. 20014
MSFC	National Aeronautics and Space Administration George C. Marshall Space Flight Center Huntsville, AL 35812
NCRP	National Commission on Radiation Protection NCRP Publications P.O. Box 4867 Washington, D.C. 20008
SAE	Society of Automotive Engineers, Inc. 400 Commonwealth Drive Warrendale, PA 15096

1.8 INDEX

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1.9 NOTES

1.9.1 MIL-HDBK-728/1, /2, /3, /4, /5 and /6 supersede the following documents:

MIL-HDBK-54
15 October 1965

MIL-HDBK-55
1 April 1966

MIL-HDBK-726
10 June 1974

MIL-HDBK-333
10 April 1975

AMCP 702-10
April 1970

Custodians:

Army -- MR
Navy -- AS
Air Force -- 20

Review activities:

Army -- AR
Navy -- OS

Preparing activity:

Army -- MR

Project No. NDTI-0047

(WP# ID-1336P/DISC 0010v. FOR AMMRC USE ONLY.)

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(See Instructions – Reverse Side)

1. DOCUMENT NUMBER
MIL-HDBK-728/1

2. DOCUMENT TITLE
NONDESTRUCTIVE TESTING

3a. NAME OF SUBMITTING ORGANIZATION

4. TYPE OF ORGANIZATION *(Mark one)*

☐ VENDOR

☐ USER

☐ MANUFACTURER

☐ OTHER *(Specify)*: ______

b. ADDRESS *(Street, City, State, ZIP Code)*

5. PROBLEM AREAS

a. Paragraph Number and Wording:

b. Recommended Wording:

c. Reason/Rationale for Recommendation:

6. REMARKS

7a. NAME OF SUBMITTER *(Last, First, MI)* – Optional

b. WORK TELEPHONE NUMBER *(Include Area Code)* – Optional

c. MAILING ADDRESS *(Street, City, State, ZIP Code)* – Optional

8. DATE OF SUBMISSION *(YYMMDD)*

DD FORM 1426 82 MAR

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MIL-HDBK-728/4A
28 December 1993
SUPERSEDING
MIL-HDBK-728/4
16 December 1985

MILITARY HANDBOOK

MIL-HDBK-728/4A

MAGNETIC PARTICLE TESTING

DEPARTMENT OF DEFENSE
UNITED STATES OF AMERICA

NO DELIVERABLE DATA REQUIRED BY THIS DOCUMENT

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1. SCOPE

* 1.1 General. This document is intended to provide information on the use of magnetic particle testing and inspection both broad and specific applications. The use of this handbook requires MIL-HDBK-728/1, on Nondestructive Testing, to provide introductory material for the general subject, and to indicate how magnetic particle testing and inspection are an integral part of NDT.

It has been updated and is consistent with MIL-STD-1949, on Magnetic Particle Inspection, and agrees on basic principles with ASTM E709 and ASTM E1444, which are Standard Guide and Standard Practice for Magnetic Particle Examination respectively.

2. REFERENCED DOCUMENTS

* 2.1 Government documents.

* 2.1.1 Specifications, standards, and handbooks. The following specifications, standards, and handbooks form a part of this document to the extent specified herein. Unless otherwise specified, the issues of these documents are those listed in the issue of the Department of Defense Index of Specifications and Standards (DODISS) and supplement thereto, cited in the solicitation.

STANDARDS

MILITARY

MIL-STD-1907 - Inspection, Liquid Penetrant and Magnetic Particle Soundness Requirements for Materials, Parts, and Weldments

MIL-STD-1949 - Magnetic Particle Inspection

HANDBOOKS

MIL-HDBK-728/1 - Nondestructive Testing
MIL-HDBK-728/3 - Liquid Penetrant Testing

(Unless otherwise indicated, copies of federal and military specifications, standards, and handbooks are available from the Standardization Documents Order Desk, Bldg. 4D, 700 Robbins Avenue, Philadelphia, PA 19111-5094.)

* 2.2 Other publications.

* 2.2.1 Non-Government publications. The following documents form a part of this specification to the extent specified herein. Unless otherwise specified, the issues of the documents which are DoD adopted are those listed in the issue of the DODISS cited in the solicitation. Unless otherwise specified, the issues of documents not listed in the DODISS are the issues of the documents cited in the solicitation.

AMERICAN SOCIETY FOR TESTING AND MATERIALS (ASTM)

ASTM E125	- Standard Reference Photographs for Magnetic Particle Indications on Ferrous Castings
ASTM E1316 (Section G)	- Standard Terminology for Nondestructive Examinations - Magnetic Particle Examination
ASTM E709	- Standard Guide for Magnetic Particle Examination
ASTM E1444	- Standard Practice for Magnetic Particle Examination

(Application for copies should be addressed to the American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103.)

* 2.2.2 Technical references and articles. General technical references for information purposes and for elaboration of background material in theory and usage practice for this handbook are listed at the end of this handbook, as REFERENCES.

3. DEFINITIONS

* 3.1 _Definitions_. Definitions given herein shall be as specified in ASTM E1316 (Section G), "Standard Terminology for Nondestructive Examinations - Magnetic Particle Examination" (1991b)

4. SAFETY NOTICE

* 4.1 General. Magnetic particle testing involves the use of magnetic fields usually produced by electrical currents. The use of electrical currents requires that standard safety practices associated with electrical equipment be observed. The magnetic forces established can impart motion to loose parts which can result in pinched fingers or other harm to personnel or damage to the parts.

* 4.2 Chemical The particles and liquids used in magnetic particle inspection are relatively low hazard chemical materials. However, some safe practices associated with the handling of chemical materials must be considered. Detailed information is provided in Paragraph 12.

* 4.3 Black Lights. The black lishts used with fluorescent magnetic particles are long wavelength ultraviolet (UV-A). Exposure to properly filtered black light (UV-A) does not cause an epidermal (erythemal) action or reddening of the skin. There are some safety precautions that should be observed when using high intensity (1,000µW/Sq cm or greater) black lights. These precautions are detailed in Paragraph 12.

5. INTRODUCTION

5.1 General. Magnetic particle testing is used to detect surface and near surface flaws in ferromagnetic (magnetizable) materials. The indications provided by this type of test occur at the surface of the part, directly above the location of the flaws, and the general size, shape, and orientation of the flaws can usually be directly inferred. Magnetic particle testing is used in receiving inspections, in in-process or final inspections, and in in-service inspections. Magnetic particle testing can be used for forgings and castings, for crankshafts and simple plates, for large and small parts and for welding inspections. It is one of the best established nondestructive testing methods used on ferromagnetic materials. MIL-HDBK-728/4 presents the fundamental principles and guidelines associated with magnetic particle testing. This handbook includes descriptions of the basic theory of operation, the equipment and materials used, the advantages and disadvantages of the method, various applications and standards, and guides for specific disciplines.
MIL-HDBK-728/1 contains general NDT information that should be studied along with MIL-HDBK-728/4A for a more complete understanding of magnetic particle testing and its comparison with other methods.

6. BASIC PRINCIPLES

6.1 General. Magnetic particle testing requires the induction of a magnetic field into the part to be tested. If the part has discontinuities in its magnetic permeability, singularities in the magnetic field can exist. These field singularities - or leakage fields - can attract and hold small ferromagnetic particles. Therefore, when a magnetic field is established in a part, and small ferromagnetic particles are applied over the surface, some of these particles will collect at leakage field locations thereby forming indications that can be associated with underlying discontinuities. The basic principles associated with magnetic particle testing involve magnetic properties of materials, magnetic fields, and the visual detection of small particles.

6.2 Magnetic fields. There are difficulties in studying magnetic fields because historically there have been a large number of magnetic units and concepts utilized. There are some systems that establish relationships with the strength of the magnetic sources in terms of magnetic moments, ampere-turns per meter, or in fictitious magnetic monopoles - all of which are usually constants for any one problem. Then there is the magnetic field intensity due to these magnetic sources in terms of the "H" field - which is also a constant for most problems. Then there is the induced magnetic field, B, inside the part, which often is the magnetic field intensity changed into different units, but can also be modified or affected by the presence of "permeable" matter. This type of magnetic field is seldom linear or constant, but varies with several characteristics of these materials.

6.2.1 Relationships among magnetic fields. In most cases in this handbook, equations are given where the B field is directly calculated from various sources. Usually this "bypassing" of H is accomplished by assuming the absence of, or ignoring the effects of, magnetically permeable materials which might be present. Although it is not possible to point out all of the relationships between these magnetic variables in this handbook, some of the more important relationships that are generally applicable to magnetic particle testing are presented.

6.2.2 Sources of magnetic fields. The magnetic fields used in magnetic particle testing are usually created by the flow of current, but permanent magnets can also be used. Figure 1 shows a simple bar magnet with its magnetic field indicated by magnetic flux lines, or lines of force, with direction arrows. All magnets have a north (N) and a south (S) pole, all magnetic flux lines are continuous and form closed loops. The strength of the magnetic field, at any point, can be measured in terms of the number of lines of force per unit area, the area being at right angles to the lines of force at the point being measured. The direction of the flux lines, shown by the arrows, indicates the direction that an infinitely small north (N) monopole (which exists only theoretically) would move if it were placed at that point in the field. (Inside the magnet, these arrows go from S to N; outside the magnet they follow a path which goes from N to S.)

(B)

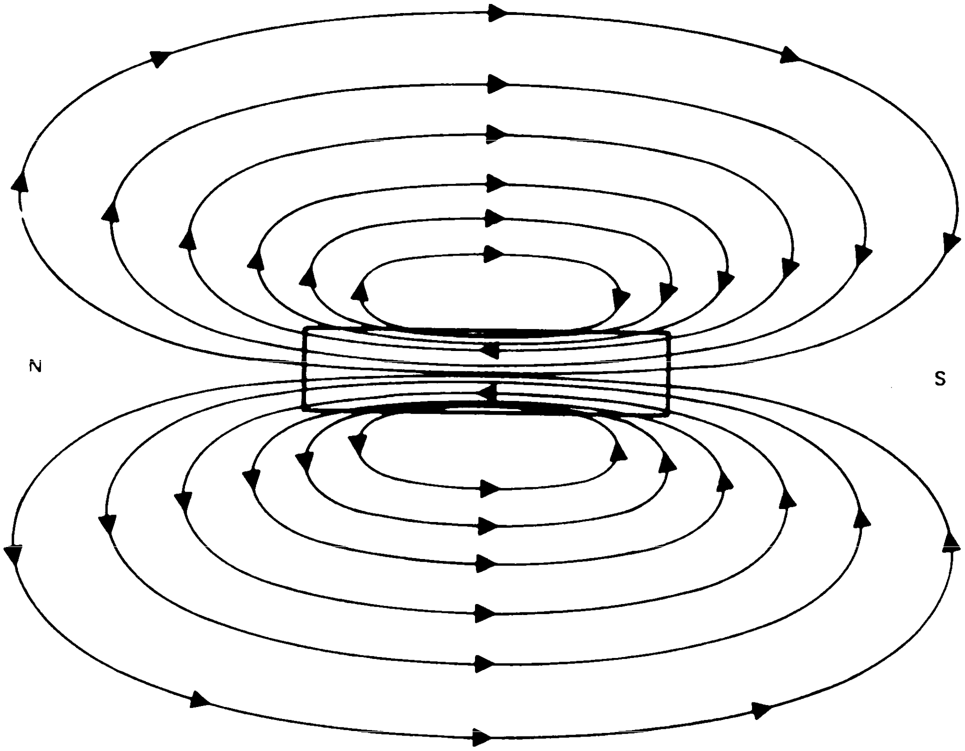


FIGURE 1. Magnetic-induction field around a simple bar magnet.

* 6.2.3 Relationships between sources and fields. Relationships exist between the strength of the magnet (the source), the strength of the field, and the reluctance of the path of the lines of force, that are similar to the relationships between electromotive force (voltage), current, and resistance in electrical circuits. The magnetic relationships, however, are much more difficult to apply because their effects are not confined to discrete paths - they readily extend through empty space - and the total effects are therefore based upon the combined results of an infinite number of parallel paths. Magnetic fields are linearly dependent on currents, but have a tensor dependence on magnetic materials. Also, results are often affected by previous conditions such that all of the conditions are not always directly repeatable; i.e., hysteresis effects are normally involved. Therefore, exact relationships are not easily established by equations, and a nonlinear relationship between sources and the magnetic induction fields invariably exist.

As far as working relationships and effective use for testing are concerned, the most important thing to understand is that the magnetic field is the strongest at the poles (at corners or edges near the poles), and testing is usually enhanced when the magnetic reluctance of the flux paths is reduced by having the magnet in direct contact with the part.

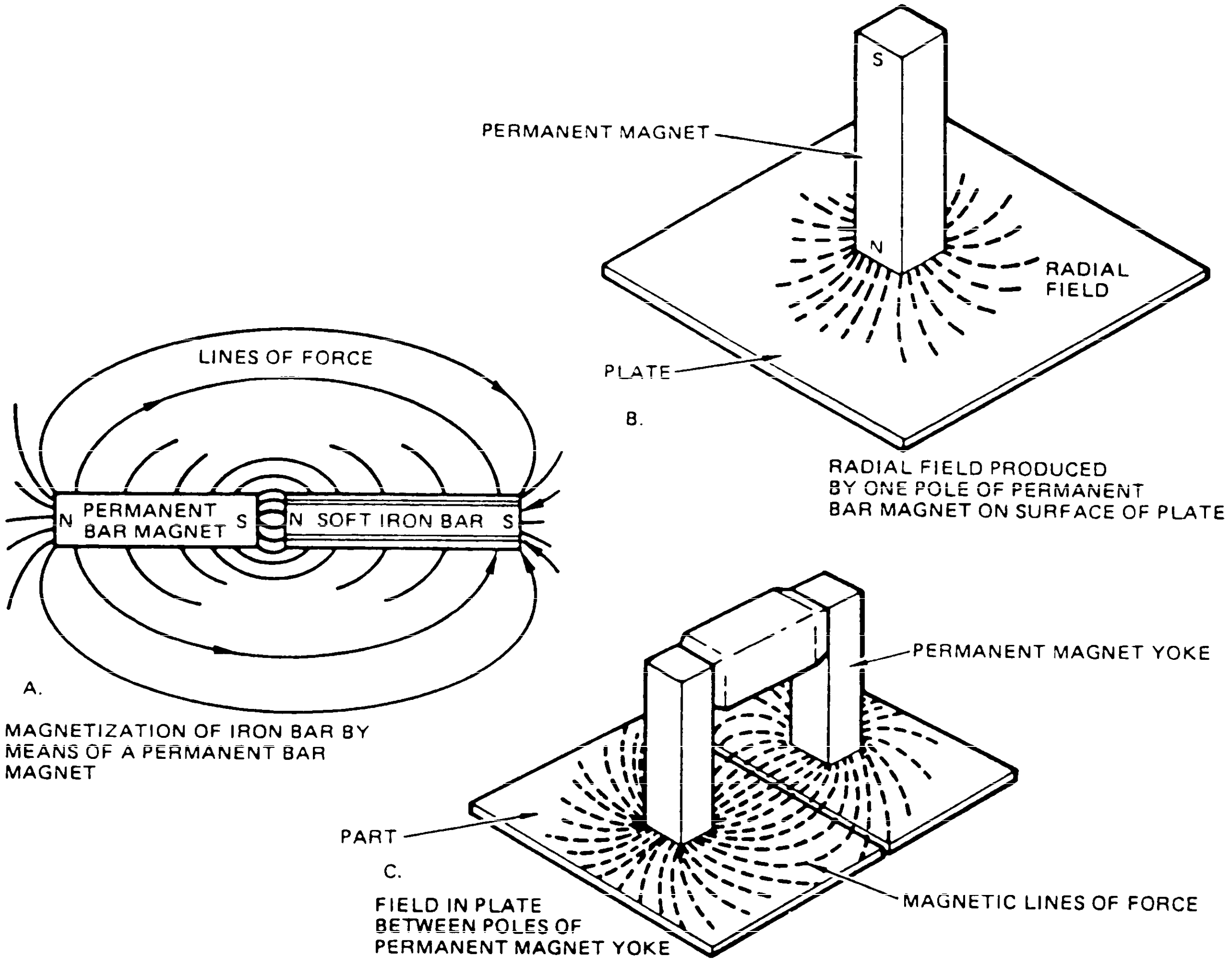


FIGURE 2. Permanent magnet magnetization.

* 6.2.4 Consideration of permanent magnets. To facilitate this reduction of the reluctance, permanent magnets used for inspecting are sometimes arranged in a "U" shape so that both poles can touch a flat surface close together at the same time. Figure 2 shows some examples of permanent magnets and their uses. Permanent magnets should not be exposed to mechanical shocks or to high temperatures. They should, when not in use, have a "keeper bar" (usually a soft iron bar) placed between the poles so that the magnetic flux is maintained at a high level.

Permanent magnets are not to be used for magnetic particle inspection unless specifically authorized by the contracting agency. When permanent magnets are used, adequate magnetic field strength shall be established according to guidelines in MIL-STD-1949.

Note that when a magnetic field is being generated or naturally exists, it is "H". When something solid is placed in the magnetic field, then the induction field inside the solid is "B". The magnetic induction field inside the solid is a combination of the original field plus magnetization within the solid.

For iron, the B field inside is much larger than outside this ferromagnetic material. If the bar consists of nonmagnetic material, the magnetic induction field is the same as outside. Reference back to figure 1 clarifies this. Concentration of field lines always indicates field strength.

* 6.2.5 Relationships between electrical currents and magnetic fields. When electrical currents are used to establish magnetic fields, the following relationships are useful: The strength of the induced magnetic field, B, in Wb/m^2 (webers per square meter), around a long, straight conductor carrying a current, I, in amperes, is given by the equation:

*

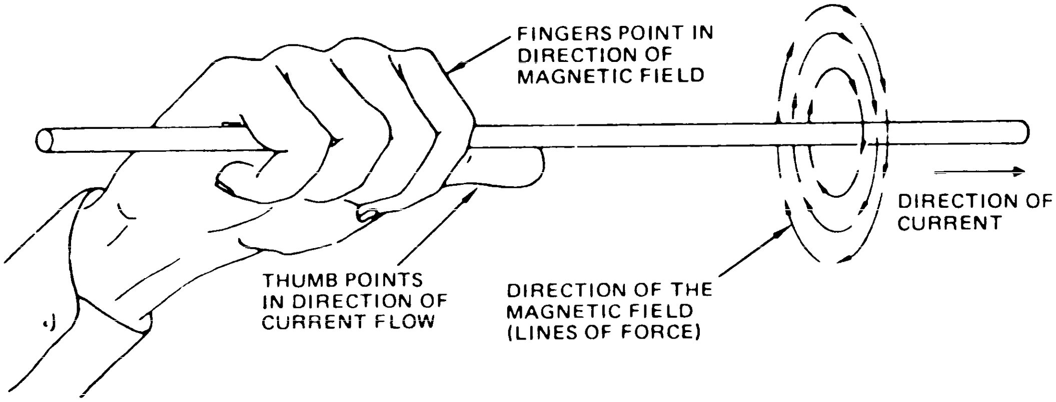
$$B = \frac{\mu_o}{2\pi}\frac{I}{x} = 1/2\pi(4\pi \times 10^{-7})\ \frac{I}{x}\ \frac{Wb}{m^2} \qquad (1)$$

where

* x = distance from the center of the conductor, in meters

μ_o = magnetic permeability of free space (essentially the same as in air), defined to be $4\pi \times 10^{-7}$ Wb/A·m.

Figure 3 shows that the direction of this field depends upon the direction of current flow, and can be determined by use of the right-hand rule.



* FIGURE 3. Right-hand rule demonstrated on a straight conductor.

The strength of the induced magnetic field, B, at the center of a flat coil of N turns, each carrying I amperes, is:

*

$$B = \frac{1}{2}\mu_o\frac{NI}{r} = 1/2\ (4\pi \times 10^{-7})\ \frac{NI}{r}\ \frac{Wb}{m^2} \qquad (2)$$

where

r = radius of the coil in meters

Figure 4 shows the field distribution of a flat circular coil. The right-hand rule also applies to this type of coil.

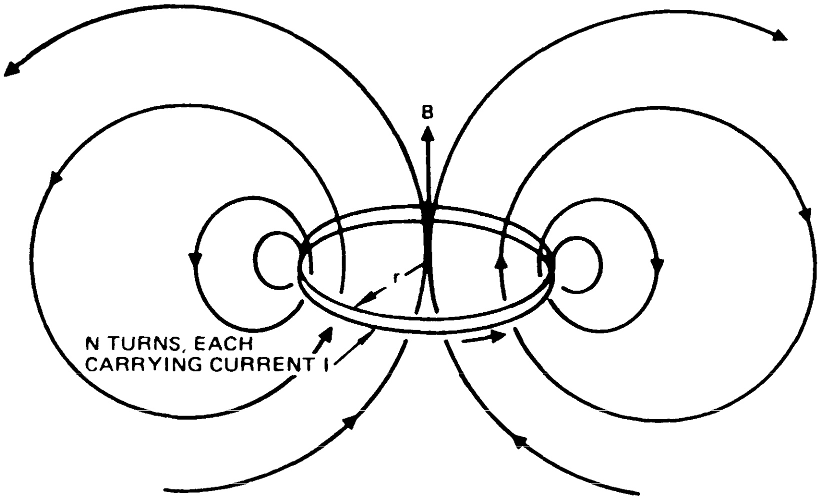


FIGURE 4. Magnetic-induction field at the center of a flat circular coil.

The magnetic-induction field in the central region of a long, straight solenoid is essentially uniform and its strength, B, is equal approximately to:

* $$B = \mu_0 nI = (4\pi \times 10^{-7})\ nI\ \frac{Wb}{m^2} \qquad (3)$$

where

n = number of turns per meter length of coil
I = current, in amperes, flowing in coil

Figure 5 shows the right-hand rule for finding the direction of the field.

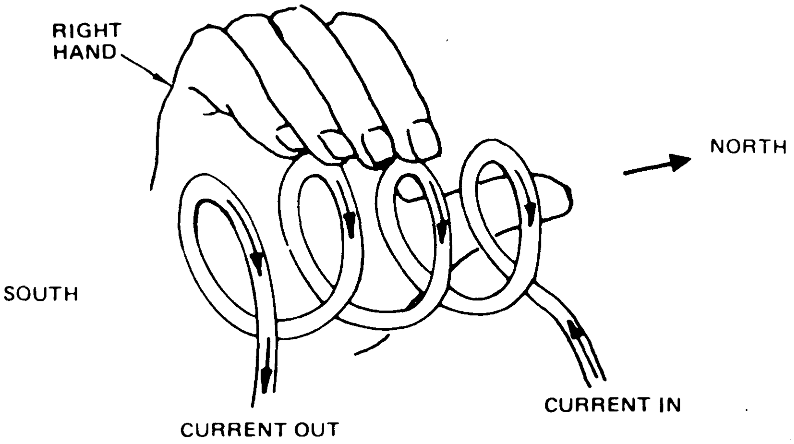


FIGURE 5. Direction of a magnetic field in a coil.

6.2.6 Relationship of field strengths to currents in test specimens. In many practical applications current is sometimes carried directly in the test specimen, which may be either a solid bar, a tube, or a flat plate.

Figures 6 through 9 indicate the magnetic field distribution produced by these common configurations.

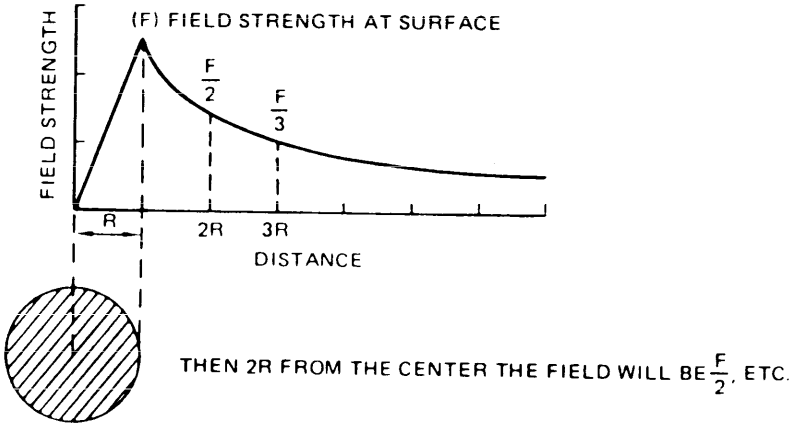


FIGURE 6(a). Field distribution in and around a solid nonmagnetic conductor carrying direct current.

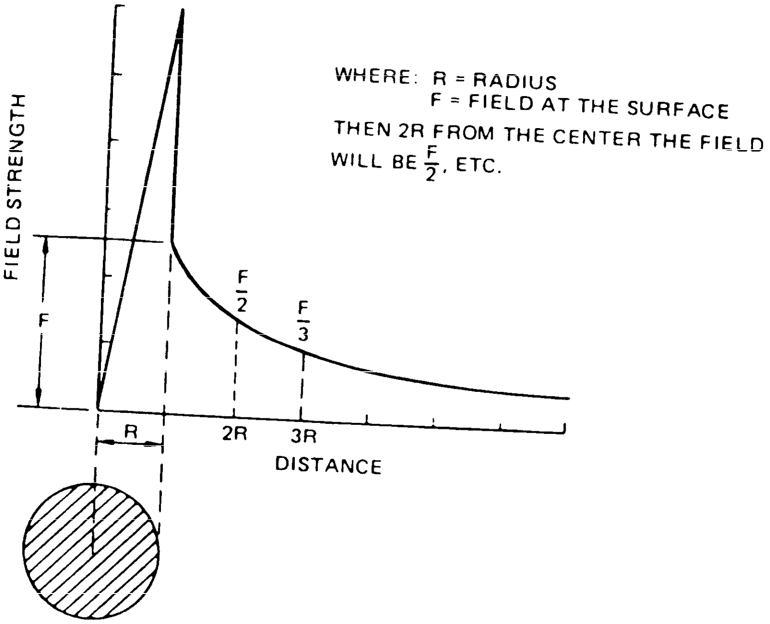


FIGURE 6(b). Field distribution in and around a solid magnetic conductor carrying direct current.

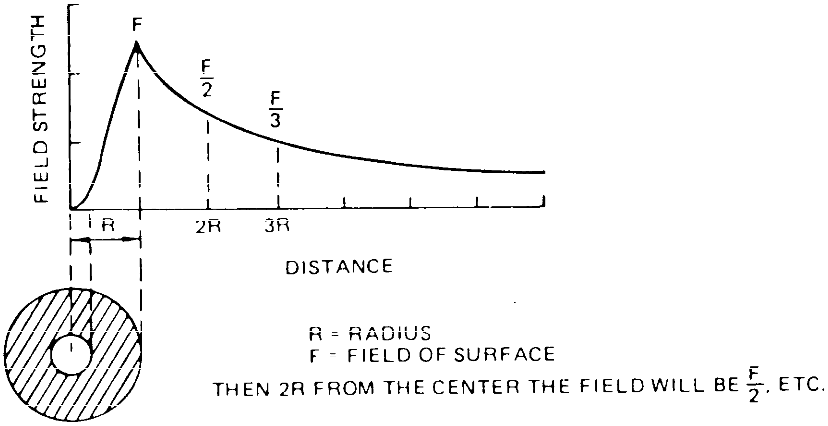


FIGURE 7(a). Field distribution in and around a hollow nonmagnetic conductor carrying direct current.

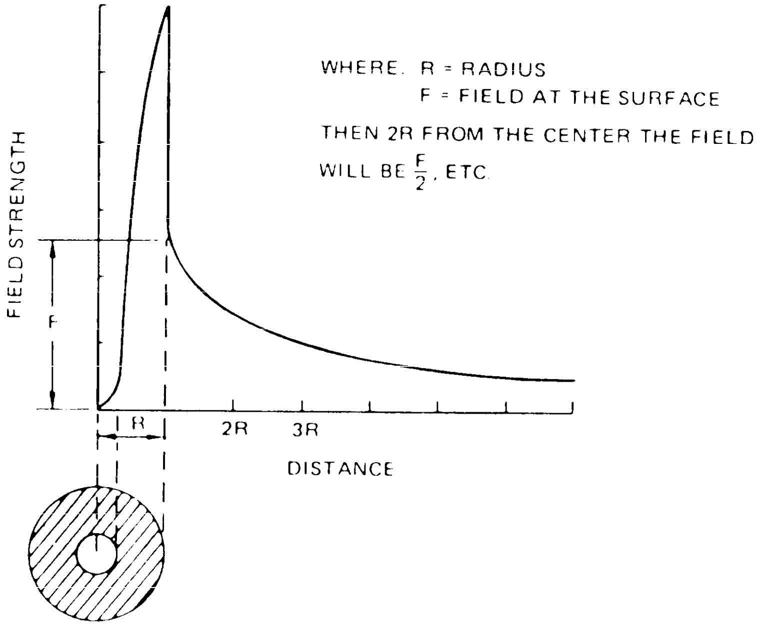
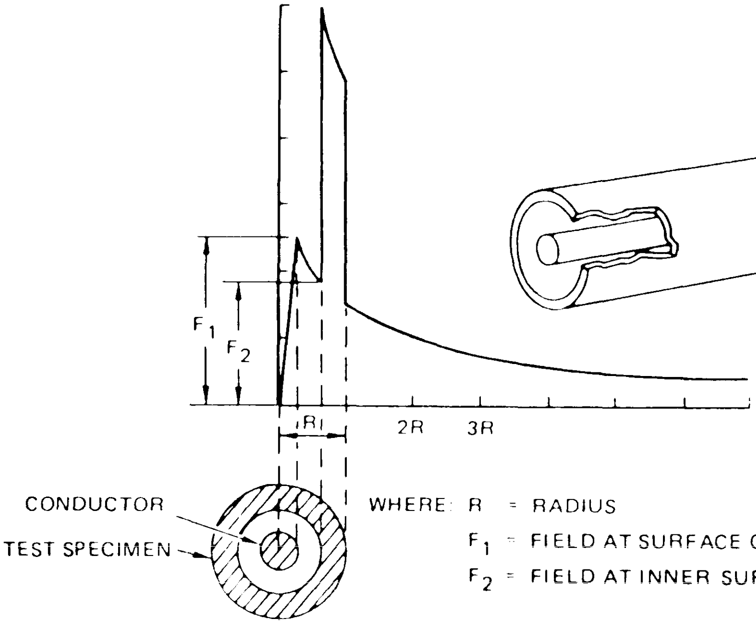
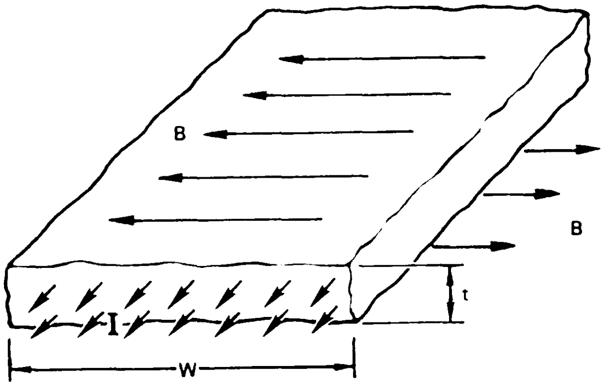


FIGURE 7(b). Field distribution in and around a hollow magnetic conductor carrying direct current.



WHERE: R = RADIUS
F_1 = FIELD AT SURFACE OF CONDUCTOR
F_2 = FIELD AT INNER SURFACE OF SPECIMEN

FIGURE 8. Field distribution in and around a hollow magnetic cylinder with central conductor carrying direct current.



A LARGE FLAT SLAB BEARING A UNIFORM DISTRIBUTION OF THE CURRENT ESTABLISHES A UNIFORM MAGNETIC-INDUCTION FIELD OUTSIDE THE MATERIAL. THE MAGNITUDE OF THE FIELD AT THE SURFACE IS: $B = \frac{1}{2}\mu_0 I/W$.

FIGURE 9. Field distribution in and around a large, flat slab.

6.2.7 Relationship of magnetic permeability to magnetic susceptibility. Equation 4 shows the relationship between the magnetically-induced field, B, and the "magnetizing" force field, H.

$$B = \mu H, \tag{4}$$

where

μ = the magnetic permeability

When there are no magnetizing materials present (when we are in free space),

$$\mu = \mu_o. \tag{5}$$

When simple magnetizing materials (that form isotropic fields) are present

$$\mu = \mu_o (1 + X_m), \tag{6}$$

where X_m is the magnetic susceptibility of the material. Its value can range from 0, for completely nonmagnetic materials, to very large values, in the thousands, for highly magnetic materials. Although X_m is not a fixed constant even for any one material, it often has common or limited ranges for most materials that allow it to have some utility.

6.3 Magnetic properties of materials. The main magnetic property of a material is its susceptibility, normally described in terms of its magnetic permeability. Magnetic permeability is qualitatively the "ease of magnetization of the material." In equation form, it is the ratio of the induced magnetic flux density, B, to the magnetizing force field, H, that is present. It is the "μ" in Equation 4 of paragraph 6.2.7. The "relative" magnetic permeability and the "effective" magnetic permeability terms are also used. The relative permeability is the permeability divided by the magnetic permeability of free space, μ_o, as defined previously. Thus, it is dimensionless, and has the same value in all unit systems. It is equal to one plus the susceptibility (see Equation 6 in paragraph 6.2.7). The "effective" permeability is the ratio of the existing B field in a material divided by the B field that is present without the material. These two permeabilities, the "effective" and the "relative," are essentially identical when long, bar materials are placed in the direction of the magnetic field. The effective and relative permeabilities are not the same when short length-to-width material shapes are used. The effective permeability includes the geometric factor that recognizes the effects of the poles established at the end boundaries of the material which can reduce the effects of the original external magnetic force field within the material.

* 6.3.1 Effective permeability of magnetic materials. For a sphere, the reduced field results in an effective permeability around 3, even if the true relative permeability is 1000. This field reduction is referred to as a demagnetization effect and, as can be seen with the sphere, it can be a very sizable effect. It is, therefore, the effective permeability that must be considered for magnetic particle testing. Thus geometry of the part being tested is important along with the actual permeability of the material.

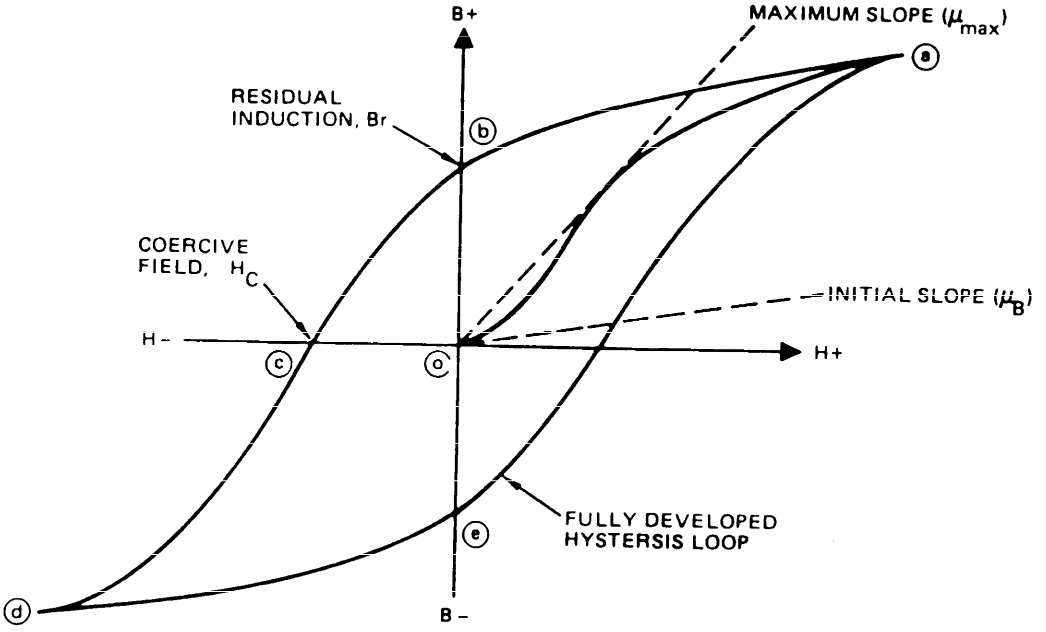


FIGURE 10. A generic hysteresis curve for ferromagnetic materials.

Each material has its own permeability characteristics. These characteristics can be shown on a B versus H curve. Figure 10 shows an example of one of these curves from which various definitions can be obtained. The specimen is completely demagnetized at the starting point (0) of the fig- ure. As the magnetic force, H, is increased, the total flux in the specimen increases until it reaches a point beyond which any additional increase in the magnetizing force does not cause significantly further increases in B. This curve, from 0 to a, is defined as the virgin curve. The virgin curve provides the "maximum permeability" of the material, which is the slope of the line from the zero point to the tangent point on the curve. The point at which significant increases in B cease is known as the "saturation" point. If the magnetizing force is then reduced back to zero, the curve a to b is obtained. The amount of magnetism that the material retains at point b is called residual magnetism. If the magnetizing force is reversed (the current is caused to flow in the opposite direction), the residual magnetism will eventually disappear at point c. The value of "H" at this point represents the "coercive force" for the material, or the magnetizing force required to remove the residual magnetism. As the reversed magnetic force is increased beyond c, the specimen is again saturated as indicated at point d. Returning the magnetizing force back to zero takes the curve to point e. Repeating the start of the cycle for H then takes the curve back up to a where the full hysteresis curve has now been completed. Each material, with its own characteristic curve, exhibits a different amount of saturation, residual magnetism, and coercive force. These variables are all important in magnetic particle testing. The material being tested should be slightly below saturation. If it is too close to saturation, too many field lines will be leaving the surface of the material at arbitrary points, producing false indications. If the material is not near enough to saturation, flux lines, when they meet a discontinuity, can move into the non-saturated middle of the material and not produce visible indications.

If a material shows high residual magnetism, the material can be tested even after it is removed from a magnetic field. Also, demagnetization might be required, and the coercive force will indicate the degree of difficulty in obtaining the demagnetization.

6.4 Small magnetic particles and their visual detection. When a small magnetizable particle (usually with high permeability but low retentivity or low residual magnetism) is placed in a magnetic field, a dipole is formed. That is, opposite magnetic poles, separated by the effective size or length of the particle, are induced on opposite sides of the particle. The strength of these poles multiplied by the effective distance between them (the "size" of the particle) is the magnitude of the dipole moment. Within a magnetic field, dipoles will tend to move in the direction of the field gradient. The force acting on the particle will be proportional to the strength of the gradient and the strength of the dipole moment. Therefore, the strength of the magnetic field (which determines the strength of the induced poles), and the strength of the gradient of the magnetic field are all important. Magnetic gradients, under normal conditions, increase as the poles of a magnet are approached. The shape of the field gradient is determined by the B field, but the direction of the gradient is not necessarily the direction of the lines of force that make up the B field. The lines of force show the direction of orientation that a dipole particle would tend to assume, but the net force acting upon a dipole particle will include components of forces perpendicular to B in most regions of the field. Because gradients are large at the poles, or at points where the magnetic lines of force leave the surface of a magnetic material, small magnetic particles, acting as dipoles, will tend to move and attach themselves to these locations. Because these particles form their own poles, they can hang together end-to-end, and not all collect side-by-side at the same concentrated point. This formation effectively extends the size of the gradient, and can actually amplify the indication to a size several hundred times larger than the actual discontinuity. This allows easy observation of flaws or other anomalies.

6.4.1 Methods for increasing the detectability of indications. Additional enhancement of the observations can be accomplished by several means: a contrasting background can be applied over the inspected part before the test begins, and/or the magnetic particles can be dyed a bright color, or the particles can even be made to be fluorescent. The strengths of these magnetic gradients are not always great; therefore the "mobility" of these small magnetic particles is important. Particle size and shape, the medium in which they are carried, if any, and any mechanical vibration or other inducement to move become important considerations. The material the particles are made of, and their size and shape, also affect the magnetic moment that can be induced. Thus, a wide variety of characteristics can be associated with the magnetic particles used, and the expected visual detection capabilities that can be obtained will depend upon several characteristics of the particles used.

7. EQUIPMENT AND MATERIALS

7.1 General. The equipment and materials required to perform a magnetic particle test can be as simple as a strong permanent magnet and a supply of magnetic particle powders. However, sources of electrical currents, with control over the current magnitudes and directions, magnetic coils and yokes, and tanks for holding magnetic powders, either in dry or wet form, can all be considered as necessary facilities for most magnetic particle testing.

7.2 Commercial equipment for magnetic particle testing. Today there is commercial equipment available for portable, mobile, or stationary systems.

7.2.1 Portable testing units. The portable magnetic-particle testing units are available as hand-portable current sources or as hand-held magnetic yokes. A typical portable magnetic-particle unit (current source) is shown in figure 11. These portable units are generally designed for operating on 110 or 220 Vac and supplying 500 and 1000 amperes. The output voltage will range from 5 to 25V depending upon the current level being supplied. Portable units are especially desirable for inspecting small items and for inspecting in remote areas.

7.2.2 Mobile equipment. Except for added features of demagnetizing circuits, the mobile equipment may be best described as heavy-duty portable equipment on wheels. The electrical circuitry is generally designed to provide heavy currents ranging up to 3000 amperes. Since heavier transformer wires and connectors are required to carry these currents, and cooling fans are

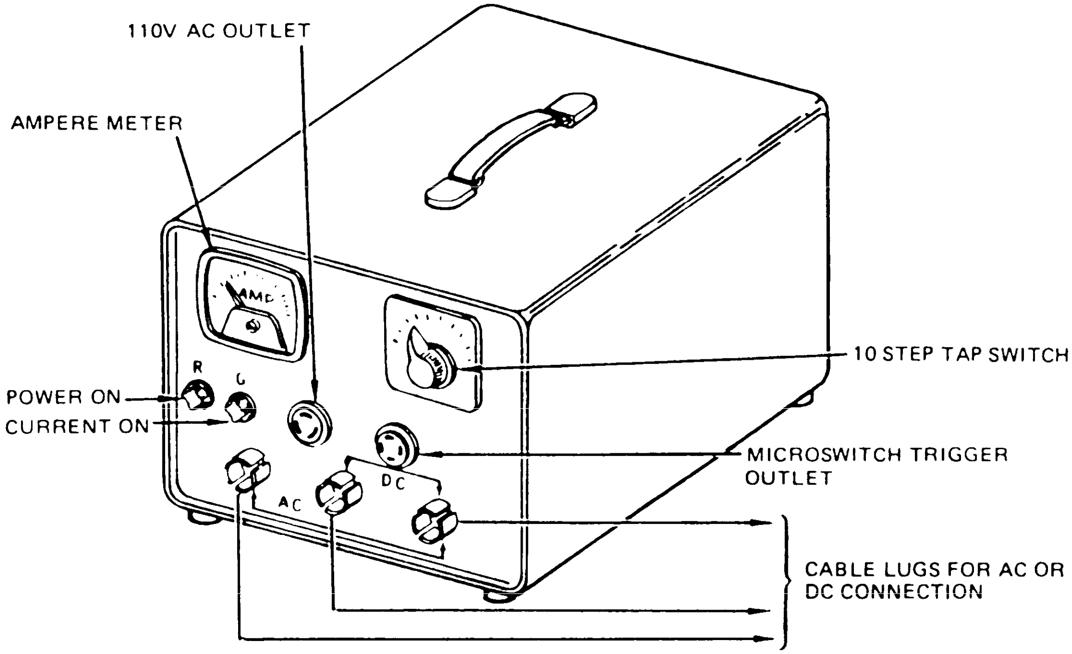
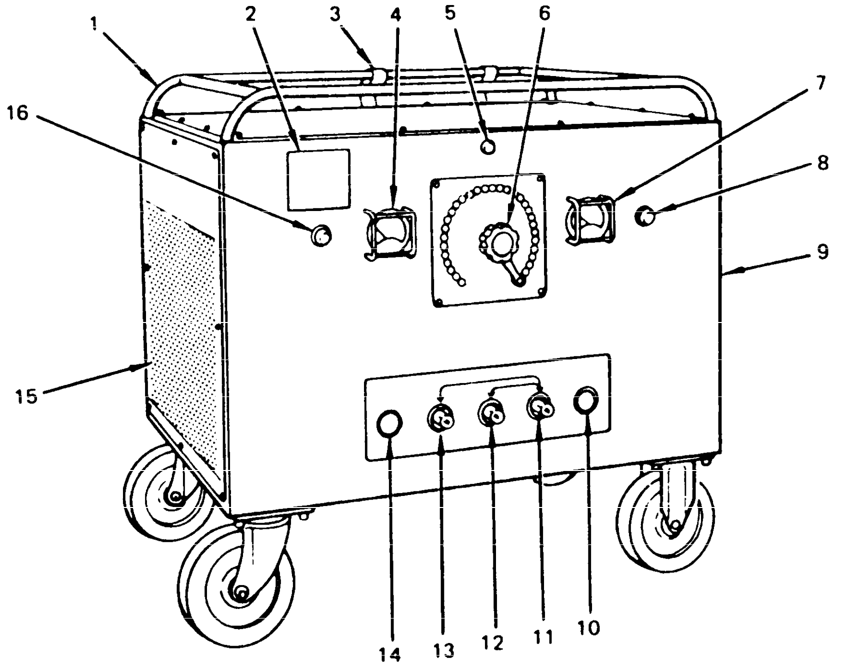


FIGURE 11. Portable magnetic particle current source.

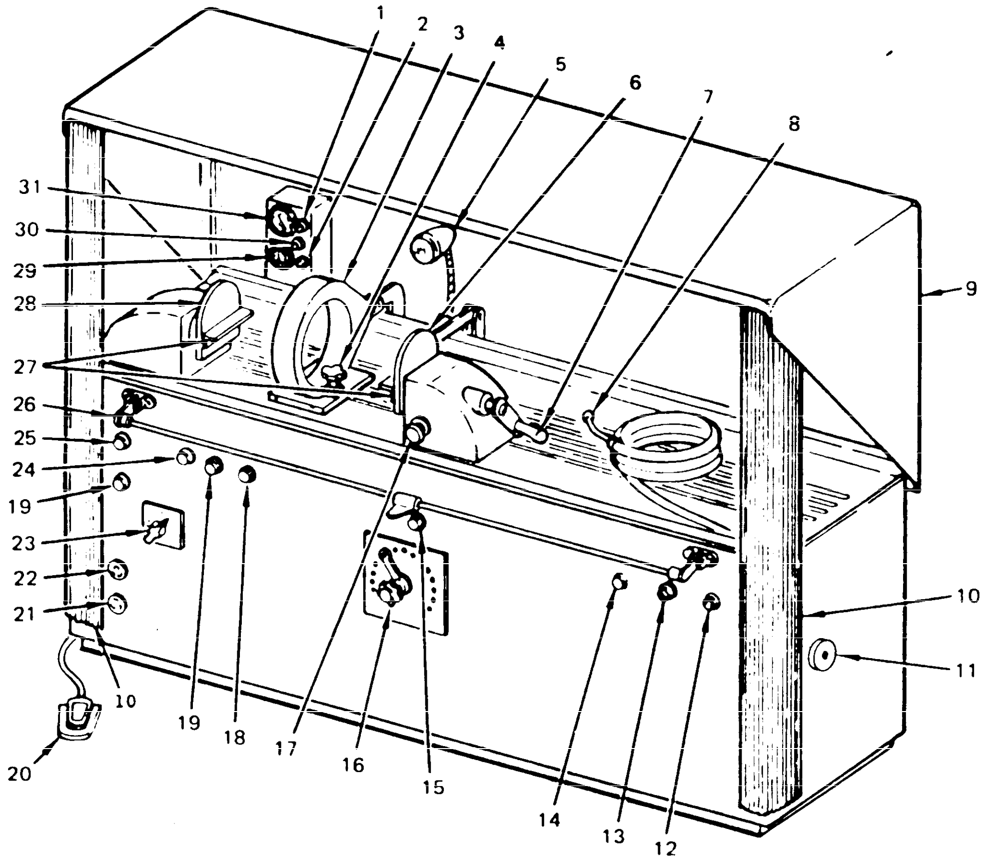
added to aid in cooling, the equipment weight becomes excessive. However, such equipment may still be used effectively in many different locations by rolling on wheels. A typical mobile magnetic particle test unit is shown in figure 12. Selection of ac or half-wave dc is easily changed by switching cables on cable lugs located in front of the unit. Cables ranging from 15 to 30 feet may be further extended by additional lengths to as much as 90 to 100 feet. When extension cables are used, a decrease in current output can be expected. Although prods are usually used with mobile equipment, solenoid or cable wrapping techniques can be used. Also, use of a central conductor hooked up between the two cables facilitates variation in test techniques. Dry magnetic particle powder is most often used with this type of equipment but the wet technique (with an external tank) or materials in kit form can also be used.



1. CARRYING RACK
2. IDENTIFICATION PLATE
3. CABLE HOOK
4. DC AMMETER (OUTPUT)
5. DEMAGNETIZATION PUSHBUTTON
6. CURRENT VALUE IS SELECTED BY TURNING OF KNOB
7. AC AMMETER (OUTPUT)
8. POWER ON LIGHT (RED)
9. POWER HOOK-UP TO THE TERMINALS IS FACILITATED AND EASILY ACCESSIBLE THROUGH A SMALL DOOR HERE
10. CABLE LEADING TO MICROSWITCH ON THE PROD HANDLE
11. CABLE LUGS (GROUND CABLE)
12. CABLE LUGS
13. CABLE LUGS
14. 110 VOLT AC EXTENSION CABLE
15. COOLING INTAKE
16. CURRENT ON LIGHT (GREEN)

FIGURE 12. Mobile magnetic particle test unit.

7.2.3 Stationary test equipment. Stationary magnetic particle test equipment may be obtained as either general-purpose or special-purpose inspection units. The general-purpose unit is primarily for use in the wet method, and has a built-in tank that contains the wet-particle bath pump which continually agitates the bath and forces the fluid through hoses onto the test article. In addition, curtains and an ultraviolet light are provided for inspection whenever fluorescent particles are used. A general-purpose stationary unit is shown in figure 13.



1 DC PILOT LIGHT
2 AC PILOT LIGHT
3 COIL
4 COIL LOCKING HANDLE
5 BLACK LIGHT
6 TAILSTOCK CONTACT PLATE
7 TAILSTOCK CRANK HANDLE
8 NOZZLE
9 HOOD
10 CURTAIN
11 FLOW CONTROL VALVE
12 DEMAG CURRENT PILOT LIGHT
13 AC TRANSFER SWITCH
14 MAGNETIZING CURRENT CONTROL
15 30 POINT SWITCH START BUTTON
16 CURRENT REGULATING SWITCH
17 TAILSTOCK LOCKING HANDLE
18 DC TRANSFER SWITCH
19 DC AC SELECTOR SWITCH
20 FOOT SWITCH
21 CONTROL CABLE RECEPTACLE
22 110V AC OUTLET
23 CURRENT CONTROL
24 LINE PILOT LIGHT
25 PUMP SWITCH
26 ACTUATOR
27 HEADSTOCK AND TAILSTOCK LEDGES
28 HEADSTOCK CONTACT PLATE
29 AC AMMETER
30 MAGNETIZING CURRENT PILOT LIGHT
31 DC AMMETER

FIGURE 13. General-purpose stationary magnetic particle test bench.

Special-purpose stationary units are designed for handling and inspecting large quantities of similar items. Generally, conveyors, automatic markers, and alarm systems are included in such units to expedite the handling and disposition of parts.

7.3 Demagnetization equipment. Most common types of demagnetization equipment consist of an open tunnel-like coil through which alternating current at the incoming frequency (usually 60 cycles) is passed (see figure 14). The larger type of equipment is frequently placed on its own stand and incorporates a track or carriage to facilitate moving large and heavy articles. Smaller demagnetization equipment such as table-top units, yokes, or plug-in cable coils, may be feasible for demagnetization of small test items. The large, stationary equipment is preferable when multidimensional test items are involved.

7.4 Accessories. The number of accessories used in magnetic particle testing are extensive. Some are available from the manufacturers of magnetic particle equipment; others are made up for specific purposes. Accessories usually depend on the type and method or application of the test selected. Such accessories are chosen primarily to facilitate and enhance the quality and performance of a given test or test technique. The following list contains frequently used accessories and their applications.

1. Cables - used to carry the current to prod or solenoid.
2. Prods - used for magnetizing of welds, sheet, or plate.

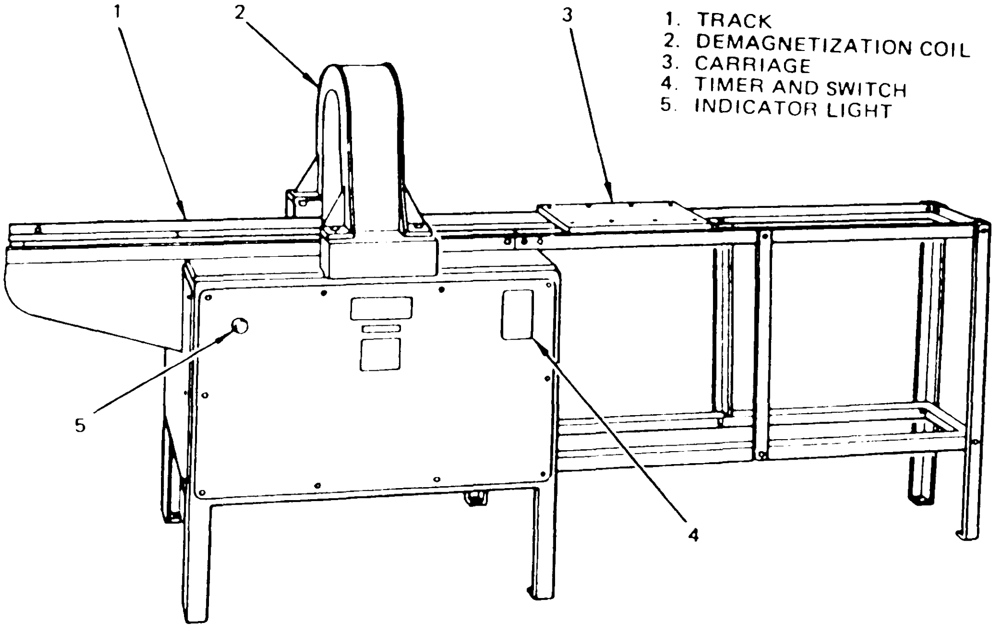


FIGURE 14. Demagnetization equipment.

3. Clamps - used instead of prods to facilitate good contact with article or when one-man operation is required.
4. Contact Blocks - used to facilitate cable connection from stationary equipment for external use of prods or coils.
5. Field Indicators - used in measuring residual magnetism in an article.
6. Metal Mesh - used between contact points and article tested to avoid sparking and burns.
7. Liquid Applicators - used in applying fluorescent or nonfluorescent test medium: can be manual, electric, or air operated.
8. Powder Applicators - used to apply magnetic particle powder to the test area: can be a powder-puff or powder blower.
9. Black Light - The use of black light is standard in fluorescent type inspection. In some instances, more than one black light may be desirable. A portable black light may be used with mobile equipment when wet method testing is performed.

7.5 Magnetic particle powders. Four properties enter into the selection of satisfactory magnetic particles: magnetic, geometric, mobility, and visibility.

7.5.1 Magnetic properties. It is desirable that the particles of the testing medium possess two important magnetic properties: high permeability and low retentivity. Permeability may be defined as the degree of ease with which a particle is magnetized. Retentivity is that property which enables particles to hold (to a greater or lesser degree) a certain amount of residual magnetism. Particles incorporating high permeability and low retentivity give maximum response in a leakage field, and at the same time do not remain magnetized when they pass out of the influence of the magnetic field.

7.5.2 Geometric properties. The spherical shaped particle offers a high degree of mobility but has low attractive power. The long, slender, jagged particle has a high degree of attractive power and low mobility. A multi-faceted nugget type particle is a good compromise in that it reasonably combines the optimum qualities of the other two types. Particle size is also an important consideration, and it is desirable to have particles of various sizes. Small particles are required to bridge a tight-lipped crack. Larger sizes are necessary for wider cracks. A weak leakage field is unable to hold a large particle but is able to fix and retain one of smaller size. Thus, dry powder, magnetic particles are usually available in a wide range of sizes - but all are small enough to pass through a 100-mesh screen. In the wet technique of magnetic particle testing, magnetic oxides of iron are generally used. Although they are extremely fine in size, they are of lower permeability than the metallic, dry particles and have neither the most desirable shape nor variety of sizes available in metallic particles. Fine magnetic oxides are generally used in the technique because they can be suspended in a liquid when a dispersing agent is employed.

7.5.3 Mobility. When the particles are brought into the influence of the leakage field of a flaw, they must be free to form a pattern or indication. This freedom is influenced by several conditions, including the shape of the particles and how they are applied to the surface.

In the dry particle technique of magnetic particle testing, particle mobility is obtained by dusting or blowing the particles over the surface of the article. This permits the magnetic field at the flaw to catch and hold some particles as they move by. Mobility is also obtained by vibrating the article after the particles have been applied. Alternating current may be used advantageously because the alternating field causes the particles to "dance" and thus enhances mobility. However, pulsating direct current is sometimes considered superior in other test characteristics.

The principal advantage of the wet technique of magnetic particle testing is the excellent mobility (freedom to move in the three dimensions) of the suspended particles. It is important to use a low viscosity liquid so that the suspended particles are retarded as little as possible by the liquid in which they are suspended.

7.5.4 Visibility. So that an indication can be made readily visible, a good light source is essential. Particle color also affects visibility. With various types of part surface finishes (from highly polished to rough castings), no one color of particle is always satisfactory. The choice of particle color is entirely dependent on the test item. The most widely used particles are gray, red, and black. The gray powder has excellent contrast against practically all surfaces (with the exception of certain silver-gray sand-blasted surfaces). Particles coated with fluorescent dye often are used to enhance visibility.

8. BASIC PROCEDURES AND TECHNIQUES

* 8.1 General. Magnetic particle testing can be broken down into five basic steps:

1. Preparation of the test surface
2. Magnetization
3. Application of magnetic particles
4. Inspection
5. Demagnetization and cleaning

Each of these steps is presented with the appropriate test techniques where applicable. ASTM E709, "Standard Practice for Magnetic Particle Examination," is useful in describing material in a more quantitative fashion on some techniques and applications discussed below, as well as in other paragraphs in this handbook.

8.2 Preparation of the test surface. The test surface should be cleaned of grease, heavy coatings of paint, rust, slag, or other materials that would interfere with the mobility of the magnetic particles and the forming of indications. A smooth surface and a uniform color are desired for optimum formation and examination of the magnetic particle pattern. When it is necessary to perform magnetic particle testing on items that have been covered with anti-corrosive protective coatings (such as primers, paints, or cadmium-, chromium-, nickel-, or zinc-plating), the coatings do not necessarily have to be removed, since flaw indications are not usually affected. The acceptable thickness limits for such coatings on test items should be checked before conducting a test. In certain cases, coatings are purposely applied to the test item to provide a contrasting background for the medium. The acceptable thickness limit of such coatings is often up to 0.125-mm (0.005 inch). All holes and openings leading to internal areas where complete removal of magnetic substances or other matter cannot be readily accomplished are plugged. Any material which can be completely removed and is not detrimental to the part may be used for plugging. When necessary, all faying surfaces or component parts that can be damaged by the bath are masked. It should be noted that the cleaning of the surface is not necessarily the same thing as cleaning materials out of cracks or flaws that might be on the surface. For liquid penetrant testing (see MIL-HDBK-728/3), the contaminants in the flaws must be removed to allow the entry of the penetrant; but for magnetic particle testing, non-magnetic contaminants do not usually have to be removed from the flaws. This can be an extensive savings in both time and expense. In magnetic particle testing, if current is to be injected into the part, the injection area should also be cleaned to allow good electrical contact.

8.3 Magnetization. To magnetize a specimen, the permeability of the material, the shape and size of the specimen, and the type, size, orientation, and location of the expected discontinuities will all need to be considered. The accessibility of the part, the facilities available, and the required sensitivity of the testing are also parameters that affect the test decisions.

8.3.1 Permanent magnet or electrical source. Basically, one has to first decide if the magnetic field source will be established by a permanent magnet or by an electric current. If a permanent magnet is used, then the distance from the poles or distances between inspection points that can be allowed to detect particular discontinuities must be determined for that particular magnet and material. This is usually determined by trial and error. When accessibility, power source, and facilities allow it, fields from current sources will normally be chosen because they provide greater flexibility in terms of the strengths of magnetic fields obtainable and in the shape and direction of those fields. Ability to demagnetize is also increased when electrical currents are available.

8.3.2 Alternating, direct, or half-wave currents. If electric currents are to be used, decisions to use alternating current, or half-wave or pulsed direct current must be made. It is generally accepted that the best types of magnetizing currents for magnetic particle testing are alternating and half-wave, rectified currents. Alternating current is best suited for locating surface discontinuities (because of skin effect). Half-wave, direct current is best suited for locating below-the-surface discontinuities.

Figure 15 compares the abilities of various methods to detect subsurface discontinuities. The graph plots amperage against depth of discontinuity. This experiment was performed using the test specimen shown at the lower right in figure 15. The lowest amperage that gave a minimum threshold indication at various discontinuity depths was recorded.

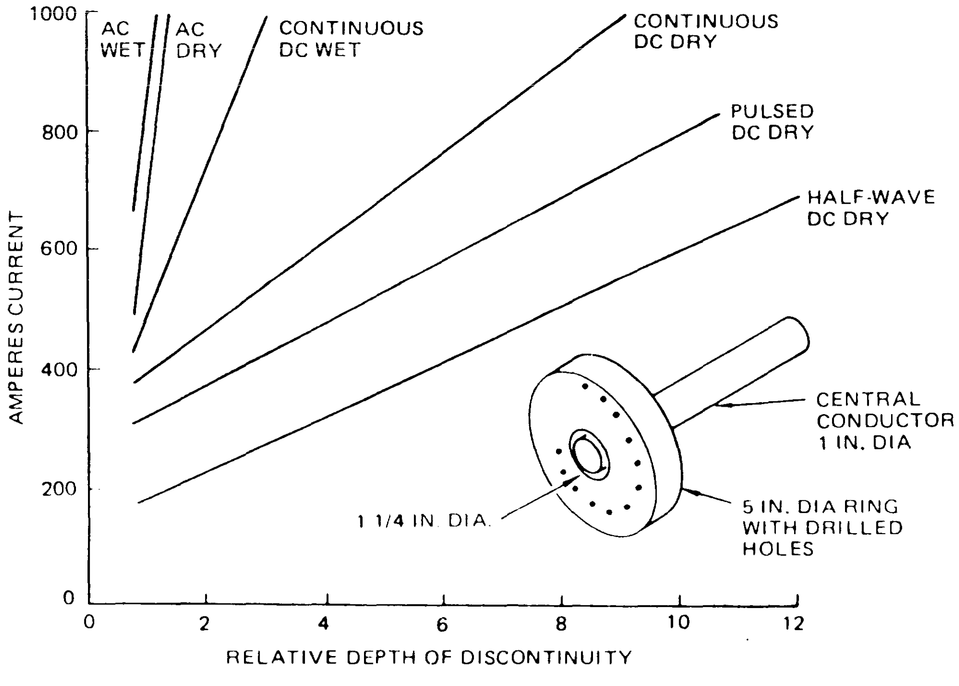


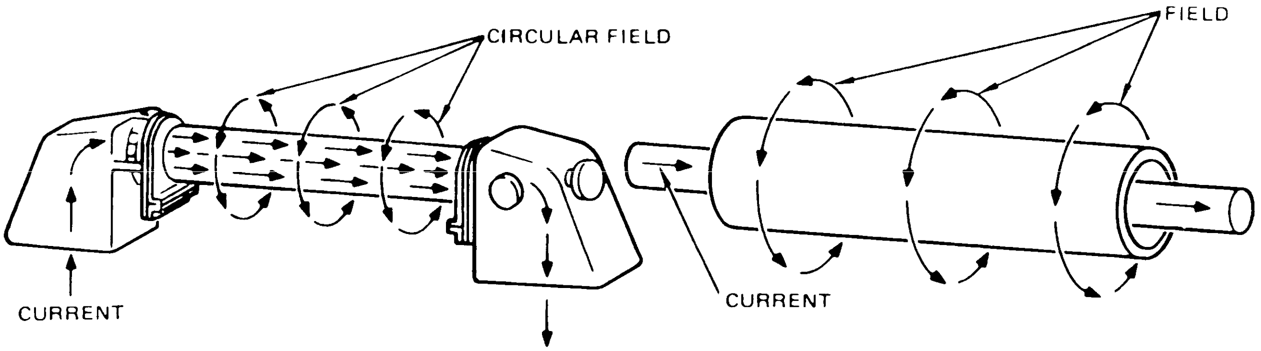
FIGURE 15. Threshold sensitivities of various test methods.

The advantage of using alternating current is that the voltage can be stepped up or down by the use of a transformer. Also, the reversal of magnetic fields, due to the alternating current, makes the magnetic particles more mobile, thus facilitating their collection at leakage fields.

The advantage of half-wave direct current is that, by the use of a rectifier, it can be generated from any commercial alternating current source. Penetration is comparable to that of straight direct current with the pulsating effects of the rectified wave being helpful in adding mobility to the magnetic particles.

8.3.3 Direction of current. After the type of current is chosen, the direction of current application must be determined. Basically, there are two directions usually considered: 1) a "head shot" that establishes a flow of current along the length of the part, resulting in circular magnetization around the part which will locate cracks orientated in the direction of the length of the part, and 2) a "coil shot" that establishes longitudinal magnetization along the length of the part, which will locate cracks oriented perpendicular to the length of the part.

Figure 16 illustrates a head shot and an alternate version where a central conductor is used. Figure 17 indicates a coil shot. Figure 18 indicates other possible current setups. Usually setups for more than one direction must be made to ensure that all discontinuities will be seen. It should be noted that in some cases the current may flow through the part, and in other cases through separate conductors or coils.



(A) HEAD SHOT

(B) CENTRAL CONDUCTOR

FIGURE 16. Circular magnetization by direct and indirect current induction.

* 8.3.4 Multidirectional magnetization. Multidirectional magnetization is defined in the glossary E1316 of the ASTM Book of Standards 03.03 as the alternative application of magnetic fields in different directions during the same time frame. Suitable circuity can be utilized to establish magnetic fields sequentially in more than one direction. The simplest techniques utilize perpendicular fields, switched back and forth. Cracks that are

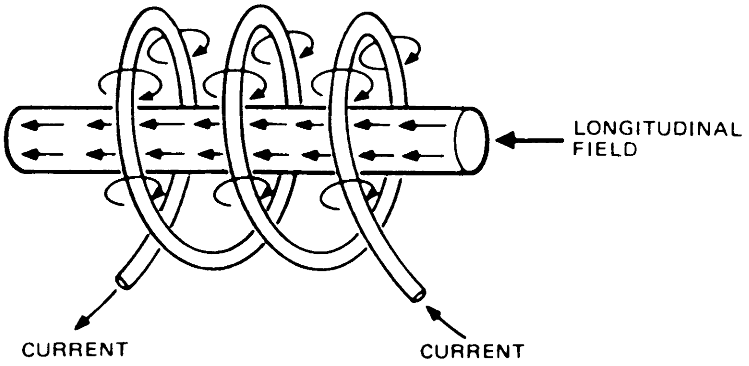


FIGURE 17. Longitudinal magnetic fields.

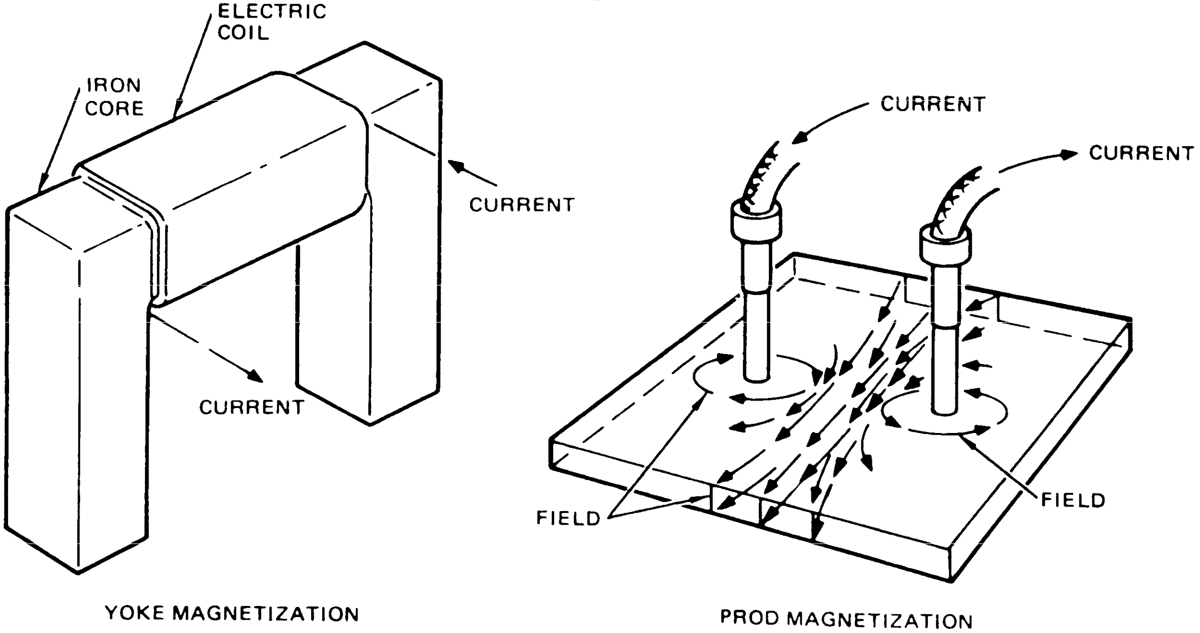


FIGURE 18. Magnetization with prods and yokes.

perpendicular to the magnetic flux lines are observed. Thus, by having flux produced both in circular and longitudinal directions, cracks that are oriented predominantly longitudinally and circulary respectively will be detected clearly.

* 8.3.4.1 Balanced magnetic fields. For general purposes, only two directions of magnetization are usually required: circular and longitudinal. When setting up for the multidirectional methods, the fields are usually balanced so that equivalent magnetization capability exists in the two directions during the operation. This can be attained successfully by using artificial-flaw standards at various locations on the test objects. There may be situations in which the magnetizing fields can be somewhat different. In these cases, it is important that a predetermination (or calibration) be performed to assure usefulness. In most applications, balanced fields are

desirable. Even then, there may be a lack of confidence that they have been achieved inside complex parts. However, the usefulness for inspection still exists, and even small discontinuities can be detected successfully with multidirectional fields.

* 8.3.4.2 Multi-directional magnetization. Three-dimensional magnetic particle inspection units have been set up that have potential for developing two field directions or more for magnetic particle inspection. These can be tailored for specific applications, according to Hagemeier in a review article. (7) It is critical that the magnetic fields are demonstrably balanced so that equivalent magnetizing force exists in all directions during the operation for inspection. Two perpendicular directions are usually selected. It has been found that multidirectional magnetization improves detectability of indication significantly because blind spots are less probable if the technique is properly applied.

8.3.5 Direct and indirect application of current. Magnetization by injecting current into the test item is usually preferred whenever maximum sensitivity to tiny flaws is desired or whenever a magnetic field cannot be conveniently induced in the test item by other methods. However, if the part under inspection is magnetized by injecting current into its surface, care must be taken to avoid arcing as this may severely damage the surface, particularly whenever hand-held prods are used to inject current. Arcing tends to occur whenever the current contacts are dirty or are moved during excitation. A simple way around the arcing problem is to securely clamp the contacts to a clean area. When magnetization is induced by placing the part in an external magnetic field, the arcing problem does not occur.

* 8.3.6 The current and magnetic field strength. The required amount of magnetizing current is affected by the permeability of the material, the shape and thickness of the test specimen, and the type of discontinuity sought. When an article is not uniform in section, it is necessary to use one value of current for the thinner sections and a second, third, or more values of current for heavier sections. In circular magnetization the length of the test specimen does not affect the current requirement. The electrical resistance will, however, increase with length and so will require more electrical energy to develop the required amperage. In longitudinal magnetization, specimen length is a factor to be considered. It is always proper to use the smaller current value first to test the thinner section and then proceed with successively higher currents to test the increasingly larger sections. This procedure avoids overmagnetization of the thinner sections. Whenever a stronger field has been imposed than is required for a subsequent test, it is necessary to demagnetize the specimen before applying the lower amperage. As summarized in ASTM E1444 and here, adequate magnetic field strength can be calculated from various formulas relating it to applied current, with certain approximations being used. Formulas are included for historical continuity. If used, they should be limited to parts that have a simple shape. Appropriate field strength can also be determined by testing parts having known or artificial defects of the type, size, and location specified in acceptance requirements. Various magnetic field indicators, such as a Hall effect gauge, can also be used to measure the peak value of the field tangential to the surface. Judicious use of formulas together with choice of standards and appropriate measurement can yield sufficient but not excessive magnetic field strength for consistent results for indications.

* 8.3.6.1 Circular magnetization. For direct circular magnetization or indirect circular magnetization using a centrally localized conductor, only enough current to show the indication is normally used. The test gauge of magnetizing current strength is a test specimen with a typical indication. The test specimen is kept and used as a reference and the current required to reproduce the indication is checked from time to time. The recommended values for circular magnetization vary because of the different factors involved for different setups and different spatial factors. An acceptable rule is to use from 300 to 800 amperes per inch (120 to 320 amperes per centimeter) diameter or greatest diagonal width of cross section of the part. The amperages shown in table I, therefore, are only suggested averages for various diameters and widths, and may be incorrect for certain alloys and shapes. For indirect circular magnetization using an offset central conductor, the specimen diameter is replaced with the sum of the diameter of the central conductor plus twice the specimen wall thickness. Figure 19 shows test specimens of several sizes and shapes, both in English and metric units.

* 1. View A of figure 19 shows a multiple diameter, solid specimen, the smaller diameter being 2 inches, and the larger 3 inches. Following table I, and recalling the foregoing discussion, the thinner section is magnetic-particle-tested first, requiring 600 to 1600 amperes. The second "shot," for the 3-inch diameter section, requires 900 to 2400 amperes.

* 2. View B of figure 19 illustrates a tubular section to be tested by a head shot. It can be seen from table I, that the current required is 1200 to 3200 amperes. If a centrally located conductor is used to inspect this article, the current requirement remains the same.

* 3. View C of figure 19 illustrate the use of an offset central conductors. It can be seen that calculating the amperage based upon the diameter of the central conductor plus twice the wall thickness yields a current range of 450 to 1200 amperes.

* 4. View D of figure 19 illustrates a number of smaller articles (nuts) requiring testing on an offset central conductor. The maximum outer diameter is 4 centimeters. From table I, we obtain a current requirement of 300 to 800 amperes.

8.3.6.2 Longitudinal magnetization using coils. When a coil is used for longitudinal magnetization, the strength of the field is determined by the product of the number of amperes and the number of turns in the coil. For example, a current of 800 amperes through a five-turn coil creates a magnetizing force of 4,000 ampere turns; it is necessary to know how many turns there are in a coil to calculate the magnetizing force. On most stationary equipment, this information is usually shown on the coil; if not, it may be obtained from the equipment manufacturer. Another type of coil used is the wrapped cable. This is frequently used when an article is either odd-shaped or too big to handle on the equipment. For reliable coil magnetization (longitudinal), the article to be magnetized must be at least twice as long as its diameter, or width. This relationship is known as the length-diameter (L/D) ratio. The L/D ratio and the number of turns in a coil determine the required amperage for coil shots, providing the following conditions are met.

1. The article has an L/D ratio of between 2 and 15.
2. The article or section thereof to be magnetized is not greater than 18 inches (46 cm) long.
3. The cross-sectional area of the article is not greater than 1/10 the area of the coil opening.
4. The article is held against the inside wall of the coil and not positioned in the center of the coil.

If the foregoing conditions are met, then the formula for determining a correct amperage is:

$$A = \frac{45{,}000}{L/D} \times \frac{1}{N} \text{ or } \frac{45{,}000\ D}{LN}$$

where:

* 45,000 = constant
L = length
D = diameter
N = number of turns in coil
A = amperes

Assuming a solid article, 12 inches long (L) by 3 inches in diameter (D), and a coil consisting of 5 turns (N) was available, then the required amperage is determined as follows:

$$\frac{45{,}000\ D}{LN} = \frac{45{,}000 \times 3}{12 \times 5} = 2250 \text{ Amperes}$$

The formula may be used for any number of coil turns. Theoretically, the more turns of cable, the stronger the field though there is a limit to the number of turns (5 when using alternating current) that will increase the flux density. Also, an excessive number of turns will have a heating effect. Since the effective field is limited by the size of the coil, several shots may be required when testing a long article.

8.3.6.3 Use of prods for dual circular fields. The correct flux density is somewhat easier to determine when using prods because it is possible to vary either the current setting on the equipment or the spacing between the prods. If the accumulation of particles between the points of the prods is too heavy, the particles tend to form bands. Banding indicates that the field strength is too great and should be reduced by either lowering the amperage or increasing the space between the prods. Spacing between the prods varies, depending on the size and thickness of the article to be tested; 6- to 8-inch (15 to 20 cm) spacing is found to be most effective on larger articles. American Society for Testing and Materials Standard E709 and MIL-STD-1949 provide additional guides on magnetization requirements.

8.4 Application of magnetic particles. Once the proper level of magnetic flux has been established in a part, magnetic particles are applied. Normally this application is made while the magnetic field source is "on." It is possible, however, where materials exhibit high retentivity, for the residual magnetic field to be adequate for testing, and the magnetizing source can be removed. When the magnetizing source can be removed, the test specimen can be placed in an immersion bath where the magnetic particles are suspended in a liquid. A bath allows maximum particle mobility and usually uniform coverage of the part by the magnetic particles with improved sensitivity and consistency in the test results.

8.4.1 Dry method for testing. Often the application of particles is by a dry method or by a wet flow. The dry magnetic particles are commonly applied from shaker cans or bulbs. The dry method is probably the simplest application method, but certainly not always the best. Automatic particle-blowing equipment can be used. Methods utilizing such equipment are economical in their use of particles and, on most tests, are an acceptable way of "flowing" dry particles over the test surface. A minimum flow velocity is desired in this process.

* TABLE I. Magnetizing current for circular magnetization of solid and tubular articles.

Tubular and Solid Articles Greatest Diameter* or diagonal In Inches	 in Centimeters	 Magnetizing Current (Approx) in Amperes
0.4	1.0	100 - 320
0.5	1.3	150 - 400
0.75	1.9	225 - 600
0.8	2.0	240 - 640
1.0	2.5	300 - 800
1.2	3.0	360 - 960
1.5	3.8	450 - 1200
1.6	4.0	480 - 1280
2.0	5.0	600 - 1600
2.4	6.0	720 - 1920
2.5	6.3	750 - 2000
2.8	7.0	840 - 2240
3.0	7.6	900 - 2400
3.2	8.0	960 - 2560
3.5	8.9	1050 - 2800
3.6	9.0	1080 - 2880
4.0	10.0	1200 - 3200

* For an offset Central Conductor, use the Conductor Diameter plus Twice the Wall Thickness.

8.4.2 Wet method for testing. Wet suspensions can be sprayed or otherwise caused to flow over the surface. Again, velocity of flow is important. The flow should not be so strong that the indications are destroyed. For the wet flow or bath method the liquid used is usually a light oil. Water, suitably treated with anti-corrosion, anti-foam, and wetting agents may also be used. Ideally, this liquid should not be fluorescent and, for safety purposes, the liquid should be non-toxic and non-volatile and should have a high flashpoint.

8.4.2..1 Wet bath considerations. The particles are usually obtainable in a dry form, a paste form, or in a highly concentrated liquid form and may be either fluorescent or nonfluorescent. To achieve the required test sensitivity, the degree of particle concentration in the bath must be correct - too light a concentration leads to very light indications of discontinuities; too heavy a concentration results in too much overall surface coverage, which may mask or cause incorrect interpretation of discontinuity indications.

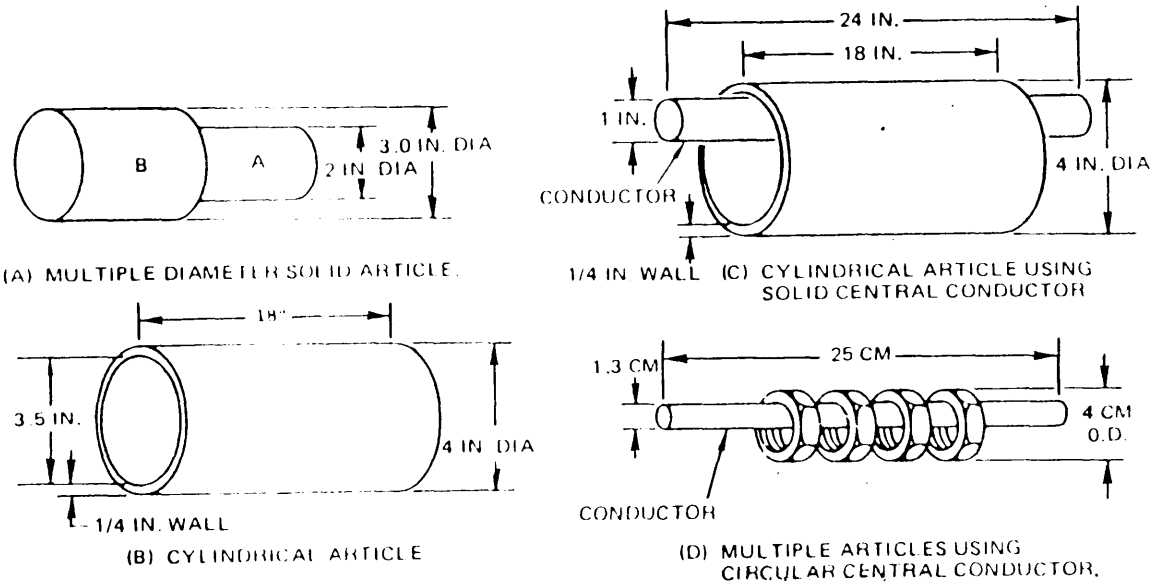


FIGURE 19. Circular magnetization of typical specimens using head-shot or central conductor. (1)

Table II lists the preferred particle concentration for wet suspensions. Check applicable specifications for exact allowable concentrations. While the bath is in use, it must be constantly agitated to maintain the particles in suspension. A short period of agitation prior to use is desirable. Agitation is usually accomplished by electrically driven pumps or by compressed air. Compressed air agitation, while effective, is the less desirable since moisture and foreign matter carried by the air may contaminate the bath and shorten its useful life. The particle concentration should be checked periodically since the liquid can evaporate and particles are lost as they are removed from the bath on the test specimens.

TABLE II. Concentration for wet suspensions.

Type Particles	Oz. Particles/Gal Suspension	ML or CC Particles/ 100 ML or 100 CC Liquid
Nonfluorescent	See Manufacturer's Instructions	1.2 - 2.4
Fluorescent		0.1 - 0.5

8.4.2.2 Wet bath settling test to determine usefulness. A simple test for particle concentration is the "settling test" shown in figure 20. The suspension is agitated for 30 minutes to assure an even distribution of the particles in the liquid. Then, 100 cc (ml) of the bath is pumped through the hose nozzle into the pear-shaped centrifuge tube and allowed to settle for a minimum of 30 minutes. The amount of particles (measured in cc or ml) settling in the bottom of the centrifuge indicates the concentration of solid matter (particles) in the bath. In measuring the solid matter in the centrifuge, foreign material such as lint and dirt, which settles on top of the particles, is not considered. If the particle reading is high, liquid (vehicle) is added; if low, paste or liquid concentrate containing particles is added. Paste is never directly added to the bath because it might not disperse properly. The paste should be premixed with sufficient bath solution that it can be poured into the holding tank.

When in use, the bath eventually becomes contaminated by dirt, lint, and chips to a degree that efficient formation of discontinuity indications is hindered. Degree of contamination is determined by the amount of foreign matter settling with the paste in the bottom of the centrifuge tube during the settling test. The bath should be checked on a regular schedule depending on the inspection volume: weekly if the volume is high; monthly if the volume is low. When the bath is contaminated beyond usefulness it is discarded, the bath tank and the liquid system are thoroughly cleaned, and a new bath is mixed. Contamination can be minimized by keeping the bath covered when not in use.

8.4.2.3 Control of bath for production procedures. For water-based vehicles, a clean part is flooded with conditioned water to obtain a continuous even film over the entire part, provided sufficient wetting agent is present. If the suspension film breaks, exposing bare surface, insufficient wetting agent is present, or the part has not been cleaned adequately, or the water vehicle is no longer usuable. When wet particle concentration/lack of contamination are not within limits determined by MIL-STD-1949/ASTM E1444, then it is time to dump the bath, clean the tank, and charge a new bath. If settled particles appear as loose agglomerates rather than as a solid layer over two sequential samples, then the bath also needs to be replaced; this is required by MIL-STD-1949/ASTM E1444.

8.5 Inspection Indications of discontinuities located on the surface usually appear in sharp distinct lines, whereas discontinuities located below the surface appear as irregular, rough, hazy indications. The width of a subsurface discontinuity indication varies with the depth of its location below the surface. Correct interpretation of indications caused by subsurface discontinuities requires a certain amount of skill and experience on the part of the operator.

8.6 Demagnetization and cleaning. Ferrous materials usually retain some residual magnetism after the magnetizing current is shut off. The strength of the residual field depends upon the retentivity of the material, and the strength and direction of the magnetizing force. Complete demagnetization is difficult if not impossible to obtain; thus, the demagnetization process is limited to reducing the residual field to an acceptable level. The basis for all demagnetization methods is the subjecting of the magnetized article to the influence of a continuously reversing magnetic field that gradually reduces in strength causing a corresponding reversal and reduction of the field in the article. Although some residual magnetization will remain, the method quickly reduces the field to insignificant proportions. Figure 21 shows graphically how the method works. On the right the graph represents the reversing and reducing magnetic field in the article. On the left are the hysteresis curves corresponding to this action.

8.6.1 Demagnetization (general). The most convenient method of demagnetization uses a specially built demagnetization coil (see figures 14 and 22). When such a coil is energized by passing the current through its windings, it induces a magnetic field in the article placed in the coil. Since current direction reverses itself, the polarity of the induced magnetic field also reverses with each reversal of the current. As the article is withdrawn from the coil, the magnetic field becomes weaker the further the article is withdrawn from the coil. Demagnetization is accomplished only if the article is removed from the influence of the demagnetizing coil while the current is flowing; if the current is stopped while the article is still in the influence of the magnetic field the article may still retain some magnetism.

8.6.2 Demagnetization - effecting. Since the magnetic field produced by alternating current does not penetrate very deeply below the surface of the material, some articles may be difficult to demagnetize completely. This is particularly true with large, heavy, or unusually shaped articles. Direct current can be used to demagnetize if provisions for controlling the amount of current and for reversing the direction of the current are made. Direct current demagnetization is usually more complete and effective than alternating current demagnetization. Some magnetic particle testing equipment is provided with facilities for dc demagnetization. Without such equipment, dc demagnetization is a slow operation. Demagnetization is preferably done on individual articles rather than on groups of articles. To demagnetize with direct current, the article is placed in a coil connected to a source of direct current. The current is adjusted to a value at least as great (but usually greater) than that initially used to magnetize the article. A magnetizing shot is given at this initial value. The direction of the current is then reversed, the current value reduced, and a magnetizing shot is given at the new value. This process of reversing and reducing the current is continued until the lowest value is reached.

8.6.3 Demagnetization-geometrical considerations. For best results in demagnetization, the diameter of the demagnetization coil is just large enough to accommodate the article. If demagnetization of a small article is performed in a large coil, the article is placed close to the inside wall or corner of the coil, since the demagnetization force is strongest in that area.

8.6.4 Demagnetization-practical considerations. For practical purposes, it is always correct to utilize a field indicator after performing demagnetization to determine that residual field strength has been reduced to a desired level. The field indicator is a small, pocket-sized device that measures the strength of a field against a set of small, enclosed, permanent magnets which restricts the needle movement on a relative scale. Whether to demagnetize an article or not depends on a number of factors.

8.6.5 Demagnetization - criteria for use. Demagnetization is usually required if:

1. A strong residual field interferes with subsequent operations, such as welding or machining. Strong fields can "flow" the weld metal as it is deposited, or magnetic chips may cling to the cutting tool and interfere with machining.

2. The article is a moving part of an assembly and a deposit of accumulated magnetized particles might cause wear.
3. Leakage fields interfere with nearby instruments that work on magnetic principles; for example, compasses or indicators of various types.

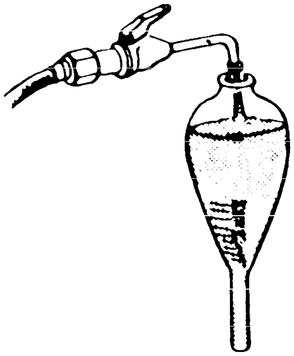
4. Residual fields interfere with proper cleaning of the article.

5. The article is to be magnetized at a lower magnetizing force in a different direction than the original or previous test.

6. Specified by procedural standards.

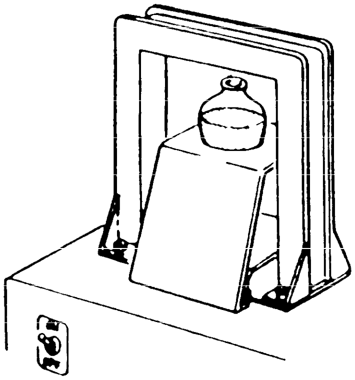
1 AGITATE THE SUSPENSION THOROUGHLY TO ASSURE PARTICLE DISTRIBUTION

2 FILL 100cc (100 ML) SAMPLE FROM THE DELIVERY HOSE INTO A 100cc (100 ML) GRADUATED CENTRIFUGE TUBE OR GRADUATE.



3. PLACE CENTRIFUGE IN STAND

4 DEMAGNETIZE, IF NECESSARY (IF CLUMPING OCCURS).



5 ALLOW TO SETTLE FOR 30 MINUTES.

6 TAKE READING AND RECORD IN THE LOG.

7 ADJUST BATH EITHER BY ADDING PARTICLES OR LIQUID AS NECESSARY.

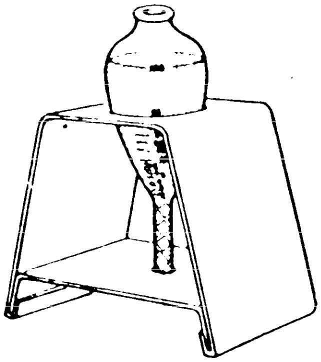


FIGURE 20. Settling test procedure.

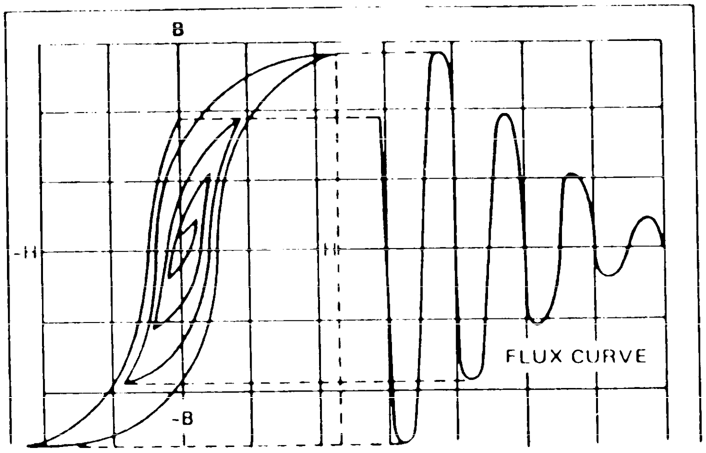


FIGURE 21. Demagnetization flux-curve projected from hysteresis curve.

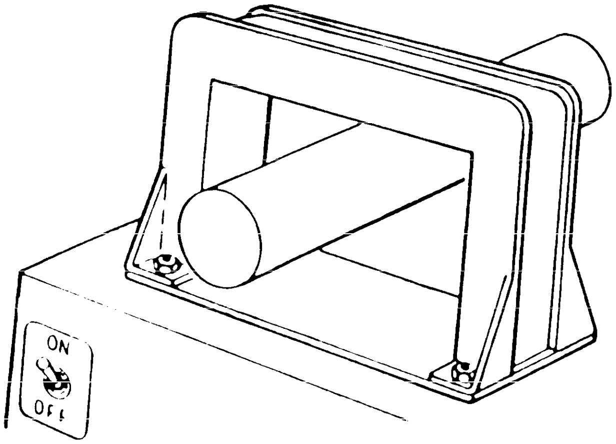


FIGURE 22. Demagnetization coil.

Demagnetization is usually not required or necessary:

1. On articles of soft steel or iron where retentivity is low.
2. If, after the magnetic particle test, the article is to be heat-treated.
3. On large castings, weldments, or vessels where residual fields will have no material effect.
4. If the article is to be magnetized again in another direction with the same or a greater magnetic force.
5. If the article is likely to become remagnetized during handling by being placed on a magnetic chuck, or lifted with an electromagnetic lifting fixture.

8.6.6 Cleaning after demagnetization. Magnetic particles should be completely removed from the specimen after test and demagnetization. Cleaning is accomplished by use of air, solvents, washes, and wiping equipment suitable to the size and complexity of the task. After cleaning, the article is returned to its original state by the removal of all plugs used to seal holes and cavities during the testing process.

*9. MAGNETIC FIELD INDICATION AND SYSTEM VERIFICATION

* 9.1 General. Use of discontinuity standards can be established for magnetic particle inspection as well as for the other nondestructive inspection methods. Quantitative generic standards (such as the IQI's used in radiology) are presently unavailable, although numerous efforts are being made to develop them. An advantage of magnetic particle method is the appearance of the indications over the discontinuities, and the interpretation of their significance by experienced inspectors. For simple test pieces, the adequacy of the magnetic field can be judged by experienced operators, who can determine when a weak field misses indications and when too strong a field masks a significant small discontinuity. As test objects have become more complex and as the types of defects have become more critical, true generic standards will be required to supplement the replicative discontinuity standards and the magnetic field indicators. Magnetic field strength determination (outside the test piece) as well as system verification are presently achievable as described below.

* 9.2 Discontinuity standards and magnetic field indicators. Standards are used to verify that the system is operating satisfactorily and that the applied magnetic field is appropriate for giving indications of discontinuities/defects that the test was designed for. Two types of these "standards" are described below: (1) Discontinuity standards made from test parts identical to or close to those being inspected and (2) System verification test parts for magnetic field indication or external magnetic field measuring instruments.

* 9.2.1 Discontinuity "standards". Discontinuity standards are used to demonstrate that the performance of a magnetic particle testing system is appropriate and sufficient for intended use. Among other purposes, these standards can be used to ensure that the system achieves appropriate field strength and direction to obtain accurate indications. As described in MIL-STD-1949 (or ASTM E1444), the ideal test parts for these goals are production parts that contain defects of the type, location, and size specified in the acceptance requirements.

If actual production parts with these defects are not available or are impractical for use, fabricated test parts with appropriate artificial defects should be used. Artificial defects on the parts may be put in to simulate anticipated discontinuities in similar actual parts or they may be used as magnetic field indicators with a magnetic particle inspection system in which repetitive testing occurs.

* 9.2.2 System verification standards/magnetic field indicators. Two types of indicators are useful for system verification. The first type includes magnetic specimens or pieces with artifically removed material that simulate possible defects in various types of test parts. Thus, during magnetic particle inspection, magnetic flux is shared (as completely as possible) between the object being inspected and this artifical discontinuity specimen. Two common examples of this are the pie gauge and shims. The second type of magnetic field indicators useful for system verification are those that read the magnetic field directly and electronically. These include Hall effect meters and eddy current devices (5). Eddy current instruments have greater

flexibility, but also much poorer repeatability, and thus are generally not useful.

* 9.2.3 Magnetic field determination from formulas. An alternative method for determining the applied current needed to obtain the magnetic field required for producing satisfactory indications is by the use of formulas such as those given in the paragraphs following 6.3.7 of ASTM E1444. Better values for the required fields in specific instances can be achieved from variations of the formulas that can be gotten through the use of known artificial standards and the correlation of the observed indications with the applied current values. Whenever formulas are used, current levels may be adjusted to values verified to be in conformance with the magnetic field strength that has been determined as needed (30 to 60 gauss is often indicated).

10. APPLICATIONS

10.1 General. Magnetic particle testing can be applied to finished articles, billets, hot-rolled bars, castings, and forgings of all ferromagnetic or magnetizable materials. It can also be used to check that processing operations such as heat treat, machining, and grinding did not uncover or cause discontinuities in these materials. Since a large amount of structural parts today are made of magnetizable materials, magnetic particle testing is one of the most widely applied nondestructive test methods.

10.2 Comparison of magnetic particle testing with other NDT methods. For ferromagnetic materials, magnetic particle testing is normally better than liquid penetrant testing for two important reasons: the magnetic particle testing can find subsurface flaws that liquid penetrant testing cannot find and, for most cases, the contamination in surface flaws does not have to be removed. Also, the magnetic particle testing can be quicker, since the dwell times required for liquid penetrant are not needed.

10.3 Non-applicability of magnetic particle method. There are conditions when the application of magnetic particle testing is inappropriate. There are situations where special demagnetization problems may prevent the use of this method. The presence of residual magnetic forces may interfere with subsequent operations or use of the part. Normally, however, magnetic particle testing can be applied throughout all phases of the manufacturing cycle and service life of production parts that are made from ferromagnetic materials. The fluorescent dyes used on the magnetic particles are much less brilliant than the fluorescent pigments used in liquid penetrants.

10.4 Problems in application of magnetic particle method. The biggest problem with magnetic particle testing is human error. Visual inspection is the means for segregating cracks from scratches. Magnetic particle testing can become impractical when the signatures of cracks are identical to the signatures of scratches.

10.5 Use of residual magnetism. In the residual magnetization method, the particles are applied to the test object just as or immediately after the magnetic field has been turned off. Recalling the hysteresis loop, a small to moderate field remains. Specific requirements call for this practice. It is also sometimes useful to help in interpretation when used in conjunction with the usual continuous method. As mentioned in MIL-STD-1949/ASTM E1444, it is especially useful to detect certain fatigue cracks. The usefulness is also degree directly related to the degree of retentivity of inspected parts. It is sometimes necessary to use the residual method for surfaces of some parts with complex shapes or the inner part of long tubes, where it is difficult to use the continuous method. When a central conductor is used, inspection can take place after the removal of the central conductor for discontinuities in cavities inside the test piece. Some ingenuity in particle application may be required in these instances. The only useful general approach to assure detection of discontinuities/defects is to use test parts that have the same material, processing steps, and similar geometry to the actual parts being inspected. As indicated in the ASNT Nondestructive Testing Handbook on Magnetic Particle Testing (5) and in T.O. 33B-1-1(10), the residual method is reliable for the detection of some surface discontinuities only.

10.6 Coatings. Magnetic particle inspection can be performed with some thin conductive coatings on the ferromagnetic substrate of the piece being inspected. Limits on thickness of various permissible coatings are given in MIL-STD-1949 (ASTM E1444) and the ASNT Handbook on Magnetic Particle Testing. Also, limits are given in T.O. 33B-1-1. The least stringent requirements, under special conditions,allow coating thickness of 0.125 mm (0.005 in).

10.7 Use of reference photographs. Reference photgraphs are sometimes used to show indications for purposes of comparison with magnetic particle indications observed in actual castings. It is critical that comparable ferrous materials are analyzed. Sufficient correlation of test pieces being inspected and the pieces from which the photographs were generated is essential to provide useful results for the indications. The color, size, and orientation must all be considered. Distance scales placed on the top or bottom or both sides of each photographed image should be used to establish the true perspective exhibited by the photograph. Reference photographs should show both acceptable and non-acceptable conditions. In addition, reference photographs showing actual limits - indications this large or smaller are acceptable, or indications this small or larger are rejectable - are of value. ASTM E125, "Reference Photographs for Magnetic Particle Indications on Ferrous Castings," describes old quality reference photographs that are commercially available for ferrous castings. These are of limited value. MIL-STD-1907 and MIL-STD-1035 for acceptance criteria may also be used.

11. SPECIFIC GUIDELINES

* 11.1 General. The guidelines for specific individuals and areas must be combined with the guidelines given in HDBK-728/1 to be complete. HDBK-728/1 includes general guidelines for all NDT methods.

11.2 Guidelines for designers. Designers are not always aware of the magnetic properties of their materials. Errors are often made by requiring magnetic particle testing of nonmagnetic materials (such as austenitic stainless steels) or by overlooking the use of magnetic particle testing on materials that are magnetic. Magnetic materials include most of the iron, nickel, and cobalt alloys. Some materials are magnetic only after aging (17-4 PH, 17-7 PH, and 15-4 PH stainless steels). All magnetic materials lose their magnetic properties when their temperature is at or above the curie point. For many materials, this is approximately 760°C (1400°F). Materials that are not magnetic include aluminum, magnesium, copper, titanium, and most of their alloys.

* 11.3 Guidelines for production engineers. Magnetic particle testing is extensively used by production engineers when components are manufactured from ferromagnetic materials. The fact that magnetic particle testing can also be used to inspect most manufacturing equipment is often overlooked. This inservice testing, checking for developing cracks, etc., can save much time and expense by preventing delays and down-times due to unexpected failures of the manufacturing equipment itself.

* 11.4 Guidelines for quality assurance. Magnetic particle testing, as with most NDT methods, is highly dependent upon the NDT technician for successful operations. Training and proper attitudes are a must, and constant attention should be given to all areas that affect these important parameters. Standards, although not as important in magnetic particle testing as for many of the other NDT methods, are still necessary, and should be a part of any formal program.

* 11.5 Guidelines for the NDT engineer. There is great flexibility in magnetic particle testing. New uses and methods are continuously coming forth. Magnetic paints, magnetic rubber, and magnetic printing methods are examples of specialized approaches. Positive or permanent recordings of indications are possible with lacquer or plastic-film sprays. There is a wide range of magnetic sources that produces a variety of shapes and magnitudes of magnetic fields. Magnetic particles can vary in their shape, size, permeability, color, retentivity, and mobility. There is always room for experimenting and perfecting new methods and procedures. As an engineer in magnetic particle testing, there is no room for complacency. New methods or approaches should be continuously considered. Magnetic particle testing has great merit when used during the start-up of production. Magnetic particle testing rapidly reveals the locations where flaws occur. This information permits quick modifications in production to reduce the occurrence of flaws.

* 11.6 Guidelines for the NDT technician. In magnetic particle testing, attention to details, as in all NDT methods, is vital. Magnetic particle testing equipment is subject to breakdowns, magnetic particles can become

contaminated or "diluted," and "permanent" magnets are not always permanent. Therefore, if differences in the tests are observed or suspected, they should be noted and discussed with the NDT engineer. A magnetic particle inspector should be sensitive to the degree of magnetic saturation that is being applied. An inspector should often check this magnetization. Too much magnetization or full saturation causes false indications to appear. These false indications can usually be identified by their shape and location. They usually shift locations as the probes are moved and do not remain at fixed points on the part. Too little magnetization can result in loss of valid indications. An inspector, that does not have a gauss meter, can change the distances between the probes and/or the amount of current being used to check these saturation limits. The inspector should vary the probe spacing and/or current as often as necessary to remain within an acceptable range. If the material being tested has high retentivity, then the inspector must exercise some care if the same point on the part is to be used to explore for the saturation limits. A complete demagnetization between each check is ideal. If direct current is being used, a change in current direction (or exchanging the positions of the probes) between each test can help reduce the retentivity effect. In no case should a check at a lower current follow a higher current check without appropriate demagnetization.

* 11.7 Written procedure. Magnetic particle inspection should be undertaken with a written procedure that is pertinent to the group of parts or elements of structures that are being tested. A sketch is frequently advisable to clarify the location of potential critical areas and the specific magnetic particle method and field distribution, as well as sensitivity for demonstrating discontinuities. Relationship of test to acceptance criteria and rejectable discontinuities should be included, with limits on parameters to be used and quantitative validity of results. Written procedures should be approved by an individual with knowledge and experience in magnetic particle inspection. Reference to ASTM E709 and MIL-STD-1949 (ASTM E1444) should be made when written procedures are being written and approved.

12. SAFETY

12.1 General. Where electrical currents are used to establish magnetic fields and to demagnetize parts, standard safety practices relating to electrical equipment must be observed. This includes the care and handling of electrical cords, observing proper connections and grounding of equipment, and the use of fuses and/or circuit breakers. The magnetic circuit itself is usually a low voltage, high current circuit. Therefore, the greatest danger is from heat, high temperatures, or arcing generated at the points of contact of the circuit.

* 12.2 Chemical. The particles used in magnetic particle inspection are usually highly magnetic oxides with a bonded dye material coating. They are relatively inert however, when used in the dry powder method some respiratory protection (face mask or filter) is advisable. This is especially important when performing inspection of vetical or overhead surfaces.

The wet method uses either an oil base vehicle or a conditioned water to suspend the particles. The oil base is a petroleum product while the conditioned water contains a wetting agent. Both materials are excellent solvents and if in prolonged contact with skin will remove the natural oils from the skin. Protective clothing such as gloves, aprons and face shields are recommended. If contact does occur, the solutions should be removed as soon as possible by washing with soap and water. The natural skin oils should be replaced using a lanolin or equivalent skin cream.

The manufacturer or supplier is obligated to provide a Materials Safety Data Sheet (MSDS) detailing the hazards of the materials. The recommendations in the MSDS should be followed.

* 12.3 Black light or ultraviolet. While the wavelength of black lights does not cause erythemal action, there is evidence indicating that UV-A radiation in excess of 1,000 $\mu W/cm^2$ can be hazardous if allowed to fall upon the eyes or skin without limit. The use of suitable gloves, protective ultraviolet absorbing eyewear and opaque or closely woven clothing to cover potentially exposed dermal areas are recommended to personnel operating in areas where the black light intensity exceeds 1,000 $\mu W/cm^2$.

The typical 100 watt black light bulb has a high operating temperature. They must not be operated if any flammable vapors are present. They also heat the surfaces of the lamp housing and care must be exercised to prevent any exposed part of the body from contacting the surface of the lamp.

12.4 Magnetic equipment/mechanical effects. Loose magnetic specimens, or even loose magnetic coils, etc., can be a problem when strong magnetic forces exist. Pinched fingers or damage to parts can occur if loose parts are pulled together or moved out of position due to these magnetic forces.

* 12.5 Vehicle/bath use. Dry cleaning solvents may not be used for suspending particles in the wet particle technique because they have an inherently low flash point (below 100°C or 212°F). Proper safety precautions must be adhered to when they are used for cleaning. The use of light oils with higher flash points is recommended as a suspensoid for safety reasons. Precautions should be taken to prevent inhaling of dry particle materials. The use of suitable face masks is recommended.

13. NOTES

* 13.1 Subject term (key word) listing.

Magnetic particle testing
Nondestructive testing

* 13.2 Changes from previous issue. The margins of this handbook are marked with asterisks to indicate where changes (additions, modifications, corrections, deletions) from the previous issue were made. This was done as a convenience only and the Government assumes no liability whatsoever for any inaccuracies in these notations.

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2. NASA SP-5113, "Nondestructive Testing, A Survey," (U.S. Government Printing Office, Washington D.C.) 1973.

3. Metals Handbook, Vol. 11, "Nondestructive Inspection and Quality Control," (American Society for Metals, Metals Park, OH.) 1976 (8th Edition).

4. W.J. McGonnagle, "Nondestructive Testing," (McGraw-Hill Book Co, N.Y), 1961.

* 5. P. McIntire, "Nondestructive Testing Handbook, Magnetic Particle Testing", Second Edition, Volume 6 (ASNT, Columbus, OH), 1989.

* 6. Annual Book of ASTM Standards, Section 3, Volume 03.03, "Nondestructive Testing," (American Society for Testing and Materials, Philadelphia) 1992.

* 7. Hagemeier, D.J., "Quality Indicators for Magnetic Particle Inspection", Materials Evaluation, pp. 346-350, March 1991.

* 8. Swartzendruber, L., ASTM Proposed Draft for Shim Use in Magnetic Particle Examination, 1991.

* 9. Microswitch Company, "Hall Effect Transducers: How to Apply Them as Sensors," Freeport, IL, 1982.

* 10. Military T.O. 33B-1-1, Magnetic Particle Method, Revised 1993.

shielded exposure area the simplest, most effective safety consideration is

Custodians:
  Army - MR
  Navy - AS
  Air Force - 11

Review activities:
  Army - AR
  Navy - OS

Preparing activity:
Army - MR

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MIL-HDBK-728/6
16 December 1985

MILITARY HANDBOOK

ULTRASONIC TESTING

DEPARTMENT OF DEFENSE
UNITED STATES OF AMERICA

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6.0 SAFETY NOTICE

Ultrasonic testing involves electrical equipment. Standard laboratory safety procedures for the handling of electrical equipment should be employed in ultrasonic testing. In many facilities, where automated scanning devices exist, caution must be exercised with respect to moving machinery, rotating gears and/or drive belts. Additional safety comments are presented in Section 6.8.

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6.1 INTRODUCTION

Ultrasonic testing employs high-frequency mechanical waves to detect various material variables. These variables can be surface or internal variables, and their locations and/or geometries can be reasonably delineated.

Ultrasonic testing is unique in several areas. Ultrasonics and radiography provide deep, internal inspection capabilities. Normally ultrasonics provides the deepest penetration. (The penetration of X-rays in steel is measured in inches, ultrasonic beams can penetrate twenty feet or more.) Ultrasonics does not require an intrusion of a foreign substance into a material, such as high energy photons of an X-ray beam, but it consists of simple movements of the internal atoms already there. Therefore, ultrasonics can be considered to be the safest of all the inspection methods and is especially adaptable for medical use. Ultrasonic testing has very few restrictions on the kinds of materials it can inspect. The materials do not have to be magnetic (as they must be for magnetic particle testing), they do not have to be electrically conductive (as for eddy current testing), and they do not have to exhibit an adhesive affinity for a liquid (as required for liquid penetrant testing). They do not even have to be a solid. Any volumetrically elastic material can be inspected by this method.

Ultrasonic testing can involve a wide variety of variables. Material variables relating to flaws, voids, inclusions, bonding, thicknesses, and densities can almost always be effectively inspected by ultrasonics. Therefore, ultrasonics is one of the basic nondestructive test methods.

This chapter provides the fundamental principles and guides associated with ultrasonic testing. It includes the theory of operation, the type of equipment, the advantages and disadvantages of the method, various applications and standards, and guides for specific disciplines. The information contained in Chapter 1 should be included with this chapter for general guidelines to the employment of all NDT methods and for a more complete understanding of ultrasonic testing as it compares with other basic methods.

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6.2 BASIC PRINCIPLES

Ultrasonic testing requires the generation of high-frequency mechanical waves which are usually directed as beams to interact with various property variables of a material or specimen. The interactions of these mechanical waves result in the attenuation of the original waves and/or in returned reflections. The detection of these waves after interactions or reflections after these interactions produces information relatable to the variables. A study of the basic principles of ultrasonic testing must therefore include the means of generating high-frequency mechanical waves, the characteristics of these waves, how they can be directed, how they interact with material variables, how they are ultimately detected, the information they contain, and how the information is displayed.

6.2.1 MECHANICAL WAVES

All materials that hold a natural shape (or a constant density) do so because their atoms (or molecules) are held in mutual balance between attractive and repulsive forces. These forces are "short range" forces and only extend between atoms that are reasonably close together. In this state of balance, any relative displacement of an atom will cause these forces to change in such a way that the displaced atom will tend to return to its original position. At the same time, the displacement of any atom will cause a change in the force balance seen by all the nearby atoms. Although this change in the force balance is seen almost instantaneously by the surrounding atoms, due to their inertia a finite period of time is required for the surrounding atoms to fully respond to this unbalance. Eventually, however, the atoms experience their own displacement due to the displacement of the original atom. In this way, a disturbance at one point can progress to another point and can eventually progress throughout the material.

There are several kinds of disturbances that can be generated. For those disturbances that are small and are in what is called the elastic range, the disturbances are wave-like in nature. These waves have a velocity that is determined by the characteristics of the material (the magnitude of the interatomic force gradients and the inertia of their atoms, etc.). Besides this velocity, frequency and wavelength can be associated with these waves. Also associated with these waves is amplitude, either as a relative displacement measurement (the distance the atoms are moved from their balance points), or as a pressure (relating to the unbalanced forces being generated between the displaced atoms), or as an energy function (the energy associated with the atom's potential energy due to their displacements or the kinetic energy due to their motions, each of these having equal maximum magnitudes). It is these elastic disturbances that are used in ultrasonic testing. Equations 1 through 8 show some of the basic relationships between velocity, frequency, and wavelength, and between time, position, displacements, pressures, and energies.

$$V = f\lambda \tag{1}$$

where

V = velocity of a wave (cm/sec),

f = frequency of the wave (Hertz, or cycles/sec),

λ = wavelength (cm).

and

$$A(t) = A_o \sin(\omega t + K_1) \tag{2}$$

where

$A(t)$ = amplitude of displacement at time, t,

A_o = maximum amplitude, a constant,

ω = radians per unit time (in terms of the frequency, it equals: $2\pi f$),

K_1 = phase constant that allows for differences in times between the nearest time of zero amplitude and the origin of the time scale.

and

$$A(X) = A_o \sin \frac{2\pi X}{\lambda} + K_2 \tag{3}$$

where

$A(X)$ = amplitude of displacement at position, X,

X = distance along the line of wave travel from a fixed origin,

K_2 = phase constant that allows for differences in positions between the nearest position of zero amplitude and the origin of the position scale.

Equations 2 and 3 can be combined to give:

$$A(X,t) = A_o \sin \frac{2\pi X}{\lambda} - \omega t + K_3 \tag{4}$$

where

$A(X,t)$ = amplitude for any given position, X, and given time, t.

K_3 = phase constant, combined function of K_1 and K_2 above.

The difference in signs between the X and t functions in Equation 4 depends on the *direction of the waves*. The sign shown is for the case where the wave is moving in the positive X direction.

In Equations 2, 3, and 4, λ or the f in ω can at any time be expressed in equivalent variables obtained from Equation 1. Also A, the displacement amplitude in Equations 2, 3 and 4, can be replaced with pressure, P, to give:

$$P(t) = P_o \sin (\omega t + K_1) \tag{5}$$

$$P(X) = P_o \sin \frac{2\pi X}{\lambda} + K_2 \tag{6}$$

$$P(X,t) = P_o \sin \frac{2\pi X}{\lambda} - \omega t + K_3 \tag{7}$$

where P_o is the maximum pressure, a constant, and P(t), P(X), and P(X,t) are pressures as a function of time, t, position, X, or combined position and time, respectively.

It should always be clear that there is a difference between the motion of the atoms that make up the waves and the velocity of the waves. Each atom essentially returns to its place of origin. It is only the energy transferred between atoms that "moves" through the material and determines the wave velocity.

The energy of the waves, normally expressed as intensity, I, or energy per unit time per unit area, can be related to either the maximum displacement amplitude, A_o, or the maximum pressure, P_o:

$$I = \frac{1}{2} \rho V (2\pi f)^2 A_o^2 = \frac{1}{2} \frac{P_o^2}{\rho V} \tag{8}$$

where I is the effective intensity of a beam expressed as energy per unit time per unit area and ρ is the density of the material, mass per unit volume.

The function, ρV, the density times the wave velocity, will be a common function appearing throughout this section and is called the characteristic impedance or the acoustic impedance of the material.

In the elastic range, four main kinds of disturbances or waves can exist: 1) compression, or longitudinal, waves, 2) shear, or transverse, waves, 3) surface, or Rayleigh, waves, and 4) plate, or Lamb, waves. (Other disturbances, e.g., shock waves, bar waves, Love waves, and torsional waves will not be discussed.)

a. Compression or Longitudinal Waves. When the relative motions and/or displacements between the atoms are in the same direction (upon the same line) as the wave propagation, the wave is called a compression, or longitudinal, wave. The compression wave is the fastest of all the elastic propagations that can be transmitted in a material. All forms of materials can support this kind, or mode, of wave, and it is the kind of wave that is normally generated by transducers. Figure 6.2(1) illustrates a compression wave.

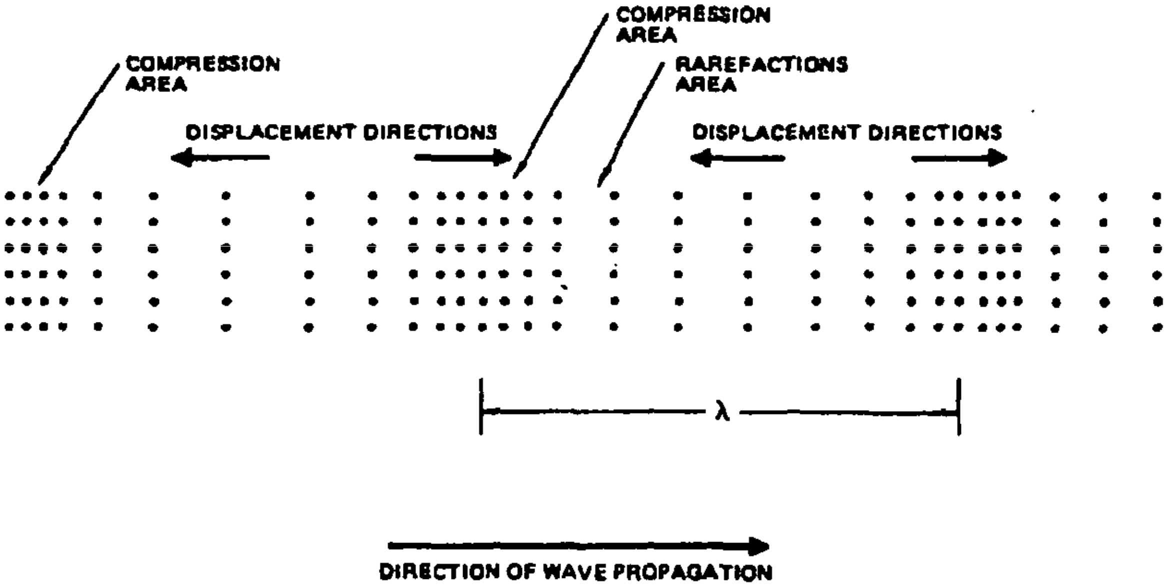


Figure 6.2(1). Compression or longitudinal wave motions.

The velocity of a longitudinal wave, V_L is:

$$V_L = \sqrt{\frac{Y(1-\sigma)}{\rho(1+\sigma)(1-2\sigma)}} = \sqrt{\frac{K + \frac{4}{3}\mu}{\rho}} \qquad (9)$$

where

Y = Young's modulus, force per unit area;

ρ = density, mass per unit volume;

σ = Poisson's ratio, dimensionless;

μ = shear modulus, force per unit area;

K = Bulk modulus, force per unit area.

This velocity equation assumes that the material is uniform and isotropic and that dimensions are large enough that surface effects are small. The longitudinal wave velocities for different materials are shown in Table 6.2(1).

Table 6.2(1). Acoustic properties of materials.

MATERIAL	DENSITY	LONGITUDINAL WAVES		SHEAR (TRANSVERSE) WAVES		SURFACE (RAYLEIGH) WAVES	
	ρ-GM/CM^3	VELOCITY V_L = CM/μSEC	IMPEDANCE Z_L = GMX 10^3/CM^2 - SEC	VELOCITY V_T = CM/μSEC	IMPEDANCE Z_T = GMX 10^3/CM^2 - SEC	VELOCITY V_R = CM/μSEC	IMPEDANCE Z_R = GMX10^3/CM^2 -SEC
AIR	0.001	0.033	0.33	-	-	-	-
ALUMINUM 250	2.71	0.635	1,720	0.310	840	0.290	788
ALUMINUM 17ST	2.80	0.625	1,750	0.310	868	0.279	780
BARIUM TITANATE	0.56	0.550	310	-	-	-	-
BERYLLIUM	1.82	1.280	2,330	0.871	1,600	0.787	1,420
BRASS (NAVAL)	8.1	0.443	3,610	0.212	1,720	0.195	1,580
BRONZE (P-5%)	8.86	0.353	3,120	0.223	1,980	0.201	1,780
CAST IRON	7.7	0.450	2,960	0.240	1,850	-	-
COPPER	8.9	0.466	4,180	0.228	2,010	0.193	1,720
CORK	0.24	0.051	12	-	-	-	-
GLASS, PLATE	2.51	0.577	1,450	0.343	865	0.314	785
GLASS, PYREX	2.23	0.557	1,240	0.344	765	0.313	698
GLYCERINE	1.261	0.192	242	-	-	-	-
GOLD	19.3	0.324	6,260	0.120	2,320	-	-
ICE	1.00	0.398	400	0.199	199	-	-
LEAD, PURE	11.4	0.216	2,460	0.070	788	0.063	717
MAGNESIUM, AM 35	1.74	0.579	1,010	0.310	539	0.287	499
MOLYBDENUM	10.09	0.629	6,350	0.335	3,650	0.311	339
NICKEL	8.8	0.563	4,950	0.296	2,810	0.264	2,320
OIL, TRANSFORMER	0.92	0.138	127	-	-	-	-
PLASTIC (ACRYLIC RESIN-PLEXIGLASS)	1.18	0.267	320	0.112	132	-	-
POLYETHYLENE	-	0.153	-	-	-	-	-
QUARTZ, FUSED	2.20	0.593	1,300	0.375	825	0.339	745
SILVER	10.5	0.360	3,800	0.159	1,670	-	-
STEEL	7.8	0.585	4,560	0.323	2,530	0.279	2,180
STAINLESS 302	8.03	0.566	4,550	0.312	2,500	0.312	2,500
STAINLESS 410	7.67	0.739	5,870	0.299	2,290	0.216	2,290
TIN	7.3	0.332	2,420	0.167	1,235	-	-
TITANIUM (TI 150A)	4.54	0.610	2,770	0.312	1,420	0.279	1,420
TUNGSTEN	19.25	0.518	9,980	0.287	5,520	0.265	5,100
WATER	1.00	0.149	149	-	-	-	-
ZINC	7.1	0.417	2,960	0.241	1,710	-	-

b. Shear, or Transverse, Waves. When the relative motions and/or displacements between the atoms are in directions perpendicular to the wave propagation, the wave is called a shear, or transverse, wave. Only solids can normally support this kind, or mode, of wave. For any one material, shear waves travel at a slower velocity (approximately half) than the longitudinal waves, with, for equal frequencies, shorter wavelengths. The nature of this motion is illustrated in Figure 6.2(2).

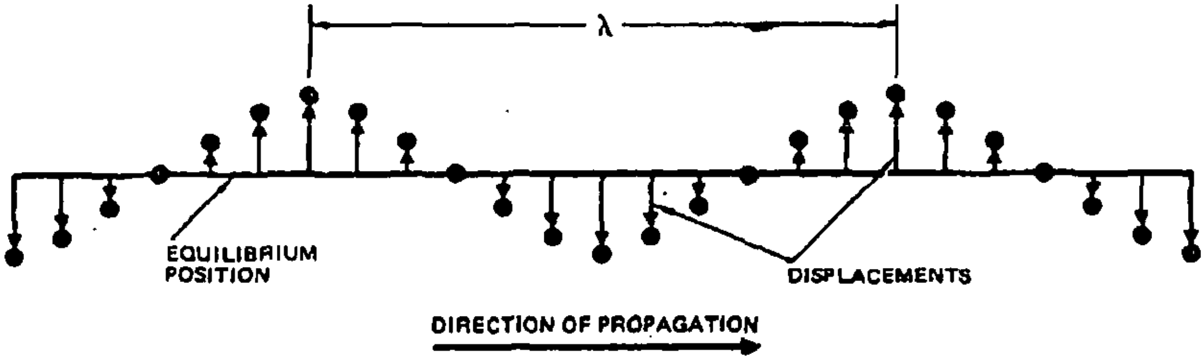


Figure 6.2(2). Shear or transverse wave motions.

The velocity of a shear wave, V_S, is:

$$V_S = \sqrt{\frac{\mu}{\rho}} = \sqrt{\frac{Y}{\rho} \frac{1}{2(1+\sigma)}} \qquad (10)$$

(See Equation 9 for definitions of variables.) Again, this equation assumes that the material is uniform and isotropic and has large enough dimensions that surface effects are small. See Table 6.2(1) for the shear wave velocities of various materials.

c. Surface or Rayleigh Waves. Surface or Rayleigh waves are a combination of shear and compression waves where the atom motion is elliptical. The larger amplitudes or the ellipse is perpendicular to the surface of the part. The wave motion is confined to the surface (or free boundary) of a solid of extensive thickness. For any one material, surface waves propagate with a velocity slightly less than for true shear waves (approximately $0.9V_S$). Their energy falls off sharply with distance into the material so that the majority of the energy is confined to within one wavelength of the surface. When a material is in air, these waves usually travel with less attenuation than longitudinal or shear waves in the same material, but if the material is in a liquid, or other non-negligible medium, the surface waves will quickly disappear. These waves will reflect at sharp edges, and so are effective for locating surface cracks, but they will propagate around smooth rounded edges and can be used to inspect parts that have complex contours if the contour radii are large compared to the wavelengths. Table 6.2(1) lists the surface wave velocities for different materials.

d. Plate, or Lamb, Waves. When a material is very thin, only a few wavelengths in thickness, an infinite number of various waves can be established that are a combination of both surface and bulk motions. These complex interactions are called plate, or Lamb, waves. Lamb waves can consist of one set of waves that is symmetrical about the center line of the plate or another set that is asymmetrical. Each of these sets has an infinite number of different orders or modes, each with different wavelengths and velocities. The frequency of the wave and the plate thickness affect their velocities along with the other normal material variables. In general, the wave velocities can range from zero to almost the longitudinal propagation rate, but any one mode will normally approach the transverse velocity (or more correctly, the surface wave velocity) as the frequency or the relative thickness of the plate increases. (In the mathematical descriptions of these waves in certain other texts, the terms "phase" velocities and "group" velocities are sometimes used. The "group" velocities are the velocities at which the energy is actually transferred and should normally be used as the velocity of the waves.)

6.2.2 GENERATION OF WAVES

Today, almost all high frequency ultrasonic beams are generated by transducers that transform electrical energy into mechanical wave energy by the piezoelectric effect. Materials such as quartz, lithium sulfate, and polarized ceramics will slightly change their dimensions when an electric charge is applied across opposing faces of the material. The reverse also occurs. When these materials are forced to change their dimensions, the change in dimensions produces a charge of electricity. This effect allows the same transducer to be used as a transmitter to convert electrical signals into a mechanical wave, and then to act as a receiver to detect the return mechanical wave signals and reconvert them back into electrical signals.

Different types of piezoelectric materials have different properties, and the materials vary in their abilities to act as transmitters or as receivers. The materials differ in their chemical, electrical and thermal stabilities, and in their wear-resistance and expected life-time in use. Table 6.2(2) lists some piezoelectric materials and their main characteristics.

Table 6.2(2). Piezoelectric material characteristics.

MATERIALS	CHARACTERISTICS
QUARTZ.	QUARTZ HAS EXCELLENT CHEMICAL, ELECTRICAL, AND THERMAL STABILITY. IT IS INSOLUBLE IN MOST LIQUIDS AND IS VERY HARD AND WEAR-RESISTANT. QUARTZ ALSO HAS GOOD UNIFORMITY AND RESISTS AGING. IT IS THE LEAST EFFICIENT GENERATOR OF ACOUSTIC ENERGY OF THE COMMONLY USED MATERIALS AND REQUIRES HIGH VOLTAGE TO DRIVE IT AT LOW FREQUENCIES.
CERAMIC. (E.G. BARIUM TITANATE, LEAD METANIOBATE, OR LEAD ZIRCONATE TITANATE.	POLARIZED CERAMIC TRANSDUCERS ARE THE MOST EFFICIENT GENERATORS OF ULTRASONIC ENERGY; THEY OPERATE WELL ON LOW VOLTAGE, ARE USABLE UP TO ABOUT 300C. THEY ARE LIMITED BY RELATIVELY LOW MECHANICAL STRENGTH, AND HAVE A TENDENCY TO AGE.
LITHIUM SULFATE.	LITHIUM SULFATE TRANSDUCERS ARE THE MOST EFFICIENT RECEIVERS OF ULTRASONIC ENERGY AND ARE INTERMEDIATE AS A GENERATOR OF ULTRASONIC ENERGY. THEY DO NOT AGE. LITHIUM SULFATE IS VERY FRAGILE, SOLUBLE IN WATER, AND LIMITED TO USE AT TEMPERATURE BELOW 74C.

Transducers come in different sizes and configurations. Normally, a small transducer produces higher frequencies and sharper geometric resolutions, but they normally produce very little energy. A large transducer produces more energy with smaller ultrasonic beam angles (less beam spread), and therefore provides deeper penetrations. Transducers can be designed to produce beams at various angles that can be used to obtain shear waves. Transducers can be designed to produce beams wider than they are deep (for a "paint brush" like inspection), or they can be made to focus the ultrasonic beam towards a focal point or line.

One of the most important variables of a transducer is its frequency spectrum. The transducer, depending upon its use, may need to have a very broad band (highly damped for critical depth resolutions), or a very narrow band (a ringing transducer that can produce a large amount of energy). The frequency must often be matched with the material, the expected attenuation losses, the expected type and size of flaws, and the geometry of the part. Therefore, the choice of a transducer is often critical in the success of any particular test. Vendor data should be obtained on the transducer to determine these variables and a selection of transducers should always be available to optimize each test to the specific conditions or requirements of the test.

6.2.3 BEAM PROPAGATION LIMITS

In ultrasonics, the inspection is almost always done with an ultrasonic beam. Beam physics are important in the generation and propagation of a beam. Since an ultrasonic beam is not anything concrete in itself, but is really a group action of a large number of atoms (or molecules), there are real limits in what a "beam" of ultrasonic energy can do.

First of all, a beam of ultrasonic energy does not and cannot have sharp boundaries. A distribution of energy normally exists across the width of a beam with the maximum energy near the center of the beam and with the energy decreasing as the "edges" are approached. Distribution of the ultrasonic beam energy can only be in ways that can be maintained by group actions of the atoms that make up the medium. When ultrasonic energy is produced by a transducer, the face of the transducer, in its motion, is not producing the exact same energy distribution that is necessary to sustain a steady beam.* It takes a finite amount of time, or distance, before the energy in a beam can become "adjusted" to an in-phase steady condition. The area wherein this out-of-phase is occurring is known as the near-field zone or area. Within the near-field zone, the ultrasonic beam is very unstable and inconsistant from point to point and normally inspections in this zone should be discouraged. The dimension of the near field can be approximated by Equation 11 using the diameter, D, of the face of the transducer and the ultrasonic wavelength, :

$$\text{Near-field dimension} \approx \frac{D^2}{4\lambda} \qquad (11)$$

*"That is, the face of the transducer does not vibrate back and forth like the head of a piston. Rather, the face of a transducer vibrates with stationary node points; adjacent segments vibrate 180 degrees out of phase to one another. This complex movement causes reinforcement and cancellations in the near field".

As can be seen from this equation, the near-field dimension can be reduced by increasing the wavelength (or lowering the frequency), or by decreasing the diameter of the transducer.

Even after beam stability is achieved, the natural result of the group actions of atoms produces a slow divergence of the beam. Equation 12 gives an approximate estimation of the beam spread:

$$\theta = \sin^{-1}\left(\frac{1.2\lambda}{D}\right) \qquad (12)$$

This angle, , represents half the apex angle of a cone within which the total energy of the primary beam is travelling. Figures 6.2(3) and (4) illustrate these relationships. The angle at which the energy of the beam has decreased to one-half of the maximum energy that exists at the center of the beam (the half-power angle) is:

$$\theta_{\frac{1}{2}} = \sin^{-1}\left(\frac{0.72\lambda}{D}\right) \qquad (13)$$

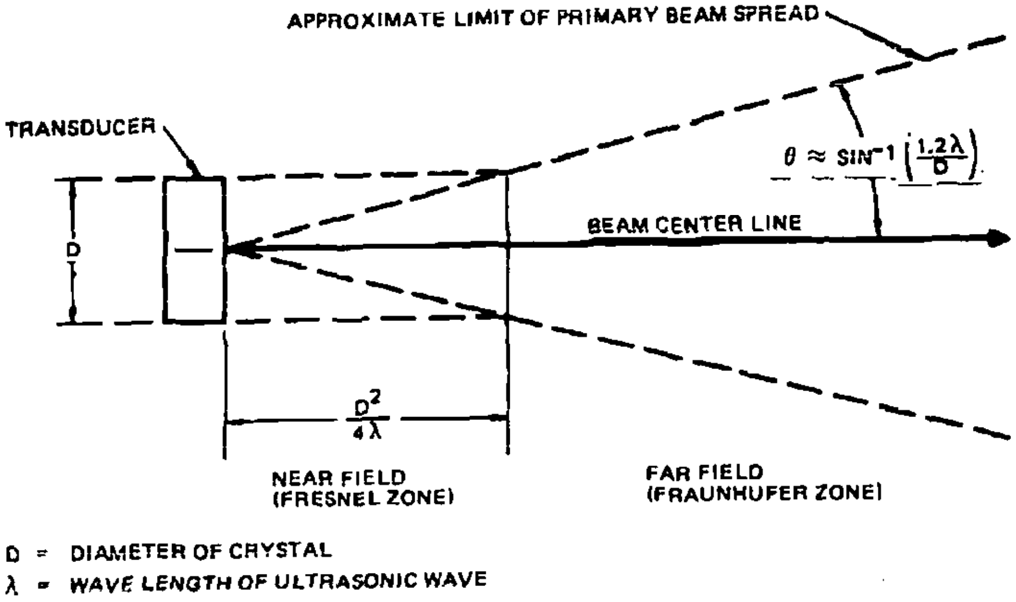
If the transducer's face is small compared to the ultrasonic wavelength, side lobes will be produced as beam stability is obtained. (These side lobes can be greatly affected by the mounting of the transducer crystal and the freedom of motion that exists at the edges of the crystal.)

Because waves are group actions of atoms, an ultrasonic beam cannot be focused to a sharp point. When a point focus of an ultrasonic beam is attempted, the beam approaches a point, but near the focus point it forms a "chimney" (a fixed-width path) from which it again spreads out beyond the focal point. This chimney effect often provides a reasonable path length over which inspection resolutions are fairly constant, but normally at no point can the expected geometric resolutions be much better than one wavelength.

In ultrasonics, a pulse of energy rather than a continuous wave is often desired. Again, because an ultrasonic wave pulse is dependent upon the group actions of atoms, there is a finite limit to the length of the pulse (the extent of space it must occupy in the direction of its propagation). This limitation again approaches approximately one wavelength. In addition to this geometric limit, a wave pulse becomes limited in its frequency representation as its pulse length decreases. This kind of relationship exists for all forms of waves and is not due to the limitations caused by group actions of atoms. In general, if we let X equal the "length" of a wave pulse, and $\Delta\lambda$ the range of wavelengths that have appreciable amplitude representations within this pulse, then:

$$(\Delta X)\ (\Delta\lambda) \geq \lambda_o^2 \qquad (14)$$

where λ_o represents the center, maximum, or primary wavelength.



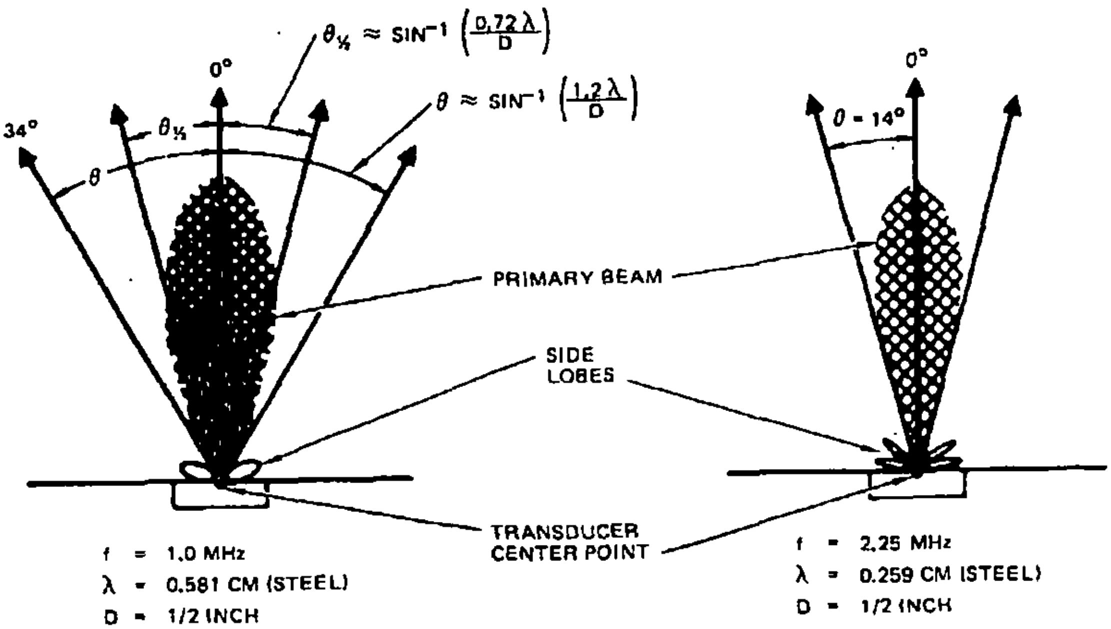
BEAM SPREAD ANGLES, θ, IN STEEL FOR DIFFERENT FREQUENCIES AND DIFFERENT SIZE TRANSDUCERS

FREQUENCY MHz	λ CM (STEEL)	TRANSDUCER DIAMETER (D) INCHES			
		3/8	1/2	3/4	1.0
1.0	0.581	48°10'	34°	21°52'	16°13'
2.25	0.259	19°23'	14°25'	9°33'	7°9'
5.0	0.116	8°34'	6°25'	4°16'	3°12'

Figure 6.2(3). Near-field dimensions and beam-spread angles.

When ΔX becomes small, $\Delta\lambda$ becomes large, and the wave pulse then becomes subjected to dispersions and differential attenuations because of the wide range of frequencies that are effectively present.

The importance of the length of the wave pulse cannot be overlooked. When inspecting a material in which depth information is important, the length of the wave pulse produces a "dead zone" which limits the depth resolutions that can be obtained. This dead zone (often referred to as "ringing") limits how close the transducer can inspect from its own face, and limits the inspection distance from all other interfaces that produce measurable return signals.



NOTE

IN THIS FIGURE, THE "DISTANCE" FROM A TRANSDUCER CENTER POINT TO A POINT ON A PROFILE REPRESENTS INTENSITY AND NOT DISTANCES TO POINTS IN THE ULTRASONIC FIELD. THIS TYPE OF INTENSITY PROFILE EXISTS IN THE FAR FIELD ONLY, AND REPRESENTS THE PROFILE MEASURED AT A FIXED DISTANCE IN THIS FIELD. THE PROFILE GIVES ONLY RELATIVE INTENSITIES, THE ACTUAL INTENSITIES WOULD VARY WITH BOTH THE ANGLE AND THE DISTANCE AT WHICH IT IS MEASURED. A DRAWING OF CONTOUR INTENSITIES, AS THEY WOULD EXIST ON A DISTANCE PLOT, WOULD BE SIMILAR TO THIS FIGURE IN PLACES, BUT THEY DEFINITELY ARE NOT THE SAME.

Figure 6.2(4). Far-field intensity profile.

The dead zone is not the same as the near-field zone, although both affect the inspectability close to the transducer. On an A-scan (see paragraph 6.2.5), the dead zone would be indicated by the width of the pulses shown on the scan.

6.2.4 INTERACTIONS OF ULTRASONIC WAVES WITH MATERIAL VARIABLES

Ultrasonic wave interactions with materials include transmissions, reflections, refractions, diffractions, mode conversions, scattering and absorption. There also exists standing waves and constructive and destructive interferences, usually associated with reflection and diffractions. Reflections, refractions, and mode conversions can occur at an interface between two different materials. These interactions depend upon the difference in the acoustic impedances of the two materials (impedance mismatch) and on the angle of incidence of the ultrasonic beam.

Figure 6.2(5) shows a transducer sending a longitudinal wave into water. The water transmits the beam to the test piece, a block of steel. When the longitudinal (L) wave is incident to the surface of the test specimen in the normal (perpendicular) direction, 0° incidence, the beam is transmitted into the second medium as a longitudinal beam. No refraction and no mode conversions take place. Not all of the energy, however, enters into the steel. Some of the energy (most of it, in this particular case) is reflected.

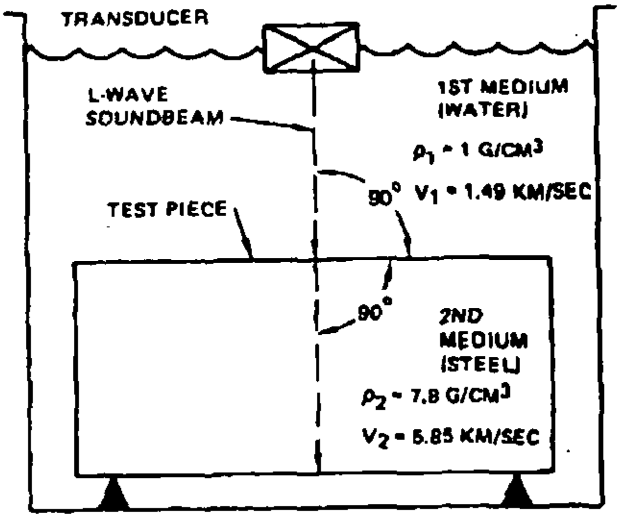


Figure 6.2(5). Normal incident beam.

The maximum pressure amplitude of the reflected wave, P_r, for 0° incidences, is:

$$P_r = P_o \left(\frac{\rho_2 V_2 - \rho_1 V_1}{\rho_2 V_2 + \rho_1 V_1} \right) \qquad (15)$$

where

P_o = Maximum incident pressure amplitude

ρ_1 = density of the first medium (incident side)

ρ_2 = density of the second medium

V_1 = Wave velocity of the first medium

V_2 = Wave velocity of the second medium

For steel, as shown in Figure 6.2(5), the amplitude of the reflected wave would be approximately 0.94 P_o. Note that the reflected wave is large when there is a large difference in the acoustic impedance and that the reflected wave would disappear (have zero pressure amplitude) if the two materials had identical acoustic impedances. (If the two materials were identical, it would be the same as if there were no interface, and therefore no reflections could be expected.) Also note that the sign of the pressure of the reflected wave is opposite to the incident pressure sign when the acoustic impedance of the first medium is greater than that of the second. The change in sign means that a positive pressure pulse would be reflected as a rarefaction (a negative pressure pulse), or a negative pressure pulse would reflect as a positive pressure pulse. The energy or intensity that is reflected, I_r, is:

$$I_r = I_o\left(\frac{\rho_2 V_2 - \rho_1 V_1}{\rho_2 V_2 + \rho_1 V_1}\right)^2 \tag{16}$$

where I_o represents the intensity of the incident beam.

The pressure and intensity of the transmitted wave, P_t and I_t, are:

$$P_t = P_o\left(\frac{2\rho_2 V_2}{\rho_2 V_2 + \rho_1 V_1}\right) \tag{17}$$

$$I_t = I_o\left(\frac{4\rho_2 V_2 \rho_1 V_1}{(\rho_2 V_2 + \rho_1 V_1)^2}\right) \tag{18}$$

These equations show that as long as a second medium exists, it will always transmit a pressure and it is always in the same phase or sign as the incident wave. These equations are the natural results of conservation of energy (using the pressure relationships of Equation 8 and setting $I_o = I_r + I_t$), the pressure being continuous across an interface, and that small pressures from two or more waves add linearly (setting $P_o + P_r = P_t$). These relationships, when solved simultaneously, produce Equations 15 through 18.

Equations 15 through 18 all assume semi-infinite mediums on each side of the boundary. When actual geometrics are small, with edges or back surfaces near *the point of incidence, these equations often break down. In some literature,* a "specific acoustic impedence" term is used to account for these differences. One of the important interactions affecting these relationships is standing waves or interferences that can be developed when thicknesses approach the dimensions of a small number of wavelengths and/or is less than one-half of the pulse length. Thicknesses that are exact multiples of half-wavelengths will experience an increase in transmission energies and a minimum in reflection energies. Thicknesses that are odd quarter-wavelengths will experience a decrease in transmission energies and an increase in the reflected energies. The reflected energy can often be made to approach zero, but the transmitted energy will always be finite. Attenuation losses, if present, will reduce these interference effects.

In ultrasonic testing, you cannot inspect a part unless beam energy is able to penetrate the part and then return to a receiver. It cannot do this without passing through several interfaces. Each time an interface is crossed, potentially a large percentage of the energy can be lost.

Using Equation 18 for water and steel, only 12% of the energy will enter the steel. If all of this energy inside the material could be reflected back (which of course is not likely), this energy must still return back through the steel-water interface, and the same loss factor will occur again. Only 1.4% (12% of 12%) of the energy can return to the transducer, even if there were no other losses. Table 6.2(3) lists some of the energy reflections expected at the interfaces of various materials.

Table 6.2(3). Percentage of energy reflected.

	SECOND MEDIUM												
ONE MEDIUM	ALUMINUM	STEEL	NICKEL	COPPER	BRASS	LEAD	MERCURY	GLASS	QUARTZ	POLY-STYRENE	BAKELITE	WATER	OIL
ALUMINUM	0	21	24	18	14	3	1	2	0.3	60	42	72	74
STEEL		0	0.2	0.3	1	9	16	31	27	77	76	88	89
NICKEL			0	0.8	2	12	19	34	29	79	75	89	90
COPPER				0	0.2	7	13	19	22	75	71	87	88
BRASS					0	5	10	23	16	73	68	86	87
LEAD						0	1	9	8	62	55	79	80
MERCURY							0	4	1	6	6	75	76
GLASS								0	0.8	40	32	65	67
QUARTZ									0	46	17	68	71
POLYSTYRENE										0	1	12	17
BAKELITE											0	18	23
WATER												0	0.6
OIL (TRANSFORMER)													0

SAME VALUES HERE AS FOR OPPOSITE POSITIONS ACROSS THE DIAGONAL

NOTE

FOR ENERGY, THE ORDER OF THE MEDIUMS ARE NOT IMPORTANT. THE SAME ENERGY IS REFLECTED WITH PROPAGATION GOING IN WATER TOWARDS STEEL OR IN STEEL TOWARDS WATER.

The final energy received can often be a thousandth of the initial energy. Knowledge of these energy losses, and how to control them, are therefore important. In order to get energy into a part, a couplant must normally be used. This is a grease or other liquid or paste-like material.

When use of a couplant is required between a transducer and a specimen, minimum loss of energy occurs when an impedance match is achieved. Theoretically, a maximum impedance match is obtained when:

$$Z_c = \sqrt{Z_1 Z_2} \tag{19}$$

where

Z_c = impedance of the couplant

Z_1 = impedance of first medium (transducer)

Z_2 = impedance of second medium (specimen)

As the incident angle is changed from the initial zero degrees incident to a value like 5 degrees, as shown in Figure 6.2(6), refraction and mode conversion occur. The original longitudinal beam is transmitted, in the second medium, as varying percentages of both longitudinal (L) and shear (S) wave beams. As shown, the refracted angle for the L-wave beam is four times the incident angle, and the S-wave beam angle is a little more than twice the incident angle. If the incident angle is increased further, the refraction angles of the L-wave and the S-wave increase. The energy in each beam also varies as the angle is changed.

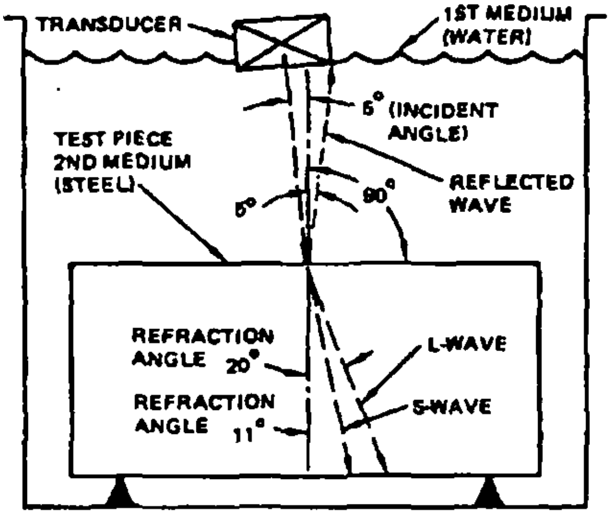


Figure 6.2(6). Five-degree incident beam.

The laws of reflection angles and refraction angles are all based on Snell's Law, that the ratios of the velocities to the sines of the angles are equal.

In equation form:

$$\frac{\sin\theta_i}{V_i} = \frac{\sin\theta_r}{V_r} = \frac{\sin\theta_t}{V_t} \qquad (20)$$

where

θ_i = incident angle
V_i = velocity of incident wave
θ_r = reflected beam angle
V_r = velocity of reflected wave
θ_t = transmitted beam angle
V_t = velocity of transmitted wave

Since the reflected beam is always in the same medium as the incident beam, then their velocities are equal (unless a mode conversion has occurred). If their velocities are equal, then the angle of reflection will be equal to the angle of incident. The transmitted wave, however, is in a different medium, and thus the velocities will normally be different (whether mode conversions occur or not) and thus a change in angles will be expected. If mode conversions occur and more than one type of wave exists, they will each have a different velocity, and thus a different angle of refraction. Since the shear wave velocity is less than the longitudinal wave velocity, it will always have the smallest angle of refraction. As the incident angle is further increased, both refracted angles will increase. The first beam to reach a refraction angle of 90 degrees will be the L-wave.

In Figure 6.2(7) the transducer has been rotated (in this case, 15 degrees) until the refracted angle of the L-wave has increased to 90 degrees. At this point, the L-wave no longer exists in the material. The incident angle at which this occurs is called the first critical angle, the angle where the L-wave first "disappears" and only S-waves remain in the material. (The actual amplitude of the S-wave, at this point, may be very small, but it is there.) Further rotation of the transducer increases the angle of the refracted shear wave beam. When the S-wave beam reaches 90 degrees , the incident angle is positioned at the second critical angle. In the entire region between the first and second critical angle, only S-wave beams are produced within the material.

Tables 6.2(4) and (5) provide critical angles for different material interfaces.

Figure 6.2(8) shows the transducer rotated enough (27 degrees in this case), so that the S-wave refraction angle has reached 90 degrees. At this point, no ultrasonic beams of any mode now appear in the material. At the surface, the beam has undergone mode conversion to a surface wave. Because the surface

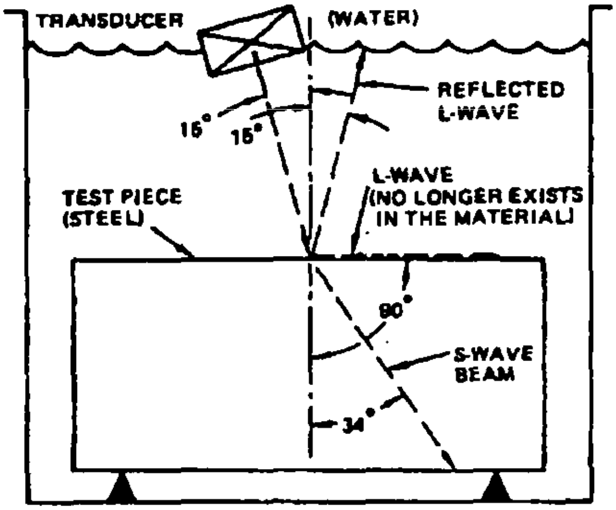


Figure 6.2(7). First critical angle.

Table 6.2(4). Critical angles, immersion testing.

FIRST MEDIUM IS H_2O (V = 0.149 CM/μSEC)

TEST MATERIAL	1ST CRITICAL ANGLE	2ND CRITICAL ANGLE	VELOCITY (CM/μSEC).	
			LONGITIDUNAL	SHEAR
BERYLLIUM	7°	10°	1.280	0.871
ALUMINUM, 17ST	14°	29°	0.625	0.310
STEEL	15°	27°	0.585	0.323
STAINLESS 302	15°	29°	0.566	0.312
TUNGSTEN	17°	31°	0.518	0.287
URANIUM	26°	61°	0.338	0.193

is in water, the surface waves are quickly damped out. In contact testing, where the test specimen is in air and surface waves are produced on the test piece when the second critical angle is reached, they can travel much longer distances before they are damped out.

In ultrasonic testing, the incident beam, because of beam spread, is a "collection" of angles or directions (see section 6.2.2 and Figures 6.2(3) and (4)). Therefore, when a beam is "at" a critical angle, actually half of the energy of the beam is at angles greater than this critical angle and the other

Table 6.2(5). Critical angles, contact testing.

FIRST MEDIUM IS PLASTIC (V = 0.267 CM/μSEC)

TEST MATERIAL	1ST CRITICAL ANGLE	2ND CRITICAL ANGLE	VELOCITY (CM/μSEC), LONGITUDINAL	SHEAR
BERYLLIUM	12°	18°	1.280	0.871
ALUMINUM, 17ST	25°	59°	0.625	0.310
STEEL	27°	56°	0.585	0.323
STAINLESS, 302	28°	59°	0.566	0.312
TUNGSTEN	31°	68°	0.518	0.287
URANIUM	52°	–	0.338	0.193

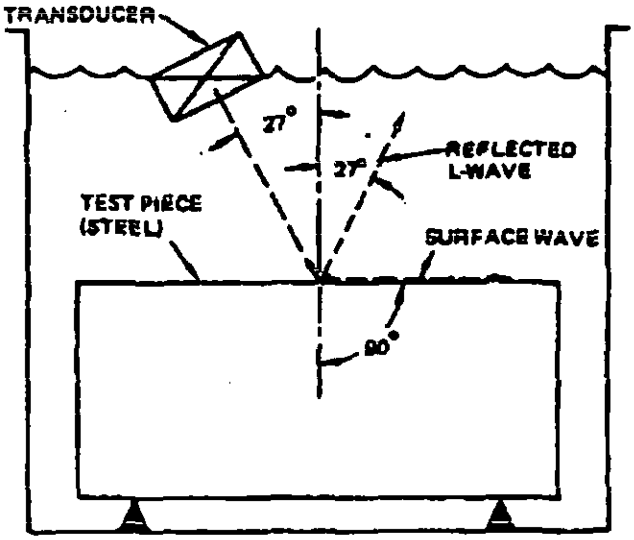


Figure 6.2(8). Second critical angle.

half at angles less than this critical angle. When a beam is "at" any particular angle of incidence, refractions are actually occurring over potentially a large range of angles. Therefore, it is possible to have in a part a great number of waves, wave directions and modes, many more than what might be theoretically expected. Within the part, if there are any complications at all to the part, or sometimes even when it is a simple part, the number of internal reflections, mode conversions, and refractions quickly multiply at every interface until there are more beams than can readily be tracked. Part of the "art" or "science" of ultrasonic testing is to always watch for unexpected beams and their reflections and to always double check that only the "proper" beams or reflections are being recorded.

Attenuation of ultrasonic energies arise from several factors. First, normal beam spread results in a loss due to geometric effects and involves the same $1/r^2$ factor used in X-rays or any other type of radiating energy ("r" is the distance from a point source.) The origin for r should be the face of a small, straight beam transducer when test points are beyond the near field or the focal point for a focus transducer. Additional attenuations can result from diffractions, reflections and refractions. All of these can be called scatter when they occur randomly or from multiple small distributive variables contained within the material.

Diffraction is a change in the direction of a wave in one material medium as the wave passes close to the edge of another medium. Diffraction is often involved around the edges of parts or the edges of internal flaws.

Energy losses can be due to absorption processes that result in heating effects. These losses within the material can be due to friction or physical imperfections in the arrangements of the atoms in crystals or grains, or other non-linearities in the kinetic energy-potential energy exchanges that occur when waves propagate. These losses are a function of frequency.

When energy losses occur uniformly throughout a material, the overall attenuation for a parallel beam follows the power law:

$$I(x) = I_o e^{-Kx} \qquad (21)$$

where

$I(x)$ = the intensity at position x

I_o = intensity at the position x = 0

K = attenuation constant

x = penetration distance .

The attenuation constant is greatly affected by frequency or wavelength compared to the size of the variables causing the scatter. Normally, the lower the frequency (the longer the wavelength), the lower the attenuation constant "K", the greater the penetration. (Attenuation constants can be given for wave pressure losses and/or for a base 10 relationship. Care must be exercised here because they will differ by a factor of 0.5 and/or 0.868 from the above defined constant.)

When a wavelength is much larger than the size of the object causing the scattering, it "flows" around the object and essentially continues on its way with no major losses or changes. This is good if it is not the variable to be inspected. This relationship, however, does point out the importance of testing with high frequencies. The size of defects that can be seen will be greatly affected by the frequency being used. The higher the frequency, the smaller will be the size of flaws that can be resolved. If the wavelength is smaller than the object causing the scattering, it will interact with that object and be reflected and transmitted by the principles previously presented. Therefore, most ultrasonic testing requires a balance between using the highest frequency possible to find the smallest possible flaws, yet keeping the frequency low enough that adequate penetrations can be obtained. Since higher frequencies create more noise, improved flaw detection signal-to-noise ratios are obtained from lower frequencies. Every inspection problem potentially has a unique choice where this relationship is maximized.

6.2.5 INFORMATION DISPLAYS

Most ultrasonic information is presented on an oscilloscope, where time is represented on the horizontal axis (or sweep direction) and the amplitude of the ultrasonic energy either being sent or received by the transducer is recorded in the vertical direction. The start of the time sweep on the horizontal is "triggered" by each transmitted pulse. The transmitted pulse is therefore the first signal or pip usually seen on the screen. The repetition rate of the transmitted pulses, and thus the signal on the screen, is fast enough that it appears continuous to the eye. Between each transmitted pulse, echoes are received back by the transducer. These echoes, depending on the distance from which they are returned, are each received at different times. In exactly the same order, each echo appears on the screen at different points along the sweep line. Each return pulse can normally be shown as "rf," where their full wave action, the plus and minus pressures in each cycle, are indicated; or the rf signal can be rectified to provide a dc pulse. The electrical amplification circuits normally have a saturation limit so that signals that would be amplified beyond a certain point on the screen all appear at the same maximum level.

The sweep circuit actually contains a delay circuit (sometimes called sweep delay) and a sweep rate control (sometimes called sweep length) which allows any portion of the total sweep to be amplified and displayed on the full screen. This display shown on the screen, where amplitude versus time is showing the echoes being received at different depths in the part, is called an A-scan. An A-scan is essentially examining the specimen along the beam line, penetrating through the specimen through only one point on the surface above which the transducer is located. To inspect an entire part by the A-scan method would require moving the transducer over every point of the surface, and observing the A-scan obtained at each point.

A B-scan is a display that shows a cross-section of a part. It is "obtained" from the A-scans produced at all the points along one line across the surface of the specimen, and thus provides in one picture a summation of what might otherwise be an unmanageable amount of information.

A B-scan display, therefore, shows the section view of a material that was "cut" (or penetrated) by an ultrasonic beam as the transducer made a one line pass across the material. On a cathode ray tube, the image is formed by a series of parallel lines, each line representing data from a single A-scan.

The distance between each line represents the distance the transducer was moved between each A-scan. Each line is formed by a spot moving across the screen whose brightness at each point is a function of the signal amplitude at that corresponding point on the A-scan.

To inspect an entire part by B-scans would require the forming of a B-scan for all the cross-section lines that exist across any one dimensional direction of the part. This, too, could still be a large number of scans and/or information to be analyzed.

A C-scan is a plan-view of the entire part. In one view, all the information, or a portion of the information, from all the A-scans can be combined and shown in this view. By use of an electronic gate, the information collected from the A-scans can be limited to a specific range of depths. If only a narrow portion of each A-scan is used, then a cross-section parallel to the inspection plane can essentially be formed. If the electronic gate is expanded to include the full depth of the inspected part, then any A-scan that showed an echo within the depth of the part would produce a mark on the C-scan. In this way, a C-scan can be a great summation of information. When a C-scan is used to collect information over the full depth of a part, a mark on the C-scan will appear no matter where the signal appears within the width of the gate. Therefore, depth information on a C-scan is always uncertain by the depth or width of the gate used. There are times, therefore, when both A-scans and C-scans are used together when more information is required than what is provided by the C-scan.

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6.3 EQUIPMENT AND MATERIALS

Ultrasonic equipment range from small portable units to large permanent facilities - some are manually operated, some have been automated in several features to include automatic scanning of specimens and recording of the information. Basic A-scan, B-scan, or C-scan type of recording methods can be used. Special types of ultrasonic equipment can be obtained to measure thicknesses, speed of ultrasonic waves, or changes in impedances. The degree of automation, the means of data analyses, and types of data displays are constantly improving largely because of recent advances in microprocessors.

Along with the basic equipment, there are transducers, automatic scanning and manipulator systems, tanks, couplant materials, and calibration and standard blocks necessary to support ultrasonic testing activities.

In immersion testing, clean, deaerated tap water, with an added wetting agent, can be used for a couplant. A fungicide and corrosion inhibitor are typically included in the immersion bath for protection. The water temperature is sometimes maintained at a fixed value by automatic controls. Wetting agents are added to the water to ensure that the surface is thoroughly wet, thereby eliminating air bubbles.

In contact testing, the choice of couplant depends primarily on the test conditions; i.e., the condition of the test surface (rough or smooth), the temperature of the test surface, and the position of the test surface (horizontal, slanted, or vertical).

One part glycerine with two parts water, and a wetting agent, is often used on relatively smooth, horizontal surfaces. For slightly rough surfaces, light oils (such as SAE 20 motor oil), with a wetting agent added, are used. Rough surfaces, hot surfaces, and vertical surfaces require the use of a heavier oil, or grease, as a couplant. In all cases, the couplant selected must be capable of forming as thin a film as possible consistent with the geometric variables that are present.

It must be understood that, other than for special portable type equipment like thickness gages, most ultrasonic testing systems require extensive electronic and mechanical support. The electronic effort is at least as technical as that required to set up and use an oscilloscope, and the mechanical support often includes automatic moving machinery with position and velocity limit controls.

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6.4 BASIC PROCEDURES AND TECHNIQUES

Ultrasonic testing, like other NDT testing, provides indications that are of no value unless interpretations can be made. Interpretations are often dependent upon calibrations or standardizations that must be performed, either before, during, or after each test. Some of the means of obtaining these calibrations or standardizations are presented in the "Standards" section, section 6.5.

Because ultrasonic testing can involve a large number of variables, and some of these variables are external variables such as temperature that have a direct affect on the velocity and the wavelengths of the waves being used, the importance of the calibration cannot be overemphasized. Once adjustments have been made that establish the proper responses of the equipment and adequate indications of known discontinuities of the range of sizes, depths, and orientations required for the test have been established, testing can be initiated. Once calibration and standardization have been accomplished, no further adjustments should be allowed unless restandardization of the equipment is accomplished.

Techniques of ultrasonic testing are accomplished with one of two basic methods: contact or immersion testing.

6.4.1 IMMERSION TESTING

In immersion testing, a waterproof transducer is used at some distance from the test specimen and the ultrasonic beam is transmitted into the material through a water path or column. The water distance appears on the display as a fairly wide space between the initial pulse and the front-surface reflection because of the reduced velocity of ultrasound in water. Because of this "distance" between the transducer and the specimen, near-field and dead zone type effects are usually minimal for immersion type testing. Also, with the transducer separated from the specimen and the coupling being automatic, the transducer is reasonably free to move, and therefore most automatic scanning methods are associated with the immersion testing method.

Any one of three techniques may be used in the immersion method: the immersion technique, where both the transducer and the test specimen are immersed in water; the bubbler or squirter technique, where the ultrasonic beam is transmitted through a column of flowing water; and the wheel transducer technique, where the transducer is mounted in the axle of a liquid-filled tire that rolls on the test surface. Figure 6.4(1) shows an example of the bubbler and the wheel-transducer techniques. An adaptation of the wheel transducer technique is a unit with the transducer mounted in the top of a water-filled tube. A flexible membrane on the lower end of the tube couples the unit to the test surface. In all three of these techniques, a further refinement is the use of focused transducers that concentrate the ultrasonic beam (much like light beams are concentrated when passed through a magnifying glass).

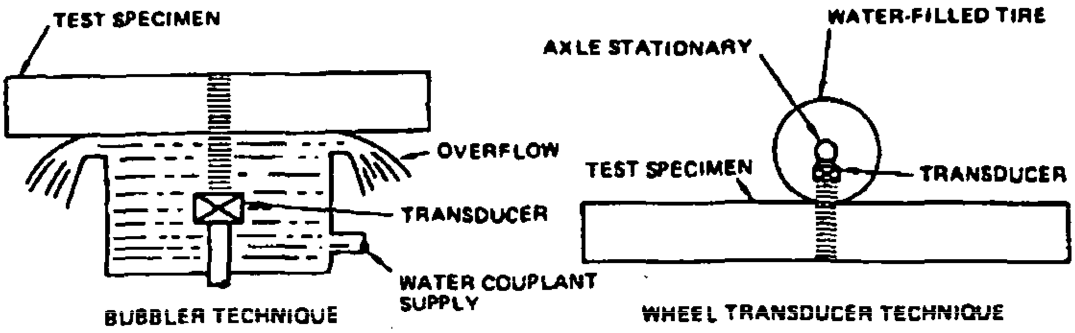


Figure 6.4(1). Bubbler and wheel transducer techniques.

In many automatic scanning operations, focused beams are used to detect near-surface discontinuities or to define minute discontinuities with the concentrated beam. Straight-beam transducer units can accomplish both straight- and angle-beam testing through manipulation and control of the beam direction.

The water-path distance is usually adjusted so that the time required to send the beam pulse through the water is greater than the time required for the pulse to travel through the test specimen. When done properly, the second front-surface reflection will not appear on the oscilloscope screen between the first front- and first back-surface reflections. In water, sound velocity is about one-quarter that of aluminum or steel; therefore, one inch of water path will appear on the oscilloscope screen as equal to four inches of metal path in steel. As a rule of thumb, position the transducer so that the water distance is equal to one-quarter the thickness of the part, plus one quarter inch. The correct water-path distance is particularly important when the test area shown on the oscilloscope screen is gated for automatic signalling and recording operations. The water-path distance is carefully set to clear the test area of unwanted signals that cause confusion and possible misinterpretation. Figure 6.4(2) shows the relationship between the actual water-path and the display.

The bubbler is usually used with an automated system for high-speed scanning of plate, sheet, strip, cylindrical forms, and other regularly shaped parts. The ultrasonic beam is projected into the material through a column of flowing water, and is directed in a normal direction (perpendicular) to the test surface to produce longitudinal waves or adjusted at an angle to the surface to produce shear waves.

Figure 6.4(3) illustrates a stationary and a moving-wheel transducer. The position and angle of the transducer mounting on the wheel axle may be constructed to project straight-beams, as shown in Figure 6.4(3), or to project angled beams as shown in Figure 6.4(4).

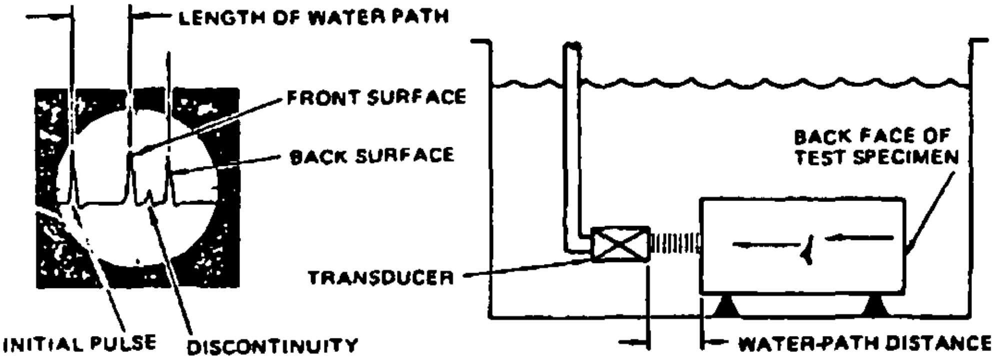


Figure 6.4(2). Water-path distance adjustment.

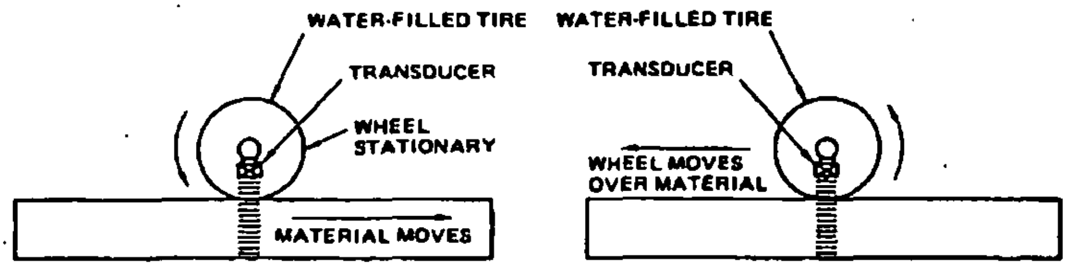


Figure 6.4(3). Stationary and moving wheel transducers.

6.4.2 CONTACT TESTING

In contact testing, the transducer is placed in direct contact with the test specimen with a thin liquid film used as a couplant. On some contact units, plastic wedges, wear plates, or flexible membranes are mounted over the face of the crystal. Transducer units are considered as being in contact whenever the beam is transmitted through a couplant other than water. The display from a contact unit usually shows the initial pulse and the front-surface reflection as superimposed or very close together. Both near-field and dead zone effects are present in contact type tests.

Contact testing is divided into three techniques, which are determined by the ultrasonic wave mode desired: the straight-beam technique for transmitting longitudinal waves in the test specimen, the angle-beam technique for generating shear waves, and the surface-wave technique for producing Rayleigh or Lamb waves.

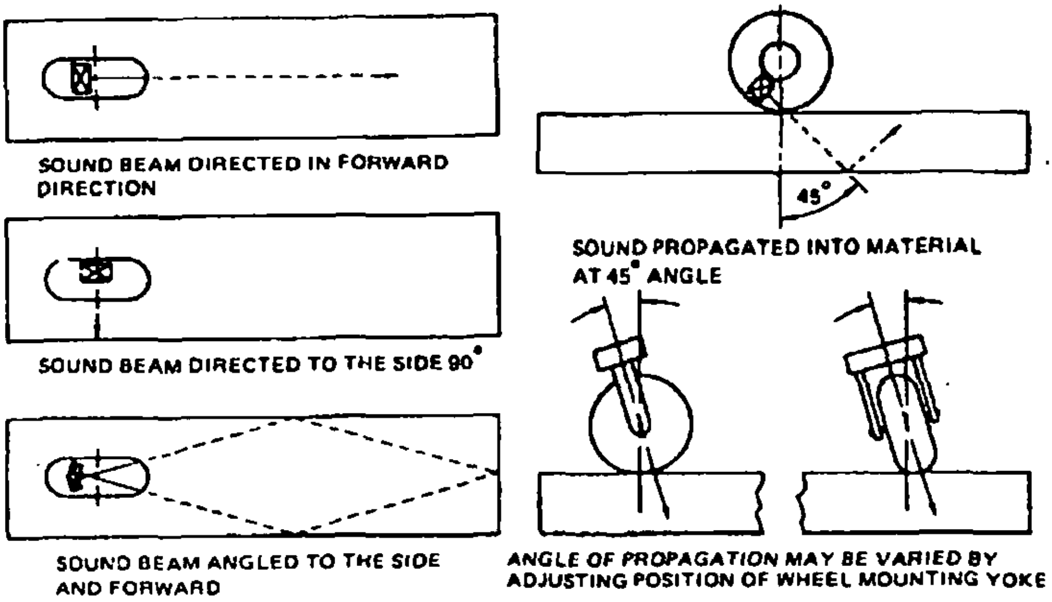


Figure 6.4(4). Wheel transducer angular capabilities.

The straight-beam technique is accomplished by projecting a beam perpendicularly to the test surface of the test specimen to obtain pulse-echo reflections (see Section 6.4.3) from the back surface or from discontinuities which lie between the two surfaces. This technique is also used in the through-transmission technique (see Section 6.4.3) using two transducers where the internal discontinuities interrupt the beam causing a reduction in the received signal.

The angle-beam technique is used to transmit sound waves into the test material at a predetermined angle to the test surface. According to the angle selected, the wave modes produced in the test material may be mixed longitudinal and shear, shear only, or surface modes. Usually, the shear-waves are used in angle-beam testing. Figure 6.4(5) shows an angle-beam unit scanning plate and pipe material. To reduce the confusion from dead-zone and near-zone effects encountered with straight-beam transducers, parts with a thickness less than 5/8 inch are tested with angle-beam units. In this technique, the beam enters the test material at an angle and proceeds by successive zigzag deflections from the specimen boundaries until it is interrupted by a discontinuity or boundary where the beam reverses direction and is reflected back to the transducer. Allowances are made when placing the angle-beam unit to account for the lessened effective length of penetration because of the zigzag path taken by the beam. Angle-beam techniques are used for testing welds, pipe or tubing, sheet and plate material, and for specimens of irregular shape where straight-beam units are unable to contact all of the surface. Angle-beam transducers are identified by case markings that show beam direction by an arrow and that indicate the angle of refraction in steel for shear waves.

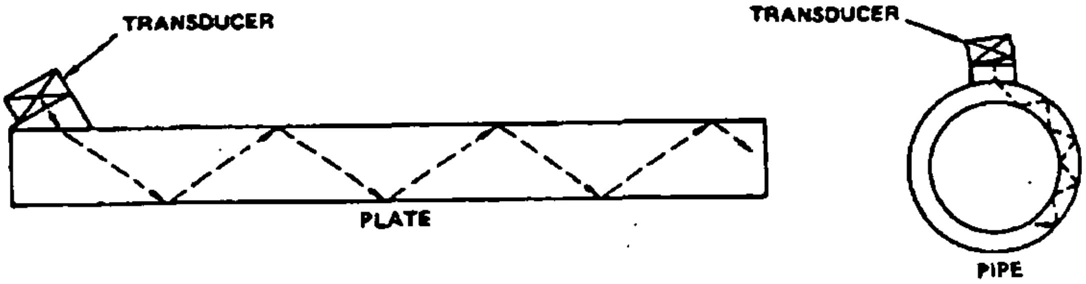


Figure 6.4(5). Shear-wave technique.

The surface-wave technique requires special angle-beam transducers that project the beam into the test specimen at a grazing angle where almost all of the beam is reflected. For test specimens where near-surface discontinuities are encountered, surface-wave transducers are used to generate Rayleigh surface waves in the test material. The surface-wave technique is shown in Figure 6.4(6).

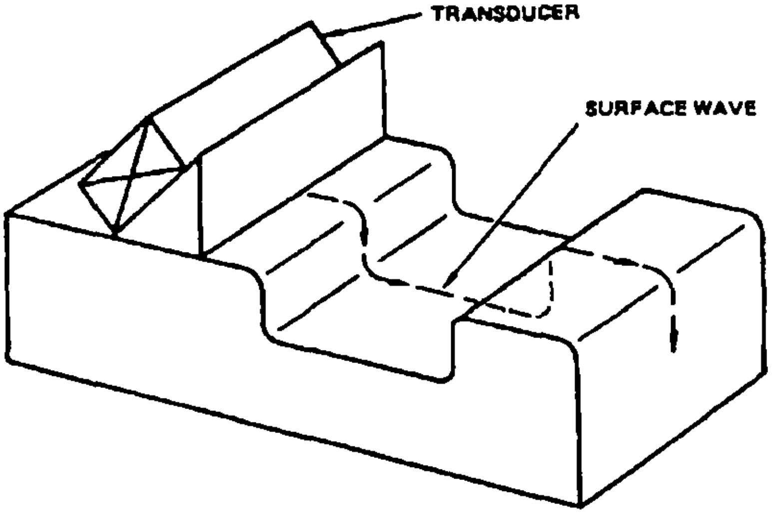


Figure 6.4(6). Surface-wave technique.

6.4.3 PULSE-ECHO AND THROUGH TRANSMISSION

In both the immersion and in the contact test methods, there are pulse-echo techniques and through transmission techniques.

Pulse-echo techniques may use either single, or double, straight-beam transducers. Figure 6.4(7) shows a contact, single unit, straight-beam transducer in use. With the single unit the transducer acts as both

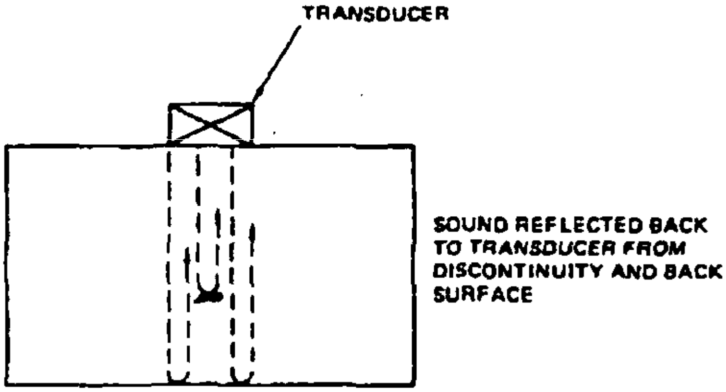


Figure 6.4(7). Single-transducer pulse-echo technique.

transmitter and receiver, projecting a pulsed beam of longitudinal waves into the specimen and receiving echoes reflected from the back surface and from any discontinuity lying in the beam path with reflecting surfaces perpendicular to the beam. The double transducer unit is useful when the test specimen flaws or back surface are irregular or are not parallel with the front surface. One transducer transmits and the other receives, as shown in Figure 6.4(8). In this case, the receiver unit is receiving back-surface and discontinuity echoes, even though both transducers may not be directly over these reflectors.

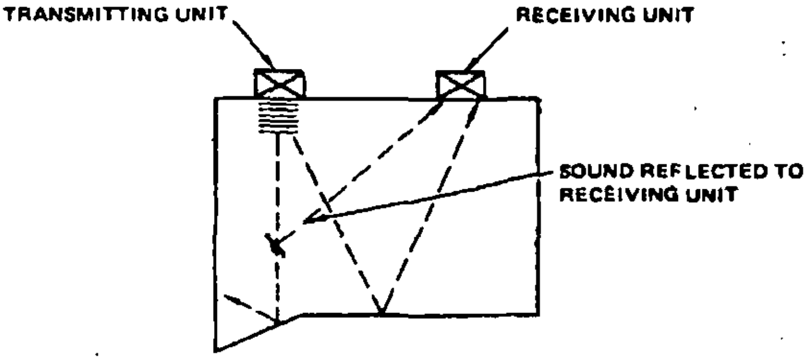


Figure 6.4(8). Double-transducer pulse-echo technique.

Two transducers are usually used in the through-transmission technique - one on each side of the test specimen, as shown in Figure 6.4(9). One unit acts as a transmitter and the other as a receiver. The transmitter unit projects a beam into the material, the beam travels through the material to the opposite surface, and the energy is picked up at the opposite surface by the receiving unit. Any discontinuities in the path of the beam cause a reduction in the amount of energy reaching the receiving unit. For best results in this

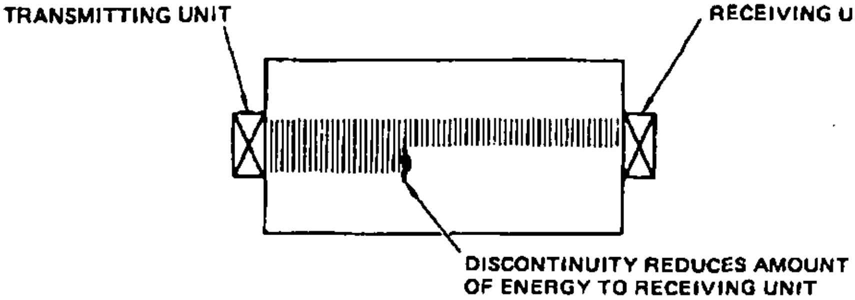


Figure 6.4(9). Through-transmission technique, two transducers.

technique, the transmitter unit selected is the best available generator of acoustic energy, and the receiver unit selected is the best available receiver of ultrasonic energy. For example, a barium titanate transmitter unit is used with a lithium sulfate receiver unit.

A variation of the through-transmission method, normally used for thin materials, consists of a single transducer, and after the wave pulse has gone through the material, it is reflected by a reflector and returned back to the original transducer. In this method, an electronic gate can be used to record the signals that come from the reflector. This essentially gives the same information that would have been received from a second transducer if it had been located at that point. This method reduces the number of transducers required, and essentially is using only a one-sided type inspection.

Basically, the pulse-echo technique can provide depth information and the through-transmission provides no depth information. In a through scan, the entire depth of the specimen is being examined. If a material is difficult to penetrate, the two transducer through-transmission technique can provide the maximum penetration.

6.4.4 GENERAL TECHNIQUE CONSIDERATIONS

Ultrasonic test preparations begin with an examination of the test specimen to determine the appropriate technique; then, components are selected from available equipment to perform the test. Many variables affect the choice of technique. For example, the test specimen may be too large to fit in the immersion tank. In the case of large, fixed structures, the testing unit is moved to the test site. This may require portable testing equipment. Other factors are the number of parts to be tested, the nature of the test material, test surface roughness, methods of joint (welded, bonded, riveted, etc.), and the shape of the specimen. If the testing program covers a large number of identical parts and a permanent test record is desirable, an immersion technique with automatic scanning and recording may be suitable. One-of-a-kind or odd-lot jobs may be tested with portable contact testing units. Each case will require some study as to the most practical, efficient technique.

When setting up any test, an operating frequency is selected, a transducer is chosen, and a reference standard is established. The test specimen is carefully studied to determine its most common or probable discontinuities. For example; in forgings, laminar discontinuities are found parallel to the forging flow lines; discontinuities in plate are usually parallel to the plate surface and elongated in the rolling direction; the common defect in pipe is a longitudinal crack, etc. If possible, a sample specimen is sectioned and subjected to metallurgical analysis.

a. Frequency Selection. Frequency is one of the most influential parameters that govern the success of ultrasonic inspection. There are a number of criteria which determine the ultrasound frequency that delivers the best sensitivity to detect flaws. These criteria include:

Material
Signal-to-noise ratio
Minimum size of a flaw

The material generally determines the best ultrasound frequency. Steel usually requires 2.25 or 5.0 MHz. Aluminum generally gives best results with 5.0MHz. The way to find out which is the best frequency for the application is by trial and error. A sample part with a natural or simulated defect is obtained and scanned with ultrasonic transducers of various frequencies. The gain setting for a defect signal of common screen height provides a good indication of the most effective frequency. That is, the frequency that requires the lowest gain setting is a preferred frequency. However, the signal-to-noise ratio must also be evaluated. Ratios of the largest signal received from a minimum sized defect as compared to the largest noise signals should be at least 10 to 1 (20 db).

Spectrum analysis can ascertain which is the best frequency. Spectrum analysis is done by comparing the frequency spectrum from a natural flaw to the frequency spectrum prior to entering the material being inspected. The later spectrum can be obtained from an echo from a polished flat surface immersed in water. Spectrums which transmit much of defect information in or near the mean value of the rated transducer frequency are what is being sought. Care must be taken to compare broadband frequency with broadband and narrow band frequency with narrow band. Narrow band frequency transducers generate a more powerful pulse than broadband transducers. This is expected as broadband transducers are heavily damped to vibrate only about one and a half cycles. Higher ultrasound frequencies are neeeded for exceedingly small minimum sized defects such as are encountered in thin wall tubing inspection for nuclear reactors. Very high strength martensitic steel has a fine grain structure that can accommodate higher ultrasound frequencies with little noise.

b. Transducer Size Selection. Just as sensitivity to the presence of flaws is the reason for selecting transducer frequency, so too it is the basis for selecting size. The first question to be answered is "Do you need a focused transducer"? If the depth (thickness) of material is a centimeter or two, then a focused transducer should be considered. However, if deep or thick material is to be ultrasonically scanned, and the minimum flaw size is not miniscule, then a flat lens transducer is often the best bet.

Focused Transducers. Noise is the variable that determines the best size and configuration for a focused transducer. Small transducers with a wide beam spread and large transducers with much refraction from the large lens cause lots of noise. It is surprising how often the moderately sized transducers of about one centimeter across the lens face turn in the best performance (of least noise).

Flat Lensed Transducers. Generally, small sized transducers work best with small sized (or thickness) parts. Larger sized transducers work well for interrogation of large, deep parts. However, sensitivity falls off with increasingly larger sized transducers when the pulser is taxed to vibrate the crystal. So the power capacity of the pulser limits the size of the transducer.

Again, trial and error with evaluation of performance data reveal the best size of transducer for a particular application.

c. Reference Standards. Commercial ultrasonic reference standards are described in detail in section 6.5. These standards are adequate for many test situations, provided the acoustic properties are matched or nearly matched between the test specimen and the test block. In most cases, responses from discontinuities in the test specimen are likely to differ from the indications received from the test block hole. For this reason, a sample test specimen is sectioned, subjected to metallurgical analysis, and studied to determine the nature of the material and its discontinuities. In some cases artificial discontinuities in the form of holes or notches are introduced into the sample to serve as a basis for comparison with discontinuities found in other specimens. From these studies, an acceptance level is determined that establishes the number and magnitude (or size) of discontinuities allowed in the test specimen. In all cases, the true nature of the test material is determined by careful study of the sample specimen, and a sensible testing program is established by an intelligent application of basic theory.

6.4.5 INDICATIONS FROM VARIOUS TECHNIQUES AND THEIR INTERPRETATIONS

Ultrasonic test indications from subsurface discontinuities within the test specimen are usually related, or compared, to indications from flat-bottomed holes of varying depths or diameters in standard test blocks. These comparisons are a fair means of evaluating the size, shape, position, orientation, and impedance of discontinuities. Test conditions, and the discontinuities themselves, are sometimes the cause of ultrasonic phenomena which are difficult to interpret. This type of difficulty can only be resolved by relating the ultrasonic indications to the probable type of discontinuity with reference to the test conditions. Impedance of the material, surface roughness, surface contour, attenuation, and angle of incidence are all to be considered when evaluating the size and location of an unknown discontinuity by the amplitude of the indication received. The simplest method is to compare the indication of the discontinuity with indications from a test block similar to the test specimen in alloy, shape, and back-surface reflections. The experienced operator also learns to discriminate between the indications of actual defects and false or nonrelevant indications.

a. Typical Immersion Test Indications

Immersion test indications, as displayed on an A-scan in a pulse-echo mode, are interpreted by analysis of three factors: the amplitude of the reflection from a discontinuity, the loss of back-surface reflection, and the distance of discontinuity from the surfaces of the article. Individual discontinuities that are small, compared with the transducer crystal diameter, are usually evaluated by comparing the amplitude of the test-specimen echoes with the test-block echoes. Since the surface of the test specimen and the surface of a discontinuity within it are not as smooth as the surface of the test block and the flat-bottomed hole in the test block, the estimated size of the discontinuity is generally a bit smaller than the actual size. Discontinuities that are larger than the crystal diameter, are evaluated by noting the distance the crystal is moved over the test specimen while an indication is still maintained. In this case, the amplitude has no quantitative meaning; the length over which the amplitude is maintained does indicate the extent of the discontinuity in one plane. A loss, or absence, of back-surface reflection is evidence that the transmitted sound has been absorbed, refracted, or reflected so that the energy has not returned to the crystal. Evaluating this loss does not always determine the size of the discontinuity as concisely as the comparison method used on small discontinuities.

When relatively large discontinuities are encountered, the discontinuity may eliminate the back-surface reflection since the beam is not transmitted through the discontinuity.

1. Small Discontinuity Indications. A significant number of the discontinuities encountered in ultrasonic testing of wrought aluminum are relatively small. Foreign materials or porosity in the cast ingot are rolled, forged, or extruded into wafer-thin discontinuities during fabrication. The forces used in fabrication tend to orient the flat plane of the discontinuity parallel to the surface of the part. Such a

discontinuity and its ultrasonic indication are shown in Figure 6.4(10). The relationship of the discontinuity indication and its amplitude is determined by comparison with a range of test block flat-bottomed hole reflections, as shown in Figure 6.4(11).

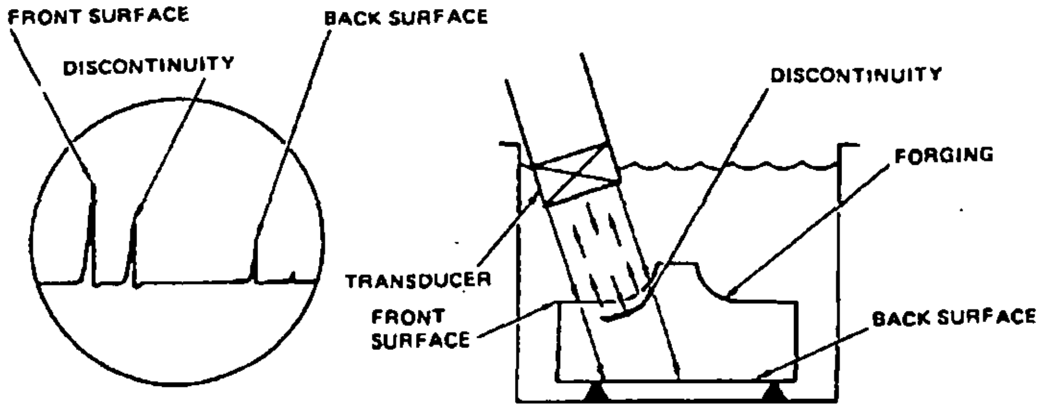
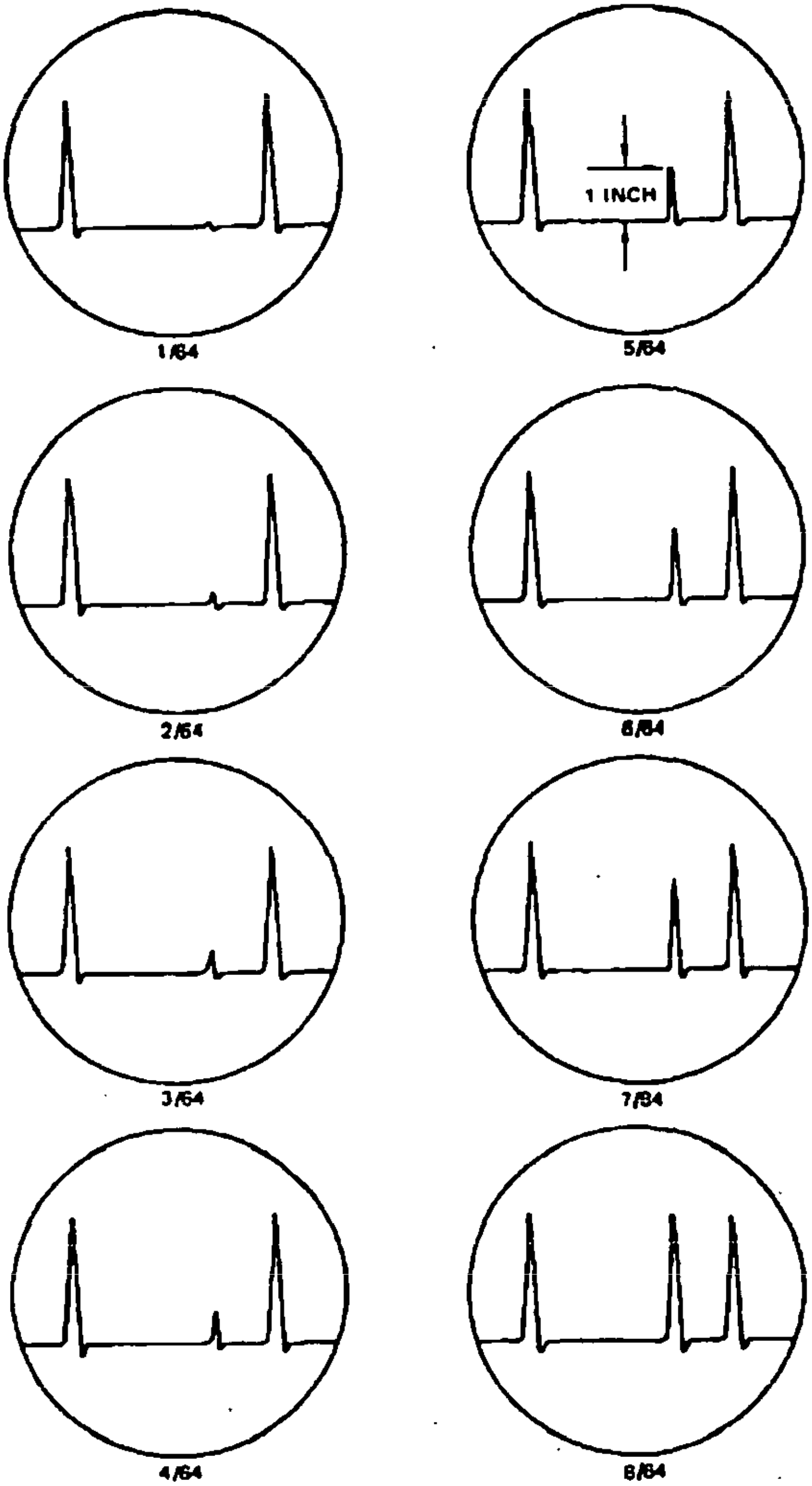


Figure 6.4(10). Force-oriented discontinuity indication.

2. Large Discontinuity Indications. Discontinuities that are large, when compared with the crystal size, usually produce a display, as shown in Figure 6.4(12). Since the discontinuity reflects nearly all of the ultrasonic energy, the partial or total loss of back-surface reflection is typical. The dimensions of the discontinuity may be determined by measuring the distance that the transducer is moved while still receiving an indication. If the discontinuity is not flat, but is three-dimensional, the extent of the third dimension may be determined by turning the article over and scanning from the back side. If the possibility of two discontinuities lying close together is suspected, the article may be tested from all four sides.

3. Loss of Back-Surface Reflection. Evaluating the loss of back-surface reflection is most important when it occurs in the absence of significant individual discontinuities. In this case, among the causes of reduction, or loss, of back-surface reflection are large grain size, porosity, and a dispersion of very fine precipitate particles. Figure 6.4(13) shows the indications received from a sound test specimen and the indications displayed from a porous specimen. Note that the back-surface reflections obtained from the porous specimen are reduced considerably.

4. Nonrelevant Indications. When considering indications that may be nonrelevant, it is a good rule to be suspicious of all indications that are unusually consistent in amplitude and appearance while the transducer is passing over the test specimen. Reflections from fillets and concave surfaces may result in responses appearing between the front and back surfaces. These are sometimes mistaken for reflections from discontinuities. Reflections from a contoured surface may be shielded off by interrupting the beam with a foreign object such as a piece of sheet metal, as shown in Figure 6.4(14). Broad-based pips, as contrasted to a sharp spike or pip, are likely to be re.lections from a contoured surface.



1/64 5/64

2/64 6/64

3/64 7/64

4/64 8/64

Figure 6.4(11). Amplitude range of 1/64 to 8/64 flat-bottomed holes.

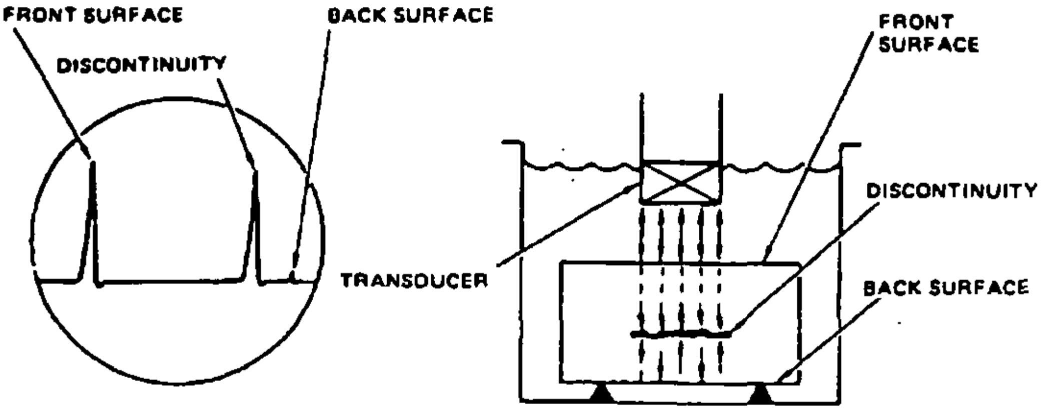


Figure 6.4(12). Large discontinuity indication.

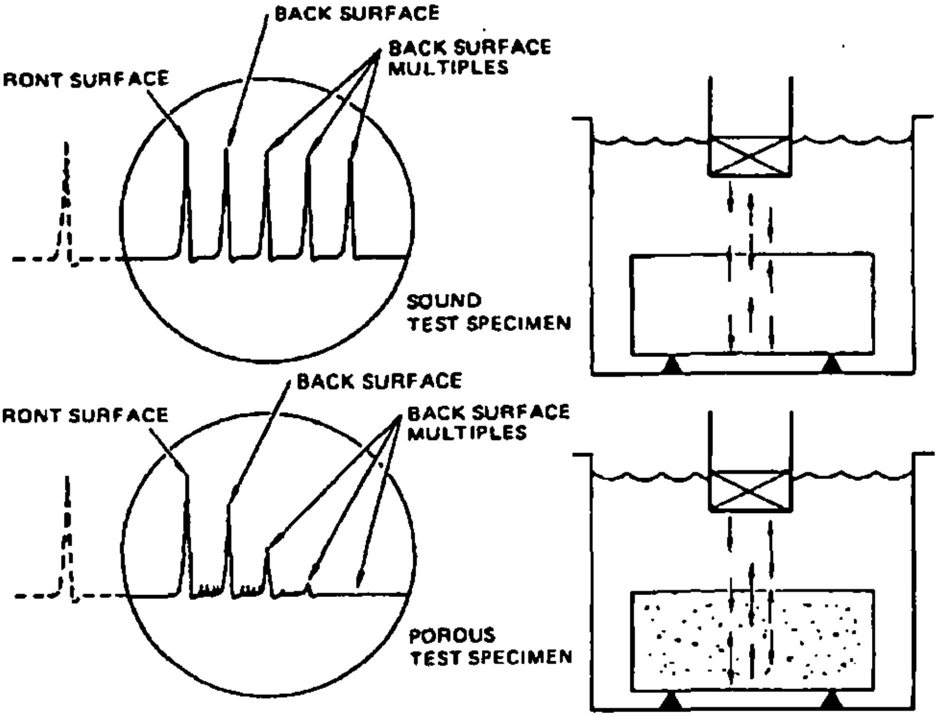


Figure 6.4(13). Reduced back reflection from porosity.

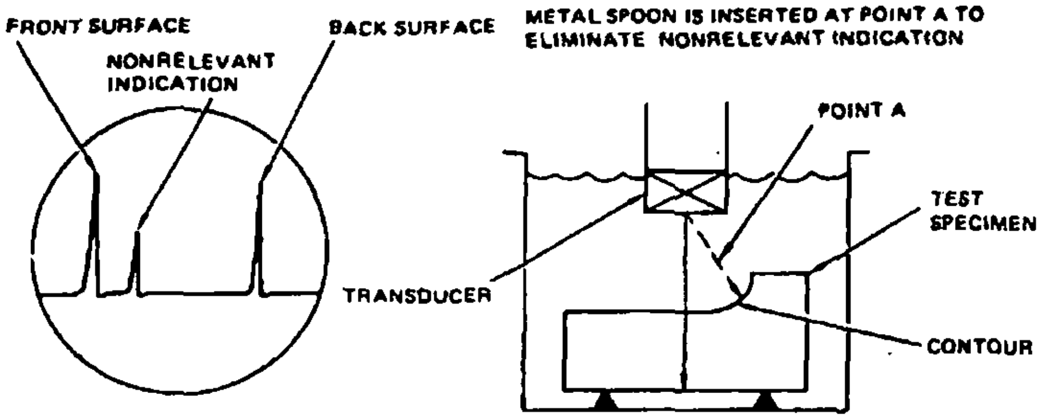


Figure 6.4(14). Nonrelevant indication from contoured surface.

Near the edges of rectangular shapes, edge reflections are sometimes observed with no loss of back-surface reflection. This type of indication usually occurs when the transducer is within 1/2-inch of the edge of the part.

Articles with smooth, shiny surfaces will sometimes give rise to false indications. For example, with a thick aluminum plate machined to a smooth finish, spurious indications which appeared to be reflections from a discontinuity located at about one-third of the article depth were received. As the transducer was moved over the surface of the plate, the indication remained relatively uniform in shape and magnitude. Apparently this type of indication results from surface waves generated on the extremely smooth surface, and possibly reflected from a nearby edge. They are eliminated by coating the surface with wax crayon or a very thin film of petroleum jelly.

5. Angled-Plane Discontinuity Indications. Discontinuities oriented with their principal plane at an angle to the front surface are sometimes difficult to detect and evaluate. Usually, it is best to scan initially at a comparatively high gain setting to detect angled-plane discontinuities. Later the transducer is manipulated around the area of the discontinuity to evaluate its magnitude. In this case, the manipulation is intended to cause the beam to strike the discontinuity at right angles to its principal plane. With large discontinuities that have a relatively flat, smooth surface but lie at an angle to the surface, the indication moves along the base line of the display as the transducer is moved because of the change in distance of beam travel. Bursts in large forgings fit this category; they tend to lie at an angle of 45 degrees to the surface.

6. Grain Size Indications. Unusually large grain size in the test specimen may produce "hash," or noise, indications, as shown in Figure 6.4(15). In the same illustration, note the clear indications received from the same type of material with fine grain. In some cases, abnormally large grain-size results in a total loss of back-surface reflection. These conditions are usually brought about by prolonged or improper forging temperatures, or high temperature during hot working and subsequent improper annealing of the test specimen.

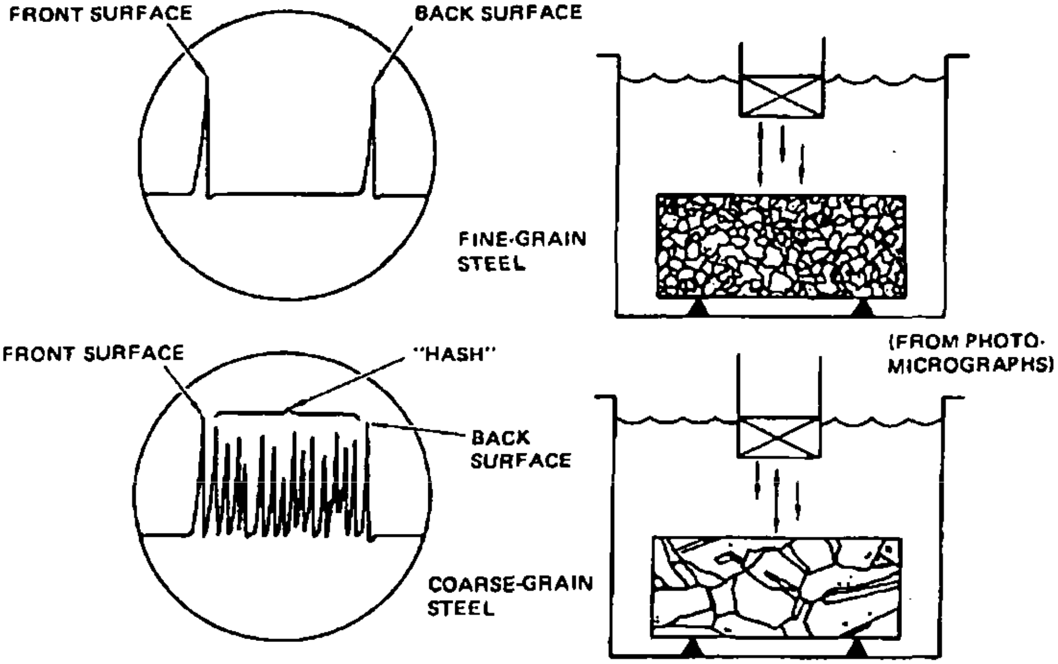


Figure 6.4(15). Grain size locations.

b. Typical Contact Test Indications

Contact test indications, in many instances, are similar or identical to those discussed in the previous paragraphs on immersion test indications. Little additional discussion will be given when contact indications are similar to immersion indications. Interference from the initial pulse at the front surface of the test specimen and variations in efficiency of coupling, produce nonrelevant effects that are sometimes difficult to recognize in contact testing. As in immersion testing, signal amplitude, loss of back reflection, and distance of the discontinuity from the surfaces of the article are all major factors used in evaluation of the display.

1. Typical Discontinuity Indications. Typical indications encountered in ultrasonic testing include those from discontinuities such as nonmetallic inclusions, seams, forging bursts, cracks, and flaking found in forgings, as shown in Figure 6.4(16).

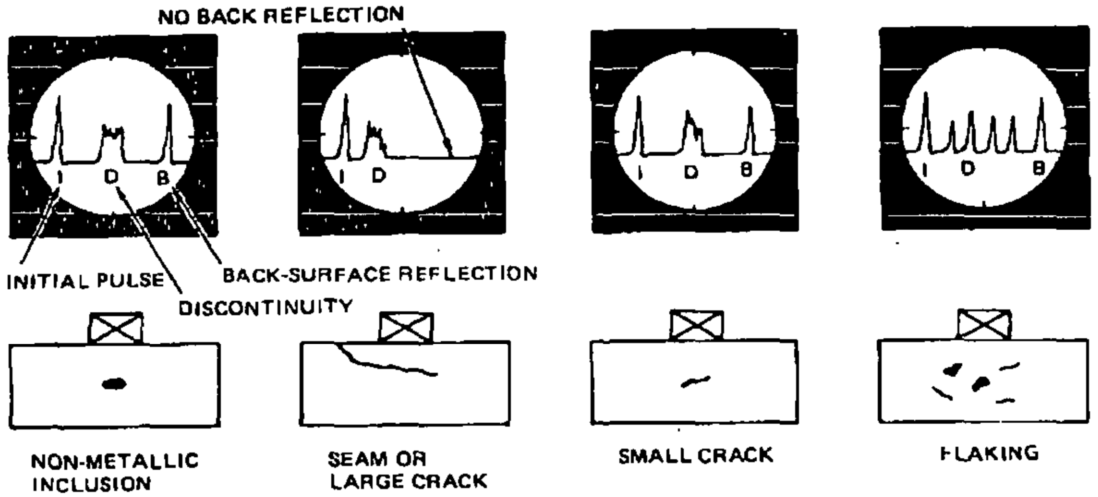
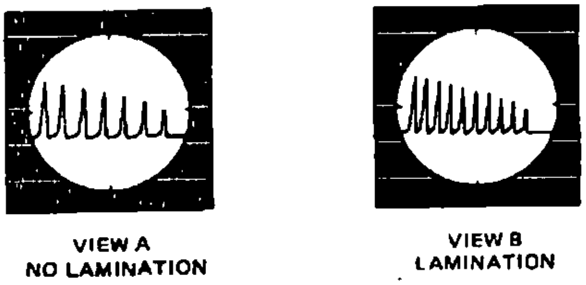


Figure 6.4(16). Typical contact test discontinuity indications.

Delaminations in rolled sheet and plate are shown by a reduction in the distance between back-surface reflection multiples, as shown in Figure 6.4(17). View A illustrates the display received from a normal plate and view B shows the back-surface reflections received when the transducer is moved over the delamination.

In angle-beam testing of welds, a satisfactory weld area is shown with the weld fusion zones clearly indicated as shown in view A of Figure 6.4(18). View B shows the same reflections for the fusion zones, but in this case, a discontinuity is located in the center of the weld. The weld seam commonly has discontinuities such as porosity and slag that produce indications as shown in Figure 6.4(19).

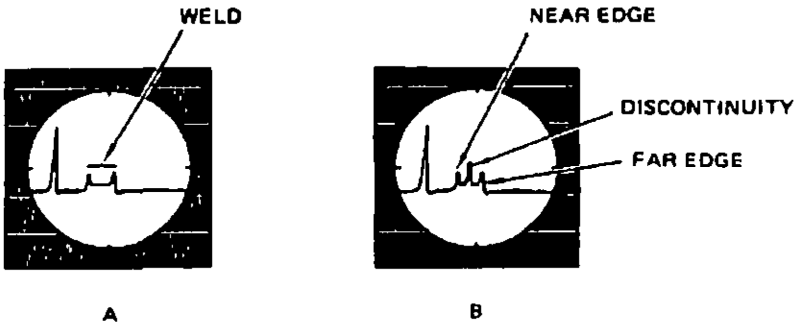
Surface cracks are sometimes detected when testing with a shear wave produced by an angle-beam transducer. Figure 6.4(20) shows a surface-wave indication from a crack in the surface of the test specimen.



VIEW A
NO LAMINATION

VIEW B
LAMINATION

Figure 6.4(17). Effect of delamination on back-surface reflection multiples.



A

B

Figure 6.4(18). Weld indications using angle-beam contact techniques.

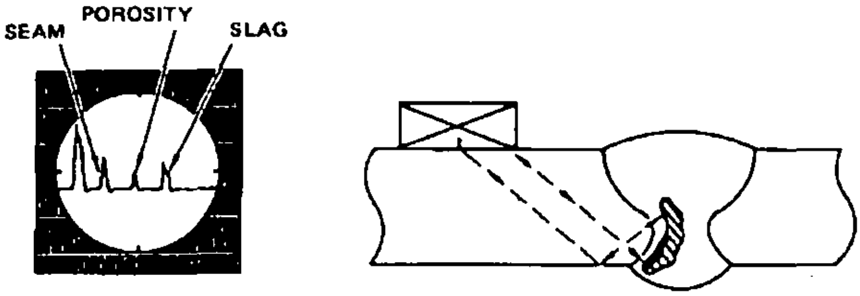


Figure 6.4(19). Porosity and slag indications in weld seam.

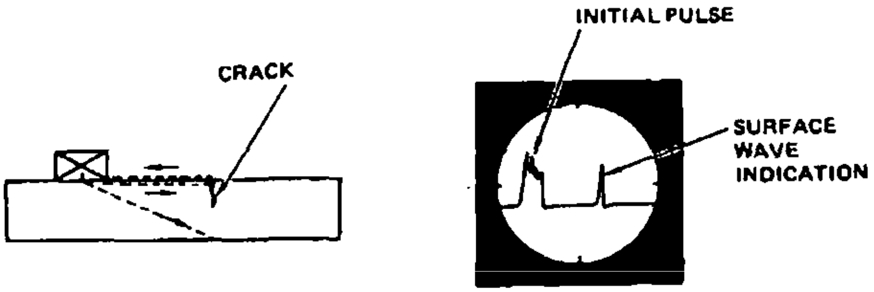


Figure 6.4(20). Surface crack indication using angle-beam technique.

With pitch-and-catch testing, using two transducers, the initial, or transmitted, pulse does not interfere with reception, as it does when using the single transducer. Figure 6.4(21) shows the indications received from a relatively thin, test specimen using two transducers. Paired angle-beam transducers are used to improve near-surface resolution. The transit time of the soundbeam when passing through the Lucite wedge on which the transducers are mounted gives an additional advantage in that the initial pulse is moved to the left in the same way the water-path separation occurs in immersion testing.

A serious problem with pitch-and-catch testing is changes in coupling efficiency. Unless a back echo is monitored, there is no way to know that coupling efficiency is changing or that the coupling is lost. This is why pitch and catch testing is not popular.

Figure 6.4(22) shows an indication from a discontinuity which lies only 0.02 inch below the surface of the material. Often, the best way to detect the presence of flaws just below the front surface is to first bounce off the back surface and then monitor.

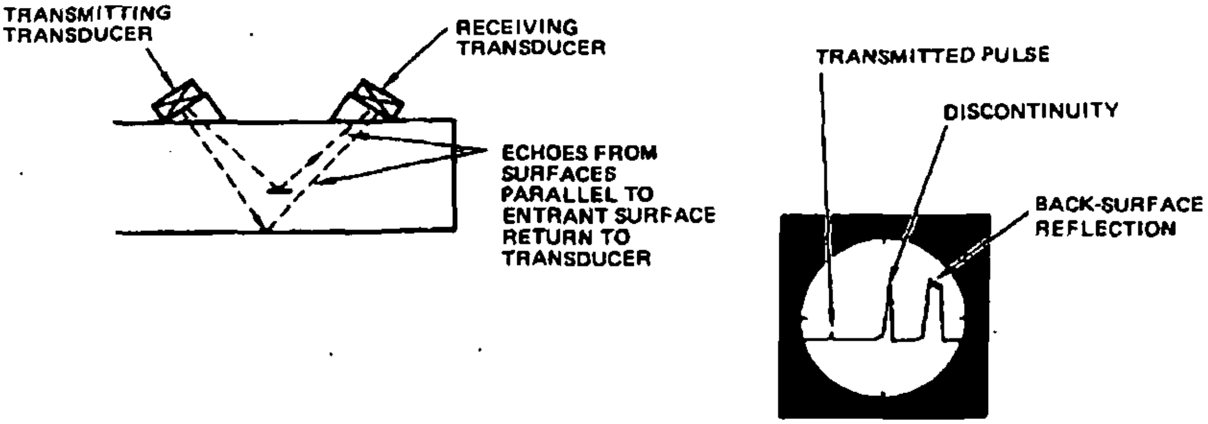


Figure 6.4(21). Two-transducer indications.

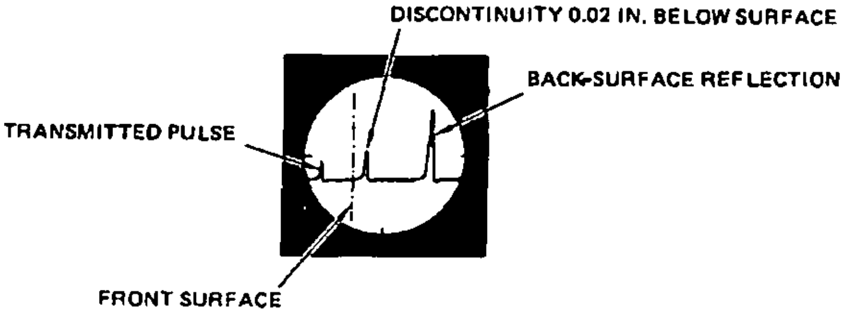


Figure 6.4(22). Indication of near-surface discontinuity.

2. Dead-Zone Indications. A dead zone exists directly beneath the front surface from which no reflections are displayed because of obstruction by the initial pulse. In most contact testing, the initial pulse obscures the front-surface indications as shown in Figure 6.4(23). Near-surface discontinuities may be difficult to detect with straight-beam transducers, because of the initial-pulse interference. Shortening the initial pulse may be effective when near-surface discontinuities are obscured by the ringing "tail" of the initial pulse. Figure 6.4(24) shows a comparison of long narrow band and short pulses broadband applied to the test specimen where the discontinuity is near the surface. In immersion testing, the initial pulse is separated from the front-surface pip by the water path. Only by inserting a standoff, such as a plastic block, can separation of these responses be achieved in contact testing. The material in the dead zone can be ultrasonically interrogated after bouncing off back surface.

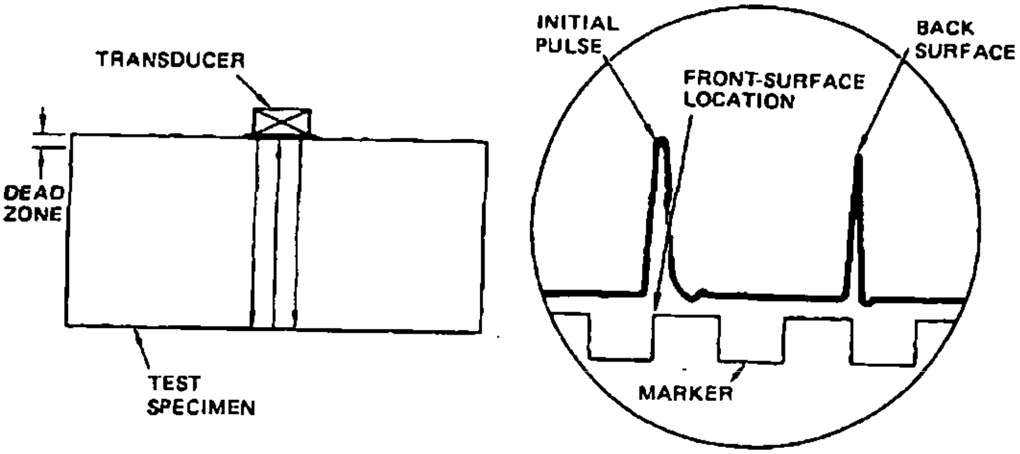


Figure 6.4(23). Dead-zone interference.

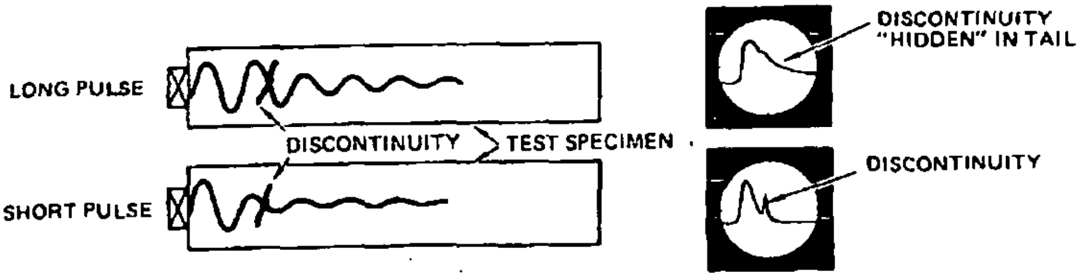


Figure 6.4(24). Long and short pulse effects on display.

3. Nonrelevant Indications. Coarse-grained material causes reflections or "hash" across the width of the display as shown in Figure 6.4(25), when the test is attempted at a high frequency. To eliminate or reduce the effect of these unwanted reflections, lower the frequency or change the direction of the beam by using an angle-beam transducer.

Figure 6.4(25). Coarse grain indications.

When testing cylindrical specimens (especially when the face of the transducer is not curved to fit the test surface), additional pips following the back-surface echo will appear as shown in Figure 6.4(26).

In testing long specimens, mode conversion occurs from the soundbeam striking the sides of the test specimen and returning as reflected shear waves as shown in Figure 6.4(27). Changing to a larger diameter transducer will lessen this problem.

Surface waves generated during straight-beam testing also cause unwanted nonrelevant indications when they reflect from the edge of the test specimen as shown in Figure 6.4(28). This type of nonrelevant indication is easily identified since movement of the transducer will cause the indication from the surface wave to move across the display with the movement of the transducer. When testing with two angle-beam transducers, it is possible to have a small surface-wave component of the soundbeam transmitted to the receiving unit as shown in Figure 6.4(29). This type of unwanted reflection is easily recognized by varying the distance between the transducers and watching the indication; when the distance is increased, the apparent discontinuity indication moves away from the initial pulse.

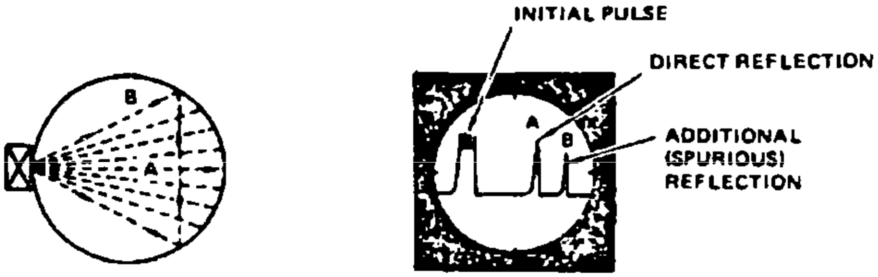


Figure 6.4(26). Nonrelevant indication from cylindrical specimen.

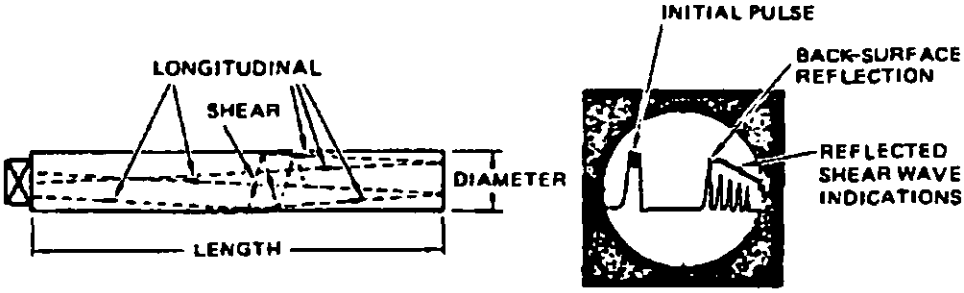


Figure 6.4(27). Nonrelevant indication from long bar specimen.

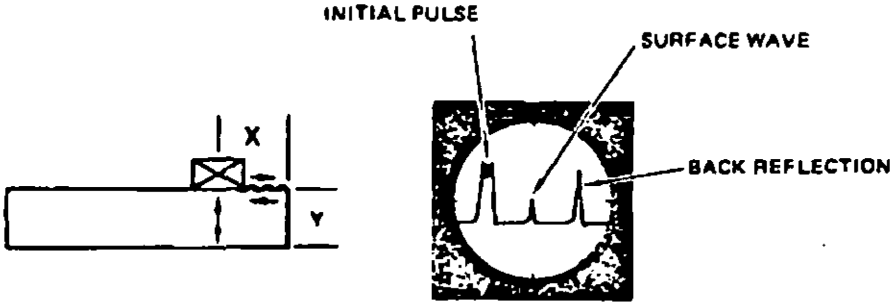


Figure 6.4(28). Nonrelevant surface-wave edge reflection.

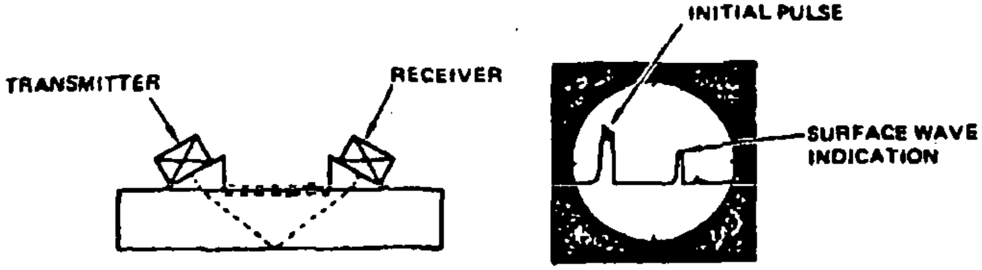


Figure 6.4(29). Nonrelevant surface-wave indication with two transducers.

When using angle-beam transducers, a certain amount of unwanted reflections are received from the wedge. These indications appear immediately following the initial pulse as shown in Figure 6.4(30). The reflections from within the wedge are easily identified because they are still present on the display when the transducer is lifted off the test specimen.

With continued use, the crystal in the transducer may come loose or fracture. When this happens, the indication is characterized by a prolonged ringing which adds a "tail" to the initial pulse as shown in Figure 6.4(31). As the prolonged ringing effect results in a reduced capability of the system to detect discontinuities, the transducer is discarded or repaired.

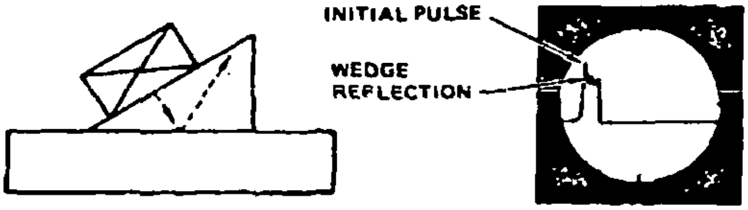


Figure 6.4(30). Nonrelevant indication from plastic wedge.

Figure 6.4(31). Nonrelevant indication from loose transducer crystal.

6.4.6 NEWEST PROCEDURES AND TECHNIQUES

For many years, several new methods of ultrasonic testing have been developed. Detailed discussions of these new methods will not be presented, but brief descriptions will be given.

6.4.6.1 Acoustic Emissions

Acoustic emissions is an ultrasonic test method. However, no active search beam or other external ultrasonic energy source is used. Acoustic emissions use transducers that detect ultrasonic pulses that are produced within the material. Normally, these pulses are produced because of induced stresses within the material, and are caused by localized displacements that result from these stresses. Therefore, acoustic emissions must normally be used in conjunction with some other test where changes in temperatures or loads are producing stresses and strains within the material. By triangulation, the location of the sources of these pulses can usually be determined; and by analyzing their relative magnitudes or other characteristics, the nature of the source can sometimes be characterized. Some basic requirements of acoustic emissions are: first, the nature of the material must be such that ultrasonic pulses are produced. This seems to be common for most materials, especially where internal defects are present, which are especially prone to the generation of mechanical slippages and dislocations. Second, the material must adequately transmit the ultrasonic energy from the source to the transducers. Third, external noise from test apparatus or other sources must be separable from the sources within the material. Last of all, some correlation or other meaning must be developed with the characteristics of the signals unless location or time correlations are the only parameters of interest.

Since some of these requirements are not always met, acoustic emissions is not always successful. There are many situations, however, where acoustic emission testing is the most useful or the only possible method. Today, the testing of arm booms made of composite materials and nuclear pressure vessels are extensively done with acoustic emissions.

One of the greatest problems with acoustic emissions is the detection system. Present day acoustic emission transducers do not in general record the true fidelity of the internal ultrasonic pulses, but merely ring at their own natural frequency. Therefore, scientific correlations between the detected signal and the source are limited.

6.4.6.2 Resonance or Acousto-Ultrasonics

Many ultrasonic testing devices inject ultrasonic energy into a part and measure the changes produced in the standing waves or reflections established within or between the material and the transducer. In some cases, these changes include both phase and amplitude parameters. These test methods do not normally "image" a defect or other variable, but usually reflect the total response of the test region. Because the response is a general response, it is capable of easy interpretation, but for the same reason, it cannot always provide the details that may be desired. In acousto-ultrasonics, changes in the injected ultrasonic signal, as it travels from one transducer to another, are used as a correlation parameter. Again, no "imaging" of defects is produced by these test methods, but they can often generalize the material in such a way that very effective test measurements are established.

6.4.6.3 Scanning Laser Acoustic Microscope (SLAM)

This method uses high frequency (30 to 500 MHz) ultrasonic waves that are transmitted through a specimen to an image plane. The image plane can be the surface of the specimen or any light reflective surface acoustically connected to the specimen. The ultrasonic waves extend over the entire image area and form a pattern on the image plane that is a function of the acoustic variables within the imaged area. This pattern is detected by a scanning laser beam and displayed in real time on a CRT screen. Because of the high frequencies, very small variables can be detected, as small as 5μm, at the 500 MHz range. However, the penetration depth is also limited by the high frequency, and thus this method is fairly limited to small specimens.

6.4.6.4 Ultrasonic Holography

Ultrasonic holography is another real time inspection system which uses a laser beam to detect an ultrasonic hologram formed on a liquid surface. The ultrasonic hologram is formed by the interference of two ultrasonic beams, one of which has been transmitted through the specimen. Adaptations of this method presently include methods that allow electrical signal references and nonimmersion techniques.

6.5 STANDARDS

In ultrasonic testing, discontinuity indications are normally compared to indications received from testing a reference standard. The reference standard may be any one of many reference blocks, or sets of blocks, specified for a given test or it may be an actual part to be tested containing a known natural or simulated flaw. Standards made from such parts are hard to beat in production. When standards can be used to check the accuracy of the ultrasonic inspection, just feed the standard into the test equipment. Observe that it is rejected, and remove the standard from the production line. Extreme caution must be exercised to remove the part or parts from the production line. In comparison, ultrasonic standard reference blocks are more useful in a laboratory. Reference blocks are flexible but slow in use.

Ultrasonic standard reference blocks, often called test blocks, are used in ultrasonic testing to standardize the ultrasonic equipment and to evaluate the discontinuity indication received from the test part. Standardizing does two things: it verifies that the instrument/transducer combination is performing as required; it establishes a sensitivity, or gain setting at which all discontinuities of the size specified, or larger, will be detected. Evaluation of discontinuities within the test specimen is accomplished by comparing their indications with the indication received from an artificial discontinuity of known size, and at the same depth, in a standard reference block of the same material.

Standard test blocks are made from carefully selected ultrasonically inspected stock that meets predetermined standard of ultrasonic attenuation, grain size, and heat treat. Discontinuities are represented by carefully drilled flat-bottomed holes. Test blocks are made and tested with painstaking care so that the only discontinuity present is the one that was added intentionally. The three most familiar sets of reference blocks are the Alcoa-Series A, area amplitude blocks; the Alcoa-Series B, or Hitt, distance/amplitude blocks; and the ASTM basic set of blocks that combine area/amplitude and distance/amplitude blocks in one set.

6.5.1 AREA/AMPLITUDE BLOCKS SET

The Alcoa Series A set consists of eight blocks, each 3-3/4-inches long and 1-15/16-inches square. A 3/4-inch deep, flat-bottomed hole (FBH) is drilled in the bottom center of each block. The hole diameters are 1/64-inch in the No. 1 block through 8/64-inch in the No. 8 block, as shown in Figure 6.5(1). As implied, the block numbers refer to the FBH diameter; e.g., a No. 3 block has a 3/64-inch diameter FBH.

Area/amplitude blocks provide a means of checking the linearity of the test system; that is, they confirm that the amplitude (height) of the indication on the oscilloscope screen increases in proportion to the increase in size of the discontinuity. Similar area/amplitude reference blocks are made from 2-inch diameter round stock.

6.5.2 DISTANCE/AMPLITUDE BLOCKS SET

The set of Alcoa Series B, or Hitt, blocks consists of nineteen, 2-inch diameter, cylindrical blocks, all with 3/4-inch deep FBH of the same diameter drilled in the center at one end. These blocks are of different lengths to provide metal distances of 1/16-inch to 5-3/4 inches from the test surface to the FBH. Sets with 3/64-, 5/64-, or 8/64-inch diameter holes are available. The metal distances in each set are 1/16-inch, 1/8-inch through 1-inch in eighth-inch increments, and 1-1/4 inch through 5-3/4 inch in half-inch increments, as shown in Figure 6.5(2).

Distance/amplitude blocks serve as a reference by which the size of discontinuities at varying depths within the test material may be evaluated. They also serve as a reference for setting or standardizing the sensitivity, or gain, of the test system so that the system will display readable indications on the oscilloscope screen for all discontinuities of a given size and over, but will not flood the screen with indications of smaller discontinuities that are of no interest. On instruments so equipped, these blocks are used to set the sensitivity time control (STC) or distance amplitude correction (DAC) so that a discontinuity of a given size will produce an indication of the same amplitude on the oscilloscope screen regardless of its distance from the front surface.

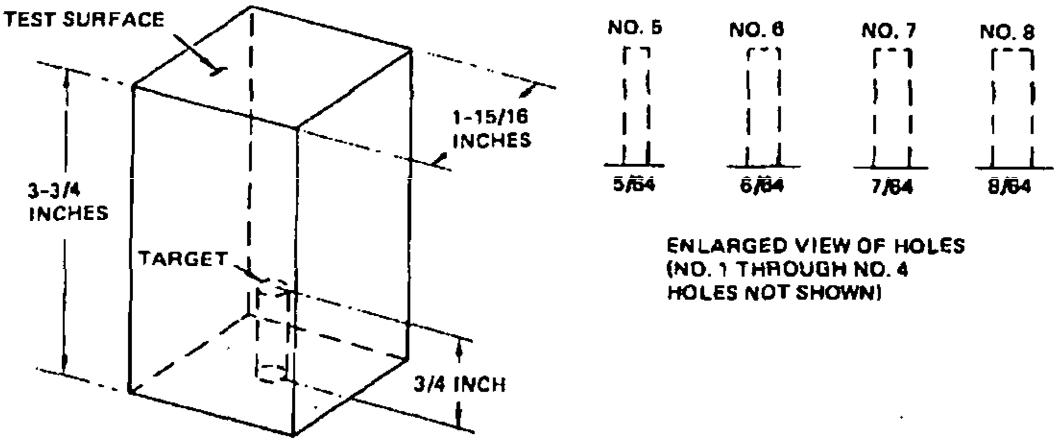
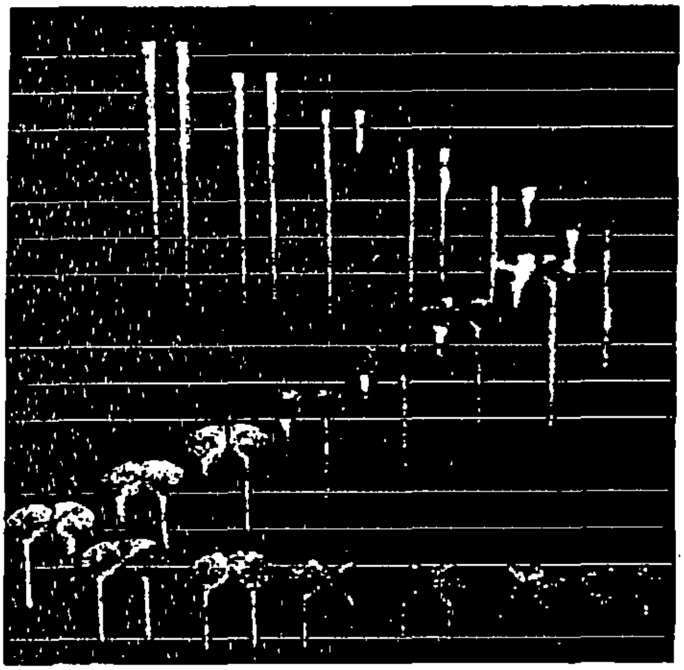
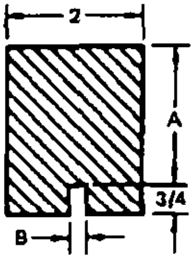


Figure 6.5(1). Area/amplitude reference blocks.





DIMENSION A	
1/16	1 3/4
1/8	2 1/4
1/4	2 3/4
3/8	3 1/4
1/2	3 3/4
5/8	4 1/4
3/4	4 3/4
7/8	5 1/4
1	5 3/4
1 1/4	

DIMENSION B
3/64
5/64
8/64

Figure 6.5(2). Distance/amplitude reference blocks (Hitt).

6.5.3 BASIC BLOCKS SET

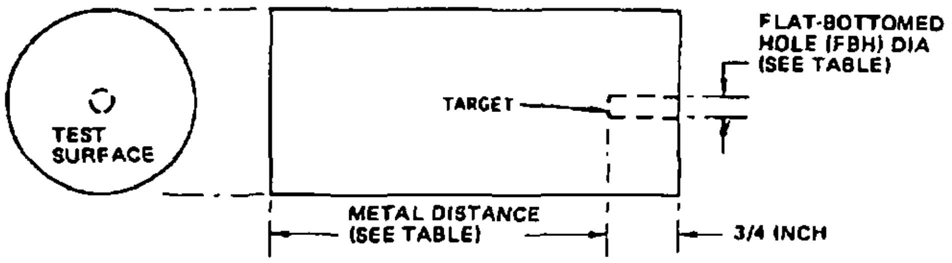
The ASTM basic set shown on Figure 6.5(3) consists of ten, 2-inch diameter blocks that have 3/4-inch deep, FBH drilled in the center at one end. One block has a 3/64-inch diameter FBH and a metal distance of 3 inches from the test surface to the FBH. The next seven blocks each have a 5/64-inch FBH but metal distances are 1/8, 1/4, 1/2, 3/4, 1-1/2, 3, and 6 inches from the test surface to the FBH. The two remaining blocks each have an 8/64-inch diameter FBH and metal distances of 3 inches and 6 inches. In this basic set, the three No. 3, 5, and 8 blocks with the 3-inch metal distance, provide the area/amplitude relationship, and the seven blocks with the 5/64-inch diameter FBH (No. 5) and varying metal distances, provide the distance/amplitude relationship.

It is important that the test block material be the same, or similar to, that of the test specimen. Alloy content, heat treatment, degree of hot or cold working from forging, rolling, etc., all affect the acoustical properties of the material. If test blocks of identical material are not available, they must be similar in ultrasonic attenuation, velocity, and impedance.

6.5.4 SPECIAL BLOCKS

The International Institute of Welding (IIW) reference block and the miniature angle beam field calibration block, shown in Figure 6.5(4) are examples of other reference standards in common use.

For irregularly shaped articles, it is often necessary to make one of the test articles into a reference standard by adding artificial discontinuities in the form of flat-bottomed holes, saw cuts, notches, etc. In some cases, these artificial discontinuities can be placed so that they will be removed by subsequent machining of the article. In other cases, a special individual standardizing technique is developed by carefully studying an article ultrasonically, and then verifying the detection of discontinuities in the article, by destructive investigation. The results of the study then become the basis for the testing standard.



METAL DISTANCE, INCHES	1/8	1/4	1/2	3/4	1-1/2	3	3	3	6	6
FBH DIA IN 64THS INCH	5	5	5	5	5	3	5	8	5	8

Figure 6.5(3). ASTM reference blocks, basic set.

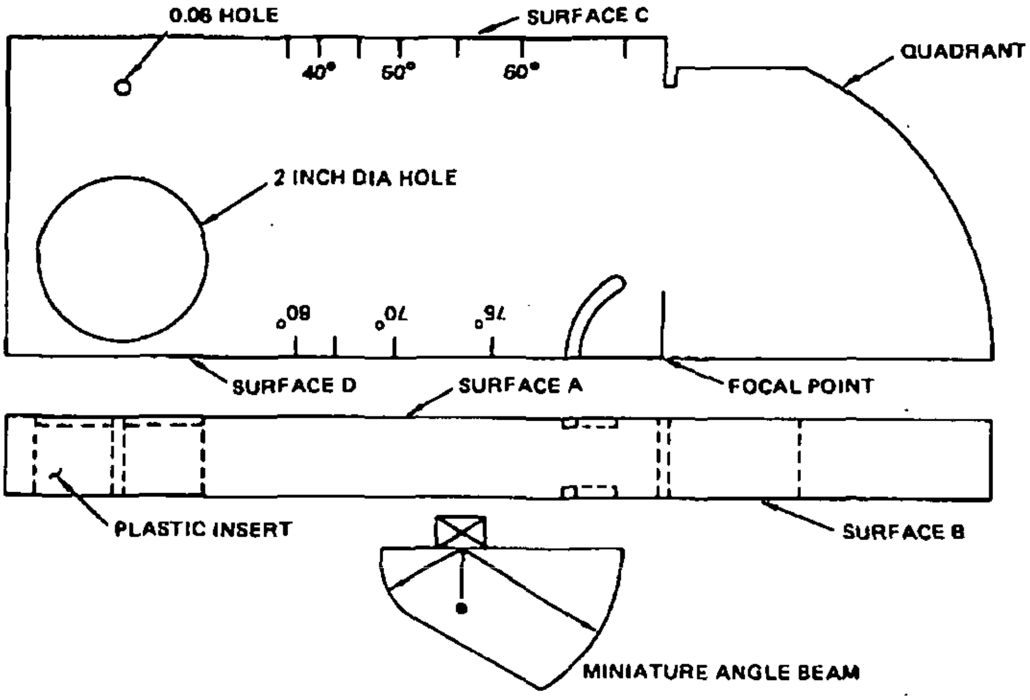


Figure 6.5(4). Special reference blocks.

6.5.5 TYPICAL CALIBRATION PROCEDURE

A typical calibration procedure is outlined in the paragraphs that follow. The procedures assume conditions and equipment as follows:

a. Test Instrument. Any of several commercially available pulse-echo ultrasonic testing instruments.

b. Test Frequency. The test frequency shall be 15 MHz.

c. Transducer. A quartz immersion transducer of 3/8-inch diameter with an operational frequency of 15 MHz.

d. Power Source. Line voltage with regulation ensured by a voltage regulating transformer.

e. Immersion Tank. Any container that holds couplant and is large enough to allow accurate positioning of the transducer and the reference block is satisfactory.

f. Couplant. Clean deaerated water is used as a couplant. The same water, at the same temperature, is used when comparing the responses from differing reference blocks.

g. Bridge and Manipulator. The bridge is strong enough to support the manipulator and rigid enough to allow smooth, accurate positioning of the transducer. The manipulator adequately supports the transducer and provides fine angular adjustment in two vertical planes normal to each other.

h. Reference Blocks. An area/amplitude set and a distance/amplitude set of reference blocks are required. (A basic set which combines both area and distance responses may be used; for example, the ASTM basic set consisting of ten reference blocks. For area/amplitude relationships use blocks containing a 3-inch metal distance and 3/64-, 5/64-, and 8/64-inch diameter holes. For distance/amplitude relationships use blocks of varying length which contain 5/64-inch diameter holes.)

i. Fundamental Reference Standard. When calibrating area/amplitude responses of the test set, an alternate to the reference blocks described in the preceding step is a set of 15 steel balls, free of corrosion and surface marks and of ball-bearing quality, ranging in size from 1/8- to 1-inch diameter in 1/16-inch increments. A suitable device, such as a tee pin, is necessary to hold each ball.

Area/Amplitude Check

The linear range of the instrument is determined by obtaining the ultrasonic responses from each of the area/amplitude-type reference blocks (the steel balls may be used as an alternate for the reference blocks) as follows.

a. Place a No. 5 area/amplitude reference block (a block containing a 5/64-inch diameter hole) in the immersion tank with the drilled hole down. Position the transducer over the upper surface of the block, slightly off-center, at a water distance of 3 inches within a + or - tolerance of 1/32-inch, between the face of the crystal and the surface of the block. This accurate distance is obtained by using a gage between the block and the transducer

b. Adjust the transducer with the manipulator to obtain a maximum pip height from the front-surface reflection of the block. This indication proves that the soundbeam is perpendicular to the top surface of the block. A maximum number of back-surface reflection pips serves the same purpose.

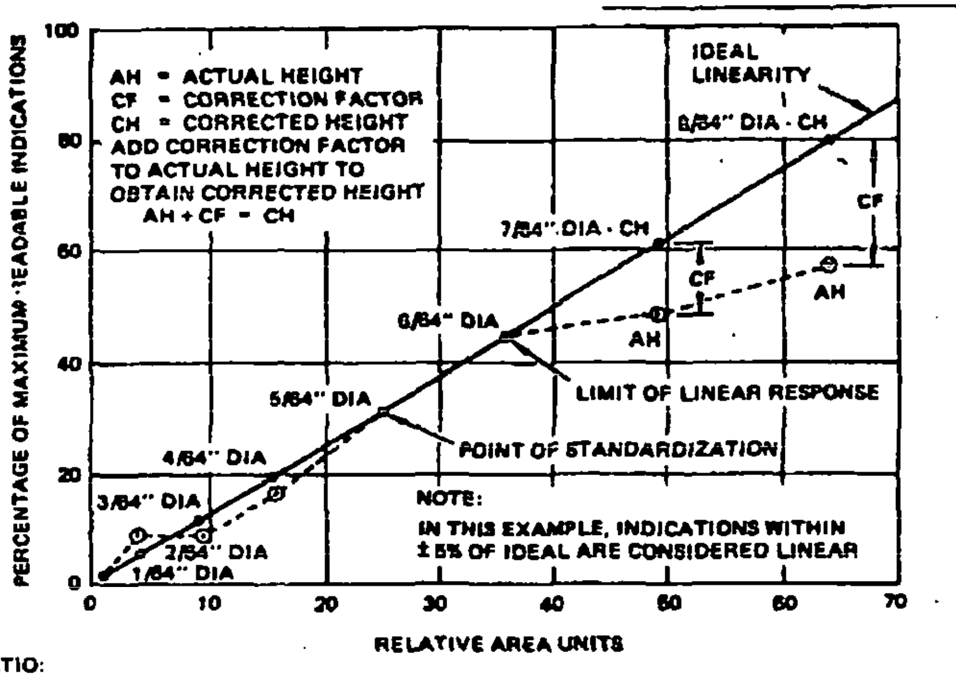
c. Move the transducer laterally until the maximum response is received from the FBH.

d. Adjust the instrument gain control until the hole pip height is 31 percent of the maximum obtainable on the cathode ray tube screen. Do not repeat this step for the remaining blocks in the set.

e. Replace that reference block with each of the other blocks in the set. Repeat steps b and c for each block and record the indications. Maintain a water distance of 3 inches for each block except for the No. 7 and No. 8 blocks, which require a water distance of 6 inches.

f. Plot a curve of the recorded indications as shown in Figure 6.5(5). In the example shown, the point where the curve of responses deviates from a straight line defines the limit of linearity in the instrument. Amplitudes plotted below the limit of linear response (in this example) are in the linear range of the instrument and no correction is required. Amplitudes of indications above the limiting point are in the non-linear range and are increased to the ideal linearity curve. This is done by projecting a vertical line upward from the actual height of indication until the ideal curve is intercepted. The point of interception defines the corrected height (CH) of indication in percent of maximum amplitude that the instrument can display. The difference between the corrected height (CH) and the actual height (AH) is the correction factor (CF). For each indication that appears in the non-linear range a different correction factor (CF) is plotted because the deviation is not constant. When the actual indication height is displayed, the corrected indication height is computed by adding the correction factor directly to the actual indication height as follows:

$$AH + CF = CH$$



RATIO:
1/64TH = 1, 2/64TH = 4, 3/64TH = 9, 4/64TH = 16, 5/64TH = 25, 6/64TH = 36, 7/64TH = 49 AND 8/64TH = 64. DYNAMIC RANGE: 64 TO 1, INTERMEDIATE PIP HEIGHTS IN PROPORTION)

Figure 6.5(5). Typical area/amplitude response curve.

g. The linear range of the instrument may also be determined by recording the ultrasonic responses from the back-surface of each of 15 steel balls ranging in size from 1/8- to 1.0-inch in diameter in 1/16-inch increments. The immersion method is used following previous steps a through f, except that in step d, the instrument gain control is adjusted until the pip height is 50% of the maximum obtainable on the oscilloscope screen with the transducer positioned over the 1/2-inch diameter steel ball. For each ball, the water distance is maintained constant at 3 ± 1/32 inch and the transducer is positioned for maximum response from each ball. The recorded indications are plotted on a curve as shown in Figure 6.5(6).

Distance/Amplitude Check

The distance/amplitude characteristics of the instrument are determined by obtaining the ultrasonic responses from each of the reference blocks in a set of blocks of varying metal distance with a 5/64-inch diameter hole in each block. The resultant indications are recorded on a curve as outlined in the following procedure.

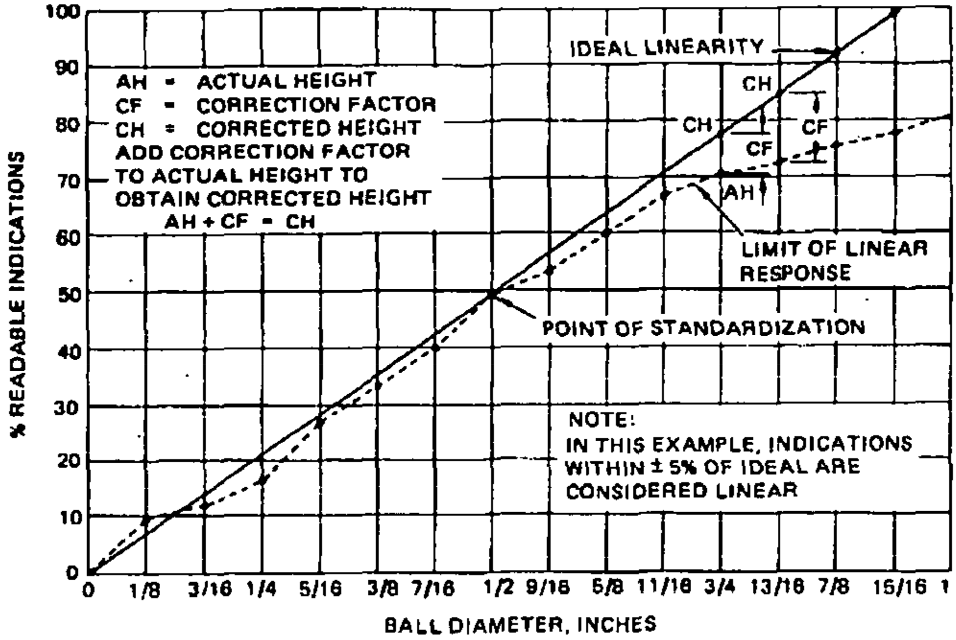


Figure 6.5(6). Steel ball area/amplitude response curve.

a. Select a reference block containing a 5/64-inch FBH hole with a metal distance of 3.000 inches from the top surface to the hole bottom and place it in the immersion tank. Position the transducer over the upper surface of the block, slightly off-center, at a water distance of 3 inches between the face of the transducer and the surface of the block. Adjust this distance accurately, within a + or - tolerance of 1/32 inch, by using a gage between the block and the transducer.

b. Adjust the transducer with the manipulator to obtain a maximum pip height from the front-surface reflection of the block. This indication proves that the soundbeam is perpendicular to the top surface of the block. A maximum number of back-surface reflections serves the same purpose.

c. Move the transducer laterally until the maximum response is received from the FBH. Adjust the instrument gain control until the pip height is 25% of the maximum obtainable on the cathode ray tube screen.

d. Replace that reference block with each of the other blocks in the set. Repeat steps b and c for each block and record the indications. Maintain water distance of 3 inches for each block.

e. Plot a curve of the recorded indications as shown in Figure 6.5(7). In the example shown, the near field (fresnel) zone extends from the 1/2-inch metal distance indication to the 2-inch metal distance indication. As the metal distance increases beyond 2 inches, the indications attenuate, or decrease, in height.

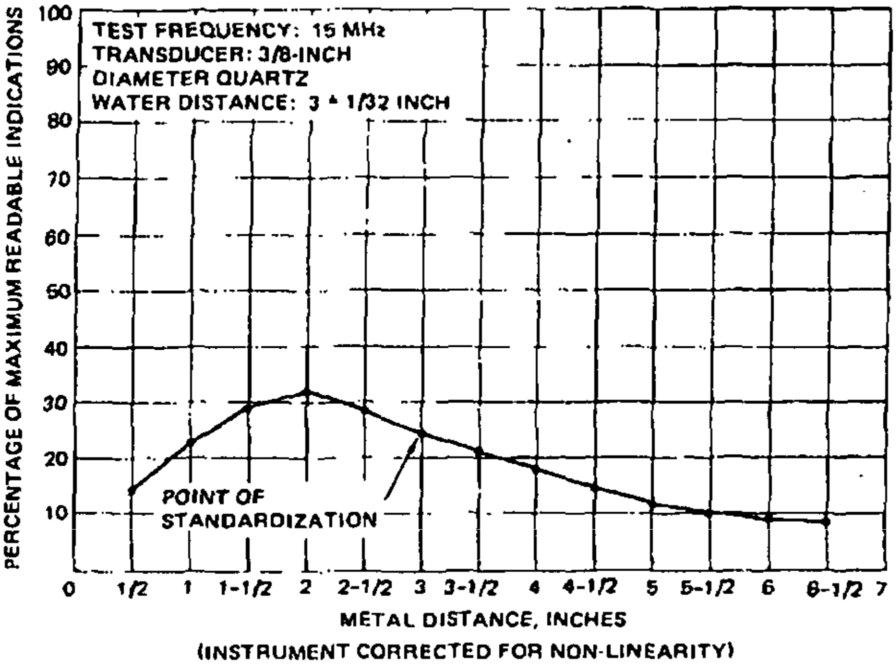


Figure 6.5(7). Typical distance/amplitude response curve.

Transducer Check

To improve accuracy during test equipment calibration, the characteristics of the transducer, as modified or distorted by the test instrument, are determined by recording a distance/amplitude curve from a 1/2-inch diameter steel ball immersed in water. A beam pattern, or plot, can also be obtained from the same steel ball at a fixed water-distance of 3 inches. It is well to remember that the curve and beam plot recorded in this procedure are not valid if the transducer is subsequently used with any test instrument other than the one used in this procedure. A complete analysis of transducer characteristics cannot be accomplished with the commercial ultrasonic testing equipment used in this procedure. To ensure maximum accuracy, the transducer may be calibrated with special equipment. In the procedure that follows, the apparatus used for checking the transducer is the same as that prescribed in the previous paragraphs for calibrating the instrument with reference blocks. The manipulator is set to allow a range in water distance of 0 to at least 6 inches from the face of the transducer to the ball surface.

a. Adjust the instrument gain control until the pip height is 50% of the maximum obtainable on the oscilloscope screen with the transducer positioned at a water distance of 3 ± 1/32 inch from the face of the transducer to the top surface of the ball. Exercise care in producing a true maximum indication by locating the transducer beam center on the center of the ball. Record this point of standardization.

b. After standardizing the instrument, set the water distance at 1/4 inch. Again, exercise care in using the manipulator to locate the transducer beam center on the center of the ball. Record the maximum indication. Do not readjust the instrument gain control in this or succeeding steps of the procedure.

c. Vary the water distance in 1/8-inch increments through a range of 1/4 to 6 inches. Record the maximum indication for each increment of water distance, using care each time the transducer is moved back that the beam center remains centered on the ball.

d. As shown in Figure 6.5(8), plot the recorded indications (corrected for any non-linearity) on a graph to demonstrate the axial distance/amplitude response of the transducer and particular test instrument used in the test.

e. Determine the transducer beam pattern by relocating the manipulator to obtain a 3 ± 1/32-inch water distance from the 1/2-inch diameter steel ball to the face of the transducer. While scanning laterally, 3/8-inch total travel, the height of the indication from the ball is observed while the transducer passes over the ball. Three distinct lobes or maximums are observed. The symmetry of the beam is checked by making four scans; displacing each scan by rotating the transducer in its mounting 45 degrees. The magnitude of the side lobes should not vary more than 10% about the entire perimeter of the ultrasonic beam. An acceptable transducer will produce a symmetrical beam profile which has side lobes with magnitudes no less than 20%, nor more than 30%, of the magnitude of the center lobe. The beam pattern or plot of an acceptable transducer is shown in Figure 6.5(9).

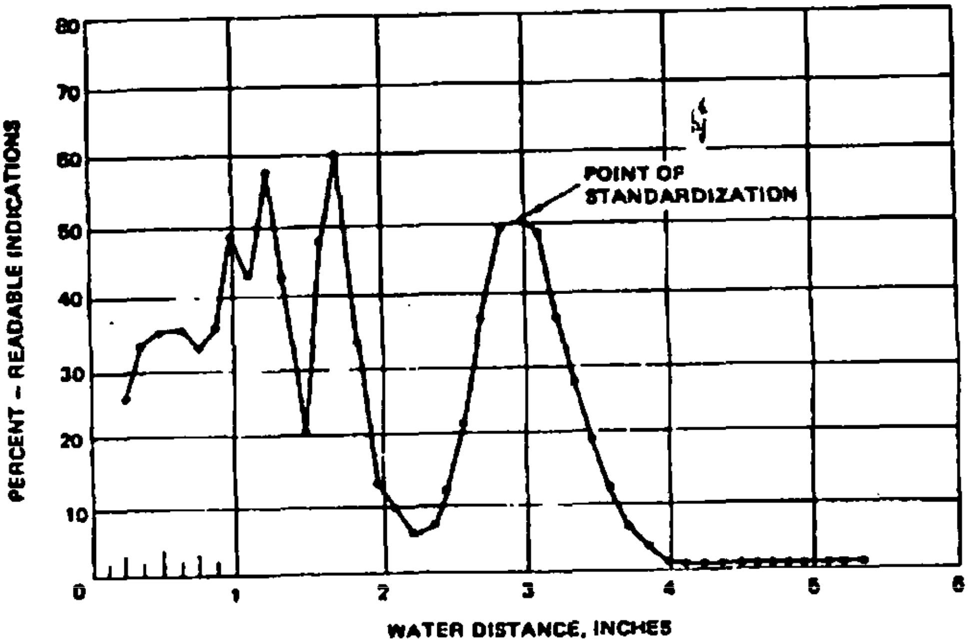


Figure 6.5(8). Transducer axial distance/amplitude characteristics.

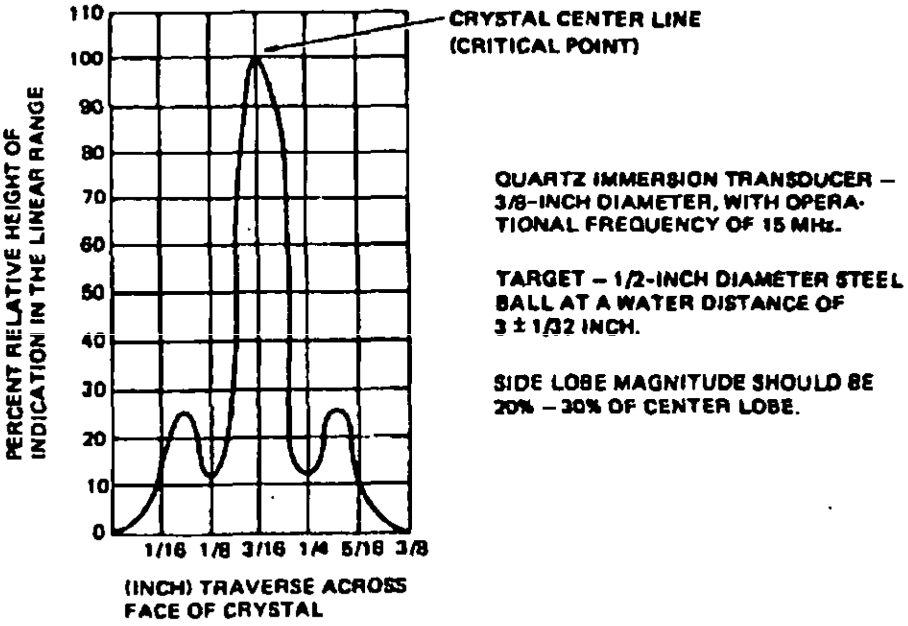


Figure 6.5(9). Transducer beam pattern.

6.6 APPLICATIONS

Ultrasonic examination is used in a wide range of applications. The principal one is the detection of internal flaws in most engineering metals and alloys. Bonds produced by welding, brazing, soldering and adhesive bonding can be ultrasonically inspected.

The flaws to be detected include voids, cracks, inclusions, pipe, laminations, bursts and flakes. They may be inherent in the new material, may result from fabrication and heat treatment, or may occur in service from fatigue, corrosion or other causes.

Ultrasonics can also be used to measure thickness of metal sections. Structural material from a few thousandths of an inch to several feet in thickness can be measured to accuracies better than 1%.

Special ultrasonic techniques and equipment have been used on such diverse problems as the rate of growth of fatigue cracks, detection of bore hole eccentricity, measurement of elastic moduli, study of press fits, determination of nodularity in cast iron, and metallurgical research on phenomena such as structure, hardening, and inclusion count in various metals.

Ultrasonic examination can be used to detect both large and small discontinuities located either at the surface or deep within the part. The part can be made of a ferrous or nonferrous metal or of a nonmetal. Testing can be done by manual scanning or can be fully automated, with either visual interpretation or permanent recording of results. Ultrasonic examination can be performed on either flat or curved surfaces, and can be performed when only one surface of a part is accessible, even when the area to be inspected is remote from the accessible surface.

The only limitations in its applications for materials are usually foams, where high porosity exists, or for materials where high damping exists (certain corks, rubbers, etc.). Geometric limitations exist in terms of part designs, orientations, surface finishes, etc.

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6.7 SPECIFIC GUIDELINES

Ultrasonic testing, as all NDT methods, requires wise applications with full knowledge of the limitations involved. The following guidelines can be of value only as they can be intelligently applied to each individual problem.

6.7.1 GUIDELINE FOR DESIGNERS

Designers should know the following: choosing the proper specifications for NDT is important, but most specifications such as MIL-I-6870 and MIL-STD-2154 are general and do not provide the details required to actually perform an inspection. Some designers believe that with the choice of a specification, everything else is automatic. Close communications must be established with QA and materials and testing engineers to ensure that the details and decisions required after a general specification is chosen will accomplish the original intent of the design. In ultrasonics, the cost of calibrating and standardizing normally increases as the limit in the size of flaws to be detected decreases. If the minimum defect size approaches the inspection beam size, and especially if it approaches wavelength size, extensive correlations may be required before the ultrasonic testing can be effective. Therefore, when tight specifications are required, the design engineer must become aware of these costs and give guidance to possible trade-offs. Ideally, changes in design that reduce inspection costs should be made early. This cannot occur unless the designer has personally taken the interest necessary to understand these choices.

The designer should read section 6.4.4 on reference standards and section 6.4.5 on interpretations of indications where it is pointed out that standards and calibrations are valid only to the degree that the standards match the alloy, shape, and acoustic property of the specimen. When designers are able to place one or more artificial reflectors in their design to represent critical flaw sizes, then the NDT inspection has a standard that is exactly the same alloy, shape, and acoustic property, since it is the part itself that is being used. This approach saves much calibration time and increases the reliability of the inspection. Designers, if they consider these possibilities early in the design phase, can often accomplish this at far less cost than that required to inspect without them.

6.7.2 GUIDELINE FOR PRODUCTION ENGINEERS

Ultrasonic inspection is extensively used by production engineers, to inspect raw materials before they are processed, to inspect parts during their fabrication, and to actually control some of their machine operations. Coordinations of the inspections of the parts during their fabrications are usually made with QA. In some large operations, all materials are originally brought and inspected at a standard quality level. Then portions of that material may later be needed where a higher quality level may be required. Reinspection is then performed to "upgrade" the material for this new use. This effort of inspecting quality "into" a part is rarely successful and should be brought to a designer's attention when this occurs.

6.7.3 GUIDELINES FOR QA PERSONNEL

Ultrasonics, especially where C-scans are produced with a direct "black and white" readout, can often be assumed to be real. That is, images seen on the scan (indications) are often assumed to be the images of the flaws or of variables in the material. The images formed by ultrasonics, especially for small dimensional shapes, are very non-linear and thus indication images cannot be used as flaw images except through proper calibration and the interpretations that it can provide.

Many times, QA must work with both NDT research engineers and NDT production engineers. They need to understand that basic differences can exist between these disciplines. The production engineers are paid to run efficient inspections, and this requires maximum inspection rates that just barely allow detection of the smallest unacceptable flaws. This approach and orientation rarely provide maximum inspection information. At the same time, one in a research environment, trained to maximize the inspection information, should not routinely be used by QA to determine acceptable production rates. A need often exists for input from both, and a clear understanding of their differences in background should be recognized and appreciated.

6.7.4 GUIDELINES FOR NDT ENGINEERS

In ultrasonics, the NDT Engineer has a duty to explain and instruct those interested in the results, of the limitations and interpretations of the results. Where a pulse-echo method is employed, as an example, the equipment sends out a wave pulse and listens for an echo. When an echo is received, the machine does not know why an echo is received. The machine cannot know what caused the echo to be returned. Only the operator, with his knowledge of the situation, his knowledge of the part being inspected, and his ability to weigh various possibilities, is in a position to make an immediate interpretation. Because of multiple reflections, standing waves, interference patterns, near-field effects, and a multitude of non-linear interactions that can occur in ultrasonics, proper interpretations are critical. The NDT Engineer has the greatest responsibility in seeing that these interpretations are correct and are properly used.

6.7.5 GUIDELINES FOR NDT TECHNICIANS

Technicians must stay alert to changes in their equipment. In ultrasonics, the equipment is complicated, both electronically and mechanically. The final results are based upon a series of interdependent operations, and therefore the results are almost always being affected in some small degree first in one direction and then another. Transducers can age. What was a good transducer yesterday may not be a good one today. Noting small differences is often important. In ultrasonics, where immersion test methods are conducted, the presence of air bubbles will be one of the biggest problems. There is much air in water (that is why fish can live in water) and the amount of air in the water depends upon its temperature. Air bubbles can appear even though care is used to originally place a part in water without any air bubbles attached.

Air bubbles can actually grow, collecting air from the water itself. This especially occurs if fresh water has just come from a cold, high pressure source, or the part is warmer than the water, or the average temperature of the water is increasing. These problems also depend upon the interfacial energy relationship between the water and the material and whether there are "nucleation" sites upon which the bubbles can grow. Therefore, some parts may never have these problems, and others will always have these problems. They are common enough, though, that they should always be watched for and care exercised that they do not produce false indications. Properly designed standards will reveal many of the ultrasonic test problems that can occur during production inspection.

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6.8 SAFETY

Standard laboratory safety procedures for the handling of electrical equipment are applicable to almost all ultrasonic systems. The transducers are often in circuits that use 300 to 1000 volts. Proper grounding and insulation should always be employed. Where automatic scanning devices are employed, great care must be exercised to protect personnel from moving belts or drives and of being caught between moving parts. There should also be safety switches and position limit switches to ensure that moving machinery does not go beyond certain safe limits. In large operations or the inspection of large parts, safety in the handling of the inspected parts cannot be overlooked. Many times large hoists or cranes are involved, and methods of placing and adjusting heavy parts must be checked and approved. Large amounts of water, and various additives, are sometimes involved in ultrasonic testing. The unexpected release of these liquids, due to a rupture of the water tank (by accident or otherwise), might be a safety consideration. A fungicide shall be added to an immersion bath to protect the health of the operator.

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6.9 GLOSSARY

AMPLITUDE The vertical pulse height of a received ultrasonic signal, usually base to peak, when indicated by an A-scan presentation.

ANGLE BEAM A wave train introduced into a test object so that the ultrasonic beam axis centerline is at an angle, other than 0 degrees, to the normal to the entry plane of the test object.

ANGLE OF INCIDENCE The angle that the axis of an ultrasonic beam makes with the normal to a surface at the point of incidence.

ANGLE OF REFLECTION The angle that the axis of a reflected ultrasonic beam makes with the normal to a reflecting surface at the point of incidence.

ANGLE OF REFRACTION The angle between the axis of a refracted beam and the line normal to the boundary between two media with different speed of sound.

AREA-AMPLITUDE RESPONSE CURVE A curve showing the changes in the amplitude of ultrasonic response to reflectors of different areas located at equal distances from the search unit in an ultrasonic-conducting medium.

A-SCAN A method of data presentation utilizing a horizontal base line that indicates distance, or time, and a vertical deflection from the base line which indicates ultrasonic amplitude.

ATTENUATION The loss of ultrasonic energy within a medium due to scattering and absorption.

ATTENUATION COEFFICIENT Factor that describes the decrease in ultrasound amplitude with distance in a given medium. Normally expressed in decibels per unit length.

ATTENUATOR A device for altering the amplitude of an ultrasonic signal in known increments, usually decibels.

BACK REFLECTION Indication of the ultrasonic echo from the far boundary of the material under test.

BASELINE The distance/time axis in an A-scan display.

BEAM AXIS The acoustic centerline of an ultrasonic search unit's beam pattern as described by the locus of points of maximum sound pressure in the far field, and its extension into the near field.

BEAM SPREAD A divergence of the ultrasonic wave train as it travels through a medium.

BOTTOM ECHO See Back Reflection.

B-SCAN PRESENTATION A method of data presentation in which the travel time of an ultrasonic pulse is represented as a displacement along one axis, and probe movement (generally rectilinear) is represented as a displacement along the other axis. In the display, reflected pulses are shown in contrast to the background.

BUBBLER A device using a liquid stream to couple an ultrasonic beam to the test piece.

COMPRESSIONAL WAVE See Longitudinal Wave.

CONTACT TESTING A method of testing in which the transducer contacts the test surface, usually through a thin layer of complaint.

CORNER EFFECT The reflection of a sound beam in a direction parallel to an incident beam directed normal to the intersection of two perpendicular planes.

COUPLANT A substance used between the search unit and test surface to permit or improve transmission of ultrasonic energy.

CRITICAL ANGLE The incident angle of the sound beam beyond which a specific refracted or reflected mode of vibration no longer exists.

CRYSTAL See Element, Piezoelectric.

C-SCAN A method of data presentation yielding a plan view of the test object and the discontinuities therein.

DAMPING Limiting the duration of vibration in an ultrasonic search unit by either electrical or mechanical means.

DEAD ZONE Corresponds to the distance in the material from the surface of the test object to the nearest inspectable depth. It is determined by the characteristics of the material, ultrasonic test instrument and search unit.

DECIBEL (dB) Twenty times the logarithmic expression of the ratio of two amplitudes. $dB = 20 \log_{10}$ (amplitude ratio).

DEFECT A discontinuity or group of disconinuities which produce indications that do not meet a specified acceptance criteria.

DELAYED SWEEP A horizontal sweep whose start is delayed in order to prevent the appearance of unwanted early response information on the screen.

DGS-DISTANCE GAIN SIZE Distance amplitude curves permitting prediction of reflector size compared to the response from a back surface reflection.

DISCONTINUITY A detectable interruption in the material which may or may not have undesirable connotations.

DISTANCE AMPLITUDE CORRECTION (DAC) (Swept Gain, Time corrected gain, time variable gain, etc.) Electronic charge of amplification to provide equal amplitude from equal reflectors at different distances.

DISTANCE-AMPLITUDE CURVE A curve relating ultrasonic echo amplitudes from equal reflectors at different distances in the material.

DIVERGENCE See Beam Spread.

DUAL SEARCH UNIT (TWIN PROBE) A search unit containing two elements, one a transmitter, the other a receiver.

DYNAMIC RANGE The ratio of maximum to minimum reflective areas that can be distinguished on the display at a constant gain setting.

ECHO Indication of reflected energy.

ELEMENT, PIEZOELECTRIC Portion of a single crystal or polycrystalline sintered ceramic having piezoelectric properties, used for the generation and/or detection of ultrasonic energy.

EQUIVALENT FLAT BOTTOM HOLE The flat bottomed hole reflector in a similar material and geometry with a diameter that produces the same ultrasonic echo amplitude as the reflector under evaluation.

FALSE INDICATION In nondestructive inspection, an indication that may be interpreted erroneously as a discontinuity or defect; a non-relevant indication, e.g., artifacts.

FAR FIELD The zone of the ultrasonic beam of a non-focused search unit that extends beyond approximately $D^2/4\lambda$ (where D is the diameter of the transducer and λ is the wavelength). In this zone the amplitude of the ultrasonic waves decrease steadily with distance.

FLAW An irregularity in the material which is generally undesirable, but may or may not be severe enough to immediately render the part unfit for intended use.

FOCUSED BEAM Converging energy of the sound beam at a specified distance.

FREQUENCY.(ACOUSTIC) The number of oscillations per second experienced by a particle or point in a medium caused by the passage of an acoustic wave through it.

FREQUENCY (CENTER) See Frequency (Dominant).

FREQUENCY (DOMINANT) That frequency at which the overall response of an ultrasonic pulse-echo flaw detection system is a maximum. NOTE: the 'system' includes the pulser, the transducer as a transmitting element, the pulse propagation path, the transducer as a receiving element, and electronic instrumentation associated with receiving, amplifying and displaying a received signal.

FREQUENCY (EXAMINATION) The nominal frequency at which the examination is performed.

FREQUENCY (FUNDAMENTAL RESONANCE) The lowest acoustic frequency which will cause a condition of resonance to be established in a given material of given thickness. NOTE: This frequency will be such that the wavelength in the given material is equal to twice the given thickness.

FREQUENCY (PULSE REPETITION) The number of times per second an electroacoustic transducer is excited to produce a pulse of acoustic energy.

FRESNEL FIELD (FRESNEL ZONE) See Near Field.

GATE A selected transit time range from which signals may be monitored or extracted for further processing.

GATE THRESHOLD An adjustable level such that while any echo within the gate exceeds the set level, an on/off signal (e.g., to a light or a recording pen) is activated.

GHOST ECHO See Wrap Around.

GRASS See Hash.

GRAZING INCIDENCE Immersion inspection with the beam directed at a glancing angle to the test surface.

HASH Numerous small indications along the baseline of the display indicative of background noise sometimes caused by many small inhomogeneities in the material.

HOLOGRAPHY (ACOUSTIC) An inspection system using the phase interference between ultrasonic waves from an object and a reference signal to obtain an image of reflectors in the object under test.

IMMERSION TESTING An examination method where the transducer and the material are submerged at least locally in a fluid, usually water.

IMPEDANCE (ACOUSTIC) The product of density and sound velocity. The property which determines acoustic transmission/reflection characteristics at a boundary between two media.

INDICATION In nondestructive evaluation, evidence of a discontinuity that requires interpretation to determine its significance.

INITIAL PULSE (MAIN BANG) Response of the ultrasonic system display to the transmitted pulse.

INTERFACE The boundary between two materials.

IRRELEVANT INDICATION An indication resulting from something other than a discontinuity of interest.

LAMB WAVE A type of wave that propagates within the thickness of a plate, and that can only be generated at particular values of angle of incidence, frequency, and plate thickness. The velocity of the wave is dependent on the mode of propagation and the product of plate thickness and frequency.

LINEARITY (AMPLITUDE) The characteristic of an ultrasonic testing system indicating its ability to display amplitudes proportional to amplitudes of ultrasonic waves coming back from a reflector.

LINEARITY (DISTANCE) The characteristic of an ultrasonic testing system indicating its ability to display signals at spacings proportional to the sound path distance between corresponding reflectors.

LONGITUDINAL WAVE Those waves in which the particle motion of the material is in the same direction as the wave propagation.

LOSS OF BACK REFLECTION Absence of or a significant reduction of an ultrasonic indication from the back surface of the article being inspected.

MATERIAL ENVELOPE The portion of material at the surface of a test piece which will later be removed to produce the finished part.

MODE The manner in which acoustic energy is propagated through a material as characterized by the particle motion of the ultrasonic wave.

MODE CONVERSION The process by which a wave of a given mode of propagation generates waves of other modes of propagation by reflection or refraction.

MULTIPLE BACK REFLECTIONS Successive echoes from the far boundary of the material being examined.

NEAR FIELD The zone directly in front of an ultrasonic transducer extending to a distance of approximately $D^2/4\lambda$ (where D is the diameter of the transducer and λ is the wavelength). In this zone components of the ultrasonic wave from different portions of the transducer interfere to produce pressure maxima and minima.

NOISE Unwanted disturbances from equipment or the material under test superposed upon the received ultrasonic signal.

NORMAL INCIDENCE Condition in which the transducer beam is perpendicular to the test surface.

PAINTBRUSH TRANSDUCER A rectanglar transducer usually constructed with a number of piezoelectric elements which has a wide beam to sweep out large areas.

PENETRATION The maximum depth in a material from which useful ultrasonic back reflections could be obtained.

PIEZOELECTRIC EFFECT The characteristic of certain materials to generate electrical charges when subjected to mechanical vibrations, and conversely to generate mechanical vibrations when subjected to electrical pulses.

PLATE WAVE See Lamb Wave.

PROBE See Transducer or search unit.

PULSE A short wave train.

PULSE ECHO METHOD An ultrasonic inspection method in which the presence and position of a reflector are indicated by the reflected pulse amplitude and time.

PULSE LENGTH A measure of the duration of a wave train, expressed in time or number of cycles.

PULSE RATE See Frequency

RF (RADIO FREQUENCY) DISPLAY A display showing unrectified ultrasonic signals.

RANGE The ultrasonic path length that is displayed.

RAYLEIGH WAVE An ultrasonic surface wave in which the particle motion is elliptical and the effective penetration is approximately a wave length. The waves follow the curvature of the part and reflections occur only at sudden changes in the surface.

REFERENCE BLOCK A specimen with geometry and material designed to produce ultrasonic reflections of known characteristics for purposes of comparison.

REFLECTION See Echo.

REFLECTOR An interface at which a ultrasonic beam encounters a change in acoustic impedance, and reflects at least part of the energy.

REFRACTION The change in direction of the ultrasonic beam as it passes obliquely from one medium to another, with a different sound wave velocity.

REJECT (SUPPRESSION) A electronic control which minimizes or eliminates low amplitude signals (or noise) but may cause display non-linearity.

RESOLUTION The ability of ultrasonic equipment to give simultaneous, separate indications from discontinuities having nearly the same range and/or lateral position with respect to the beam axis.

RESONANCE METHOD A technique in which continuous ultrasonic waves are varied in frequency to discriminate some property of the part, such as thickness stiffness, or bond integrity.

SATURATION Condition observed on the display resulting from a signal of such a magnitude that an increase in the signal produces no observable increase in the display amplitude.

SCANNING Relative movement of the transducer and the test piece in order to interrogate a volume of material.

SCATTERING The perturbation of a ultrasonic beam by small reflectors in the propagation path.

SCANNING INDEX The distance the transducer is moved perpendicular to the traverse direction after one transverse of the part.

SE PROBE See Dual Search Unit.

SEARCH UNIT OR TRANSDUCER An electro-acoustic device used to transmit and/or receive ultrasonic energy in order to interrogate a specimen. The device frequently consists of piezoelectric element(s), backing material, case, connector and a front protective covering or lens or wedge.

SENSITIVITY A measure of the ability of an ultrasonic system to detect small discontinuities.

SHEAR WAVE Wave motion in which the particle motion is perpendicular to the direction of ultrasonic propagation.

SHEAR WAVE TRANSDUCER (Y CUT QUARTZ SEARCH UNIT) A transducer used for generating and detecting normal incidence shear waves.

SIGNAL-TO-NOISE RATIO The ratio of the amplitude of an ultrasonic indication to the amplitude of the background noise.

SKIP DISTANCE In angle beam testing, the distance along the test surface from the sound entry point to the point at which the sound returns to the same surface, having been reflected from the far surface of the test object.

STRAIGHT BEAM See Normal Incidence.

SURFACE WAVE See Rayleigh Wave.

SWEPT GAIN See DAC.

THROUGH TRANSMISSION METHOD A method in which reflectors in an object are detected by monitoring the ultrasonic energy incident on a receiving transducer after the energy has propagated through the object from a transmitting transducer.

TRANSDUCER OR SEARCH UNIT An electro-acoustic device used to transmit and/or receive ultrasonic energy in order to interrogate a specimen. The device frequently consists of piezoelectric element(s), backing material, case, connector and a front protective covering or lens or wedge.

TRANSFER MECHANISM A procedure to account for differences in ultrasonic response due to differences in surface texture, curvature, attenuation, etc., between a reference block and the test object.

TRANSVERSE WAVE See Shear Wave.

ULTRASONIC Pertaining to mechanical vibrations having a frequency greater than approximately 20,000 Hz.

ULTRASONIC SPECTROSCOPY Analysis of the frequency content of an ultrasonic wave.

VEE PATH The angle-beam path in material starting at the transducer examination surface, through the material to the back surface, continuing to the examination surface in front of the search unit, and reflection back along the same path to the transducer if a discontinuity is encountered. The path is usually shaped like the letter "V".

VERTICAL LIMIT The maximum readable level of vertical indications determined either by an electrical or a physical limit of an A-scan presentation.

VIDEO PRESENTATION Display of the rectified and usually filtered rf ultrasonic signal.

WATER PATH (WATER TRAVEL) The distance from the transducer to the test surface in immersion or water column testing.

WAVE FRONT A continuous surface drawn through the most forward points in a wave disturbance which have the same phase.

WAVE INTERFERENCE A series of pressure minima and maxima resulting from the superpositon of waves.

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6.11 INDEX

Custodians:

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Review activities:

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Project No. NDTI-0047

(WP ID # 1343P DISK 0282A. FOR AMMRC USE ONLY.)

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