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METRICATION OF MIL-HDBK-5C

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This final report describes the development and preparation of a "soft" metric version of MIL-HDBK-5C.

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PREFACE

This final report was submitted by Battelle's Columbus Laboratories, 505 King Avenue, Columbus, Ohio 43201, under Contract F33615-77-C-5036 with the Air Force Wright Aeronautical Laboratory, Wright-Patterson Air Force Base, Ohio. Mr. C. L. Harmsworth (MLSA) was the laboratory project monitor. This report covers the period of work from April 25, 1977, through August 29, 1980. The author wishes to express his appreciation to Messrs. S. C Ford, R. C. Rice, T. P. Forte, R. D. Galliher, and D. J. Jones for their assistance and support during the conduct of this program. This report was submitted by the author, Mr. Paul E. Ruff, in August 1980.

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SUMMARY

A "soft" metric version of MIL-HDBK-5C (excluding Chapters 8 and 9) has been developed and is presented in the Appendix. No major problems were encountered in accomplishing this "soft" conversion. This report is intended to be used in conjunction with soft converted designs and standards as the usefulness of a "soft" metric version of MIL-HDBK-5 as a source of design allowables for "hard" metric products will be limited. A recent publication of metric standards and data for aluminum alloys indicates that specification thickness ranges, ultimate tensile strength, tensile yield strength, and elongation values are different for the "hard" metric products than for the SI values obtained by converting from U.S. units. Metric standards for other alloy systems are expected to also be different. Likewise, the design values for metric fasteners will require verification and may not be equivalent to fasteners currently manufactured in U.S. units. Most of the "soft" converted data, such as stress-strain curves, tangent-modulus curves, elevated temperature curves, fatigue curves, fatigue-crack-propagation curves, fracture toughness, creep curves, physical properties, etc., which are presented on a "typical" basis, will be valid since the data are not greatly affected by product size differences in the two measurement systems or by slight variations in specification tensile property values.

Eventually, a "hard" metric MIL-HDBK-5 will be required as industry changes to the metric system. However, before work can begin on such a document, "hard" metric standards, such as preferred sizes, procurement (material) specifications, and testing standards must be published for the aerospace alloys as well as fastener systems.

It will be necessary that "hard" metric mill products as well as fasteners be readily available from production lots so that data can be generated, accumulated, and analyzed to verify design values for metric products. At the present rate of progress, it would appear that these conditions will not come about for some time.

INTRODUCTION

The Military Standardization Handbook, MIL-HDBK-5, is recognized as the primary source for design allowable data required by the Department of Defense (DoD), other Government agencies, and aerospace contractors responsible for aerospace vehicle design. The Handbook contains design allowable data on metallic materials, fasteners, joints, and other structural elements. The maintenance of this document is achieved through the cooperative efforts of the Air Force, Navy, Army, Federal Aviation Agency (FAA), and industrial users and suppliers of metallic aerospace materials. The DoD has designated the Air Force as the activity responsible for preparing this Handbook. As such, the Air Force Wright Aeronautical Laboratory (AFWAL) has contracted with Battelle's Columbus Laboratories (BCL) to provide the planning, coordination, implementation, and testing necessary to develop and maintain current design allowable data and other related information in MIL-HDBK-5.

Other final reports have described in detail the functional and technical activities performed by BCL in connection with the MIL-HDBK-5 program. Since the functional as well as some of the technical activities are somewhat repetitive from year to year, this final report describes the effort involved in developing and preparing a "soft" metric version of MIL-HDBK-5C.

The policies for the use of the metric system of measurement within the Department of Defense (DoD) are delineated in Reference (1). One of the policies as stated in this DoD Directive is:

> "Emphasis will be placed on keeping pace with the conversion or development of specifications, standards, and other general purpose technical data. When the item in question is a military item without a commercial counterpart, the Preparing Activity will assume a leadership role in development of the applicable metric document as the need arises."

In compliance with the reference DoD Directive, the Chairman of the MIL-HDBK-5 Coordination Committee initiated action to convert MIL-HDBK-5 to the metric system of measurement. As such, Battelle's Columbus Laboratories was assigned this task as a part of the MIL-HDBK-5 program.

(1) Department of Defense Directive Number 4120.18 dated December 10, 1976.

Although ultimately a "hard" metric MIL-HDBK-5 will be required, "hard" metric material specifications, standard metric product thicknesses, metric test specimen configurations, and metric testing specifications and standards have not been published for most materials used in aerospace applications. Consequently, this effort was directed to the development of a "soft" metric conversion of MIL-HDBK-5 as an interim document which could be used in conjunction with "soft" converted designs and standards. Although it is recognized that such a document will be limited in its usefulness, it was believed that such an effort would reveal any problems associated with the conversion to metric design values and the presentation of metric design data. Users of this document are encouraged to submit their comments and suggestions to AFWAL/MLSA, Wright Patterson AFB, Ohio 45433 so that such imput can be incorporated into any "hard" version of MIL-HDBK-5 which may ultimately be developed and become a controlling standardization document.

OBJECTIVE

The objective of this program was to develop a "soft" metric MIL-HDBK-5 Handbook based upon the conversion of existing United States (U.S.) units to the metric system of measurement and to publish the metric version of MIL-HDBK-5 as an Air Force technical report.

TECHNICAL APPROACH

The approach was to convert existing MIL-HDBK-5 to the metric system by changing all U.S. units of measurement to equivalent metric units. As required by Reference (1), the metric system used was The International System of Units (SI). In making the metric conversion, the conversion factors listed in Reference (2) were utilized. (The applicable conversion factors are shown in Table 1.2.2 of MIL-HDBK-5C).

In general, the rules for conversion and rounding delineated in Reference (2) were observed. However, some exceptions to these rules were taken.

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(2) ASTM E380-76, "Standard for Metric Practice."

The Handbook contains two digit and three digit design values in Ksi units with two and three significant figures, respectively. For the Ksi units with two significant figures, the corresponding MPa values should have only two significant figures so as to maintain the implied accuracy of the data. However, adherence to this procedure would result in three digit MPa values rounded to two significant figures for 680 MPa (99Ksi = 683 MPa) and below, and three digit MPa values to three significant figures for 690 MPa (100 Ksi = 690, 101 Ksi = 696 MPa, etc.) and above. This would give the appearance that the MPa values have been inconsistently rounded. Consequently, Ksi values have been converted to MPa units having three significant figures, rounded to the nearest whole number. More importantly, this procedure is consistent with the policy adopted for AMS specifications which contain "soft" metric equivalent mechanical property requirements. Many room temperature design allowable tables in MIL-HDBK-5C are based upon specification (AMS) values; consequently, it is important that the metric MIL-HDBK-5 design values agree with the "soft" metric specification values. For consistency, K_{Ic} values as well as elastic and physical property units have also been converted to three significant figures even though the U.S. units may have contained only two significant figures.

In the conversion, some arbitrary decisions were made for practical reasons. For most mill products, the design values vary with thickness. Consequently, the room temperature design allowable property tables list design values according to thickness ranges.

Although thickness in inches is shown to three decimal places, it would seem appropriate to round the converted thickness ranges to the nearest millimeter. This could result in an error of 0.054 inch in the 4 to 5 inch thickness range as follows:

3.001 - 4.000 inch = 77 - 102 mm

4.001 - 5.000 inch = 103 - 127 mm

103 mm = 4.055 inches

Although this potential error in thickness range is probably acceptable, for thickness ranges covering 0.039 inches and under the equivalent thickness is less than one millimeter. Consequently, two decimal places for the metric thickness ranges were required to provide sufficient precision in separating these thin thickness ranges. For consistency in table format, this precision was adopted for all metric thickness ranges. Even so, conversion of the U.S. thickness range resulted in a gap of coverage for most thickness ranges in millimeters. For example, 0.250-0.499 inch range converts to 6.35-12.67 millimeters and the adjacent thickness range of 0.500-1.000 inch converts to 12.70-25.40 millimeters. Consequently, product thicknesses of 12.68 and 12.69 millimeters would not have design values. Similar gaps occurred at each change in thickness range. In order to circumvent this problem, 0.01 mm was added to the larger thickness and subtracted from the smaller thickness in each range. As a result, the above thickness ranges would be listed as 6.34-12.68 and 12.69-25.41 mm. The thickness ranges in MIL-HDBK-5C are normally the same as those in the applicable material specification. For those design allowables based upon specification minimum values, it is imperative that the thickness ranges shown in MIL-HDBK-5 be the same as those in the material application. Consequently, it was desirable to maintain the existing and converted thickness ranges the same.

In order to minimize the cost and time of converting the room temperature mechanical property tables, a computer program was developed to perform the conversions and print out a room temperature design allowable table in MIL-HDBK-5 format. Utilizing a specific keypunching format, keypunching was accomplished directly from existing MIL-KDBK-5 tables with no encoding required.

In order to accomplish this conversion by computer, some concessions were necessary with regard to print and symbols for the room temperature design allowable tables only as listed below.

(a) All letters and words are upper case. In order not to confuse e with E, e was changed to EL.

(b) Subscripts and superscripts cannot be accommodated by computer; consequently, they were printed conventionally.

(c) Letters of the Greek alphabet cannot be accommodated by computer; consequently, symbols for physical properties were changed as follows:

υ = mu

ω = omega

α = alpha

(d) Footnote indicators were typewritten.

Because of width limitations on computer printout paper, some large tables required division into two tables. Consequently, there may be some variation in metric table numbers (letter only) with U.S. equivalent tables.

The metric room temperature design allowable tables were copied directly from the computer printout.

The typical stress-strain and compressive tangent-modulus curves were redrawn in metric units by utilizing a computer program. Values for typical yield strength, typical modulus of elasticity, and Ramberg-Osgood (nondimensional) were converted from U.S. to metric units which were utilized in conjunction with the Ramberg-Osgood relationships presented in Section 9.3.2.3 of MIL-HDBK-5C. Those stress-strain and tangent-modulus curves for which the Ramberg-Osgood relationships were not valid were drawn manually.

The ordinate scale for elevated temperature curves is percent. Consequently, only the abssisca scale required conversion. By reducing the size of the abscissa grid in conjunction with conversion to Kelvin scale, many of the elevated temperature curves could be traced without individual conversion of points on the curve. By the utilization of a proportionately sized grid, the constant-life fatigue curves and the residual strength curves could also be traced without individual conversion of points on the curve. Other curves such as those showing the effect of temperature on specific heat, thermal conductivity, and thermal expansion were manually converted and redrawn. Creep and all other remaining curves were also manually converted and redrawn.

The "soft" metric MIL-HDBK-5 is based upon MIL-HDBK-5C with the following exceptions:

(1) The stress-strain and compressive targent-modulus curves in MIL-HDBK-5C were constructed using the Ramberg-Osgood equation

$$e_{pl} = kf^{n} - 0.0001$$

The 0.0001 subtraction factor was incorporated in this expression to define a proportional limit. At the 52nd MIL-HDBK-5 Coordination Committee Meeting (October 1976), it was decided to delete this proportionality limit so as to improve the fit of the compressive tangent-modulus curve to actual test data. Consequently, existing compressive tangent-modulus curves were replaced with new curves based upon the revised Ramberg-Osgood equation in Change Notice 1. In order to eliminate the need for reconstructing the metric compression tangent-modulus curves in the future, the metric tensile and compressive stress-strain and compressive tangent-modulus curves are based upon the Ramberg-Osgood equation

$$e_{pl} = kf^n$$

(2) In several instances, compressive stress-strain curves were presented in MIL-HDBK-5C without the corresponding compressive tangent-modulus curves. In the metric version the corresponding compression tangent-modulus curves have been added for completeness.

(3) Due to difficulty in determining accurately the modulus of elasticity from the existing stress-strain curves in MIL-HDBK-5C, especially for materials, such as magnesium alloys, with low moduli at elevated temperatures, the elevated temperature moduli were computed utilizing the modulus value in the room temperature table and the factors from the elevated temperature moduli curves. However, in some cases an elevated temperature modulus curve was not available in MIL-HDBK-5C or the issue did not extend to all temperatures depicted by stress-strain curves. A metric version of those elevated temperature stress-strain curves, for which an elevated temperature modulus could not be determined due to lack of an elevated temperature modulus curve, was not included. These same stress-strain curves were deleted in Change Notice 2 based upon action taken at the 56th MIL-HDBK-5 Coordination Committee Meeting.

(4) Tensile tangent-modulus curves had previously been deleted from MIL-HDBK-5. However, several tensile tangent-modulus which had apparently been missed in the deletions remain in MIL-HDBK-5C. These were deleted in Change Notice 1 and have also been deleted from the metric version.

(5) Obvious typesetting errors were corrected in the metric version.

Chapters 8 and 9 of MIL-HDBK-5C were not converted to the metric system and were not included in the "soft" metric version for the reasons given in the Discussion.

The "soft" metric version of MIL-HDBK-5 is presented in the Appendix.

DISCUSSION

There is some concern regarding the usefulness of a "soft" metric MIL-HDBK-5, particularly the room temperature design allowable tables. Work on "hard" metric standards for the aluminum alloys has progressed farther than for other alloy systems. Reference (3) presents metric (SI) standards and data for aluminum alloys. The preferred metric product sizes are different than converted U.S. sizes. Tensile strength increments of five MPa rather than one MPa have been used. Although not a metrication change per se, the gage length of a metric tensile test specimen has been changed to 5D for round specimens and 50 mm for flat specimens to agree with the international 5D gage length resulting in a reduction in elongation values. It is believed that metric standards for other alloy systems will follow the same pattern. Consequently, when "hard" metric material specifications are published, the thickness ranges, the tensile ultimate strength, the tensile yield strength, and the elongation specification values will not agree with the converted U.S. values in the room temperature tables for aluminum alloys.

Drawings for parts made from the quenched and tempered, low alloy steels usually specify a heat treat range of 20 Ksi, for example, 180-200 Ksi, 200-220 Ksi, etc. In changing to the metric system, these heat treat limits will probably be changed to preferred metric ranges; for example, 180-200 Ksi = 1241-1278 MPa. This could be rounded to 1240-1380 MPa. However, the preferred metric heat treat range might be 1200-1350 MPa (174-196 Ksi). Consequently, it is likely the converted design values for the quenched and tempered alloy steels will not be valid for "hard" metric heat treat ranges.

Likewise, for tables containing the static joint strength design values for fasteners, the dimensions of the "hard" metric fastener diameters and "hard" metric sheet gages will not correspond to currently manufactured fasteners and sheet thicknesses. Consequently, the usefulness of converting design values to metric units for current fastener systems designed with U.S. units is questionable. The design values for metric fasteners will require verification and may not be equivalent to currently manufactured fasteners. Hence, the presentation of such data could be confusing and somewhat hazardous.

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(3) "Aluminum Standards and Data 1978 Metric SI", The Aluminum Association, First Edition, March 1978.

Therefore, Chapter 8 on Structural Joints was not converted to the "soft" metric system. Most of the other "soft" converted typical data, such as stress-strain curves, tangent-modulus curves, elevated temperature curves. fatigue curves, fatigue-crack-propogation curves, fracture toughness data, creep-rupture curves, etc. will be valid since these data are not greatly affected by product size differences in the two measurement systems or slight variations in specification properties.

Chapter 9 of MIL-HDBK-5C contains guidelines for the analysis and presentation of data for the Handbook. Since the units of measure used in explaining data analysis procedures and methods of presenting data are not of great importance, the cost of converting this chapter to metric units did not appear jutified at the present time. No problems are anticipated in converting this chapter to metric units. Meanwhile, Chapter 9 of MIL-HDBK-5C can be used for reference.

The "soft" metric MIL-HDBK-5 is based upon MIL-HDBK-5C. As such, the metric version will be somewhat out of date since Change Notices 1 and 2 to MIL-HDBK-5C have already been published.

APPENDIX

SOFT METRIC VERSION OF MIL-HDBK-5C

SOFT METRIC VERSION OF MIL-HDBK-5C

The metric design data contained in this document were derived from design data determined from products manufactured and tested in U.S. units of measure by applying appropriate conversion factors. In the preparation of this document, no testing was conducted to verify that these design data are valid for metric products.

In general, this soft metric version is based on MIL-HDBK-C dated 15 September 1976. This document will not be maintained or updated.

EXPLANATION OF NUMERICAL CODE

In the chapters containing materials properties, the following system of numerical identification is used. A somewhat similar numerical system is used in Chapter 1 to sectionalize various portions of the text:

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 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 and reduction of area 5

Stress-strain curves, tangent-modulus curves 6

Creep 7

Fatigue 8

Fracture toughness 9

NOTICE

The room temperature design allowable tables have been converted from U.S. units to SI units by computer and the computer output has been used directly in this document to achieve economy. Consequently, symbols and print for the room temperature design allowable tables varies somewhat from the symbols and print used throughout the remainder of the document. The specific variations in these tables to accommodate computer processing are listed below:

(a) All letters and words are upper case. In order not to confuse e with E, e was changed to EL.

(b) Subscripts and superscripts were printed conventionally.

(c) Symbols from the Greek alphabet were changed as follows:

μ = mu

ω = omega

α = alpha.

(d) Footnote indicators were typewritten.

Because of width limitations on computer printout paper, some large tables required division into two tables. Consequently, there may be some variation in metric table numbers (letter only) with U.S. equivalent tables in MIL-HDBK-5C.

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Chapter 1

GENERAL

1.1 Purpose and Use of Document

1.1.1 INTRODUCTION.—Since many aircraft and missile manufacturers supply products for both commercial and military use, standardization of the requirements of the various Government procuring or certification agencies is of direct benefit to the manufacturer. Although the types and purpose of military products often differ greatly from those of commercial products necessitating certain differences in the structural requirements, the requirements for st...gth of materials and elements are often identical. This publication is issued, therefore, to provide uniform data and to minimize the necessity for referring to numerous materials handbooks and bulletins to obtain the allowable stresses and other related properties of materials and structural elements With a few exceptions (which are noted in the appropriate places), the data contained herein or appearing as approved items in 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 data not contained herein or appearing in the minutes as noted above.

1.1.2 SCOPE OF DOCUMENT.—This document is intended primarily as a source of design allowables which are those strength properties of metals and elements (primarily fasteners) that have received general acceptance for use in design This document also contains strength properties, e.g., fracture toughness and fatigue data, which are for information only and are not mandatory for use. Those properties presented as design allowables are usually listed as A, B, or S values (see Section 1.4.1.1). Other values are normally for information, except for those tables or ratio plots which are used in conjunction with A, B, or S values to calculate effect of temperature. The materials included in this document are standardized with regard to composition and processing methods.

In the interest of timeliness, it is sometimes possible that new properties for established materials will appear in the document. Although substantiating data have been scarce in some of these cases, the evaluation has been based on the best possible engineering judgment, and the properties are considered to be suitable for design use. Whenever needed properties are not available in the document, special rulings for allowable strengths should be obtained from the procuring or certificating agency. These rulings will be based upon data from specimen tests and will eventually form a basis for design allowable additions to the Handbook.

In addition to the properties of the materials and elements themselves, there are contained herein some of the more commonly used methods and formulas by which the strengths of various structural elements or components are calculated. In some cases, the methods presented are empirical and subject to further refinements. Any further expansion of information on element behavior in MIL-HDBK-5 will emphasize those material characteristics needed to assist the design function. Methods of structural analysis are not within the scope of this document.

Where available, applicable references are listed at the end of each chapter. The reference numbers correspond to the paragraph to which they most generally apply. In general, specific mention of the references is not made. References are provided for guidance to further information on a particular subject, but since data therein may not have met the guidelines criteria of Chapter 9, such referenced material is not necessarily to be considered approved by virtue of its listing.

Engineers making use of the material contained herein are invited to submit comments and suggestions as to the expansion and improvement of the document. Such comments should be submitted to Chairman, MIL-HDBK-5 Coordination Activity, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio 45433.

1.1.3 USE OF DESIGN MECHANICAL PROPERTIES.—It is customary to assign minimum values to certain mechanical properties of materials as procurement specification requirements. In the absence of acceptable statistical data, the design mechanical properties given herein are based on these minimum values (see S Basis, Section 1.4.1.1). The manner in which these design mechanical properties are to be used will depend on the type of structure being considered and will be specified in the detailed structural requirements of the procuring or certificating agency. The use of the different design mechanical properties, such as ultimate tensile strength, yield strength, etc.; the factors of safety associated with them; and the arbitrary reductions in allowable stresses (which may be in the nature of specific requirements, or may be considered necessary in particular cases); will not be taken up in detail since information of this sort does not affect the material properties as such.

1.2 Symbols, Abbreviations, and Systems of Units

1.2.1 SYMBOLS AND ABBREVIATIONS.—The symbols and abbreviations used in this document are defined in this section with the exception of statistical symbols. These latter symbols are defined in Chapter 9.

A — Area of cross section, square inches, ratio of stress amplitude to mean stress; subscript "axial"; A basis for mechanical-property values (see Section 1.4.1.1)

a — Subscript "allowable"; amplitude; crack or flaw dimension

B — Biaxial ratio (see Equation 1.3.2.8), B basis for mechanical-property values (see Section 1.4.1.1)

b — Width of sections; subscript "bending"

br — Subscript "bearing"

C — Circumference; specific heat

c — Fixity coefficient for columns, distance from neutral axis to extreme fiber; subscript "compression"; crack or flaw dimension

cr — Subscript "critical"

D — Diameter

d — Depth or height; mathematical operator denoting differential

E — Modulus of elasticity in tension, average ratio of stress to strain for stress below proportional limit

e — Elongation in percent, this factor being a measure of the ductility of the material and being based on a tension test, unit deformation or strain; eccentricity; subscript for Euler's formula; subscript "fatigue or endurance", the minimum distance from a hole center to the edge of the sheet

E_c — Modulus of elasticity in compression, average ratio of stress to strain below proportional limit

E_s — Secant modulus

E_t — Tangent modulus

F Allowable stress; Fahrenheit

f Internal (or calculated) stress

F_b Allowable bending stress, modulus of rupture in bending

f_b Internal (or calculated) primary bending stress

f_b' Internal (or calculated) precise bending stress

f_{br} Internal (or calculated) bearing stress

F_{bru} Ultimate bearing stress

F_{bry} Bearing yield stress

F_c Allowable compressive stress

f_c Internal (or calculated) compressive stress

F_{cc} Allowable crushing or crippling stress (upper limit of column stress for local failure)

F_{co} Column yield stress (upper limit of column stress for primary failure)

F_{cp} Proportional limit in compression

F_{cu} Ultimate compressive stress

F_{cy} Compressive yield stress at which permanent strain equals 0.002 (from tests of standard specimens)

F_n Allowable normal stress

f_n Internal (or calculated) normal stress

F_s Allowable shearing stress

f_s Internal (or calculated) shearing stress

F_{scr} Critical shear stress for buckling of rectangular panels

F_{sp} Proportional limit in shear

F_{st} Modulus of rupture in torsion

F_{su} Ultimate stress in pure shear (this value represents the average shearing stress over the cross section)

F_t Allowable tensile stress

f_t Internal (or calculated) tensile stress

F_{tp}	Proportional limit in tension
F_{tu}	Ultimate tensile stress (from tests of standard specimens)
F_{ty}	Tensile yield stress at which permanent strain equals 0.002 (from tests of standard specimens)
G	Modulus of rigidity
H	Subscript "hoop"
h	Height or depth, especially the distance between centroids of chords of beams and trusses
I	Moment of inertia
i	Slope (due to bending) of neutral plane of a beam, in radians (1 radian = 57.3°)
I_p	Polar moment of inertia
J	Torsion constant (= I_p for round tubes)
j	Stiffness factor = $\sqrt{EI/P}$
K	A constant, generally empirical; thermal conductivity; stress intensity
K_{Ic}	Plane strain fracture toughness
ksi	Kips (1,000 pounds) per square inch
L	Length; subscript "lateral"; longitudinal (grain direction)
LT	Long transverse grain direction
M	Applied moment or couple, usually a bending moment
m	Subscript "mean" stress
M_a	Allowable bending moment
N	Cycles to failure, fatigue
n	Subscript "normal"; cycles applied in failure; exponent; and shape parameter for the standard stress-strain curve (Ramberg-Osgood Parameter)
P	Applied load (total, not unit, load)
p	Subscript "polar"; subscript "proportional limit"

P_a Allowable load

psi Pounds per square inch

Q Static moment of a cross section

q Not assigned

R Stress ratio, ratio of minimum stress to maximum stress in a cycle

r Radius

S Shear force; nominal stress, fatigue; S basis for mechanical-property values (see Section 1.4.1.1); span length

S_a Stress amplitude, fatigue

S_e Fatigue limit

S_m Mean stress, fatigue

s Subscript "shear"

ST Short transverse grain direction

T Applied torsional moment; transverse grain direction

t Thickness, subscript "tension"

T_a Allowable torsional moment

U Factor of utilization

u Subscript "ultimate"

x Distance along a coordinate axis

Y Nondimensional calibration factor scaling flaw size with structural size

y Deflection (due to bending) of elastic curve of a beam; distance from neutral axis to given fiber; subscript "yield"

Z Section modulus, I/y

Z_p Polar section modulus = I_p/y (for round tubes)

α Coefficient of thermal expansion, mean

δ Deflection

ϕ Angular deflection

ρ Radius of gyration

μ Poisson's ratio

ω Density

' In general, denotes an "effective" or precise value

1.2.2 U.S. UNITS OF MEASURE

The design values listed in this "soft" metric version of MIL-HDBK-5C are given in the International Systems of Units (SI). Table 1.2.2 may be used to assist in the conversion of these units to U.S. units.

TABLE 1.2.2. *Conversion of SI Units of Measure to U.S. Units*

Quantity or Property	To Convert From SI Unit[b]	Divide by[a]	U.S. Unit
Area	mm^2	645.16[c]	in.^{2}
Force	N	4.4482	lb
Length	mm	25.4[c]	in.
Stress	MPa[d]	6.985	ksi
Stress intensity factor	$MPa \cdot m^{1/2}$ [d]	1.0989	ksi$\sqrt{in.}$
Modulus	GPa[d]	6.895	10^3 ksi
Temperature	°K	$\frac{F + 459.67}{1.8}$	°F
Density (ω)	Mg/m^3	27.680	lb/in.^{3}
Specific heat (C)	$J/(g \cdot K)$ or $J \cdot g^{-1} \cdot K^{-1}$	4.1868[c]	Btu/lb-F (or $BTU \cdot lb^{-1} \cdot F^{-1}$)
Thermal conductivity (K)	$W/(m \cdot K)$ or $W \cdot m^{-1} \cdot K^{-1}$	1.7307	Btu/[(hr)(ft^2)(F)/ft] (or $Btu \cdot hr^{-1} \cdot ft^{-2} \cdot F^{-1} \cdot ft$)
Thermal expansion (α)	$m/(m \cdot K)$ or $m \cdot m^{-1} \cdot K^{-1}$	1.8	in./in./F (or $in. \cdot in.^{-1} \cdot F^{-1}$)

[a] Conversion factors to give significant figures are as specified in ASTM Standard E-380, NASA SP-7012, second revision, NBS Special Publication 330, and Metals Engineering Quarterly.

[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/metre^2.

1.3 Commonly Used Fo :las

1.3.1 GENERAL.—The formulas in the following sections are listed for reference purposes. The sign conventions generally accepted in their use are that quantities associated with tensile action (load, stress, strain, etc.) are considered as positive, and quantities associated with compressive action are considered as negative. When compressive action is of primary interest, however, it is sometimes convenient to consider the associated quantities to be positive. In Chapter 9, formulas for statistical computations are presented that are used in obtaining design allowables in this document.

1.3.2 SIMPLE UNIT STRESSES

1.3.2.1 $f_t = P/A$ (tension)
1.3.2.2 $f_c = P/A$ (compression)
1.3.2.3 $f_b = My/I = M/Z$
1.3.2.4 $f_s = S/A$ (average direct shear stress)
1.3.2.5 $f_s = SQ/Ib$ (longitudinal or transverse shear stress)
1.3.2.6 $f_s = Ty/Ip$ (shear stress in round tubes due to torsion)
1.3.2.7 $f_s = T/2\,At$ (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)
1.3.2.8 $f_A = Bf_H$; $f_T = Bf_L$

1.3.3 COMBINED STRESSES (See Section 1.5.3.5)

1.3.3.1 $f_n = f_c + f_b$ (compression and bending)
1.3.3.2 $f_{smax} = \sqrt{f_s^2 + (f_n/2)^2}$ (compression, bending, and torsion)
1.3.3.3 $f_{nmax} = (f_n/2) + f_{smax}$

1.3.4 DEFLECTIONS (AXIAL)

1.3.4.1 $e = \delta/L$ (unit deformation or strain)
1.3.4.2 $E = f/e$ (This equation applies when E is to be found from tests in which f and e are measured.)
1.3.4.3 $\delta = eL = (f/E)L$
$= PL/AE$. (This equation applies when the deflection is to be calculated using a known value of E.)

1.3.5 DEFLECTIONS (BENDING)

1.3.5.1 $di/dx = M/EI$ (change of slope per unit length of beam, radians per unit length)
1.3.5.2 $i_2 = i_1 + \int_{x_1}^{x_2} (M/EI)\,dx$—slope at point 2. (The integral denotes the area under the curve of M/EI plotted against x, between the limits of x_1 and x_2.)
1.3.5.3 $y_2 = y_1 + i_1(x_2 - x_1) + \int_{x_1}^{x_2} (M/EI)\,(x_2 - x)\,dx$ - deflection at point 2. (The integral denotes the area under a curve having ordinates equal to M/EI multiplied by the corresponding distances to point 2, plotted against x, between the limits of x_1 and x_2.)
1.3.5.3(a) $y_2 = y_1 + \int_{x_1}^{x_2} i\,dx$ - deflection at point 2. (The integral denotes the area under the curve of (i) plotted against x, between the limits x_1 and x_2.)

1.3.6 DEFLECTIONS (TORSION)

1.3.6.1 $d\phi/dx = T/GJ$ (change of angular deflection or twist per unit length of member, radians per unit length)

1.3.6.2 $\phi = \int_{x_1}^{x_2} T/GT)\, dx$ = total twist over a length from x_1 to x_2. (The integral denotes the area under the curve of T/GJ plotted against x, between the limits of x_1 and x_2.)

1.3.6.2(a) $\phi = TL/GJ$ (used when torque T/GJ is constant over length L)

1.3.7 BIAXIAL ELASTIC DEFORMATION

1.3.7.1 $\mu = \dfrac{\text{unit laterial deformation.}}{\text{unit axial deformation}}$ (Poisson's ratio in uniaxial loading)

1.3.7.2 $Ee_x = f_x = \mu f_y$

1.3.7.3 $Ee_y = f_y - \mu f_x$

1.3.7.4 $E_{biaxial} = E/(1 - \mu B)$ (biaxial elastic modulus)

1.3.8 BASIC COLUMN FORMULA

$F_c = \pi^2 E_t/(L/\rho)^2$ where $L' = L\sqrt{c}$

1.4 Basic Principles and Definitions

1.4.1 GENERAL.—It is assumed that engineers using this document are thoroughly familiar with the basic principles of strength of materials, such as can be found in any standard textbook on this subject. A brief summary of such material is presented here for the sake of uniformity and to emphasize certain principles of special importance. The design mechanical properties of various metals and elements are given in the tables in each chapter.

As a means of maintaining uniformity in the presentation of mechanical-property values in this document and a high level of assurance in the values reported, statistical techniques are employed where possible and requirements have been established to insure the adequacy of supporting data and the fullest description of the material or product represented by the mechanical-property values.

1.4.1.1 *Basis.*—Primary strength properties (F_{tu}, F_{ty}, F_{cy}, F_{su}, F_{bru}, and F_{bry}) presented in the design mechanical property tables are minimum values at room temperature, established on an A, B, or S basis, as defined below. Properties at other temperatures, when determined in accordance with Section 1.4.1.3, shall be regarded as having the same basis as the corresponding room-temperature values.

Elongation and reduction in area properties presented in the design mechanical-property tables are minimum values at room temperature, established on an A or S basis as defined below. Elongation and reduction in area at other temperatures, as well as elastic properties (E, E_c, G, and μ), physical properties (ω, C, K, and α), creep properties, fatigue properties, and fracture toughness properties shall be regarded as average or typical values unless a data basis is specifically indicated.

A Basis.—At least 99 percent of the population of values is expected to equal or exceed the A basis mechanical property allowable, with a confidence of 95 percent.

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.

S Basis.—The S basis mechanical property allowable is the minimum value specified by the appropriate Federal, Military, or SAE Aerospace Material specification for the material. The statistical assurance associated with this value is not known. See Section 9.2.2.1 for exception.

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

1.4.1.2 *Directly Calculated Values.*—Directly calculated values having an A basis are equal to $\bar{x}$-ks_x where k is $k_{.99,\ .95,\ n}$ (where .99 = probability, .95 = confidence, and n = number of measurements). Those having a B basis are equal to $\bar{x}$-ks_x, where k is $k_{.90,\ .95,\ n}$. These formulas assume that the distribution of mechanical-property values is normal. See Section 9.2.7.

Where there is evidence of an inherent distribution other than normal, nonparametric analysis is used to approximate this same degree of assurance. See Section 9.2.8.

When a property varies continuously with thickness, regression analysis is used. See Section 9.2.10.

Data requirements for establishing allowables in this manner must be adequate to represent the current process capability of a material. Normally, a minimum of 100 individual measurements are required. These contain data from at least 10 production heats from a majority of the major producers of the material. If possible, tests conducted by more than one source are included. These requirements apply to each significant variable, such as form, heat treated condition or temper, size or thickness range, and testing direction, that may affect the distribution of properties.

1.4.1.3 *Derived Values.*—A derived value is a mechanical property that is determined through its relationship to an established property. A derived property may be a tensile strength in a different grain direction from the established direction, or it may be another strength property (compression, shear, or bearing), or it may be the same strength property at a different temperature. See Sections 9.2.9 and 9.3.1.

Derived values are presented in tabular form in stress units in design mechanical properties tables or in graphical form in percentage units of the room temperature strength property. Tabular values will have both their dimensional units and data basis indicated. These values represent the product of a reduced ratio and the value of an established primary strength property.

Percentages selected from effect-of-temperature curves represent reduced ratios of the property-at-temperature to the room-temperature value for that property. The product of a percentage and the room-temperature value for a property shall be regarded as yielding a property-at-temperature value having the same basis as that indicated for the room-temperature value for the property.

Unless otherwise indicated, the percentage curves for these properties apply to all forms and thicknesses shown in the design mechanical property table for the temper indicated. Normally, these curves represent materials exposed at testing temperatures for times up to one-half hour and strained at the rate specified for the individual property. Where data are adequate, curves for other exposure times are also presented and are labeled appropriately.

1.4.2 STRESS

1.4.2.1 *General.*—The term "stress" as used herein always 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 1.3.3.1 and 1.3.2.2). The stress distribution may or may not be uniform, depending on the nature of the loading condition. For example, tensile stresses as found from Equation 1.3.2.1 are considered to be uniform. The bending stress determined from Equation 1.3.2.3 refers to the stress at a point located at a distance y from the neutral axis. The shear stress over the cross section of a member subjected to bending is not uniform. (Equation 1.3.2.4 gives the average shear stress.)

1.4.2.2 *Normal, Shear, and Principal Stresses.*—The stresses acting at a point in any stressed member can be resolved into components acting on planes through the point.

The normal and shear stresses acting on any particular plane are the stress components perpendicular and parallel, respectively, to the plane. A simple conception of these stresses is that normal stresses tend to pull apart (tensile stresses) or press together (compressive stresses) adjacent particles of the material, whereas shear stresses tend to cause such particles to slide on each other. Tensile stresses are denoted arbitrarily (+) stresses and compressive stresses are called negative (-) stresses.

If one selects three mutually perpendicular planes through a point, there is always some orientation of this system such that only normal stresses exist, all other stresses being zero. These normal stresses are known as principal stresses, and the numerically largest of these is called the maximum principal stress.

1.4.2.3 *State of Stress.*—A triaxial stress state is defined as one in which there are three principal stresses, none of which is equal to zero. When one of the principal stresses is equal to zero, the stress state is called biaxial. When two of the principal stresses are equal to zero, uniaxial state of stress is said to exist.

1.4.3 STRAIN

1.4.3.1 *General.*—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 direction or directions of the applied stresses.

1.4.3.2 *Normal and Principal Strains; Poisson's Ratio.*—A normal strain is that strain that is associated with a normal stress; a normal strain takes place in the direction in which its associated normal stress acts. Normal strains that result from an increase in length are denoted arbitrarily as positive (+) strains and those that result from a decrease in length are called negative (-) strains.

If one selects three mutually perpendicular planes through a point, there is always some orientation of this system such that only normal strains exist, all shearing strains being zero. These normal strains are known as principal strains. The direction of the principal strains coincide with the direction of the principal stresses only for isotropic materials.

In uniaxial loading, strain in the direction of the applied stress varies with that stress. The ratio of stress to strain has a constant value (E) within the elastic range of a material but decreases when plastic strain is encountered. The axial strain is always accompanied by lateral strains of opposite sign in the two directions mutually perpendicular to the axial strain. Under uniaxial conditions, the absolute value of the ratio of either of the lateral strains to the axial strain is called Poisson's ratio. For stresses within the elastic range, this ratio is approximately constant. For stresses beyond the elastic limit, this ratio is a function of the axial strain and is then sometimes called the lateral-contraction ratio. Information on the variation of Poisson's ratio with strain and with testing direction is available in Reference 1.4.3.2.

In multiaxial loading, the strains resulting from the application of each of the stresses are additive, thus, the strains in each of the principal directions must be calculated, taking into account each of the principal stresses and Poisson's ratio (see Equations 1.3.7.2 and 1.3.7.3 for biaxial loading).

1.4.3.3 *Shearing Strain.*—If an element of uniform thickness is subjected to pure shear, there will be a displacement of each side of the element relative to the opposite side. The shearing strain is obtained by dividing this displacement by the distance between the sides of the element. It should be noted that shearing strain is obtained by dividing a displacement by a distance at right angles to the displacement, whereas axial strain is obtained by dividing the deformation by a length measured in the same direction as the deformation.

1.4.3.4 *Strain Rate.*—Loads on structures will result in conditions ranging from those where strains are constant to those where strains are rapidly changing. The stress-strain curve, ultimate tensile strength, and ductility of some materials are affected by changes in the rate of strain. For this reason, where available, statements or data relative to strain-rate effects are provided in connection with specific metals. These data apply only up to the value stated or to a rate of 1 percent per second, which is considered the maximum rate apt to occur in aircraft or missile structures except for nuclear effects. Unless otherwise stated for specific materials, strain rates can be assumed to have been between 0.001 and 0.01 m/m per minute for property measurements. Property variations in this range are considered too small to necessitate consideration in design. Most of the strain rates were between 0.003 and 0.007 metre per metre per minute, and data from this range will be used where possible in the future.

1.4.3.5 *Elongation.*—Elongation is measured generally in accordance with specification ASTM E8.

1.4.4 TENSILE PROPERTIES

1.4.4.1 *General.*—When a specimen of a certain material is tested in tension using the standard testing procedures of Reference 1.4.4.1, it is customary to plot the results of such a test as a "stress-strain diagram". Typical tensile diagrams, not to scale, are shown in Figure 1.4.4.1. Typical stress-strain diagrams drawn to scale appear in appropriate chapters for the general information of the users of this document. These diagrams have been adjusted in such a manner that the slopes of the straight-line portions of the curves are equal to the elastic modulus values reported elsewhere for the specific material. It should be noted that the strain scale is nondimensional, whereas the stress scale is in pounds per square inch. The important mechanical properties which can be shown in the stress-strain diagram are discussed in the following sections.

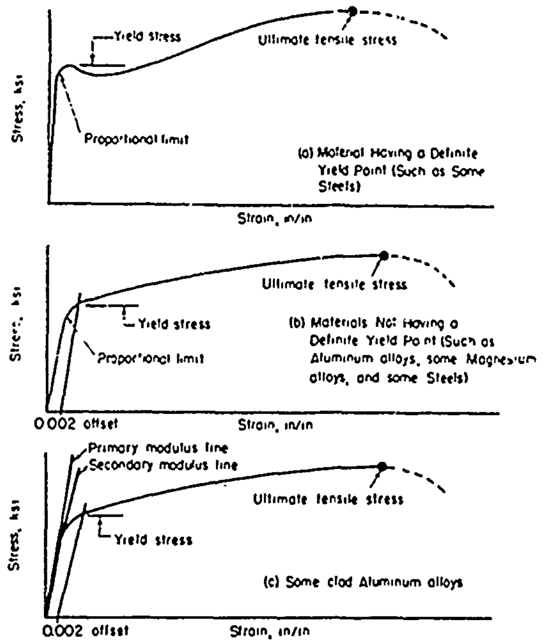

FIGURE 1.4.4.1. *Typical tensile stress-strain diagrams.*

1.4.4.2 *Modulus of Elasticity (E).*—Referring to Figure 1.4.4.1, it will be noted that the first part of the diagram is substantially a straight line. This indicates a constant ratio between stress and strain over that range. The numerical value of the ratio is called the "modulus of elasticity", denoted by E. It will be noted that E is the slope of the straight portion of the stress-strain diagram and is determined by dividing the stress (in pounds per square inch) by the strain (which is nondimensional) (see Equation 1.3.4.2). Therefore, E has the same dimensions as a stress, in this case, pounds per square inch.

Other moduli that are often of interest are the tangent modulus, E_t, and the secant modulus, E_s. E_t and E_s change with stress above the proportional limit. The tangent modulus for a particular stress is the slope of the stress-strain diagram at a point corresponding to that stress, and the corresponding secant modulus is the slope of a line drawn through the origin and a point on the diagram at the same stress.

Clad aluminum alloys may have two separate modulus values, as indicated in the typical curve presented in Figure 1.4.4.1. The initial, or primary, modulus is substantially an average of the elastic moduli of the core and cladding; it applies only up to the proportional limit of the cladding. Immediately above this point there is a short transition range, and the material then exhibits a secondary modulus up to the proportional limit of the core material. This secondary modulus is the slope of the second straight-line portion of the diagram. In some cases, the cladding is so little different from the core that a single modulus value is used.

1.4.4.3. *Tensile Proportional Limit (F_{tp}).*—Since it is practically impossible to precisely determine the stress at which the stress-strain diagram begins to depart from a straight line, it is customary to assign a small value of permanent strain for this purpose. In this document, the limit of proportionality, if used, will be taken as the stress at which the stress-strain diagram departs from a straight line by a strain of 0.0001.

1.4.4.4 *Tensile Yield Stress (F_{ty}).*—The stress-strain diagrams for some steels show a sharp break at a stress below the ultimate tensile stress. At this critical stress, the material elongates considerably with no increase in stress (see Figure 1.4.4.1). The stress at which this takes place is referred to as the yield point. Most nonferrous metals and most high strength steels do not show this sharp break, but yield more gradually so that there is no yield point. This condition is illustrated in Figure 1.4.4.1. Since permanent deformations of any appreciable amount are undesirable in most structures, it is customary to adopt an arbitrary amount of permanent strain that is considered admissible for general purposes. The value of this strain has been established by material testing engineers as 0.002, and the corresponding stress is called the yield stress. For practical purposes, this may be determined from the stress-strain diagram by drawing a line parallel to the straight (or elastic) portion of the curve through a point representing zero stress and 0.002 strain (see Figure 1.4.4.1). The yield stress is taken as the stress at the intersection of this straight line with the stress-strain curve.

1.4.4.5 *Ultimate Tensile Stress (F_{tu}).*—Figure 1.4.4.1 shows how the ultimate tensile stress is determined from the stress-strain diagram. It is simply the stress at the maximum load reached in the test. It should be noted that all stresses are based on the original cross-sectional area of the test specimen, without regard to the lateral contraction of the specimen which actually occurs during the test. The ultimate tensile stress is commonly used as a criterion of the strength of the material for structural application, but it should be borne in mind that other strength properties may often be more important.

1.4.5 COMPRESSIVE PROPERTIES

1.4.5.1 *General.*—The results of compression tests can be plotted as stress-strain diagrams similar to those shown in Figure 1.4.4.1 for tension. The preceding remarks (with the exception of those pertaining to ultimate stress) concerning the specific tensile properties of the material apply in a similar manner to the compressive properties. It should be noted that the moduli of elasticity in tension and compression are approximately equal (or slightly greater in compression) for most of the commonly used structural materials. Special considerations concerning the ultimate compressive stress are taken up in the following section. An evaluation of techniques of obtaining compressive strength properties of thin sheet material is outlined in Reference 1.4.5.1.

1.4.5.2 *Ultimate Compressive Stress (F_{cu}).*—It is difficult to discuss this property without reference to column action. Almost any piece of material, unless very short, tends to buckle laterally as a column under compressive loadings, and the load at failure usually depends on the relation of the length of the piece to its cross-sectional dimensions. Column failure cannot occur, however, when a piece is very short in comparison with its cross-sectional dimensions, or when it is restrained laterally by external means. Under these conditions, some materials, such as stone, wood, and a few metals, will fail by fracture, thus giving a definite value for the ultimate compressive stress. Most metals, however, are so ductile that no fracture is encountered in compression. Instead of fracturing, the material yields and swells out, so that the increasing area continues to support the increasing load. It is almost impossible to select a value for the ultimate compressive stress of such materials without having some arbitrary criterion. For wrought metals, it is common practice to assume that the ultimate compressive stress is equal to the ultimate tensile stress. For some cast metals which are relatively weak in tension, an ultimate compressive stress higher than the ultimate tensile stress may be obtained from tests on short compact specimens. When tests are made on such specimens having an L/p approximately equal to 12, the ultimate stress obtained is called the block compressive stress.

1.4.6 SHEAR PROPERTIES

1.4.6.1 *General.*—The results of torsion tests on round tubes or round solid sections are sometimes plotted as torsion stress-strain diagrams. The modulus of elasticity in shear as determined from such a diagram is a basic shear property. Other properties, such as the proportional limit and ultimate shearing stress, cannot be treated as basic properties because of the "form factor" effects.

1.4.6.2 *Modulus of Rigidity (G).*—This property is the ratio of the shearing stress to the shearing strain at low loads, or simply the initial slope of the stress-strain diagram for shear. It is also called the modulus of elasticity in shear. The relation between this property, Poisson's ratio, and the modulus of elasticity in tension is expressed for homogeneous isotropic materials by the following equation:

$$G = \frac{E}{2(1 + \mu)} \qquad (1.4.6.2)$$

1.4.6.3. *Proportional Limit in Shear (F_{sp}).*—This property is of particular interest in connection with formulas which are based on considerations of perfect elasticity, as it represents the limiting value of shearing stress to which these formulas can be accurately applied. As previously noted, this property cannot be determined directly from torsion tests. The results of research at the National Bureau of Standards show that the ratio of the proportional limit in shear to the proportional limit in tension can be assumed to be approximately 0.55 for the commonly used materials.

1.4.6.4 *Yield and Ultimate Stress in Shear.*—These properties, as usually obtained from torsion 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 be used only with specimens which are geometrically similar to those from which the test results were obtained.

The values for ultimate shear stress reported in the room-temperature property tables for the aluminum and magnesium sheet alloys are based on "punch" shear-type tests except as noted. Heavy section data are based on pin tests. The shear data on other alloys were obtained also from "pin" shear tests, except where thicknesses were too small.

1.4.7 BEARING PROPERTIES

1.4.7.1 *General.*—Bearing strengths are of value in the design of joints and lugs. Only yield and ultimate values are obtained from bearing tests. The bearing stress is obtained by dividing the load on a pin which bears against the edge of a hole, by the bearing area, where the area is the product of the pin diameter and sheet thickness.

The bearing test requires the use of special cleaning procedures as specified in ASTM E238-68. In the various room-temperature property tables in this document, when the indicated values are based on tests with clean pins, the values are footnoted as "dry pin values". See Reference 1.4.7.1 for discussion of this matter.

In the definition of bearing values, t is sheet thickness, D is the hole diameter, and e is the edge distance measured from the hole center to the edge of the material in the direction of applied stress. Tabular values are for e/D equal to 2, unless otherwise stated. Bearing stress values for e/D of 1.5 shall not be used for e/D < 1.5. Bearing values for e/D < 1.5 shall be substantiated by adequate tests, subject to the approval of the procuring or certificating agency. For edge distance ratios between e/D equal to 2 and e/D equal to 1.5, linear interpolation may be used.

Bearing values are applicable to D/t ratios from 1 to 5.5. Bearing values for D/t > 5.5 or < 1 must be substantiated by test. The percentage curves showing temperature effects on bearing strength may be used with e/D values of 1.5 and 2.0.

1.4.7.2 *Yield and Ultimate Bearing Stresses.*—F_{bru} is the maximum stress withstood by a bearing specimen and F_{bry} is the stress at an offset of 2 percent of the hole diameter of a bearing stress-deformation curve.

1.4.8 TEMPERATURE EFFECTS

1.4.8.1 *Low Temperature.*—Temperatures below room temperature generally cause an increase in all strength properties of metals. Ductility usually decreases. 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 metals. This decrease is dependent on many factors, such as temperature and time of exposure and the characteristics of the material. 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 given hereafter for specific materials apply only to the stated test condition.

In this Handbook, the effect of temperature on the static mechanical properties of various metals is illustrated by means of a series of graphs of property (as percent of room temperature design allowable) versus temperature. The data for these graphs have been obtained from tests made over a limited range of strain rate. Some caution should be observed in using these static property curves at very high temperatures, particularly if the strain rate in the structure is much less than the strain rate used to obtain the basic material properties. The reason for this is that at very low strain rates or under sustained stresses, 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*

General.—Creep is defined as the 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. 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 load and temperature. Creep data are sometimes obtained under conditions of cyclic uniaxial load and constant temperature (see Section 1.4.9.2, Dynamic Creep, for further information). It is recognized that, when significant creep appears likely to occur, it may be necessary to test under actual service conditions because of difficulties in extrapolating from the simple to the complex stress-temperature-time conditions.

Damage incurred in a material as a result of creep (including effects resulting from elevated-temperature exposure) is cumulative.

This damage may involve the tempering or annealing of hardened materials and the initiation and growth of cracks and voids (initially of microscopic size) within a material. Its effects are often recognizable as a reduction in short-time strength properties or ductility, both at room and at elevated temperatures.

Creep-Rupture Curve.—The results of tests of materials under a constant load and temperature are usually plotted as strain versus time up to rupture. A typical plot of creep-rupture data is shown in Figure 1.4.8.2.1(a). The strain indicated in this curve includes both the instantaneous deformation due to loading and the plastic strain due to creep.

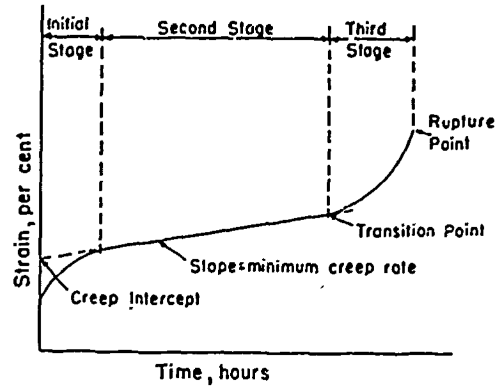

FIGURE 1.4.8.2.1(a). *Typical creep-rupture curve.*

Total Deformation (or Strain).—This value is defined as the total strain at any given time, including instantaneous loading strain (which may include plastic strain in addition to elastic strain) and creep strain, but not including thermal expansion.

Creep Strain.—Creep strain is the time-dependent part of the strain resulting from stress, excluding instantaneous loading strain and thermal expansion.

Plastic Strain.—Plastic strain includes the creep strain at any given time and the inelastic portion of the instantaneous loading strain.

Minimum Creep Rate.—Following an initially high rate of straining after loading, the strain rate gradually decreases to a minimum value that may remain constant for an extended period of time. This strain rate is defined as the minimum creep rate.

Transition Point.—Following the period of constant creep, the creep rate again increases until rupture occurs. This inflection point between the constant creep rate and the increasing creep rate is defined as the transition point.

Rupture Stress.—The stress at which rupture occurs is defined as the rupture stress. This stress varies inversely with time for constant-temperature conditions. Rupture-stress data are often used in design if the amount of total deformation is not a limiting factor.

Creep-Design Curves.—Creep properties in this document are presented sometimes in the format of curves on figures showing (1) time to reach specified amounts of total deformation or total deformation, plus thermal expansion, and (2) time to rupture; both plotted as a function of stress. Each of the figures contains data representing a single test temperature.

Creep Nomographs.—Creep properties also are illustrated by means of creep nomographs, one type of which is described (see Reference 1.4.8.2.1). The presentation of creep properties in this manner requires the use of a comparatively large number of results of tests conducted over the ranges of stress, temperature, and time of particular interest for the specific material. Furthermore, these data must be capable of being represented by a mathematical equation relating these three variables with strain. Constants in the equation are determined by least-squares-regression techniques, following which the equation is plotted as a nomograph as illustrated in Figure 1.4.8.2.1(b).

This nomograph presents creep strain as a function of initial stress (load divided by initial cross-sectional area), temperature, and time for constant-load, constant-temperature conditions. Creep strains obtained using the indicated dashed line analysis on Figure 1.4.8.2.1(b) are mean strain values. Maximum and minimum strain values for a given mean strain can be obtained by laying off a length above and below the mean value whose magnitude is equal to the indicated length of one standard deviation. With this construction, the maximum strain is a value that will be expected to be exceeded by about 5 percent of data; whereas the minimum strain is a value that 5 percent of the data will be below. Since limit design stresses do not exceed the short time yield strength of a material at service temperature, stress-temperature parameters are terminated at this stress. The nomograph is utilized by entering

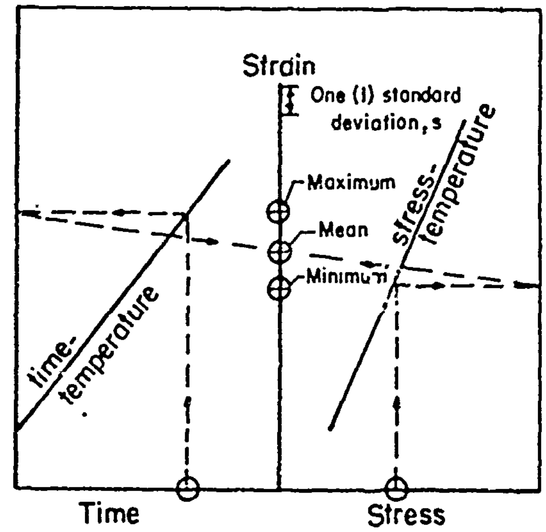

FIGURE 1.4.8.2.1(b). *Schematic creep nomograph.*

it through any two of the parameters, stress-temperature, time-temperature, and creep-strain (indicated by circles in the illustration), and determining the inter-section with the scale for the third parameter. Instantaneous loading strains are not indicated in the nomograph and should be obtained from stress-strain curves or other sources.

1.4.9 FATIGUE PROPERTIES

1.4.9.1 *General.*—Repeated loads are one of the major causes for reducing design allowable stresses below those listed in the various tables of static properties (F_{tu}, F_{ty}, etc.) These reductions vary extensively in degree and are a function of the design practices of the producer of parts. Therefore, no discussion of design use of fatigue (repeated load) data is included herein. However, some basic laboratory test data are useful in the materials selection and preliminary design processes and such data are therefore provided in the appropriate materials section, whenever available.

In the past, common methods of obtaining and reporting repeated load (fatigue) data included axial-loading tests, plate bending tests, rotating bending tests, and torsion tests. Rotating bending tests apply completely reversed (tension-compression) stressing to round specimens. Tests of this type are now seldom conducted for aerospace use and have therefore been dropped. For similar reasons, flexure fatigue data also have been dropped. No significant amount of torsional fatigue data have ever been available. Axial loading tests, the only type retained herein, not only can consist of completely reversed loading (mean stress equals zero), but the mean stress can be varied.

1.4.9.2 *Fatigue Symbols and Definitions.*—A number of symbols and definitions are commonly used in fatigue. The most important of these are presented in this section (see Reference 1.4.9.2).

Stress Cycle.—The smallest section of the stress-time function which is repeated periodically and identically. Figure 1.4.9.2 illustrates diagrammatically many of the following terms.

Nominal Stress (S).—The stress calculated on the net section by simple theory such as S = P/A without taking into account the variation in stress conditions caused by geometrical discontinuities such as holes, grooves, fillets, etc.

Maximum Stress (S_{max}).—The highest algebraic value of the stress in the stress cycle, tensile stress being considered positive and compressive stress negative.

Minimum Stress (S_{min}).—The lowest algebraic value of the stress in the stress cycle, tensile stress being considered positive and compressive stress negative.

Range of Stress (S_r).—The algebraic difference between the maximum and minimum stresses in one cycle, i.e., $S_r = S_{max} - S_{min}$.

Alternating Stress Amplitude (or Variable Stress Component) (S_a).—One-half the range of stress, i.e., $S_a = S_r/2$.

Mean Stress (or Steady Stress Component) (S_m).—The algebraic mean of the maximum and minimum stresses in one cycle, i.e., $S_m = (S_{max} + S_{min})/2$.

Stress Ratio (R).—The algebraic ratio of the minimum stress to the maximum stress in one cycle, i.e., $R = S_{min}/S_{max}$.*

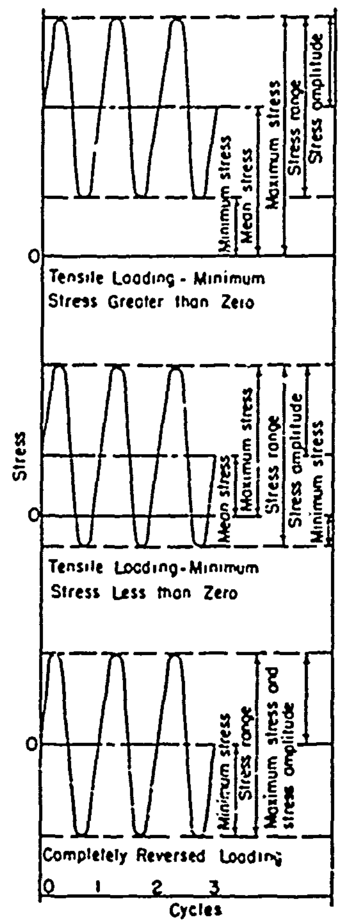

FIGURE 1.4.9.2. *Typical fatigue loadings.*

* Another ratio, $A = \frac{\text{stress amplitude } (S_a)}{\text{mean stress } (S_m)}$ is being used, particularly in high-temperature fatigue work. A is related to R as follows:

$$R = \frac{1 - A}{1 + A} \; ; A = \frac{1 - R}{1 + R}$$

Stress Cycles Endured (n).—The number of cycles which a specimen has endured at any stage of a fatigue test.

Fatigue Life (N).—The number of stress cycles which can be sustained before failure for a given test condition.

S-N Diagram.—A plot of stress against number of cycles to failure. It is usually plotted S versus log N, but a plot of log S versus log N is sometimes used.

Constant-Lifetime Diagram.—A summary graph prepared from a group of S-N curves on a material, each S-N curve obtained at a different stress ratio. In this document the diagram shows the relationship between the alternating stress amplitude and the mean stress and between maximum stress and minimum stress of the stress cycle for various constant lifetimes (for example, 10^4, 10^5, 10^7 cycles). The diagrams may be constructed for a fracture criterion, for various dynamic creep criteria, or other criteria as desired.

Dynamic Creep.—The permanent deformation that can occur in a fatigue test (usually conducted at elevated temperature), and for which the stress ratio (R or A) is such that a tensile means stress exists throughout the test.

Fatigue Limit (or Endurance Limit) (S_e).—The limiting value of the stress below which a material can presumably endure an infinite number of stress cycles, that is, the stress at which the S-N diagram becomes horizontal and appears to remain so. The limit may be hundreds of millions of cycles.

Stress at the Fatigue Limit.—This stress may be expressed in terms of the alternating stress amplitude or the maximum stress; whichever of these methods are used, the value of the mean stress, minimum stress, or stress ratio must also be stated.

Fatigue Strength.—The greatest stress (consistent with the preceding paragraph) which can be sustained for a given number of cycles without fracture. The number of cycles should always be given.

1.4.9.3 *Graphical Display of Fatigue Data.*—The results of axial-load fatigue tests are usually reported on S-N diagrams. Figure 1.4.9.3(a) shows a family of axial load S-N curves for a material, the data for each curve having been taken at a single stress ratio, R.

Fatigue data as presented in Figure 1.4.9.3(a) are helpful to the designer; however, it also has been found useful to present a summary plot of fatigue data as a modified Goodman-type diagram or constant-life fatigue diagram, as shown in Figure 1.4.9.3(b) for the same curves illustrated in Figure 1.4.9.3(a).

For elevated-temperature design, it may be useful to consider creep and fatigue simultaneously; i.e., a component may fail either as a consequence of excessive plastic deformation or by fracture from repeated stress. This is illustrated in Figure 1.4.9.3(c) where S-N curves are shown for a material tested at elevated temperature at one stress ratio. In the figure, S-N curves are shown for failure by fatigue fracture and for two dynamic creep criteria.

Again, by means of a constant-life diagram shown in Figure 1.4.9.3(d), a summary plot can be made of families of S-N curves for the fracture criterion and for one or more dynamic creep criteria.

The fatigue data provided in the various constant-life diagrams in each material chapter were derived from average (or typical) S-N curves which would lie at about the center of scatter bands of existing unnotched and notched data.

To provide some idea of the extent of data on which the diagrams are based, the radiating R or A lines which correspond to the specific test conditions for which data were available are marked by a rectangular symbol along the outer extremities of the diagram. Some tests are conducted under constant mean stress conditions. In these cases, the rectangles are close to the mean stress axis. These curves may not apply directly to the design of structures because they may not take into account the effect of the specific stress concentration associated with reentrant corners, notches, holes, joints, rough surfaces, and other similar conditions which are present in fabricated

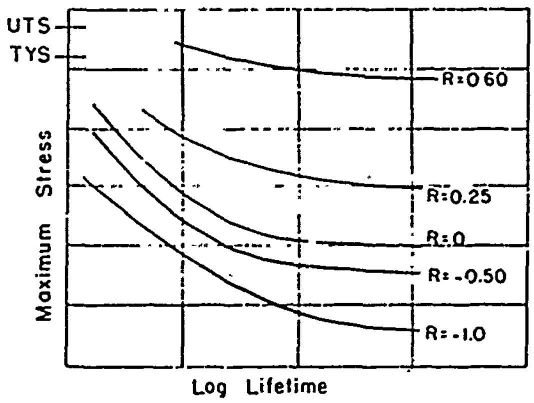

FIGURE 1.4.9.3(a). *S-N curves for a material at various stress ratios.*

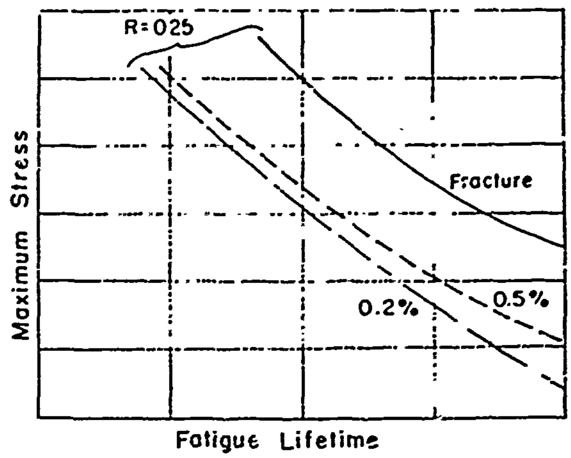

FIGURE 1.4.9.3(c). *S-N curves for fatigue fracture and two dynamic creep criteria.*

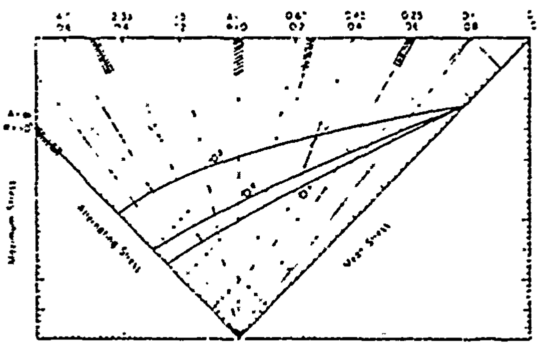

FIGURE 1.4.9.3(b). *Constant-life diagram from S-N curves for Figure 1.4.9.3(a).*

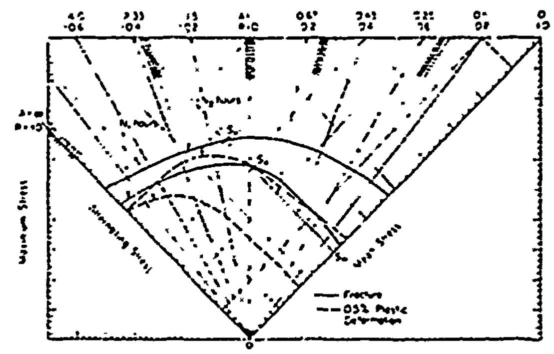

FIGURE 1.4.9.3(d). *Constant-life diagram for fracture and one creep criterion.*

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. They 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. Fabricated parts in test have been found to fail at less than 50,000 repetitions of load when the nominal stress was far below that which could be repeated many millions of times on a smooth machined specimen.

The notched fatigue data in the figures are presented so that by comparing the notched data with those from smooth specimens, the serious effect of a sharp notch on fatigue strength can be seen. The notch fatigue strengths, like the smooth specimen fatigue strengths, are not to be used directly as the allowable stress values for design, but are included for information.

References 1.4.9.3(a) and (b) contain much more specific information on fatigue testing procedures, organization of data, the influence of various factors on fatigue, and on design considerations.

1.4.10 METALLURGICAL INSTABILITY.

—In addition to the retention of load-carrying ability 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 by carbide precipitation, spheroidization, sigmaphase formation, temper embrittlement, and internal or structural transformation, depending upon the material and conditions.

Environmental conditions which may influence metallurgical stability include (a) heat, (b) stress, (c) oxidizing or corrosive media, and (d) nuclear radiation. The effect of the environment on the material may be indicated as either improvement or deterioration of properties, depending upon the way the material is evaluated. For example, prolonged heating may progressively raise the strength of a metal as measured on smooth tensile or fatigue specimens, but at the same time lower the ductility to such an extent that notched behavior is erratic or unpredictable. The metallurgy of each alloy should be considered in selecting any material listed herein.

Under normal temperatures, i.e., between 219 K and 344 K, the stability of most structural materials is relatively independent of time. However, as the temperature increases, the metallurgical stability of a material becomes increasingly time dependent and the factor of time assumes a more prominent role in material behavior and selection.

1.4.11 BIAXIAL PROPERTIES

1.4.11.1 *General.*—Discussions up to this point have been directed primarily to uniaxial conditions, whether the subject was static, fatigue, or creep loading. In actuality, many structural geometries, or load applications, are such that induced stresses are not uniaxial, but are bi- or triaxial. Because of the difficulty in testing, few triaxial stress data exist. However, considerable biaxial testing has been conducted and the following paragraphs describe how the results are presented in this Handbook. If stresses are referred to the mutually perpendicular x, y, and z directions of the usual rectangular coordinates, a biaxial stress is a condition such that there are either positive or negative stresses in the x and y directions and the stress in the z direction is essentially zero. Most of the discussion hereafter is concerned with x and y direction stresses which are both tensile (see Reference 1.4.11.1).

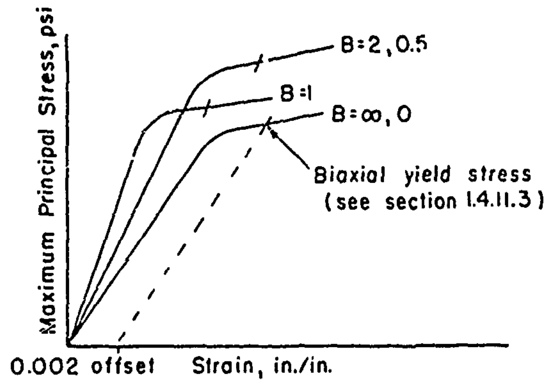

FIGURE 1.4.11.1. *Typical biaxial stress-strain diagrams for isotropic materials.*

When a specimen of a material is tested under biaxial loading conditions, it is customary to plot the results of such a test as a "biaxial stress-strain diagram". These diagrams are similar to the tensile stress-strain diagrams shown in Figure 1.4.4.1. Usually, only the maximum (algebraically larger) principal stress and strain are shown for each test. When tests of the same material are conducted at various biaxial ratios, the resulting curves may be plotted simultaneously, producing a "family" of biaxial stress-strain curves as shown in Figure 1.4.11.1 for an isotropic material. For an anisotropic material, the curve for a given biaxial ratio would not coincide with the curve for the reciprocal of the biaxial ratio. The reference direction for biaxial ratio (i.e., direction corresponding to B = O) should clearly be indicated on the figure. The reference direction is the longitudinal (rolling) direction for flat products and the hoop (circumferential) direction for shells of revolution (tubes, cones, etc.).

The biaxial property data presented in the Handbook are to be considered as basic material properties obtained from tests on carefully prepared specimens. The stress values reported here may not be attainable in full-scale structures, depending upon weld quality and other fabricational factors (see Reference 1.4.11.1 for further information).

1.4.11.2 *Biaxial Modulus of Elasticity.*—Referring to Figure 1.4.11.1, it will be noted that the first part of the diagram is substantially a straight line. In uniaxial tension, the slope of this line is defined as the "modulus of elasticity" (see Section 1.4.4.2). Under biaxial loading conditions this slope, now called the "biaxial modulus of elasticity", is affected by the biaxial ratio and Poisson's ratio (see Equation 1.3.7.4).

1.4.11.3 *Biaxial Yield Stress.*—Just as the tensile yield stress (F_{ty}) is defined arbitrarily as the uniaxial stress at 0.002 m/m "offset" or permanent strain, as determined from the tensile stress-strain curve, the biaxial yield stress is defined as the maximum principal stress at 0.002 m/m offset strain, as determined from the biaxial stress-strain curve.

In design of aircraft and missile structures, biaxial ratios other than those normally used in biaxial testing are frequently encountered. For convenience in interpolating at intermediate biaxial ratios, biaxial yield-stress values are shown as biaxial yield-stress "envelopes", as illustrated in Figure 1.4.11.3. In preparing these envelopes, data are first reduced to nondimensional form (percent of uniaxial tensile yield stress in the specified reference direction), then a best curve is fitted to the reduced data. Biaxial yield-strength values for design are then obtained by multiplying the F_{ty} for the specified material by the coordinates of the curve (in percent) at the appropriate biaxial ratio. To avoid possible confusion, the reference direction used for the uniaxial yield strength is indicated on each figure.

The local value of the biaxial ratio should be used in applying biaxial yield stress data to design. Thus, although a sheet may have a gross loading with a biaxial ratio of one, at each free (unloaded) edge or hole, the local stress system is uniaxial and the local biaxial ratio is either zero or infinity. A similar precaution applies to material in the vicinity of loaded holes (e.g., rivet holes, bolt holes) and to discontinuities in cross section, such as those occurring as a result of integral stiffeners.

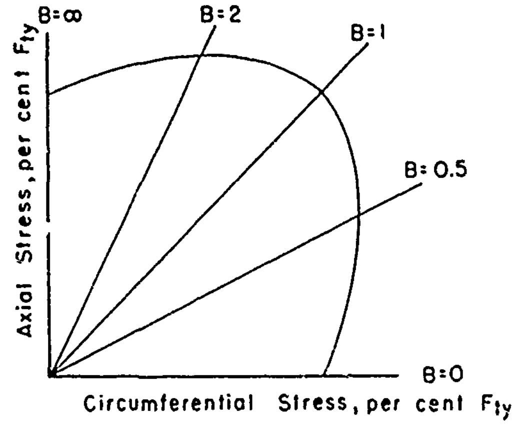

FIGURE 1.4.11.3. *Typical biaxial yield stress envelope.*

1.4.11.4 *Biaxial Ultimate Stress.*—Biaxial ultimate stress is defined as the highest nominal principal stress reached in specimens of a given configuration, tested at a given biaxial ratio. Unlike uniaxial ultimate tensile stress (F_{tu}), biaxial ultimate stress is often highly dependent upon the geometrical configuration. Thus, ultimate-stress data obtained from tests on cylindrical vessels should be limited to cylindrical-vessel applications, flat-sheet data only to flat-sheet applications, etc.

The method of presenting biaxial ultimate-stress data is similar to that described in Section 1.4.11.3. When nominal strains at biaxial ultimate stress values are available, they are reported as a function of biaxial ratio.

1.4.12 FRACTURE STRENGTH

1.4.12.1 *General.*The occurrence of flaws in a structural component is an unavoidable circumstance of material processing, fabrication, or service. These flaws may be cracks, metallurgical inclusions or voids, weld defects, design discontinuities, or some combination thereof. If severe enough, these flaws can induce structural failure at loads below those of the nominal design. The fracture strength of a component containing a flaw is dependent on the flaw size, the component geometry, and a material property termed "fracture toughness".

The fracture toughness of a material is literally a measure of its resistance to fracture. It also is considered a measure of its tolerance or lack of sensitivity to flaws. As with many other material properties, fracture toughness is dependent on processing variables, product form, geometry, temperature, loading rate, and other environmental factors. Many measures of fracture toughness have evolved. Those based on crack stress or strain analysis are more meaningful for use in design applications. Other measures are useful for qualitative evaluation of materials; however, they have proven to be difficult to apply to specific design configurations.

While there are several types of fracture, this discussion is limited to brittle fracture which is characteristic of high-strength materials in structural configurations which approach plane-strain conditions by nature of their bulk thickness or geometric constraint. Little plasticity accompanies the fracture. The following is based on the current practice of testing specimens of materials 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.

1.4.12.2 *Brittle Fracture.*—For materials which 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 1.4.12.2. Since little or no plastic effects are noted, this mode is termed brittle fracture. This mode of fracture is somewhat characteristic of the very high-strength metallic materials under plane-strain conditions.

1.4.12.2.1 *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 a very general form, the stress intensity factor, K, can be expressed as

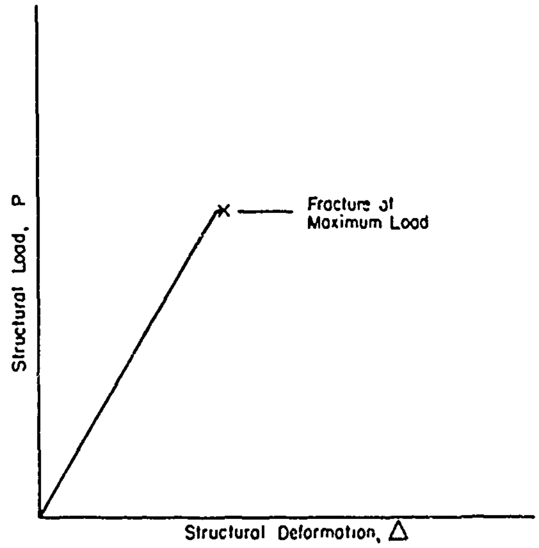

FIGURE 1.4.12.2 *Typical load-deformation record of a structural component containing a flaw subject to brittle fracture.*

$$K = f\sqrt{a}\,Y,\ \text{MPa} \cdot \text{m}^{1/2} \qquad (1.4.12.2.1)$$

where

f = stress applied to the gross, flawed section, MPa

a = measure of flaw size, inches

Y = factor relating component geometry and flaw size, nondimensional. See Reference 1.4.12.2.1(a) for values.

For every structural material which exhibits brittle fractures (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-24 on Fracture Testing of Metals has been evolving testing and analytical techniques for many practical situations of flaw occurrence subject to brittle fracture. These are well summarized in References 1.4.12.2.1(a), 1.4.12.2.1(b), and 1.4.12.2.1(c) and are updated by committee notes and reports.

1.4.12.3 *Critical Plane-Strain Fracture Toughness Values.*—In the general discussion prefacing each alloy chapter, a tabulation of fracture toughness values is presented where information is available. These values are average critical plane-strain fracture toughness values, K_{Ic}, which have been determined by the recommended ASTM testing practice. Since the data on a given alloy and product form are generally limited, these data are for information only and do not have the statistical reliability normally associated with the room temperature mechanical properties. In general, these data are available only for the high strength alloys in relatively thick sections.

The directional significance of the fracture toughness value relative to the grain direction of the material may be identified by an ordered pair of grain direction symbols. The first digit of the pair denotes the grain direction normal to the crack plane; the second digit of the pair denotes the grain direction parallel to the fracture direction. Thus, the six principal fracture path directions may be denoted as:

L-T	T-S
L-S	S-L
T-L	S-T

Figure 1.4.12.3 illustrates the six principal fracture path directions.

1.4.12.3.1 *Environmental Effects.*—As noted in Section 1.4.12.1, all fracture-toughness data presented in this document represent data obtained under a single application of a steadily increasing load in air. Cyclic loading, even well below the fracture threshold stress, may result in propagation of flaws, leading to fracture. Strain rates in excess of those normally used in testing may cause variations in material behavior. There

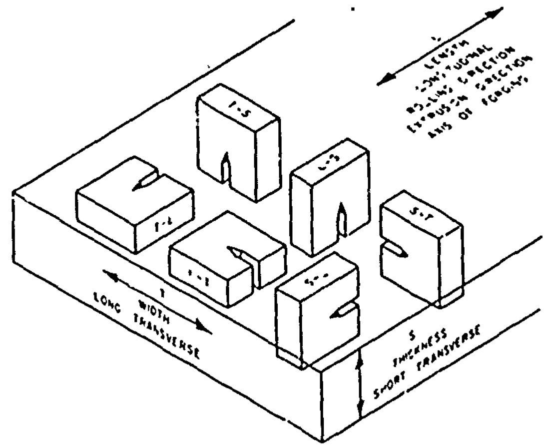

FIGURE 1.4.12.3. *Typical principal fracture path directions.*

are distinct effects of temperature on fracture-toughness properties.

A very limited quantity of effect of temperature data are available for fracture toughness properties. Where these are available, they will be incorporated in the X.X.X.X.9 section of each chapter.

It has been noted that under sustained loads some materials exhibit increased flaw-propagation tendencies in aqueous or corrosive environments. When such is known to be the case, appropriate precautionary notes have been included in the alloy chapters.

1.4.12.4 *Fracture in Plane Stress and Transitional Stress States.*—In many structural components, plane strain conditions are never manifested because of the thinness of the product form and the intrinsic ductility of the material. In these cases, the actual stress state may approach the opposite extreme, plane stress, or, more generally, some intermediate or transitional stress state. Flaws or cracks which may occur in these stress states behave differently than those in plane strain. Under loading, due to lesser crack tip constraint, significant plastic zones may develop adjacent to the crack tip, and stable extension of the crack may occur by a slow tearing process This more complex behavior is exhibited in the compliance record as a significant nonlinearity prior to fracture such as shown in Figure 1.4.12.4. This nonlinearity results from the lessening stiffness

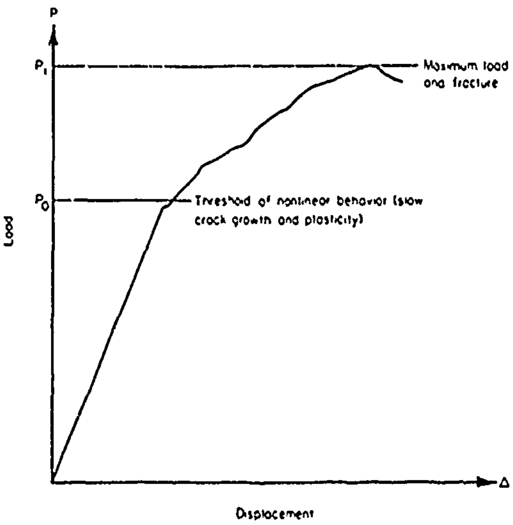

FIGURE 1.4.12.4. *Typical load-deformation record for nonplane strain fracture.*

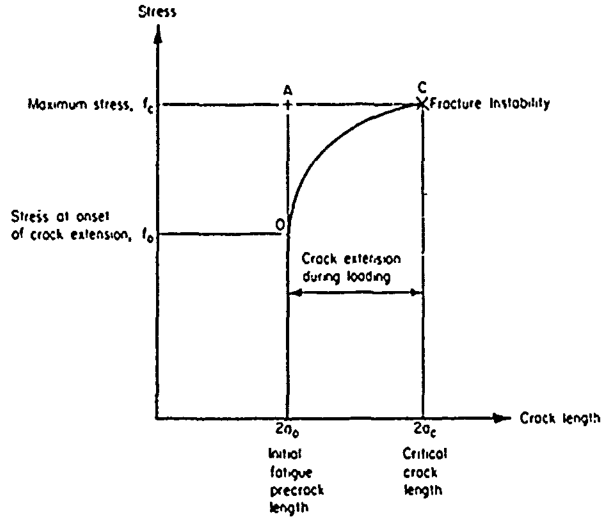

FIGURE 1.4.12.4.1. *Crack growth curve.*

which accompanies plastic-zone development and from the reduced cross-sectional area resulting from crack extension.

1.4.12.4.1 *Analysis of Plane Stress and Transitional Stress State Fracture.*—Although the physical problem is much more complex, the basic concepts of linear elastic fracture mechanics as used in plane strain fracture analysis may be applied here also. The stress intensity factor concept, as expressed in general form by Expression 1.4.12.2.1., is used to relate load or stress, flaw size, component geometry, and fracture toughness. However, the interpretation and assignation of critical stress intensity factors must be accomplished with much greater care. In Figure 1.4.12.4., it can be seen that there are at least two and possibly more points on the load-deformation curve to which it would be important to assign K values. These are the point of onset of nonlinearity and the point of fracture, each of which generally will occur at different stress levels, as well as different crack lengths due to stable tear.

This becomes clearer when the compliance record is transformed into the crack growth curve on the stress-flaw size coordinate system format illustrated in Figure 1.4.12.4.1. In most practical cases, however, the definition and precise experimental discrimination of the point of onset of nonlinearity and the point of fracture are very elusive.

As a result, an alternate characterization of the fracture behavior can be achieved by calculating an artificial or "apparent" stress-intensity factor,

$$K_{app} = f\sqrt{a_o Y}, \qquad (1.4.12.4.1)$$

using the maximum stress and the initial flaw size. This datum coordinate corresponds to the point A in Figure 1.4.12.4.1 and its associated stress-intensity factor, K_{app}, is a first approximation to the actual K values which may be associated with either the onset of nonlinearity or the point of fracture.

1.4.12.5 *Apparent Fracture Toughness Values for Plane Stress and Transitional Stress States.*—In each alloy chapter, basic fracture data are presented on a graphical format of stress versus flaw size for each alloy, temper, product form, grain direction, thickness, and specimen configuration where data are available. The data points shown represent the initial flaw size and maximum stress for that test point. The data presented have been screened to assure that there was a bona fide elastic instability at fracture consistent with the 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 *Center-Cracked Tension Panels.*— The formulation of the apparent fracture toughness for center-cracked tension panels is

$$K_{app} = f_c (\pi a_0 \sec \pi a_0/W)^{1/2} \quad (1.4.12.5.1(a))$$

The data points used to determine the K_{app} values have been screened to assure that the net section stress at failure did not exceed 80% of the tensile yield strength; that is, they satisfied the criterion

$$f_c \leq 0.8(TYS)/(1 - 2a/W) \quad (1.4.12.5.1(b))$$

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 additional information, where data are available, the propensity for slow stable tear prior to fracture is indicated by a crack extension ratio, $2a/2a_{o}$. In some cases, where data exist covering a wide range of thickness, graphs of K_{app} versus thickness are presented.

1.5 Types of Failures

1.5.1 GENERAL.—In the following discussion, the term "failure" will usually denote actual fracture of the member, or the condition of the member when it has just attained its maximum load.

1.5.2 MATERIAL FAILURES

1.5.2.1 *General.*—Fracture of a metal can be very complex and will therefore not be discussed thoroughly herein. Many references can be consulted for such information. It should be noted, however, that fracture can occur in either a ductile or brittle fashion, in the same material, depending on the state of stress and the environment. Additionally, metals are being used which have higher and higher strengths and this has resulted in lower ductility prior to fracture. Fracture can occur after elongation of the metal over a relatively large uniform length, or after a concentrated elongation in a short length. Shear deformation will also vary depending on the metal and the stress state. Because of these variations in magnitude and mode of deformation, the ductility of a metal can have a profound effect on the ability of a fabricated part to withstand applied loads. Although not a specific design property, some ductility data are provided for each metal to assist in materials selections. Following paragraphs discuss the relation of failure to applied or induced stresses.

1.5.2.2 *Direct Tension or Compression.*—This type of failure is associated with the ultimate tensile or compressive stress of the material. For compression, it can apply only to members having large cross-sectional dimensions as compared with the length in the direction of the load (see also Section 1.4.5.2).

1.5.2.3 *Shear.*—Pure shear failures are usually obtained only when the shear load is transmitted over a very short length of the member. This condition is approached in the case of rivets and bolts. In cases where the ultimate shear stress is relatively low, a pure shear failure may result, but in general a member subjected to a shear load fails under the action of the resulting normal stress (Equation 1.3.3.3), usually the compressive stress. The failure of a tube in torsion, for instance, is not usually caused by exceeding the allowable shear stress, but by exceeding a certain allowable normal compressive stress, which causes the tube to buckle. It is customary, for convenience, to determine the allowable stresses for members subjected to shear in the form of shear stresses. Such allowable shear stresses are therefore an indirect measure of the stresses actually causing failure.

1.5.2.4 *Bearing.*—The failure of a material in bearing may consist of crushing, splitting, or progressive rapid yielding in the region where the load is applied. Failure of this type will depend, to a large extent, on the relative size and shape of the two connecting parts. The allowable bearing stress will not always be applicable to cases in which one of the contacting members is relatively thin. It is also necessary, for practical reasons, to limit the working bearing stress to low values in such cases as joints subjected to reversals of load or in bearings between movable surfaces. These special cases are covered by specific rulings of the procuring or certificating agency, involving the use of higher factors of safety in most cases.

1.5.2.5 *Bending.*—For compact sections not subject to instability, a bending failure can be classed as a tensile or compressive failure caused by exceeding a certain allowable stress in some portion of the specimen. It is customary to determine, experimentally, the "modulus of rupture in bending", which is a stress derived from test results through the use of Equation 1.3.2.3, in which case M is the value of bending moment which caused failure. For compact sections not subject to instability, the treatment of bending in the plastic range by linear analog methods, for example, Cozzone (Reference 1.5.2.5), provides a method by which actual bending stresses above the material proportional limit can be related to the "bending modulus of rupture". From simple bending theory, the bending modulus of rupture is determined by Equation 1.3.2.3. When the modulus of rupture is less than or equal to the proportional limit, it represents an actual stress. When the modulus of rupture is greater than the proportional limit, it represents an apparent stress which cannot be considered as the actual stress at the point of rupture. This should be borne in mind in dealing with combined stresses such as bending and compression or bending and torsion.

1.5.2.6 *Failure Due to Stress Concentration.*—The static strength properties listed for various materials were determined on machined specimens containing no notches, holes, or other avoidable stress raisers. In the design of aircraft structures, such simplicity is unattainable, and stress distributions are not of the uniform type obtained in the specimen tests. Consideration must be given to the effect of stress raisers since maximum stress in a material and not average stress, is the critical factor in design. The effects of stress raisers vary, and references to available specific data are given in the sections pertaining to each material.

1.5.2.6.1 *Failure Due to Unintentional Flaws.*—As stated in Section 1.4.12.1, unintentional flaws may be metallurgical defects, such as inclusions, voids, seams, weld defects; they also may be surface defects from service, such as corrosion pits, stress-corrosion cracks, and fatigue cracks. Some high-strength materials are extremely sensitive to such small cracks or flaws, and their use has resulted in structural failure. In this context, the word "sensitive" means that for certain of the high-strength materials that inadvertently contain flaws, failure of the material or a part fabricated from it may occur at gross stress levels substantially below the yield strength. Universal agreement on a design accounting for this type of failure still is evolving. One approach involving plane-strain fracture toughness data has led to the inclusion of such data in certain material chapters. Since for these high-strength materials premature fracture may occur, the possibility should be considered in design. The "Aerospace Structural Metals Handbook" (Reference 1.5.2.6.1) also contains fracture-toughness data.

1.5.2.7 *Failure Resulting From Fatigue.*—Aircraft structures are subjected to repeated loads. It is well known that the strength of a material under such repeated loads is less than it would be under static loading. This phenomenon of the decreased strength of a material under repeated loading is commonly called fatigue. Stress raisers, such as abrupt changes in cross section, holes, notches, and reentrant corners, have a much greater effect on the fatigue strength than they do on static strength. The local high stress concentrations caused by such stress raisers are often greatly in excess of the nominal calculated stress on the part, and consequently it is at such locations that fatigue fractures usually begin. Other factors of major importance in fatigue are the range of the repeated stress cycle (from maximum to minimum stress), and the mean stress in the stress cycle. In the following chapters of this document, fatigue data are presented for various materials from axial load fatigue tests. The data are average or typical data and are not to be used as allowable stress values unless their applicability to the case at hand has been established.

1.5.2.8 *Failure From Combined Stresses.*—In 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 has received wide acceptance as a simple working basis in the case of isotropic ductile materials. It should be noted that this theory interprets failure as the first yielding of the materials, so that any extension of the theory to cover conditions of final rupture must be based on the experience of the designer. The failure of brittle materials under combined stresses can generally be treated by the "maximum stress" theory. Section 1.4.11 has a more complete discussion of biaxial behavior.

1.5.3 INSTABILITY FAILURES

1.5.3.1 *General.*—Practically all structural members such as beams and columns, particularly those made from thin material, are subject to failure through instability. In general, instability can be classed as: (1) primary or (2) local. For example, the failure of a tube under compression may occur either through lateral deflection of the tube as a column (primary instability) or by collapse of the tube wall at a stress lower than that required to produce a general column failure. Similarly, an I-beam or other shape may fail by a general sidewise deflection of the compression flange, by local wrinkling of thin outstanding flanges, or by torsional instability. It is obviously necessary to consider all types of failure, unless it is apparent that the critical load for one type is definitely less than that for the other type.

Instability failures may occur in either the elastic range (below the proportional limit) or in the plastic range (above the proportional limit). To distinguish between these two types of action, it is not uncommon to refer to them as "elastic instability failures" and "plastic instability failures", respectively. It is important to note that instability failures are not usually associated with the ultimate stresses of the material. This should be borne in mind when correcting test results for material variations. This point also has a bearing on the choice of a material for a given type of construction, as the "strength-weight ratio" will be determined from different physical characteristics when this type of failure can be expected.

A method of determining the local stability of aluminum alloy column sections is outlined in Reference 1.7.1(b). The documents cited in Reference 1.7.1(b) are the same as those listed in Chapter 3, References 3.20.2.2.(a) through (e).

1.5.3.2 *Instability Failures Under Compressive Loading.*—Failures of this type are discussed in Section 1.6 (Columns).

1.5.3.3 *Bending Instability Failures.*—Failures of round tubes of usual size when subjected to bending are usually of the plastic-instability type. In such cases, the criterion of strength is the modulus of rupture (Equation 1.3.2.3) which was derived from theory and checked by test. Elastic-instability failures of thin-walled tubes having high D/t ratios are treated in later sections.

1.5.3.4 *Torsional Instability Failures.*—The remarks of 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.

1.5.3.5 *Failure Under Combined Loadings.*—For combined-loading conditions in which failure is caused by buckling or instability, no general theory exists which will apply in all cases. It is convenient, however, to represent such conditions by the use of "stress ratios", which can be considered as non-dimensional coefficients denoting the fraction of the allowable stress or strength which is utilized or which can be developed under special conditions. For simple stresses, the stress ratio can be expressed as

$$R = f/F, \qquad (1.5.3.5(a))$$

where

f = applied stress
F = allowable stress.

Note that the "margin of safety" as usually expressed is given by the equation

$$M.S. = 1/R - 1.0. \qquad (1.5.3.5(b))$$

Considering the case of combined loadings, the general conditions for failure can be expressed by equations of the following type:

$$R_1^x + R_2^y + R_3^z + \ldots = 1.0 \qquad (1.5.3.5(c)).$$

In this equation, R_1, R_2 and R_3 may denote, for instance, the stress ratios for compression, bending, and shear, and the exponents, x, y, z define the general relationship of the quantities. This equation may be interpreted as indicating that failure will occur only when the sum of the stress ratios is equal or greater than 1.0. An advantage of this method is that the formula yields correct results when only one loading condition is present. Consequently, it tends to give good results when any one loading condition predominates. It also permits test data to be plotted in nondimensional form, which is a decided advantage.

In many cases, it is convenient to deal directly with "load ratios", rather than stress ratios. The load ratio is simply the ratio of the applied load to the allowable load and is equal to the corresponding stress ratio.

Considering only two loading conditions, such as bending and torsion, Equation 1.5.3.5(c) can be plotted as a single interaction curve of R_b against R_s. Likewise, in the case of combined bending and compression, R_c can be plotted against R_b. When all three conditions exist, the equation represents an interaction surface, which can be plotted as a family of curves. Typical curves corresponding to various exponents are shown in Figure 1.5.3.5. The general significance of Equation 1.5.3.5(c) and Figure 1.5.3.5 is that the addition of a second loading condition will lower the percentage of the allowable stress which may be utilized in the original loading condition. If the exponents approach infinity, the curve of Figure 1.5.3.5 will approach the lines $R_1 = 1.0$ and $R_2 = 1.0$, indicating that the two loading conditions have no effect on each other.

When only two stress ratios are involved and when the two different applied stresses remain in constant proportion, the margin of safety of the member may be determined from Figure 1.5.3.5 by the following method:

(a) Locate the point on the chart representing the applied values of R_1 and R_2 computed from the applied stresses (illustrated as point 1 on Figure 1.5.3.5).
(b) Draw a straight line through this point and the origin (shown as a diagonal dotted line on Figure 1.5.3.5).

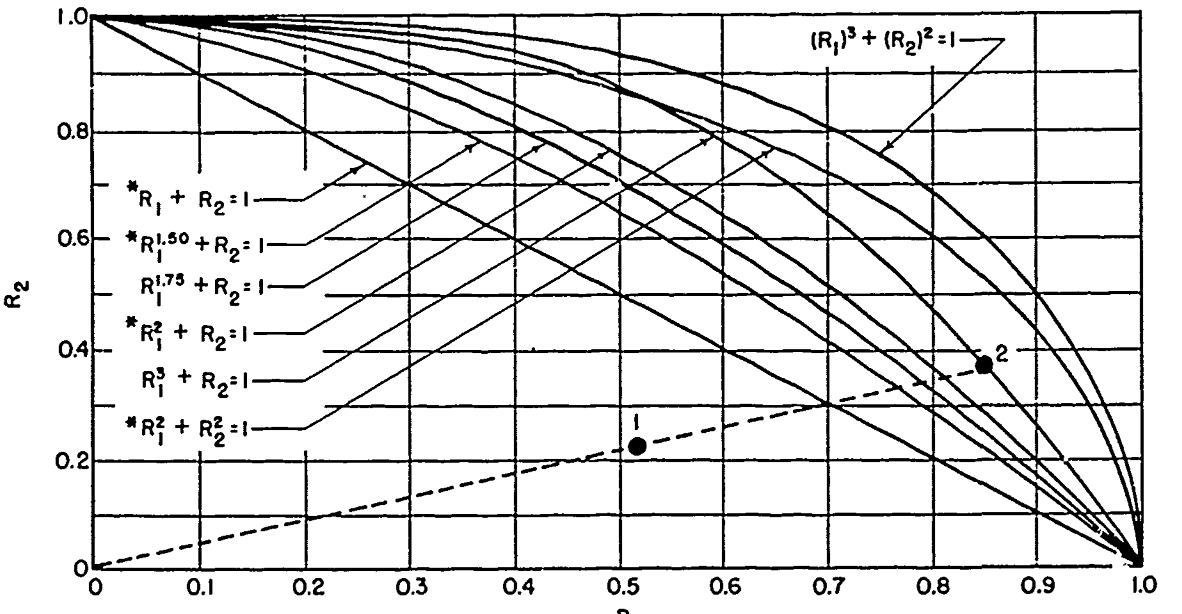

FIGURE 1.5.3.5. *Typical interaction curves for combined loading conditions. *Refer to Section 1.5.3.5 for analytical margin of safety.*

(c) Extend this line to intersect the proper stress-ratio curve (corresponding to the condition under consideration) at point 2.

(d) Read the allowable values R_{1a} and R_{2a} as the ordinate and abscissa, respectively, of point 2.

(e) The factor of utilization or strength ratio is obtained as the ratio of the applied to the allowable value of either stress ratio, as follows:

$$U = R_1/R_{1a} = R_2/R_{2a} \ . \qquad (1.5.3.5(d))$$

(f) The true margin of safety, then, can be computed from the following equation:

$$M.S. = \frac{1}{U} - 1 \ . \qquad (1.5.3.5(e))$$

Note that, when the following stress-ratio expressions are used, the margins of safety can be computed as indicated:

For $R_1 + R_2 = 1$,

$$M.S. = \frac{1}{(R_1 + R_2)} - 1 \quad ;$$

For $R_1^2 + R_2^2 = 1$,

$$M.S. = \frac{1}{\sqrt{R_1^2 + R_2^2}} - 1 \quad .$$

Other M.S. formulas can be determined, of course, for the more complicated stress-ratio expressions.

The general formula for the margin of safety stated analytically for interaction equations where any or all of x, y, and z are 1 or 2 but no other figure (except one term may be missing) is as follows:

$$M.S. = \frac{2}{[R' + \sqrt{(R')^2 + 4(R'')^2}]} - 1 \quad .$$

Here, the R' designates the sum of all first-power ratios, $(R')^2$ is the square of the same sum, and $(R'')^2$ the sum of the squares of all second-power ratios. The following tabulation gives all combinations:

Interaction formula	Margin of safety
$R_1 + R_2^2 = 1.0$	$\frac{2}{R_1 + \sqrt{R_1^2 + 4R_2^2}} - 1$
$R_1 + R_2 + R_3 = 1.0$	$\frac{1}{R_1 + R_2 + R_3} - 1$
$R_1 + R_2 + R_3^2 = 1.0$	$\frac{2}{R_1 + R_2 + \sqrt{(R_1 + R_2)^2 + 4R_3^2}} - 1$
$R_1 + R_2^2 + R_3^2 = 1.0$	$\frac{2}{R_1 + \sqrt{R_1^2 + 4(R_2^2 + R_3^2)}} - 1$
$R_1^2 + R_2^2 + R_3^2 = 1.0$	$\frac{1}{\sqrt{R_1^2 + R_2^2 + R_3^2}} - 1$

The practical application of Equation 1.5.3.5(c) is shown in the following examples.

1.5.3.5.1 *Round Tubes in Bending and Compression.*—The general theory of failure under combined loadings is given in Section 1.5.3.5. In the case of combined bending and compression, it is necessary to consider the effects of secondary bending, that is, bending produced by the axial load acting in conjunction with the lateral deflection of the column. In general, Equation 1.5.3.5(c) can be used in the following form for safe values:

$$\frac{f_b}{F_b} + \frac{f_c}{F_c} = 1.0 \quad ,$$

$$M.S. = \frac{1}{R_b + R_c} - 1$$

where

f_b = maximum bending stress, including effects of secondary bending

F_b = bending modulus of rupture

f_c = axial compressive stress

F_c = allowable compressive stress.

In no case shall the axial compressive stress, f_c, exceed the allowable, F_c, for a simple column.

1.5.3.5.2 *Tubes in Bending and Torsion.*—Equation 1.5.3.5(c) can be used in the following forms for safe values:

$$\left(\frac{f_b}{F_b}\right)^2 + \left(\frac{f_s}{F_{st}}\right)^2 = 1.0 \quad :$$

Round tubes: $R_b^2 + R_s^2 = 1.0$,

$$M.S. = \frac{1}{\sqrt{(R_b)^2 + (R_s)^2}} - 1 \quad :$$

Streamline tubes. $R_b + R_s = 1.0$,

$$M.S. = \frac{1}{R_b + R_s} - 1 \quad .$$

where

f_s = shear stress
F_{st} = torsional modulus of rupture.

Higher values can be used if substantiated by adequate test data.

1.5.3.5.3 *Tubes in Bending, Compression, and Torsion.*—The bending stresses should include the effects of secondary bending due to compression. The following empirical equation will serve as a working basis, pending a more thorough investigation of the subject.

$$\left(\frac{f_b}{F_b}\right)^2 + \left(\frac{f_s}{F_{st}}\right)^2 = \left(1 - \frac{f_c}{F_c}\right)^2.$$

$$M.S. = \frac{1}{R_c + \sqrt{(R_b)^2 + (R_s)^2}} - 1.$$

In no case shall the axial compressive stress, f_c, exceed the allowable stress, F_c, for a simple column.

1.6 Columns

1.6.1 GENERAL.—A theoretical treatment of columns can be found in standard textbooks on the strength of materials. The problems confronting the designer, however, include many points which are not well defined by theory and which frequently cause some confusion. These will be taken up in this Section. Actual strengths of columns of various types are given in subsequent chapters.

1.6.2 PRIMARY INSTABILITY FAILURES

1.6.2.1 *General.*—A column may 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 information available on twisting instability is somewhat limited, it may be advisable to conduct tests on all columns subject to this type of failure.

1.6.2.2 *Columns with Stable Sections.*—The tangent modulus formula for columns which fail by lateral bending is given by Equation 1.3.8. No explanation of this formula need be offered, as its derivation can be found in many standard textbooks on the strength of materials. The value to be used for the restraint coefficient, c, depends upon the degree of end fixity.

The true significance of the restraint coefficient is best understood by considering the end restraint as modifying the effective column length, as indicated by Equation 1.3.8. For a pin-ended column having zero end restraint, c = 1.0 and L′ = L. A fixity coefficient of 2 corresponds to a reduction of the effective length to $1/\sqrt{2}$ or 0.707 times the total length.

The tangent modulus Equation 1.3.8 takes into account the plasticity of the material and is valid if 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 has occurred.

(c) Load is concentric with the longitudinal axis of the unloaded column.

(d) The cross section of the column does not vary along the column length.

The value of the tangent modulus E_t at any given compressive stress F_c can be determined from stress strain curves for the material. Figure 1.6.2.2 illustrates the use of this equation. For example, assume an L'/ρ of 22.2, and computing $\pi^2/(L'/\rho)^2$ gives a value of 0.02, which also equals F_c/E_t. Plot the line $F_c/E_t=0.02$ on the tangent modulus curve. The point of intersection gives a value of 60 ksi for F_c and 3×10^6 psi for E_t.

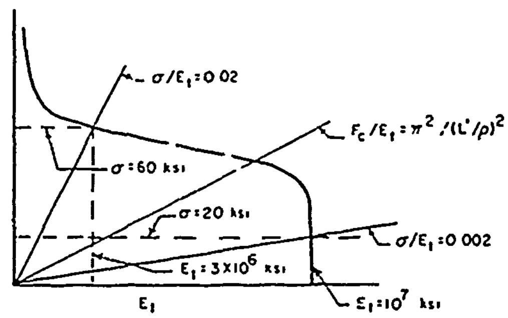

FIGURE 1.6.2.2 *Relation of $\pi^2/(L'/\rho)^2$ to tangent modulus.*

1.6.2.3 *Column Yield Stress (F_{co}).*—The upper limit of the allowable column stress for primary failure, designated F_{co}, may be obtained when not available elsewhere, from the tangent modulus Equation 1.3.8 for columns including those having geometrical proportions for low values of L'/ρ, with the restriction that F_{co} shall not exceed F_{cu}, the material ultimate compressive stress. As discussed in 1.4.5.2, it is common practice to assume for wrought metals that the material ultimate compressive stress F_{cu} is equal to the ultimate tensile stress.

1.6.2.4 *Other Considerations.*—Methods of analysis are available by which column failing stresses can be computed taking into account various fixities, torsional instability, load eccentricity, combined lateral loads, or varying column sections. References 1.6.2.4(b), (c), and (d) present such methods.

1.6.3 LOCAL INSTABILITY FAILURE

1.6.3.1 *General.*—Columns may fail by a local collapse of the wall at a stress below the primary failure stress. The buckling analysis of a column subject to local instability requires taking into account the shape of the column cross section and may be quite complex. Local buckling, which may combine with primary buckling, leads to an instability failure commonly termed crippling.

1.6.3.2 *Crushing or Crippling Stress (F_{cc}).*—The upper limit of the allowable column stress for local failure is called the crushing or crippling stress and is designated F_{cc}. The crushing or crippling stresses of round tubes have been investigated frequently and considerable useful data exist. Fewer data are available for stresses of columns having other section configurations, and testing may be required to establish the curve of transition from local to primary failure.

1.6.4 CORRECTION OF COLUMN TEST RESULTS

1.6.4.1 *General.*—In the case of columns having unconventional cross sections which are particularly subject to local instability, it is necessary to establish the curve of transition from local to primary failure. In determining the strength curves for such columns, sufficient tests should be made to cover the following points.

1.6.4.2 *Nature of "Short-Column Curve".*—The test specimens should cover a range of L'/ρ which will extend to the Euler range, or at least well beyond the values to be used in construction. When columns are to be attached eccentrically in the structure, some tests should be made to determine the effects of eccentricity. This is important particularly in the case of open sections, as the allowable loads may be affected considerably by the location of the point of application of the column load.

1.6.4.3 *Local Failure.*—When local failure occurs, the crushing or crippling stress, F_{cc}, can be determined by extending the "short-column" curve for the specific cross section under consideration to a point corresponding to zero L'/ρ. When a family of columns of the same general cross section is used, it is often possible to determine a relationship between F_{cc} and some factor depending on the wall thickness, width, diameter, or some combination of these dimensions. Extrapolations of such data should be avoided by covering an adequate range in the tests.

1.6.4.4. *Reduction of Test Results on Aluminum and Magnesium Alloys to Standard.*—The use of the correction factors given in Figures 1.6.4.4(a) through (j) is considered satisfactory and is acceptable to the Air Force, Navy, Army, and the Federal Aviation Administration for use in connection with tests on aluminum and magnesium alloys. (Note that an alternate method is given in Section 1.6.4.5.) In using Figures 1.6.4.4(a) through (j), the correction of the test results to standard is made by multiplying the stress developed in a test of a column specimen by the factor K. This factor may be considered applicable regardless of the type of failure involved (i.e., column crushing or twisting). In Figures 1.6.4.4(a) through (j), f_c is the maximum test column stress of the test column material, and F_{cy} is the compressive yield stress as given in the mechanical and physical-property tables for the individual alloys.

Acceptable methods for obtaining compressive yield strengths for use in determining values of K from Figures 1.6.4.4(a) through (j) are as follows:

(a) Direct compressive stress-strain measurements of the material of which the test column is made in the direction of loading of the test column.

(b) If Method (a) is not feasible, the compressive stress desired may be obtained from the tensile yield stress as follows: Determine the tensile yield stress of the column test specimen materials by direct tensile stress-strain measurements in a direction parallel to the test-column length. Compute the compressive yield stress along the length of the test column by multiplying the tensile yield strength by the proper ratio of the design allowable compressive yield strength to the design allowable tensile yield strength; the ratio chosen should account for the grain direction of the test column. In case the compression test column is manufactured indiscriminately with respect to material grain, the tensile test specimen should be made with the grain parallel to its length and the with-the-grain ratio of the design allowable compressive yield to design allowable tensile yield strength for the material should be used.

(c) If neither Method (a) nor Method (b) is feasible or applicable, it should be assumed that the compressive yield of the column test specimen parallel to its length is 15 percent greater than the minimum established design allowable yield strength for the material in the column test specimen.

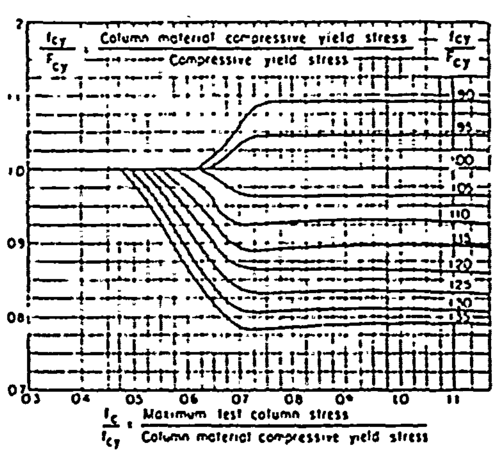

FIGURE 1.6.4.4(a). *Nondimensional material correction chart for 2024-T3 sheet.*

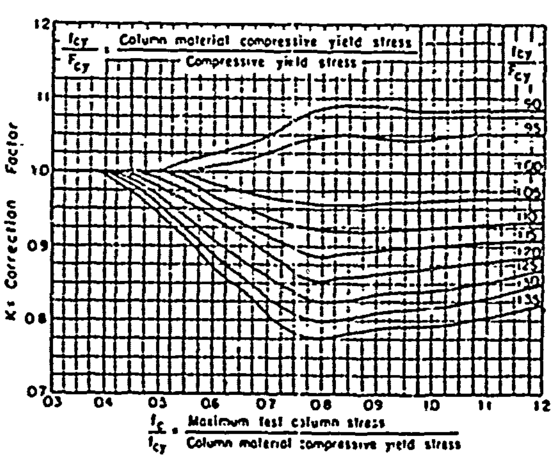

FIGURE 1.6.4.4.(b). *Nondimensional material correction chart for clad 2024-T3 sheet.*

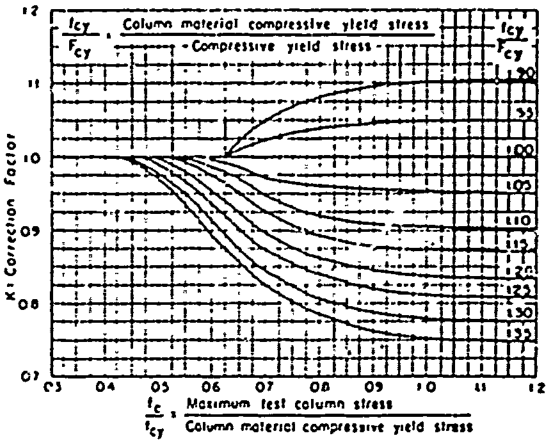

FIGURE 1.6.4.4(c). *Nondimensional material correction chart for 2024-T4 extrusions less than 1/4 inch thick.*

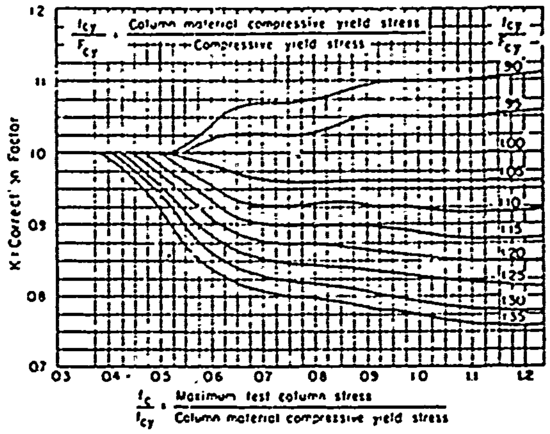

FIGURE 1.6.4.4(e). *Nondimensional material correction chart for 2024-T3 tubing.*

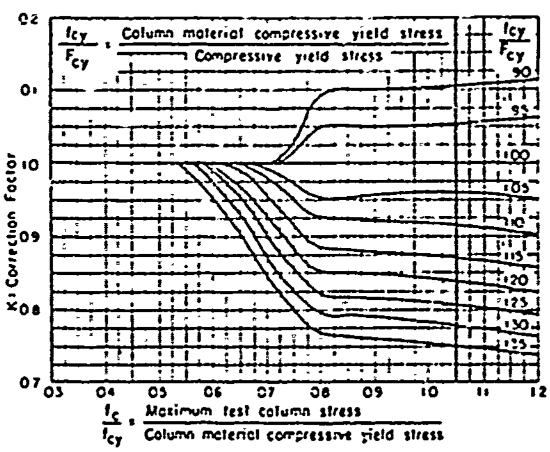

FIGURE 1.6.4.4(d). *Nondimensional material correction chart for 2024-T4 extrusions 1/4 to 1-1/2 inches thick.*

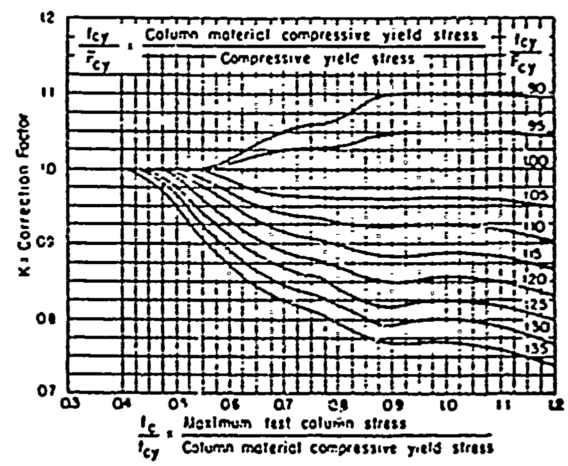

FIGURE 1.6.4.4(f). *Nondimensional material correction chart for clad 2014-T3 sheet.*

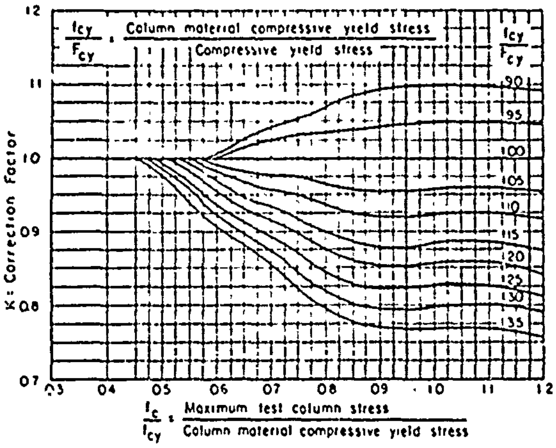

FIGURE 1.6.4.4(g). *Nondimensional material correction chart for clad 7075-T6 sheet.*

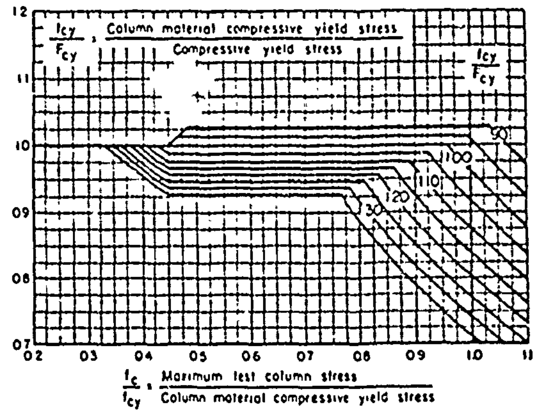

FIGURE 1.6.4.4(i). *Nondimensional material correction chart for AZ80A-T5 open extrusions.*

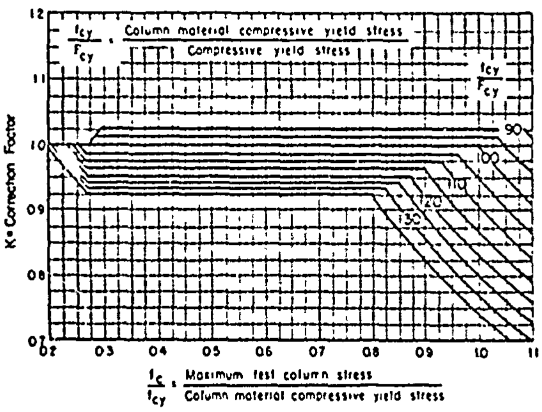

FIGURE 1.6.4.4(h). *Nondimensional material correction chart for AZ31B-F, AZ61A-F, or AZ80A-F open extrusions.*

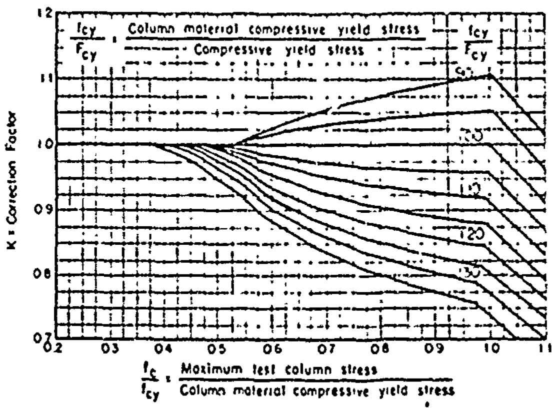

FIGURE 1.6.4.4(j). *Nondimensional material correction chart for AZ31B-H24 sheet.*

1.6.4.5 *Reduction of Test Results to Standard—Alternate Method.*—For materials which are not covered by Figures 1.6.4.4(a) through (j), the following method may be used to reduce test results to standard. This method is acceptable to the Air Force, Navy, Army, and the Federal Aviation Administration.

(a) Determine F_{cy}, E, n, and F_{cy}. F_{cy} may be determined by one of the methods outlined in paragraphs 1.6.4.4(a), (b), and (c).

(b) Plot a curve of F_c versus F_c/F_t for the standard material.*

(c) Compute F_c'/E_t' for the test data.*

(d) Read the corrected F_c from the curve of F_c versus F_c/F_t for the computed F_c'/E_t'.

*The ratios, $\frac{F_c}{E_t}$ and $\frac{F_c'}{E_t'}$ can be developed using the "Method of Strains", as follows:

For the standard material

$$\frac{F_c}{E_t} = e_e + ne_p = \frac{F_c}{E} + ne_p \quad .$$

For the test data

$$\frac{F_c'}{E_t'} = \frac{F_c'}{E} + ne'_p \quad .$$

The plastic strain e_p can be evaluated from a plot on log paper of F_c versus e_p for the standard material. For the standard material F_{cy} and n are known; therefore, the stress at a plastic strain of 0.002 in./in. is known and a line with a slope, n, can be drawn through this point at $F = F_{cy}$ and $e_p = 0.002$ in./in. The plastic strain curve for the test material is parallel to that for the standard material and passes through the point $F = F_{cy}'$ and $e_p' = 0.002$ in./in. Values of e_p' corresponding to F_c' can be read and F_c'/E_t' computed.

This method is applicable at elevated temperatures provided Young's moduli of the test material and the standard material are equal in the elastic range at the elevated temperature.

Modification of the procedure is necessary when the test column or panel is made of two different materials.

1.7 Thin-Walled and Stiffened Thin-Walled Sections

1.7.1 GENERAL.—A bibliography of information on thin-walled and stiffened thin-walled sections are contained in References 1.7.1(a) and (b).

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Chapter 2

STEEL

This chapter contains the engineering properties and related characteristics of wrought 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 Section 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 with most of these major sections 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-.20C
2.4.3	9Ni-4Co-.30C
2.5	High alloy steels
2.5.1	18Ni Maraging steels
2.6	Precipitation and transformation hardening steels (stainless)
2.6.1	AM-350
2.6.2	AM-355
2.6.3	Custom 450
2.6.4	Custom 455
2.6.5	PH13-8Mo
2.6.6	PH14-8Mo
2.6.7	15-5PH
2.6.8	PH15-7Mo
2.6.9	17-4PH
2.6.10	17-7PH
2.7	Austenitic stainless steels
2.7.1	AISI Type 301

2.1.2 MATERIAL PROPERTIES.—One of the major factors contributing to the general utility of steels is the wide range of mechanical properties they are capable of attaining. 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 them to a high temperature, or "austenitizing", then 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 steels quenched rapidly to avoid the nose of the isothermal transformation curve is a function in general of the alloy content, and is particularly a function of 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. For easy reference, the room-temperature properties are shown in tables following the comments for individual steels. The room-temperature properties F_{tu} and F_{ty} are minimum values contained in the appropriate specifications covering the product indicated. The other strength properties, F_{cy}, F_{su}, F_{bru}, and F_{bry} are "derived" values, established as described in Section 9.2.9. The variations in strength properties with temperature are presented graphically as percentages of the corresponding room-temperature strength property, also as 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 589 to 700K, 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 *Ductility.*—The measure of ductility for alloys contained in Chapter 2 is elongation under tension in a 51 mm or 4D gage length, except where otherwise noted. These data are presented for various sheet thicknesses when it is known that sheet thickness affects elongation. The elongation values presented in this chapter apply in both the longitudinal and transverse directions, unless otherwise noted. Elongation in the short transverse (thickness) direction may be lower then the values shown.

It is well recognized that tensile elongation is an inadequate measure of ductility. Reduction in area offers more useful information for some applications, but it is difficult to use with sheet materials. Various bend, cup, and bulge tests are also used to predict the ability of a sheet material to withstand specific forming operations. These data are sometimes useful in the selection of materials but are not considered appropriate for inclusion in this document.

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 increases 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.

Typical values 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. Effect of temperature data are presented in the respective alloy sections where the information is available.

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 *Creep.*—Generally the well-substantiated creep data for steels have not been suitable for MIL-HDBK-5, since they cover longer times or higher deformations than those used in current airframe design. As data of the desired type become available they will be included as described in Sections 9.3.5.4 and 9.3.5.5.

2.1.2.1.6 *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 or as constant-life diagrams as described in Sections 9.3.4.4 through Section 9.3.4.7 in the appropriate alloy section. Surface finish, surface finishing procedures, metallurgical effects from heat treatment, environment and other factors influence fatigue behavior. Specific information on these effects, when documented, are summarized in the individual alloy sections.

2.1.2.2 *Physical Properties.*—The physical properties (ω, C, K, and α) of the steels in this chapter 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 temperatures 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.

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

Alloy	Product	Heat Treat Condition	TUS, MPa	Product Thickness Range, mm	K_{Ic}, $MPa\text{-}mm^{1/2}$									
					L-T[c]					T-L[c]				
					No. of Lots	Specimen Thickness[b], mm	Minimum	Average	Maximum	No. of Lots	Specimen Thickness[b], mm	Minimum	Average	Maximum
4340	Plate	Q & T	1820	10	3	10	54	58	69	1	10	57	58	59
5Cr-Mo-V	Plate	Q & T	1779	13-19	1	13	31	37	42	1	13	30	35	40
17-4PH	Plate	H900	1338	13	2	13	38	46	52	2	13	38	42	49
9Ni-4Co-0.20C	Bar	Q & T	1407	63-178	9	38	143	152	191	6	38	135	145	160
9Ni-4Co-0.20C	Bar	Q & T	1379	51	1	51	121	134	142	1	51	124	125	126
D6AC	Plate	Q & T	1655	25	1	13	57	59	62	--	--	--	--	--
Custom 450	Bar	H900	1296	102	1	25	75	78	82	--	--	--	--	--
Custom 455	Bar	H950	1673	89	1	25	55	58	62	--	--	--	--	--
Custom 455	Bar	H1000	1469	89	1	25	71	74	78	--	--	--	--	--

[a] These values are for information only.

[b] Minimum thickness of specimen on which values were obtained.

[c] Refer to Figure 1.4.12.3 for definition of symbols.

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 422 to 644 K.

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 improved 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.

2.2.0.3 Environmental Considerations.—Carbon steels have poor oxidation resistance above about 755 to 811 K, and 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. Strength and oxidation-resistance criteria generally preclude the use of carbon steels above 755 K.

Carbon steels exhibit a fairly abrupt drop in notch toughness as the service or testing temperature is lowered below room temperature. The subject of the notch toughness of steels is reviewed in the ASM Metals Handbook, 8th edition, pages 225 to 243.

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.

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 the resulfurized types of free-machining steels, but the resulting surface finish is poorer.

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).

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

Specification	Form
MIL-S-7097, Comp. 3	Bars
MIL-T-5066	Tubing
MIL-S-7952, 1025	Sheet and strip

TABLE 2.2.1.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF AISI 1025 CARBON STEEL

SPECIFICATION	MIL-S-7952	MIL-T-5066	MIL-S-7097
	1025		COMP. 3
FORM	SHEET AND STRIP	TUBING	BARS
CONDITION	COLD ROLLED	NORMALIZED	ALL
THICKNESS, MM	...	...	...
BASIS	S	S	S[a]
MECHANICAL PROPERTIES:			
FTU, MPA:			
L	379	379	379
LT	379	379	379
ST	...	...	379
FTY, MPA:			
L	248	248	248
LT	248	248	248
ST	...	...	248
FCY, MPA:			
L	248	248	248
LT	248	248	248
ST	...	...	248
FSU, MPA	241	241	241
FBRU, MPA:			
(E/D=1.5)	...	...	...
(E/D=2.0)	621	621	621
FBRY, MPA:			
(E/D=1.5)	...	...	...
(E/D=2.0)	...	...	...
EL, PERCENT:			
L	...	b	a,b
LT	b	...	...
ST	...	...	...
E, GPA	200.0		
EC, GPA	200.0		
G, GPA	75.8		
MU	0.32		
PHYSICAL PROPERTIES:			
OMEGA, MG/M3	7.86		
C, J/(G*K)	0.49 (323 TO 373 K)		
K, W/(M*K)	52 (AT 273 K)		
ALPHA, 10-6 M/(M*K)	12.2 (293 TO 373 K); 12.6 (293 TO 473 K)		

[a] GRAIN DIRECTION NOT SPECIFIED.
[b] SEE APPLICABLE SPECIFICATION FOR VARIATION IN MINIMUM ELONGATION WITH ULTIMATE STRENGTH.

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 in this section 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.

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 at low temperatures to achieve very high strength should be avoided when toughness is an important consideration.

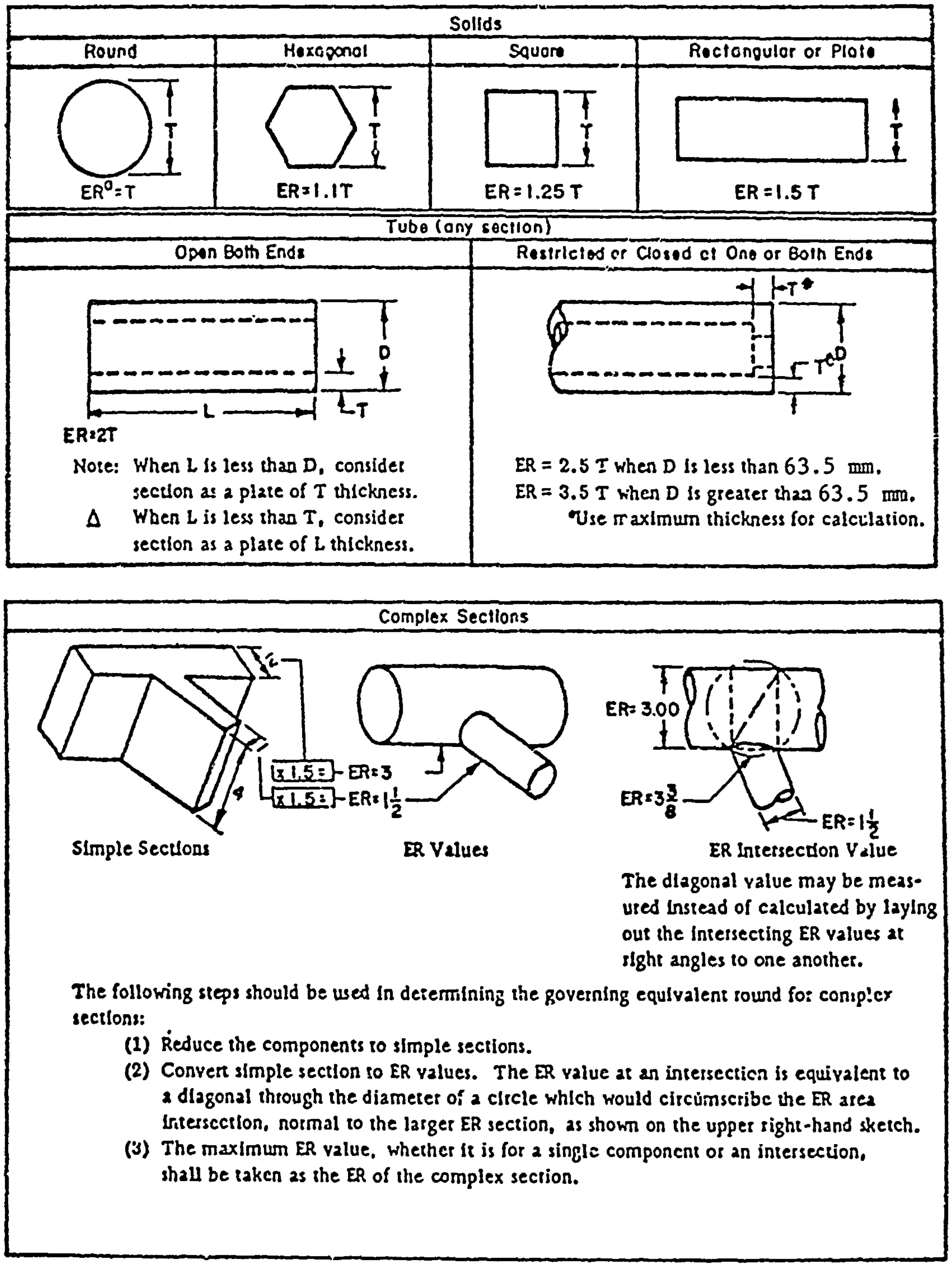
In addition, these steels may be embrittled by tempering or by prolonged exposure under stress within the "blue brittle" range (approximately 533 to 644 K). Strength levels that necessitate tempering within this range should be avoided.

The mechanical properties are unless otherwise indicated for air melted steel heat treated to produce a quench structure containing 90 percent martensite at the center, then 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 2.3.0.1(a). Limiting dimensions for common shapes other than round are determined by means of the "equivalent round" concept of Figure 2.3.0.1. 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.

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 13 mm without a reduction in strength occurring are listed in Table 2.3.0.1(b). These values are approximately 55 K below typical tempering temperatures used to achieve the designated strength levels.

2.3.0.2 *Manufacturing Considerations*

Forging.—The alloy steels are only slightly more difficult to forge than carbon steels. However, maximum recommended forging temperatures are generally about 30 K lower than for carbon steels of the same carbon content. Slower heating rates, shorter soaking periods, and slower cooling rates are also required for alloy steels.



[a]ER = Equivalent round diameter of round bars.

FIGURE 2.3.0.1 *Correlation between significant dimensions of common shapes other than round, and the diameters of round bars.*

TABLE 2.3.0.1(a). Maximum Round Diameters for Alloy Steel Bars (Through Hardening to at Least 90 Percent Martensite at Center)

F_{tu}	Diameter of round or equivalent round, mm						
	13	20	25	43	63	89	127
1931 MPa	--	--	--	--	--	--	300M[c] 98BV 40[c]
1793 MPa	--	--	--	AISI 4340[b]	AISI 4340[c]	AISI 4340[d]	--
1517 MPa	--	--	--	AMS Grades[be]	AMS Grades[ce]	D6AC[b]	D6AC[c]
1379 MPa	--	AISI 8740	AISI 4140	AISI 4340[b] AMS Grades[be]	AISI 4340[c] AMS Grades[ce]	AISI 4340[d] D6AC[b]	D6AC[c]
1241 MPa and lower	AISI 4130 and 8630	AISI 8735 and 8740	AISI 4140	AISI 4340[b] AMS Grades[be]	AISI 4340[d] AMS Grades[ce]	AISI 4340[d]	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 61 meters per minute.

[d] Quenched in water at a flow rate of 61 meters per minute.

[e] 4330Si, 4330V, 4335V, and AMS 6418.

TABLE 2.3.0.1(b). Temperature Exposure Limits for Alloy Steels

Alloy	F_{tu}, MPa[a]							
	862	1034	1245	1379	1517	1655	1793	1931
AISI 4130 and 8630	769	686	575	...	...	...	...	...
AISI 4140 and 8740	825	742	658	603	...	...	...	...
AISI 4340	866	783	700	644	...	...	450	...
AISI 8735	797	714	631	...	...	...	...	...
D6AC	894	853	811	783	755	...	561	...
AMS 6418	742	672	616	561	505	...	...	...
4330Si and 4330V	769	728	686	644	533	...	...	...
4335 V	797	742	686	644	533	...	...	...
98BV40	...	...	...	...	...	...	...	478
300M	...	...	...	...	...	...	...	519

[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.

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 (366 to 589K) is usually necessary. At higher carbon levels, higher preheating temperatures, and often post-welding 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.

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. As a rule, elevated-temperature service for heat-treated alloy steels is limited to temperatures 55 K below the normal tempering temperatures or, for very short-time service life, up to 110 K above the normal tempering temperatures.

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 1035 MPa 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 and seamless tubing. Bar stock of this material is also used for small forgings under one-half inch in thickness.

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

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

There are available a number of steels the compositions of which represent modifications of the

AISI grades described above. Five of these that have been used rather extensively at F_{tu} =1515 MPa include D6AC, 4330Si, AMS 6418, 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 533 to 644 K. In addition, 4340 and four modified grades are utilized at strength levels of F_{tu} = 1790 MPa or higher. These modified grades include D6A, D6AC 98BV40, and 300 M which are available either air melted, vacuum melted, or vacuum degassed. 300 M is available in various modifications involving different carbon ranges. Specification MIL-S-8844 covers the carbon range 0.40 to 0.46.

Material specifications for the steels are presented in Table 2.3.1.0(a).

Room-Temperature Properties

The room-temperature mechanical and physical properties for these steels are presented in Tables 2.3.1.0(b) through 2.3.1.0(f). 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 effect-of-temperature curves on the physical properties of AISI 4130 steel.

2.3.1.1 *Heat-Treated Condition.*—Effect-of-temperature curves for heat-treated AISI alloy steels are presented in Figures 2.3.1.1.1(a) 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).

TABLE 2.3.1.0(a). *Material Specifications for Alloy Steels*

Alloy	Form		
	Sheet, strip, and plate	Bars and forgings	Tubing
4130	MIL-S-18729	MIL-S-6758	MIL-T-6736
4140	...	MIL-S-5626	AMS 6381, 6390
4340	AMS 6359	MIL-S-5000	AMS 6415
...	...	MIL-S-8844	MIL-S-8844
8630	MIL-S-18728	MIL-S-6050	MIL-T-6732
...	...	...	MIL-T-6734[a]
8735	...	MIL-S-6098	MIL-T-6733
8740	AMS 6358	MIL-S-6049	AMS 6323
D6AC	MIL-S-8949	MIL-S-8949	...
4330 Si	...	AMS 6407	...
AMS 6418	...	AMS 6418	...
4330V	...	AMS 6427	...
4335V	AMS 6434	AMS 6429	...
300M	...	MIL-S-8844	MIL-S-8844
98BV40	...	AMS 6423	AMS 6423

[a]Welded tubing.

TABLE 2.3.1.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF LOW-ALLOY STEELS

ALLOY [FOR SPECIFICATION SEE TABLE 2.3.1.0(A)]	AISI 4130 8630 AND 8735		SEE STEELS LISTED IN TABLE 2.3.0.1(A) FOR THE APPLICABLE STRENGTH LEVELS			
FORM	SHEET, STRIP, PLATE, TUBING		ALL WROUGHT FORMS			
CONDITION	N		QUENCHED AND TEMPERED[a]			
THICKNESS, MM	≤4.75	>4.75	...			
BASIS	S	S	S	S	S	S
MECHANICAL PROPERTIES:						
FTU, MPA	655	621	862	1030	1240	1380
FTY, MPA	517	483	710	910	1120	1210
FCY, MPA	517	483	779	1000	1190	1250
FSU, MPA	393	372	517	621	745	827
FBRU, MPA:						
(E/D=1.5)	...	...	1340	1510	1720	1880
(E/D=2.0)	1380	1310	1730	1980	2250	2450
FBRY, MPA:						
(E/D=1.5)	...	...	1040	1300	1590	1760
(E/D=2.0)	889	827	1240	1500	1770	1930
EL, PERCENT	b	b	c	c	c	c
E, GPA	200.0					
EC, GPA	200.0					
G, GPA	75.8					
MU	0.32					
PHYSICAL PROPERTIES:						
OMEGA, MG/M3	7.83					
C, J/(G*K)	0.48 (AT 273 K)					
K, W/(M*K)	38 (AT 273 K)					
ALPHA, 10-6 M/(M*K)	11.3 (255 TO 366 K)					

[a] VALUES IN THESE COLUMNS ARE APPLICABLE ONLY TO STEELS FOR WHICH THE INDICATED FTU HAS BEEN SUBSTANTIATED THROUGH ADEQUATE QUALITY-CONTROL INSPECTION TESTING.

[b] SEE TABLE 2.3.1.0(D).

[c] SEE TABLE 2.3.1.0(E).

Typical tangent-modulus and stress-strain curves for several steels are presented in Figures 2.3.1.1.6(a) through 2.3.1.1.6(f).

Typical biaxial stress-strain curves and yield-stress envelopes for AISI 4340 alloy steel are presented in Figures 2.3.1.1.6(g) through 2.3.1.1.6(j). Typical constant-life fatigue diagrams for this steel are presented in Figures 2.3.1.1.8(a) through 2.3.1.1.8(g).

Typical constant-life fatigue diagrams for 300M steel are presented in Figures 2.3.1.1.8(h) through 2.3.1.1.8(l).

An effect of temperature curve for plane-strain fracture toughness of heat treated AISI 4340 steel at the 1790 MPa strength level is shown in Figure 2.3.1.1.9.

TABLE 2.3.1.0(C). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF LOW-ALLOY STEELS[c]

ALLOY [FOR SPECIFICATION SEE TABLE 2.3.1 0(a)]	AMS 6418	4330 SI 4330 V	D6AC 4335 V	4340[a] D6A	4340	98BV40[a]	300M
FORM	ALL WROUGHT FORMS				BARS, FORGINGS, TUBING		
CONDITION	QUENCHED AND TEMPERED				QUENCHED AND TEMPERED		
THICKNESS, MM	SEE TABLE 2.3.0.1(a)				SEE TABLE 2.3.0.1(a)		
BASIS	S	S	S	S	S	S	S
MECHANICAL PROPERTIES:							
FTU, MPA	1520	1520	1520	1790	1790[e]	1930	1930[e]
FTY, MPA	1240	1280	1310	1480	1480[e]	1590	1590[e]
FCY, MPA	1300	1340	1370	1650	1650	...	1700
FSU, MPA	910	910	910	1080	1080	1160	1160
FBRU, MPA:							
(E/D=1.5)	2050	2050	2050	2390	2390	...	2960[f]
(E/D=2.0)	2650	2650	2650	3030	3030	...	3620[f]
FBRY, MPA:							
(E/D=1.5)	1790	1850	1890	2130	2130	...	2480[f]
(E/D=2.0)	1970	2040	2080	2360	2360	...	2730[f]
EL, PERCENT:							
L	...	...	...	10	...	...	...
LT	5[d]	5[d]	5[d]	3	5[e]	5	5[e]
E, GPA	200.0						
EC, GPA	200.0						
G, GPA	75.8						
MU	0.32						
PHYSICAL PROPERTIES:							
OMEGA, MG/M3	7.83						
C, J/(G*K)	0.48 (AT 273 K)						
K, W/(M*K)	38 (AT 273 K)						
ALPHA, 10-6 M/(M*K)	11.3 (255 TO 366 K)						

[a] AIR MELTED STEEL ONLY.

[b] VALUES IN THESE COLUMNS ARE APPLICABLE ONLY TO STEELS FOR WHICH THE INDICATED FTU HAS BEEN SUBSTANTIATED THROUGH ADEQUATE QUALITY-CONTROL INSPECTION TESTING.

[c] THE USE OF HEAT TREATMENTS OF FTU = 1317MPA OR HIGHER IS SUBJECT TO THE SPECIFIC APPROVAL OF THE PROCURING OR CERTIFICATING AGENCY.

[d] SHEET 1.000 TO 1.499 MM, INCL., 4; 0.508 TO 0.999 MM, INCL., 2. SEE TABLE 2.3.1.0(F) FOR ELONGATION APPLICABLE TO CONSUMABLE-ELECTRODE VACUUM-MELTED D6AC (BILLETS) AND 4330V (ALL PRODUCT FORMS).

[e] VALUES ARE FOR TRANSVERSE DIRECTION.

[f] BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

TABLE 2.3.1.0(d). Minimum Ductility Values for Low Alloy Steels in Condition N

Form	Thickness, mm	Elongation, percent	
		Full tube	Strip
Sheet, strip, and plate......	Less than 1.57	...	8
	Over 1.57 to 3.18 incl.	...	10
	Over 3.18 to 4.75 incl.	...	12
	Over 4.75 to 6.32 incl.	...	15
	Over 6.32 to 19.02 incl. ...	...	16
	Over 19.02 to 38.1 incl. ...	...	18
Tubing (L)	Up to 0.89 incl. (wall)	10	5
	Over 0.89 to 4.78 incl.	12	7
	Over 4.78	15	10

TABLE 2.3.1.0(e). Minimum Ductility Values for Heat Treated Low Alloy Steels

F_{tu}, MPa	Round specimens (L)		Elongation, percent				
			Sheet specimens			Tubing (L)	
	Elongation, percent	Reduction of area, percent	Less than 0.81 mm thick	0.81 to 1.52 mm thick	Over 1.52 mm thick	Full tube	Strip
862	17	55	5	7	10	12	7
1034	14	52	4	6	9	10	6
1241	12	47	3	5	7	8	5
1379	10	43	3	4	6	6	5

TABLE 2.3.1.0(f). Minimum Ductility Values for Heat-Treated Consumable-Electrode Vacuum-Melted Steels[a]

Form	Size	Elongation, percent	
		L	T
Billets	≤322 sq cm	12	10
	>322, ≤1290 sq cm	12	8
	>1290 sq cm	10	7
Plate	<15.87 mm	10	8
Sheet	≥3.04 mm	...	8
	≥2.53 to 3.03 mm	...	7
	≥2.03 to 2.52 mm	...	6
	≥1.52 to 2.02 mm	...	5
	≥1.01 to 1.51 mm	...	4
	≥0.51 to 1.00 mm	...	2

[a] Values in this table are applicable to D6AC (billets) and 4330V (all products) at F_{tu} = 1517 MPa.

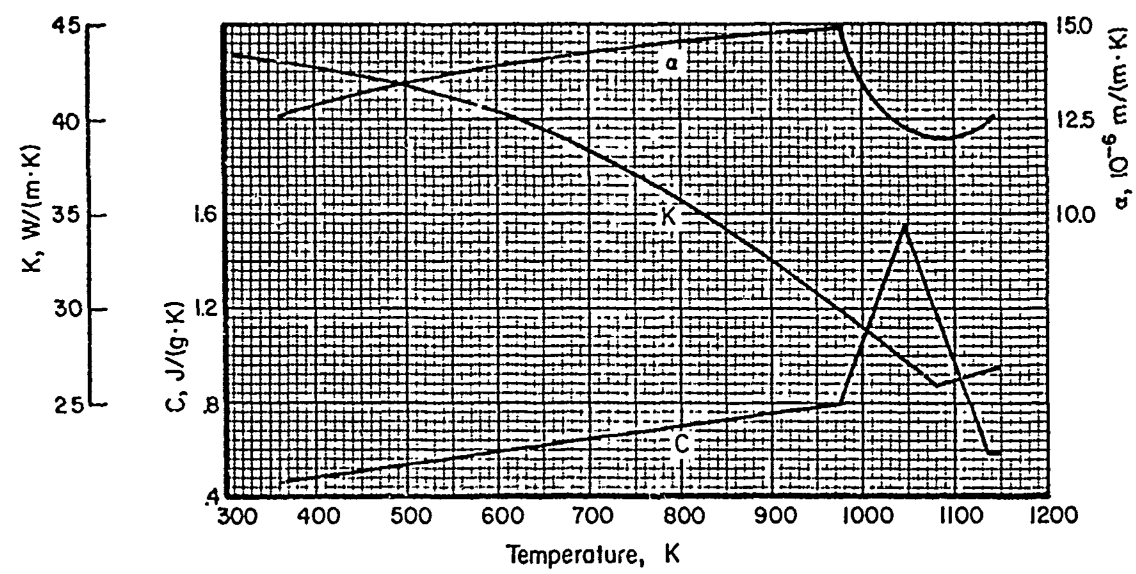


FIGURE 2.3.1.0. Effect of temperature on the physical properties of AISI 4130.

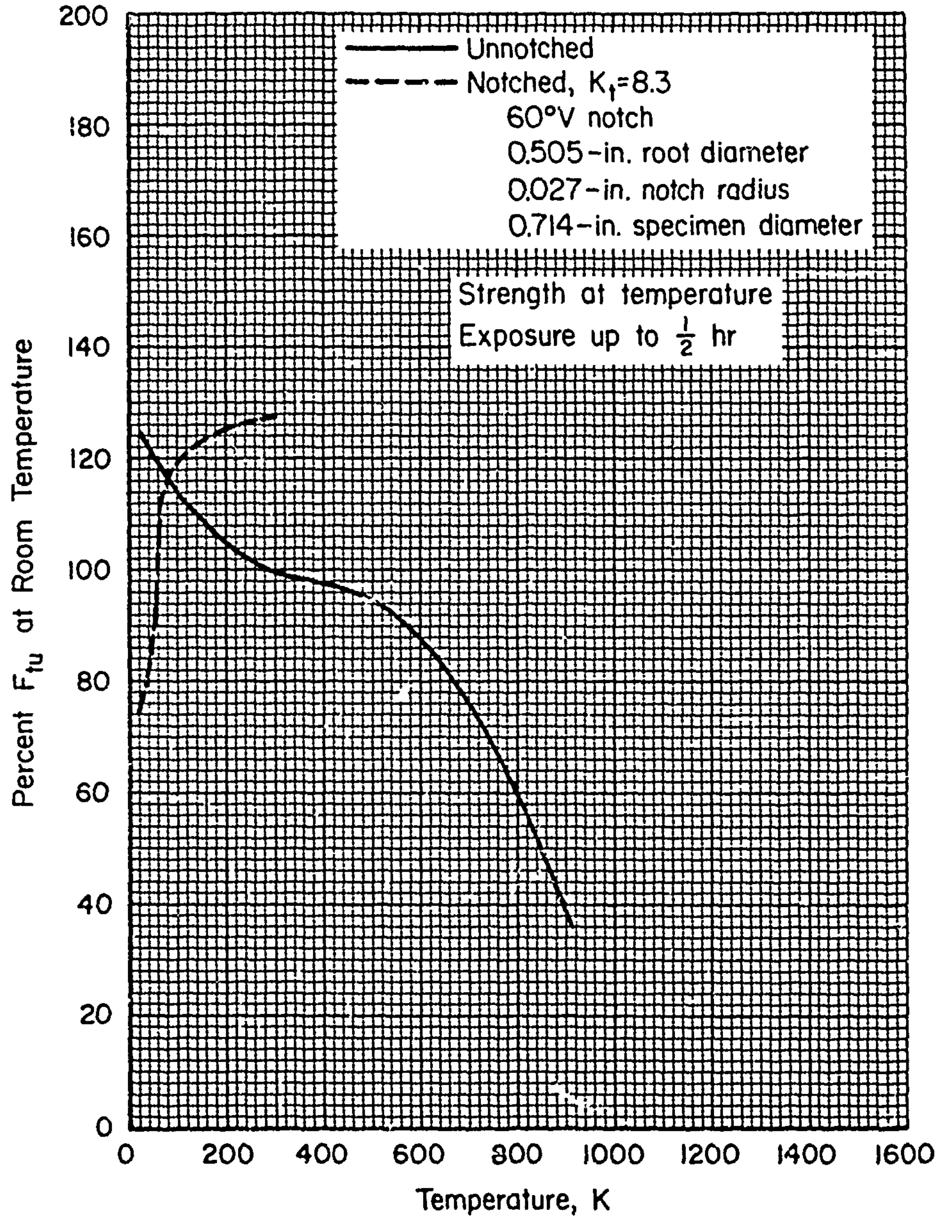


FIGURE 2.3.1.1.1(a). Effect of temperature on the ultimate strength (F_{tu}) of AISI alloy steels.

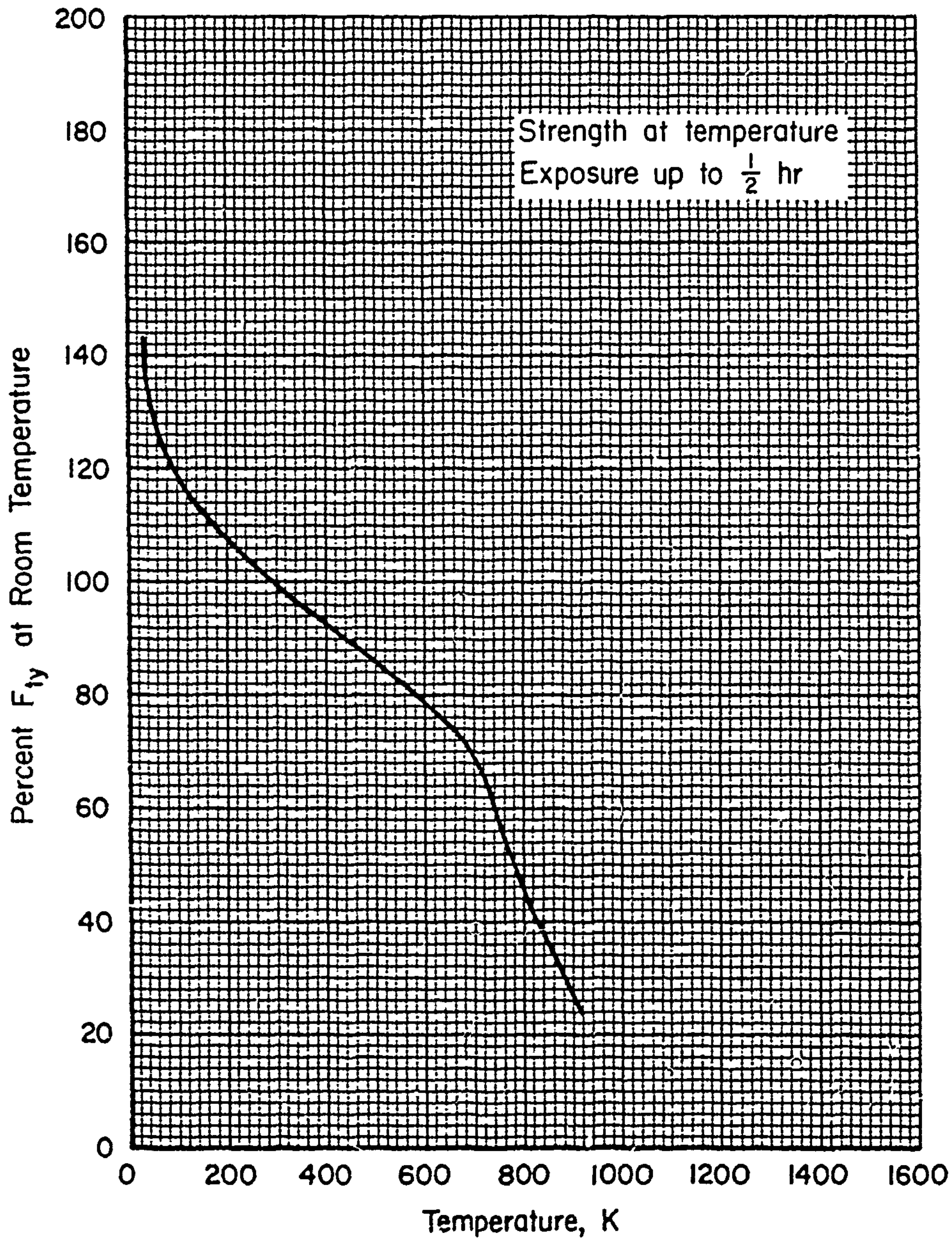


FIGURE 2.3.1.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of AISI alloy steels.

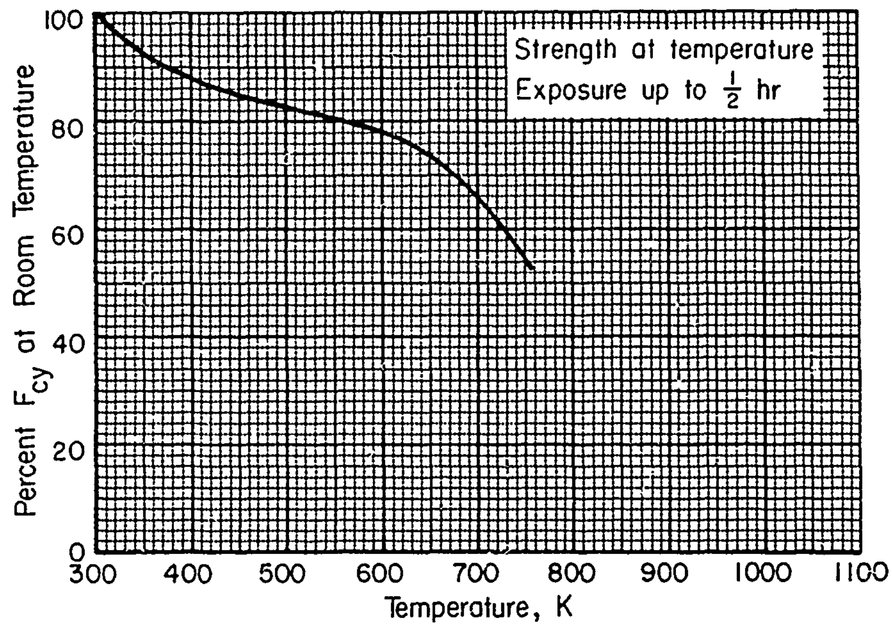


FIGURE 2.3.1.1.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of heat-treated AISI alloy steels.

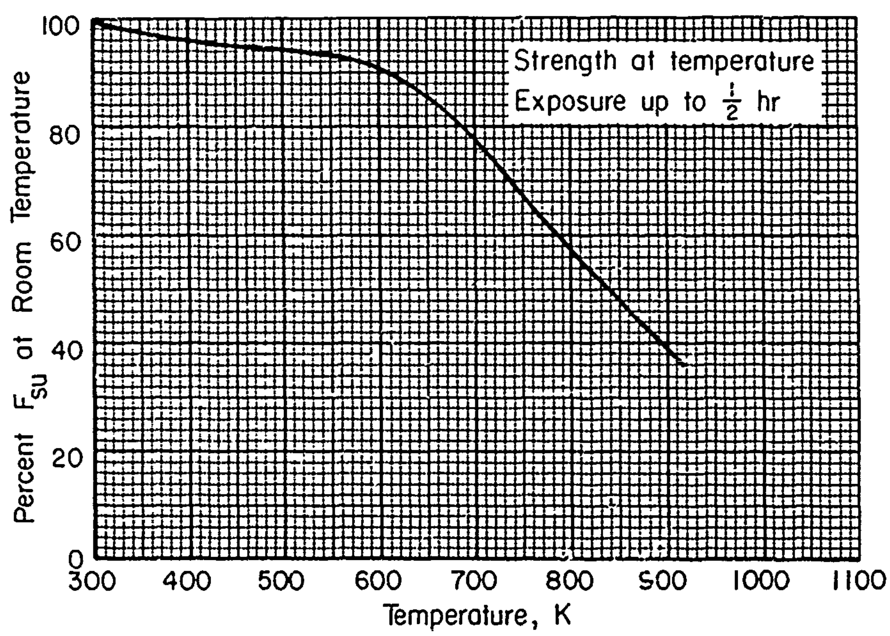


FIGURE 2.3.1.1.2(b). Effect of temperature on the ultimate shear strength (F_{su}) of heat-treated AISI alloy steels.

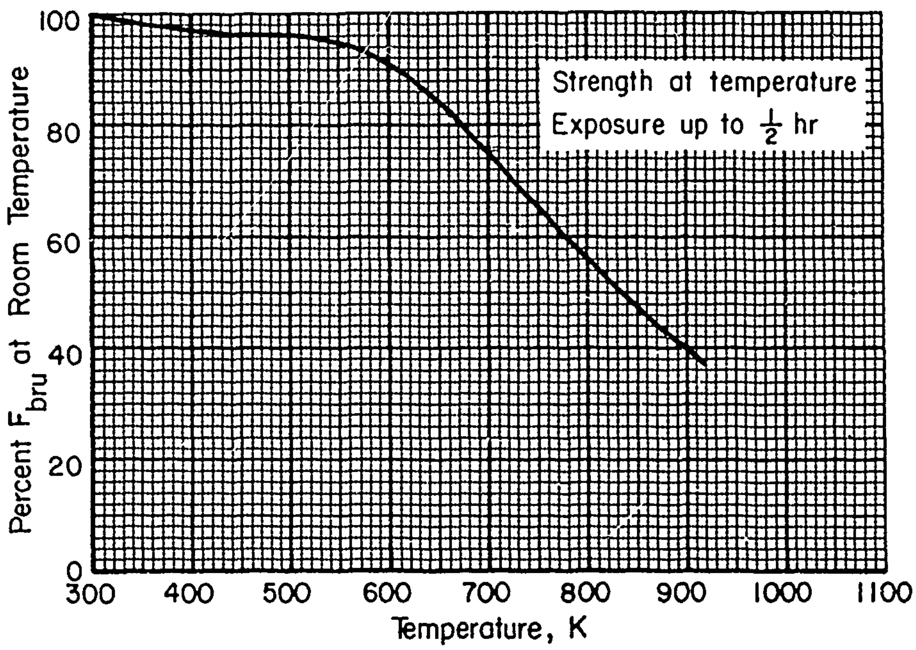


FIGURE 2.3.1.1.3(a). Effect of temperature on the ultimate bearing strength (F_{bru}) of heat-treated AISI alloy steels.

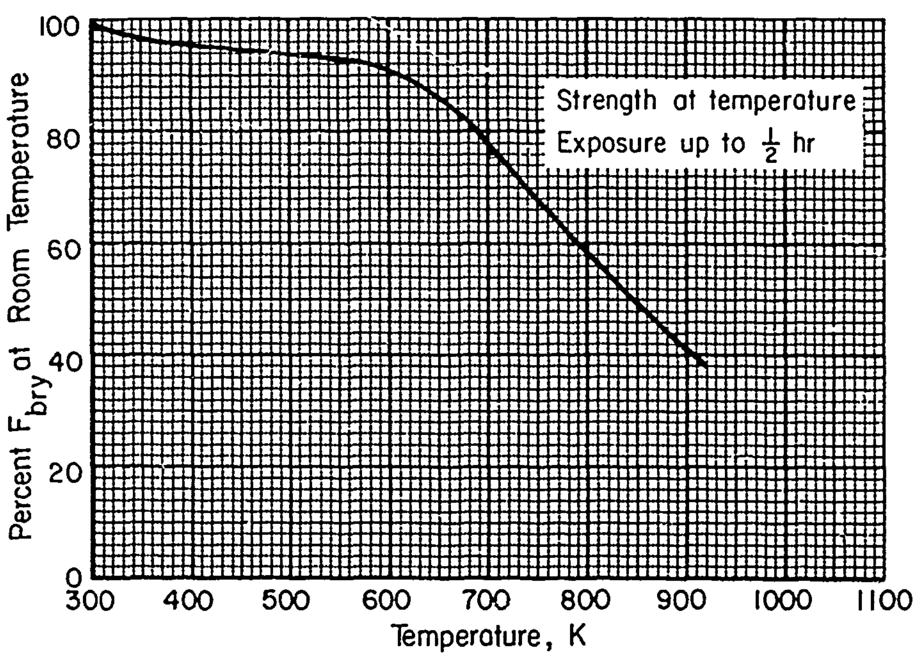


FIGURE 2.3.1.1.3(b). Effect of temperature on the bearing yield strength (F_{bry}) of heat-treated AISI alloy steels.

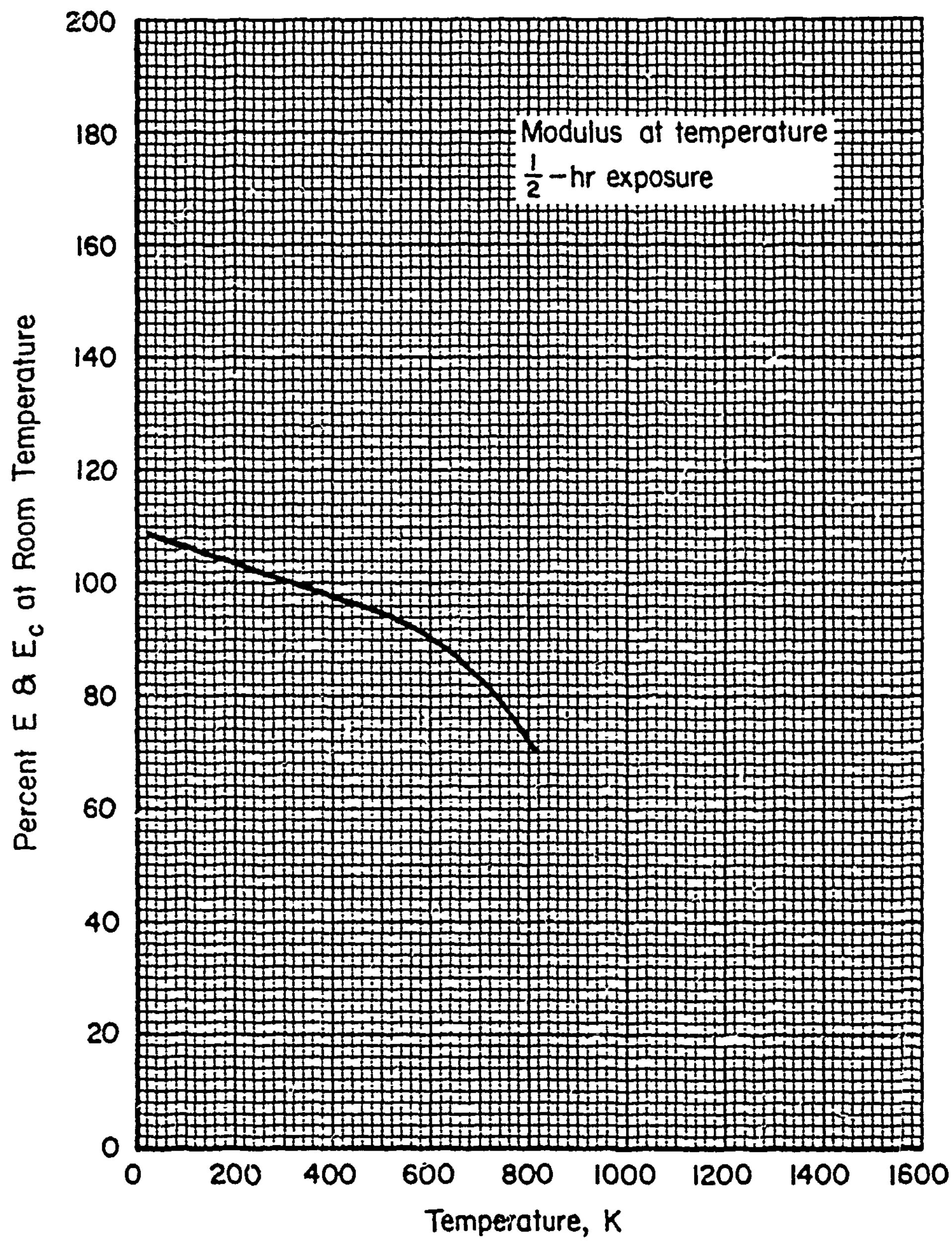


FIGURE 2.3.1.1.4. Effect of temperature on the tensile and compressive modulus (E and E_c) of AISI alloy steels.

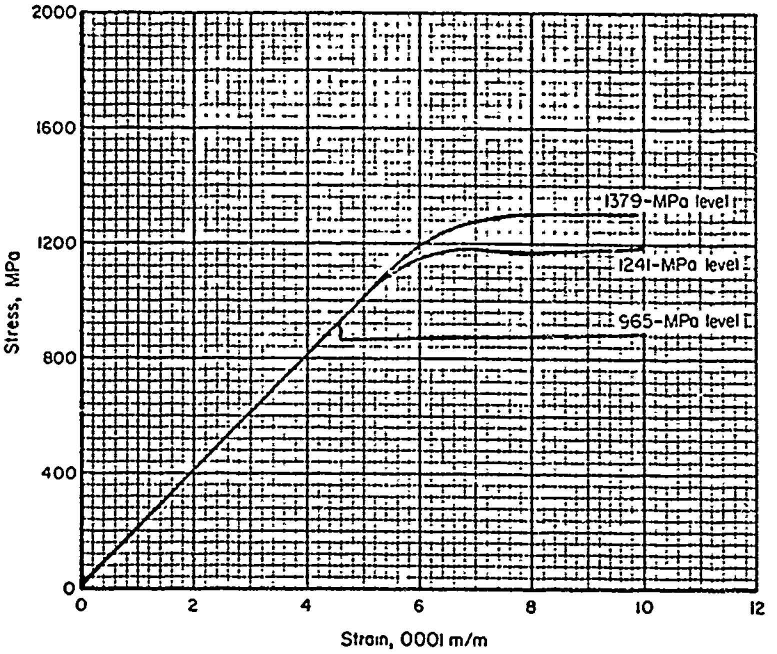


FIGURE 2.3.1.1.6(a). Typical tensile stress-strain curves at room temperature for heat-treated AISI 4340 alloy steel.

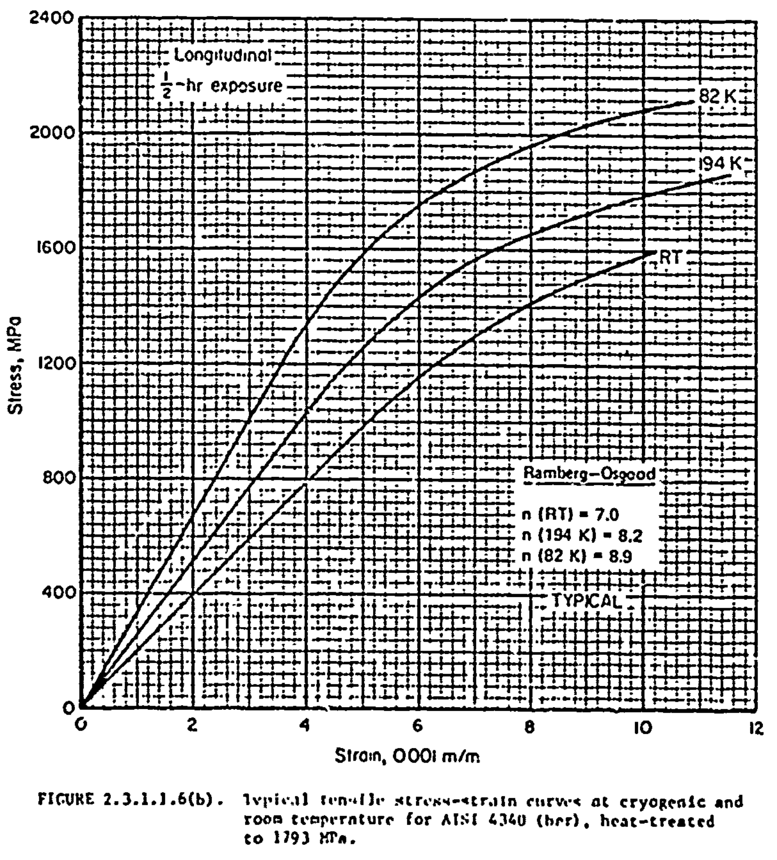


FIGURE 2.3.1.1.6(b). Typical tensile stress-strain curves at cryogenic and room temperature for AISI 4340 (bar), heat-treated to 1793 MPa.

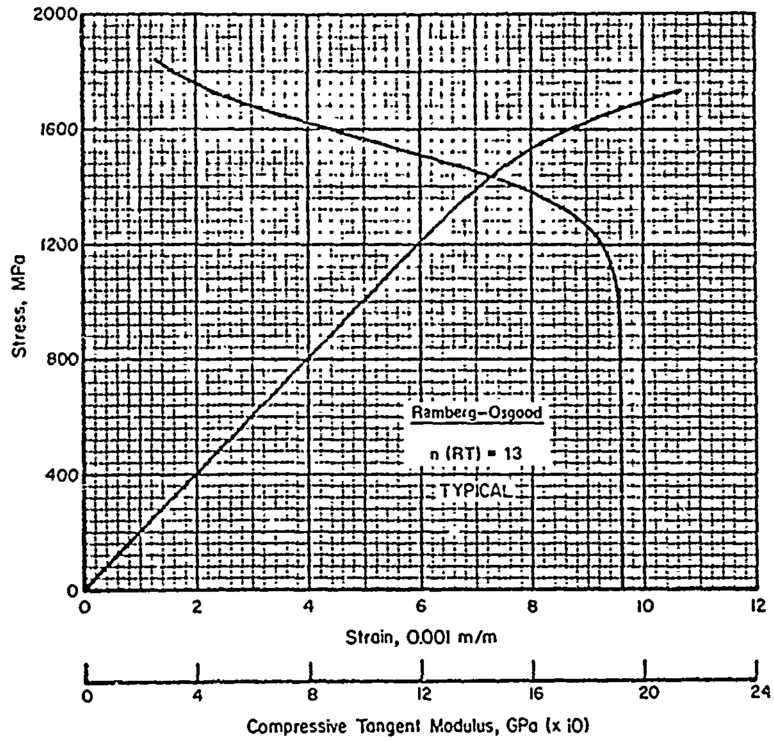


FIGURE 2.3.1.1.6(c). Typical compressive stress-strain and tangent-modulus curve at room temperature for AISI 4340 alloy steel (bar), heat-treated to 1793 MPa.

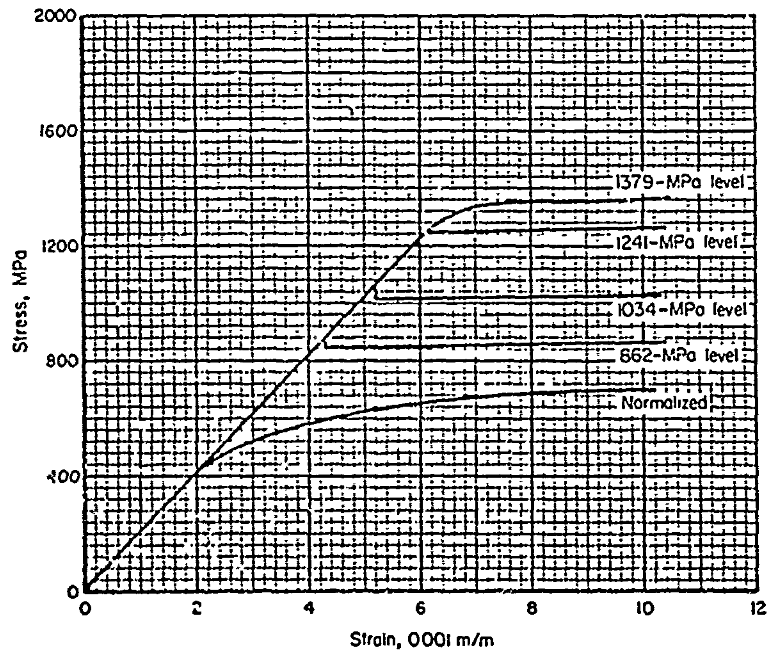


FIGURE 2.3.1.1.6(d). Typical tensile stress-strain curves at room temperature for heat-treated AISI 8630 alloy steel.

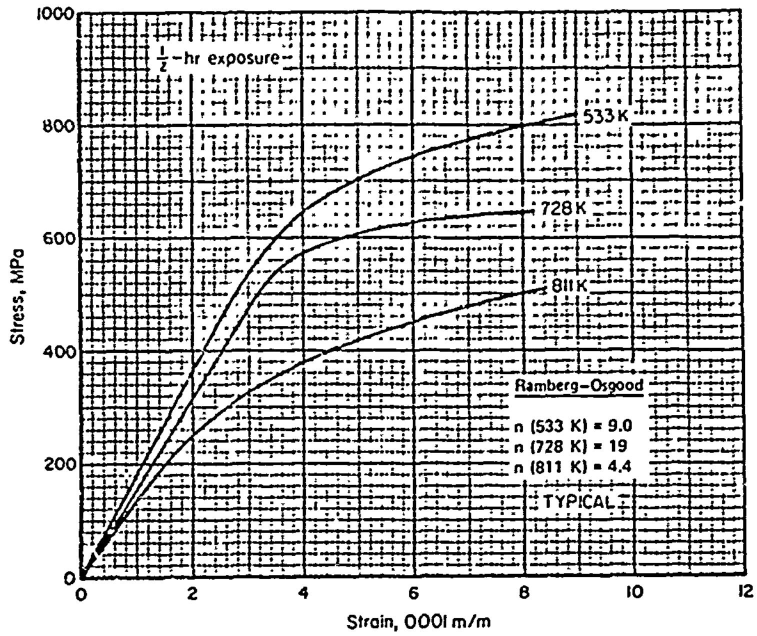


FIGURE 2.3.1.1.6(e). Typical tensile stress-strain curves at elevated temperatures for heat-treated AISI 8630 alloy sheet (F_{tu} = 862 MPa).

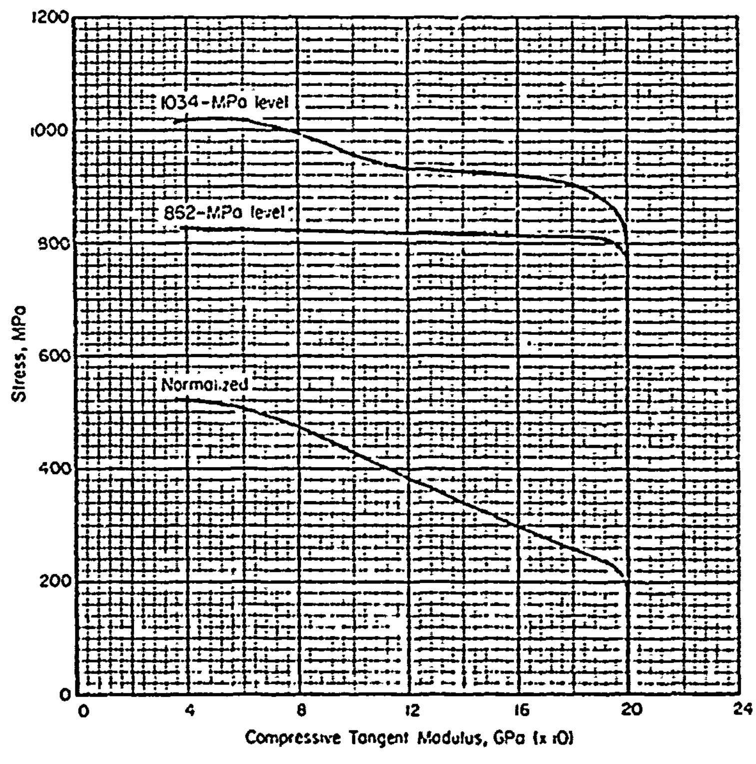


FIGURE 2.3.1.1.6(f). Typical compressive tangent-modulus curves at room temperature for heat-treated AISI 8630 steel.

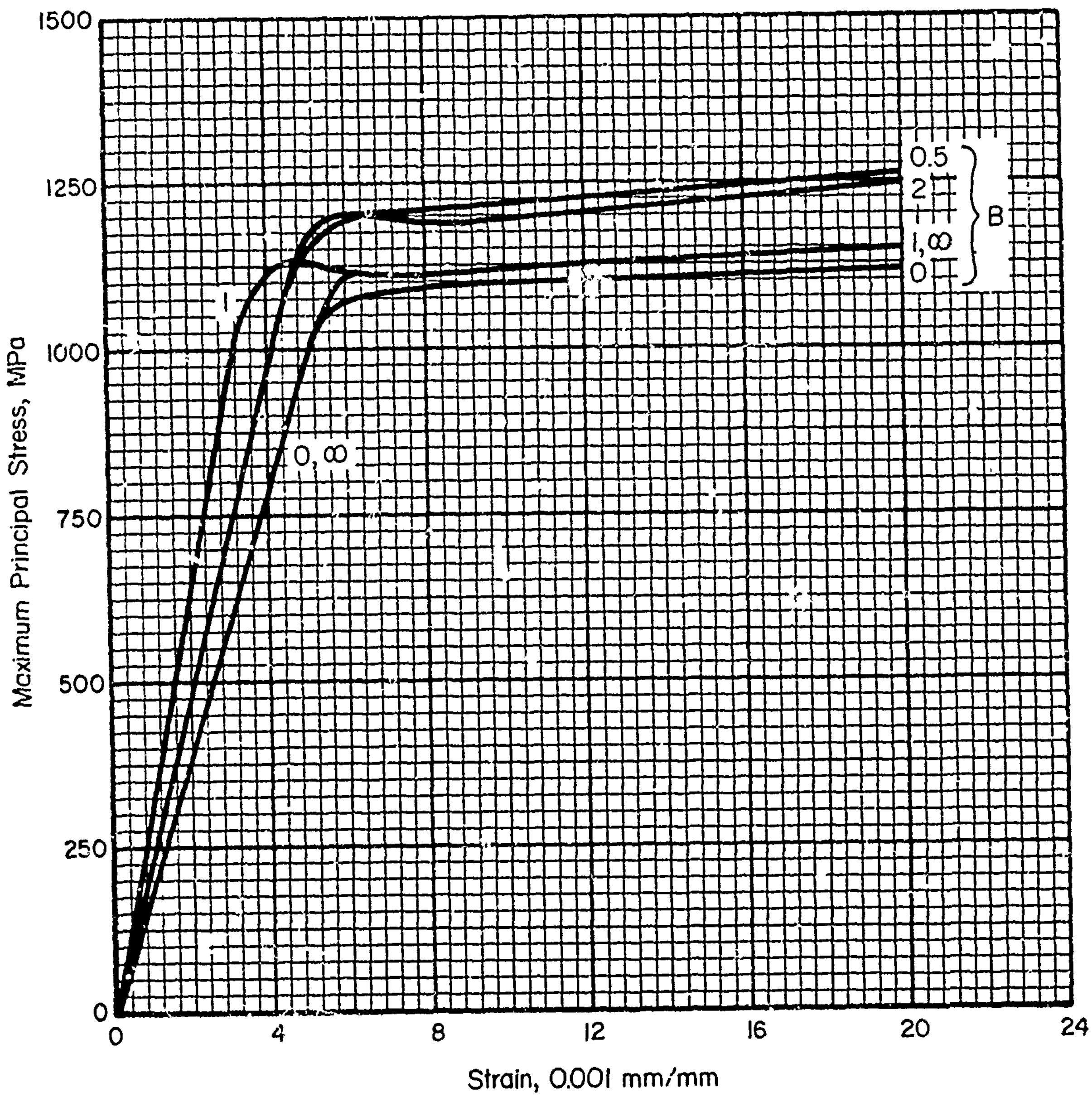


FIGURE 2.3.1.1.6(g). Typical biaxial stress-strain curves at room temperature for AISI 4340 alloy steel (machined thin-wall cylinders, axial direction = longitudinal direction of bar stock), F_{tu} = 1241 MPa. A biaxial ratio B of zero corresponds to the hoop direction.

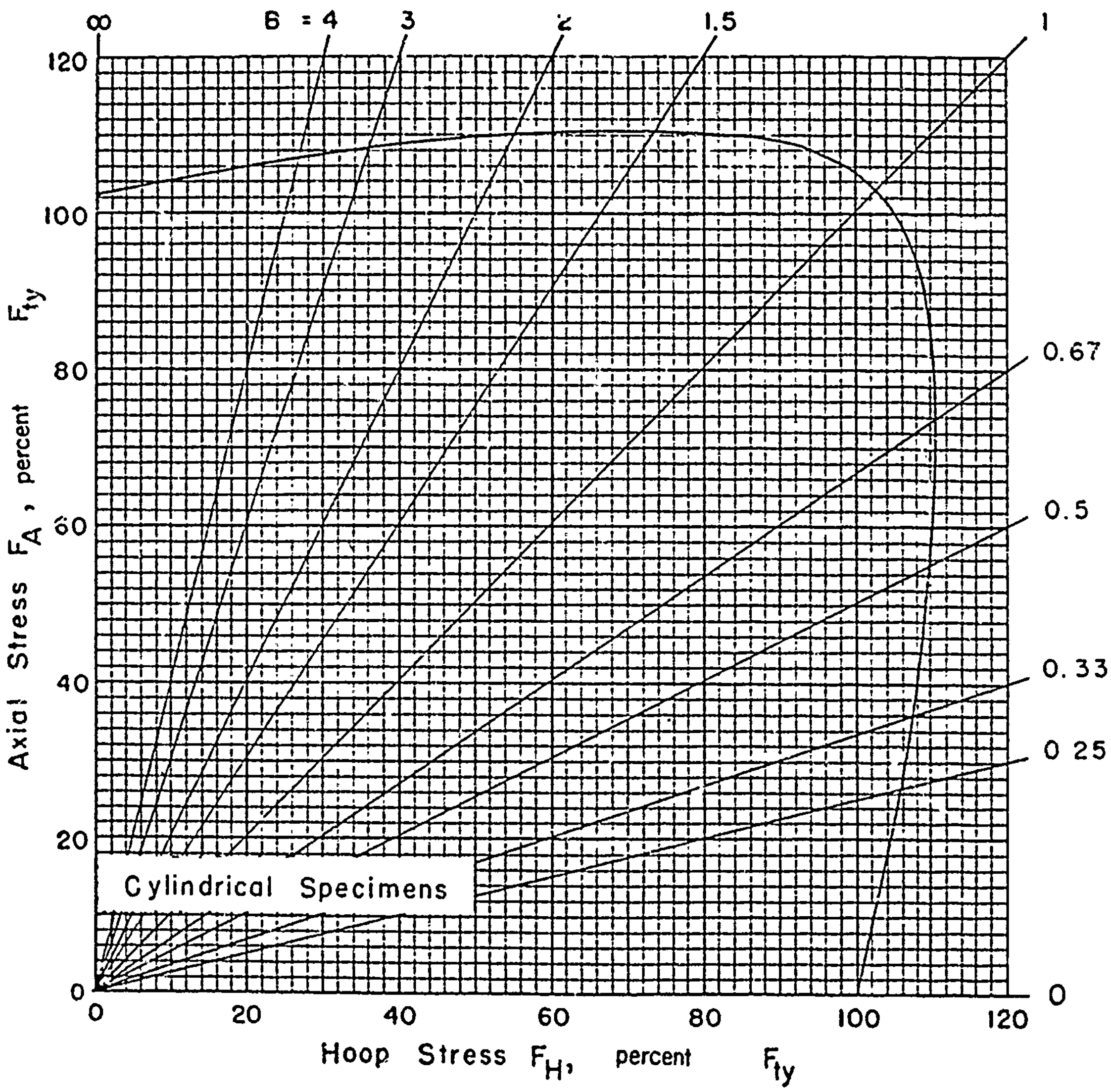
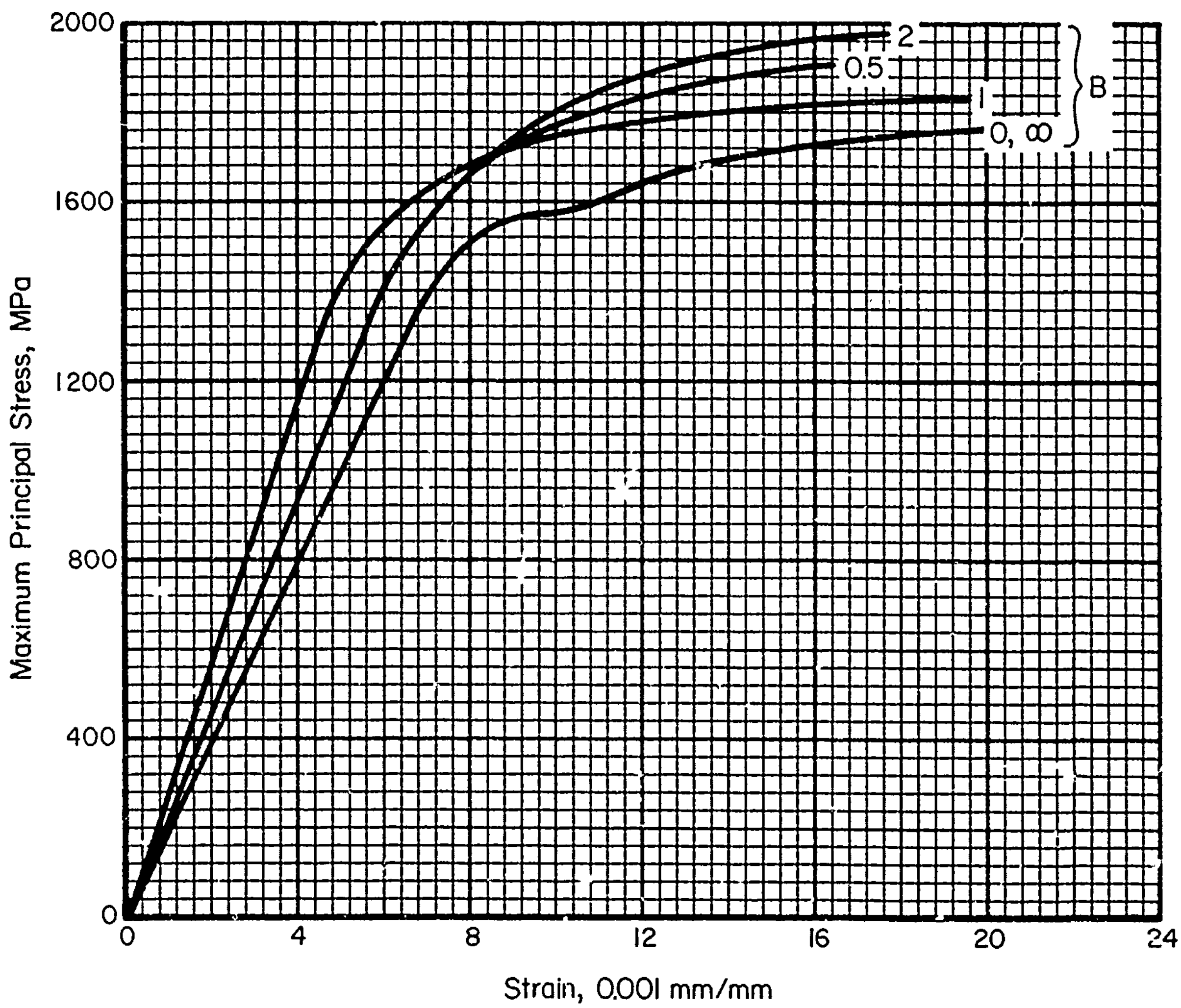


FIGURE 2.3.1.1.6 (h). Biaxial yield-stress envelope at room temperature for AISI 4340 alloy steel (machined thin-wall cylinders, axial direction = longitudinal direction of bar stock), F_{tu} = 1241 MPa; F_{ty} measured in the hoop direction.



FI'URE 2.3.1.1.6(i). 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} = 1793 MPa. A biaxial ratio B of zero corresponds to the hoop direction.

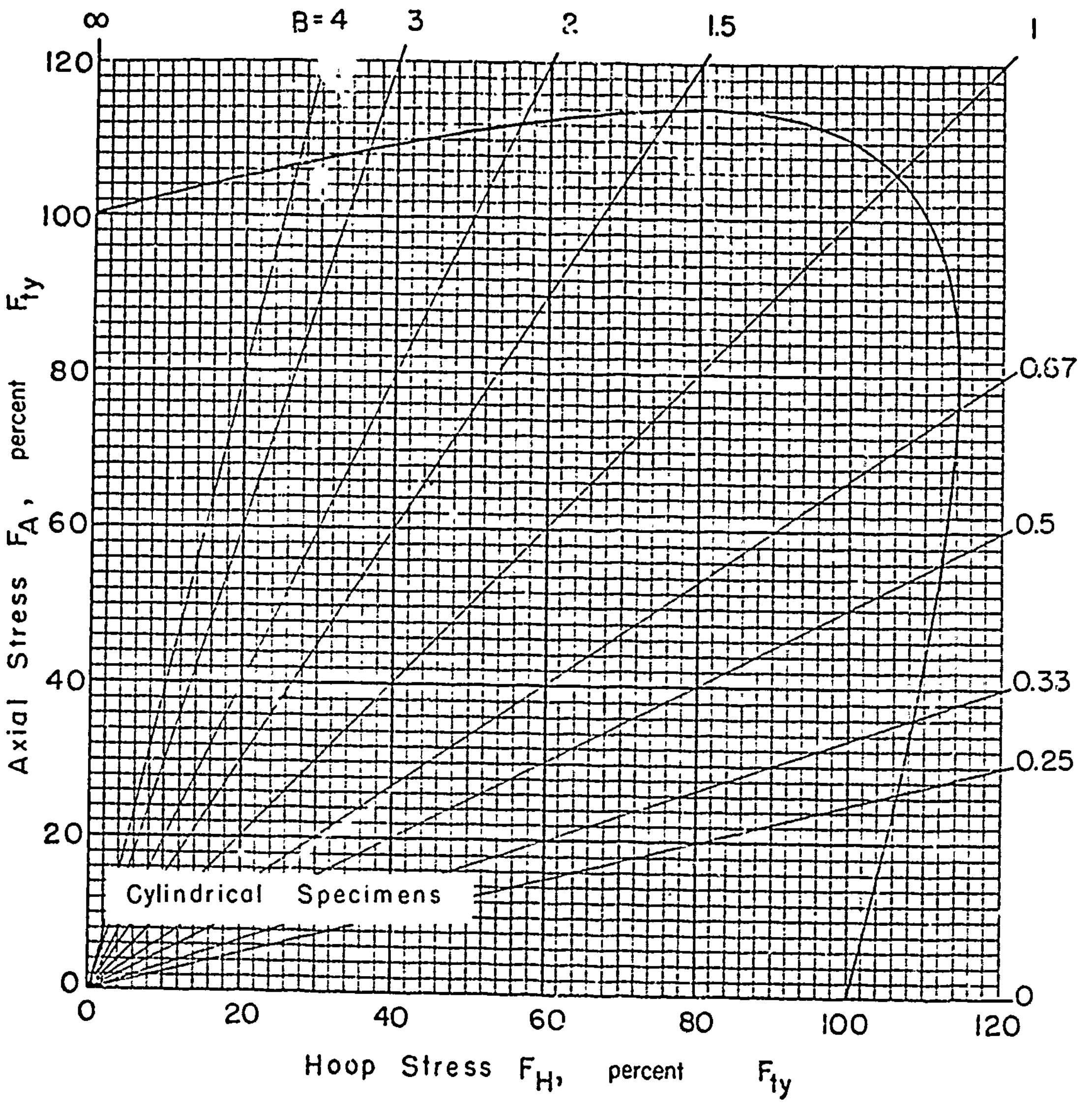


FIGURE 2.3.1.1.6 (j). Biaxial yield-stress envelope at room temperature for AISI 4340 alloy steel (machined thin-wall cylinders, axial direction = longitudinal direction of bar stock), F_{tu} = 1793 MPa; F_{ty} measured in the hoop direction.

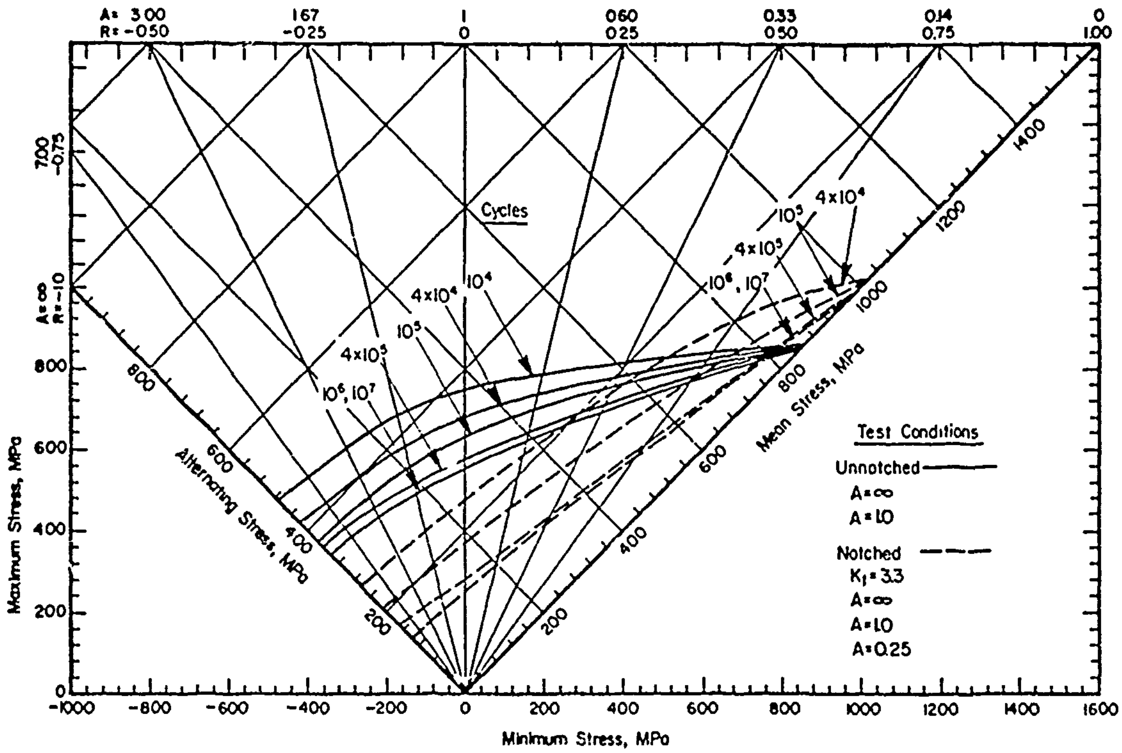


FIGURE 2.3.1.1.8(a). Typical constant-life fatigue diagram for heat-treated AISI 4340 alloy steel (bar), F_{tu} = 862 MPa

Correlative Information for Figure 2.3.1.1.8(a)

Product Form: Rolled Bar, 28.6 mm inches diameter

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

Properties:

TUS, MPa	TYS, MPa	Temp, K
860	—	RT (Unnotched)
1040	—	RT (Notched)

Specimen Details:

Unnotched:
10.16 mm diameter

Notched, V-Groove, $K_t = 3.3$
11.42 mm gross diameter
10.16 mm net diameter
0.25 mm root radius, r
60° flank angle, ω

$K_N = 2.34$, $\rho = 0.0584$ mm, where $K_N = 1 + \dfrac{K_t - 1}{1 + \dfrac{\pi}{\pi - \omega}\sqrt{\dfrac{\rho}{r}}}$

Surface Condition:
Unnotched: Hand polished to 0.284 micrometres RMS
Notched: Lathe turned to 0.254 micrometres RMS

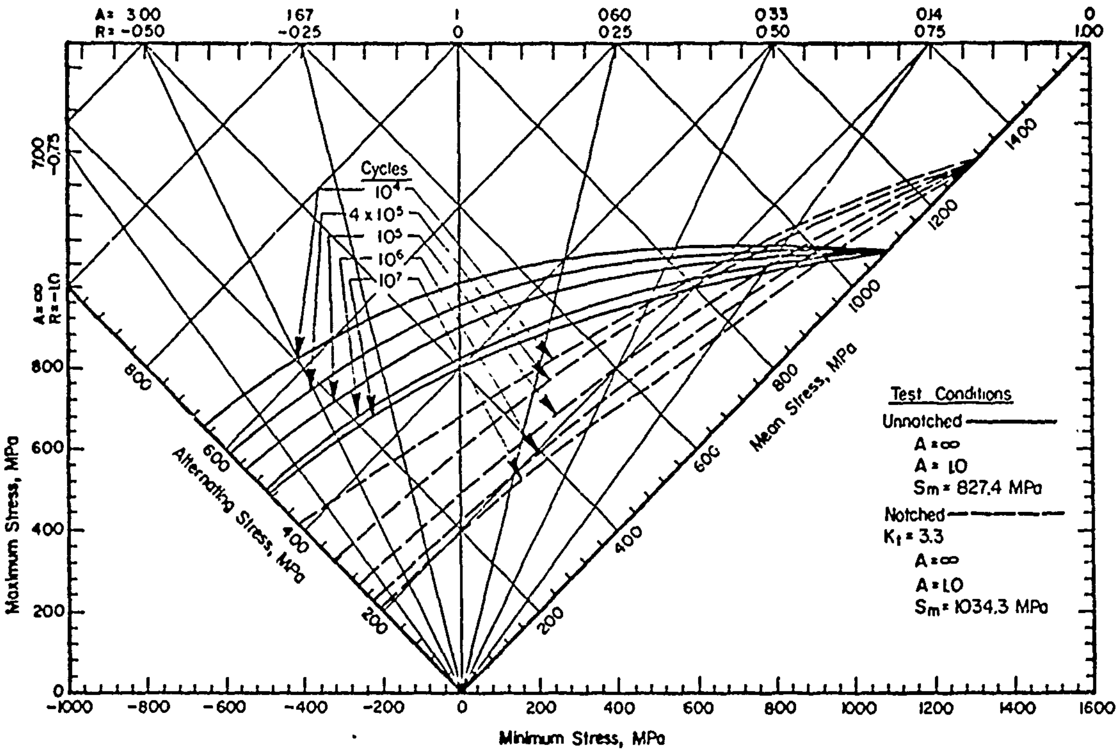


FIGURE 2.3.1.1.8(b). Typical constant-life fatigue diagram for heat-treated AISI 4340 alloy steel (bar), F_{tu} = 1034 MPA

Correlative Information for Figure 2.3.1.1.8(b)

Product Form: Rolled Bar, 28.6 mm diameter

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

Properties:

TUS, MPa	TYS, MPa	Temp, K
1090	1010	RT (Unnotched)
1310	—	RT (Notched)

Specimen Details:

Unnotched:
10.16 mm diameter

Notched, V-Groove, $K_t = 3.3$
11.42 mm gross diameter
10.16 mm net diameter
0.25 mm root radius, r
60° flank angle, ω

$K_N = 2.54$, $\rho \approx 0.025$ mm, where $$K_N = 1 + \frac{K_t - 1}{1 + \frac{\pi}{\pi - \omega}\sqrt{\frac{\rho}{r}}}$$

Surface Condition:
Unnotched: Hand polished to 0.254 micrometres RMS
Notched: Lathe turned to 0.254 micrometres RMS

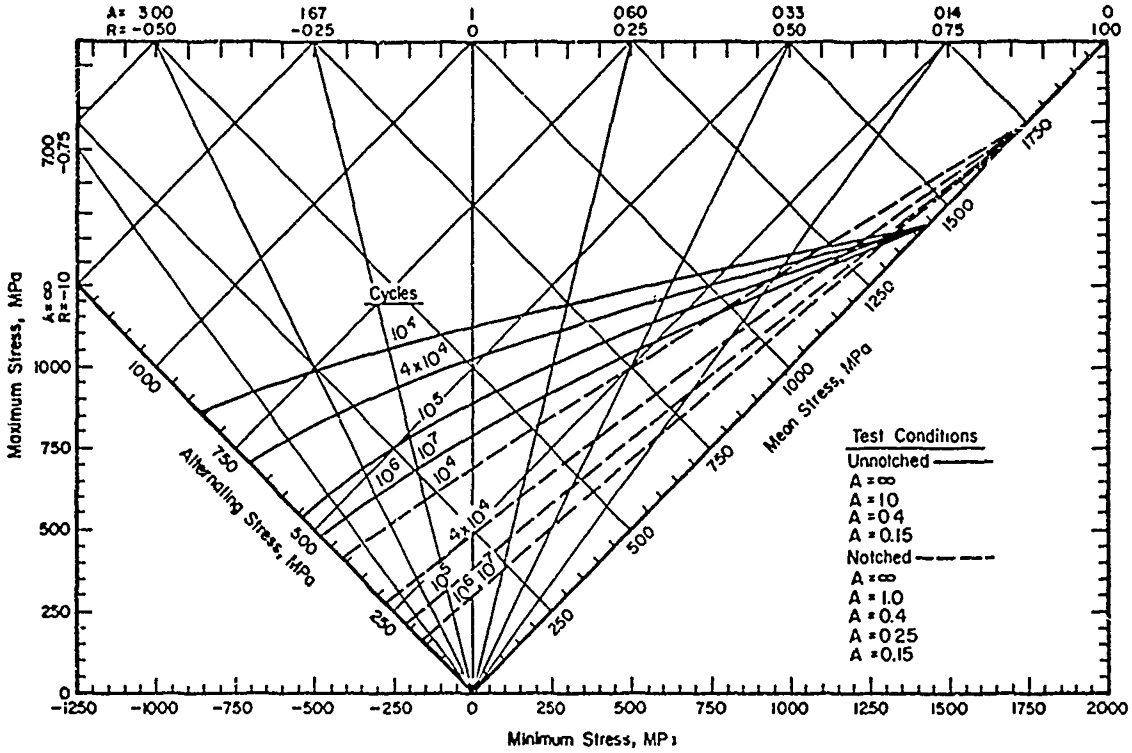


FIGURE 2.3.1.1.8(c). Typical constant-life fatigue diagram for heat-treated AISI 4340 alloy steel (bar), F_{tu} = 1379 MPa

Correlative Information for Figure 2.3.1.1.8(c).

Product Form: Rolled Bar, 28.6 mm diameter

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

Properties:

TUS, MPa	TYS, MPa	Temp, K
1430	—	RT (Unnotched)
1730	—	RT (Notched)

Specimen Details:

Unnotched: 10.16 mm diameter

Notched, V-Groove, $K_t = 3.3$
- 11.43 mm gross diameter
- 10.16 mm net diameter
- 0.25 mm root radius, r
- 60° flank angle, ω

$$K_N = 2.90;\ \rho = 0.0051\text{mm},\ \text{where } K_N = 1 + \frac{K_t - 1}{1 + \frac{\pi}{\pi - \omega}\sqrt{\frac{\rho}{r}}}$$

Surface Condition:
- Unnotched: Hand polished to 0.254 micrometres RMS
- Notched: Lathe turned to 0.254 micrometres RMS

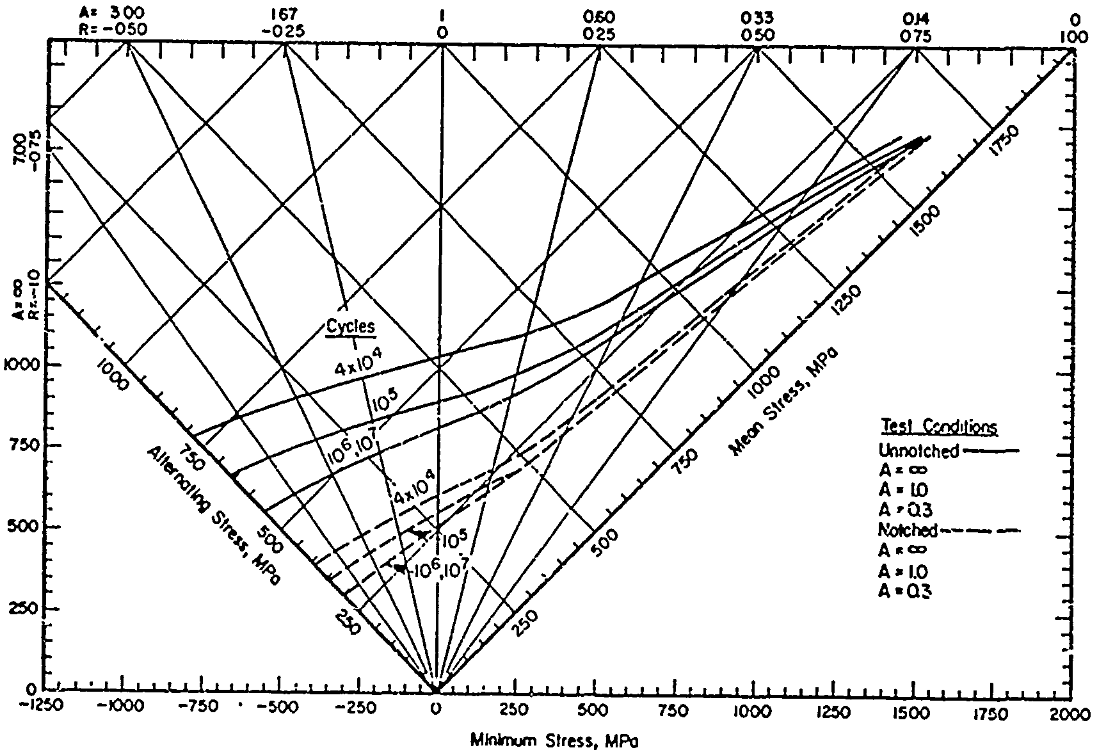


FIGURE 2.3.1.1.8(d). Typical constant-life fatigue diagram for heat-treated AISI 4340 alloy steel (bar), F_{tu} = 1793 MPa

Correlative Information for Figure 2.3.1.1.8(d).

Product Form: Rolled Bar, 28.6 mm diameter

Properties:

TUS, MPa	TYS, MPa	Temp, K
1830	1600	RT (Unnotched)
2430	—	RT (Notched)

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

Specimen Details: Unnotched
10.16 mm diameter

Notched, V-Groove, $K_t = 3.0$
6.86 mm gross diameter
5.59 mm net diameter
0.25 mm root radius, r
60° flank angle, ω

$$K_N = 2.91;\ \rho = 0.000229\ \text{mm, where}\ K_N = 1 + \frac{K_t - 1}{1 + \frac{\pi}{\pi - \omega}\sqrt{\frac{\rho}{r}}}$$

Surface Condition: Unnotched: Hand polished to 0.254 micrometres RMS
Notched: Lathe turned to 0.254 micrometres RMS

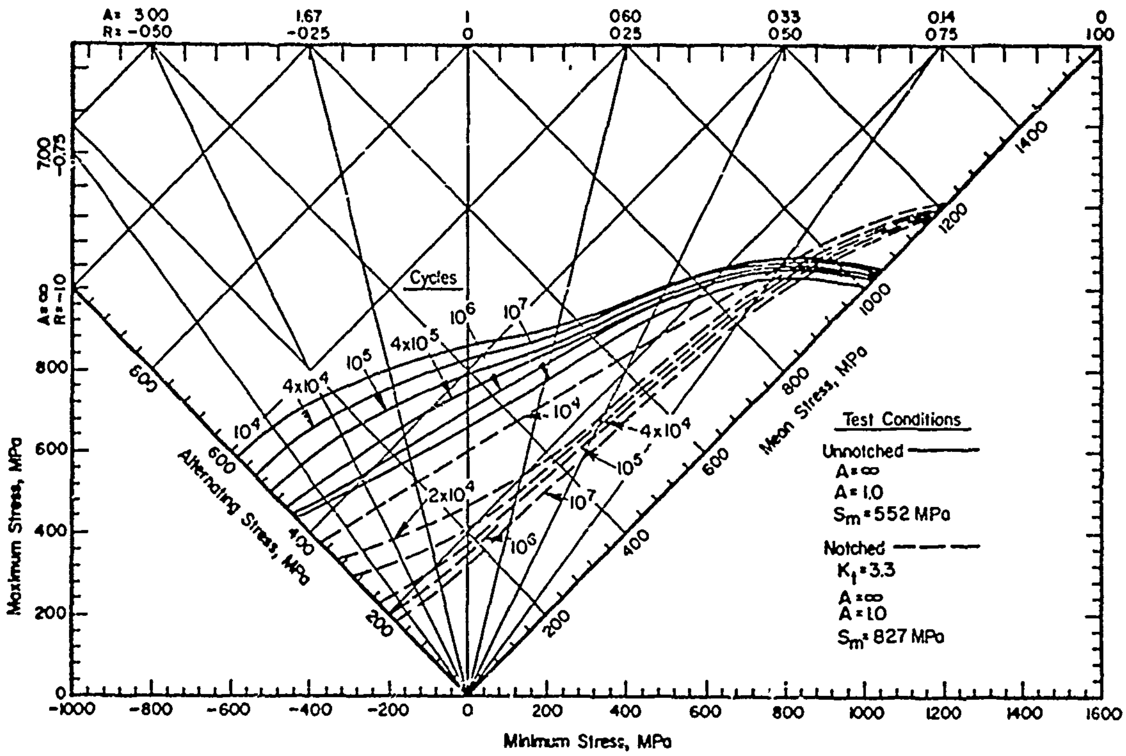


FIGURE 2.3.1.1.8(e). Typical constant-life fatigue diagram for heat-treated AISI 4340 alloy steel (bar) at 598 K, F_{tu} = 1034 MPa

Correlative Information for Figure 2.3.1.1.8(e).

Product Form: Rolled Bar, 28.6 mm diameter

Test Parameters:
- Loading - Axial
- Frequency - 2000 to 2500 cpm
- Temperature - 589 K
- Atmosphere - Air

Properties:

TUS, MPa	TYS, MPa	Temp, K
1090	1010	RT (Unnotched)
1050	840	589 (Unnotched)
1310	—	RT (Notched)
1210	—	589 (Notched)

Specimen Details:

Unnotched:
10.16 mm diameter

Notched, V-Groove, $K_t = 3.3$
11.43 mm gross diameter
10.16 mm net diameter
0.25 mm root radius, r
60° flank angle, ω

$K_N = 2.52$ (589 K); $\rho = 0.02921$ mm, where $K_N = 1 + \dfrac{K_t - 1}{1 + \dfrac{\pi}{\pi - \omega}\sqrt{\dfrac{\rho}{r}}}$

Surface Condition:
- Unnotched: Hand polished to 0.254 micrometres RMS
- Notched: Lathe turned to 0.254 micrometres RMS

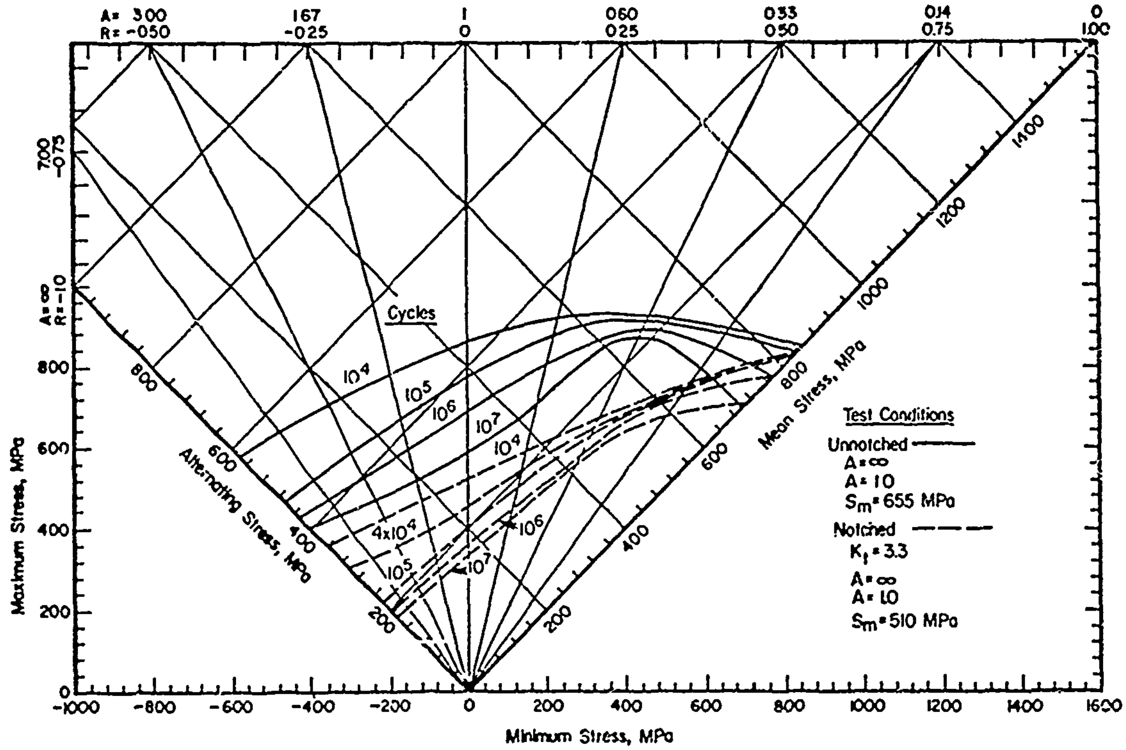


FIGURE 2.3.1.1.8(f). Typical constant-life fatigue diagram for heat-treated AISI 4340 alloy steel (bar), at 700 K, F_{tu} = 1034 MPa

Correlative Information for Figure 2.3.1.1.8(f).

Product Form: Rolled Bar, 28.6 mm diameter

Test Parameters:
- Loading - Axial
- Frequency - 2000 to 2500 cpm
- Temperature - 700 K
- Atmosphere - Air

Properties:

TUS, MPa	TYS, MPa	Temp, K
1090	1010	RT (Unnotched)
860	700	700 (Unnotched)
1310	—	RT (Notched)
1060	—	700 (Notched)

Specimen Details:

Unnotched: 10.16 mm diameter

Notched, V-Groove, $K_t = 3.3$
- 11.43 mm gross diameter
- 10.16 mm net diameter
- 0.25 mm root radius, r
- 60° flank angle, ω

$K_N = 2.52$ (700 K); $\rho = 0.0584$ mm, where $K_N = 1 + \dfrac{K_t - 1}{1 + \dfrac{\pi}{\pi - \omega}\sqrt{\dfrac{\rho}{r}}}$

Surface Condition:
- Unnotched: Hand polished to 0.254 micrometres RMS
- Notched: Lathe turned to 0.254 micrometres RMS

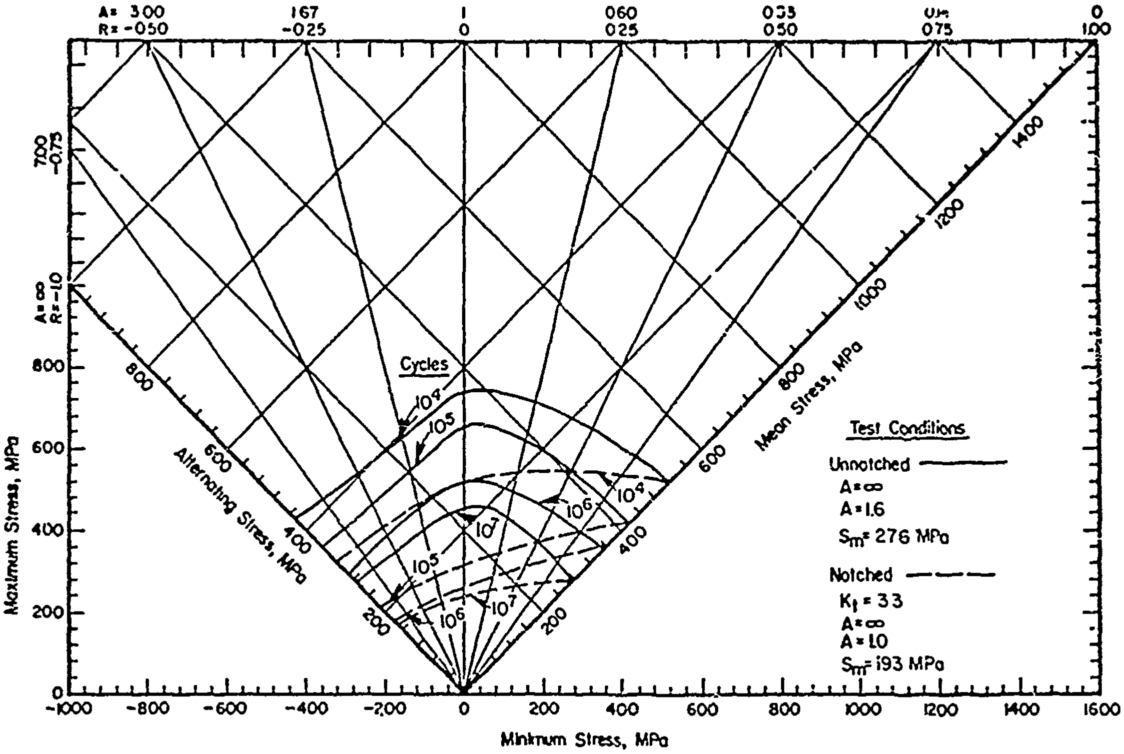


FIGURE 2.3.1.1.8(g). Typical constant-life fatigue diagram for heat-treated AISI 4340 alloy steel (bar) at 811 K, F_{tu} = 1034 MPa

Correlative Information for Figure 2.3.1.1.8(g).

Product Form: Rolled Bar, 28.6 mm diameter

Test Parameters:
Loading - Axial
Frequency - 2000 to 2500 cpm
Temperature - 811 K
Atmosphere - Air

Properties:

TUS, MPa	TYS, MPa	Temp, K
1090	1010	RT (Unnotched)
560	430	811 K (Unnotched)
1310	—	RT (Notched)
680	—	811 K (Notched)

Specimen Details:

Unnotched:
10.16 mm diameter

Notched, V-Groove, $K_t = 3.3$
11.43 mm gross diameter
10.16 mm net diameter
0.25 mm root radius, r
60° flank angle, ω

$K_N = 2.05$ (811 K); ρ = 0.1626 mm, where $K_N = 1 + \dfrac{K_t - 1}{1 + \dfrac{\pi}{\pi - \omega}\sqrt{\dfrac{\rho}{r}}}$

Surface Condition: Unnotched: Hand polished to 0.254 micrometres RMS
Notched: Lathe turned to 0.254 micrometres RMS

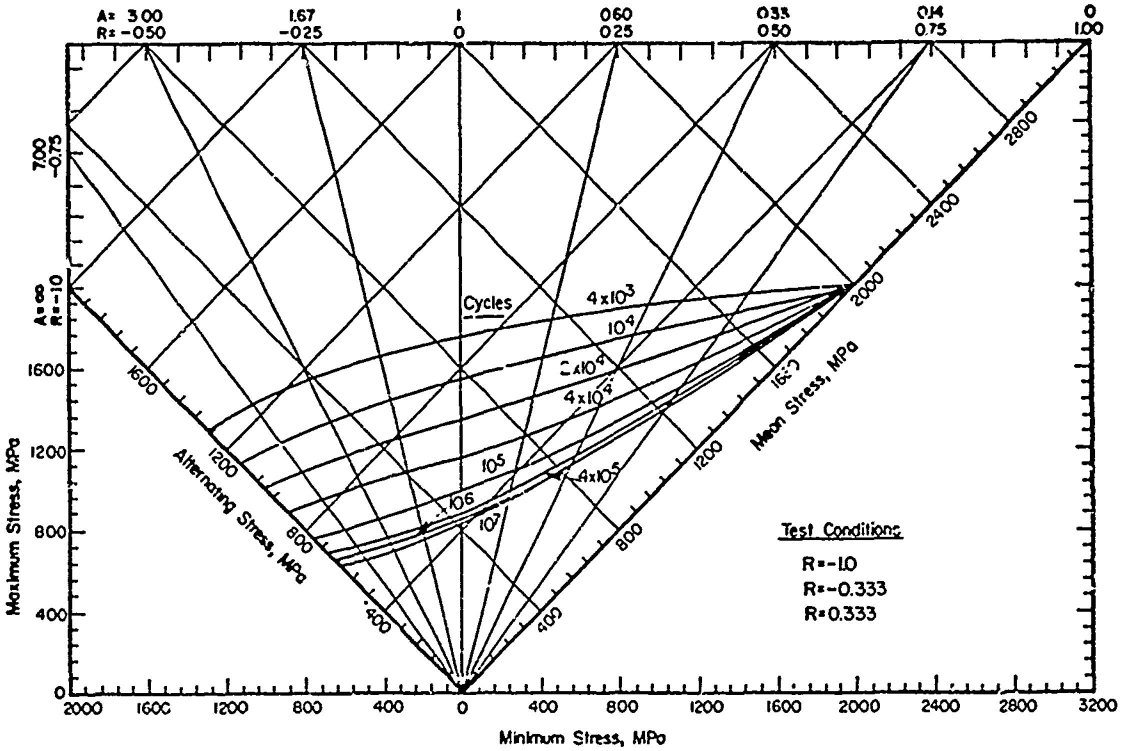


FIGURE 2.3.1.1.8(h). Typical constant-life fatigue diagram for 300M alloy, unnotched, F_{tu} = 1931 MPa.

Correlative Information for Figure 2.3.1.1.8(h).

Product Form: Forgings

Properties:

TUS, MPa	TYS, MPa	Temp, K
2000	1670	RT

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

Specimen Details: Unnotched:
6.35 mm diameter

Surface Condition:

Heat treat and finish grind to a surface finish of 63 ± 5 RMS with light grinding parallel to specimen length, stress relieve.

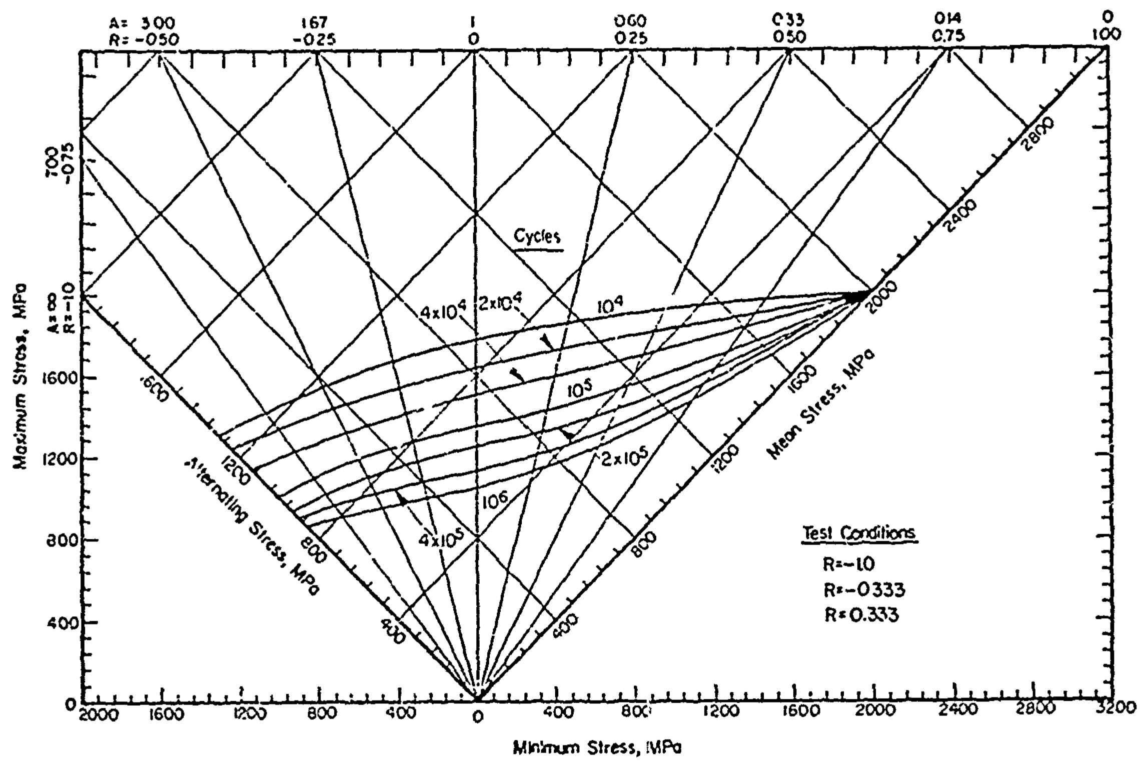


FIGURE 2.3.1.1.8(i). Typical constant-life fatigue diagram for 300M alloy, decarburized and shot peened, F_{tu} = 1931 MPa.

Correlative Information for Figure 2.3.1.1.8(i).

Product Form: Forgings

Properties: TUS, MPa 2000; TYS, MPa 1670; Temp, K RT

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

Specimen Details: Unnotched:
6.35 mm diameter

Surface Condition:

Heat treat and finish grind to a surface finish of 63 ± 5 RMS with light grinding passes parallel to specimen length, stress relieve; shot peen with Number 230 size shot to Almen intensity of A10-12 with high intensity coverage. Ground surface showed 0.076 to 0.152 mm decarburization prior to shot peening.

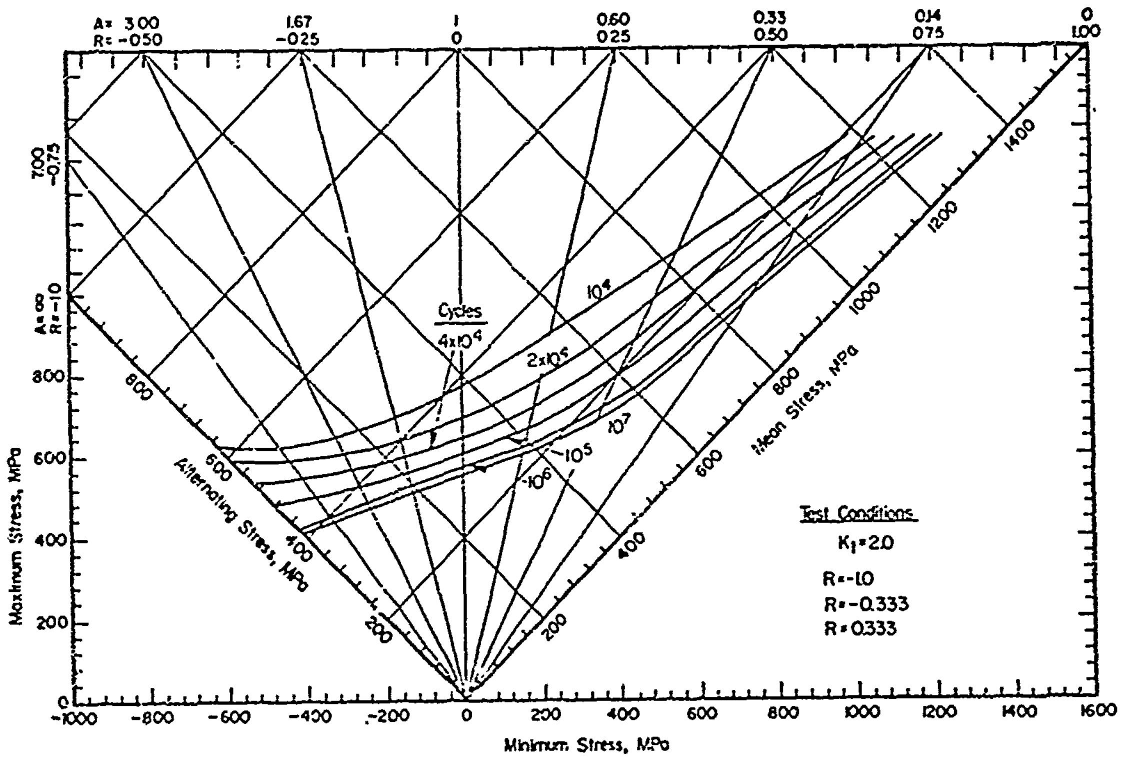


FIGURE 2.3.1.1.8(j). Typical constant-life fatigue diagram for 300M alloy, notched K_t = 2.0, F_{tu} = 1931 MPA

Correlative Information for Figure 2.3.1.1.8(j).

Product Form: Forgings

Properties:	TUS, MPa	TYS, MPa	Temp, K
	2000	1670	RT (Unnotched)
	3140	—	RT (Notched)

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

Specimen Details: Notched, 60° V-Groove, K_t = 2.0
12.70 mm gross diameter
6.35 mm net diameter
1.02 mm root radius, r
60° flank angle, ω

$$K_N = 1.98;\ \rho = 0.000229 \text{ mm, where } K_N = 1 + \frac{K_t - 1}{1 + \frac{\pi}{\pi - \omega}\sqrt{\frac{\rho}{r}}}$$

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

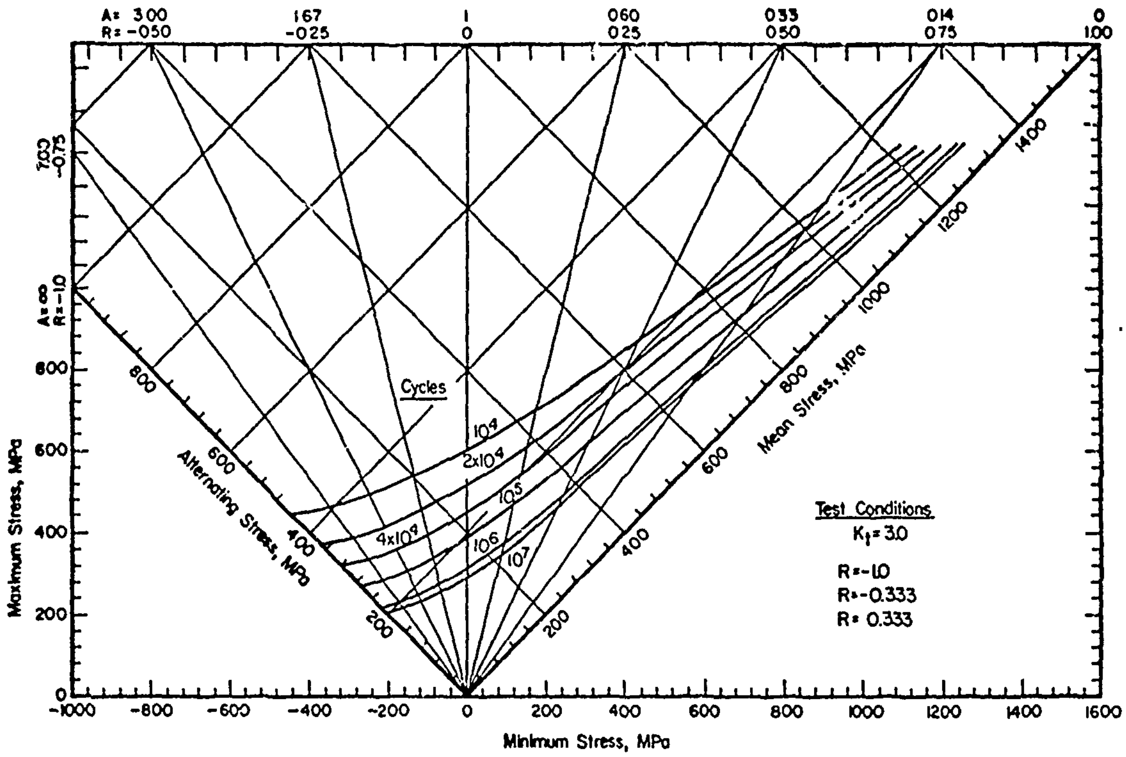


FIGURE 2.3.1.1.8(k). Typical constant-life fatigue diagram for 300M alloy, notched K_t = 3.0, F_{tu} = 1931 MPA

Correlative Information for Figure 2.3.1.1.8(k).

Product Form: Forgings

Properties:

TUS, MPa	TYS, MPa	Temp, K
2000	1670	RT (Unnotched)
3000	—	RT (Notched)

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

Specimen Details: Notched, 60° V-Groove, $K_t = 3.0$
- 12.70 mm gross diameter
- 6.35 mm net diameter
- 0.3683 mm root radius, r
- 60° flank angle, ω

$$K_N = 2.93;\ \rho = 0.000229 \text{ mm, where } K_N = 1 + \frac{K_t - 1}{1 + \frac{\pi}{\pi - \omega}\sqrt{\frac{\rho}{r}}}$$

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

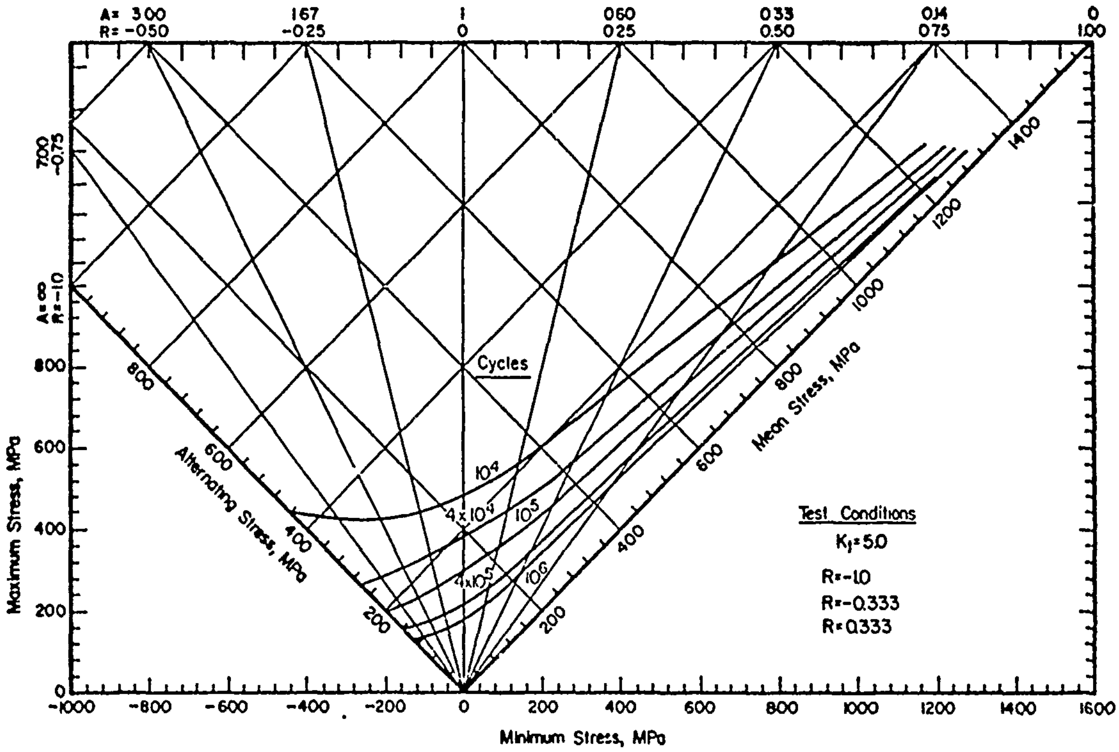


FIGURE 2.3.1.1.8(1). Typical constant-life fatigue diagram for 300M alloy, notched K_t = 5.0, F_{tu} = 1931 MPa

Correlative Information for Figure 2.3.1.1.8(1).

Product Form: Forgings

Properties:	TUS, MPa	TYS, MPa	Temp, K
	2000	1670	RT (Unnotched)
	2600	—	RT (Notched)

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

Specimen Details: Notched, 60° V-Groove, K_t = 5.0
- 12.70 mm gross diameter
- 6.35 mm net diameter
- 0.1067 mm root radius, r
- 60° flank angle, ω

$$K_N = 1.98;\ \rho = 0.000229 \text{ mm, where } K_N = 1 + \frac{K_t - 1}{1 + \frac{\pi}{\pi - \omega}\sqrt{\frac{\rho}{r}}}$$

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

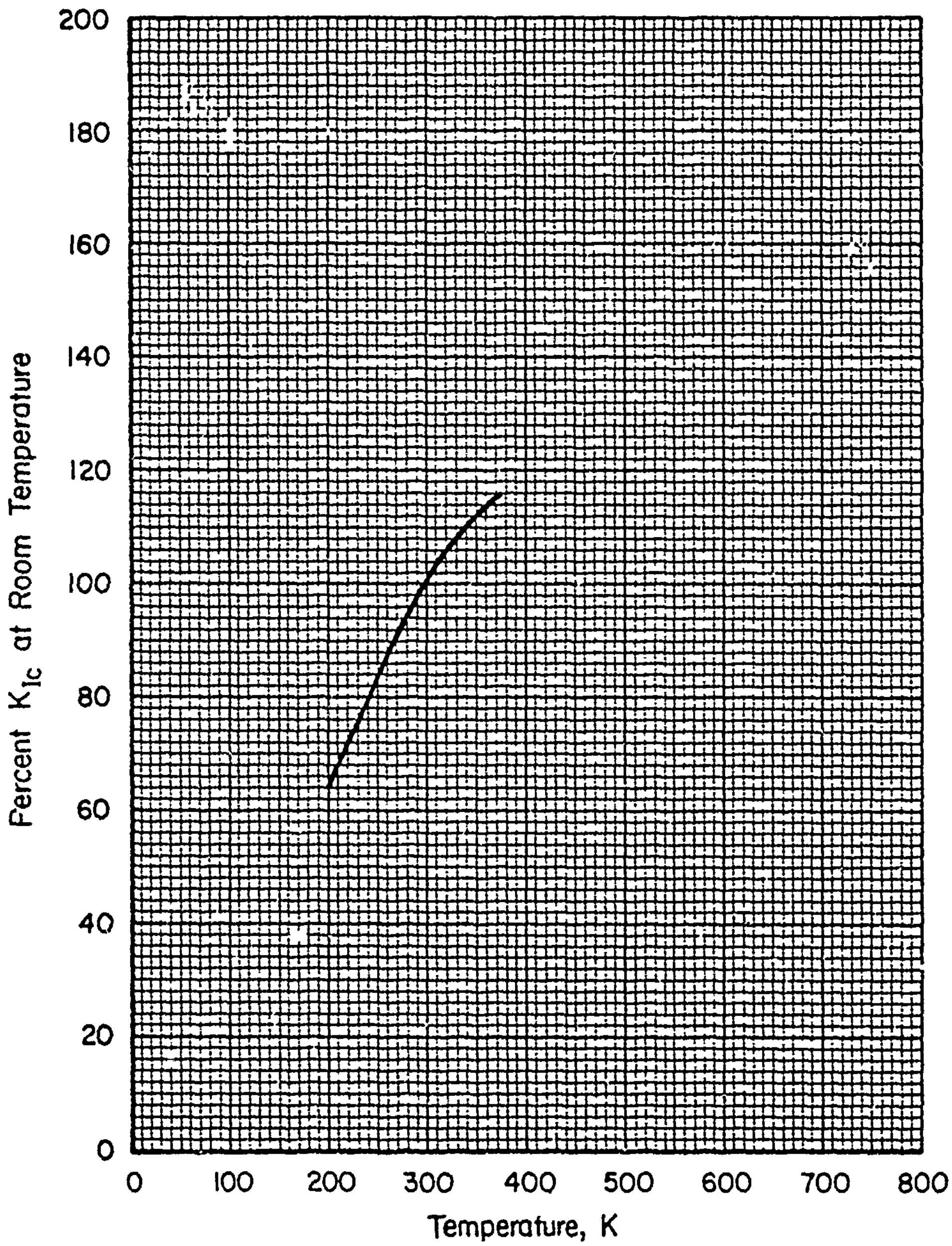


FIGURE 2.3.1.1.9. Typical effect of temperatures on the plane strain fracture toughness (K_{Ic}) of heat treated AISI 4340 alloy steel, F_{tu} = 260 ksi, (L) (T) fracture path.

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 alloys 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.*—5Cr-Mo-V aircraft steel exhibits high strength in the temperature range up to 811 K. Its characteristics also include air hardenability in heavy sections; as a result of this, little distortion is encountered in heat treating this steel.

Material specifications for 5Cr-Mo-V aircraft steel are presented in Table 2.4.1.0(a).

TABLE 2.4.1.0(a). *Material Specifications for 5Cr-Mo-V Aircraft Steel*

Specification	Form
AMS 6437	Sheet, strip, and plate.
AMS 6485	Bar, forging, and forging stock.

The heat treatment recommended for this steel consists of heating to 1283 K ± 28 holding 15 to 25 minutes for sheet or 30 to 60 minutes for bars, depending on section size, and cooling in air to room temperature, then tempering three times by heating to the temperature specified in Table 2.4.1.0(b) for the strength level desired, holding at temperature for 2 to 3 hours, and cooling in air.

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.

TABLE 2.4.1.0(b). Tempering Temperatures for 5Cr-Mo-V Aircraft Steel

F_{tu}, MPa	Temperature, K	Hardness, R_c
1931	811 ± 5	54-56
1793	828 ± 5	52-54
1655	838 ± 5	49-52
1517	855 ± 5	46-49

Room-Temperature Properties

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.

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 55 K below the tempering temperature for the desired strength level.

Figure 2.4.1.0 presents room temperature and elevated temperature physical property information for K and α.

2.4.1.1 *Heat Treated Condition.*—The effect of temperature on various mechanical properties for heat treated 5Cr-Mo-V aircraft steel are presented in Figures 2.4.1.1.1(a) through 2.4.1.1.4. In addition elevated temperature requirements are specified in AMS 6437 and 6485. Figure 2.4.1.1.9 contains an effect of temperature curve for plane strain fracture toughness, K_{Ic}, for this alloy in the heat treated condition.

TABLE 2.4.1.0(C). 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, MM	≤304.80		
BASIS	S[a,b,c]	S[a,b,c]	S[a,b,c]
MECHANICAL PROPERTIES:			
FTU, MPA:			
L	...	...	...
LT	1650	1790	1930
FTY, MPA:			
L	...	...	...
LT	1380	1520	1650
FCY, MPA:			
L	...	...	...
LT	1520	1650	1790
FSU, MPA	1000	1070	1170
FBRU, MPA:			
(E/D=1.5)	...	...	...
(E/D=2.0)	2760	3000	3210
FBRY, MPA:			
(E/D=1.5)	...	...	...
(E/D=2.0)	2170	2340	2520
EL, PERCENT:			
LT (SHEET[d] IN 50.8 MM)	6	5	4
LT (SHEET[d] IN 25.4 MM)	8	7	6
E, GPA	206.8		
EC, GPA	206.8		
G, GPA	75.8		
MU	0.36		
PHYSICAL PROPERTIES:			
OMEGA, MG/M3	7.78		
C, J/(G*K)	0.46[e] (273 K)		
K, W/(M*K)	29 (478 TO 866 K)		
ALPHA, 10-6 M/(M*K)	12.8 (300 TO 700 K); 13.3 (300 TO 922 K)		

[a] MINIMUM PROPERTIES EXPECTED WHEN HEAT TREATED AS RECOMMENDED IN SECTION 2.4.1.0.

[b] THE USE OF HEAT TREATMENTS OF FTU = 1517 MPA OR HIGHER IS SUBJECT TO THE SPECIFIC APPROVAL OF THE PROCURING OR CERTIFICATING AGENCY.

[c] TEST DIRECTION LONGITUDINAL FOR WIDTHS LESS THAN 228.6 MM; TRANSVERSE FOR WIDTHS 228.0 MM AND OVER.

[d] FOR SHEET THICKNESS GREATER THAN 1.27 MM.

[e] CALCULATED VALUE.

TABLE 2.4.1.0(D). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 5CR-MO-V AIRCRAFT STEEL (BARS AND FORGINGS)

SPECIFICATION	AMS 6485		
FORM	BARS AND FORGINGS		
CONDITION	QUENCHED AND TEMPERED		
THICKNESS, MM	≤304.80		
BASIS	S[a,b]	S[a,b,c]	S[a,c]
MECHANICAL PROPERTIES:			
FTU, MPA:			
L	...	...	...
T	1650	1790	1930
FTY, MPA:			
L	...	...	...
T	1380	1480	1650
FCY, MPA:			
L	...	...	...
T	1520	1610	1790
FSU, MPA	1000	1070	1170
FBRU, MPA:			
(E/D=1.5)	...	...	...
(E/D=2.0)	2760	3000	3210
FBRY, MPA:			
(E/D=1.5)	...	...	...
(E/D=2.0)	2170	2300	2520
EL, PERCENT:			
L	...	8[c]	...
T	9	d	7
E, GPA	206.8		
EC, GPA	206.8		
G, GPA	75.8		
MU	0.36		
PHYSICAL PROPERTIES:			
OMEGA, MG/M3	7.78		
C, J/(G*K)	0.46[e] (273 K)		
K, W/(M*K)	29 (478 TO 866 K)		
ALPHA, 10-6 M/(M*K)	12.8 (300 TO 700 K); 13.3 (300 TO 922 K)		

a MINIMUM PROPERTIES EXPECTED WHEN HEAT TREATED AS RECOMMENDED IN SECTION 2.4.1.0.

b THE USE OF HEAT TREATMENTS OF FTU = 1517 MPA OR HIGHER IS SUBJECT TO THE SPECIFIC APPROVAL OF THE PROCURING OR CERTIFICATING AGENCY.

c TEST DIRECTION LONGITUDINAL FOR CROSS-SECTIONAL AREAS LESS THAN 161.3 SQ.CM., TRANSVERSE FOR AREAS > 161.3 SQ. CM.

d ELONGATION: OVER 161.3 TO 483.9, EXCLUSIVE, 6 PERCENT: 483.9 TO 645.2, 6: 645.2 TO 967.7 INCL., 5; 967.7 TO 1451.6, INCL., 4: 1451.6 TO 1651.6, INCL.,3.

e CALCULATED VALUE.

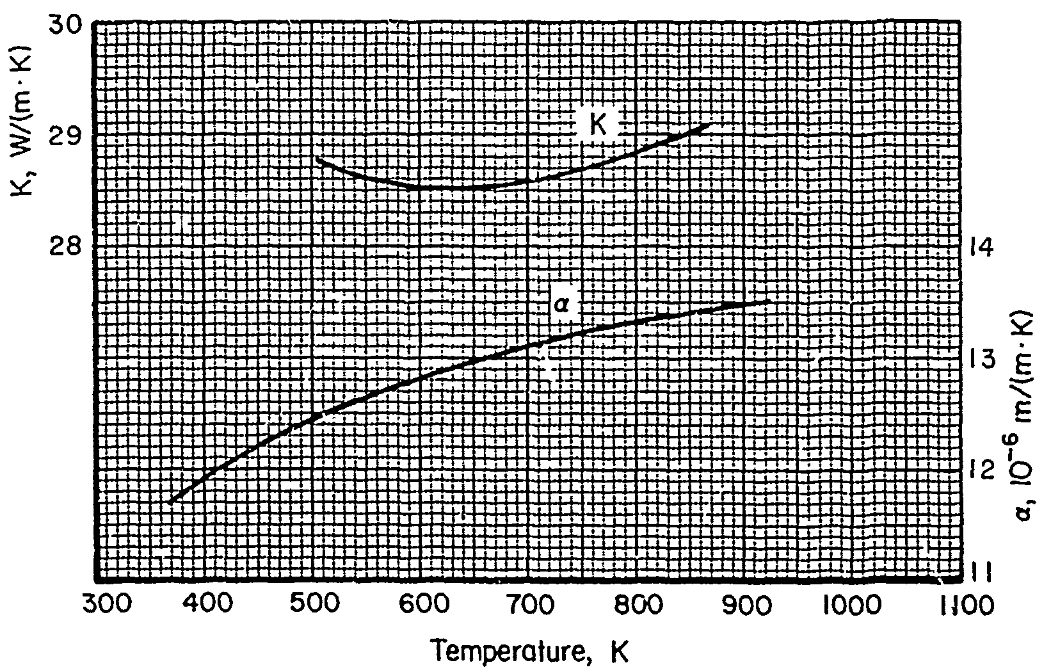


FIGURE 2.4.1.0. Effect of temperature on the physical properties of 5Cr-Mo-V aircraft steel.

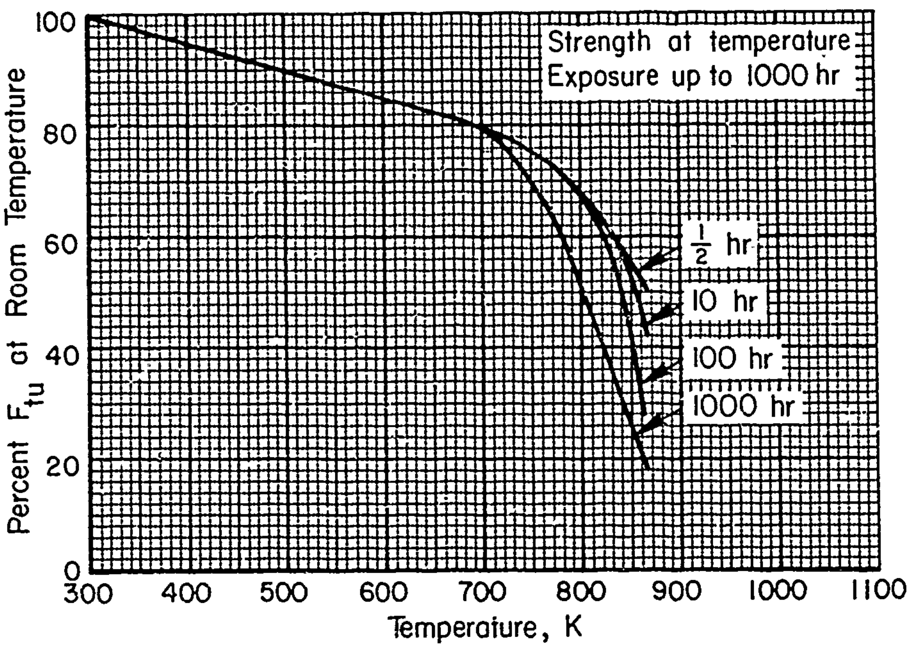


FIGURE 2.4.1.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of 5Cr-Mo-V aircraft steel

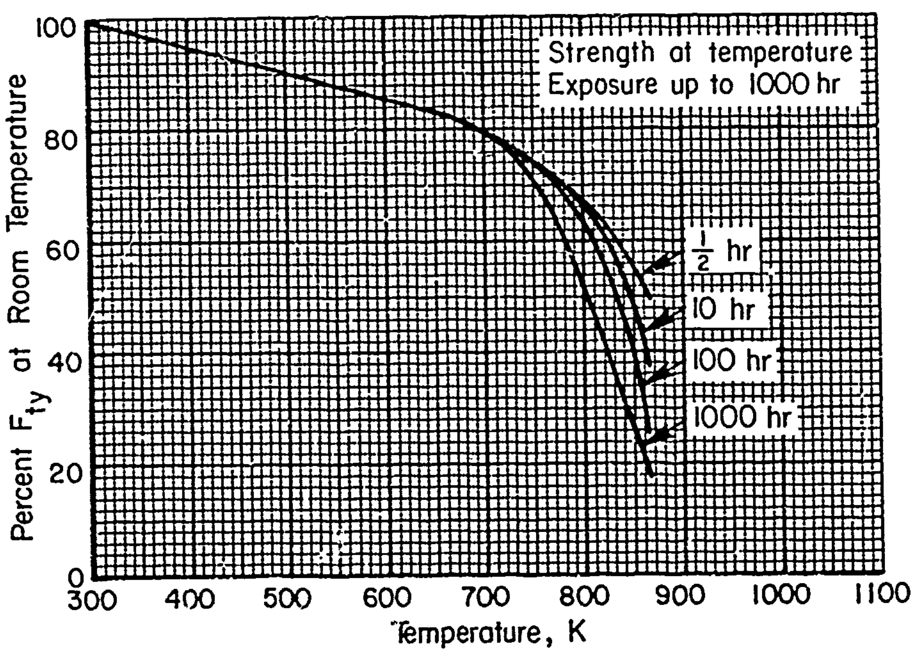


FIGURE 2.4.1.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of 5Cr-Mo-V aircraft steel.

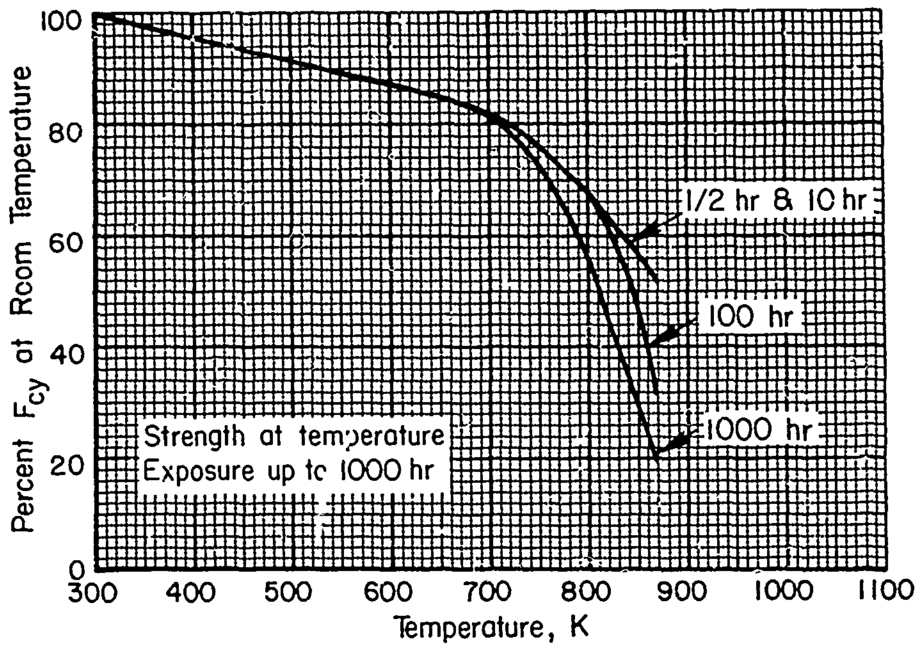


FIGURE 2.4.1.1.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of 5Cr-Mo-V aircraft steel.

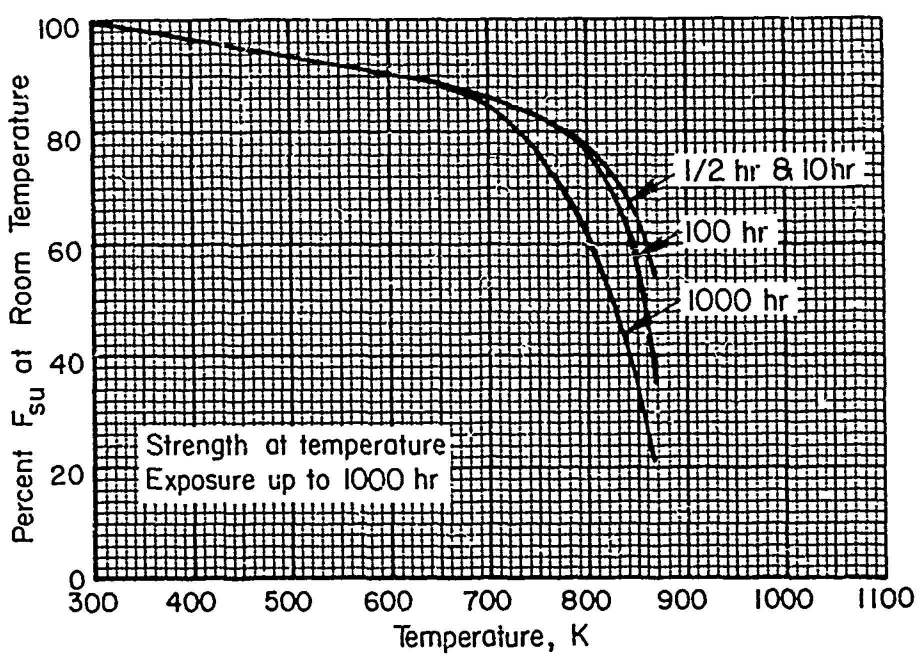


FIGURE 2.4.1.1.2(b). Effect of temperature on the ultimate shear strength (F_{su}) of 5Cr-Mo-V aircraft steel.

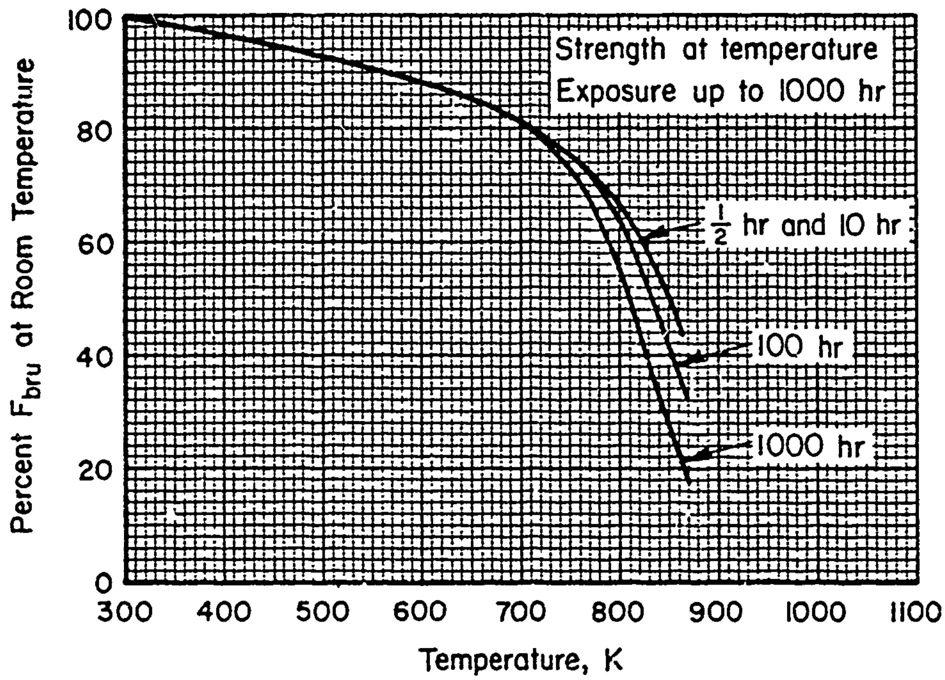


FIGURE 2.4.1.1.3(a). Effect of temperature on the ultimate bearing strength (F_{bru}) of 5Cr-Mo-V aircraft steels.

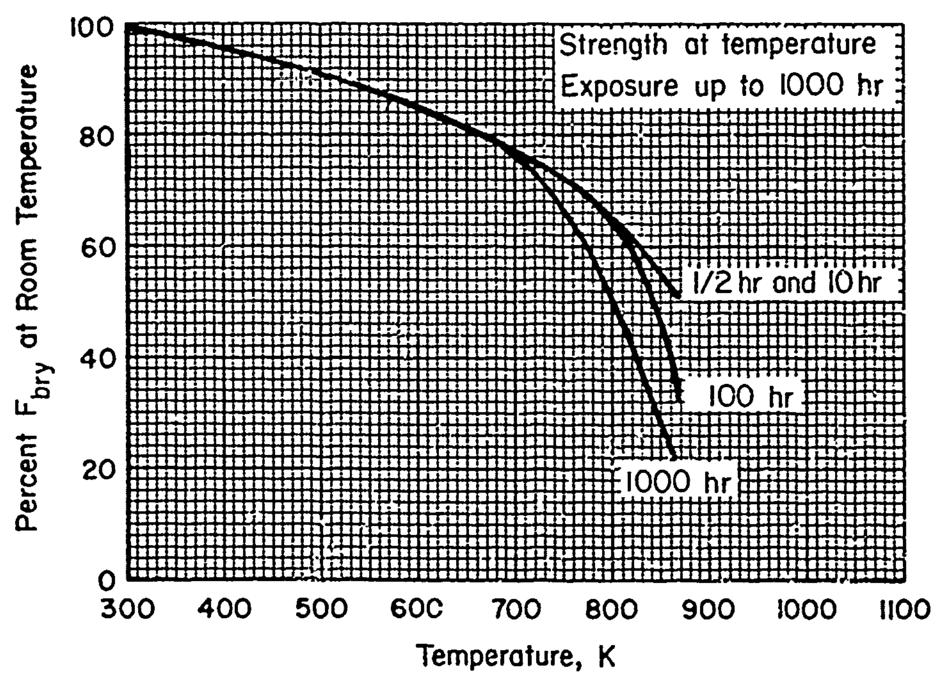


FIGURE 2.4.1.1.3(b). Effect of temperature on the bearing yield strength (F_{bry}) of 5Cr-Mo-V aircraft steels.

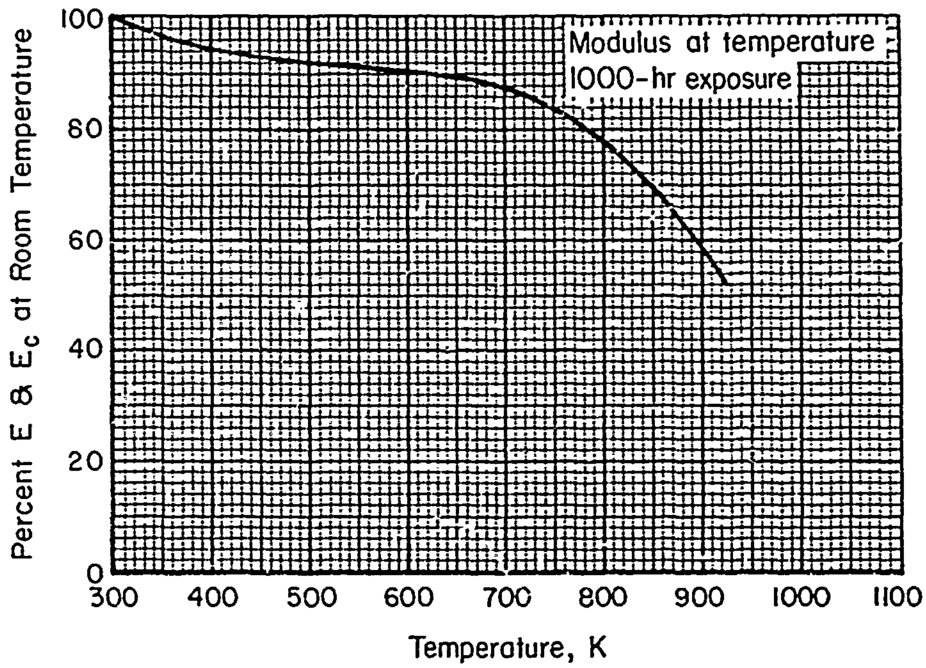


FIGURE 2.4.1.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of 5Cr-Mo-V aircraft steel.

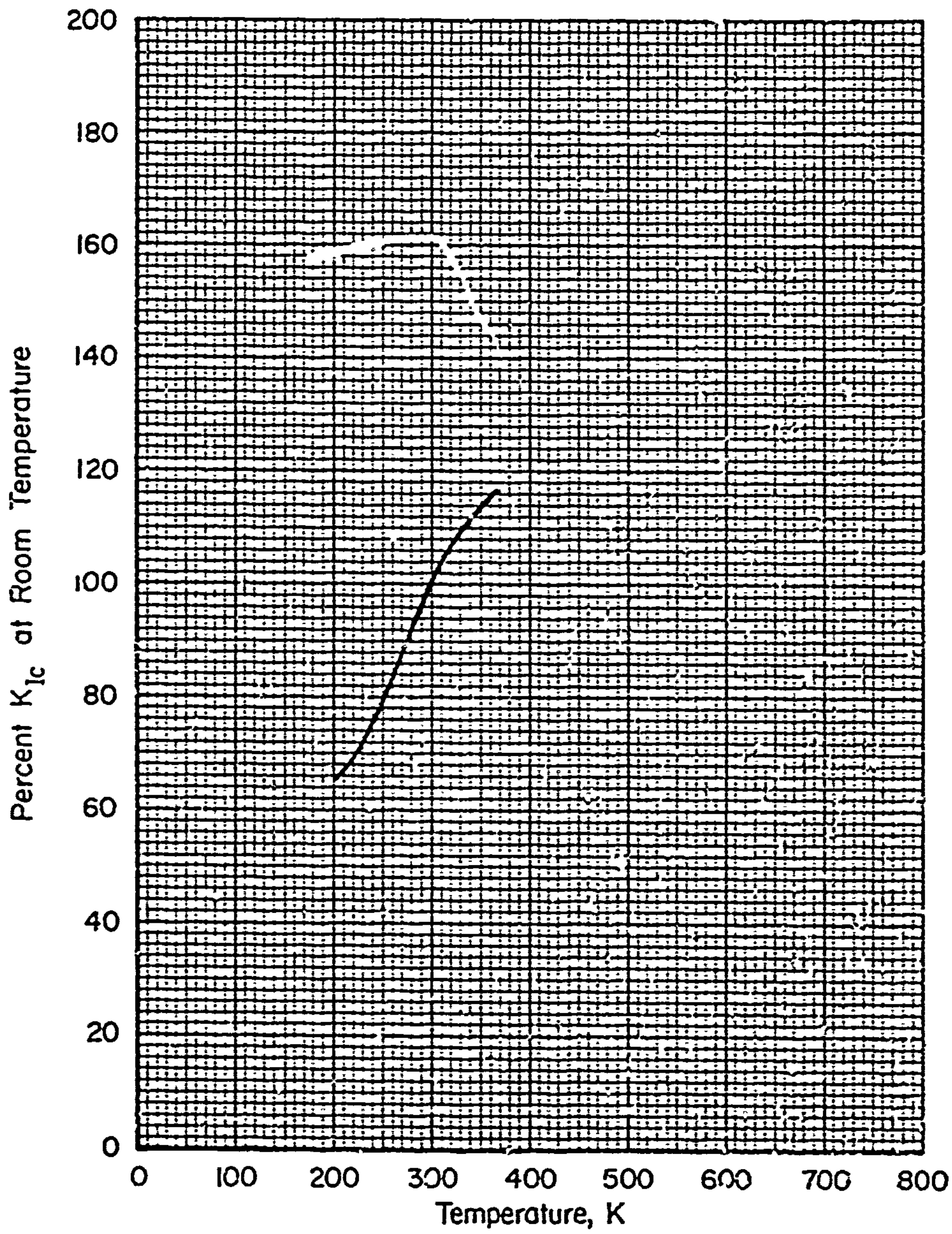


FIGURE 2.4.1.1.9. Typical effect of temperature on the plane strain fracture toughness (K_{Ic}) of 5Cr-Mo-V aircraft steels, (L) (T) fracture path.

2.4.2 9Ni-4Co-.20C

2.4.2.0 *Comments and Properties.* —The 9Ni-4Co-.20C alloy was developed specifically to have excellent fracture toughness, excellent weldability, and high hardenability when heat treated to 1310-1450 MPa 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 200 mm thick. The alloy may be exposed to temperatures up to 755 K (approximately 55 K below typical tempering temperature) without microstructural changes which degrade strength.

A material specification for 9Ni-4Co-.20C steel is presented in Table 2.4.2.0(a).

TABLE 2.4.2.0(a). *Material Specification for 9Ni-4C0-.20C Steel*

Specification	Form
AMS 6523	Sheet, strip, and plate

The heat treatment for this alloy consists of normalizing at 1172±15 K for 1 hour per 25 mm of cross section, cooling in air to room temperature, heating to 1103±15 K for 1 hour per 25 mm of cross section, quenching in oil or water, treating at 198±10 K for 1-2 hours within 2 hours after quenching, and tempering at 825±10 K for 4 hours. AMS 6523 does not require low temperature treatment.

Room Temperature Properties

Room temperature mechanical and physical properties are shown in Table 2.4.2.0(b).

2.4.2.1 *Heat Treated Condition.* —Effect of temperature on various mechanical properties are presented in Figures 2.3.2.1.1(a) through 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(8). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 9NI-4CO-.20C STEEL (PLATE)

SPECIFICATION............	AMS 6523
FORM....................	PLATE
CONDITION...............	QUENCHED AND TEMPERED
THICKNESS, MM...........	...
BASIS...................	S[a,b,c]
MECHANICAL PROPERTIES:	
FTU, MPA:	
L................	...
T................	1310
FTY, MPA:	
L................	...
T................	1240
FCY, MPA:	
L................	...
T................	1330
FSU, MPA............	821
FBRU, MPA:	
(E/D=1.5).........	...
(E/D=2.0).........	...
FBRY, MPA:	
(E/D=1.5).........	...
(E/D=2.0).........	...
EL, PERCENT:	
L................	...
T................	10
E, GPA..............	198.6
EC, GPA.............	198.6
G, GPA..............	76.5
MU..................	0.30
PHYSICAL PROPERTIES:	
OMEGA, MG/M3.........	7.83
C, J/(G*K)...........	...
K, W/(M*K)...........	277 (297 K)
ALPHA, 10-6 M/(M*K)..	11.5 (294 TO 366 K)

[a] THESE DESIGN ALLOWABLE PROPERTIES ARE APPLICABLE ONLY WHEN THE INDICATED FTU HAS BEEN SUBSTANTIATED THROUGH ADEQUATE QUALITY CONTROL INSPECTION TESTING.

[b] THESE DESIGN ALLOWABLE PROPERTIES ARE APPLICABLE ONLY TO MATERIAL FOR WHICH THE HEAT TREAT PROCEDURE INCLUDES SUBZERO TREATING AT 200 ± 11 K FOR 1-2 HOURS AFTER OIL QUENCHING. SPECIFICATION AMS 6523 DOES NOT REQUIRE SUBZERO TREATMENT.

[c] TEST DIRECTION LONGITUDINAL FOR WIDTHS LESS THAN 228.6 MM; TRANSVERSE FOR WIDTHS 228.6 MM AND OVER.

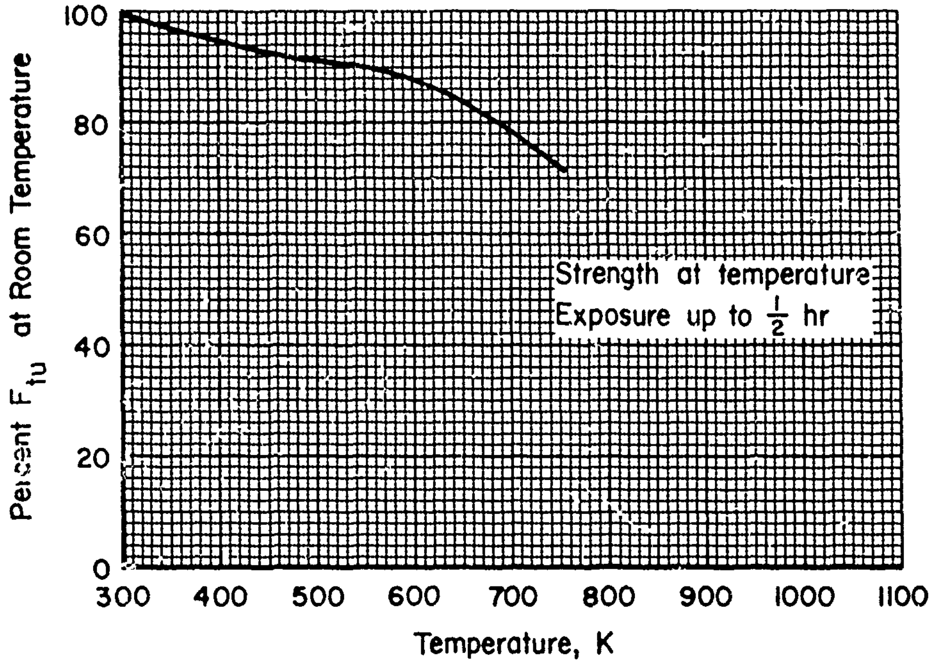


FIGURE 2.4.2.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of 9Ni-4Co-.20C steel (plate).

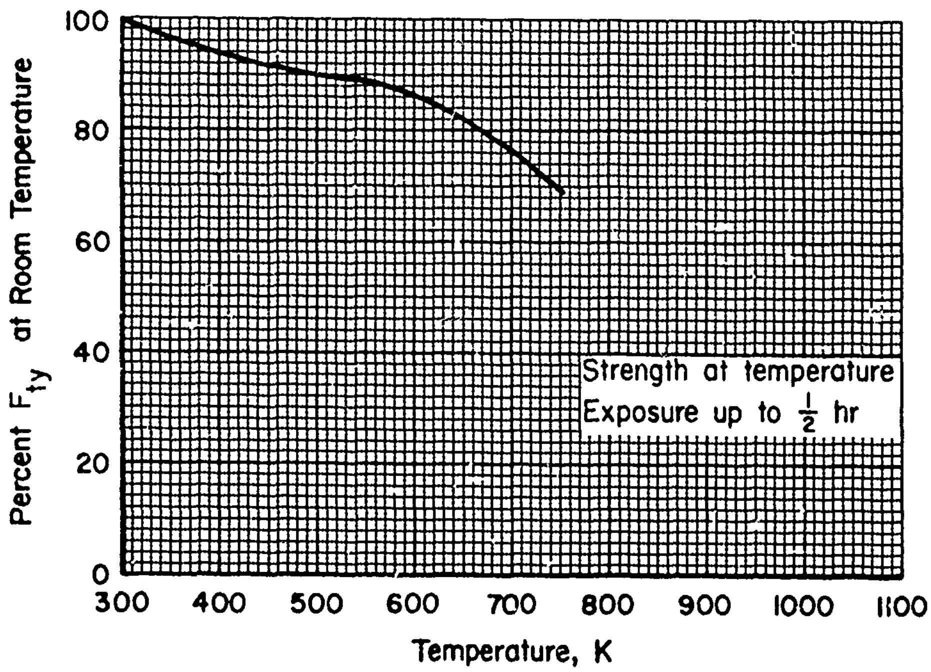


FIGURE 2.4.2.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of 9Ni-4Co-.20C steel (plate).

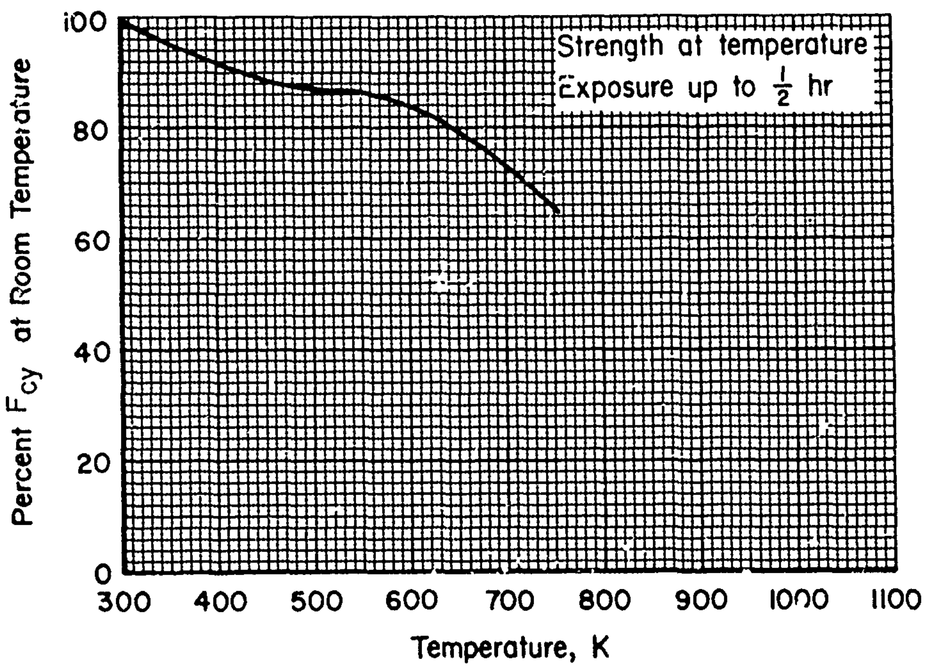


FIGURE 2.4.2.1.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of 9Ni-4Co-.20C steel (plate).

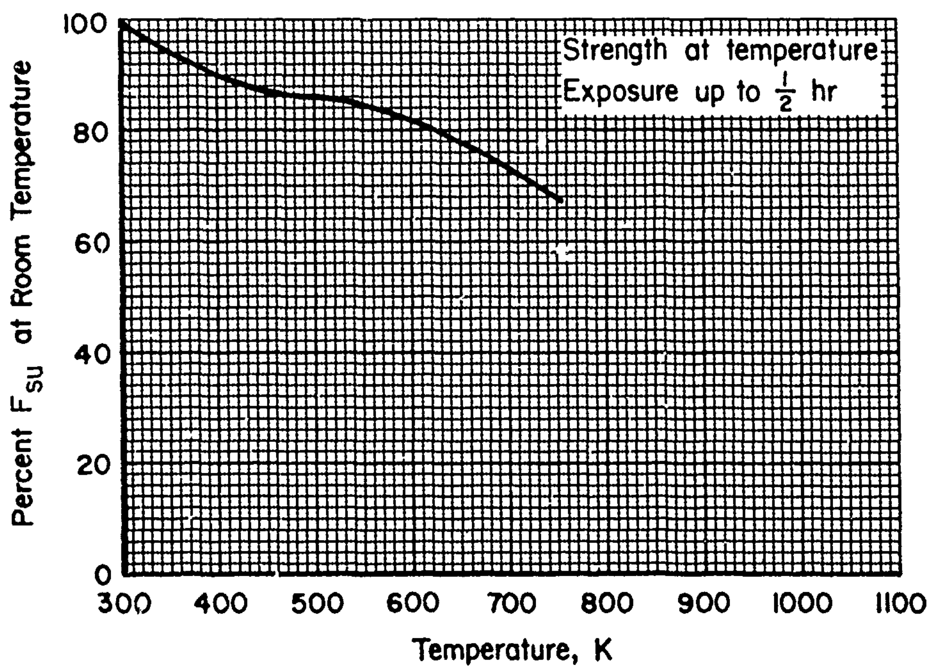


FIGURE 2.4.2.1.2(b). Effect of temperature on the ultimate shear strength (F_{su}) of 9Ni-4CO-.20C steel (plate).

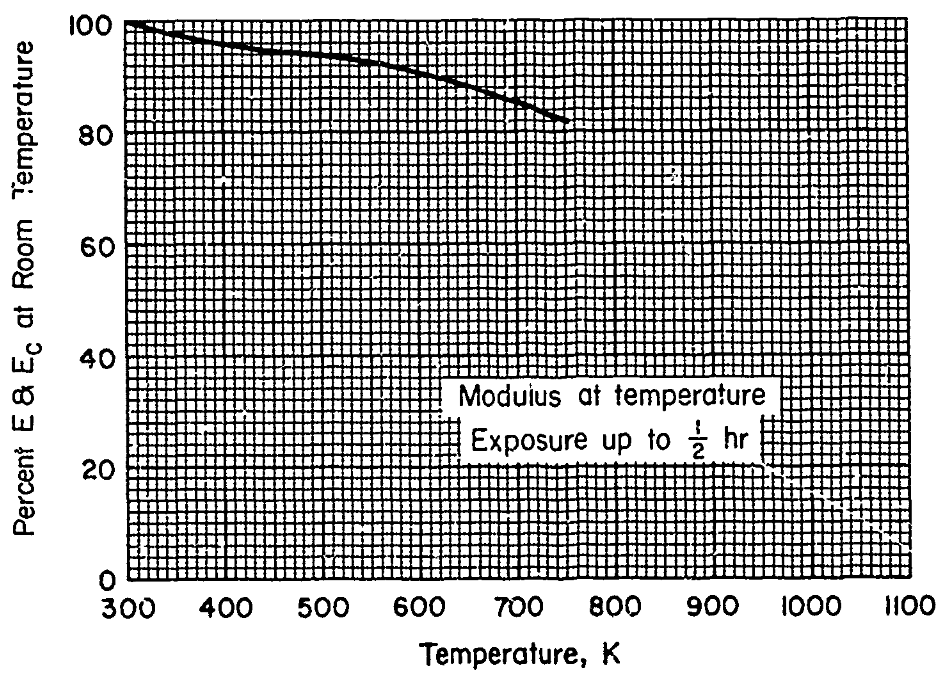


FIGURE 2.4.2.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of 9Ni-4Co-.20C steel (plate).

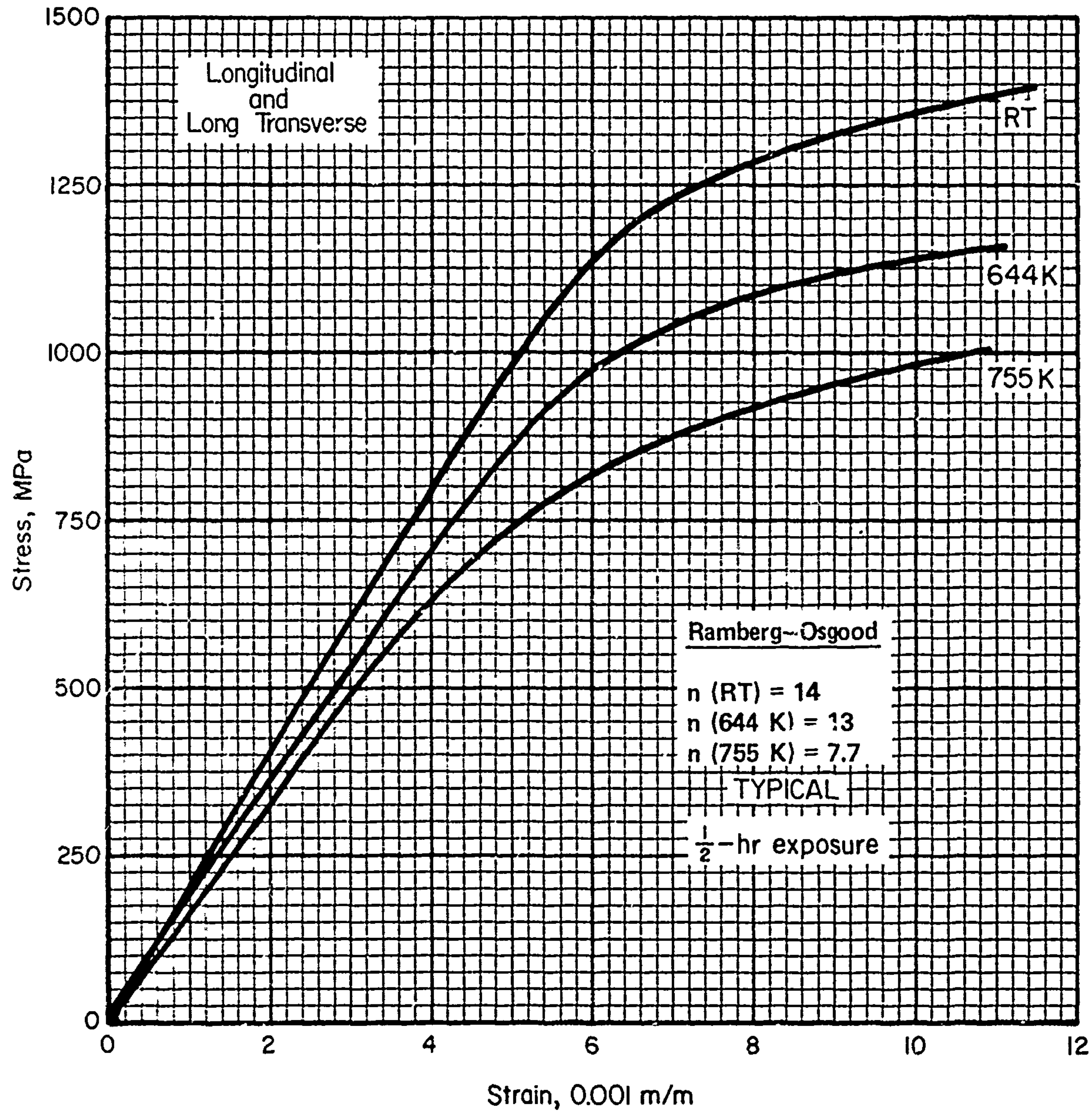


FIGURE 2.4.2.1.6(a). Typical tensile stress-strain curves for 9Ni-4Co-.20C steel (plate) at various temperatures.

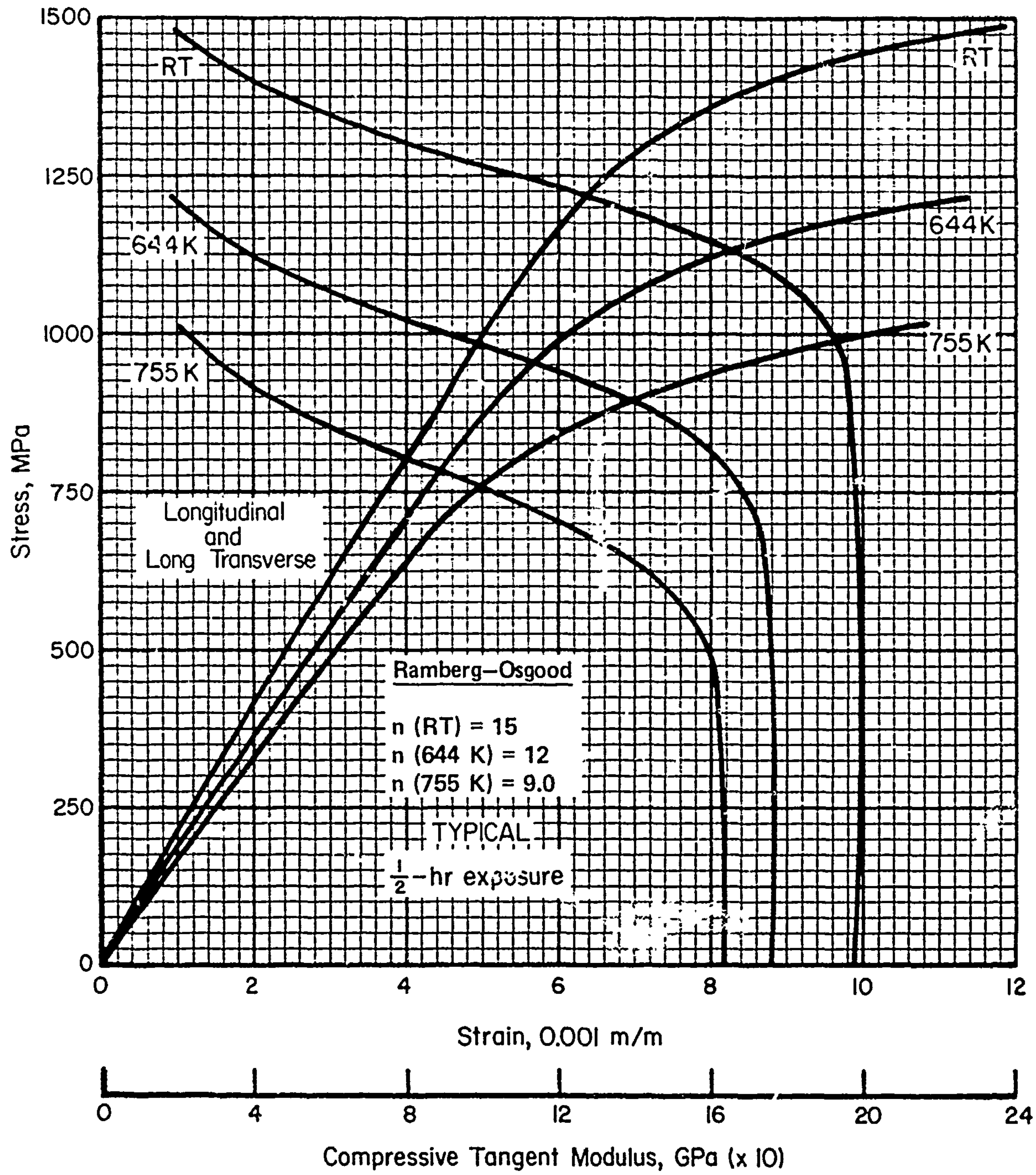


FIGURE 2.4.2.1.6(b). Typical compressive stress-strain and tangent-modulus curves for 9Ni-4Co-.20C steel (plate) at various temperatures.

2.4.3 9Ni-4Co-.30C

2.4.3.0 *Comments and Properties.* —The 9Ni-4Co-.30C alloy was developed specifically to have high hardenability and good fracture toughness when heat treated to 1520–1655 MPa ultimate tensile strength. The alloy is through hardening in section sizes up to 150 mm thick. The alloy may be exposed to temperatures up to 755 K (approximately 55 K below typical tempering temperature) without microstructural changes which degrade 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.

Materials specifications for 9Ni-4Co-.30C steel are presented in Table 2.4.3.0(a).

TABLE 2.4.3.0(a). *Material Specifications for 9Ni-4Co-.30C Steel*

Specification	Form
AMS 6524	Sheet, strip, and plate
AMS 6526	Bars, forgings, and tubing

The heat treatment for this alloy consists of normalizing at 1172±15 K for 1 hour per 25 mm of cross section, cooling in air to room temperature, heating to 1116±15 K for 1 hour per 25 mm of cross section but not less than 1 hour, quenching in oil or water, treating at 194 K for 1-2 hours, and double tempering at 797±5 K (sheet, strip, and plate) or 811±5 K (bars, forgings, and tubing) for 2 hours. The AMS specifications do not require the low temperature treatment.

Room Temperature Properties

The room temperature mechanical and physical properties are shown in Table 2.4.3.0(b).

2.4.3.1 *Heat Treated Condition.* —Effect of temperature on various mechanical properties are presented in Figures 2.4.3.1.1(a) 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-.30C STEEL

SPECIFICATION	AMS 6524		AMS 6526
FORM	SHEET, STRIP[a], AND PLATE		BARS, FORGINGS AND TUBING
CONDITION	QUENCHED AND TEMPERED		QUENCHED AND TEMPERED
THICKNESS, MM	≤6.33[b]	≥6.34[b]	≤152.40[b]
BASIS	S	S	S
MECHANICAL PROPERTIES:			
FTU, MPA:			
L	...	...	1520
LT	1520	1520	...
FTY, MPA:			
L	...	...	1310
LT	1280	1310	...
FCY, MPA:			
L	...	...	1440
LT	...	1440	...
FSU, MPA	...	945	945
FBRU[d], MPA:			
(E/D=1.5)	...	2390	2390
(E/D=2.0)	...	3030	3030
FBRY[d], MPA:			
(E/D=1.5)	...	2010	2010
(E/D=2.0)	...	2220	2220
EL, PERCENT:			
L	...	...	10
LT	6	10	...
E, GPA	196.5		
EC, GPA	205.5		
G, GPA	...		
MU	...		
PHYSICAL PROPERTIES:			
OMEGA, MG/M3	7.75		
C, J/(G*K)	...		
K, W/(M*K)	277 (297 K)		
ALPHA, 10-6 M/(M*K)	11.3 (294 TO 366 K)		

[a] TEST DIRECTION LONGITUDINAL FOR WIDTHS LESS THAN 228.6 MM; TRANSVERSE FOR WIDTHS 228.6 MM AND OVER.

[b] VALUES IN THESE COLUMNS ARE APPLICABLE ONLY WHEN THE INDICATED FTU HAS BEEN SUBSTANTIATED THROUGH ADEQUATE QUALITY CONTROL INSPECTION TESTING.

[c] THESE DESIGN ALLOWABLE PROPERTIES ARE APPLICABLE ONLY TO MATERIAL FOR WHICH THE HEAT TREATMENT PROCEDURE INCLUDES SUBZERO TREATING AT 200 K FOR 2 HOURS AFTER OIL QUENCHING. SPECIFICATION AMS 6524 DOES NOT REQUIRE SUBZERO TREATMENT.

[d] BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

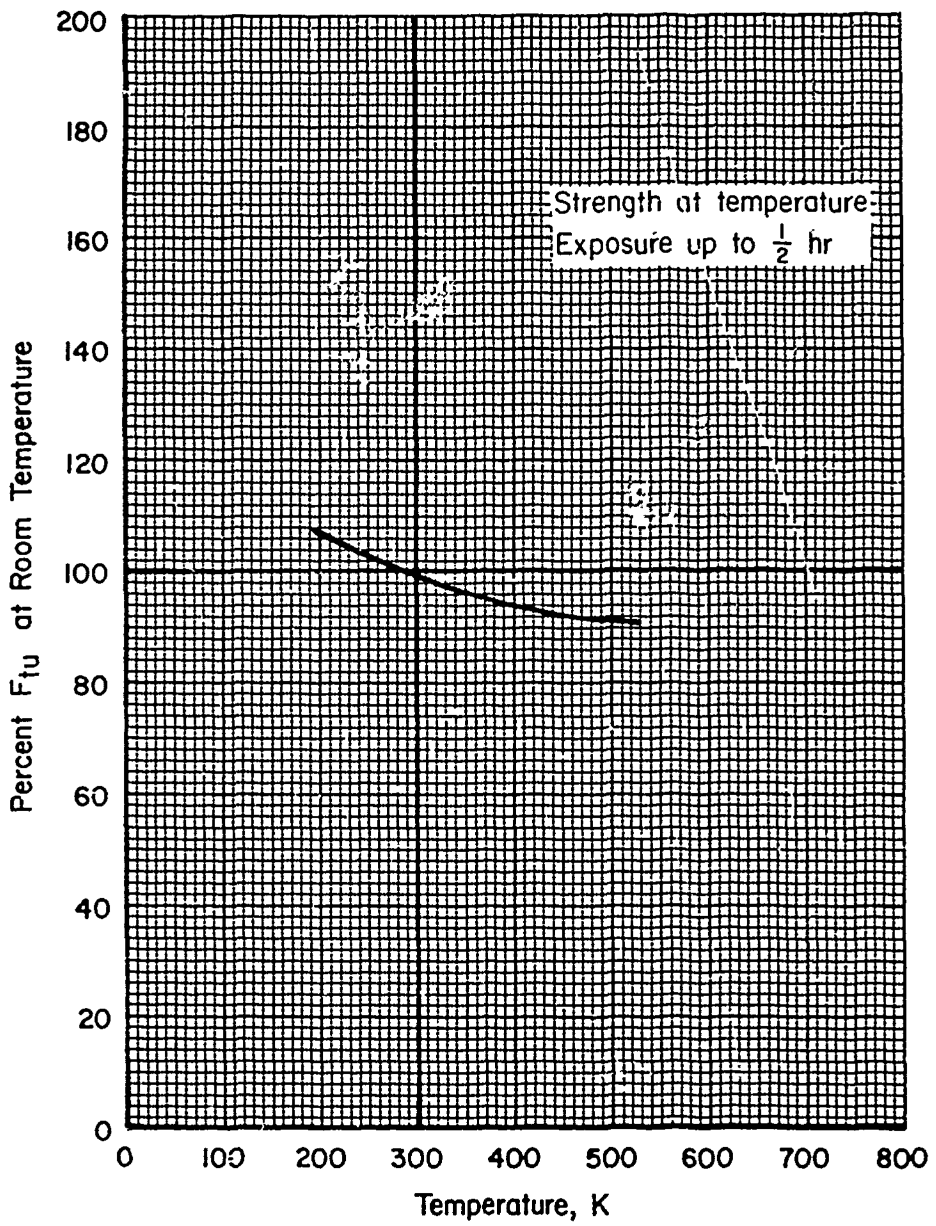


FIGURE 2.4.3.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of 9Ni-4Co-.30C steel.

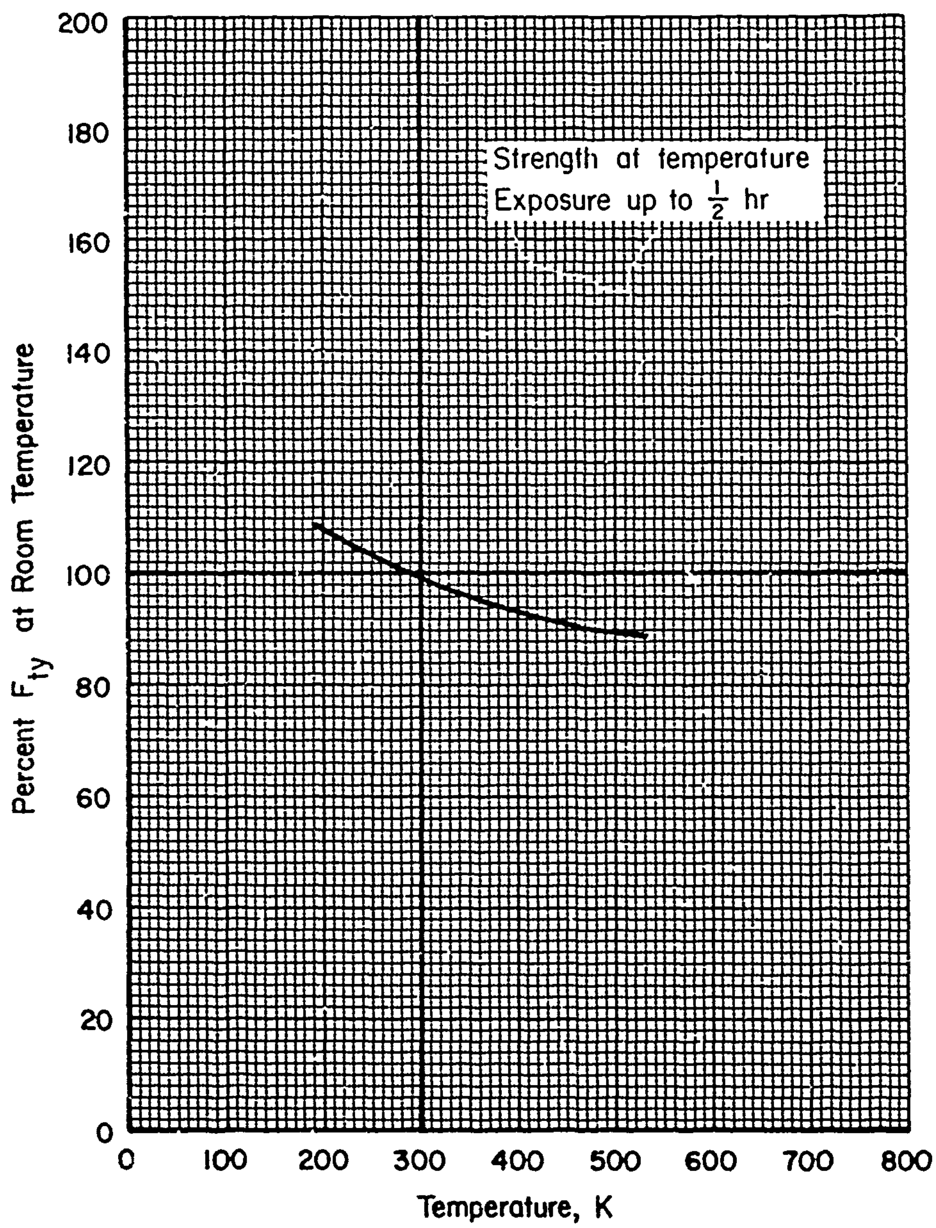


FIGURE 2.4.3.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of 9Ni-4Co-.30C steel.

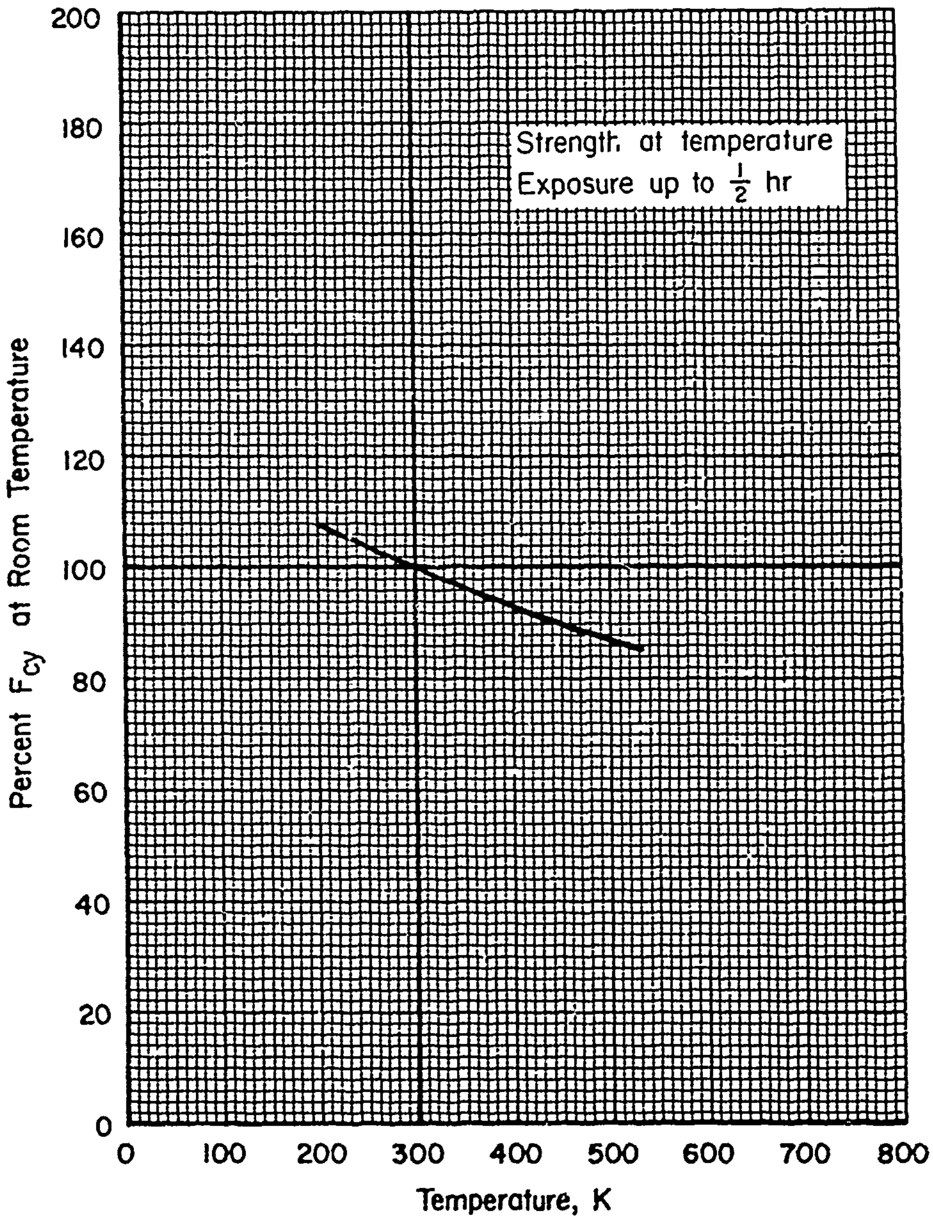


FIGURE 2.4.3.1.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of 9Ni-4Co-.30C steel.

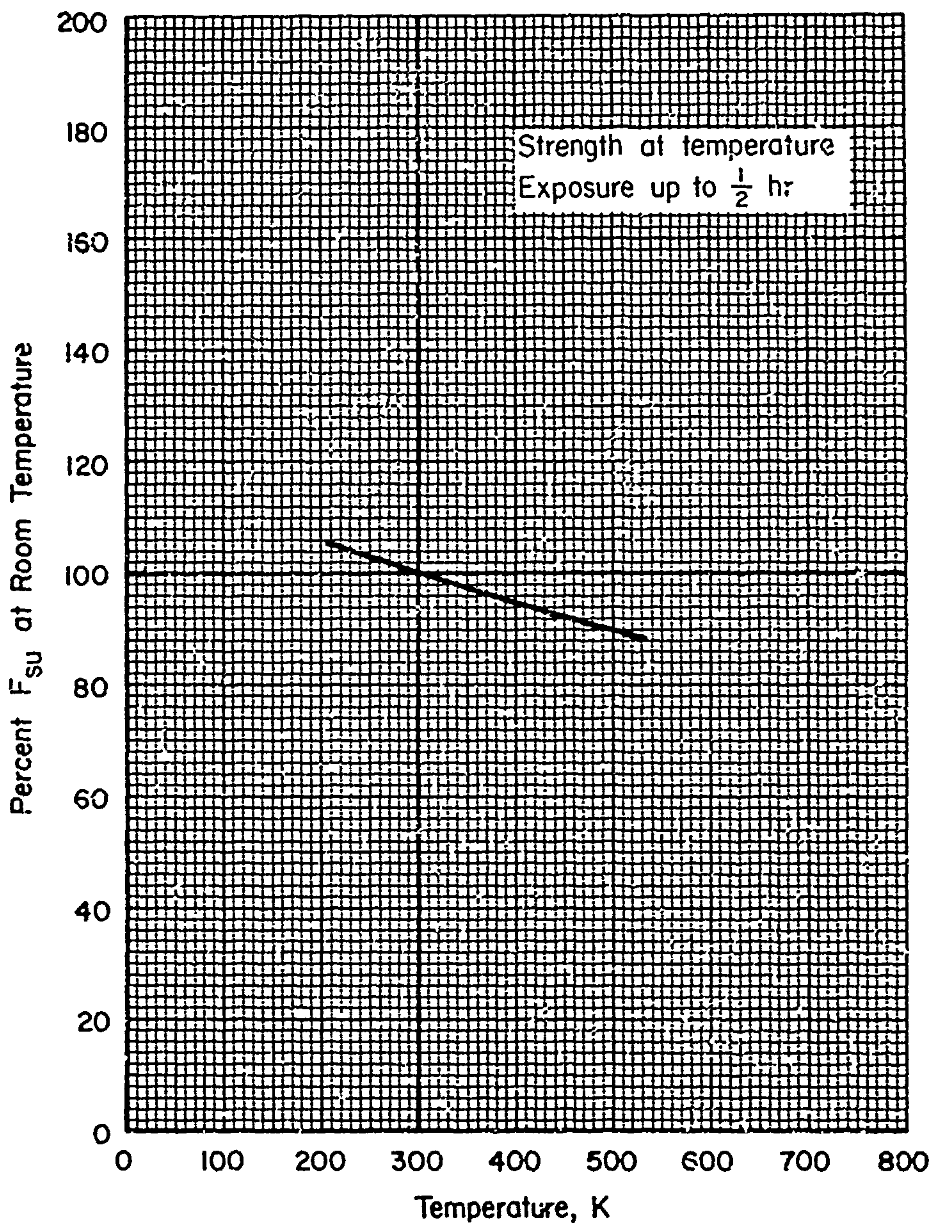


FIGURE 2.4.3.1.2(b). Effect of temperature on the ultimate shear strength (F_{su}) of 9Ni-4Co-.30C steel.

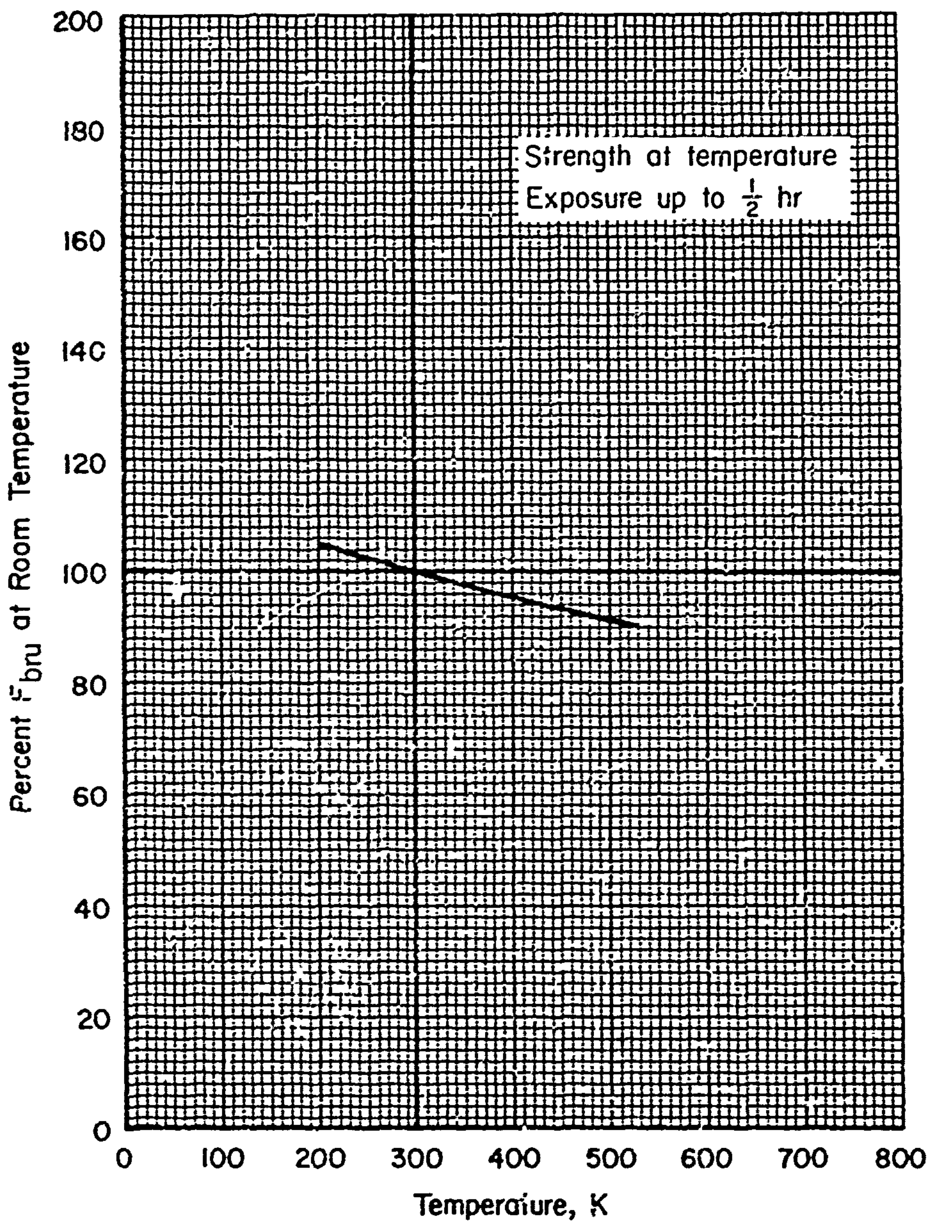


FIGURE 2.4.3.1.3(a). Effect of temperature on the ultimate bearing strength (F_{bru}) of 9Ni-4Co-.30C steel.

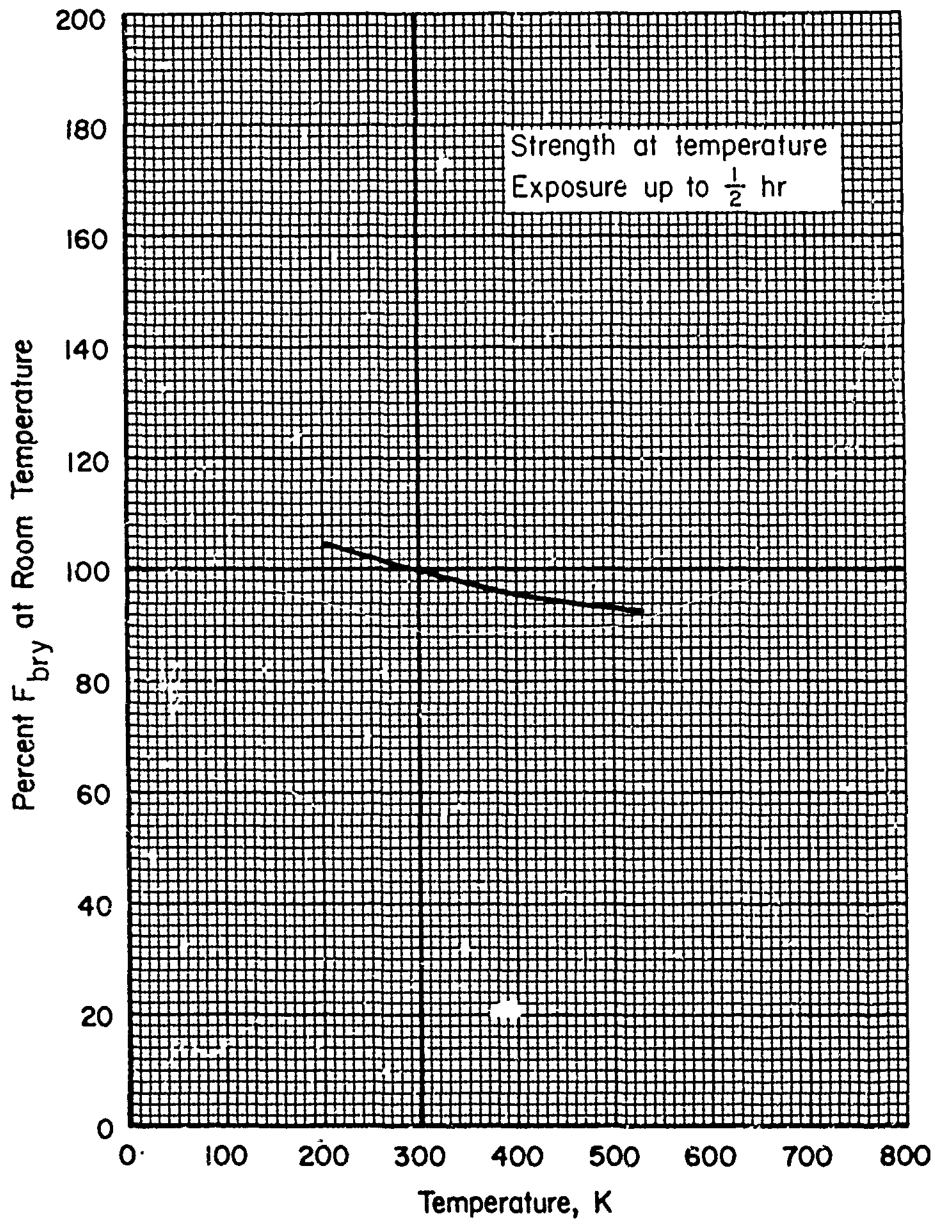


FIGURE 2.4.3.1.3(b). Effect of temperature on the bearing yield strength (F_{bry}) of 9Ni-4Co-.30C steel.

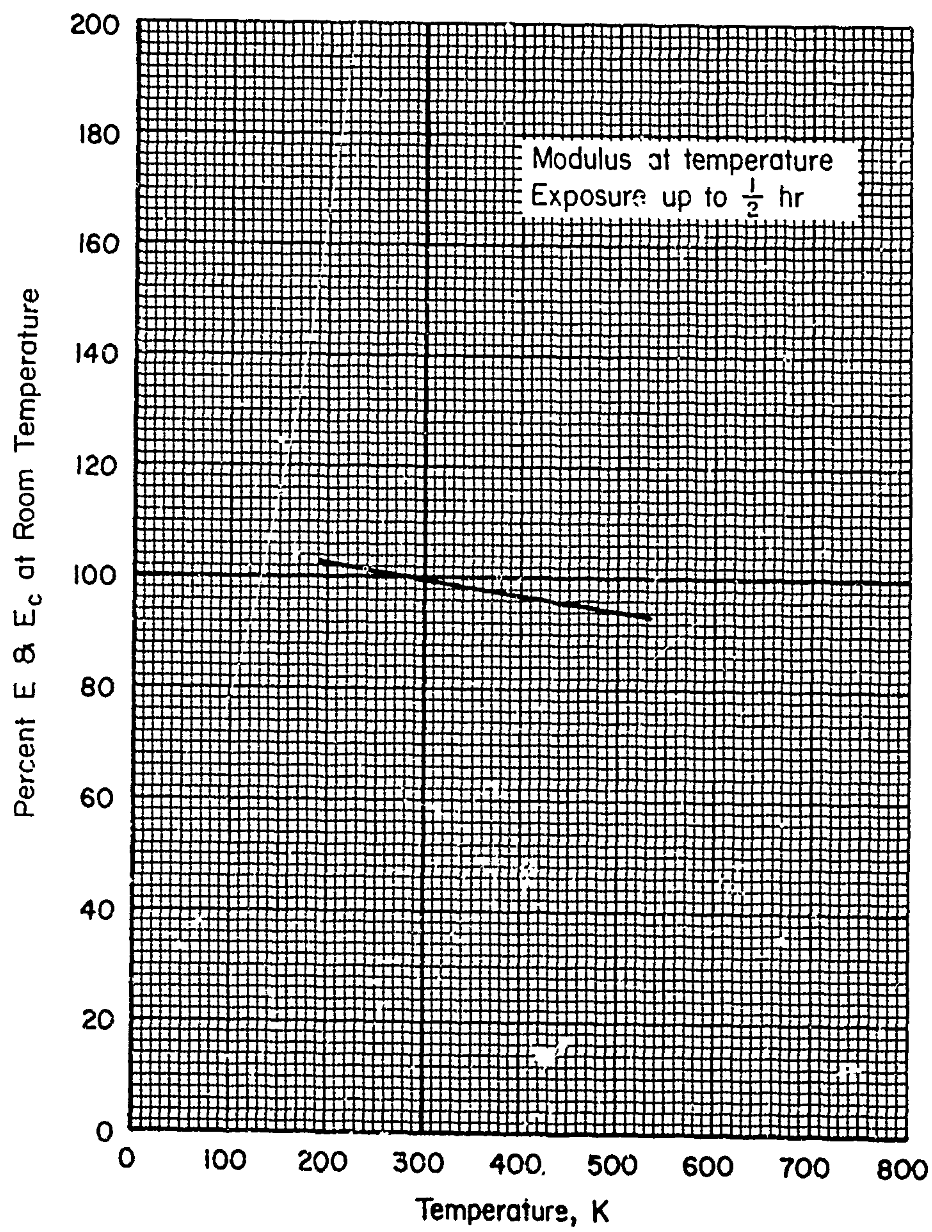


FIGURE 2.4.3.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of 9Ni-4Co-.30C steel.

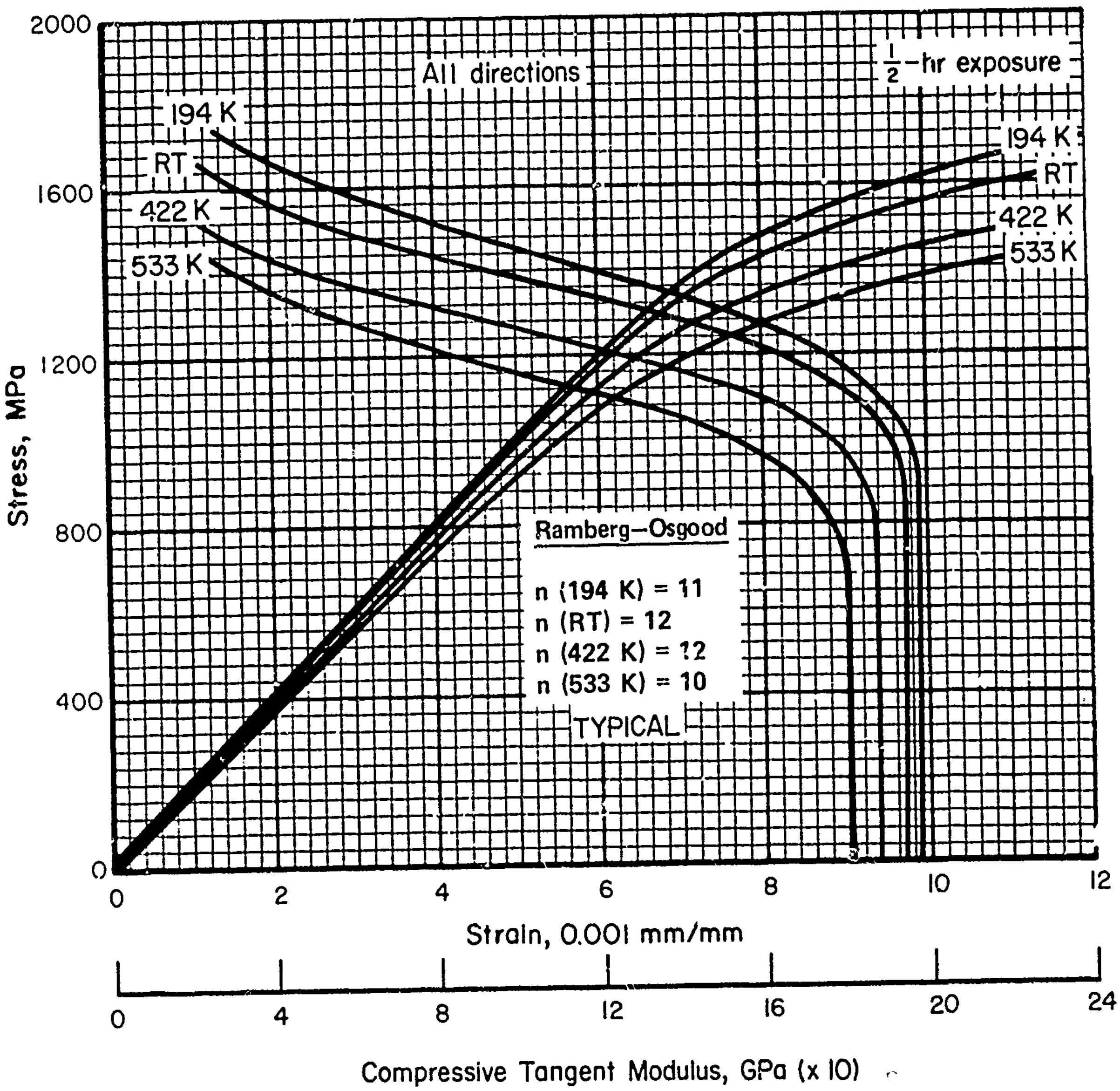


FIGURE 2.4.3.1.6(a). Typical compressive stress-strain and tangent-modulus 9Ni-4Co-.30C steel (billet) at various temperatures.

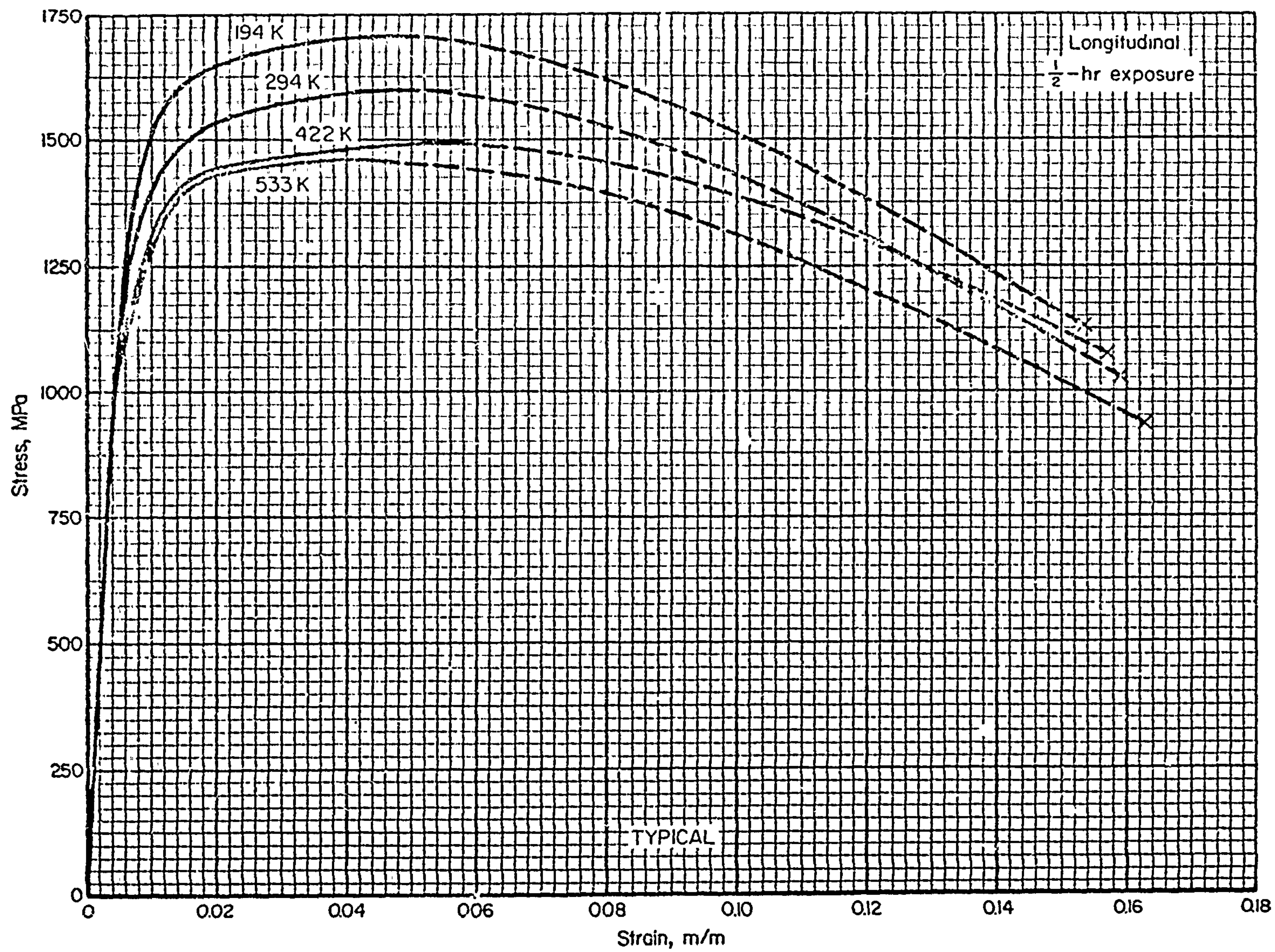


FIGURE 2.4.3.1.6(b). Typical full range tensile stress-strain curves for 9Ni-4Co-.30C (billet) at various temperatures.

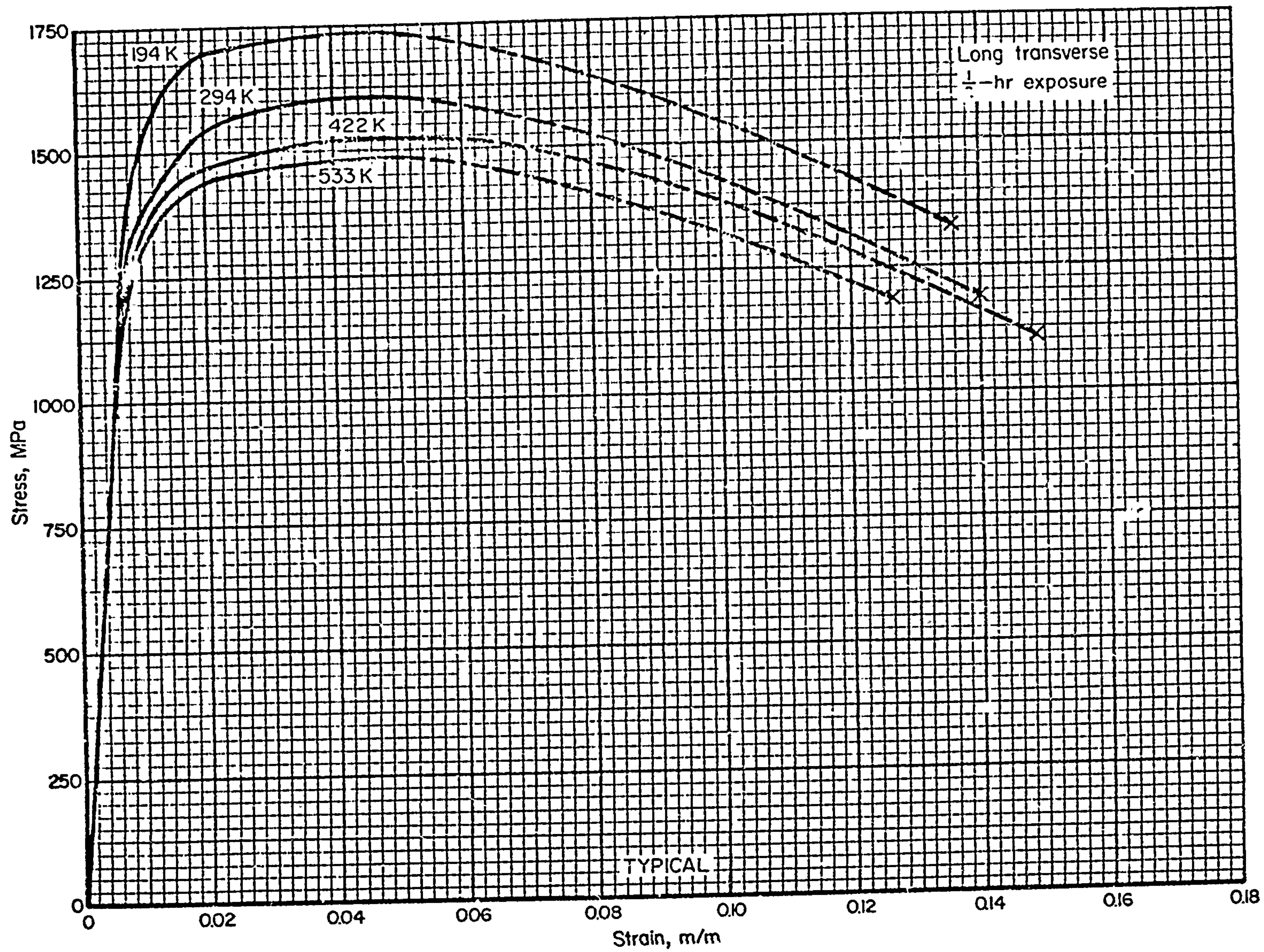


FIGURE 2.4.3.1.6(c) Typical full range tensile stress-strain curves for 9Ni-4Co-.30C (billet) at various temperatures.

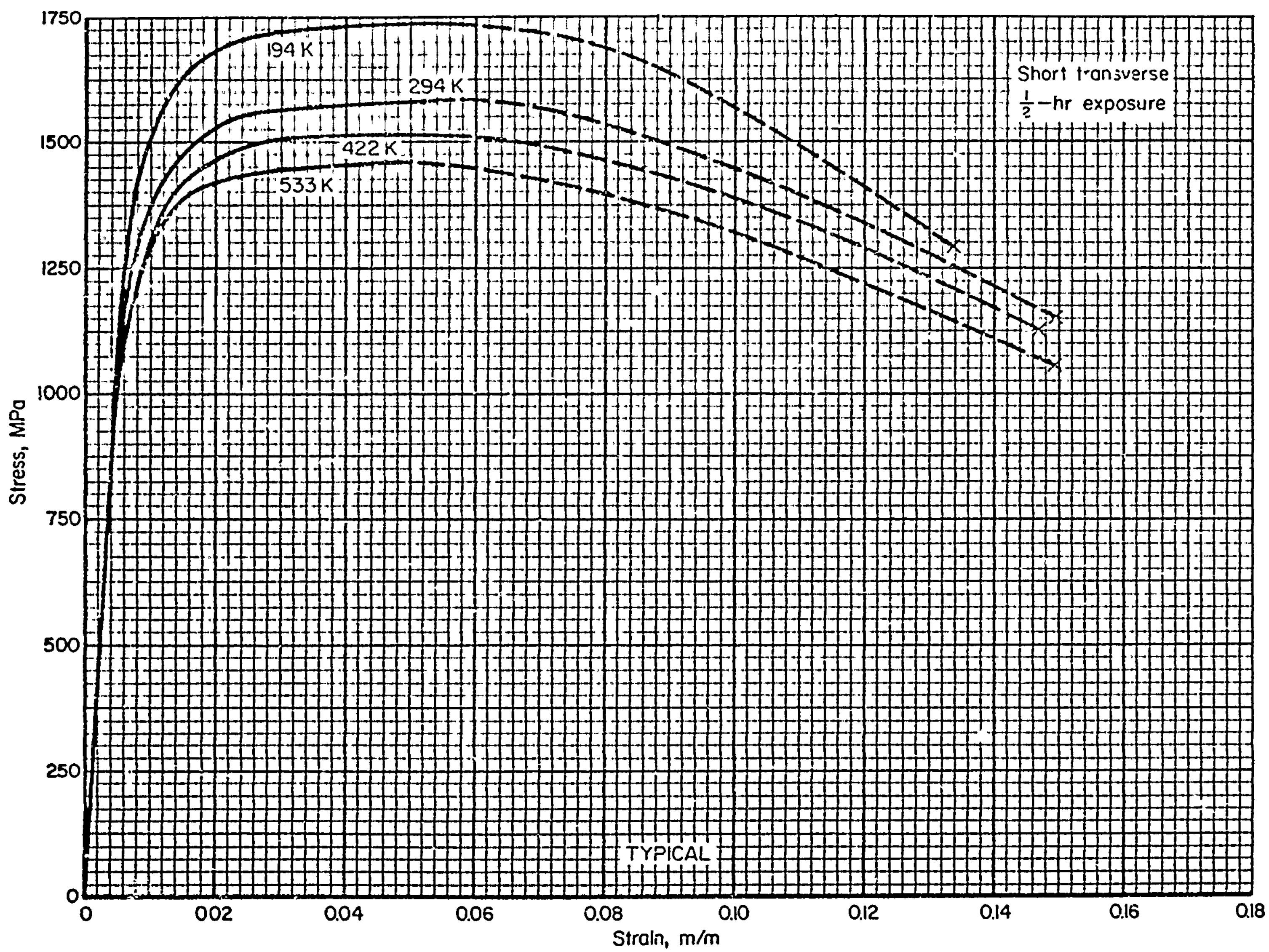


FIGURE 2.4.3.1.6(d). Typical full range tensile stress-strain curves for 9Ni-4Co0.30C (billet) at various temperatures.

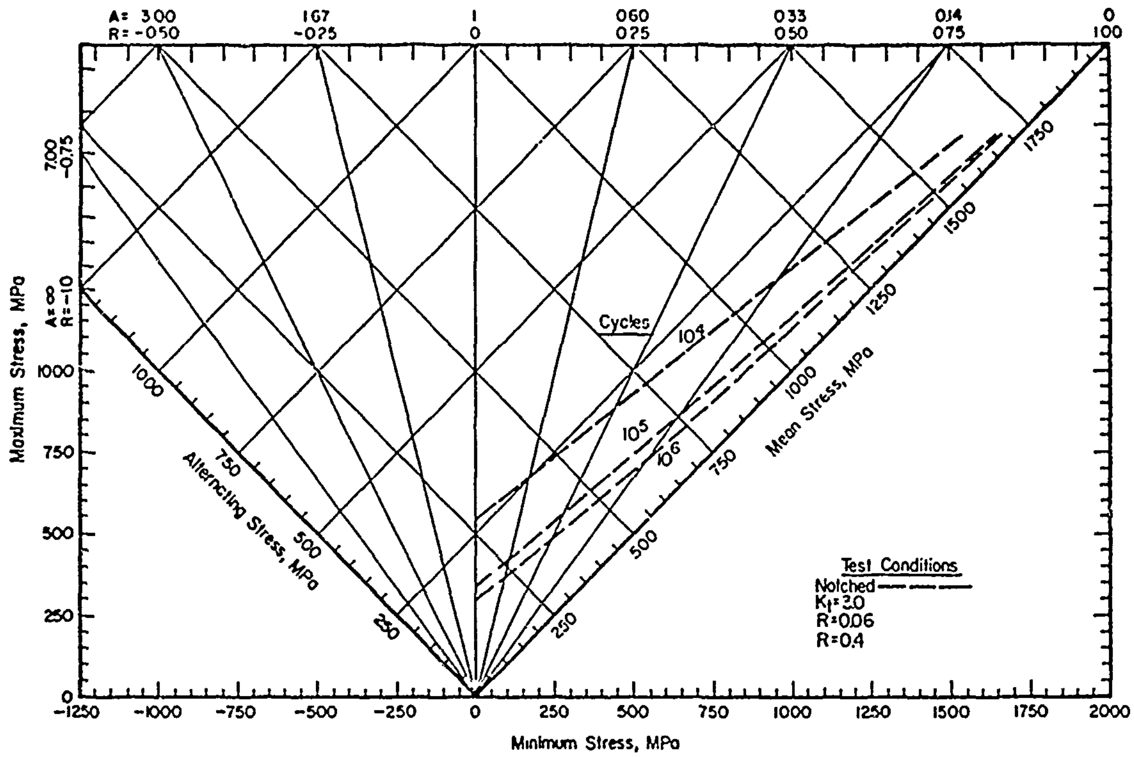


FIGURE 2.4.3.1.8. Typical constant-life fatigue diagram for notched 9Ni-4Co-.30 C steel (billet) at room temperature

Correlative Information for Figure 2.4.3.1.8

Product Form: 76 x 229 mm forged billet

Properties:

TUS, MPa	TYS, MPa	Temperature, K
1590	1360	RT (Unnotched)
2440	—	RT (Notched)

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

Specimen Details:

Notched, V-Groove $K_t = 3.0$
8.99 mm gross diameter
6.35 mm net diameter
0.25 mm root radius
60° flank angle, ω

Surface Condition: Not specified.

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. Typical of the high alloy steels is the 18 Ni maraging steels.

2.5.0.1 *Metallurgical Considerations.* —The 18 Ni maraging steels are iron base alloys with nominally 18% nickel, 7-9% cobalt, 3-5% molybdenum, less than 1% titanium, and very low carbon content, below 0.03%. 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 low temperature, 900 F.

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 755 K for 3 hours. 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. Only the consumable electrode-vacuum-melted quality grades are considered in this section. The applicable material specifications for these steels are shown in Table 2.5.1.0(a).

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

Grade	Specification	Form
250	AMS 6512	Bar
280 (300)	AMS 6514	Bar

The two alloys are available in the form of sheet, plate, bar, and die forgings although only bar is covered 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 machineability 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 755 K 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.

Room Temperature Properties

The room temperature properties for material aged at 755 K are shown in Table 2.5.1.0(b) and the effect of temperature on physical properties is shown in Figure 2.5.1.0.

2.5.1.1 *Maraged Condition* (aged at 755 K).— Effect of temperature curves for 250 and 280 grade maraging steels are presented in Figures 2.5.1.1.1(a) 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 AND 280 MARAGING STEEL (BAR)

ALLOY	250		280	
SPECIFICATION	AMS 6512		AMS 6514	
FORM	BAR		BAR	
CONDITION	MARAGED AT 900 F		MARAGED AT 900 F	
THICKNESS, MM	≤254.00		≤254.00	
BASIS	A	B	A	B
MECHANICAL PROPERTIES:				
FTU, MPA:				
L	1680	1710	1850	1920
T	1680	1710	1850	1920
FTY, MPA:				
L	1630	1670	1790	1850
T	1630	1670	1790	1850
FCY, MPA:				
L	1630	1670	1790	1850
T	1630	1670	1790	1850
FSU, MPA	993	1010	1100	1140
FBRU, MPA:				
(E/D=1.5)	...	...	...	...
(E/D=2.0)	...	...	...	...
FBRY, MPA:				
(E/D=1.5)	...	...	...	...
(E/D=2.0)	...	...	...	...
EL, PERCENT:				
L	3	...	2	...
T	3	...	2	...
E, GPA	182.7		182.7	
EC, GPA:				
L	194.4		197.2	
T	202.7		204.1	
G, GPA	...		...	
MU	0.31		0.31	
PHYSICAL PROPERTIES:				
OMEGA, MG/M3	7.92			
C, J/(G*K)	SEE FIGURE 2.5.1.0			
K, W/(M*K)	SEE FIGURE 2.5.1.0			
ALPHA, 10-6 M/(M*K)	SEE FIGURE 2.5.1.0			

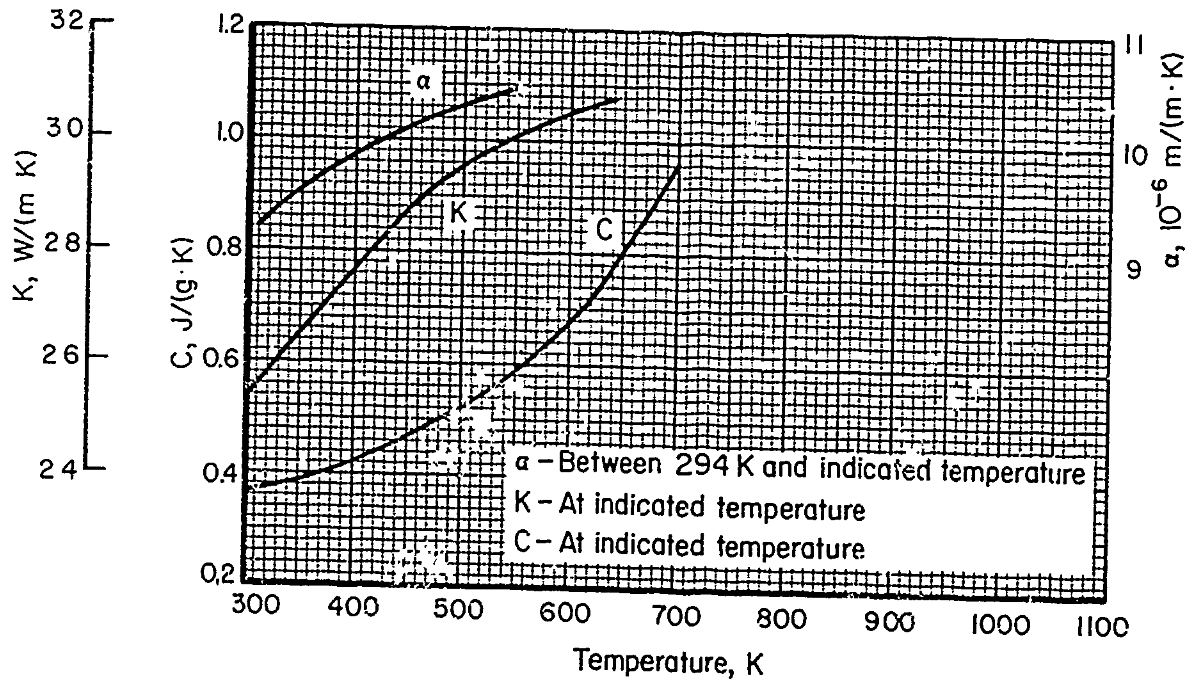


FIGURE 2.5.1.0. Effect of temperature on the physical properties of 250 and 280 maraging steel.

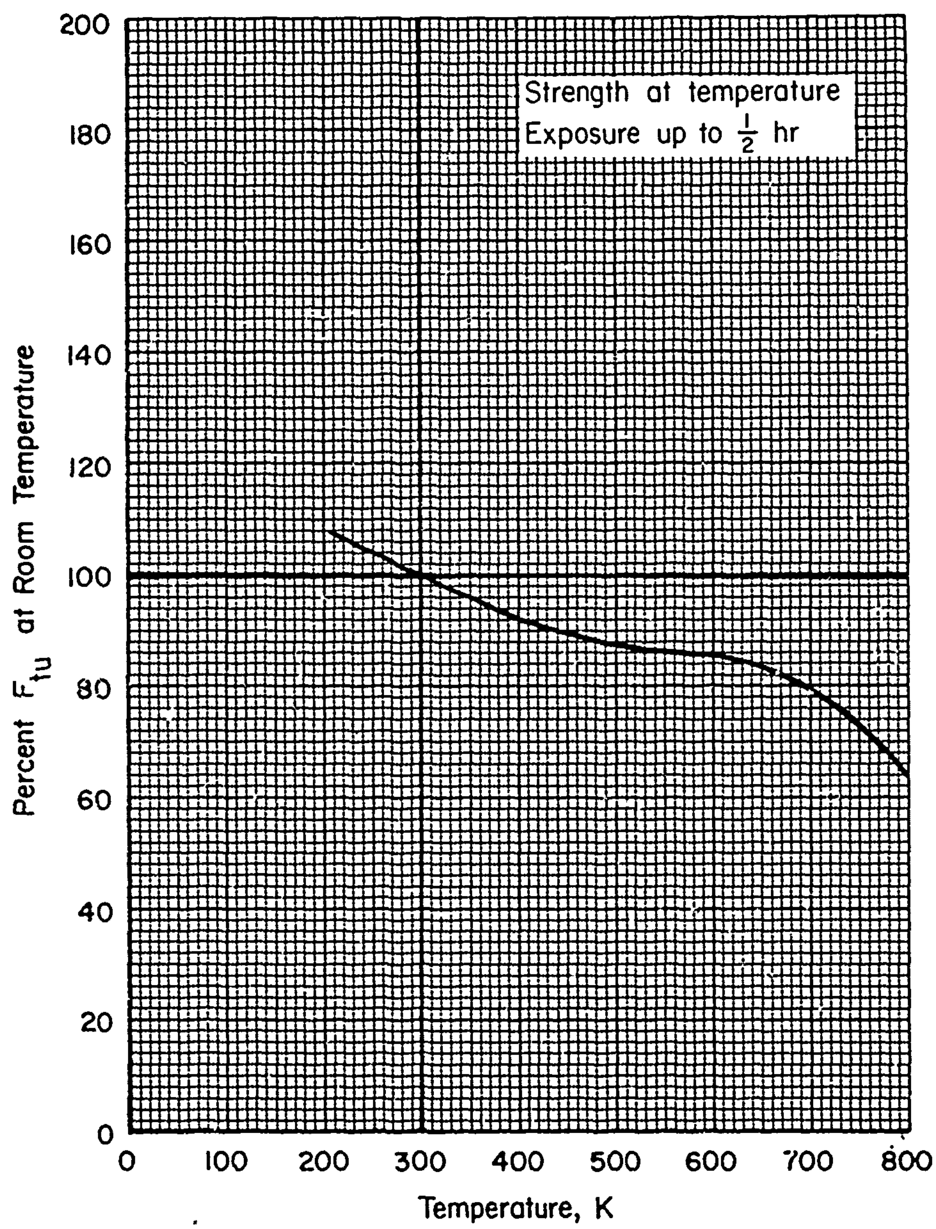


FIGURE 2.5.1.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of 250 and 280 maraging steel.

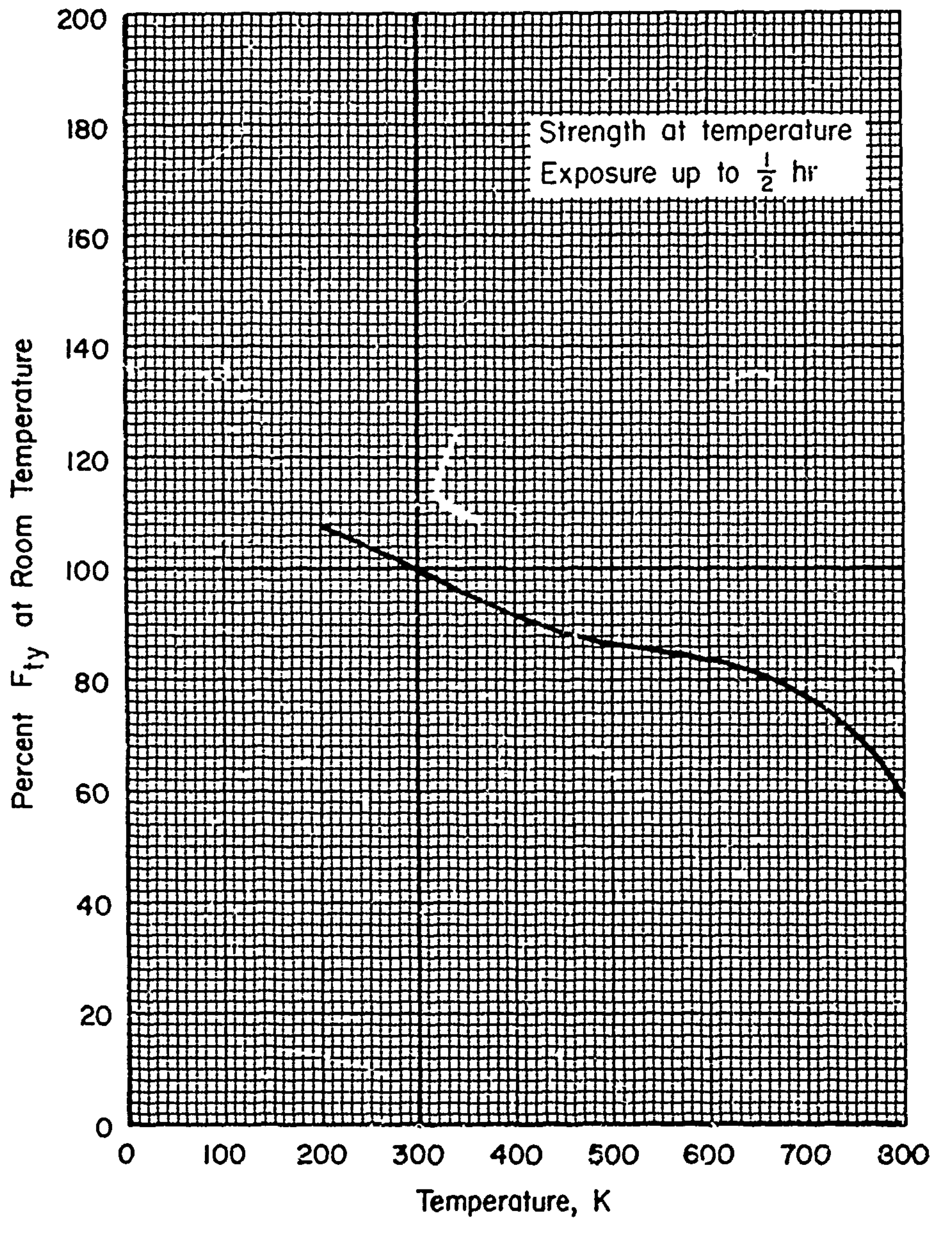


FIGURE 2.5.1.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of 250 and 280 maraging steel.

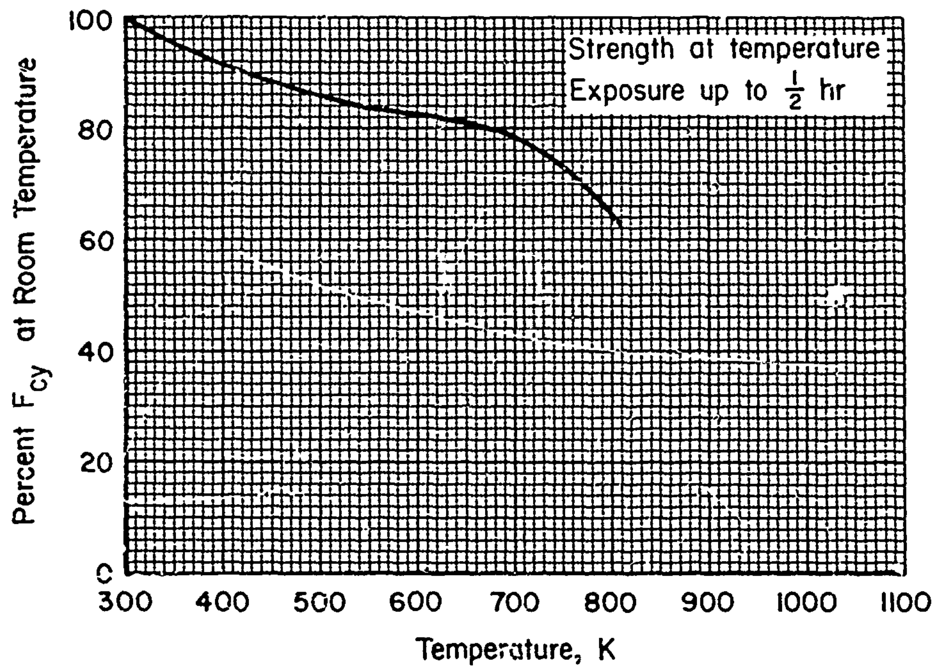


FIGURE 2.5.1.1.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of 250 and 280 maraging steel.

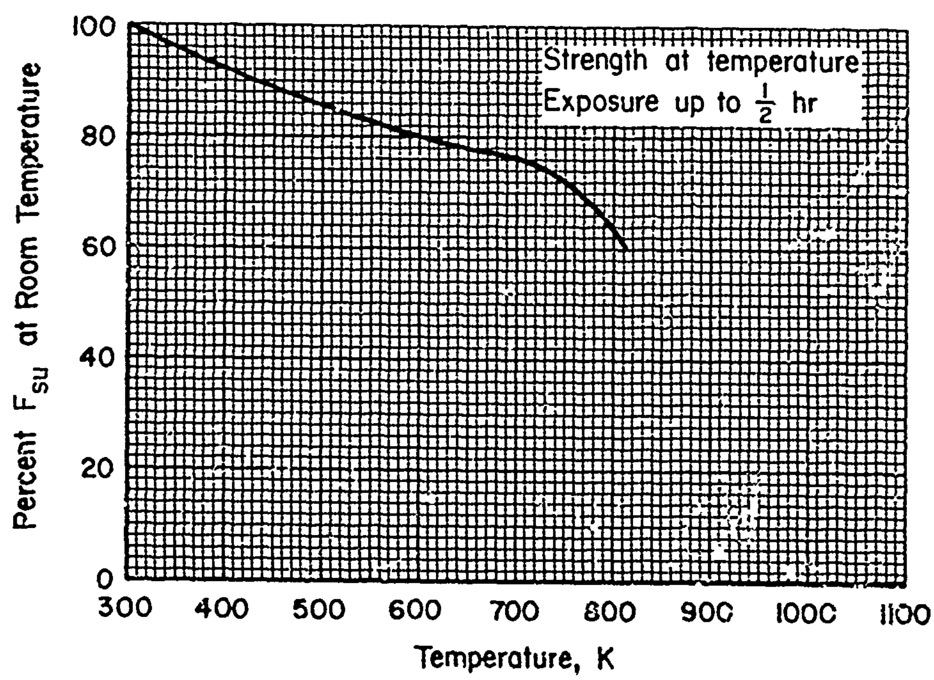


FIGURE 2.5.1.1.2(b). Effect of temperature on the ultimate shear strength (F_{su}) of 250 and 280 maraging steel.

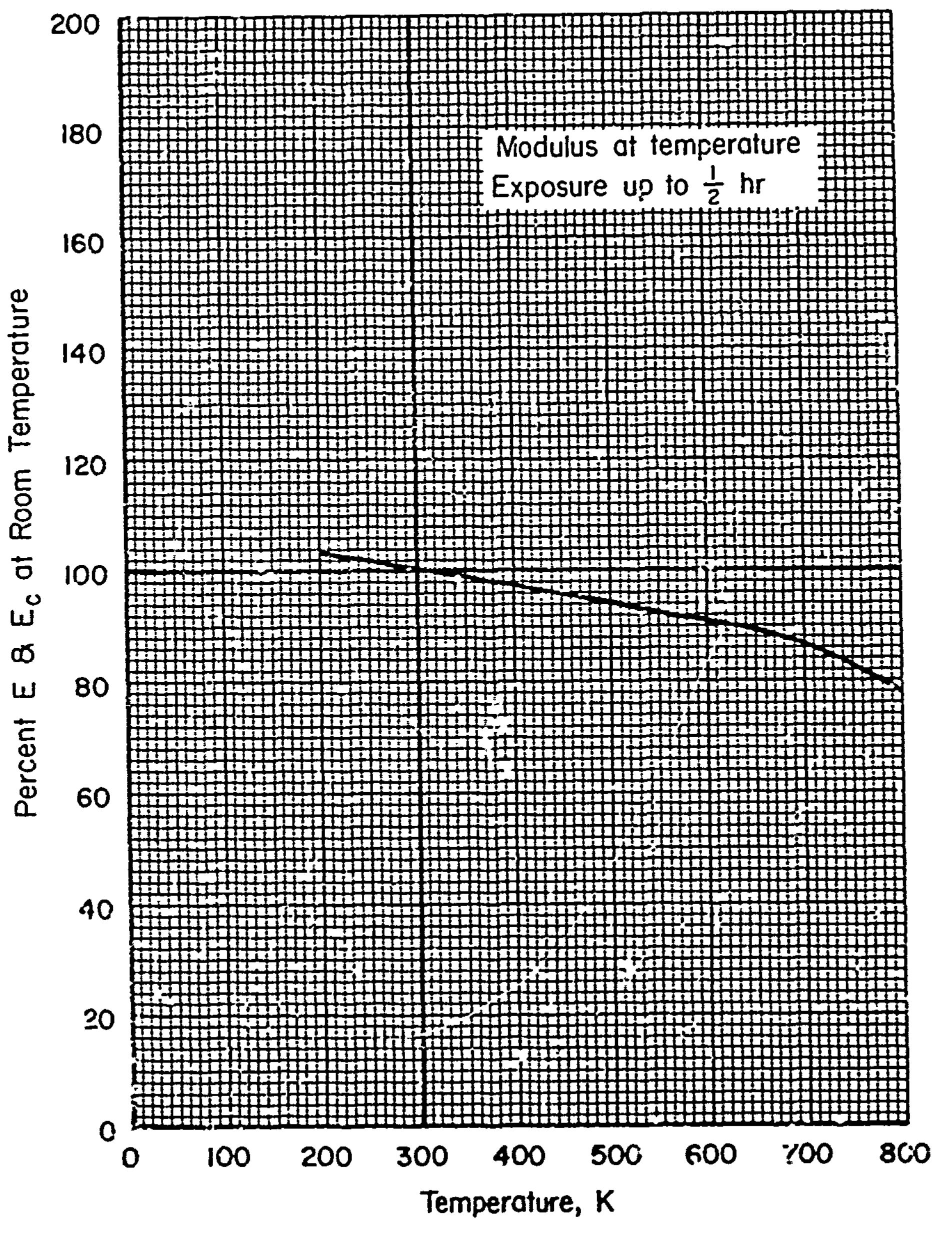


FIGURE 2.5.1.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of 250 and 280 maraging steel.

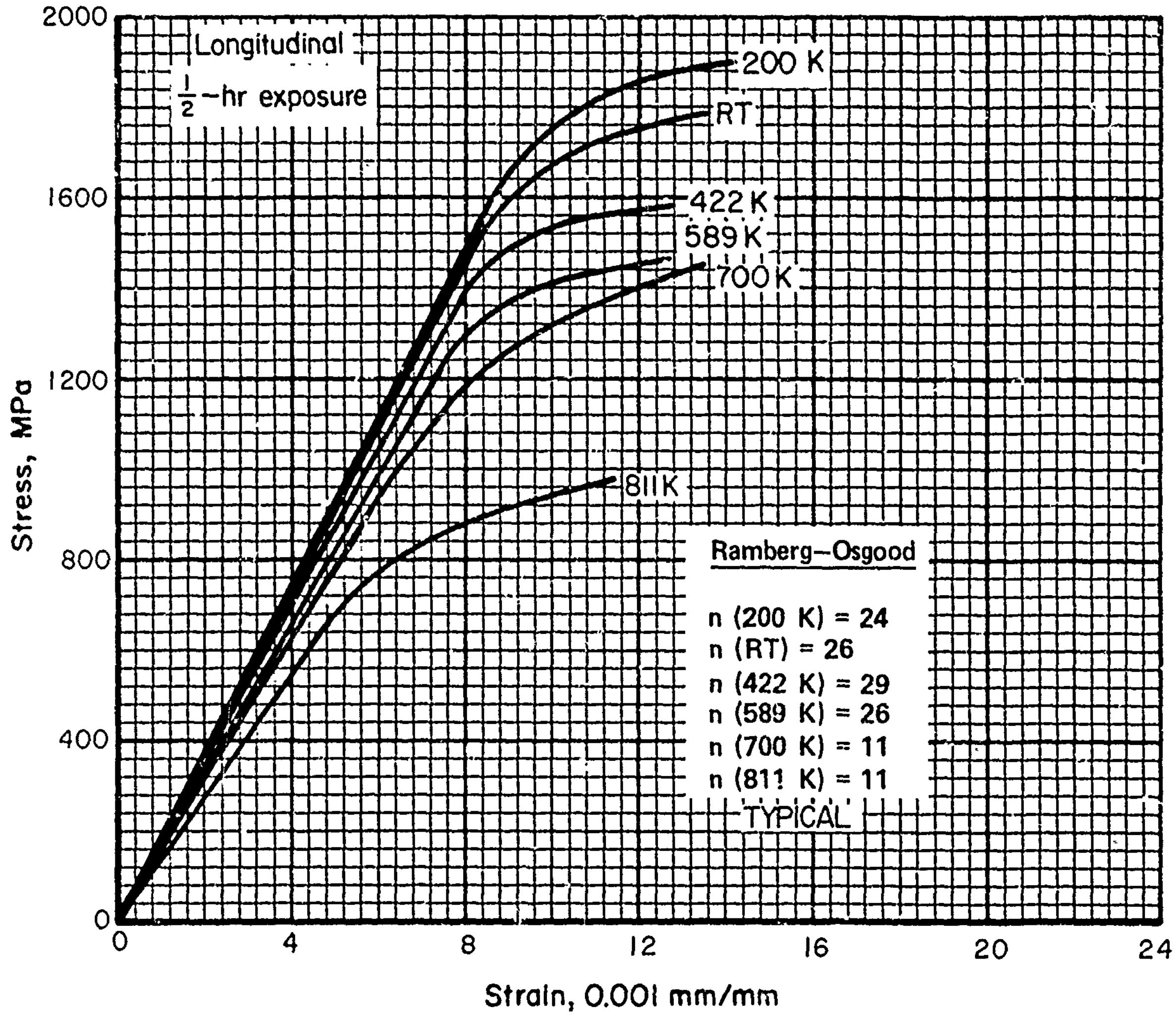


FIGURE 2.5.1.1.6(a). Typical tensile stress-strain curves at room and elevated temperatures for 250 maraging steel (bar).

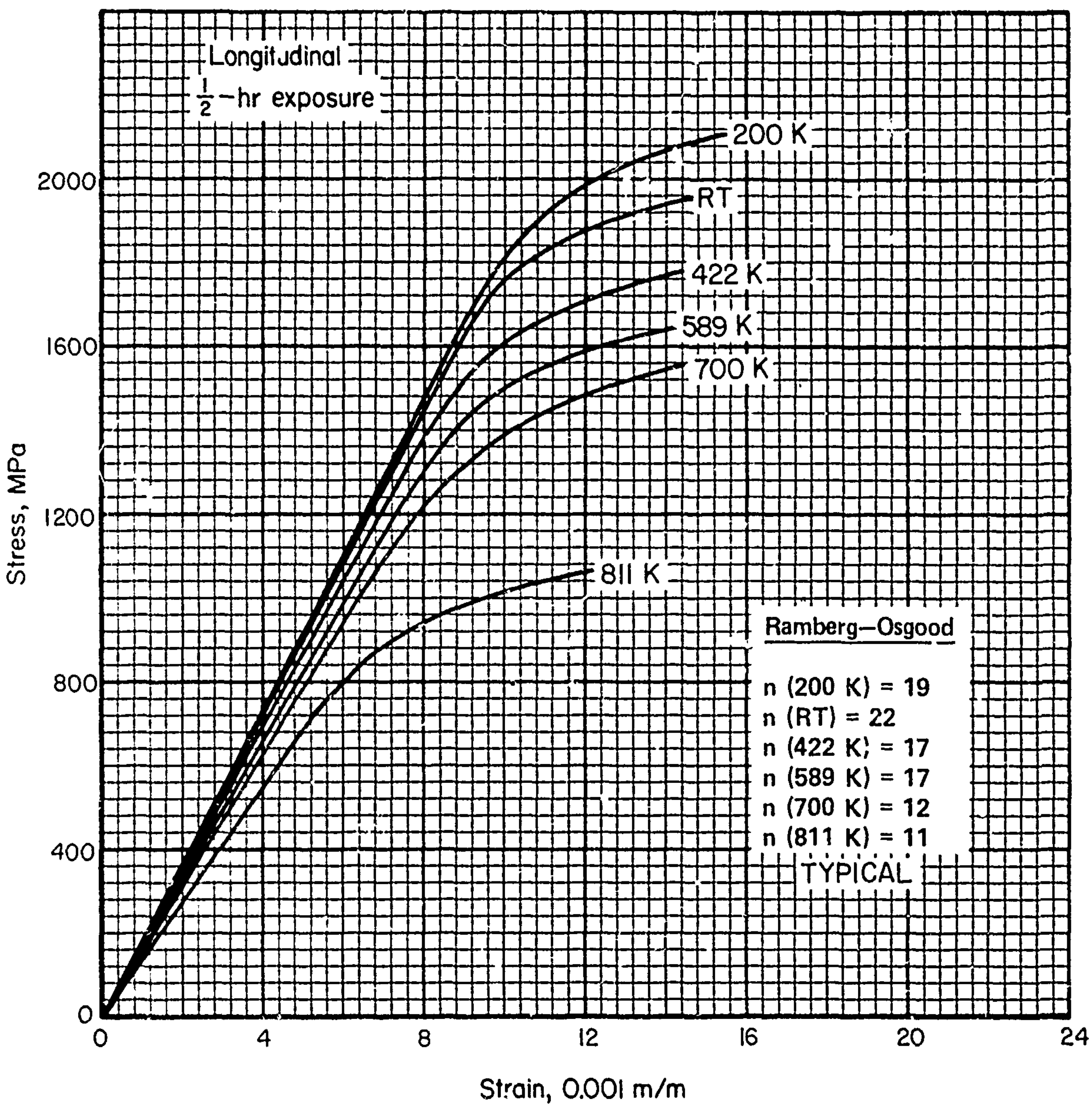


FIGURE 2.5.1.1.6(b). Typical tensile stress-strain curves at room and elevated temperatures for 280 maraging steel (bar).

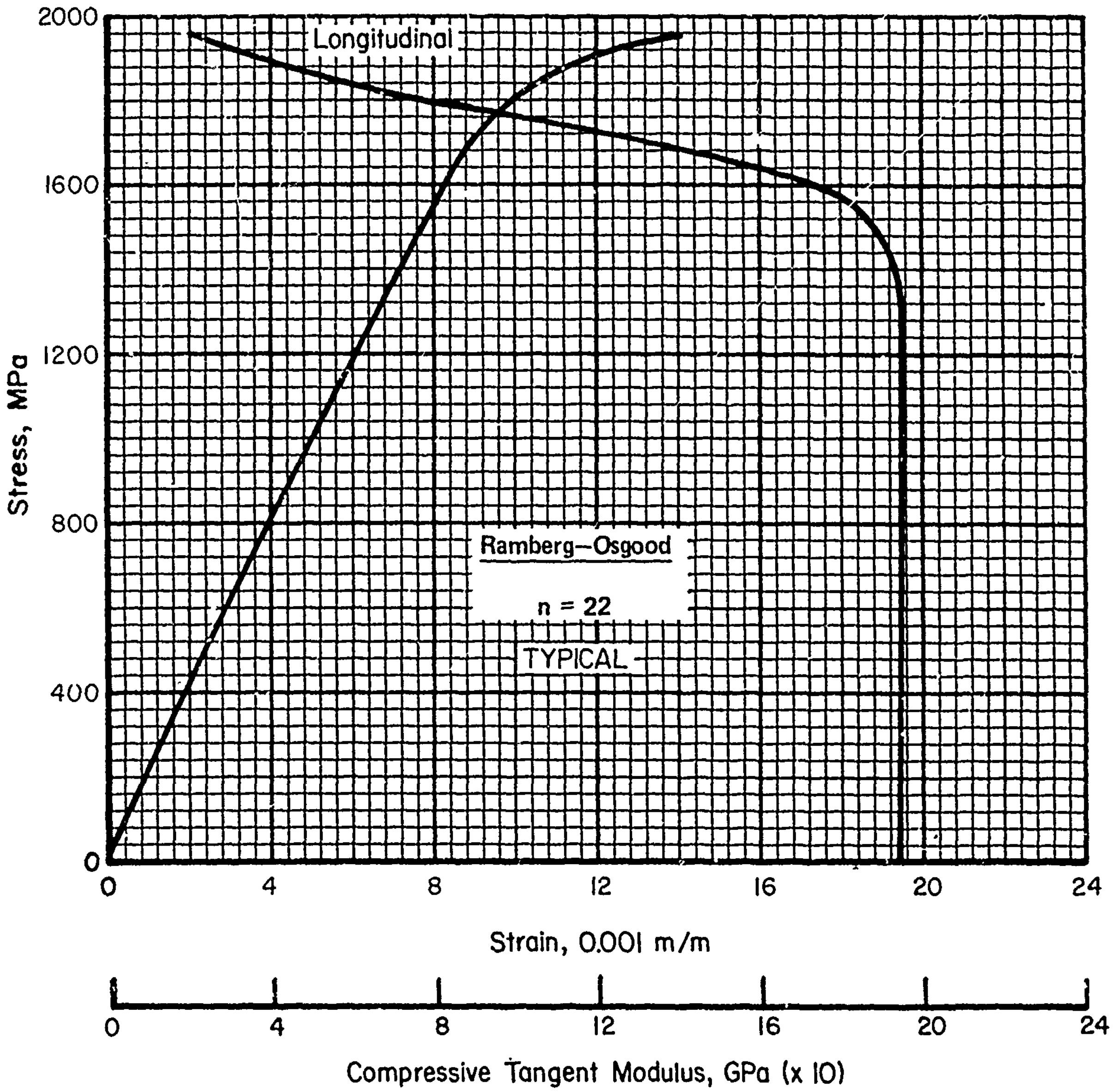


FIGURE 2.5.1.1.6(c). Typical compressive stress-strain and tangent-modulus curves for 250 maraging steel (bar) at room temperature.

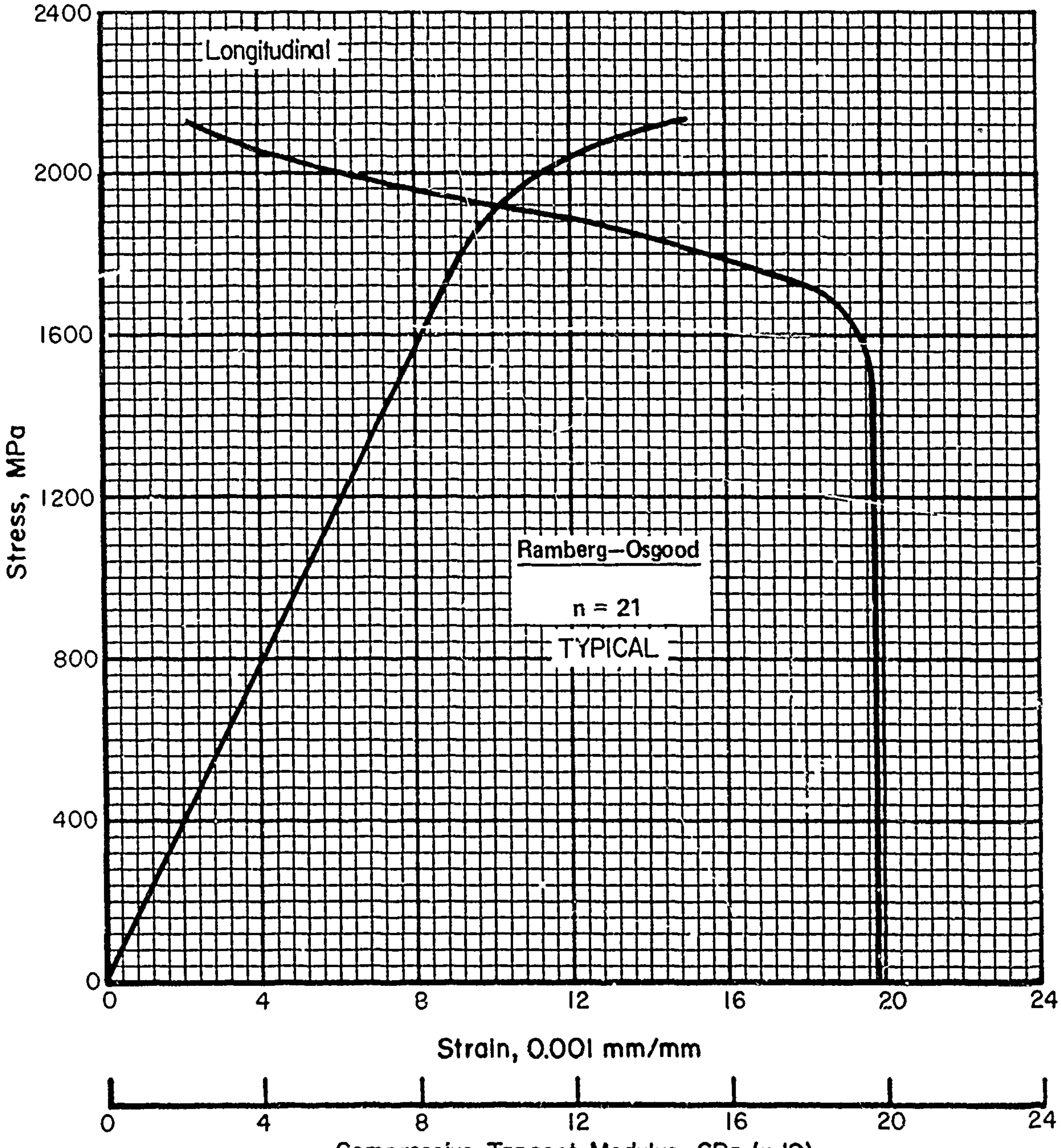


FIGURE 2.5.1.1.6(d). Typical compressive stress-strain and tangent-modulus curves for 280 maraging steel (bar) at room temperature.

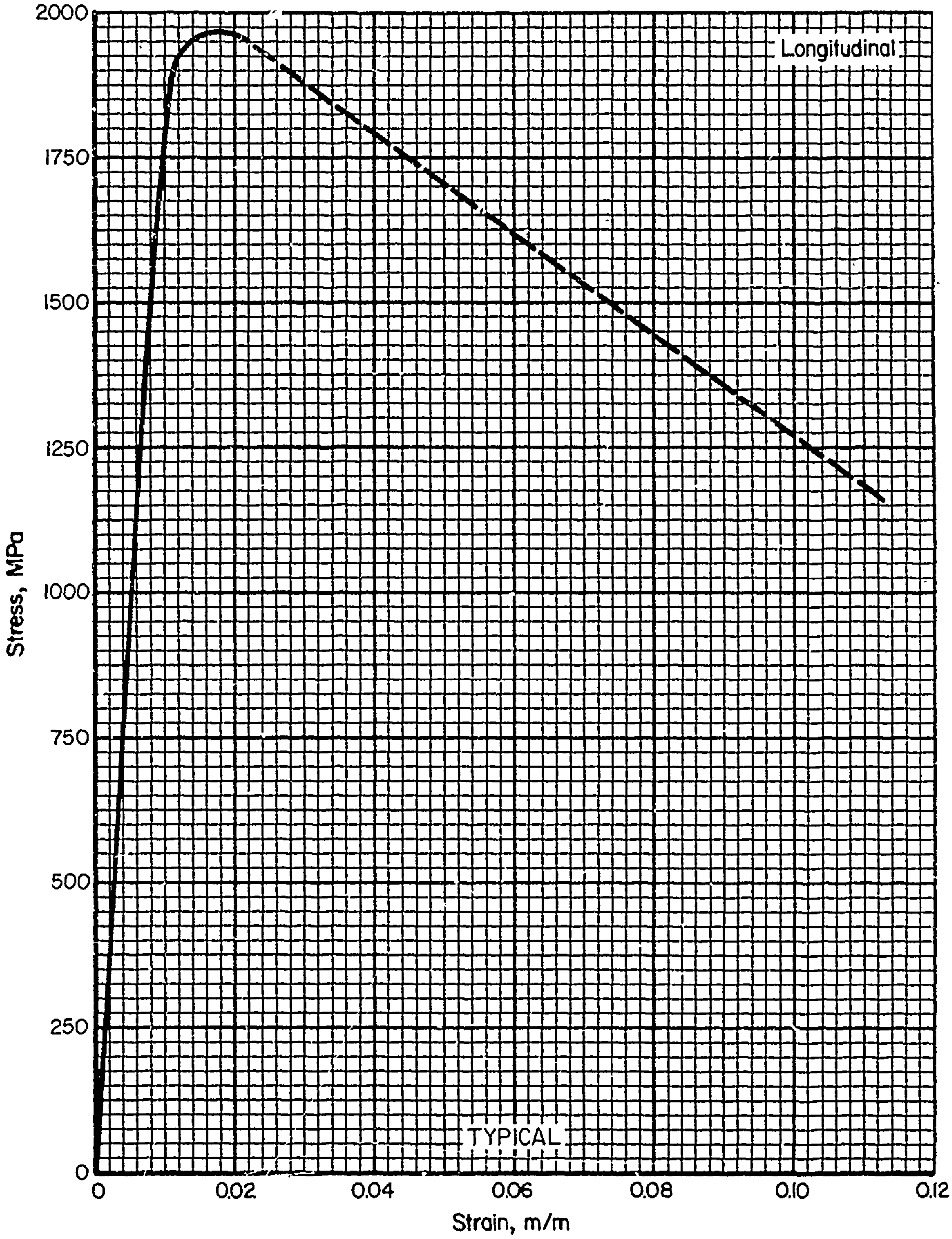


FIGURE 2.5.1.1.6(e). Typical tensile stress-strain curve (full range) for 280 maraging steel (bar) at room temperature.

2.6 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 m/m occurs during the transformation from the austenitic to the martensitic condition; during aging, a contraction of about 0.0005 metre per metre 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 acid pickling operations.

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

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 589 K and below the tempering range may cause further hardening, with possible decrease in ductility. Prolonged exposures in or above the tempering range result in loss of strength due to overtempering, overaging, or reaustenitizing.

2.6.1 AM-350

2.6.1.0 *Comments and Properties.*—AM-350 has high strength up to 700 K and good oxidation resistance up to about 811 K. The alloy can be hardened by subzero cooling and tempering (Condition SCT).

Material specification for AM-350 stainless steel is presented in Table 2.6.1.0(a).

TABLE 2.6.1.0(a). *Material Specification for AM-350 Stainless Steel*

Specification	Form
AMS 5548	Sheet and strip

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 589 to 700 K range for 1,000 hours at stress levels below the short-time yield strength tends to increase room-temperature yield strength and room-temperature tensile strength slightly. Exposure at 700 K results in a decrease in elongation. Typical data are presented in Table 2.6.1.0(b).

Room-Temperature Properties

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.

2.6.1.1 *SCT850 Condition.*—Effect of temperature curves on various mechanical properties of AM-350 in this condition are presented in Figures 2.6.1.1.1(a) 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) through (b).

TABLE 2.6.1.0(b). Effect of Elevated Temperature Exposure on Typical Tensile Properties of AM-350 Alloy in the SCT850 Condition

Exposure temp., K	Exposure stress, MPa	Exposure time, hr	Room temperature properties		
			TUS, MPa	TYS, MPa	e, %
RT	...	...	1386	1089	12.0
589	414	1,000	1365	1117	14.0
644	414	1,000	1407	1165	11.0
700	414	1,000	1517	1310	7.0
589	621	1,000	1393	1220	13.0
644	621	1,000	1420	1241	11.0
700	621	1,000	1476	1324	7.0

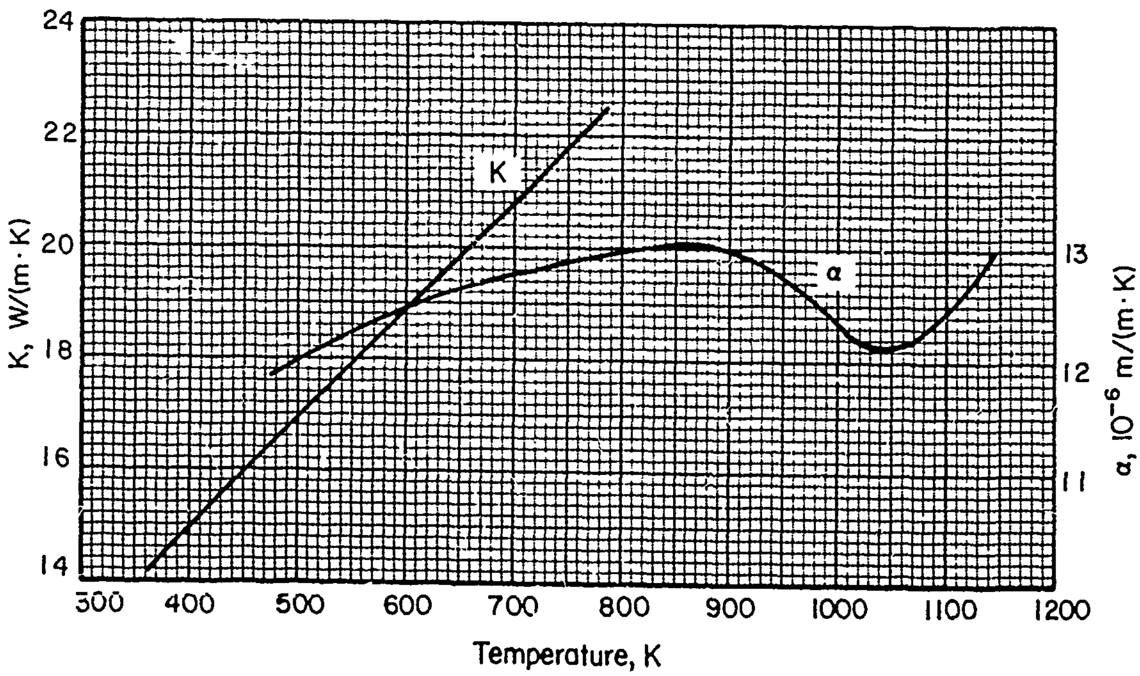


FIGURE 2.6.1.0. Effect of temperature on the physical properties of AM-350 stainless steel.

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	SCT850
THICKNESS, MM	≤ 4.75
BASIS	S
MECHANICAL PROPERTIES:	
FTU, MPA:	
L	...
T	1280
FTY, MPA:	
L	...
T	1030
FCY, MPA:	
L	...
T	1090
FSU, MPA	827
FBRU, MPA:	
(E/D=1.5)	2100
(E/D=2.0)	2550
FBRY, MPA:	
(E/D=1.5)	1550
(E/D=2.0)	1700
EL, PERCENT:	
L	...
T	10[b]
E, GPA	200.0
EC, GPA	206.8
G, GPA	75.8
MU	0.32
PHYSICAL PROPERTIES:	
OMEGA, MG/M3	7.81
C, J/(G*K)	...
K, W/(M*K)	SEE FIGURE 2.6.1.0
ALPHA, 10-6 M/(M*K)	SEE FIGURE 2.6.1.0

[a] TEST DIRECTION LONGITUDINAL FOR WIDTHS LESS THAN 228.6 MM; TRANSVERSE FOR WIDTHS 228.6 MM AND OVER.

[b] ELONGATION IS 8 PERCENT FOR SHEET THICKNESSES IN THE RANGE 0.254 TO 1.27 MM INCH. LISTED VALUE IS FOR THICKNESSES ≥1.27 MM.

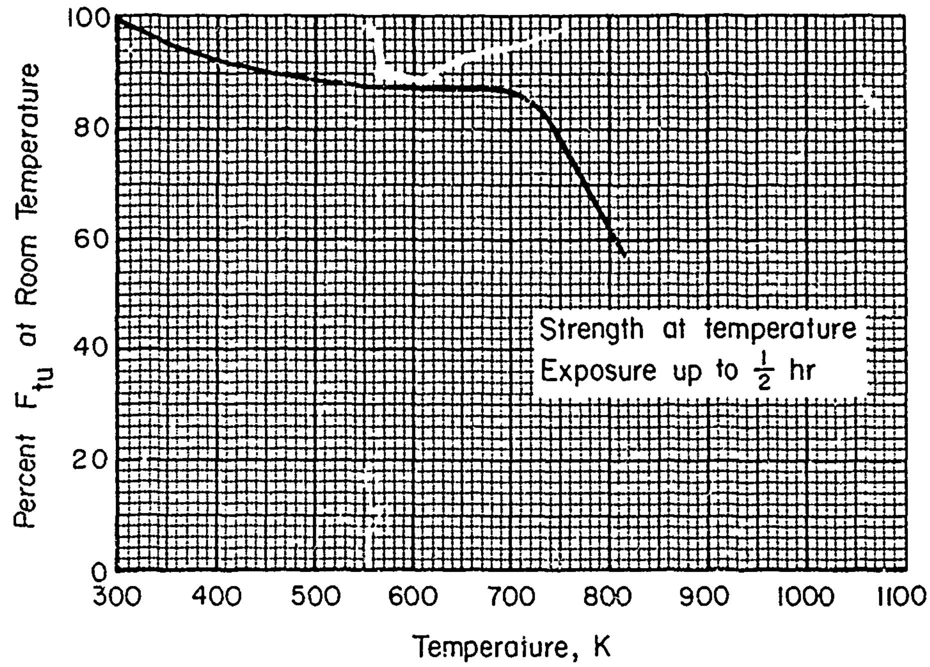


FIGURE 2.6.1.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of AM-350 (SCT850) stainless steel.

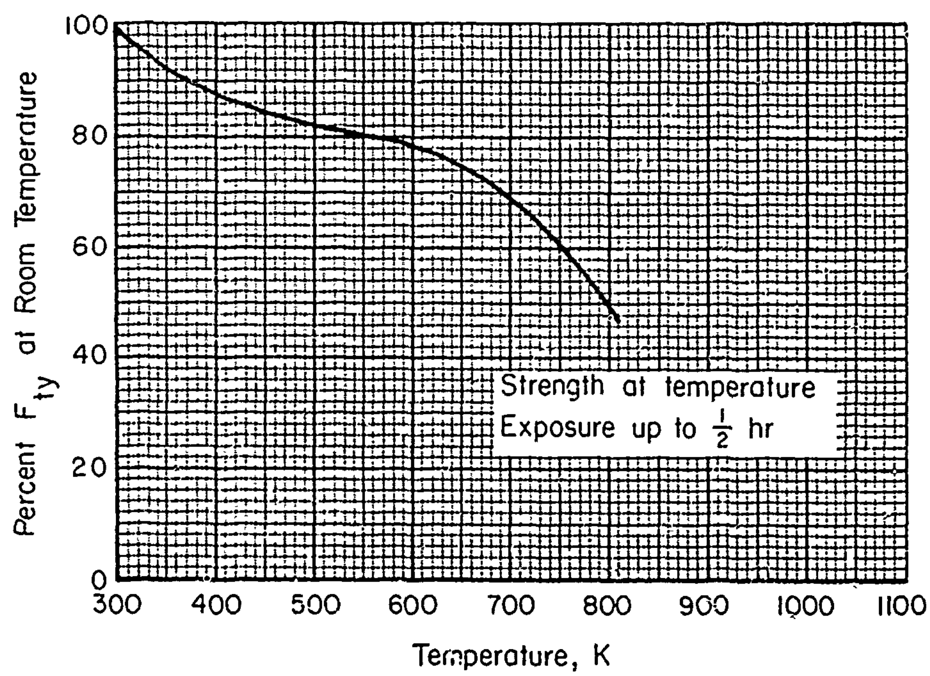


FIGURE 2.6.1.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of AM-350 (SCT850) stainless steel.

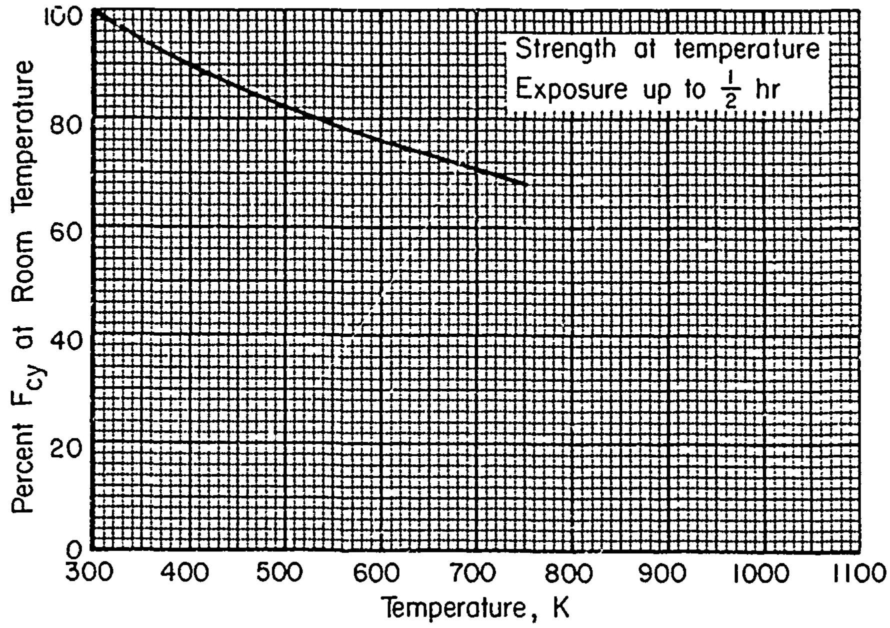


FIGURE 2.6.1.1.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of AM-350 (SCT850) stainless steel.

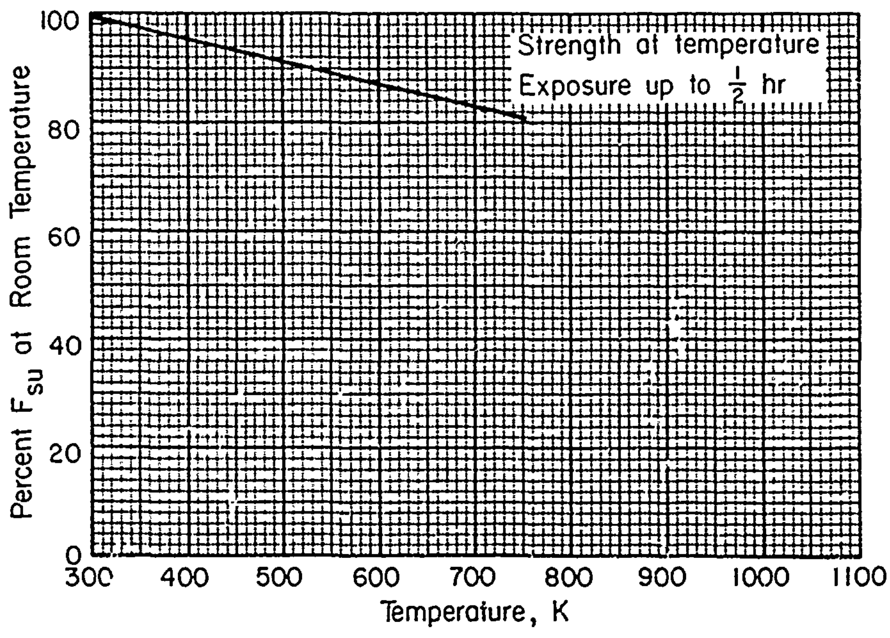


FIGURE 2.6.1.1.2(b). Effect of temperature on the ultimate shear strength (F_{su}) of AM-350 (SCT850) stainless steel.

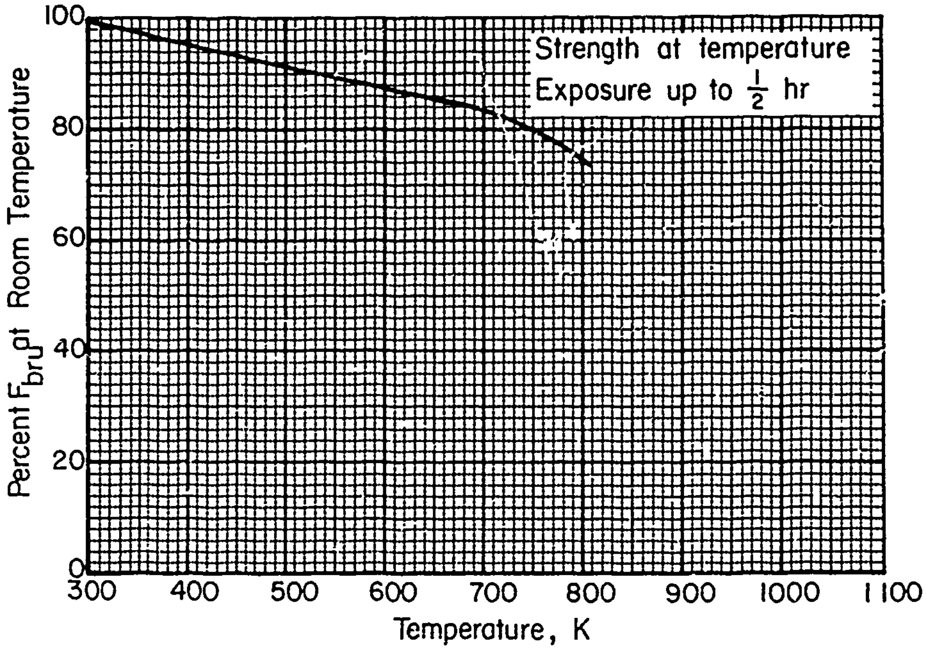


FIGURE 2.6.1.1.3(a). Effect of temperature on the ultimate bearing strength (F_{bru}) of AM-350 (SCT850) stainless steel.

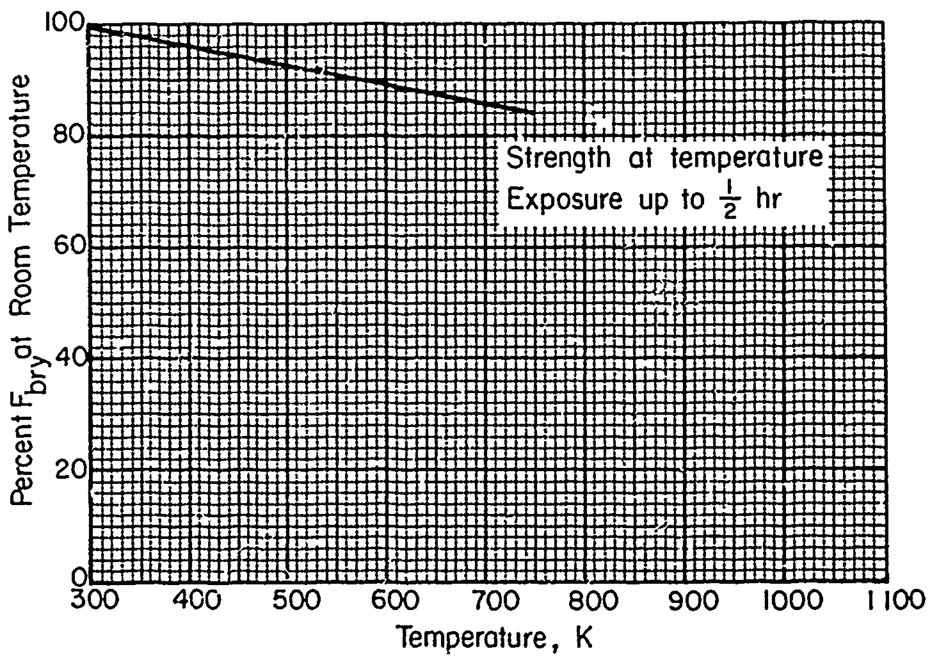


FIGURE 2.6.1.1.3(b). Effect of temperature on the bearing yield strength (F_{bry}) of AM-350 (SCT850) stainless steel.

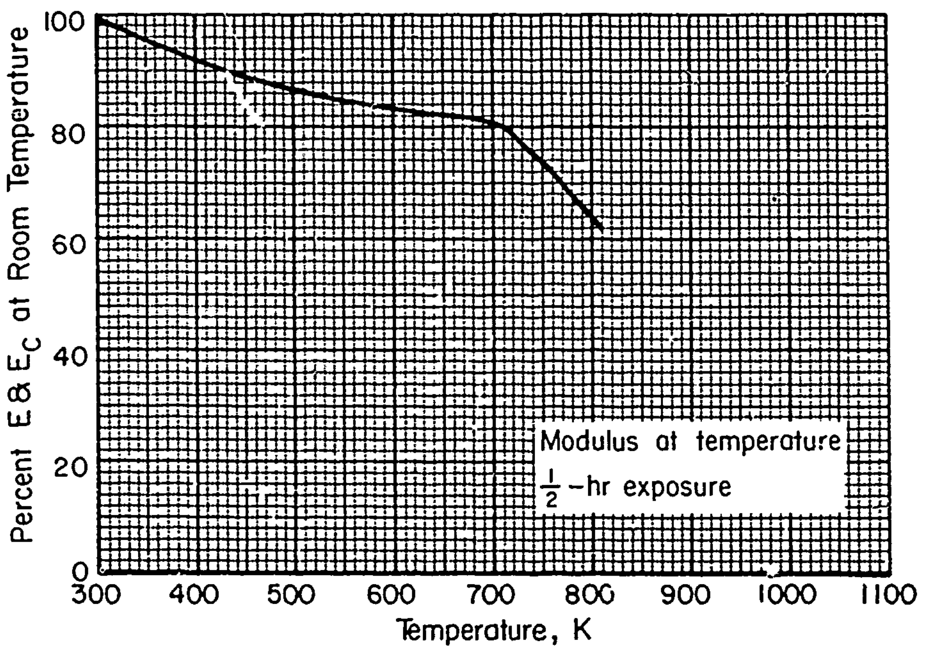


FIGURE 2.6.1.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of AM-350 (SCT850) stainless steel.

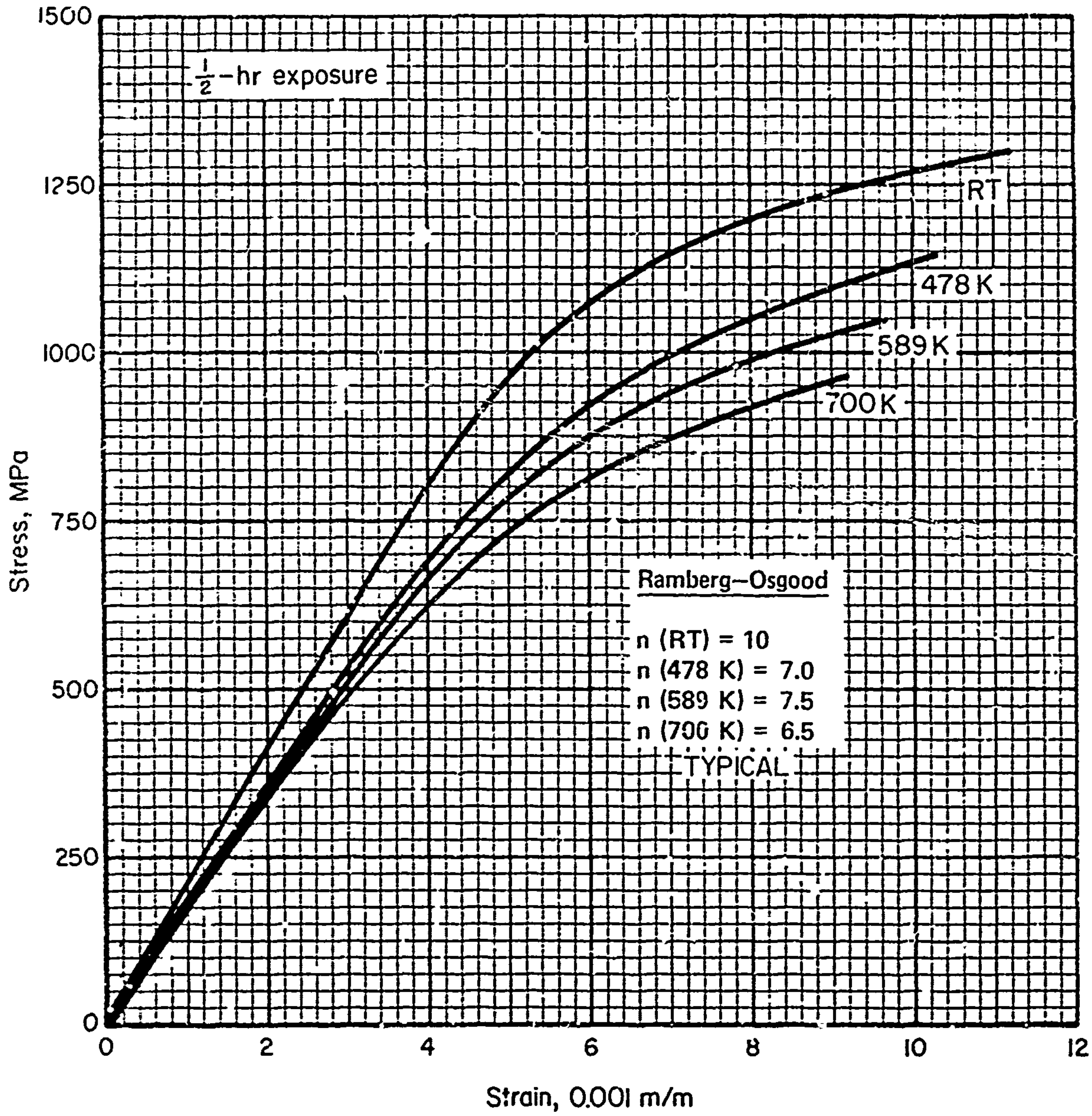


FIGURE 2.6.1.1.6(a). Typical tensile stress-strain curves at various temperatures for AM-350 (SCT850) stainless steel (sheet).

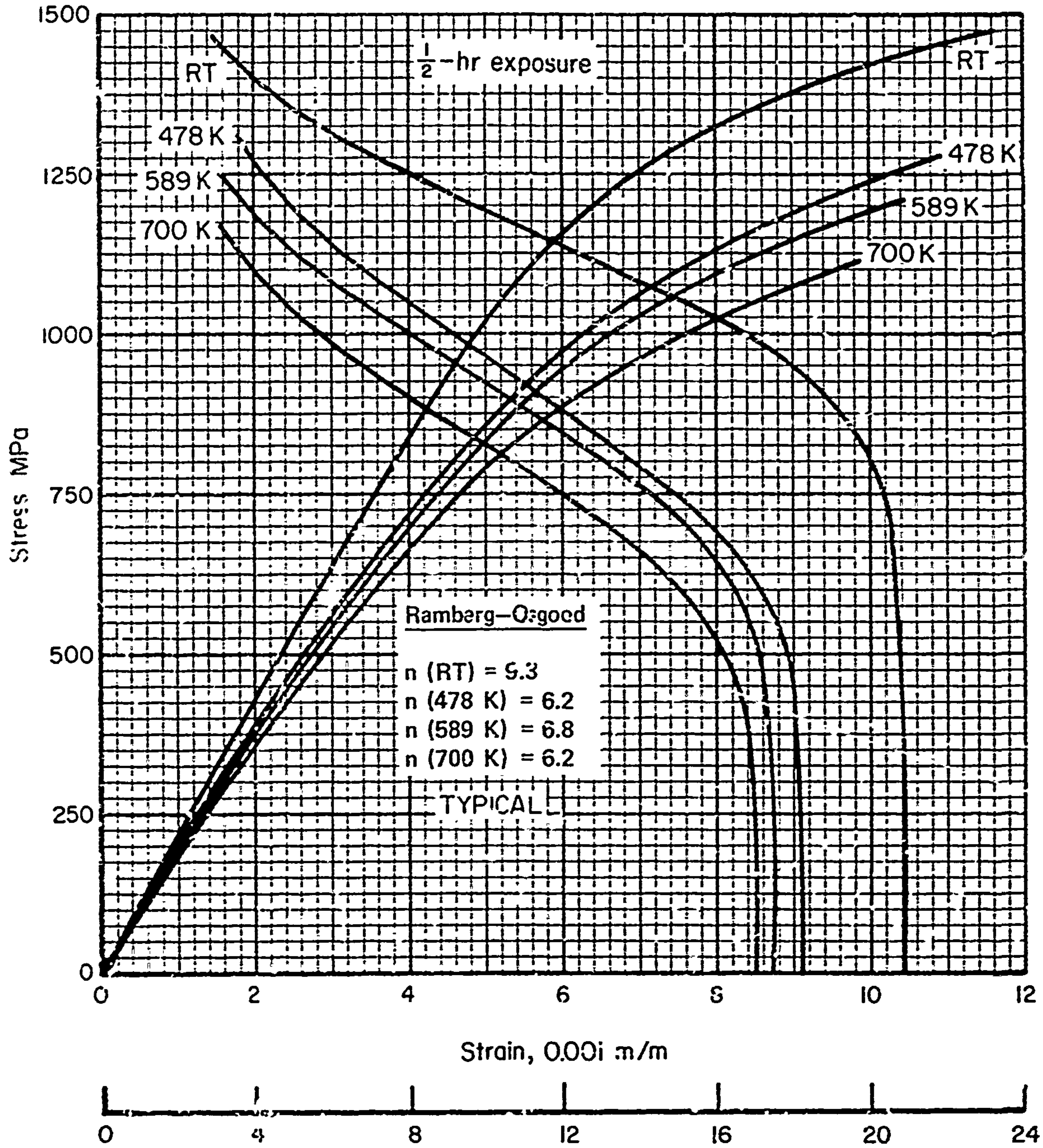


FIGURE 2.6.1.1.6(.). Typical compressive stress-strain and tangent-modulus curves at various temperatures for AM-350 (SCT850) stainless steel (sheet).

2.6.2 AM-355

2.6.2.0 *Comments and Properties.*—AM-355, like AM-350, has high strength up to 700 K and good oxidation resistance up to 800 K. 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 811 to 866 K.

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.

Material specifications for AM-355 are presented in Table 2.6.2.0(a).

Environmental Considerations.—Exposure in the 589 to 700 K 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(b).

TABLE 2.6.2.0(a). *Material Specifications for AM-355 Stainless Steel*

Specification	Form
AMS-5547	Sheet and strip
AMS-5549	Plate
AMS-5743	Bars, forgings and forging stock

Room-Temperature Properties

The room-temperature properties of AM-355 SCT are shown in Tables 2.6.2.0(c) and (e). The physical properties of this alloy at room and elevated temperatures are presented in Figure 2.6.2.0.

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(a) through 2.6.2.1.4.

TABLE 2.6.2.0(b). Effect of Elevated Temperature Exposure on Typical Tensile Properties of AM-355 Alloy in the SCT850 Condition

Exposure temp., K	Exposure stress, MPa	Exposure time, hr	Room Temperature Properties		
			TUS, MPa	TYS, MPa	e, %
RT	...	...	1455	1172	11.5
589	455	1000	1469	1186	12.0
644	448	1000	1503	1227	10.5
700	427	1000	1565	1379	12.5
589	683	1000	1476	1241	10.5
644	669	1000	1503	1303	11.5
700	641	1000	1544	1407	12.5

TABLE 2.6.2.0(d). Elongation Values for AM-355 Stainless Steel (SCT850)

Thickness, mm	e, percent in 51 mm
0.013 to 0.038	2
Over 0.038 to 0.051	3
Over 0.051 to 0.127	5
Over 0.127 to 0.250	7
Over 0.250 to 4.762	8

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]		BARS AND FORGINGS[b]	
CONDITION	SCT850[c]	SCT1000	SCT850[c]	SCT1000
THICKNESS, MM	0.13-4.75	0.25-4.75	...	...
BASIS	S	S	S	S
MECHANICAL PROPERTIES:				
FTU, MPA:				
L	...	...	1380	1170
T	1310	1140	...	...
FTY, MPA:				
L	...	...	1140	1070
T	1140	965	...	...
FCY, MPA:				
L	...	...	...	...
T	1230	1030	...	...
FSU, MPA	848	738	...	...
FBRU, MPA:				
(E/D=1.5)	2160	1860	...	...
(E/D=2.0)	2620	2280	...	...
FBRY, MPA:				
(E/D=1.5)	1700	1450	...	...
(E/D=2.0)	1880	1590	...	...
EL, PERCENT:				
L	...	...	10	12
T	d	10	...	...
E, GPA	200.0			
EC, GPA	200.0			
G, GPA	75.8			
MU	0.32			
PHYSICAL PROPERTIES:				
OMEGA, MG/M3	7.81			
C, J/(G*K)	...			
K, W/(M*K)	SEE FIGURE 2.6.2.0			
ALPHA, 10-6 M/(M*K)	SEE FIGURE 2.6.2.0			

[a] TEST DIRECTION LONGITUDINAL FOR WIDTHS LESS THAN 228.6 MM; TRANSVERSE FOR WIDTHS 228.6 MM AND OVER.

[b] TEST DIRECTION LONGITUDINAL; NOT APPLICABLE FOR SHORT TRANSVERSE (THICKNESS) DIRECTION.

[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] SEE TABLE 2.6.2.0(D).

TABLE 2.6.2.0(E). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF AM-355 STAINLESS STEEL (PLATE)

SPECIFICATION	AMS 5549			
FORM	PLATE			
CONDITION	SCT850[a,b]			SCT1000[b]
THICKNESS, MM	≤9.52	9.52-25.40	>25.40	...
BASIS	S	S	S	S
MECHANICAL PROPERTIES:				
FTU, MPA:				
L	...	...	...	...
T	1310	1310	1310	1140
FTY, MPA:				
L	...	...	...	...
T	1140	1030	c	965
FCY, MPA:				
L	...	...	...	...
T	1230	1090	...	1030
FSU, MPA	848	848	848	738
FBRU, MPA:				
(E/D=1.5)	2160	2160	2160	1860
(E/D=2.0)	2620	2620	2620	2280
FBRY, MPA:				
(E/D=1.5)	1700	1550	...	1450
(E/D=2.0)	1880	1700	...	1590
EL, PERCENT:				
L	...	...	...	...
T	10	10	10	12
E, GPA	200.0			
EC, GPA	200.0			
G, GPA	75.8			
MU	0.32			
PHYSICAL PROPERTIES:				
OMEGA, MG/M3	7.81			
C, J/(G*K)	...			
K, W/(M*K)	SEE FIGURE 2.6.2.0			
ALPHA, 10-6 M/(M*K)	SEE FIGURE 2.6.2.0			

[a] 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.

[b] TEST DIRECTION LONGITUDINAL FOR WIDTHS LESS THAN 228.6 MM: TRANSVERSE FOR WIDTHS 228.6 MM AND OVER.

[c] AS AGREED UPON BY PURCHASER AND VENDOR.

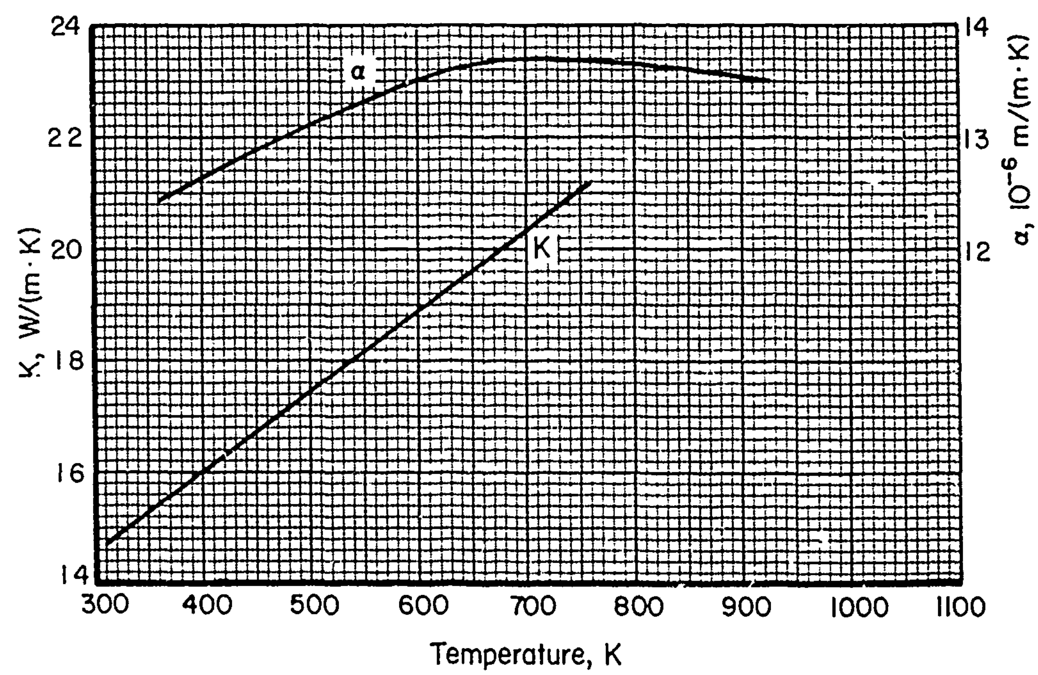


FIGURE 2.6.2.0. Effect of temperature on the physical properties of AM-355 stainless steel.

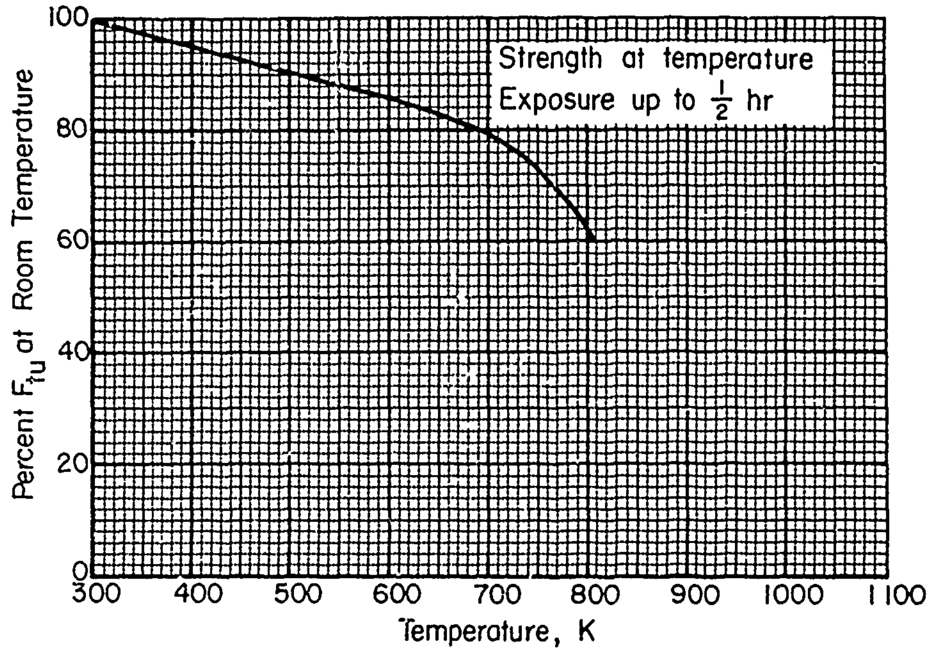


FIGURE 2.6.2.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of AM-355 (SCT) stainless steel.

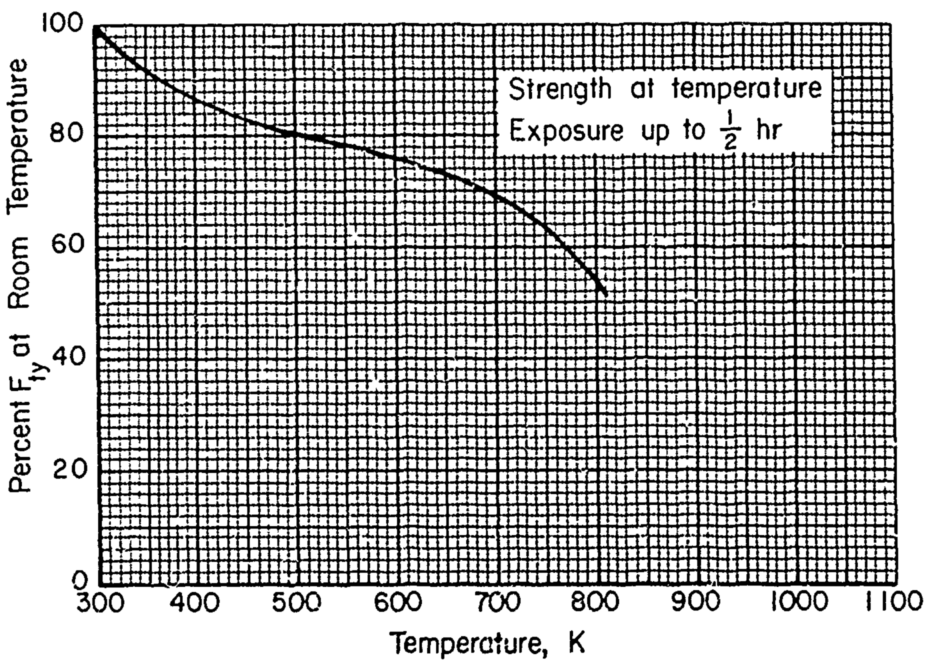


FIGURE 2.6.2.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of AM-355 (SCT) stainless steel.

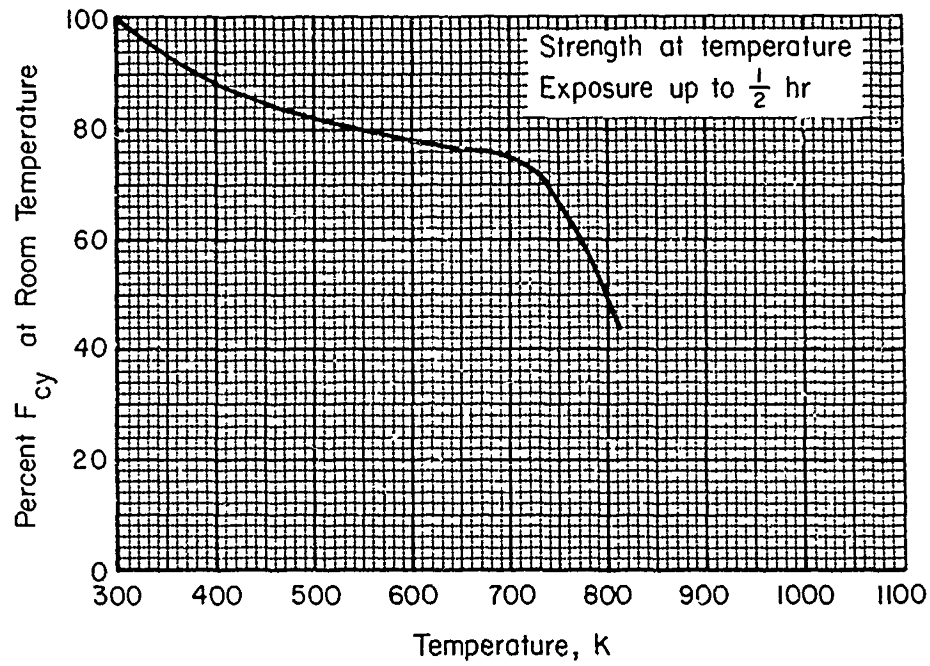


FIGURE 2.6.2.1.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of AM-355 (SCT) stainless steel.

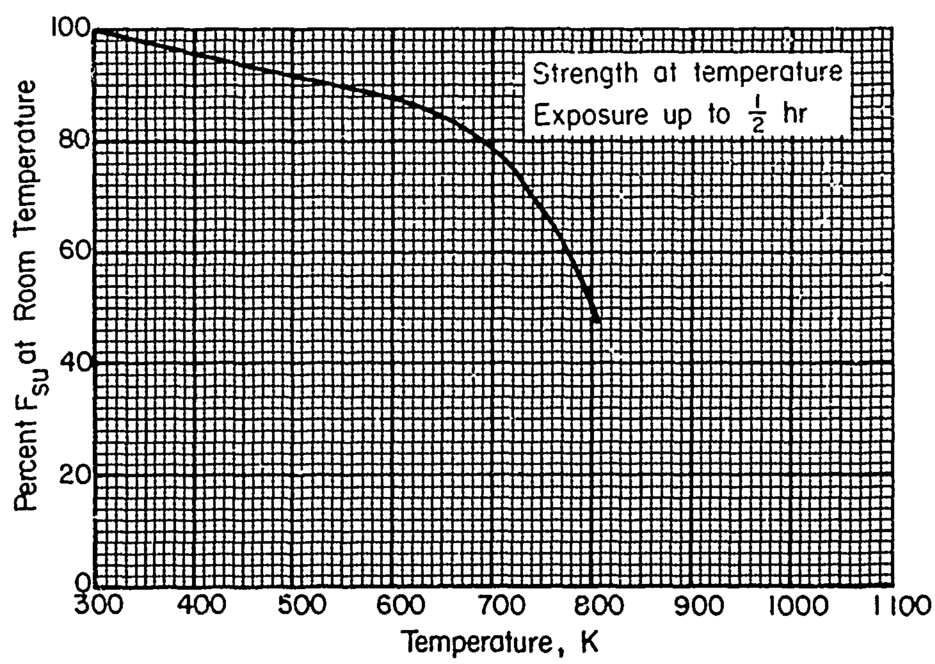


FIGURE 2.6.2.1.2(b). Effect of temperature on the ultimate shear strength (F_{su}) of AM-355 (SCT) stainless steel.

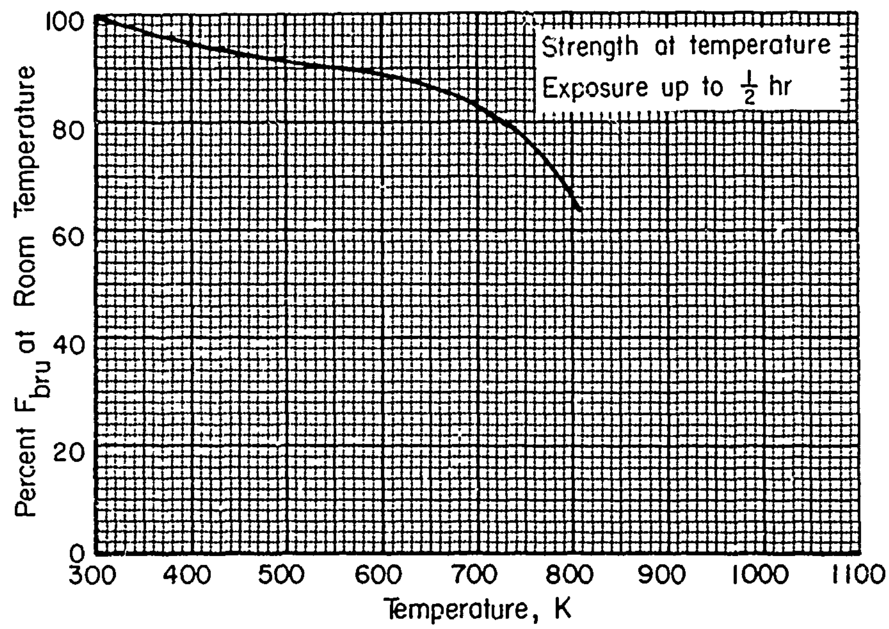


FIGURE 2.6.2.1.3(a). Effect of temperature on the ultimate bearing strength (F_{bru}) of AM-355 (SCT) stainless steel.

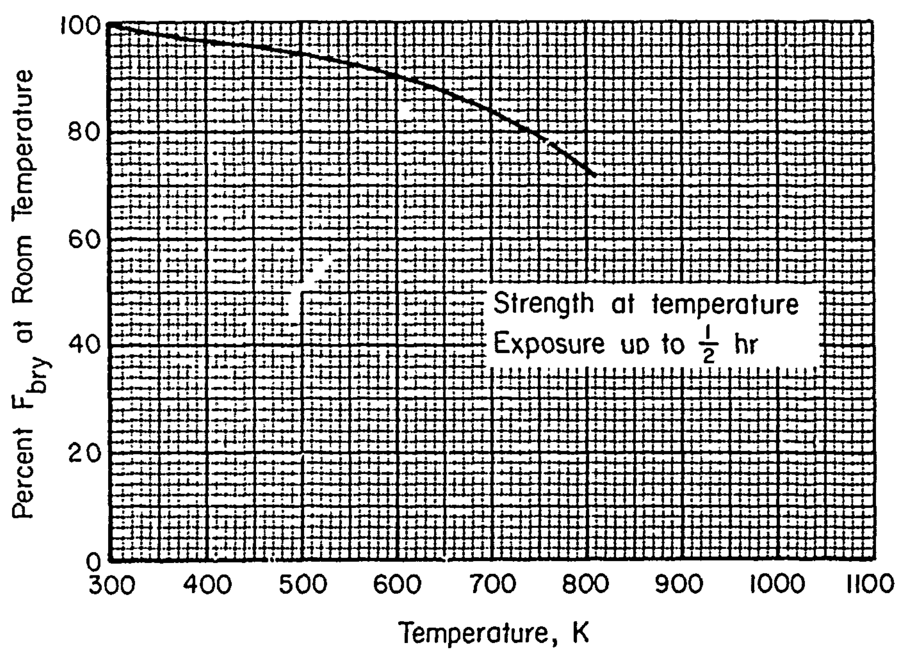


FIGURE 2.6.2.1.3(b). Effect of temperature on the bearing yield strength (F_{bry}) of AM-355 (SCT) stainless steel.

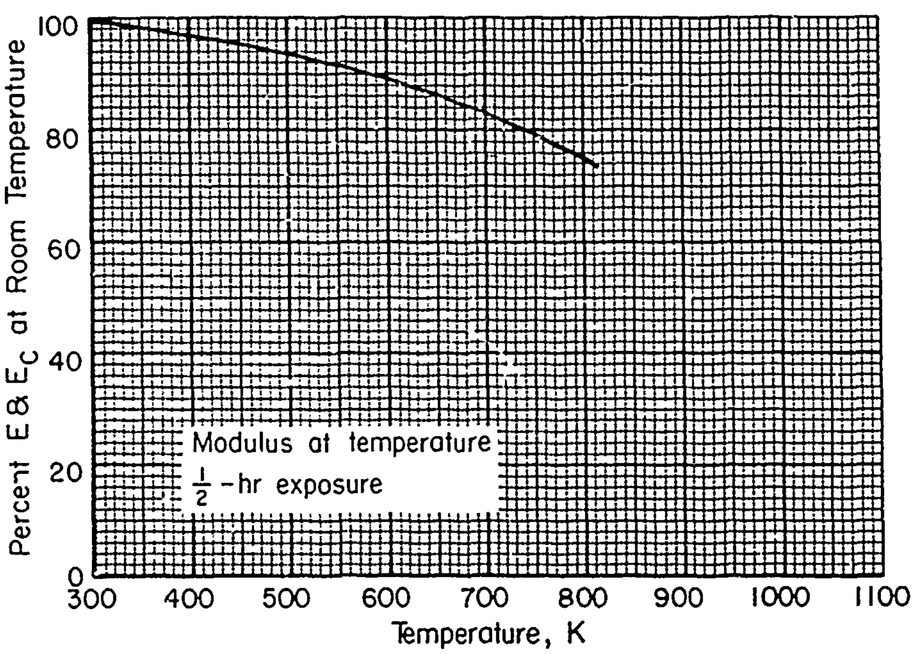


FIGURE 2.6.2.1.4. Effect of temperature on the tensile modulus (E) of AM-355 (SCT) stainless steel.

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 700 K for aged conditions. It is normally produced by air melting and is available in the form of forgings, billet, bar, wire, strip and welded tubing.

A material specification for Custom 450 is shown in Table 2.6.3.0(a).

TABLE 2.6.3.0(a). *Material Specification for Custom 450 Stainless Steel*

Specification	Form
AMS 5763	Bars, forgings, tubing, wire and rings

Manufacturing Considerations.—Custom 450 is normally supplied and fabricated in the solution annealed condition except wire for cold heading is supplied in the over-aged 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 annealed condition at temperatures up to 533 K. The alloy can also be heat treated to several strength levels. The heat treatment of Custom 450 is as follows:

Operation		Condition
Solution Anneal	1311 ± 5 K, 1 hr., rapid cool	A
Hardening	755 ± 8 K, 4 hrs., air cool	H900
	839 ± 8 K, 4 hrs., air cool	H1050

In all heat treat conditions, Custom 450 has excellent ductility and toughness. Cryogenic properties are optimum in the overaged H1150 condition. Maximum strength is achieved with the 755 K aging treatment while optimum fatigue life is exhibited with a 839 K age.

When the as-supplied solution annealed 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 m/m with the 755 K age and about 0.001 m/m for the 839 K 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 annealed 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 894 K. The general corrosion resistance is very slightly decreased by the higher aging temperatures.

Room-Temperature Properties

The room-temperature mechanical properties of Custom 450 are presented in Table 2.6.3.0(b). Physical properties at elevated temperatures are presented in Figure 2.6.3.0.

2.6.3.1 *H900 Condition.* —Effect-of-temperature curves are presented in Figures 2.6.3.1.1(a) through 2.6.3.1.5(b).

2.6.3.2 *H1050 Condition.* —Effect-of-temperature curves are presented in Figures 2.6.3.2.1(a) through 2.6.3.2.5(b).

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, MM	≤304.80	≤304.80	≤304.80
BASIS	S	S	S[a]
MECHANICAL PROPERTIES:			
FTU, MPA:			
L	862	1240	1000
ST	...	1230	993
FTY, MPA:			
L	655	1170	931
ST	...	1160	917
FCY, MPA:			
L	...	1210	986
ST	...	1190	972
FSU, MPA	...	786	641
FBRU, MPA:			
(E/D=1.5)	...	2050	1650
(E/D=2.0)	...	2630	2120
FBRY, MPA:			
(E/D=1.5)	...	1830	1410
(E/D=2.0)	...	2250	1770
EL, PERCENT:			
L	10	10	12
ST	...	...	...
EL, PERCENT:			
L	40	40	45
ST	...	...	...
E, GPA	193.1	200.0	202.0
EC, GPA	...	213.7	213.7
G, GPA	...	77.2	77.9
MU	...	0.29	0.29
PHYSICAL PROPERTIES:			
OMEGA, MG/M3	7.75		
C, J/(G*K)	...		
K, W/(M*K)	...		
ALPHA, 10-6 M/(M*K)	SEE FIGURE 2.6.3.0		

[a]SUPPLIERS GUARANTEED MINIMUM PROPERTIES.

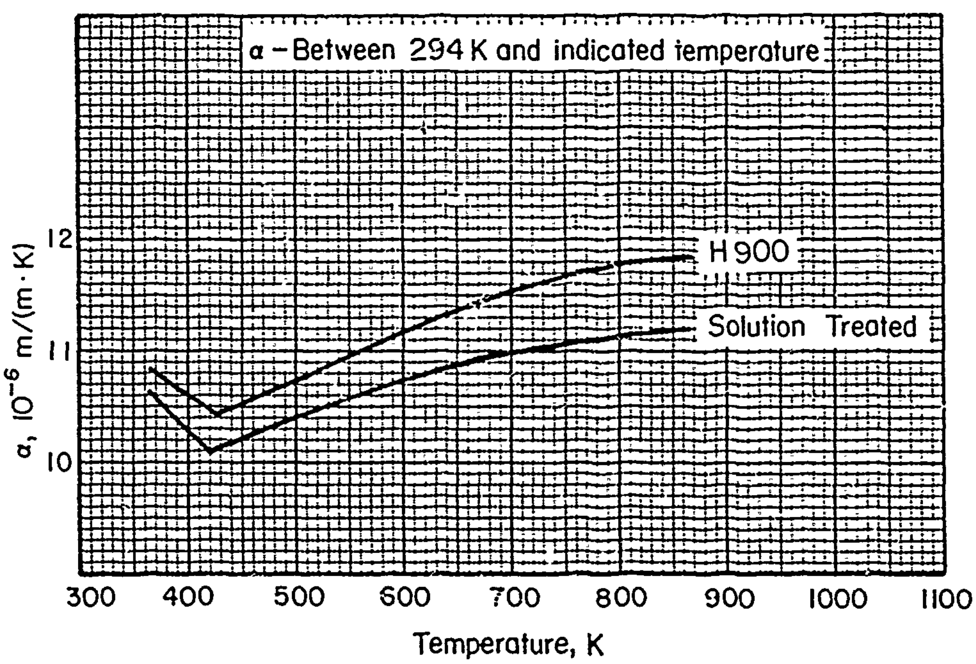


FIGURE 2.6.3.0. Effect of temperature on the physical properties of Custom 450 stainless steel.

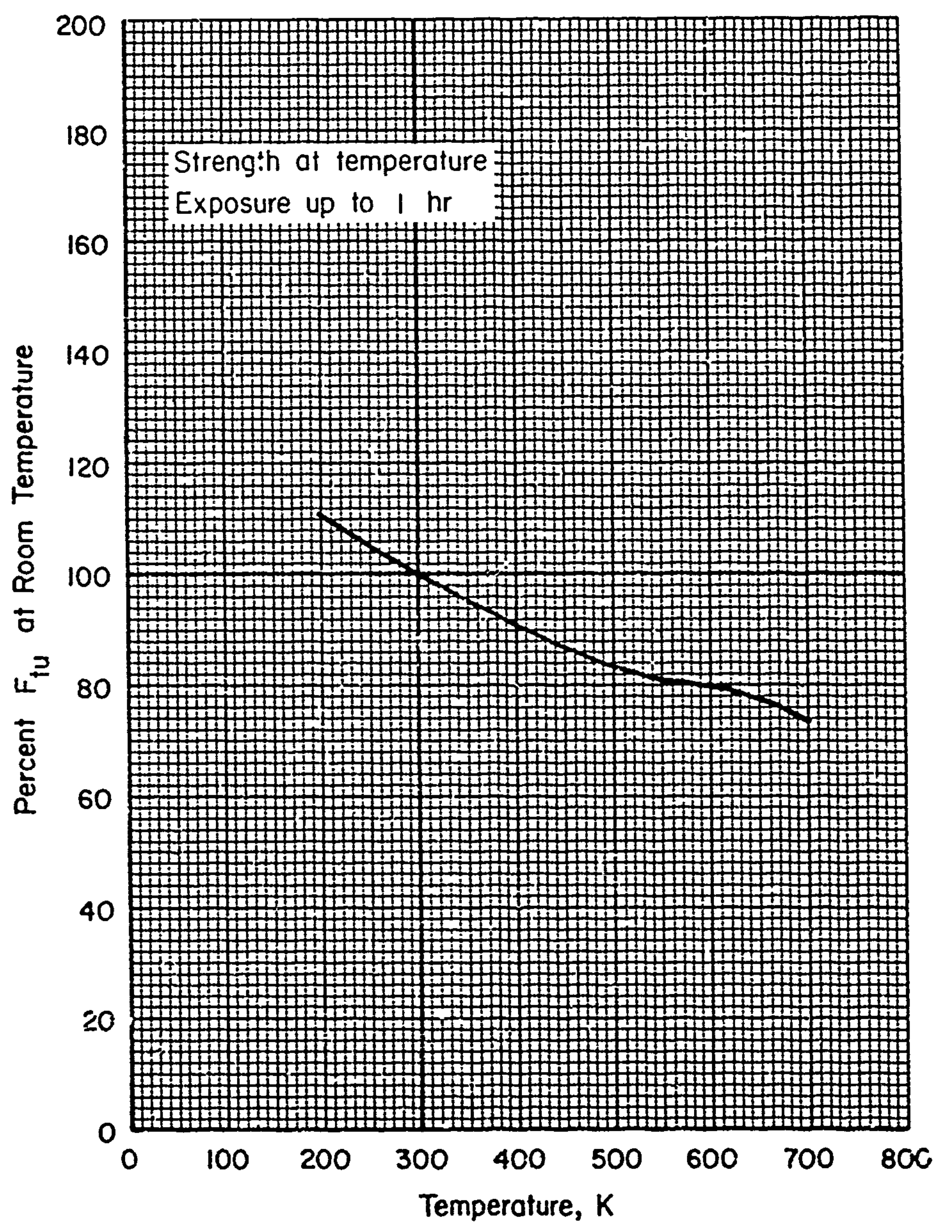


FIGURE 2.6.3.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of Custom 450 (H900) stainless steel bar.

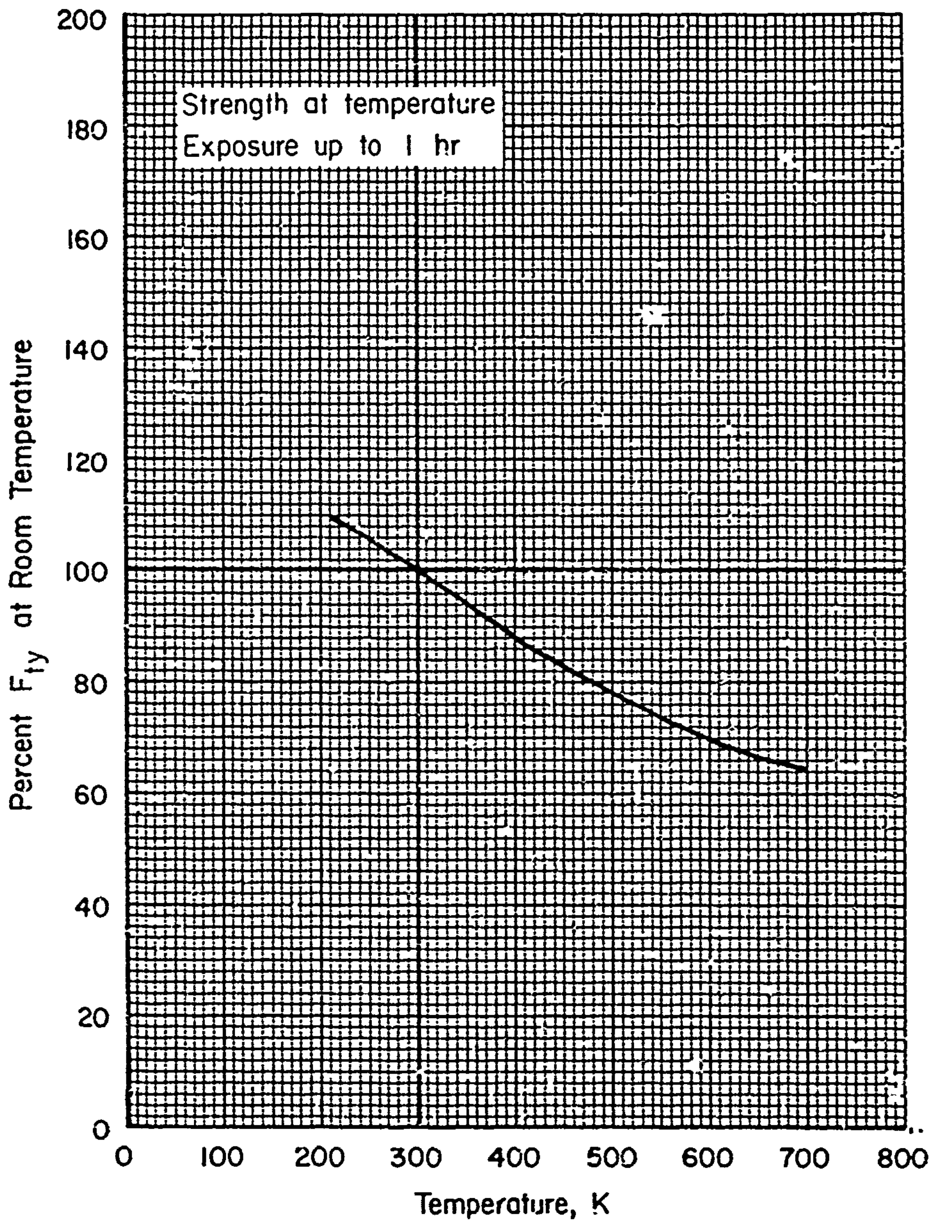


FIGURE 2.6.3.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of Custom 450 (H900) stainless steel bar.

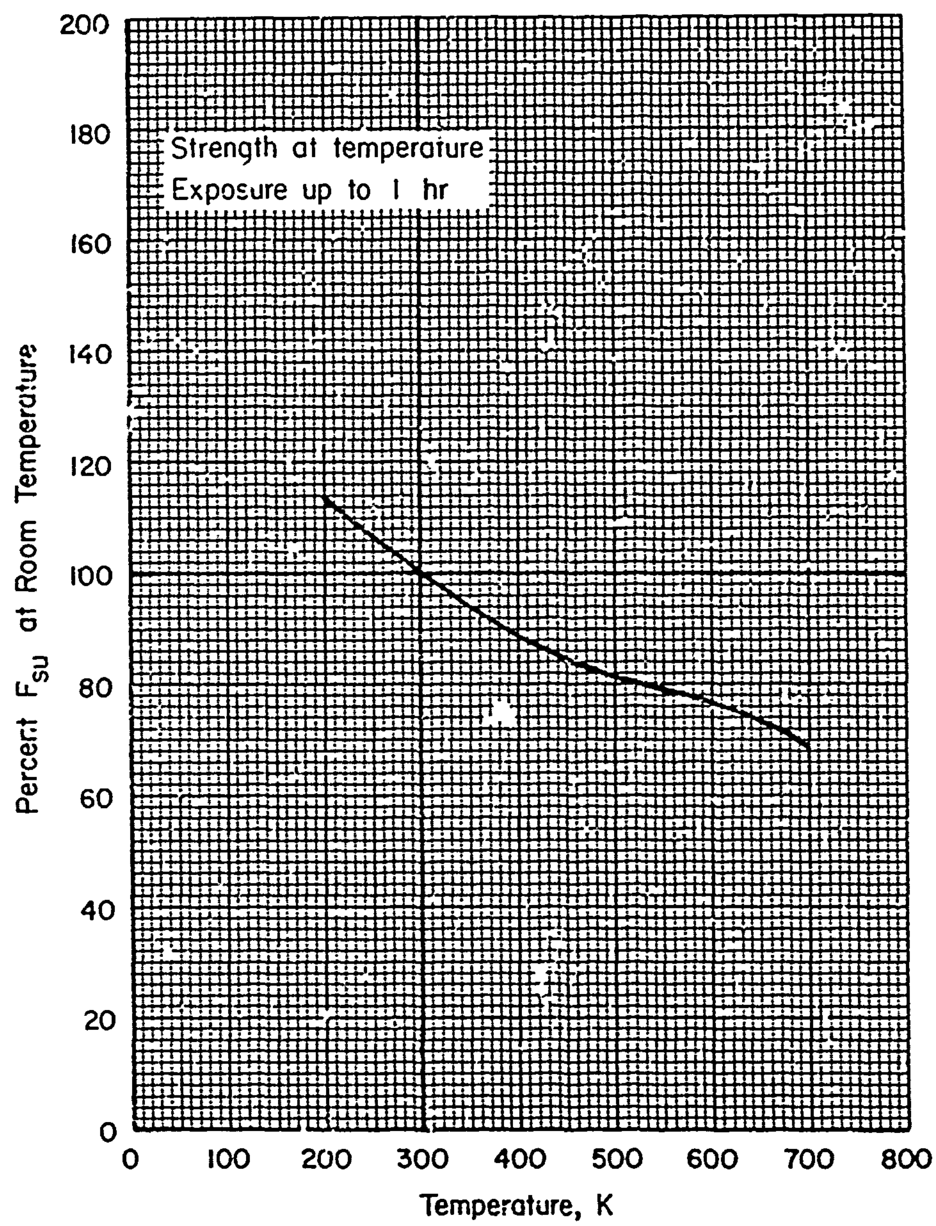


FIGURE 2.6.3.1.2. Effect of temperature on the ultimate shear strength (F_{su}) of Custom 450 (H900) stainless steel bar.

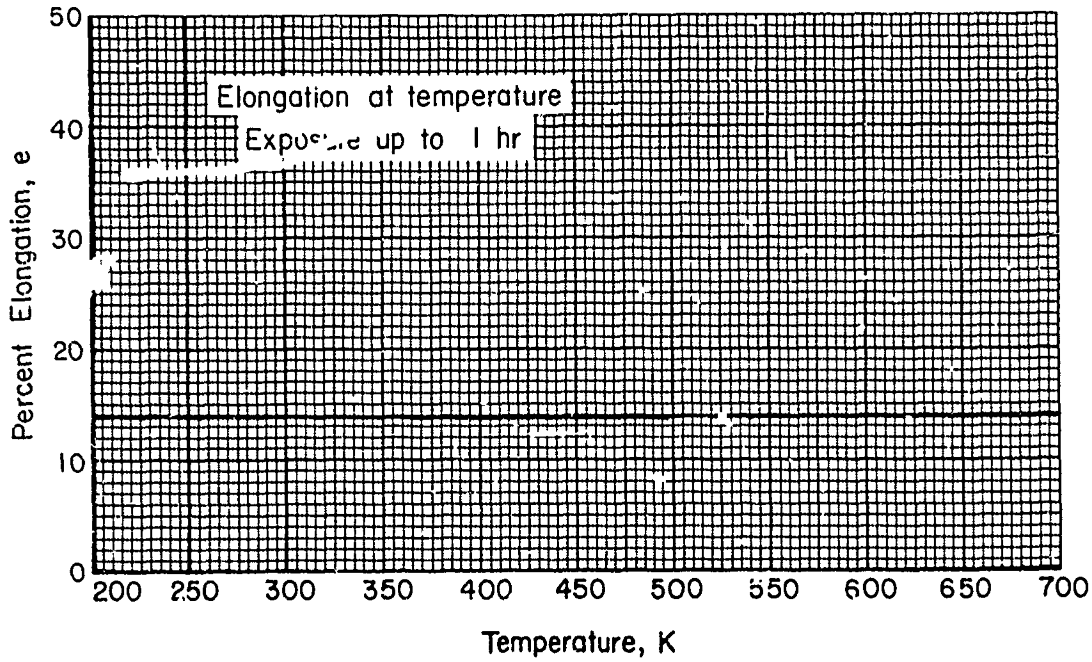


FIGURE 2.6.3.1.5(a). Effect of temperature on the elongation (e) of Custom 450 (H900) stainless steel bar.

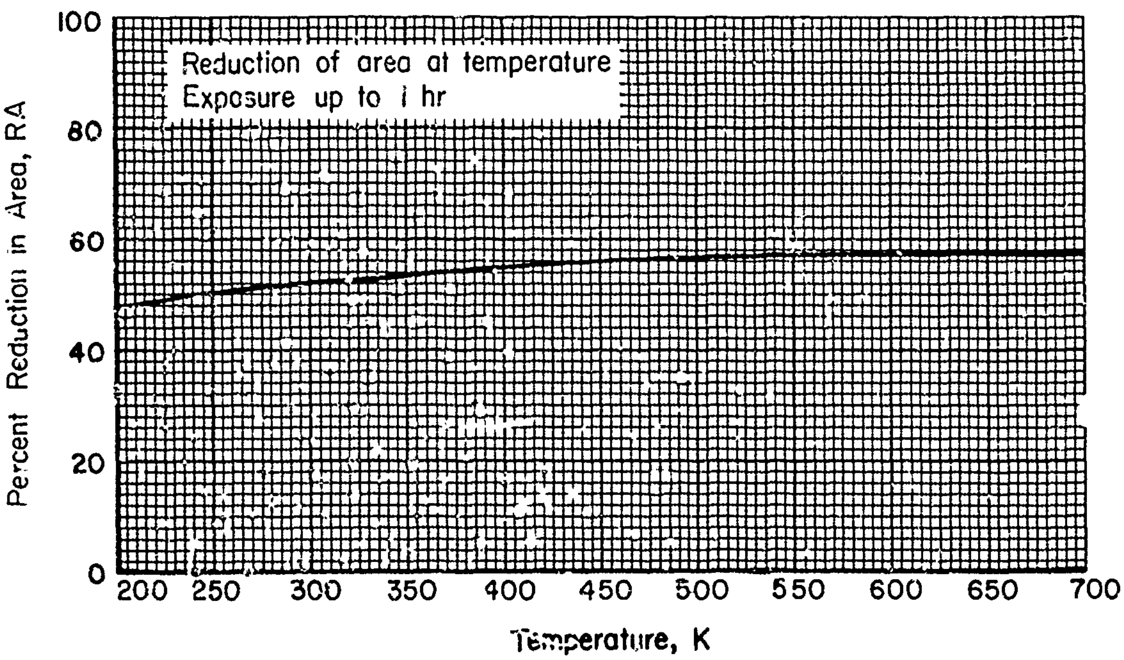


FIGURE 2.6.3.1.5(b). Effect of temperature on the reduction in area (RA) of Custom 450 (H900) stainless steel bar.

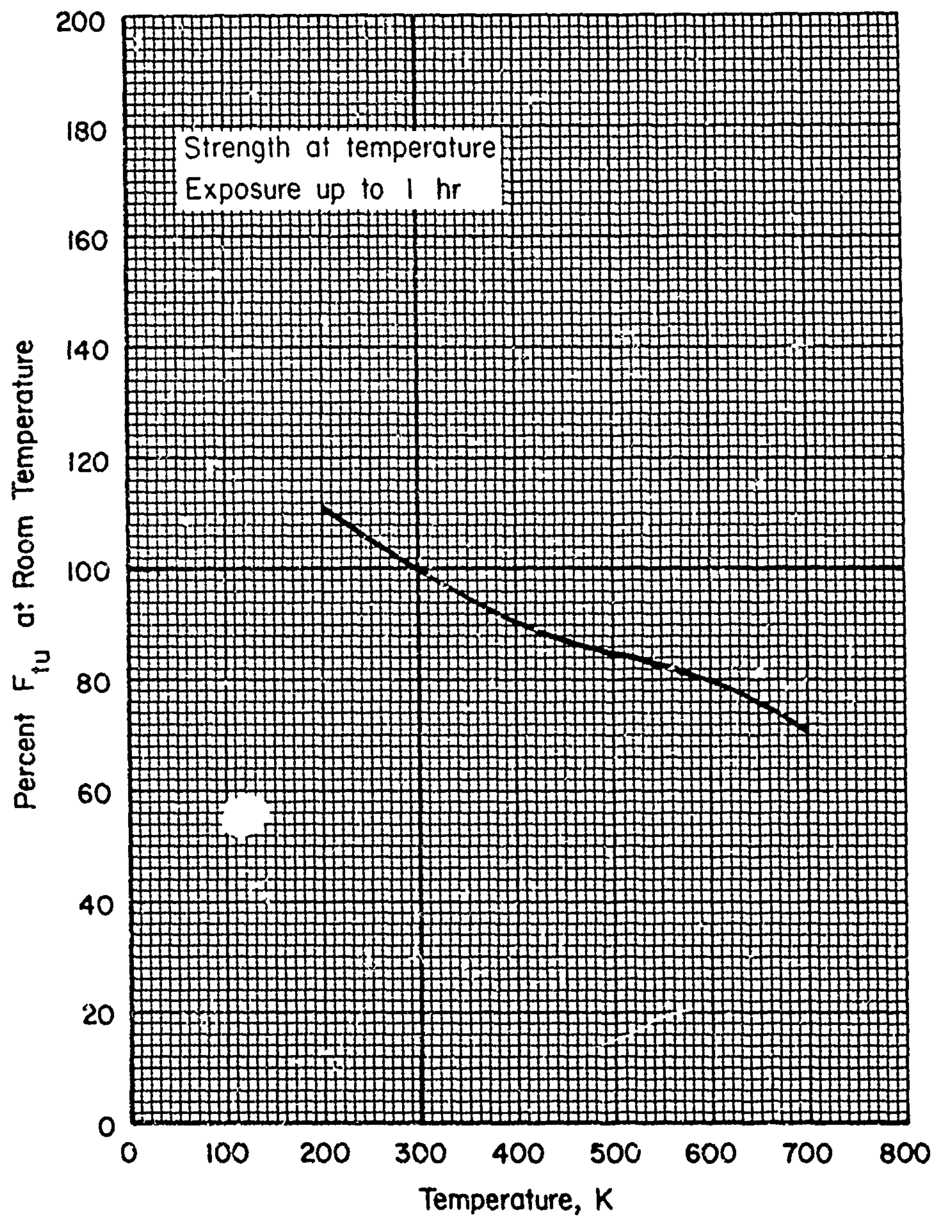


FIGURE 2.6.3.2.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of Custom 450 (H1050) stainless steel bar.

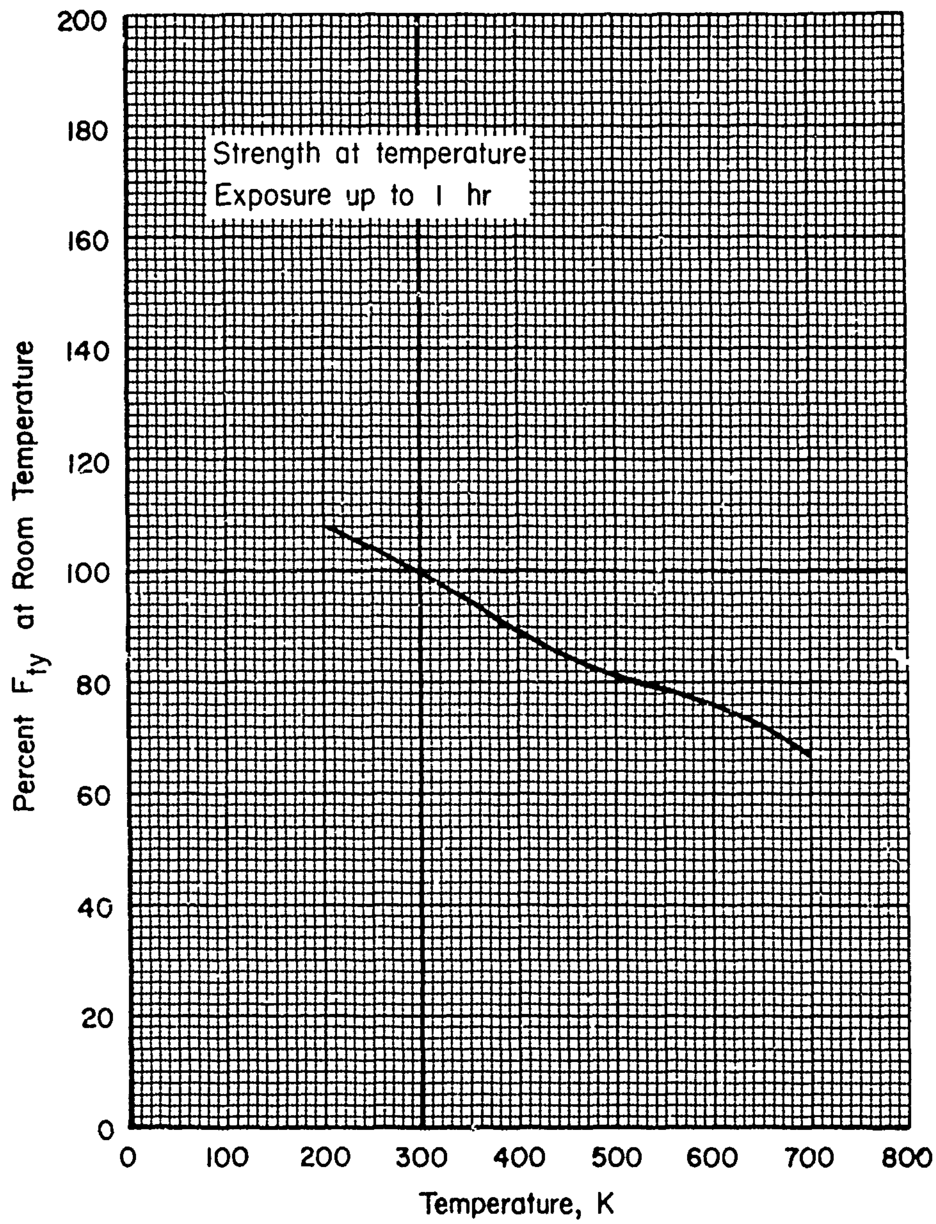


FIGURE 2.6.3.2.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of Custom 450 (H1050) stainless steel bar.

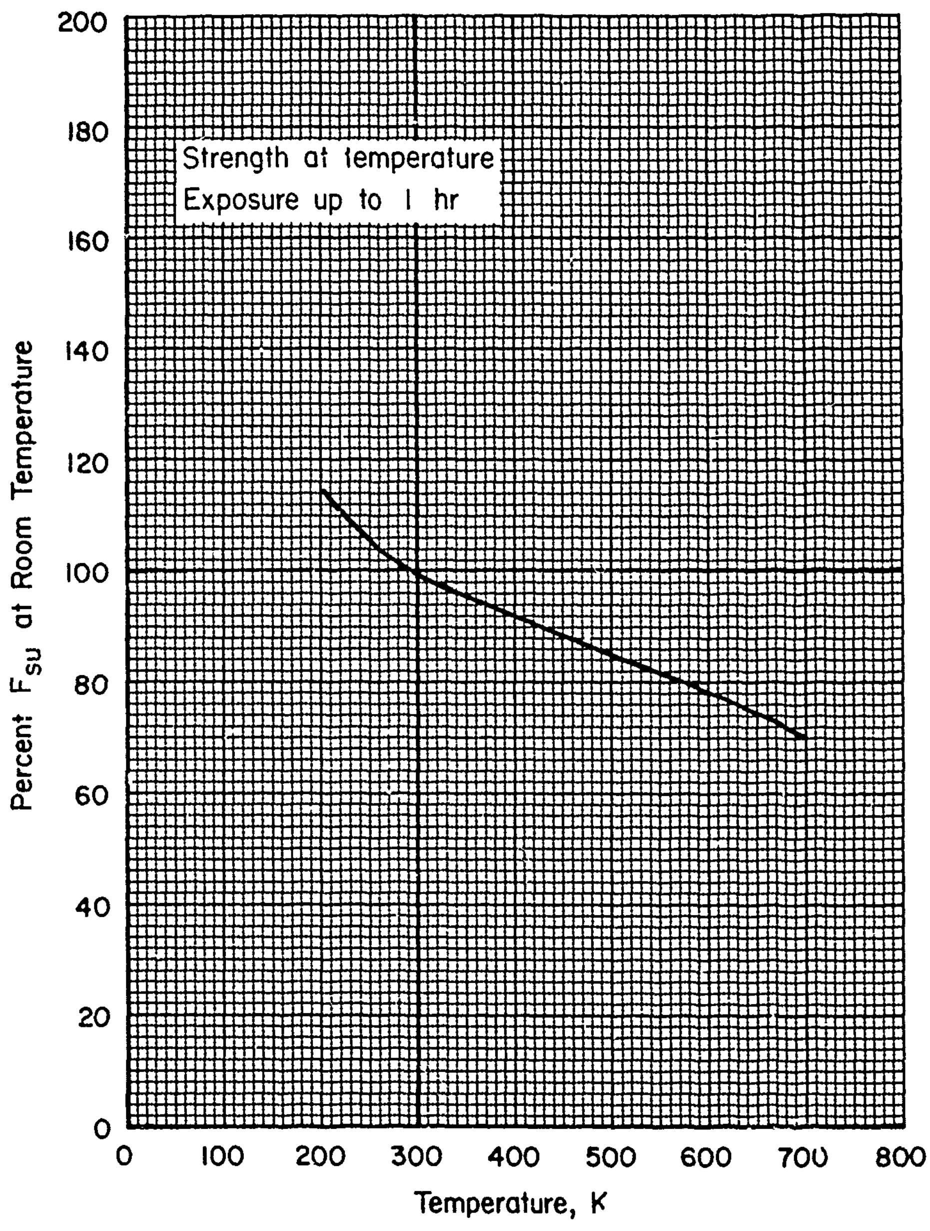


FIGURE 2.6.3.2.2. Effe[illegible] of temperature on the ultimate shear str[illegible]th (F_{su}) of Custom 450 (H1050) [illegible]nless steel bar.

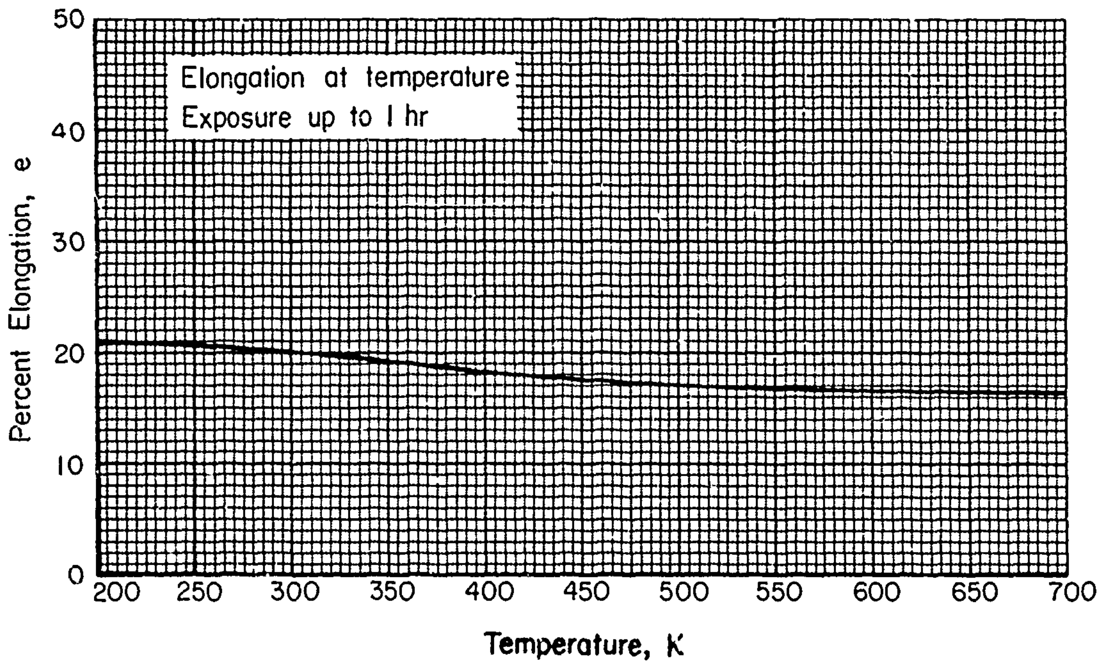


FIGURE 2.6.3.2.5(a). Effect of temperature on the elongation (e) of Custom 450 (H1050) stainless steel bar.

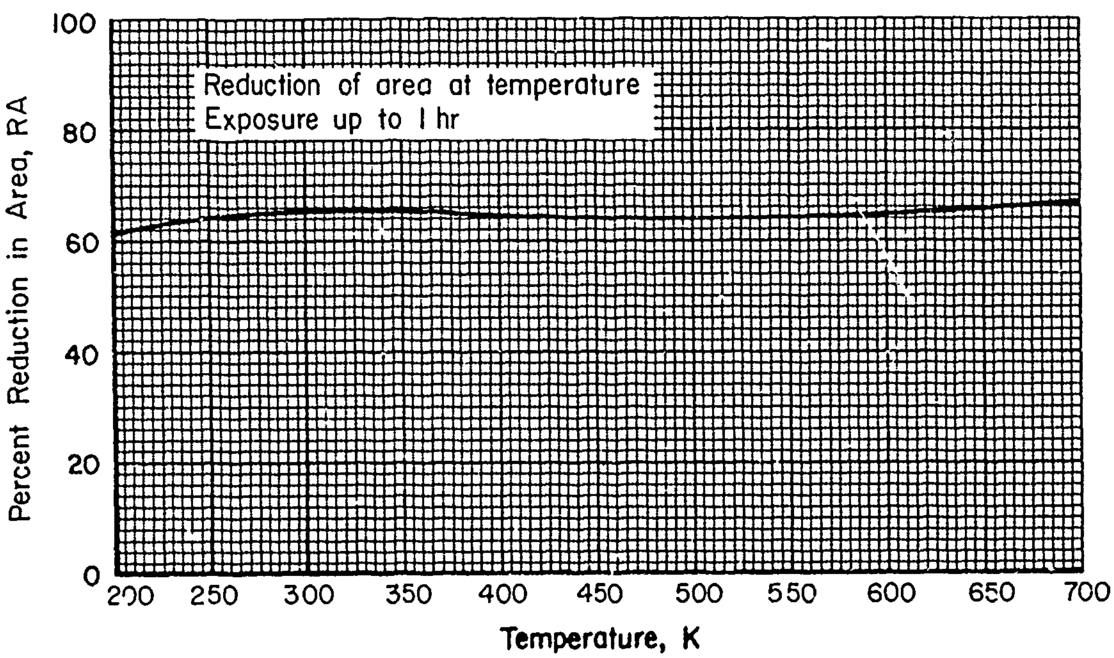


FIGURE 2.6.3.2.5(b). Effect of temperature on the reduction in area (RA) of Custom 450 (H1050) stainless steel bar.

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 700 K. It is produced by consumable electrode remelting and is available in the form of forgings, billet, bar, wire, strip, and welded tubing.

Material specifications for Custom 455 are presented in Table 2.6.4.0(a).

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

Specification	Form
AMS 5578	Tubing (welded)
AMS 5617	Bars and Forgings

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 heat treatment of Custom 455 is as follows:

Operation		Condition
Annealing	1103 K±15 K, 1/2 hr at heat, water quench	A
Hardening	783 K± 5 K, 4 hr at heat, air cool	H950
	811 K± 5 K, 4 hr at heat, air cool	H1000

The minimum recommended hardening temperature to produce the optimum combination of strength, fracture toughness, and stress corrosion cracking resistance is 783 K. Higher strength is attainable with the 755 K 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 755 K to 811 K.

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 m/m . should be expected with the 783 K 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 755 K 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 644 K. For most applications, the loss in toughness which occurs is not detrimental to performance.

Room-Temperature Properties

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.

2.6.4.1 *H950 Condition.*—Effect of temperature curves are presented in Figures 2.6.4.1.1(a) through 2.6.4.1.5(b).

2.6.4.2 *H1000 Condition.*—Effect of temperature curves are shown in Figures 2.6.4.2.1(a) through 2.6.4.2.5(b).

TABLE 2.6.4.0(8). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF CUSTOM 455 STAINLESS STEEL

SPECIFICATION	AMS 5578		AMS 5617	
FORM	TUBING (WELDED)		BARS FORGINGS	
CONDITION	H950		H950	H1000
THICKNESS[a], MM	0.51-1.57	>1.57	≤152.40	≤152.40
BASIS	S	S	S	S[b]
MECHANICAL PROPERTIES:				
FTU, MPA:				
L	1520	1520	1520	1410
LT	...	...	...	...
ST	...	...	...	...
FTY- MPA	...	...	...	...
L	1410	1410	1410	1280
LT	...	...	...	...
ST	...	...	...	...
FCY, MPA:				
L	...	...	1480	1330
LT	...	...	...	...
ST	...	...	...	...
FSU, MPA	...	...	896	876
FBRU, MPA:				
(E/D=1.5)	...	...	2390	2290
(E/D=2.0)	...	...	3030	2900
FBRY, MPA:				
(E/D=1.5)	...	...	2090	1970
(E/D=2.0)	...	...	2470	2360
EL, PERCENT:				
L	3	4	10	10
LT	...	...	...	...
ST	...	...	...	...
EL, PERCENT:				
L	...	...	40	40
LT	...	...	...	...
ST	...	...	...	...
E, GPA	196.5			199.3
EC, GPA	206.8			206.8
G, GPA	77.9			79.3
MU	0.27			0.26
PHYSICAL PROPERTIES:				
OMEGA, MG/M3	7.75			
C, J/(G*K)	...			
K, W/(M*K)	SEE FIGURE 2.6.4.0			
ALPHA, 10-6 M/(M*K)	SEE FIGURE 2.6.4.0			

[a] WALL THICKNESS FOR TUBING.
[b] SUPPLIERS GUARANTEED MINIMUMS FOR FTU, FTY, EL, AND RA.

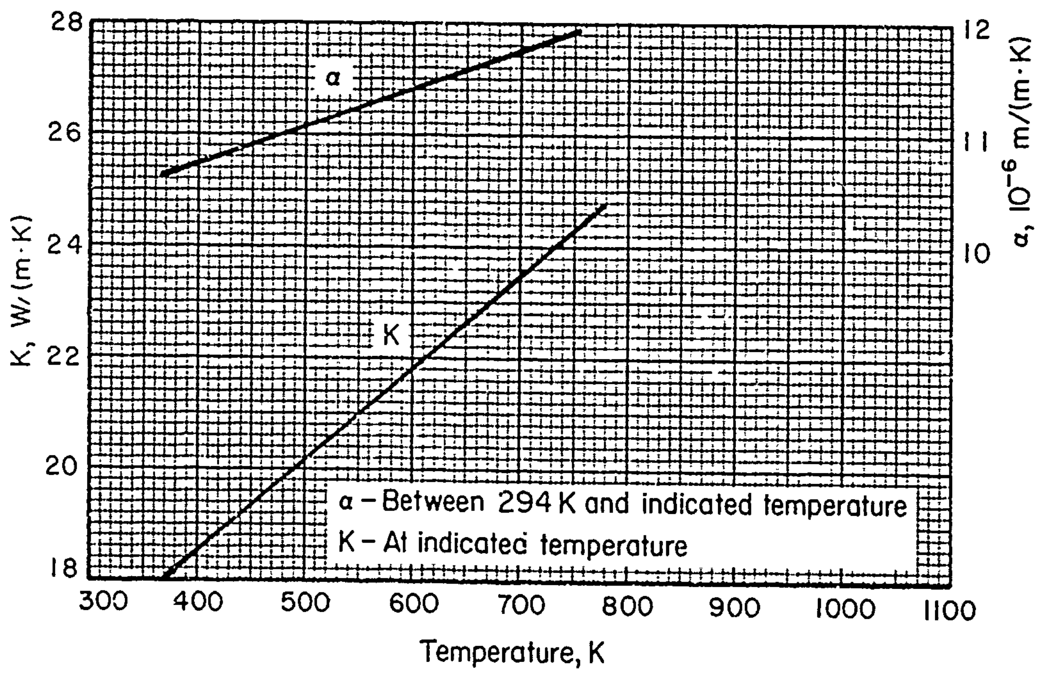


FIGURE 2.6.4.0. Effect of temperature on the physical properties of Custom 455 (H950) stainless steel.

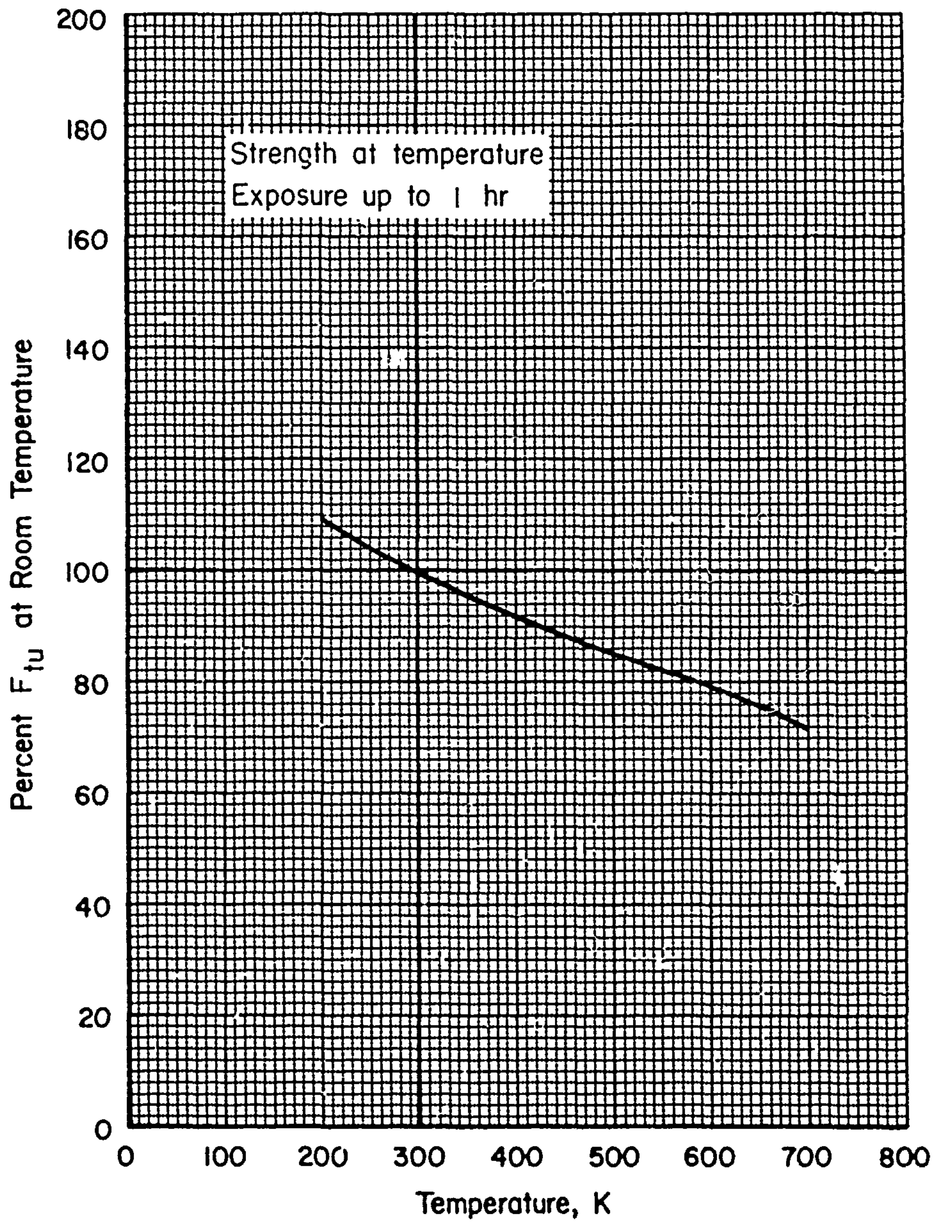


FIGURE 2.6.4.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of Custom 455 (H950) stainless steel bar.

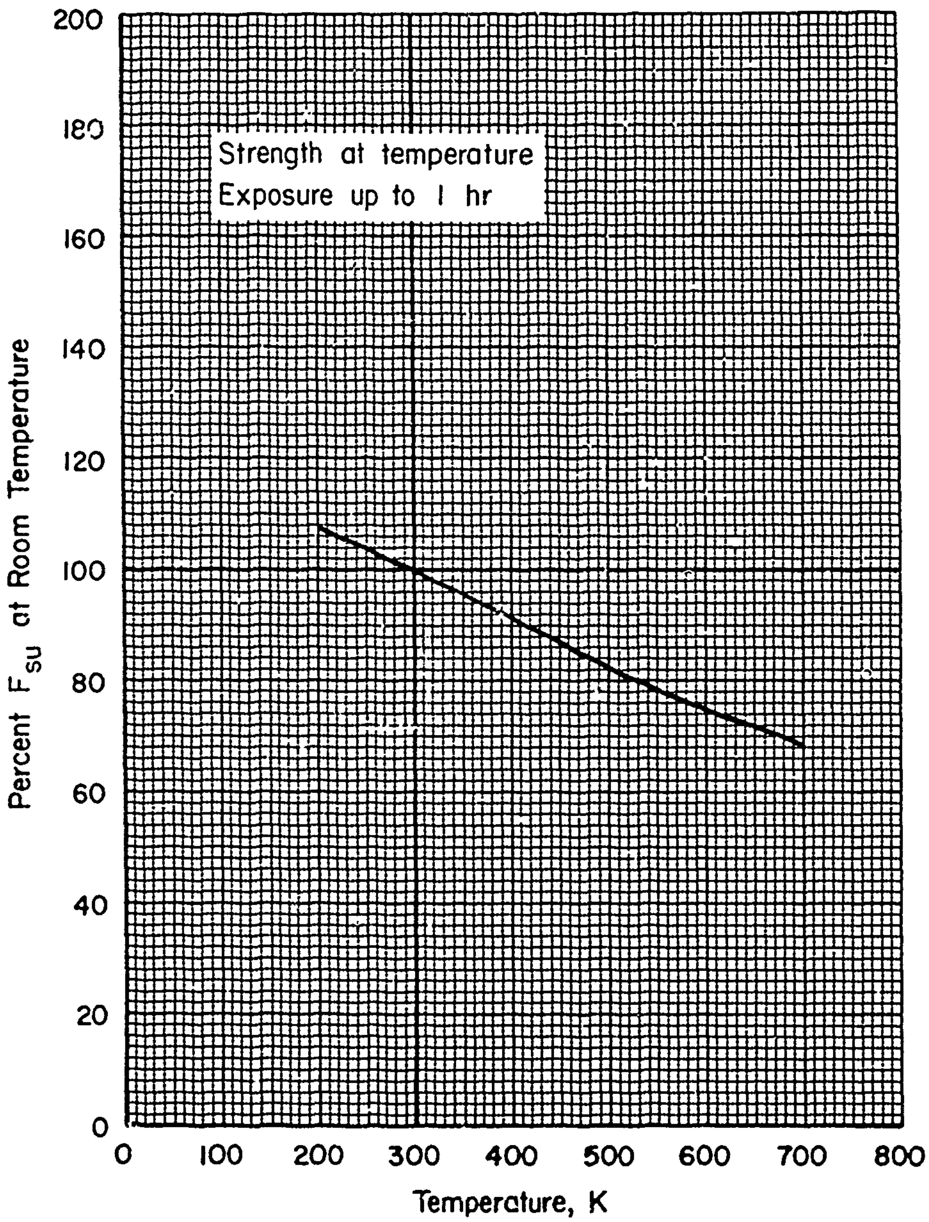


FIGURE 2.6.4.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of Custom 455 (H950) stainless steel bar.

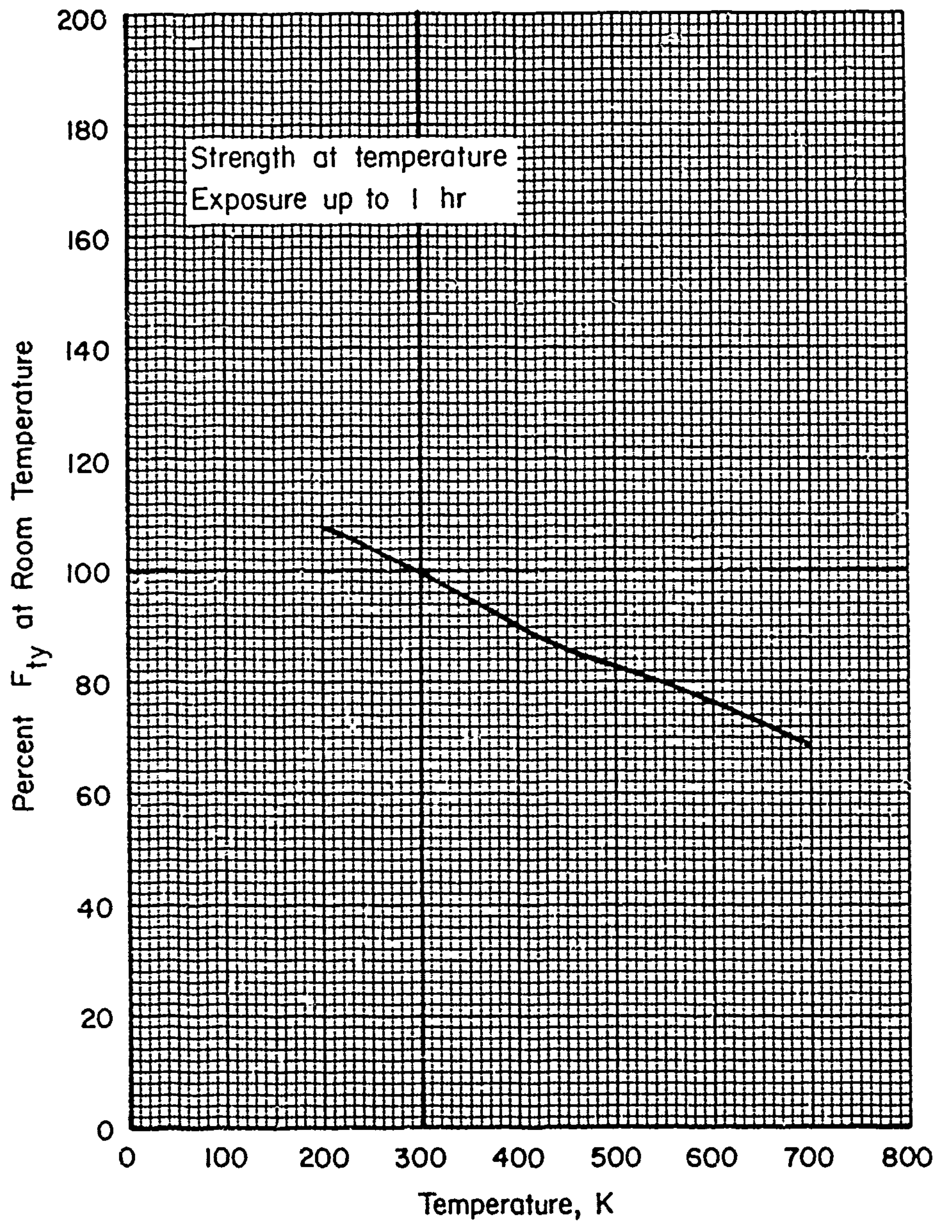


FIGURE 2.6.4.1.2. Effect of temperature on the ultimate shear strength (F_{su}) of Custom 455 (H950) stainless steel bar.

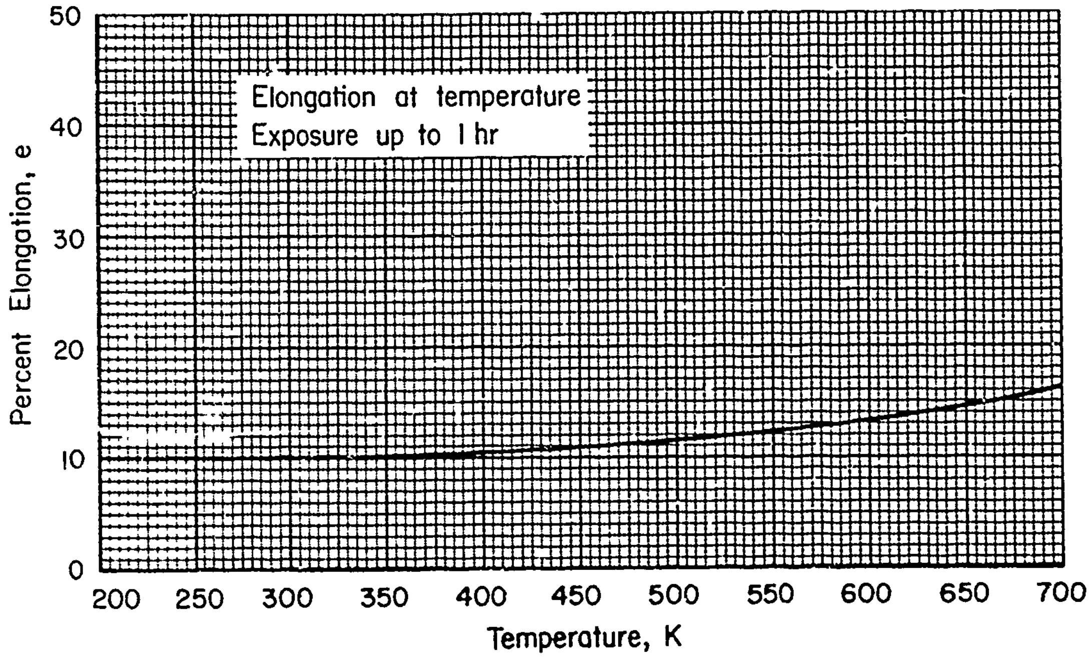


FIGURE 2.6.4.1.5(a). Effect of temperature on the elongation (e) of Custom 455 (H950) stainless steel b.r.

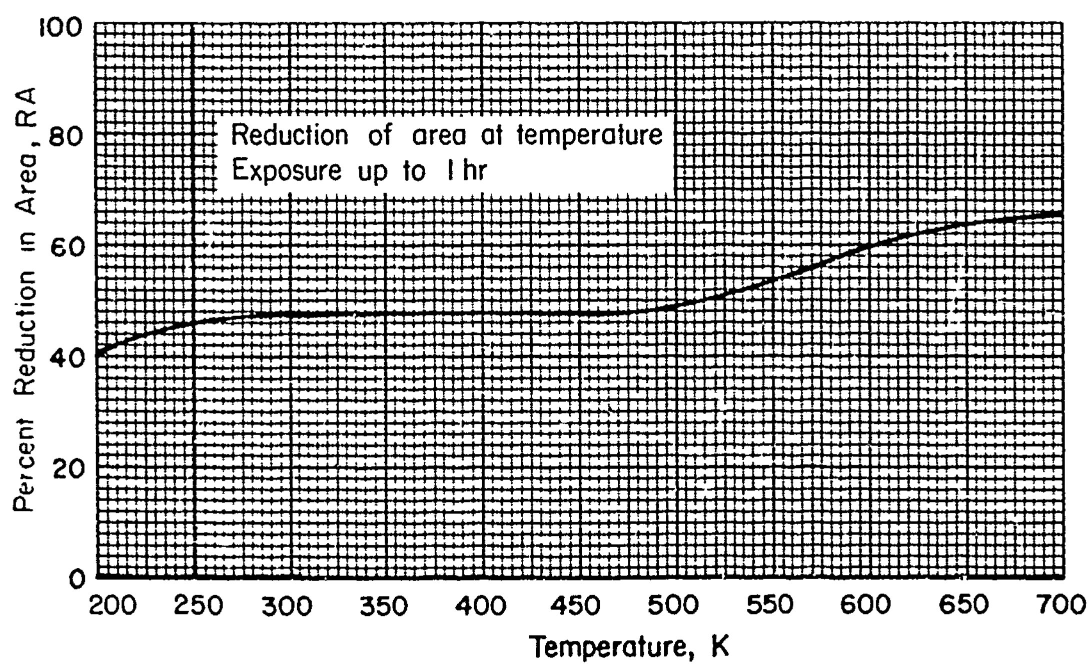


FIGURE 2.6.4.1.5(b). Effect of temperature on the reduction in area (RA) of Custom 455 (H950) stainless steel bar.

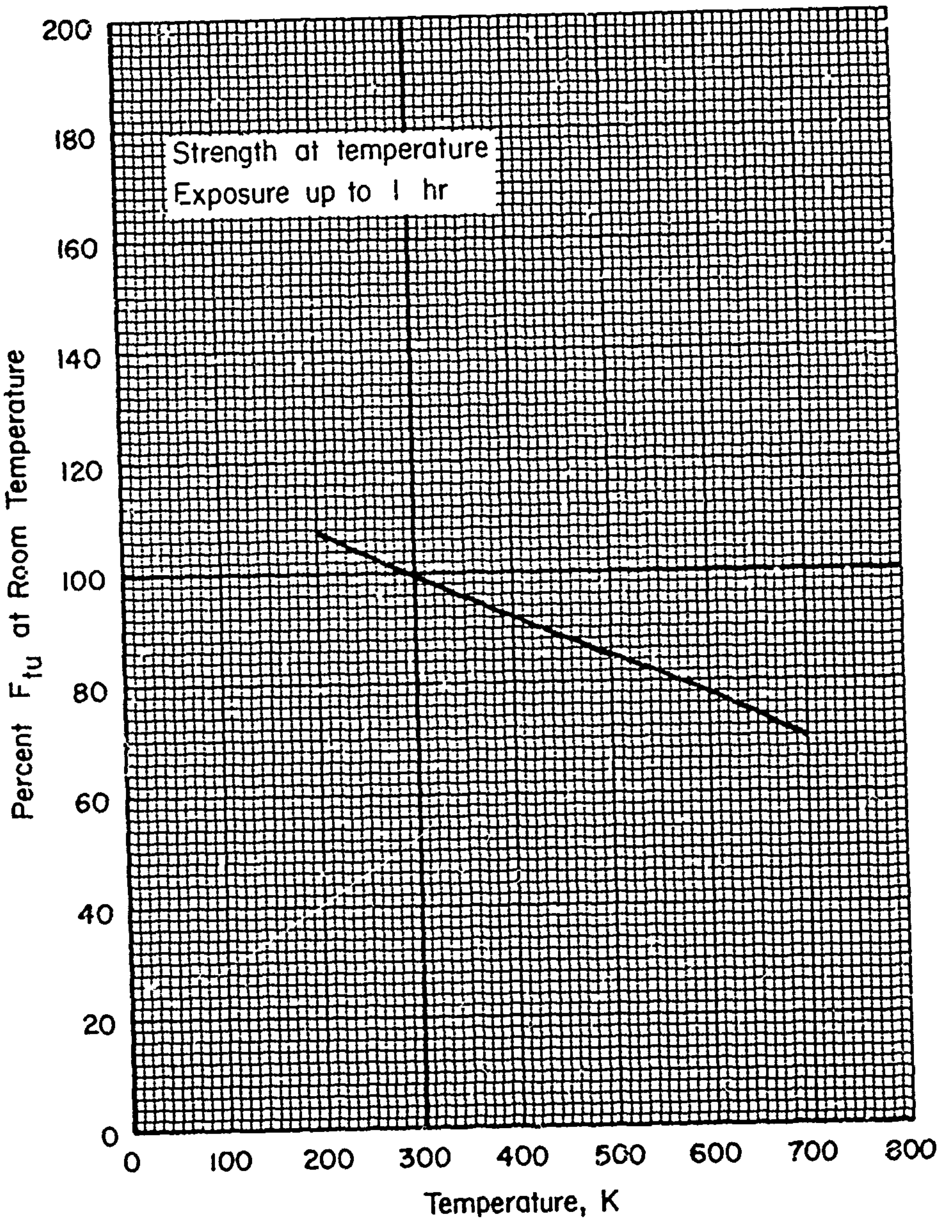


FIGURE 2.6.4.2.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of Custom 455 (H1000) stainless steel bar.

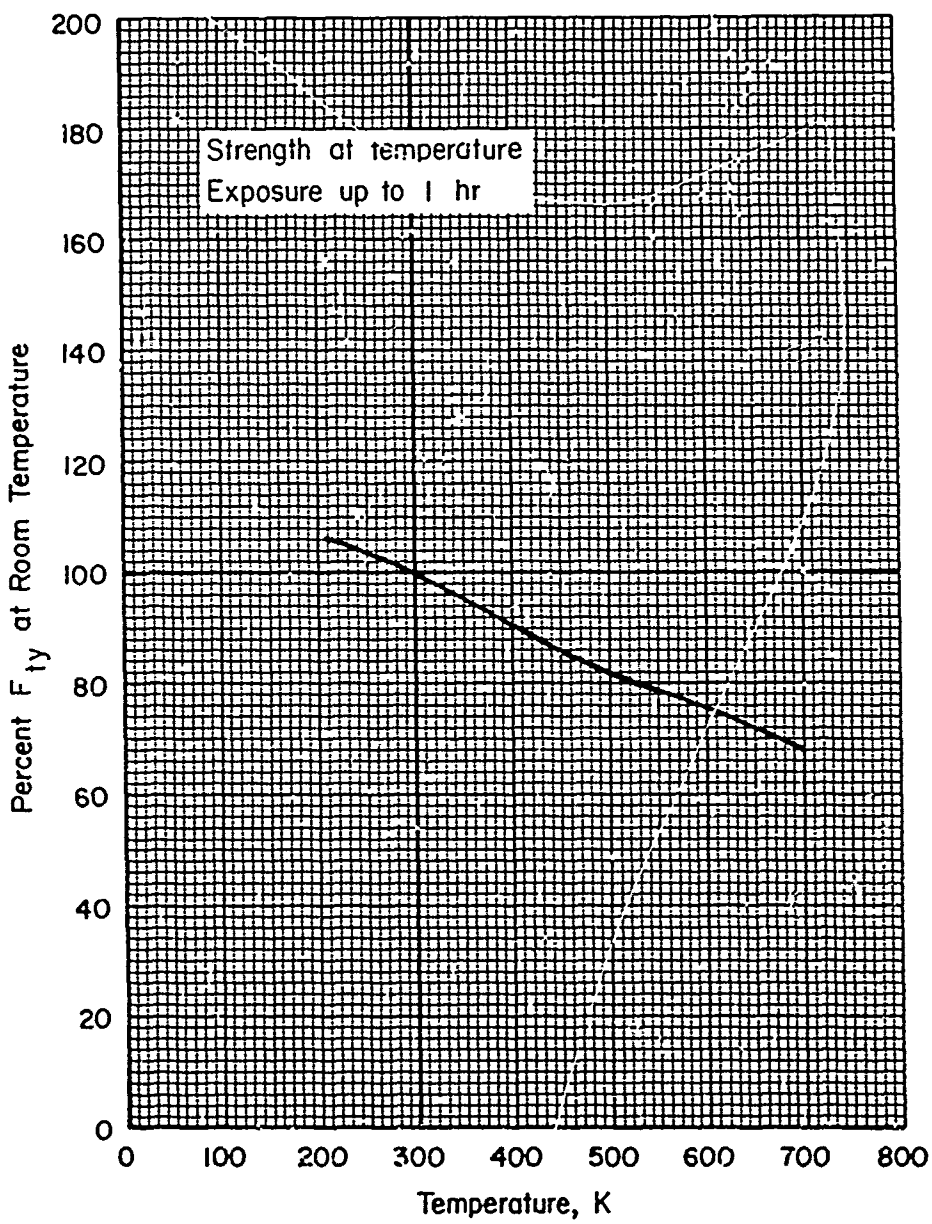


FIGURE 2.6.4.2.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of Custom 455 (H1000) stainless steel bar.

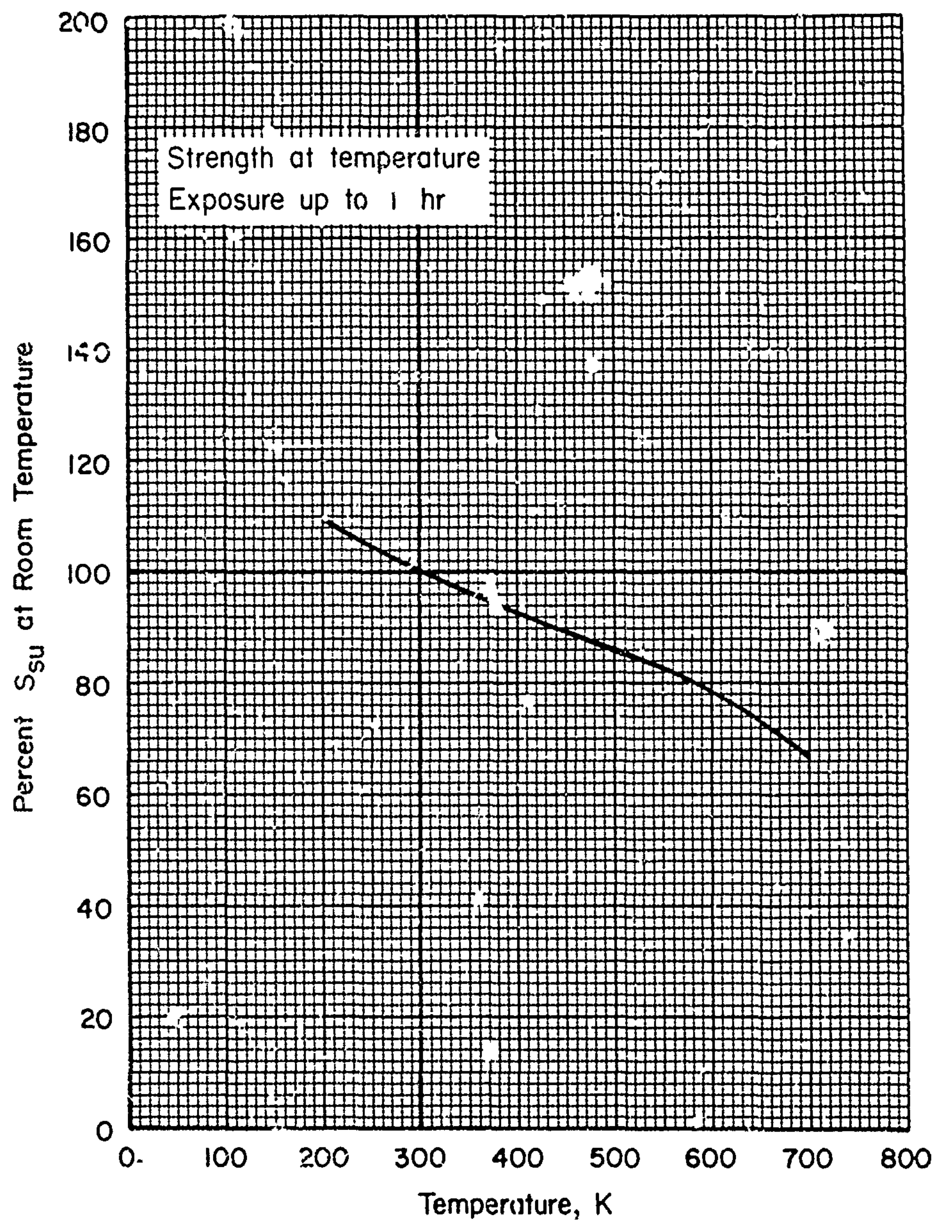


FIGURE 2.6.4.2.2. Effect of temperature on the ultimate shear strength (F_{su}) of Custom 455 (H1000) stainless steel bar.

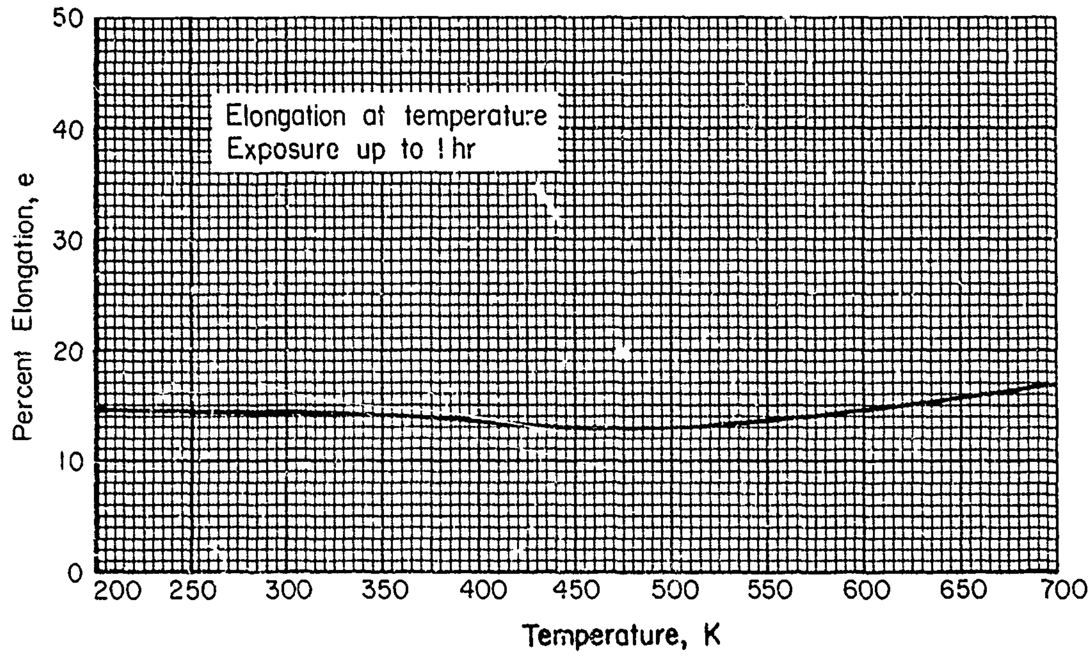


FIGURE 2.6.4.2.5(a). Effect of temperature on the elongation (e) of Custom 455 (H1000) stainless steel bar.

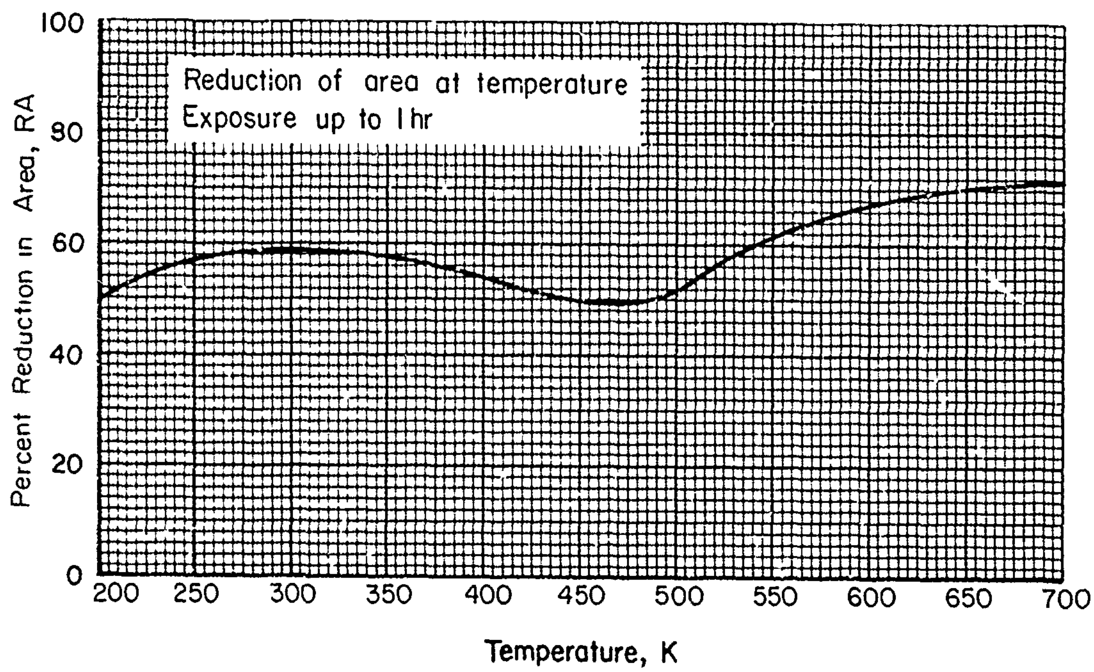


FIGURE 2.6.4.2.5(b). Effect of temperature on the reduction in area (RA) of Custom 455 (H1000) stainless steel bar.

2.6.5 PH13-8Mo

2.6.5.0 *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 700 K. When used at temperatures between 589 and 700 K, some loss in notch toughness will occur. The loss is time-temperature dependent and will occur gradually over thousands of hours at 589 K and hundreds of hours at 700 K. 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.

The material specification for PH13-8Mo is presented in Table 2.6.5.0(a).

TABLE 2.6.5.0(a). *Material Specification for PH13-8Mo Stainless Steel*

Specification	Form
AMS 5629	Bars, forgings, and rings (double-vacuum melted)

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 0.0004-0.0006 and 0.0008-0.0012 m/m 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 heat treatment to anneal (solution treat) PH13-8Mo is:

Treatment	Condition Designation
1200 K ± 15K, 30 Min.-Air Cool or Oil Quench Below 289 K	Condition A

The alloy can be heat treated to develop a wide range of properties. The hardening treatments for PH13-8Mo are presented in Table 2.6.5.0(b).

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 applications 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 811 K for 4 hours minimum aging time.

Room-Temperature Properties

The room-temperature mechanical and physical properties for PH13-8Mo are presented in Table 2.6.5.0(c). The physical properties of this alloy at room and elevated temperatures are presented in Figure 2.6.5.0.

2.6.5.1 *H950 and H1000 Conditions.*—Effect of temperature curves for tensile yield and ultimate strengths are presented in Figures 2.6.5.1.1(a) and (b).

Typical tensile, compressive, and tangent modulus stress-strain curves for the H1000 condition at room temperature are depicted in Figures 2.6.5.1.6(a) and (b). Figure 2.6.5.1.6(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 Figure 2.6.5.1.8.

TABLE 2.6.5.0(b). Nominal Hardening Treatment for PH13-8Mo Condition A (Annealed) Stainless Steel Bars, Forgings, and Rings

F_{tu}, MPa	Hardening Treatment	Condition Designation
1517	783 ± 5 K-4 Hours-Air Cool	H950
1386	811 ± 5 K-4 Hours-Air Cool	H1000
1207	839 ± 5 K-4 Hours-Air Cool	H1050
1034	866 ± 5 K-4 Hours-Air Cool	H1100
931	894 ± 5 K-4 Hours-Air Cool	H1150

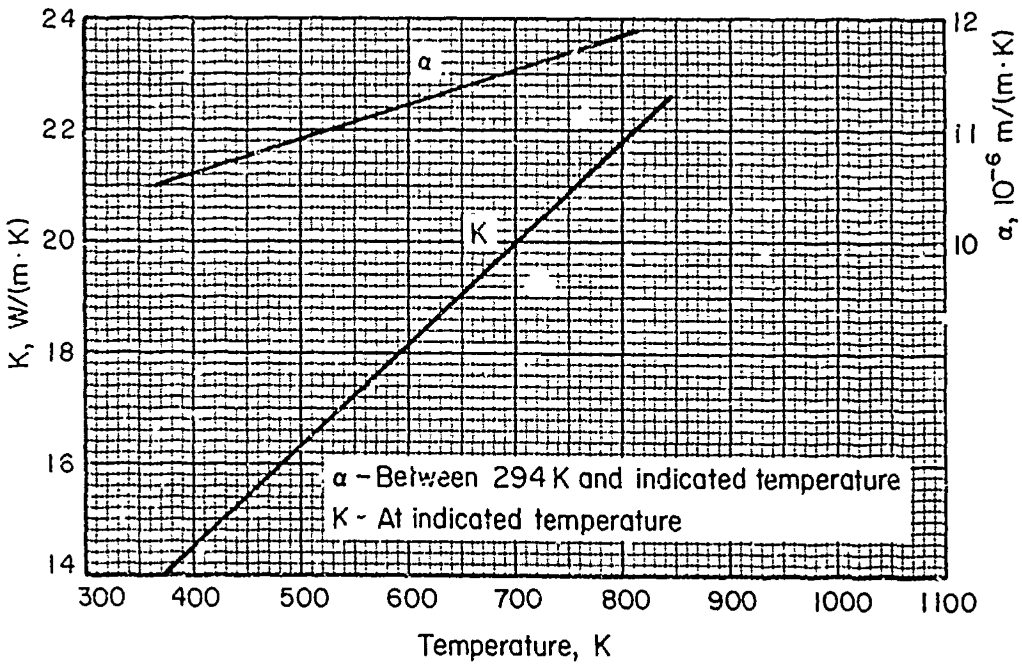


FIGURE 2.6.5.0. Effect of temperature on the physical properties of PH13-8Mo stainless steel.

TABLE 2.6.5.0(C). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF PH13-8MO STAINLESS STEEL

SPECIFICATION	AMS 5629											
FORM	ROUND, HEX, SQUARE AND FLAT BARS							DIE FORGINGS				
CONDITION	≤950		H1000		H1050	H1100	H1150	H950	H1000	H1050	H1100	H1150
THICKNESS, MM	<228.60		<203.20		<304.80			<304.80				
BASIS	A	B	A	B	S[a]	S[a]	S[a]	S	S[a]	S[a]	S[a]	S[a]
MECHANICAL PROPERTIES:												
FTU, MPA:												
L	1500	1520	1390	1430	1210	1030	931	1520	1410	1210	1030	931
T	1500	1520	1390	1430	1210	1030	931	1520	1410	1210	1030	931
FTY, MPA:												
L	1370	1410	1310[b]	1380	1140	931	621	1410	1310	1140	931	621
T	1370	1410	1310[b]	1380	1140	931	621	1410	1310	1140	931	621
FCY, MPA:												
L	...	...	1380[c]	1450[c]	...	...	...	...	...	...	...	...
T	...	...	1380[c]	1450[c]	...	...	...	...	...	...	...	...
FSU, MPA	...	...	821[c]	855[c]	...	...	...	...	...	...	...	...
FBRU, MPA:												
(E/D=1.5)	...	...	2080	2160	...	...	...	...	...	...	...	...
(E/D=2.0)	...	...	2770[c]	2870[c]	...	...	...	...	...	...	...	...
FBRY, MPA:												
(E/D=1.5)	...	...	1810	1910	...	...	...	...	...	...	...	...
(E/D=2.0)	...	...	2330[c]	2450	...	...	...	...	...	...	...	...
EL, PERCENT:												
L	10	...	10	...	13	16	18	10	10	13	16	18
T	10	...	10	...	13	16	18	10	10	13	16	18
E, GPA	195.1											
EC, GPA	202.7											
G, GPA	75.8											
MU	0.28											
PHYSICAL PROPERTIES:												
OMEGA, MG/M3	7.72											
C, J/(G*K)	0.46 (273 - 373 K) EST.											
K, W/(M*K)	SEE FIGURE 2.6.5.0											
ALPHA, 10-6 M/(M*K)	SEE FIGURE 2.6.5.0											

[a] ONLY H950 CONDITION COVERED BY AMS 5629. PROPERTIES FOR OTHER CONDITIONS REFLECT PRODUCERS GUARANTEED MINIMUM TENSILE PROPERTIES.
[b] THE A VALUE OF 1331 MPA IS HIGHER THAN THE PRODUCER'S GRARANTEED MINIMUM.
[c] TENTATIVE VALUES BASED ON LIMITED DATA.

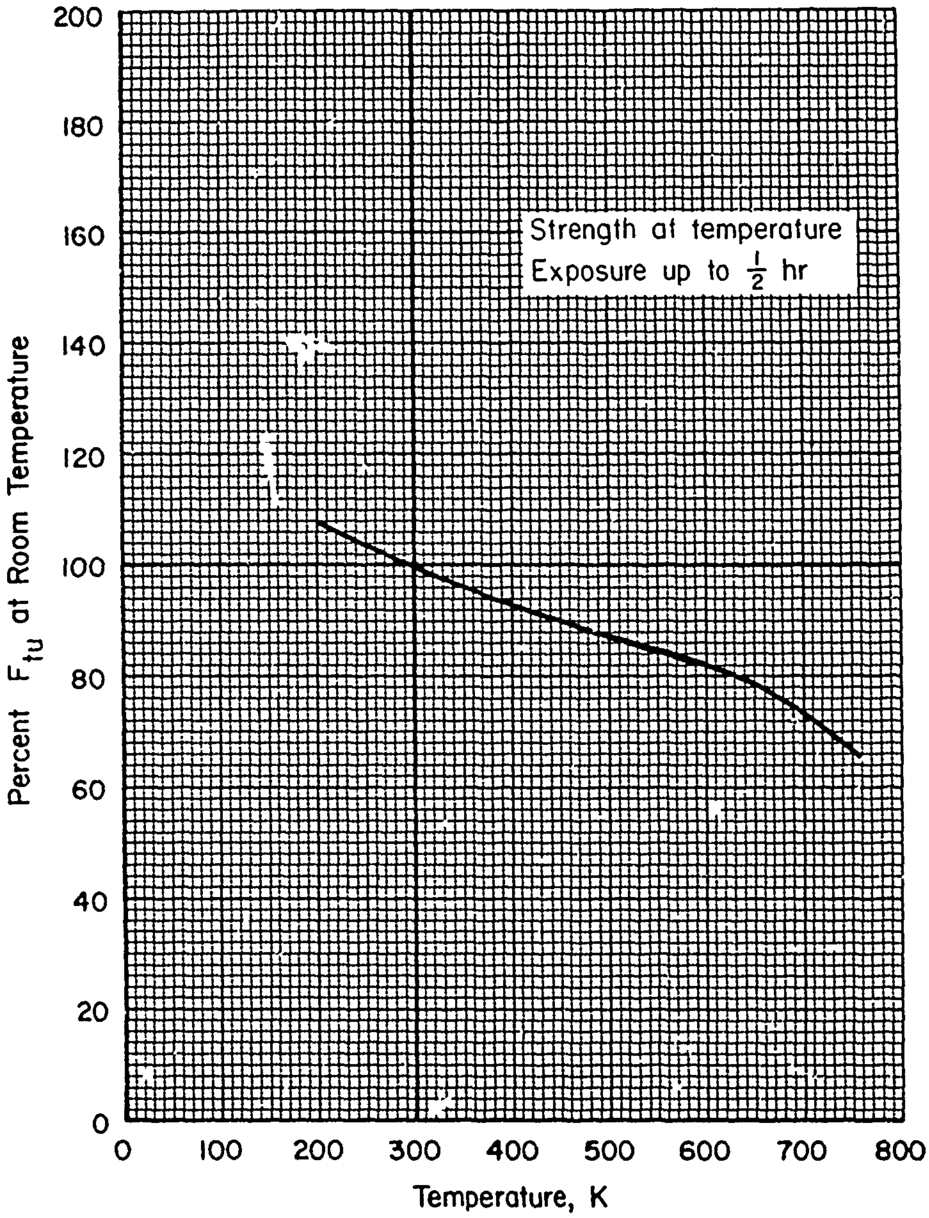


FIGURE 2.6.5.1.1(a). Effect of temperature on the tensile ultimate strength (F_{tu}) of PH 13-8 Mo (H950 and H1000) stainless steel (bar).

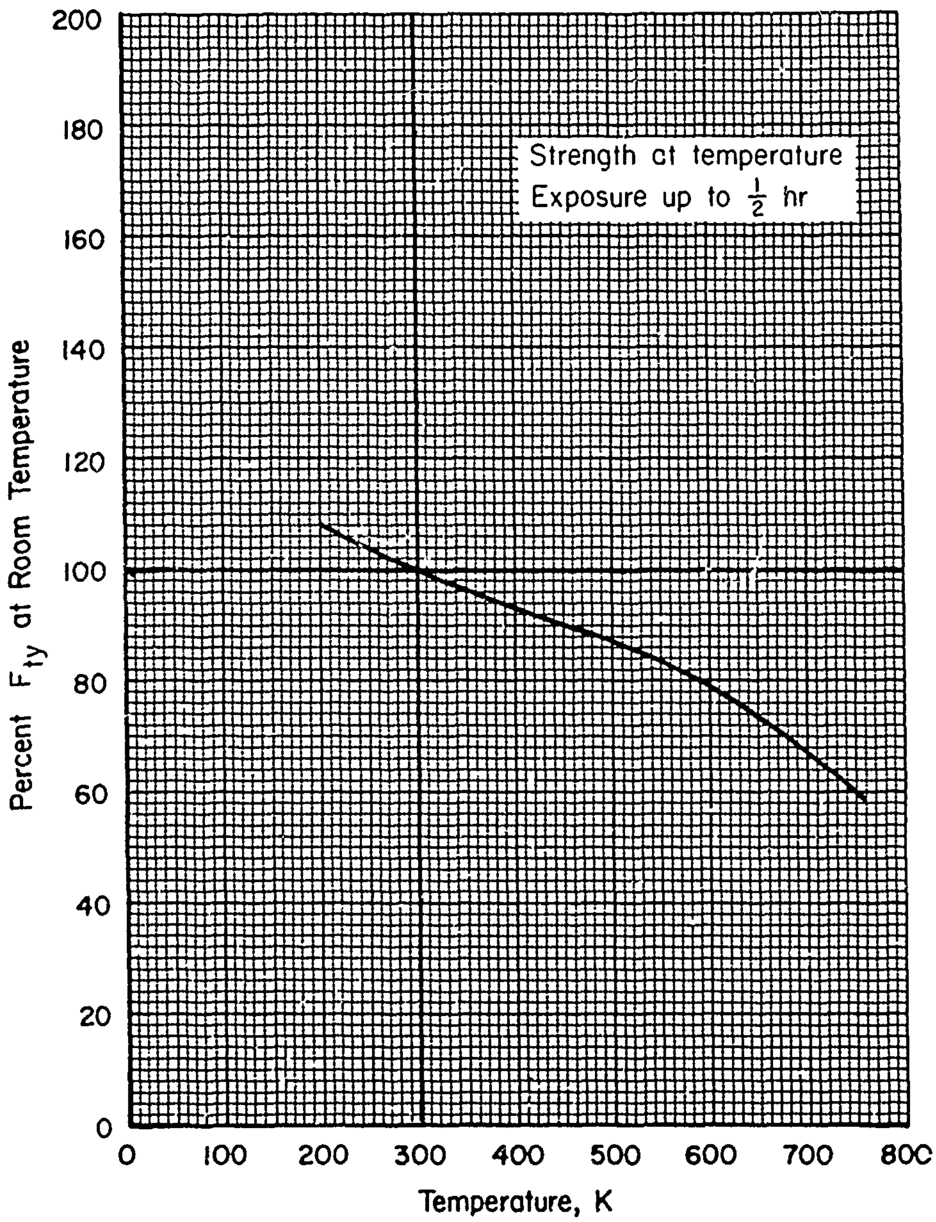


FIGURE 2.6.5.1.1(b). Effect of temperature in the tensile yield strength (F_{ty}) of PH 13-8 Mo (H950 and H1000) stainless steel (bar).

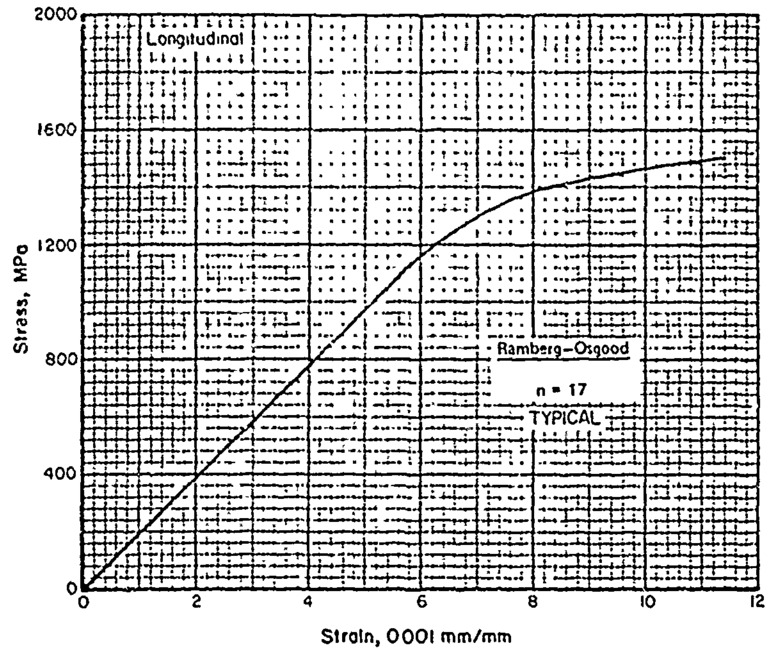


FIGURE 2.6.5.1.6(a). Typical tensile stress-strain curve at room temperature for PH13-8Mo (H1000) stainless steel (bar).

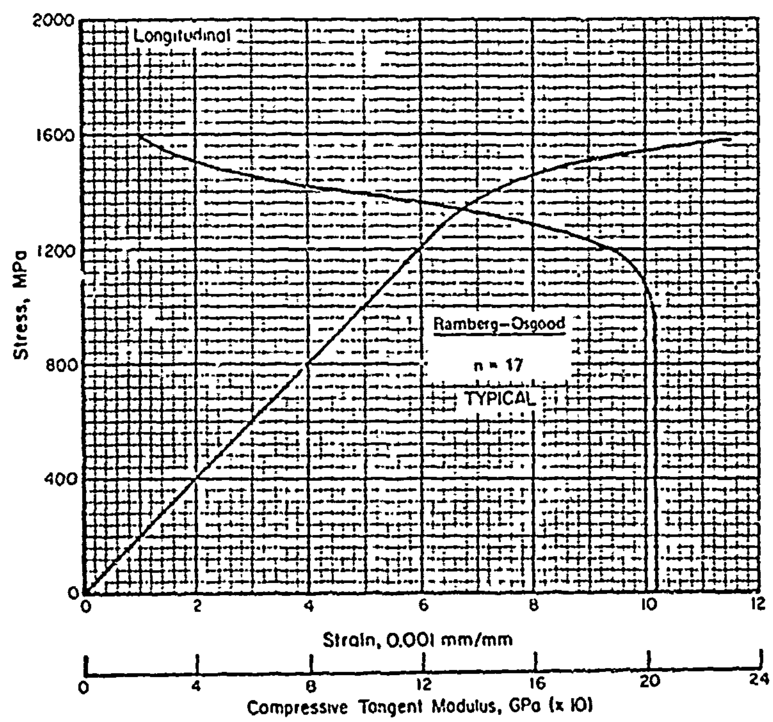


FIGURE 2.6.5.1.6(b). Typical compressive stress-strain and tangent-modulus curves at room temperature for PH13-8Mo (H1000) stainless steel (bar).

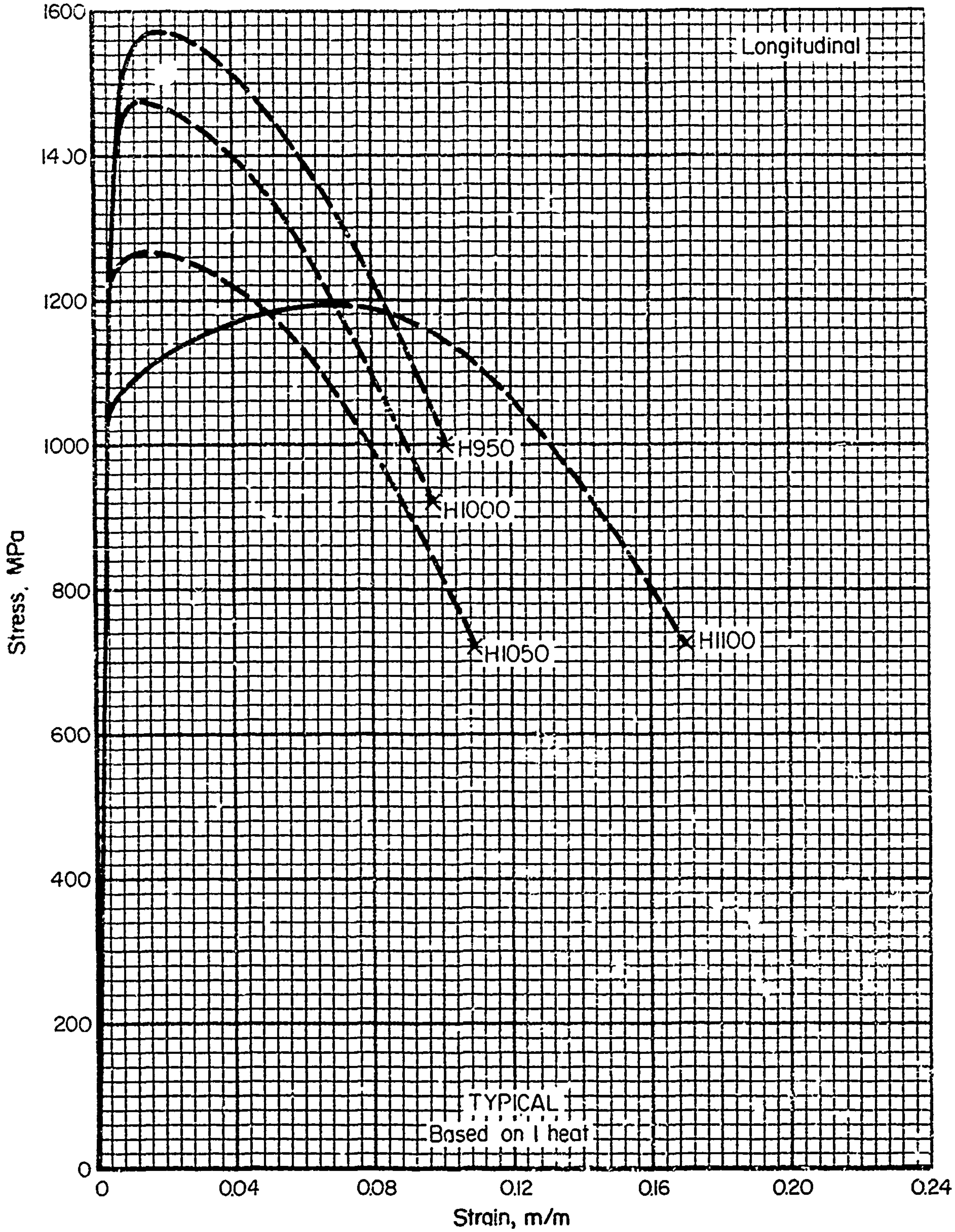


FIGURE 2.6.5.1.6(c). Typical tensile stress-strain curves (full range) at room temperature for various heat treated conditions of PH13-8Mo stainless steel (bar).

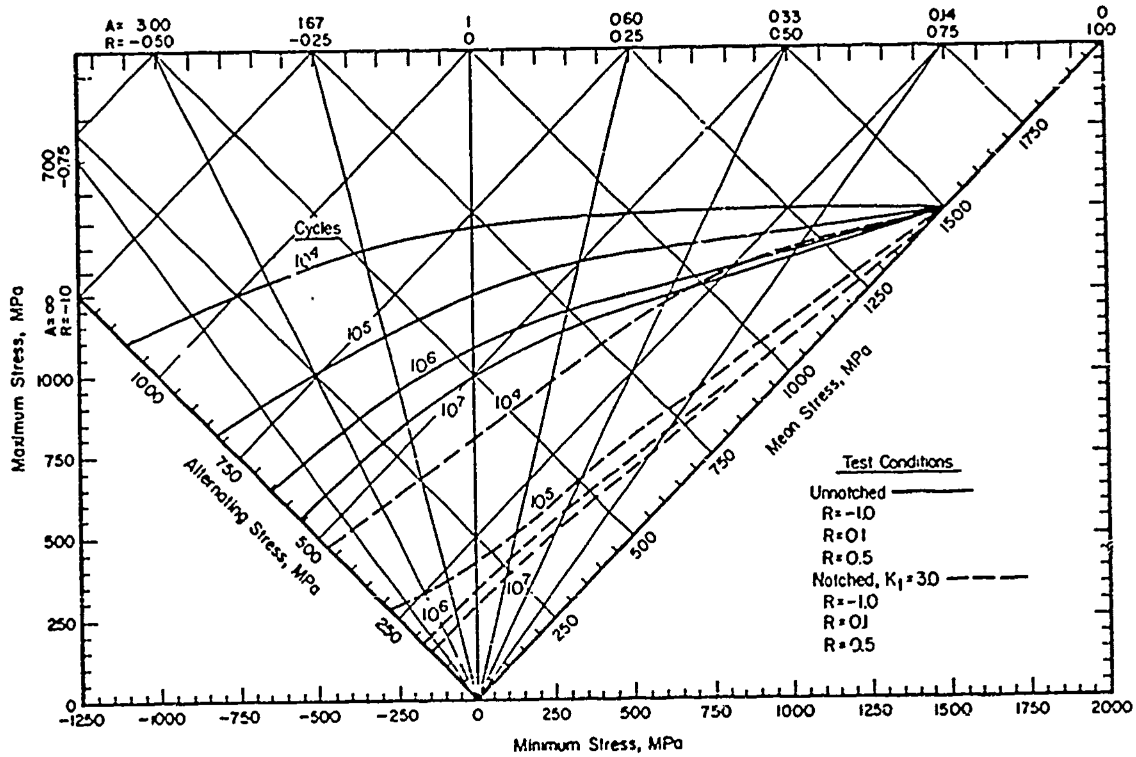


FIGURE 2.6.5.1.8. Typical constant-life fatigue diagram for PH 13-8 Mo (H1000) stainless steel (bar) at room temperature (longitudinal and long transverse)

Correlative Information for Figure 2.6.5.1.8

Product Form: Bar, 51 x 152 mm

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

Properties:

TUS, MPa	TYS, MPa	Temp, K
1500	1430	RT (Unnotched)

Specimen Details:

Unnotched: 6.40 mm diameter

Notched, V-Groove, $K_t = 3.0$
- 9.07 mm gross diameter
- 6.40 mm net diameter
- 0.33 mm root radius, r
- 60°° flank angle, ω

$$K_N = 2.75;\ \rho = 0.00305 \text{ mm, where } K_N = 1 + \frac{K_t - 1}{1 + \frac{\pi}{\pi - \omega}\sqrt{\frac{\rho}{r}}}$$

Surface Condition: Unnotched: Mechanically polished in longitudinal direction. Notched: Polished mechanically with abrasively charged wire.

2.6.6 PH14-8Mo

2.6.6.0 *Comments and Properties.*—PH14-8Mo is a semiaustenitic precipitation-hardening stainless steel used for parts requiring corrosion resistance, high-strength, high-fracture toughness, and oxidation resistance up to 700 K. When used at temperatures between 589 and 700 K, some loss in notch toughness will occur. The loss is time-temperature dependent and will occur gradually over thousands of hours at 589 K and hundreds of hours at 700 K. Depending upon the application, this loss in notch toughness may not be important, and useful engineering properties may still be available. PH14-8Mo is produced by vacuum-induction melting and is available in sheet and strip, normally furnished in the solution-treated (A) condition.

The material specification for PH14-8Mo is presented in Table 2.6.6.0(a).

TABLE 2.6.6.0(a). *Material Specification for PH14-8Mo Stainless Steel*

Specification	Form
AMS 5603	Sheet and strip (vacuum-induction-melted)

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.

Heat Treatment.—PH14-8Mo must be used in the heat-treated condition and should not be placed in service in Condition A. Condition A should be restored by resolution treating when this condition has been altered during processing operations, such as hot working, welding, or brazing. PH14-8Mo is most frequently used in one of a variety of brazing-cycle-heat-treated (BCHT) tempers. The tempers designated in Table 2.6.6.0(b) represent those commonly specified by the users for certification purposes and are defined in AMS 5603.

A net dimensional expansion of about 0.004 m/m will occur in heat treating PH14-8Mo to Conditions SRH950 or SRH1050 from Condition A.

The heat treatment to anneal PH14-8Mo stainless sheet and strip is:

Treatment	Condition Designation
1269 K ± 15 K - Equalize - Air Cool	Condition A

The transformation treatment from Condition A is as follows:

Treatment	Condition Designation
1200 K ± 8 K - within 1 Hour start cooling to 194 K ± 5K - 8 Hours - Air Warm	SR100

PH14-8Mo then can be hardened from SR100 by either of the following treatments:

Hardening Treatment	Condition Designation
783 K ± 5 K - 60 Minutes - Air Cool	SRH950
839 K ± 5 K - 60 Minutes - Air Cool	SRH1050

Room-Temperature Properties

The room-temperature properties for PH14-8Mo are presented in Table 2.6.6.0(b).

The physical properties of this alloy at room and elevated temperatures are presented in Figure 2.6.6.0.

2.6.6.1 *SRH950 and SRH1050 Conditions.*—Effect of temperature on various mechanical properties for these conditions are presented in Figures 2.6.6.1.1(a) through 2.6.6.1.1(b).

A typical tensile stress-strain curve at room temperature for SRH1050 condition is presented in Figure 2.6.6.1.6.

TABLE 2.6.6.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF PH14-8MO STAINLESS STEEL (SHEET AND STRIP)

SPECIFICATION	AMS 5603					
FORM	SHEET AND STRIP					
CONDITION	SRH 950			SRH 1050		
THICKNESS, MM	0.13-0.50	0.51-4.76		0.13-0.50	0.51-4.76	
BASIS	S[a]	A[b]	B[b]	S[a]	A[b]	B[b]
MECHANICAL PROPERTIES:						
FTU, MPA:						
L	...	...	...	...	...	...
T	1520	1480	1520	1380	1330	1370
FTY, MPA:						
L	...	...	...	...	...	...
T	1310	1310[c]	1410	1240	1240[c]	1320
FCY, MPA:						
L	...	...	...	...	...	...
T	...	...	...	...	...	...
FSU, MPA	...	...	...	...	...	...
FBRU, MPA:						
(E/D=1.5)	...	...	...	...	...	...
(E/D=2.0)	...	...	...	...	...	...
FBRY, MPA:						
(E/D=1.5)	...	...	...	...	...	...
(E/D=2.0)	...	...	...	...	...	...
EL, PERCENT:						
L	...	...	...	...	...	...
T	d	4	...	d	4	...
E, GPA	200.0					
EC, GPA	...					
G, GPA	...					
MU	...					
PHYSICAL PROPERTIES:						
OMEGA, MG/M3	7.70					
C, J/(G*K)	...					
K, W/(M*K)	...					
ALPHA, 10-6 M/(M*K)	SEE FIGURE 2.6.6.0					

[a] S-BASIS PROPERTIES REPRESENT HEAT-TREAT CAPABILITY REQUIREMENTS: TRANSVERSE DIRECTION FOR WIDTHS 228.6 MM AND OVER, LONGITUDINAL FOR WIDTHS LESS THAN 228.6MM.

[b] APPLICABLE TO MATERIAL AGED BY USER FROM CONDITION A: TRANSVERSE DIRECTION.

[c] THE INDICATED VALUES HAVE AN S DATA BASIS. THE CORRESPONDING A VALUES ARE 1372 MPA FOR SRH950, AND 1276 MPA FOR SRH1050.

[d] ELONGATION: 0.127 TO 0.252 MM - 2 PERCENT.
0.253 TO 0.5055 MM - 3 PERCENT.

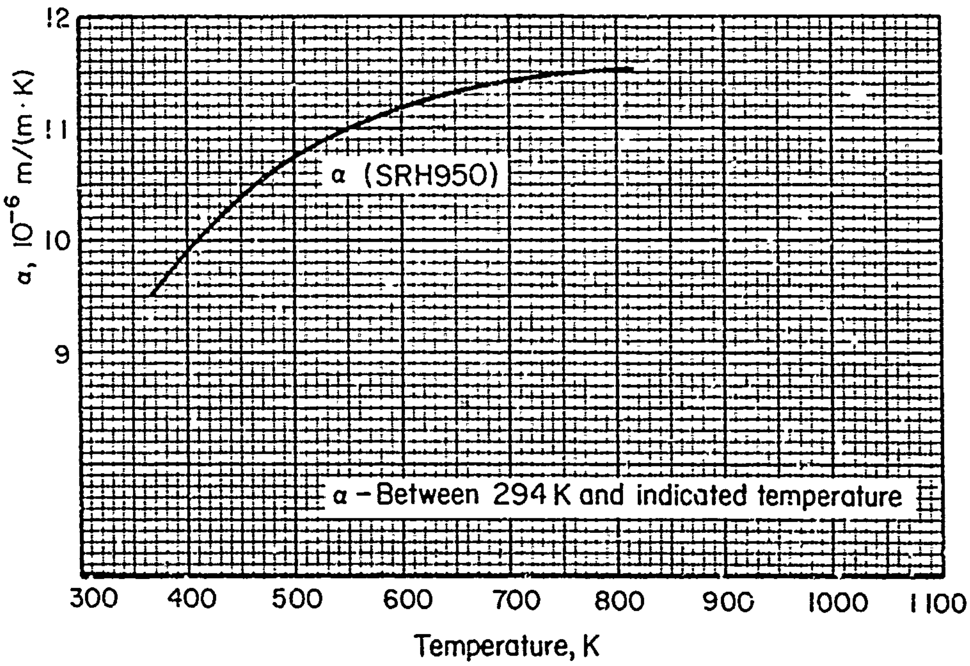


FIGURE 2.6.6 0. Effect of temperature on the physical properties of PH14-8Mo stainless steel.

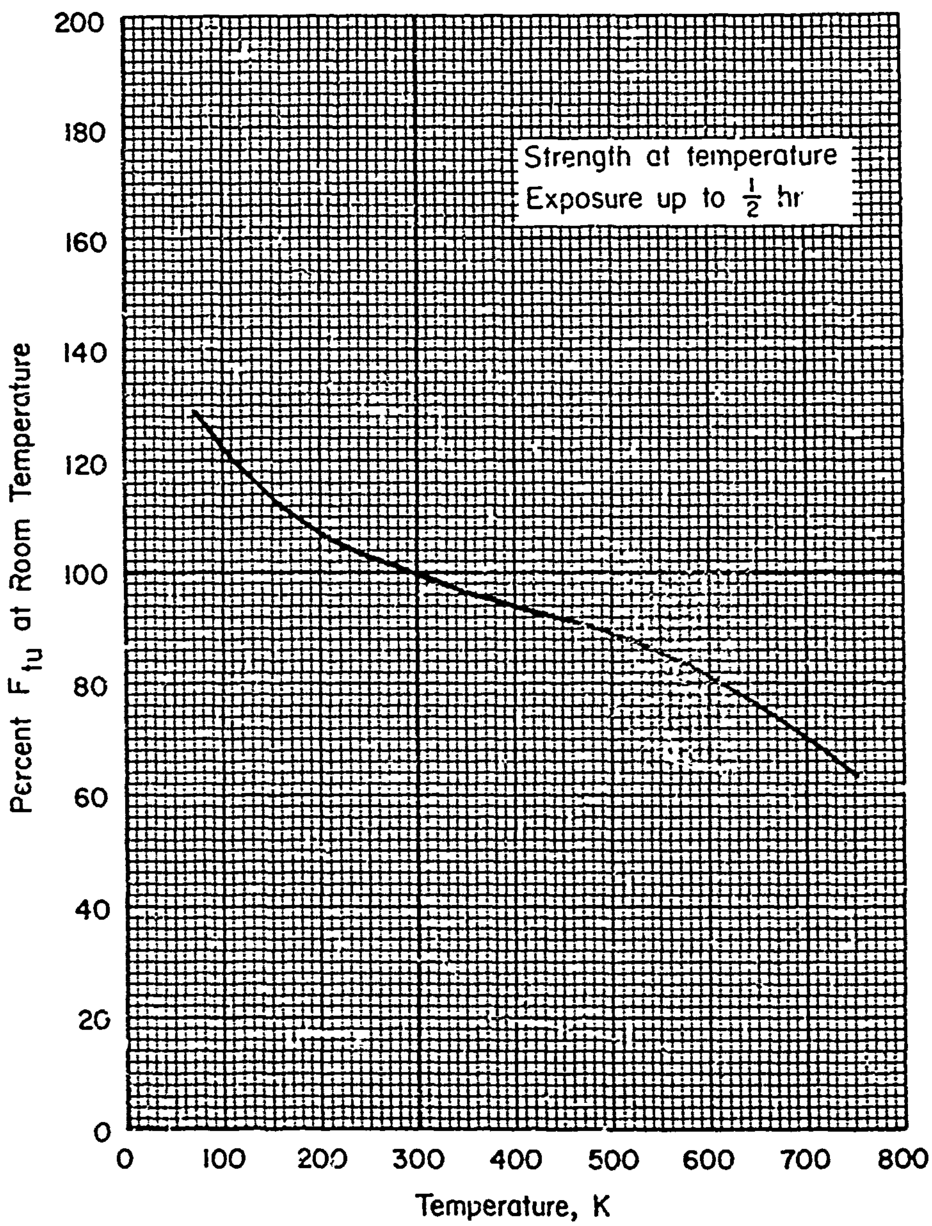


FIGURE 2.6.6.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of PH 14-8 Mo (SRH950 and SRH1050) stainless steel (sheet).

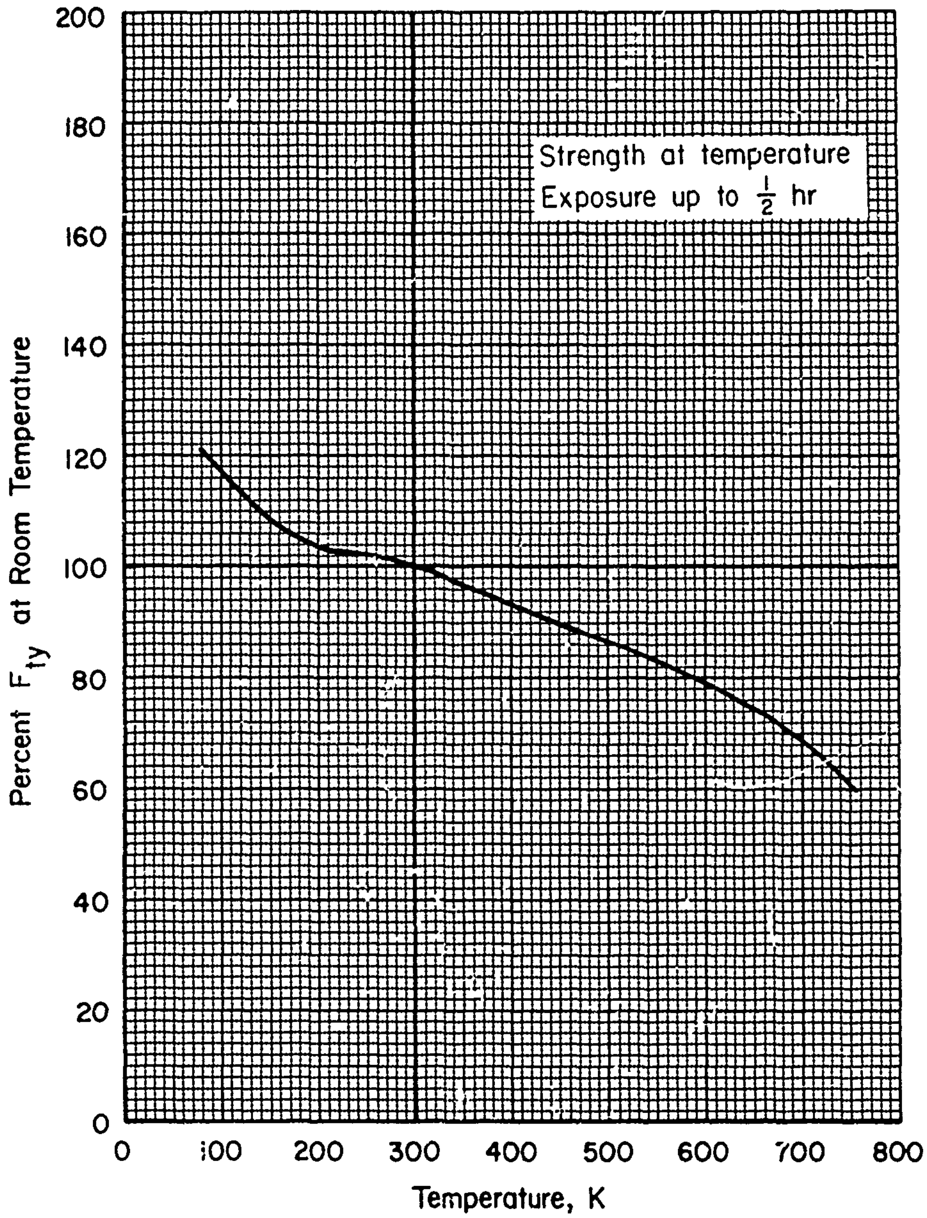


FIGURE 2.6.6.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of PH 14-8 Mo (SRH950 and SRH1050) stainless steel (sheet).

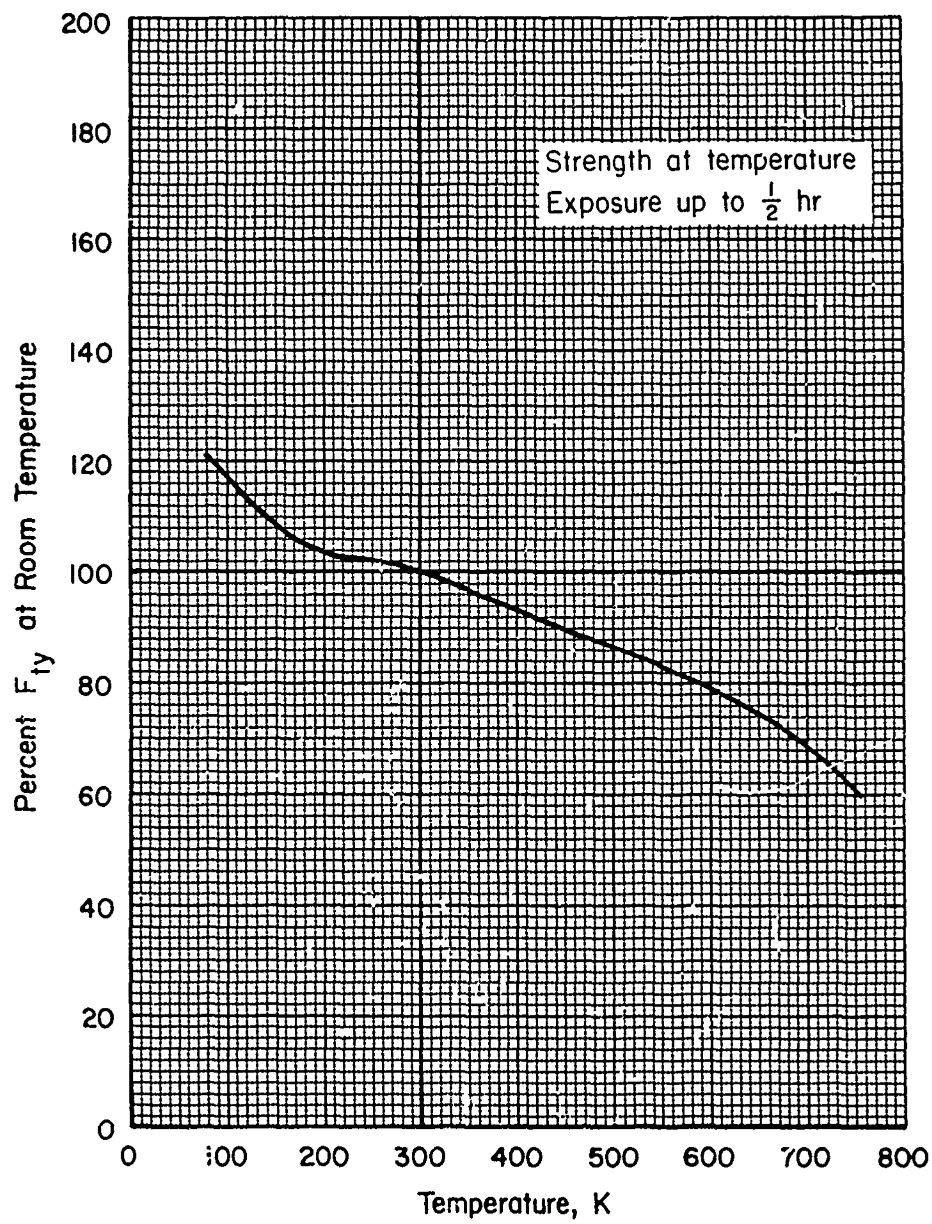


FIGURE 2.6.6.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of PH 14-8 Mo (SRH950 and SRH1050) stainless steel (sheet).

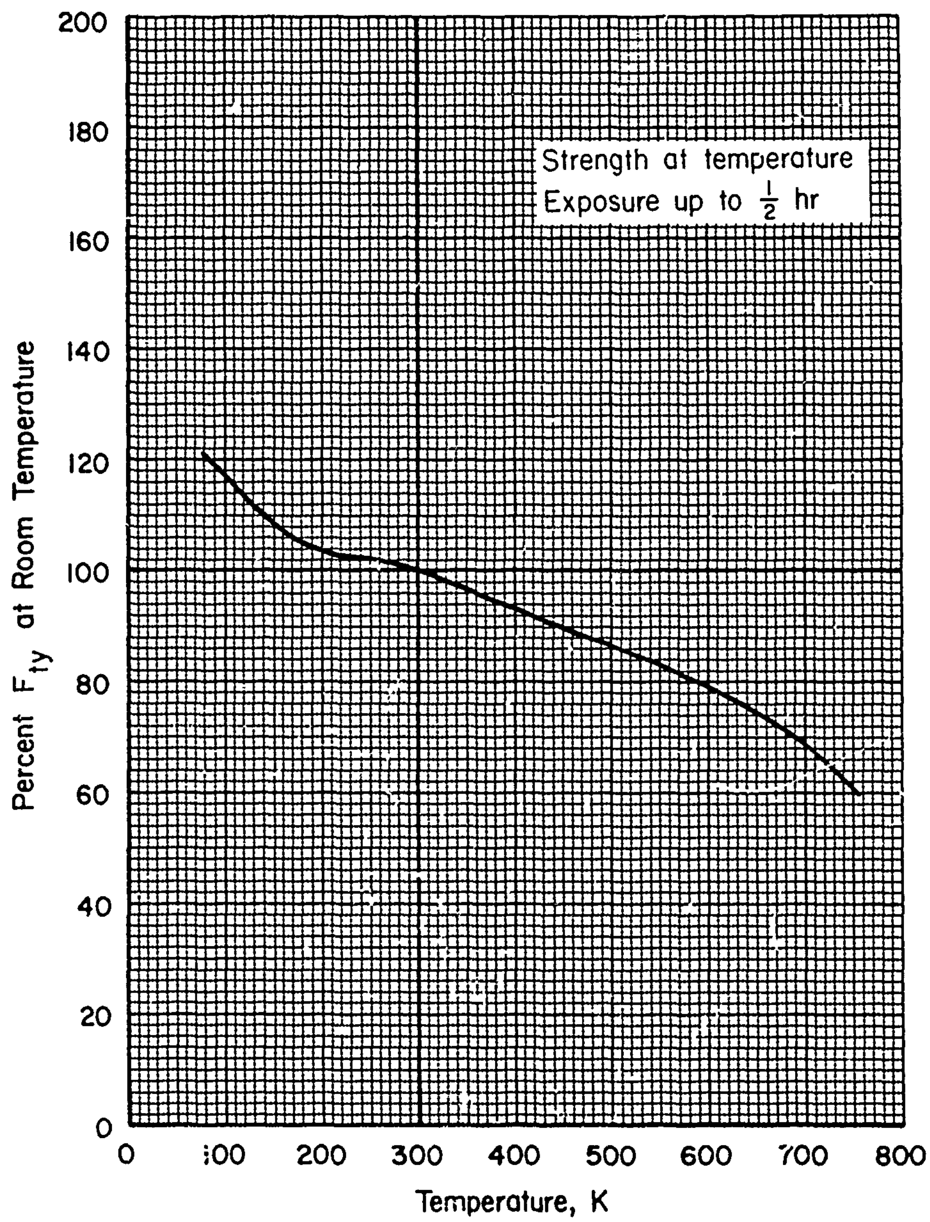


FIGURE 2.6.6.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of PH 14-8 Mo (SRH950 and SRH1050) stainless steel (sheet).

TABLE 2.6.7.0(b). Nominal Hardening Treatments for 15-5PH Condition A (Annealed) Stainless Steel Bars, Forgings, and Rings

F_{tu}, MPa	Hardening Treatment	Rockwell Hardness	Condition Designation
1310	755 ± 5 K-1 Hour-Air Cool	C40/47	H900
1172	764 ± 5 K-4 Hours-Air Cool	C38/45	H925
1069	825 ± 5 K-4 Hours-Air Cool	C35/42	H1025
1000	853 ± 5 K-4 Hours-Air Cool	C31/39	H1075
965	866 ± 5 K-4 Hours-Air Cool	C32/38	H1100
931	894 ± 5 K-4 Hours-Air Cool	C28/37	H1150
793	1033 ± 15 K-2 Hours-Air Cool plus 894 ± 5 K-4 Hours-Air Cool	C24/30	H1150M

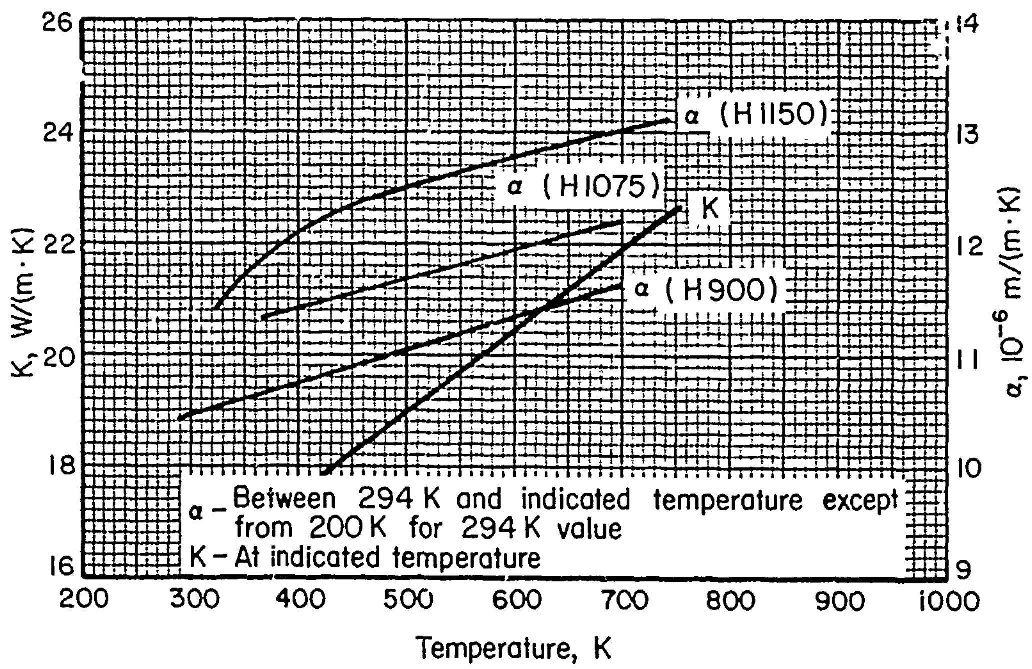


FIGURE 2.6.7.0. Effect of temperature on the physical properties of 15-5PH stainless steel.

TABLE 2.6.7.0(C). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 15-5PH STAINLESS STEEL (BARS AND FORGINGS)

SPECIFICATION	AMS 5659						
FORM	BARS AND FORGINGS						
CONDITION	H900	H925	H1025	H1075	H1100	H1150	H1150M
THICKNESS, MM	<304.80	<304.80	<304.80	<304.80	<304.80	<304.80	<304.80
BASIS	S	S[a]	S[a]	S[a]	S[a]	S[a]	S[a]
MECHANICAL PROPERTIES:							
FTU, MPA:							
L	1310	1170	1070	1000	965	931	793
T	1310	1170	1070	1000	965	931	793
FTY, MPA:							
L	1170	1070	1000	862	793	724	517
T	1170	1070	1000	862	793	717	517
FCY, MPA:							
L	...	...	986	...	...	683	...
T	...	...	986	...	...	683	...
FSU, MPA	...	...	669	...	...	586	...
FBRU[b], MPA:							
(E/D=1.5)	...	...	1520	...	...	...	...
(E/D=2.0)	...	...	1970	...	...	...	...
FBRY[b], MPA:							
(E/D=1.5)	...	...	1300	...	...	...	...
(E/D=2.0)	...	...	1530	...	...	...	...
EL, PERCENT:							
L	10	10	12	13	14	16	18
T	6	7	8	9	10	11	14
E, GPA	196.5						
EC, GPA	201.3						
G, GPA	77.2						
MU	0.27						
PHYSICAL PROPERTIES:							
OMEGA, MG/M3	7.83						
C, J/(G*K)	...						
K, W/(M*K)	SEE FIGURE 2.6.7.0						
ALPHA, 10-6 M/(M*K)	SEE FIGURE 2.6.7.0						

[a] ONLY THE H900 CONDITION IS PRESENTLY COVERED BY AMS 5659. PROPERTIES FOR OTHER CONDITIONS REFLECT PRODUCERS GUARANTEED MINIMUM TENSILE PROPERTIES.
[b] BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

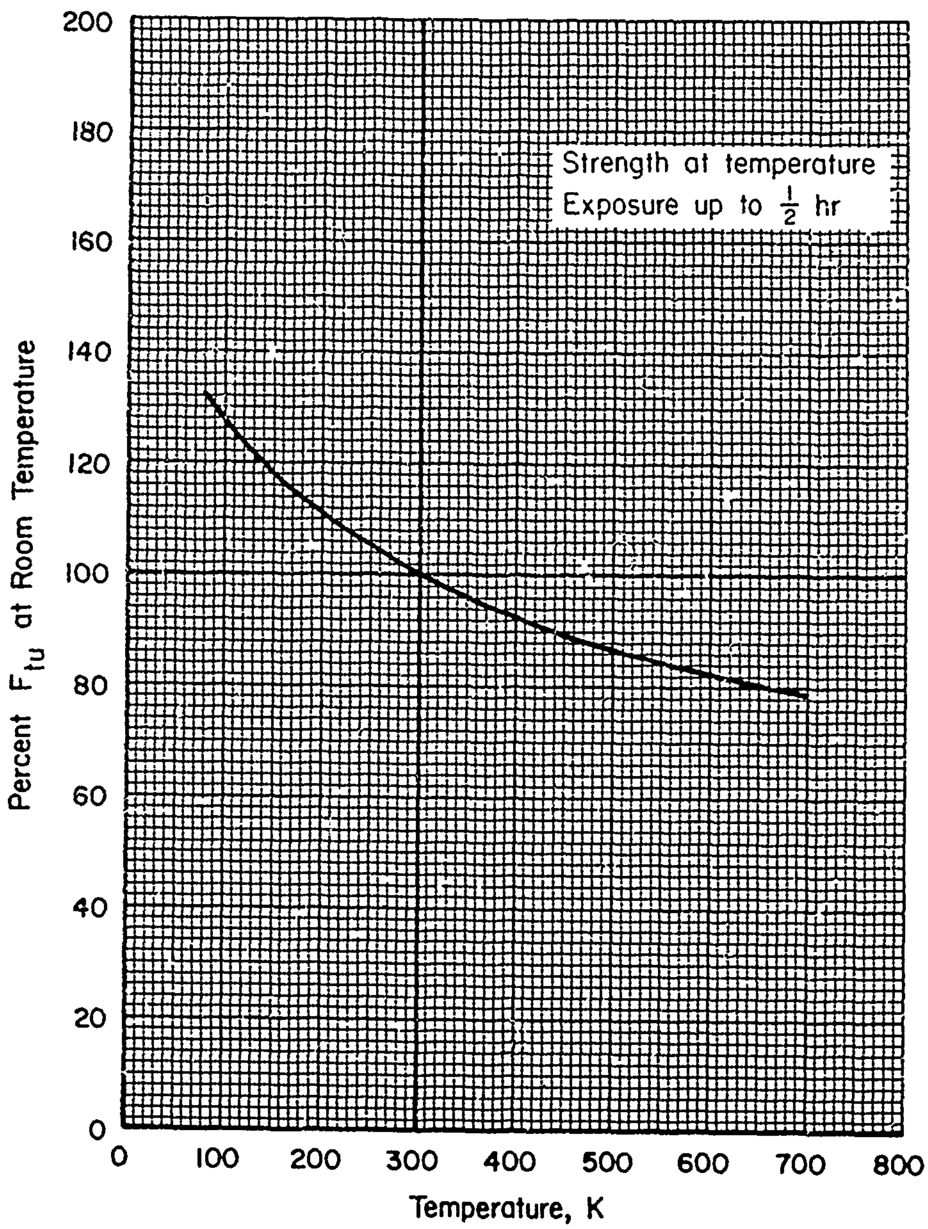


FIGURE 2.6.7.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of 15-5 PH (H925, H1025, and H1100) stainless steel (bar).

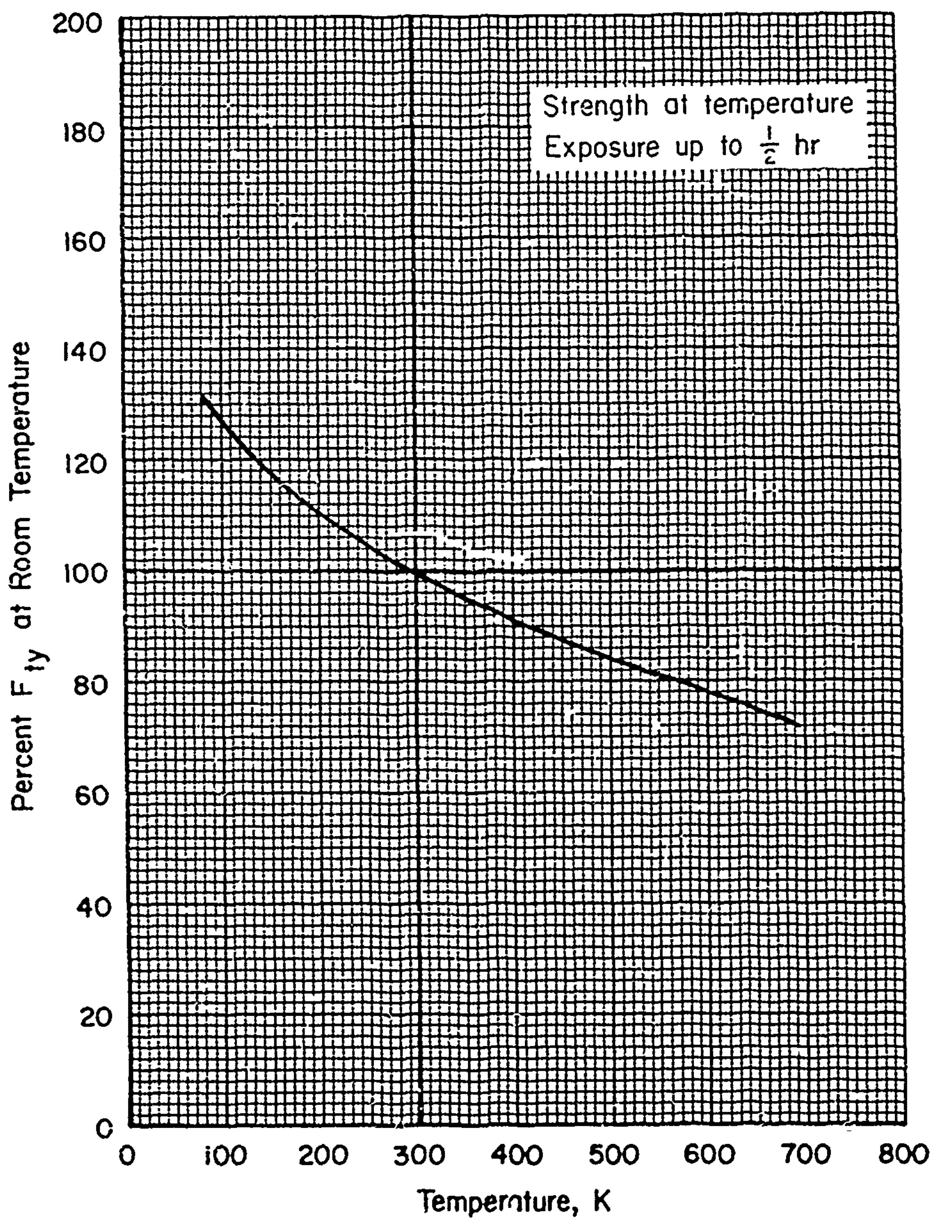


FIGURE 2.6.7.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of 15-5 PH (H925, H1025, and H1100) stainless steel (bar).

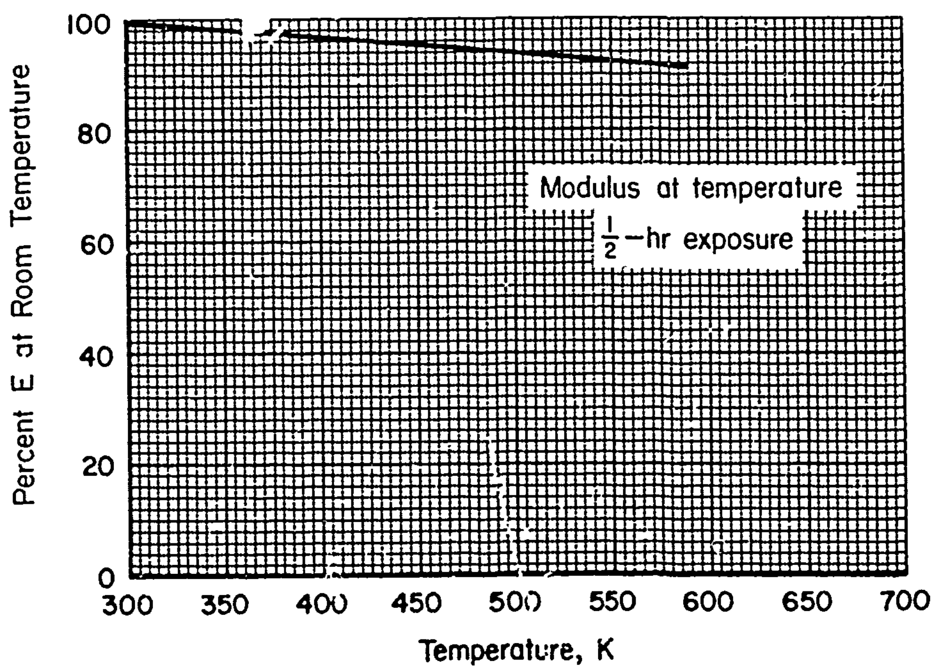


FIGURE 2.6.7.1.4. Effect of temperature on the tensile modulus (E) of 15-5 PH stainless steel.

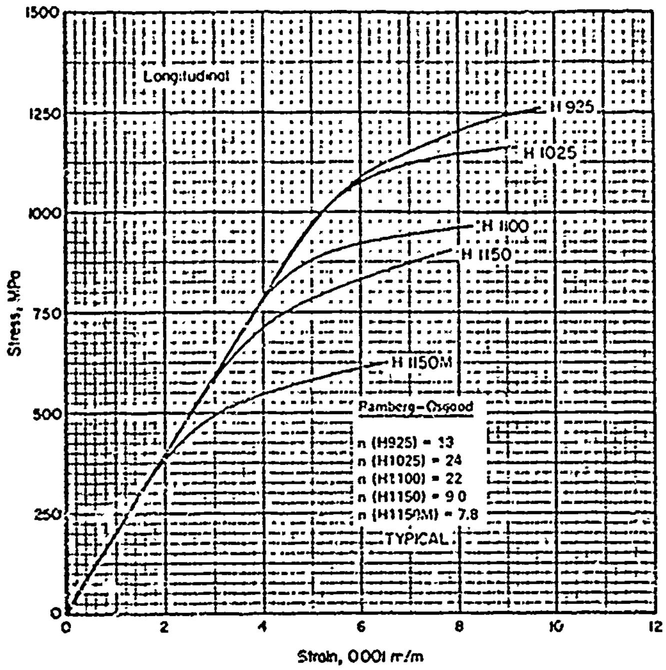


FIGURE 2.6.7.1.6(a). Typical tensile stress-strain curves at room temperature for various heat treated conditions of 15-5PH stainless steel (bar).

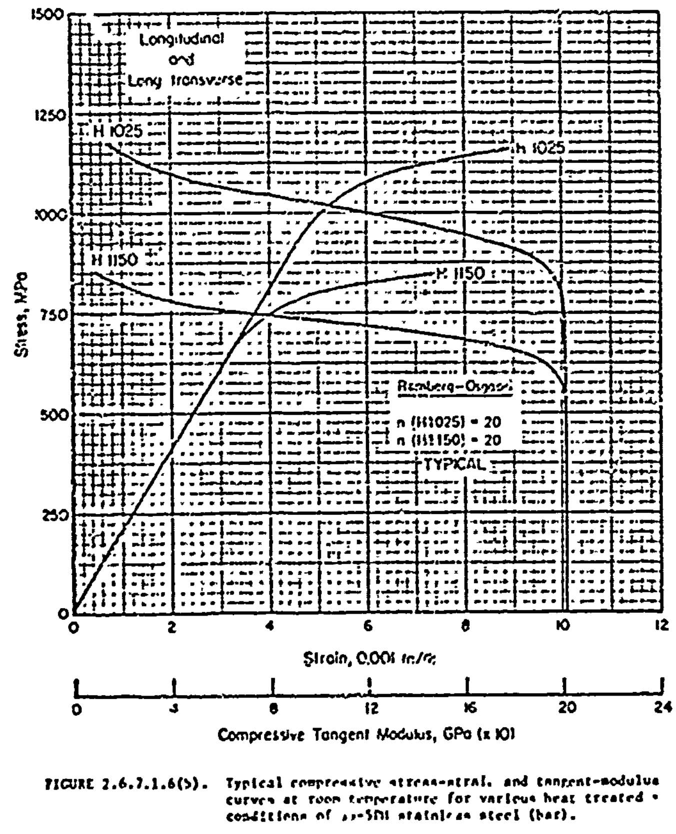


FIGURE 2.6.7.1.6(b). Typical compressive stress-strain and tangent-modulus curves at room temperature for various heat treated conditions of 15-5PH stainless steel (bar).

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 589 K. This steel is supplied in Condition A for ease of forming or in Condition C when highest strength is required.

Material specifications for PH15-7Mo stainless steel are presented in Table 2.6.8.0(a).

TABLE 2.6.8.0(a). *Material Specifications for PH15-7Mo Stainless Steel*

Specification	Form
AMS 5520	Plate, sheet, and strip
AMS 5657	Bar and forgings

Manufacturing Considerations.—PH15-7Mo in Condition A is readily cold formed or cold drawn. 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.

The designer should be aware that the properties shown for the high strength conditions are not representative for the thickness direction. Use of this steel in Conditions T and R-100 is not recommended.

In hardening this steel from Condition A to Condition TH1050 a net dimensional growth of 0.004 m/m should be anticipated.

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.

Room-Temperature Properties

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.

2.6.8.1 *TH1050 Condition.*—Effects of temperature on various mechanical properties for this condition are presented in Figures 2.6.8.1.1(a) through 2.6.8.1.4.

Typical stress-strain 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 temperature and at 533 K are illustrated in Figures 2.6.8.1.8(a) and (b).

TABLE 2.6.8.0(c). Elongation Values for PH15-7Mo (TH1050) Stainless Steel Sheet

Thickness, mm	e, percent in 51 mm
0.038 to 0.125	2
0.126 to 0.252	3
0.253 to 0.493	4
0.494 to 4.761	5
4.762 to 12.70	6

TABLE 2.6.8.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF PH15-7MO STAINLESS STEEL

SPECIFICATION	AMS 5520	AMS 5657
FORM	SHEET, STRIP, AND PLATE	BARS AND FORGINGS
CONDITION	TH1050	TH1050
THICKNESS, MM	0.04- 12.70	≤152.40
BASIS	S[a]	S
MECHANICAL PROPERTIES:		
FTU, MPA:		
L	...	1240
LT	1310	...
FTY, MPA:		
L	...	1100
LT	1170	...
FCY, MPA:		
L	...	1160
LT	1230	...
FSU, MPA	848	807
FBRU, MPA:		
(E/D=1.5)	2160	2050
(E/D=2.0)	2620	2480
FBRY, MPA:		
(E/D=1.5)	1760	1650
(E/D=2.0)	1930	1820
EL, PERCENT:		
L	...	8
LT	b	...
RA, PERCENT:		
L	...	25
LT	...	...
E, GPA	200.0	
EC, GPA	206.8	
G, GPA	75.8	
MU	0.32	
PHYSICAL PROPERTIES:		
OMEGA, MG/M3	7.67	
C, J/(G*K)	...	
K, W/(M*K)	SEE FIGURE 2.6.8.0	
ALPHA, 10-6 M/(M*K)	SEE FIGURE 2.6.8.0	

[a]TEST DIRECTION LONGITUDINAL FOR WIDTHS LESS THAN 228.6 MM: TRANSVERSE FOR WIDTHS 228.6 MM AND OVER.

[b]SEE TABLE 2.6.8.0(C).

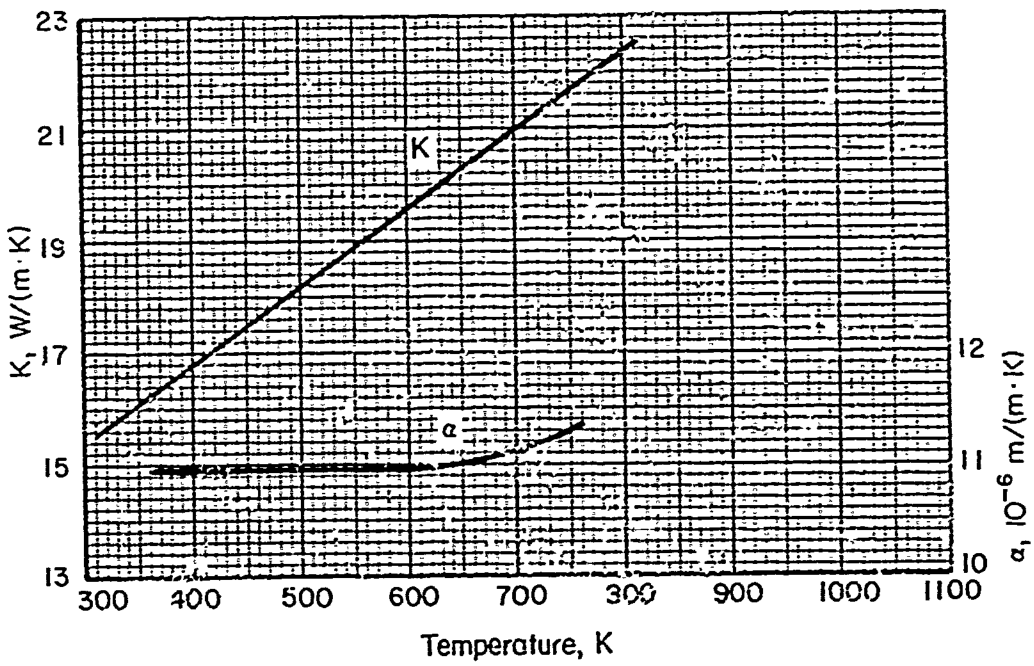


FIGURE 2.6.8.0. Effect of temperature on the physical properties of PH15-7Mo stainless steel.

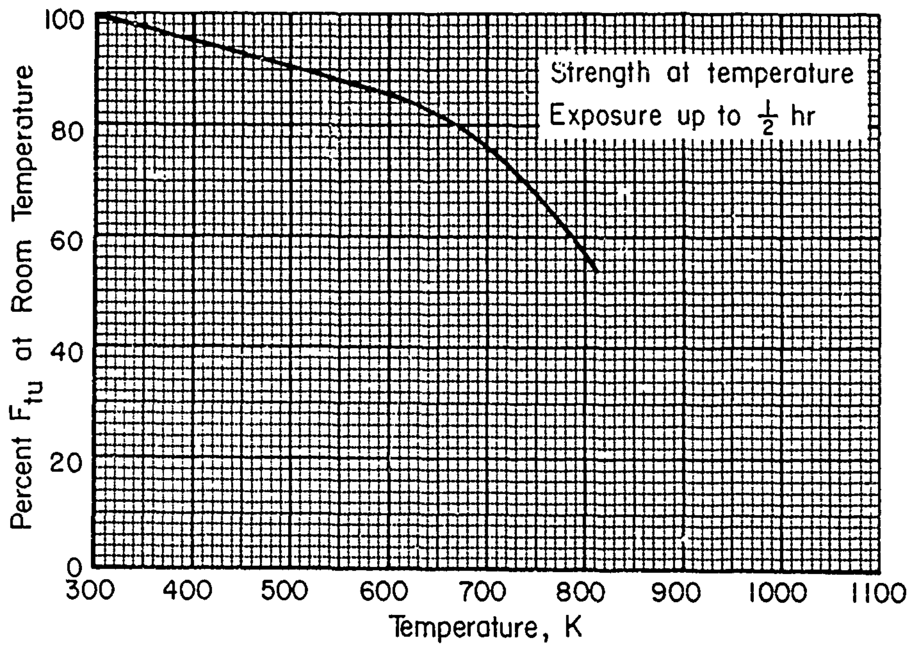


FIGURE 2.6.8.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of PH15-7Mo (TH1050) stainless steel.

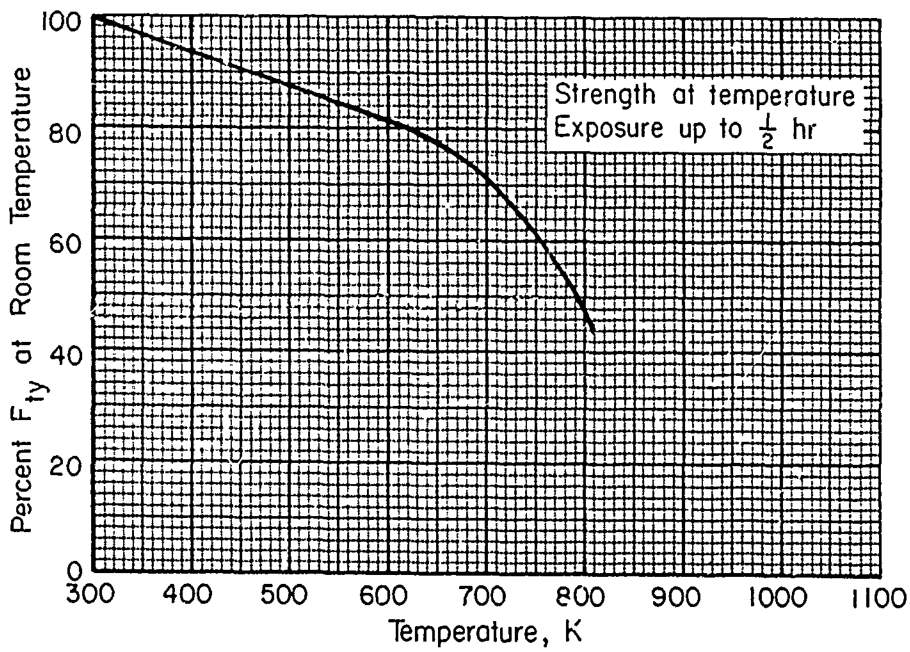


FIGURE 2.6.8.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of PH15-7Mo (TH1050) stainless steel.

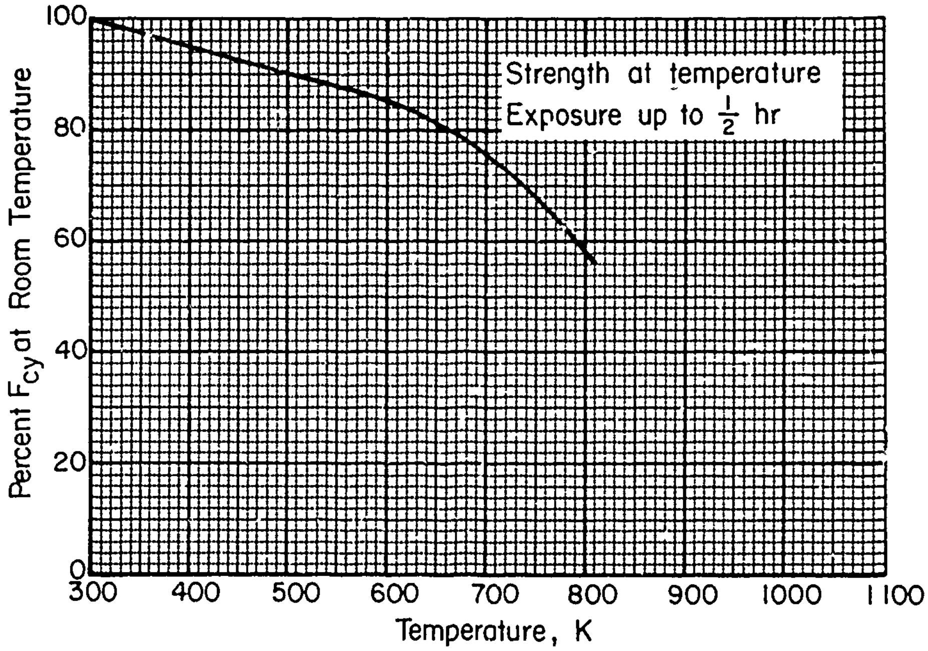


FIGURE 2.6.8.1.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of PH15-7Mo (TH1050) stainless steel.

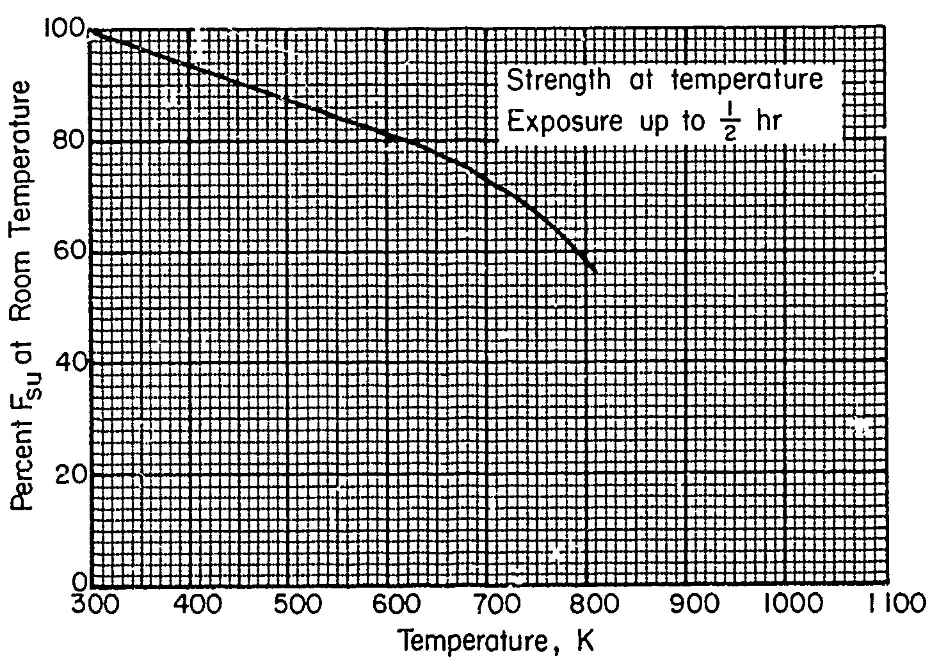


FIGURE 2.6.8.1.2(b). Effect of temperature on the ultimate shear strength (F_{su}) of PH15-7Mo (TH1050) stainless steel.

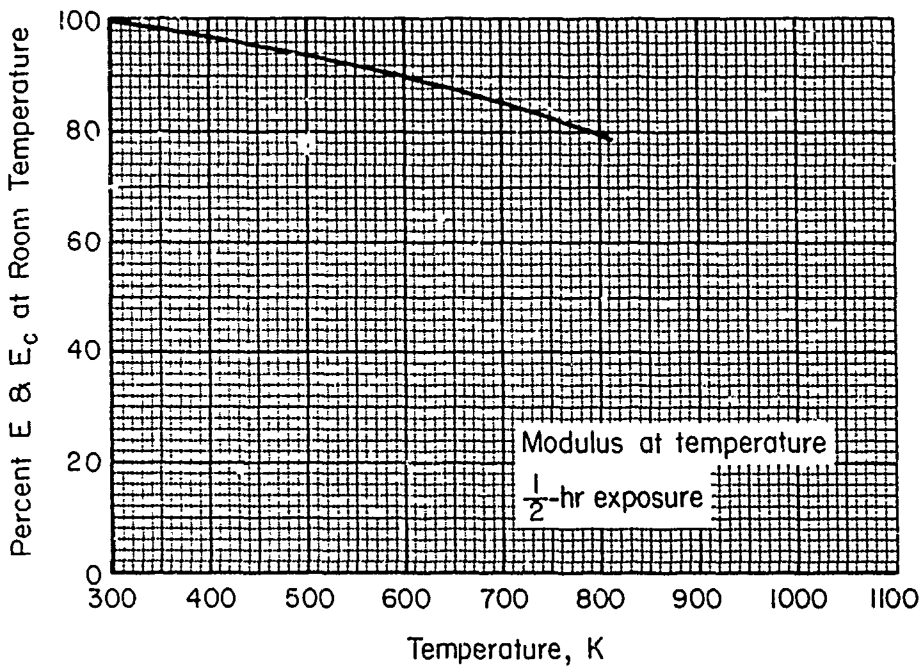


FIGURE 2.6.8.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of PH15-7Mo (TH1050) stainless steel.

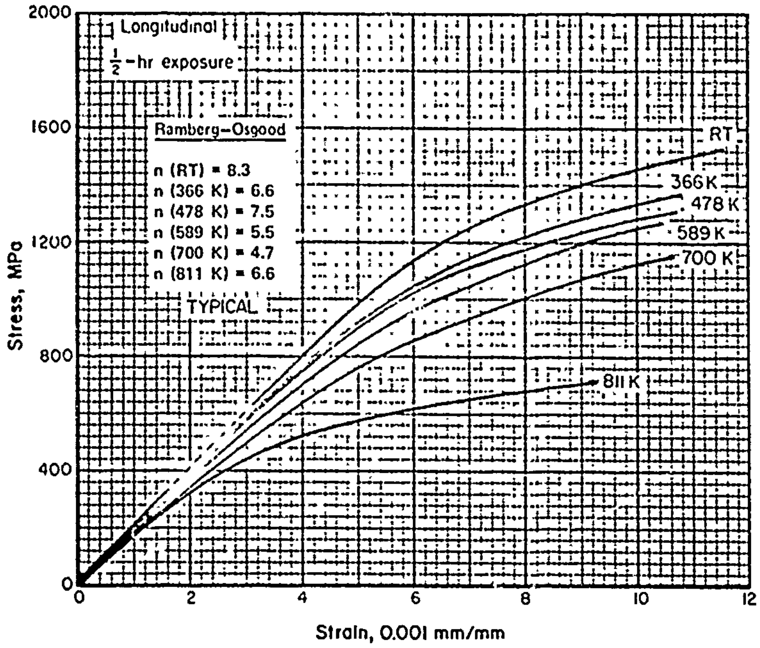


FIGURE 2.6.8.1.6(a). Typical tensile stress-strain curves at various temperatures for PH15-7Mo (TH1050) stainless steel (sheet).

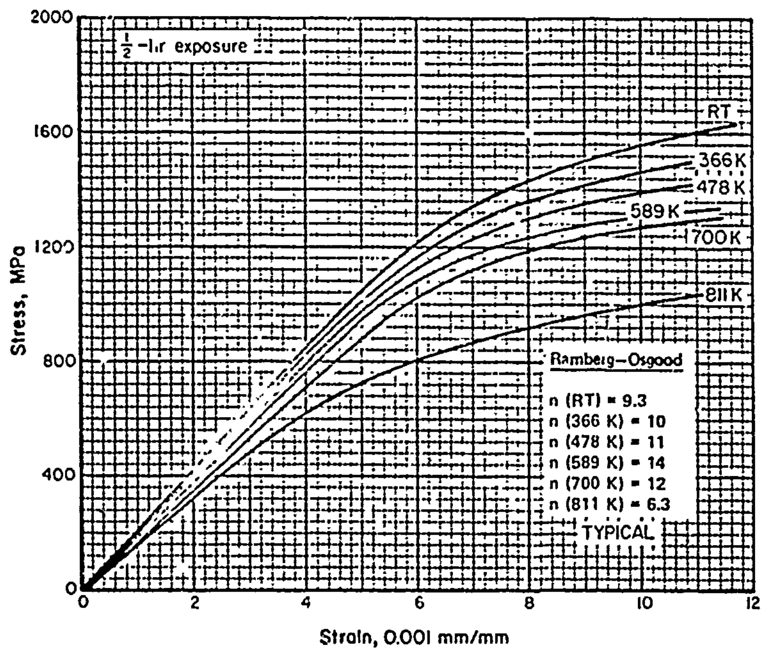


FIGURE 2.6.8.1.6(b). Typical compressive stress-strain curves at various temperatures for PH15-7Mo (TH1050) stainless steel (sheet).

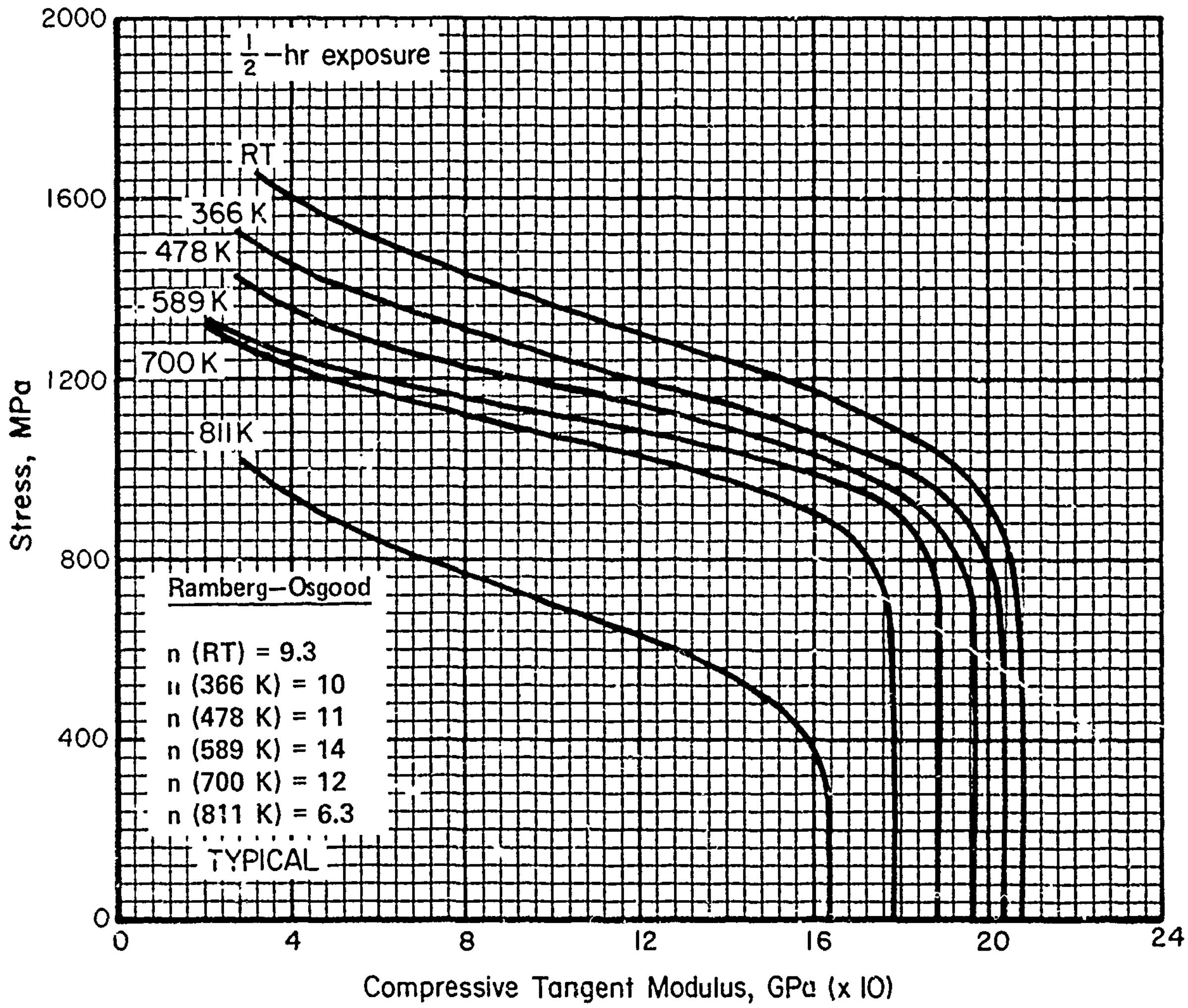


FIGURE 2.6.8.1.6(c). Typical compressive tangent-modulus curves at various temperatures for PH15-7Mo (TH1050) stainless steel (sheet).

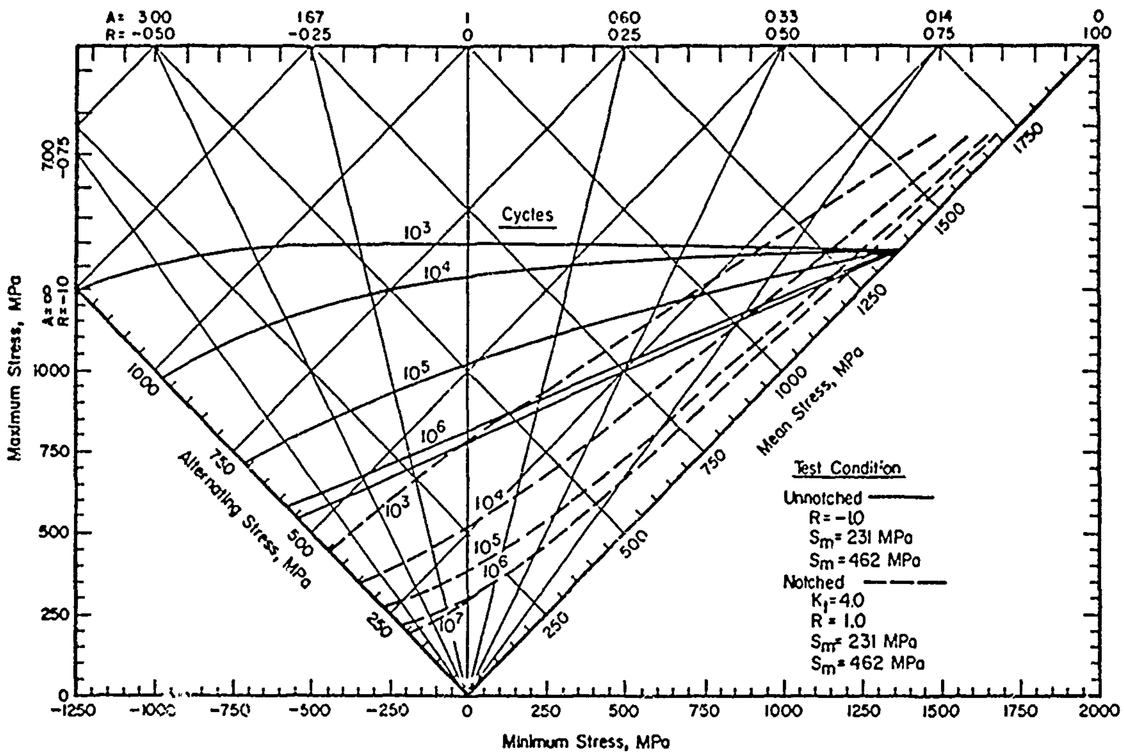


FIGURE 2.6.8.1.8(a). Typical constant-life fatigue diagram for PH15-7Mo (TH 1050) at room temperature

Correlative Information for Figure 2.6.8.1.8(a)

Product Form: Sheet, 0.635 mm thick

Properties:	TUS, MPa	TYS, MPa	Temp, K
	1390	1350	RT (Unnotched)
	2240	—	RT (Notched)

Test Parameters:
- Loading — Axial
- Frequency — 24 and 1800 cpm
- Temperature — RT
- Atmosphere — Air

Specimen Details:

Unnotched:
19.1 mm width

Notched, Edge Notch, $K_t = 4.0$
57.3 mm gross width
38.1 mm net width
1.47 mm root radius, r
0°, flank angle, ω

$K_N = 3.09, \rho = 0.279$ mm, where $K_N = 1 + \dfrac{K_t - 1}{1 + \frac{\pi}{\pi - \omega}\sqrt{\frac{\rho}{r}}}$

Surface Condition. Unnotched Specimens. Specimen edge machined in lathe with longitudinal tool marks; edges beveled with 320 grit emery cloth to a 45° bevel, 0.076 mm across. Machining was done after heat treating in argon.
Notched Specimens: Edge notches formed by drilling holes at edges and milling slots from the edges of the specimens; corners of the notch root were beveled with a rubber abrasive to a 45° bevel, 0.076 mm across. Machining was done after heat treating in argon.

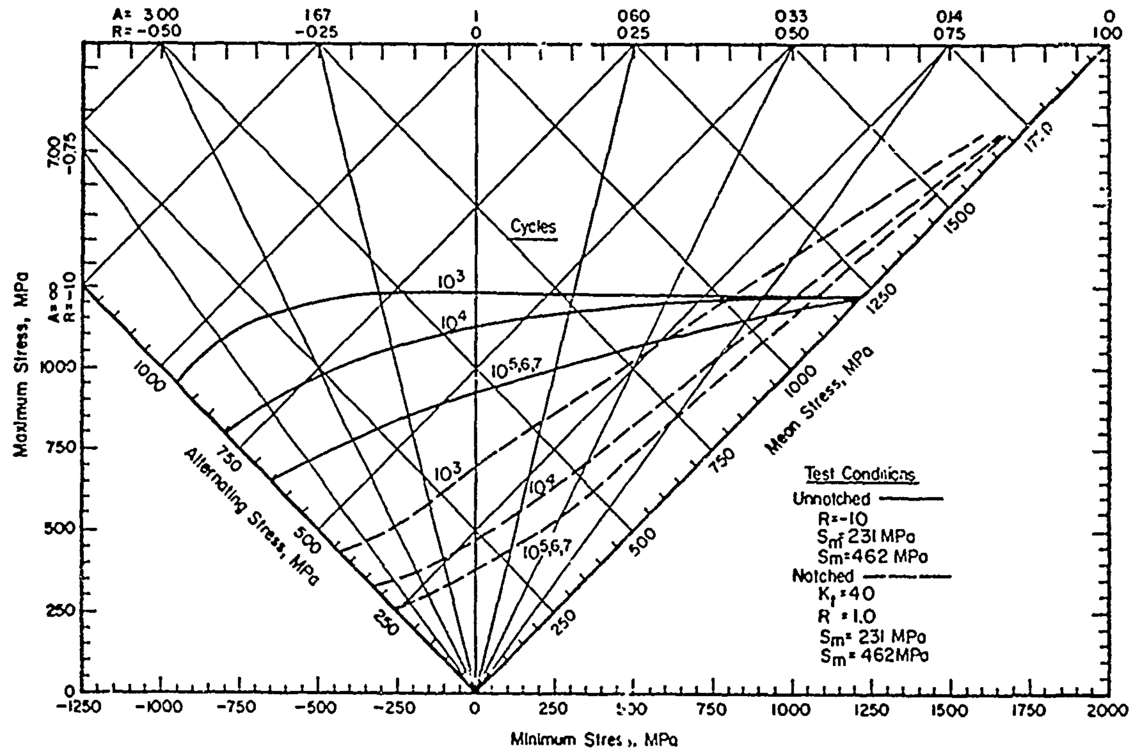


FIGURE 2.6.8.1.8(b). Typical constant-life fatigue diagram for PH 15-7 Mo (TH 1050) at 533 K

Correlative Information for Figure 2.6.8.1.8(b)

Product Form: Sheet, 0.635 mm thick

Properties:

TUS, MPa	TYS, MPa	Temp, K
1230	1190	533 (Unnotched)
1971	—	533 (Notched)

Test Parameters:
Loading — Axial
Frequency — 24 and 1800 cpm
Temperature — 533 K
Atmosphere — Air

Specimen Details:

Unnotched:
19.1 mm width

Notched, Edge Notch, $K_t = 4.0$
57.2 mm gross width
38.1 mm net width
1.47 mm root radius, r
0°, flank angle, ω

$K_N = 3.09$, $\rho = 0.279$ mm, where $K_N = 1 + \dfrac{K_t - 1}{1 + \frac{\pi}{\pi - \omega}\sqrt{\frac{\rho}{r}}}$

Surface Condition: Unnotched Specimens: Specimen edge machined in lathe with longitudinal tool marks; edges beveled with 320 grit emery cloth to a 45° bevel, 0.076 mm across. Machining was done after heat treating in argon.
Notched Specimens: Edge notches formed by drilling holes at edges and milling slots from the edges of the specimens: corners of the notch root were beveled with a rubber abrasive to a 45° bevel, 0.076 mm across. Machining was done after heat treating in argon.

2.6.9. 17-4PH

2.6.9.0 *Comments and Properties.* —17-4PH is a precipitation-hardening, martensitic stainless steel used for parts requiring high strength and good corrosion and oxidation resistance up to 589 K.

Material specifications for 17-4PH are presented in Table 2.6.9.0(a).

TABLE 2.6.9.0(a). *Material Specifications for 17-4PH Stainless Steel*

Specification	Form
AMS 5604	Sheet, strip and plate
MIL-S-81506	Sheet, strip and plate
AMS 5643	Bars, forgings and rings
MIL-C-24111	Bars, rods and forgings
AMS 5342	Investment castings (H1100)
AMS 5343	Investment castings (H1000)
AMS 5344	Investment castings (H900)
AMS 5355	Investment castings
MIL-S-81591	Investment castings
AMS 5398	Sand and centrifugal castings

Manufacturing Consideration. — 17-4PH is readily forged, 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 0.0004-0.0006 and 0.0008-0.0010 m/m occurs upon hardening to the H900 and H1150 conditions, respectively. When heavy sections are to be welded under conditions of high restraint, prior stress relief obtained by 4 hours of heating at 866 to 894 K is advisable to maximize fracture toughness properties and preclude cracking in planes normal to the thickness direction. When permanent deformation is performed, as in cold straightening of hardened parts, reaging is recommended to minimize internal stresses. Parts should never be used in Condition A. When good fracture toughness or impact properties are required, or where parts require these properties in the transverse direction, both at or below room temperature, conditions H900, H925, H950, H975, and H1000 should not be used. Conditions H1025, H1050, H1075, H1100, H1125, and H1150 provide greater transverse ductility, lower transition temperatures, and more useful levels of fracture toughness than the higher strength conditions. However, the use of 17-4PH in any condition should be regarded with caution for structural applications requiring good transverse impact properties at temperatures below 219 K.

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 for strength properties 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 most 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.

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 825 K for 4 hours minimum aging time.

Heat Treatment. — The heat treatments to develop the various conditions for 17-4PH are described in the following tables. Table 2.6.9.0(b) describes the annealing (solution treating) treatments for various products. Table 2.6.9.0(c) describes the hardening treatment for all products except investment castings. The hardening treatments for investment castings are listed in Table 2.6.9.0(d).

Room Temperature Properties

Room temperature mechanical and physical properties for various conditions of 17-4PH products are presented in Tables 2.6.9.0(e) through (g) The physical properties of this alloy at room and elevated temperatures are presented in Figure 2.6.9.0.

2.6.9.1 *H900 Condition.* — Effect of temperature curves for various mechanical properties are presented in Figures 2.6.9.1.2(a) through 2.6.9.1.4. Effect of temperature curves for F_{tu} and F_{ty} are shown in Figures 2.6.9.2.1(a) and (b).

Unnotched and notched fatigue information at room temperature is presented in Figure 2.6.9.1.8.

2.6.9.2 *Various Heat Treat Conditions.* — Effect of temperature curves for tensile yield and ultimate strengths are depicted in Figures 2.6.9.2.1(a) and (b). Room temperature stress-strain curves are shown in Figures 2.6.9.2.6(a) and (b).

2.6.9.3 *H1150 Condition.* — Effect of temperature curves for tensile yield and ultimate strengths are shown in Figures 2.6.9.3.1(a) and (b).

TABLE 2.6.9.0(b). Annealing (Solution Treating) Treatments for 17-4PH Stainless Steel Investment Castings, Bars, Forgings, Rings, Plate, Sheet and Strip

Product	Treatment	Condition Designation
Investment Casting	1422 ± 15 K, 90 minutes, air cool below 305 K[a]	Homogenized
Investment Casting	1311 ± 15 K, 30 minutes, air cool below 305 K	Condition A
Bars and Forgings	1311 ± 15 K, 30 minutes, air cool or oil quench below 305 K	Condition A
Plate	1325 ± 15 K, 30 minutes per 25.4 mm of thickness, air cool below 305 K	Condition A
Sheet and Strip	1311 ± 15 K, 30 minutes per 2.54 mm of thickness, air cool below 305 K	Condition A

[a] Castings must be homogenized prior to Condition A treatment.

TABLE 2.6.9.0(c). Nominal Hardening Treatments for 17-4PH Condition A (Annealed) Stainless Steel Bars, Forgings, Rings, Plate, Sheet and Strip

F_{tu}, MPa	Hardening Treatment	Rockwell Hardness	Condition Designation
1310	755 ± 5 K, 1 Hour, Air Cool	C40/47	H900
1172	769 ± 5 K, 4 Hours, Air Cool	C38/45	H925
1131	783 ± 5 K, 4 Hours, Air Cool	C37/44	H950
1117	797 ± 5 K, 4 Hours, Air Cool	C36/43	H975
1089	811 ± 5 K, 4 Hours, Air Cool	C35/42	H1000
1069	825 ± 5 K, 4 Hours, Air Cool	C35/42	H1025
1034	839 ± 5 K, 4 Hours, Air Cool	C33/40	H1050
986	853 ± 5 K, 4 Hours, Air Cool	C31/39	H1075
965	866 ± 5 K, 4 Hours, Air Cool	C32/38	H1100
945	881 ± 5 K, 4 Hours, Air Cool	C30/37	H1125
[illegible]	894 ± 5 K, 4 Hours, Air Cool	C28/37	H1150
[illegible]	1033 ± 15 K, 2 Hours, Air Cool Plus 894 ± 5 K, 4 Hours, Air Cool	C24/30	H1150M

TABLE 2.6.9.0(d). Nominal Hardening Treatments for 17-4PH Condition A (Annealed) Investment Castings

F_{tu}, MPa	Hardening Treatment	Rockwell Hardness	Condition Designation
1241	755 ± 5 K, 1-1/2 Hours, Cir Cool	C40/45	H900
1172	769 ± 5 K, 1-1/2 Hours, Air Cool	C40/45	H925
1034	811 ± 5 K, 4 Hours[a], Air Cool	C38/43	H1000
896	866 ± 5 K, 4 Hours[a], Air Cool	C33/38	H1100

[a] Per MIL-H-6875.

TABLE 2.6.9.0(E). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 17-4PH STAINLESS STEEL

SPECIFICATION	AMS 5604, MIL-S-81506, AMS 5643, MIL-C-24111											
FORM	ALL WROUGHT PRODUCTS EXCEPT BARS											
CONDITION	H900	H925	H950	H975	H1000	H1025	H1050	H1075	H1100	H1125	H1150	H1150M
THICKNESS, MM	<203.20											
BASIS	S[b]	S[a,b]	S[a,b]	S[a,b]	S[a,b]	S[a,b]	S[a,b]	S[a,b]	S[a,b]	S[a,b]	S[a,b]	S[a,b]
MECHANICAL PROPERTIES:												
FTU, MPA	1310	1170	1140	1120	1090	1070	1030	1000	965	945	931	793
FTY, MPA	1170	1070	1050	1030	1010	1000	931	862	793	758	724	517
FCY, MPA	1170	...	...	...	...	...	...	...	...	...	...	...
FSU, MPA	648	...	...	...	...	...	...	...	...	...	...	...
FBRU, MPA:												
(E/D=1.5)	2160	...	...	...	...	...	...	...	...	...	...	...
(E/D=2.0)	2620	...	...	...	...	...	...	...	...	...	...	...
FBRY, MPA:												
(E/D=1.5)	1760	...	...	...	...	...	...	...	...	...	...	...
(E/D=2.0)	1930	...	...	...	...	...	...	...	...	...	...	...
EL, PERCENT:												
L												
L	5	5	...	...	...	5	...	5	...	...	8	...
LT	8	8	...	...	...	8	...	9	...	...	10	...
ST	10	10	...	...	...	12	...	13	...	...	16	...
ST	10	10	10	11	11	12	[illegible]	13	14	15	16	18
E, GPA	196.5											
EC, GPA	206.8											
G, GPA	77.2											
MU	0.27											
PHYSICAL PROPERTIES:												
OMEGA, MG/M3	7.81 (H900), 7.85 (H1075), 7.86 (H1150)											
C, J/(G*K)	SEE FIGURE 2.6.9.0											
K, W/(M*K)	SEE FIGURE 2.6.9.0											
ALPHA, 10-6 M/(M*K)	SEE FIGURE 2.6.9.0											

[a] ONLY H900 CONDITION COVERED BY AMS SPECIFICATIONS. PROPERTIES FOR OTHER CONDITIONS REFLECT PRODUCERS# GUARANTEED MINIMUM TENSILE PROPERTIES. CHECK MIL-S-81506 AND MIL-C-24111 FOR CONDITIONS COVERED AND MECHANICAL PROPERTIES.

[b] TEST DIRECTION LONGITUDINAL; THESE PROPERTIES NOT APPLICABLE TO THE SHORT TRANSVERSE (THICKNESS DIRECTION).

TABLE 2.6.9.0(F). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 17-4PH STAINLESS STEEL (BARS)

SPECIFICATION	AMS 5643 AND MIL-C-24111																
FORM	BARS																
CONDITION	H900		H925		H950		H975	H1000	H1025	H1050	H1075		H1100	H1125	H1150		H1150M
THICKNESS, MM									≤203.20								
BASIS	A	B	A	B	A	B	S[a]	S[a]	S[a]	S[a]	A	B	S[a]	S[a]	A	B	S[a]
MECHANICAL PROPERTIES:																	
FTU, MPA:																	
L	1310	1340	1170	1230	1130	1190	1120	1090	1070	1030	986	1030	965	945	862	924	793
T	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
FTY, MPA:																	
L	1170	1210	1070[b]	1150	1050[c]	1140	1030	1010	1000	931	862[d]	986	793	758	689	793	517
T	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
FCY, MPA:																	
L	1170	1210	...	...	...	...	...	...	958	...	...	...	...	...	621	717	...
T	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
FSU, MPA	848	869	...	...	...	...	...	...	655	...	...	...	...	...	545	586	...
FBRU, MPA:																	
(E/D=1.5)	2160	2220	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
(E/D=2.0)	2620	2690	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
FBRY, MPA:																	
(E/D=1.5)	1760	1810	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
(E/D=2.0)	1930	1990	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
EL, PERCENT:																	
L	5	...	5	...	4	...	11	11	12	13	10	...	14	15	13	...	18
T	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
E, GPA	196.5																
EC, GPA	206.8																
G, GPA	77.2																
MU	0.27																
PHYSICAL PROPERTIES:																	
OMEGA, MG/M3	7.81 (H900), 7.83 (H1075), 7.86 (H1150)																
C, J/(G*K)	SEE FIGURE 2.6.9.0																
K, W/(M*K)	SEE FIGURE 2.6.9.0																
ALPHA, 10-6 M/(M*K)	SEE FIGURE 2.6.9.0																

[a] ONLY H900 CONDITION COVERED BY AMS 5643. PROPERTIES FOR OTHER CONDITIONS REFLECT PRODUCERS' GUARANTEED MINIMUM TENSILE PROPERTIES. CHECK MIL-C-24111 FOR CONDITIONS COVERED AND MECHANICAL PROPERTIES.
[b] THE A VALUE OF 1083 MPA IS HIGHER THAN PRODUCERS' GUARANTEED MINIMUM.
[c] THE A VALUE OF 1069 MPA IS HIGHER THAN PRODUCERS' GUARANTEED MINIMUM.
[d] THE A VALUE OF 938 MPA IS HIGHER THAN PRODUCERS' GUARANTEED MINIMUM.

TABLE 2.6.9.0(G). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 17-4PH STAINLESS STEEL (CASTINGS)

SPECIFICATION	AMS 5342, AMS 5343, AMS 5344, AMS 5355, AMS 5398, MIL-S-81591			
FORM	CASTINGS			
CONDITION	H900	H925	H1000	H1100
THICKNESS, MM	...	...	...	...
BASIS	S[a]	S[a]	S[a]	S[a]
MECHANICAL PROPERTIES:				
FTU, MPA	1240	1170[b]	1030	896
FTY, MPA	1100	1030	896	827
FCY, MPA	...	...	...	...
FSU, MPA	...	...	...	...
FBRU, MPA:				
(E/D=1.5)	...	...	...	...
(E/D=2.0)	...	...	...	...
FBRY, MPA:				
(E/D=1.5)	...	...	...	...
(E/D=2.0)	...	...	...	...
EL, PERCENT	6	6	6	8
E, GPA	196.5			
EC, GPA	206.8			
G, GPA	87.6			
MU	0.27			
PHYSICAL PROPERTIES:				
OMEGA, MG/M3	7.81(H900)			
C, J/(G*K)	SEE FIGURE 2.6.9.0			
K, W/(M*K)	SEE FIGURE 2.6.9.0			
ALPHA, 10-6 M/(M*K)	SEE FIGURE 2.6.9.0			

[a]FOR CAST BARS. SPECIMENS MACHINED FROM LARGER CASTINGS MAY HAVE LOWER PROPERTIES.

[b]VALUE IS LOWER THAN SPECIFIED IN AMS 5355.

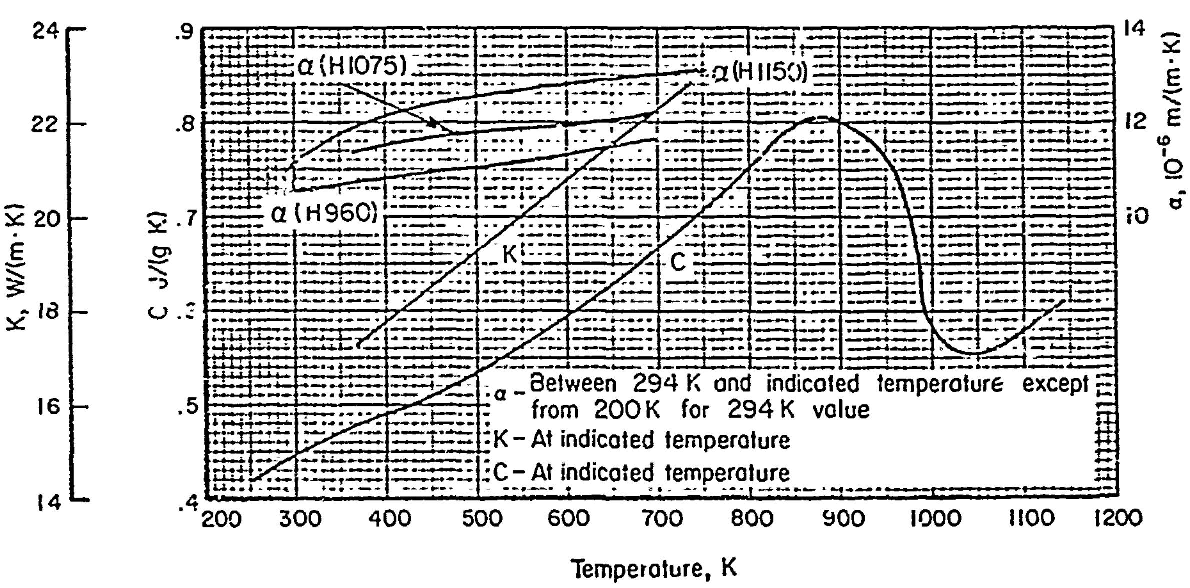


FIGURE 2.6.9.0. Effect of temperature on the physical properties of 17-4PH stainless steel.

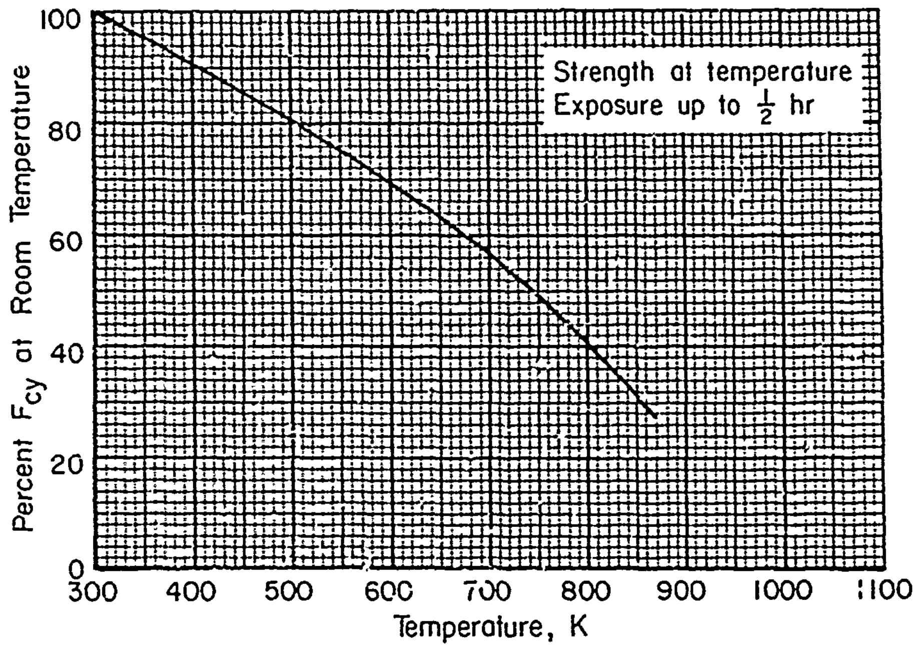


FIGURE 2.6.9.1.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of 17-4PH (H900) stainless steel (bar and forgings).

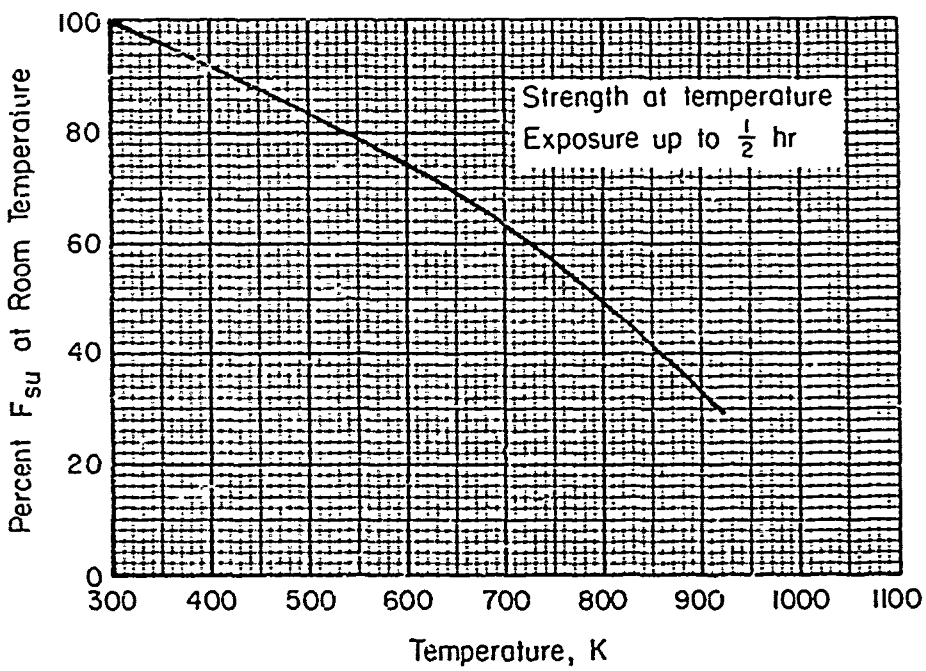


FIGURE 2.6.9.1.2(b). Effect of temperature on the ultimate shear strength (F_{su}) of 17-4PH (H900) stainless steel (bar and forgings).

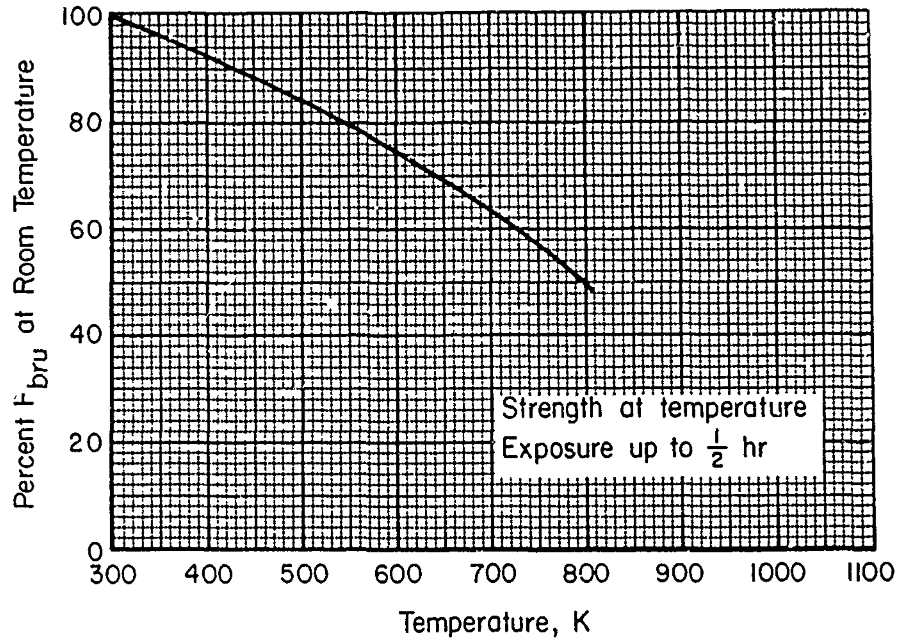


FIGURE 2.6.9.1.3(a). Effect of temperature on the ultimate bearing strength (F_{bru}) of 17-4PH (H900) stainless steel (bar and forgings).

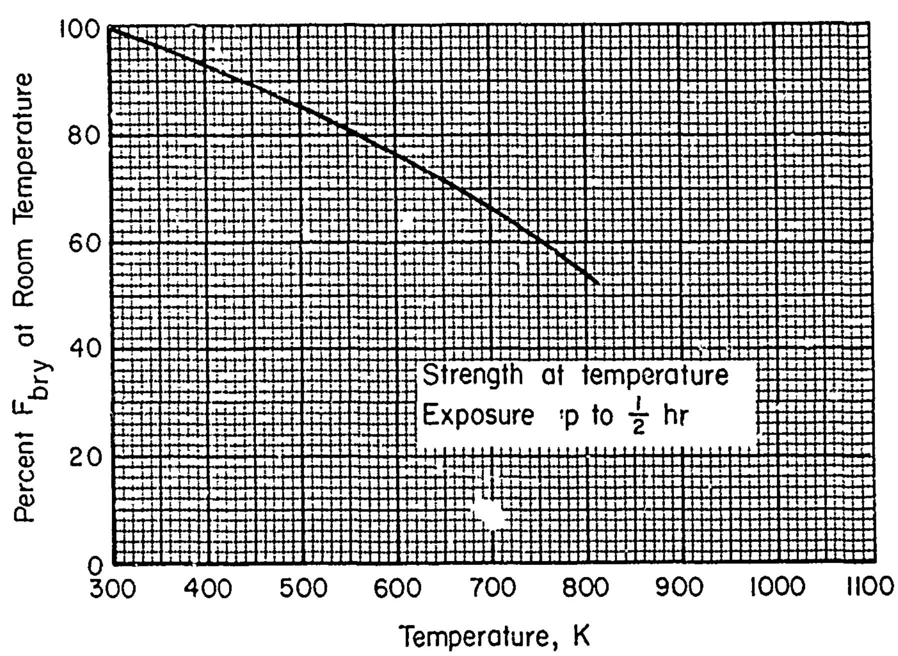


FIGURE 2.6.9.1.3(b). Effect of temperature on the bearing yield strength (F_{bry}) of 17-4PH (H900) stainless steel (bar and forgings).

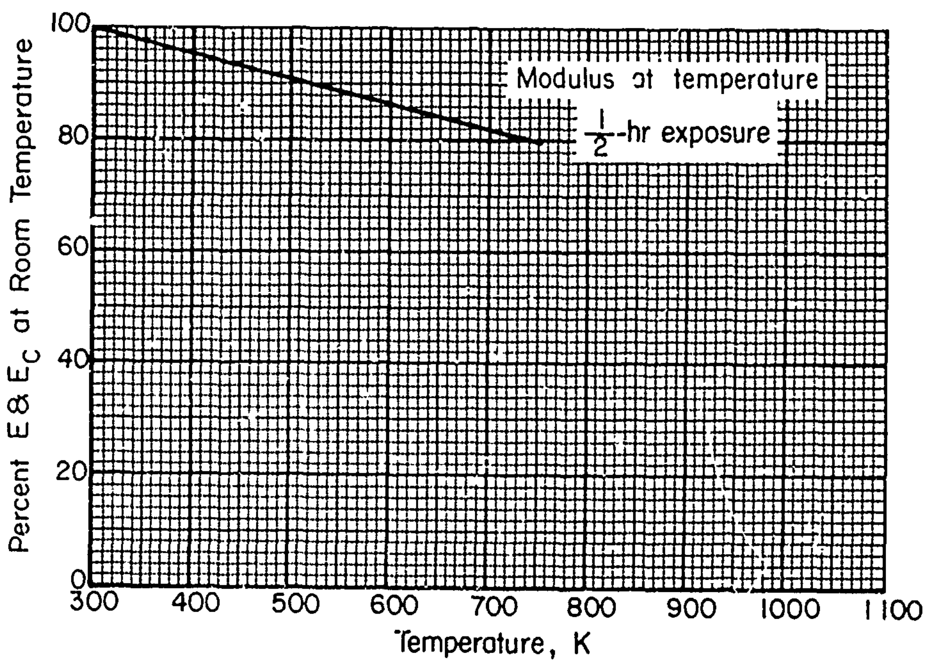


FIGURE 2.6.9.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of 17-4PH (H900) stainless steel (bar and forgings).

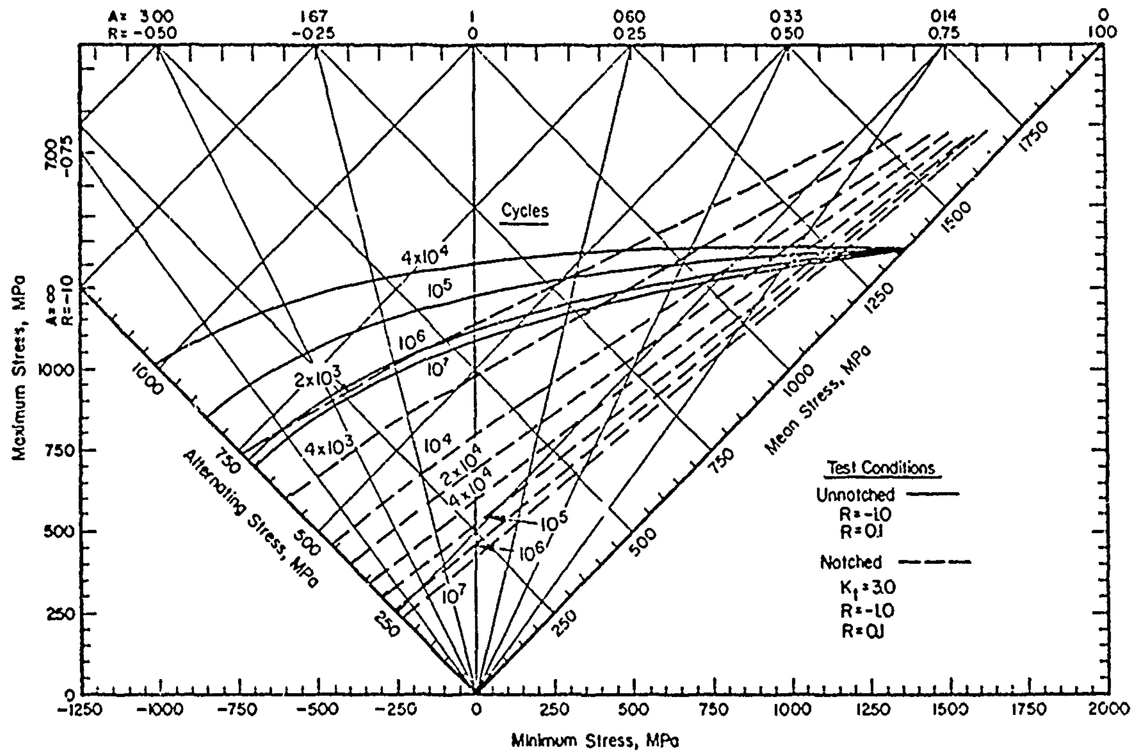


FIGURE 2.6.9.1.8. Typical constant-life fatigue diagram for 17-4PH (H900) bar at room temperature.

Correlative Information for Figure 2.6.8.1.8

Product Form: Bar, 25.4 and 28.6 mm diameter

Properties:

TUS, MPa	TYS, MPa	Temp, K
1390	1340	RT (Unnotched)
2230	—	RT (Notched)

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

Specimen Details:

Unnotched:
6.40 mm diameter

Notched, V-Groove, K_t = 3.0
- 9.07 mm gross diameter
- 6.40 mm net diameter
- 0.33 mm root radius, r
- 60° flank angle, ω

$$K_N = 2.65; \rho = 0.0066, \text{where } K_N = 1 + \frac{K_t - 1}{1 + \frac{\pi}{\pi - \omega}\sqrt{\frac{\rho}{r}}}$$

Surface Condition:
- Unnotched: Longitudinal hand polish with 400 grit paper
- Notched: Hand polished

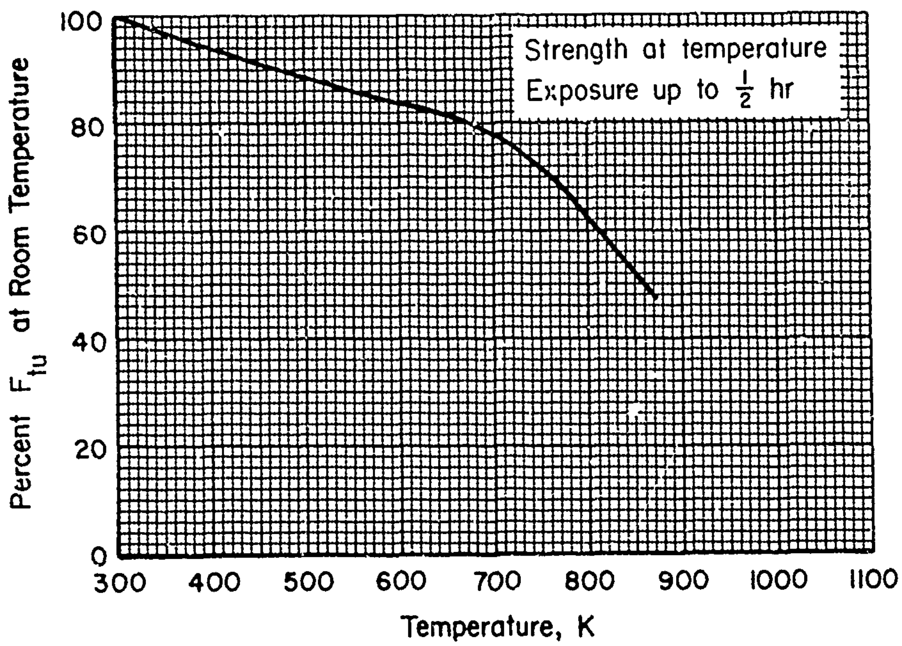


FIGURE 2.6.9.2.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of 17-4 PH (H900, H1025, and H1075) stainles steel (bar).

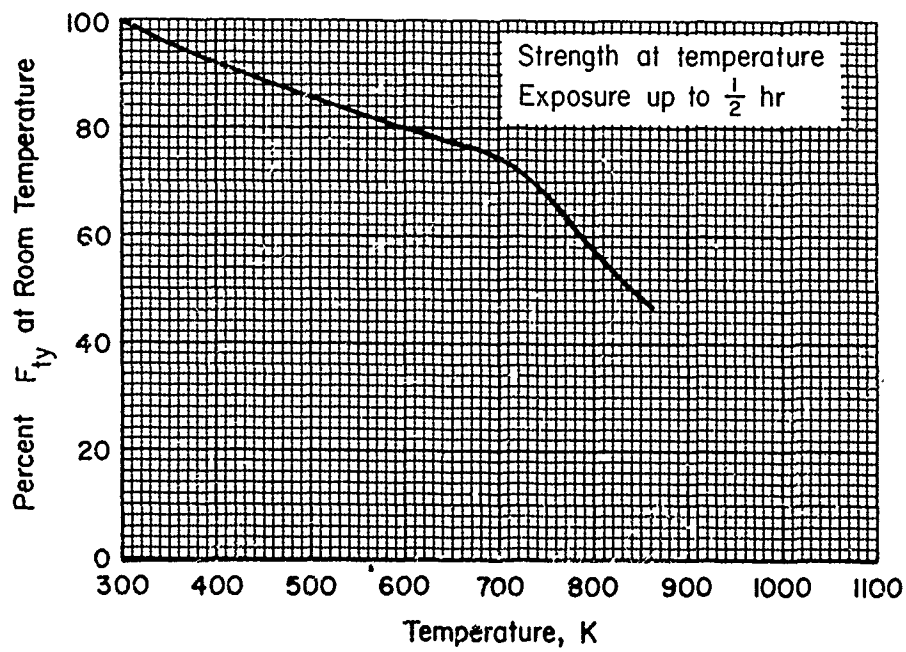


FIGURE 2.6.9.2.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of 17-4 PH (H900, H925, H1025, and H1075) stainless steel (bar).

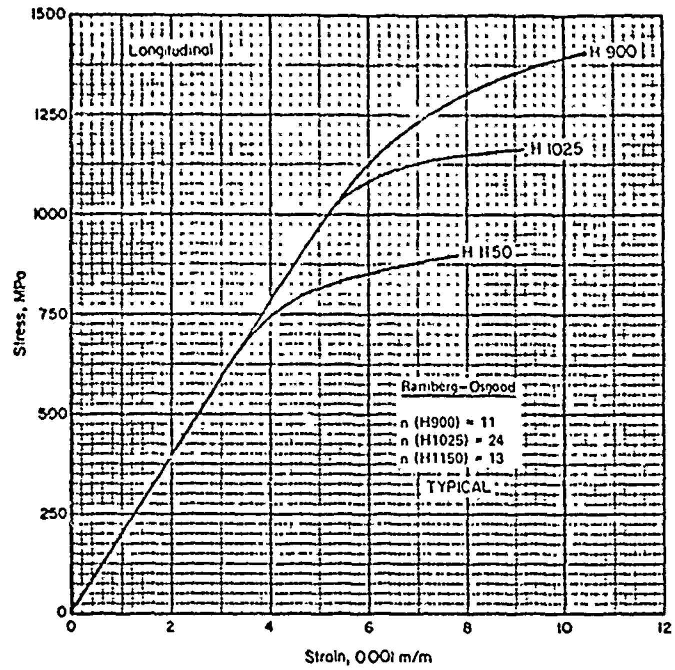


FIGURE 2.6.9.2.6(a). Typical tensile stress-strain curves at room temperature for various heat treated conditions of 17-4 PH stainless steel (bar).

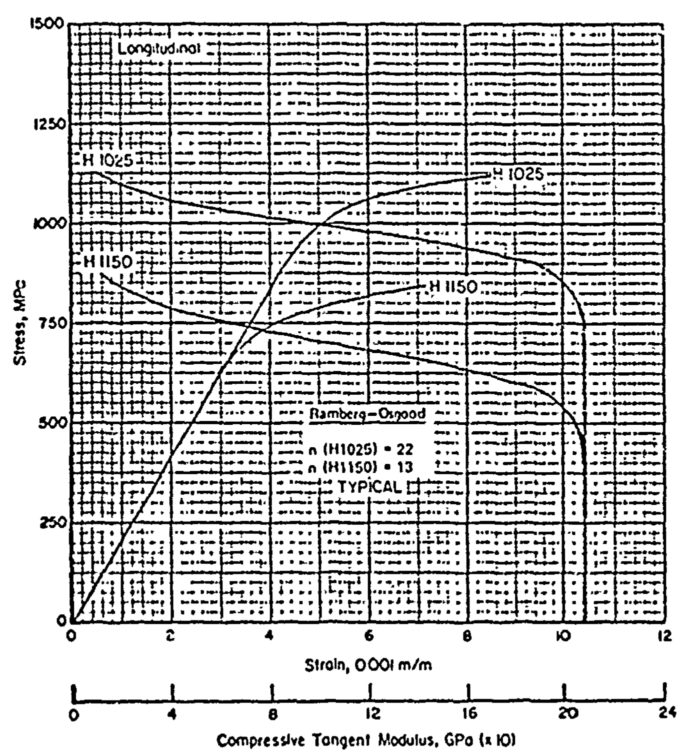


FIGURE 2.6.9.2.6(b). Typical compressive stress-strain and tangent-modulus curves at room temperature for various heat treated conditions of 17-4PH stainless steel (bar).

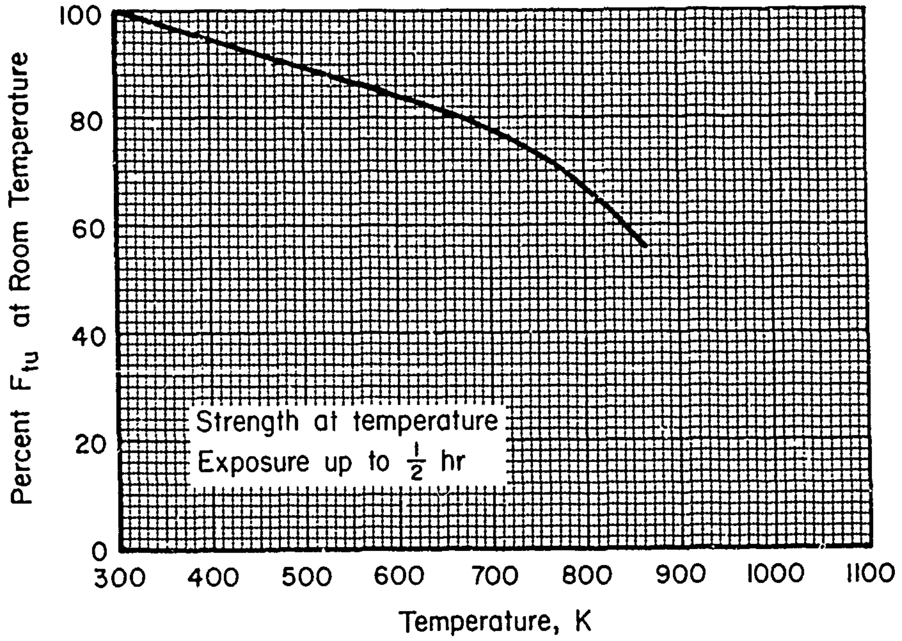


FIGURE 2.6.9.3.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of 17-4PH (H1150) stainless steel (bar).

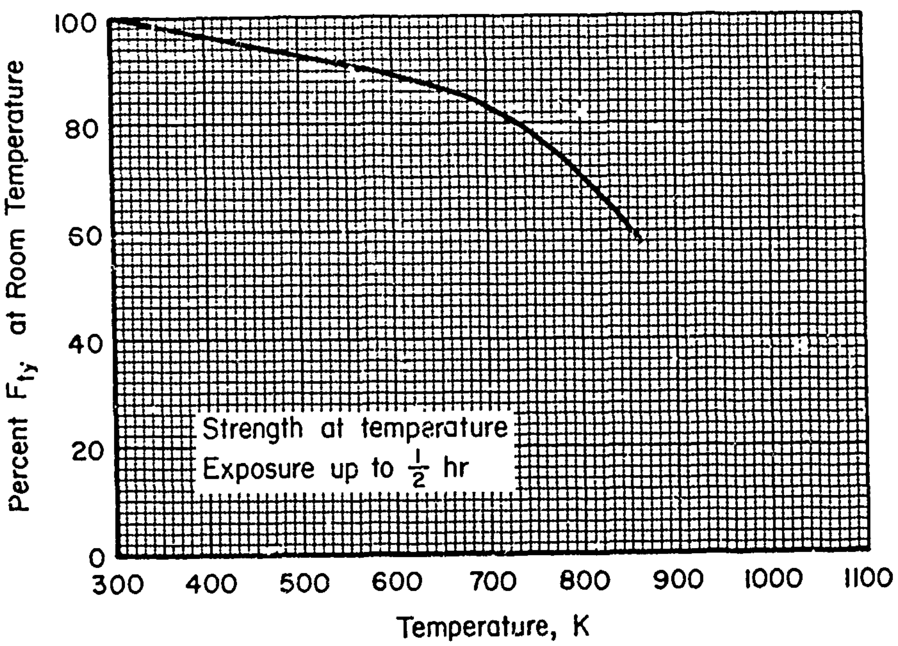


FIGURE 2.6.9.3.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of 17-4PH (H1150) stainless steel (bar).

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 589 K. This steel is supplied in Condition A for ease of forming.

Material specifications for 17-7PH stainless steel are presented in Table 2.6.10.0(a).

TABLE 2.6.10.0(a). *Material Specifications for 17-7PH Stainless Steel*

Specification	Form
MIL-S-25043	Plate, sheet, and strip
AMS 5644	Bars and forgings

Manufacturing Considerations.—17-7PH in Condition A is readily cold formed or cold drawn. 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 m/m will occur.

The heat treatment to anneal 17-7PH is:

Treatment	Condition Designation
1311 ± 15 K - Air Cool	Condition A

The transformation treatment from Condition A is as follows:

Treatment	Condition Designation
1033 ± 15 K - 90 Min. Cool to 289 $^{-5}_{+0}$ K for 30 Minutes	Condition T

The hardening treatment for 17-7PH is:

Treatment	Condition Designation
839 K ± 5 K - 90 Min. 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 797 K for periods longer than one-half hour.

Room-Temperature Properties

The room-temperature properties of 17-7PH are shown in Table 2.6.10.0(b) and (c).

The physical properties of this alloy at room and elevated temperatures are presented in Figure 2.6.10.0.

2.6.10.1 *TH1050 Condition.*—Effect of temperature curves for various mechanical properties are presented in Figures 2.6.10.1.1(a) through 2.6.10.1.4.

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(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 17-7PH STAINLESS STEEL

SPECIFICATION	MIL-S-25043		AMS 5644
FORM	PLATE, SHEET, AND STRIP		BAR AND FORGING[a]
CONDITION	TH1050		TH1050
THICKNESS, MM	0.13-12.70		≤76.20
BASIS	A[b]	B[b]	S
MECHANICAL PROPERTIES:			
FTU, MPA:			
L	...	...	1170
T	1220	1270	...
FTY, MPA:			
L	...	...	965
T	1030	1170	...
FCY, MPA:			
L	...	...	1010
T	1090	1230	...
FSU, MPA	793	827	765
FBRU, MPA:			
(E/D=1.5)	2010	2100	1930
(E/D=2.0)	2440	2540	2340
FBRY, MPA:			
(E/D=1.5)	1550	1740	1450
(E/D=2.0)	1700	1920	1590
EL, PERCENT:			
L	...	...	6
T	c	...	...
E, GPA	200.0		
EC, GPA	206.8		
G, GPA	75.8		
MU	0.32		
PHYSICAL PROPERTIES:			
OMEGA, MG/M3	7.64		
C, J/(G*K)	...		
K, W/(M*K)	SEE FIGURE 2.6.10.0		
ALPHA, 10-6 M/(M*K)	SEE FIGURE 2.6.10.0		

[a] THESE PROPERTIES ARE NOT APPLICABLE TO THE TRANSVERSE DIRECTIONS. BAR AND FORGINGS SHOULD NOT BE USED FOR PARTS SUBJECT TO TRANSVERSE LOADS.

[b] THE A AND B VALUES REPRESENT MATERIAL THAT HAS NOT BEEN COLD WORKED PRIOR TO FINAL HEAT TREATMENT. DIFFERENT ABSOLUTE VALUES MAY BE FOUND IN MATERIAL THAT IS COLD WORKED AND THEN HEAT TREATED.

[c] SEE TABLE 2.6.10.0(C).

TABLE 2.6.10.0(c). Percent Elongation Values for 17-7PH (TH1050) Stainless Steel (Sheet, Strip and Plate)

Thickness, mm	Elongation (LT), percent
0.038 to 0.125	3
0.126 to 0.252	4
0.253 to 0.506	5
0.507 to 4.761	6
4.762 to 12.70	7

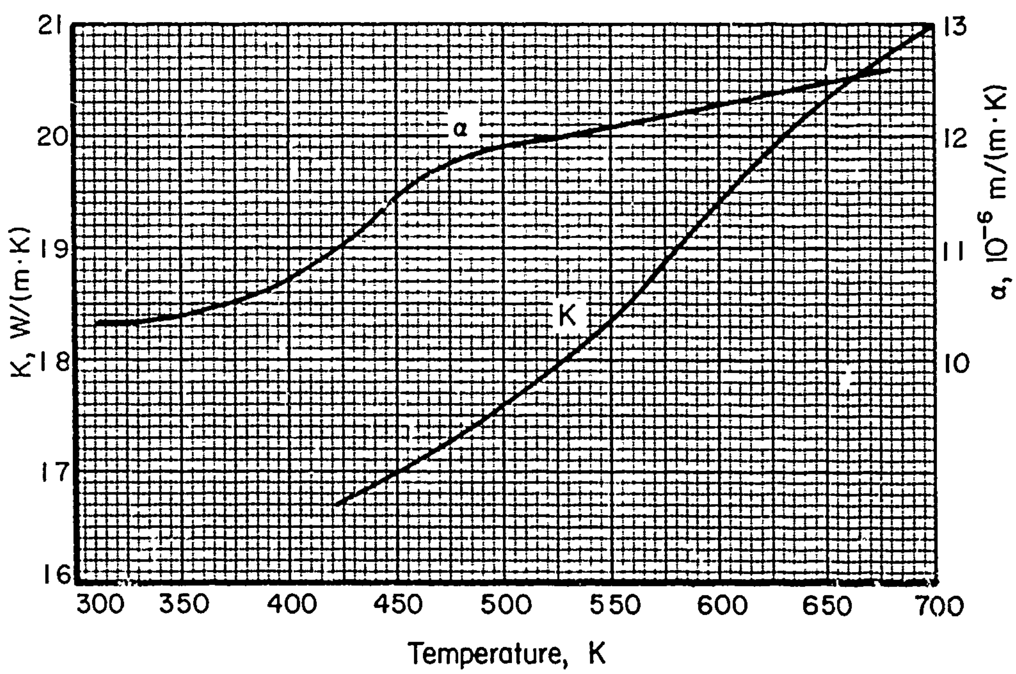


FIGURE 2.6.10.0. Effect of temperature on the physical properties of 17-7PH stainless steel.

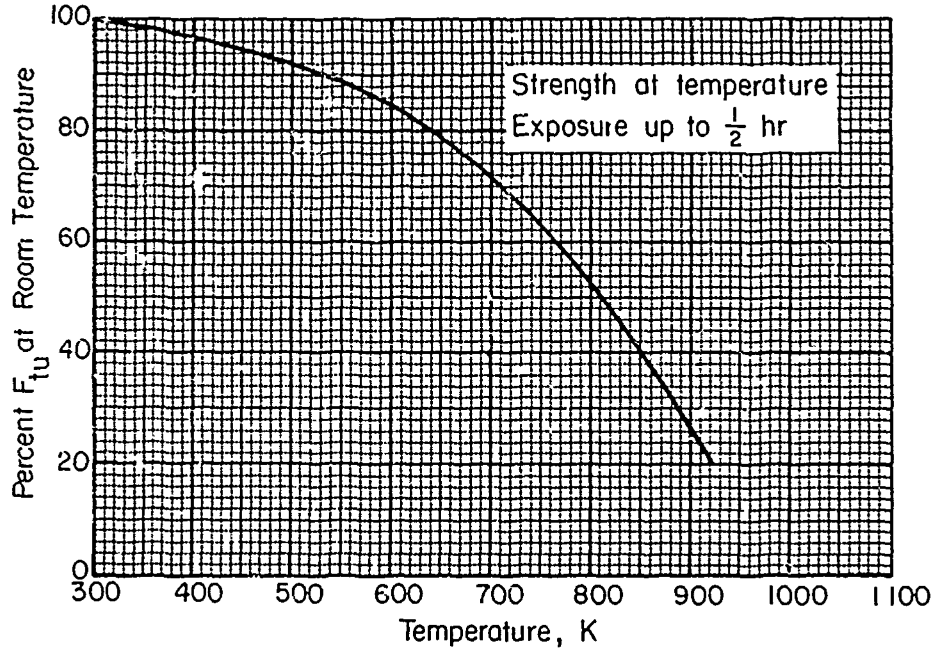


FIGURE 2.6.10.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of 17-7PH (TH1050) stainless steel.

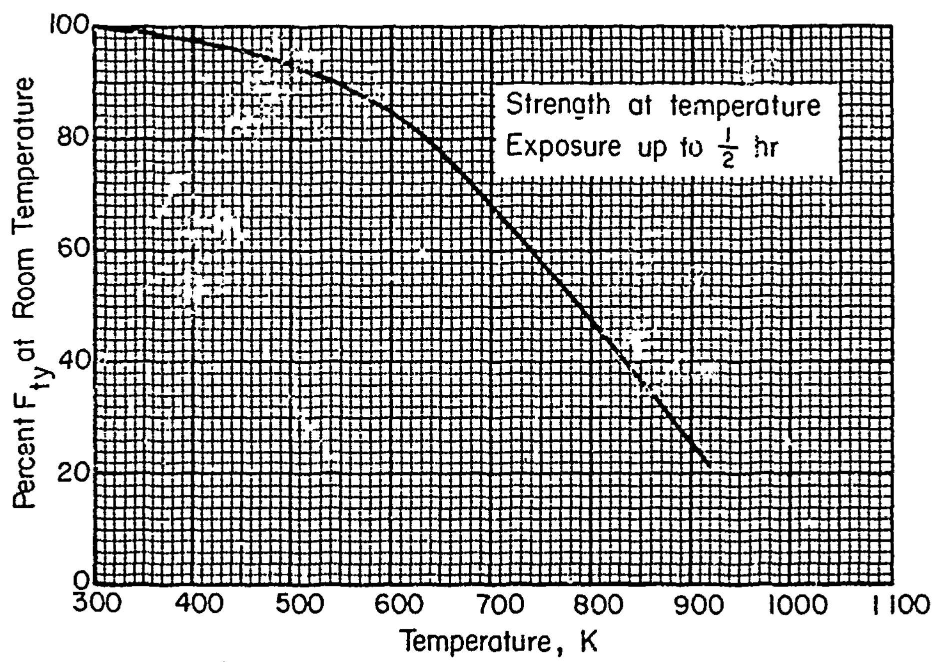


FIGURE 2.6.10.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of 17-7PH (TH1050) stainless steel.

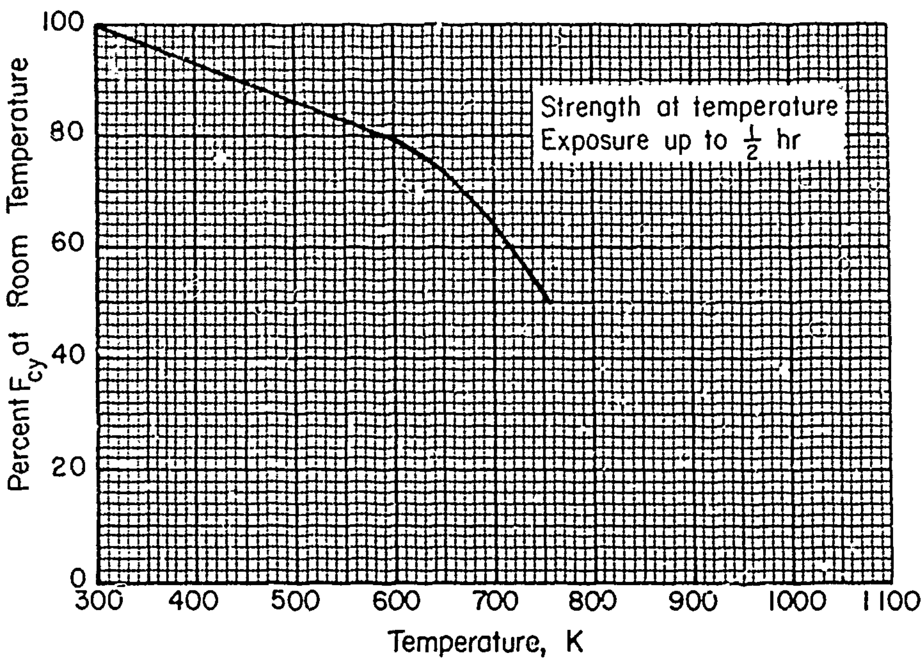


FIGURE 2.6.10.1.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of 17-7PH (TH1050) stainless steel.

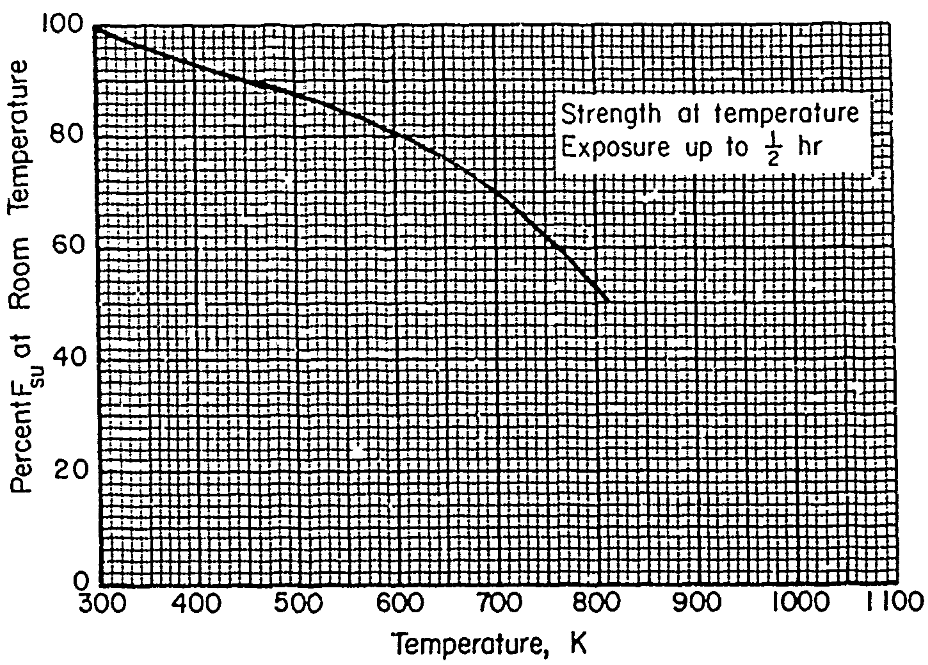


FIGURE 2.6.10.1.2(b). Effect of temperature on the ultimate shear strength (F_{su}) of 17-7PH (TH1050) stainless steel.

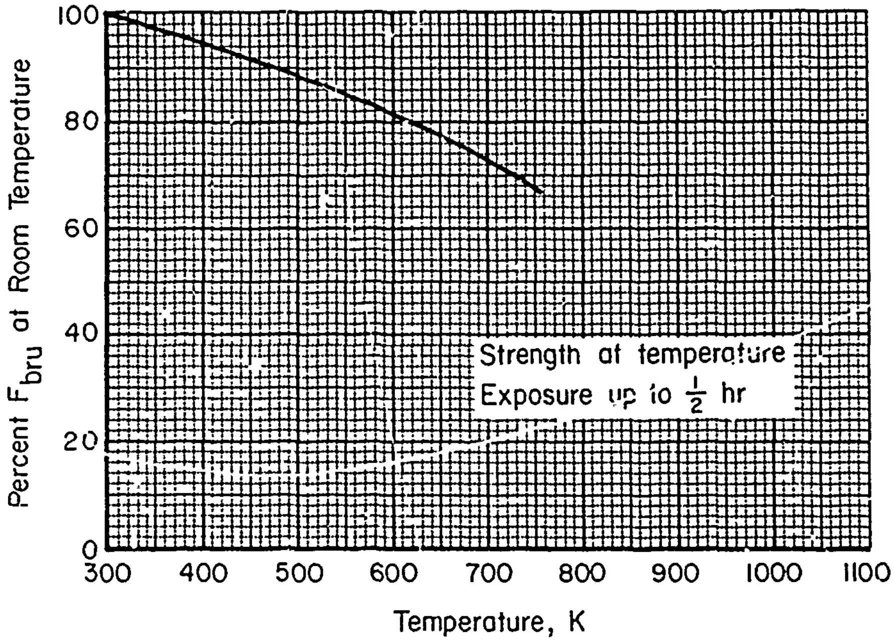


FIGURE 2.6.10.1.3(a). Effect of temperature on the ultimate bearing strength (F_{bru}) of 17-7PH (TH1050) stainless steel.

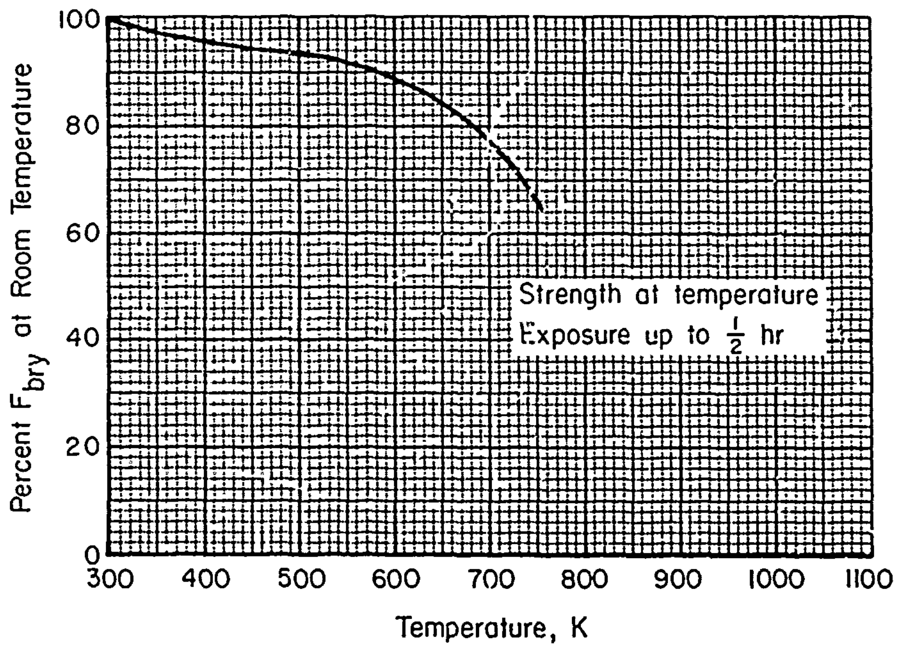


FIGURE 2.6.10.1.3(b). Effect of temperature on the bearing yield strength (F_{bry}) of 17-7PH (TH1050) stainless steel.

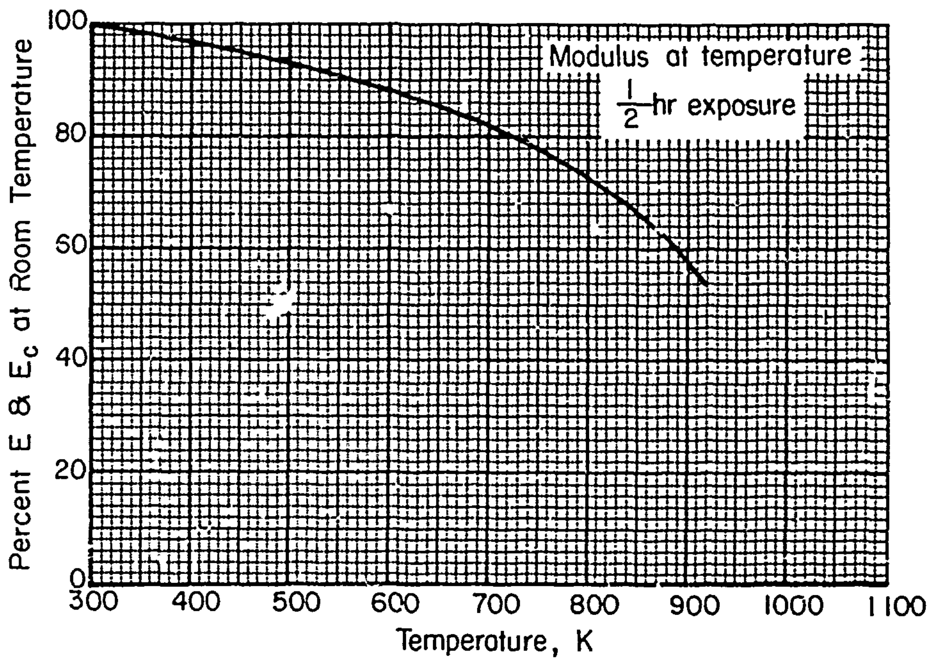


FIGURE 2.6.10.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of 17-7PH (TH1050) stainless steel.

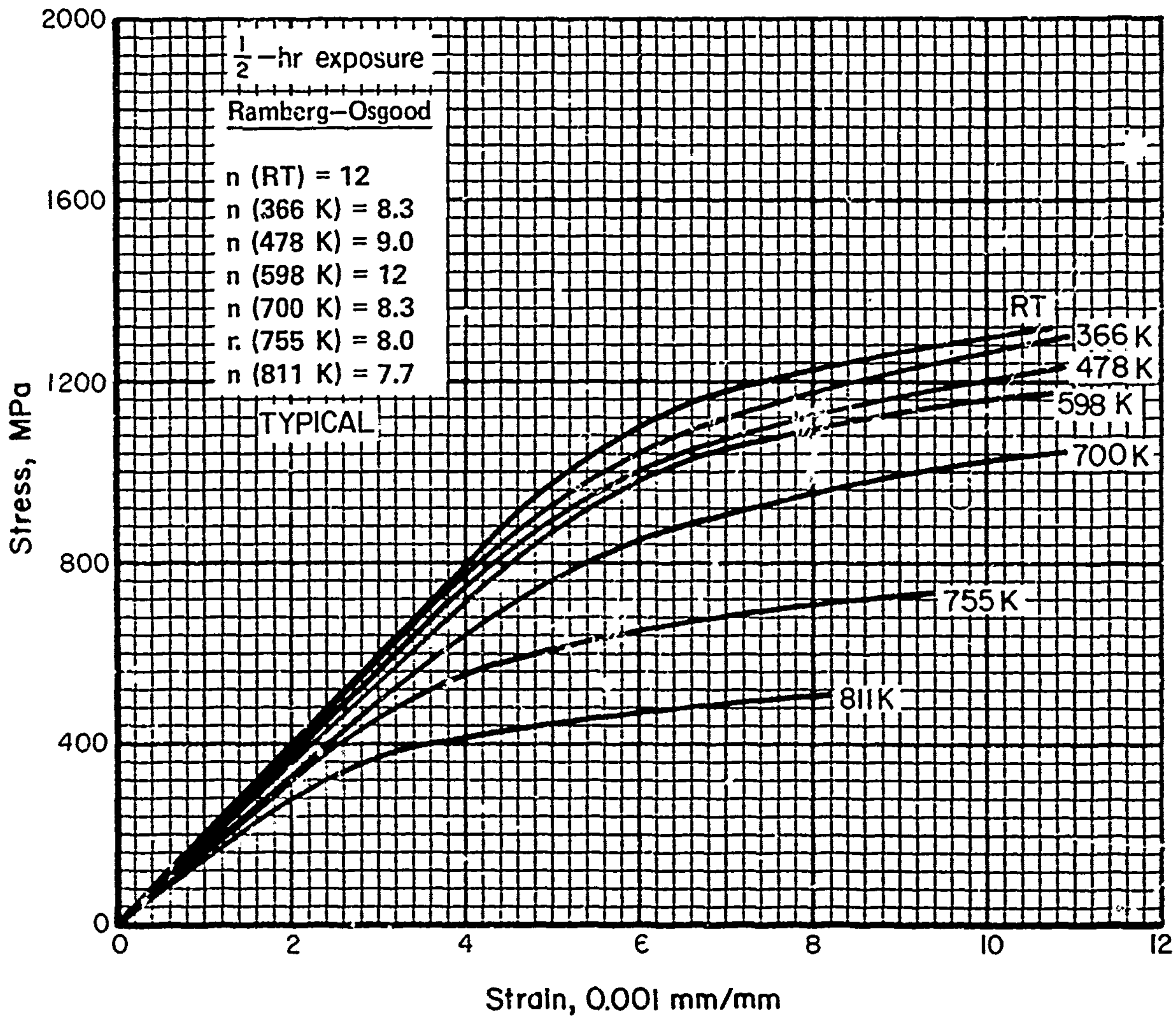


FIGURE 2.6.10.1.6(a). Typical tensile stress-strain curves at various temperatures for 17-7PH (TH1050) stainless steel (sheet).

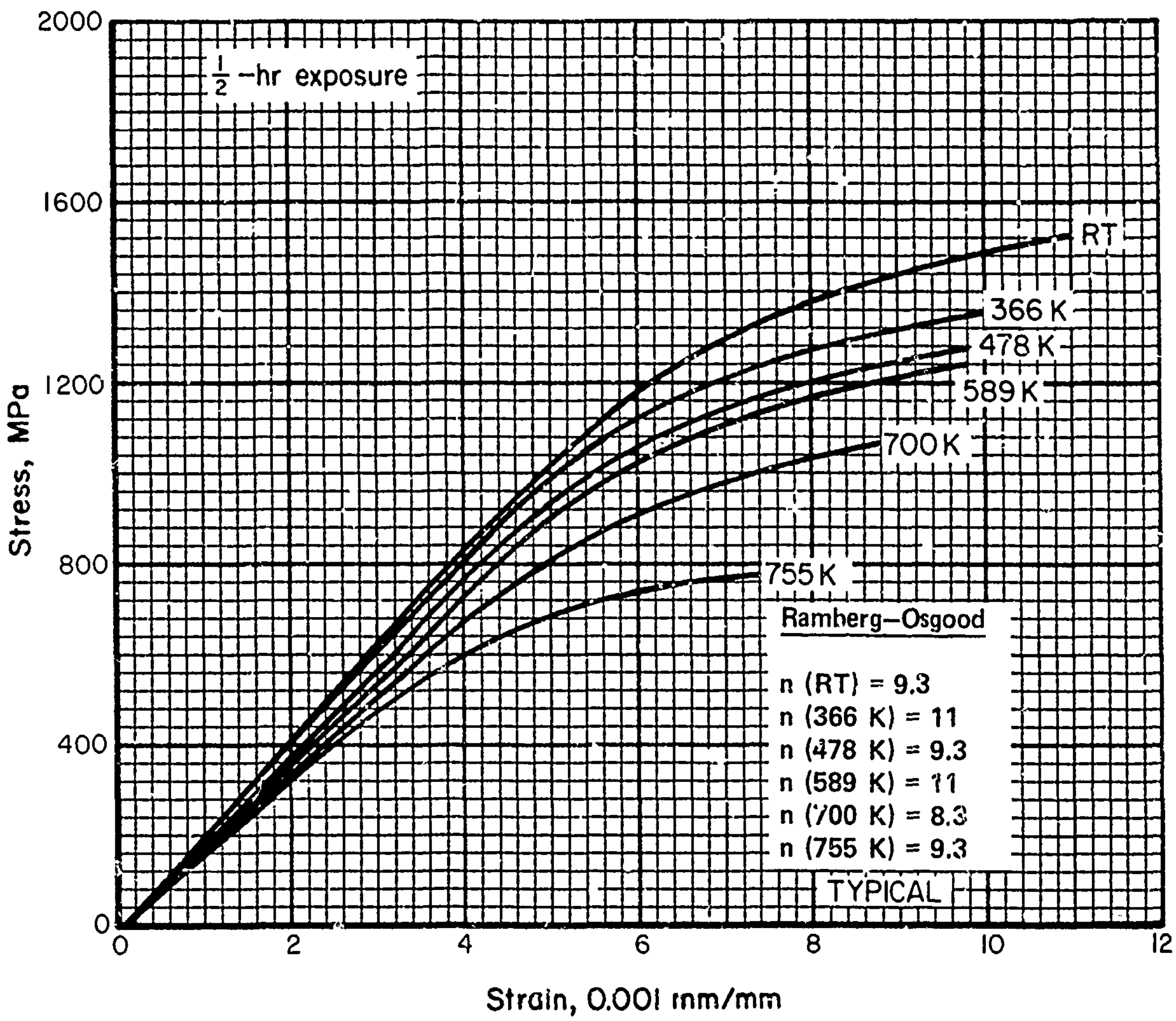


FIGURE 2.6.10.1.6(b). Typical compressive stress-strain curves at various temperatures for 17-7PH (TH1050) stainless steel (sheet).

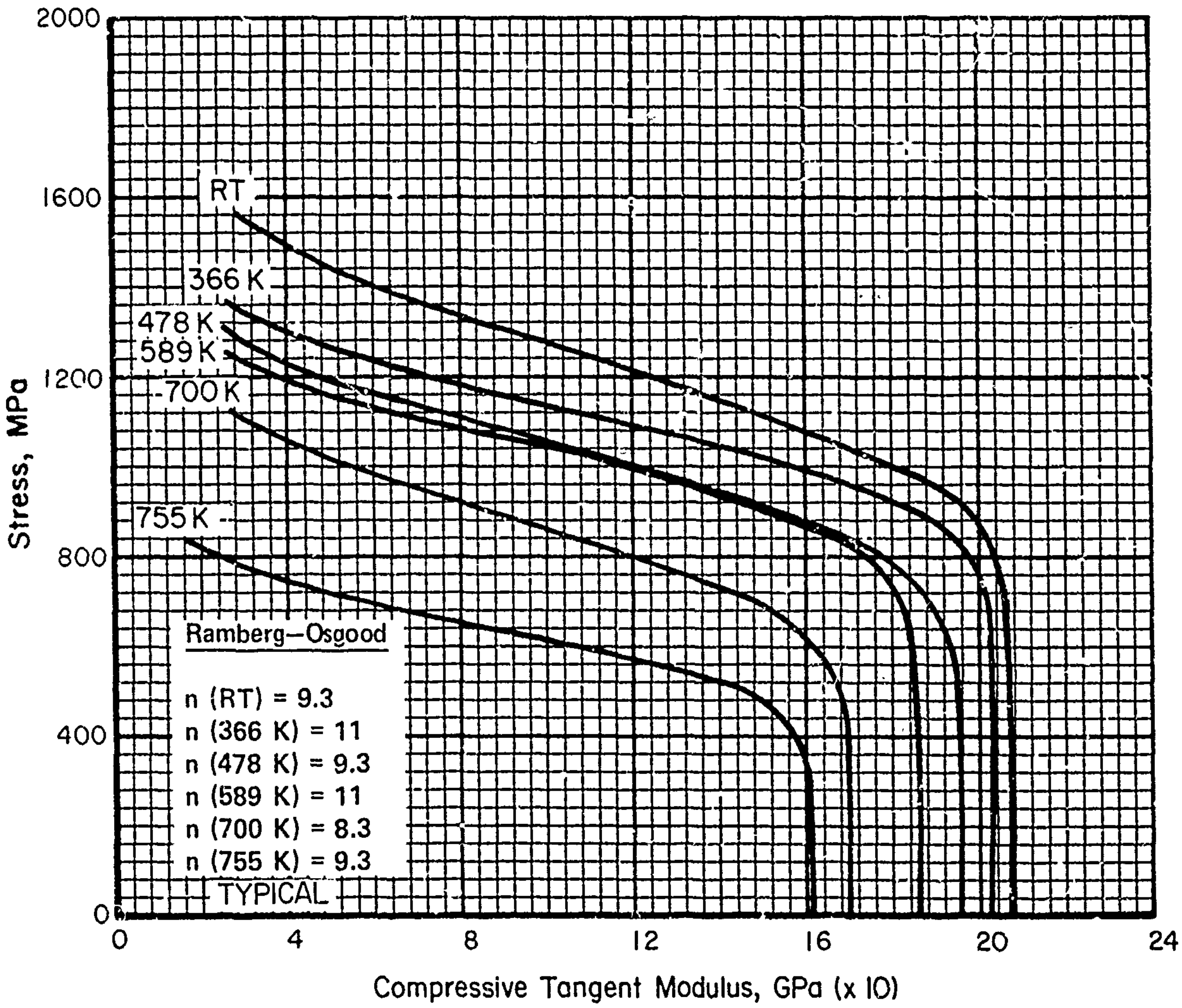


FIGURE 2.6.10.1.6(c). Typical compressive tangent-modulus curves at various temperatures for 17-7PH (TH1050) stainless steel (sheet).

2.7.0 COMMENTS ON AUSTENITIC STAINLESS STEELS

2.7.0.1 *Metallurgical Considerations.*—The austenitic or "18-8" stainless steels were developed originally as corrosion-resistant alloys. However, they also possess excellent oxidation resistance and good creep strength at elevated temperatures, together with good cold formability and other properties of interest in airframe and missile applications. They are presently being used extensively 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 main alloying elements in the austenitic stainless steels are chromium and nickel. Chromium imparts corrosion and oxidation resistance and high-temperature strength, and nickel gives these alloys an austenitic structure, with its associated toughness and ductility. Columbium or titanium is usually added as a stabilizer when welding is involved. Sulfur and selenium are often added to improve machinability.

These alloys are not hardenable by heat treatment but are capable of achieving high strength levels through cold working. The strength imparted by cold working is decreased by exposure to temperatures above about 755 K.

2.7.0.2 *Manufacturing Considerations.*

Forging.—The stainless steels have much lower thermal conductivity than the 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 soaking temperatures and times must be controlled carefully to limit grain growth when small reductions are involved during forging. At forging temperatures, the stainless steels are stronger than the 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 conditions. They are considerably stronger than mild steels and require more powerful equipment. They work harden rapidly, and intermediate anneals may be required in deep drawing.

Machining.—The machining of the austenitic stainless steels is not particularly 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 of the usual techniques 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 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 for these steels 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 non-stabilized grades to temperatures between 644 and 1172 K makes them susceptible to intergranular corrosion.

2.7.1 AISI 301

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.

Material specification for AISI 301 stainless steel is presented in Table 2.7.1.0(a).

Type 301 should not be used for extended periods at temperatures of 672 and 1172 K and should not be cooled slowly from higher temperatures through this range.

TABLE 2.7.1.0(a). *Material Specification for AISI 301 Stainless Steel*

Specification	Form
MIL-S-5059	Plate, sheet and strip

Type 301 is strengthened by cold working. If cold-worked Type 301 is subjected to temperatures above 755 K, its room-temperature strength is reduced.

Room-Temperature Properties

The room-temperature mechanical and physical properties for AISI 301 stainless steel are presented in Tables 2.7.1.0(b) and 2.7.1.0(c).

The physical properties of this alloy at room and elevated temperatures are presented in Figure 2.7.1.0.

2.7.1.1 *Annealed Conditions.*—No elevated-temperature properties are presented for this condition. Typical room-temperature tangent-modulus curves are presented in Figures 2.7.1.3.6(a) through (b).

2.7.1.2 *Quarter-Hard Condition.*—No elevated-temperature properties are presented for this condition. Typical room-temperature tangent-modulus curves are presented in Figures 2.7.1.3.6(a) through (b).

2.7.1.3 *Half-Hard Condition.*—Effect of temperature curves for various mechanical properties for this condition are presented in Figures 2.7.1.3.1(a) through 2.7.1.3.4. Typical tangent-modulus curves for this condition are presented in Figures 2.7.1.3.6(a) through (b).

2.7.1.4 *Three-Quarter-Hard Condition.*—No elevated-temperature properties are presented for this condition. Typical room-temperature tangent-modulus curves are presented in Figures 2.7.1.3.6(a) through (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.

Effect of temperature curves for various mechanical properties for this condition are presented in Figures 2.7.1.5.1(a) through 2.7.1.5.4. Typical room-temperature compressive tangent-modulus curves are presented in Figures 2.7.1.3.6(a) through (b). 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(c). Elongation Values for AISI 301 Stainless Steel

Condition	Thickness, mm	Elongation, percent
Annealed.......	0.39 and under	40
	0.40 to 0.77	45
	0.78 and over	50
Quarter-hard...	0.39 and under	25
	0.40 and over	25
Half-hard......	0.39 and under	15
	0.40 and over	18
Three-quarter-hard.........	0.39 and under	10
	0.40 and over	12
Full-hard......	0.39 and under	8
	0.40 and over	9

TABLE 2.7.1.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF AISI 301 STAINLESS STEEL

SPECIFICATION	MIL-S-5059[a]								
FORM	SHEET AND STRIP								
CONDITION	ANNEALED	1/4 HARD		1/2 HARD		3/4 HARD		FULL HARD	
THICKNESS, MM	...	...		...		...		...	
BASIS	S	A[b]	B	A[b]	B	A[b]	B	A[b]	B
MECHANICAL PROPERTIES:									
FTU, MPA:									
L	517	855	889	972	1040	1080	1160	1200	1280
LT	517	855	876	979	1050	1120	1190	1210	1280
FTY, MPA:									
L	207	476	572	641	758	814	931	945	1050
LT	207	462	565	634	724	779	917	862	979
FCY, MPA:									
L	186	317	386	434	496	538	627	593	676
LT	186	510	627	703	807	869	1020	958	1090
FSU, MPA	345	455	476	531	565	607	641	655	689
FBRU, MPA:									
(E/D=1.5)	...	...	...	...	...	...	...	...	...
(E/D=2.0)	1030	1680	1750	1960	2100	2250	2390	2410	2560
FBRY, MPA:									
(E/D=1.5)	...	...	...	...	...	...	...	...	...
(E/D=2.0)	345	862	1050	1150	1320	1380	1630	1660	1990
EL, PERCENT	c	c	c	c	c	c	c	c	c
E, GPA:									
L	200.0	186.2		179.3		179.3		179.3	
LT	200.0	193.1		193.1		193.1		193.1	
EC, GPA:									
L	193.1	179.3		179.3		179.3		179.3	
LT	193.1	186.2		186.2		186.2		186.2	
G, GPA	86.2	82.7		79.3		75.8		75.8	
MU	...	...		...		...		...	
PHYSICAL PROPERTIES:									
OMEGA, MG/M3	7.92								
C, J/(G*K)	SEE FIGURE 2.7.1.0								
K, W/(M*K)	SEE FIGURE 2.7.1.0								
ALPHA, 10-6 M/(M*K)	SEE FIGURE 2.7.1.0								

[a]PROPERTIES FOR ANNEALED CONDITION ALSO APPLICABLE TO AISI 301 PLATE AND TO ANNEALED AISI 302, 303, 304, 321, AND 347.

[b]FTU AND FTY VALUES LESS THAN SPECIFICATION VALUES.

SEE TABLE 2.791.0(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 533 TO 700K.

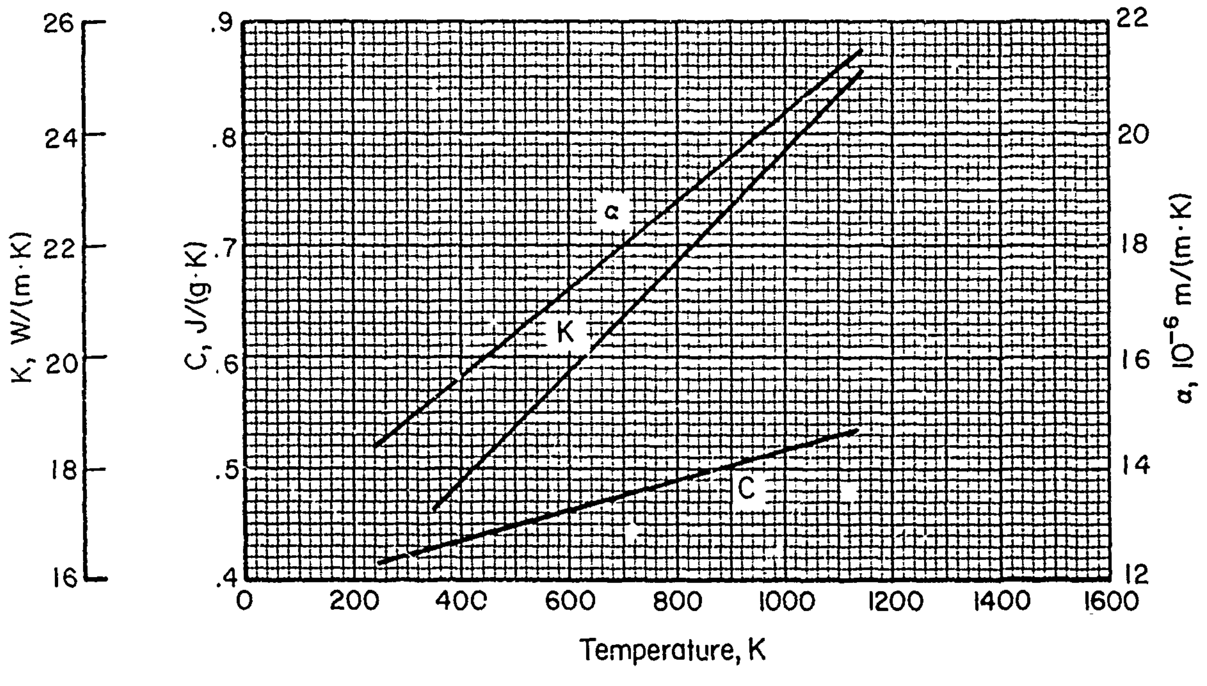


FIGURE 2.7.1.0. Effect of temperature on the physical properties of AISI 301 stainless steel.

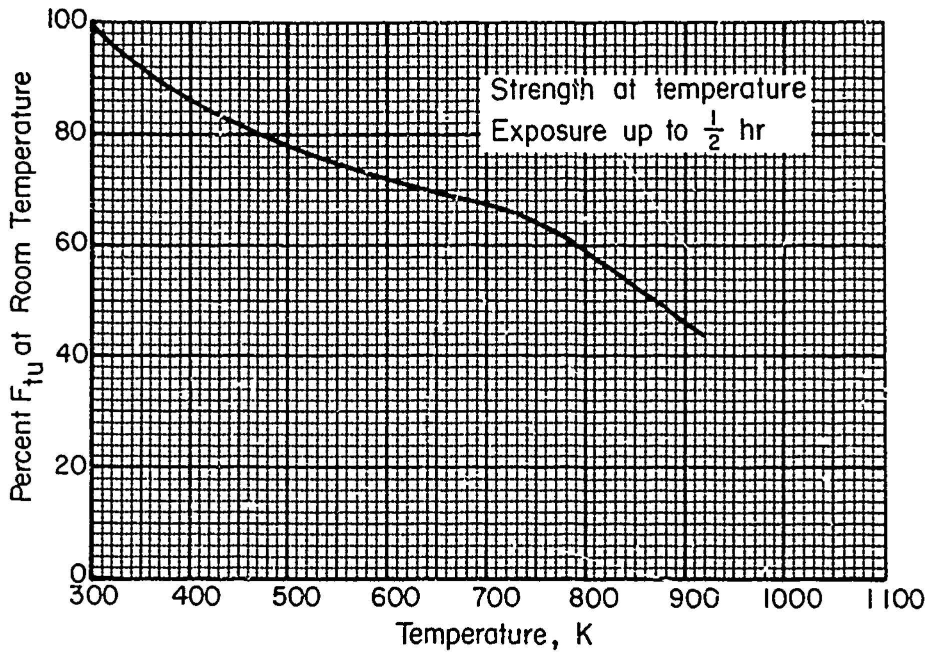


FIGURE 2.7.1.3.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of AISI 301 (half-hard) stainless steel.

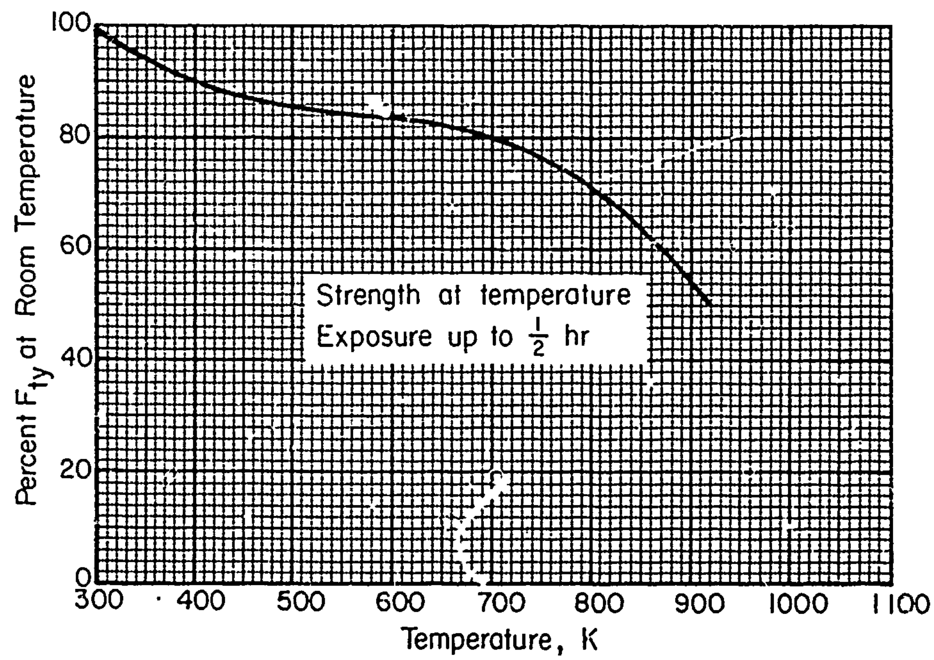


FIGURE 2.7.1.3.1(b). Effect of temperature on the tensile yeild strength (F_{ty}) of AISI 301 (half-hard) stainless steel.

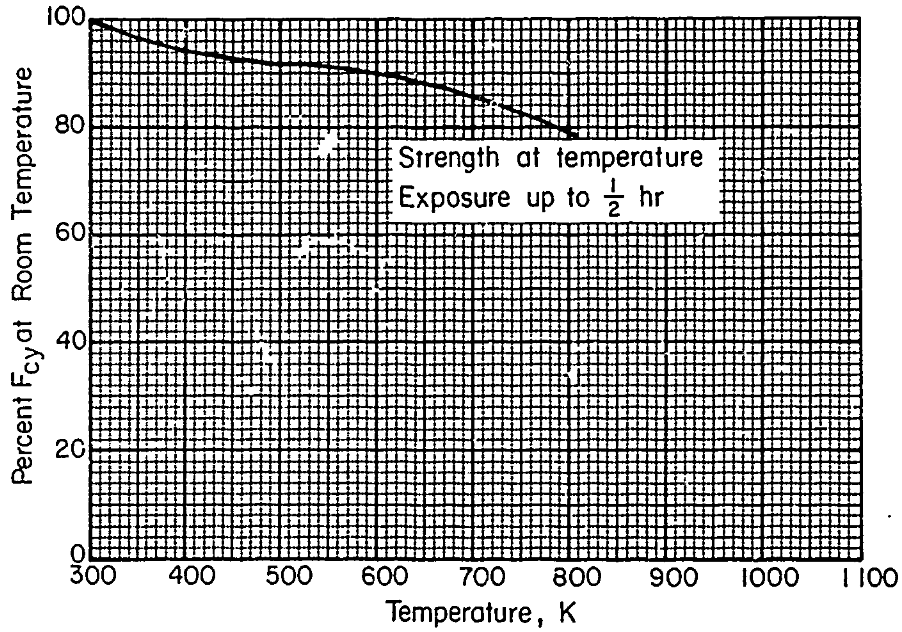


FIGURE 2.7.1.3.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of AISI 301 (half-hard) stainless steel.

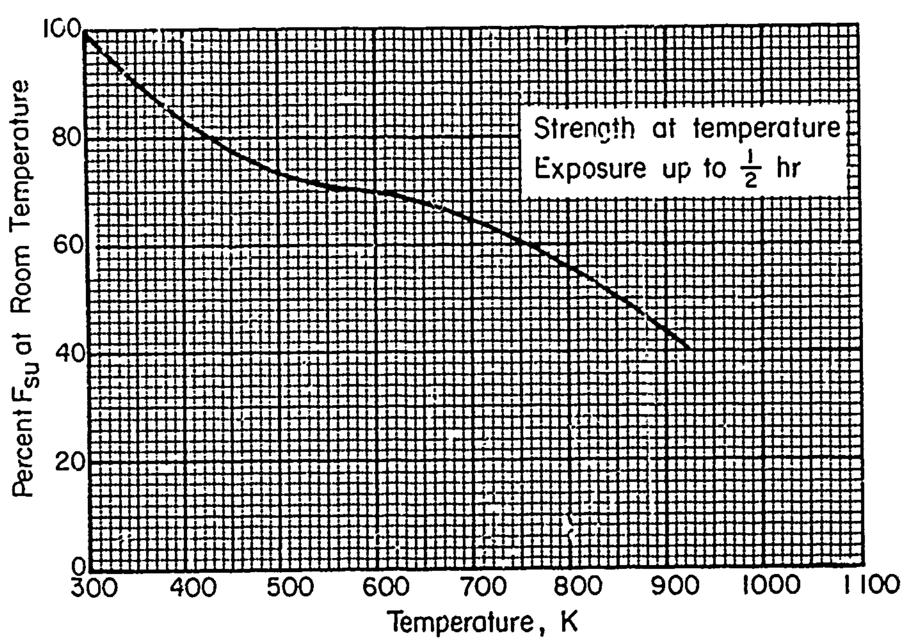


FIGURE 2.7.1.3.2(b). Effect of temperature on the ultimate shear strength (F_{su}) of AISI 301 (half-hard) stainless steel.

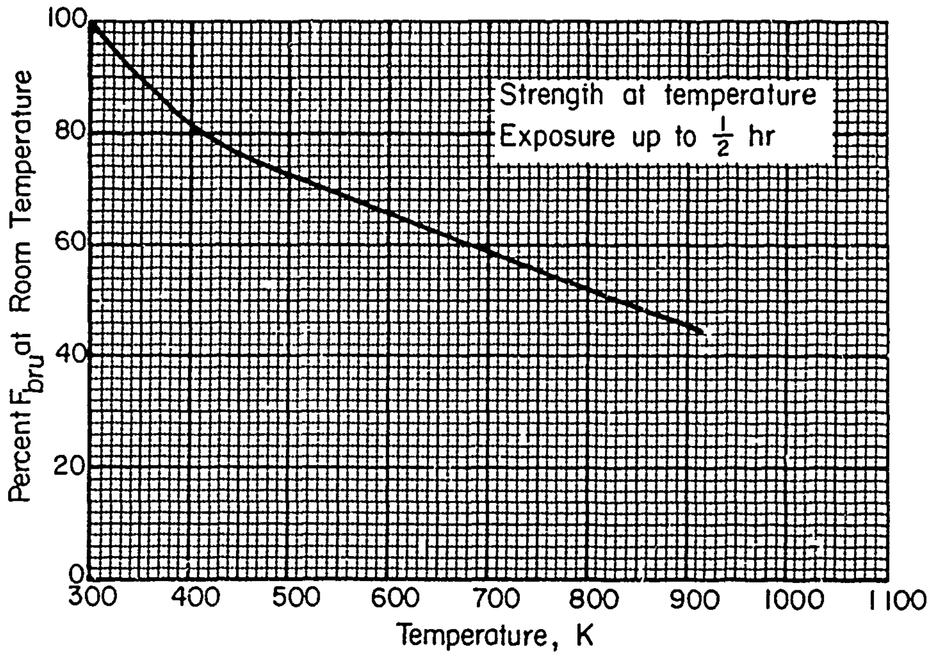


FIGURE 2.7.1.3.3(a). Effect of temperature on the ultimate bearing strength (F_{bru}) of AISI 301 (half-hard) stainless steel.

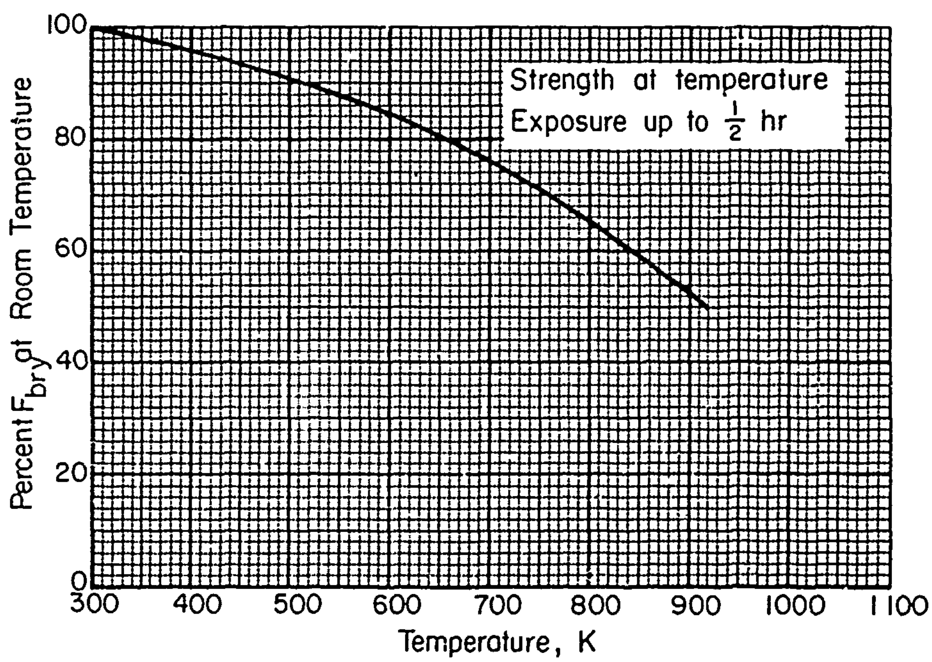


FIGURE 2.7.1.3.3(b). Effect of temperature on the bearing yield strength (F_{bry}) of AISI 301 (half-hard) stainless steel.

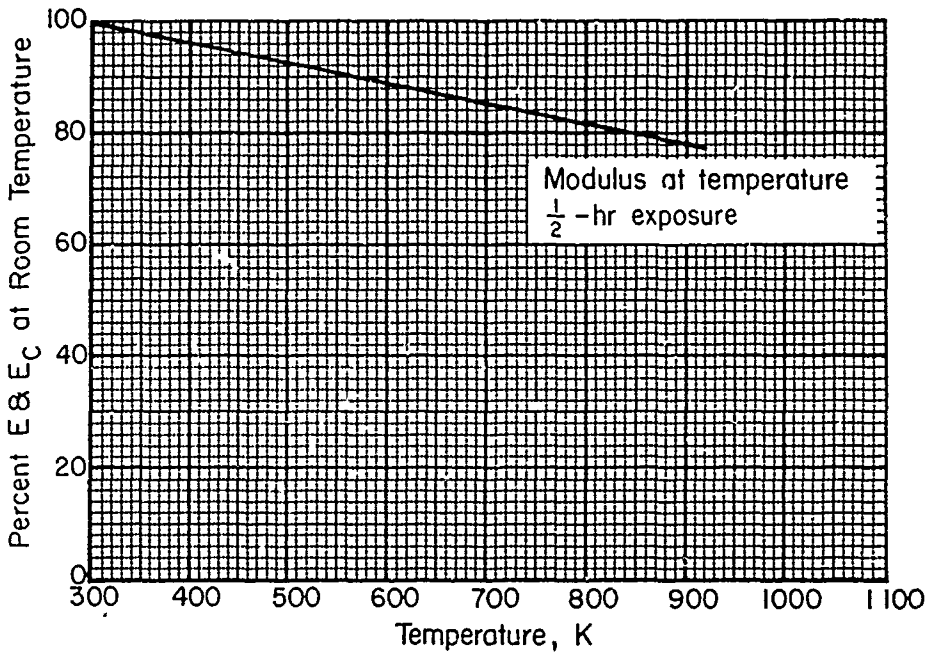


FIGURE 2.7.1.3.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of AISI 301 (half-hard) stainless steel.

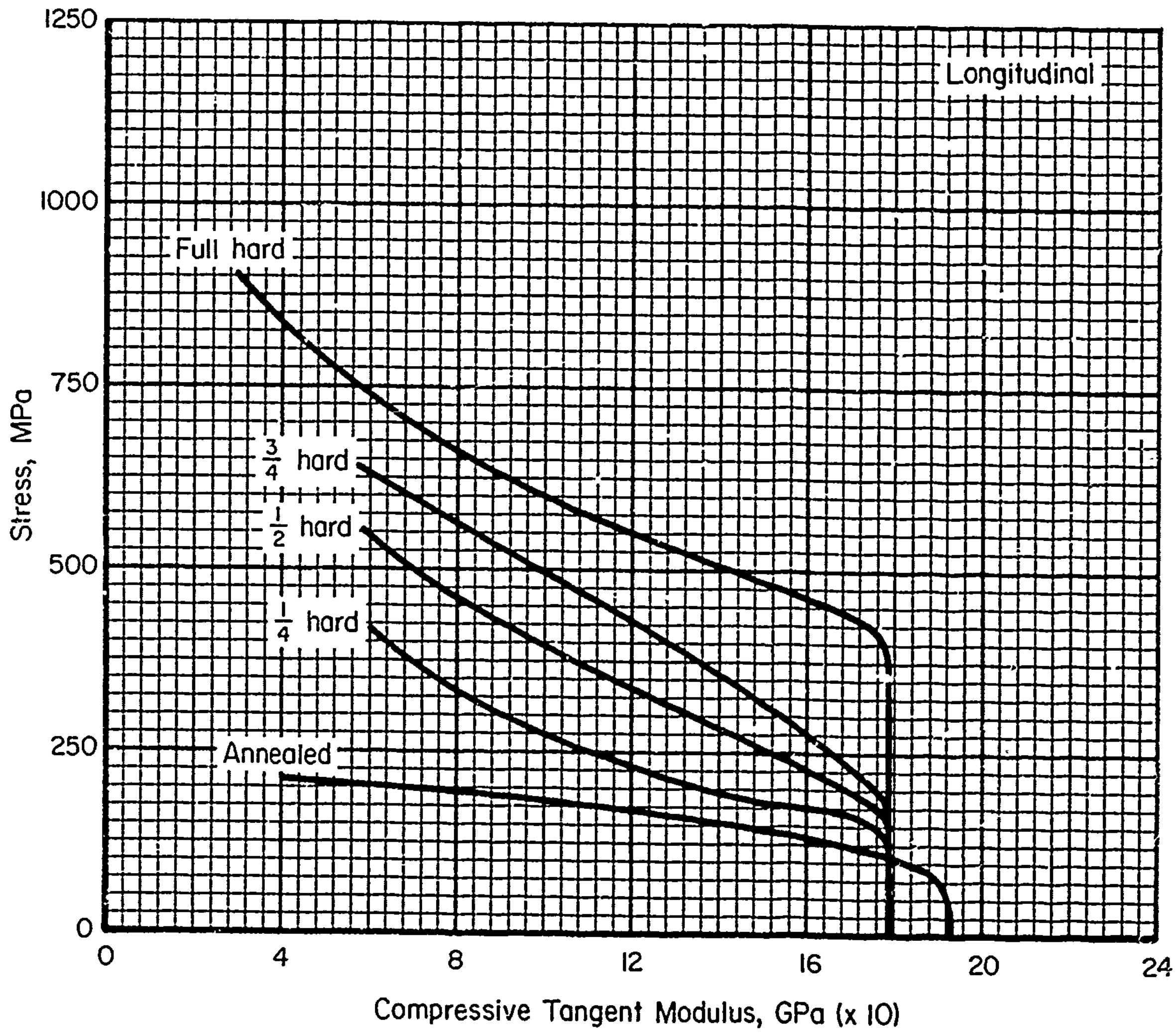


FIGURE 2.7.1.3.6(a). Typical compressive tangent-modulus curves for AISI 301 stainless steel (sheet and plate) at room temperature.

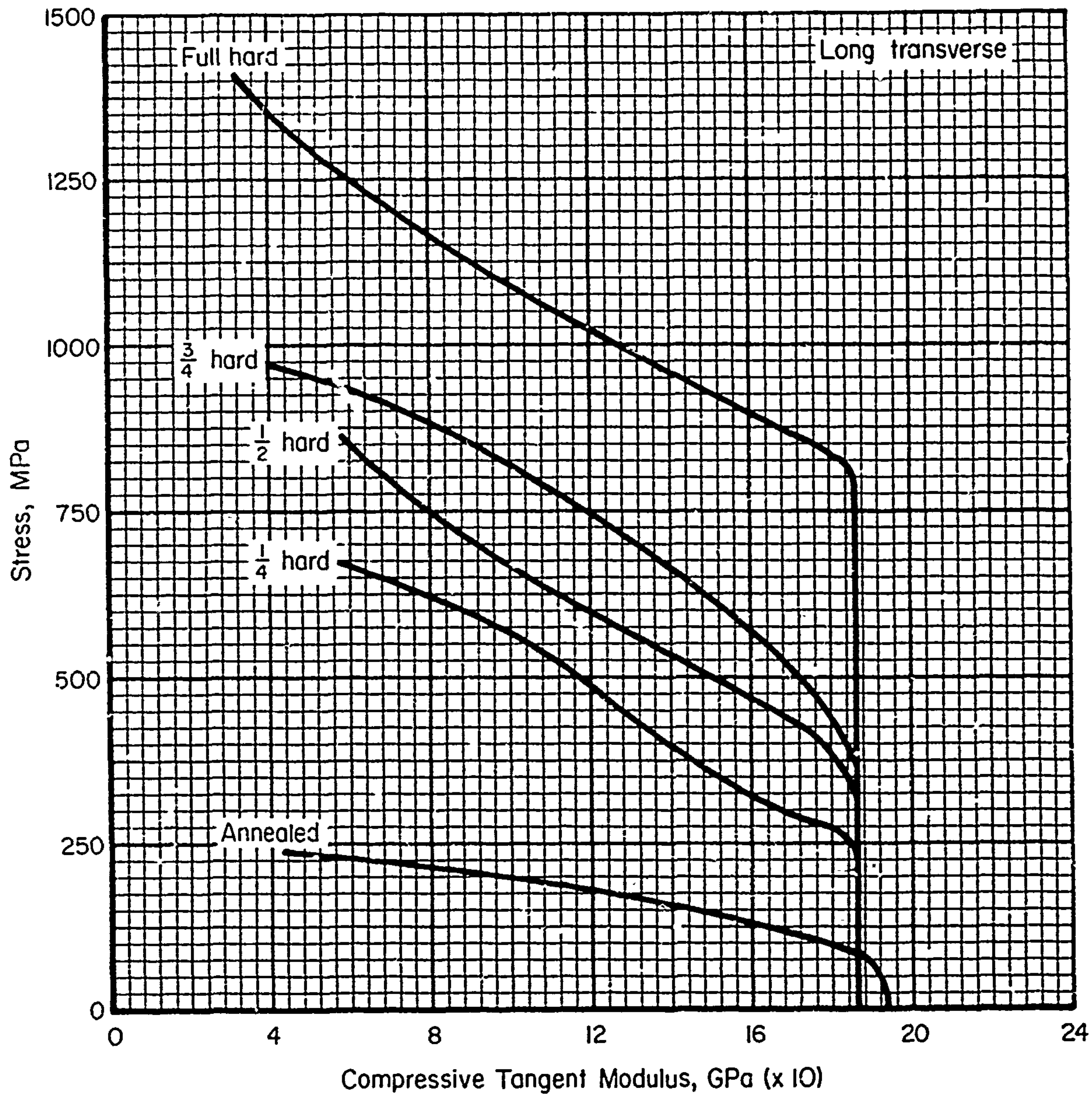


FIGURE 2.7.1.3.6(b). Typical compressive tangent-modulus curves for AISI 301 stainless sheet (sheet and plate) at room temperature.

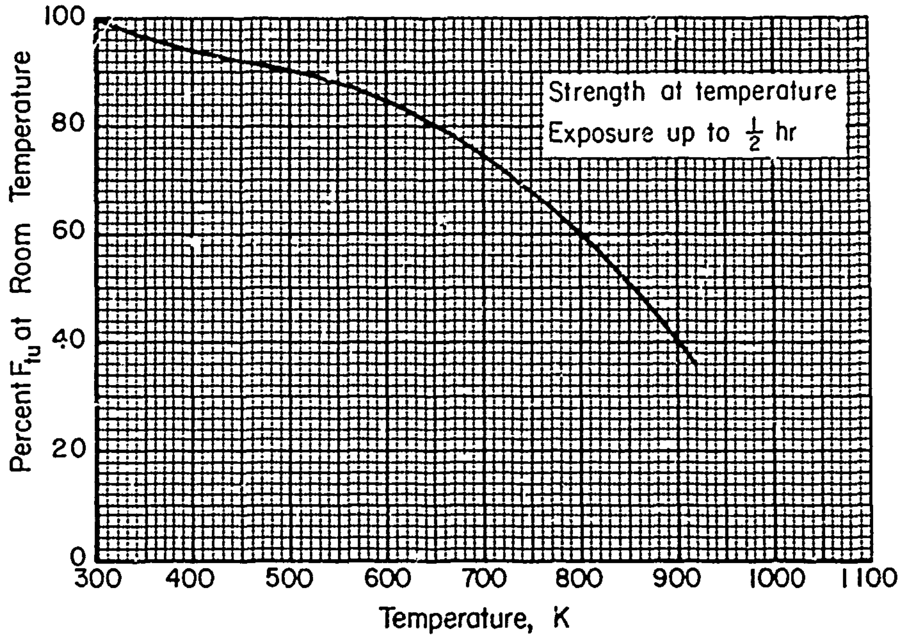


FIGURE 2.7.1.5.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of AISI 301 (full-hard) stainless steel.

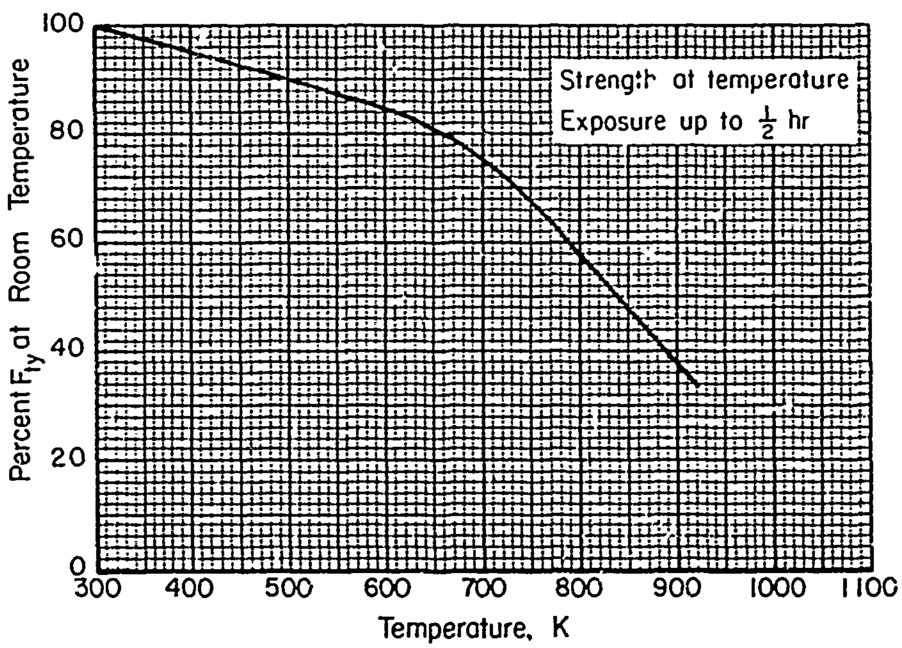


FIGURE 2.7.1.5.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of AISI 301 (full-hard) stainless steel.

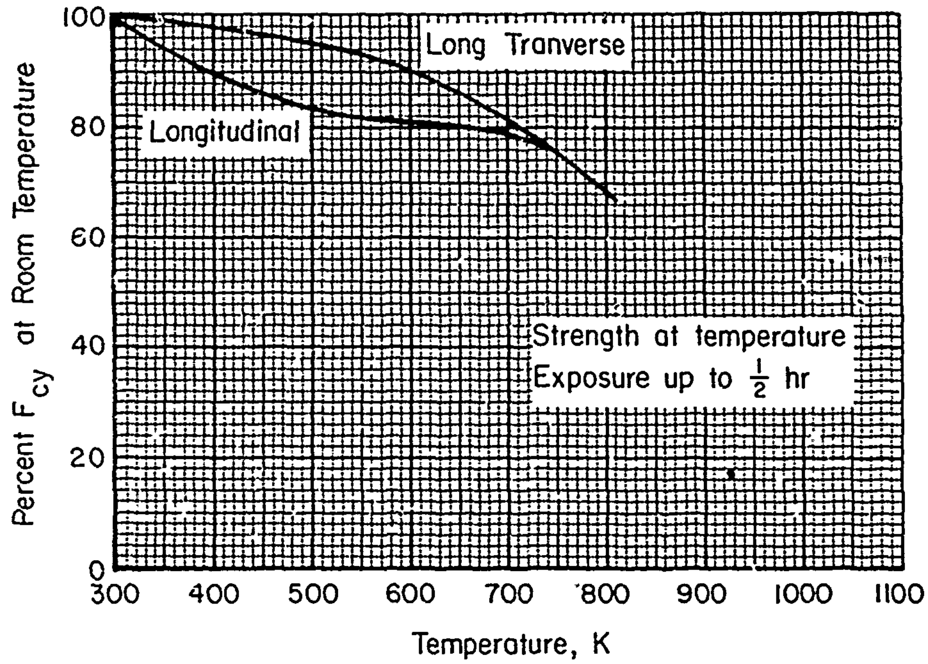


FIGURE 2.7.1.5.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of AISI 301 (half-hard) stainless steel.

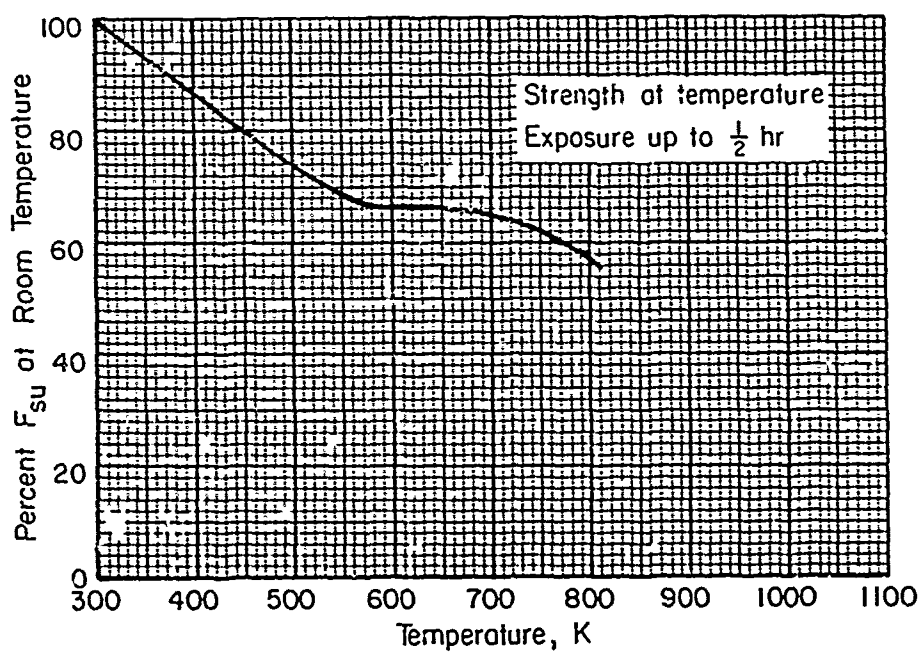


FIGURE 2.7.1.5.2(b). Effect of temperature on the ultimate shear strength (F_{su}) of AISI 301 (full-hard) stainless steel.

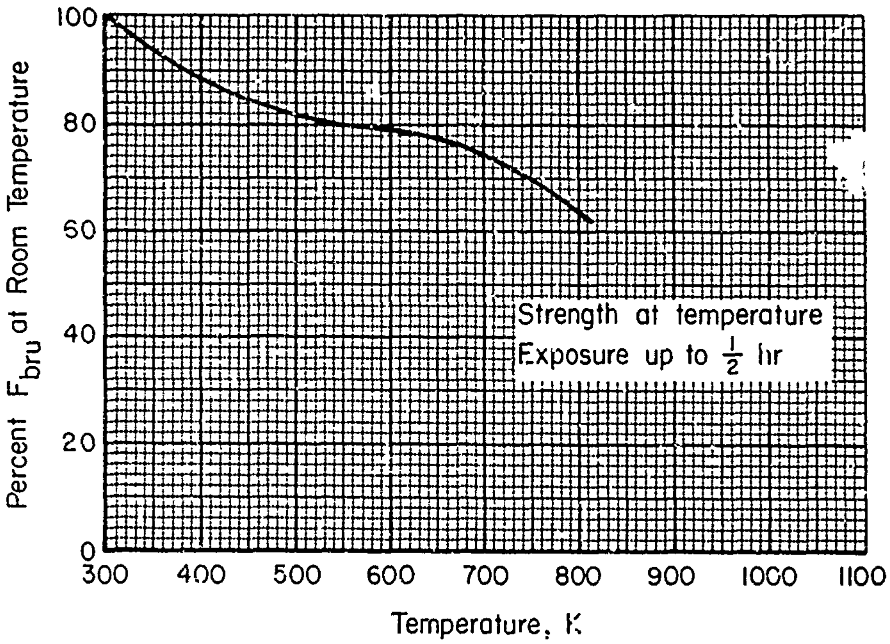


FIGURE 2.7.1.5.3(a). Effect of temperature on the ultimate bearing strength (F_{bru}) of AISI 301 (full-hard) stainless steel.

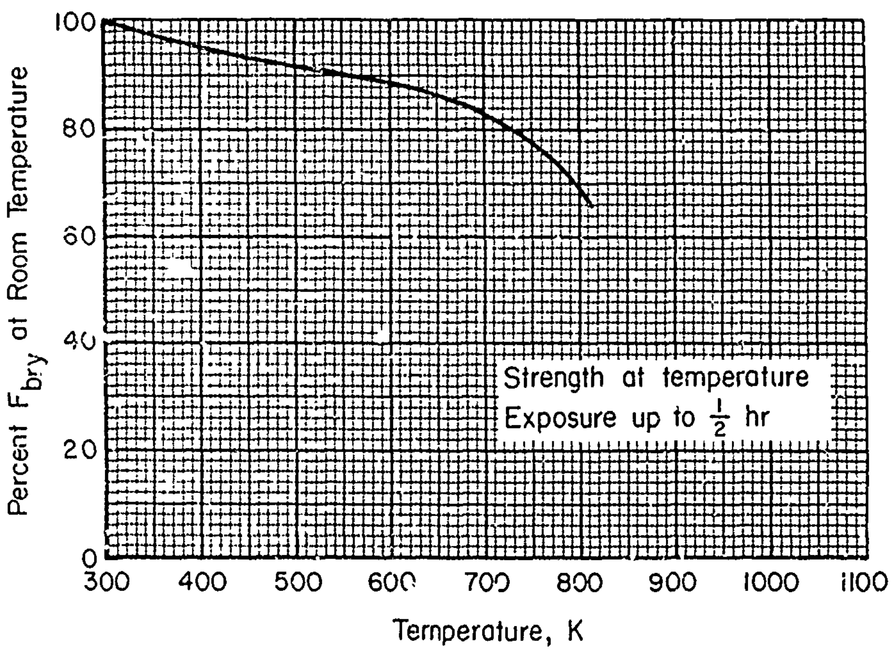


FIGURE 2.7.1.5.3(b). Effect of temperature on the bearing yield strength (F_{bry}) of AISI 301 (full-hard) stainless steel.

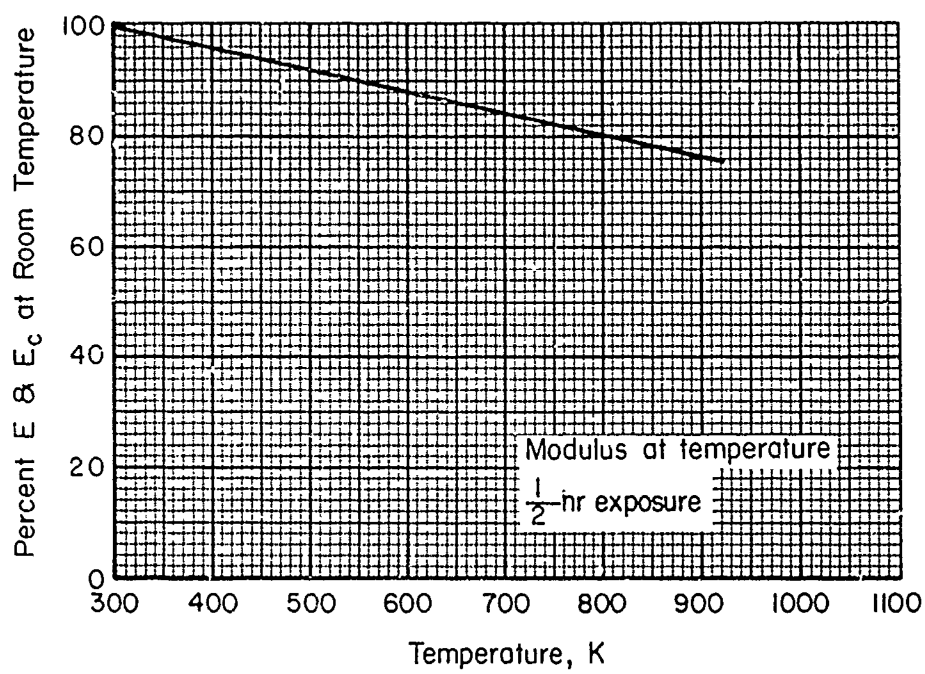


FIGURE 2.7.1.5.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of AISI 301 (full-hard) stainless steel.

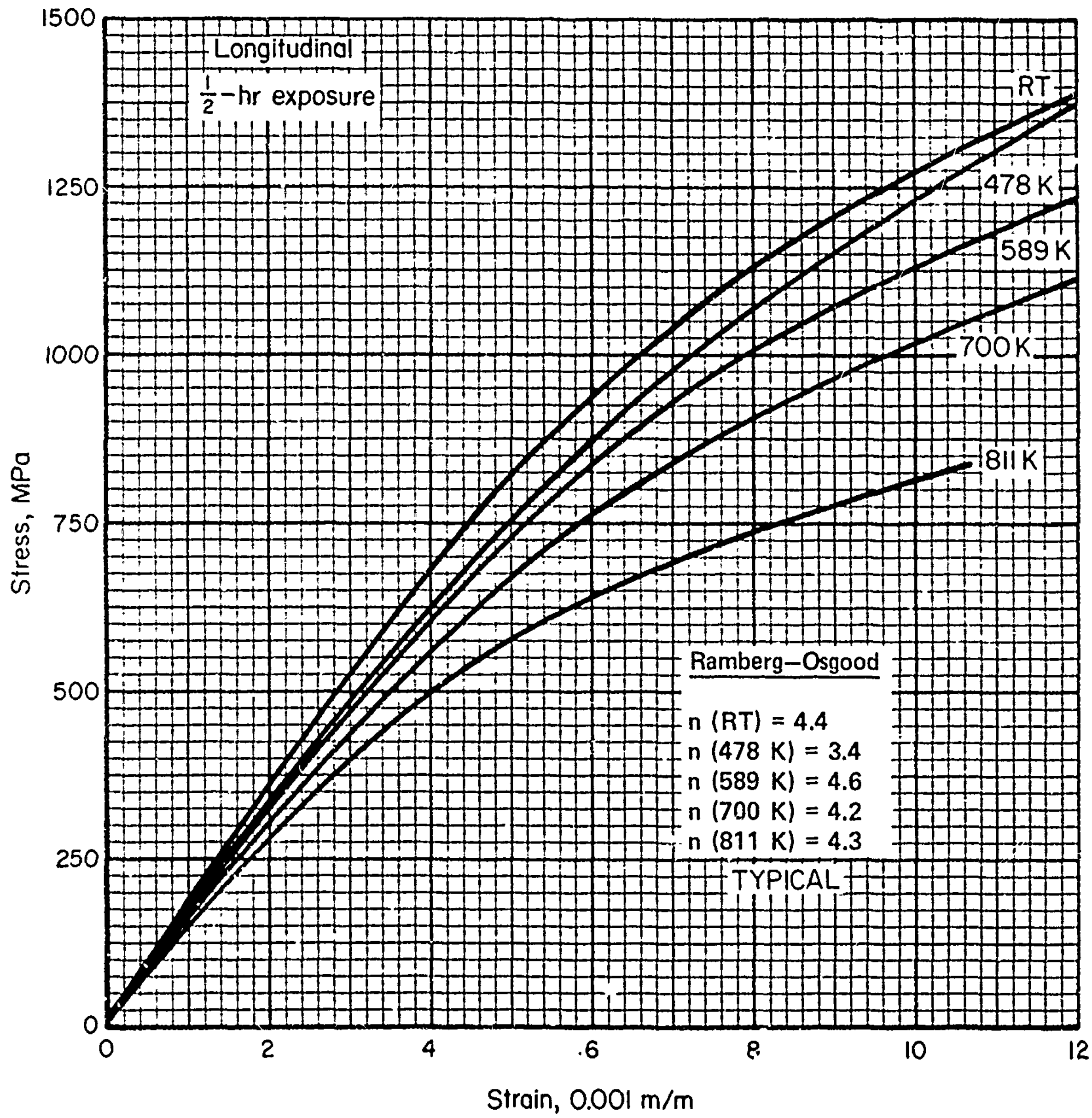


FIGURE 2.7.1.5.6(a). Typical tensile stress-strain curves at room and elevated temperatures for AISI 301 (full-hard) stainless steel.

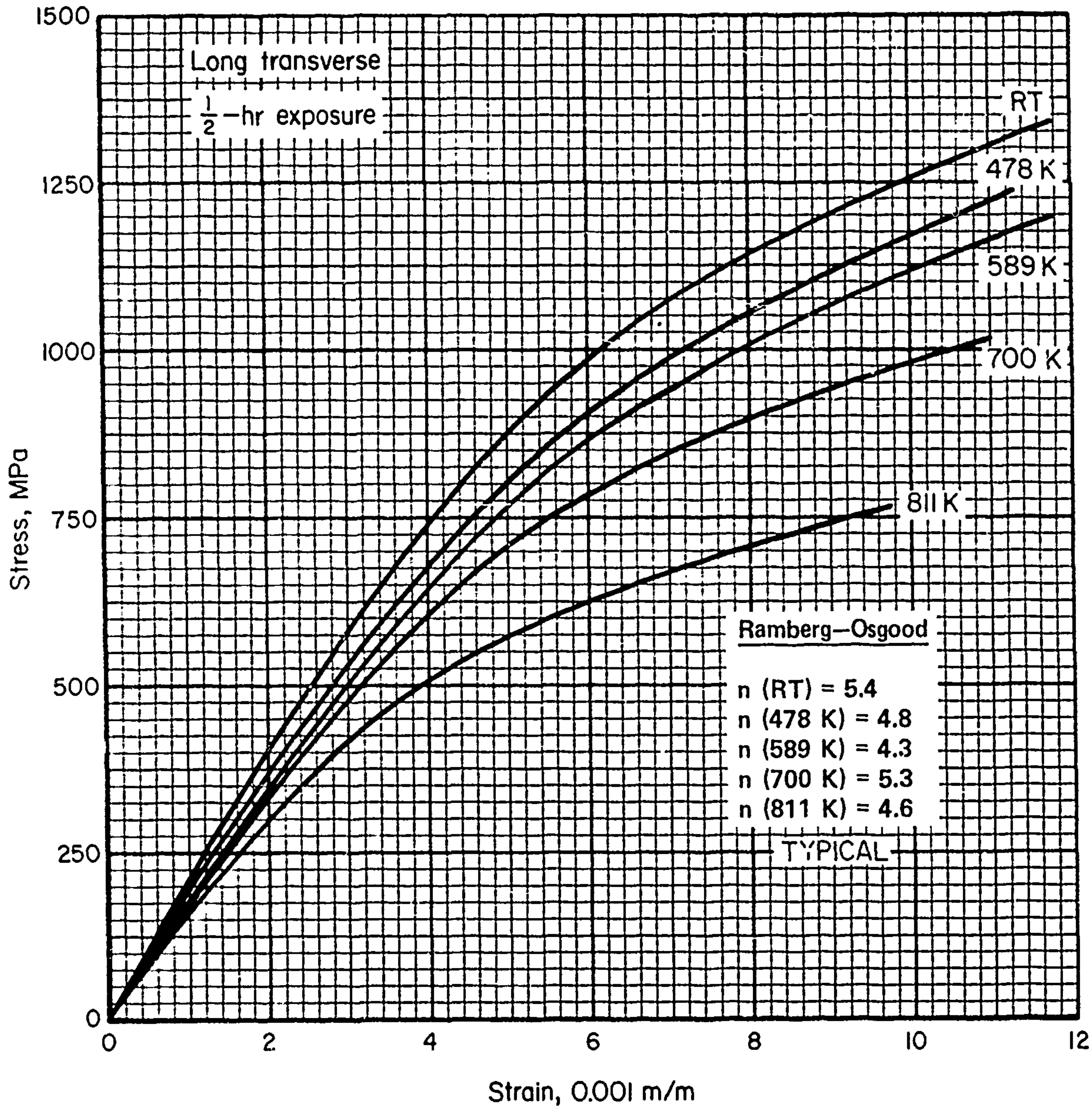


FIGURE 2.7.1.5.6(b). Typical tensile stress-strain curves at room and elevated temperatures for AISI 301 (full-hard) stainless steel.

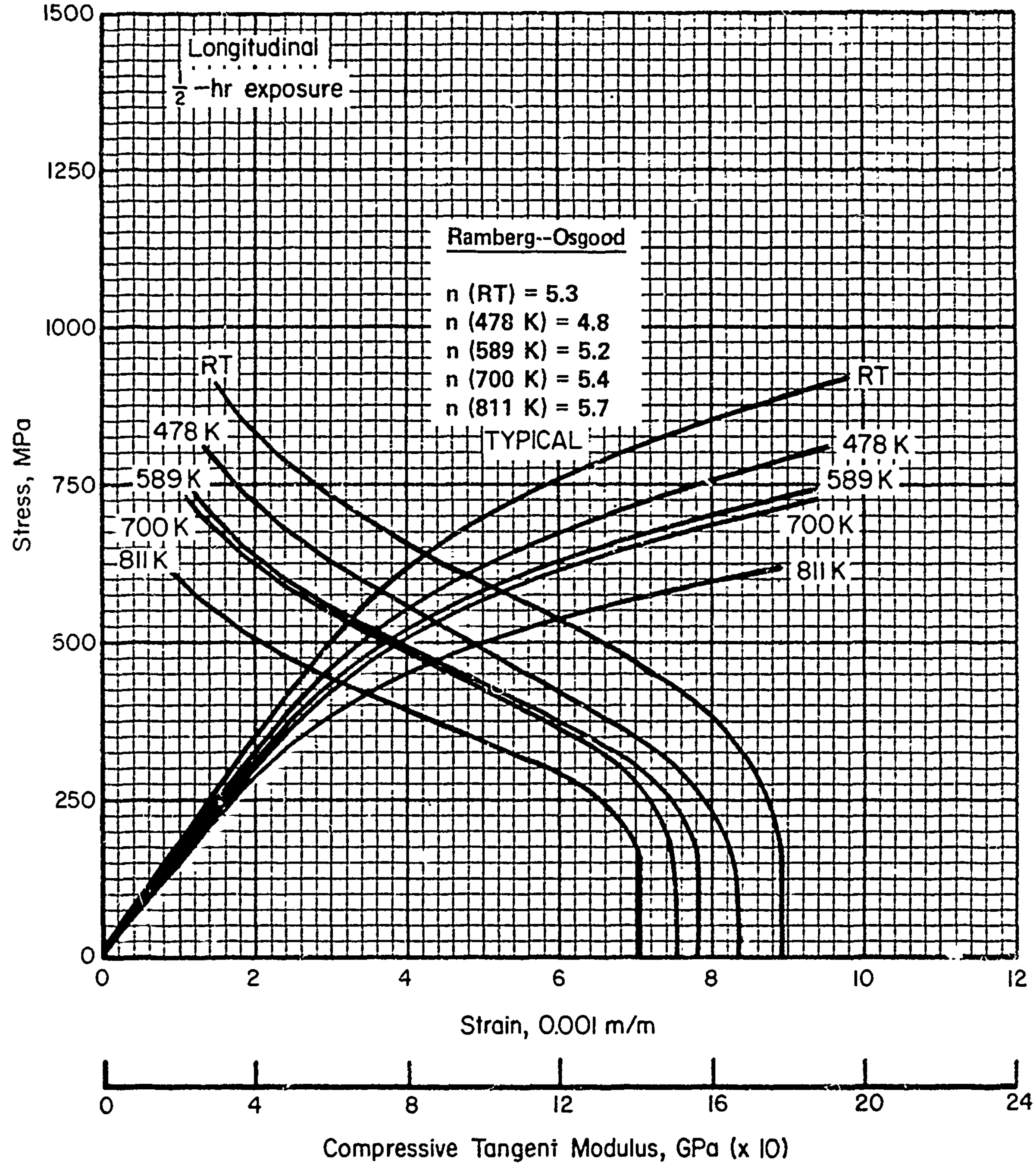


FIGURE 2.7.1.5.6(c). Typical compressive stress-strain and tangent-modulus curves temperatures for AISI 301 (full-hard) stainless steel.

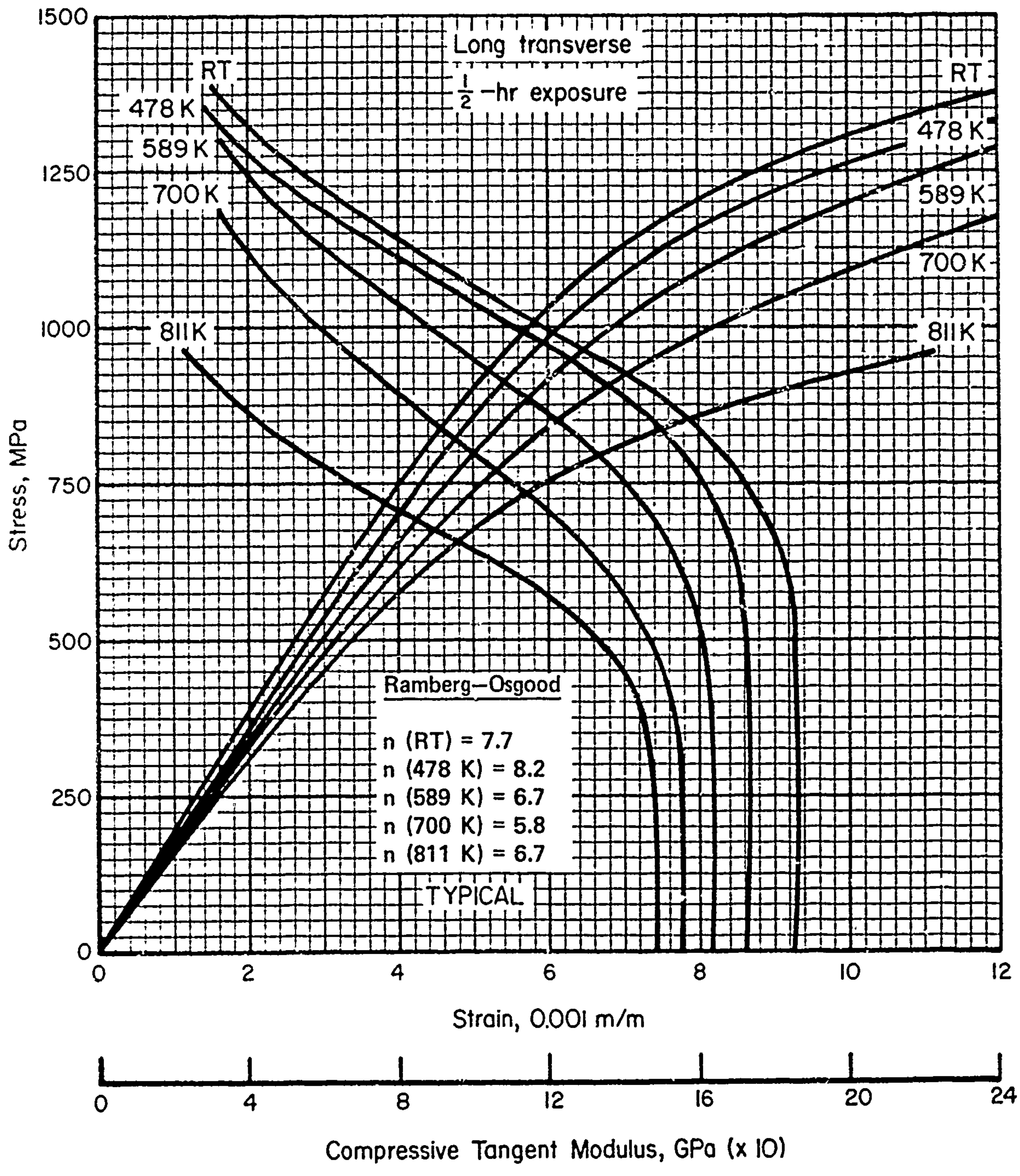


FIGURE 2.7.1.5.6(d). Typical compressive stress-strain and tangent-modulus curves at room and elevated temperatures for AISI 301 (full-hard) stainless steel.

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.

Round Tubes.—For round tubes, the value of F_b, will depend on the D/t ratio, as well as the ultimate tensile stress. Figure 2.8.1.1 gives 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 shall not exceed a "cut-off" stress which accounts for the effect of welding on the local failure of the column.

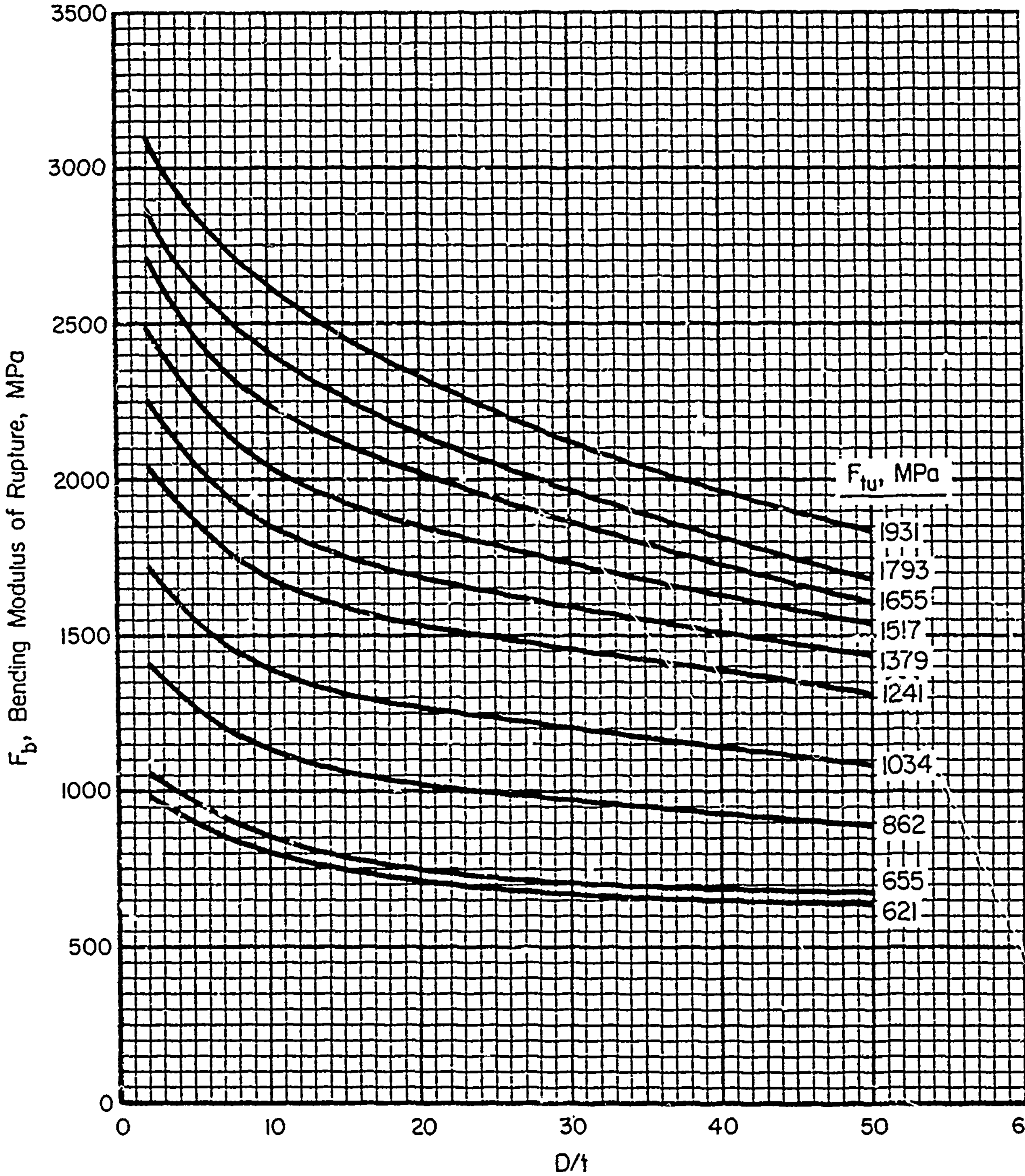


FIGURE 2.8.1.1. Bending modulus of rupture for round low-alloy-steel tubing.

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 thicknesses 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.

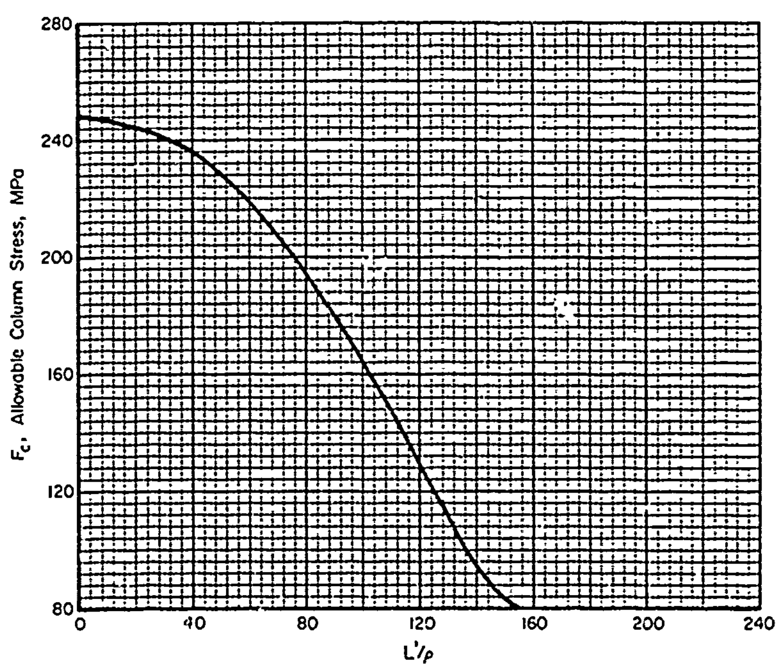


FIGURE 2.8.2.3(a). Allowable column stress for 1025 steel round tubing.

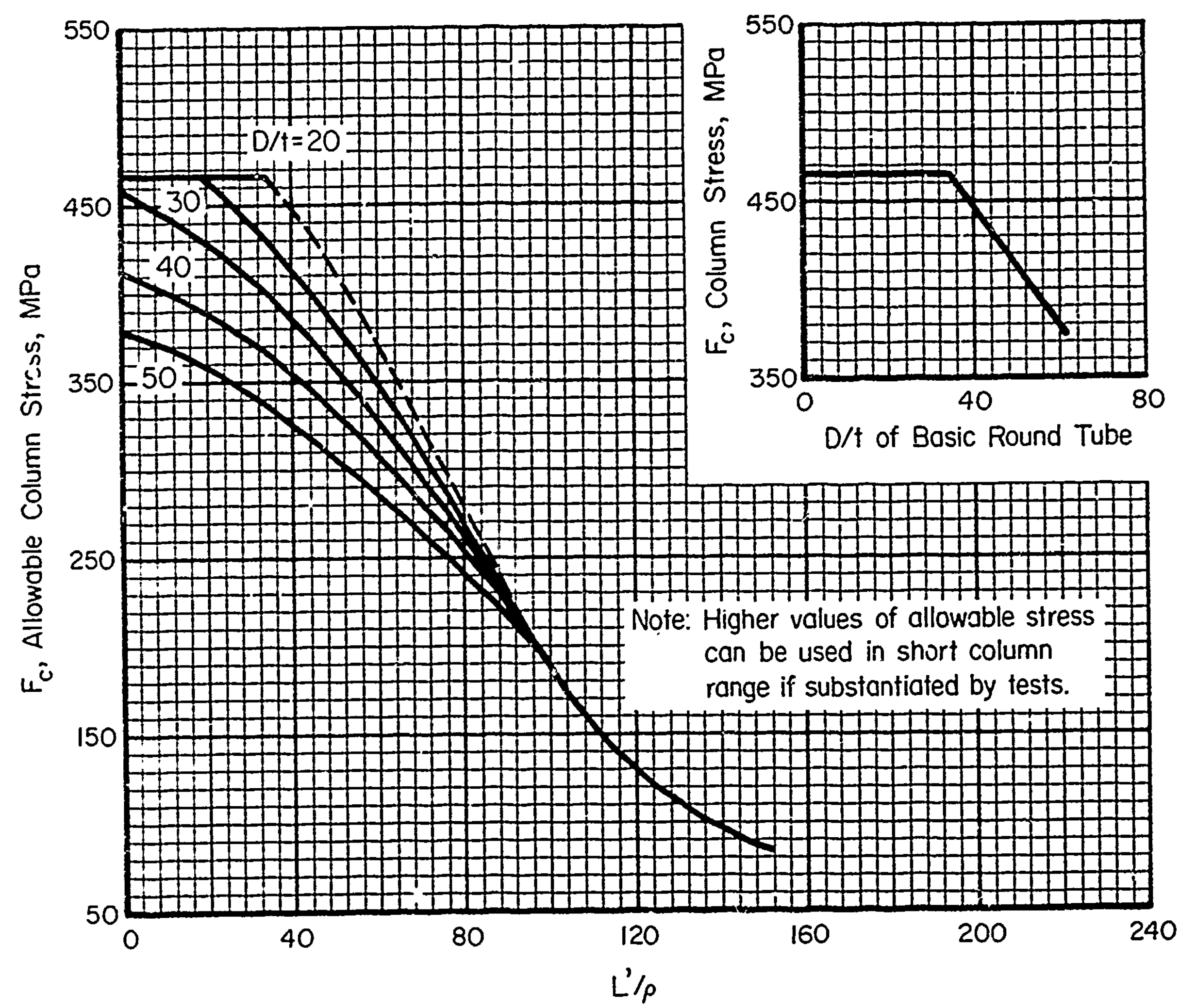


FIGURE 2.8.2.3 (b). Allowable column and crushing stresses for chromium molybdenum streamline tubing; F_{tu}=517 MPa.

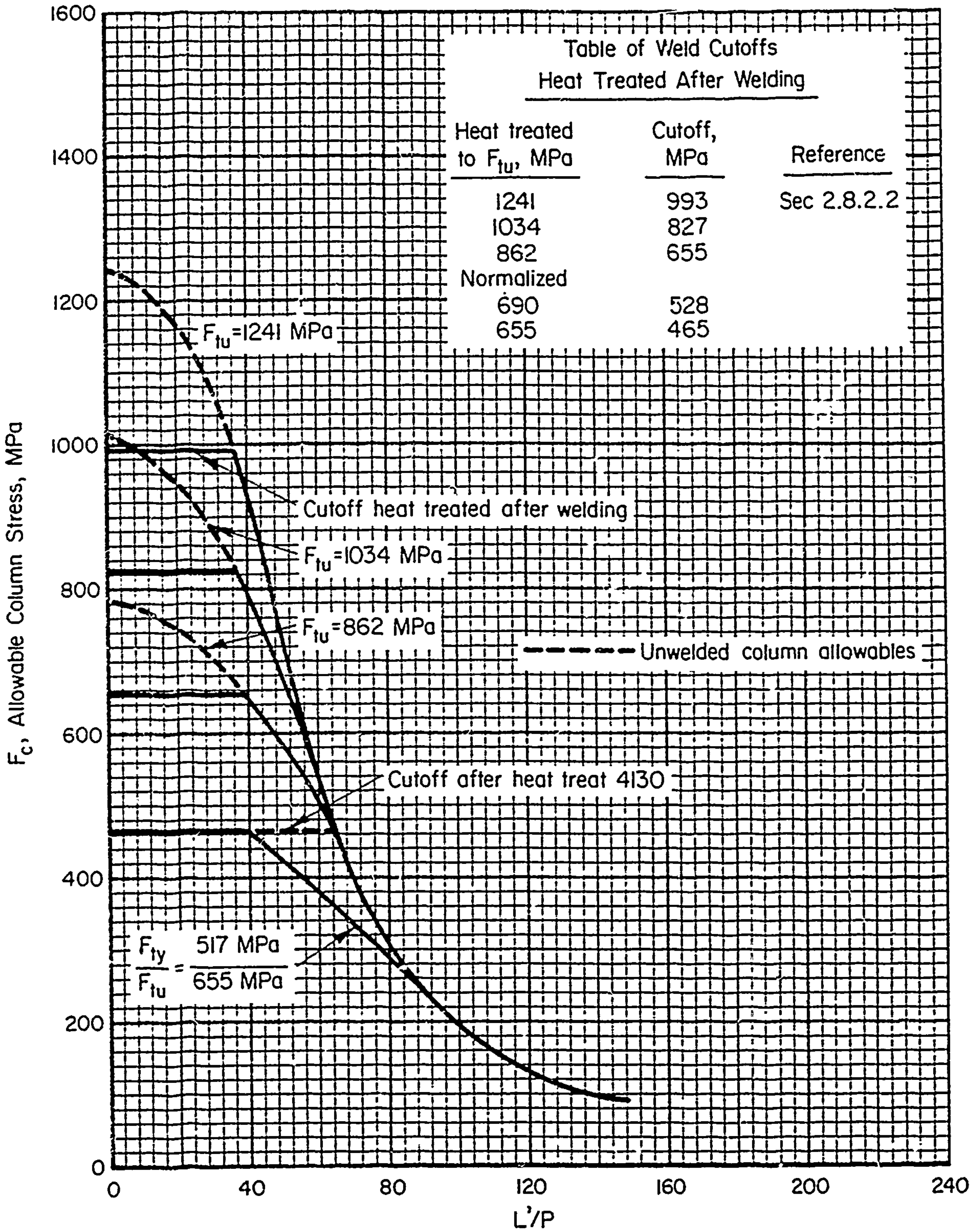


FIGURE 2.8.2.3(c). Allowable column stress for heat-treated alloy-steel round tubing.

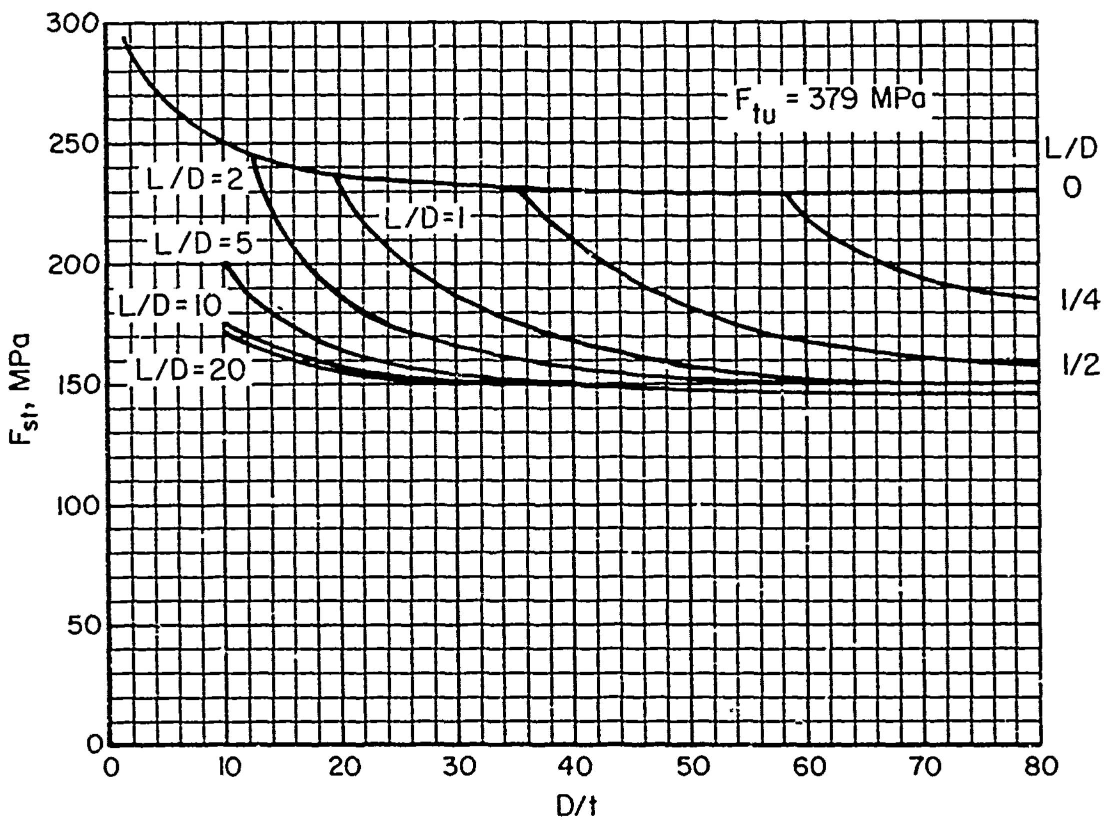


FIGURE 2.8.3.2(a). Torsional modulus of rupture - plain carbon steels F_{tu} = 379 MPa.

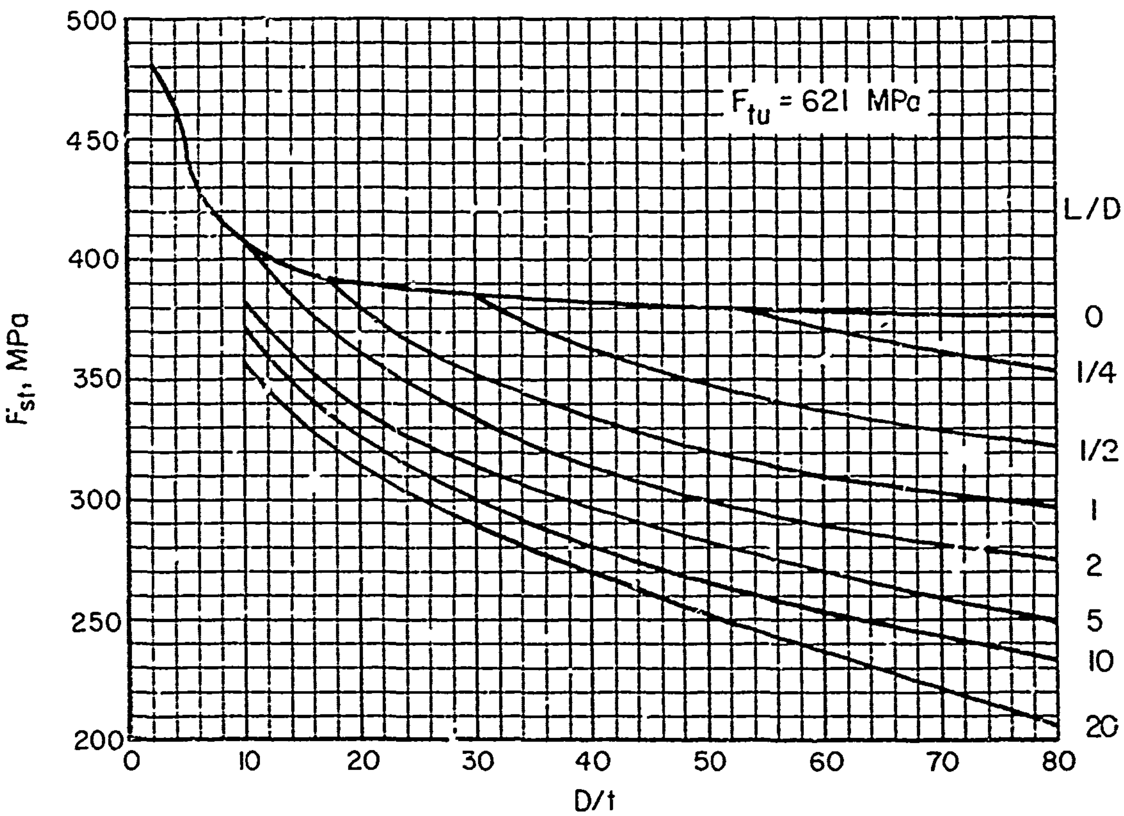


FIGURE 2.8.3.2(b). Torsional modulus of rupture - alloy steels heat treated to F_{tu} = 621 MPa.

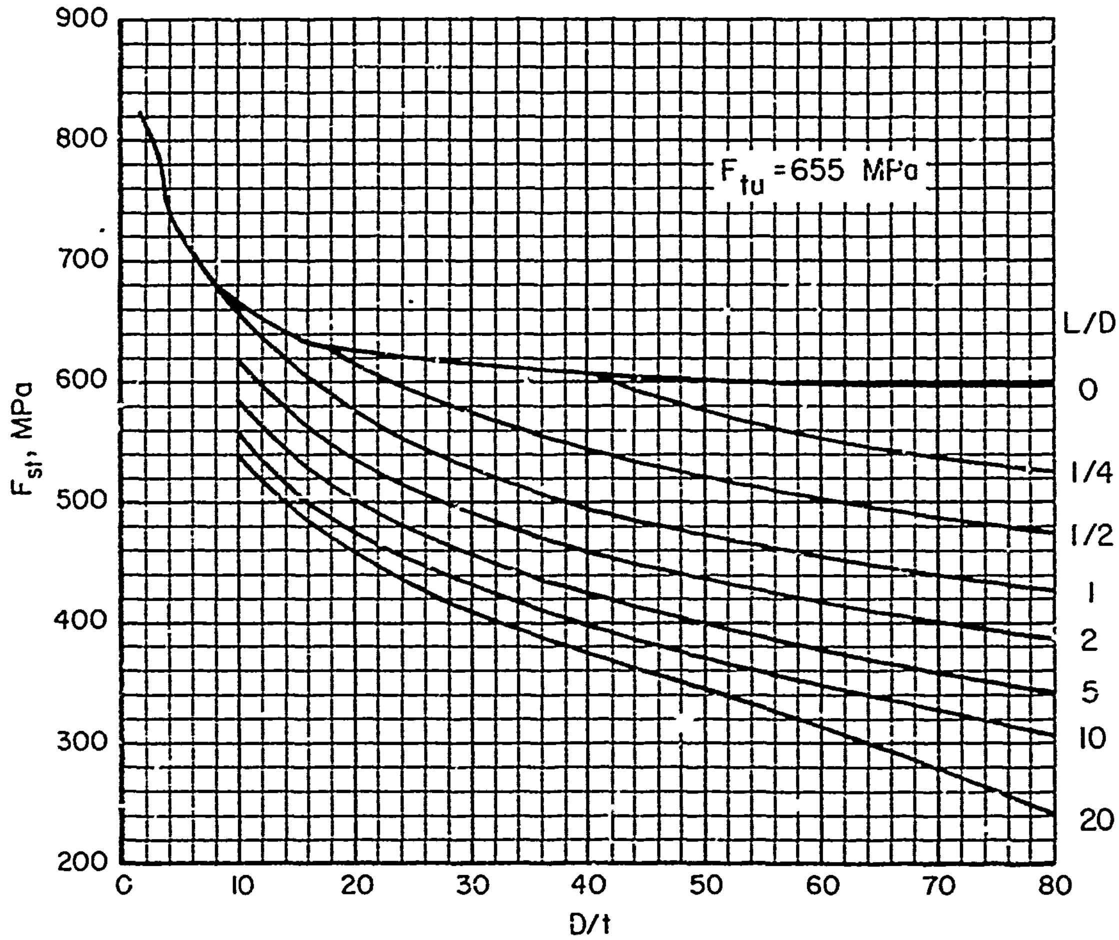


FIGURE 2.8.3.2(c). Torsional modulus of rupture - alloy steels heat treated to F_{tu} = 655 MPa.

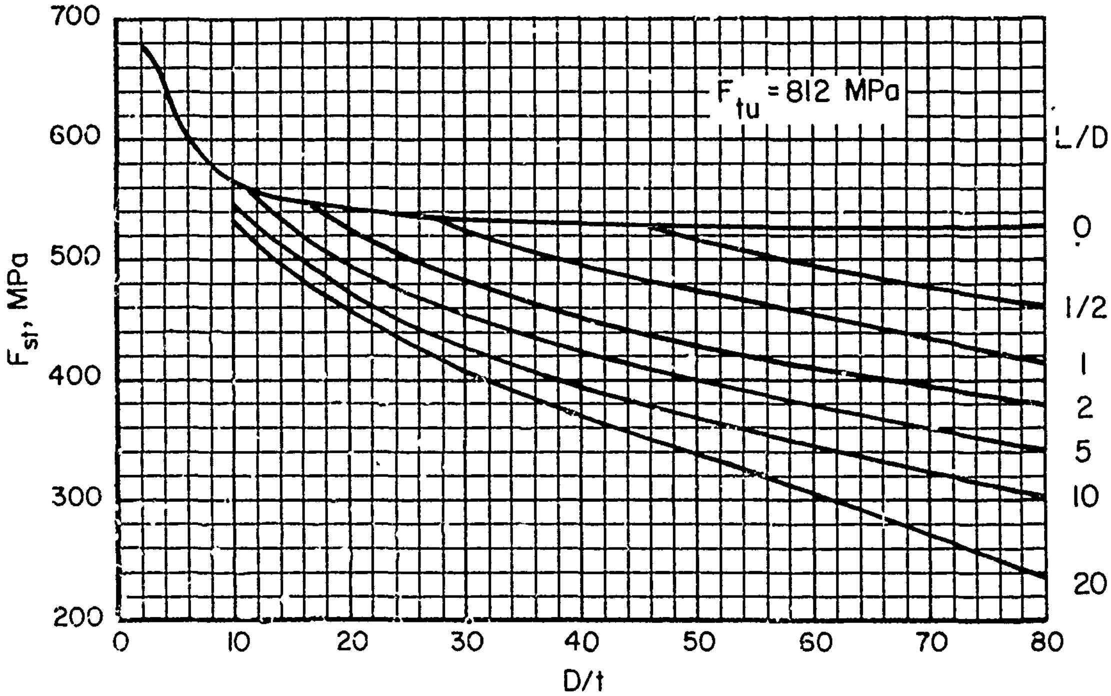


FIGURE 2.8.3.2(d). Torsional modulus of rupture - alloy steels, heat treated to F_{tu} = 862 MPa.

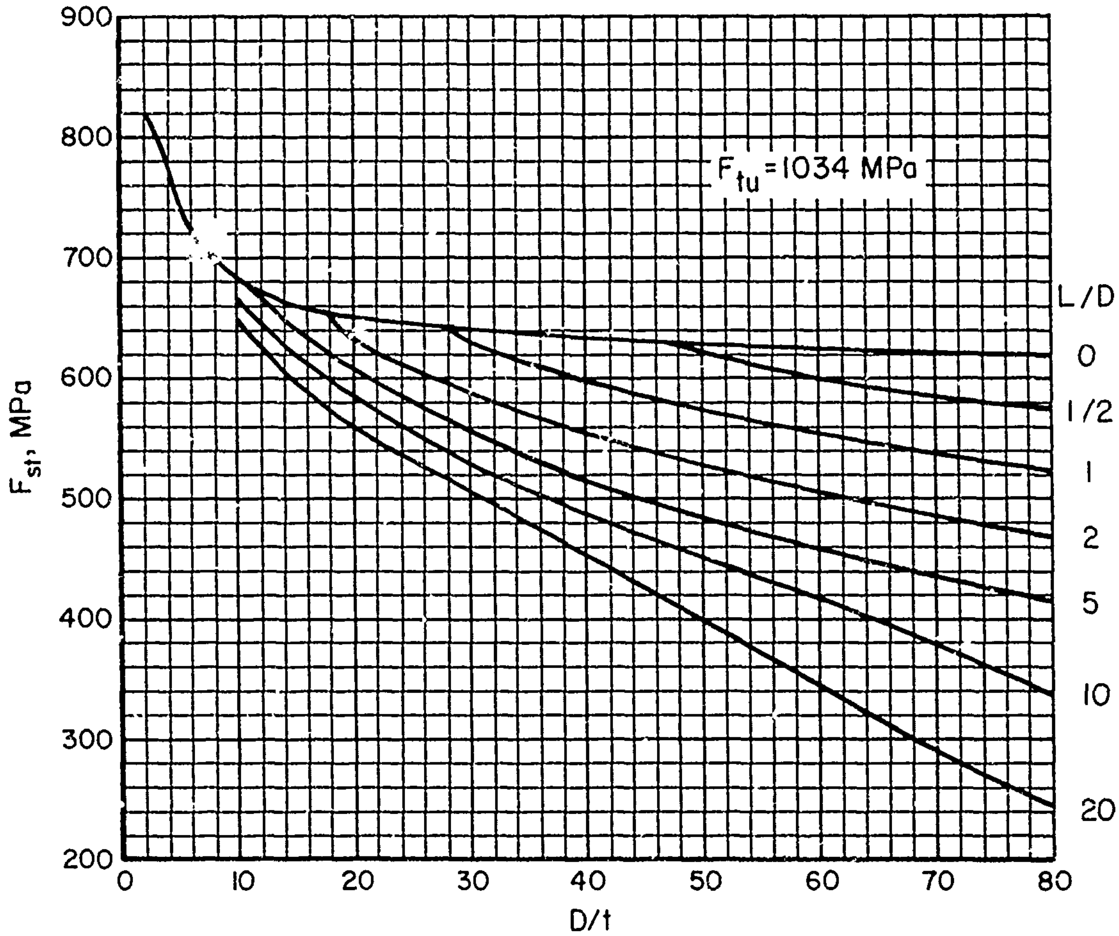


FIGURE 2.8.3.2(e). Torsional modulus of rupture - alloy steels heated to F_{tu} = 1034 MPa.

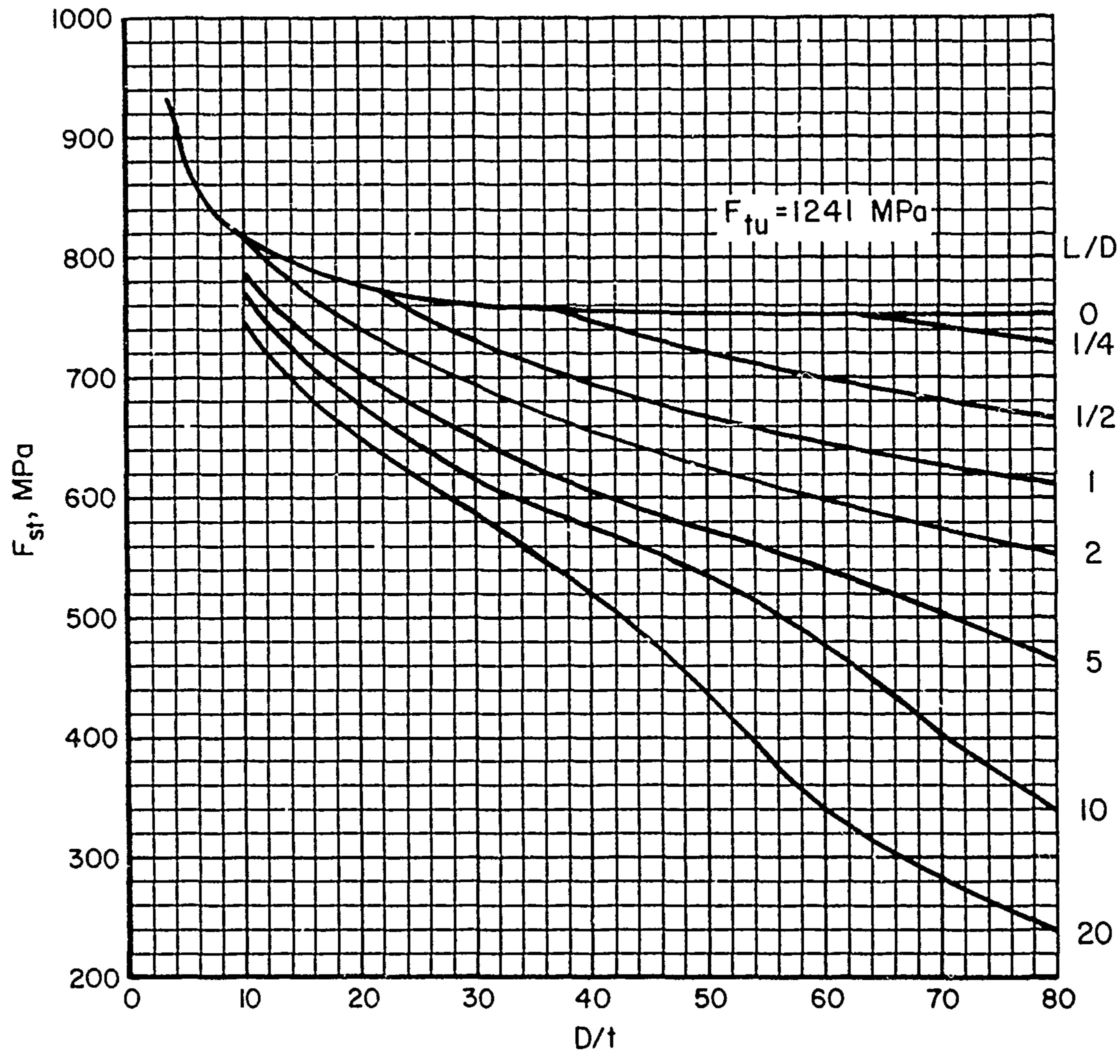


FIGURE 2.8.3.2(f). Torsional modulus of rupture - alloy steels heat treated to F_{tu} = 1241 MPa.

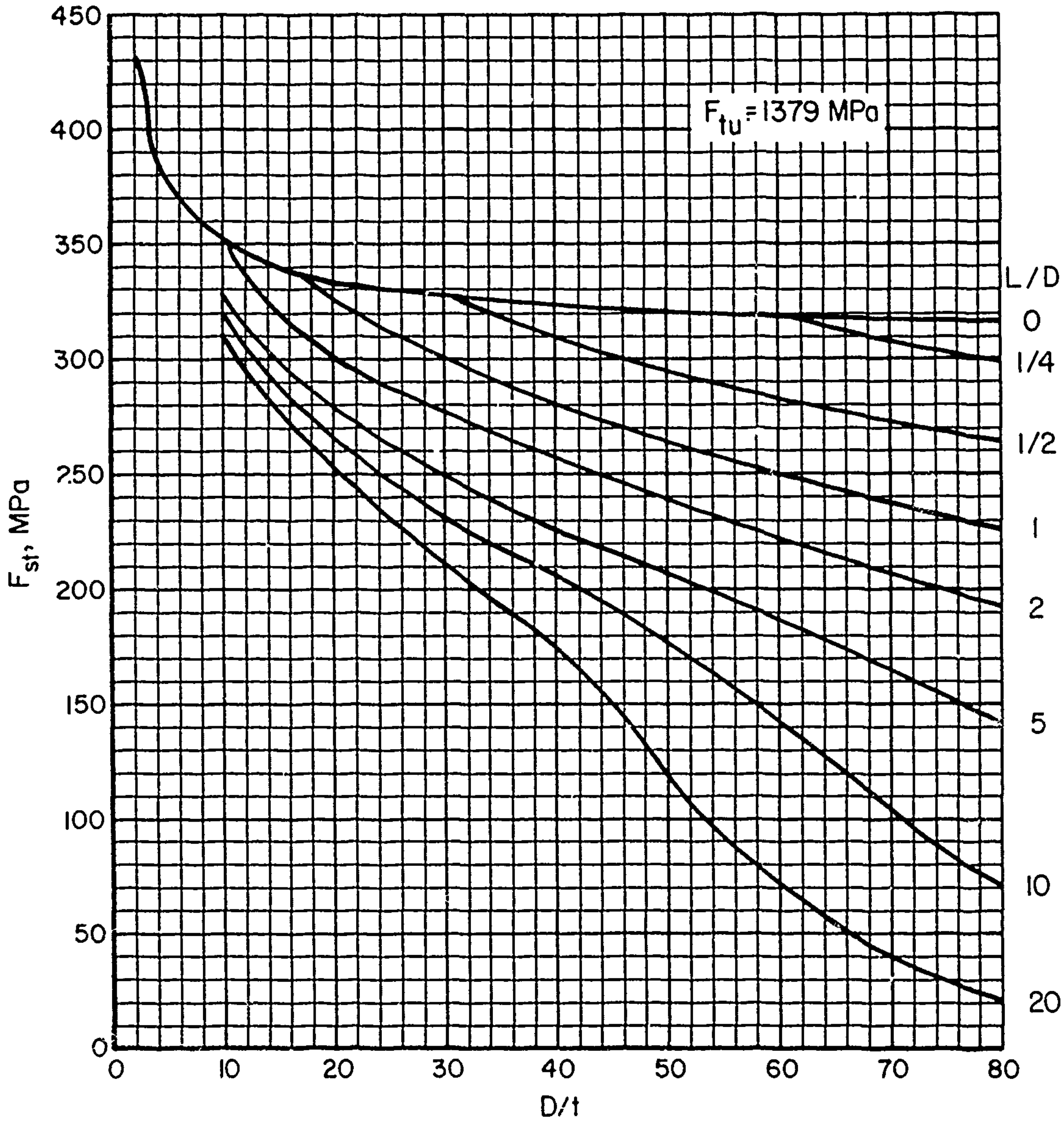


FIGURE 2.8.3.2(g). Torsional modulus of rupture - alloy steels heat treated to F_{tu} = 1379 MPa.

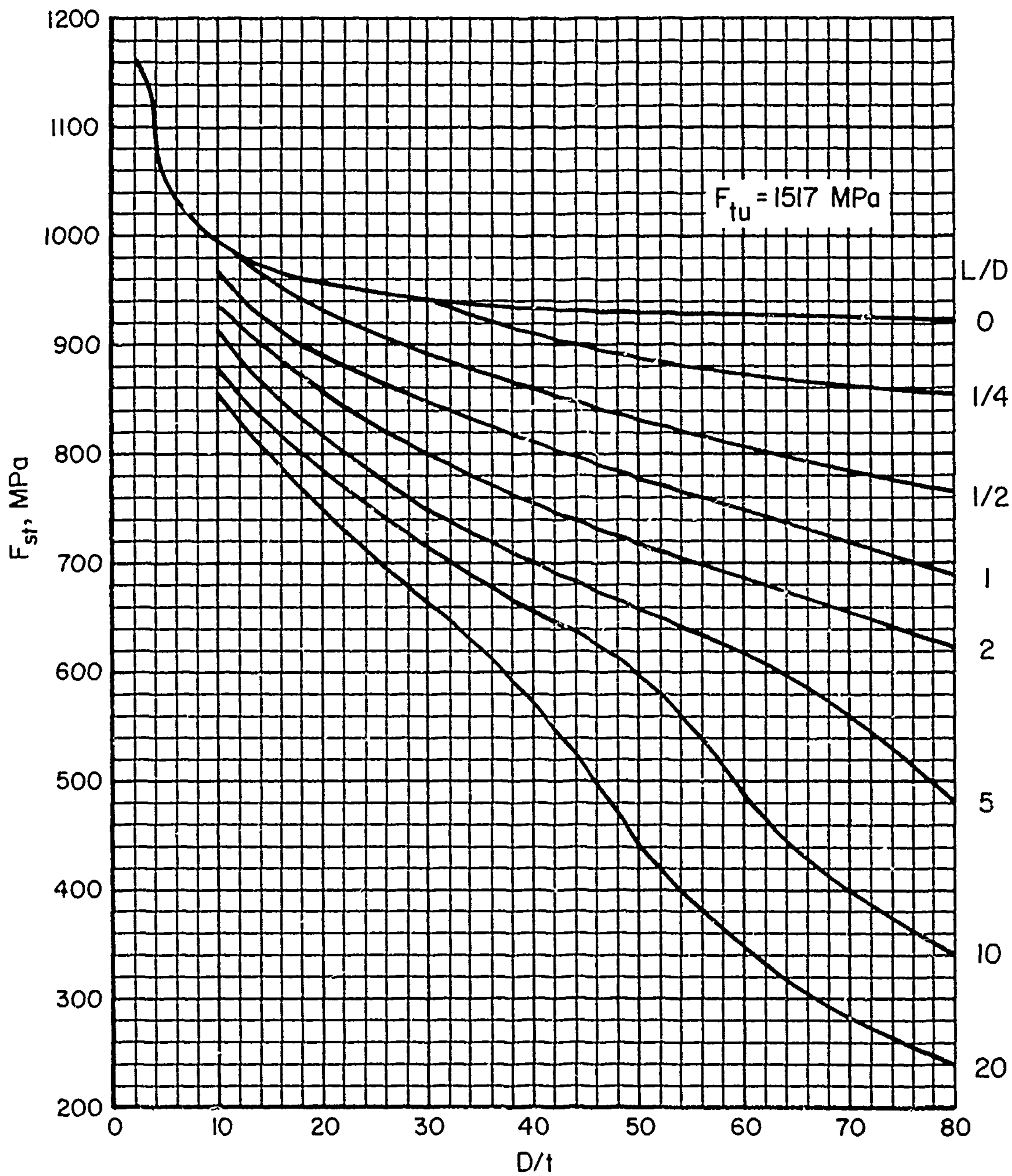


FIGURE 2.8.3.2(h). Torsional modulus of rupture - alloy steels heat treated to F_{tu} = 1517 MPa.

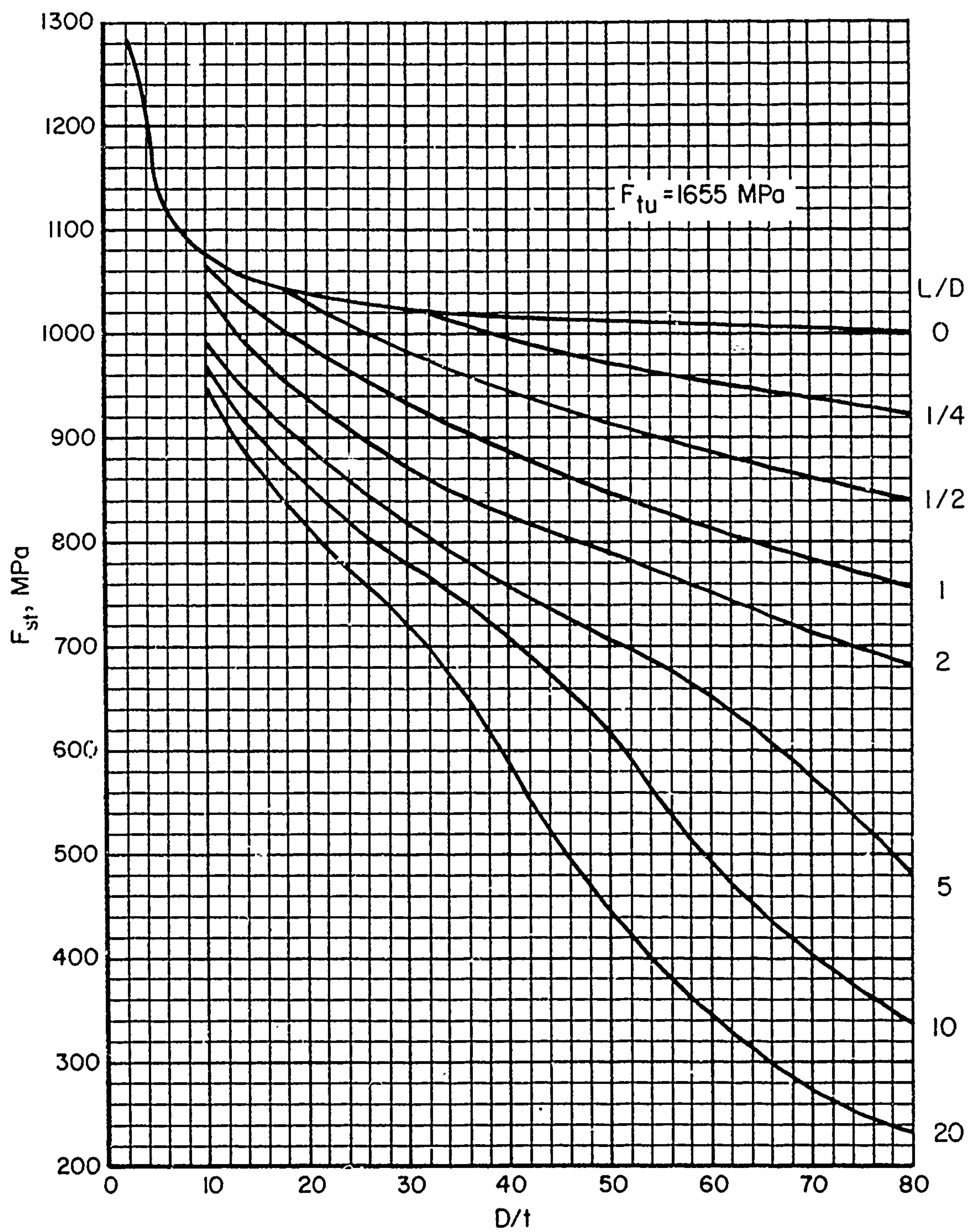


FIGURE 2.8.3.2(i). Torsional modulus of rupture - alloy steels heat treated to F_{tu} = 1655 MPa.

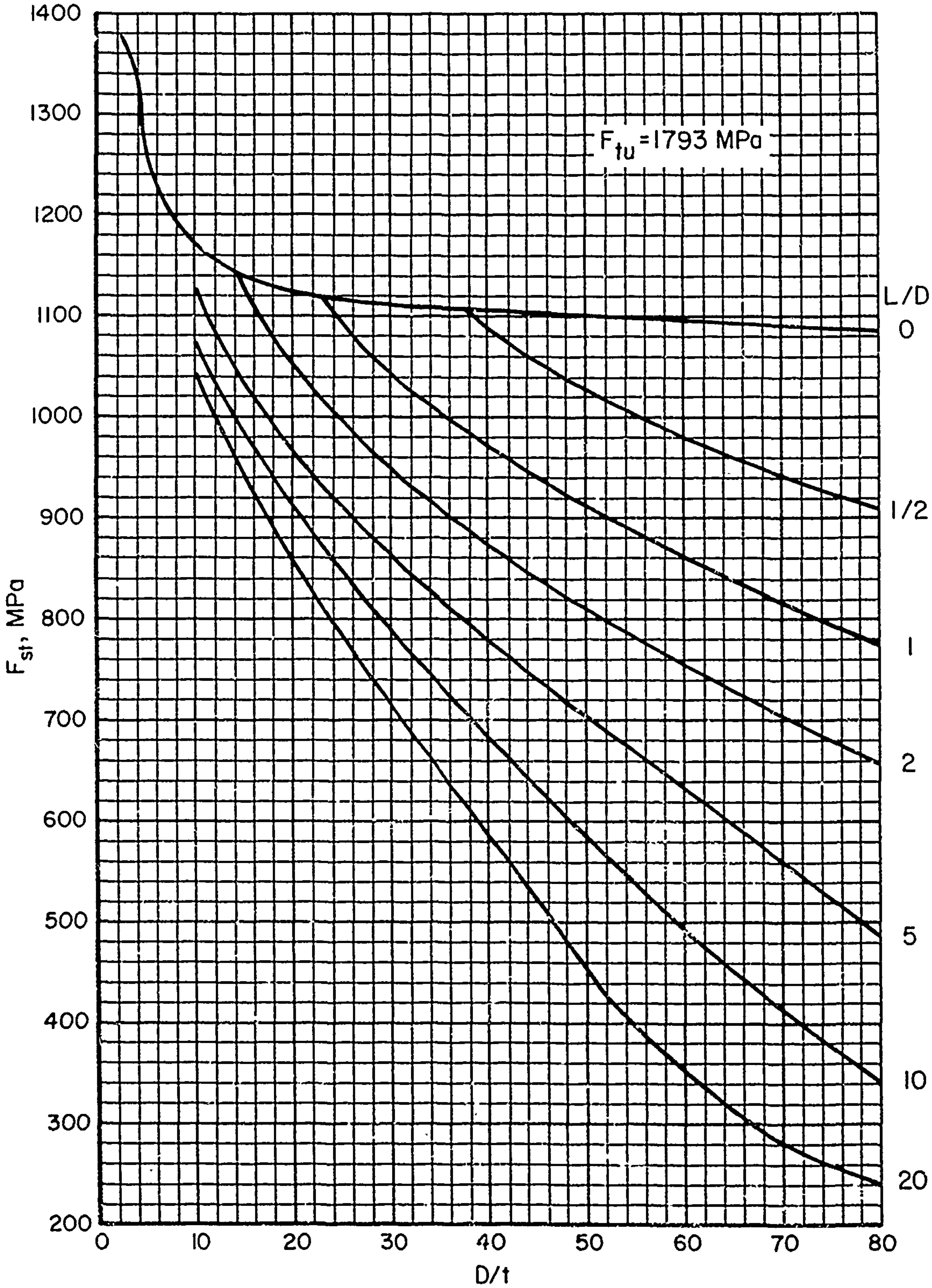


FIGURE 2.8.3.2(j). Torsional modulus of rupture - alloy steels heat treated to F_{tu} = 1793 MPa.

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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 3.19. Element properties are presented in Section 3.20.

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 alloys are identified by a four-digit number, the first digit of which generally identifies the major alloying element as in Table 3.1. For casting alloys, the fourth digit is separated from the first three digits by a decimal point, and indicates the form, i.e., casting or ingot.

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).] Major sections are set up to permit the introduction into the Handbook of wrought or cast alloys in each major alloy number series from 2XXX to 9XXX, any time a particular alloy becomes of interest. On this basis, Table 3.1.1 is the aluminum alloy index that illustrates both the general section layout as well as the details of those specific aluminum alloys presently contained in this chapter. It is to be noted that the wrought alloys are in Sections 3.2 through 3.9; whereas the cast alloys are in Sections 3.12 through 3.19.

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, 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

TABLE 3.1. *Basic Designation for Wrought and Cast Aluminum Alloys [Reference 3.1(b)]*

Alloy Number	Major Identifying Elements	Alloy Number	Major Identifying Elements
	Wrought Alloys		Cast Alloys
1XXX	99.00 percent minimum aluminum	1XX.X	99.00 percent minimum aluminum
2XXX	Copper	2XX.X	Copper
3XXX	Manganese	3XX.X	Silicon with added copper and/or magnesium
4XXX	Silicon	4XX.X	Silicon
5XXX	Magnesium	5XX.X	Magnesium
6XXX	Magnesium and Silicon	6XX.X	Unused series
7XXX	Zinc	7XX.X	Zinc
8XXX	Other elements	8XX.X	Tin
9XXX	Unused series	9XX.X	Other elements

TABLE 3.1.1. *Aluminum Alloy Index*[a]

Section	Alloy Designation	Section	Alloy Designation
3.2	2XXX wrought alloys	3.8	8XXX wrought alloys
3.2.1	2014	3.9	9XXX wrought alloys
3.2.2	2017	3.10	Unused
3.2.3	2024	3.11	Unused
3.2.4	2025	3.12	2XXX cast alloys
3.2.5	2124	3.12.1	201.0
3.2.6	2219	3.12.2	224.0
3.2.7	2618	3.12.3	295.0 (195)
3.3	3XXX wrought alloys	3.13	3XXX cast alloys
3.4	4XXX wrought alloys	3.13.1	354.0
3.5	5XXX wrought alloys	3.13.2	355.0
3.5.1	5052	3.13.3	C355.0
3.5.2	5083	3.13.4	356.0
3.5.3	5086	3.13.5	A356.0
3.5.4	5454	3.13.6	A357.0
3.5.5	5456	3.13.7	359.0
3.6	6XXX wrought alloys	3.14	4XXX cast alloys
3.6.1	6061	3.15	5XXX cast alloys
3.6.2	6151	3.15.1	520.0 (220)
3.7	7XXX wrought alloys	3.15.2	535.0 (Al-Mg 35)
3.7.1	7049	3.16	6XXX cast alloys
3.7.2	7050		
3.7.3	7075	3.17	7XXX cast alloys
3.7.4	7079	3.17.1	D712.0 (40-E)
3.7.5	7175	3.18	8XXX cast alloys
3.7.6	7178	3.19	9XXX cast alloys

[a] Numbers in parenthesis after certain cast alloy identification numbers are the old designations.

percentages may be applied directly to the room temperature minimum properties. Other properties, such as the stress-strain curves, fatigue and fracture toughness data, are average or typical values which should be considered 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.
tions of stress and environment have been investigated, and that 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 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 non-heat 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.

TABLE 3.1.2. *Basic Temper Designations and Subdivisions for Aluminum Alloys in MIL-HDBK-5C*

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 (wrought products only).** Applies to wrought products which are fully annealed to obtain the lowest strength condition.

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 1/2 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 the 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 by a low temperature thermal treatment which results in slightly lowered tensile strength and improved 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 before the stabilization treatment.

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 322 K) of approximately 75 percent following a full anneal. Tempers between 0 (annealed) and 8 are designated by numerals 1 through 7. Material having an ultimate tensile strength about midway between that of the 0 temper and that of the 8 temper is designated by the numeral 4; about midway between the 0 and 4 tempers by the numeral 2; and about midway between the 4 and 8 tempers by the

[a] 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 provided (1) the temper is used or is available for use by more than one user, (2) mechanical property limits are registered, (3) the 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. Zero has been assigned to indicate variations negotiated between the manufacturer and purchaser which are not used widely enough to justify registration.

numeral 6. Numeral 9 designates tempers whose minimum ultimate tensile strength exceeds that of the 8 temper by 14 MPa 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[a], when used, indicates a variation of a two-digit 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 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 is at least as close to that of the corresponding two-digit H temper as it is to the adjacent two-digit H tempers.

Three-digit H Tempers

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.

The following three-digit H temper designations have been assigned for wrought products in alloys containing over a nominal 4 percent magnesium.

H311 Applies to products which are strain-hardened less than the amount required for a controlled H31 temper.

H321 Applies to products which are strain-hardened less than the amount required for a controlled H32 temper.

H323 **H343** Applies to products which are specially fabricated to have acceptable resistance to stress corrosion cracking.

Subdivisions of T Temper: Thermally Treated

Numerals 1 through 10 following the T indicate specific sequences of basic treatments, as follows[b]:

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.

T2 **annealed (cast products only).** Applies to cast products which are annealed to improve ductility and dimensional stability.

T3 **solution heat-treated and then cold worked.** 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.

T4 **solution heat-treated 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

[b]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.

[c]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 provided (1) the temper is used or is available for use by more than one user, (2) mechanical property limits are registered, (3) the 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 produc., 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. Variations in treatment which do not alter the characteristics of the product are considered alternate treatments for which additional digits are not assigned

or straightening may not be recognized in mechanical property limits.

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 which are 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 and then stabilized.** Applies to products which 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 mechanical property limits.

T9 **solution heat-treated, artificially aged, and then cold worked.** Applies to products which are cold worked to improve strength.

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 casting or extrusion, and then cold worked to further improve strength.

Additional digits[c], the first of which shall not be zero, may be added to designations T1 through T10 to indicate a variation in treatment which significantly alters the characteristics of the product.

The following specific additional digits have been assigned for stress-relieved tempers of wrought products:

TX51 **stress relieved by stretching.** Applies to the following products when stretched the indicated amounts after solution heat-treatment or cooling from an elevated temperature shaping process.

Plate . . . . 1-1/2 to 3% permanent set
Rod, bar, shapes,
extruded tube . . 1 to 3% permanent set
Drawn tube . . . 1/2 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, shapes and tube and to drawn tube when designated as follows:

TX510 Products that receive no further straightening after stretching.

TX511 Products that may 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, or cooling from an elevated temperature shaping process to produce a permanent set of 1 to 5 percent.

TX54 **stress-relieved by combined stretching and compressing.** Applies to die forgings which are stress relieved by restriking cold in the finish die.

The following temper designations have been assigned for wrought products heat-treated from O or F temper to demonstrate response to heat-treatment.

T42 Solution heat-treated from the O or F temper to demonstrate response to heat-treatment, and naturally aged to a substantially stable condition.

T62 Solution heat-treated from the O or F temper to demonstrate response to heat-treatment, 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.

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.

Shear and bearing strengths are given without reference to direction and may be assumed to be about the same in all directions, with the exception that a reduction factor is used for edgewise bearing loads 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 the products 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.

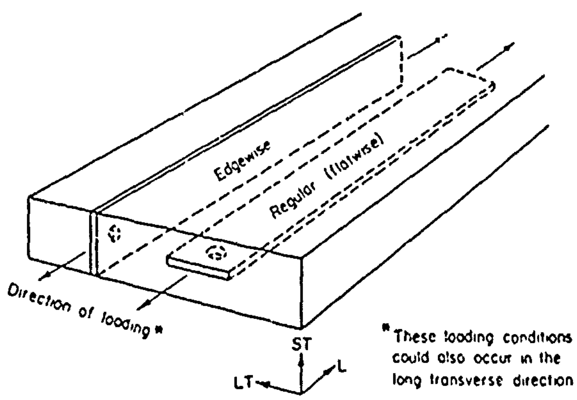


FIGURE 3.1.2.1.1. *Bearing specimen orientation in thick plate.*

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 Methods [Reference 3.1.2.1(a)] which call for clean pins and specimens [Reference 3.1.2.1.1(b)]. Designers may wish to consider this in applying these values to structural analyses. 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)].

TABLE 3.1.2.1.1. *Bearing Property Reductions for Thick Plate of 2000 and 7000 Series Alloys*

	Bearing property reduction, percent
Thickness (mm).........	25.4 –152.4
F_{bru} (e/D=1.5)............	15
F_{bru} (e/D=2.0)............	10
F_{bry} (e/D=1.5)............	5

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 (≤ 11.40 mm), 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 ≥ 12.70 mm in thickness, the quality-control test specimens are machined from the core and 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.

3.1.2.1.2 *Ductility (Elongation).* — Elongation is not used directly in design but may be of some use in comparing materials where large changes in ductility with temperature or time may be of concern. Elongation values have been taken directly from the applicable specifications or material producers' quality-control data and are included in the tables of room-temperature mechanical-properties for the individual alloys. 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 unless so stated.

3.1.2.1.3 *Stress-Strain Relations.* The stress-strain relations presented, which include elastic and tangent moduli, are typical curves based on one 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 relations are no less useful, since there are well-known methods for using these curves in design by reducing them to a minimum curve affine to the typical curve or by using Ramberg-Osgood parameters obtained from the typical curves.

3.1.2.1.4 *Creep and Stress Rupture.* — Creep and stress rupture data are presented graphically for 2024 (heat-treated), 2024 (heat-treated, cold-worked, and aged), and 7075 (heat-treated and aged) aluminum alloys in Figures 3.2.3.1.7(a) through (g), Figures 3.2.3.5.7(a) through (g) and Figures 3.7.3.1.7(a) through (h), respectively. The graphs show curves for various creep criteria (0.2 percent, 0.5 percent, 1.0 percent, etc.) and rupture plotted as stress (percent F_{tu} at room temperature) versus time in minutes or hours. On those graphs containing a time scale in minutes (Figures 3.2.3.1.7(a) through (d), Figures 3.2.3.5.7(a) through (d), and Figures 3.7.3.1.7(a) through (d)), specimens were tested by applying a dead load at room temperature, heating rapidly by using a welding transformer to apply a large electric current to the specimen, and then measuring the total deformation, including thermal expansion. Details of the procedure are given in Reference 3.1.2.1.4.

All of the creep data shown in the above listed figures were obtained on clad sheet. However, the percentages are considered applicable to non-clad sheet and other wrought materials of 2024 heat-treated and 7075 heat-treated and aged material.

The creep and stress-rupture properties presented were developed from investigations in which there were too few data to establish bands or any degree of statistical significance; the values should be considered to be representative for the respective alloys and tempers.

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.

3.1.2.1.5 *Fatigue.*—Modified Goodman Diagrams are presented in Sections 3.2 through 3.9 for those alloys for which sufficient fatigue data are available. Data for both smooth and notched specimens are presented. The data from which the diagrams 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 lower 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 1.2.3.1(b) for a general discussion of designing for fatigue.

3.1.2.1.6 *Fracture Toughness.*—Typical values of plane-strain fracture toughness, K_{Ic} (Reference 3.1.2.1.6(a)) for several high-strength aluminum alloys are presented in Table 3.1.2.1.6 for information only. These are average values for the alloys and tempers for which valid data are available (References 3.1.2.1.6(b) and (c)) and are thus representative of the various products, but they do not have the statistical reliability of the room-temperature mechanical properties.

TABLE 3.1.2.1.6. Typical Values of Room Temperature Plane-Strain Fracture Toughness of Aluminum Alloys[a]

				K_{Ic}, MPa-mm$^{1/2}$														
				L-T					T-L					S-L				
Alloy	Product	Temper	Product Thickness Range[b], mm	No. of Lots	Specimen Thickness[c], mm	Min.	Avg.	Max.	No. of Lots	Specimen Thickness[c], mm	Min.	Avg.	Max.	No. of Lots	Specimen Thickness[c], mm	Min.	Avg.	Max.
2014	Plate	T651	25-50	3	25	24	25	26	4	25	21	23	25	1	13	..	20	..
	Forgings	T652	51-152	4	19	27	32	37	4	19	21	25	33	2	13	20	21	21
2024	Plate	T351	38	..	38	..	..	..	..	..	..	..	..	2	25	22	25	29
	Extrusions	T3510,1	38-51	2	38	..	51	..	..	..	..	..	..	..	..	..	..	..
	Plate	T851	25-51	4	35	24	25	27	2	35	22	22	22	1	25	..	19	..
	Extrusions	T8510,1	19-102	5	19	24	31	35	4	19	18	19	20	..	..	..	..	..
	Forgings	T852	81-152	5	19	25	29	33	4	19	19	20	22	3	6	18	18	19
2219	Plate	T851	25-51	2	35	34	36	40	2	25	32	33	33	1	19	..	22	..
		T87	19-25	3	19	29	30	31	..	..	..	..	..	1	13	..	22	..
7075	Plate	T651	13-51	6	13	27	29	30	4	13	22	24	25	2	13	17	18	20
	Extrusions	T6510,1	13-102	10	13	29	31	35	10	13	21	24	29	4	6	20	21	24
	Forgings	T652	51-152	2	13	26	29	31	1	13	..	25	..	1	13	..	19	..
	Plate	T7351	35	1	35	..	33	..	2	25	27	32	36	2	13	21	22	23
	Extrusions	T73510,1	13-102	2	16	34	36	37	5	13	24	26	31	1	25	..	22	..
	Forgings	T7352	25-127	5	19	30	34	38	3	19	25	27	28	3	13	21	23	27
7079	Plate	T651	25-76	3	25	30	32	33	2	25	26	26	26	1	13	..	18	..
	Forgings	T652	51-152	2	19	31	33	34	3	19	23	25	27	3	6	19	20	20
7178	Plate	T651	13-51	3	25	24	25	29	4	13	21	23	25	1	13	..	16	..
	Extrusions	T6510,1	13-38	1	25	..	27	..	4	13	18	21	22	1	25	..	15	..
	Plate	T7671	13-51	3	13	29	32	33	2	13	24	24	24	1	13	..	19	..
	Extrusions	T7650,1	13-51	5	13	29	32	34	3	16	20	24	31	1	13	..	18	..

[a] These values are for information only.

[b] In case of K_{Ic} values for S-L orientation, the minimum product thickness evaluated was at least 25.4 mm.

[c] Minimum thickness of specimen on which these values were obtained.

Graphical displays of the residual strength behavior of center-cracked tension panels of aluminum alloys are presented in Figures 3.1.2.1.6(a) through (r). The points denote the experimental data from which the curve of apparent fracture toughness was derived.

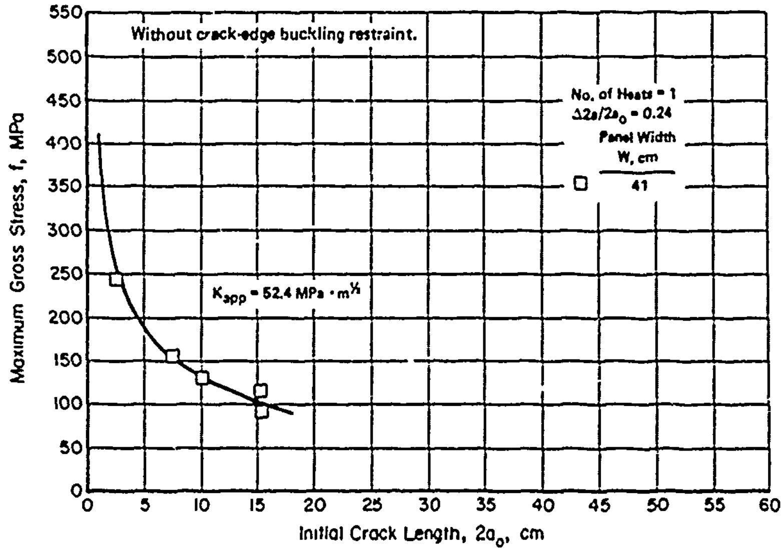


FIGURE 3.1.2.1.6(a). Residual strength behavior of 1.60-mm-thick 2024-T861 aluminum alloy sheet at room temperature. Crack orientation is T-L. (Reference 3.1.2.1.6(d).)

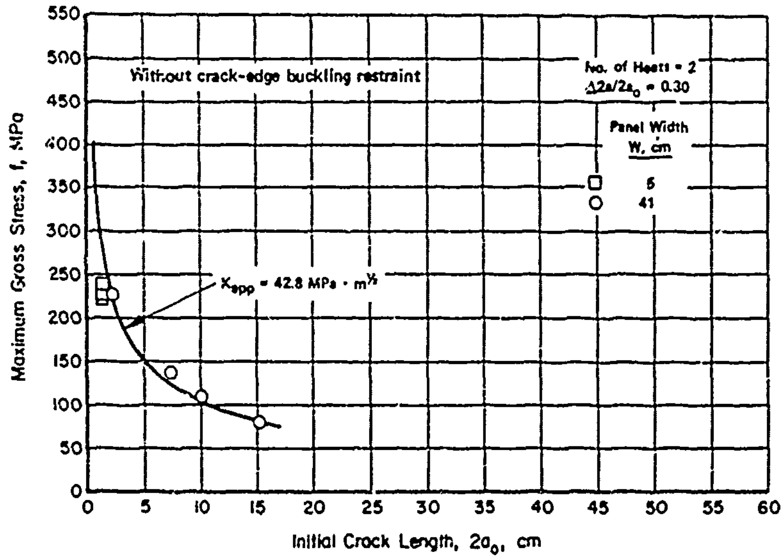


FIGURE 3.1.2.1.6(b). Residual strength behavior of 1.60-mm-thick 2024-T861 aluminum alloy sheet at room temperature. Crack orientation is L-T. (Reference 3.1.2.1.6(d).)

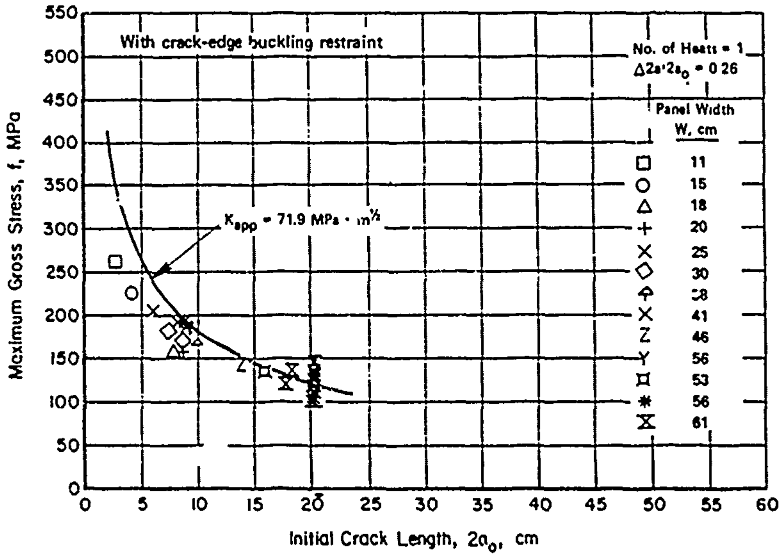


FIGURE 3.1.2.1.6(c). Residual strength behavior of 1.60-mm-thick 7075-T6 aluminum alloy sheet at room temperature. Crack orientation is T-L. (Reference 3.1.2.1.6(f).)

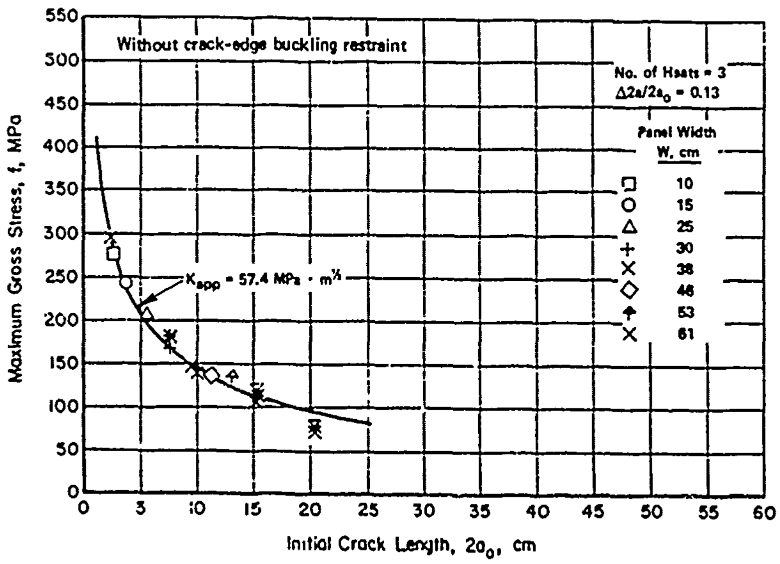


FIGURE 3.1.2.1.6(d). Residual strength behavior of 1.60-mm-thick 7075-T6 aluminum alloy syeet at room temperature. Crack orientation is T-L. (References 3.1.2.1.6(d) and (f).)

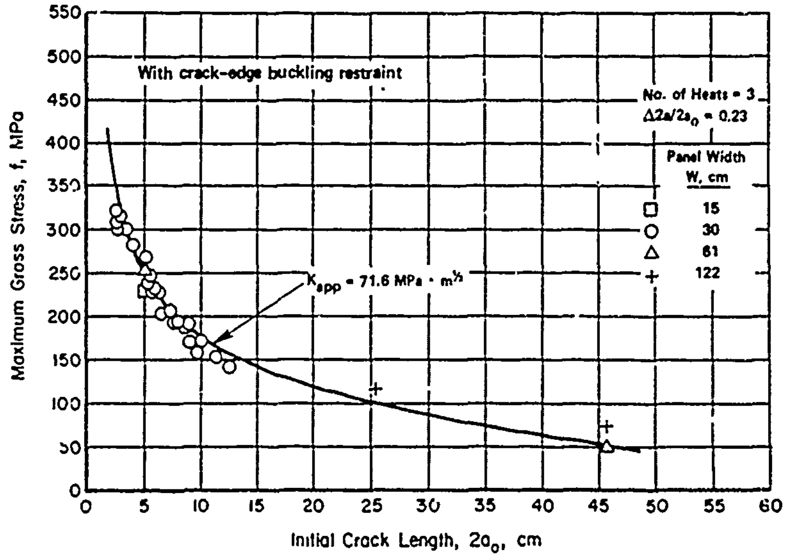


FIGURE 3.1.2.1.6(e). Residual strength behavior of 2.286- and 2.54-mm-inch-thick 7075-T6 alloy sheet at room temperature. Crack orientation is L-T. (References 3.1.2.1.6(e), (g), and (h).)

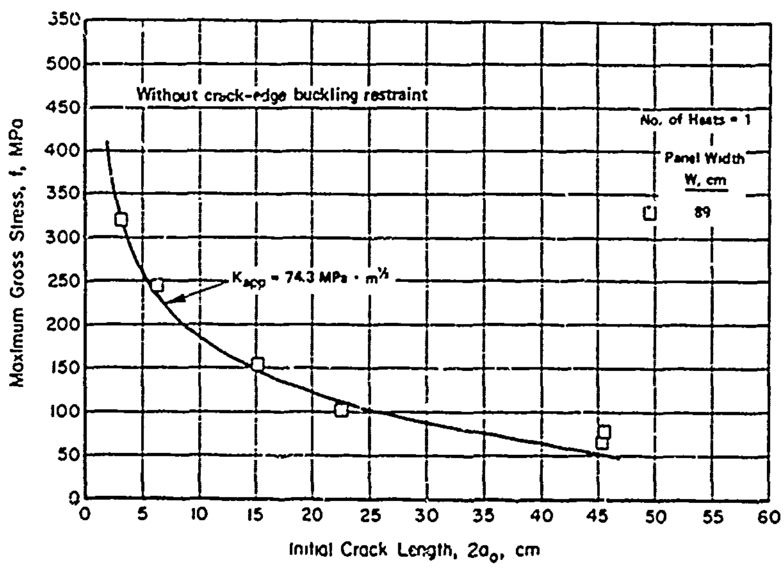


FIGURE 3.1.2.1.6(f). Residual strength behavior of 2.54-mm-thick 7075-T6 aluminum alloy sheet at room temperature. Crack orientation is L-T. (Reference 3.1.2.1.6(g).)

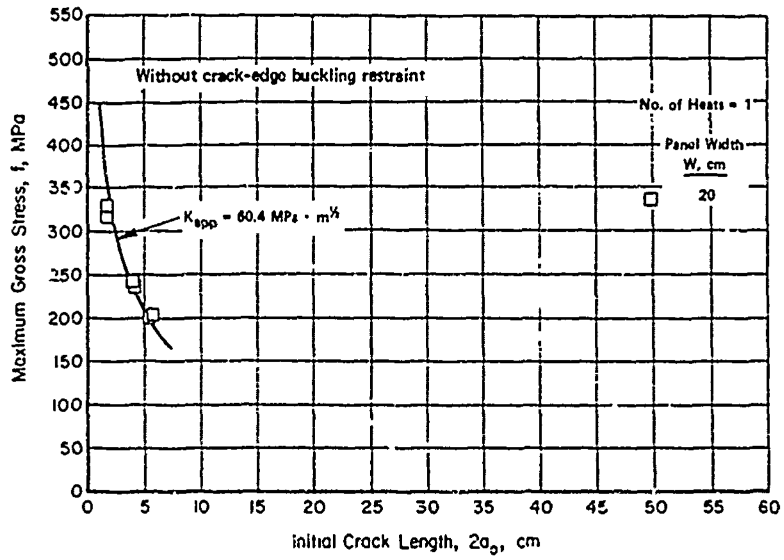


FIGURE 3.1.2.1.6(g). Residual strength behavior of 7.95-mm-thick 7075-T6 aluminum alloy plate at room temperature. Crack orientation is L-T. (Reference 3.1.2.1.6(g).)

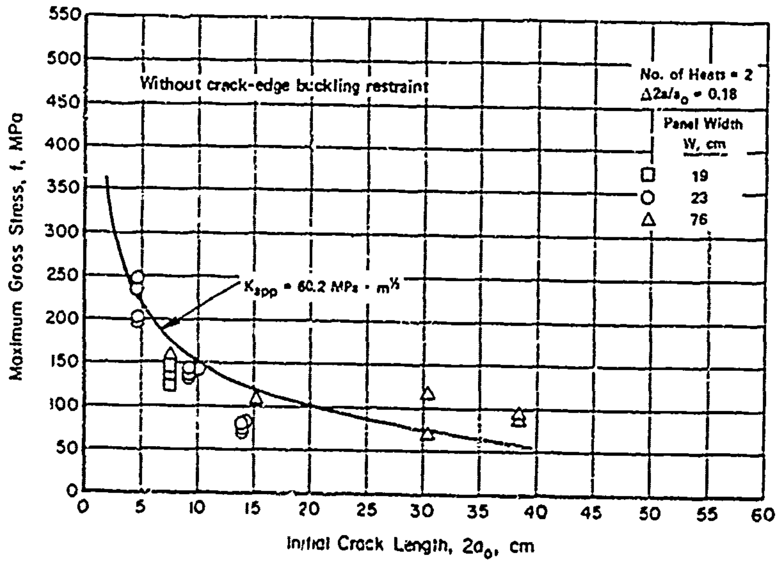


FIGURE 3.1.2.1.6(h). Residual strength behavior of 1.016-mm-thick 7075-T6 clad aluminum alloy sheet at room temperature. Crack orientation is L-T. (References 3.1.2.1.6(f) and (i).)

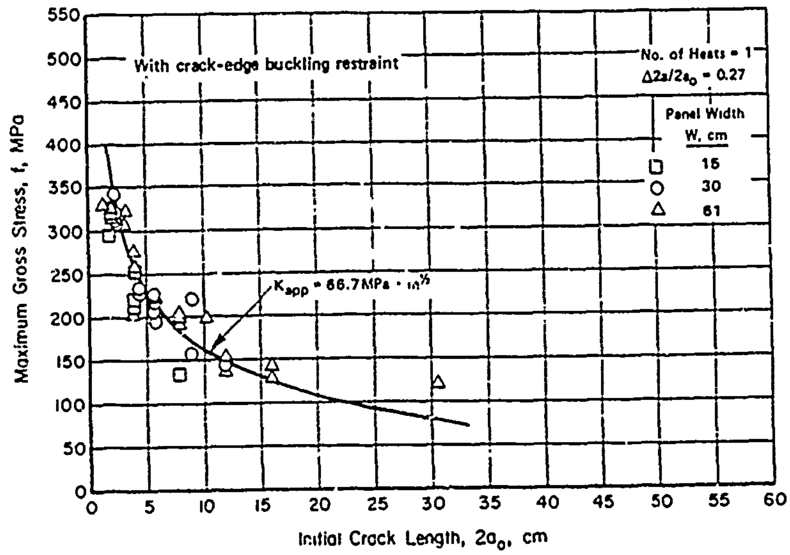


FIGURE 3.1.2.1.6(i). Residual strength behavior of 2.032-mm-thick 7075-T6 clad aluminum alloy sheet at room temperature. Crack orientation is L-T. (References 3.1.2.1.6(j) and (k).)

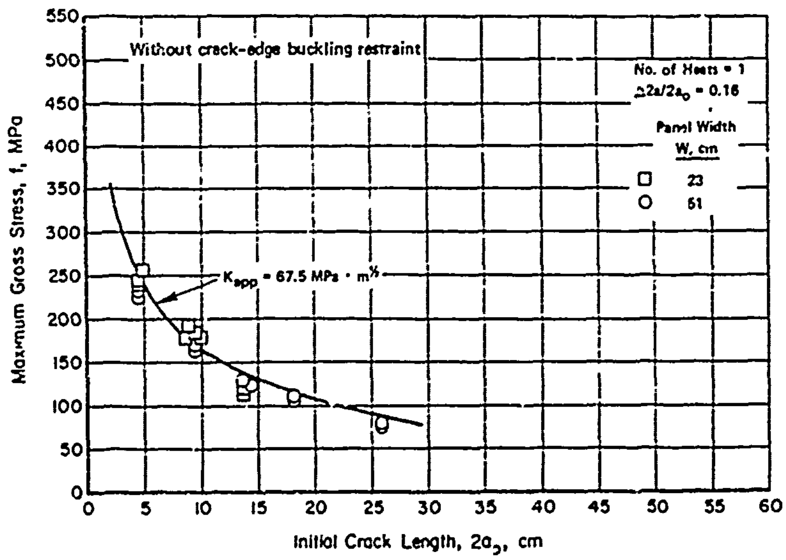


FIGURE 3.1.2.1.6(j). Residual strength behavior of 2.286-mm-thick 7075-T6 clad aluminum alloy sheet at room temperature. Crack orientation is L-T. (Reference 3.1.2.1.6(i).)

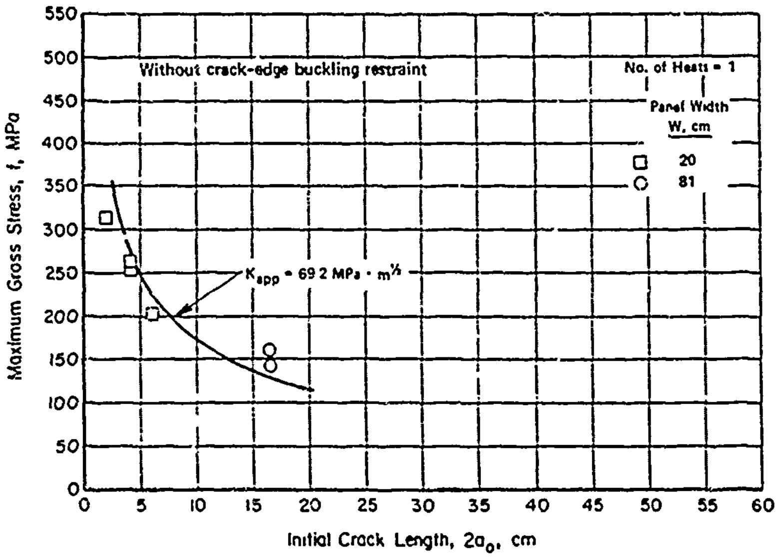


FIGURE 3.1.2.1.6(k). Residual strength behavior of 15.24-mm-thick 7075-T7351 aluminum alloy plate at room temperature. Crack orientation is L-T. (Reference 3.1.2.1.6(g).)

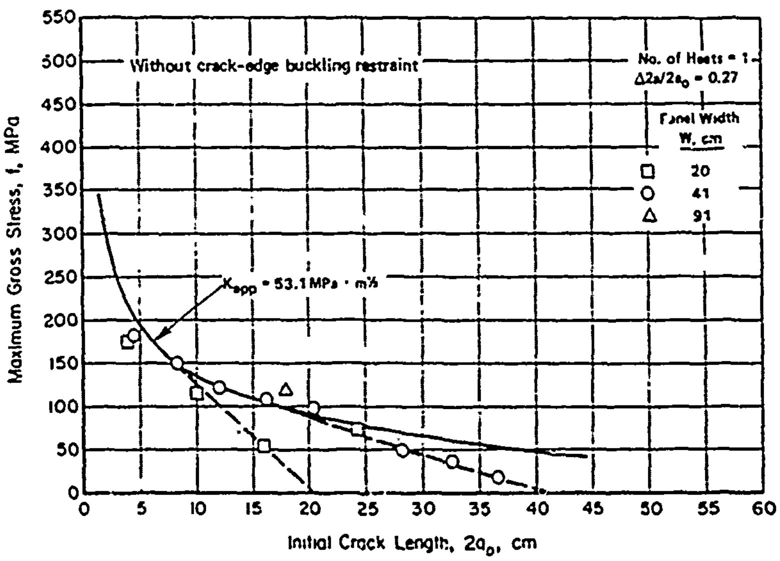


FIGURE 3.1.2.1.6(l). Residual strength behavior of 25.4-mm-thick 7075-T7351 aluminum alloy plate at room temperature. Crack orientation is L-T. (Reference 3.1.2.1.6(l).)

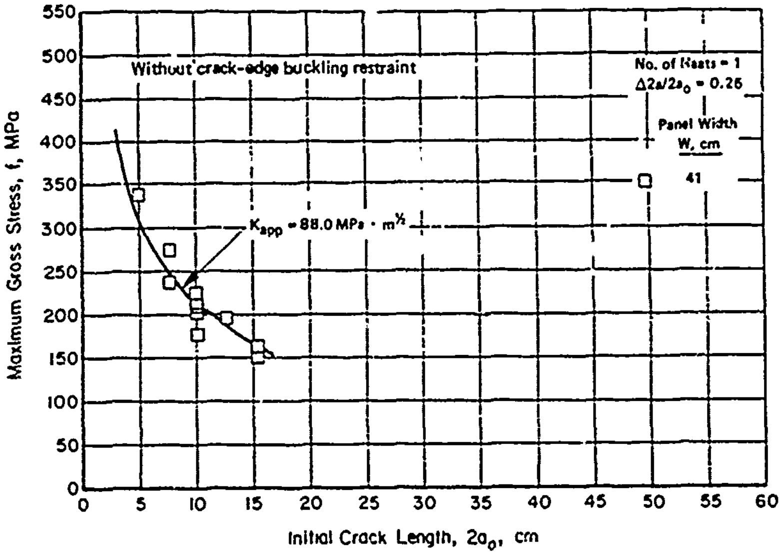


FIGURE 3.1.2.1.6(m). Residual strength behavior of 1.60-mm-thick 7475-T61 aluminum alloy sheet at room temperature. Crack orientation is L-T. (References 3.1.2.1.6(d) and (m).)

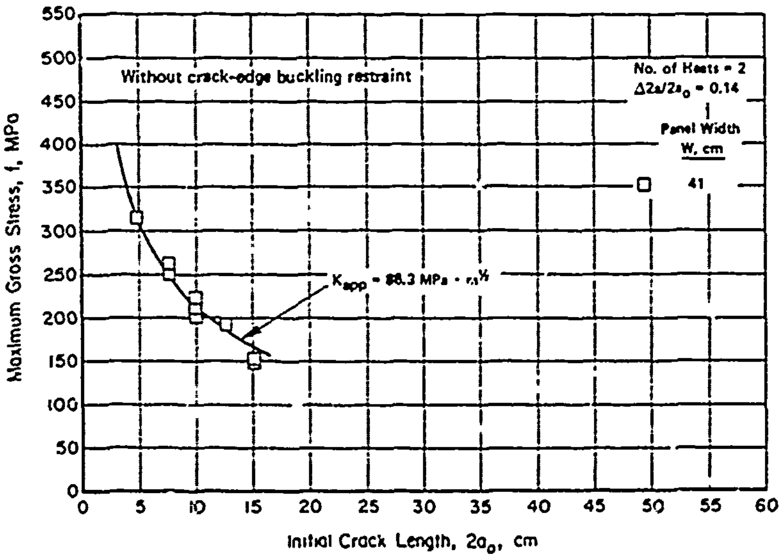


FIGURE 3.1.2.1.6(n). Residual strength behavior of 1.60-mm-thick 7475-T61 aluminum alloy sheet at room temperature. Crack orientation is T-L. (References 3.1.2.1.6(d) and (m).)

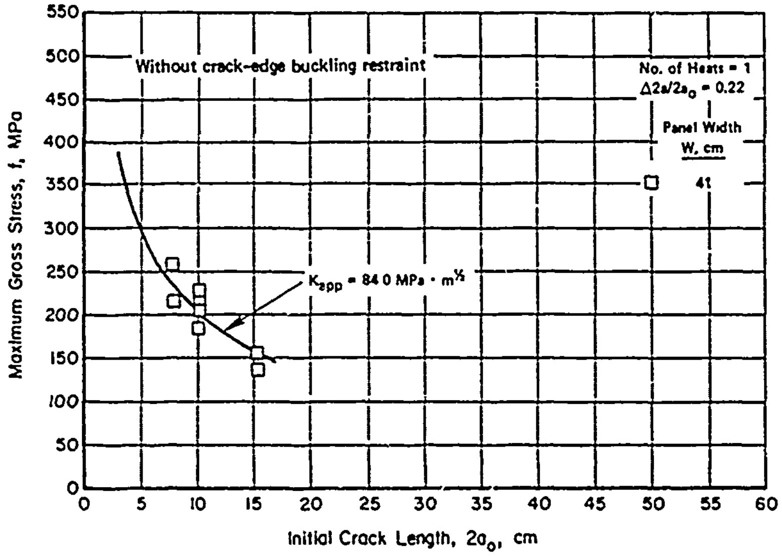


FIGURE 3.1.2.1.6(o). Residual strength behavior of 1.60-mm-thick 7475-T61 clad aluminum alloy sheet at room temperature. Crack orientation is L-T. (Reference 3.1.2.1.6(m).)

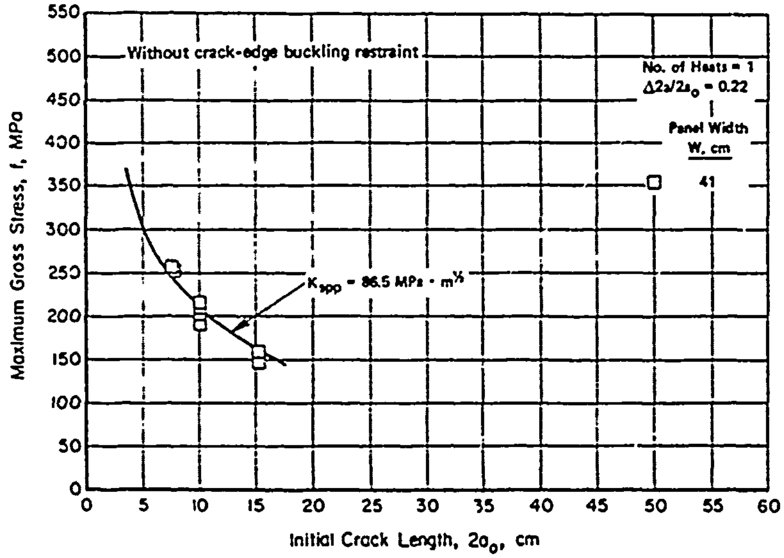


FIGURE 3.1.2.1.6(p). Residual strength behavior of 1.60-mm-thick 7475-T61 clad aluminum alloy sheet at room temperature. Crack orientation is T-L. (Reference 3.1.2.1.6(m).)

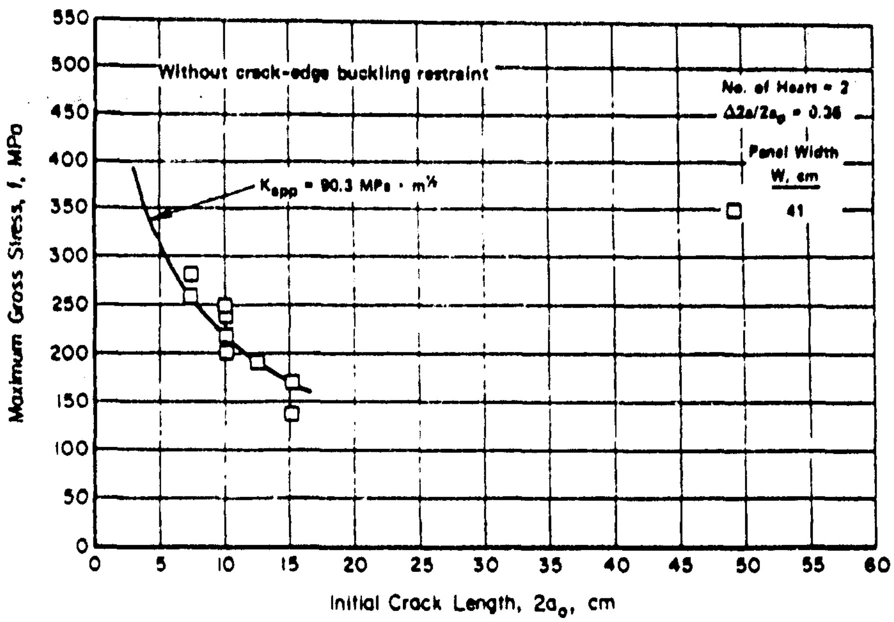


FIGURE 3.1.2.1.6(q). Residual strength behavior of 1.60-mm-thick 7475-T761 aluminum alloy sheet at room temperature. Crack orientation is L-T. (References 3.1.2.1.6(d) and (m).)

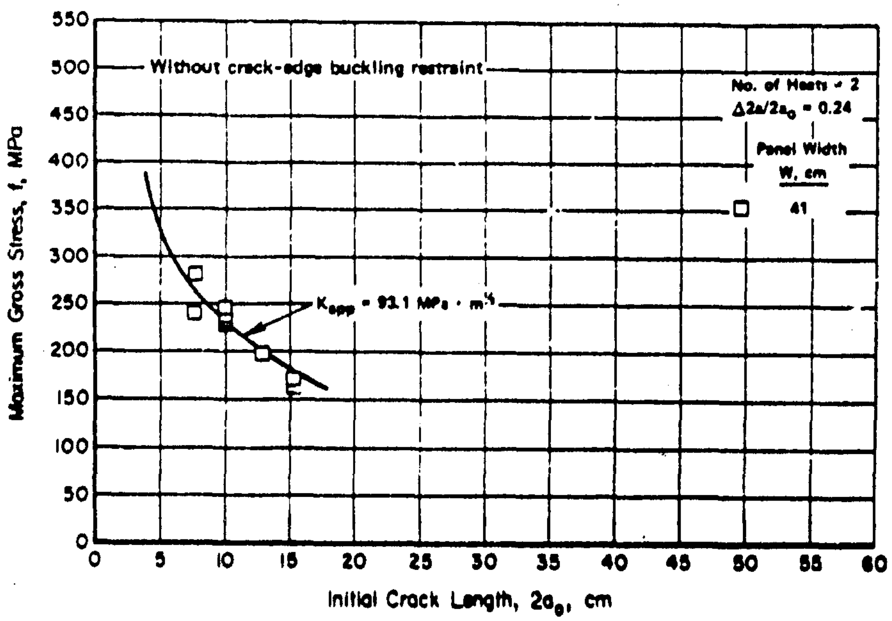


FIGURE 3.1.2.1.6(r). Residual strength behavior of 1.60-mm-thick 7475-T761 aluminum alloy sheet at room temperature. Crack orientation is T-L. (References 3.1.2.1.6(d) and (m).)

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 200 to 20 K (liquid hydrogen temperature); the strengths at 4 K (liquid helium temperature) are nearly the same as at 20 K [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 200, 78, and 20 K, 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 373 to 478 K. 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.)

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 Mg/m^3, the specific heat, C, in J/(g•K), the thermal conductivity, K, in W/(m•K) ; and the mean coefficient of thermal expansion, α, in m/(m•K). 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)]. 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, 7075, 7079, and 7178 in the T6-type tempers and 2014, 2024, and 2219 in the T3 and T4-type tempers. Other alloy-temper combinations, notably 2024 and 2219 in the T6 or T8-type tempers and 7049, 7075 and 7175 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 T76 temper of 7075 and 7178 provides 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. A measure of the degree of susceptibility of various products of these alloys and tempers is given in Table 3.1.2.3.1.

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 5456 should not be used under high constant applied stress for continuous service at temperatures exceeding 339 K, 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.

In the recommended tempers, H113 and H321 for sheet and plate, cold forming of 5083 and 5456 should be held to a minimum radius of 5T. Hot forming of the 0 temper of alloys 5083 and 5456 is recommended, and is preferred for the H113 and H321 tempers in order to avoid excessive cold work and high residual stress. If the

TABLE 3.1.2.3.1. Comparison of the Resistance to Stress Corrosion of Various Aluminum Alloys and Products

		Estimate of Highest Sustained Tension Stress (MPa)[e] at Which Test Specimens of Different Orientation to the Grain Structure Would Not Fail in the 3½% NaCl Alternate Immersion Test in 84 Days[f]				
				Extruded Shapes Section Thickness, mm		
Alloy and Temper	Test Direction	Plate	Rolled Rod and Bar	0.35-25.4	>25.4-50.8	Hand Forgings
2014-T6	L	310	310	345	310	207
	LT	207	..	186	152	172
	ST	55[a]	103[b]	..	55[a]	55[a]
2219-T8	L	276[c]	..	241[c]	241[c]	262[c]
	LT	262[c]	..	241[c]	241[c]	262[c]
	ST	262[c]	..	..	241[c]	262[c]
2024-T3,T4	L	241	207	345[c]	345[c]	..
	LT	138	..	255	124	..
	ST	55[a]	69[b]	..	55[a]	..
2024-T8	L	345[c]	324[c]	414[c]	414[c]	296[c]
	LT	345[c]	..	345	345	296
	ST	207	296[b]	..	310[c]	103
7075-T6	L	345	345	414	414	241
	LT	310	..	345	221	172
	ST	55[a]	103[b]	..	55[a]	55[a]
7075-T76	L	338[c]	..	359[c]	..	..
	LT	338[c]	..	338[c]	..	..
	ST	172	..	172	..	..
7075=T73	L	345[c]	345	372	365[c]	345[c]
	LT	331[c]	331	331	331[c]	331[c]
	ST	296[c,d]	296[c,d]	317[c]	317[c,d]	296[c,d]
7079-T6	L	376[c]	..	414	414[c]	345[c]
	LT	276	..	345	241	207
	ST	55[a]	..	..	55[a]	55[a]
7178-T6	L	376	..	448	448	..
	LT	272	..	310	172	..
	ST	55[a]	..	..	55[a]	..
7178-T76	L	359[c]	..	379[c]	..	..
	LT	359[c]	..	359[c]	..	..
	ST	172	..	172	..	..

[a] Lowest stress at which tests were conducted; failures were obtained.

[b] Ratings are for transverse specimens machined from round or square bar stock.

[c] Highest stress at which tests were conducted; on failure observed.

[d] These values will be lower for sections greater than 76 mm thick, but will be at least 75% of the guaranteed yield strength.

[e] See Section 9.5.2 for test method used to determine values.

[f] Tests performed at Alcoa Research Laboratories.

H113, H321, H323, and H343 tempers are heated for hot forming, a slight decrease in mechanical properties, particularly yield strength, may result.

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 and 7178 provides a very high resistance to exfoliation, i e., decidedly superior to that of the T6 temper, and almost the immunity provided by the T73 temper of 7075 alloy.

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, should be avoided in these high strength alloys: 2014-T451, T4, T6, T651, T652; 2024-T3, T351, T4; 7075-T6, T651, T652; 7079-T6, T651, T652; 7178-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 stresses 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.

Specific guidance on safe stress levels from the stress corrosion standpoint are provided in Section 3 1.2.3.1. These stresses represent the algebraic sum of all the continuous tension and compression surface stresses resulting from any source such as quenching, forming, assembly, and in some cases, design. In most cases the design stresses (developed by functional loads) are not continuous and hence would not be involved in the summation of stresses.

3.1.3.2 *Cold-Formed Heat-Treatable Aluminum Alloys.* — Cold working, such as stretch forming of aluminum alloys prior to solution heat treatment may result in recrystallization or grain growth during heat treatment. The resulting strengths, particularly yield strengths, may be significantly below the specified minimum values. For critical applications, the strengths should be determined on the parts 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 strengths 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 alloys during thermal treatments 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 0.0010 to 0.0015 m/m . may be anticipated. Additional growth of as much as 0.0010 m/m . may occur during subsequent service of a year or more at 422 K 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 strongly 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 have been 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 QQ-R-566 also contains much useful information. MIL-HDBK-5 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 or MIL-HDBK-5C.

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,c] Inert Gas Metal or Tungsten Arc	Resistance Spot[b]
3.2.1	2014	0	C	D
		T4, T6, TX51	B	B
3.2.2	2017	T4, TX51	C	B
3.2.3	2024	0	D	D
		T3, T351, T4	C	B
		T361, T6, T81, T851, T861	C	B
3.2.4	2025	T6	C	B
3.2.5	2124	T851	C	B
3.2.6	2219	0	A	B-D
		T31, T37, TX51, T81, T87	A	A
3.2.7	2618	T61	C	B
3.5.1	5052	0	A	B
		H32, H34, H36, H38	A	A
3.5.2	5083	0	A	B
		H321, H323, H343, H111,	A	A
		H116, H117	A	A
3.5.3	5086	0	A	B
		H32, H34, H36, H38, H111,	A	A
		H116, H117	A	A
3.5.4	5454	0	A	B
		H32, H34, H111	A	A
3.5.5	5456	0	A	B
		H111, H321, H323, H343,	A	A
		H116, H117	A	A
3.6.1	6061	0	A	B
		T4, T6, TX51	A	A
3.6.2	6151	T6, TX52	A	A
3.7.1	7049	All	C	B
3.7.2	7050	All	C	B
3.7.3	7075	All	C	B
3.7.4	7079	All	C	B
3.7.5	7175	All	C	B
3.7.6	7178	All	C	B

[a]Ratings A through D are relative ratings defined as follows:

A-Readily weldable by commercial procedures and methods.

B-Weldable with special techniques or for specific applications which may require 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. This method is not recommended.

[b]See MIL-W-6858 for permissible combinations.

[c]When using filler wire, the wire should contain less than 0.0008 percent beryllium to avoid toxic fumes.

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
3.12.1	201.0	C	C
3.12.2	224.0	B	A
3.12.3	295.0	C	C
3.13.1	354.0	B	B
3.13.2	355.0	B	B
3.13.2	C355.0	B	B
3.13.4	356.0	A	A
3.13.5	A356.0	A	A
3.13.6	A357.0	A	B
3.13.7	359.0	A	B
3.15.1	520.0	C-D	C
3.15.2	535.0	C-D	A
3.17.1	D712.0	C-D	C

[a]Weldability related to joining a casting to another cast part of same composition. The weldability ratings are not applicable to minor weld repairs. Such repairs shall be governed by the contractors procedure for in-process welding of castings, after approval by the procuring activity.

[b]Ratings A through D are relative ratings defined as follows:
A-Readily weldable by commercial procedures and methods.
B-Weldable with special techniques or for specific applications which may require 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. This method is not recommended.

[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. 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 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). Figure 3.2.1.0 shows the effect of temperature on the physical properties of 2014 alloy.

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.*—Cryogenic, room, and elevated temperature data for these tempers are presented in Figures 3.2.1.1.1(a) through 3.2.1.1.8 as follows:

Figures 3.2.1.1.1(a) through 3.2.1.1.5(b) present effect-of-temperature curves for various mechanical properties.

TABLE 3.2.1.0(a). *Material Specifications for 2014 Aluminum Alloy*

Specification	Form
AMS 4014	Bare sheet and plate
AMS 4028	Bare sheet and plate
AMS 4029	Bare sheet and plate
QQ-A-250/3	Clad sheet and plate
QQ-A-225/4	Rolled or drawn bars, rods, and wire
QQ-A-200/2	Extruded bar, rod and shapes
MIL-A-22771	Forgings

Figures 3.2.1.1.6(a) through (r) present tensile and compressive stress-strain curves 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.

Figure 3.2.1.1.8 provides room-temperature fatigue curve for various wrought products in the T6 temper.

TABLE 3.2.1.0(B1). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 2014 ALUMINUM ALLOY (SHEET AND PLATE)

SPECIFICATION	AMS 4029				AMS 4014											
FORM	SHEET				PLATE											
TEMPER	T6 AND T62[c,d]				T651[a]											
THICKNESS, MM	0.51-1.00		1.01-6.33		6.34-12.68		12.69-25.41		25.42-50.81		50.82-63.51		63.52-76.21		76.22-101.60	
BASIS	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
MECHANICAL PROPERTIES:																
FTU, MPA:																
L	448	462	462	476	455	469	455	462	455	462	448	455	434	441	414	421
LT	441	455	455	462	462	476	462	469	462	469	448	455	434	441	407	414
ST	...	...	...	...	...	...	...	...	...	...	414	421	400	407	372	379
FTY, MPA:																
L	400	414	407	414	414	427	414	421	414	427	407	421	400	414	386	400
LT	393	407	400	407	407	421	407	414	407	421	400	414	393	407	379	393
ST	...	...	...	...	...	...	...	...	...	...	414	421	400	407	372	379
FCY, MPA:																
L	400	414	407	414	400	414	400	407	400	414	393	407	386	400	372	386
LT	400	414	414	421	421	434	421	427	421	434	414	427	407	421	393	407
ST	...	...	...	...	...	...	...	...	...	...	414	427	407	421	393	407
FSU, MPA	269	276	276	283	276	283	276	283	276	283	269	276	262	269	248	248
FBRU[b], MPA:																
(E/D=1.5)	669	689	689	710	731	752	731	738	731	738	710	717	683	696	641	655
(E/D=2.0)	843	876	876	903	931	959	931	945	931	945	903	917	876	889	821	834
FBRY[b], MPA:																
(E/D=1.5)	558	579	572	579	621	641	621	634	621	641	614	634	600	621	579	600
(E/D=2.0)	641	662	648	662	738	758	738	752	738	758	724	752	710	738	689	710
EL, PERCENT:																
L	6	...	7	...	7	...	6	...	6	...	4	...	4	...	3	...
LT	6	...	7	...	7	...	6	...	4	...	2	...	2	...	1	...
ST	...	...	...	...	...	...	...	...	...	...	1	...	1	...	...	...
E, GPA	72.4				73.8											
EC, GPA	73.8				75.2											
G, GPA	27.6				27.6											
MU	0.33				0.33											
PHYSICAL PROPERTIES:																
OMEGA, MG/M3	2.80															
C, J/(G°K)	0.96 (AT 373 K)															
K, W/(M°K)	156 (AT 298 K)															
ALPHA, 10-6 M/(M°K)	22.5 (293 TO 373 K)															

a BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.
b SEE TABLE 3.1.2.1.1.
c THE ALLOWABLES SHOWN FOR THESE TEMPERS ARE BASED ON AND HAVE BEEN DETERMINED FROM THE RESULTS OBTAINED ON TESTING OF T6 TEMPER MATERIAL AND ON THE TESTING OF T62 TEMPER SAMPLES FOR SPECIFICATION CONFORMANCE.
d 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.

TABLE 3.2.1.0(B2). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 2014 ALUMINUM ALLOY (SHEET)

SPECIFICATION	AMS 4028								
FORM	PLATE								
TEMPER	T62[a]								
THICKNESS, MM	6.35–12.68		12.69–25.41		25.42–50.81		50.82–63.51	63.52–76.21	76.22–101.60
BASIS	A	B	A	B	A	B	S	S	S
MECHANICAL PROPERTIES:									
FTU, MPA:									
L	469	483	469	483	462	469	446	434	407
LT	462	476	462	476	462	469	445	434	345
ST	...	...	...	...	...	...	414	400	372
FTY, MPA:									
L	414	427	414	427	407	427	400	393	379
LT	407	421	407	421	407	427	400	393	379
ST	...	...	...	...	...	...	372	365	352
FCY, MPA:									
L	414	427	414	427	421	441	414	407	393
LT	421	434	421	434	421	441	414	407	393
ST	...	...	...	...	...	...	414	407	393
FSU, MPA	283	290	283	290	283	283	276	269	255
FBRU[b], MPA:									
(E/D=1.5)	703	724	703	724	696	703	676	648	607
(E/D=2.0)	869	917	869	917	876	869	855	827	772
FBRY[b], MPA:									
(E/D=1.5)	579	600	579	600	572	600	558	552	531
(E/D=2.0)	662	653	662	653	646	683	641	627	607
EL, PERCENT:									
L	7	...	6	...	6	...	4	4	3
LT	7	...	6	...	4	...	2	2	1
ST	...	...	...	...	...	...	1	1	...
E, GPA	73.8								
EC, GPA	75.2								
G, GPA	27.6								
MU	0.33								
PHYSICAL PROPERTIES:									
OMEGA, MG/M3	2.80								
C, J/(G*K)	0.96 (AT 373 K)								
K, W/(M*K):	156 (AT 298 K)								
ALPHA, 10-6 M/(M*K)	22.5 (293 TO 373 K)								

a 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.

b SEE TABLE 3.1.2.1.1.

TABLE 3.2.1.0(C1). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF CLAD 2014 ALUMINUM ALLOY (SHEET AND PLATE)

SPECIFICATION	QQ-A-250/3															
FORM	SHEET				PLATE											
CONDITION	T6 AND T62[d,e]				T651[a]											
THICKNESS, MM	0.51-1.00		1.01-6.33		6.34-12.68[b]		12.69-25.41[b]		25.42-50.61[b]		50.82-63.51[b]		63.52-76.21[b]		76.22-101.60	
BASIS	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
MECHANICAL PROPERTIES:																
FTU, MPA:																
L	427	441	448	462	434	448	434	441	434	441	427	434	414	421	393	400
LT	421	434	441	455	441	455	441	448	441	448	427	434	414	421	386	393
ST	...	...	...		...	...	...	...	...	...	414	421	400	407	372	379
FTY, MPA:																
L	372	386	393	407	400	414	393	400	393	407	386	400	379	393	365	379
LT	365	379	386	400	393	407	386	393	386	400	379	393	372	386	359	372
ST	...	...	...	...	...	...	...	...	...	...	372	386	365	379	352	365
FCY, MPA:																
L	372	386	393	407	386	400	379	386	379	393	372	386	365	379	352	365
LT	379	393	400	414	407	421	400	407	400	414	393	407	386	400	372	386
ST	...	...	...	...	...	...	...	...	...	...	414	427	407	421	393	407
FSU, MPA	262	269	269	276	269	276	269	269	269	255	262	246	255	234	234	
FBRU[c], MPA:																
(E/D=1.5)	641	662	676	696	696	717	696	710	696	710	676	683	655	662	607	621
(E/D=2.0)	814	834	855	876	869	917	889	903	889	903	862	876	834	848	779	793
FBRY[c], MPA:																
(E/D=1.5)	517	538	552	572	600	621	593	600	593	614	579	600	572	593	552	572
(E/D=2.0)	600	621	627	648	710	735	696	710	696	724	689	710	676	696	648	676
EL, PERCENT:																
L	7	...	8	...	8	...	6	...	6	...	4	...	4	...	3	...
LT	7	...	6	...	8	...	6	...	4	...	2	...	2	...	1	...
ST	...	...	...	...	...	...	...	...	...	...	1	...	1	...	...	...
E, GPA	72.4				73.8											
EC, GPA	73.8				75.2											
G, GPA	27.6				27.6											
MU	0.33				0.33											
PHYSICAL PROPERTIES:																
OMEGA, KG/M3	2.80															
C, J/(G*K)	0.96 (AT 373 K)															
K, W/(M*K)	156 (AT 298 K)															
ALPHA, 10-6 M/(M*K)	22.5 (293 TO 373 K)															

a BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

b THESE VALUES, EXCEPT IN THE ST DIRECTION, HAVE BEEN ADJUSTED TO REPRESENT THE AVERAGE PROPERTIES ACROSS THE WHOLE SECTION, INCLUDING THE 2.5 PERCENT PER SIDE NOMINAL CLADDING THICKNESS.

c SEE TABLE 3.1.2.1.1.

d THE ALLOWANCES SHOWN FOR THESE TEMPERS ARE BASED ON AND HAVE BEEN DETERMINED FROM THE RESULTS OBTAINED ON TESTING OF T6 TEMPER MATERIAL AND ON THE TESTING OF T62 TEMPER SAMPLES FOR SPECIFICATION CONFORMANCE.

e 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.

TABLE 3.2.1.0(c2). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF CLAD 2014 ALUMINUM ALLOY (PLATE)

SPECIFICATION	QQ-A-250/3							
FORM	PLATE							
CONDITION	T62[a]							
THICKNESS, MM	6.34-12.68		12.69-25.41[b]		25.42-50.81[b]	50.82-63.51[b]	63.52-76.21[b]	76.22-101.60[b]
BASIS	A	B	A	B	S	S	S	S
MECHANICAL PROPERTIES:								
FTU, MPA:								
L	448	462	448	462	441	427	414	386
LT	441	455	441	455	441	427	414	366
ST	...	...	...	...	...	414	400	372
FTY, MPA:								
L	400	407	393	407	386	379	372	359
LT	393	400	386	400	386	379	372	359
ST	...	...	...	...	...	372	365	352
FCY, MPA:								
L	400	407	393	407	400	393	386	372
LT	407	414	400	414	400	393	386	372
ST	...	...	...	...	...	414	407	393
FSU, MPA	269	276	269	276	269	262	255	241
FBRU,[c] MPA:								
(E/D=1.5)	676	696	676	696	662	641	621	579
(E/D=2.0)	855	876	855	876	841	814	786	731
FBRY,[c] MPA:								
(E/D=1.5)	556	565	552	565	545	531	524	503
(E/D=2.0)	641	655	627	655	621	607	593	572
EL, PERCENT:								
L	8	...	6	...	6	4	4	3
LT	8	...	6	...	4	2	2	1
ST	...	...	...	...	...	1	1	...
E, GPA	73.8							
EC, GPA	75.2							
G, GPA	27.6							
MU	0.33							
PHYSICAL PROPERTIES:								
OMEGA, MG/M3	2.80							
C, J/(G*K)	0.96 (AT 373 K)							
K, W/(M*K)	156 (AT 298 K)							
ALPHA, 10-6 M/(M*K)	22.5 (293 to 373 K)							

[a] 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.

[b] THESE VALUES EXCEPT IN THE ST DIRECTION, HAVE BEEN ADJUSTED TO REPRESENT THE AVERAGE PROPERTIES ACROSS THE WHOLE SECTION, INCLUDING THE 2.5 PERCENT PER SIDE NOMINAL CLADDING THICKNESS.

[c] SEE TABLE 3.1.2.1.1.

TABLE 3.2.1.0(D). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 2014 ALUMINUM ALLOY (BAR, ROD, WIRE AND SHAPES)

SPECIFICATION..........	QQ-A-225/4						
FORM..................	BAR,ROD,WIRE AND SHAPES,ROLLED OR DRAWN						
CONDITION.............	T6,T651, AND T62[c]						
THICKNESS, MM..........	≤25.41	25.42-50.81	50.82-76.21	76.22-101.61	101.62-127.01[a]	127.02-152.41[a]	152.42-203.20[a]
BASIS.................	S	S	S	S	S	S	S
MECHANICAL PROPERTIES:							
FTU, MPA:							
L..................	448	448	448	448	448	448	448
T..................	441	434	427	421	414	407	...
FTY, MPA:							
L..................	379	379	379	379	379	379	379
T..................	365	359	352	345	338	331	...
FCY, MPA:							
L..................	365	365	365	365	365	365	365
T..................	...	...	...	...	...	...	...
FSU, MPA..............	262	262	262	262	262	262	262
FBRU, MPA:							
(E/D=1.5)..........	676[b]	...	...	...	...	...	...
(E/D=2.0)..........	855[b]	...	...	...	...	...	...
FBRY, MPA:							
(E/D=1.5)..........	531[b]	...	...	...	...	...	...
(E/D=2.0)..........	607[b]	...	...	...	...	...	...
EL, PERCENT:							
L..................	8[b]	8	8	8	8	8	8
T..................	4[b]	3	2	1	1	1	...
E, GPA................	72.4						
EC, GPA...............	73.8						
G, GPA................	27.6						
MU....................	0.33						
PHYSICAL PROPERTIES:							
OMEGA, MG/M3..........	2.80						
C, J/(G*K)............	0.96 (AT 373 K)						
K, W/(M*K)............	156 (AT 298 K)						
ALPHA, 10-6 M/(M*K)..	22.5 (293 to 373 K)						

[a] FOR ROUNDS(ROD)MAXIMUM DIAMETER IS 203.2MM.; FOR SQUARE, RECTANGULAR, HEXAGONAL, OR OCTAGONAL BAR, MAXIMUM THICKNESS IS 101.6MM. AND MAXIMUM CROSS-SECTIONAL AREA IS 2322.6 SQ.CM.

[b] EXCEPT FOR WIRE LESS THAN 3.17MM. IN DIAMETER, OR FOR SPECIAL SHAPES LESS THAN 1.57MM. THICK.

[c] THE ALLOWABLES SHOWN FOR THESE TEMPERS ARE BASED ON AND HAVE BEEN DETERMINED FROM THE RESULTS OBTAINED ON TESTING OF T6 AND T651 TEMPER MATERIAL AND ON THE TESTING OF T62 TEMPER SAMPLES FOR SPECIFICATION CONFORMANCE. THESE ALLOWABLES ALSO 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.

TABLE 3.2.1.0(E). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 2014 ALUMINUM ALLOY (DIE FORGING)

SPECIFICATION	MIL-A-22771														
FORM	DIE FORGING														
CONDITION	T6							T652							
THICKNESS,[c] MM	≤25.41		25.42-50.81		50.82-76.21		76.22-101.60	≤25.41		25.42-50.81		50.82-76.21		76.22-101.60
BASIS	A	B	A	B	A	B	S	A	B	A	B	A	B	S
MECHANICAL PROPERTIES:															
FTU, MPA:															
L	448	462	448	462	448	462	434	448	462	448	462	448	462	434
T[a]	441	455	441	455	434	448	434	441	455	441	455	434	448	434
FTY, MPA:															
L	386	407	386	407	379	400	379	386	407	386	407	379	400	379
T	379	400	379	400	372	393	372	379	400	379	400	372	393	372
FCY, MPA:															
L	407	427	407	427	400	421	400	386	407	386	407	379	400	379
T	386	407	386	407	379	400	379	407	427	407	427	400	421	400
FSU, MPA	276	283	276	283	269	276	269	276	283	276	283	269	276	269
FBRU,[b] MPA:															
(E/D=1.5)	627	648	627	648	627	648	607	627	648	627	640	627	648	607
(E/D=2.0)	848	876	848	876	848	876	827	848	876	848	876	848	876	827
FBRY,[b] MPA:															
(E/D=1.5)	503	531	503	531	490	517	490	503	531	503	531	490	517	490
(E/D=2.0)	621	643	621	648	607	641	607	621	648	621	648	607	641	607
EL, PERCENT:															
L	6	...	6	...	6	...	6	6	...	6	...	6	...	6
T	3	...	2	...	2	...	2	3	...	2	...	2	...	2
E, GPA	72.4														
EC, GPA	74.5														
G, GPA	27.6														
MU	0.33														
PHYSICAL PROPERTIES:															
OMEGA, MG/M3	2.80														
C, J/(G*K)	0.96 (AT 373 K)														
K, W/(M*K)	156 (AT 298 K)														
ALPHA, 10-6 M/(M*K)	22.5 (293 to 373 K)														

[a] FOR DIE FORGINGS, T INDICATES ANY GRAIN DIRECTION NOT WITHIN ±15 DEGREES OF BEING PARALLEL TO THE FORGING FLOW LINES. SPECIMENS TO TEST TRANSVERSE PROPERTIES SHOULD BE LOCATED AS CLOSE TO THE SHORT TRANSVERSE DIRECTION AS POSSIBLE.

[b] BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

THE THICKNESS COLUMNS ARE FOR THE AS-HEAT-TREATED THICKNESS. TO ENTER THE TABLE USE THE HIGHER OF THE HEAT-TREAT THICKNESS OR ONE-HALF OF THE AS-FORGED THICKNESS.

TABLE 3.2.1.0(F). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 2014 ALUMINUM ALLOY (HAND FORGING)

SPECIFICATION	MIL-A-22771													
FORM	HAND FORGING[a]													
TEMPER	T6							T652						
THICKNESS, MM	≤50.81	50.32-76.21	76.22-101.61	101.62-127.01	127.02-152.41	152.42-177.81	177.82-203.20	≤50.81	50.82-76.21	76.22-101.61	101.62-127.01	127.02-152.41	152.42-177.81	177.82-203.20
BASIS	S	S	S	S	S	S	S	S	S	S	S	S	S	S
MECHANICAL PROPERTIES:														
FTU, MPA:														
L	448	441	434	427	421	414	407	448	441	434	427	421	414	407
LT	448	441	434	427	421	414	407	448	441	434	427	421	414	407
ST	...	427	421	414	407	400	393	...	427	421	414	407	400	393
FTY, MPA:														
L	386	386	379	372	365	359	352	386	386	379	372	365	359	352
LT	386	379	379	372	365	359	352	366	379	379	372	365	359	352
ST	...	379	372	365	365	359	352	...	359	352	345	345	338	331
FCY, MPA:														
L	386	386	379	372	365	...	...	386	386	379	372	365	...	...
LT	386	379	379	372	365	...	...	393	386	386	379	372	...	...
ST	...	...	...	...	...	...	...	...	393	386	379	379	...	...
FSU, MPA	276	269	269	262	262	...	...	262	255	255	248	248	...	...
FBRU[b], MPA:														
(E/D=1.5)	627	621	607	600	586	...	...	607	600	586	579	572	...	...
(E/D=2.0)	807	793	779	772	756	...	...	793	779	765	758	745	...	...
FBRY[b], MPA:														
(E/D=1.5)	538	538	531	524	510	...	...	531	524	524	510	503	...	...
(E/D=2.0)	621	621	607	593	566	...	...	627	614	614	600	593	...	...
EL, 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, GPA	72.4													
EC, GPA	74.5													
G, GPA	27.6													
MU	0.33													
PHYSICAL PROPERTIES:														
OMEGA, MG/M3	2.80													
C, J/(G*K)	0.96 (AT 373 K)													
K, W/(M*K)	156 (AT 298 K)													
ALPHA, 10-6 M/(M*K)	22.5 (293 to 373 K)													

[a] WHEN HAND FORGINGS ARE MACHINED BEFORE HEAT TREATMENT, THE SECTION THICKNESS AT TIME OF HEAT TREATMENT SHALL 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 16.516 SQ.CM.

[b] BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

TABLE 3.2.1.0(b). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 2014 ALUMINUM ALLOY (EXTRUSION)

SPECIFICATION	QQ-A-200/2										
FORM	EXTRUDED ROD, BAR, AND SHAPES										
TEMPER	T6, T6510, AND T6511										T62[a]
CROSS-SECTIONAL AREA, MM2	≤16130									>16130 ≤20650	≤20650
THICKNESS[b], MM	3.17-12.68		12.69-19.03		19.04-38.08		38.09-44.46		44.47-114.27	≥19.05	3.17-114.27
BASIS	A	B	A	B	A	B	A	B	S	S	S
MECHANICAL PROPERTIES:											
FTU, MPA:											
L	414	427	441	469	469	483	469	490	469	469	414
LT	414	427	400	421	421	434	421	441	...	...	...
FTY, MPA:											
L	365	393	400	427	414	434	414	434	414	400	365
LT	338	365	345	372	359	379	359	379	...	...	...
FCY, MPA:											
L	359	386	393	421	407	427	407	427	...	...	...
LT	365	393	365	386	379	393	379	393	...	...	...
FSU, MPA	283	296	241	255	255	262	255	269	...	269	...
FBRU[c], MPA:											
(E/D=1.5)	641	662	621	662	662	683	662	689	...	...	...
(E/D=2.0)	848	876	793	841	841	869	841	883	...	...	...
FBRY[c], MPA:											
(E/D=1.5)	510	552	503	538	524	552	524	552	...	...	...
(E/D=2.0)	600	643	586	627	607	641	607	641	...	...	...
EL, PERCENT:											
L	7	...	7	...	7	...	7	...	7	6	7[e]
LT[d]	5	...	5	...	2	...	2	...	...	...	...
E, GPA	74.5										
EC, GPA	75.8										
G, GPA	28.3										
MU	0.33										
PHYSICAL PROPERTIES:											
OMEGA, MG/M3	2.80										
C, J/(G*K)	0.96 (AT 373 K)										
K, W/(M*K)	156 (AT 298 K)										
ALPHA, 10-6 M/(M*K)	22.5 (293 to 373 K)										

[a] THESE PROPERTIES APPLY WHEN SAMPLES OF MATERIAL SUPPLIED IN THE O OR F TEMPER ARE HEAT TREATED BY THE PRODUCER TO DETERMINE THAT THE MATERIAL WILL RESPOND TO PROPER THERMAL 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.

[b] FOR EXTRUSIONS WITH OUTSTANDING LEGS, THE LOAD-CARRYING ABILITY OF SUCH LEGS SHALL BE DETERMINED ON THE BASIS OF THE PROPERTIES IN THE APPROPRIATE COLUMN CORRESPONDING TO THE LEG THICKNESS.

[c] BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

[d] NOT APPLICABLE TO SECTIONS <9.5MM. THICKNESS.

[e] FOR CROSS-SECTIONAL AREA >161.3CM., EL IS 6.

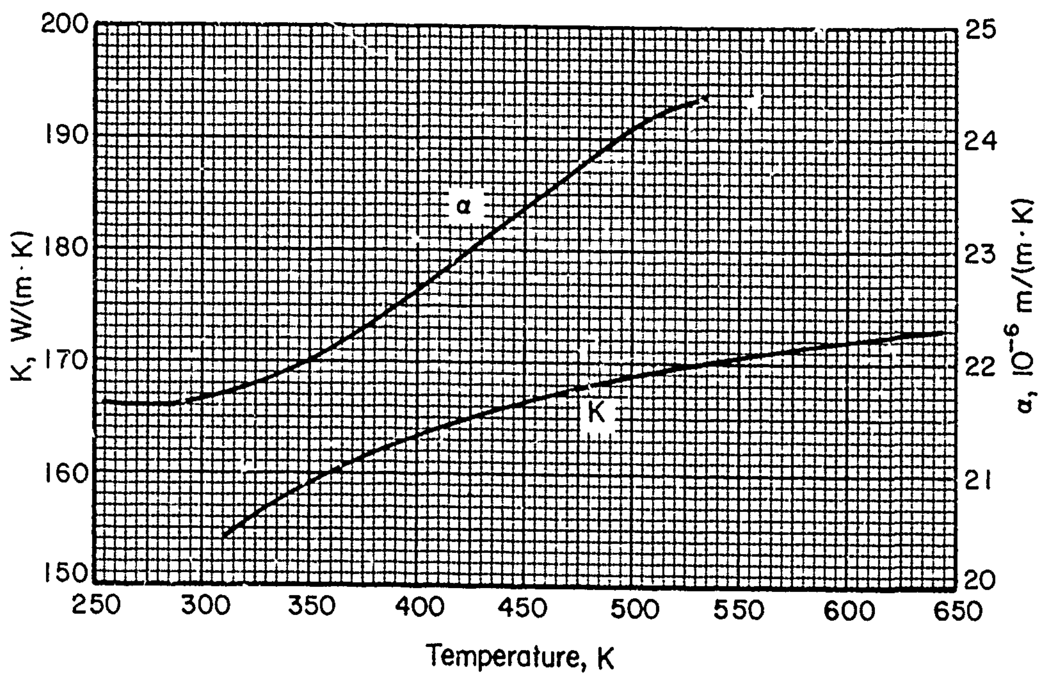


FIGURE 3.2.1.0. Effect of temperature on the physical properties of 2014 aluminum alloy.

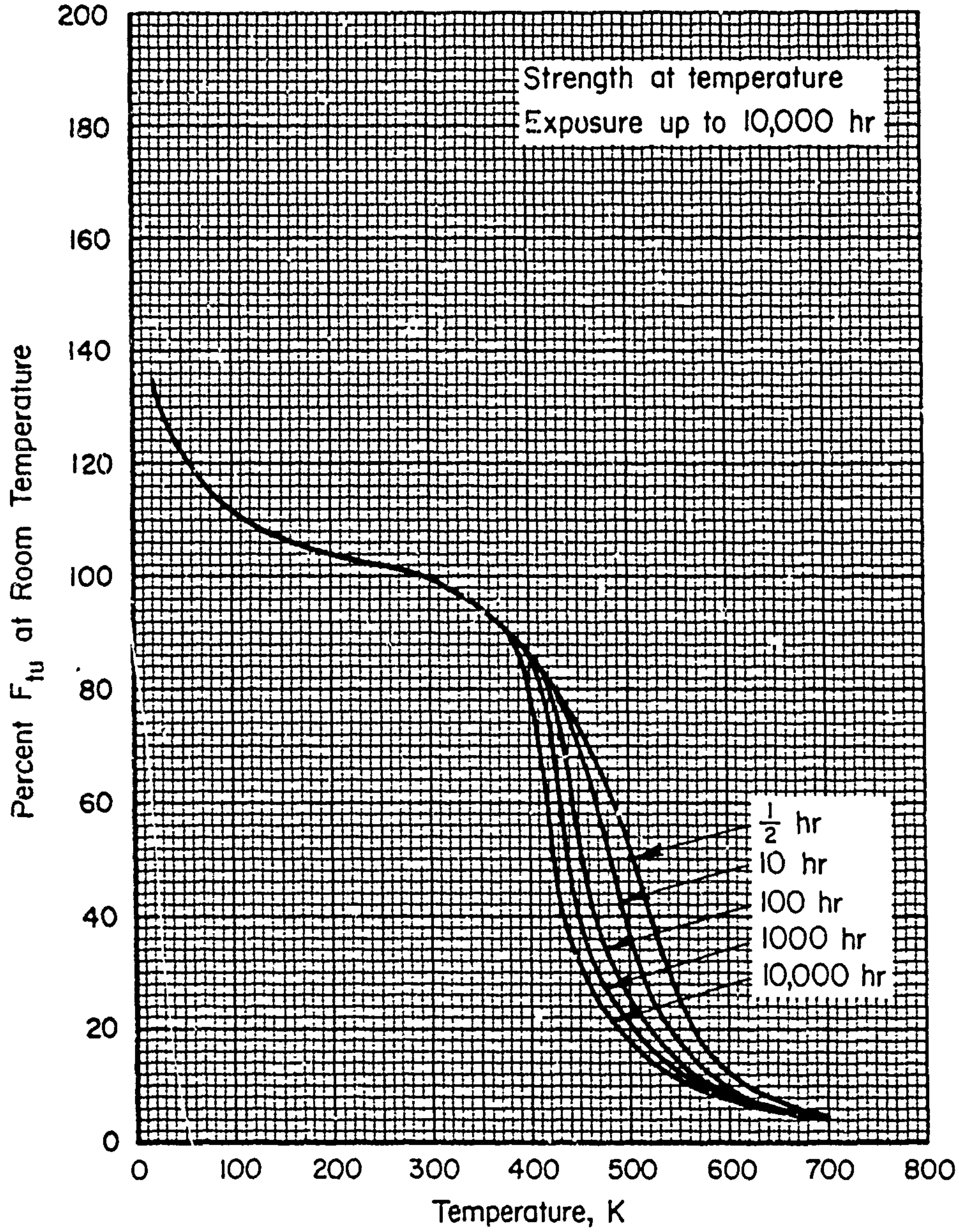


FIGURE 3.2.1.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of 2014-T6, T651, T6510 and T6511 alluminium alloy (bare and clad sheet and plate 1.016-38.1 mm thick; extruded bar, rod and shapes ≥ 19.05 mm thick with cross-sectional area ≤ 206 sq. cm.).

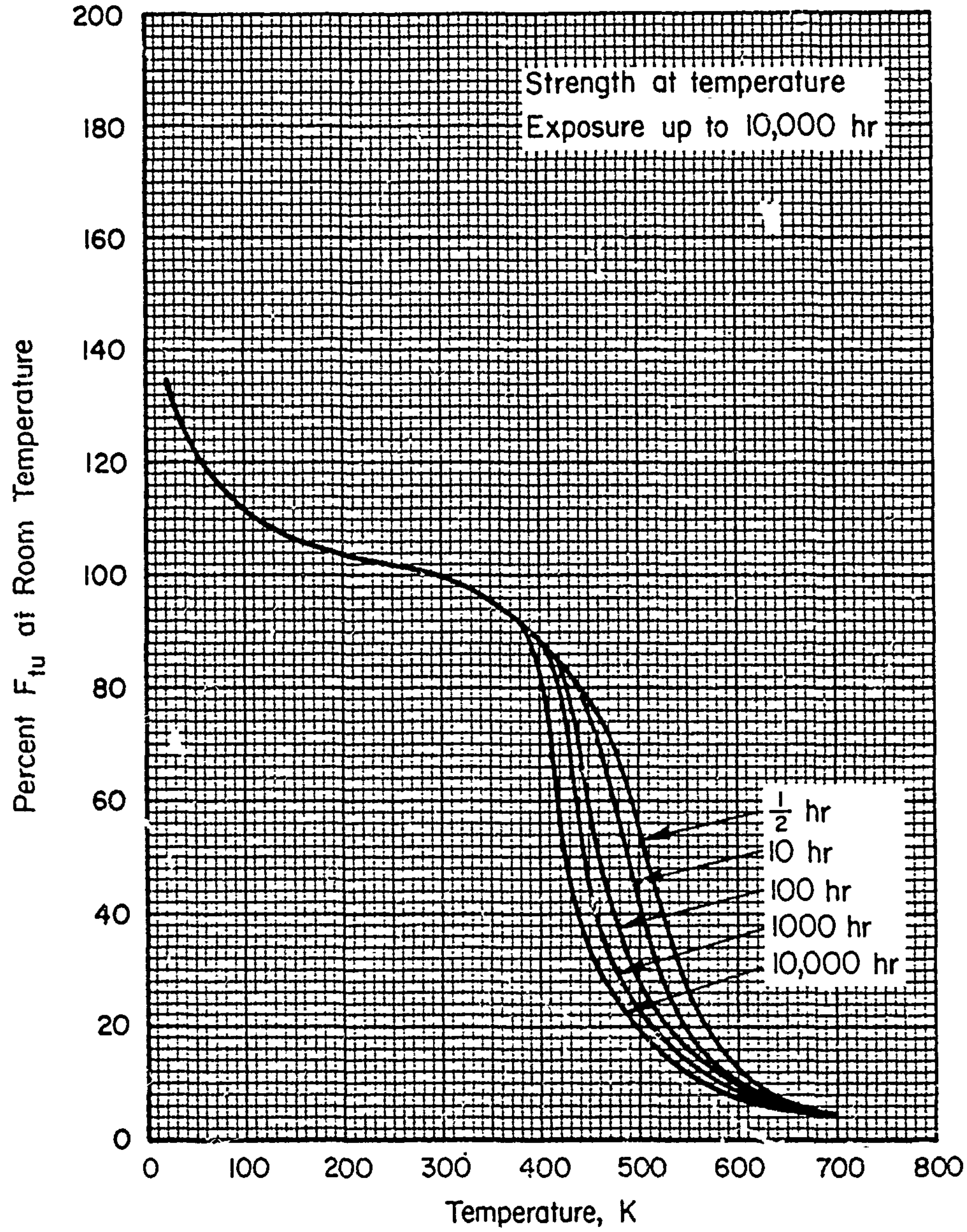


FIGURE 3.2.1.1.1(b). Effect of temperature on the ultimate strength (F_{tu}) of 2014-T6, T651, T6510 and T6511 aluminum alloy (bare and clad sheet 0.508-0.991 mm thick; bare and clad plate 38.12-101.6 mm thick; rolled bar, rod and shapes; hand and die forgings; extruded bar, rod and shapes 3.175-19.02 mm thick with cross-sectional area ≤ 161 sq. cm.).

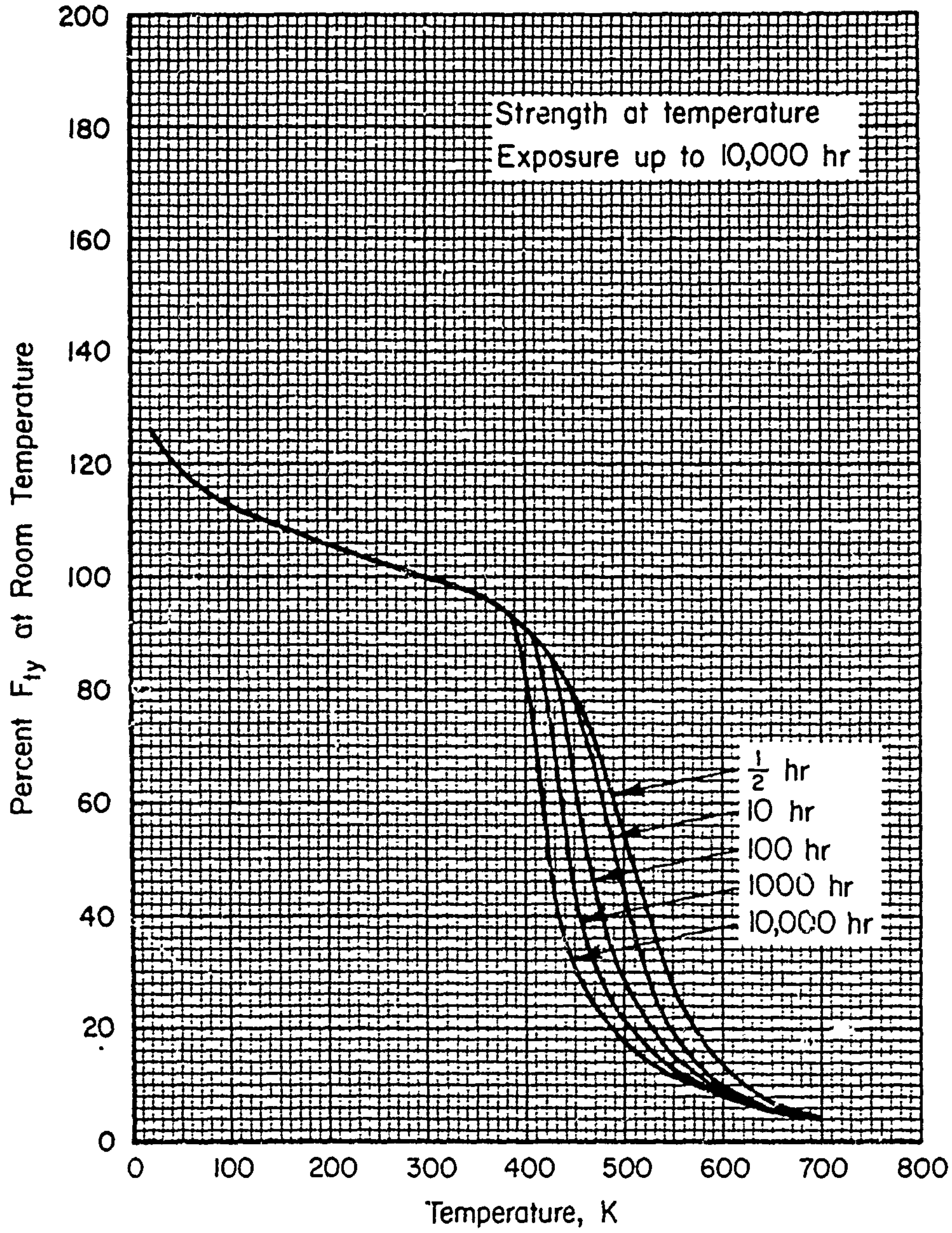


FIGURE 3.2.1.1.1(c). Effect of temperature on the tensile yield strength (F_{ty}) of 2014-T6, T651, T6510 and T6511 aluminum alloy (bare and clad plate 76.23-101.6 mm thick; rolled bar, rod and shapes; hand and die forgings; extruded bar, rod and shapes 3.175-12.67 mm thick with cross-sectional area ≤ 161 sq. cm.).

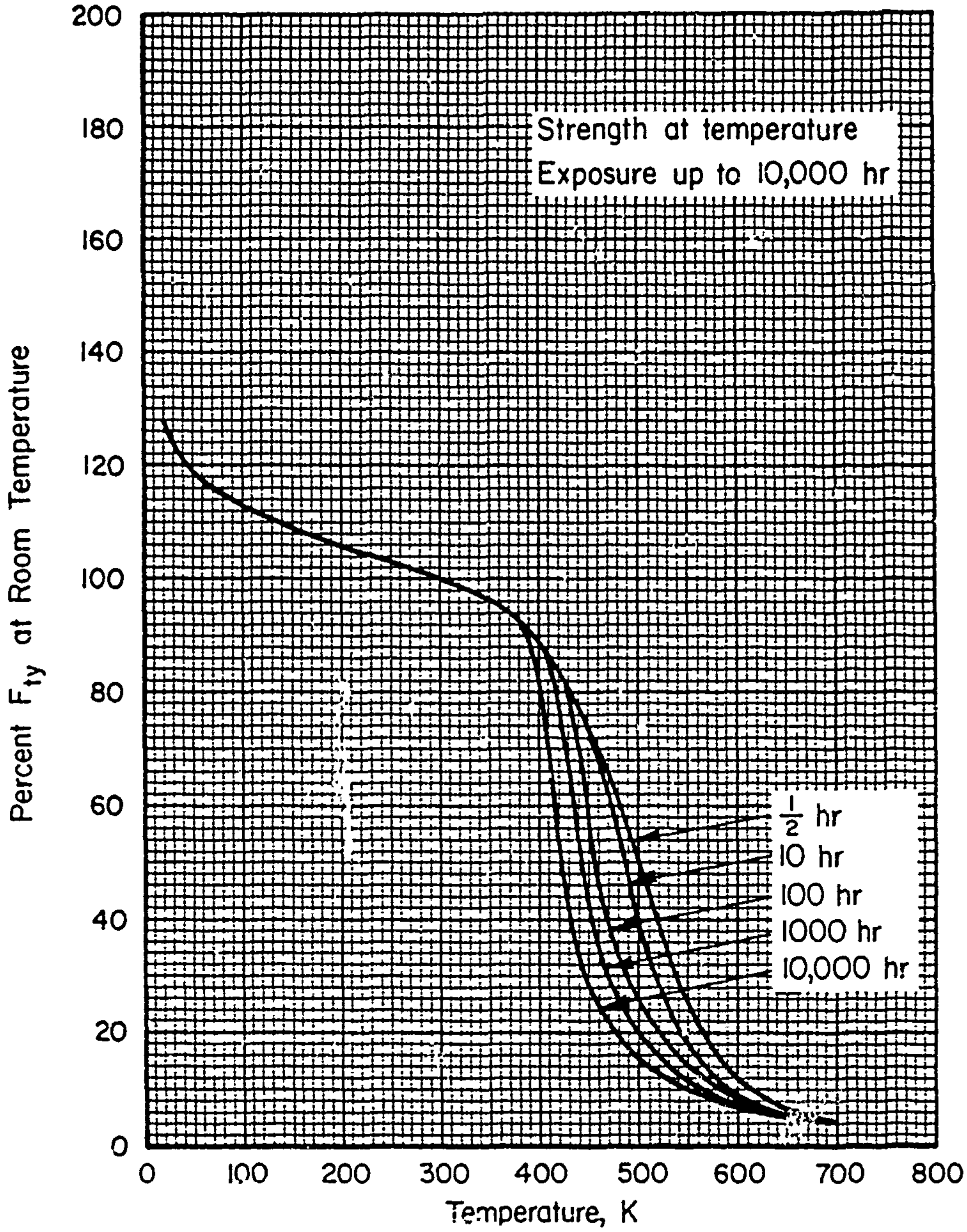


FIGURE 3.2.1.1.1.(d). Effect of temperature on the tensile yield strength (F_{ty}) of 2014-T6, T651, T6510 and T6511 aluminum alloy (bare and clad sheet and plate 0.508-76.2 mm thick; extruded bar, rod and shapes 12.7-19.02 mm thick with cross-sectional area $\leq$161 sq. cm. and $\geq$ 19.05 mm thick with cross-sectional area $\leq$ 206 sq. cm.).

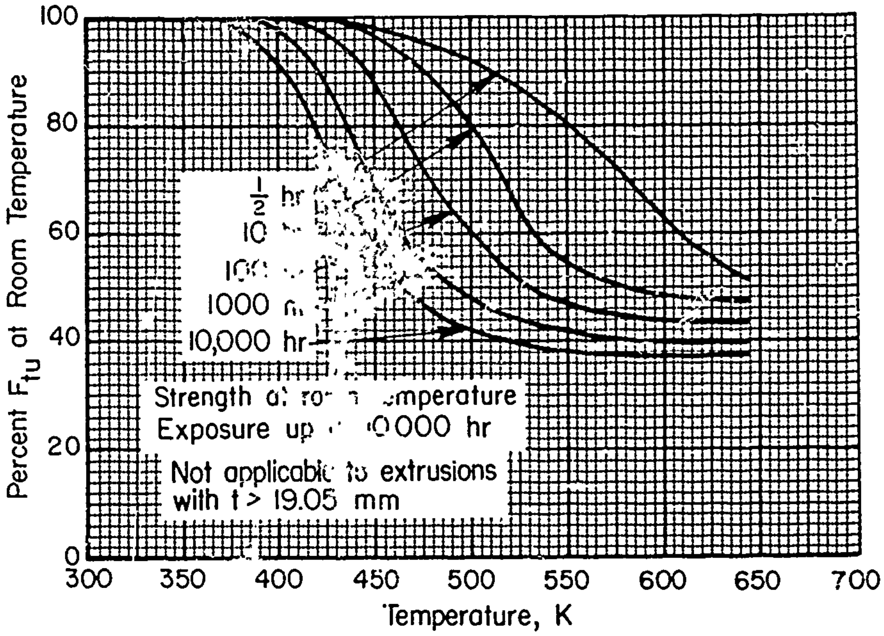


FIGURE 3.2.1.1.1(e). Effect of exposure at elevated temperatures on the room-temperature ultimate tensile strength (F_{tu}) of 2014-T6, T651, T6510, and T6511 aluminum alloy (all products except thick extrusions).

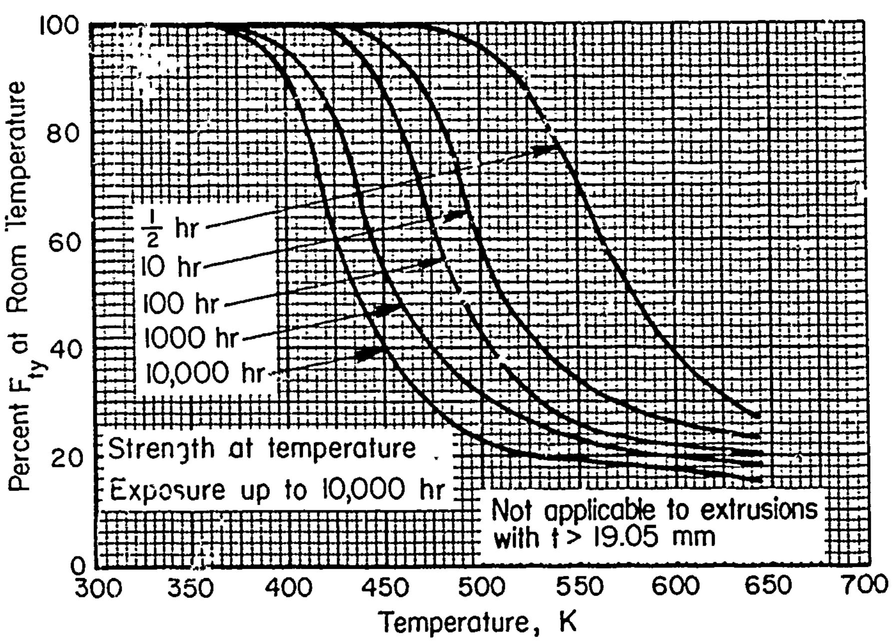


FIGURE 3.2.1.1.1(f). Effect of exposure at elevated temperatures on the room-temperature tensile yield strength (F_{ty}) of 2014-T6, T651, T6510, and T6511 aluminum alloy (all products except thick extrusions).

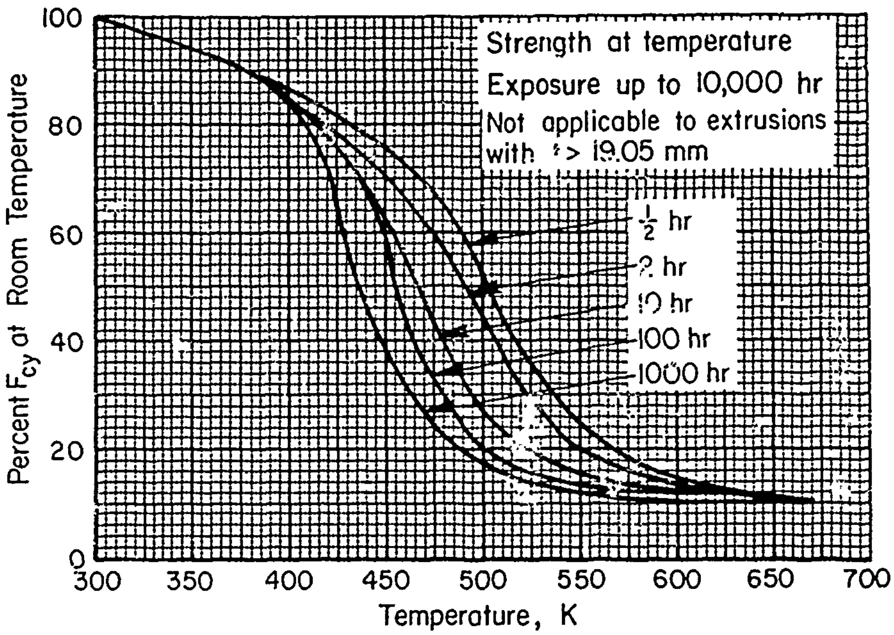


FIGURE 3.2.1.1.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of 2014-T6, T651, T6510 and T6511 aluminum alloy (all products except thick extrusions).

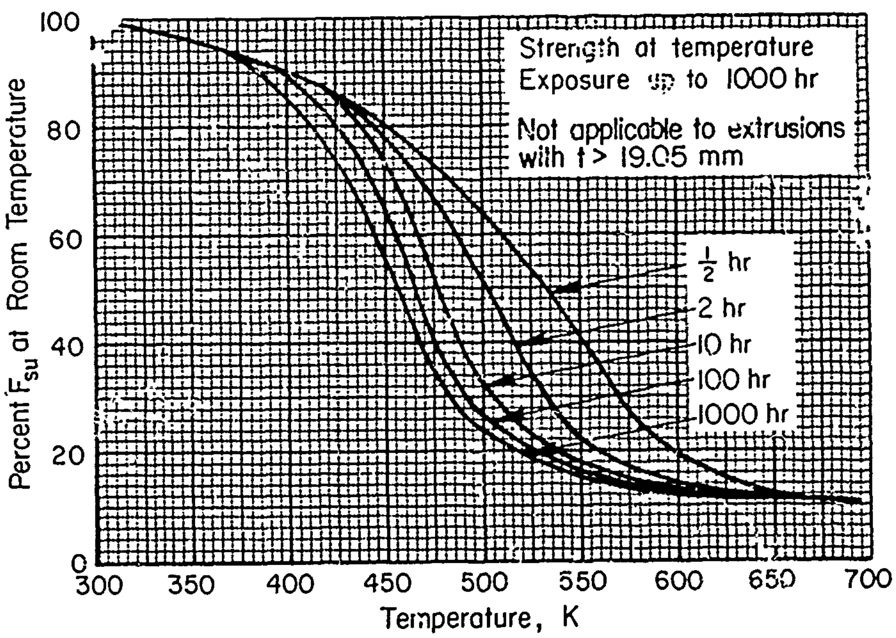


FIGURE 3.2.1.1.2(b). Effect of temperature on the ultimate shear strength (F_{su}) of 2014-T6, T651, T6510 and T6511 aluminum alloy (all products except thick extrusions).

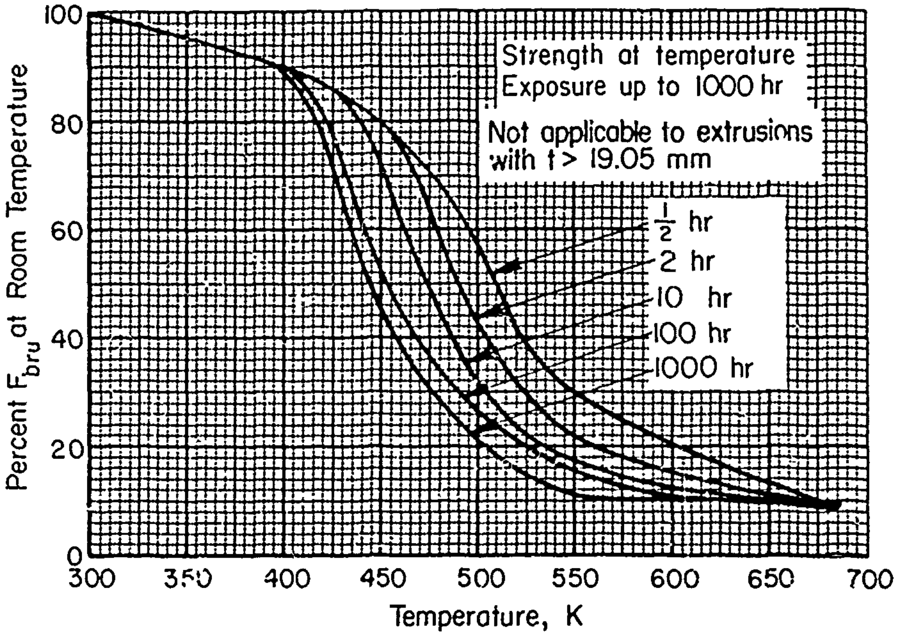


FIGURE 3.2.1.1.3(a). Effect of temperature on the ultimate bearing strength (F_{bru}) of 2014-T6, T651, T6510 and T6511 aluminum alloy (all products except thick extrusions).

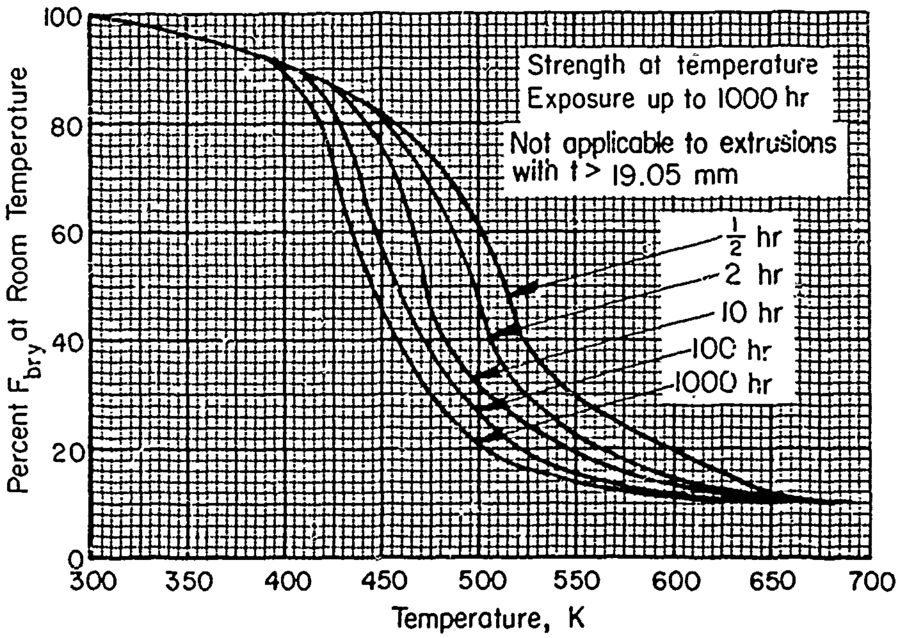


FIGURE 3.2.1.1.3(b). Effect of temperature on the bearing yield strength (F_{bry}) of 2014-T6, T651, T6510 and T6511 aluminum alloy (all products except thick extrusions).

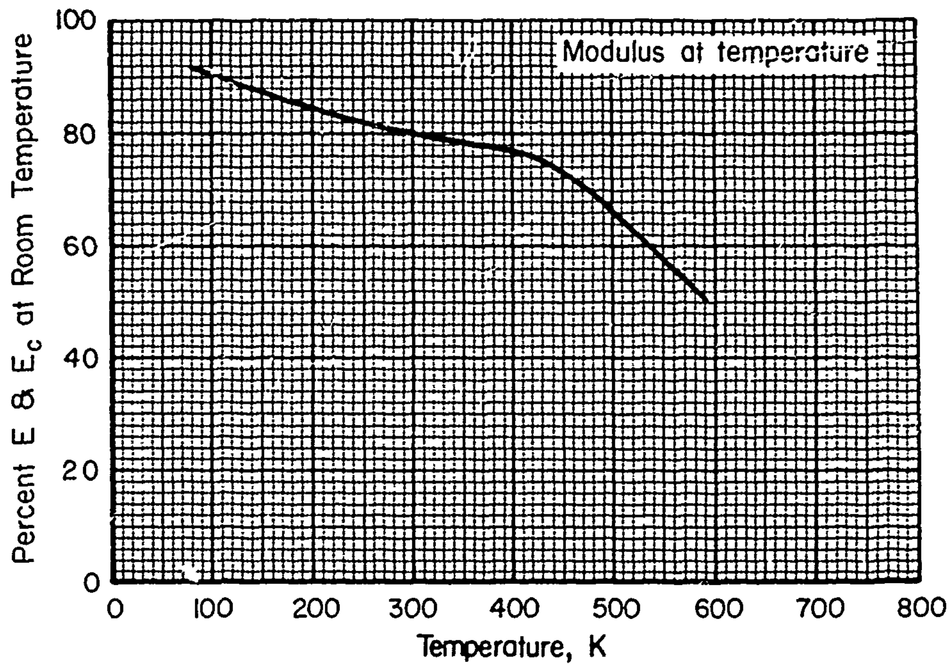


FIGURE 3.2.1.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of 2014 aluminum alloy.

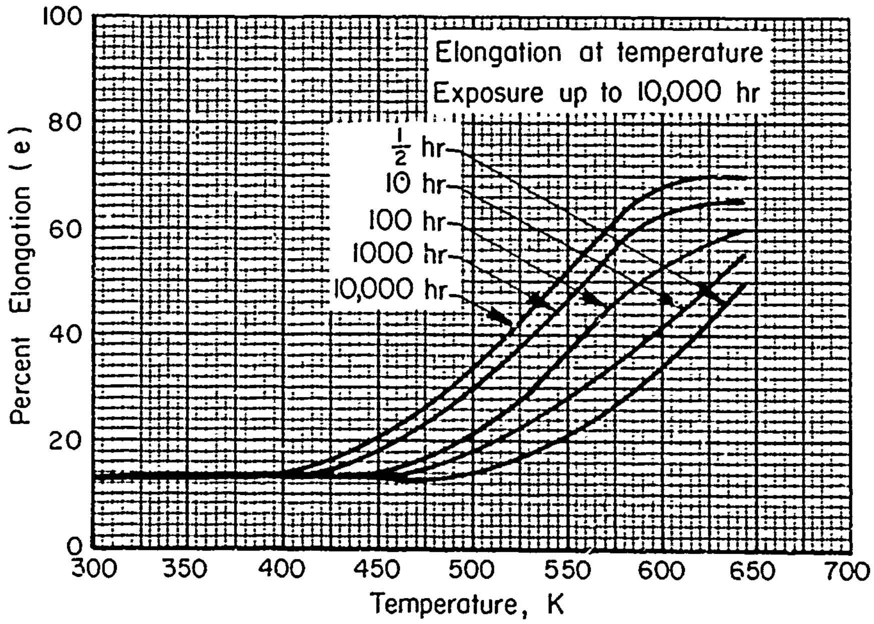


FIGURE 3.2.1.1.5(a). Effect of temperature on the elongation of 2014-T6, T651, T6510 and T6511 aluminum alloy (all products except thick extrusions).

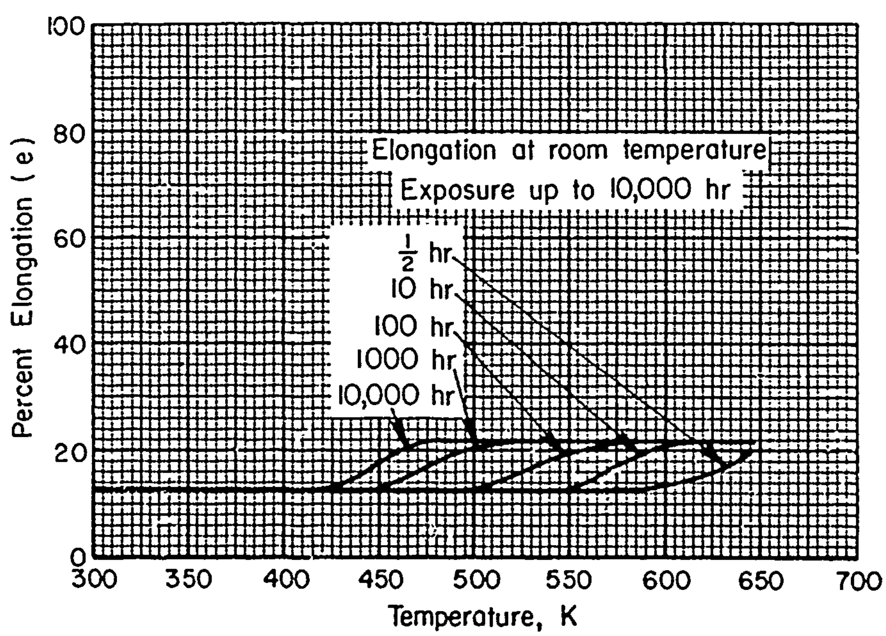


FIGURE 3.2.1.1.5(b). Effect of exposure at elevated temperatures on the room-temperature elongation of 2014-T6, T651, T6510, and T6511 aluminum alloy (all products except thick extrusions.

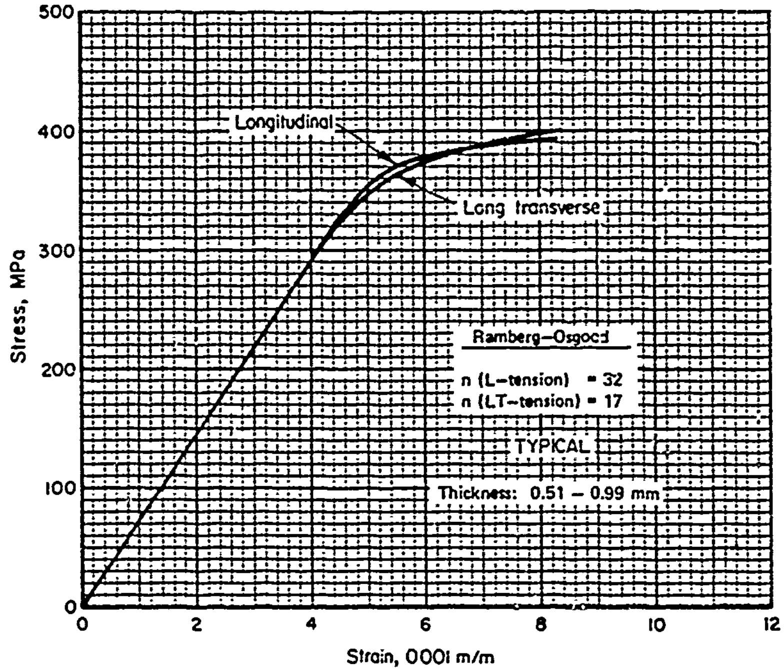


FIGURE 3.2.1.1.6(a). Typical tensile stress-strain curves for clad 2014-T6 aluminum alloy (sheet) at room temperature.

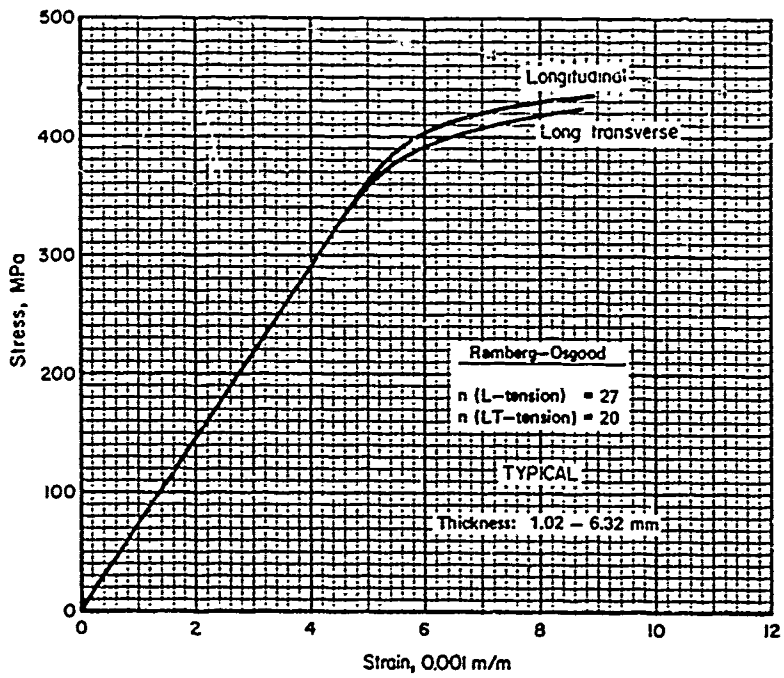


FIGURE 3.2.1.1.6(b). Typical tensile stress-strain curves for clad 2014-T6 aluminum alloy (sheet) at room temperature.

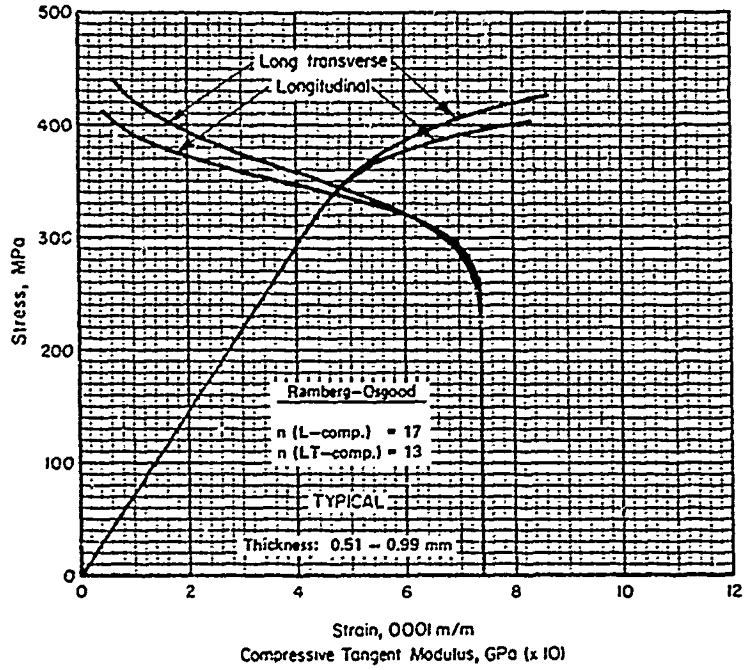


TABLE 3.2.1.1.6(c). Typical compressive stress-strain and tangent-modulus curves for clad 2014-T6 aluminum alloy (sheet) at room temperature.

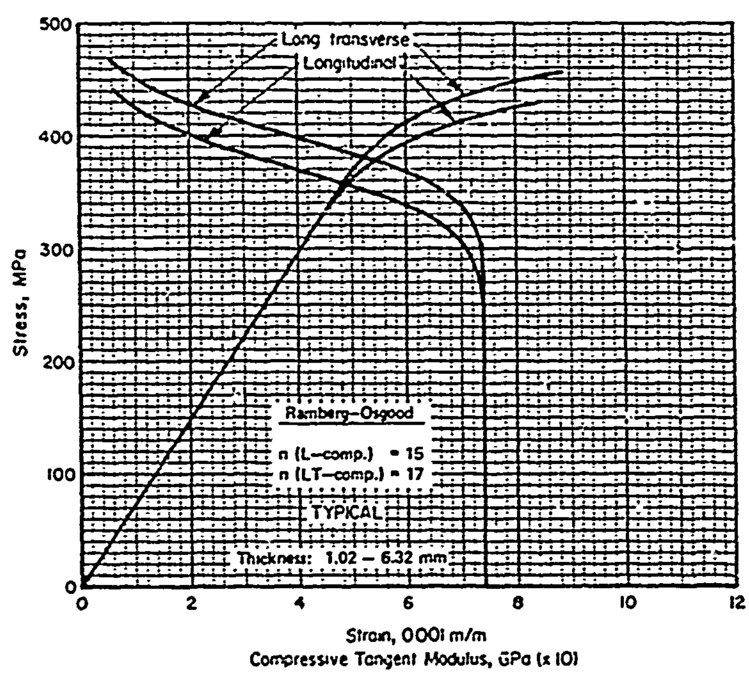


FIGURE 3.2.1.1.6(d). Typical compressive stress-strain and tangent-modulus curves for clad 2014-T6 aluminum alloy (sheet at room temperature.

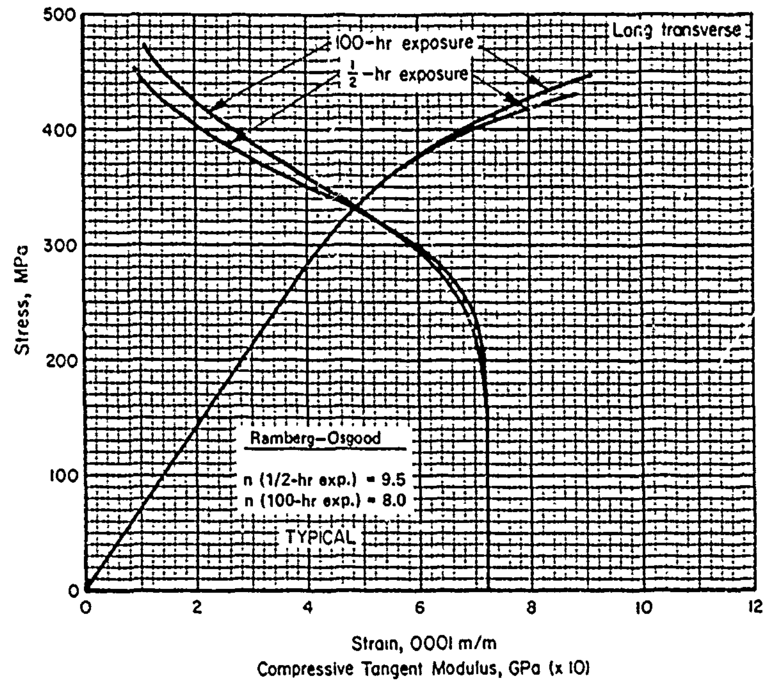


FIGURE 3.2.1.1.6(e). Typical compressive stress-strain and tangent-modulus curves for clad 2014-T6 aluminum alloy (sheet) at 366 K.

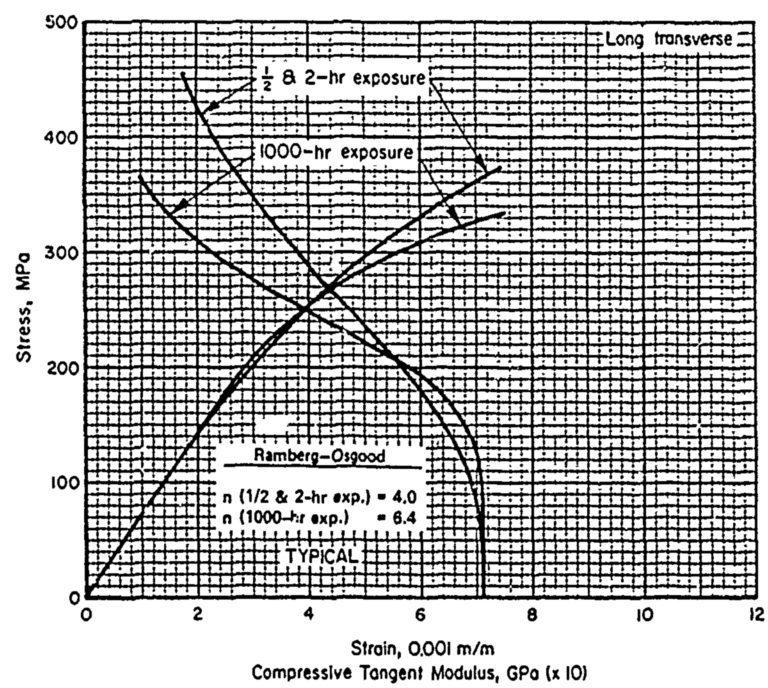


FIGURE 3.2.1.1.6(f). Typical compressive stress-strain and tangent-modulus curves for clad 2014-T6 aluminum alloy (sheet) at 422 K.

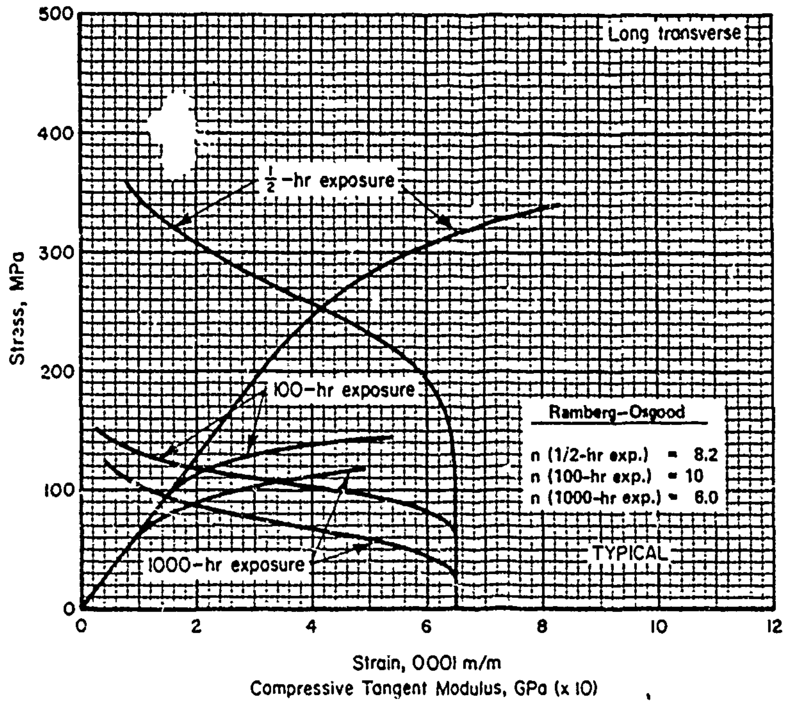


FIGURE 3.2.1.1.6(g). Typical compressive stress-strain and tangent-modulus curves for clad 2014-T6 aluminum alloy (sheet) at 477 K.

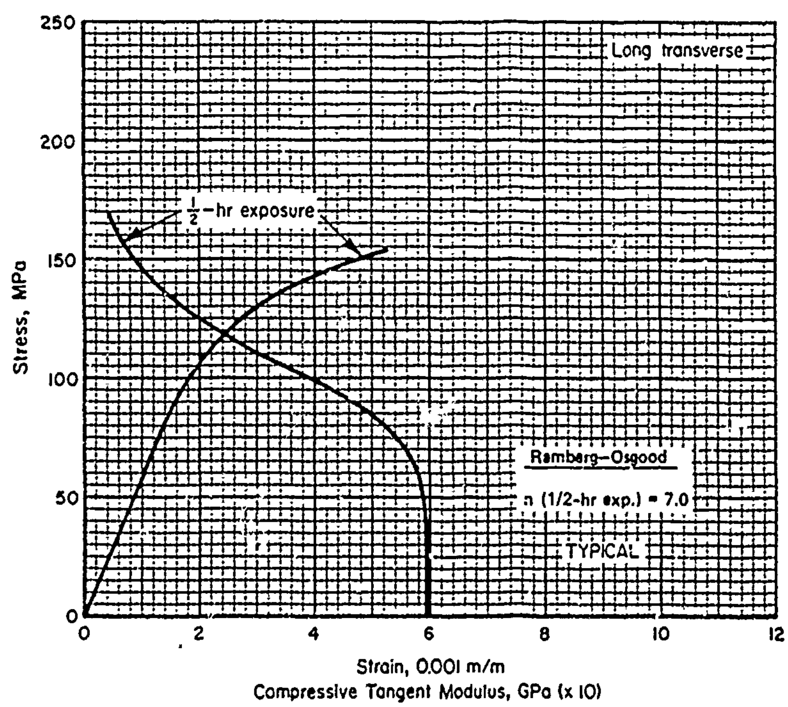


FIGURE 3.2.1.1.6(h). Typical compressive stress-strain and tangent-modulus curves for clad 2014-T6 aluminum alloy (sheet) at 533 K.

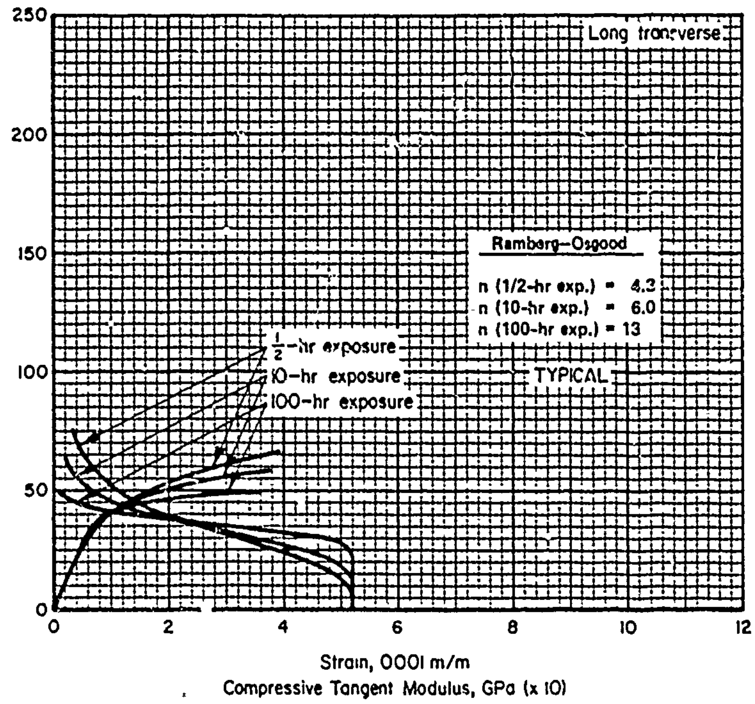


FIGURE 3.2.1.1.6(i). Typical compressive stress-strain and tangent-modulus curves for clad 2014-T6 aluminum alloy (sheet) at 589 K.

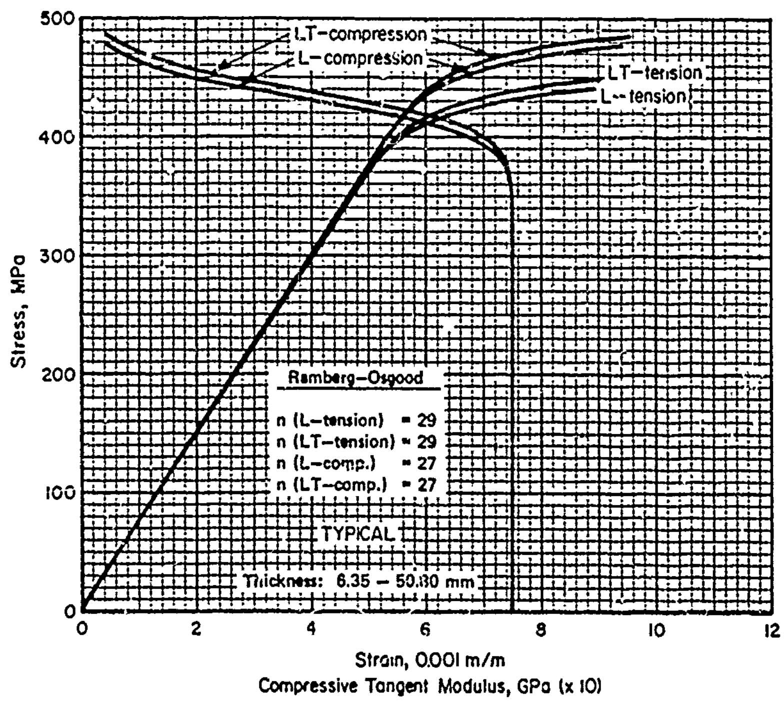


FIGURE 3.2.1.1.6(j). Typical tensile and compressive stress-strain and tangent-modulus curves for 2014-T62 aluminum alloy (plate) at room temperature.

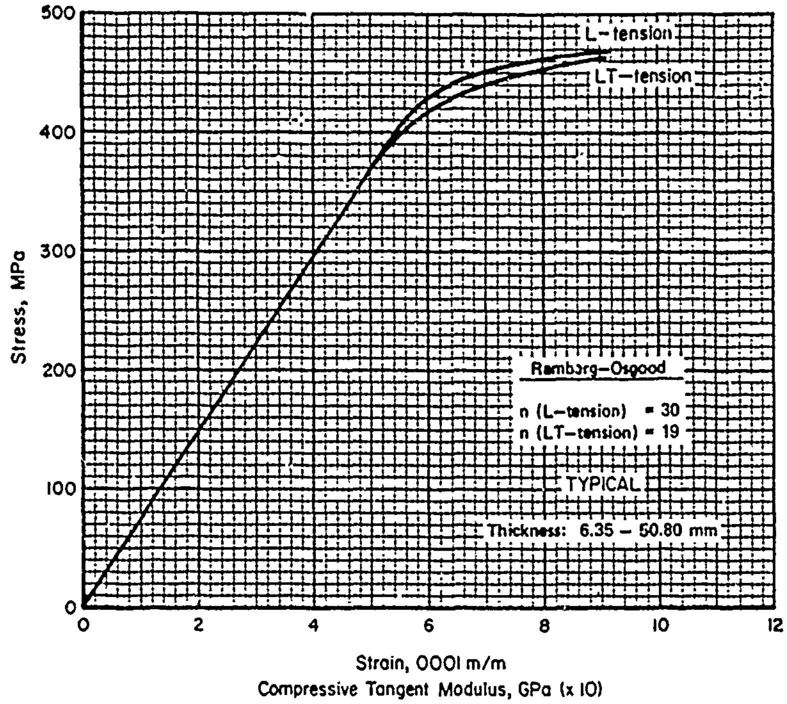


FIGURE 3.2.1.1.6(k). Typical tensile stress-strain curves for 2014-T651 aluminum alloy (plate) at room temperature.

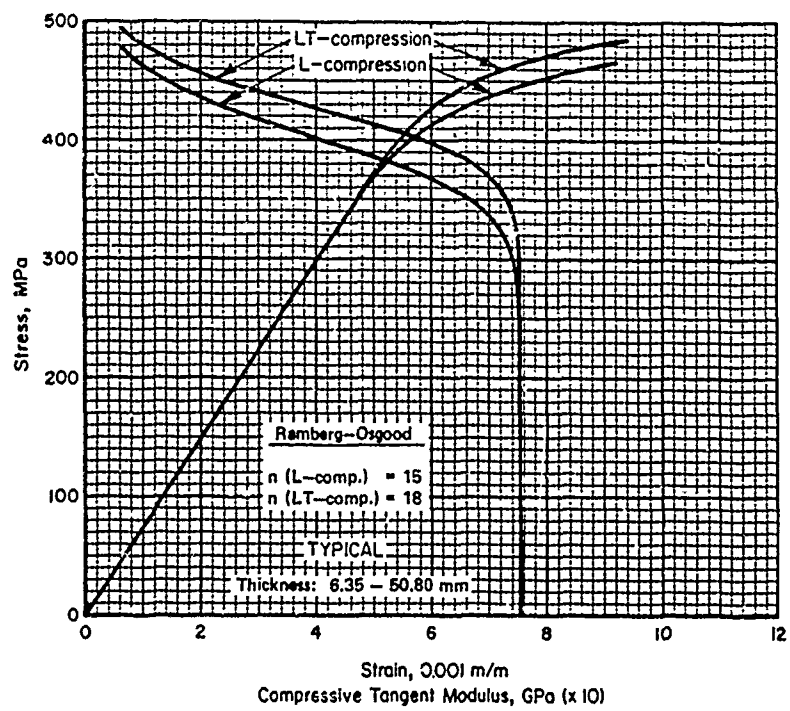


FIGURE 3.2.1.1.6(l). Typical compressive stress-strain and tangent-modulus curves for 2014-T651 aluminum alloy (plate) at room temperature.

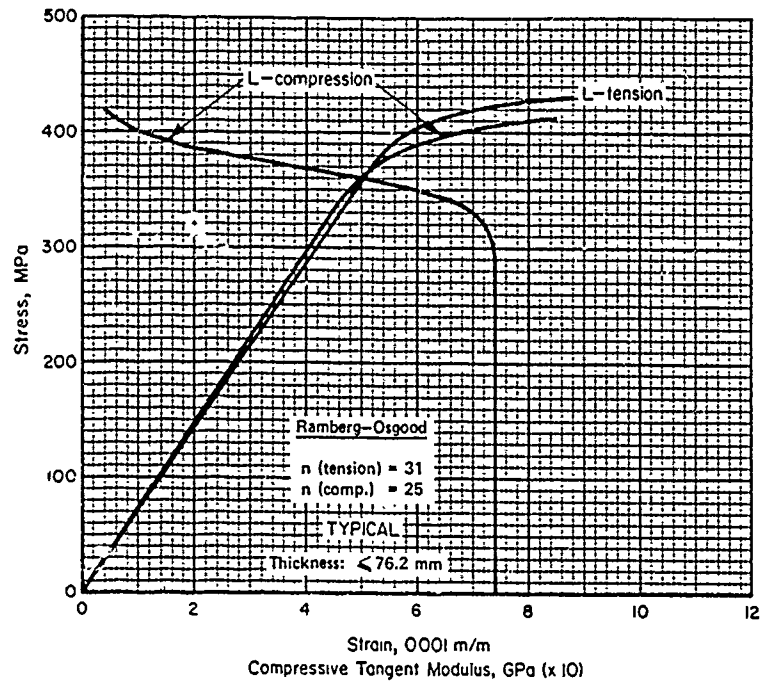


FIGURE 3.2.1.1.6(m). Typical tensile stress-strain and compressive stress-strain and tangent-modulus curves for 2014-T6 aluminum alloy (rolled bar, rod, and shapes) at room temperature.

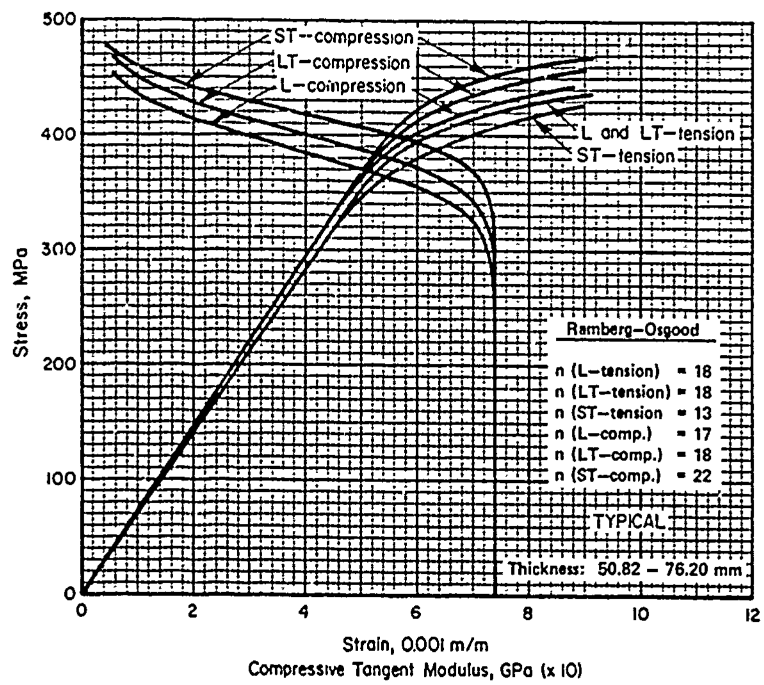


FIGURE 3.2.1.1.6(n). Typical tensile stress-strain and compressive stress-strain and tangent-modulus curves for 2014-T652 aluminum alloy (hand forging) at room temperature.

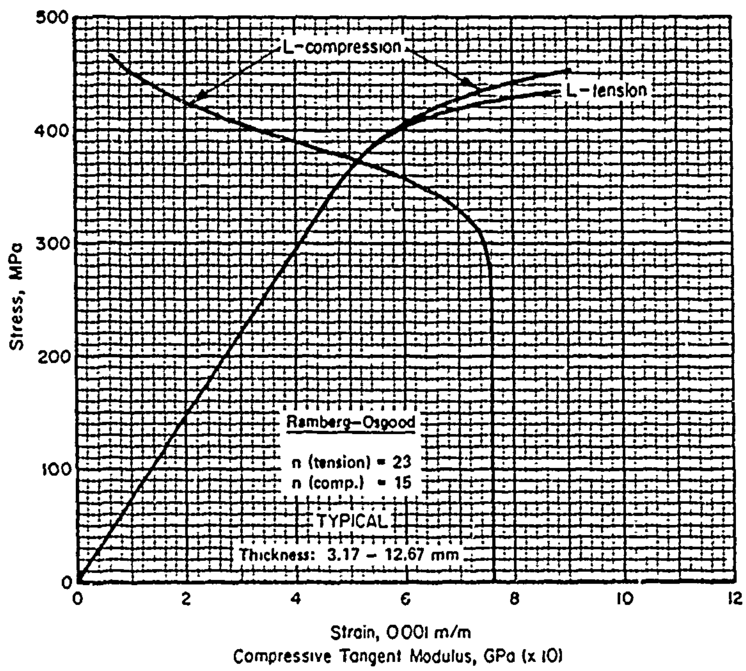


FIGURE 3.2.1.1.6(o). Typical tensile stress-strain and compressive stress-strain and tangent-modulus curves for 2014-T6 aluminum alloy (extrusion) at room temperature.

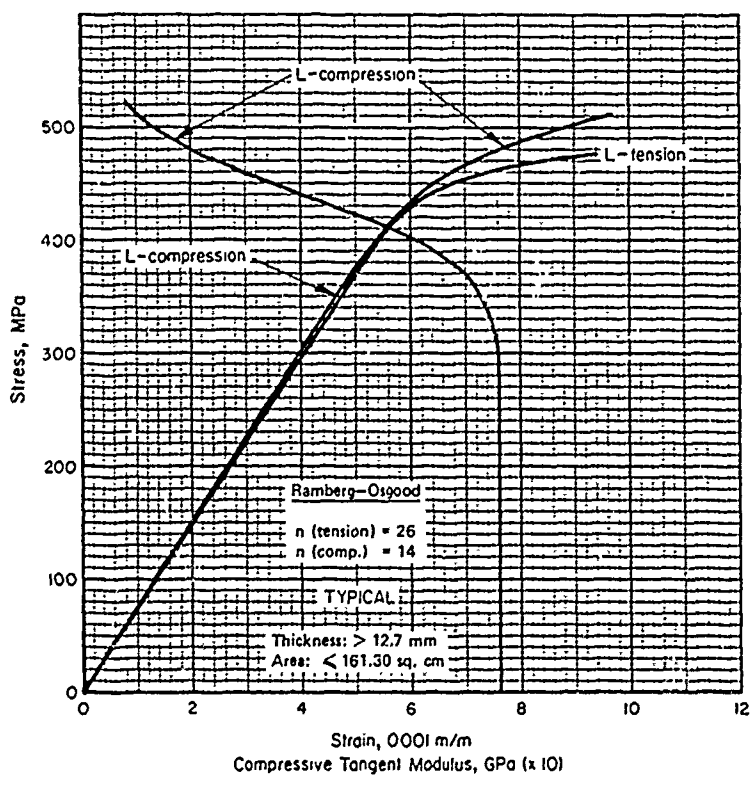


FIGURE 3.2.1.1.6 (p). Typical tensile stress-strain and compressive stress-strain and tangent-modulus curves for 2014-T6 aluminum alloy (extrusion) at room temperature.

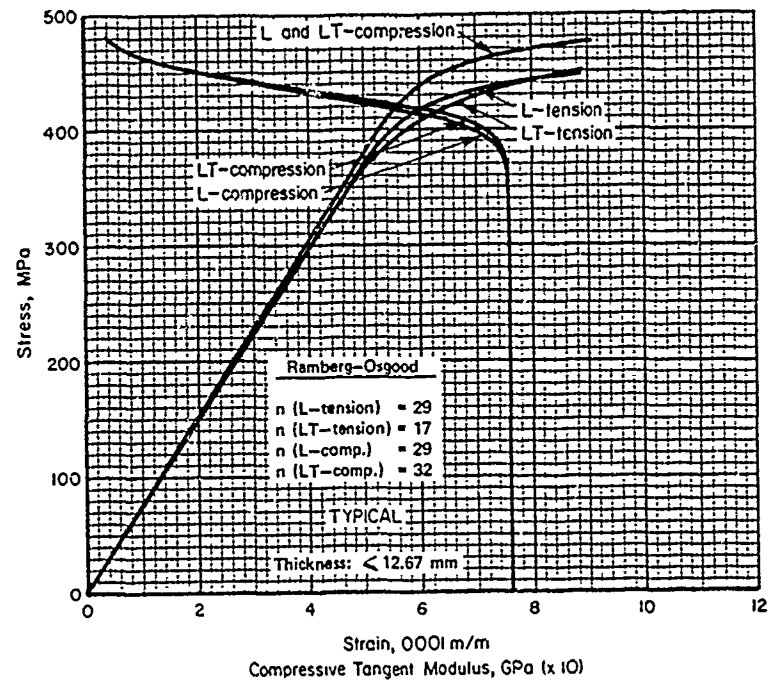


FIGURE 3.2.1.1.6(q). Typical tensile stress-strain and compressive stress-strain and tangent-modulus curves for 2014-T62 aluminum alloy (extrusion) at room temperature.

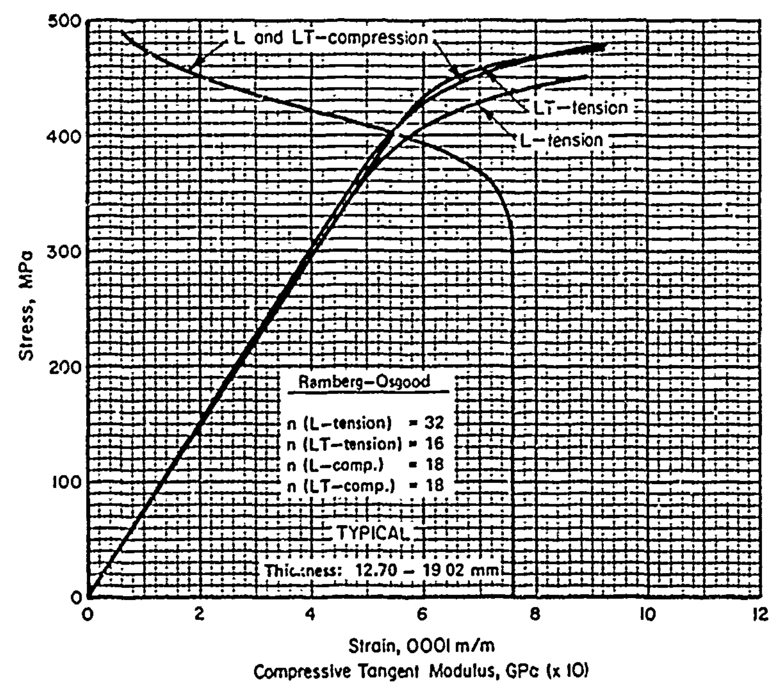


FIGURE 3.2.1.1.6(r). Typical tensile stress-strain and compressive stress-strain and tangent-modulus curves for 2014-T651X aluminum alloy (extrusion) at room temperature.

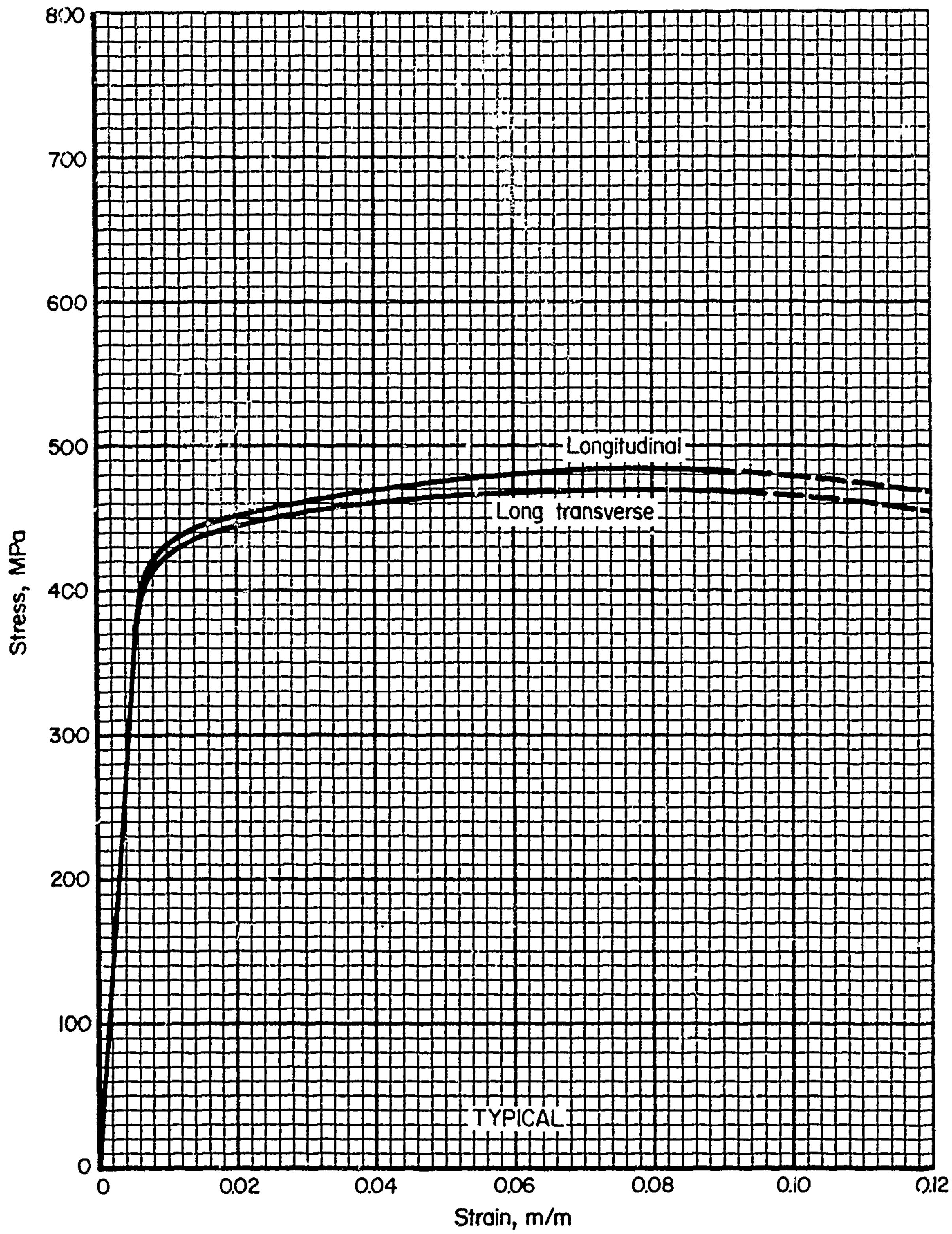


FIGURE 3.2.1.1.6(s). Typical tensile stress-strain curves (full range) for 2014-T6 aluminum alloy (forging) at room temperature.

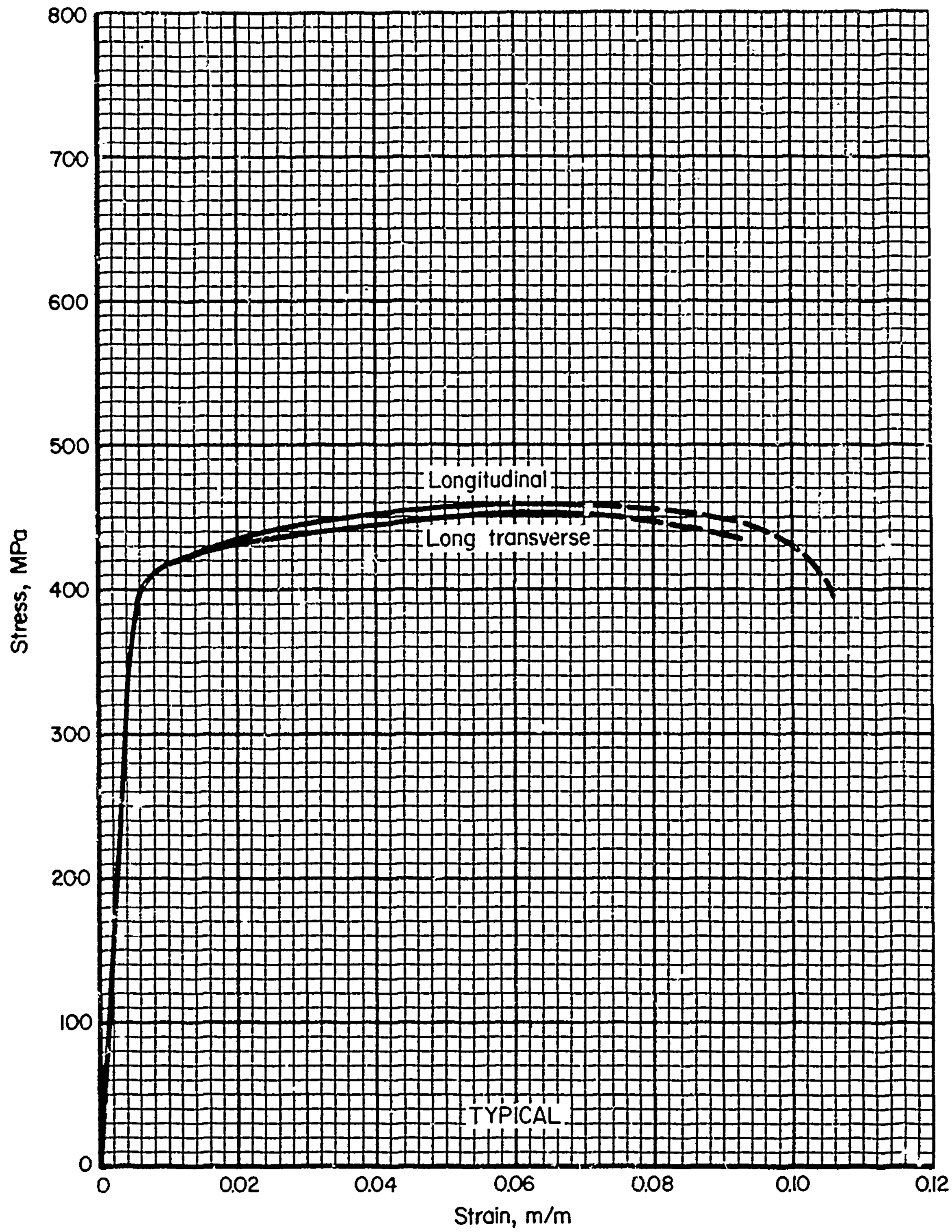


FIGURE 3.2.1.1.6(t). Typical tensile stress-strain curves (full range) for 2014-T652 aluminum alloy (forging) at room temperature.

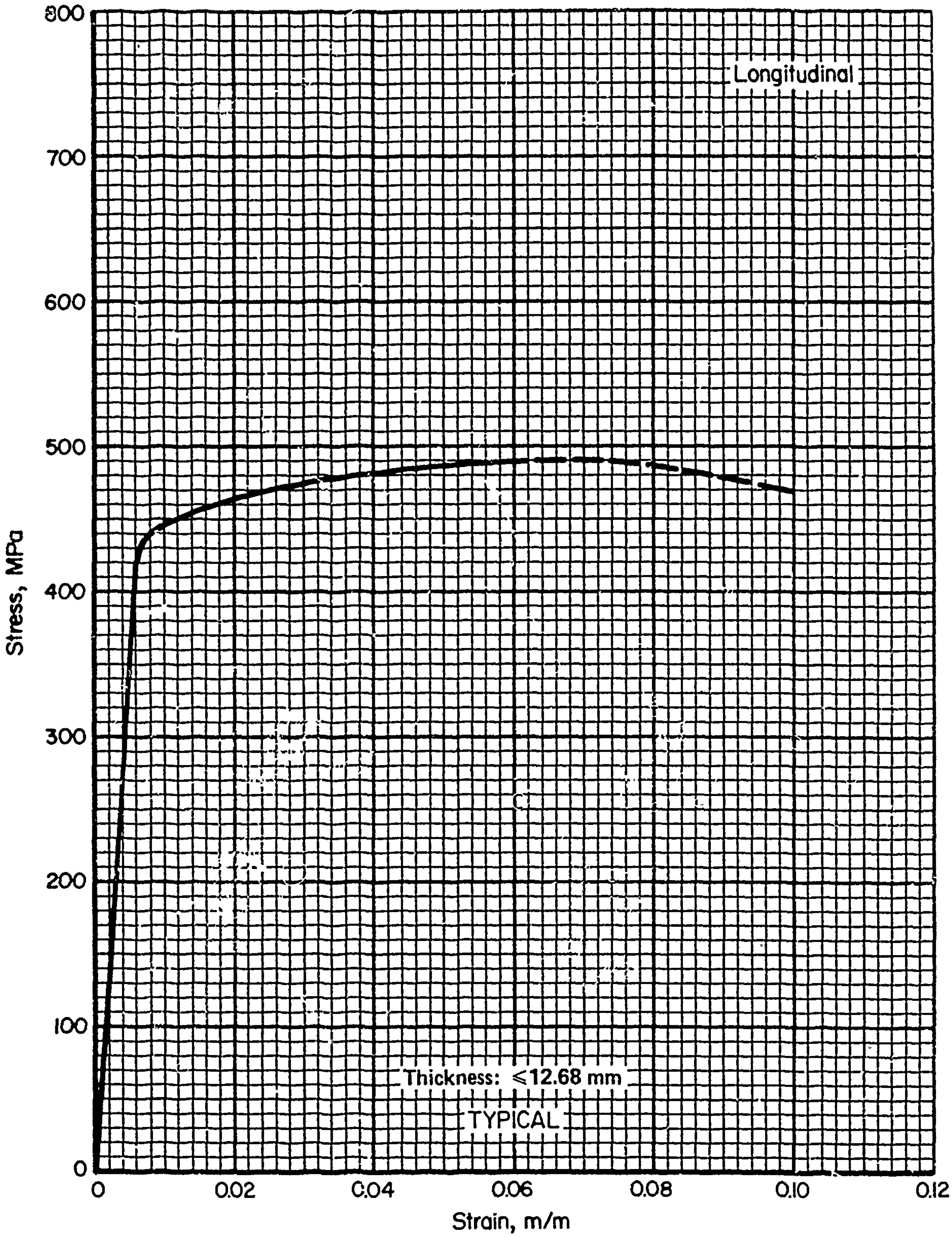


FIGURE 3.2.1.1.6(u). Typical tensile stress-strain curve (full range) for 2014-T62 aluminum alloy (extrusion) at room temperature.

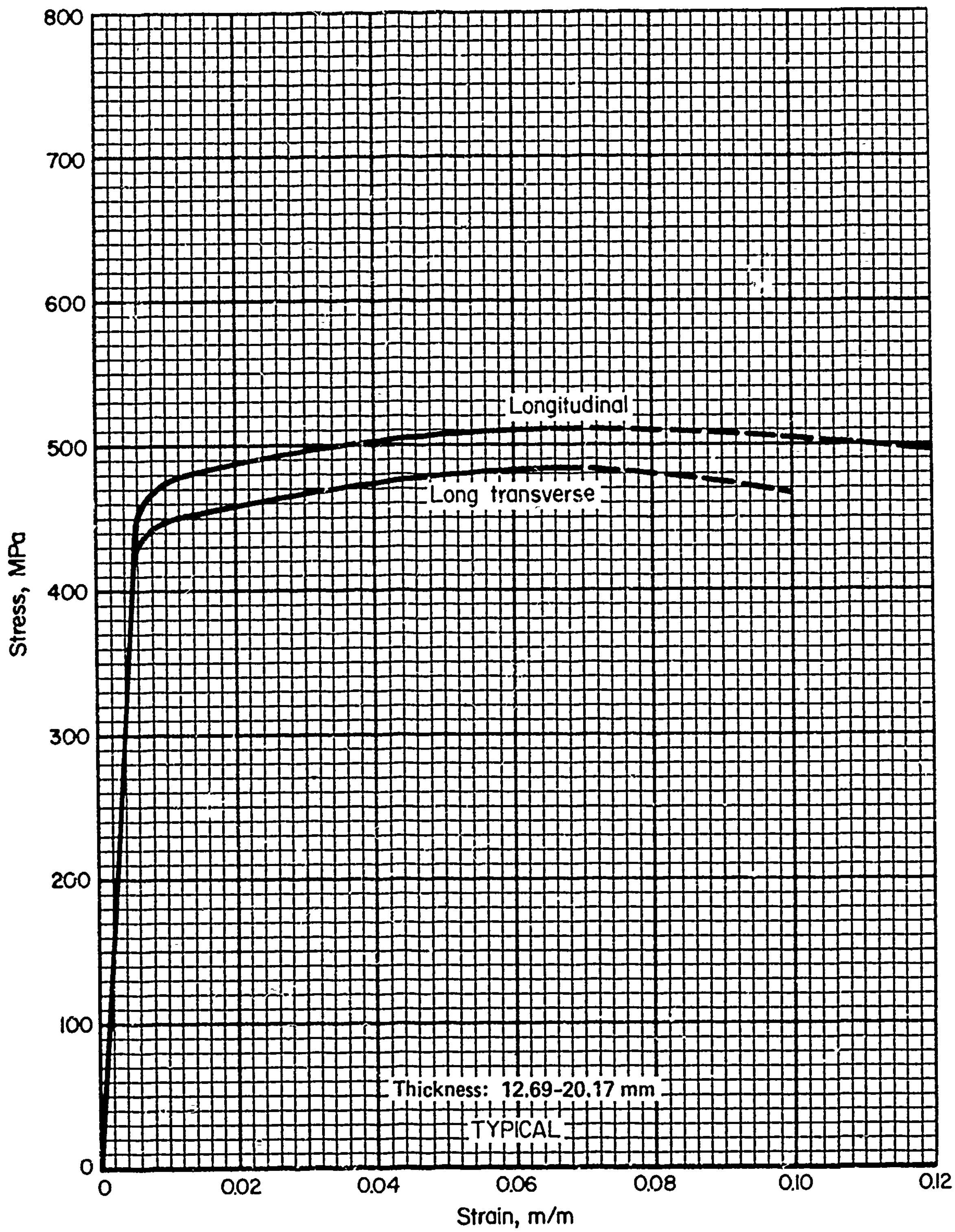


FIGURE 3.2.1.1.6(v). Typical tensile stress-strain curves (full range) for 2014-T651X aluminum alloy (extrusion) at room temperature.

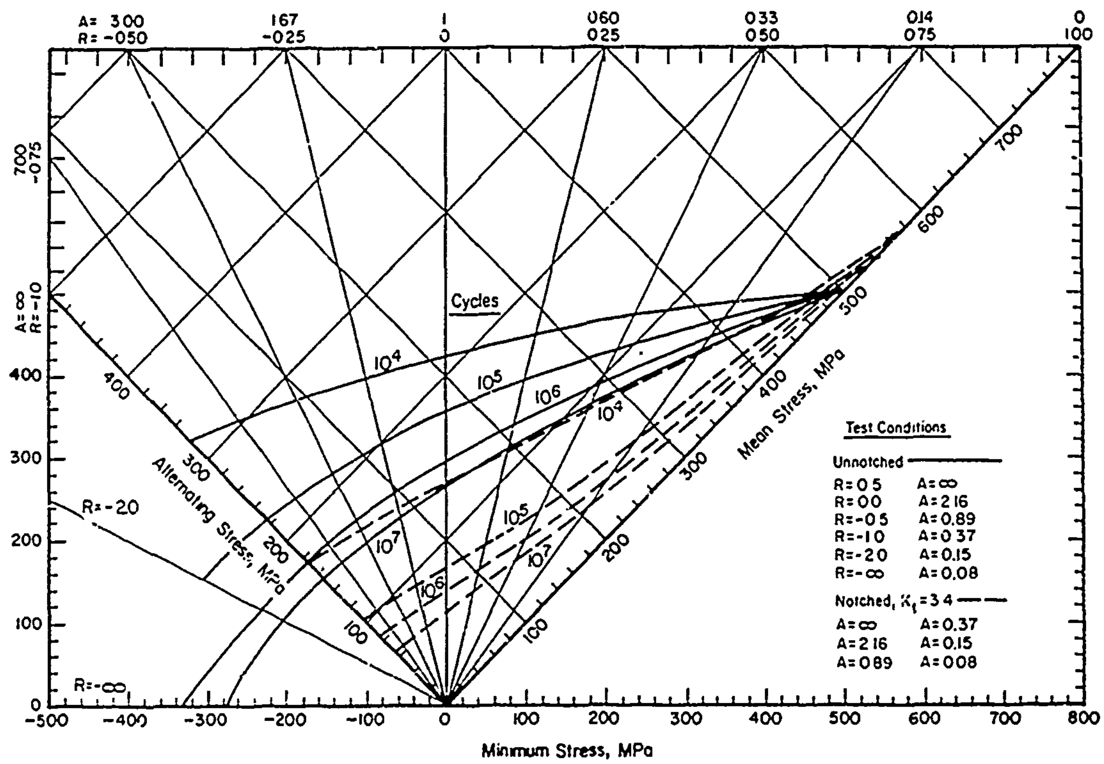


FIGURE 3.2.1.1.8. Typical constant-life diagram for fatigue behavior of various wrought products of 2014-T6 aluminum alloy

Correlative Information for Figure 3.2.1.1.8

Product Form: Drawn Rod, 19.1 mm diameter
Rolled bar, 25 x 190 mm and 28.6 mm
Forged slab, 22.2 mm thick
Extruded rod and bar, 38.8 mm diameter, 31.8 x 31.8 mm, 31.8 x 102 mm

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

Properties:

TUS, MPa	TYS, MPa	Temp, K
501	449	RT (Unnotched)
572	—	RT (Notched)

Specimen Details:

Unnotched:
10.2 mm diameter

Notched, V-Groove, $K_t = 3.4$
11.4 mm gross diameter
10.2 mm net diameter
0.25 mm root radius, r
60° flank angle, ω

$K_N = 1.89$, $\rho = 0.508$ mm, where $K_N = 1 + \dfrac{K_t - 1}{1 + \dfrac{\pi}{\pi - \omega}\sqrt{\dfrac{\rho}{r}}}$

Surface Condition: Unnotched: longitudinal polish, 900 grit
Notched: as machined.

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).

TABLE 3.2.2.0(a). *Material Specifications for 2017 Aluminum Alloy*

Specification	Form
QQ-A-225/5	Rolled bar, rod, and wire

The temper index for 2017 is as follows:

Section	Temper
3.2.2.1	T4

3.2.2.1 *T4 Temper.*—The effect of temperature on E and E_c is presented in Figure 3.2.2.1.4 for 2017 alloy.

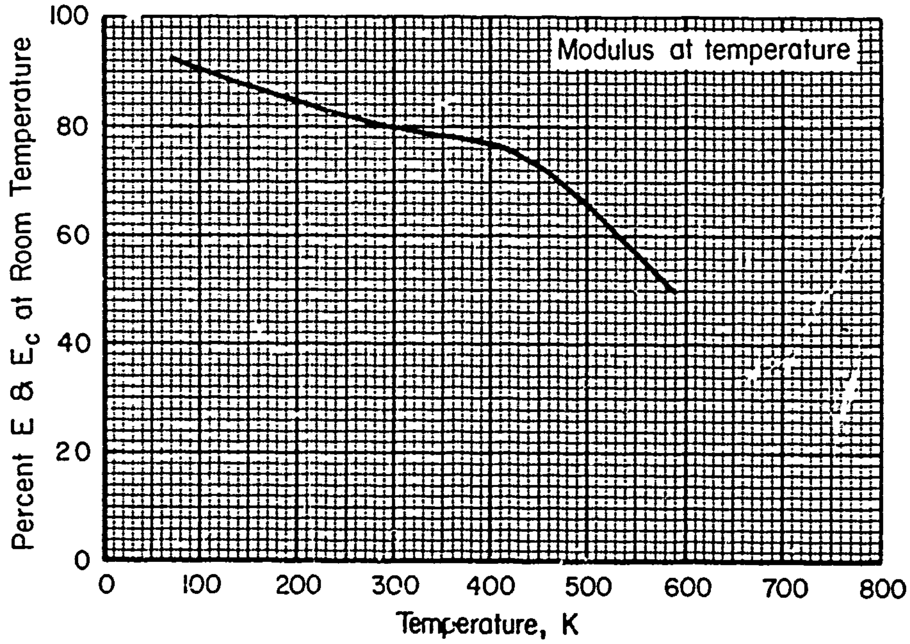


FIGURE 3.2.2.1.4. Effect of temperature on the tensile and compression moduli (E and E_c) of 2017 aluminum alloy.

TABLE 3.2.2.0(3). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 2017 ALUMINUM ALLOY (ROLLED BAR, ROD, AND WIRE)

SPECIFICATION...........	QQ-A-225/5
FORM...................	ROLLED BAR, ROD, AND WIRE
CONDITION...............	T4, T451[a] AND T42[b]
THICKNESS, MM...........	≤203.20
BASIS..................	S
MECHANICAL PROPERTIES:	
FTU, MPA:	
L.................	379
LT................	...
FTY, MPA:	
L.................	221
LT................	...
FCY, MPA:	
L.................	221
LT................	...
FSU, MPA.............	228
FBRU, MPA:	
(E/D=1.5)..........	572
(E/D=2.0)..........	724
FBRY, MPA:	
(E/D=1.5)..........	310
(E/D=2.0)..........	352
EL, PERCENT:	
L.................	12
LT................	...
E, GPA...............	71.7
EC, GPA..............	73.1
G, GPA...............	27.2
MU...................	0.33
PHYSICAL PROPERTIES:	
OMEGA, MG/M3..........	2.80
C, J/(G*K)............	0.96 (AT 373 K)
K, W/(M*K)............	135 (AT 298 K)
ALPHA, 10-6 M/(M*K)..	22.9 (293 to 373 K)

[a] FOR THE STRESS-RELIEVED TEMPER T451, ALL VALUES APPLY WITH THE EXCEPTION OF FCY WHICH MAY BE SOMEWHAT LOWER.

[b] THE ALLOWABLES SHOWN FOR THESE TEMPERS ARE BASED ON AND HAVE BEEN DETERMINED FROM THE RESULTS OBTAINED ON TESTING OF T4 AND T451 TEMPER MATERIAL AND ON THE TESTING OF T42 TEMPER SAMPLES FOR SPECIFICATION CONFORMANCE. THESE ALLOWABLES ALSO 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.

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 the T3 and T4 type tempers are noteworthy for their high toughness, while the 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, while the T3 and T4 type tempers should be considered in light of the guidelines in Section 3.1.2.3. Refer to Section 3.1.3.4 for comments regarding the weldability of the alloy. Some 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). 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
QQ-A-250/4	Bare sheet and plate
QQ-A-250/5	Clad sheet and plate
QQ-A-225/6	Rolled or drawn bars, rods, and wire
WW-T-700/3	Tubing
QQ-A-200/3	Extruded bar, rod, and shapes

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 (formerly T36)
3.2.3.3	T62
3.2.3.4	T81, T851, T8510, T8511
3.2.3.5	T861 (formerly T86)

3.2.3.1 *T3, T351, T3510, T3511, T4 and T42 Temper.*—Cryogenic, room, and elevated temperature data for these tempers are presented in Figures 3.2.3.1.1(a) through 3.2.3.1.8(f) as follows:

Figures 3.2.3.1.1(a) through 3.2.3.1.5(b) present effect-of-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 (x) are full-range, stress-strain curves at room temperature for various product forms.

Figures 3.2.3.1.7(a) through (g) are creep and stress-rupture curves for the T3 temper at several temperatures.

Figures 3.2.3.1.8(a) through (f) provide room-temperature fatigue curves for unnotched and notched specimens for T3 and T4 tempers.

3.2.3.2 *T361 (T36) Temper*

3.2.3.3 *T62 Temper.*—Figures 3.2.3.3.1(a) through 3.2.3.3.5(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 effect-of-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.*—Room and elevated temperature data for these tempers are presented in Figures 3.2.3.4.1(a) through 3.2.3.4.6(j) as follows:

Figures 3.2.3.4.1(a) through 3.2.3.4.5(b) present effect-of-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 3.7.3.1 for a detailed discussion of their use.

Figures 3.2.3.4.6(a) through (g) present some tensile and compressive stress-strain curves and tangent modulus curves for various products and tempers.

Figures 3.2.3.4.6(h) through (i) are full-range stress-strain curves at room temperature for various product forms.

3.2.3.5 *T861 (T86) Temper.*—Room and elevated temperature data for this temper are presented in Figures 3.2.3.5.1(a) through 3.2.3.5.7(g) as follows:

Figures 3.2.3.5.1(a) through 3.2.3.5.5(b) present effect-of-temperature curves for various mechanical properties.

Figures 3.2.3.5.6(a) through (d) present compressive stress-strain curves for sheet material at various temperatures.

Figures 3.2.3.5.7(a) through (g) are creep and stress-rupture curves at various temperatures.

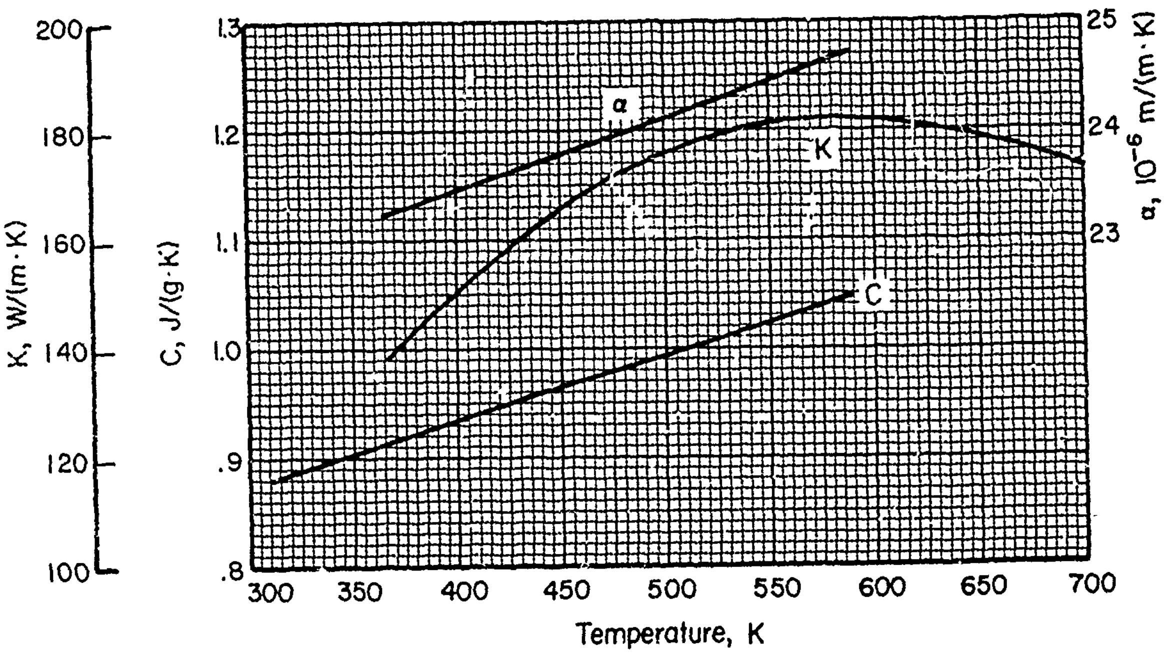


FIGURE 3.2.3.0. Effect of temperature on the physical properties of 2024 aluminum alloy.

TABLE 3.2.3.0(B1). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 2024 ALUMINUM ALLOY (SHEET)

SPECIFICATION	QQ-A-250/4				
FORM	SHEET				
TEMPER	T3				
THICKNESS, MM	0.20-0.24	0.25-3.26		3.27-6.32	
BASIS	S	A	B	A	B
MECHANICAL PROPERTIES:					
FTU, MPA:					
L	441	441[d]	448[d]	448	455
LT	434	434[d]	441[d]	441	448
FTY, MPA:					
L	324	324	331	324	331
LT	290	290	296	290	296
FCY, MPA:					
L	269	269	276	269	276
LT	310	310	317	310	317
FSU, MPA	269	269[d]	276[d]	276	283
FBRU[a,b], MPA:					
(E/D=1.5)	717	717[d]	731[d]	731	738
(E/D=2.0)	869	869[d]	903[d]	903	917
FBRY[a,b], MPA:					
(E/D=1.5)	503	503	517	503	517
(E/D=2.0)	607	607	621	607	621
EL, PERCENT:					
LT	10	c	...	c	...
E, GPA	72.4				
EC, GPA	73.8				
G, GPA	27.6				
MU	0.33				
PHYSICAL PROPERTIES:					
OMEGA, MG/M3	2.77				
C, J/(G*K)	SEE FIGURE 3.2.3.0				
K, W/(M*K)	121 (AT 298 K), SEE FIGURE 3.2.3.0				
ALPHA, 10-6 M/(M*K)	SEE FIGURE 3.2.3.0				

[a] SEE TABLE 3.1.2.1.1.

[b] BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

[c] SEE TABLE 3.2.3.0(C)

[d] THESE VALUES WERE DECREASED IN CHANGE NOTICE 3 TO MIL-HDBK-5B DUE TO A PROCESS CHANGE. THE PREVIOUS HIGHER VALUES MAY BE USED ONLY ON EXISTING DESIGNS.

TABLE 3.2.3.0(B2). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 2024 ALUMINUM ALLOY (SHEET AND PLATE)

SPECIFICATION	QQ-A-250/4														
FORM	PLATE												SHEET		PLATE
TEMPER	T351												T361		
THICKNESS, MM	6.34-12.68		12.69-25.41		25.42-38.11		38.12-50.81		50.82-76.21		76.22-101.60		0.51-1.58	1.59-6.35	6.34-12.70
BASIS	A	B	A	B	A	B	A	B	A	B	A	B	S	S	S
MECHANICAL PROPERTIES:															
FTU, MPA:															
L	448	462	434	448	427	441	427	441	414	427	393	407	469	476	462
LT	441	455	434	448	427	441	427	441	414	427	393	407	462	469	455
FTY, MPA:															
L	324	338	324	338	324	338	324	338	324	338	317	331	386	386	372
LT	290	303	290	303	290	303	290	303	290	303	283	296	345	352	338
FCY, MPA:															
L	276	290	269	283	265	283	269	276	262	276	248	262	324	331	317
LT	310	324	310	324	310	324	303	317	303	317	230	303	365	372	359
FSU, MPA	262	276	262	269	255	262	255	262	248	255	234	241	290	290	283
FBRU,[a,b] MPA:															
(E/D=1.5)	669	683	655	676	648	669	643	669	627	648	593	614	765	772	752
(E/D=2.0)	621	841	807	834	793	821	793	821	765	793	731	752	945	958	931
FBRY,[a,b] MPA:															
(E/D=1.5)	503	524	503	524	503	524	503	524	503	524	490	510	565	579	558
(E/D=2.0)	600	627	600	627	600	627	600	627	600	627	586	614	669	683	662
EL, PERCENT:															
LT	12	...	8	...	7	...	6	...	4	...	4	...	8	9	c
E, GPA	73.8												72.4		73.8
EC, GPA	75.2												73.8		75.2
G, GPA	27.6												27.6		27.6
MU	0.33												0.33		0.33
PHYSICAL PROPERTIES:															
OMEGA, MG/M3	2.77														
C, J/(G*K)	SEE FIGURE 3.2.3.0														
K, W/(M*K)	121 (AT 298 K), SEE FIGURE 3.2.3.0														
ALPHA, 10-6 M/(M*K)	SEE FIGURE 3.2.3.0														

a SEE TABLE 3.1.2.1.1.
b BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.
c SEE TABLE 3.2.3.0(C).

TABLE 3.2.3.0(B3). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 2024 ALUMINUM ALLOY (SHEET AND PLATE)

SPECIFICATION	QQ-A-250/4																
FORM	COILED SHEET		FLAT SHEET AND PLATE												SHEET		PLATE
TEMPER	T4		T42[d]				T62[d]		T72[d]	T81		T851[a]			T861[a]		
THICKNESS, MM	0.25-6.32		0.25-12.68	12.69-25.41	25.42-50.81	50.82-76.20	0.30-12.68	12.69-76.20	0.25-6.32	0.25-6.32		6.35-12.68		12.69-25.40	0.51-1.58	1.59-6.33	6.34-12.70
BASIS	A	B	S	S	S	S	S	S	S	A	B	A	B	S	S	S	S
MECHANICAL PROPERTIES:																	
FTU, MPA:																	
L	427	441	427	421	414	400	441	434	...	462	469	462	469	455	490	496	483
LT	427	441	427	421	414	400	441	434	414	462	469	462	469	455	483	499	483
FTY, MPA:																	
L	276	290	262	262	262	262	345	345	...	407	421	407	421	407	434	462	441
LT	276	290	262	262	262	262	345	345	317	400	414	400	414	400	427	455	441
FCY, MPA:																	
L	276	290	262	262	262	262	...	...	...	407	421	407	421	400	434	462	441
LT	276	290	262	262	262	262	...	...	...	400	414	407	421	407	446	476	462
FSU, MPA	255	262	255	255	248	241	...	...	...	276	263	262	269	262	276	276	276
FBRU,[b] MPA:																	
(E/D=1.5)	641	662	641	634	621	600	...	...	...	689	703	703	717	696	745	758	745
(E/D=2.0)	814	841	814	800	786	758	...	...	...	876	869	903	910	889	965	979	965
FBRY,[b] MPA:																	
(E/D=1.5)	366	407	365	365	365	365	...	...	...	572	593	600	621	600	621	552	641
(E/D=2.0)	441	462	421	421	421	421	...	...	...	648	669	703	724	703	724	772	752
EL, PERCENT:																	
LT	c	...	c	8	c	4	5	5	5	5	...	5	...	5	3	4	4
E, GPA	SEE TABLE 3.2.3.0(D)																
EC, GPA	SEE TABLE 3.2.3.0(D)																
G, GPA	SEE TABLE 3.2.3.0(D)																
MU	SEE TABLE 3.2.3.0(D)																
PHYSICAL PROPERTIES:																	
OMEGA, MG/M3	2.77																
C, J/(G*K)	SEE FIGURE 3.2.3.0																
K, W/(M*K)	121 (AT 298 K) FOR T4X; 151 (AT 298 K) FOR T6X, T7X, AND T8XX; SEE FIGURE 3.2.3.0																
ALPHA, 10-6 M/(M*K)	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.
[c] SEE TABLE 3.2.3.0(C).
[d] THESE ALLOWABLES 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.

TABLE 3.2.3.0(c). *Percent Elongation Values for Bare 2024 Aluminum Alloy (Sheet and Plate)*

Condition	Elongation (LT), percent[a]
	T3, T4 and T42
Thickness, mm	
0.25–0.51	12
0.52–6.33	15
6.34–12.69	12
12.70–25.40	8
25.41–38.10	7
38.11–50.80	6

[a]Minimum values, A or S basis, for applicable columns in Tables 3.2.3.0(b_1) and (b_2).

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, mm				
0.25–6.32	72.4	73.8	27.6	0.33
> 0.63	73.8	75.2	27.6	0.33

TABLE 3.2.3.0(E1). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF CLAD 2024 ALUMINUM ALLOY (SHEET)

SPECIFICATION..........	QQ-A-250/5							
FORM..................	FLAT SHEET							
TEMPER................	T3							
THICKNESS, MM.........	0.20-0.24		0.25-1.58		1.59-3.26		3.27-6.33	
BASIS.................	A	B	A	B	A	B	A	B
MECHANICAL PROPERTIES:								
FTU, MPA:								
L................	407	414	414	421	427[c]	434[c]	434	441
LT...............	400	407	407	414	421[c]	427[c]	427	434
FTY, MPA:								
L................	303	310	303	310	310	324	310	324
LT...............	269	276	269	276	276	290	276	290
FCY, MPA:								
L................	243	255	243	255	255	269	255	269
LT...............	290	296	290	296	296	310	296	310
FSU, MPA.............	255	255	255	262	262[c]	269[c]	269	276
FBRU[a], MPA:								
(E/D=1.5).........	662	669	669	683	696	703	703	717
(E/D=2.0).........	821	834	834	848	862[c]	876[c]	876	889
FBRY[a], MPA:								
(E/D=1.5).........	469	483	469	483	483	503	483	503
(E/D=2.0).........	565	579	565	579	579	607	579	607
EL, PERCENT:								
LT...............	10	...	b	...	15	...	15	...
E, GPA:								
PRIMARY..........	72.4							
SECONDARY........	65.5				68.9			
EC, GPA:								
PRIMARY..........	73.8							
SECONDARY........	66.9				70.3			
G, GPA...............	...							
MU...................	0.33							
PHYSICAL PROPERTIES:								
OMEGA, MG/M3..........	2.77							
C, J/(G*K)...........	...							
K, W/(M*K)...........	...							
ALPHA, 10-6 M/(M*K)..	...							

[a] SEE TABLE 3.1.2.1.1. BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.
[b] SEE TABLE 3.2.3.0(F).
[c] THESE VALUES WERE DECREASED IN CHANGE NOTICE 3 TO MIL-HDBK-5B DUE TO A PROCESS CHANGE. THE PREVIOUS HIGHER VALUES MAY BE USED ONLY ON EXISTING DESIGNS.

TABLE 3.2.3.0(E2). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF CLAD 2024 ALUMINUM ALLOY (PLATE)

SPECIFICATION	QQ-A-250/5											
FORM	PLATE											
TEMPER	T351											
THICKNESS, MM	6.34-12.68		12.69-25.41[a]		25.42-38.11[a]		38.12-50.61[a]		50.82-76.21[a]		76.22-101.60[a]	
BASIS	A	B	A	B	A	B	A	B	A	B	A	B
MECHANICAL PROPERTIES:												
FTU, MPA:												
L	427	441	421	434	414	427	414	427	400	414	379	393
LT	427	441	421	434	414	427	414	427	400	414	379	393
FTY, MPA:												
L	310	324	310	324	310	324	310	324	310	324	303	317
LT	276	290	276	290	276	290	276	290	276	290	269	283
FCY, MPA:												
L	262	276	255	269	255	269	255	269	248	262	234	248
LT	296	310	296	310	296	310	290	303	290	303	276	290
FSU, MPA	255	262	255	262	248	255	248	255	241	248	228	234
FBRU,[b] MPA:												
(E/D=1.5)	648	669	634	655	627	648	627	648	607	627	572	593
(E/D=2.0)	793	821	779	807	765	793	765	793	745	765	703	731
FBRY,[b] MPA:												
(E/D=1.5)	476	503	476	503	476	503	476	503	476	503	469	490
(E/D=2.0)	572	600	572	600	572	600	572	600	572	600	558	586
EL, PERCENT:												
LT	12	...	8	...	7	...	6	...	4	...	4	...
E, GPA:												
PRIMARY	73.8											
SECONDARY	70.3											
EC, GPA:												
PRIMARY	75.2											
SECONDARY	71.7											
G, GPA	...											
MU	0.33											
PHYSICAL PROPERTIES:												
OMEGA, MG/M3	2.77											
C, J/(G*K)	...											
K, W/(M*K)	...											
ALPHA, 10-6 M/(M*K)	...											

[a] THESE VALUES HAVE BEEN ADJUSTED TO REPRESENT THE AVERAGE PROPERTIES ACROSS THE WHOLE SECTION, INCLUDING THE 2.5 PERCENT NOMINAL CLADDING THICKNESS.

[b] SEE TABLE 3.1.2.1.1. BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

TABLE 3.2.3.0(E3). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF CLAD 2024 ALUMINUM ALLOY (SHEET AND PLATE)

SPECIFICATION..........	QQ-A-250/5							
FORM..................	FLAT SHEET AND PLATE				COILED SHEET			
TEMPER................	T361				T4			
THICKNESS, MM..........	0.51-1.58	1.59-6.33	6.34-12.69	12.70[b]	0.25-1.58		1.59-3.25	
BASIS.................	S	S	S	S	A	B	A	B
MECHANICAL PROPERTIES:								
FTU, MPA:								
L..................	427	443	448	441	400	407	421	427
LT.................	421	441	441	434	400	407	421	427
FTY, MPA:								
L..................	365	365	365	359	248	262	262	269
LT.................	324	331	331	324	246	262	262	269
FCY, MPA:								
L..................	303	310	310	303	246	262	262	269
LT.................	345	352	352	345	248	262	262	269
FSU, MPA..............	262	276	276	269	255	255	262	269
FBRU,[a,c] MPA:								
(E/D=1.5)..........	696	724	724	717	662	669	696	703
(E/D=2.0)..........	862	903	903	839	821	834	862	876
FBRY,[a,c] MPA:								
(E/D=1.5)..........	538	545	545	538	434	455	455	469
(E/D=2.0)..........	634	648	645	634	524	552	552	565
EL, PERCENT:								
LT.................	8	9	9	10	d	...	15	...
E, GPA:								
PRIMARY............	72.4	72.4	73.8		72.4		72.4	
SECONDARY..........	65.5	68.9	70.3		65.5		66.9	
EC, GPA:								
PRIMARY............	73.8	73.8	75.2		73.8		73.8	
SECONDARY..........	66.9	70.3	71.7		66.9		70.3	
G, GPA................	...							
MU....................	0.33							
PHYSICAL PROPERTIES:								
OMEGA, MG/M3..........	2.77							
C, J/(G*K)............	...							
K, W/(M*K)............	...							
ALPHA, 10-6 M/(M*K)...	...							

[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 2.5 PERCENT NOMINAL CLADDING THICKNESS.
[c] SEE TABLE 3.1.2.1.1.
[d] SEE TABLE 3.2.3.0(F).

TABLE 3.2.3.0(E4). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF CLAD 2024 ALUMINUM ALLOY (SHEET AND PLATE)

SPECIFICATION	QQ-A-250/5									
FORM	FLAT SHEET AND PLATE									
TEMPER	T42[c]									
THICKNESS, MM	0.20-0.24		0.25-1.58		1.59-6.33		6.34-12.68	12.69-25.41[a]	25.42-50.81[a]	50.82-76.20[a]
BASIS	A	B	A	B	A	B	S	S	S	S
MECHANICAL PROPERTIES:										
FTU, MPA:										
L	379	393	393	407	414	427	414	407	400	386
LT	379	393	393	407	414	427	414	407	400	386
FTY, MPA:										
L	234	241	234	241	248	262	248	248	248	248
LT	234	241	234	241	248	262	248	248	248	248
FCY, MPA:										
L	234	241	234	241	248	262	248	248	248	248
LT	234	241	234	241	248	262	248	248	248	248
FSU, MPA	228	234	234	241	248	255	248	241	241	234
FBRU, MPA:										
(E/D=1.5)	572	593	593	614	621	641	621	614	600	572
(E/D=2.0)	717	745	745	772	786	814	786	772	758	731
FBRY, MPA:										
(E/D=1.5)	331	338	331	338	345	365	345	345	345	345
(E/D=2.0)	372	386	372	386	400	421	400	400	400	400
EL, PERCENT:										
LT	10	...	b	...	15	...	12	8	b	4
E, GPA:										
PRIMARY	72.4				72.4		73.8			
SECONDARY	65.5				66.9		70.3			
EC, GPA:										
PRIMARY	73.8				73.8		75.2			
SECONDARY	66.9				70.3		71.7			
G, GPA	...									
MU	0.33									
PHYSICAL PROPERTIES:										
OMEGA, MG/M3	2.77									
C, J/(G*K)	...									
K, W/(M*K)	...									
ALPHA, 10-6 M/(M*K)	...									

[a] THE VALUES HAVE BEEN ADJUSTED TO REPRESENT THE AVERAGE PROPERTIES ACROSS THE WHOLE SECTION, INCLUDING THE 2.5 PERCENT NOMINAL CLADDING THICKNESS.
[b] SEE TABLE 3.2.3.0(F).
[c] THESE ALLOWABLES APPLY WHEN SAMPLES OF MATERIAL SUPPLIED IN THE O TO 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.

TABLE 3.2.3.0(E5). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF CLAD 2024 ALUMINUM ALLOY (SHEET AND PLATE)

SPECIFICATION	QQ-A250/5												
FORM	FLAT SHEET AND PLATE												
TEMPER	T62[d]		T72[d]		T81		T851[a]			T861[a]			
THICKNESS, MM	1.60-6.33	6.34-12.67	0.25-1.58	1.59-6.32	0.25-1.58	1.59-6.32	6.35-12.68		12.69-25.40[b]	0.51-1.58	1.59-6.33	6.34-12.69	12.70[b]
BASIS	S	S	S	S	S	S	A	B	S	S	S	S	S
MECHANICAL PROPERTIES:													
FTU, MPA:													
L	427	427	...	...	441	462	448	455	434	448	483	469	462
LT	427	427	386	400	427	448	448	455	434	441	476	469	462
FTY, MPA:													
L	338	338	...	...	393	407	393	407	393	407	448	427	421
LT	338	338	296	310	372	386	386	400	386	400	441	427	421
FCY, MPA:													
L	338	338	...	...	379	393	393	407	386	407	448	427	421
LT	338	338	...	...	379	393	393	407	393	421	462	448	441
FSU, MPA	255	255	...	...	262	269	255	262	248	248	269	269	262
FBRU, MPA[c]:													
(E/D=1.5)	641	641	...	...	662	689	683	696	662	683	738	724	717
(E/D=2.0)	814	814	...	...	841	876	876	889	849	883	952	938	924
FBRY,[c] MPA:													
(E/D=1.5)	476	476	...	...	538	572	579	600	579	579	641	621	607
(E/D=2.0)	538	538	...	...	621	648	676	703	676	683	752	724	717
EL, PERCENT:													
LT	5	5	5	5	5	5	5	...	5	3	4	4	4
E, GPA:													
PRIMARY	72.4	73.8	72.4	72.4	72.4	72.4	73.8			72.4	72.4	73.8	
SECONDARY	68.9	70.3	65.5	68.9	65.5	68.9	70.3			65.5	68.9	70.3	
EC, GPA:													
PRIMARY	73.8	75.2	73.8	73.8	73.8	73.8	75.2			73.8	73.8	75.2	
SECONDARY	70.3	71.7	66.9	70.3	66.9	70.3	71.7			66.9	70.3	71.7	
G, GPA	...												
MU	0.33												
PHYSICAL PROPERTIES:													
OMEGA, MG/M3	2.77												
C, J/(G*K)	...												
K, W/(M*K)	...												
ALPHA, 10-6 M/(M*K)	...												

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 2.5 PERCENT NOMINAL CLADDING THICKNESS.
c SEE TABLE 3.1.2.1.1.
d THESE ALLOWABLES 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.

TABLE 3.2.3.0(f). *Percent Elongation Values for Clad 2024 Aluminum Alloy (sheet and plate)*

	Elongation (LT), percent
Condition	T3, T4, T42
Thickness, mm	
0.25-0.51	12
0.52-1.57	15
25.43-38.10	7
38.11-50.80	6

TABLE 3.2.3.0(g). *Percent Elongation Values for 2024 Aluminum Alloy (Drawn Tubing)*

	Elongation (L), percent
Condition	T3, T42
Thickness, mm	
0.45-0.62	10
0.63-1.26	12
1.27-6.59	14
6.60-12.70	16

TABLE 3.2.3.0(H). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 2024 ALUMINUM ALLOY (DRAWN TUBING)

SPECIFICATION..........	WW-T-700/3		
FORM....................	DRAWN TUBING		
CONDITION...............	T3		T42[a]
THICKNESS, MM...........	0.46-12.70		0.46-12.70
BASIS...................	A	B	S
MECHANICAL PROPERTIES:			
FTU, MPA:			
L..................	441	455	441
LT.................	...	...	...
FTY, MPA:			
L..................	290	310	276
LT.................	...	...	...
FCY, MPA:			
L..................	290	310	276
LT.................	...	...	...
FSU, MPA..............	269	276	269
FBRU, MPA:			
(E/D=1.5)..........	662	663	662
(E/D=2.0)..........	641	869	841
FBRY, MPA:			
(E/D=1.5)..........	407	434	386
(E/D=2.0)..........	462	496	441
EL, PERCENT:			
L..................	b	...	b
LT.................	...	...	...
E, GPA................	72.4		
EC, GPA...............	73.8		
G, GPA................	27.6		
MU....................	0.33		
PHYSICAL PROPERTIES:			
OMEGA, MG/M3.........	2.77		
C, J/(G*K)...........	SEE FIGURE 3.2.3.0		
K, W/(M*K)...........	121 (AT 298 K), SEE FIGURE 3.2.3.0		
ALPHA, 10-6 M/(M*K)..	SEE FIGURE 3.2.3.0		

[a] 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.

[b] SEE TABLE 3.2.3.0(G).

TABLE 3.2.3.0(I1). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 2024 ALUMINUM ALLOY (BAR, ROD, AND WIRE, ROLLED AND DRAWN)

SPECIFICATION	QQ-A-225/6						
FORM	BAR, ROD AND WIRE-ROLLED, DRAWN, OR COLD-FINISHED						
TEMPER	T351						
CROSS-SECTIONAL AREA, MM2	≤3230						
THICKNESS, MM	12.70-25.41	25.42-50.81	50.82-76.21	76.22-101.61	101.62-127.01[a]	127.02-152.4[a]	152.42-165.10[a]
BASIS	S	S	S	S	S	S	S
MECHANICAL PROPERTIES:							
FTU, MPA:							
L	427	427	427	427	427	427	427
LT	421	407	393	379	372	359	...
FTY, MPA:							
L	310	310	310	310	310	310	310
LT	248	248	248	248	248	248	...
FCY, MPA:							
L	234	234	234	234	234	234	...
LT	283	283	283	283	283	283	...
FSU, MPA	255	255	255	255	255	255	...
FBRU, MPA:							
(E/D=1.5)	621	621	621	621	621	621	...
(E/D=2.0)	793	793	793	793	793	793	...
FBRY, MPA:							
(E/D=1.5)	434	434	434	434	434	434	...
(E/D=2.0)	510	510	510	510	510	510	...
EL, PERCENT:							
L	10	10	10	10	10	10	10
LT	10	5	6	4	2	...	...
E, GPA	72.4						
EC, GPA	73.8						
G, GPA	27.6						
MU	0.33						
PHYSICAL PROPERTIES:							
OMEGA, MG/M3	2.77						
C, J/(G*K)	SEE FIGURE 3.2.3.0						
K, W/(M*K)	121 (AT 298 K) FOR T3XX, SEE FIGURE 3.2.3.0						
ALPHA, 10-6 M/(M*K)	SEE FIGURE 3.2.3.0						

[a] FOR ROUNDS (ROD) MAXIMUM DIAMETER IS 165.1MM.; FOR SQUARE, RECTANGULAR, HEXAGONAL OR OCTAGONAL BAR, MAXIMUM THICKNESS IS 101.5MM.

TABLE 3.2.3.0(I2). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 2024 ALUMINUM ALLOY (BAR, ROD, AND WIRE, ROLLED AND DRAWN)

SPECIFICATION	QQ-A-225/6												
FORM	BAR, ROD AND WIRE, ROLLED, DRAWN OR COLD-FINISHED												
TEMPER	T4										T42	T6	T851
CROSS-SECTIONAL AREA, MM2	≤3230												
THICKNESS, MM	3.17-12.68	12.69-25.41	25.42-50.81	50.82-76.21	76.22-101.61	101.62-114.31[a]	114.32-127.01[a]	127.02-152.41[a]	152.42-165.11[a]	165.12-203.20[b]	≤165.10[a]	≤165.10[a]	12.70-165.10[a]
BASIS	S	S	S	S	S	S	S	S	S	S	S	S	S
MECHANICAL PROPERTIES:													
FTU, MPA:													
L	427	427	427	427	427	427	427	427	427	400	427	427	455
LT	421	421	407	393	379	372	372	359	...	...	...	...	...
FTY, MPA:													
L	310	290	290	290	290	290	276	276	276	262	276	345	400
LT	310	290	283	276	269	269	255	248	...	...	...	...	...
FCY, MPA:													
L	248	228	228	228	228	228	221	221	...	...	...	...	...
LT	...	...	...	...	...	...	...	...	...	...	...	...	...
FSU, MPA	255	255	255	255	255	255	255	255	255	...	...	...	...
FBRU, MPA:													
(E/D=1.5)	641	641	641	641	641	641	641	641	...	...	...	...	...
(E/D=2.0)	814	814	814	814	814	814	814	814	...	...	...	...	...
FBRY, MPA:													
(E/D=1.5)	434	407	407	407	407	407	386	386	...	...	...	...	...
(E/D=2.0)	496	462	462	462	462	462	441	441	...	...	...	...	...
EL, PERCENT:													
L	10	10	10	10	10	10	10	10	10	10	10	5	5
LT	10	10	8	6	4	2	2	2	...	...	...	...	...
E, GPA	72.4												
EC, GPA	73.8												
G, GPA	27.6												
MU	0.33												
PHYSICAL PROPERTIES:													
OMEGA, MG/M3	2.77												
C, J/(G*K)	SEE FIGURE 3.2.3.0												
K, W/(M*K)	121 (AT 298 K) FOR T4X; 151 (AT 298 K) FOR T6X, T7X, AND T8XX, SEE FIGURE 3.2.3.0												
ALPHA, 10-6 M/(M*K)	SEE FIGURE 3.2.3.0												

[a] FOR ROUNDS (ROD) MAXIMUM DIAMETER IS 165.1MM.; FOR SQUARE, RECTANGULAR, HEXAGONAL OR OCTAGONAL BAR, MAXIMUM THICKNESS IS 101.5MM.

[b] APPLIES TO ROD ONLY.

[c] 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.

TABLE 3.2.3.0(J1). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 2024 ALUMINUM ALLOY (EXTRUSION)

SPECIFICATION	QQ-A-200/3													
FORM	EXTRUDED BARS, RODS, AND SHAPES													
TEMPER	T4, T3510 AND T3511													
THICKNESS, MM	≤6.33		6.34-12.68		12.69-19.03		19.04-38.08		38.09-76.18		76.19-114.28		38.10-76.18	76.19-114.27
CROSS-SECTIONAL AREA, MM2	<12900								<16130				>16130, <20650	
BASIS	A	B	A	B	A	B	A	B	A	B	A	B	S	S
MECHANICAL PROPERTIES:														
FTU, MPA:														
L	393	421	414	427	414	427	448	463	483	510	483	510	469	469
LT	372	400	386	393	372	356	386	414	379	400	372	393	365	359
FTY, MPA:														
L	290	324	303	324	303	324	317	372	359	372	359	372	331	331
LT	255	283	262	276	255	269	255	296	269	283	269	283	248	248
FCY, MPA:														
L	234	262	255	269	262	276	283	331	338	345	338	352	310	310
LT	283	310	283	303	276	296	276	324	290	303	263	296	263	262
FSU, MPA	200	214	214	221	207	214	228	241	234	248	226	241	228	221
FBRU[a], MPA:														
(E/D=1.5)	579	621	538	558	538	552	579	621	607	641	593	627	593	579
(E/D=2.0)	745	786	676	696	669	696	724	779	765	8[illegible]4	752	793	745	731
FBRY[a], MPA:														
(E/D=1.5)	421	469	379	407	379	407	393	462	434	455	427	448	407	393
(E/D=2.0)	490	545	462	490	462	490	476	558	531	552	517	538	490	476
EL, PERCENT:														
L	12	...	12[b]	...	12	...	10	...	10	...	10	...	8	8
LT	...	...	6	...	6	...	5	...	2	...	2	...	...	...
E, GPA	74.5													
EC, GPA	75.8													
G, GPA	28.3													
MU	0.33													
OMEGA, MG/M3	2.77													
C, K, ALPHA	SEE FIGURE 3.2.3.0													

[a] BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.
[b] NOT APPLICABLE TO SECTION LESS THAN 9.5MM. IN THICKNESS.

TABLE 3.2.3.0(J2). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 2024 ALUMINUM ALLOY (EXTRUSION)

SPECIFICATION..........	QQ-A-200/3			
FORM..........	EXTRUDED BARS, RODS, AND SHAPES [a]			
TEMPER..........	T42 [c]	T81, T8510 AND T8511		
THICKNESS, MM..........	ALL	1.27-6.33	6.34-38.08	38.09-114.30
CROSS-SECTIONAL AREA, MM2	< 20650	<12900		<20650
BASIS..........	S	S	S	S
MECHANICAL PROPERTIES:				
FTU, MPA:				
L..........	393	441	455	455
LT..........	345	441	441	421
FTY, MPA:				
L..........	262	366	400	400
LT..........	248	379	393	393
FCY, MPA:				
L..........	262	393	407	407
LT..........	262	393	407	407
FSU, MPA..........	207	241	248	248
FBRU, MPA:				
(E/D=1.5)..........	586	648	662	634
(E/D=2.0)..........	745	846	848	807
FBRY, MPA:				
(E/D=1.5)..........	365	545	565	565
(E/D=2.0)..........	421	641	662	662
EL, PERCENT:				
L..........	b	4	5	5
LT..........	...	...	...	...
E, GPA..........	74.5			
EC, GPA..........	75.8			
G, GPA..........	28.3			
MU..........	0.33			
OMEGA, MG/M3..........	2.77			
C, K, ALPHA..........	SEE FIGURE 3.2.3.0			

[a] BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

[b] UP TO 19.04MM. INCL.-12; 19.05MM. TO 38.09MM. INCL.-10; 38.10MM. AND OVER, UP TO 161.3 SQ.CM. INCL.-10; 38.10MM. AND OVER, OVER 161.3 TO 206.5 SQ.CM. INCL.-8.

[c] THESE ALLOWABLES 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.

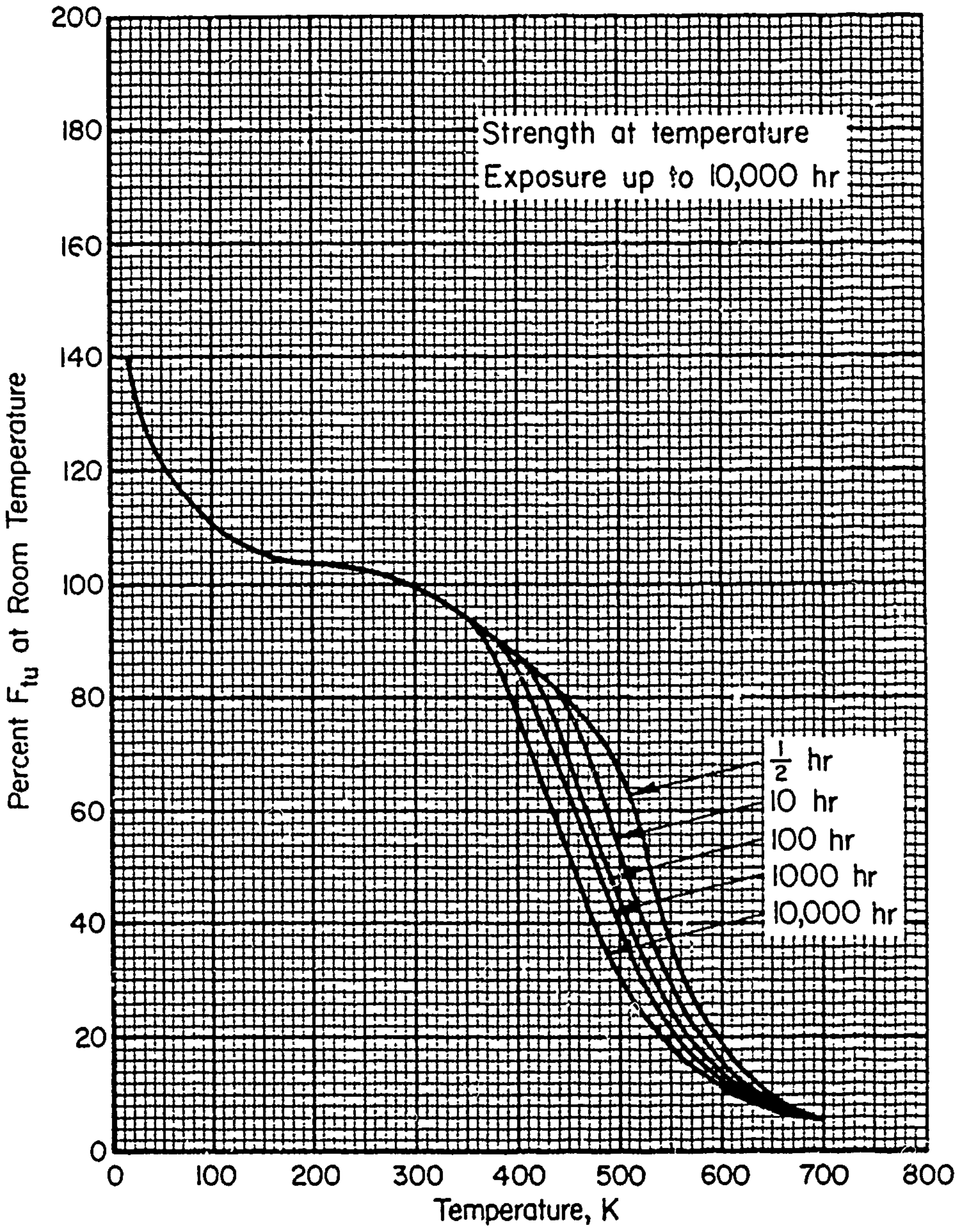


FIGURE 3.2.3.1.1.(a) Effect of temperature on the ultimate tensile strength (F_{tu}) of 2024-T3, T351 and 2024-T4 aluminum alloy (all products except extrusions).

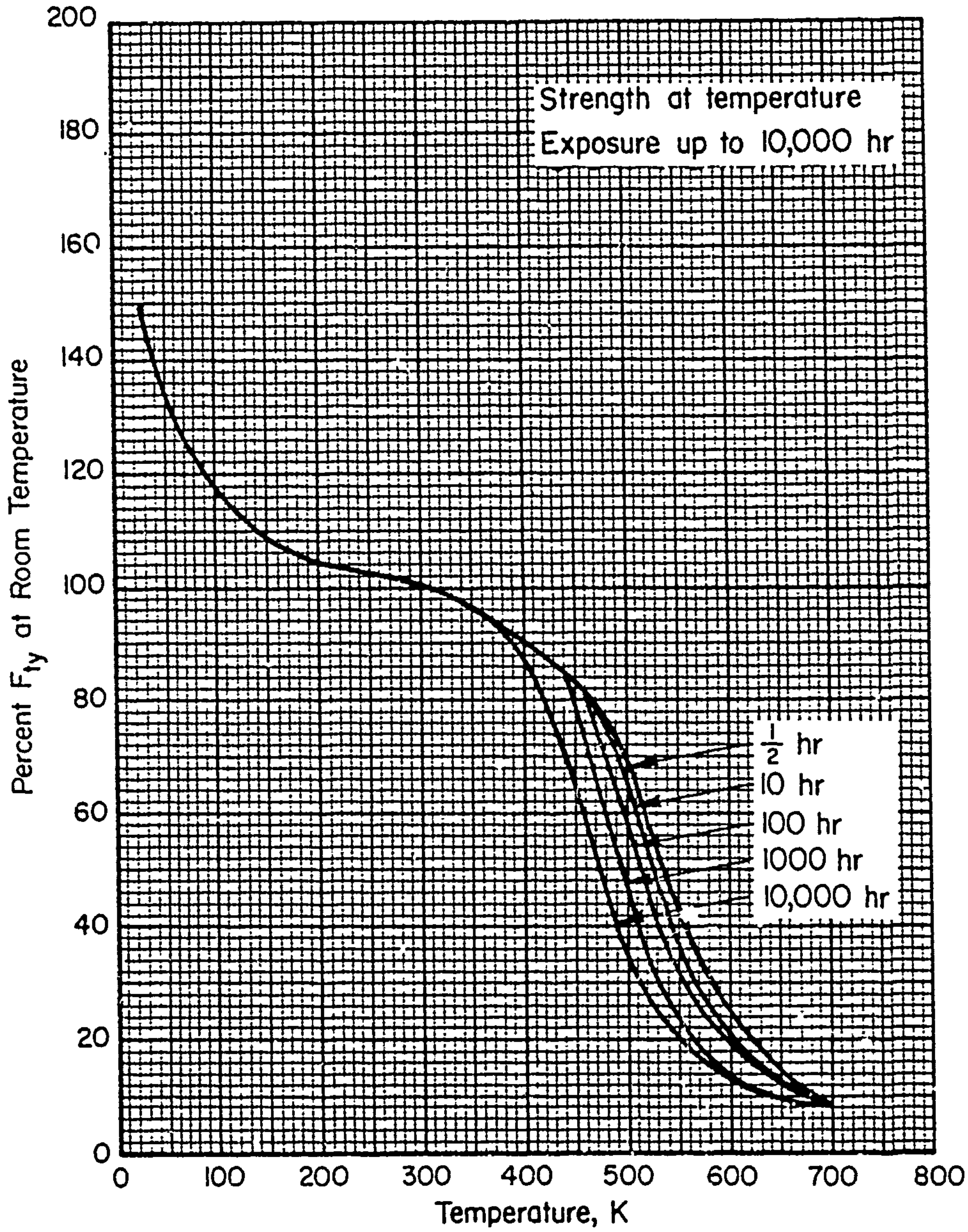


FIGURE 3.2.3.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of 2024-T3, T351 and 2024-T4 aluminum alloy (all products except extrusions).

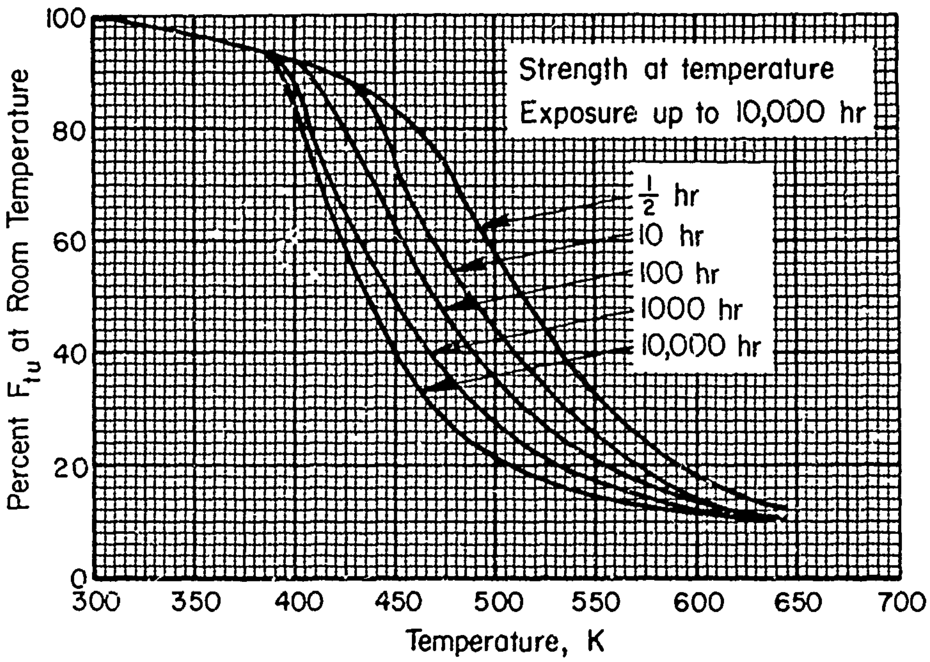


FIGURE 3.2.3.1.1(c). Effect of temperature on the ultimate tensile strength (F_{tu}) of 2024-T3 and 2024-T4 aluminum alloy (extrusions).

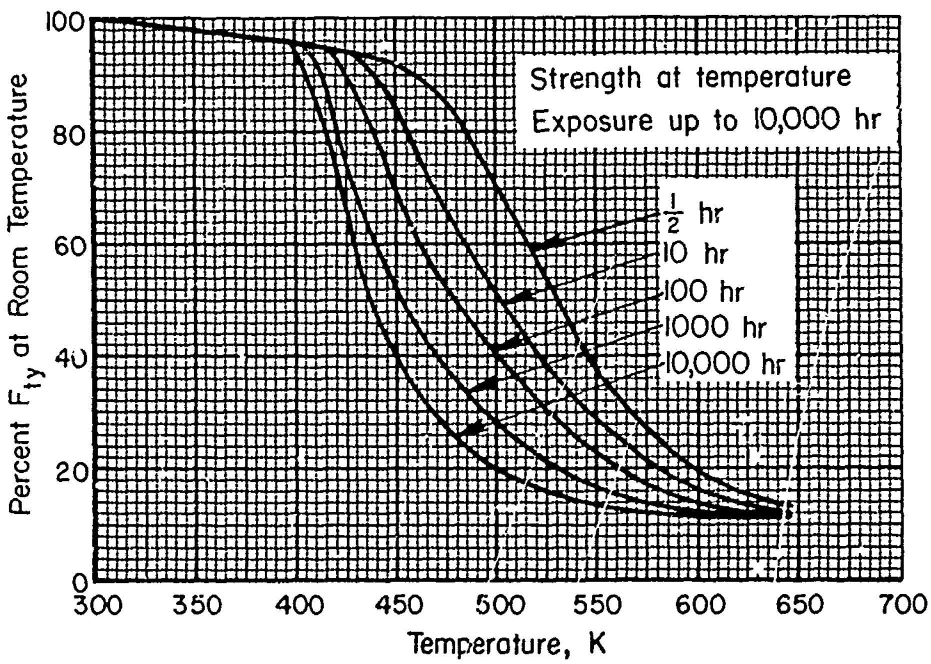


FIGURE 3.2.3.1.1(d). Effect of temperature on the tensile yield strength (F_{ty}) of 2024-T3 and 2024-T4 aluminum alloy (extrusions).

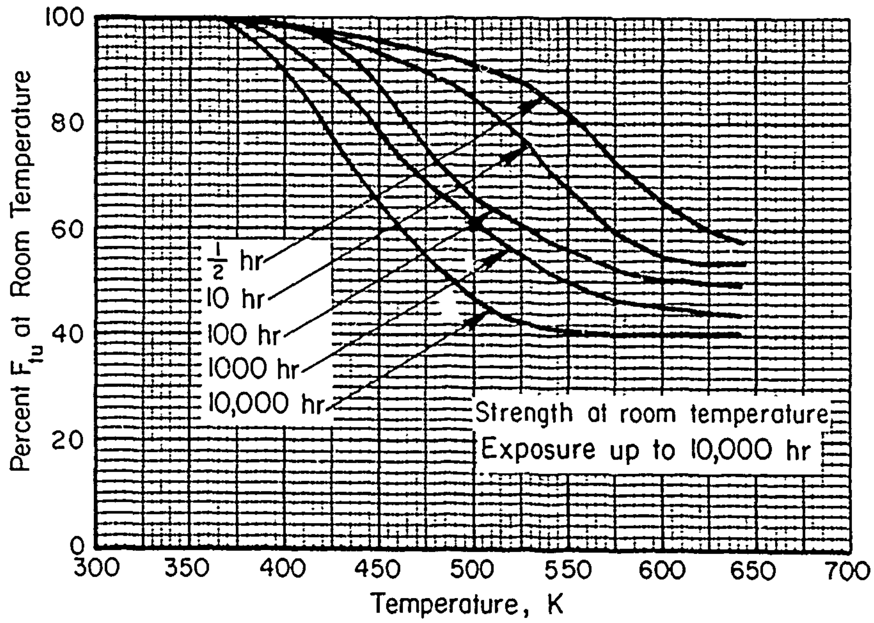


FIGURE 3.2.3.1.1(e). Effect of exposure at elevated temperatures on the room-temperature ultimate tensile strength (F_{tu}) of 2024-T3, T351 and 2024-T4 aluminum alloy (all products except thick extrusions).

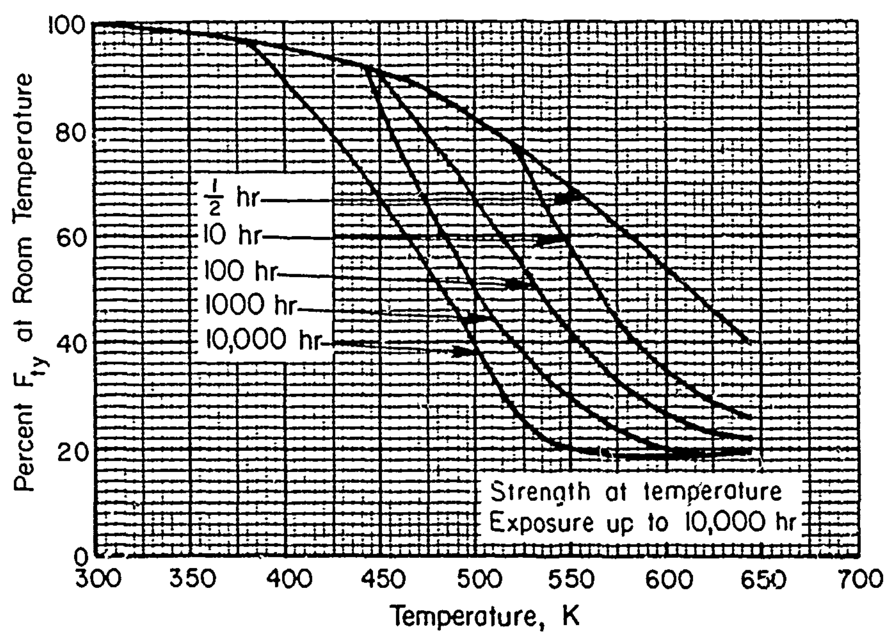


FIGURE 3.2.3.1.1(f). Effect of exposure at elevated temperatures on the room-temperature tensile yield strength (F_{ty}) of 2024-T3, T351 and 2024-T4 aluminum alloy (all products except thick extrusions).

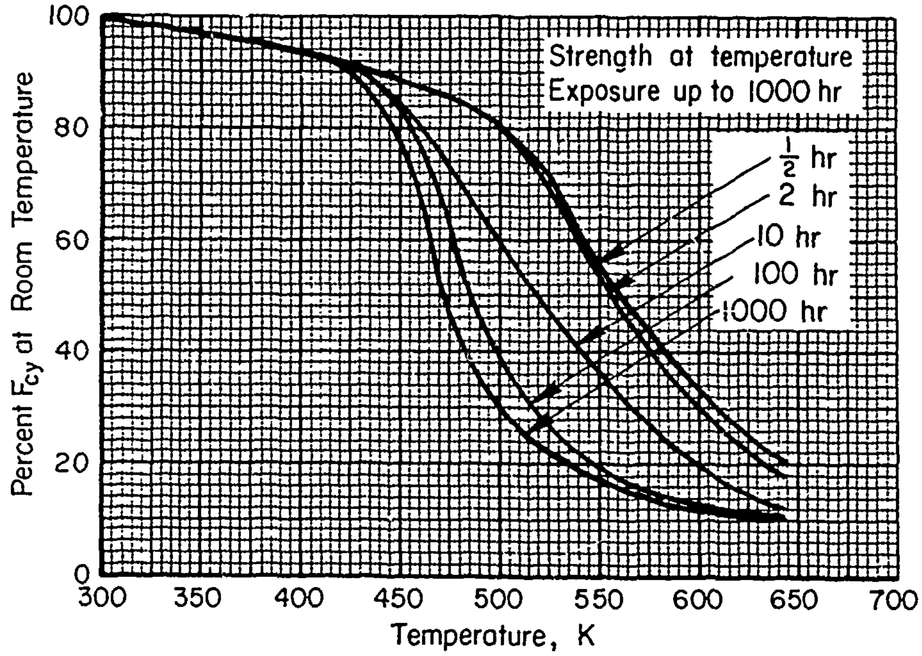


FIGURE 3.2.3.1.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of clad 2024-T3, T351 and clad 2024-T4 aluminum alloy (sheet).

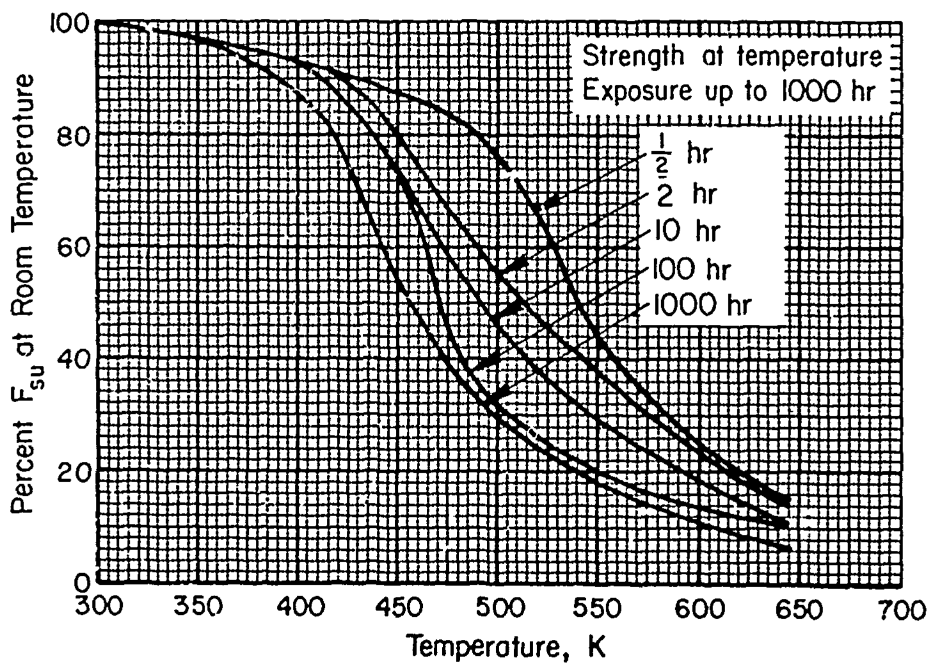


FIGURE 3.2.3.1.2(b). Effect of temperature on the ultimate shear strength (F_{su}) of clad 2024-T3, T351 and clad 2024-T4 aluminum alloy (sheet).

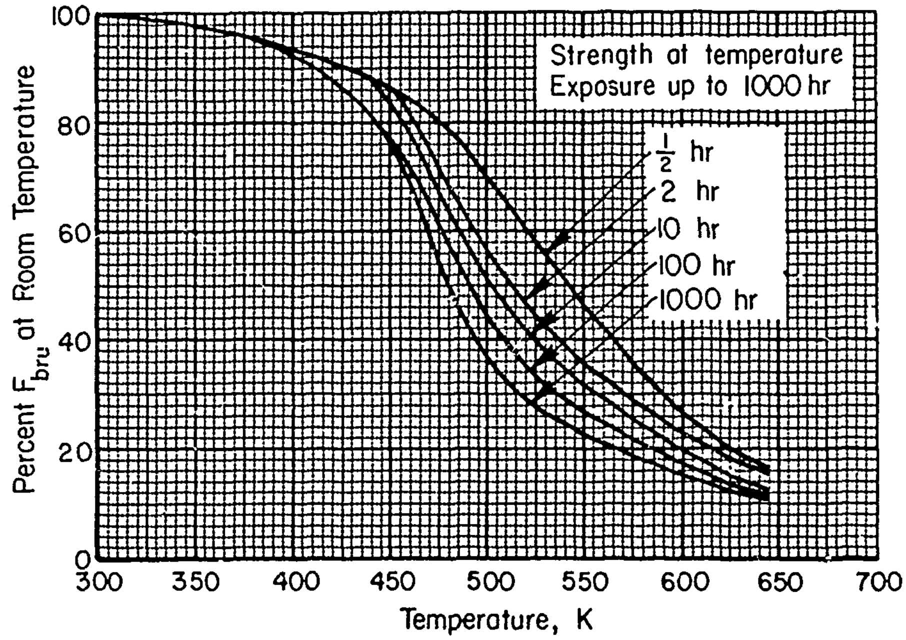


FIGURE 3.2.3.1.3(a). Effect of temperature on the ultimate bearing strength (F_{bru}) of clad 2024-T3, T351 and clad 2024-T4 aluminum alloy (sheet).

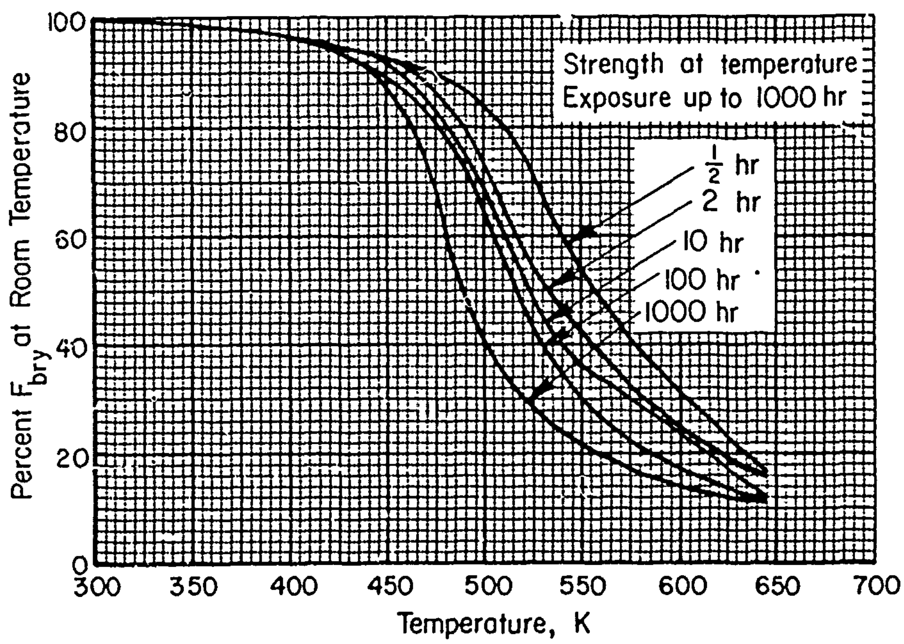


FIGURE 3.2.3.1.3(b). Effect of temperature on the bearing yield strength (F_{bry}) of clad 2024-T3, T351 and clad 2024-T4 aluminum alloy (sheet).

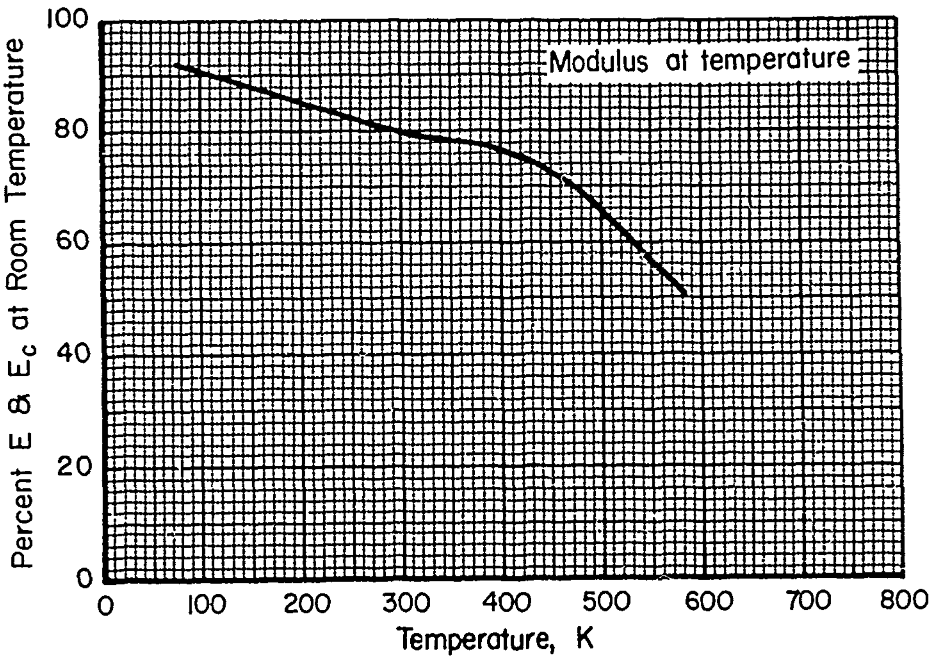


FIGURE 3.2.3.1.4. Effect of temperature on the tensil and compressive moduli (E and E_c) of 2024 aluminum alloy.

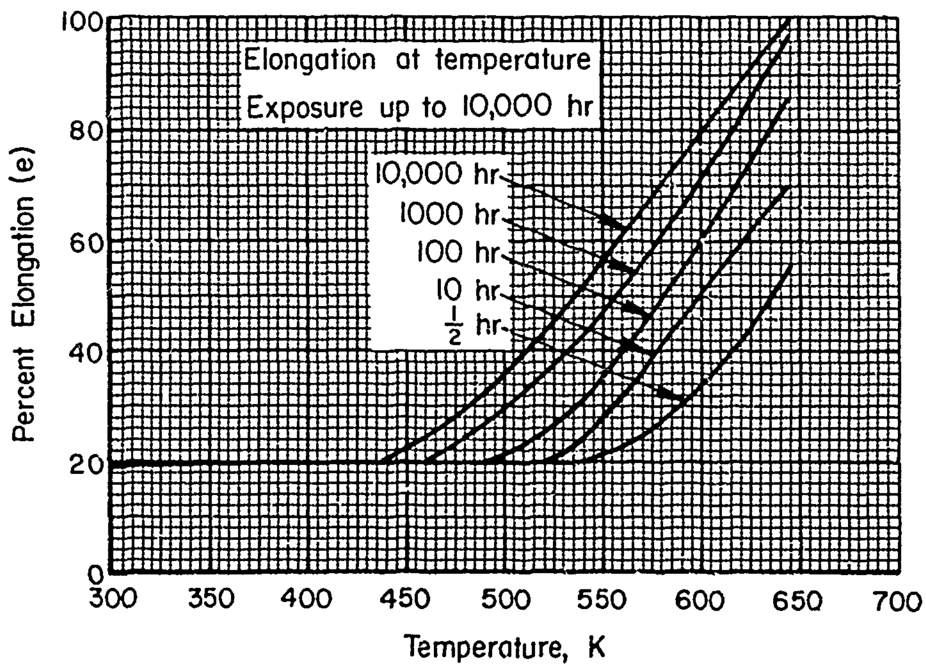


FIGURE 3.2.3.1.5(a). Effect of temperature on the elongation of 2024-T3, T351 and 2024-T4 aluminum alloy (all products except thick extrusions).

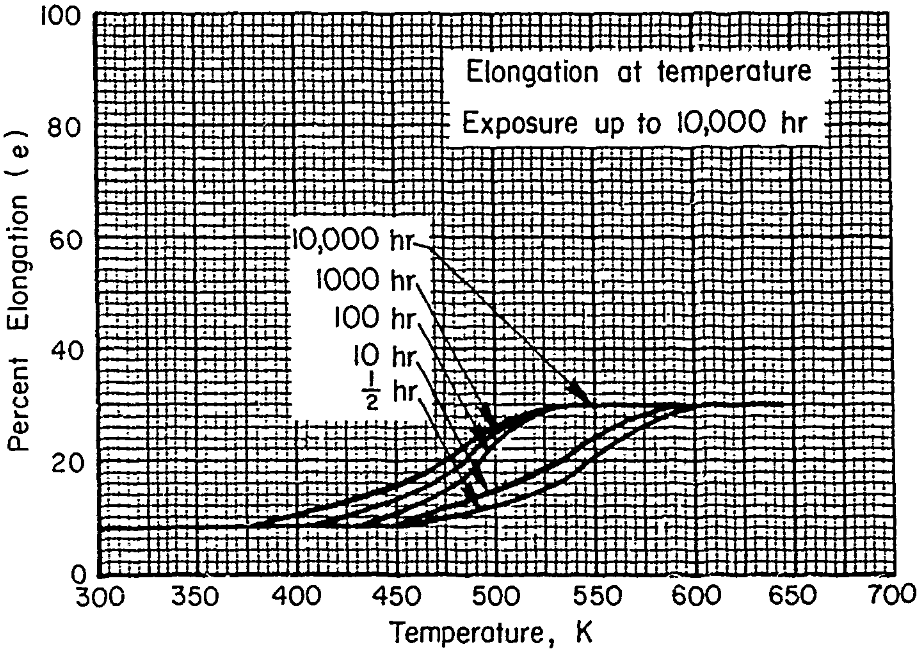


FIGURE 3.2.3.1.5(b). Effect of exposure at elevated temperature on the elongation of 2024-T3, T351 and 2024-T4 aluminum alloy (all products except thick extrusions).

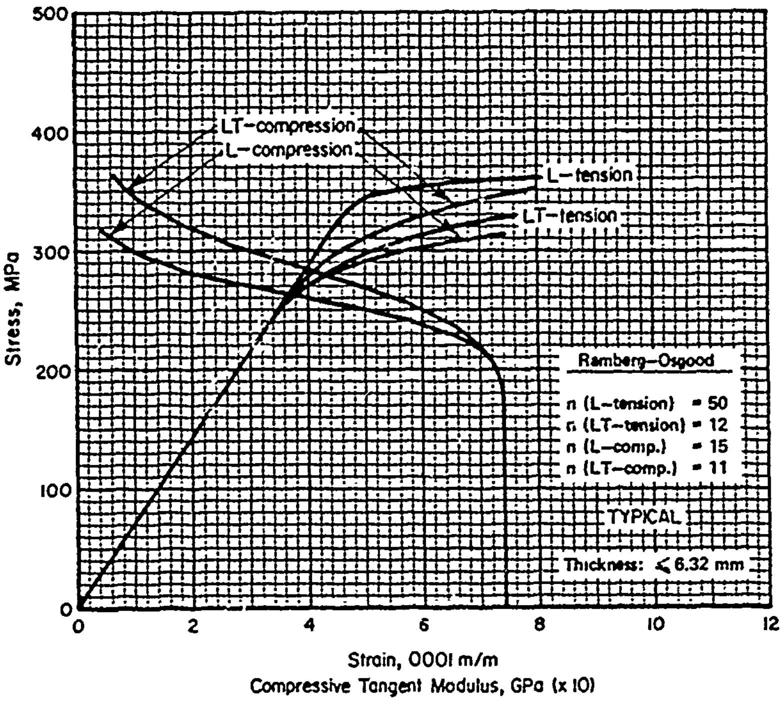


FIGURE 3.2.3.1.6(a). Typical tensile stress-strain and compression stress-strain and tangent-modulus curves for 2024-T3 aluminum alloy (sheet) at room temperature.

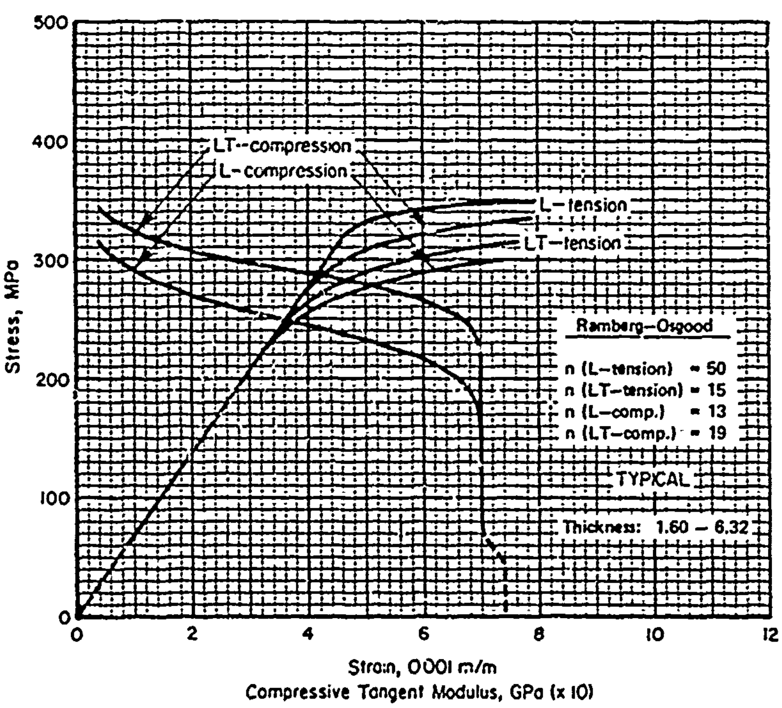


FIGURE 3.2 3.1.6(b). Typical tensile stress-strain and compressive stress-strain and tangent-modulus curves for clad 2024-T3 aluminum alloy (sheet) at room temperature.

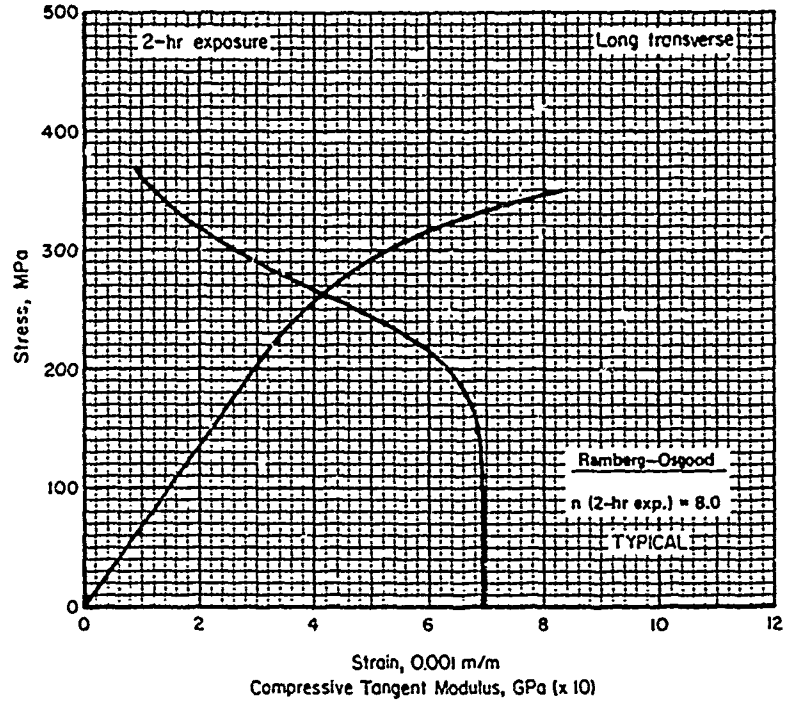


FIGURE 3.2.3.1.6(c). Typical compressive stress-strain and tangent-modulus curves for clad 2024-T3 aluminum alloy (sheet) at 373 K.

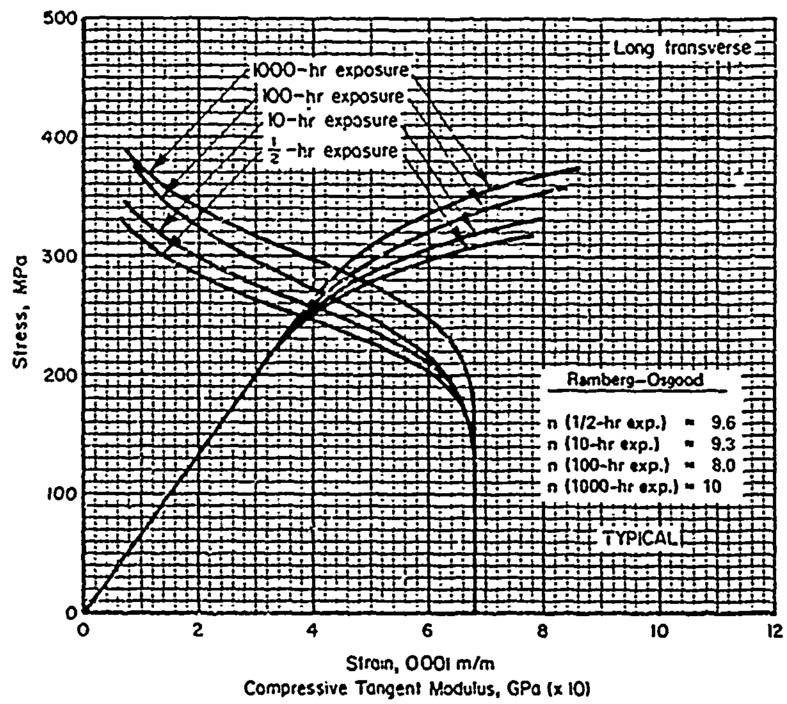


FIGURE 3.2.3.1.6(d). Typical compressive stress-strain and tangent-modulus curves for clad 2024-T3 aluminum alloy (sheet) at 422 K.

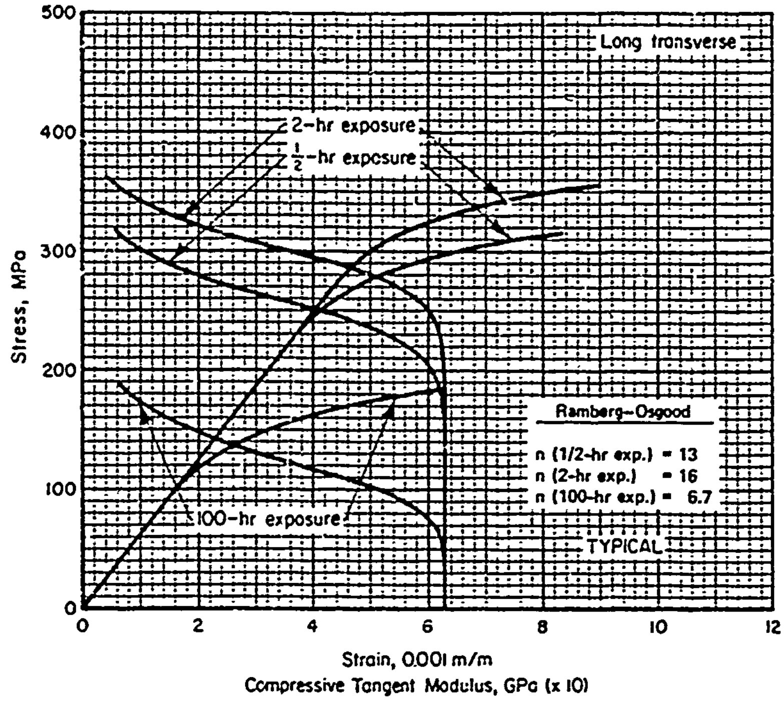


FIGURE 3.2.3.1.6(e). Typical compressive stress-strain and tangent-modulus curves for clad 2024-T3 aluminum alloy (sheet) at 477 K.

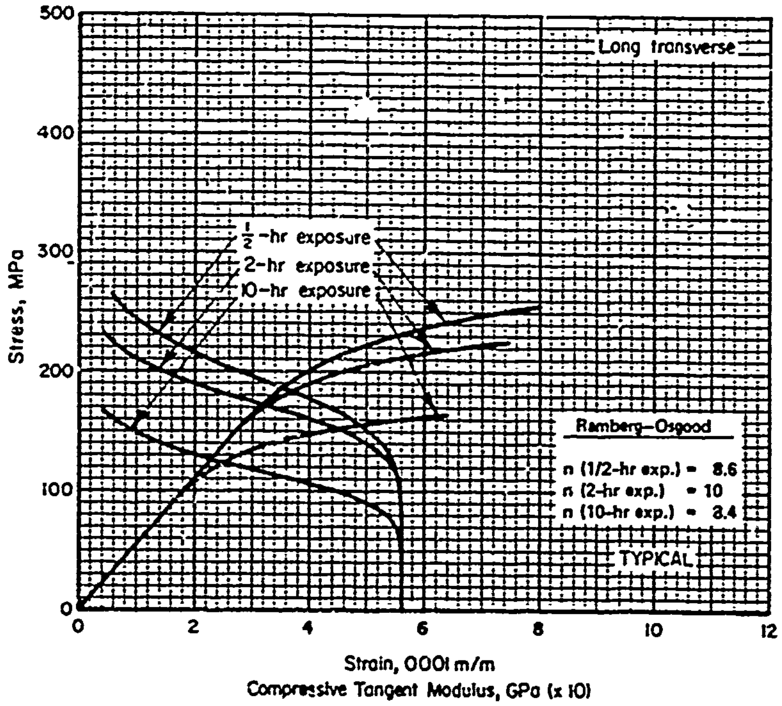


FIGURE 3.2.3.1.6(f). Typical compressive stress-strain and tangent-modulus curves for clad 2024-T3 aluminum alloy (sheet) at 533 K.

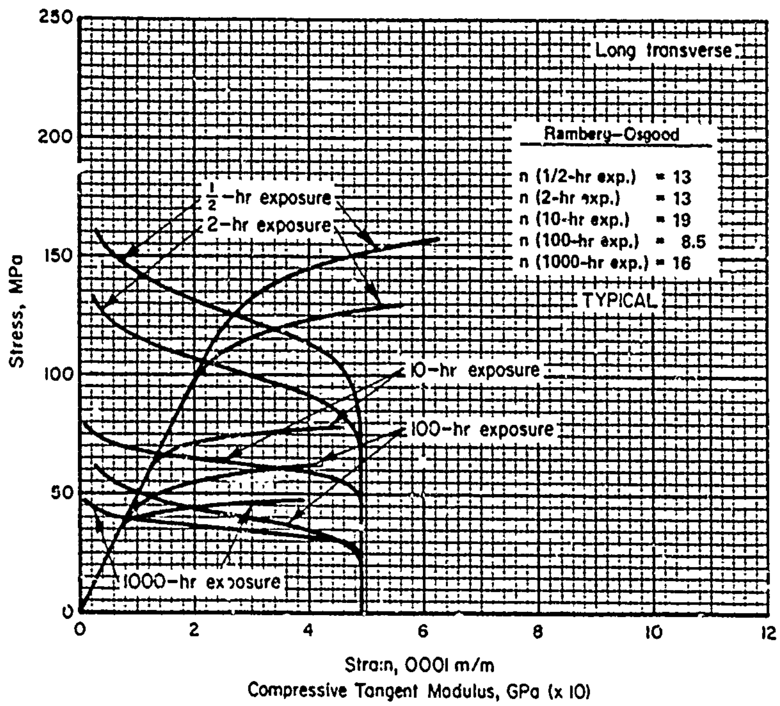


FIGURE 3.2.3.1.6(g). Typical compressive stress-strain and tangent-modulus curves for clad 2024-T3 aluminum alloy (sheet) at 588 K.

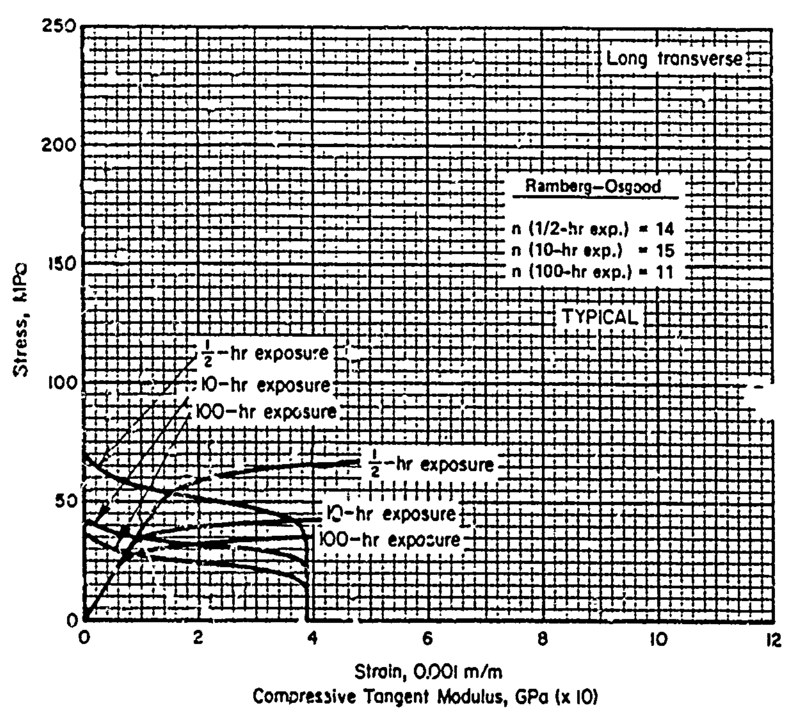


FIGURE 3.2.3.1.6(h). Typical compressive stress-strain and tangent-modulus curves for clad 2024-T3 aluminum alloy (sheet) at 644 K.

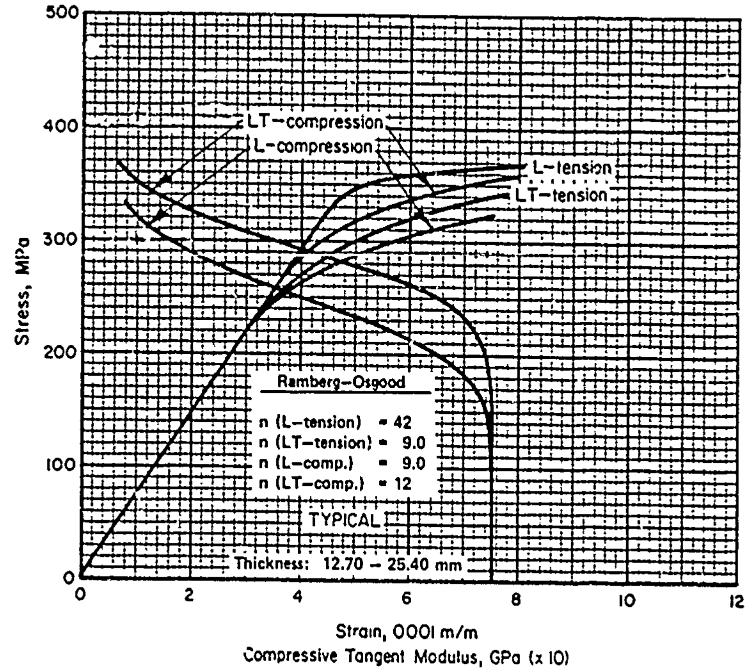


FIGURE 3.2.3.1.6(i). Typical tensile stress-strain and compressive stress-strain and tangent-modulus curves for 2024-T351 aluminum alloy (plate) at room temperature.

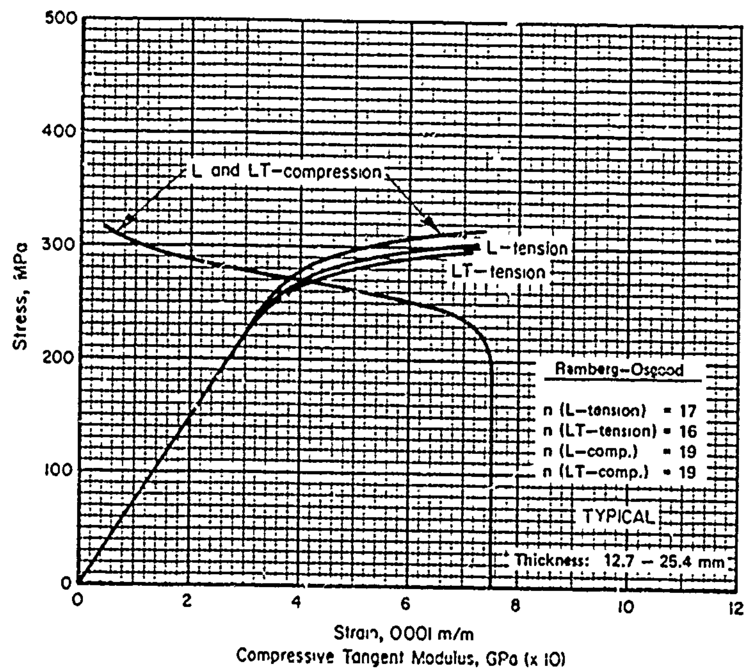


FIGURE 3.2.3.1.6(j). Typical tensile stress-strain and compressive stress-strain and tangent-modulus curves for 2024-T42 aluminum alloy (plate) at room temperature.

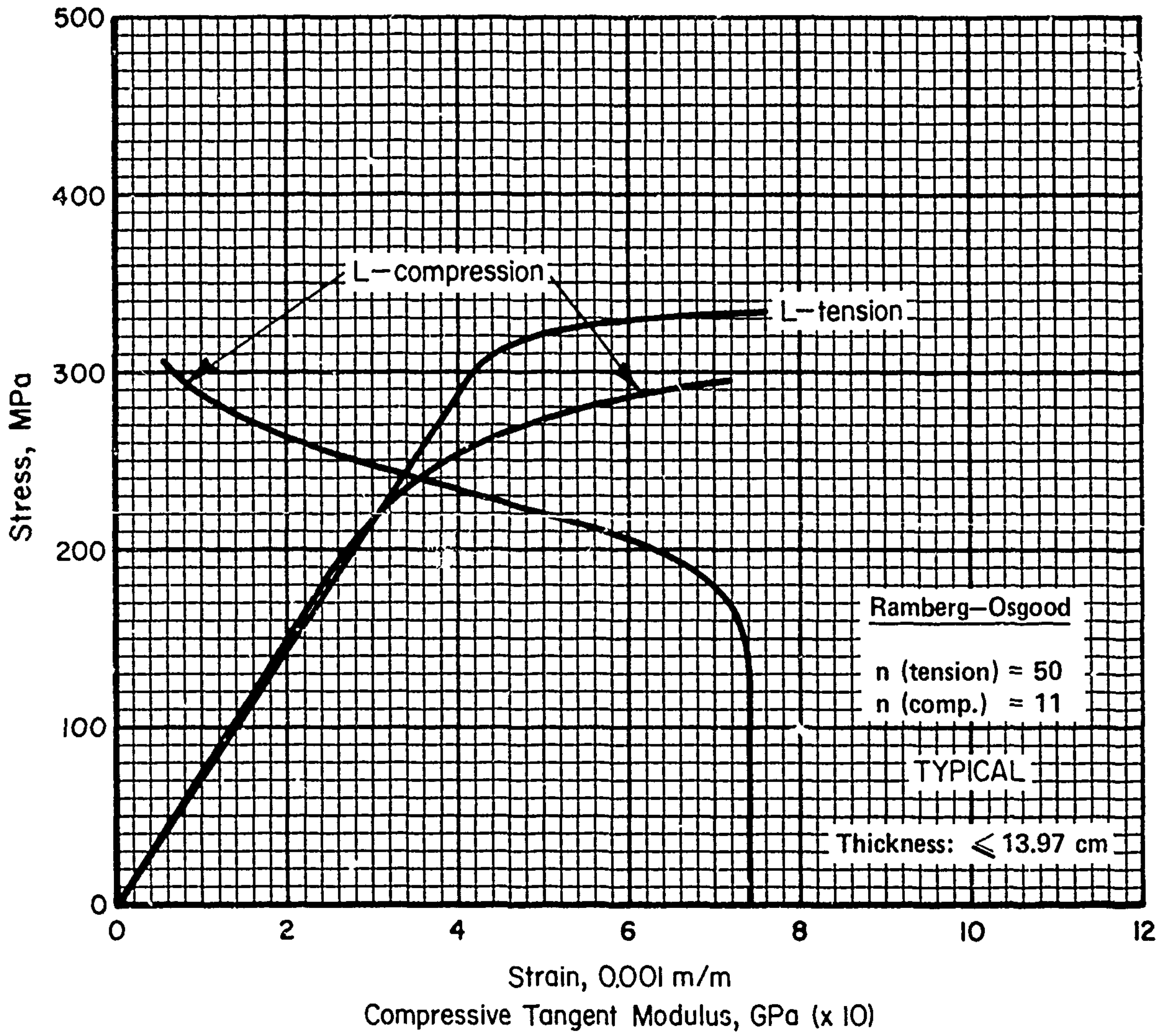


FIGURE 3.2.3.1.6(k). Typical tensile stress-strain and compressive stress-strain and tangent-modulus curves for 2024-T4 aluminum alloy (rolled bar, rod, and shapes) at room temperature.

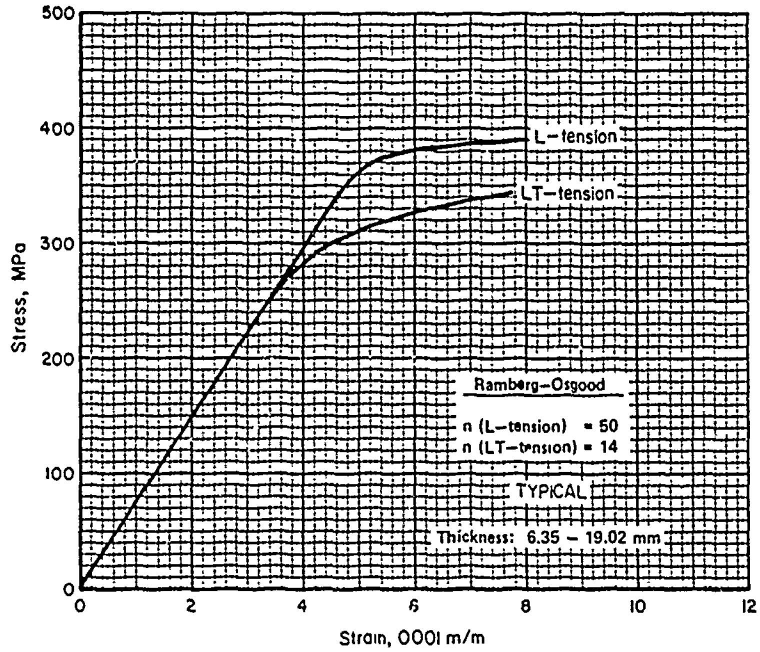


FIGURE 3.2.3.1.6(l). Typical tensile stress-strain curves for 2024-T351X aluminum alloy (extrusion) at room temperature.

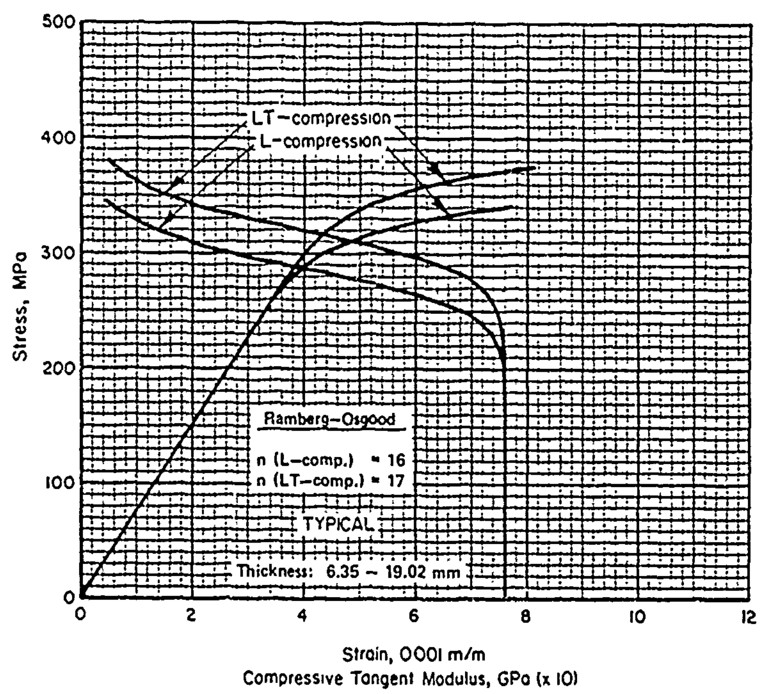


FIGURE 3.2.3.1.6(m). Typica ...essive stress-strain and tangent-modulus curves 2024-T351X aluminum alloy (extrusion) ar temperature.

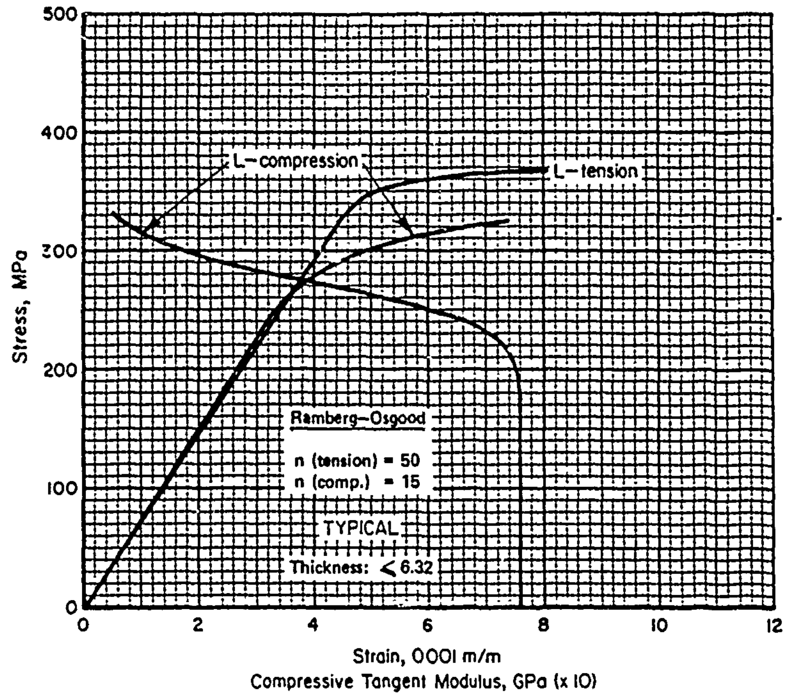


FIGURE 3.2.3.1.6(n). Typical tensile stress-strain and compressive stress-strain and tangent-modulus curves for 2024-T4 aluminum alloy (extrusion) at room temperature.

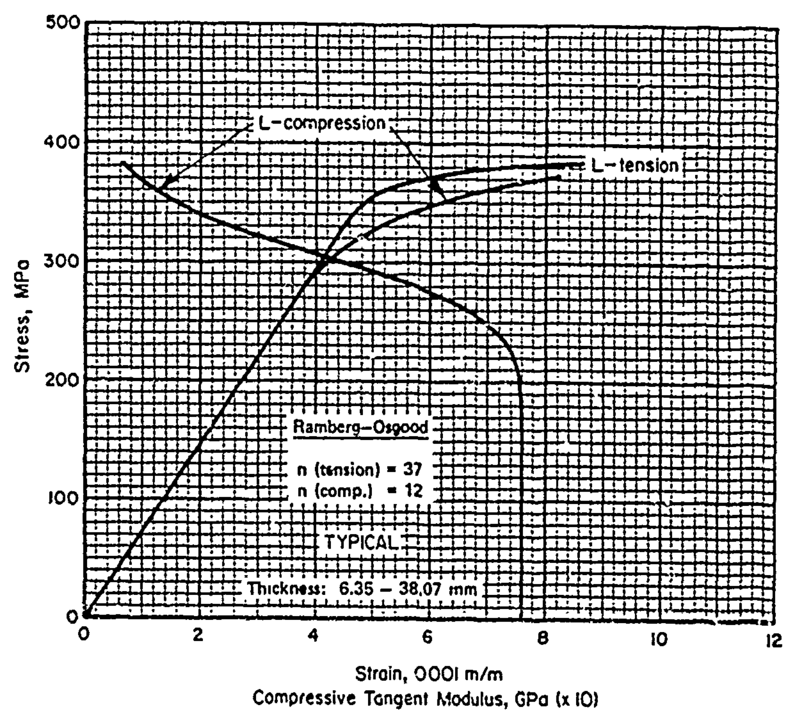


FIGURE 3.2.3.1.6(o). Typical tensile stress-strain and compressive stress-strain and tangent-modulus curves for 2024-T4 aluminum alloy (extrusion) at room temperature.

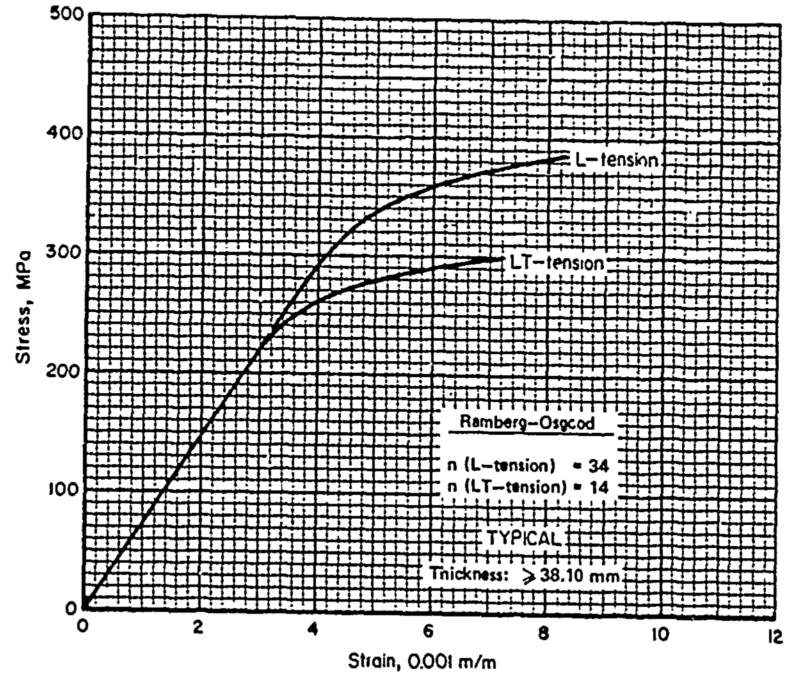


FIGURE 3.2.3.1.6(p). Typical tensile stress-strain curves for 2024-T42 aluminum alloy (extrusion) at room temperature.

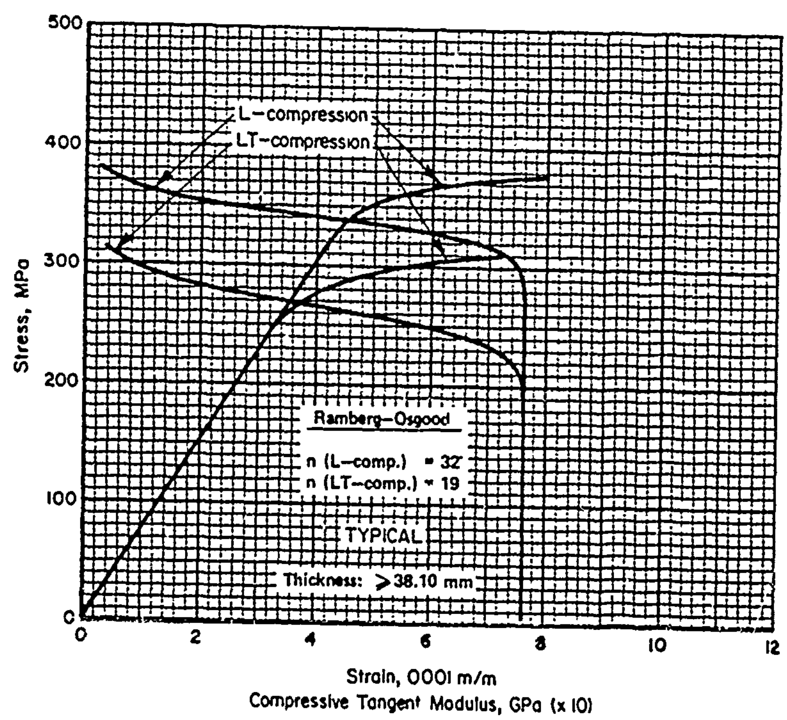


FIGURE 3.2.3.1.6(q). Typical compressive stress-strain and tangent-modulus curves for 2024-T42 aluminum alloy (extrusion) at room temperature.

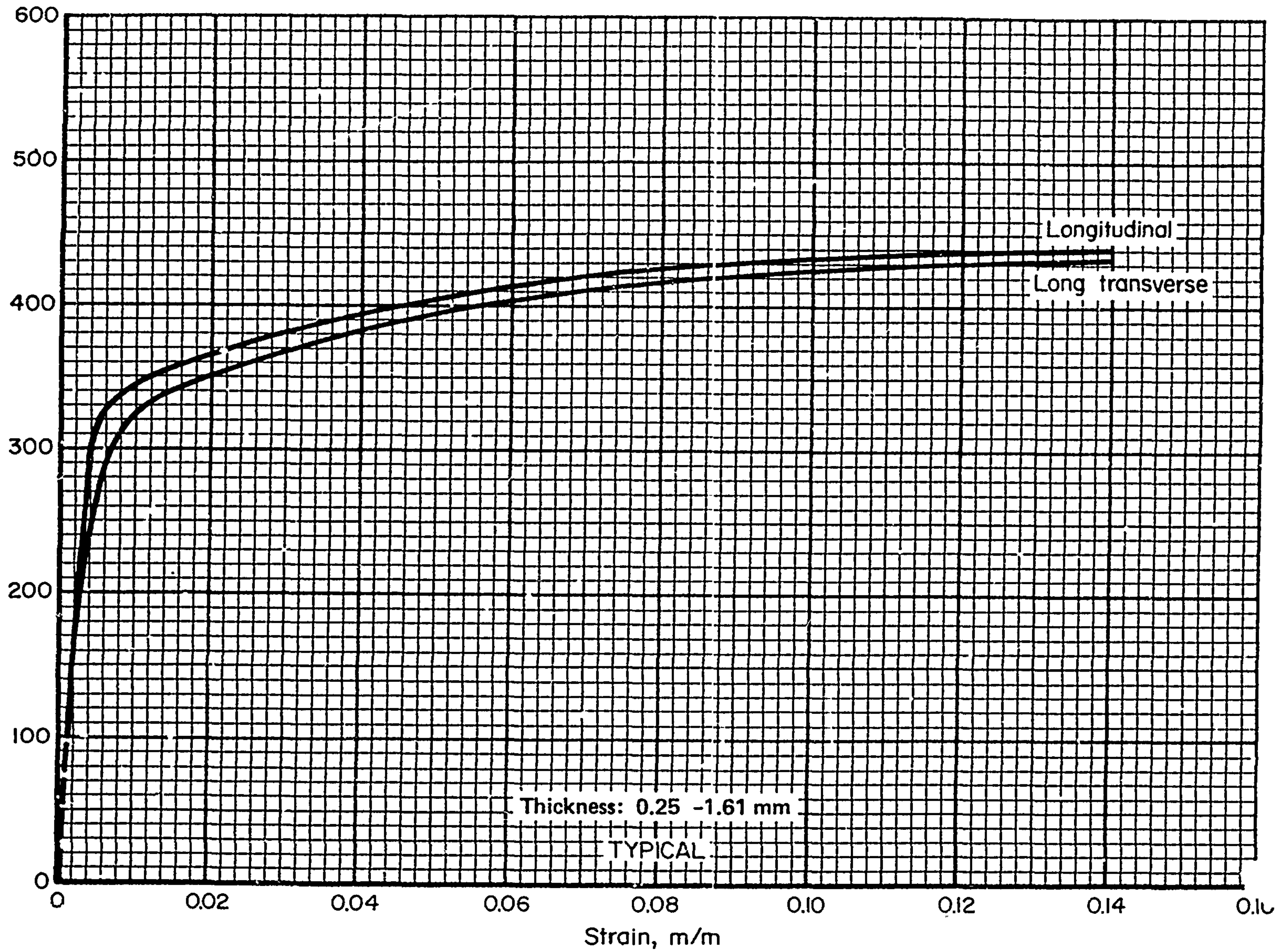


FIGURE 3.2.3.1.6(r). Typical tensile stress-strain curves (full range) for clad 2024-T3 aluminum alloy (sheet) at room temperature.

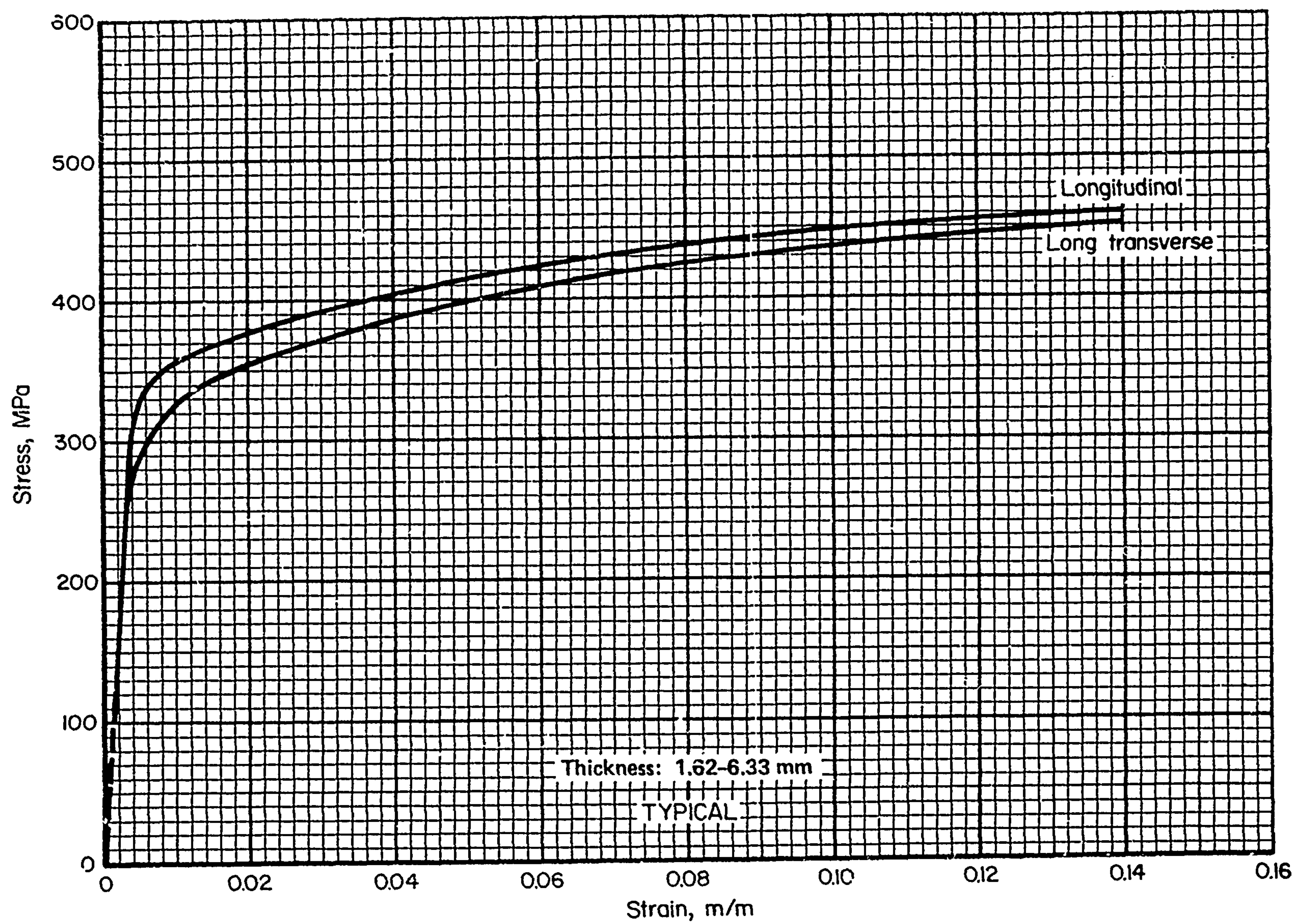


FIGURE 3.2.3.1.6(s). Typical tensile stress-strain curves (full range) for clad 2024-T3 aluminum alloy (sheet) at room temperature.

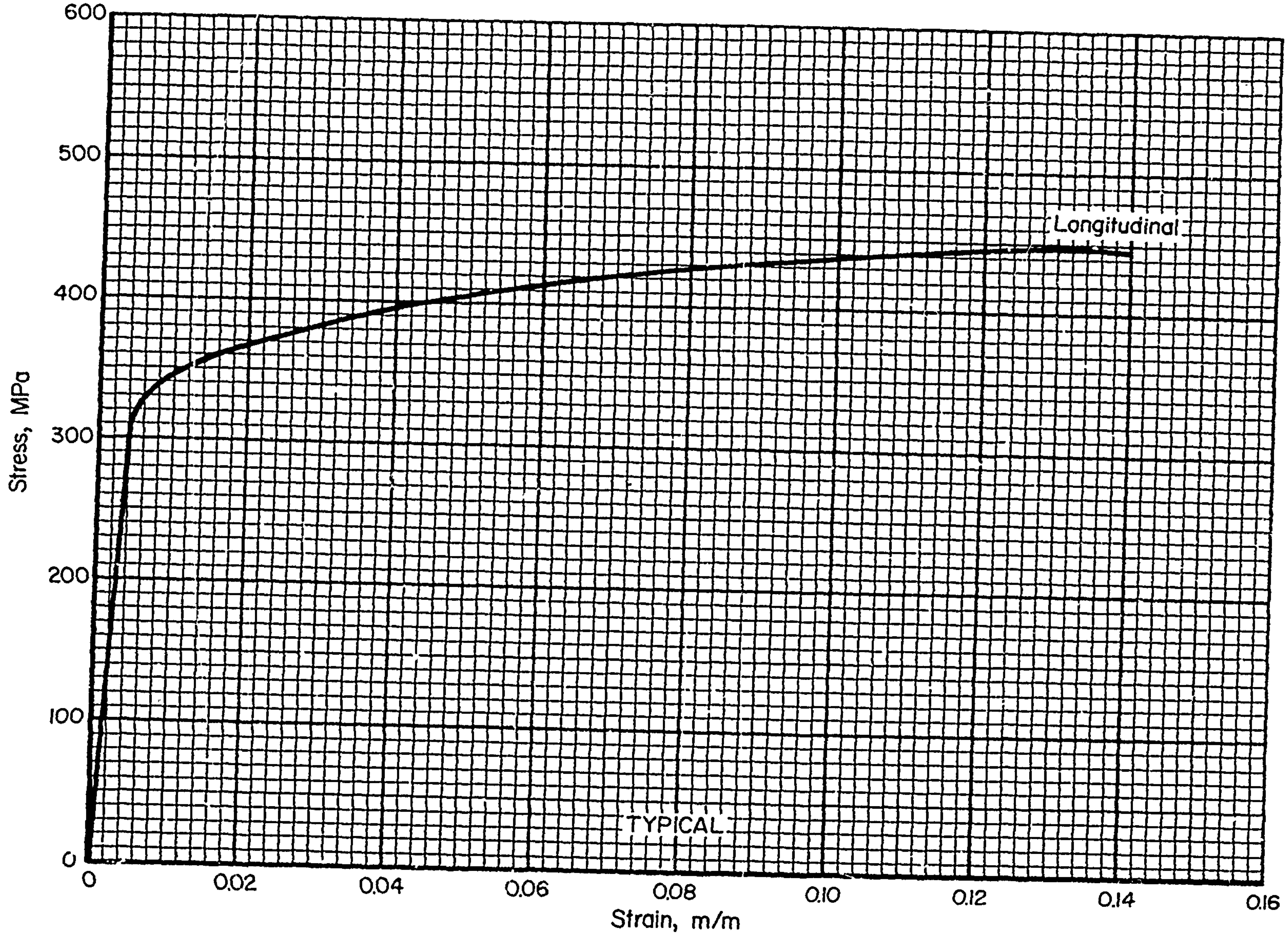


FIGURE 3.2.3.1.6(t). Typical tensile stress-strain curve (full range) for 2024-T351 aluminum alloy (rolled rod) at room temperature.

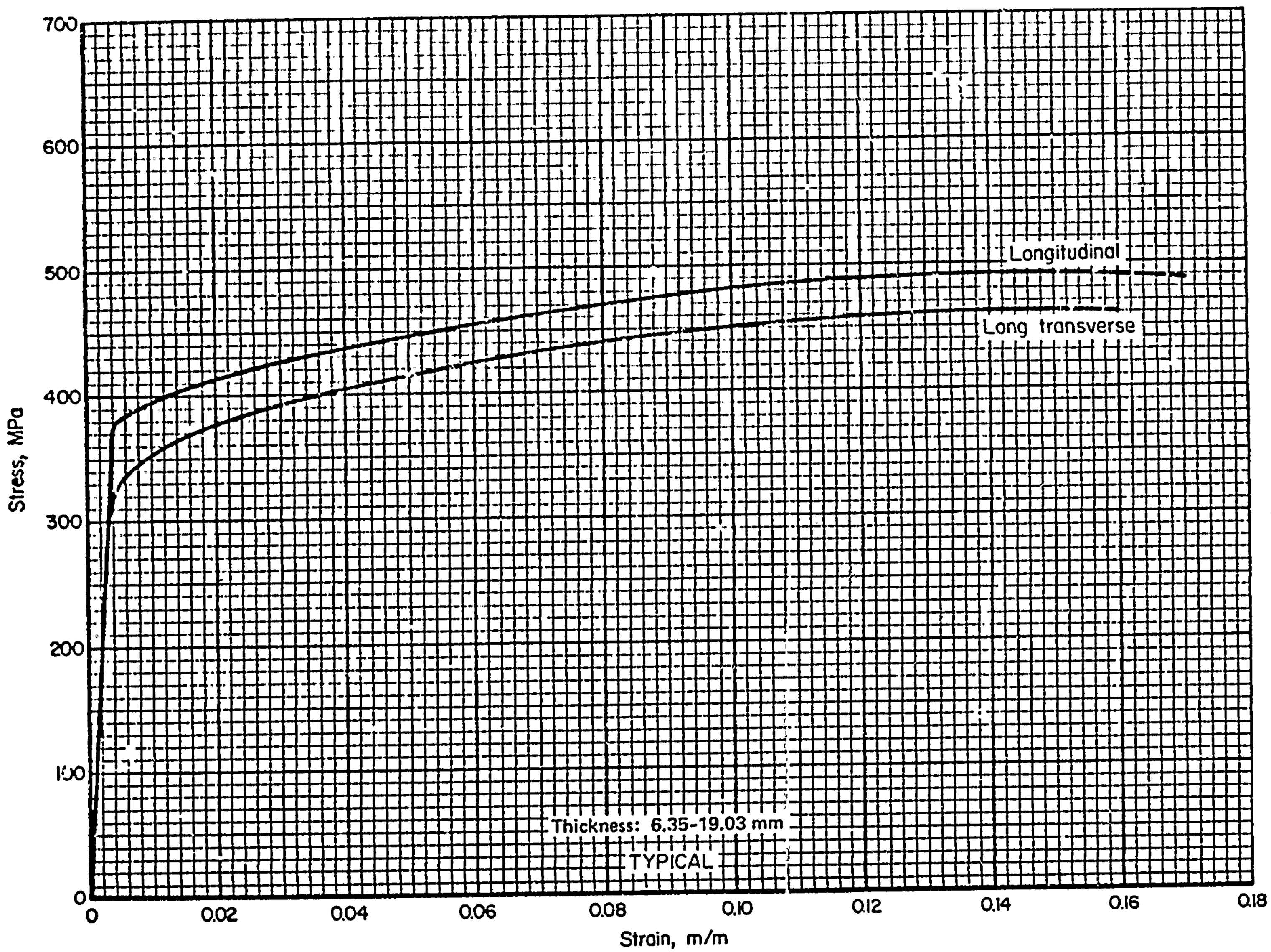


FIGURE 3.2.3.1.6(u). Typical tensile stress-strain curves (full range) for 2024-T351X aluminum alloy (extrusion) at room temperature.

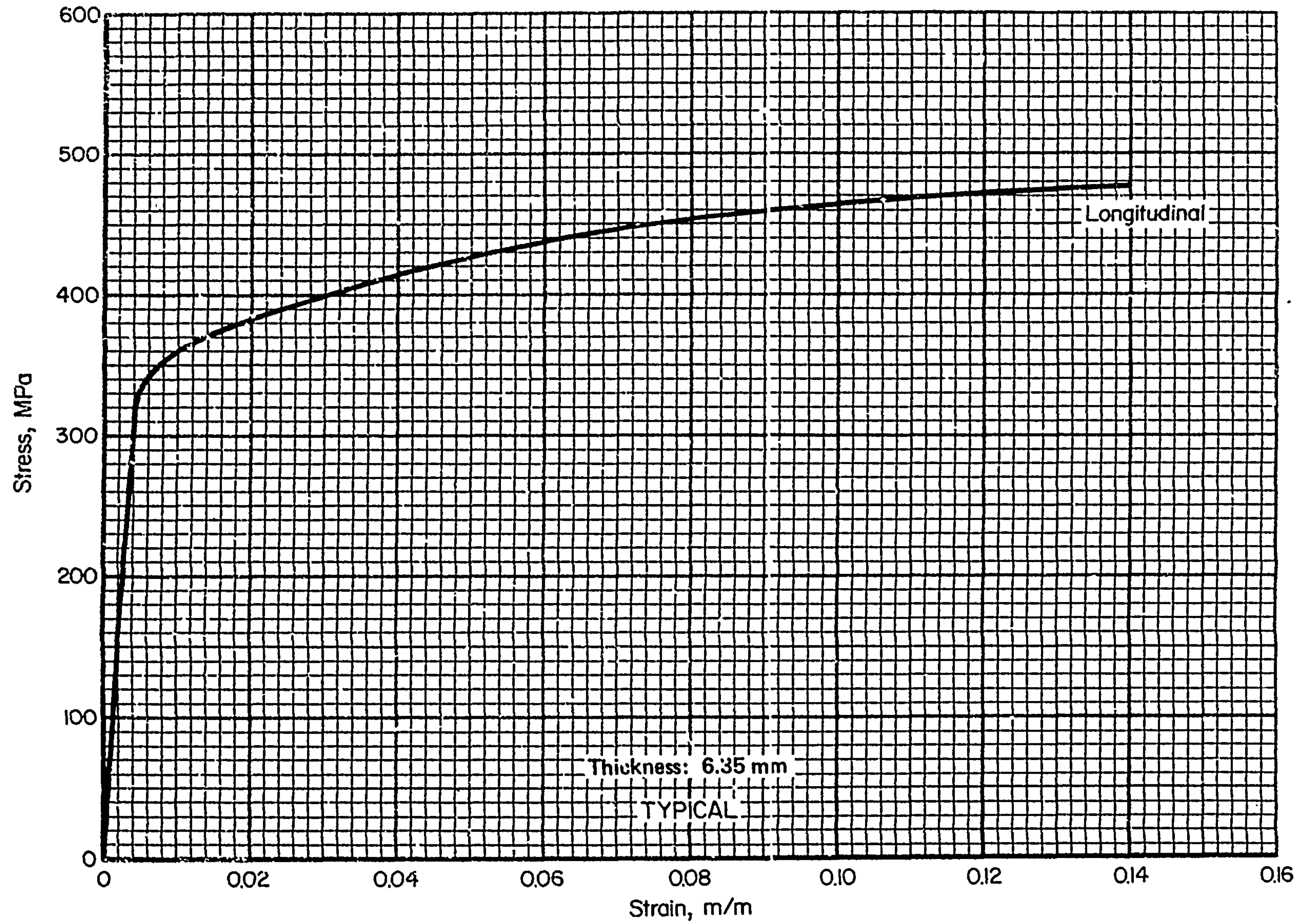


FIGURE 3.2.3.1.6(v). Typical tensile stress-strain curve (full range) for 2024-T4 aluminum alloy (extrusion) at room temperature.

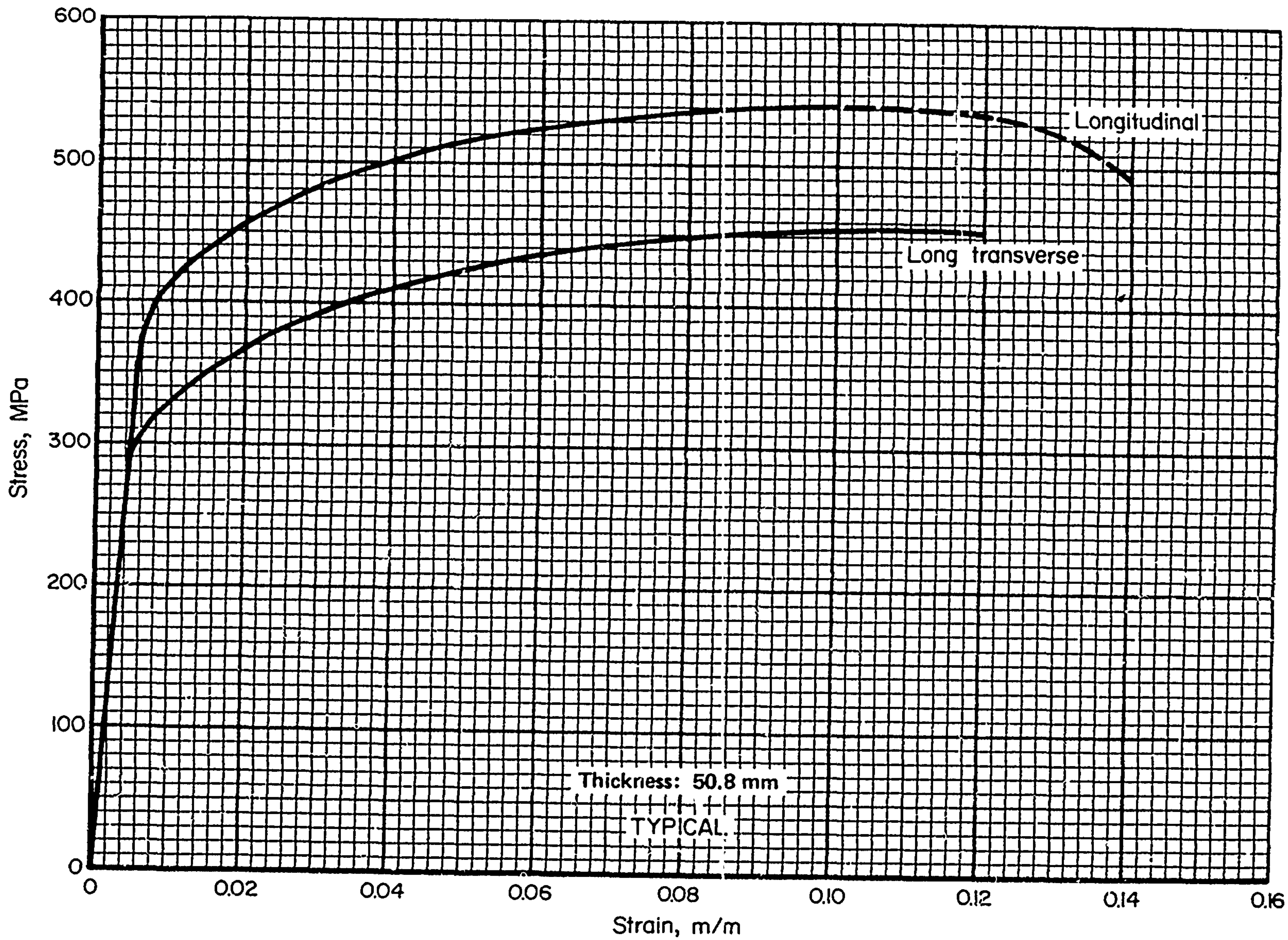


FIGURE 3.2.3.1.6(w). Typical tensile stress-strain curves (full range) for 2024-T4 aluminum alloy (extrusion) at room temperature.

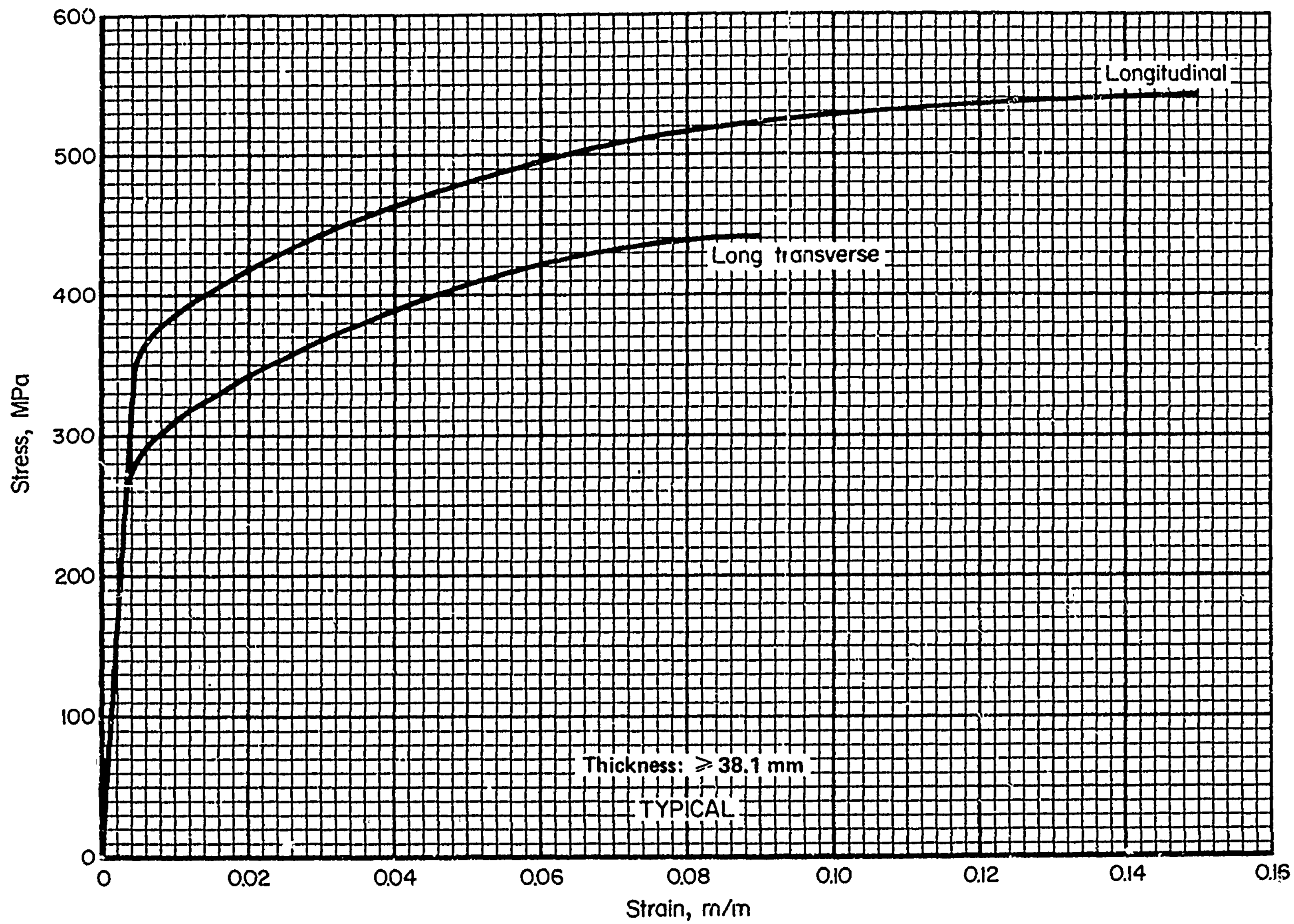


FIGURE 3.2.3.1.6(x). Typical tensile stress-strain curves (full range) for 2024-T42 aluminum alloy (extrusion) at room temperature.

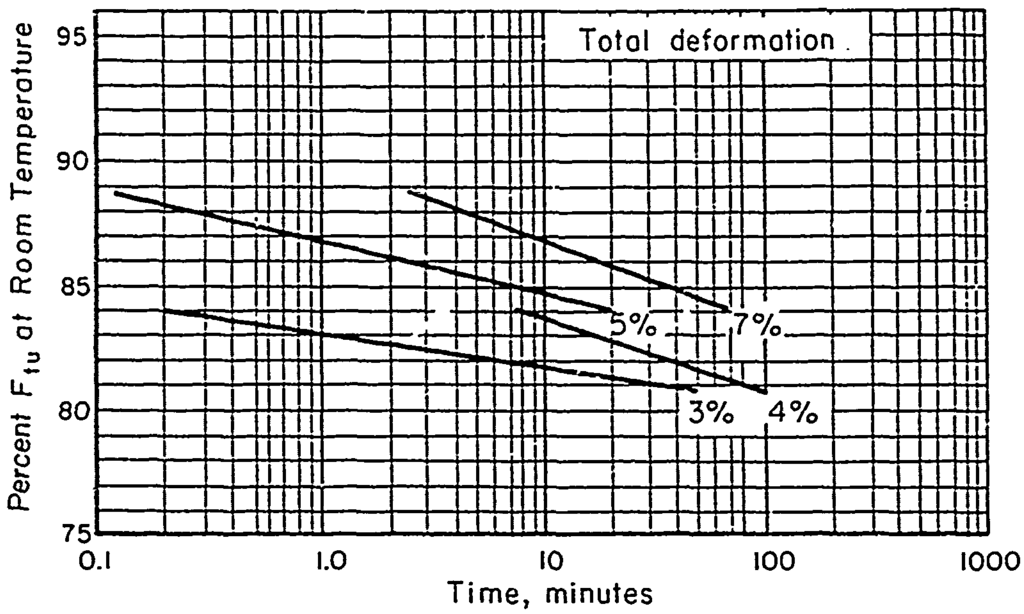


FIGURE 3.2.3.1.7(a). Creep data for 2024-T3 and 2024-T4 aluminum alloy (clad sheet) at 422 K.

Deformation includes thermal expansion of 0.25 percent. Heating rate 294 K per second.

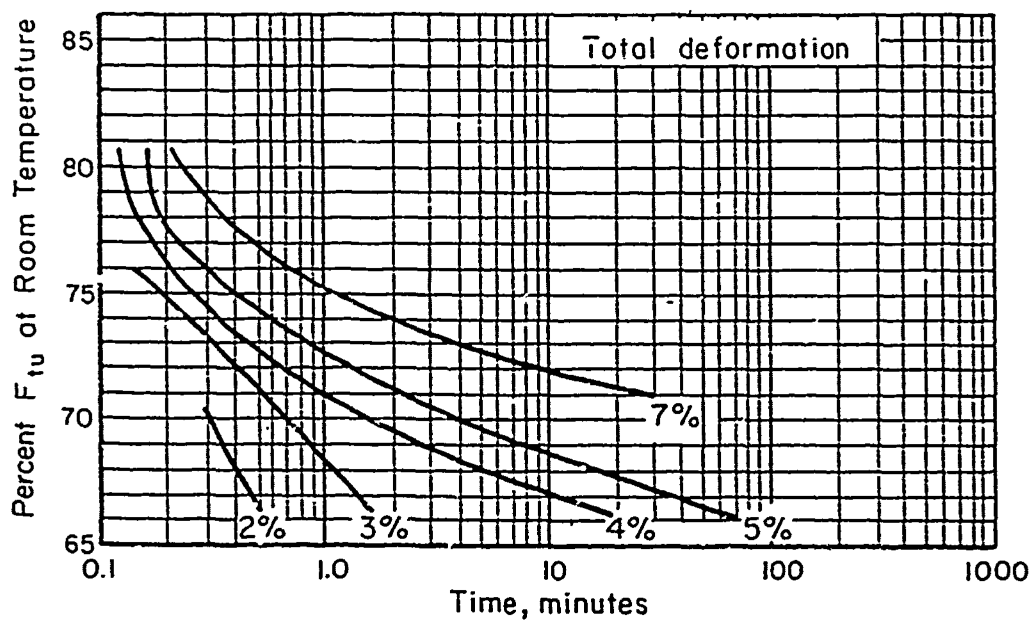


FIGURE 3.2.3.1.7(b). Creep data for 2024-T3 and 2024-T4 aluminum alloy (clad sheet) at 478 K.

Deformation includes thermal expansion of 0.44 percent. Heating rate 283 K per second.

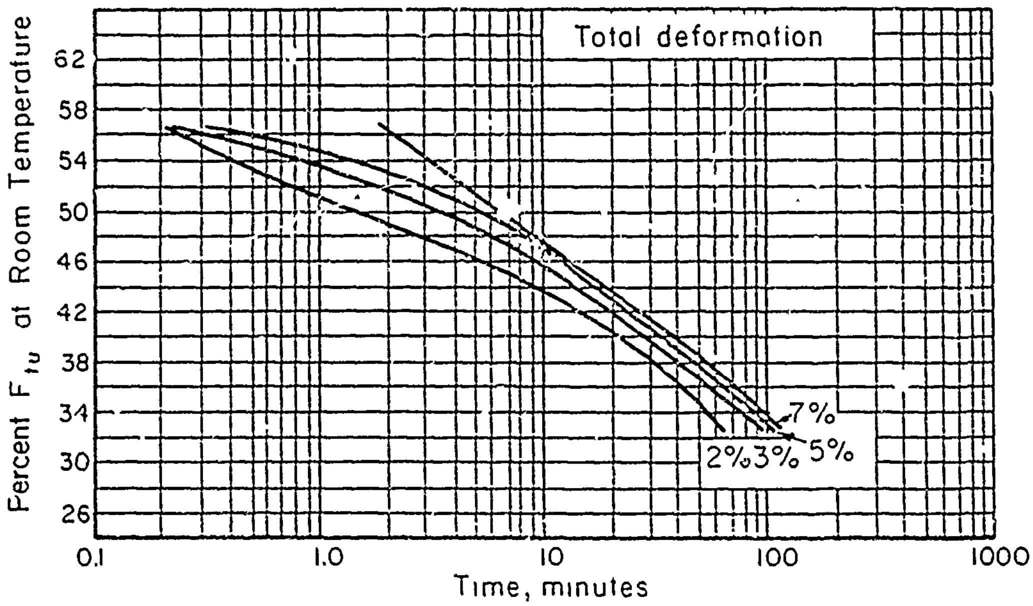


FIGURE 3.2.3.1.7(c). Creep data for 2024-T3 and 2024-T4 aluminum alloy (clad sheet) at 533 K.

Deformation includes thermal expansion of 0.55 per cent. Heating rate 283 to 297 K per second.

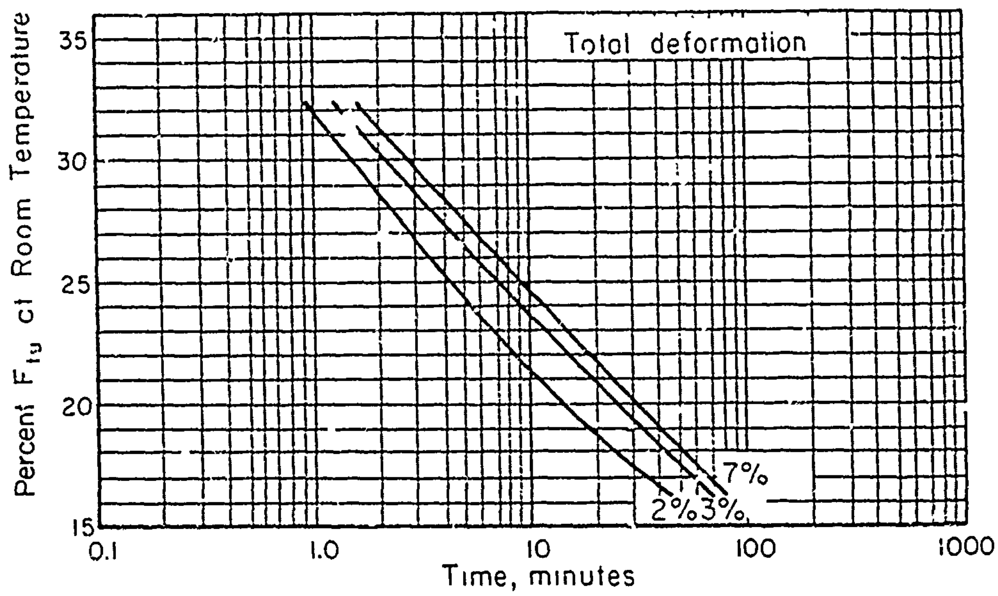


FIGURE 3.2.3.1.7(d). Creep data for 2024-T3 and 2024-T4 aluminum alloy (clad sheet) at 589 K.

Deformation includes thermal expansion of 0.69 percent. Heating rate 300 to 305 K per second.

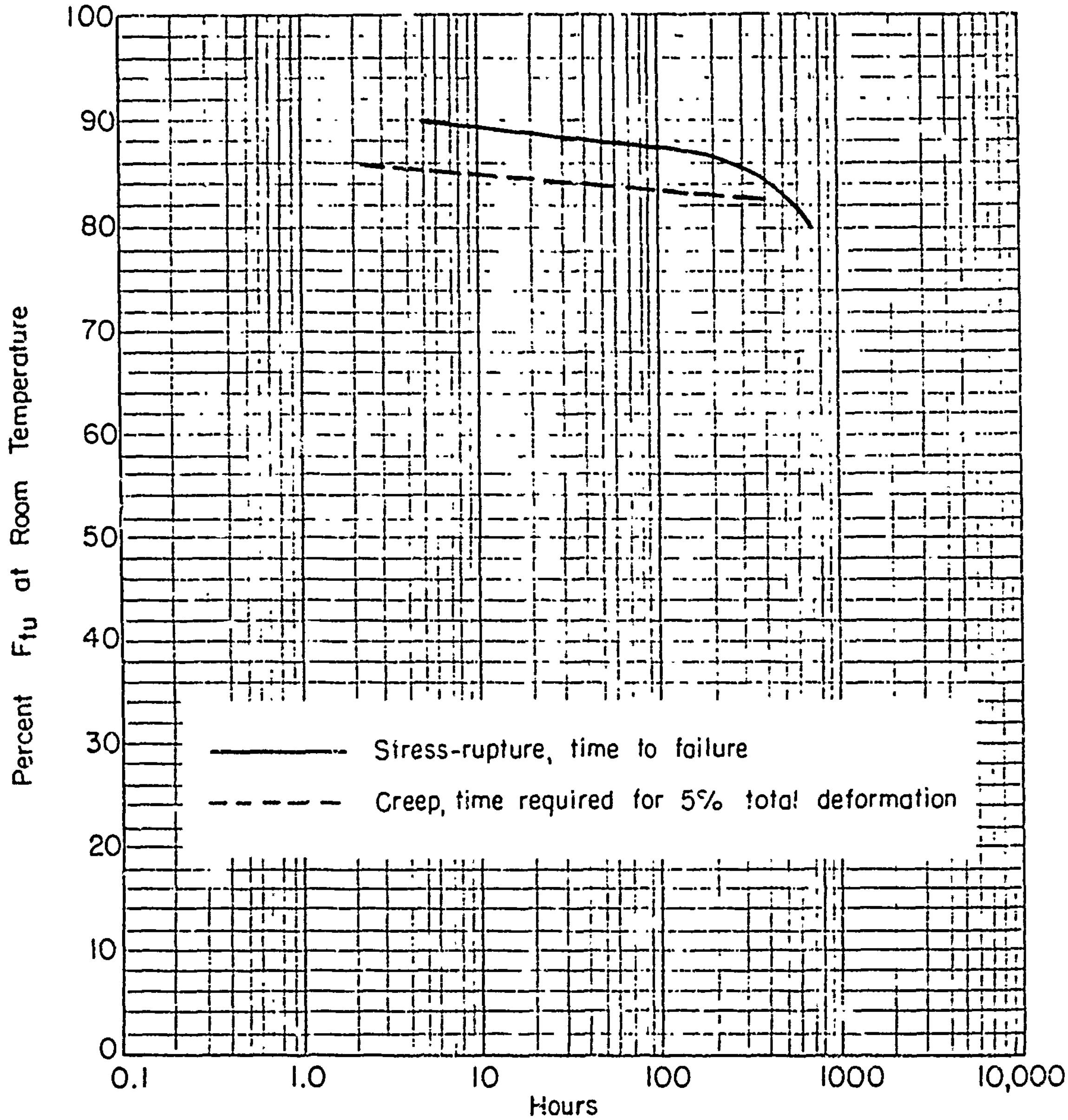


Figure 3.2.3.1.7(e) Creep and stress-rupture properties of wrought 2024-T3 aluminum alloy at 373 K.

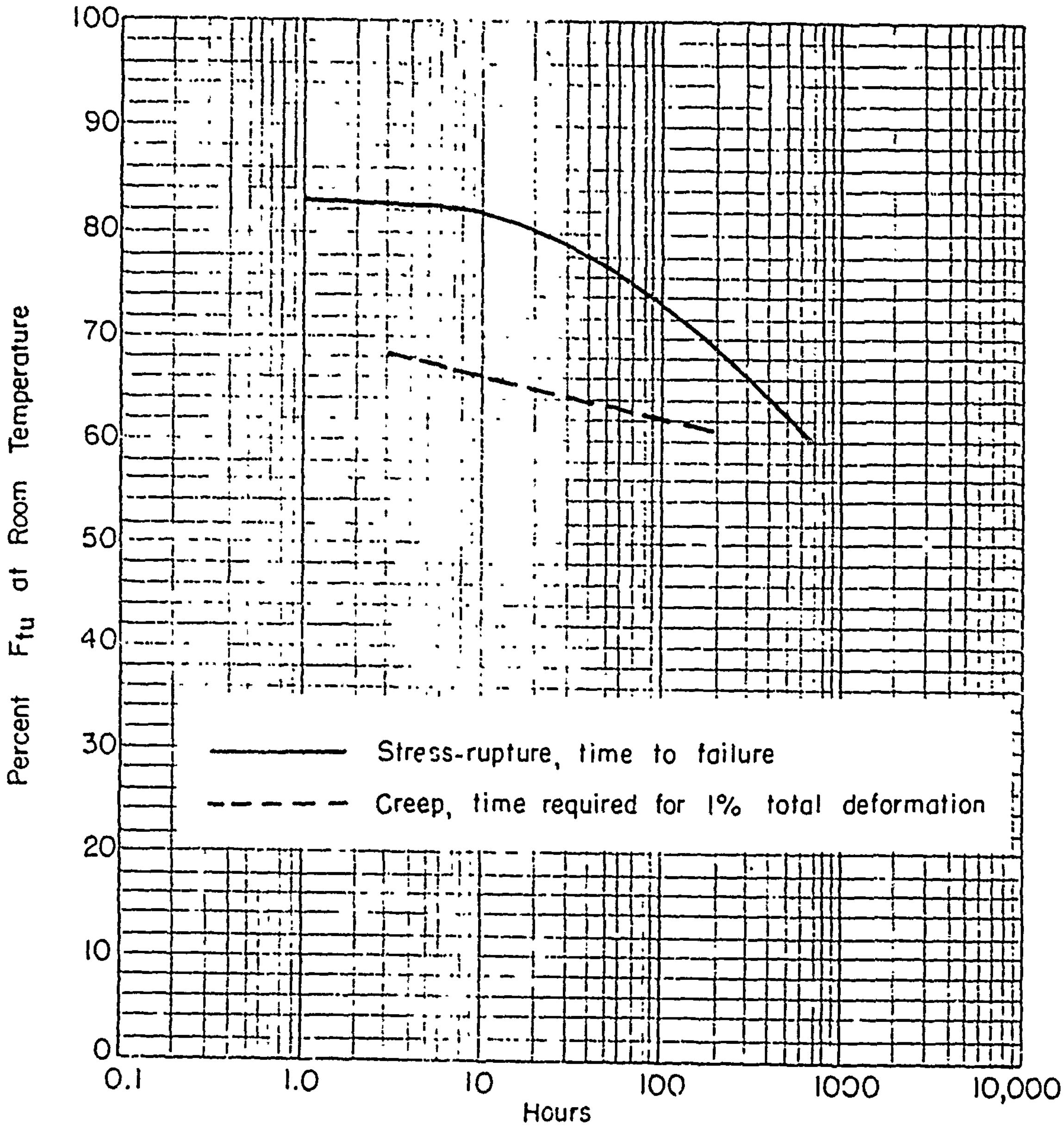


Figure 3.2.3.1.7(f) Creep and stress-rupture properties of wrought 2024-T3 aluminum alloy at 422 K.

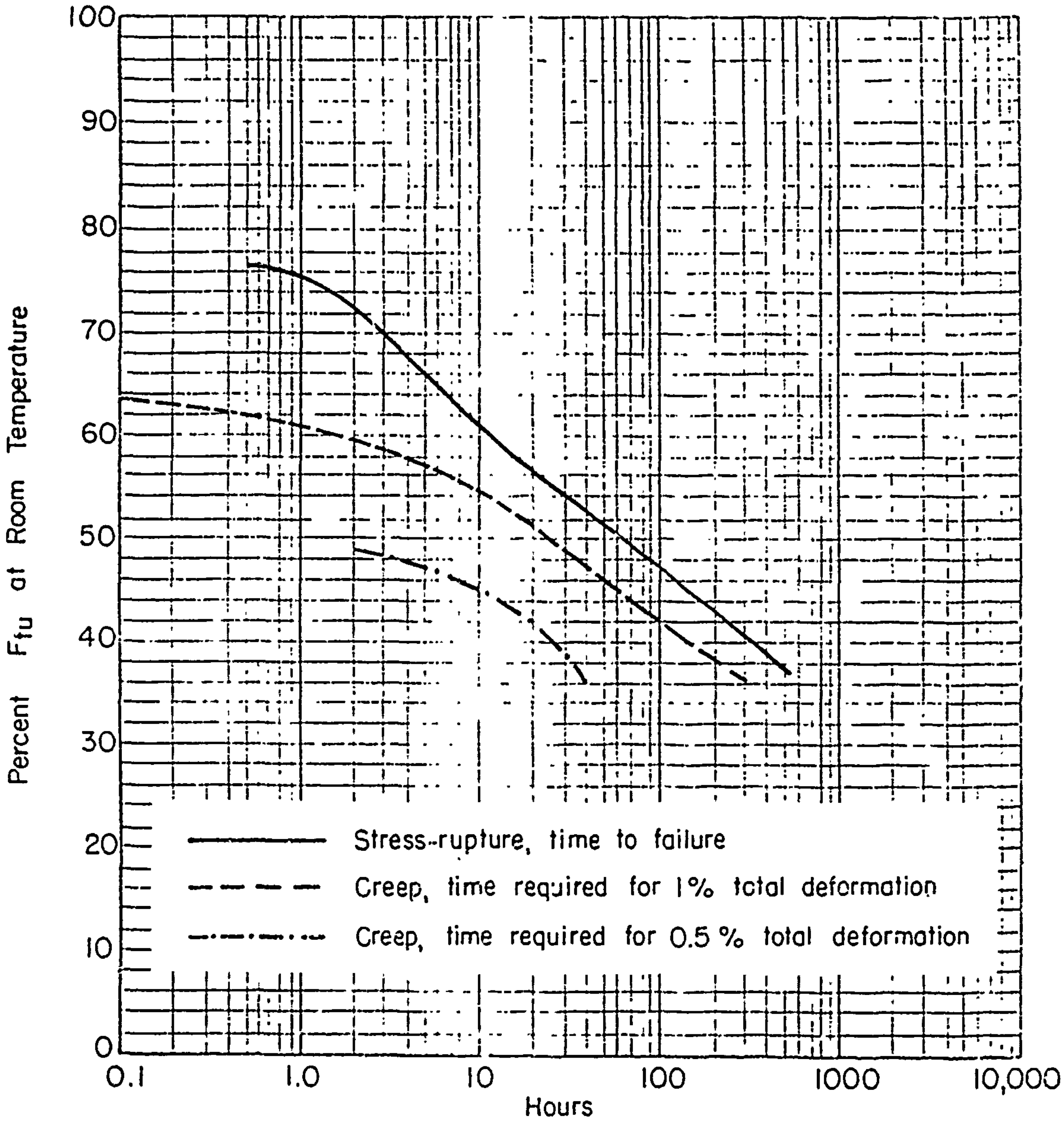


Figure 3.2.3.1.7 (g) Creep and stress-rupture properties of wrought 2024-T3 aluminum alloy at 464 K.

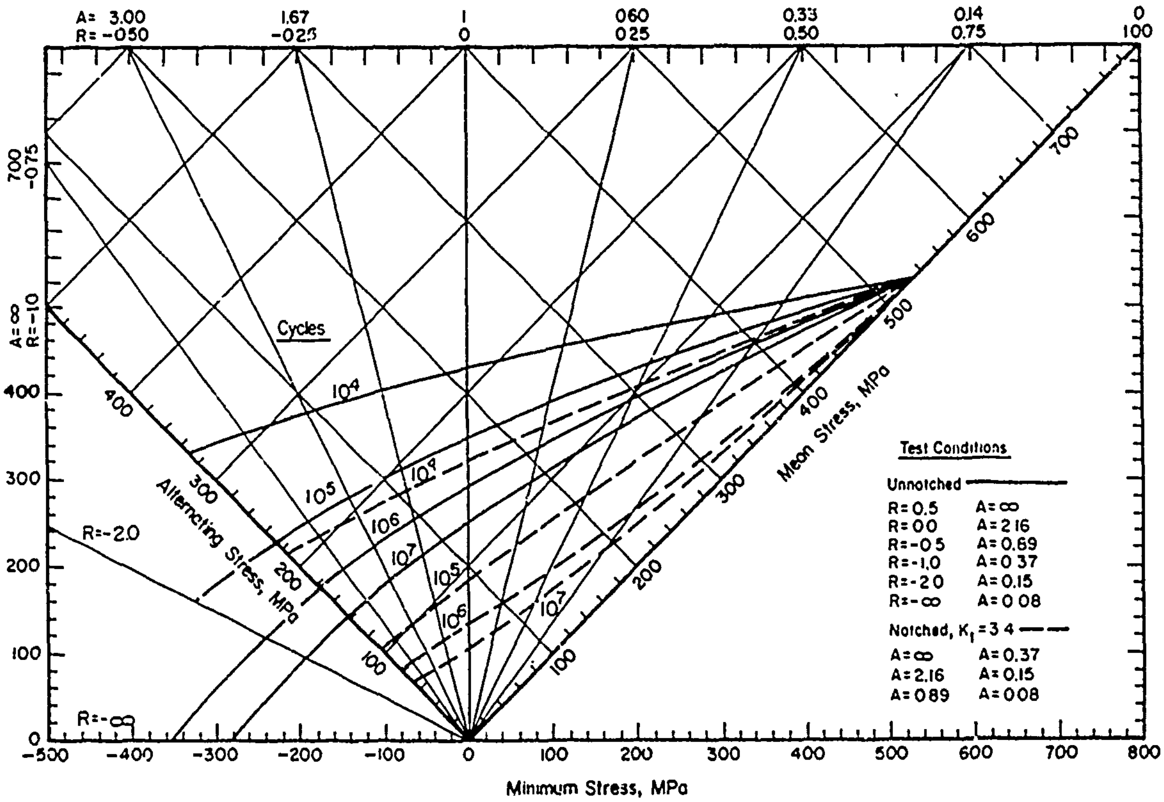


FIGURE 3.2.3.1.8(a). Typical constant-life diagram for fatigue behavior of various wrought products of 2024-T4 aluminum alloy

Correlative Information for Figure 3.2.3.1.8(a)

Product Form: Drawn rod, 19.1 mm diameter
Rolled bar, 25 x 190 mm and 28.6 mm diameter
Extruded rod and bar, 31.8 mm diameter, 31.8 x 31.8 mm, 31.8 x 102 mm

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

Properties:

TUS, MPa	TYS, MPa	Temp, K
531	381	RT (Unnotched)
531	—	RT (Notched)

Specimen Details:

Unnotched:
10.2 mm diameter

Notched, V-Groove, K_t = 3.4
11.4 mm gross diameter
10.2 mm net diameter
0.25 mm root radius, r
60° flank angle, ω

$K_N = 1.92$, $\rho = 0.457$ mm, where $K_N = 1 + \dfrac{K_t - 1}{1 + \dfrac{\pi}{\pi - \omega}\sqrt{\dfrac{\rho}{r}}}$

Surface Condition: Unnotched: longitudinal polish, 900 grit
Notched: as machined.

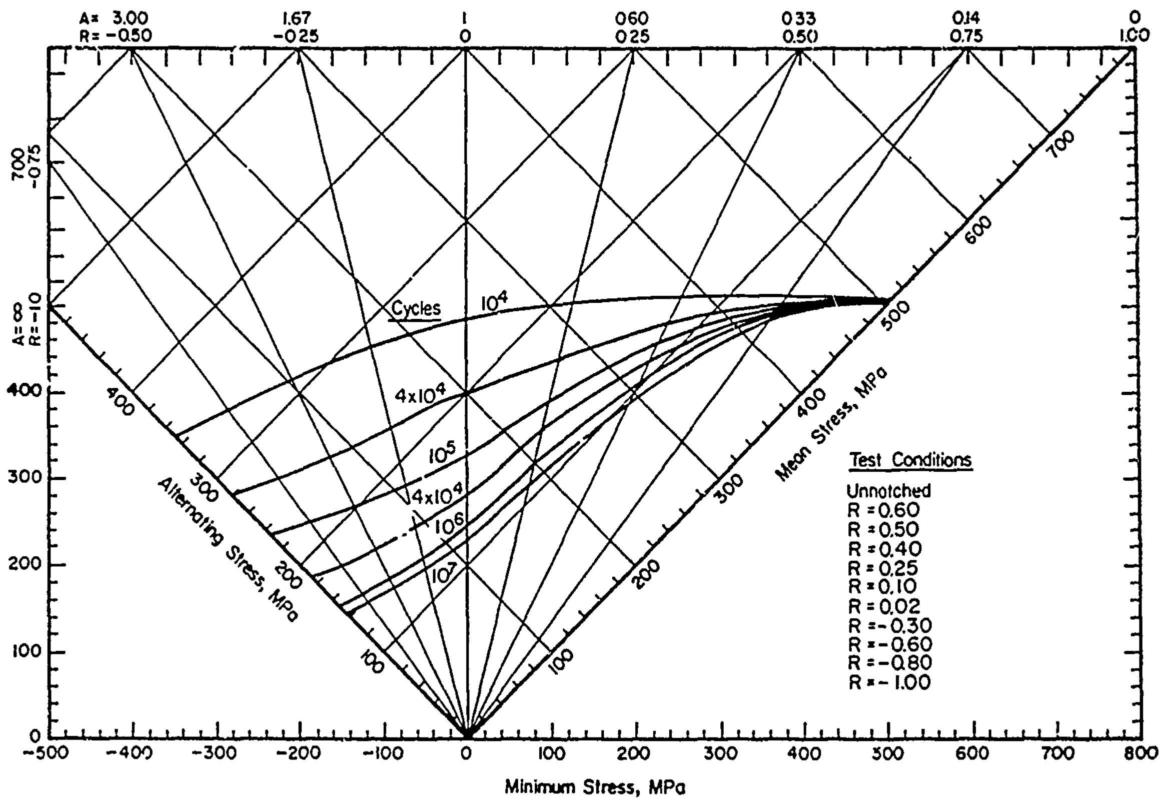


FIGURE 3.2.3.1.8(b). Typical constant-life diagram for unnotched fatigue behavior of 2024-T3 aluminum alloy

Correlative Information for Figure 3.2.3.1.8(b)

Product Form: 2.29 mm bare sheet

Properties:

TUS, MPa	TYS, MPa	Temp, K
503	372	RT

Test Parameters:
- Loading — Axial
- Frequency — 1100 to 1200 cpm
- Temperature — RT
- Atmosphere — Air

Specimen Details: Unnotched:

25.4-metre width

Surface Condition: Electropolished.

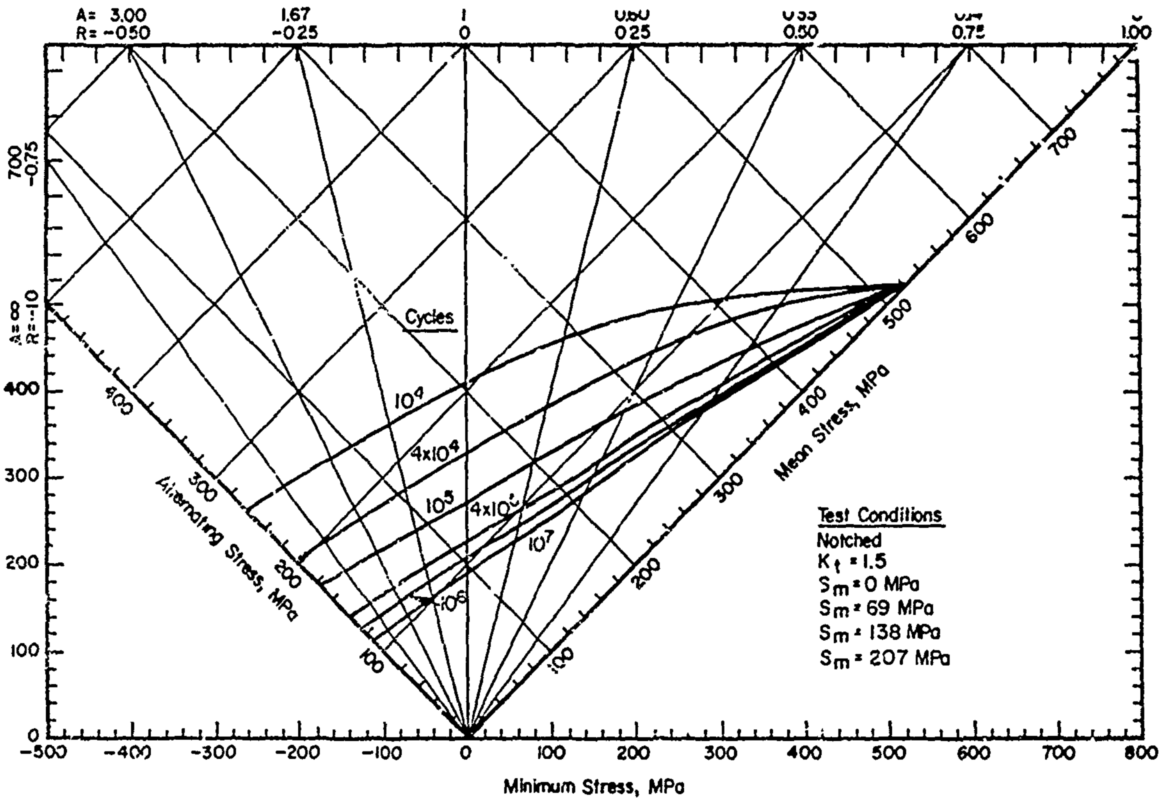


FIGURE 3.2.3.1.8(c). Typical constant-life diagram for notched fatigue behavior of 2024-T3 aluminum alloy

Correlative Information for Figure 3.2.3.1.8(c)

Product Form: 2.29 mm bare sheet

Test Parameters:
- Loading — Axial
- Frequency — 1100 to 1500 cpm
- Temperature — RT
- Atmosphere — Air

Properties:	TUS, MPa	TYS, MPa	Temp, K
	503	372	RT (Unnotched)
	523	—	RT (Notched)

Specimen Details: Notched, Edge, $K_t = 1.5$

76.2 mm gross width
38.1 mm net width
19.3 mm root radius, r
0° flank angle, ω

$K_N = 1.43$, $\rho = 0.508$ mm, where $K_N = 1 + \dfrac{K_t - 1}{1 + \frac{\pi}{\pi - \omega}\sqrt{\frac{\rho}{r}}}$

Surface Condition: Electropolished.

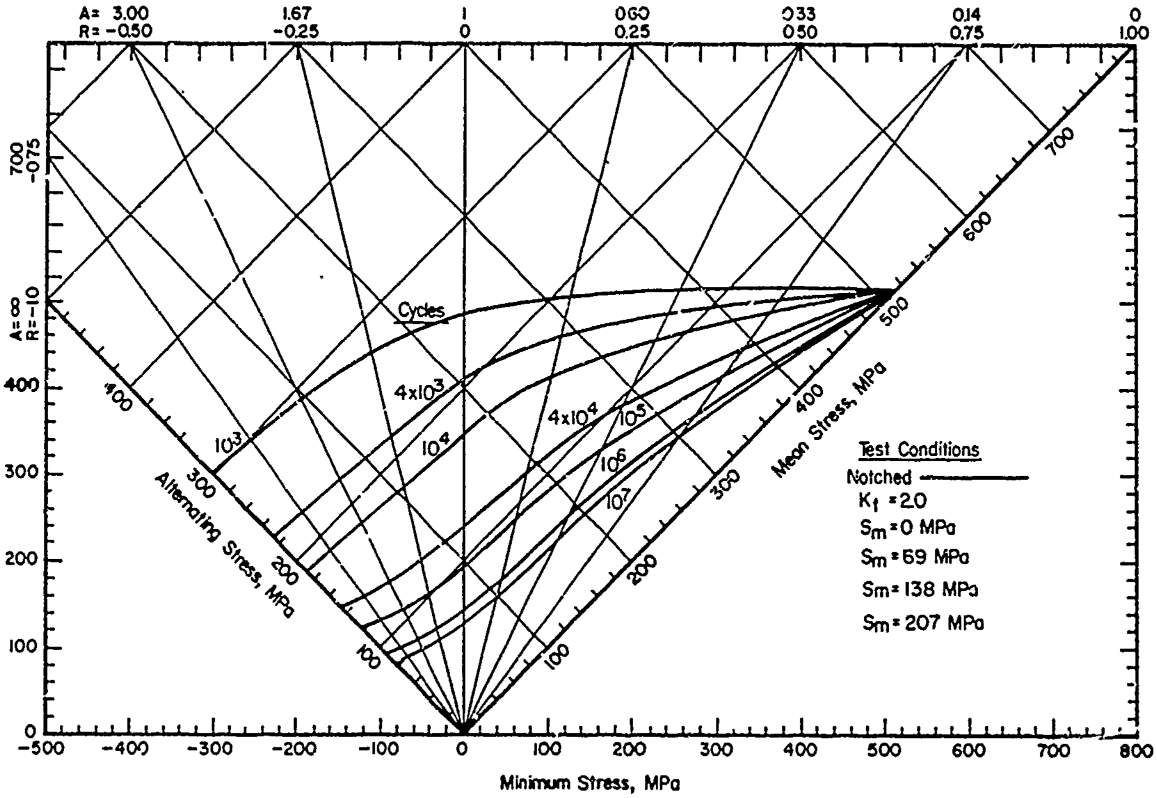


FIGURE 3.2.3.1.8(d). Typical constant-life diagram for notched fatigue behavior of 2024-T3 aluminum alloy

Correlative Information for Figure 3.2.3.1.8(d)

Product Form: 2.29 mm bare sheet

Test Parameters:
Loading — Axial
Frequency — 1100 to 1500 cpm
Temperature — RT
Atmosphere — Air

Properties:	TUS, MPa	TYS, MPa	Temp, K
	503	372	RT (Unnotched)
	514	—	RT (Notched)

Specimen Details: Notched, Edge, $K_t = 2.0$
57.2 mm gross width
38.1 mm net width
8.06 mm root radius, r
0° flank angle, ω

$K_N = 1.80$, $\rho = 0.508$, where $K_N = 1 + \frac{K_t - 1}{1 + \frac{\pi}{\pi - \omega}\sqrt{\frac{\rho}{r}}}$

Surface Condition. Electropolished.

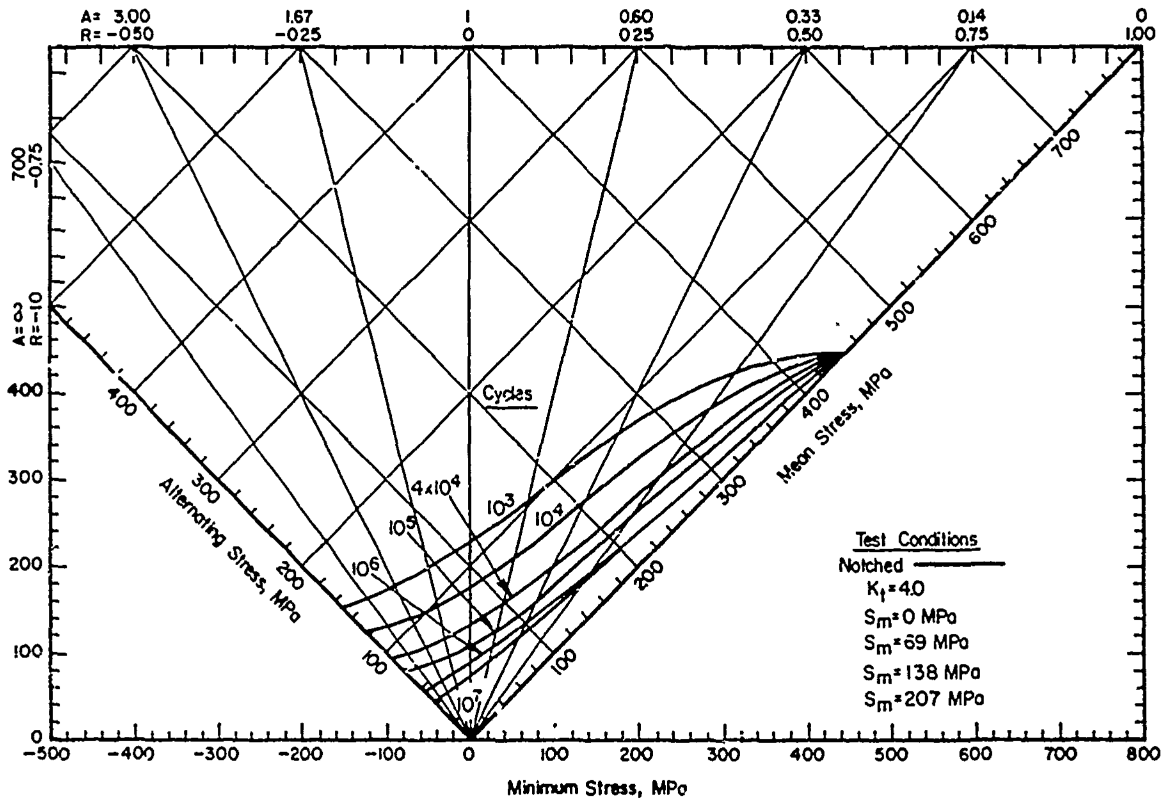


FIGURE 3.2.3.1.8(e). Typical constant-life diagram for notched fatigue behavior of 2024-T3 aluminum alloy

Correlative Information for Figure 3.2.3.1.8(e)

Product Form: 2.29 mm

Test Parameters:
Loading — Axial
Frequency — 1100 to 1500 cpm
Temperature — RT
Atmosphere — Air

Properties:	TUS, MPa	TYS, MPa	Temp, K
	503	372	RT (Unnotched)
		—	RT (Notched)

Specimen Details: Notched, Edge, $K_t = 4.0$
57.2 mm gross width
38.1 mm net width
1.45 mm root radius, r
0° flank angle, ω

$K_N = 2.88$, $\rho = 0.508$ mm, where $K_N = 1 + \dfrac{K_t - 1}{1 + \frac{\pi}{\pi - \omega}\sqrt{\frac{\rho}{r}}}$

Surface Condition: Electropolished.

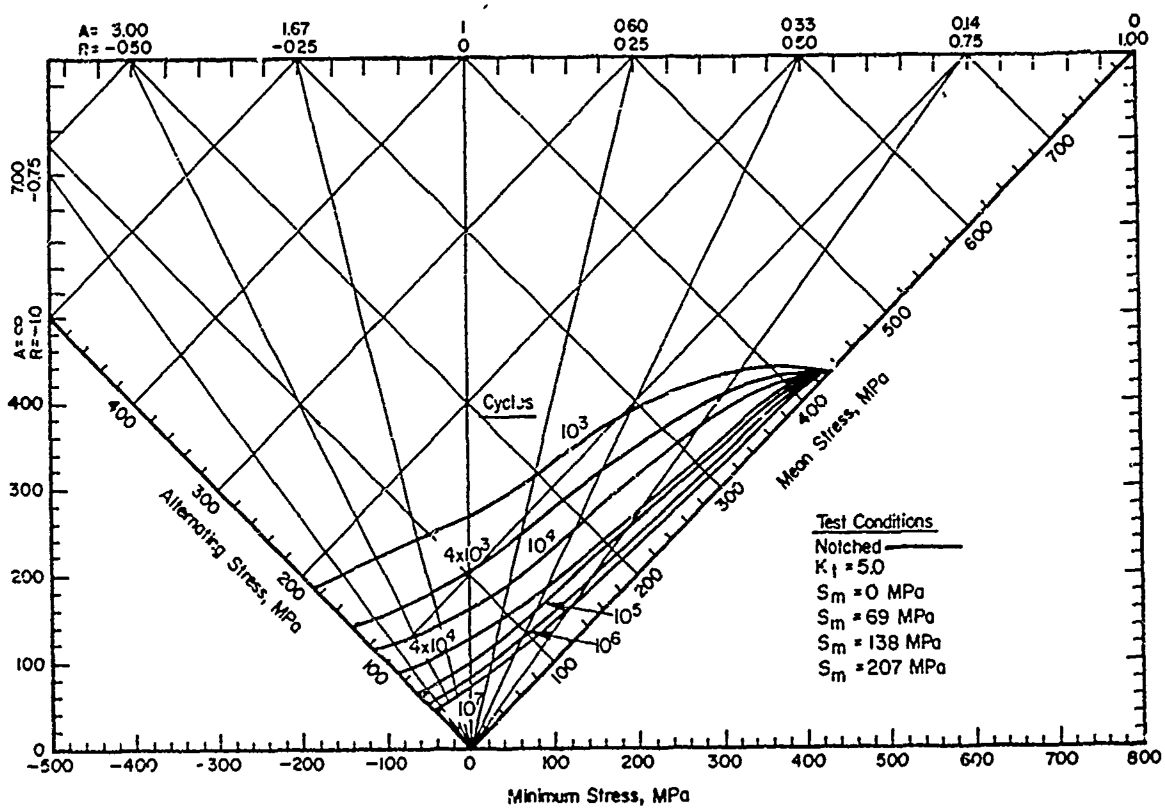


FIGURE 3.2.3.1.8(f). Typical constant-life diagram for notched fatigue behavior of 2024-T3 aluminum alloy

Correlative Information for Figure 3.2.3.1.8(f)

Product Form: 2.29 mm bare sheet

Properties:

TUS, MPa	TYS, MPa	Temp, K
503	372	RT (Unnotched)
430	—	RT (Notched)

Test Parameters:
Loading — Axial
Frequency — 1100 to 1500 cpm
Temperature — RT
Atmosphere — Air

Specimen Details: Notched, Edge, $K_t = 5.0$
57.2 mm gross width
38.1 mm net width
0.79 mm root radius, r
0° flank angle, ω

$K_N = 3.22, \rho = 0.508,$ $$K_N = 1 + \frac{K_t - 1}{1 + \frac{\pi}{\pi - \omega}\sqrt{\frac{\rho}{r}}}$$

Surface Condition: Electropolished.

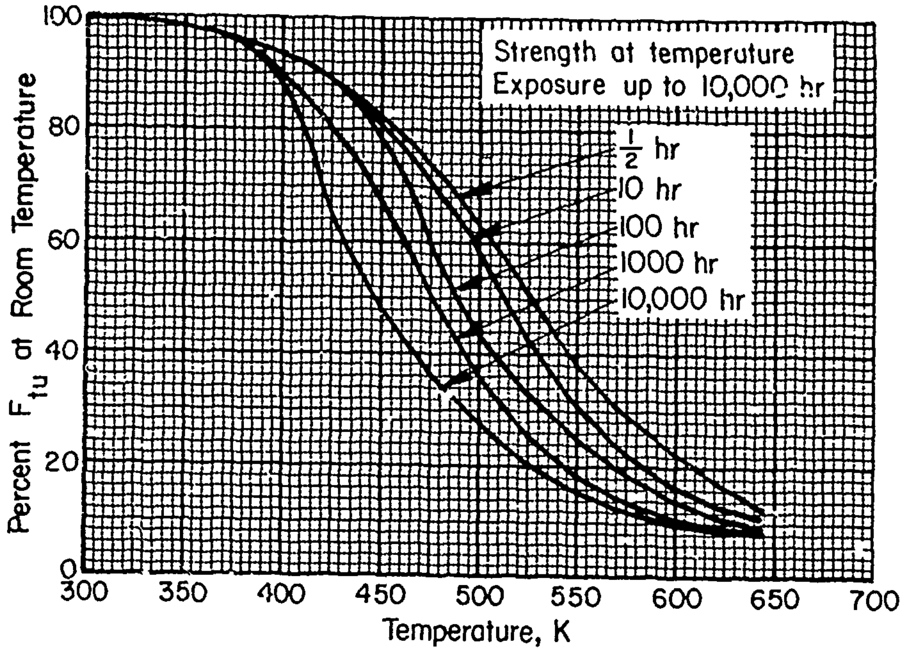


FIGURE 3.2.3.3.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of 2024-T62 aluminum alloy (all products).

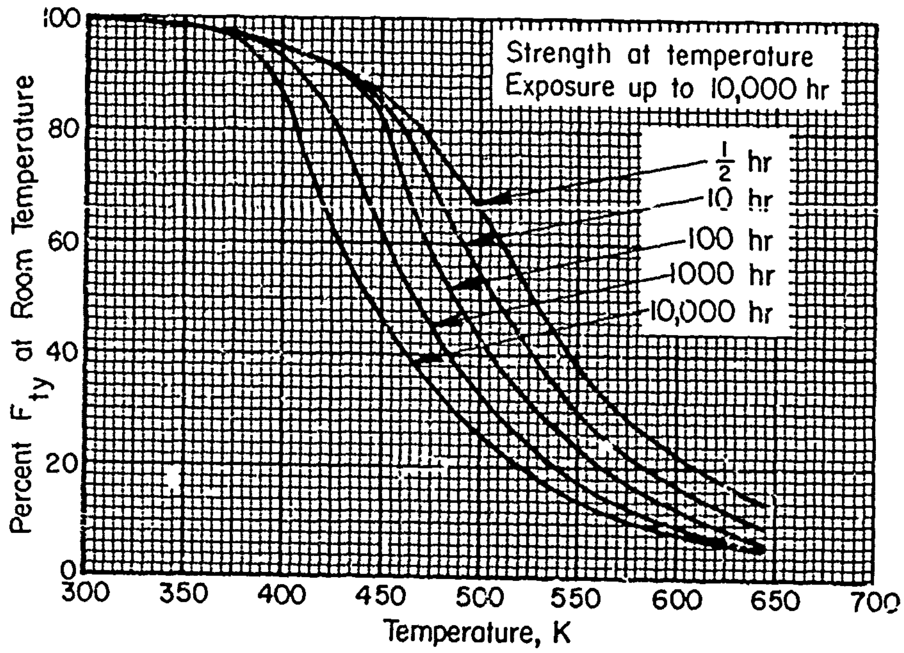


FIGURE 3.2.3.3.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of 2024-T62 aluminum alloy (all products).

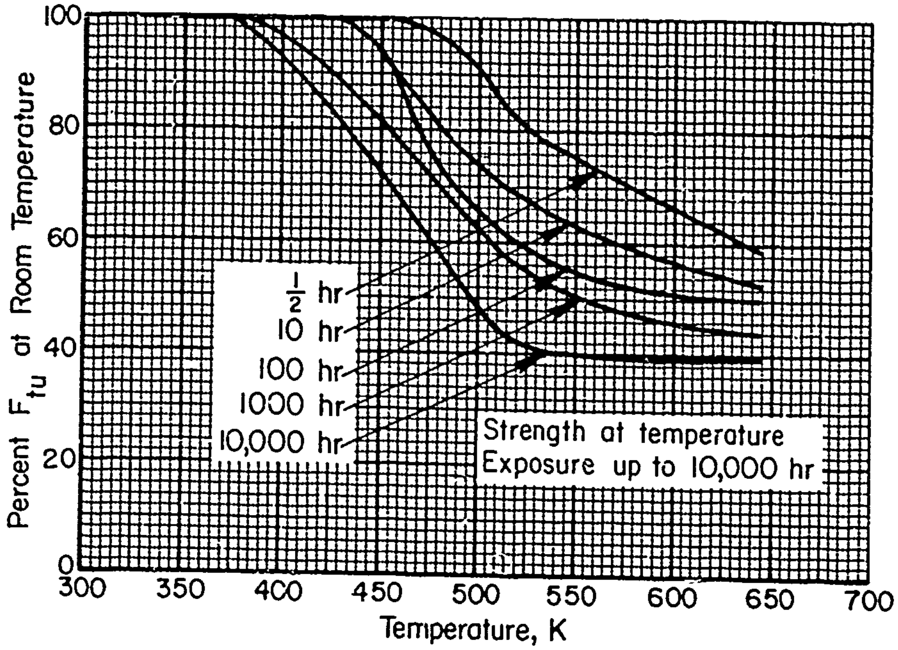


FIGURE 3.2.3.3.1(c). Effect of exposure at elevated temperatures on the room-temperature ultimate tensile strength (F_{tu}) of 2024-T62 aluminum alloy (all products).

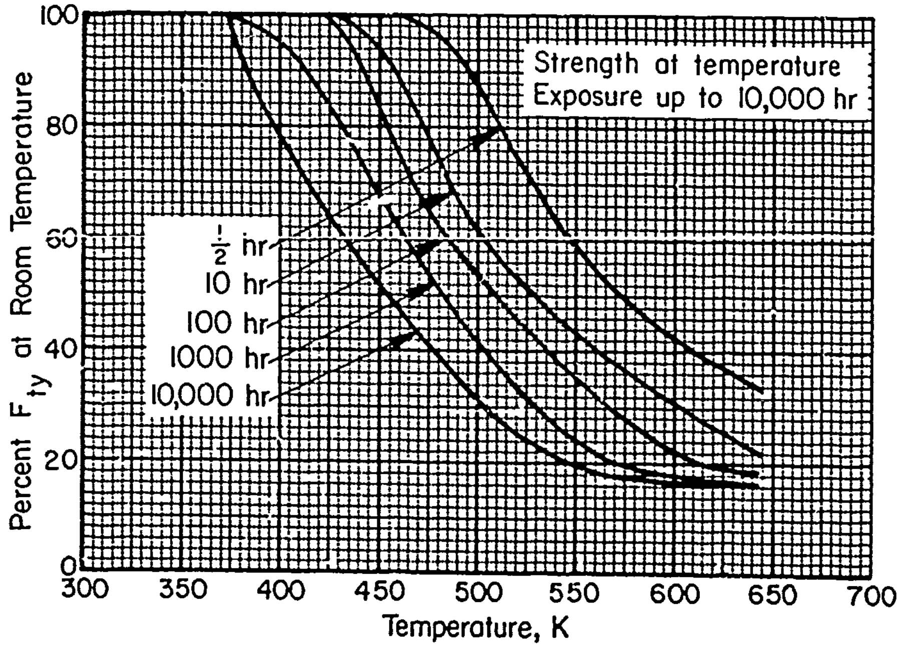


FIGURE 3.2.3.3.1(d). Effect of exposure at elevated temperatures on the room-temperature tensile yield strength (F_{ty}) of 2024-T62 aluminum alloy (all products).

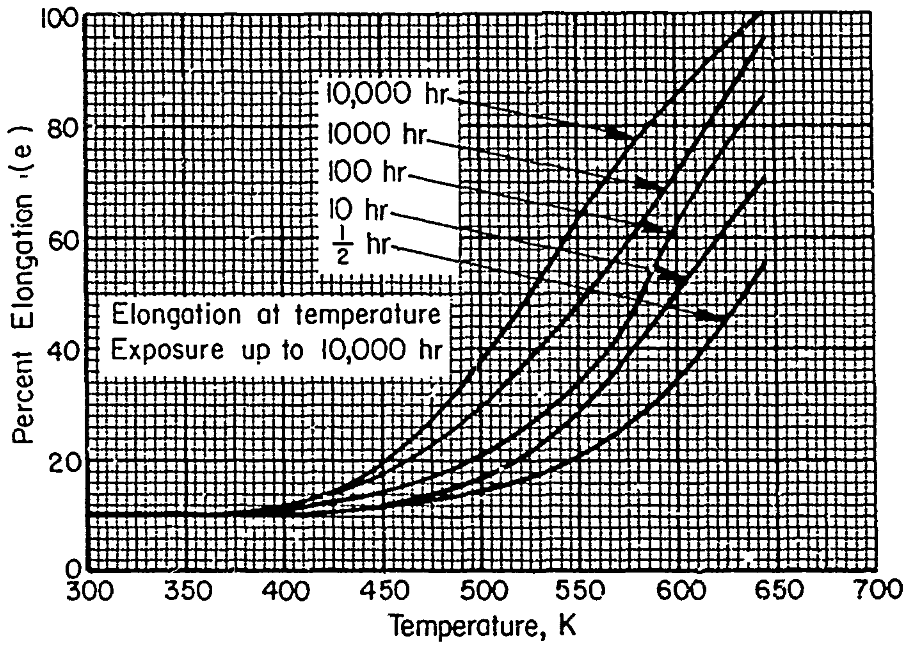


FIGURE 3.2.3.3.5(a). Effect of temperature on the elongation of 2024-T62 aluminum alloy (all products).

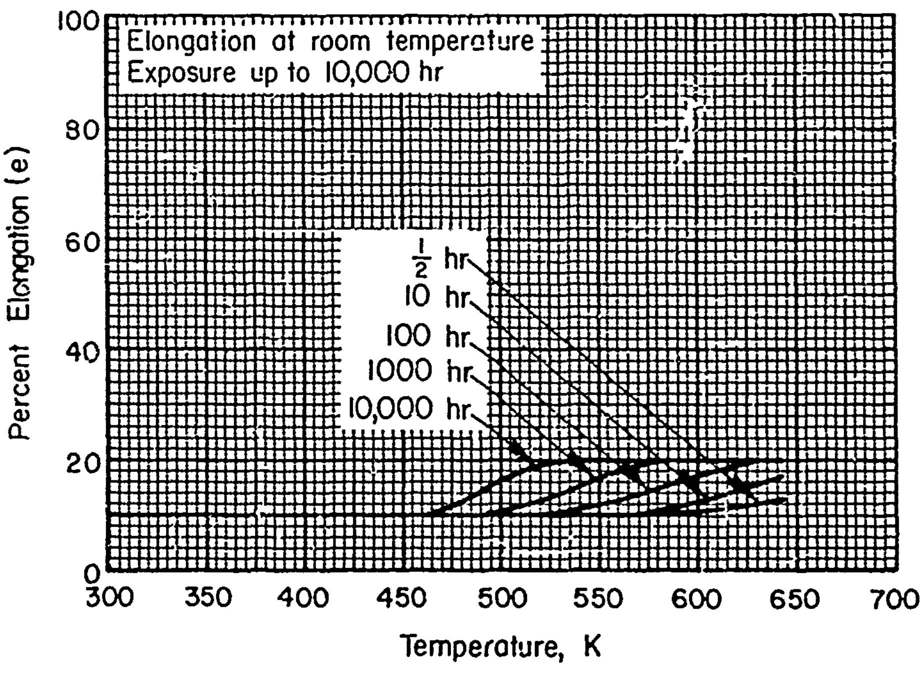


FIGURE 3.2.3.3.5(b). Effect of exposure at elevated temperatures on the elongation of 2024-T62 aluminum alloy (all products).

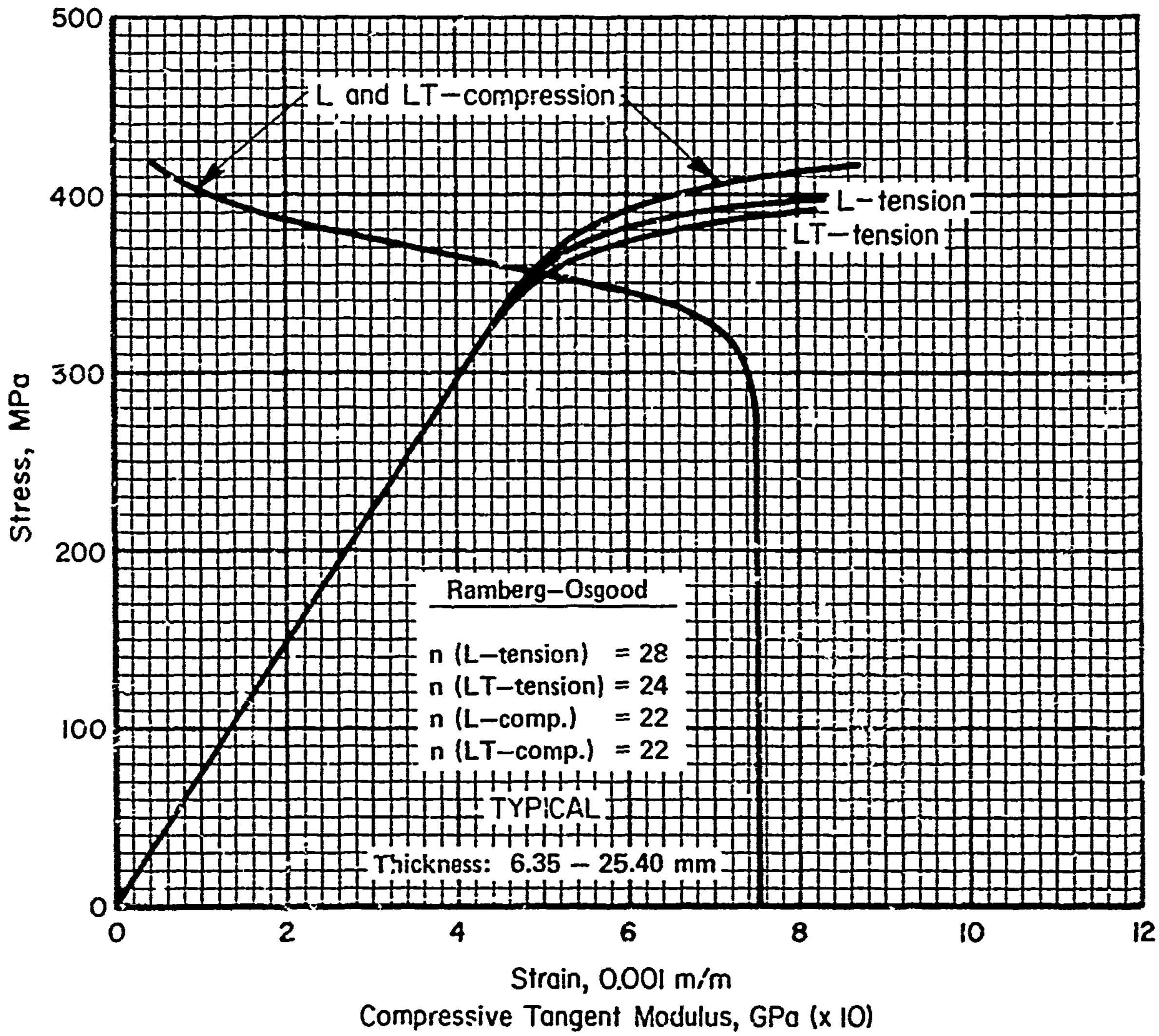


FIGURE 3.2.3.3.6. Typical tensile stress-strain and compressive stress-strain and tangent-modulus curves for 2024-T62 aluminum alloy (plate) at room temperature.

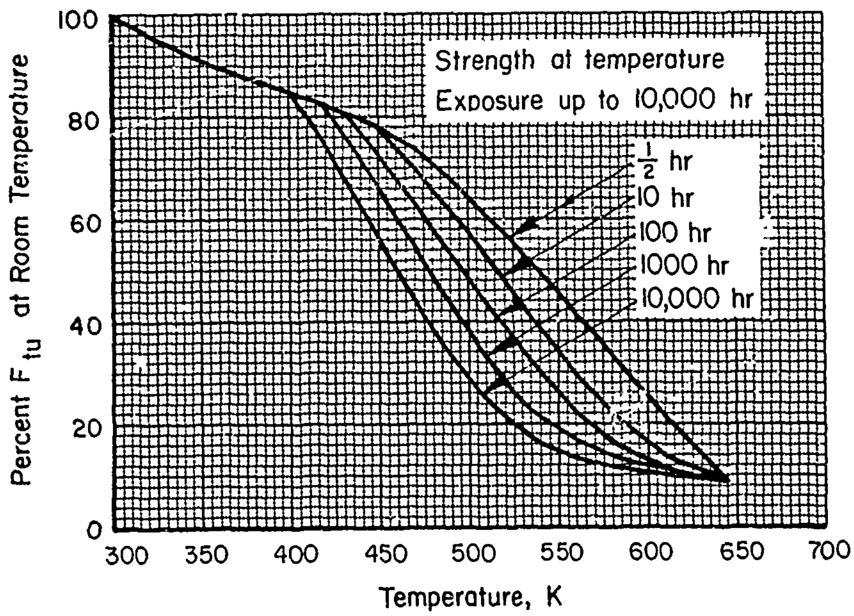


FIGURE 3.2.3.4.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of 2024-T81, T851, T8510 and T8511 aluminum alloy (all products).

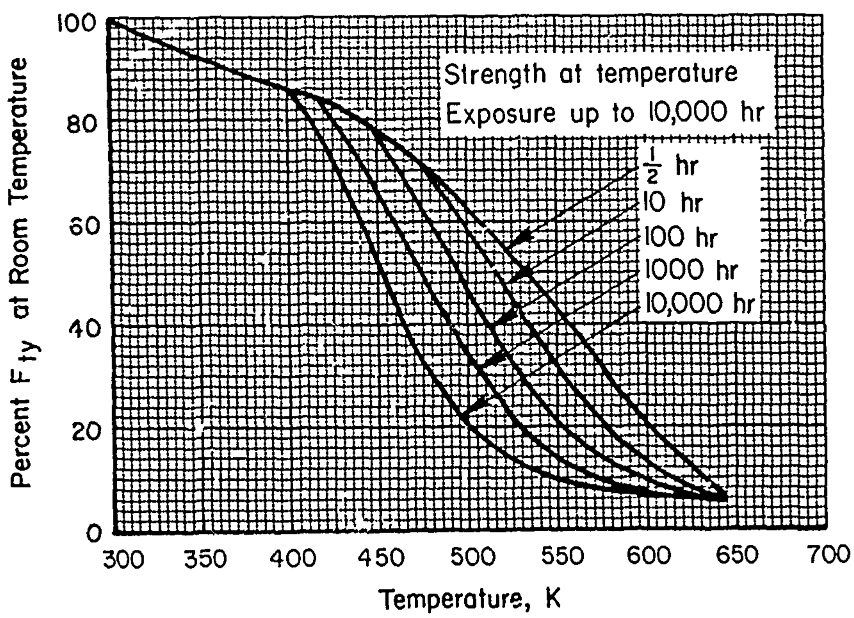


FIGURE 3.2.3.4.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of 2024-T81, T851, T8510 and T8511 aluminum alloy (all products).

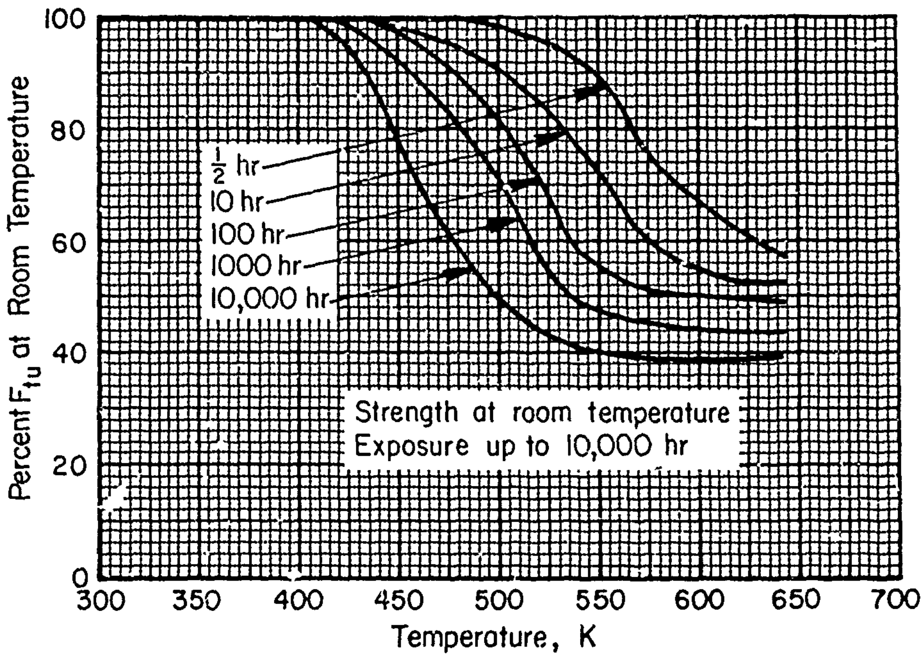


FIGURE 3.2.3.4.1(c). Effect of exposure at elevated temperatures on the room-temperature ultimate tensile strength (F_{tu}) of 2024-T81, T851, T8510 and T8511 aluminum alloy (all products).

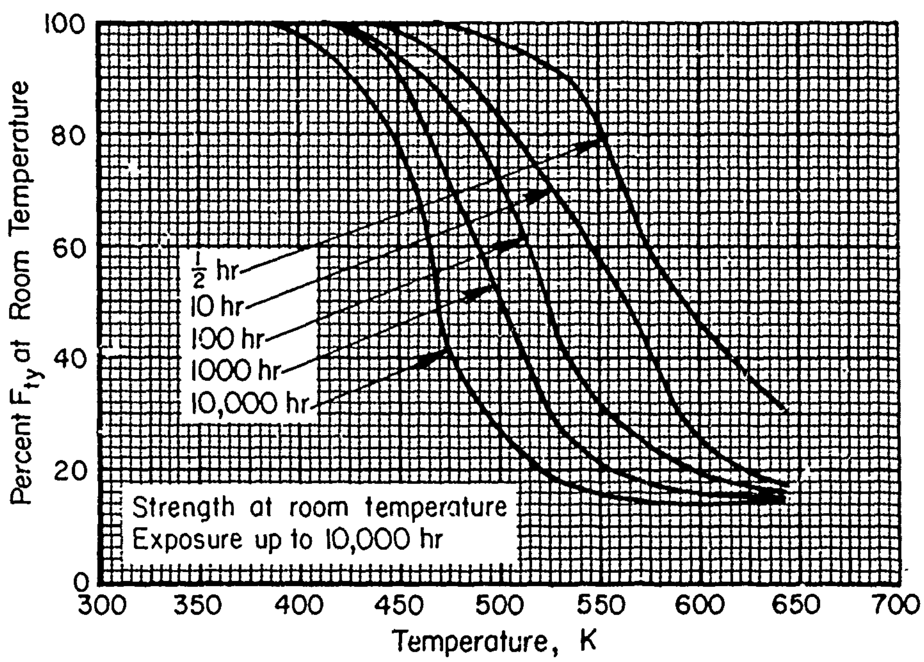


FIGURE 3.2.3.4.1(d). Effect of exposure at elevated temperatures on the room-temperature tensile yield strength (F_{ty}) of 2024-T81, T851, T8510 and T8511 aluminum alloy (all products).

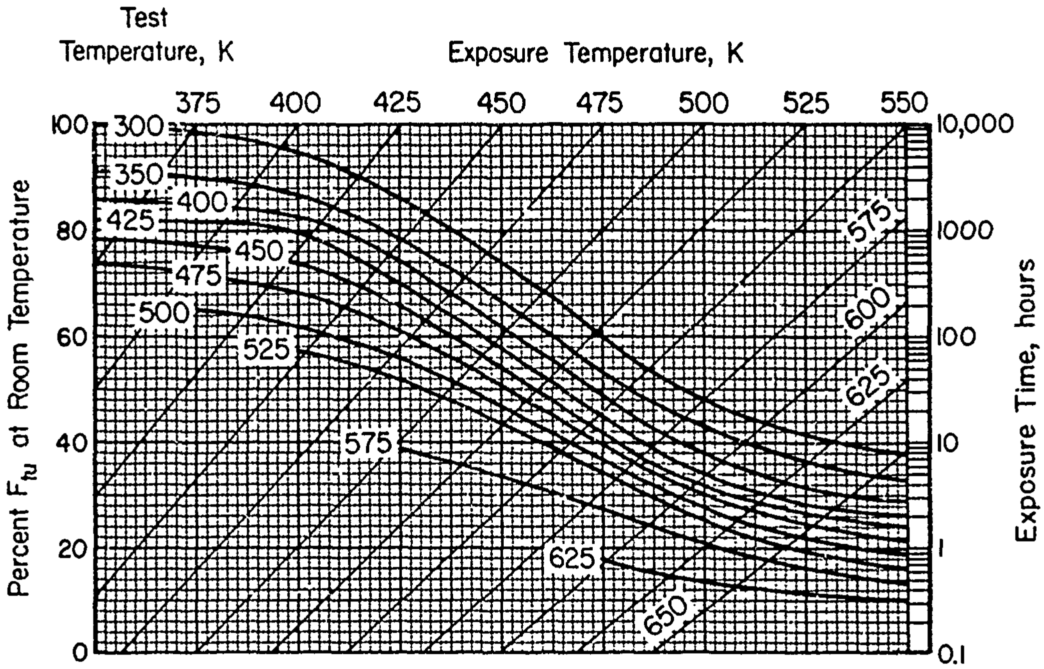


FIGURE 3.2.3.4.1(e). Effect of temperature on the ultimate tensile strength (F_{tu}) of 2024-T81 clad aluminum alloy (sheet). Note: Instructions for use of these curves are presented in Section 3.7.2.1.

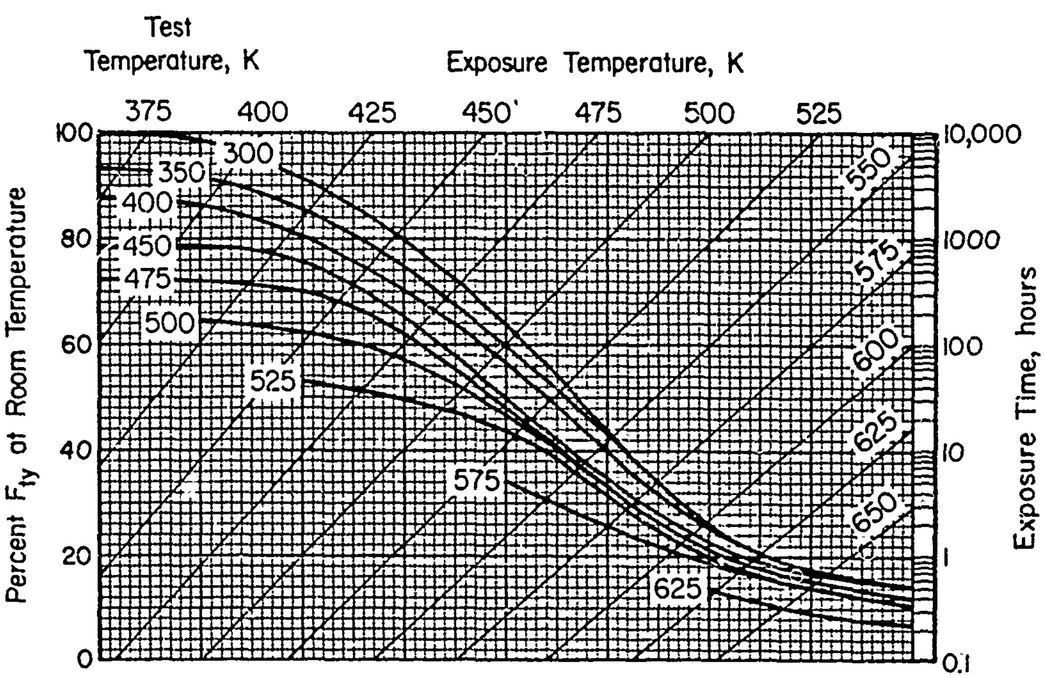


FIGURE 3.2.3.4.1(f). Effect of temperature on the tensile yield strength (F_{ty}) of 2024-T81 clad aluminum alloy (sheet). Note: Instructions for use of these curves are presented in Section 3.7.2.1.

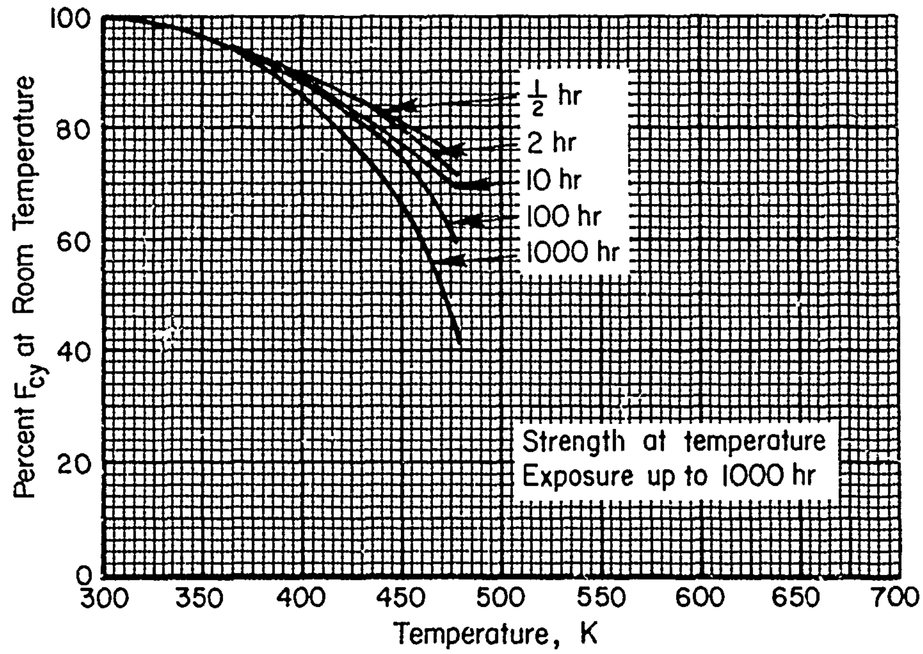


FIGURE 3.2.3.4.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of 2024-T81, T851, T8510 and T8511 aluminum alloy (all products).

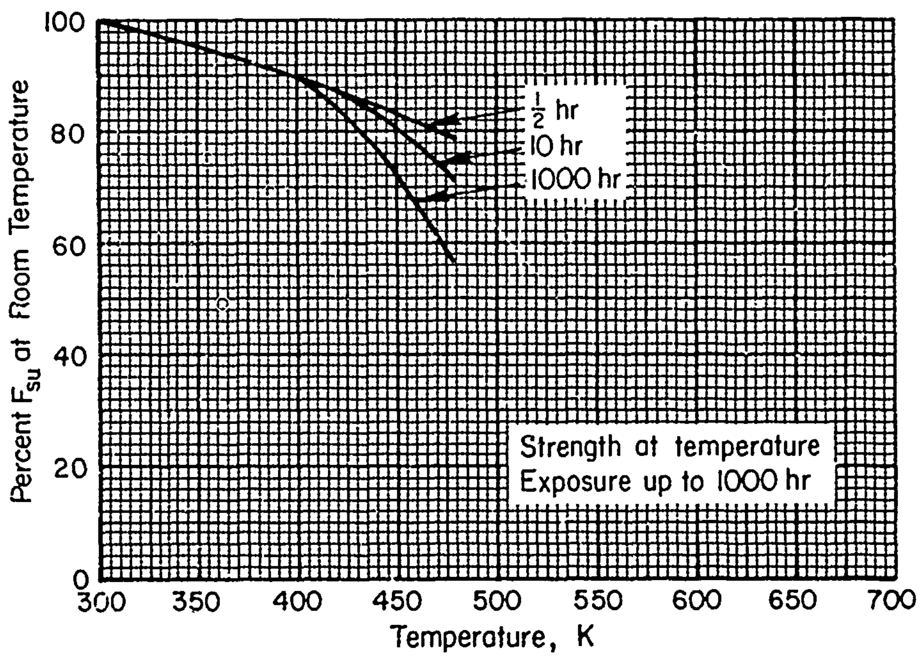


FIGURE 3.2.3.4.2(b). Effect of temperature on the ultimate shear strength (F_{su}) of 2024-T1, T851, T8510 and T8511 aluminum alloy (all products).

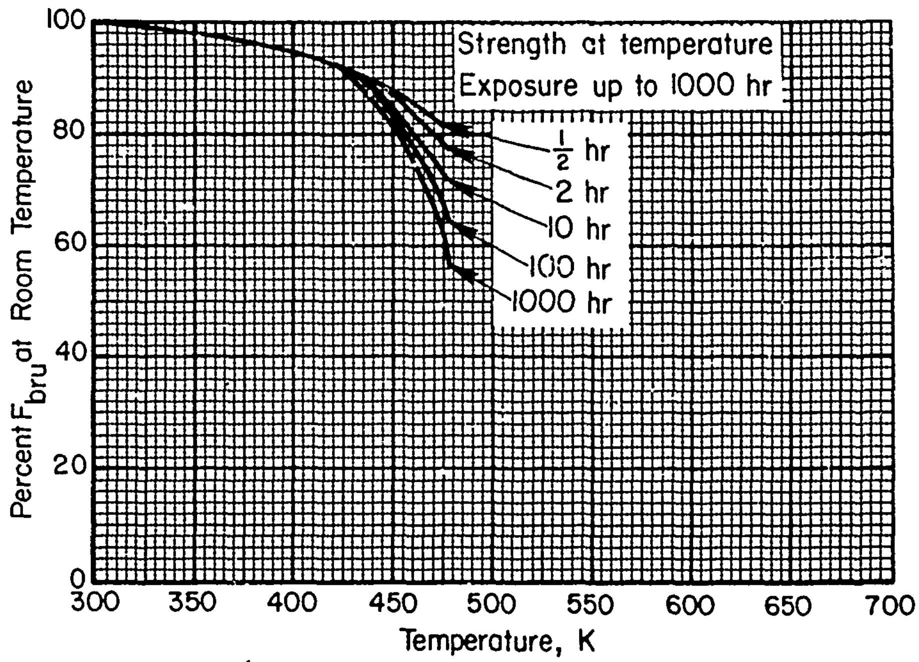


FIGURE 3.2.3.4.3(a). Effect of temperature on the ultimate bearing strength (F_{bru}) of 2024-T81, T851, T8510 and T8511 aluminum alloy (all products).

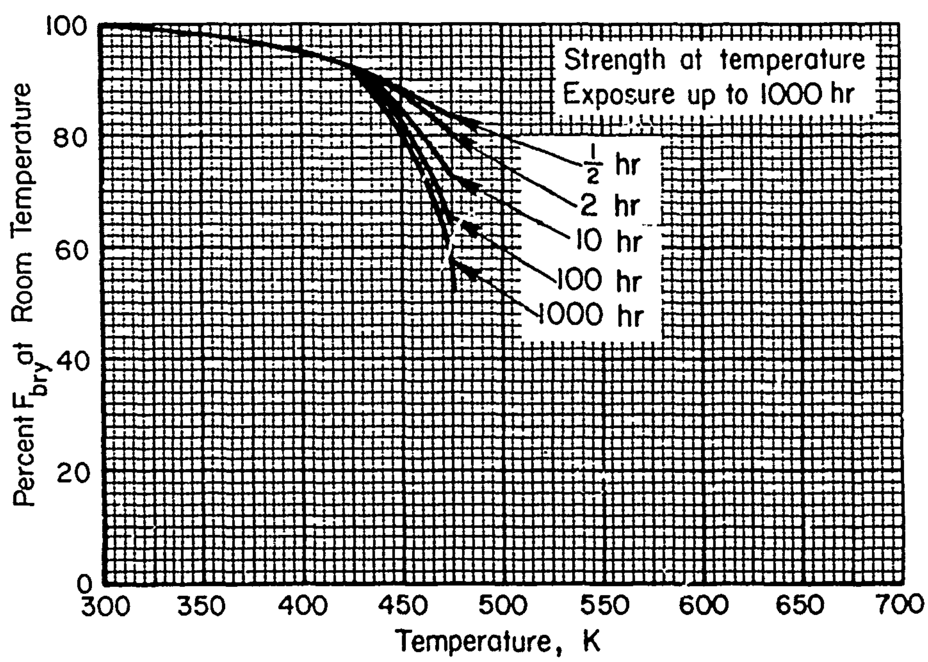


FIGURE 3.2.3.4.3(b). Effect of temperature on the bearing yield strength (F_{bry}) of 2024-T81, T851, T8510 and T8511 aluminum alloy (all products).

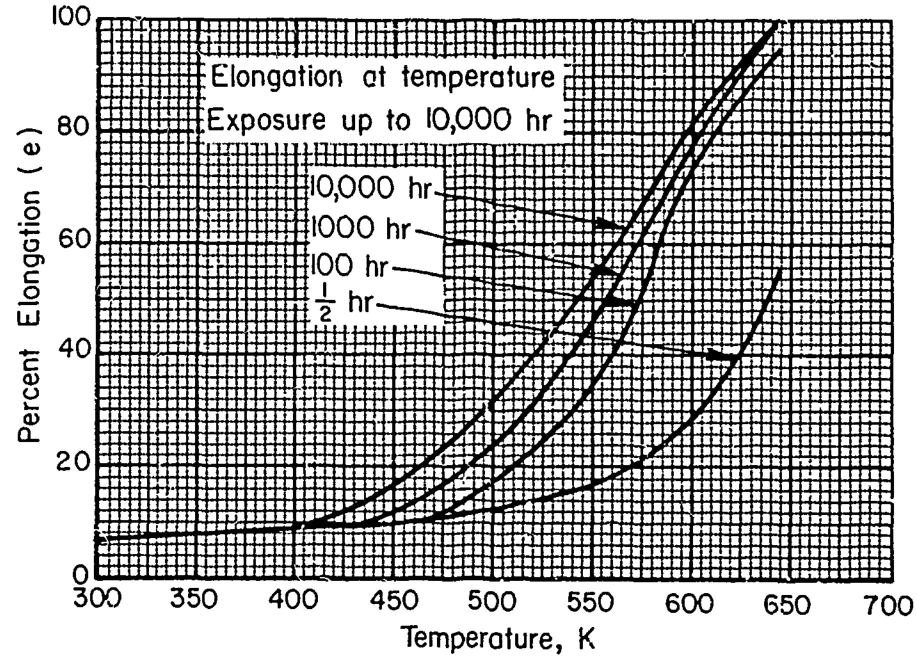


FIGURE 3.2.3.4.5(a). Effect of temperature on the elongation of 2024-T81, T851, T8510 and T8511 aluminum alloy (all products).

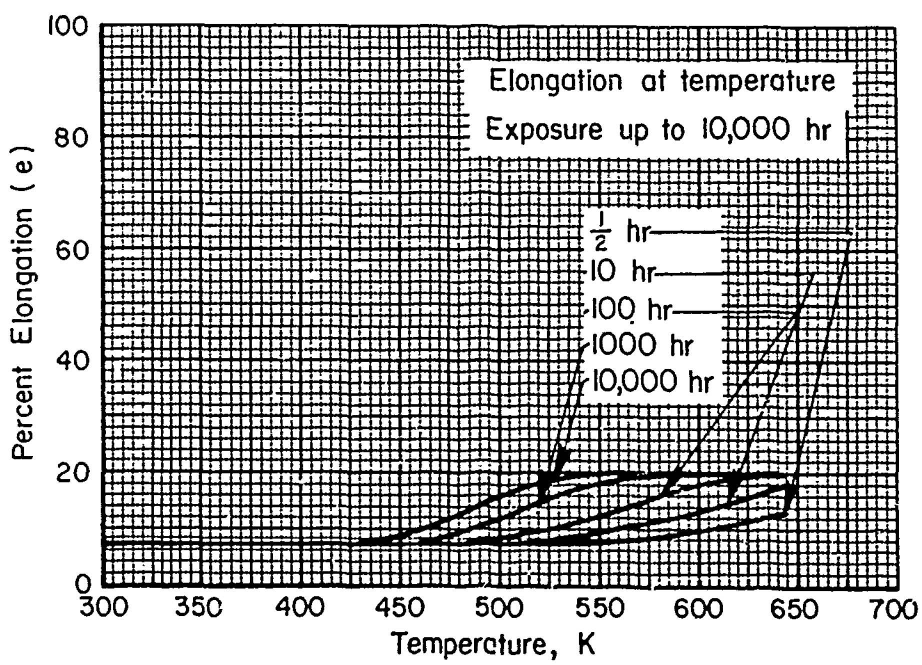


FIGURE 3.2.3.4.5(b). Effect of exposure at elevated temperatures on the elongation of 2024-T81, T851, T8510 and T8511 aluminum alloy (all products).

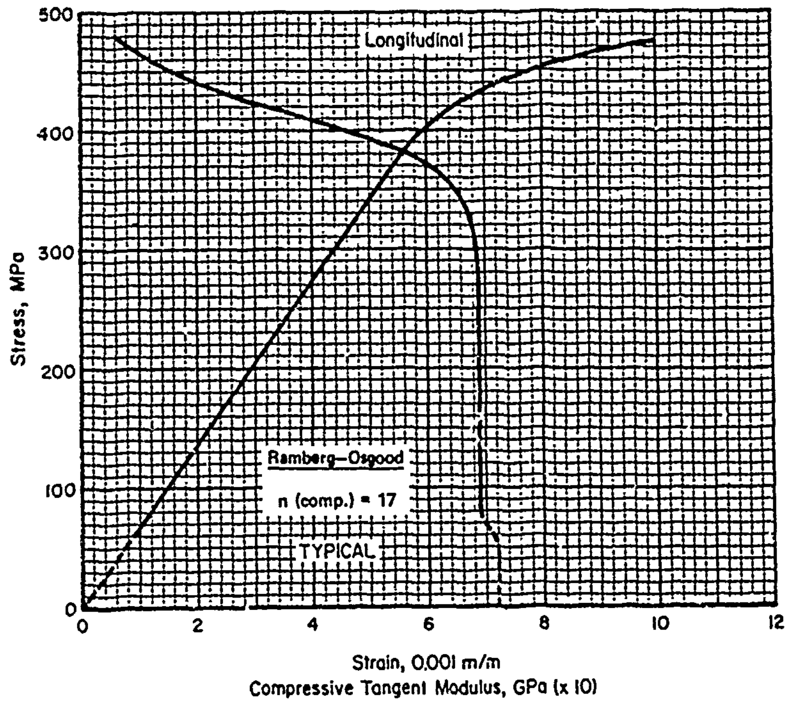


FIGURE 3.2.3.4.6(a). Typical compressive stress-strain and tangent-modulus curves for clad 2024-T81 aluminum alloy (sheet) at room temperature.

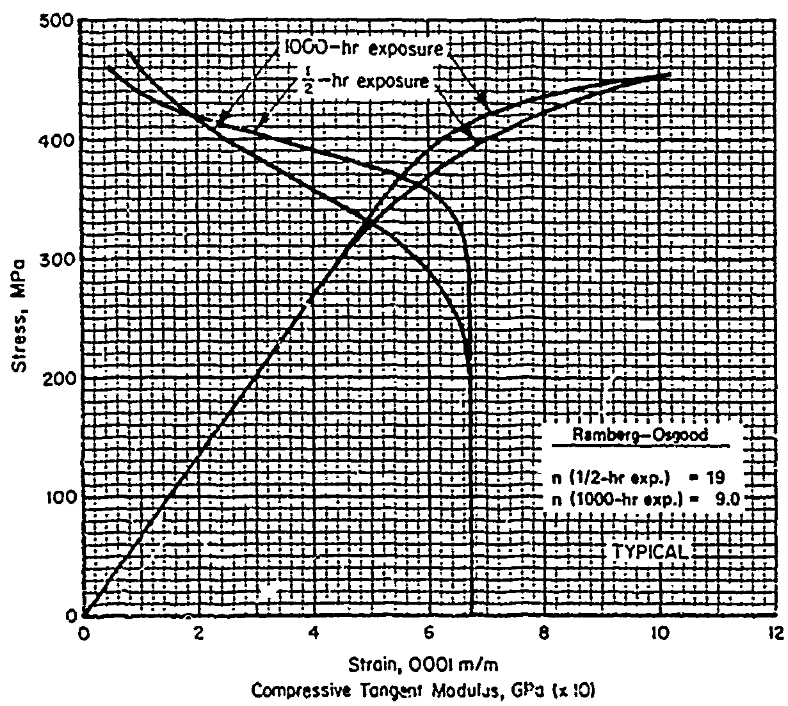


FIGURE 3.2.3.4.6(b). Typical compressive stress-strain and tangent-modulus curves for clad 2024-T81 aluminum alloy (sheet) at 366 K.

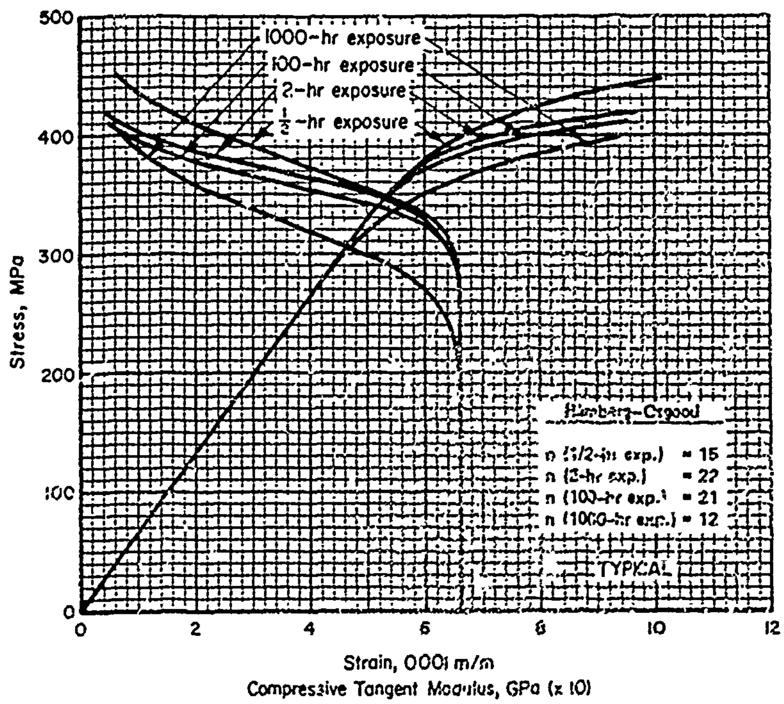


FIGURE 3.2.3.4.6(c). Typical compressive stress-strain and tangent-modulus curves for clad 2024-T81 aluminum alloy (sheet) at 422 K.

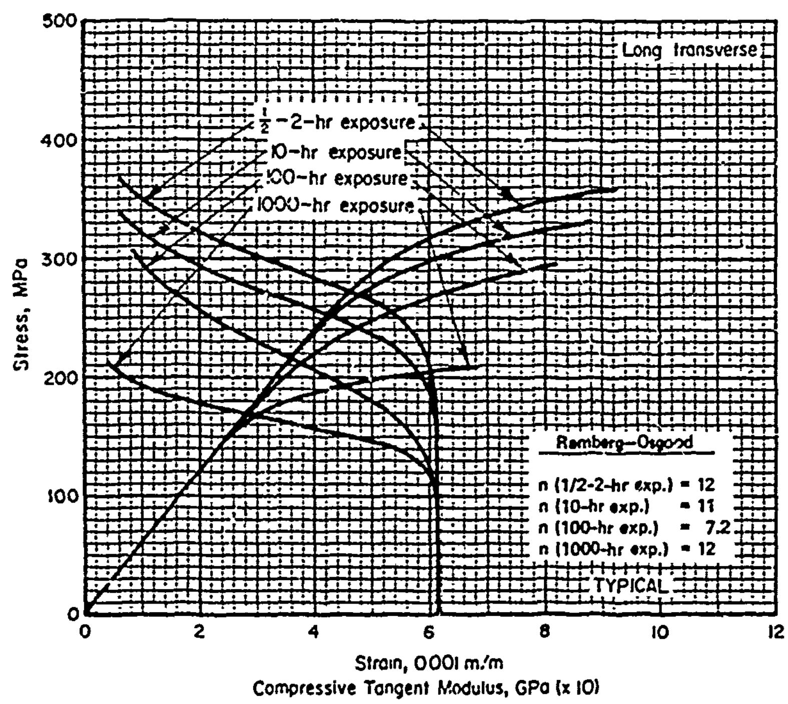


FIGURE 3.2.3.4.6(d). Typical compressive stress-strain and tangent-modulus curves for clad 2024-T81 aluminum alloy (sheet) at 477 K.

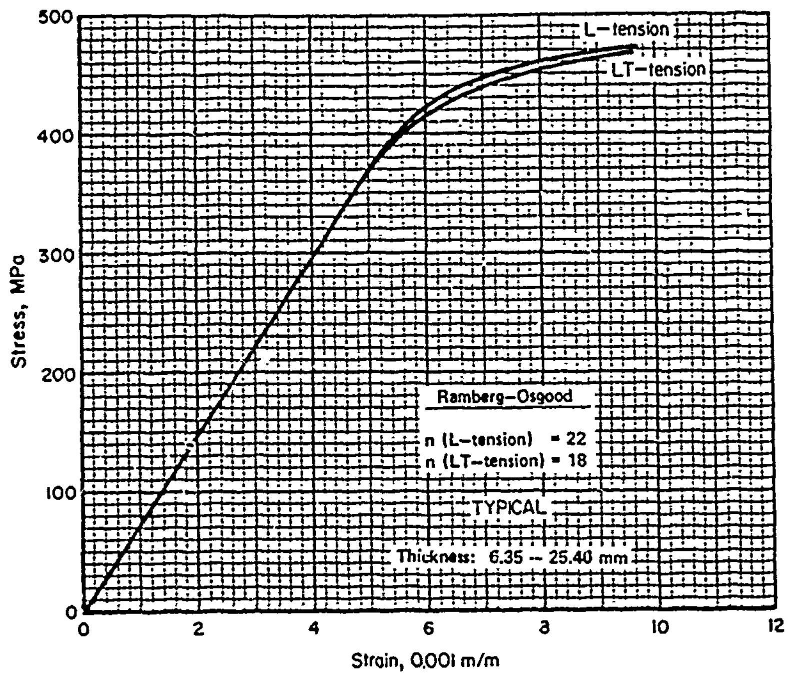


FIGURE 3.2.3.4.6(e). Typical tensile stress-strain curves for 2024-T851 aluminum alloy (plate) at room temperature.

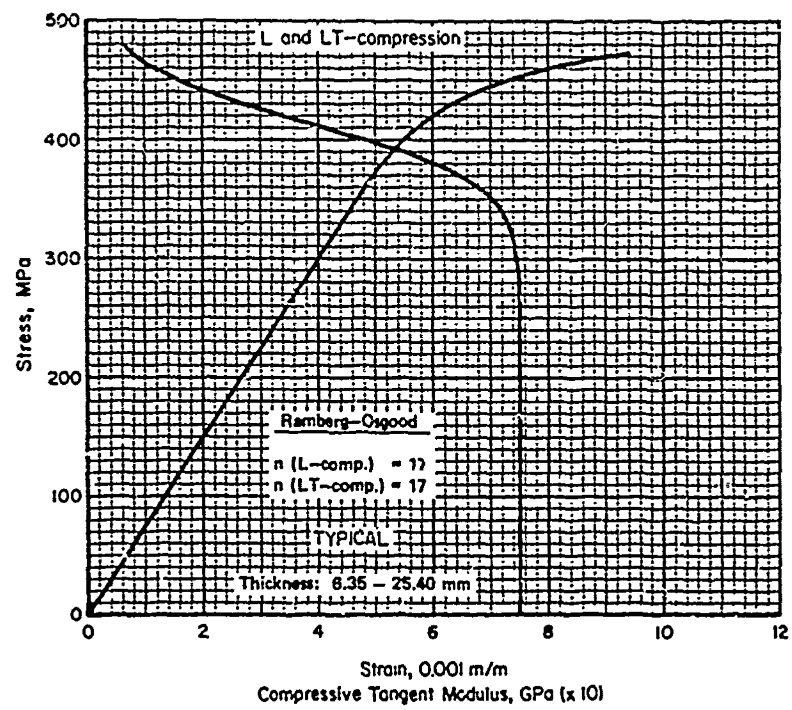


FIGURE 3.2.3.4.6(f). Typical compressive stress-strain and tangent-modulus curves for 2024-T851 aluminum alloy (plate) at room temperature.

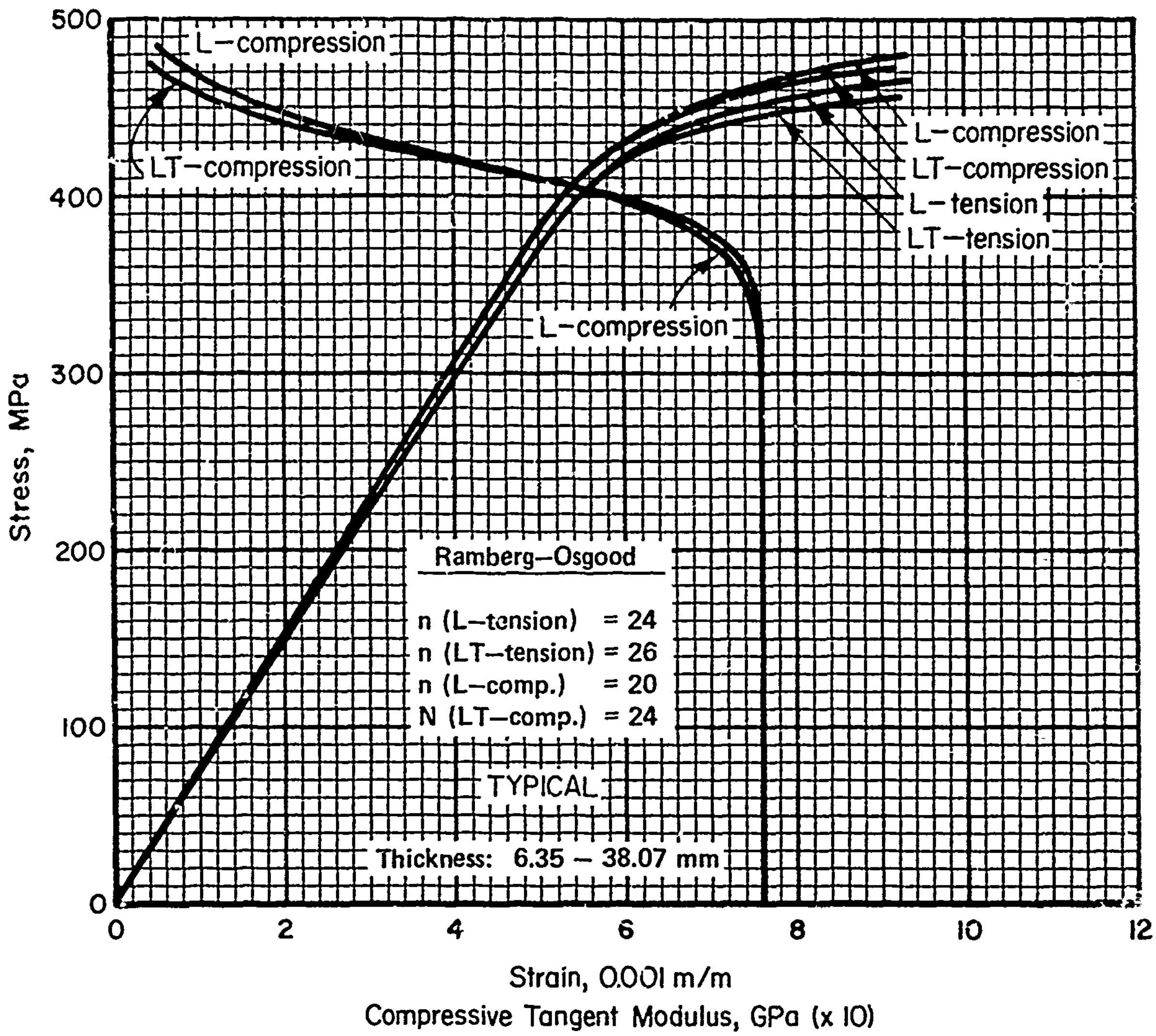


FIGURE 3.2.3.4.6(g). Typical tensile stress-strain and compressive stress-strain and tangent-modulus curves for 2024-T851 aluminum alloy (extrusion) at room temperature.

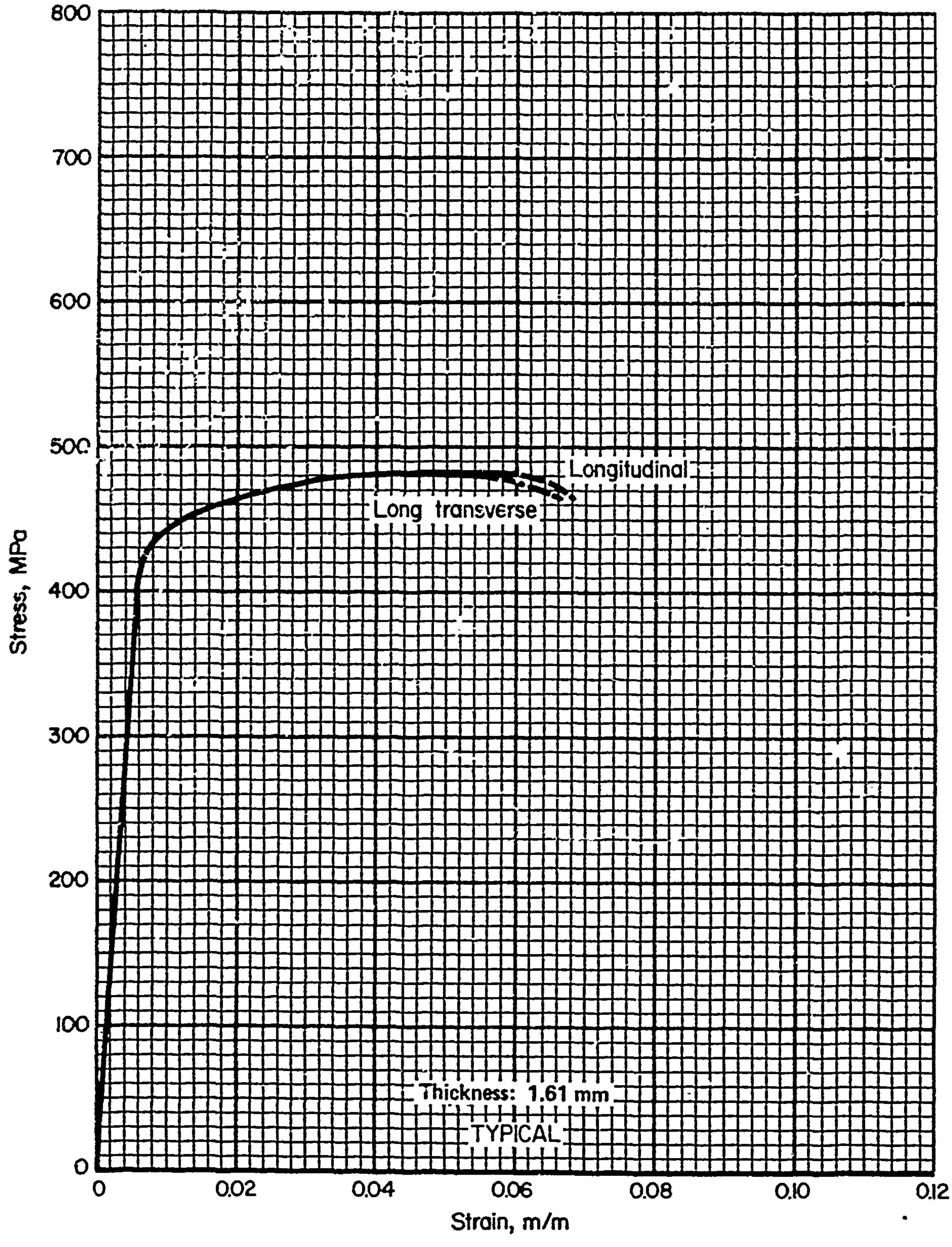


FIGURE 3.2.3.4.6(h). Typical tensile stress-strain curves (full range) for 2024-T81 aluminum alloy (sheet) at room temperature.

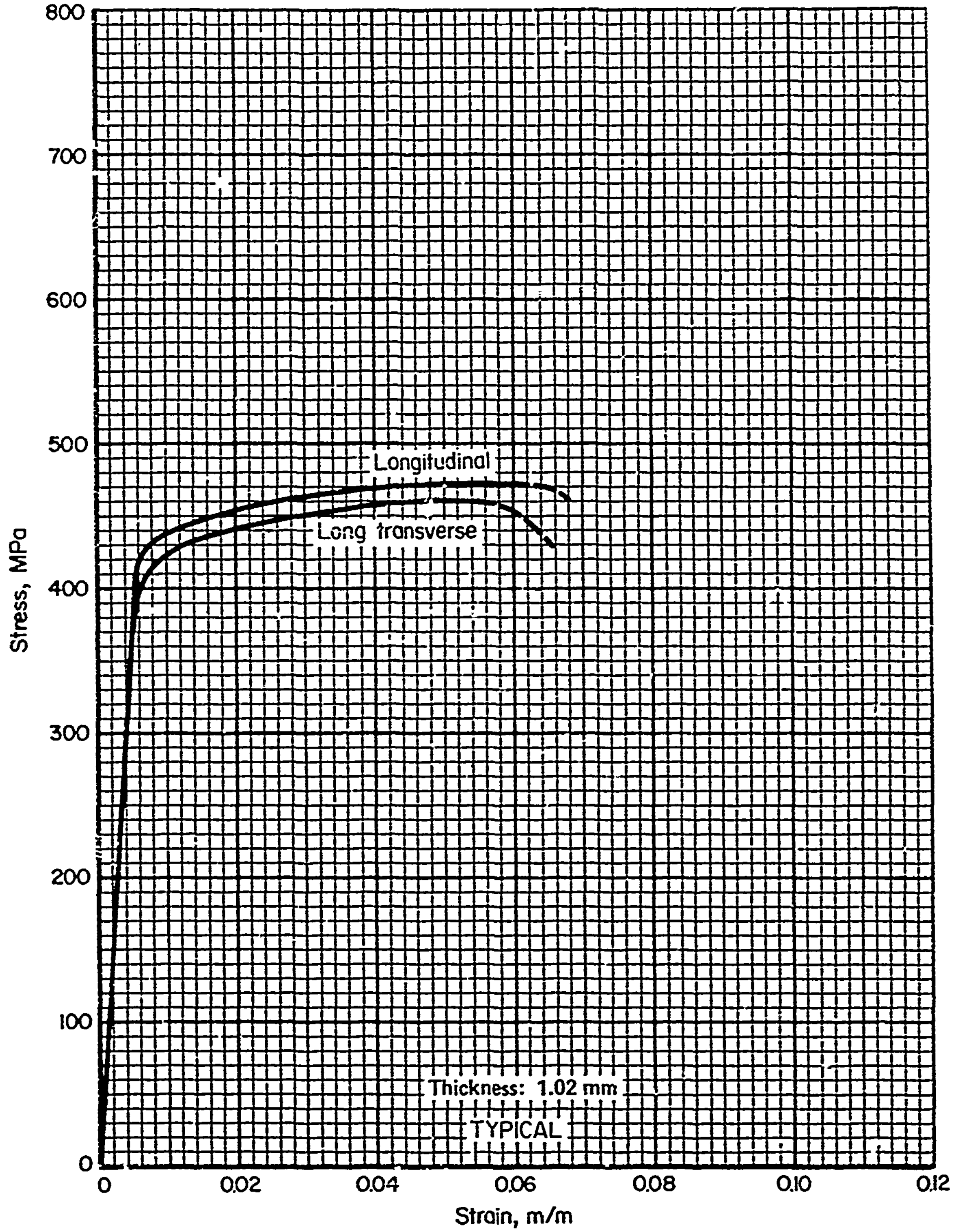


FIGURE 3.2.3.4.6(i). Typical tensile stress-strain curves (full range) for clad 2024-T81 aluminum alloy (sheet) at room temperature.

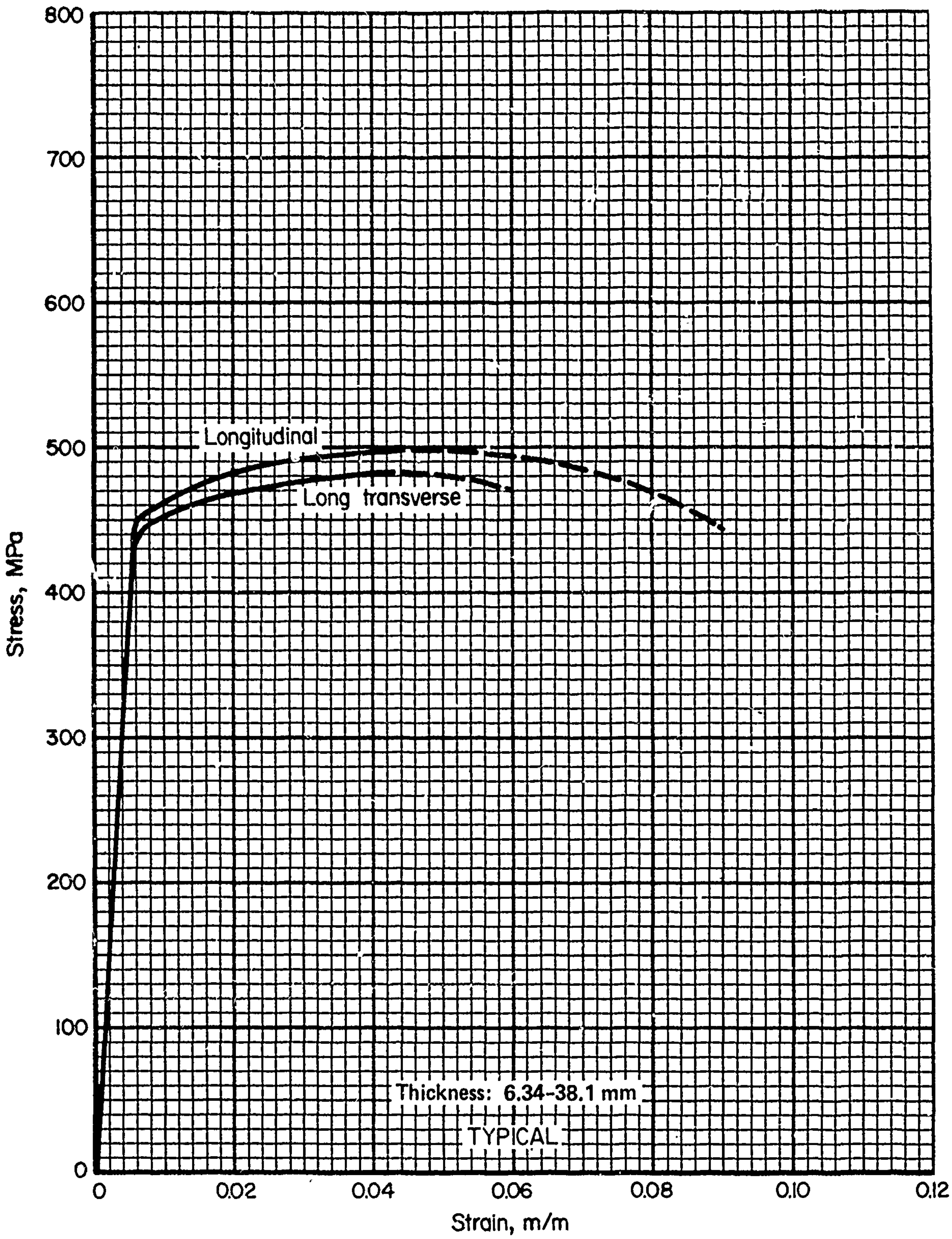


FIGURE 3.2.3.4.6(j). Typical tensile stress-strain curves (full range) for 2024-T851 aluminum alloy (extrusion) at room temperature.

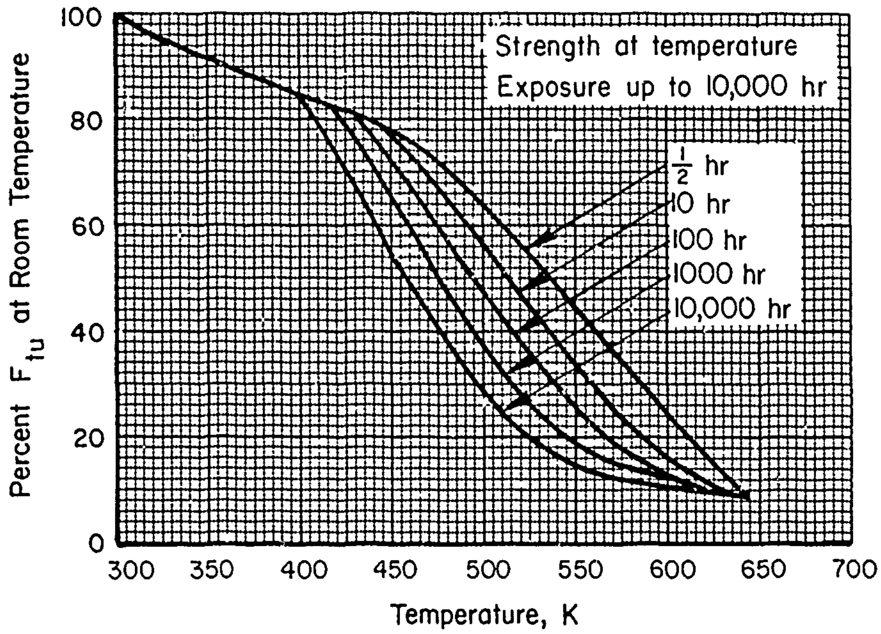


FIGURE 3.2.3.5.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of 2024-T861 (T86) aluminum alloy (sheet).

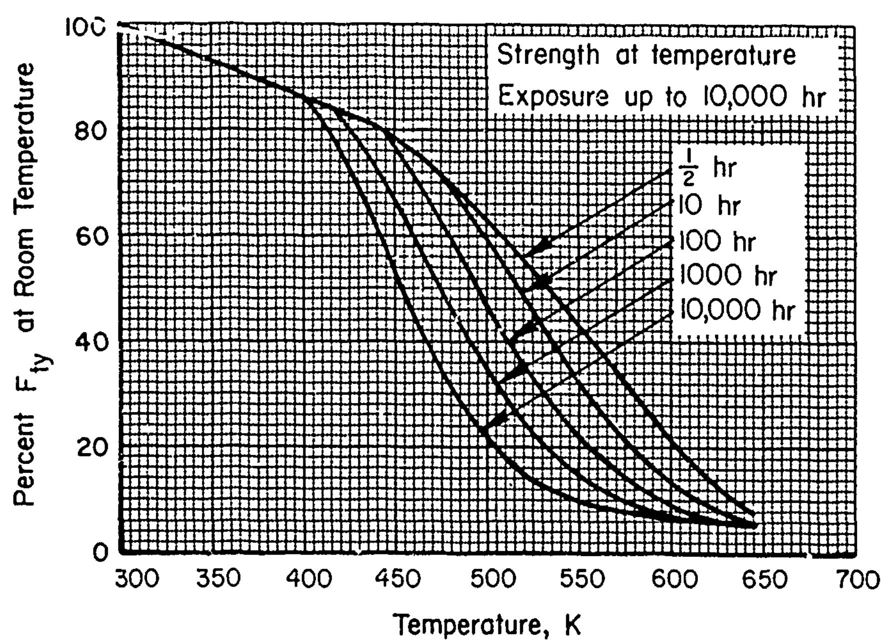


FIGURE 3.2.3.5.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of 2024-T861 (T86) aluminum alloy (sheet).

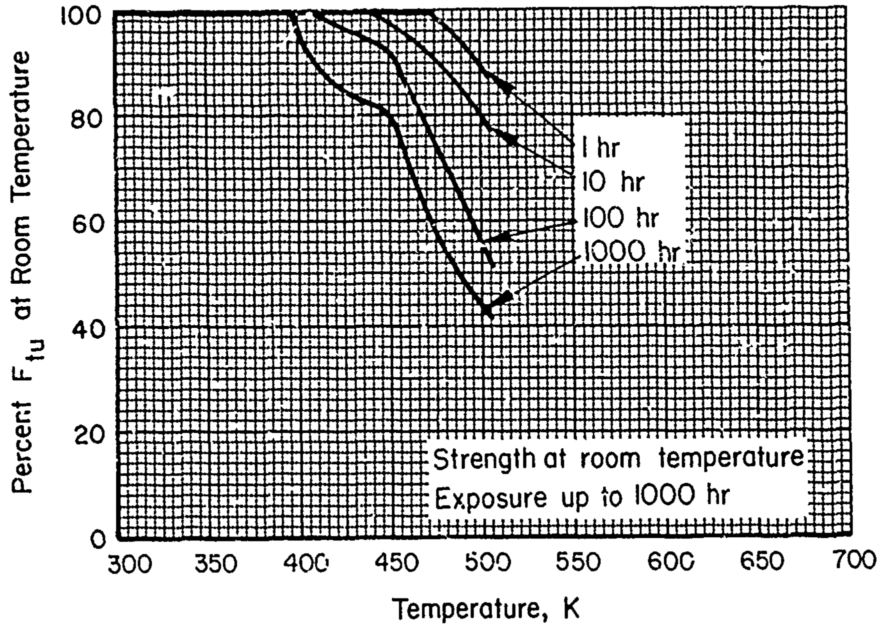


FIGURE 3.2.3.5.1(c). Effect of exposure at elevated temperatures on the room-temperature ultimate tensile strength (F_{tu}) of 2024-T861 (T86) aluminum alloy (sheet).

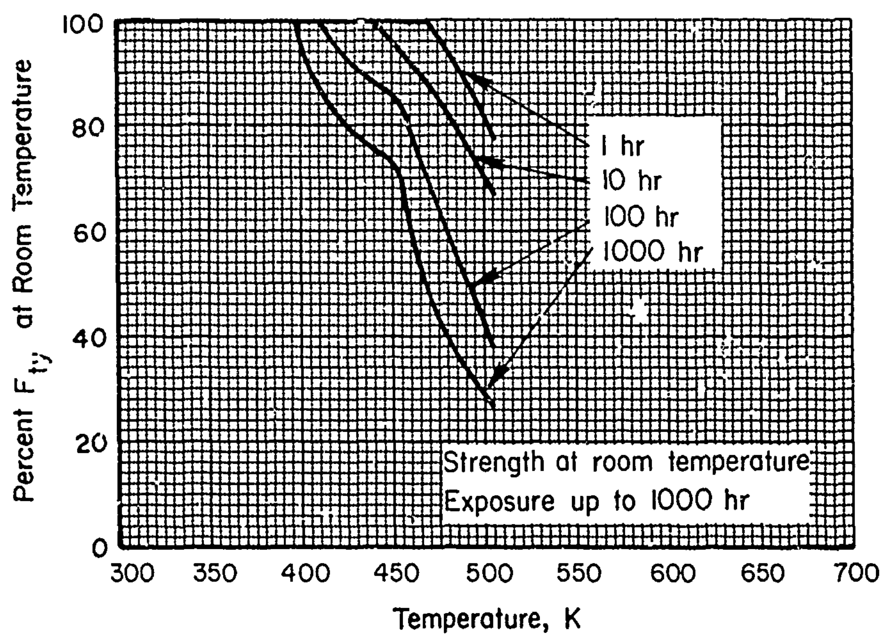


FIGURE 3.2.3.5.1(d). Effect of exposure at elevated temperatures on the room-temperature tensile yield strength (F_{ty}) of 2024-T861 (T86) aluminum alloy (sheet).

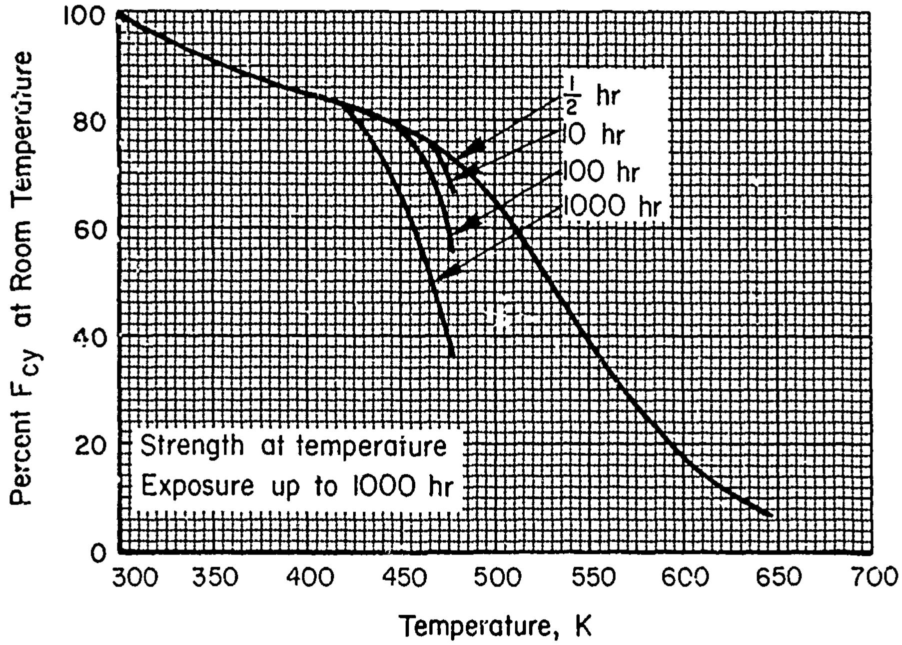


FIGURE 3.2.3.5.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of 2024-T861 (T86) aluminum alloy (sheet).

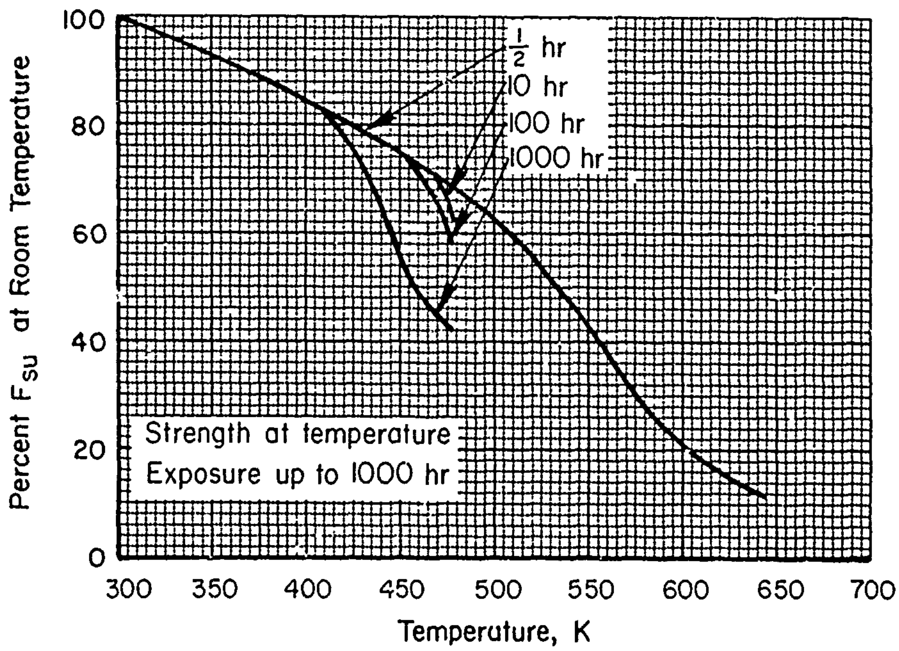


FIGURE 3.2.3.5.2(b). Effect of temperature on the ultimate shear strength (F_{su}) of 2024-T861 (T86) aluminum alloy (sheet).

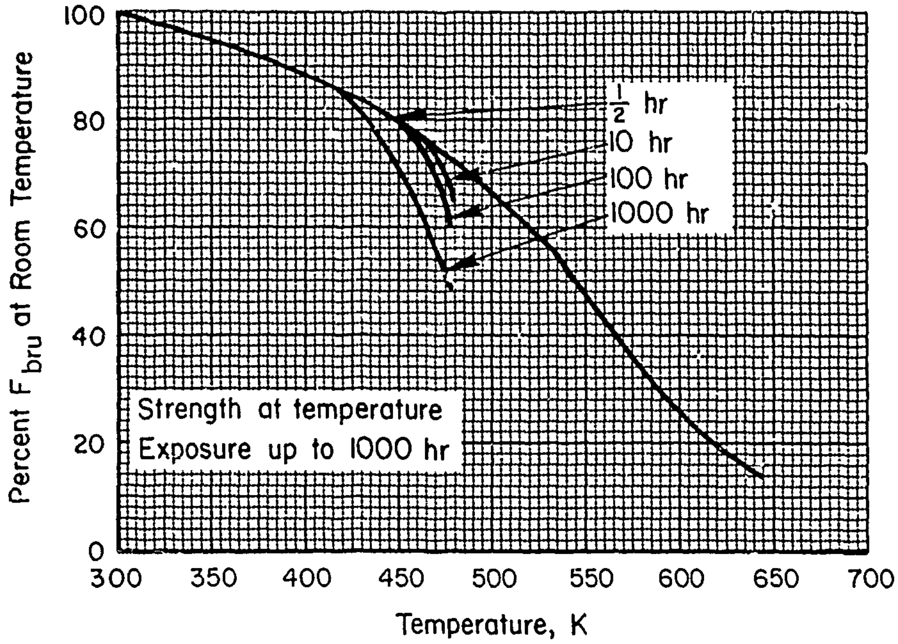


FIGURE 3.2.3.5.3(a). Effect of temperature on the ultimate bearing strength (F_{bru}, e/D = 1.5) of 2024-T861 (T86) aluminum alloy (sheet).

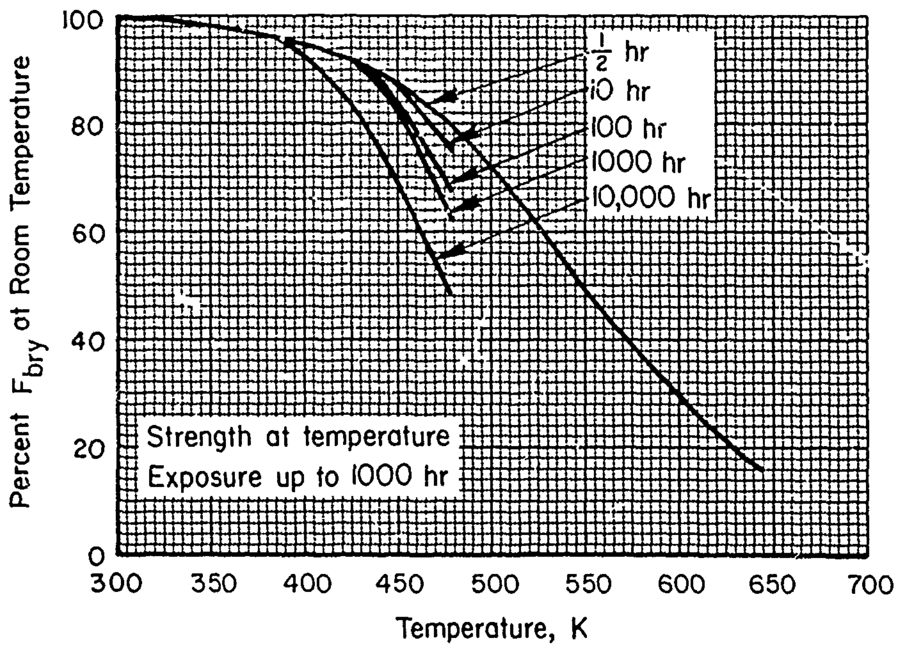


FIGURE 3.2.3.5.3(b). Effect of temperature on the bearing yield strength (F_{bry}, e/d = 1.5) of 2024-T861 (T86) aluminum alloy (sheet).

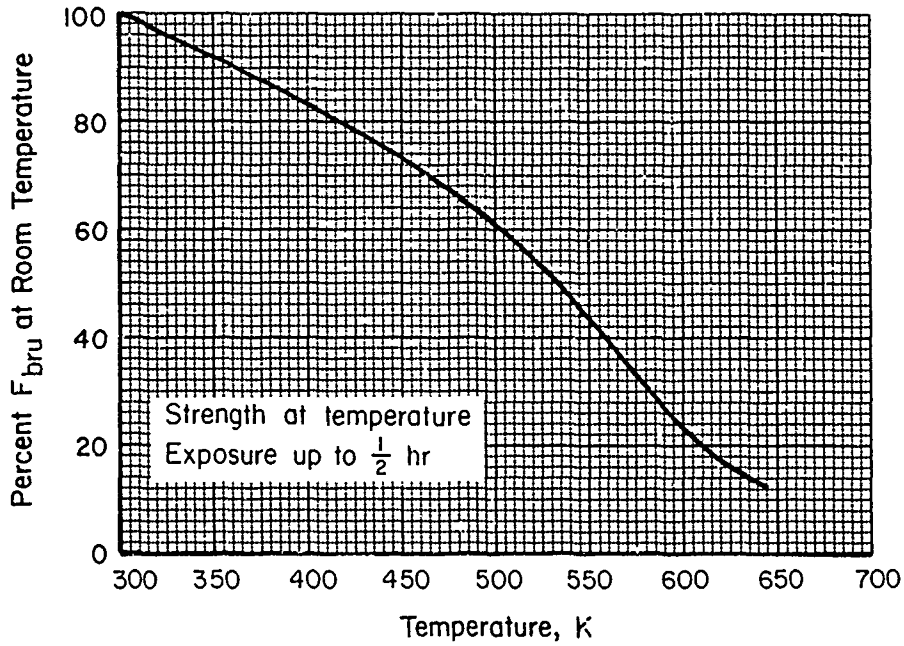


FIGURE 3.2.3.5.3(c). Effect of temperature on the ultimate bearing strength (F_{bru}, e/D = 2.0) of 2024-T861 (T86) aluminum alloy (sheet).

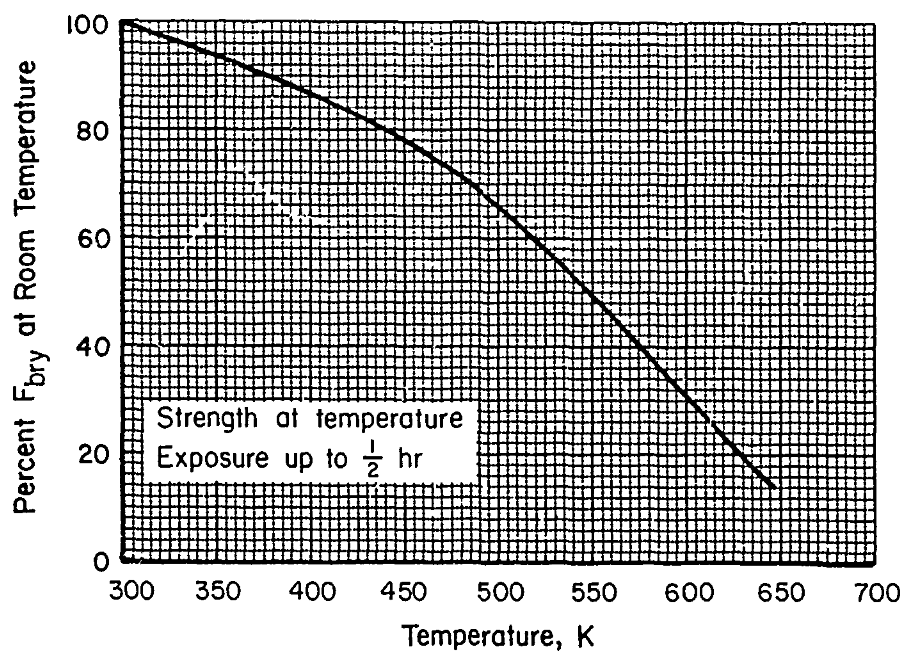


FIGURE 3.2.3.5.3(d). Effect of temperature on the bearing yield strength (F_{bry}, e/d = 2.0) of 2024-T861 (T86) aluminum alloy (sheet).

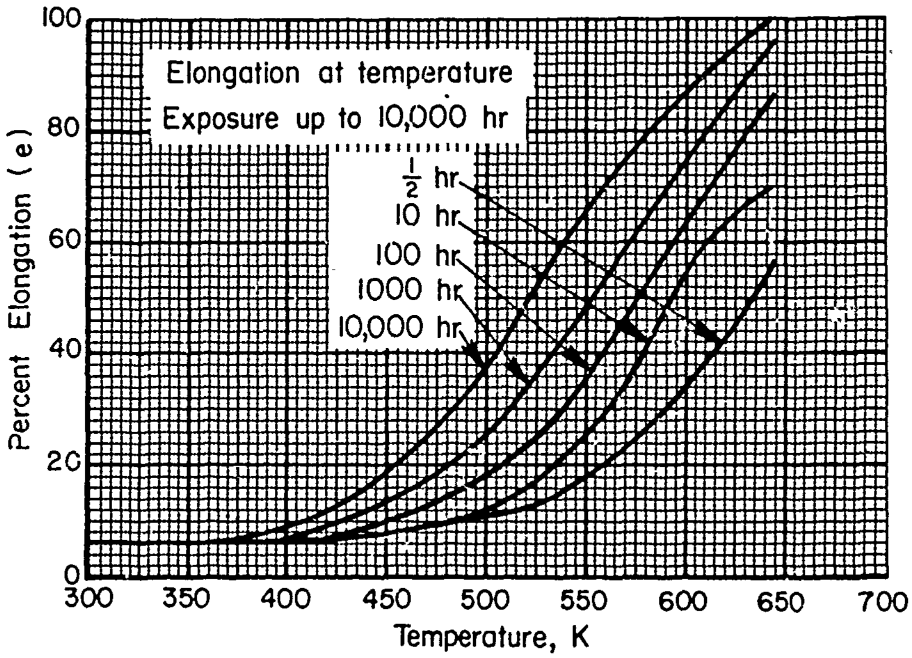


FIGURE 3.2.3.5.5(a). Effect of temperature on the elongation of 2024-T861 (T86) aluminum alloy (sheet).

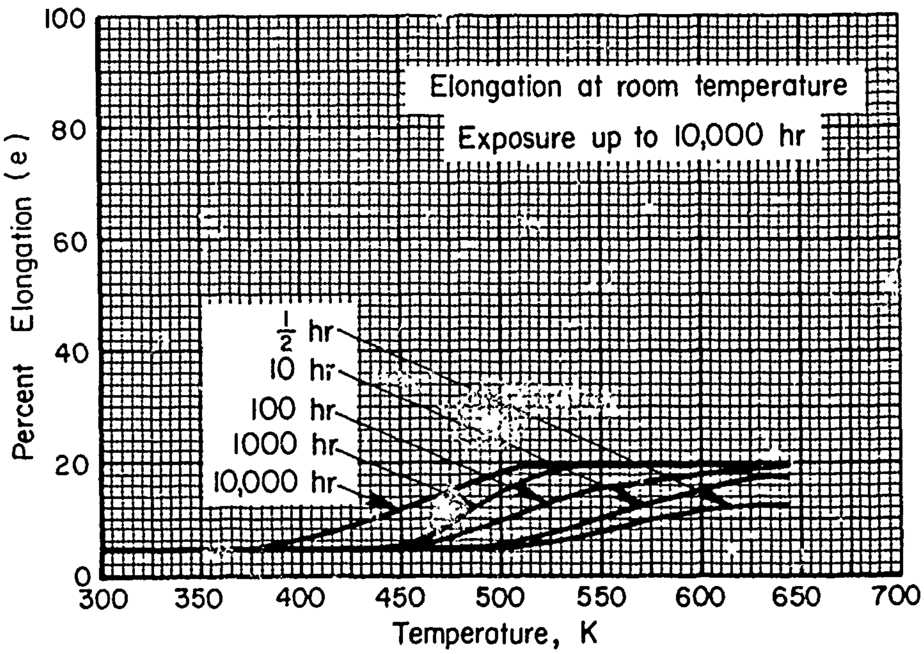


FIGURE 3.2.3.5.5(b). Effect of exposure at elevated temperatures on the elongation of 2024-T861 (T86) aluminum alloy (sheet).

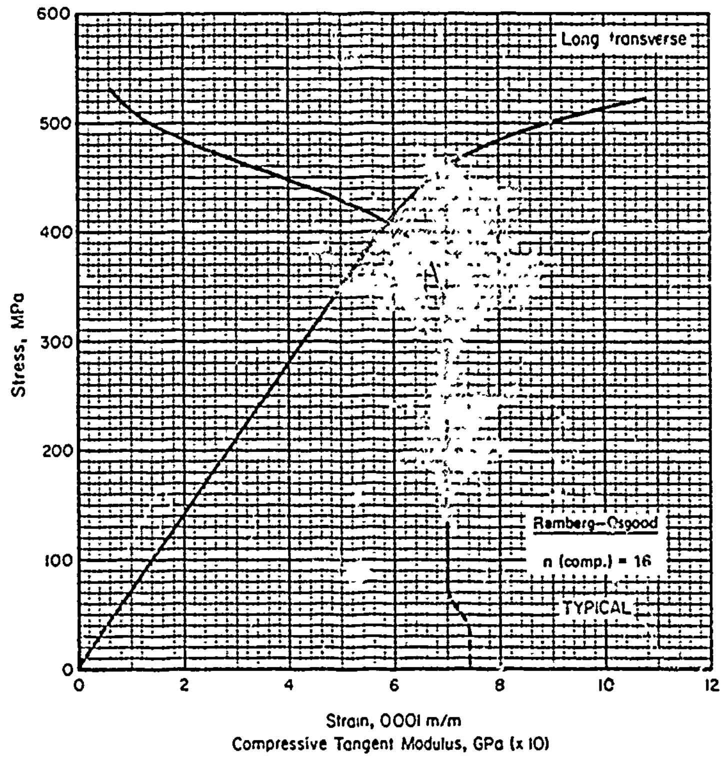


FIGURE 3.2.3.5.6(a). Typical compressive stress-strain and tangent-modulus curves for clad 2024-T861 aluminum alloy (sheet) at room temperature.

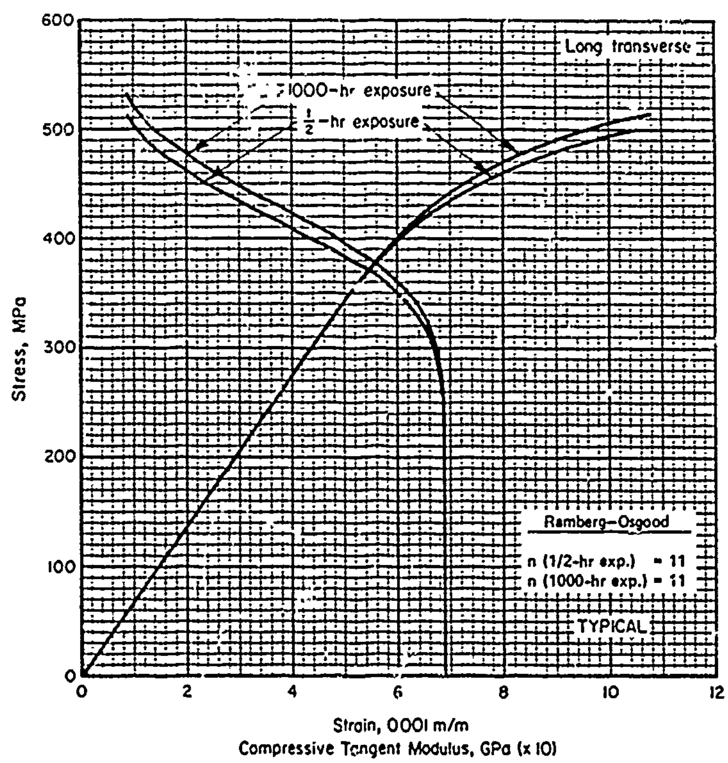


FIGURE 3.2.3.5.6(b). Typical compressive stress-strain and tangent-modulus curves for clad 2024-T861 aluminum alloy (sheet) at 366 K.

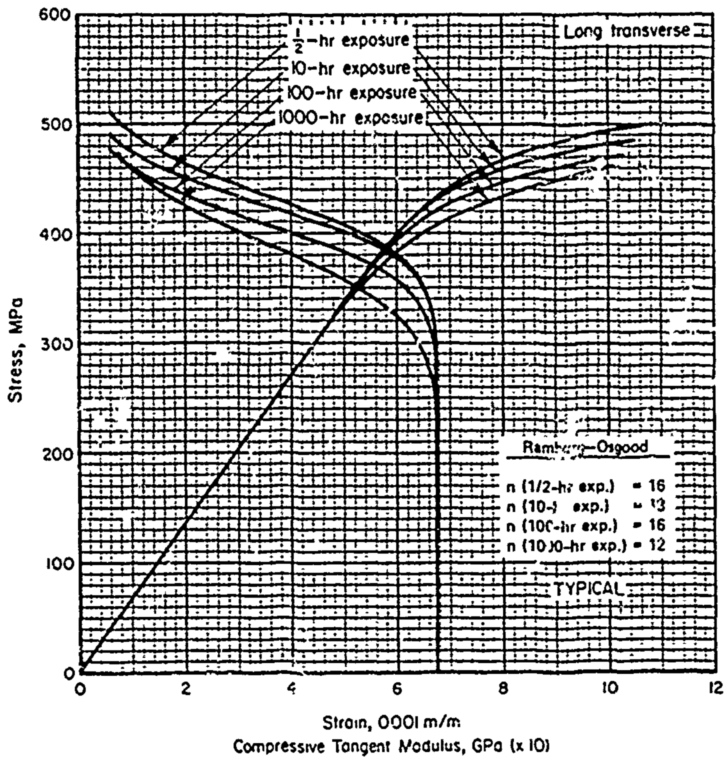


FIGURE 3.2.3.5.6(c). Typical compressive stress-strain and tangent-modulus curves for clad 2024-T861 aluminum alloy (sheet) at 422 K.

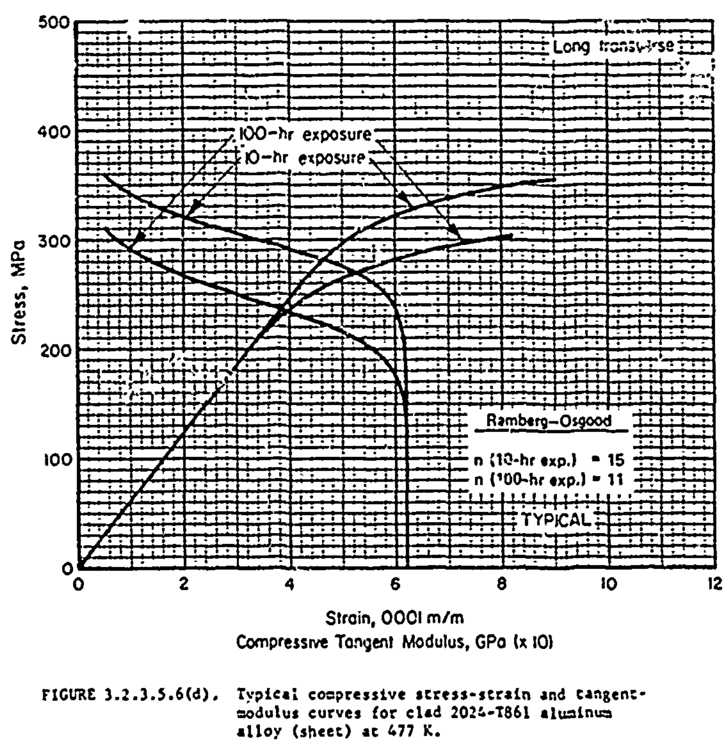


FIGURE 3.2.3.5.6(d). Typical compressive stress-strain and tangent-modulus curves for clad 2024-T861 aluminum alloy (sheet) at 477 K.

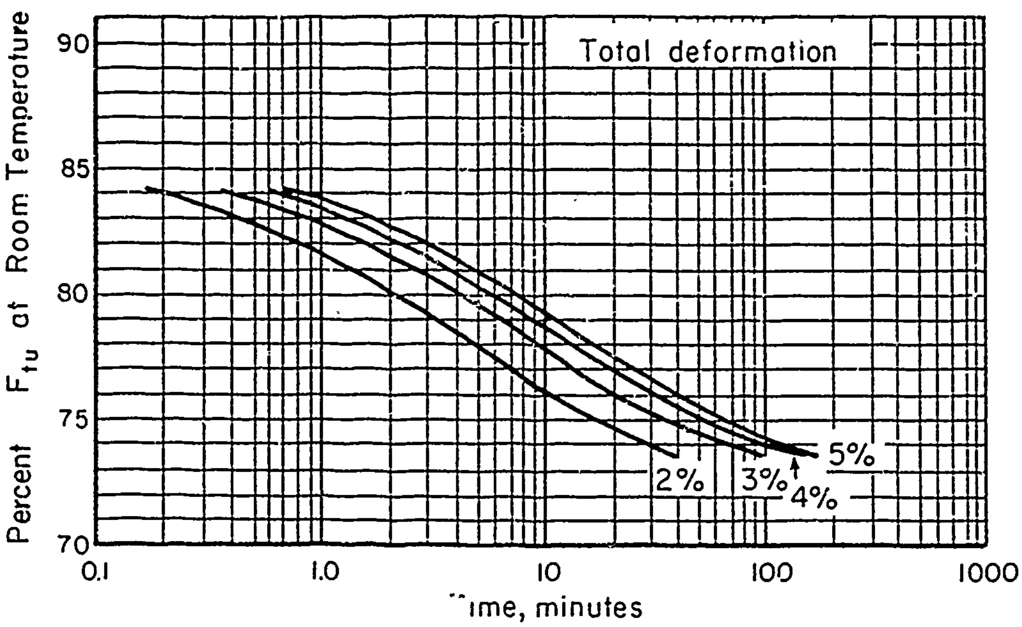


FIGURE 3.2.3.5.7(a). Creep data for 2024-T861 (T86) aluminum alloy (clad sheet) at 422 K.

Deformation includes thermal expansion of 0.25 percent. Heating rate 2;7 K per second.

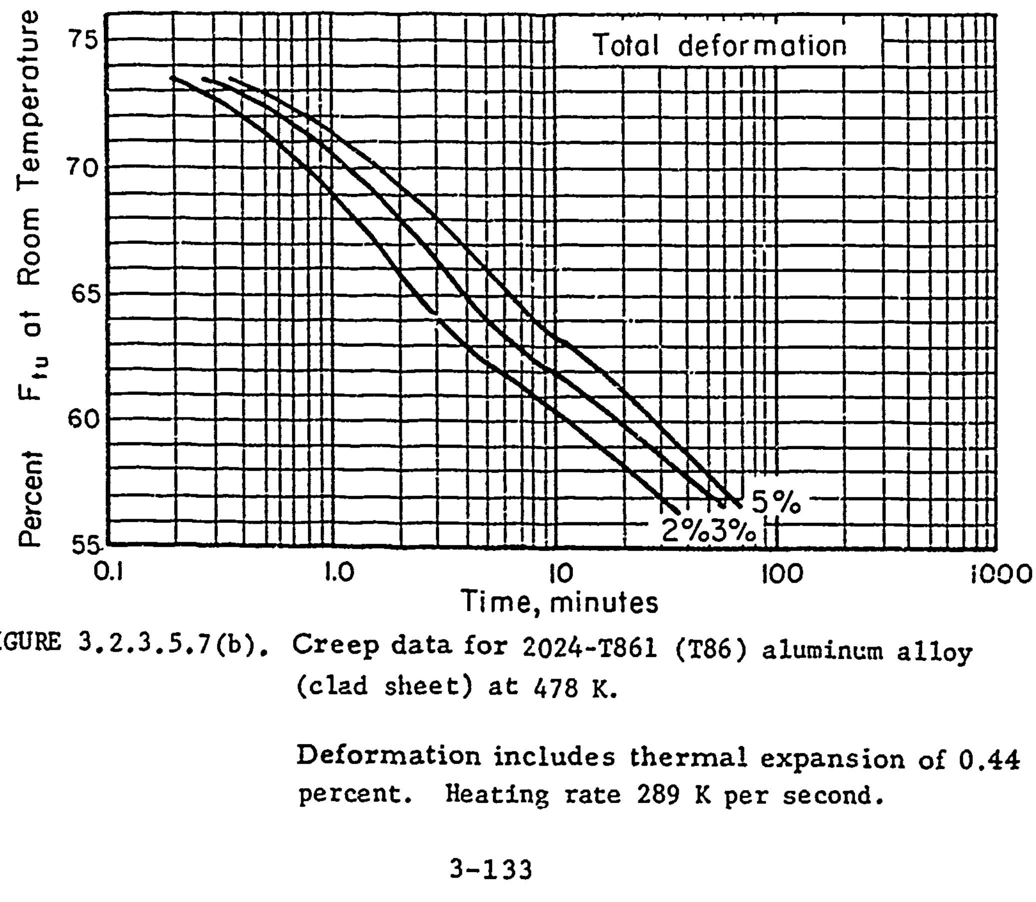


FIGURE 3.2.3.5.7(b). Creep data for 2024-T861 (T86) aluminum alloy (clad sheet) at 478 K.

Deformation includes thermal expansion of 0.44 percent. Heating rate 289 K per second.

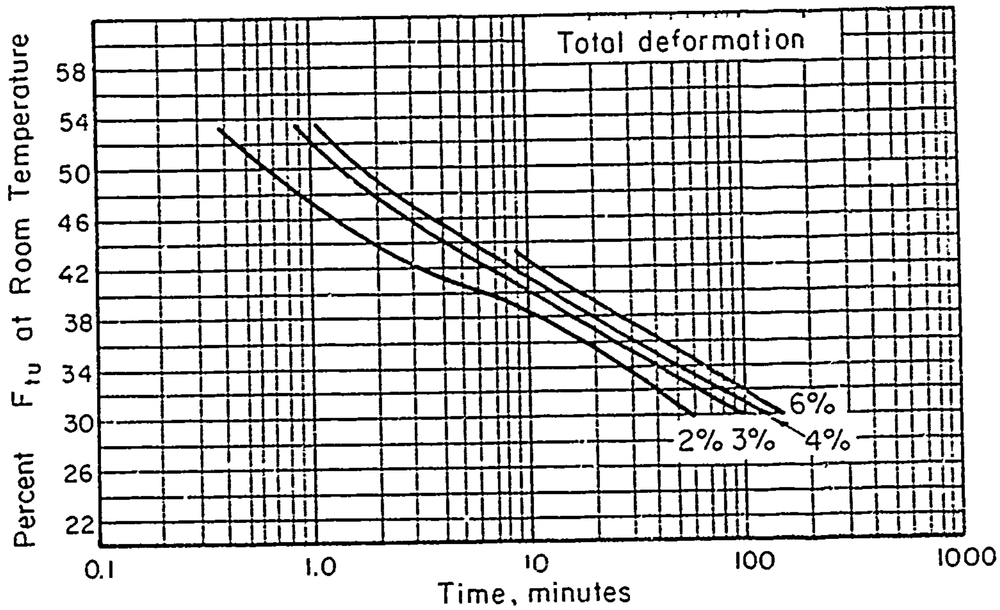


FIGURE 3.2.3.5.7(c). Creep data for 2024-T861 (T86) aluminum alloy (clad sheet) at 533 K.

Deformation includes thermal expansion of 0.55 percent. Heating rate 305 K per second.

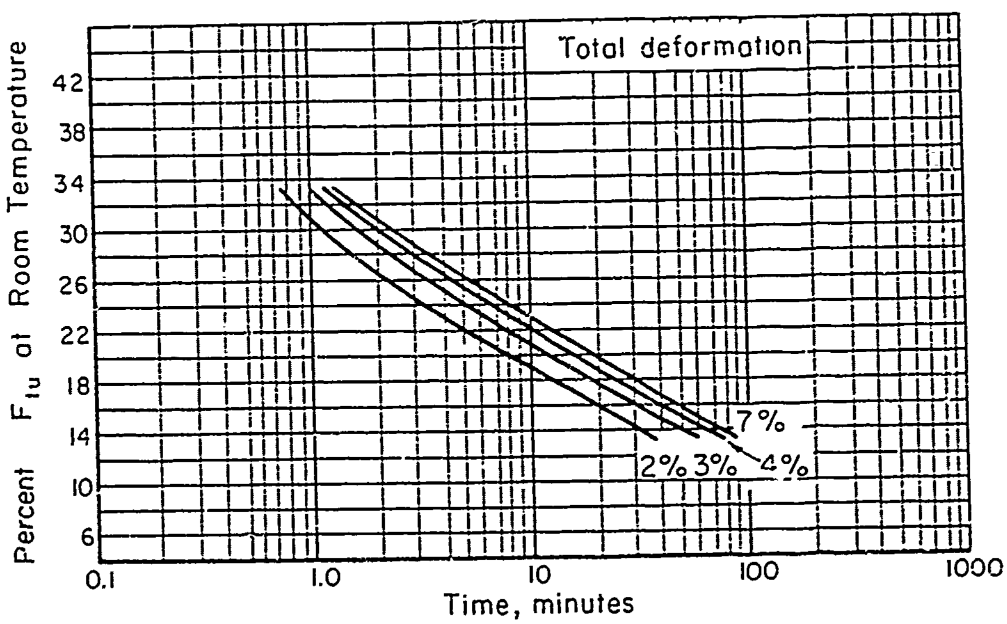


FIGURE 3.2.3.5.7(d). Creep data for 2024-T861 (T86) aluminum alloy (clad sheet) at 589 K.

Deformation includes thermal expansion of 0.69 percent. Heating rate 305 to 311 K per second.

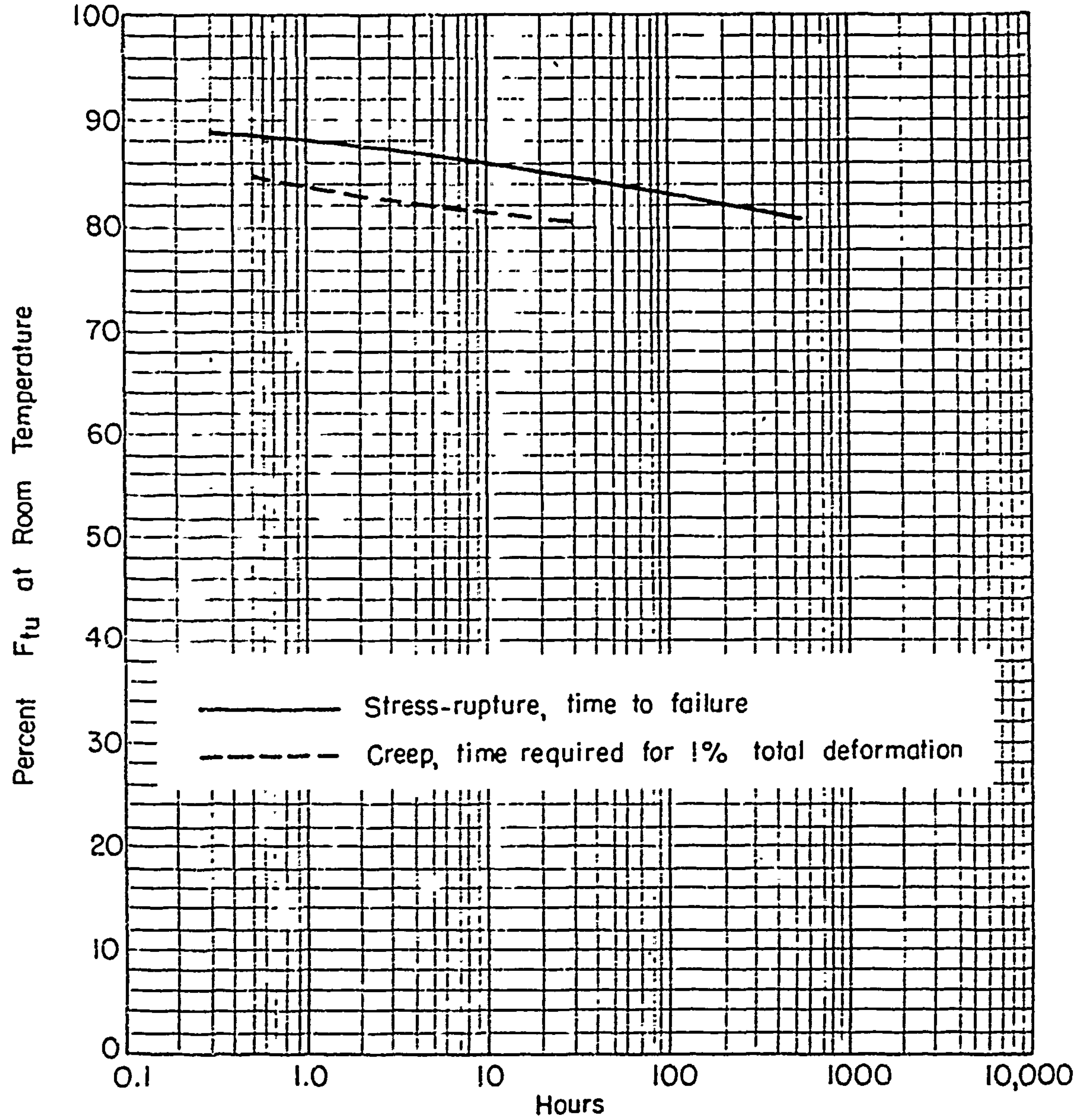


FIGURE 3.2.3.5.7(e). Creep and stress-rupture properties for 2024-T861 (T86) aluminum alloy (clad sheet) at 373 K.

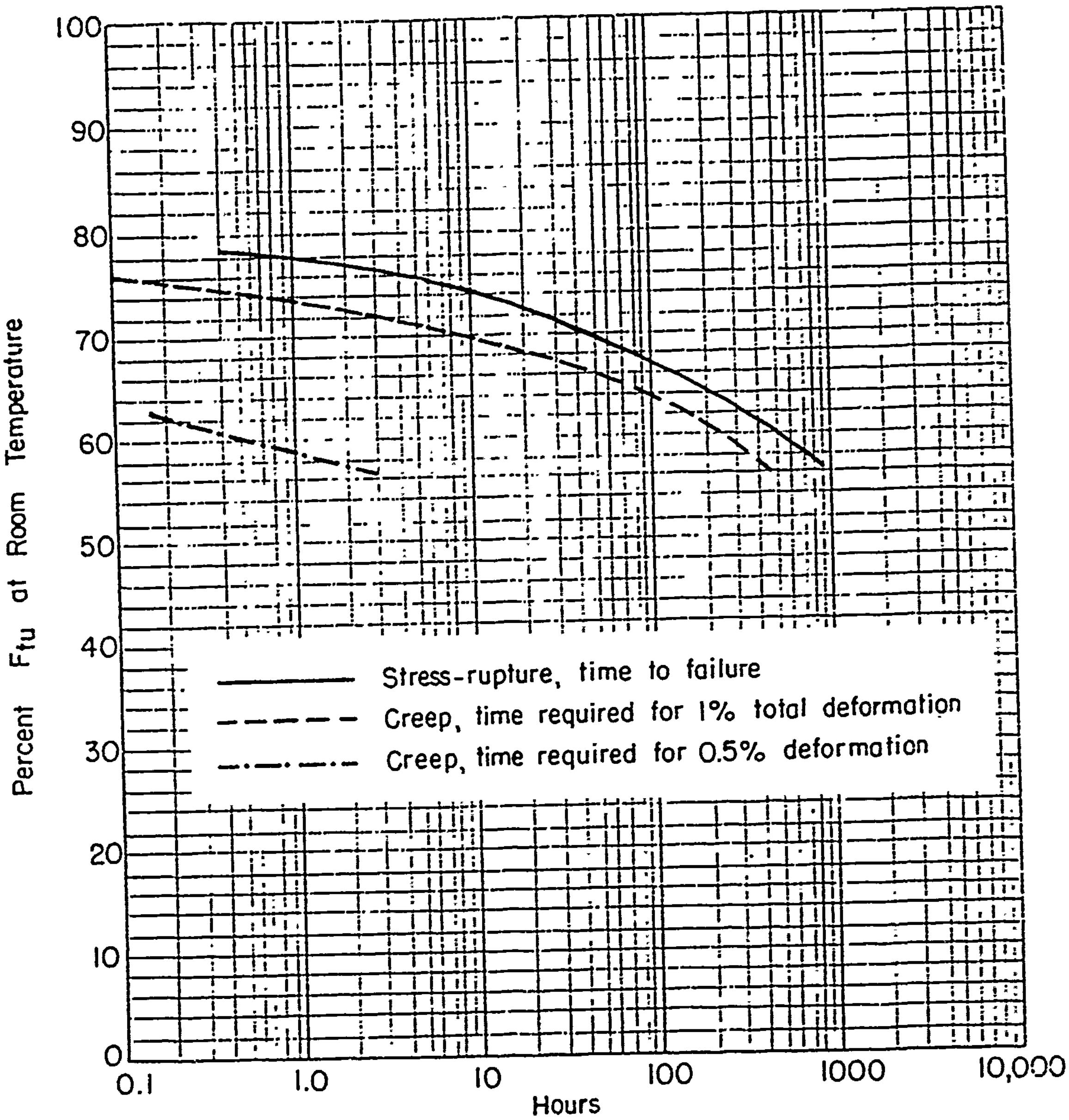


FIGURE 3.2.3.5.7(f). Creep and stress-rupture properties for 2024-T861 (T86) aluminum alloy (clad sheet) at 422 K.

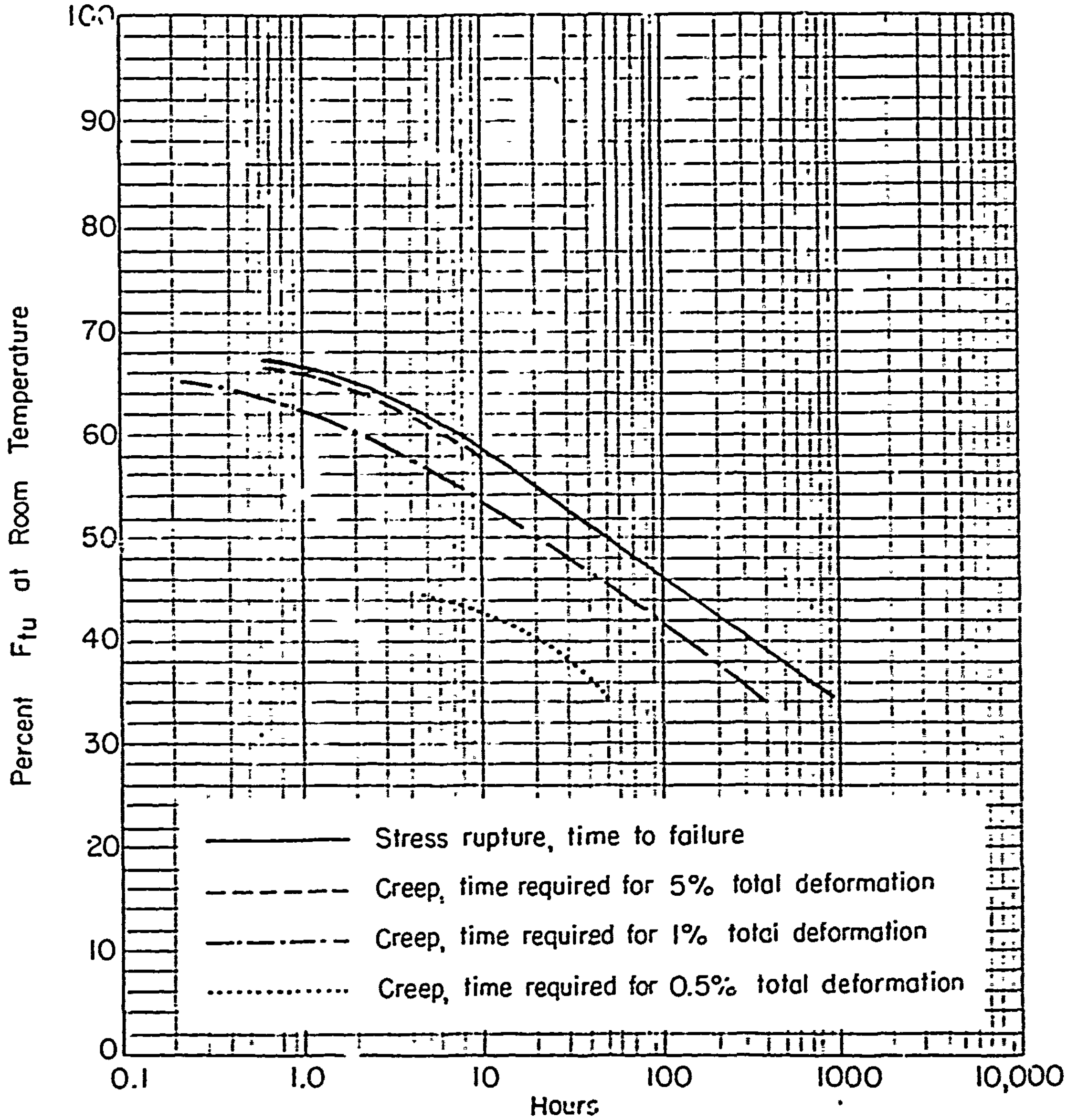


FIGURE 3.2.3.5.7(g). Creep and stress-rupture properties for 2024-T861 (T86) aluminum alloy (clad sheet) at 46[illegible] K.

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 3.1.3.4 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).

TABLE 3.2.4.0(a). *Material Specification for 2025 Aluminum Alloy*[a]

Specification	Form
QQ-A-367	Forgings

[a]This alloy is intended primarily for propeller applications

The temper index for 2025 is as follows:

Section	Temper or Condition
3.2.4.1	T6

TABLE 3.2.4.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 2025 ALUMINUM ALLOY (DIE FORGING)

SPECIFICATION	QQ-A-367
FORM	DIE FORGING
CONDITION	T6
THICKNESS, MM	≤ 101.60
BASIS	S
MECHANICAL PROPERTIES:	
FTU, MPA:	
L	359
T[a]	...
FTY, MPA:	
L	228
T	...
FCY, MPA:	
L	...
T	...
FSU, MPA	...
FBRU, MPA:	
(E/D=1.5)	...
(E/D=2.0)	...
FBRY, MPA:	
(E/D=1.5)	...
(E/D=2.0)	...
EL, PERCENT:	
L	11
T	...
E, GPA	71.0
EC, GPA	72.4
G, GPA	26.9
MU	0.33
PHYSICAL PROPERTIES:	
OMEGA, MG/M3	2.80
C, J/(G*K)	0.96 (AT 373 K)
K, W/(M*K)	156 (AT 298 K)
ALPHA, 10-6 M/(M*K)	22.7 (293 to 373 K)

[a]FOR DIE FORGINGS, T INDICATES ANY GRAIN DIRECTION NOT WITHIN ± 15 DEGREES OF BEING PARALLEL TO THE FORGING FLOW LINES. SPECIMENS TO TEST TRANSVERSE PROPERTIES SHOULD BE LOCATED AS CLOSE TO THE SHORT TRANSVERSE DIRECTION AS POSSIBLE.

3.2.5 2124 Alloy

3.2.5.0 *Comments and Properties.*—2124 is an Al-Cu alloy available in the form of plate in thicknesses of 40 through 150 mm. This alloy is a high purity version of alloy 2024. The higher purity in conjunction with special production processing provides higher elongations 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. The physical properties are essentially the same as those for 2024-T851 plate. Refer to Section 3.1.3.4 for comments regarding the weldability of the alloy.

The applicable material specification for 2124-T851 plate is presented in Table 3.2.5.0(a). Room temperature mechanical properties are shown in Table 3.2.5.0(b).

TABLE 3.2.5.0(a). *Material Specification for 2124 Aluminum Alloy*

Specification	Form
QQ-A-00250/29	Plate

The temper index for 2124 is as follows:

Section	Temper
3.2.5.1	T851

3.2.5.1 *T851 Temper.*—Typical tensile stress-strain, compressive stress-strain and compressive tangent modulus curves are presented in Figures 3.2.5.1.6(a) and (b). Elevated temperature tensile properties of 2124-T851 are similar to 2024-T851. Use effect-of-temperature curves in Figures 3.2.3.4.1(a) and (b).

TABLE 3.2.5.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 2124 ALUMINUM ALLOY (PLATE)

SPECIFICATION	QQ-A-00250/29										
FORM	PLATE										
TEMPER	T851										
THICKNESS, MM	35.10	35.11-50.81		50.82-76.21		76.22-101.61		101.62-127.01		127.02-152.40	
BASIS	S	A	B	A	B	A	B	A	B	A	B
MECHANICAL PROPERTIES:											
FTU, MPA:											
L	455	455	469	448	469	448	462	441	455	434	448
LT	455	455	469	448	469	448	462	441	455	434	448
ST	441	441	455	434	441	427	434	421	427	400	407
FTY, MPA:											
L	393	393	421	393	421	386	414	379	400	372	386
LT	393	393	421	393	421	386	414	379	400	372	386
ST	379	379	407	379	407	372	393	365	379	352	365
FCY, MPA:											
L	393	393	421	393	421	379	407	365	386	352	365
LT	393	393	421	393	421	386	414	379	400	372	386
ST	400	400	427	400	427	393	414	386	400	372	386
FSU, MPA	248	262	276	262	276	262	269	255	262	255	262
FBRU[a,b], MPA:											
(E/D=1.5)	641	676	696	662	696	662	683	655	676	641	662
(E/D=2.0)	841	876	903	862	903	862	889	848	876	834	862
FBRY[a,b], MPA:											
(E/D=1.5)	531	558	593	565	607	558	600	558	586	558	579
(E/D=2.0)	621	641	689	648	696	648	696	648	683	641	669
EL, PERCENT:											
L	6	6	...	6	...	5	...	5	...	5	
LT	5	5	...	4	...	4	...	4	...	4	...
ST	1	1	...	1	...	1	...	1	...	1	...
E, GPA	71.7										
EC, GPA	75.2										
G, GPA	27.6										
MU	0.33										
PHYSICAL PROPERTIES:											
OMEGA, MG/M3	2.77										
C, J/(G*K)	0.88 (AT 373 K)										
K, W/(M*K)	151 (AT 298 K)										
ALPHA, 10-6 M/(M*K)	22.7 (293 to 373 K)										

[a] SEE TABLE 3.1.2.1.1.
[b] BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

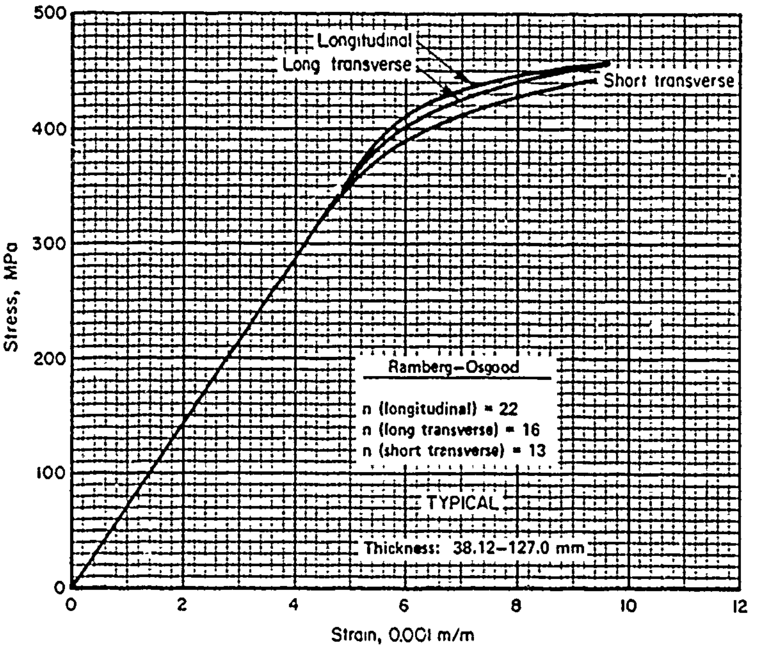


FIGURE 3.2.5.1.6 (a). Typical tensile stress-strain curves for 2124-T851 aluminum alloy (plate) at room temperature.

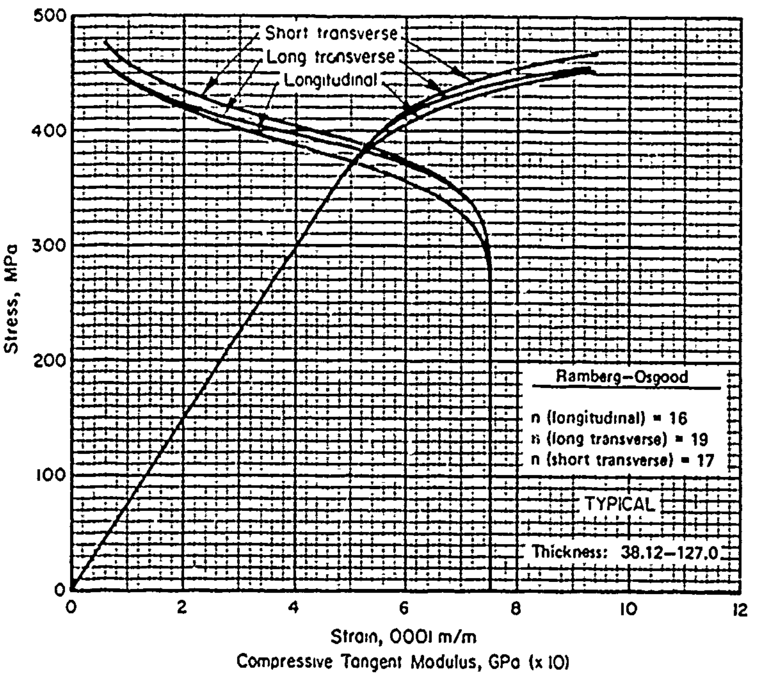


FIGURE 3.2.5.1.6(b). Typical compressive stress-strain and tangent-modulus curves for 2124-T851 aluminum alloy (plate) at room temperature.

3.2.6 2219 ALLOY

3.2.6.0 *Comments and Properties.*—2219 is an Al-Cu alloy available in a wide variety of product forms. 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 in which high strength and creep resistance at relatively high temperatures (400-600 F) are required.

Material specifications for 2219 are presented in Table 3.2.6.0(a). Room temperature mechanical and physical properties are shown in Table 3.2.6.0(b) and (c). The effect of temperature on thermal expansion is shown in Figure 3.2.6.0.

TABLE 3.2.6.0(a). *Material Specifications for 2219 Aluminum Alloy*

Specification	Form
MIL-R-8920	Sheet and plate
AMS 4162	Extrusions

The temper index for 2219 is as follows:

Section	Temper
3.2.6.1	T62
3.2.6.2	T81, T851, T8510, T8511
3.2.6.3	T87

3.2.6.1 *T62 Temper.*—Cryogenic, room, and elevated temperature data for this temper are presented in Figures 3.2.6.1.1(a) and (b).

Typical room-temperature longitudinal and transverse 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 3.2.6.1.6(a) and (b).

3.2.6.2 *T81, T851 Temper.*—Cryogenic, room, and elevated-temperature data for these tempers are presented in Figures 3.2.6.2.1(a) and (b).

Typical room-temperature longitudinal and transverse tensile and compressive stress-strain, compressive tangent-modulus, and full-range tensile stress-strain curves for 2219 aluminum alloy sheet and plate for this condition are shown in Figures 3.2.6.2.6(a) and (b).

3.2.6.3 *T87 Temper.*—Cryogenic, room, and elevated-temperature data for this temper are presented in Figures 3.2.6.3.1(a) and (b).

Typical room-temperature longitudinal and transverse 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 3.2.6.3.6(a) and (b).

TABLE 3.2.6.0(B1). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 2219 ALUMINUM ALLOY (SHEET AND PLATE)

SPECIFICATION	MIL-A-8920				MIL-A-8920											
FORM	SHEET AND PLATE				SHEET AND PLATE											
TEMPER	T62		T81		T851											
THICKNESS, MM	0.51-50.80		0.51-6.32		6.35-25.41		25.42-50.81		50.82-76.21		76.22-101.61		101.62-127.01		127.02-152.40	
BASIS	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
MECHANICAL PROPERTIES:																
FTU, MPA:																
L	372	379	427	434	427	434	427	434	...	...	...	...	...	...	...	...
LT	372	379	427	434	427	434	427	434	427	434	414	421	407	414	393	400
FTY, MPA:																
L	248	255	324	331	324	331	324	331	...	...	...	...	...	...	...	...
LT	248	255	317	324	317	324	317	324	310	317	303	310	296	303	290	296
FCY, MPA:																
L	262	269	331	338	331	338	324	331	...	...	...	...	...	...	...	...
LT	262	269	338	345	338	345	338	345	...	...	...	...	...	...	...	...
FSU, MPA	221	221	248	248	248	248	248	255	...	...	...	...	...	...	...	...
FBRU[a], MPA:																
(E/D=1.5)	579	593	655	669	655	669	655	669	...	...	...	...	...	...	...	...
(E/D=2.0)	752	765	834	848	834	848	827	841	...	...	...	...	...	...	...	...
FBRY[a], MPA:																
(E/D=1.5)	434	448	531	538	531	538	531	538	...	...	...	...	...	...	...	...
(E/D=2.0)	545	565	641	655	641	655	641	655	...	...	...	...	...	...	...	...
EL, PERCENT:																
L	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
LT[c]	b	...	b	...	8	...	7	...	6	...	5	...	5	...	4	...
E, GPA	72.4				72.4											
EC, GPA	74.5				74.5											
G, GPA	27.6				27.6											
MU	0.33				0.33											
PHYSICAL PROPERTIES:																
OMEGA, MG/M3	2.82															
C, J/(G*K)	0.96 (AT 373 K)															
K, W/(M*K)	128 (AT 298 K)															
ALPHA, 10-6 M/(M*K)	22.3 (293-373 K)															

[a] SEE TABLE 3.1.2.1.1. BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

[b] T62 AND T81: 0.51-0.99MM., 6 PERCENT: 1.02-6.32MM., 7 PERCENT: T62: 6.35-25.40MM., 8 PERCENT: 25.40-50.80MM., 7 PERCENT.

[c] THESE ALLOWABLES 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.

TABLE 3.2.6.0(B2). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 2219 ALUMINUM ALLOY (SHEET AND PLATE)

SPECIFICATION	MIL-A-8920													
FORM	SHEET AND PLATE													
TEMPER	T87													
THICKNESS, MM	0.51-1.00		1.01-6.33		6.34-25.41		25.42-50.81		50.82-76.21		76.22-101.61		101.62-127.00	
BASIS	A	B	A	B	A	B	A	B	A	B	A	B	A	B
MECHANICAL PROPERTIES:														
FTU, MPA:														
L	434	441	434	441	434	441	434	441	...	...	...	...	...	...
LT	441	448	441	448	441	448	441	448	441	448	427	434	421	427
FTY, MPA:														
L	352	359	359	365	352	359	352	359	...	...	...	...	...	...
LT	359	365	359	365	352	359	352	359	352	359	345	352	338	345
FCY, MPA:														
L	359	365	359	365	352	359	352	359	...	...	...	...	...	...
LT	379	386	379	386	372	379	372	3830	...	...	...	...	...	...
FSU, MPA	255	262	255	262	255	262	262	262	...	...	...	...	...	...
FBRU[a], MPA:														
(E/D=1.5)	683	696	683	696	683	696	683	696	...	...	...	...	...	...
(E/D=2.0)	869	883	869	883	869	883	869	883	...	...	...	...	...	...
FBRY[a], MPA:														
(E/D=1.5)	579	593	579	593	572	579	572	579	...	...	...	...	...	...
(E/D=2.0)	669	683	669	683	655	669	655	669	...	...	...	...	...	...
EL, PERCENT:														
L	...	...	...	...	...	...	...	...	...	...	...	...	...	...
LT	5	...	6	...	7	...	6	...	6	...	4	...	3	...
E, GPA	72.4													
EC, GPA	74.5													
G, GPA	2.3													
MU	0.33													
PHYSICAL PROPERTIES:														
OMEGA, MG/M3	2.82													
C, J/(G*K)	0.96 (AT 373 K)													
K, W/(M*K)	128 (AT 298 K)													
ALPHA, 10-6 M/(M*K)	22.3 (293-373 K)													

[a] SEE TABLE 3.1.2.1. BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

(Page 3-146b Blank)

TABLE 3.2.6.0 (C). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 2219 ALUMINUM ALLOY (EXTRUDED SHAPE)

SPECIFICATION..............	AMS 4162	
FORM......................	EXTRUDED SHAPE	
CONDITION.................	T8510, T8511	
THICKNESS, MM.............	≤ 12.67	12.68-76.17
BASIS.....................	S	S
MECHANICAL PROPERTIES:		
FTU, MPA:		
L.......................	400	400
LT......................	386	386
ST......................	...	...
FTY, MPA:		
L.......................	290	290
LT......................	269	269
ST......................	...	...
FCY, MPA:		
L.......................	296	290
LT......................	296	283
ST......................	...	...
FSU, MPA..................	228	225
FBRU,[a] MPA:		
(E/D=1.5)..............	600	558
(E/D=2.0)..............	779	736
FBRY,[a] MPA:		
(E/D=1.5)..............	476	462
(E/D=2.0)..............	579	565
EL, PERCENT:		
L.......................	6	6
LT......................	4	4
ST......................	...	...
E, GPA....................	72.4	
EC, GPA...................	74.5	
G, GPA....................	27.6	
MU........................	0.33	
PHYSICAL PROPERTIES:		
OMEGA, MG/M3..............	2.82	
C, J/(G*K)................	0.96 (AT 373 K)	
K, W/(M*K)................	128 (AT 298 K)	
ALPHA, 10-6 M/(M*K).......	SEE FIGURE 3.2.6.0	

[a] BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

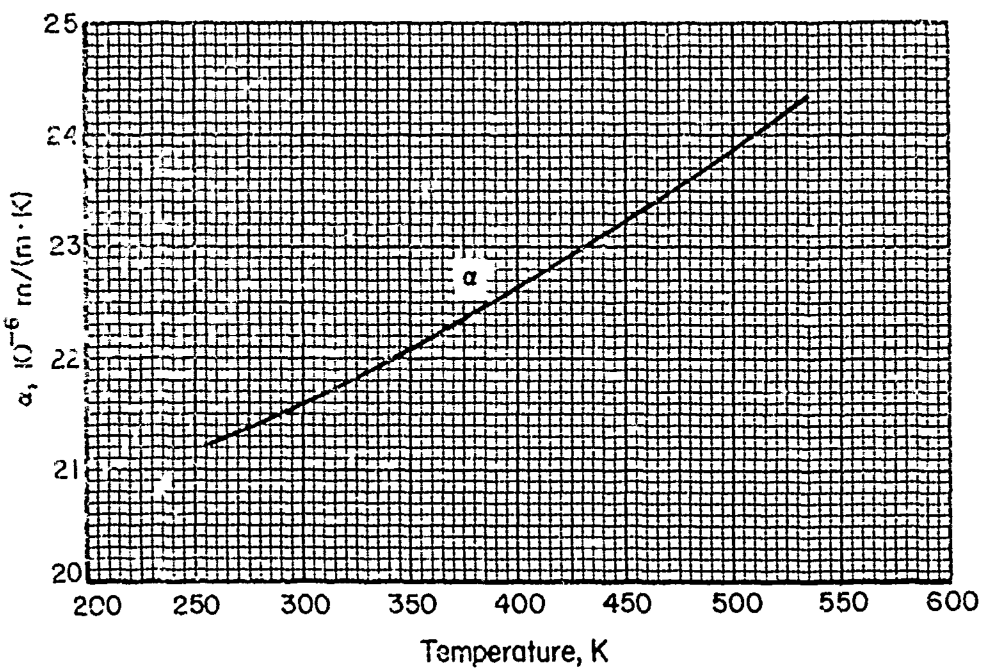


FIGURE 3.2.6.0. Effect of temperature on the physical properties of 2219 aluminum alloy.

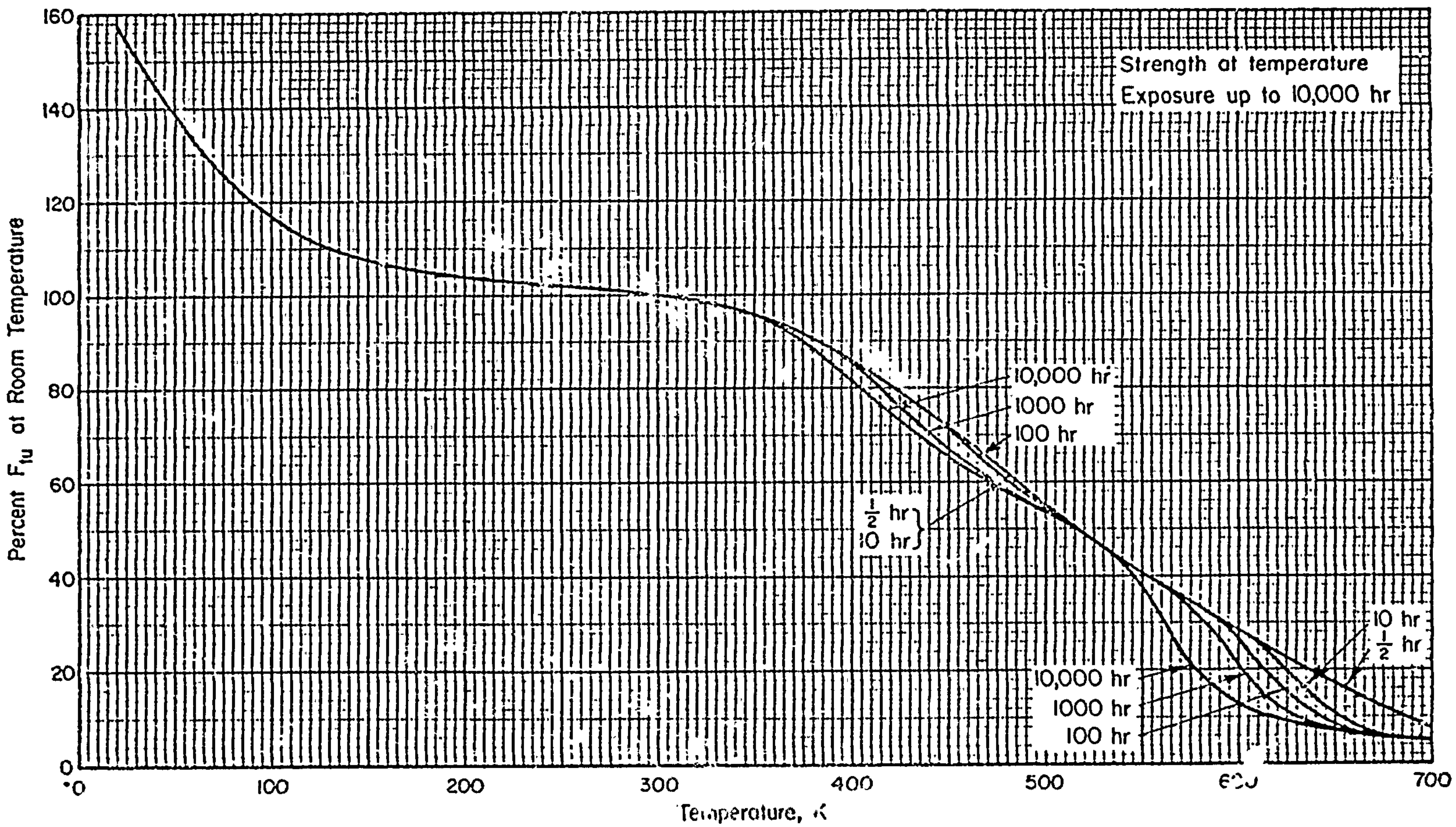


FIGURE 3.2.6.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of 2219-T62 aluminum alloy (bare and clad sheet and plate 1.016-25.4 mm thick).

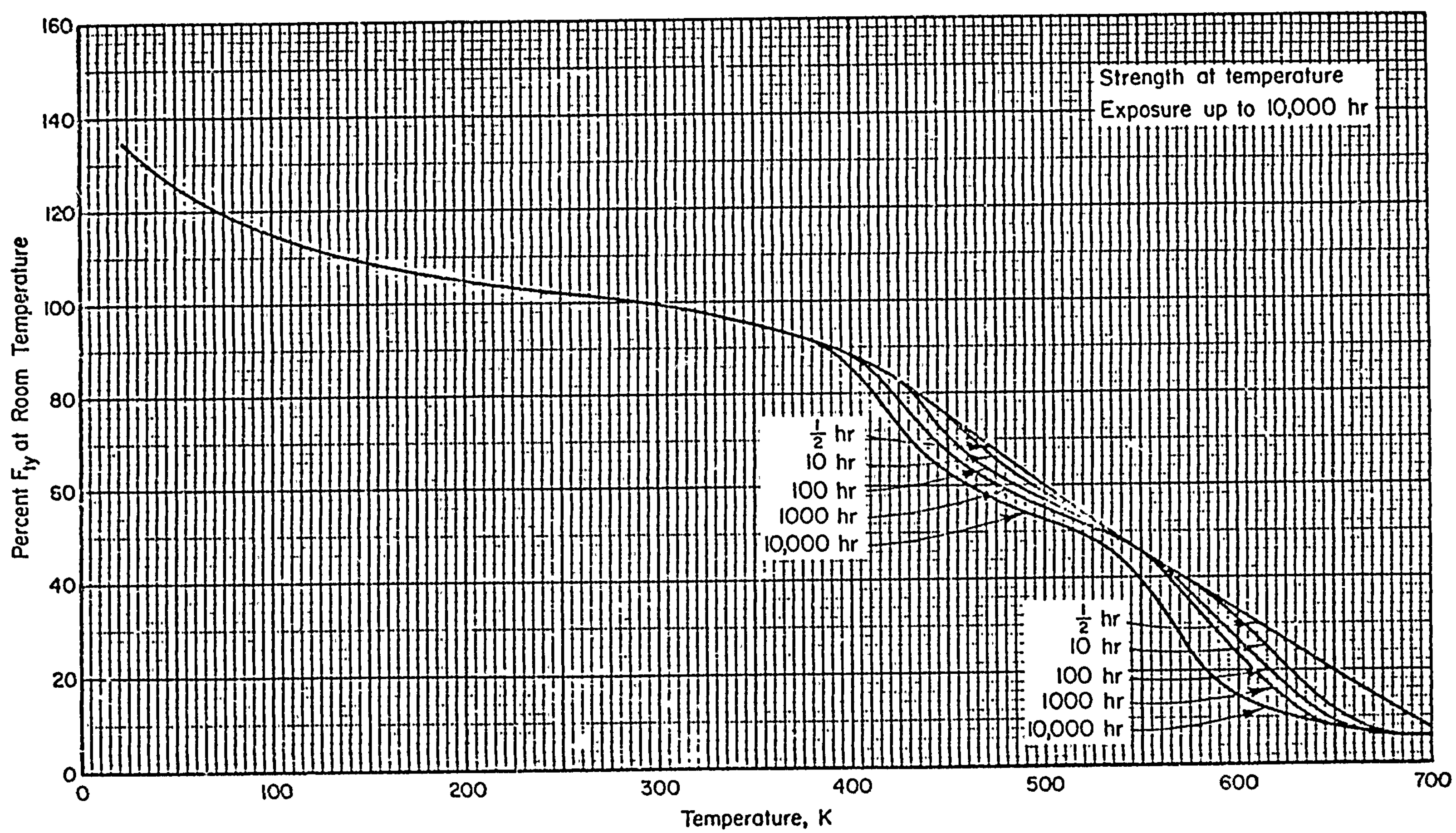


FIGURE 3.2.6.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of 2219-T62 aluminum alloy (bare and clad sheet and plate 1.016-25.4 mm thick).

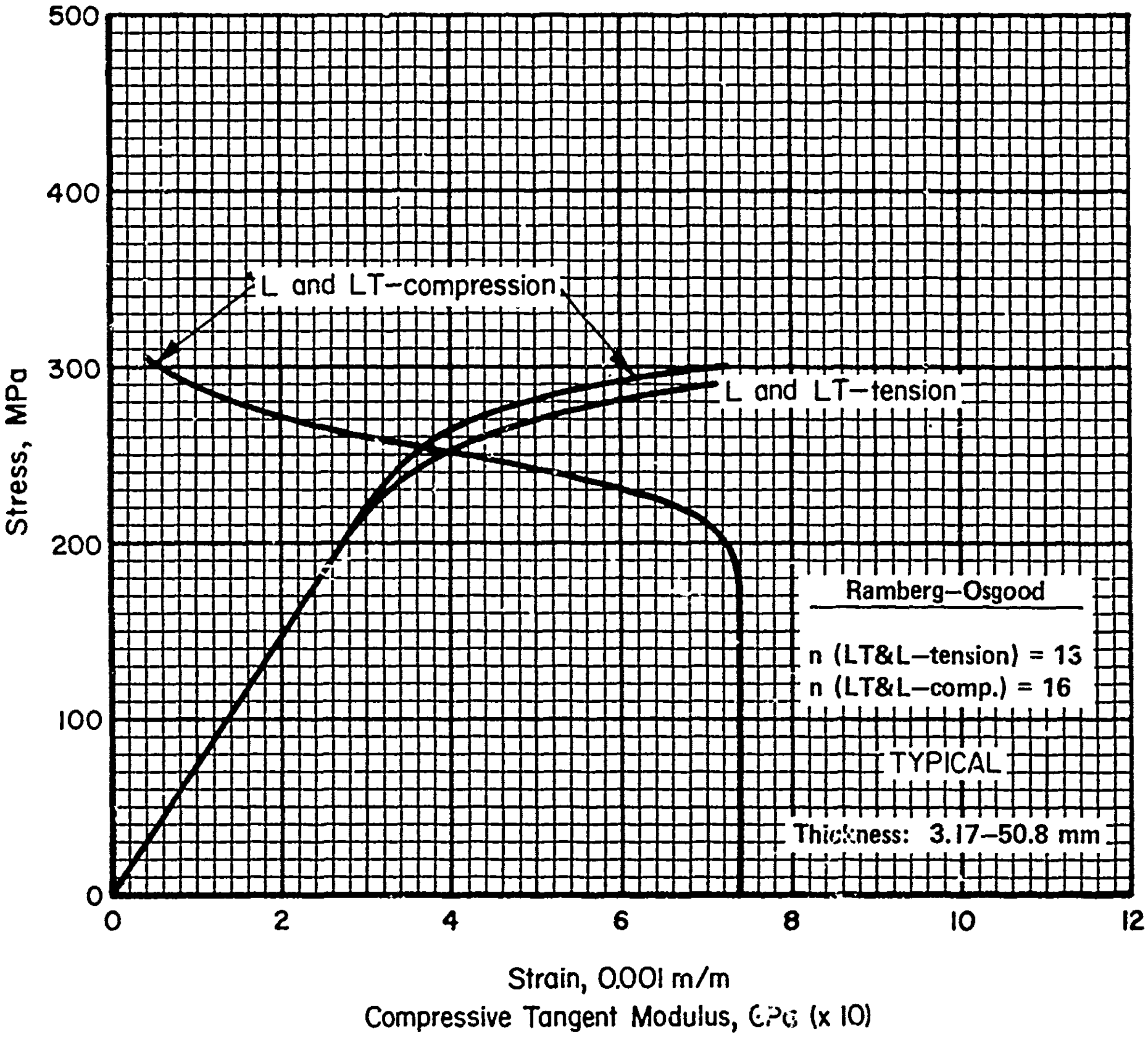


FIGURE 3.2.6.1.6(a). Typical tensile stress-strain and compressive stress-strain and tangent-modulus curves for 2219-T62 aluminum alloy (sheet and plate) at room temperature.

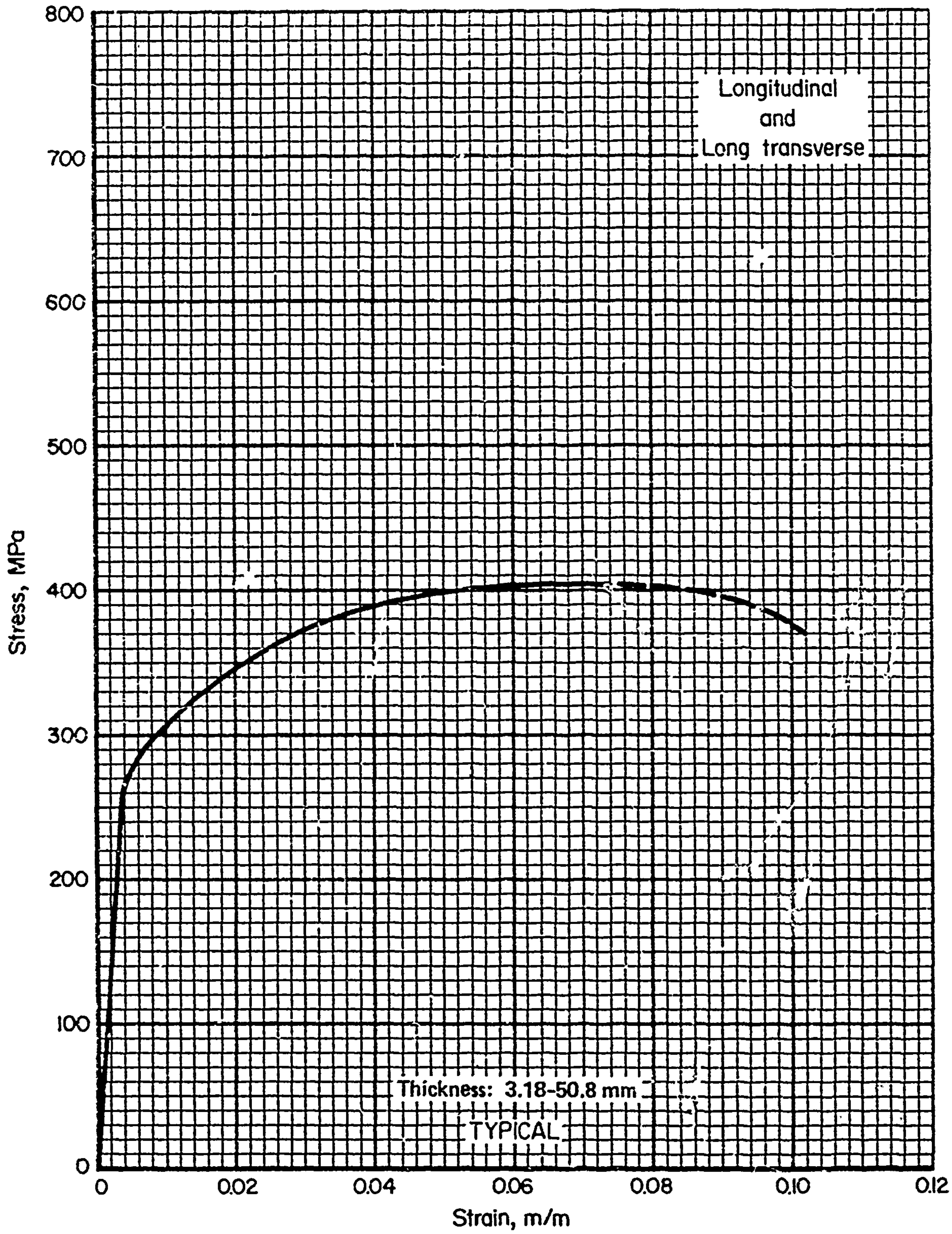


FIGURE 3.2.6.1.6(b). Typical tensile stress-strain curve (full range) for 2219-T62 aluminum alloy (sheet and plate) at room temperature.

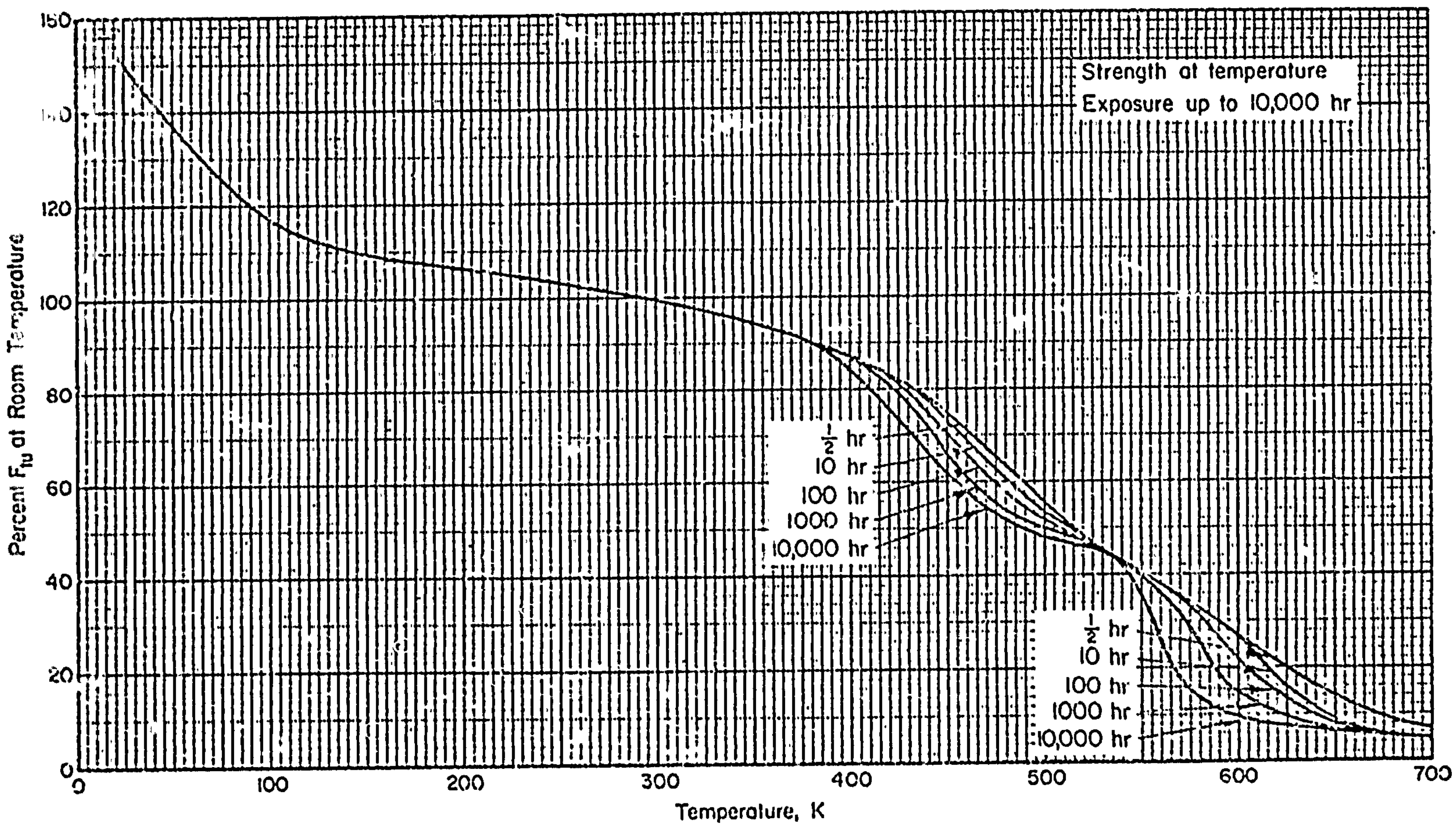


FIGURE 3.2.6.2.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of 2219-T81 and T851 aluminum alloy (bare and clad sheet and plate).

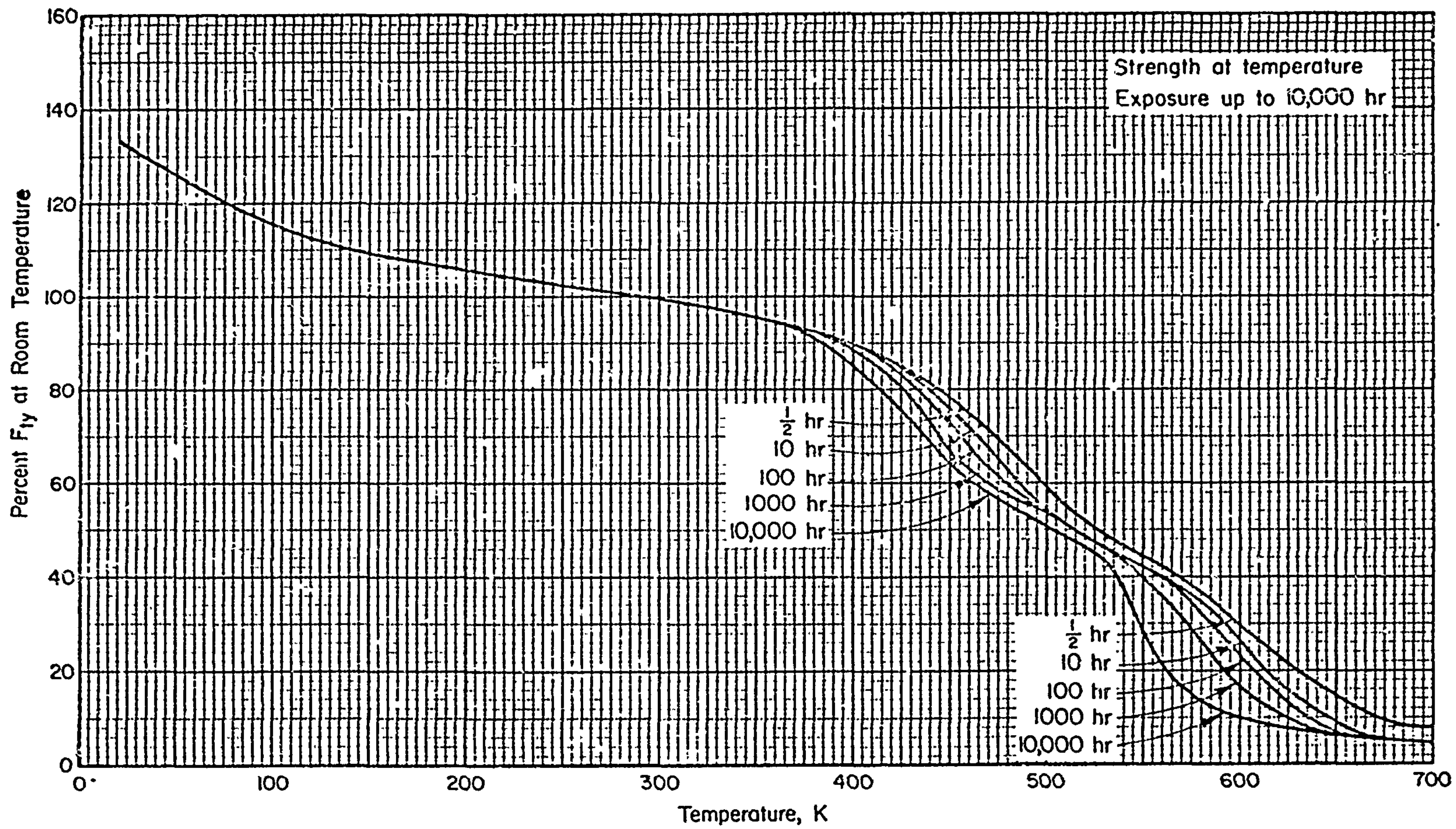


FIGURE 3.2.6.2.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of 2219-T81 and T851 aluminum alloy (bare and clad sheet and plate).

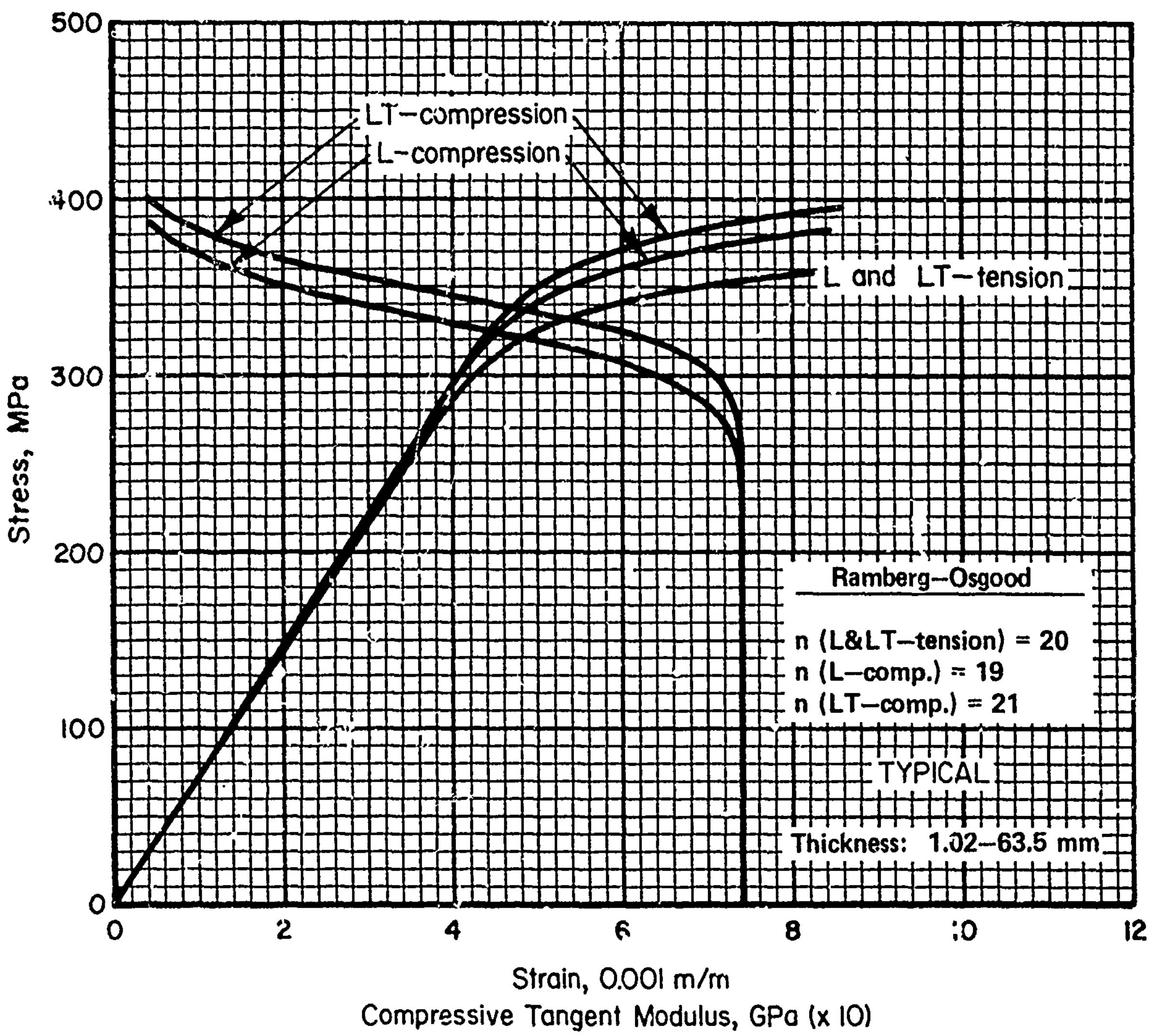


FIGURE 3.2.6.2.6(a). Typical tensile stress-strain and compressive stress-strain and tangent-modulus curves for 2219-T81 and T851 aluminum alloy (sheet and plate) at room temperature.

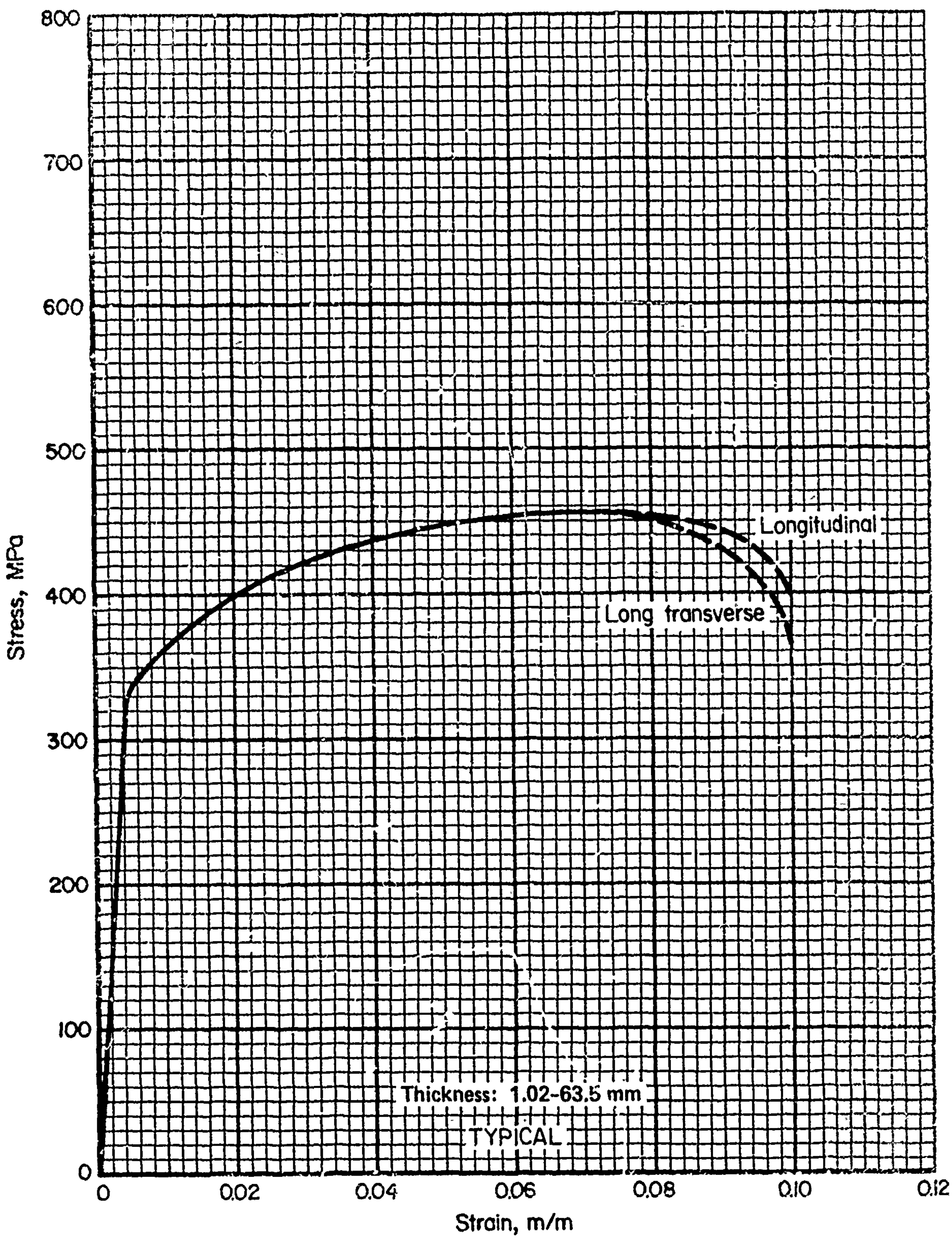


FIGURE 3.2.6.2.6(b). Typical tensile stress-strain curves (full-range) for 2219-T81 and T851 aluminum alloy (sheet and plate) at room temperature.

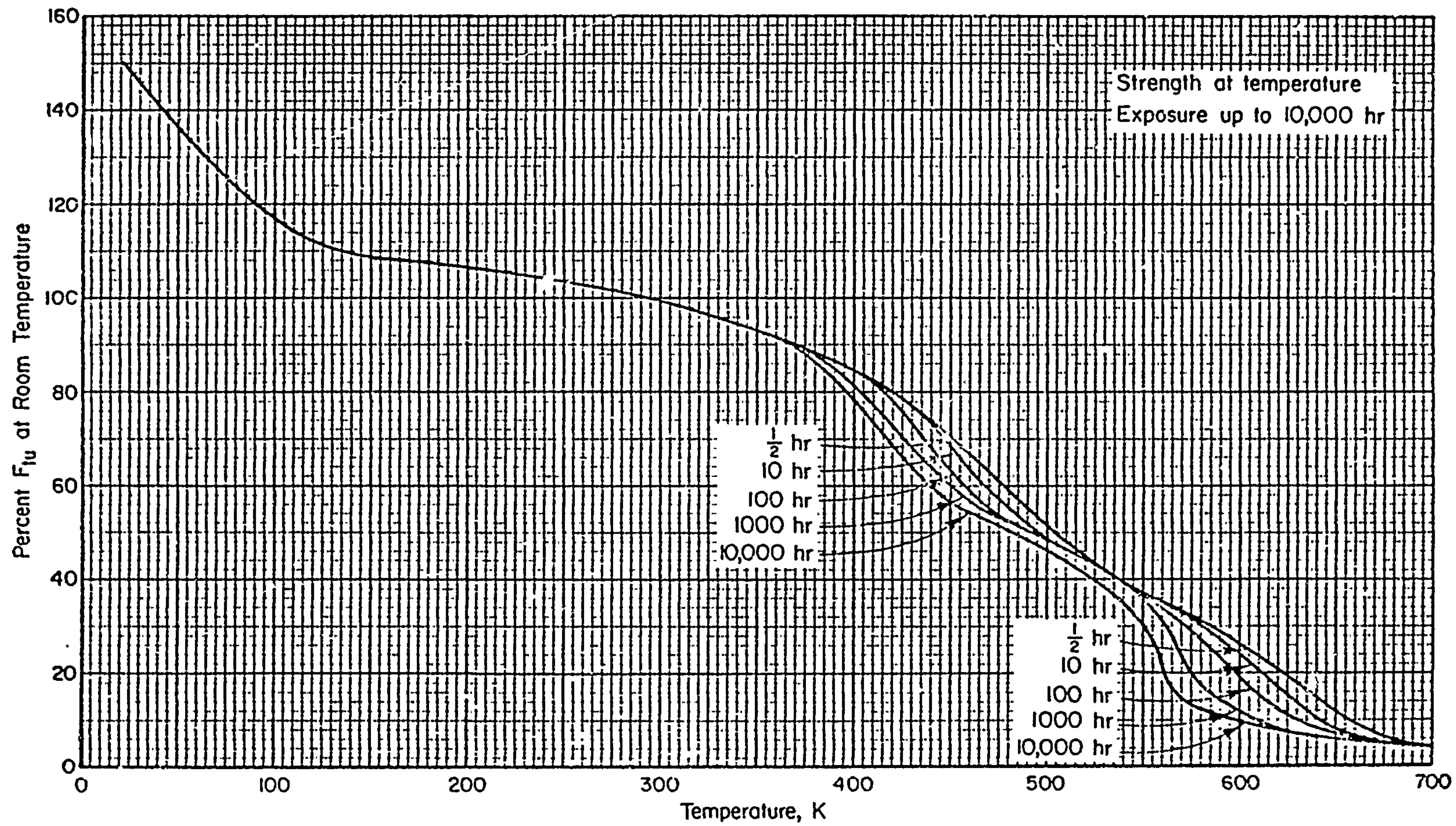


FIGURE 3.2.6.3.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of 2219-T87 aluminum alloy (bare and clad sheet and plate).

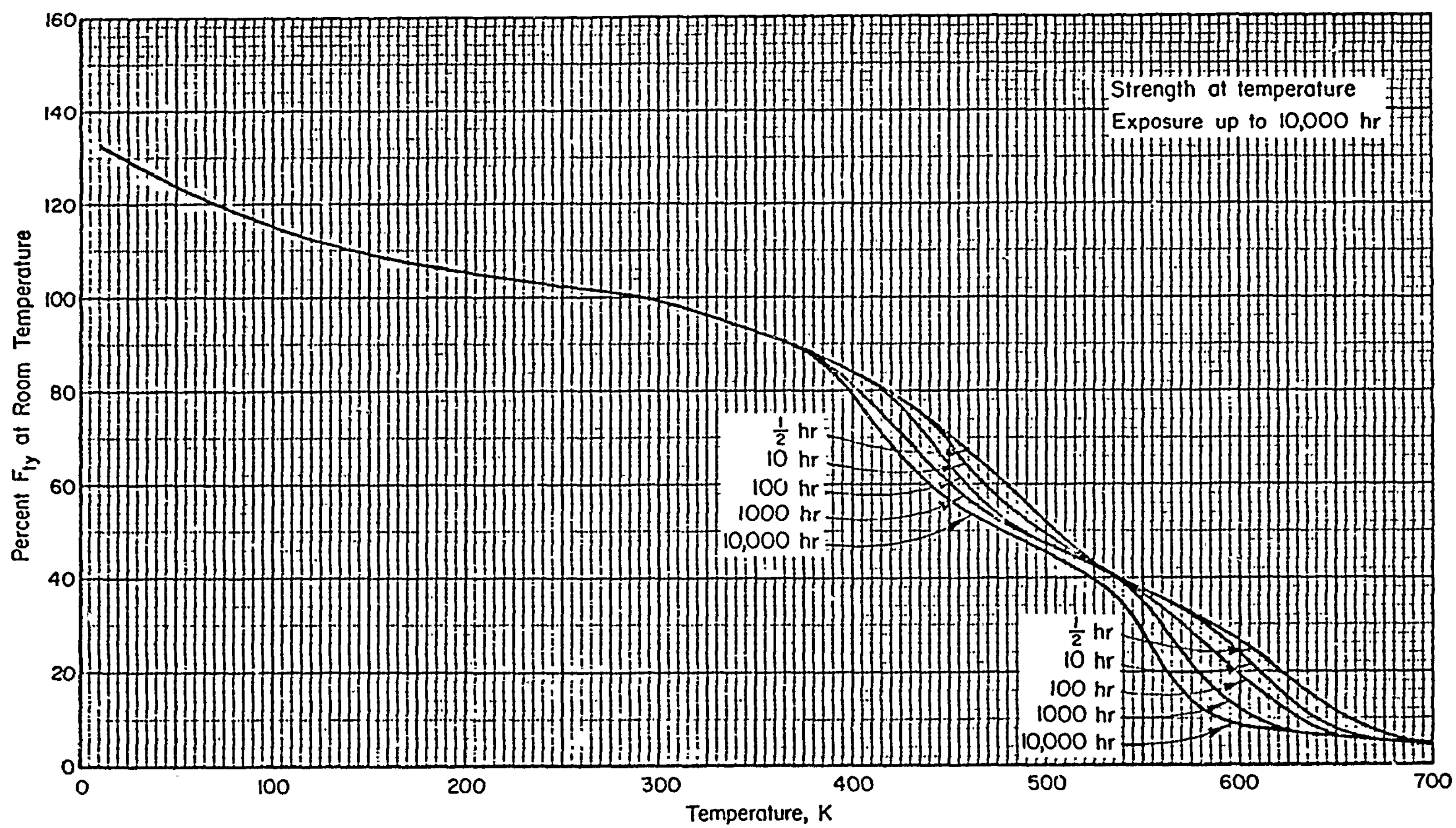


FIGURE 3.2.6.3.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of 2219-T87 aluminum alloy (bare and clad sheet and plate).

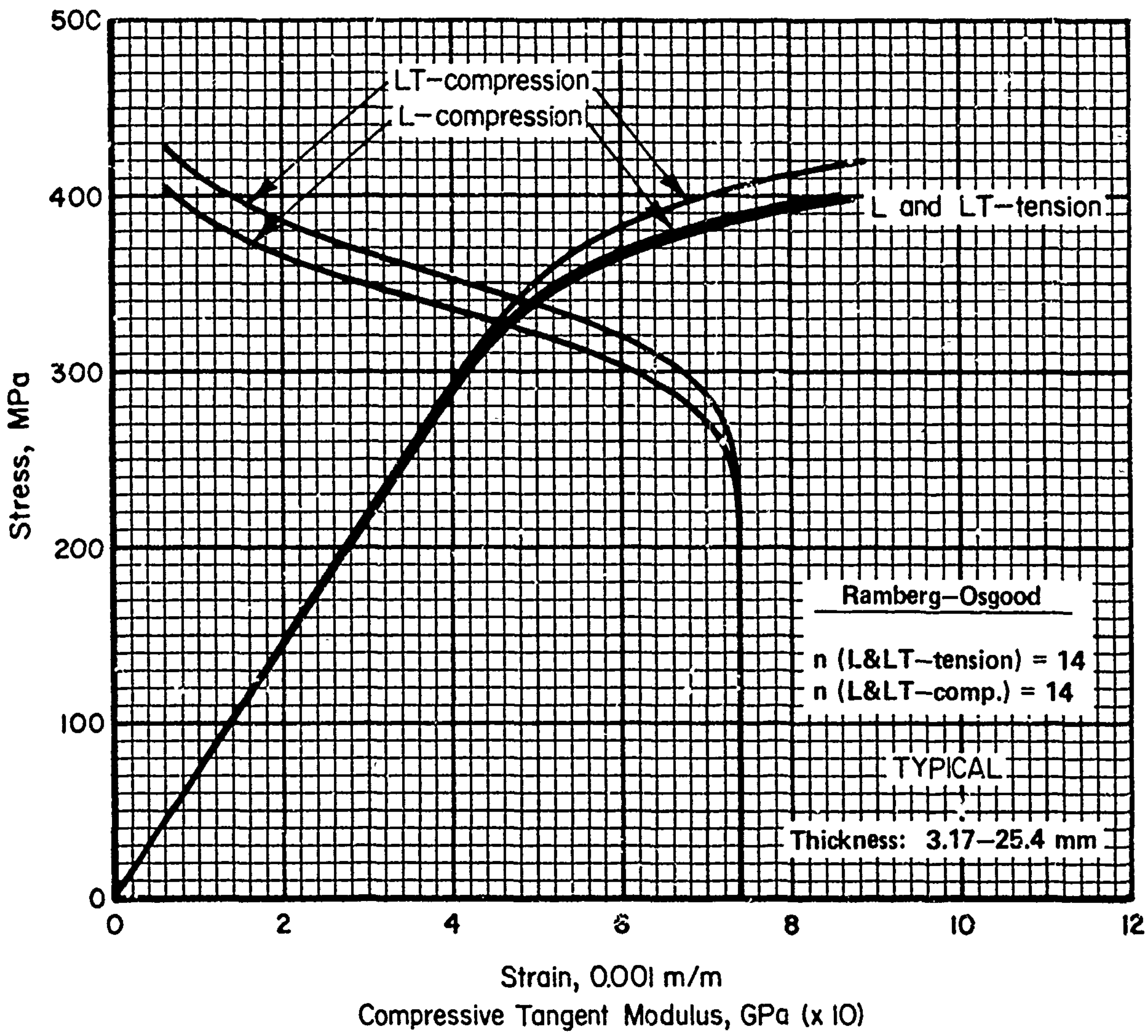


FIGURE 3.2.6.3.6(a). Typical tensile stress-strain and compressive stress-strain and tangent-modulus curves for 2219-T87 aluminum alloy (sheet and plate) at room temperature.

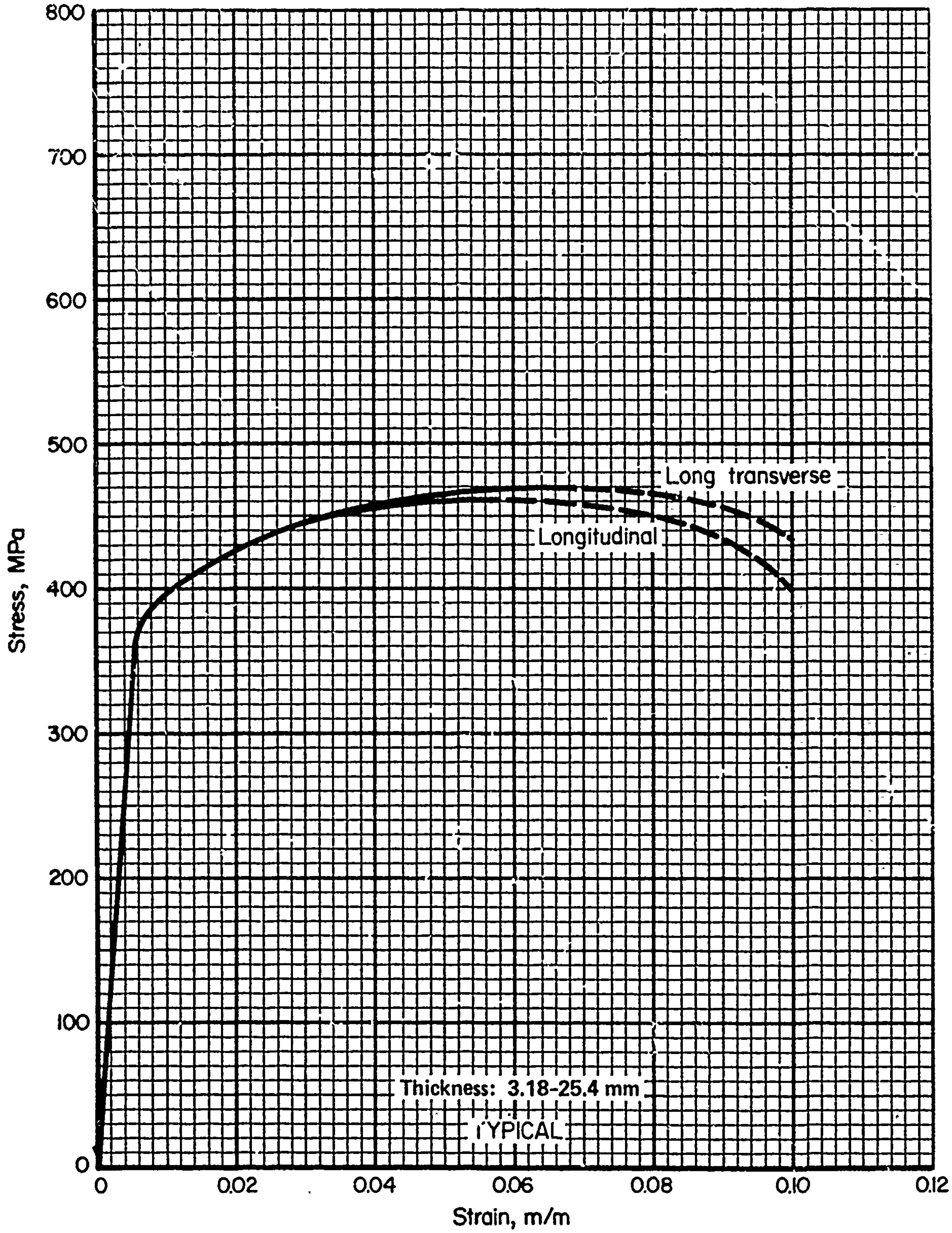


FIGURE 3.2.6.3.6(b). Typical tensile stress-strain curves (full range) for 2219-T87 aluminum alloy (sheet and plate) at room temperature.

3.2.7 2618 ALLOY

3.2.7.0 *Comments and Properties.*—2618 is an Al-Cu alloy which has been used principally for hand and die forgings. It has excellent properties over a range of temperatures from 4 to 589 K 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.

Material specifications for 2618 aluminum alloy are presented in Table 3.2.7.0(a). Room-temperature mechanical and physical properties are shown in Table 3.2.7.0(b) and (c). The effect of temperature on α is shown in Figure 3.2.7.0.

TABLE 3.2.7.0(a). *Material Specifications for 2618 Aluminum Alloy*

Specification	Type of Product
QQ-A-367	Hand forgings
MIL-A-22771	Die forgings

The temper index for 2618 is as follows:

Section	Temper
3.2.7.1	T61

3.2.7.1 *T61 Temper.*—Figures 3.2.7.1.1(a) through 3.2.7.1.5 present effect-of-temperature curves for various mechanical properties.

Figure 3.2.7.1.6(a) presents tensile and compressive stress-strain curves at room temperature. Figure 3.2.7.1.6(b) is a full-range, tensile stress-strain curve at room temperature.

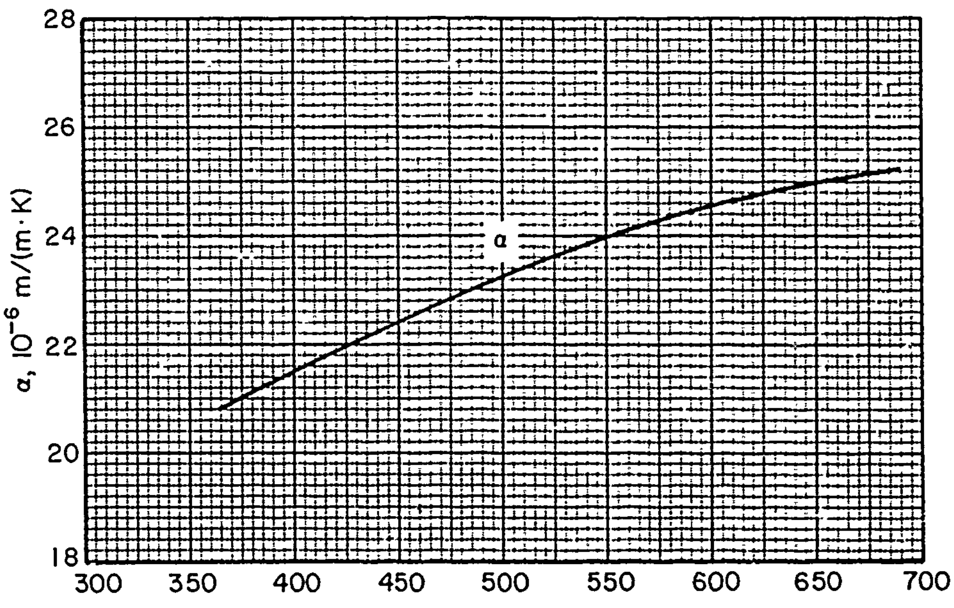


FIGURE 3.2.7.0. Effect of temperature on the physical properties of 2618 aluminum alloy.

TABLE 3.2.7.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 2616 ALUMINUM ALLOY (DIE FORGING)

SPECIFICATION............	MIL-A-22771
FORM....................	DIE FORGING
CONDITION...............	T61
THICKNESS[b], MM...........	≤ 101.60
BASIS...................	S
MECHANICAL PROPERTIES:	
FTU, MPA:	
L[a].................	400
T..................	379
FTY, MPA:	
L..................	310
T..................	290
FCY, MPA:	
L..................	...
T..................	...
FSU, MPA...............	...
FBRU, MPA:	
(E/D=1.5)..........	...
(E/D=2.0)..........	...
FBRY, MPA:	
(E/D=1.5)..........	...
(E/D=2.0)..........	...
EL, PERCENT:	
L..................	4
T..................	4
E, GPA................	73.8
EC, GPA...............	75.2
G, GPA................	28.3
MU....................	0.33
PHYSICAL PROPERTIES:	
OMEGA, MG/M3..........	2.77
C, J/(G*K)............	0.96 (AT 373 K)
K, W/(M*K)............	156 (AT 298 K)
ALPHA, 10-6 M/(M*K)..	22.1 (293 to 373 K)

[a] FOR DIE FORGINGS, T INDICATES ANY GRAIN DIRECTION NOT WITHIN ± 15 DEGREES OF BEING PARALLEL TO THE FORGING FLOW LINES. SPECIMENS TO TEST TRANSVERSE PROPERTIES SHOULD BE LOCATED AS CLOSE TO THE SHORT TRANSVERSE DIRECTION AS POSSIBLE.

[b] THE THICKNESS COLUMNS ARE FOR THE AS-HEAT-TREATED THICKNESS. TO ENTER THE TABLE USE THE HIGHER OF THE HEAT-TREAT THICKNESS OR ONE-HALF OF THE AS-FORGED THICKNESS.

TABLE 3.2.7.0(c). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 2618 ALUMINUM ALLOY (HAND FORGING)

SPECIFICATION..........	QQ-A-367		
FORM..................	HAND FORGING		
CONDITION.............	T61		
THICKNESS,[a] MM..........	<50.81	50.82-76.21	76.22-101.60
BASIS.................	S	S	S
MECHANICAL PROPERTIES:			
FTU, MPA:			
L................	400	393	386
LT...............	379	379	365
ST...............	359	359	352
FTY, MPA:			
L................	324	317	310
LT...............	290	290	276
ST...............	290	290	269
FCY, MPA:			
L................	...	338	331
LT...............	...	310	290
ST...............	...	...	...
FSU, MPA.............	...	234	226
FBRU, MPA:			
(E/D=1.5).........	...	...	...
(E/D=2.0).........	...	745	717
FBRY, MPA:			
(E/D=1.5).........	...	...	...
(E/D=2.0).........	...	517	490
EL, PERCENT:			
L................	7	7	7
LT...............	5	5	4
ST...............	4	4	4
E, GPA...............	73.8		
EC, GPA..............	75.2		
G, GPA...............	28.3		
MU...................	0.33		
PHYSICAL PROPERTIES:			
OMEGA, MG/M3........	2.77		
C, J/(G*K)...........	0.96 (AT 373 K)		
K, W/(M*K)...........	156 (AT 298 K)		
ALPHA, 10-6 M/(M*K)..	22.1 (293 TO 373 K)		

[a] WHEN HAND FORGINGS ARE MACHINED BEFORE HEAT TREATMENT, THE SECTION THICKNESS AT TIME OF HEAT TREATMENT SHALL 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 9.290.350.CM.

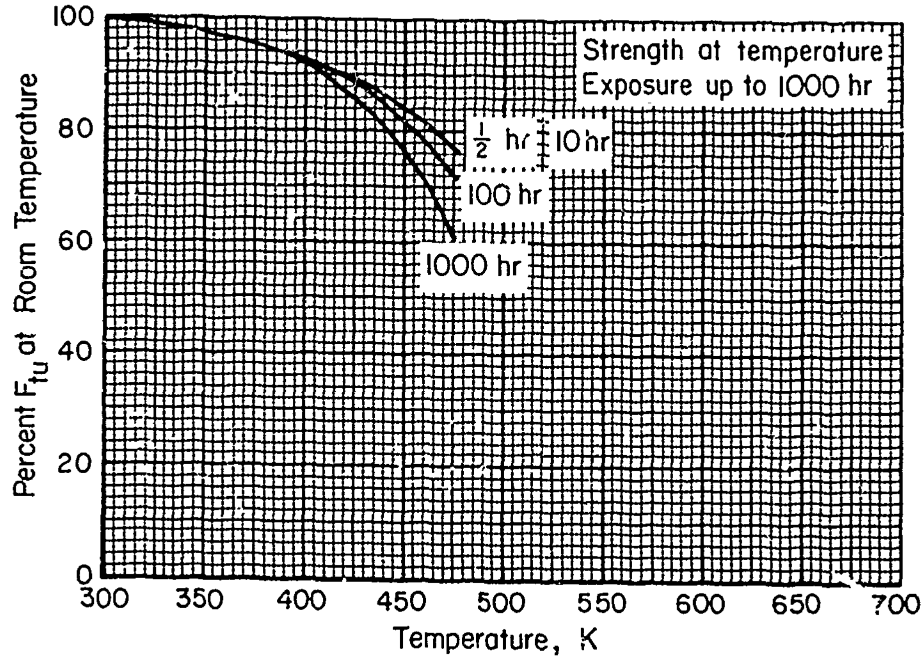


FIGURE 3.2.7.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of 2618-T61 aluminum alloy (hand-forged billet).

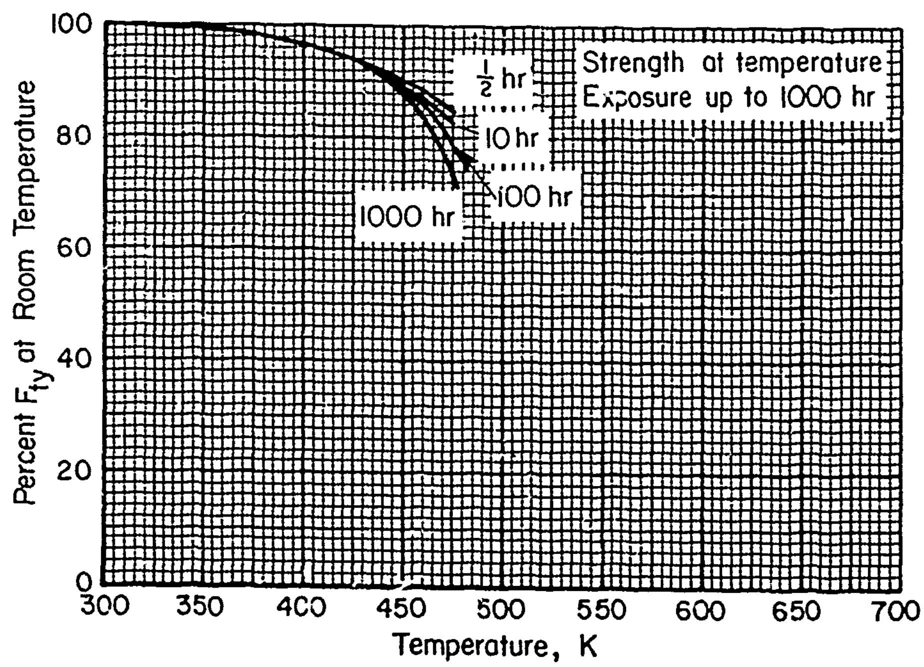


FIGURE 3.2.7.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of 2618-T61 aluminum alloy (hand-forged billet).

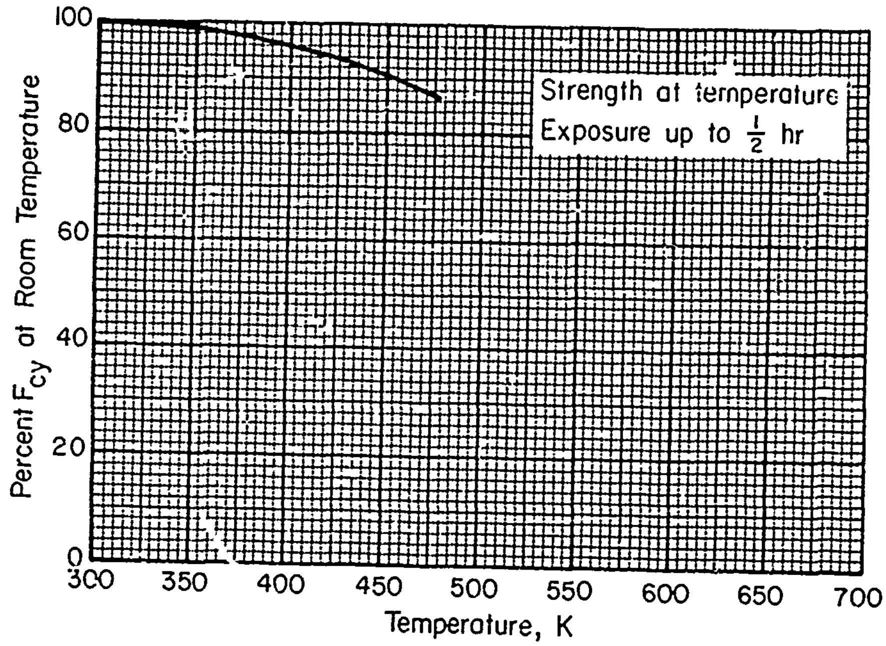


FIGURE 3.2.7.1.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of 2618-T61 aluminum alloy (hand-forged billet).

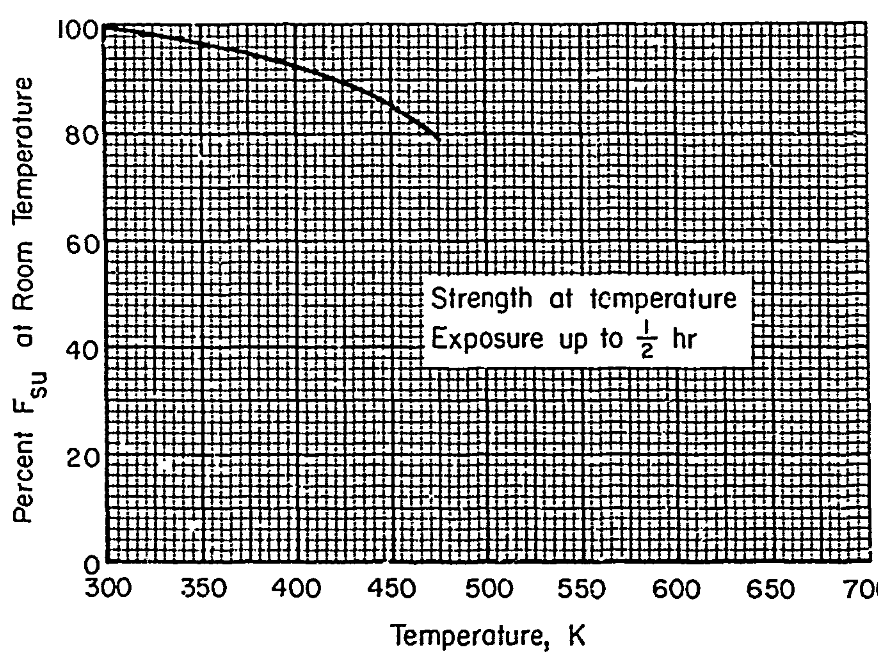


FIGURE 3.2.7.1.2(b). Effect of temperature on the ultimate shear strength (F_{su}) of 2618-T61 aluminum alloy (hand-forged billet).

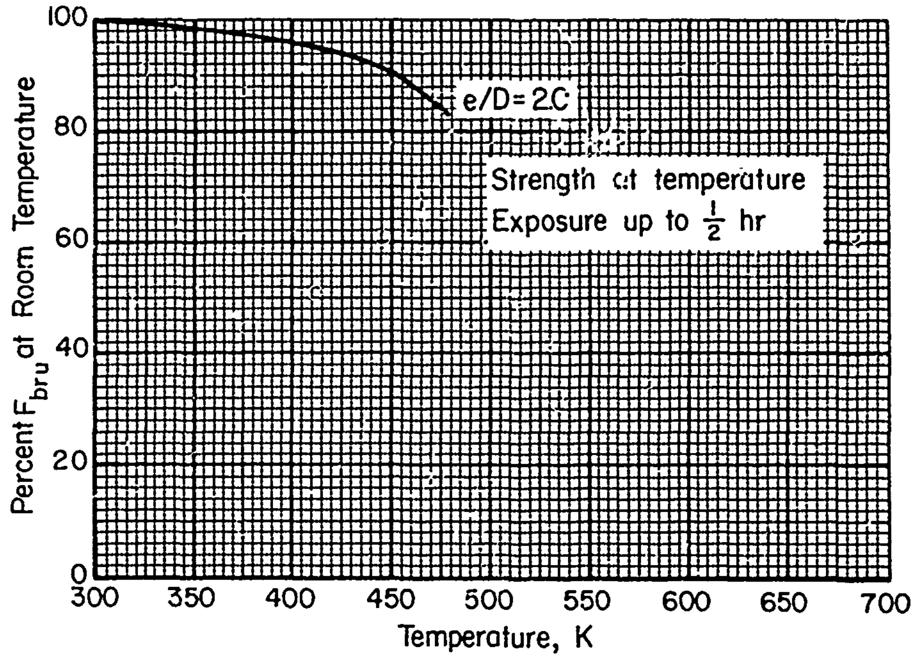


FIGURE 3.2.7.1.3(a). Effect of temperature on the ultimate bearing strength (F_{bru}) of 2618-T61 aluminum alloy (hand-forged billet).

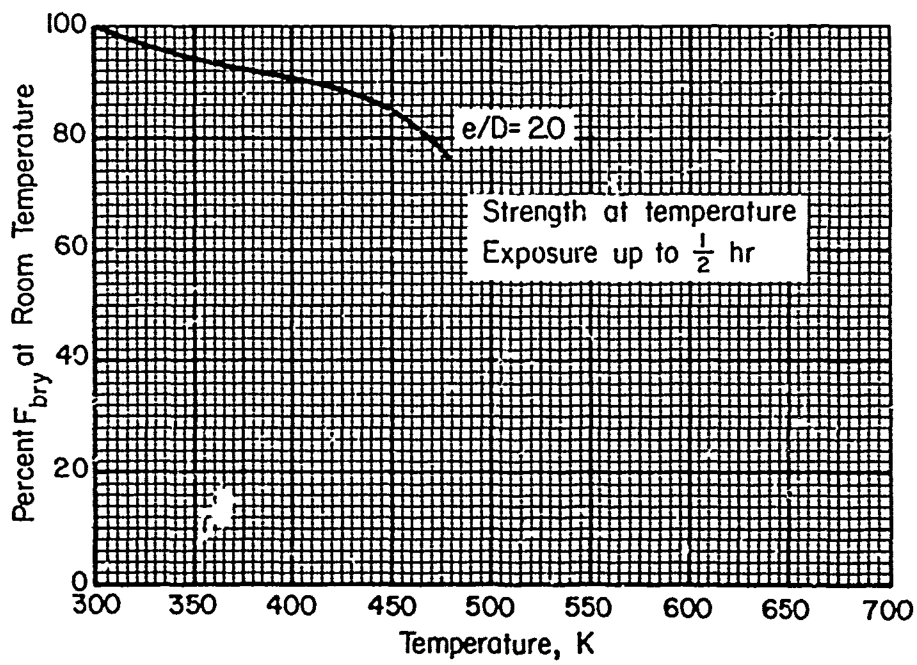


FIGURE 3.2.7.1.3(b). Effect of temperature on the bearing yield strength (F_{bry}) of 2618-T61 aluminum alloy (hand-forged billet).

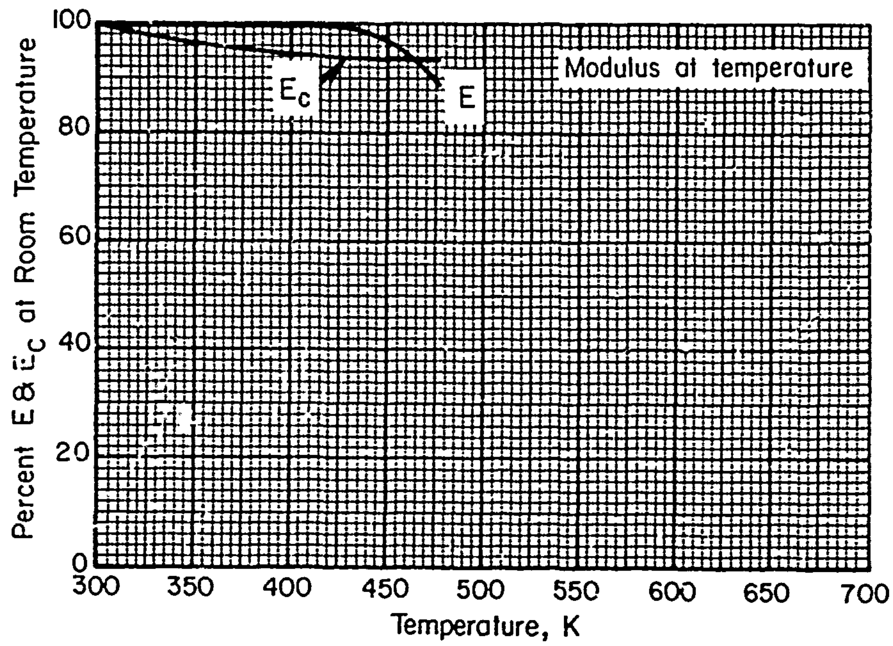


FIGURE 3.2.7.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of 2618-T61 aluminum alloy (hand-forged billet).

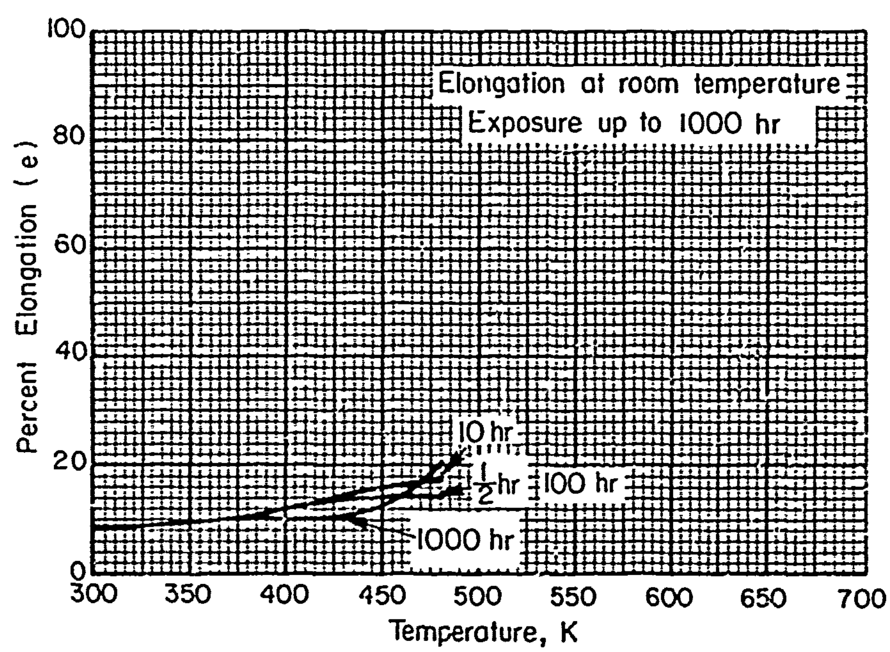


FIGURE 3.2.7.1.5. Effect of temperature on the elongation (e) of 2618-T61 aluminum alloy (hand-forged billet).

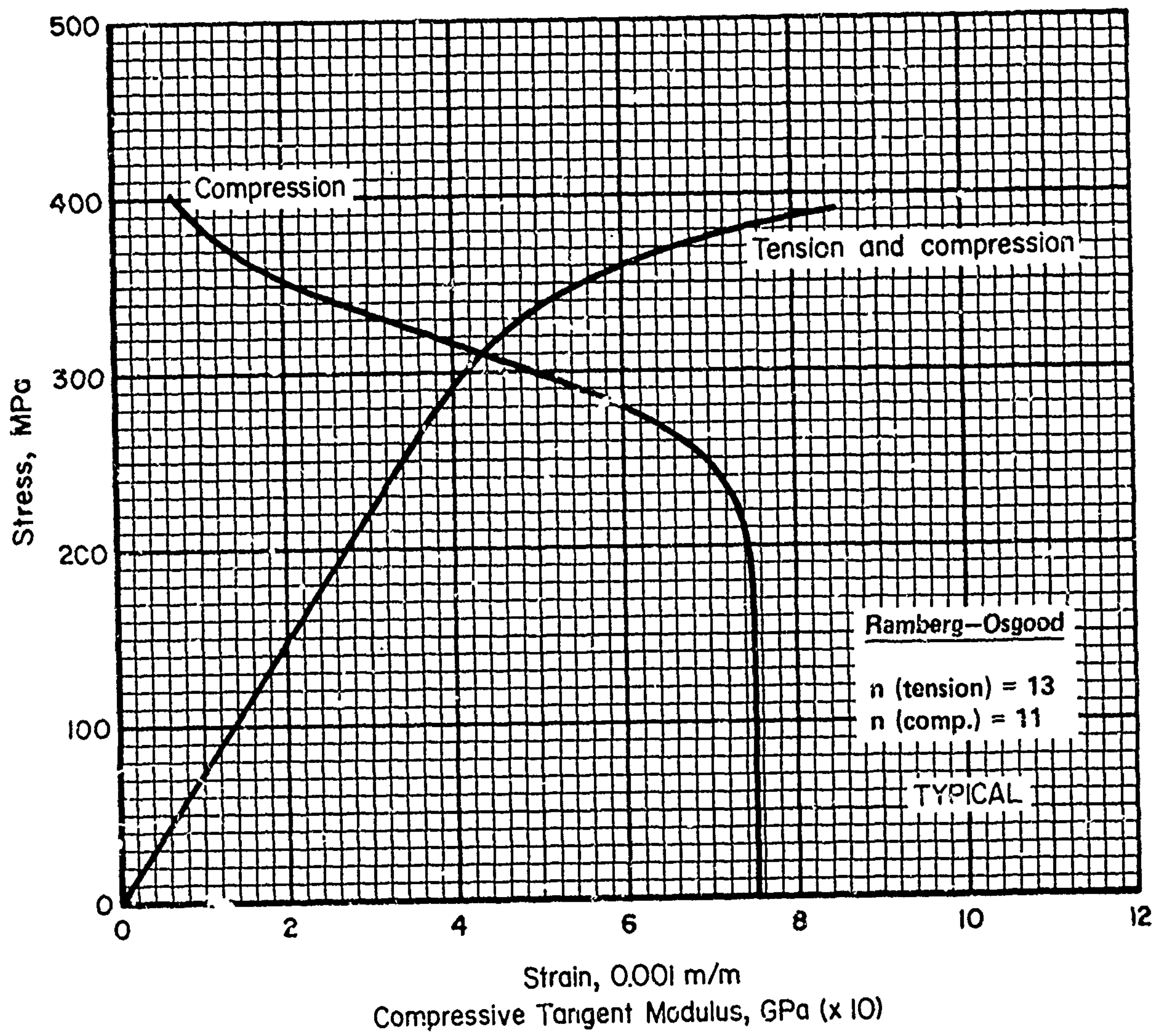


FIGURE 3.2.7.1.6(a). Typical tensile stress-strain and compressive stress-strain and tangent-modulus curves for 2618-T61 alloy (forged bar) at room temperature.

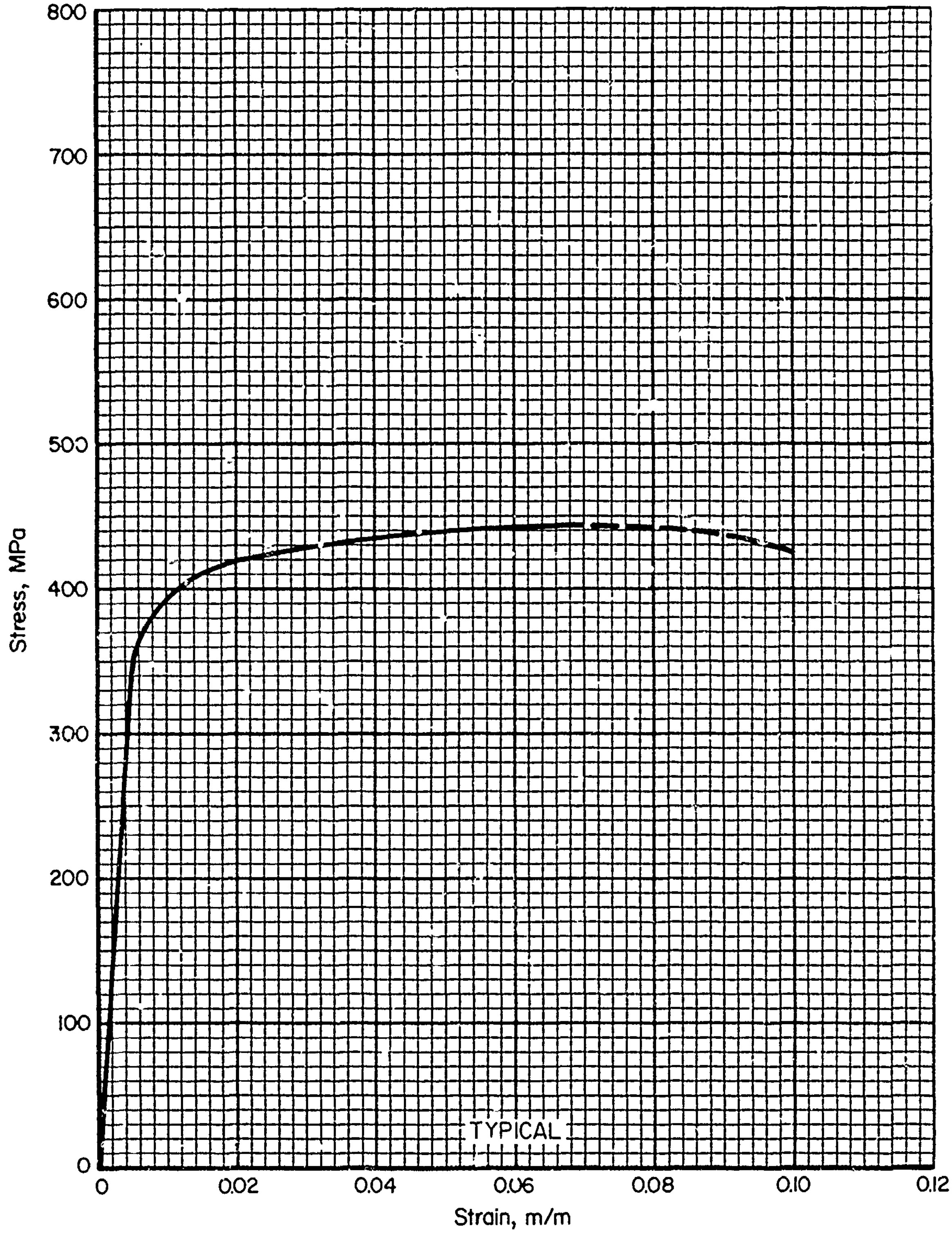


FIGURE 3.2.7.1.6(b). Typical tensile stress-strain curve (full range) at room temperature for 2618-T61 aluminum alloy (forged bar).

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 4 K, they are widely used in cryogenic applications. Strain-hardened tempers of 5000 series alloys containing more than 3 percent magnesium should not be used at temperatures above 373 K because susceptibility to stress-corrosion cracking 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.

A material specification for 5052 aluminum alloy is presented in Table 3.5.1.0(a). Room-temperature mechanical and physical properties are shown in Tables 3.5.1.0(b) and (c). The effect of temperature on physical properties is shown in Figure 3.5.1.0.

TABLE 3.5.1.0(a). *Material Specification for 5052 Aluminum Alloy*

Specification	Form
QQ-A-250/8	Sheet and plate

The temper index for 5052 is as follows:

Section	Temper
3.5.1.1	0
3.5.1.2	H32
3.5.1.3	H34
3.5.1.4	H36
3.5.1.5	H38

3.5.1.1 *O Temper.*—Effect of temperature curves for this temper for various mechanical properties are presented in Figures 3.5.1.1.1(a) through 3.5.1.1.5.

3.5.1.2 *H32 Temper.*—Figure 3.5.1.1.4 may be used for the effect of temperature curve for modulus of elasticity for this temper.

3.5.1.3 *H34 Temper.*—Effect of temperature curves for this temper for various mechanical properties are presented in Figures 3.5.1.3.1(a) through 3.5.1.3.5(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 effect of temperature curve for modulus of elasticity for this temper.

3.5.1.5 *H38 Temper.*—Effect of temperature curves for this temper for various mechanical properties are presented in Figures 3.5.1.5.1(a) through 3.5.1.5.5(b). Use Figure 3.5.1.1.4 for modulus values.

TABLE 3.5.1.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 5052 ALUMINUM ALLOY (SHEET)

SPECIFICATION	QQ-A-250/6				
FORM	SHEET				
CONDITION	O	H32	H34	H36	H38
THICKNESS, MM	0.15-6.32	0.43-6.32	0.23-6.32	0.15-4.11	0.15-3.25
BASIS	S	S	S	S	S
MECHANICAL PROPERTIES:					
FTU, MPA:					
L	172	214	234	255	269
T	...	214	234	255	269
FTY, MPA:					
L	76[b]	145	165	200	228
T	...	138	159	200	228
FCY, MPA:					
L	...	138	159	...	...
T	...	145	165	...	...
FSU, MPA	110	131	138	152	159
FBRU, MPA:					
(E/D=1.5)	...	345	372	407	427
(E/D=2.0)	...	448	490	538	565
FBRY, MPA:					
(E/D=1.5)	...	200	234	283	317
(E/D=2.0)	...	234	262	317	365
EL, PERCENT:					
L	a	a	a	a	a
T	...	...	...	...	...
E, GPA	69.6				
EC, GPA	70.3				
G, GPA	26.5				
MU	0.33				
PHYSICAL PROPERTIES:					
OMEGA, MG/M3	2.68				
C, J/(G*K)	0.96 (AT 373 K)				
K, W/(M*K)	138 (AT 298 K)				
ALPHA, 10-6 M/(M*K)	SEE FIGURE 3.5.1.0				

[a] SEE TABLE 3.5.1.0(C).
[b] DERIVED VALUE.

TABLE 3.5.1.0(c). Percent Elongation Values for 5052 Aluminum Alloy (Sheet)

Temper	Thickness range, mm	Elongation, percent
0	0.15-0.19	..
	0.20-0.31	14
	0.32-0.49	15
	0.50-0.79	16
	0.80-1.27	18
	1.28-2.87	19
	2.88-6.32	20
H32	0.43-0.49	4
	0.50-1.27	5
	1.28-2.87	7
	2.98-6.32	9
H34	0.22-0.49	3
	0.50-1.27	4
	1.28-2.87	6
	2.88-6.32	7
H36	0.15-0.19	2
	0.20-0.79	3
	0.80-4.11	4
H38	0.15-0.19	2
	0.20-0.79	3
	0.80-3.25	4

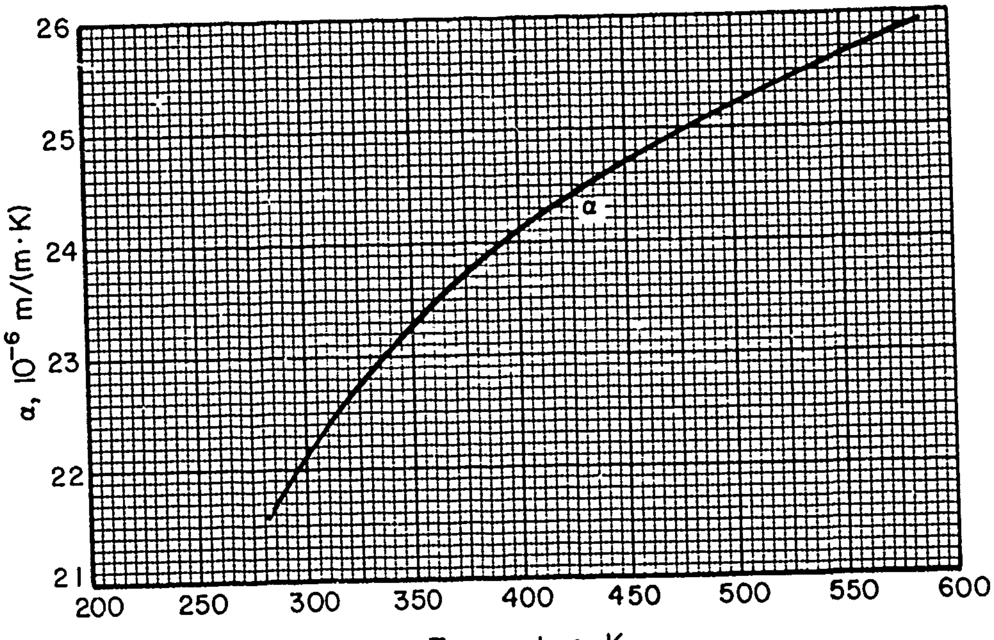


FIGURE 3.5.1.0. Effect of temperature on the physical properties of 5052 aluminum alloy.

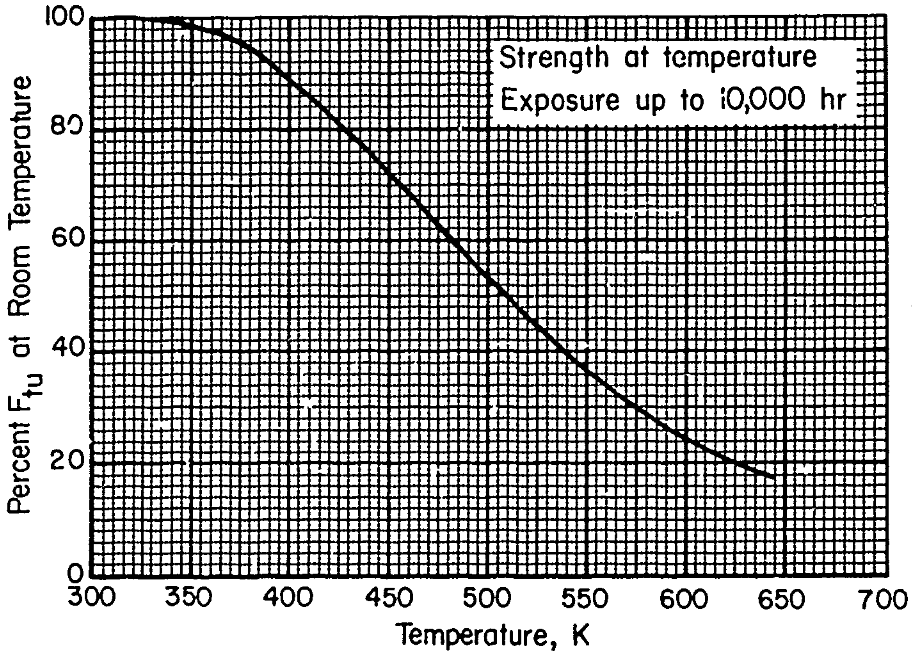


FIGURE 3.5.1.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of 5052-0 aluminum alloy (all products).

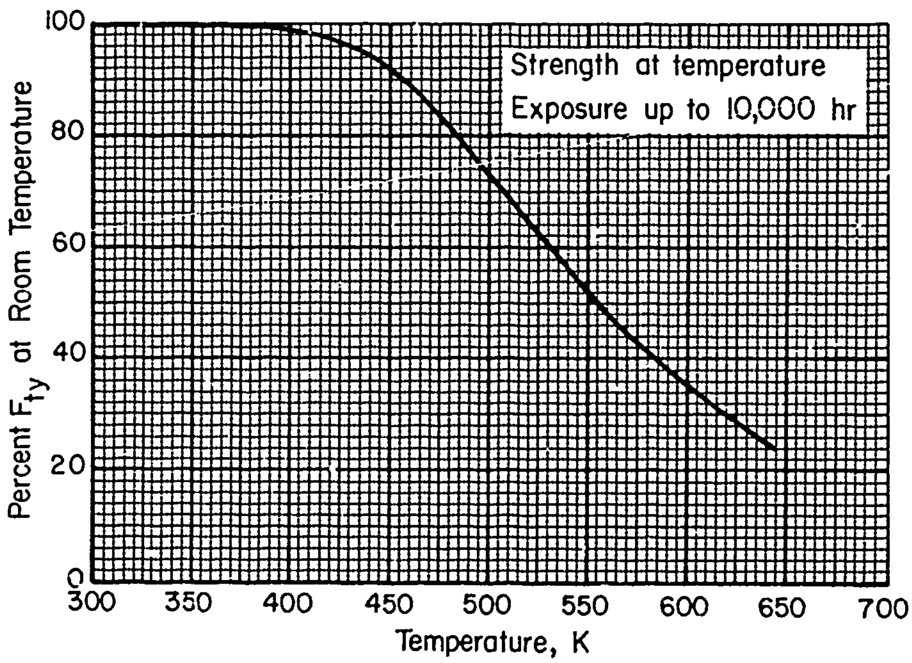


FIGURE 3.5.1.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of 5052-0 aluminum alloy (all products).

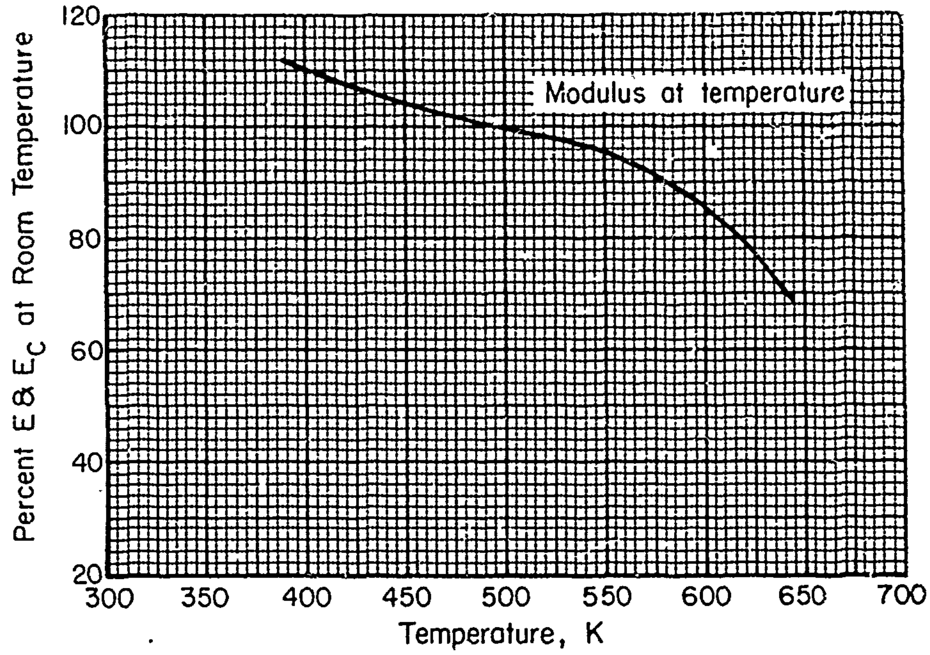


FIGURE 3.5.1.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of 5052 aluminum alloy.

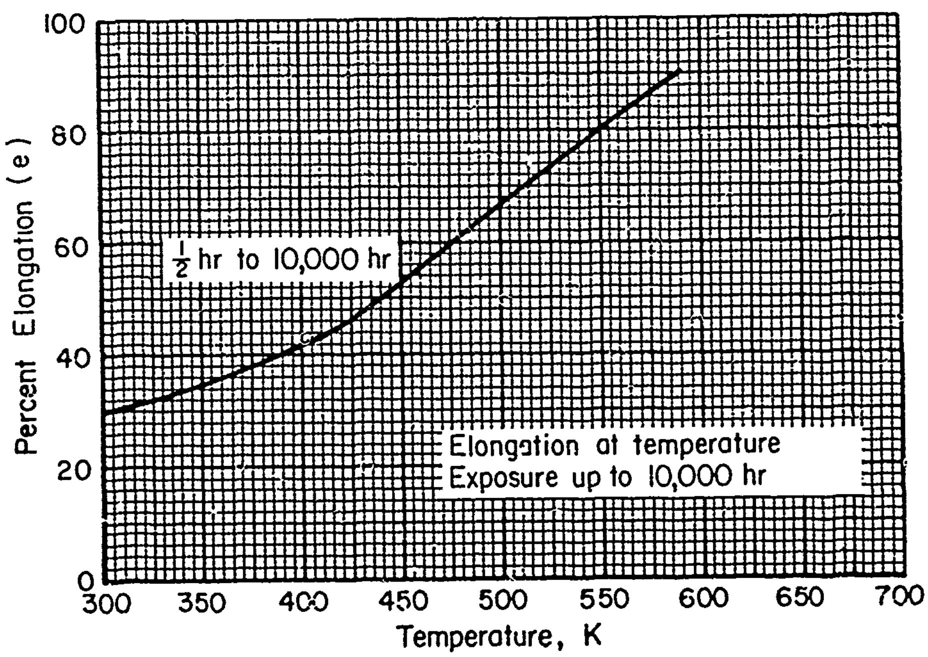


FIGURE 3.5.1.1.5. Effect of temperature on the elongation of 5052-0 aluminum alloy (all products).

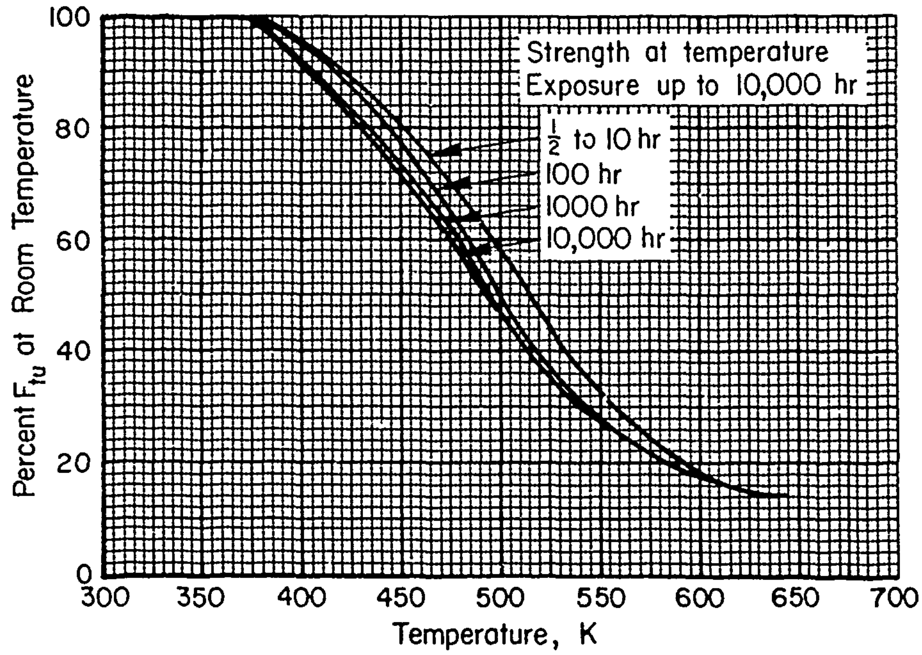


FIGURE 3.5.1.3.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of 5052-H34 aluminum alloy.

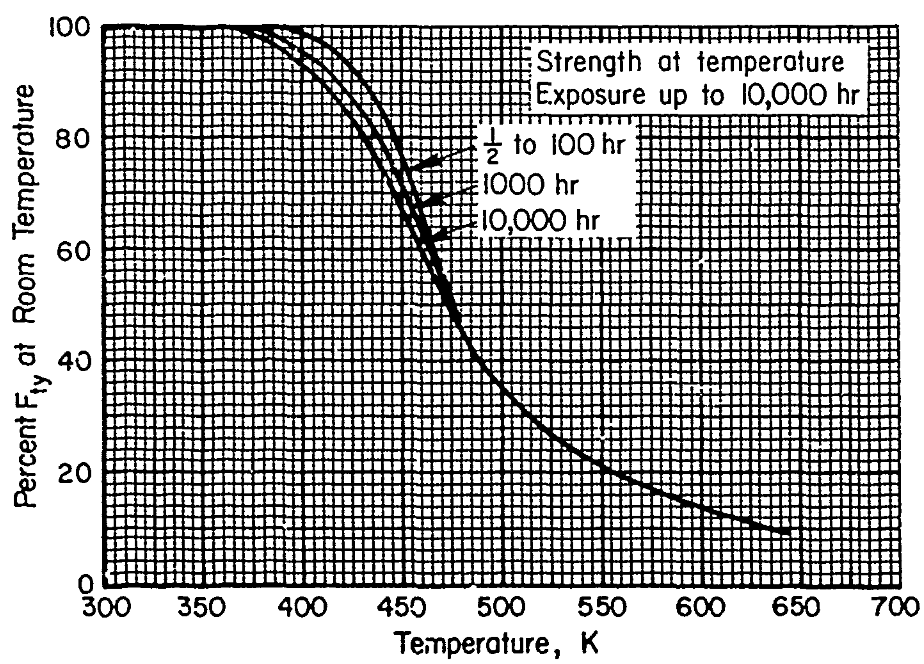


FIGURE 3.5.1.3.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of 5052-H34 aluminum alloy.

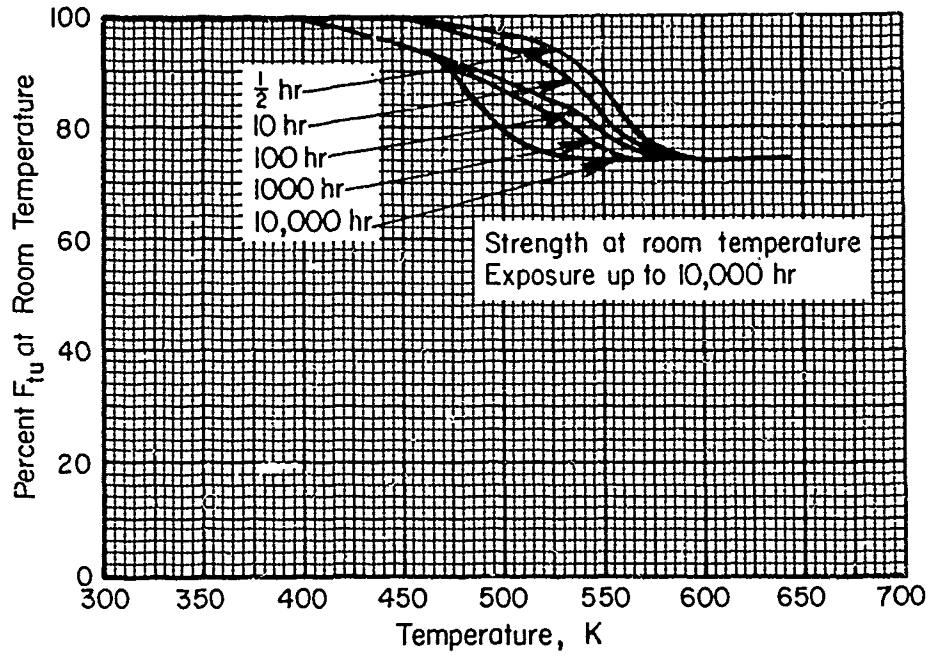


FIGURE 3.5.1.3.1(c). Effect of exposure at elevated temperatures on the room-temperature ultimate tensile strength (F_{tu}) of 5052-H34 aluminum alloy.

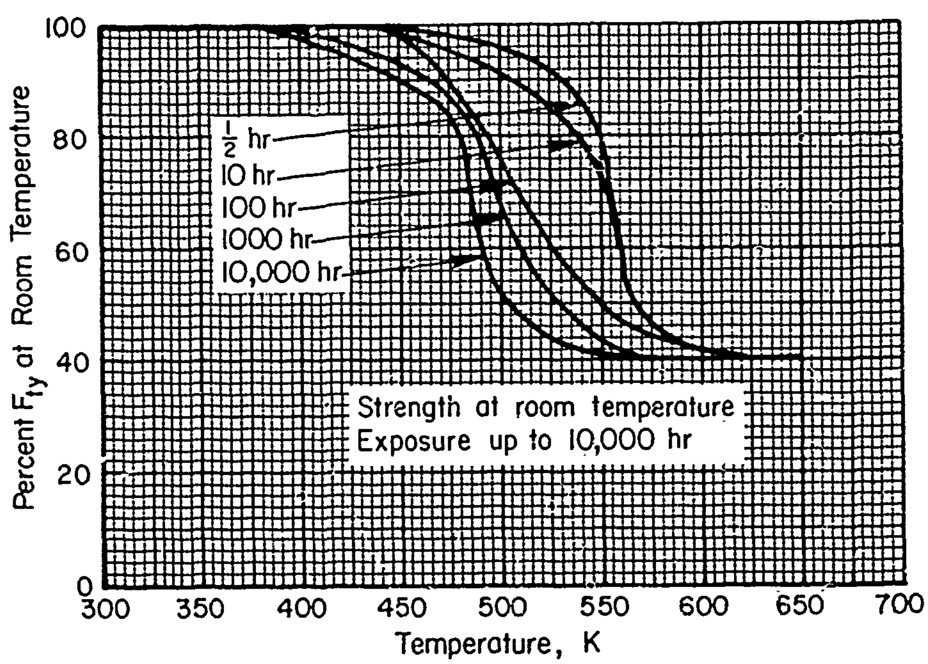


FIGURE 3.5.1.3.1(d). Effect of exposure at elevated temperatures on the room-temperature tensile yield strength (F_{ty}) of 5052-H34 aluminum alloy.

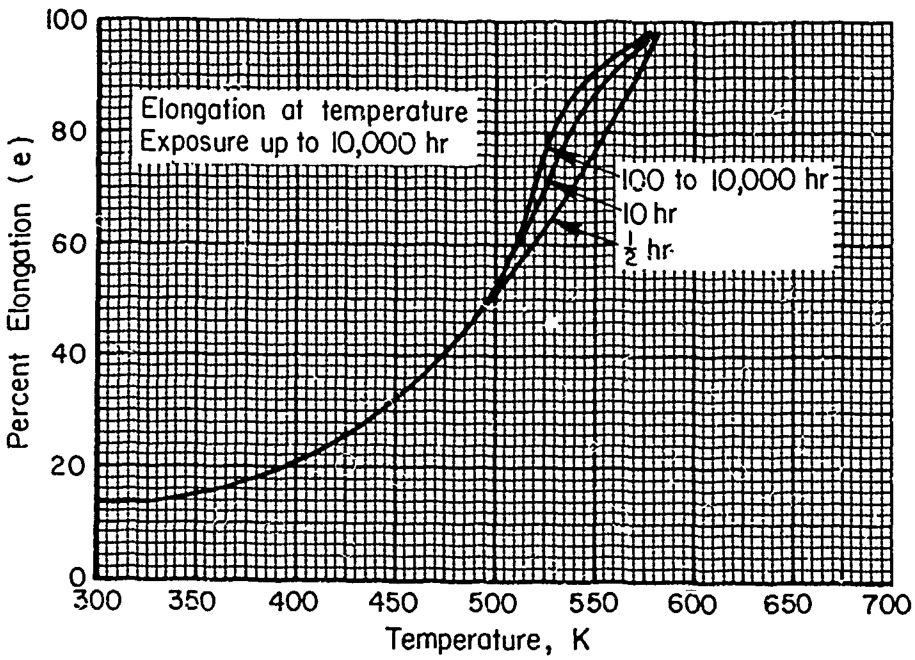


FIGURE 3.5.1.3.5(a). Effect of temperature on the elongation of 5052-H34 aluminum alloy (all products except thick extrusions).

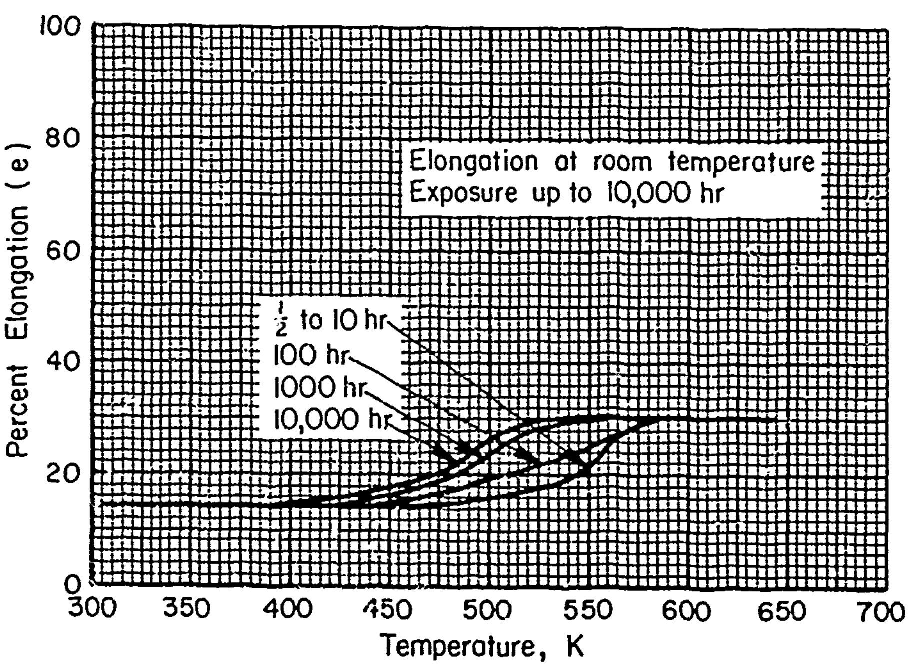


FIGURE 3.5.1.3.5(b). Effect of exposure at elevated temperatures on the elongation of 5052-H34 aluminum alloy (all products except thick extrusions).

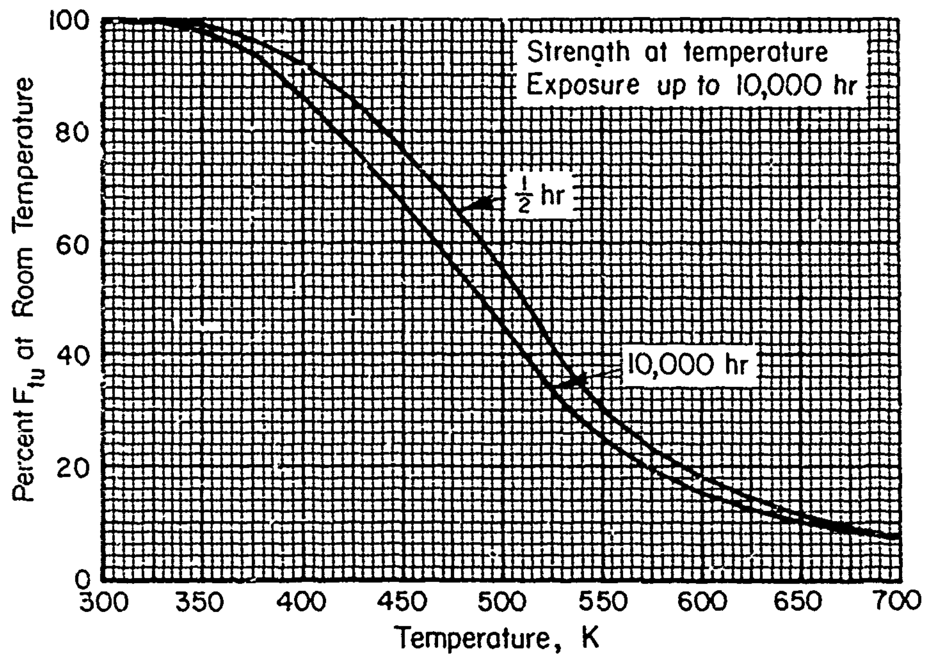


FIGURE 3.5.1.5.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of 5052-H38 aluminum alloy (all products).

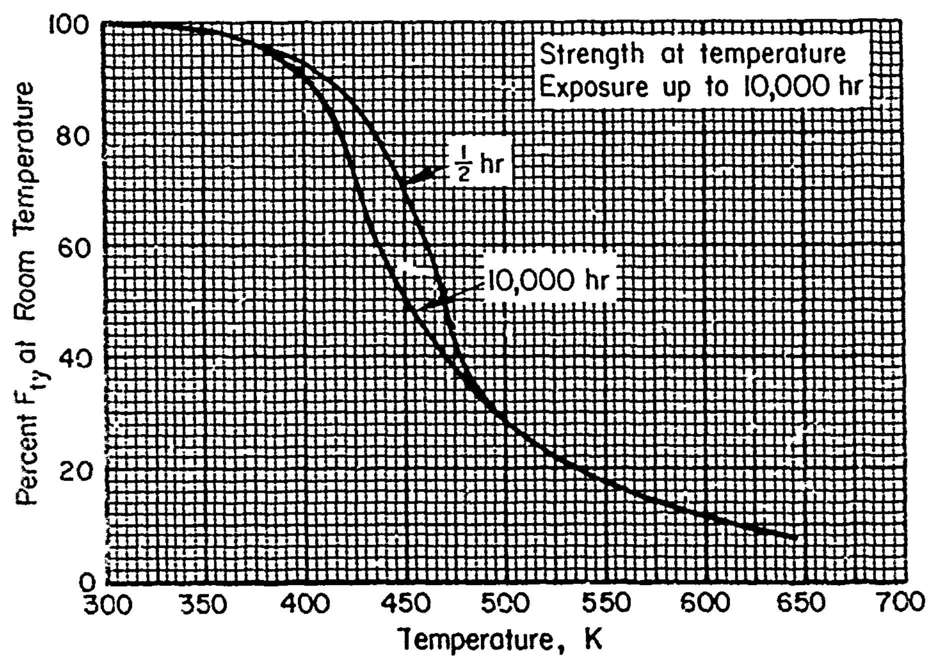


FIGURE 3.5.1.5.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of 5052-H38 aluminum alloy (all products).

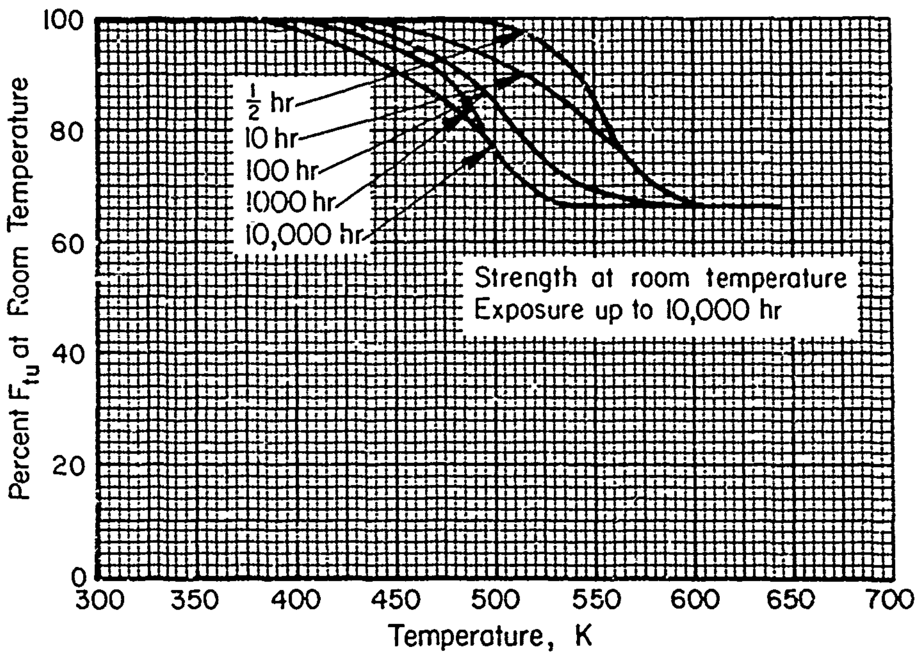


FIGURE 3.5.1.5.1(c). Effect of exposure at elevated temperatures on the room-temperature ultimate tensile strength (F_{tu}) of 5052-H38 aluminum alloy (all products).

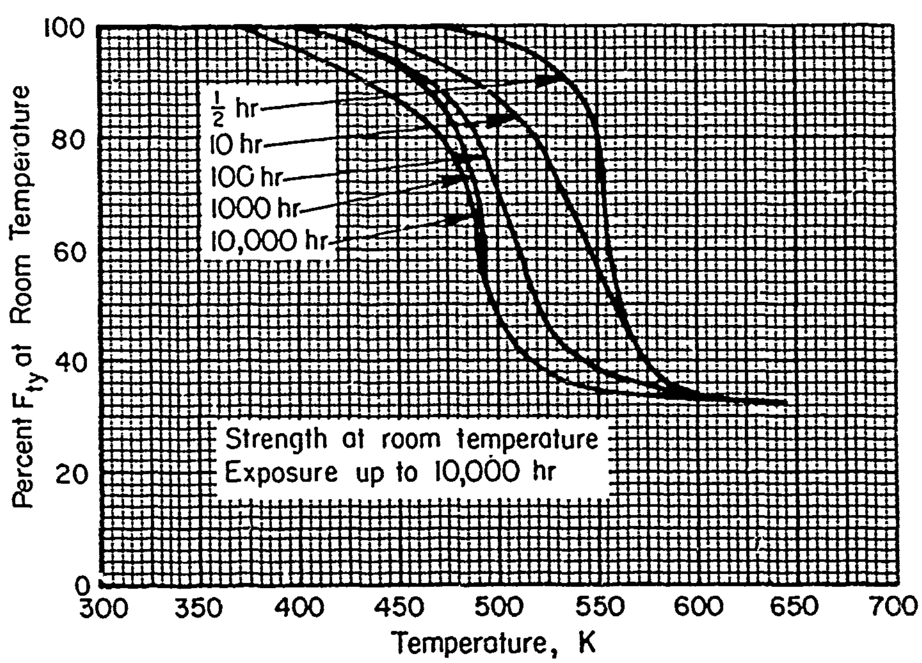


FIGURE 3.5.1.5.1(d). Effect of exposure at elevated temperatures on the room-temperature tensile yield strength (F_{ty}) of 5052-H38 aluminum alloy (all products).

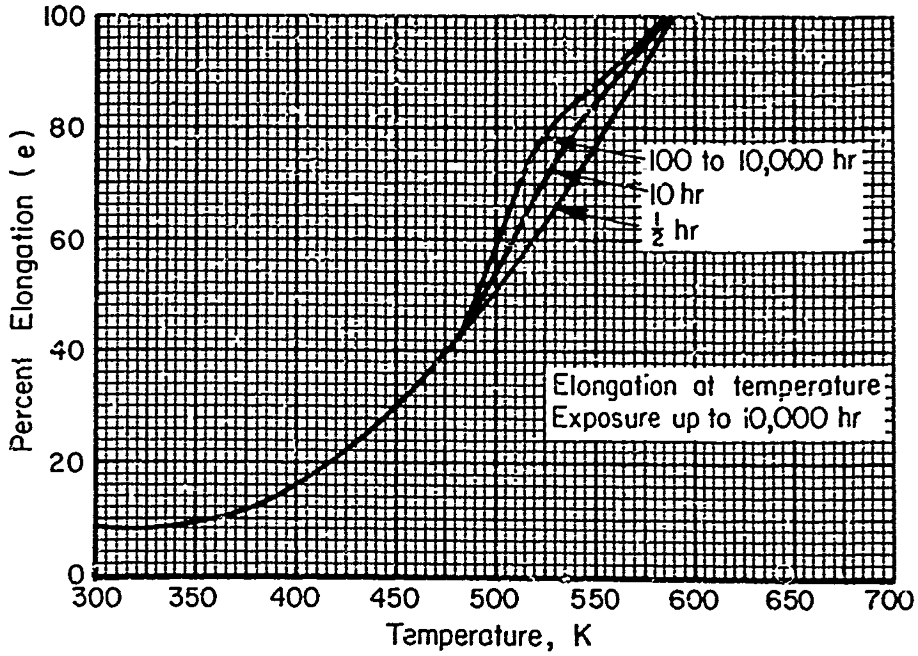


FIGURE 3.5.1.5.5(a). Effect of temperature on the elongation of 5052-H38 aluminum alloy (all products).

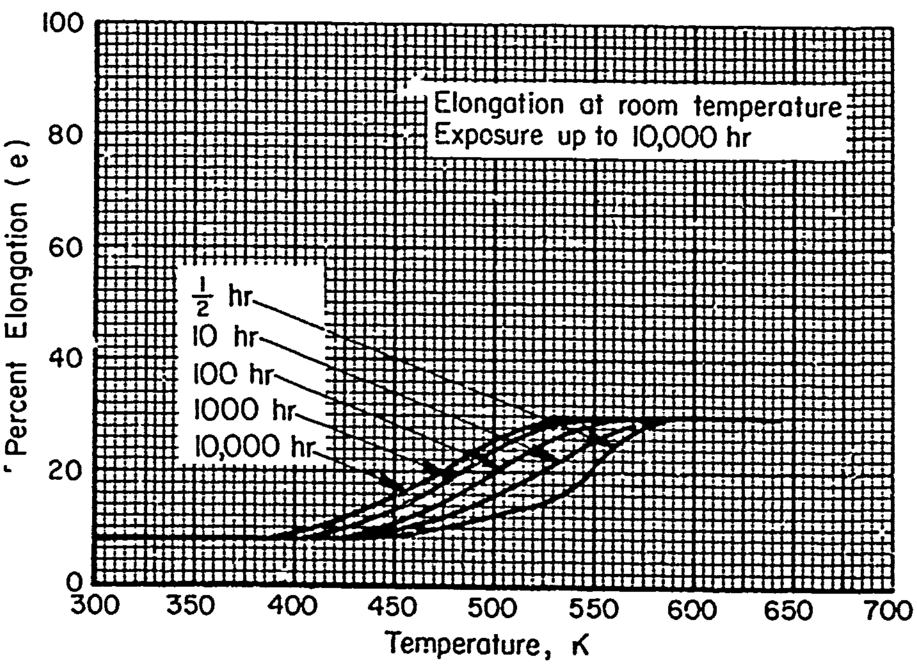


FIGURE 3.5.1.5.5(b). Effect of exposure at elevated temperatures on the elongation of 5052-H38 aluminum alloy (all products).

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 temperature 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 5083 aluminum alloy are presented in Table 3.5.2.0(a). Room-temperature mechanical and physical properties are shown in Table 3.5.2.0(b) and (c).

TABLE 3.5.2.0(a). *Material Specifications for 5083 Aluminum Alloy*

Specification	Form
QQ-A-250/6	Bare sheet and plate
QQ-A-220/4	Extruded bar, rod, and shapes

The temper index for 5083 is as follows:

Section	Temper
3.5.2.1	0
3.5.2.2	H111
3.5.2.3	H112
3.5.2.4	H321
3,5,2,4	H323
3.5.2.6	H343

3.5.2.1 *O Temper.*—Tensile and compressive stress-strain curves 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	QQ-A-250/6																
FORM	SHEET AND PLATE																
TEMPER	O							H112		H321			H323			H343	
THICKNESS, MM	1.30-38.11		38.12-76.21	76.22-101.61	101.62-127.01	127.02-177.81	177.82-203.20	6.35-38.11	38.12-76.20	4.76-38.11		38.12-76.20	1.30-3.18		3.19-6.32	1.?0-3.18	3.19-6.32
BASIS	A	B	S	S	S	S	S	S	S	A	B	S	A	B	S	S	S
MECHANICAL PROPERTIES:																	
FTU, MPA:																	
L	276	283	269	262	262	255	248	276	269	303	317	283	310	324	310	345	345
LT	276	283	...	...	...	...	...	...	...	303	317	...	...	...	...	...	...
FTY, MPA:																	
L	124	131	117	110	110	103	97	124	117	214	221	200	234	248	234	269	269
LT	124	131	...	...	...	...	...	...	...	193	200	...	...	...	...	...	...
FCY, MPA:																	
L	124	131	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
LT	124	131	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
FSU, MPA	172	179	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
FBRU, MPA:																	
(E/D=1.5)	414	427	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
(E/D=2.0)	524	538	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
FBRY, MPA:																	
(E/D=1.5)	221	234	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
(E/D=2.0)	262	276	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
EL, PERCENT:																	
L	16	...	16	16	14	14	12	12	12	12	...	12	8	...	10	6	[illegible]
LT	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
E, GPA	70.3																
EC, GPA	71.7																
G, GPA	26.5																
MU	0.33																
PHYSICAL PROPERTIES:																	
OMEGA, MG/M3	2.66																
C, J/(G°K)	0.96 (AT 373 K)																
K, W/(M°K)	118 (AT 298 K)																
ALPHA, 10-6 M/(M°K)	23.8 (293 to 373 K)																

TABLE 3.5.2.0(C). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 5083 ALUMINUM ALLOY (EXTRUSION)

SPECIFICATION..........	QQ-A-200/4			
FORM..................	EXTRUSION			
TEMPER................	O	H111		H112
THICKNESS, MM..........	<127.00[a]	≤12.71[a]	12.72–127.00[a]	<127.00[a]
BASIS..................	S	S	S	S
MECHANICAL PROPERTIES:				
FTU, MPA:				
L..................	269	276	276	269
LT.................	...	276	221	...
FTY, MPA:				
L..................	110	165	165	110
LT.................	...	165	131	...
FCY, MPA:				
L..................	...	...	...	...
LT.................	...	...	...	...
FSU, MPA..............	...	...	...	...
FBRU, MPA:				
(E/D=1.5).........	...	...	...	...
(E/D=2.0).........	...	...	...	...
FBRY, MPA:				
(E/D=1.5).........	...	...	...	...
(E/D=2.0).........	...	...	...	...
EL, PERCENT:				
L..................	14	12	12	12
LT.................	...	...	...	...
E, GPA................	70.3			
EC, GPA...............	71.7			
G, GPA................	26.5			
MU....................	0.33			
PHYSICAL PROPERTIES:				
OMEGA, MG/M3.........	2.66			
C, J/(G*K)...........	0.96 (AT 373 K)			
K, W/(M*K)...........	118 (AT 298 K)			
ALPHA, 10-6 M/(M*K)..	23.8 (293 TO 373 K)			

[a] CROSS-SECTIONAL AREA<2,064.5 SQ.CM.

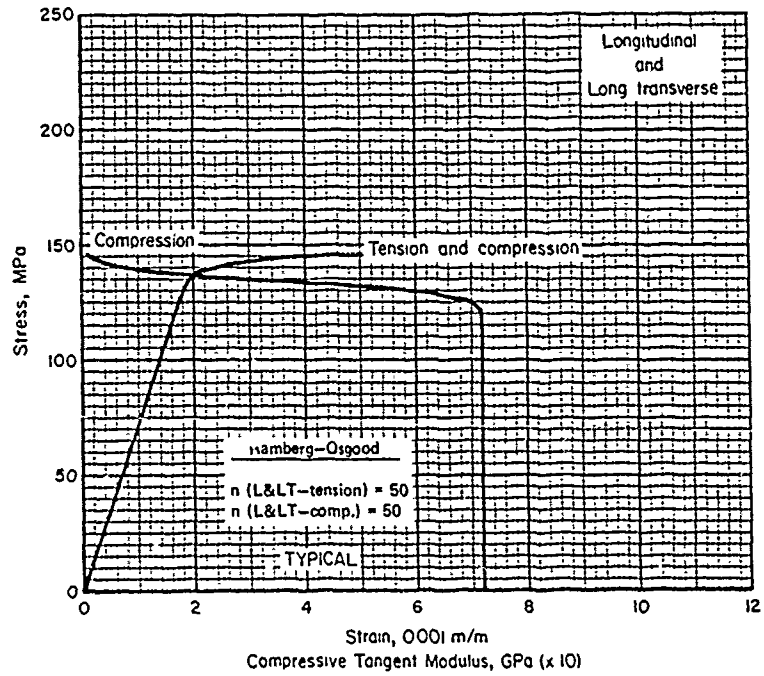


FIGURE 3.5.2.1.6(a). Typical tensile stress-strain and compressive stress-strain and tangent-modulus curves for 5083-0 aluminum alloy (sheet) at room temperature.

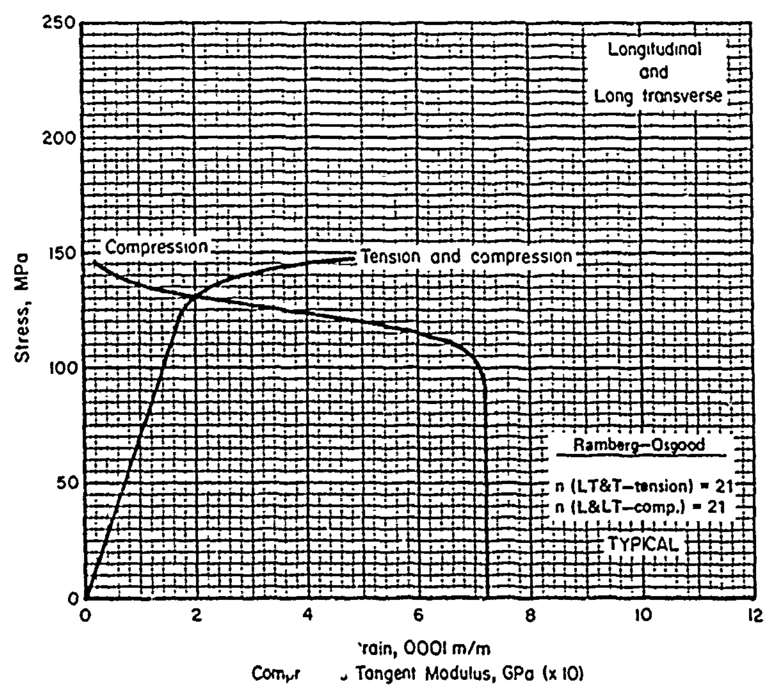
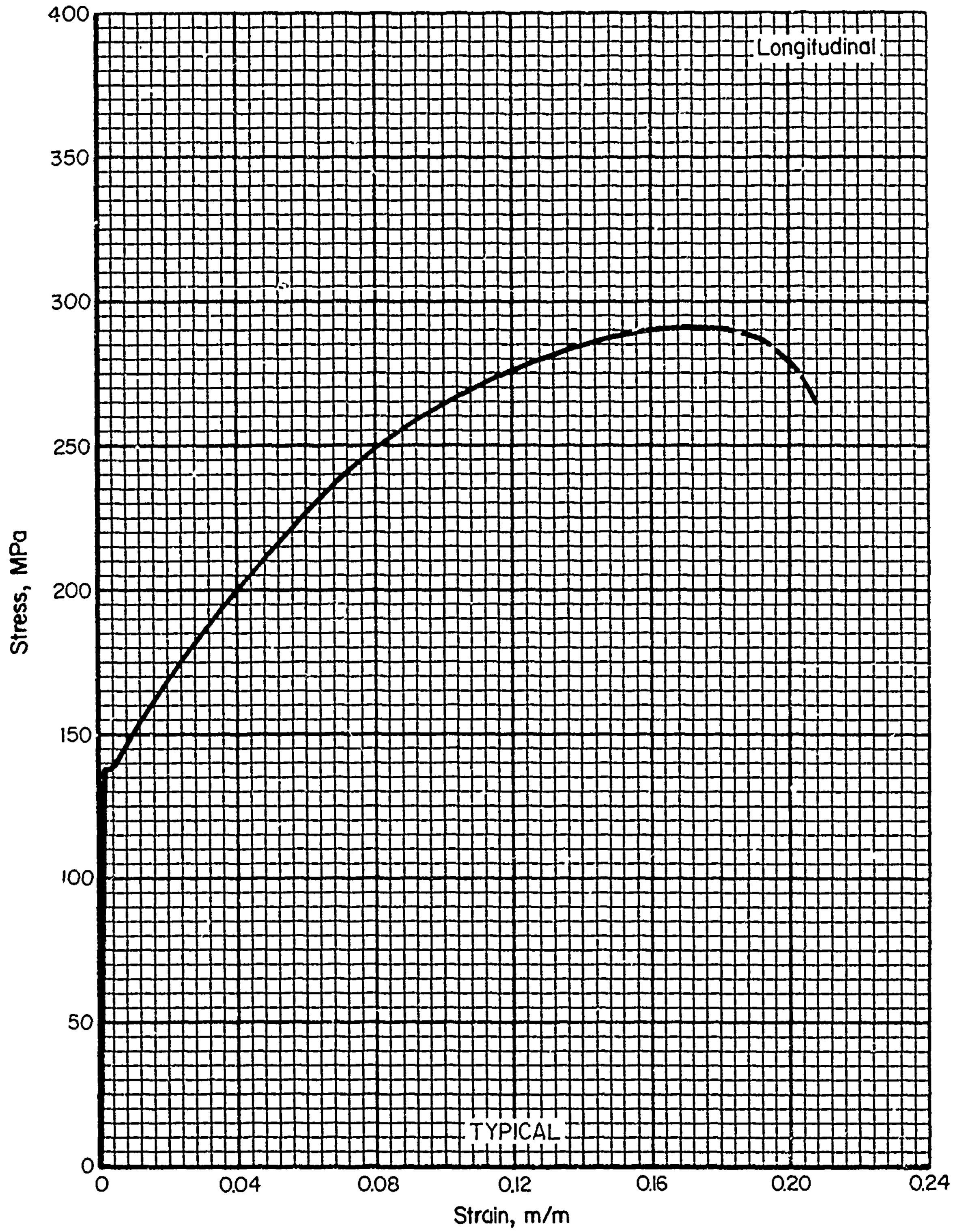


FIGURE 3.5.2.1.6 ypical tensile stress-strain and compressive stress-strain curves for 5083-0 aluminum alloy (plate) at room temperature.



F.GURE 3.5.2.1.6(c). Typical tensile stress-strain curve (full range) for 5083-? aluminum alloy (plate) at room temperature.

3.5.3 5086 ALLOY

3.5.3.0 *Comments and Properties.*—5086 is a very tough, medium-strength Al-Mg alloy suitable for application over the range of temperatures from 4 to 373 K. 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 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
QQ-A-250/7	Sheet and plate
QQ-A-200/5	Extruded bar, rod, and shapes

The temper index for 5086 is as follows:

Section	Temper
3.5.3.1	0
3.5.3.2	H32
3.5.3.3	H34
3.5.3.4	H36
3.5.3.5	H112
3.5.3.6	H111
3.5.3.7	H38

3.5.3.1 *0 Temper.*—Tensile and compressive stress-strain curves and tangent-modulus curves at room temperature are presented in Figures 3.5.3.1.6(a) through 3.5.3.1.6(b) for various 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) through 3.5.3.2.6(b) present tensile and compressive stress-strain curves and tangent-modulus curves at room temperature for this temper.

3.5.3.3 *H34 Temper.*—Figures 3.5.3.3.6(a) through 3.5.3.3.6(b) present tensile and compressive stress-strain curves for this temper. A full-range tensile stress-strain curve is presented in Figure 3.5.3.3.6(c).

3.5.3.4 *H36 Temper.*—Figure 3.5.3.4.6 presents tensile and compressive stress-strain and tangent-modulus curves at room temperature for this temper.

3.5.3.5 *H112 Temper.*—Figure 3.5.3.5.6 presents tensile and compressive stress-strain and tangent-modulus curves at room temperature for this temper.

TABLE 3.5.3.0(c). Percent Elongation Values for 5086 Aluminum Alloy (Sheet and Plate)

Temper	Thickness range, mm	Elongation, percent
0	0.50-1.27	15
	1.28-6.33	18
	6.34-50.80	14
H32	0.50-1.27	6
	1.28-6.33	8
	6.34-50.80	12
H34	0.22-0.49	4
	0.50-1.27	5
	1.28-6.33	6
	6.34-25.40	10
H36	0.15-0.49	3
	0.50-1.27	4
	1.28-4.12	6

TABLE 3.5.3.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 5086 ALUMINUM ALLOY (SHEET, PLATE AND EXTRUSION)

SPECIFICATION	QQ-A-250/7											QQ-A-200/5		
FORM	SHEET AND PLATE											EXTRUSION		
TEMPER	O		H32		H34	H36	H38	H112				O	H111	H112
THICKNESS, MM	0.51-50.80		0.51-50.80		0.23-25.40	0.15-4.11	0.15-0.51	4.78-12.68	12.69-25.41	25.42-50.81	50.82-76.20	< 127.00[a]	< 127.00[a]	< 127.00[a]
BASIS	A	B	A	B	S	S	S	S	S	S	S	S	S	S
MECHANICAL PROPERTIES:														
FTU, MPA:														
L	241	248	276	283	303	324	345	248	241	241	234	241	248	241
LT	241	248	276	283	303	324	...	248	241	241	234	...	...	...
FTY, MPA:														
L	97	103	193	207	234	262	283	124	110	97	97	97	145	97
LT	97	103	179	193	226	255	...	117	110	97	97	...	...	...
FCY, MPA:														
L	97	103	179	193	221	241	...	117	103	97	97	...	...	...
LT	97	103	193	207	234	262	...	124	110	97	97	...	...	...
FSU, MPA	145	152	165	172	179	186	...	152	145	145	138	...	...	...
FBRU, MPA:														
(E/D=1.5)	359	365	400	421	441	469	...	372	359	359	352	...	...	...
(E/D=2.0)	483	496	552	565	607	648	...	496	483	483	469	...	...	...
FBRY, MPA:														
(E/D=1.5)	165	179	269	290	331	365	...	172	165	165	165	...	...	...
(E/D=2.0)	193	207	331	352	400	448	...	214	193	193	193	...	...	...
EL, PERCENT:														
L	b	...	b	...	b	...	3	8	10	14	14	14	12	12
LT	...	...	...	...	...	...	...	...	...	...	...	...	...	...
E, GPA	70.3													
EC, GPA	71.7													
G, GPA	26.5													
MU	0.33													
PHYSICAL PROPERTIES:														
OMEGA, MG/M3	2.66													
C, J/(G*K)	0.96 (AT 373 K)													
K, W/(M*K)	125 (AT 298 K)													
ALPHA, 10-6 M/(M*K)	23.6 (293 to 373)													

a CROSS-SECTIONAL AREA <2,064.5 SQ.CM.
b SEE TABLE 3.5.3.0(C).

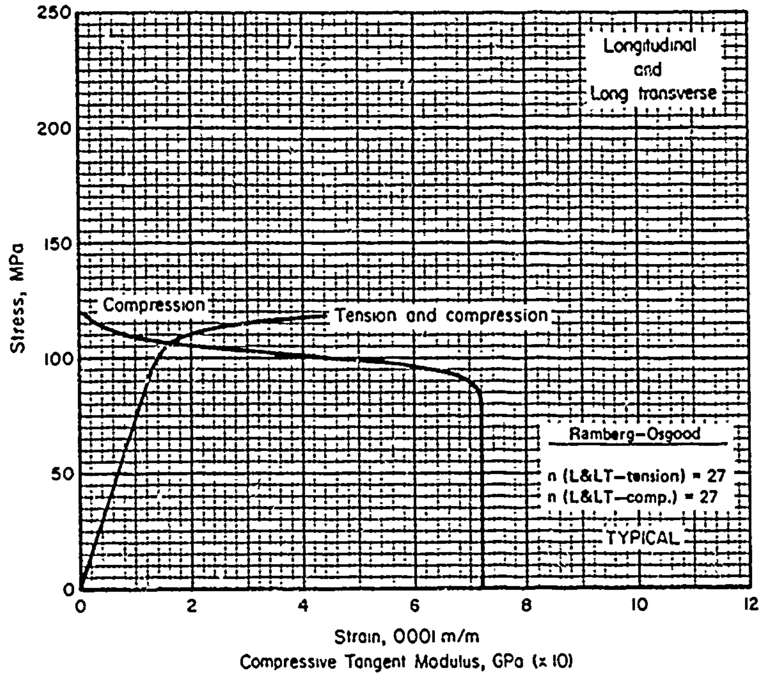


FIGURE 3 5 3.1.6(a). Typical tensile stress-strain and compressive stress-strain and tangent-modulus curves for 5086-0 aluminum alloy (sheet) at room temperature.

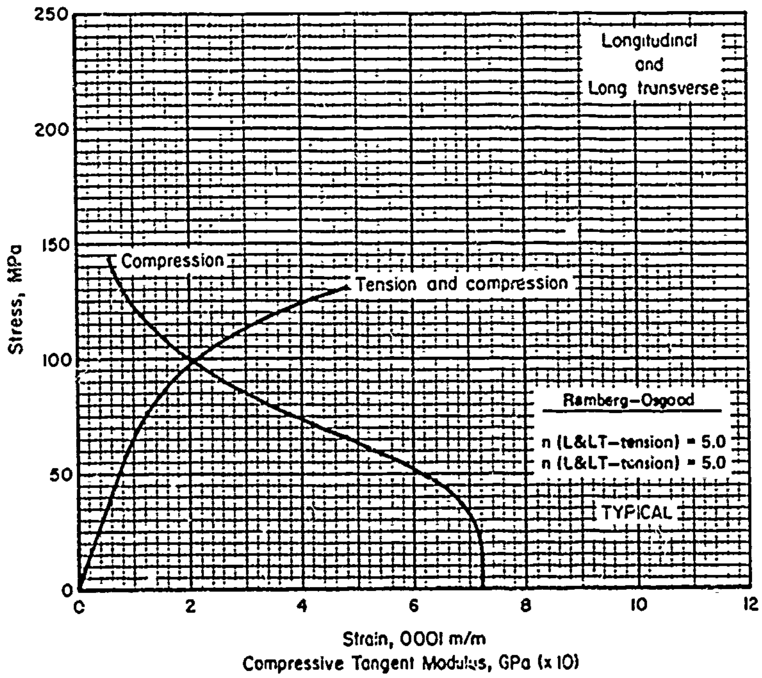


FIGURE 3.5.3.1.6(b). Typical tensile stress-strain and compressive stress-strain curves for 5086-0 aluminum alloy (plate and extrusion) at room temperature.

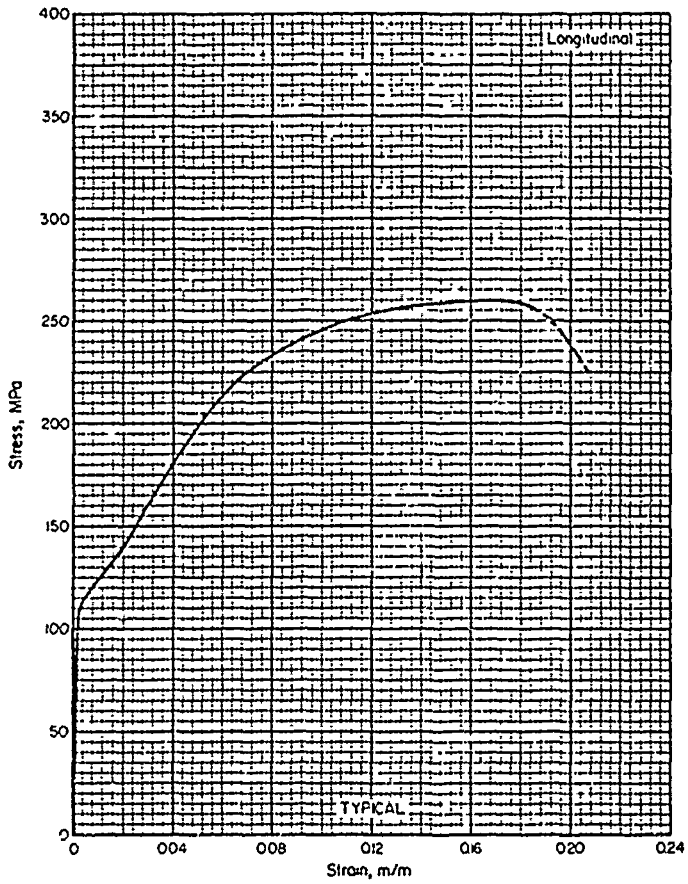


FIGURE 3.5.3.1.6(c). Typical tensile stress-strain curve (full range) for 5086-O aluminum alloy (sheet) at room temperature.

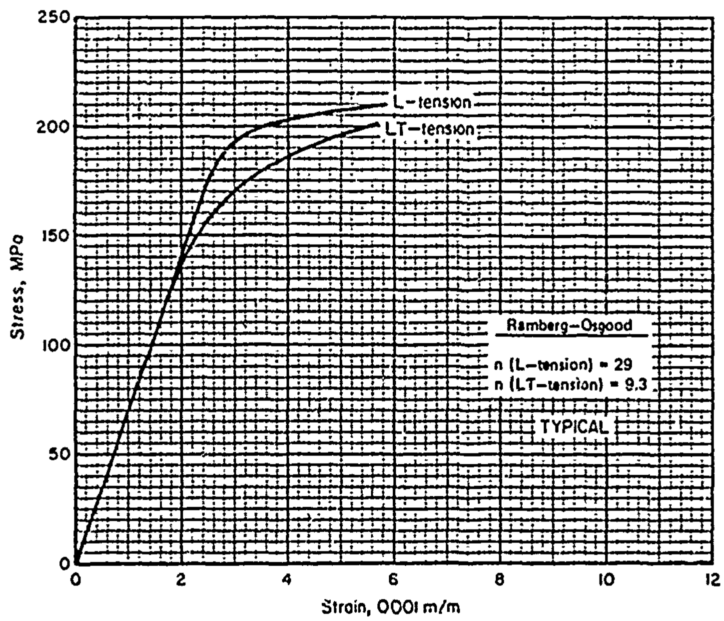


FIGURE 3.5.3.2.6(a). Typical tensile stress-strain curves for 5086-H32 aluminum alloy (sheet) at room temperature.

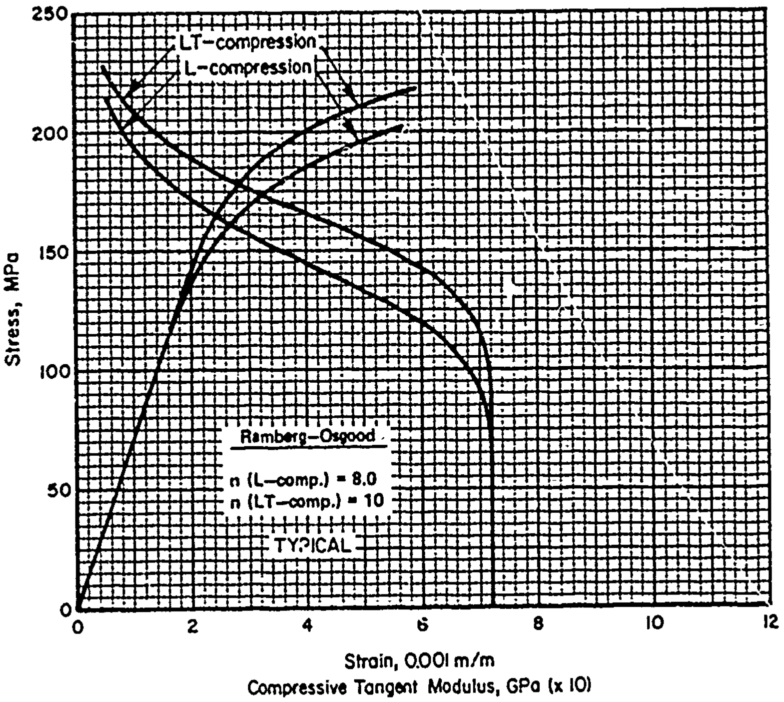


FIGURE 3.5.3.2.6(b). Typical compressive stress-strain and tangent-modulus curves for 5086-H32 aluminum alloy (sheet) at room temperature.

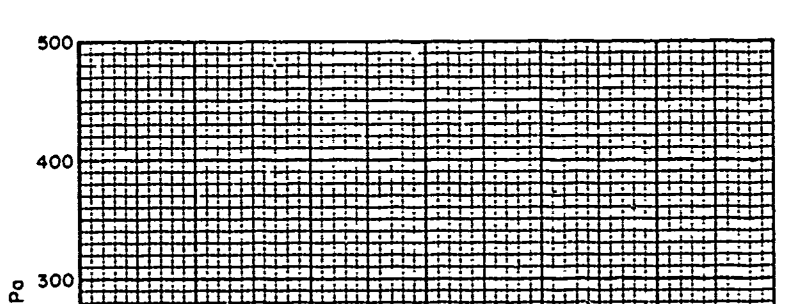


FIGURE 3.5.3.3.6(a). Typical tensile stress-strain curves for 5086-H34 aluminum alloy. (sheet) at room temperature.

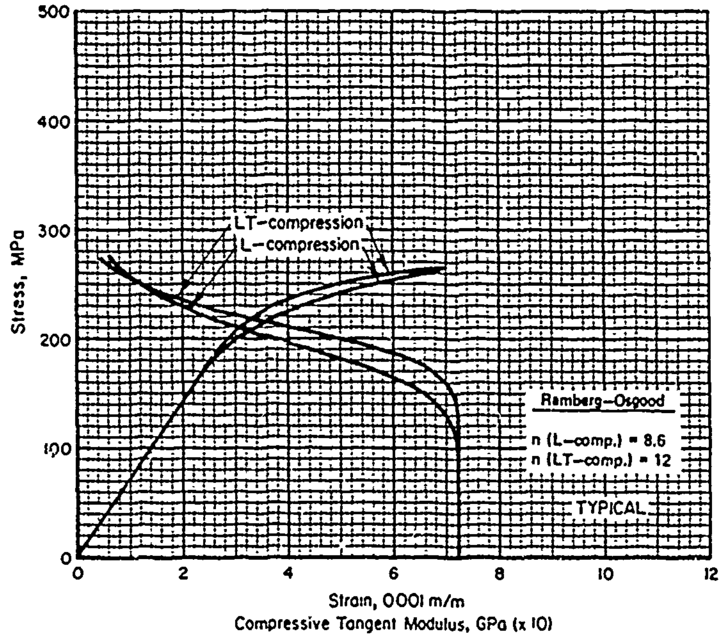


FIGURE 3.5.3.3.6(b). Typical compressive stress-strain and tangent-modulus curves for 5086-H34 aluminum alloy (sheet) at room temperature.

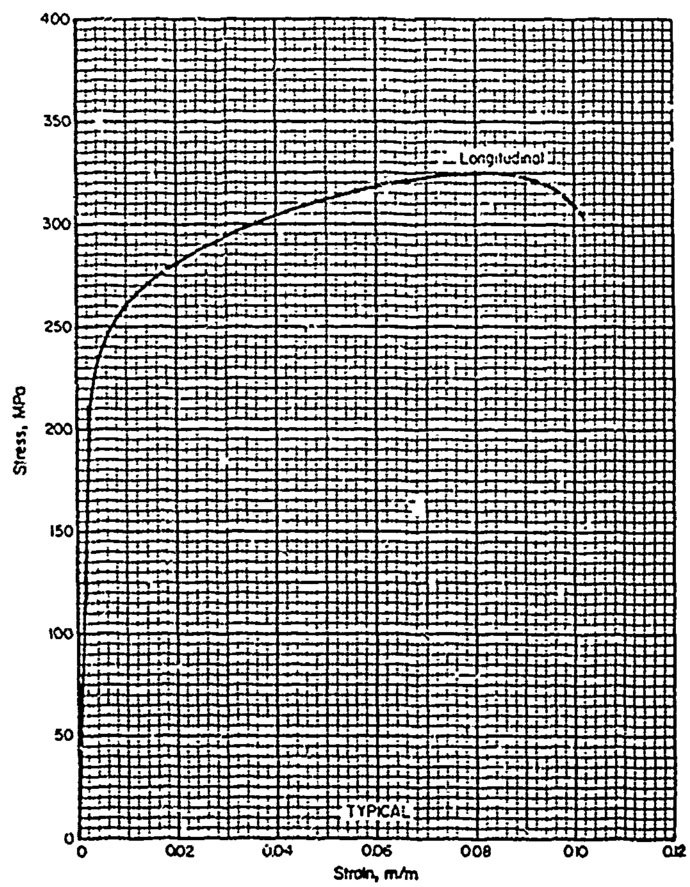


FIGURE 3.5.3.3.6(c). Typical tensile stress-strain curve (full range) for 5086-H34 aluminum alloy (sheet) at room temperature.

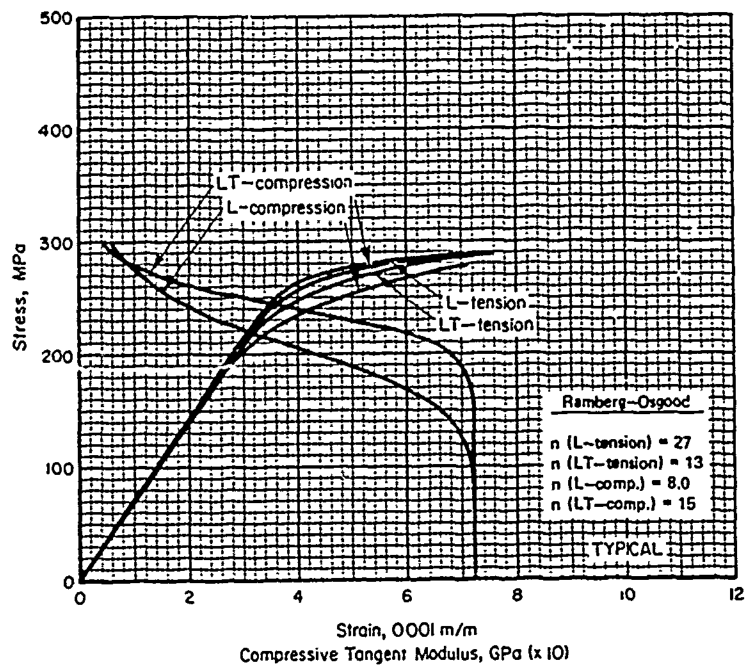


FIGURE 3.5.3.4.6. Typical tensile stress-strain and compressive stress-strain curves for 5086-H36 aluminum alloy (sheet) at room temperature.

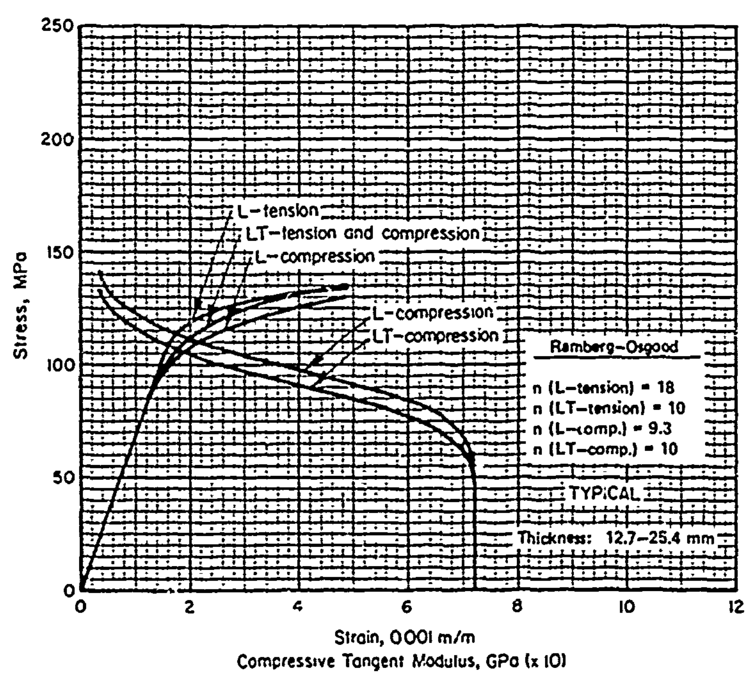


FIGURE 3.5.3.5.6. Typical tensile stress-strain and compressive stress-strain and tangent-modulus curves for 5086-H112 aluminum alloy (plate) at room temperature.

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.

Some material specifications for 5454 aluminum alloy are presented in Table 3.5.4.0(a). Room temperature mechanical and physical properties are shown in Tables 3.5.4.0(b) and (c).

TABLE 3.5.4.0(a). *Material Specifications for 5454 Aluminum Alloy*

Specification	Form
QQ-A-250/10	Sheet and plate
QQ-A-200/6	Extruded bar, rod and shapes

The temper index for 5454 is as follows:

Section	Temper
3.5.4.1	0
3.5.4.2	H32
3.5.4.3	H34
3.5.4.4	H111
3.5.4.5	H112

3.5.4.1 *0 Temper.*—Figure 3.5.4.1.6 presents tensile and compressive stress-strain curves and tangent-modulus curves at room temperature for 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 curves and tangent-modulus curves for this temper.

TABLE 3.5.4.0(c). Percent Elongation Values for 5454 Aluminum Alloy (Sheet and Plate)

Temper	Thickness range, mm	Elongation, percent
0......................	0.50-0.79	12
	0.80-1.27	14
	1.28-2.88	16
	2.89-76.20	18
H32	0.50-1.27	5
	1.28-6.33	8
	6.34-50.80	12
H34	0.50-1.27	4
	1.28-4.09	6
	4.10-6.33	7
	6.34-25.40	10
H112	1.27-50.80	11
	50.81-76.20	15

TABLE 3.5.4.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 5454 ALUMINUM ALLOY (SHEET, PLATE, AND EXTRUSIONS)

SPECIFICATION	QQ-A-250/10							QQ-A-200/6		
FORM	SHEET AND PLATE							EXTRUSIONS		
TEMPER	O		H32		H34	H112		O	H111	H112
THICKNESS, MM	0.51-76.20		0.51-50.80		0.51-25.40	6.35-12.68	12.69-76.20	... <127.00[a]	... <127.00[a]	... <127.00[a]
BASIS	A	B	A	B	S	S	S	S	S	S
MECHANICAL PROPERTIES:										
FTU, MPA:										
L	214	221	248	255	269	221	214	214	228	214
LT	214	221	248	255	269	221	214	...	...	214
FTY, MPA:										
L	83	90	179	166	200	124	83	83	131	83
LT	83	90	165	172	193	124	83	...	...	83
FCY, MPA:										
L	83	90	165	172	186	117	83	83	...	83
LT	83	90	179	186	200	124	83	...	...	83
FSU, MPA	131	138	145	152	159	138	131	...	...	131
FBRU, MPA:										
(E/D=1.5)	317	331	359	372	393	331	317	...	...	296
(E/D=2.0)	427	441	496	510	538	441	427	...	...	386
FBRY, MPA:										
(E/D=1.5)	138	152	248	262	283	172	138	...	...	138
(E/D=2.0)	165	179	303	317	338	214	165	...	...	165
EL, PERCENT:										
L	b	...	b	...	b	8	b	14	12	12
LT	...	...	...	...	...	...	...	...	...	...
E, GPA	70.3									
EC, GPA	71.7									
G, GPA	26.5									
MU	0.33									
PHYSICAL PROPERTIES:										
OMEGA, MG/M3	2.68									
C, J/(G*K)	0.96 (AT 373 K)									
K, W/(M*K)	135 (AT 298 K)									
ALPHA, 10-6 M/(M*K)	23.6 (293-373 K)									

[a] CROSS-SECTIONAL AREA 2064.5 SQ. CM.
[b] SEE TABLE 3.5.4.0(C).

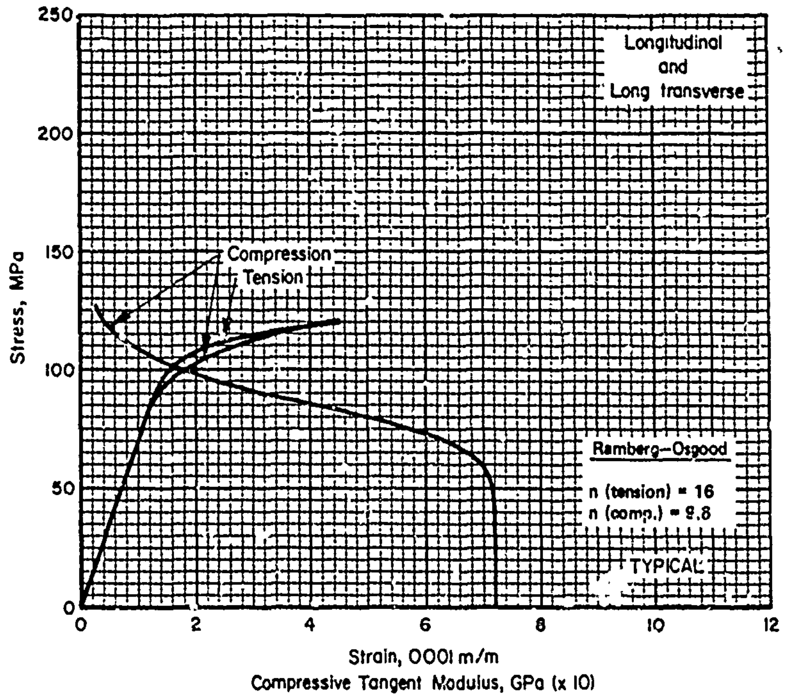


FIGURE 3.5.4.1.6. Typical tensile stress-strain and compressive stress-strain and tangent-modulus curves for 5454-0 aluminum alloy (sheet, plate, extrusion) at room temperature.

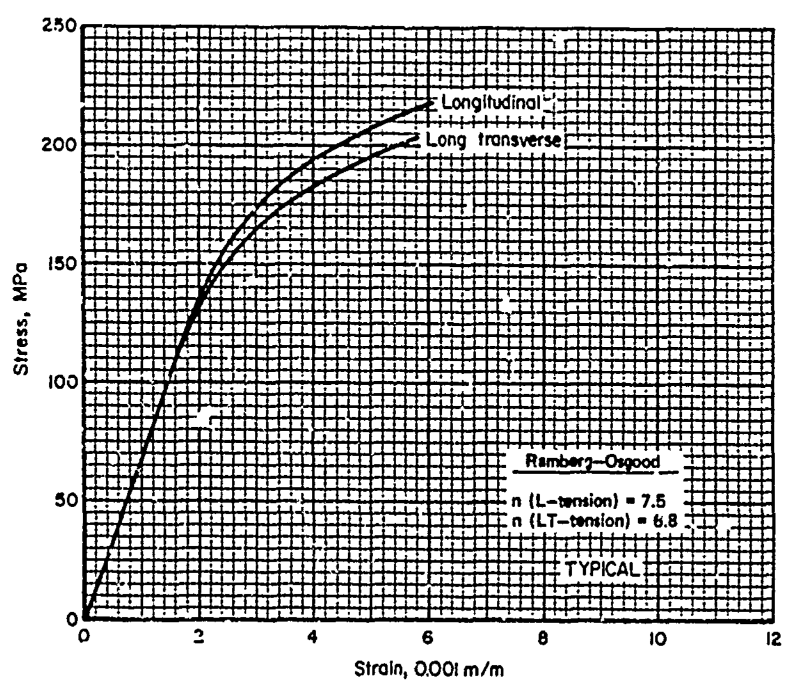


FIGURE 3.5.4.2.6. Typical tensile stress-strain curves for 5452-H32 aluminum alloy (plate) at room temperature.

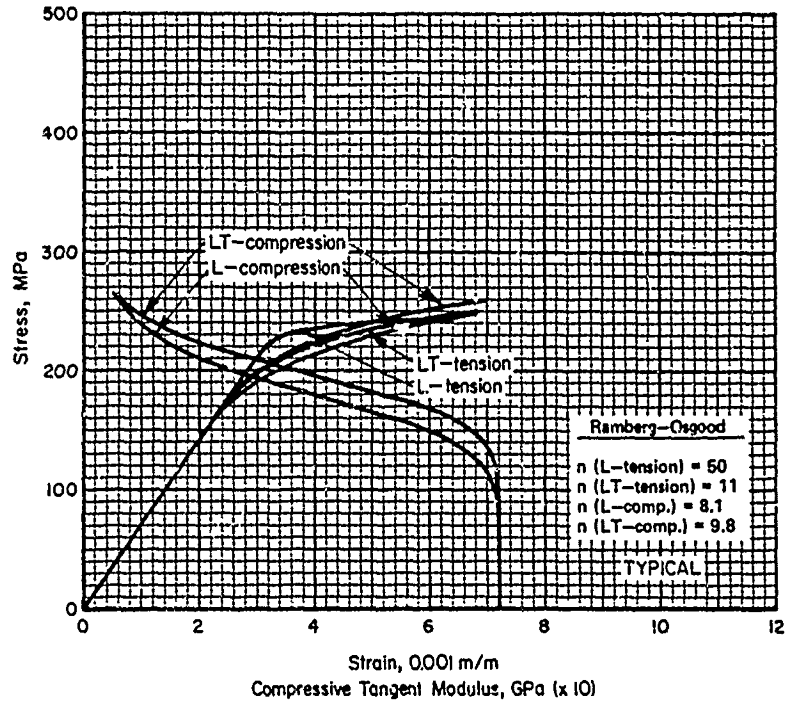


FIGURE 3.5.4.3.6(a). Typical tensile stress-strain and compressive stress-strain and tangent modulus curves for 5454-H34 aluminum alloy (sheet) at room temperature.

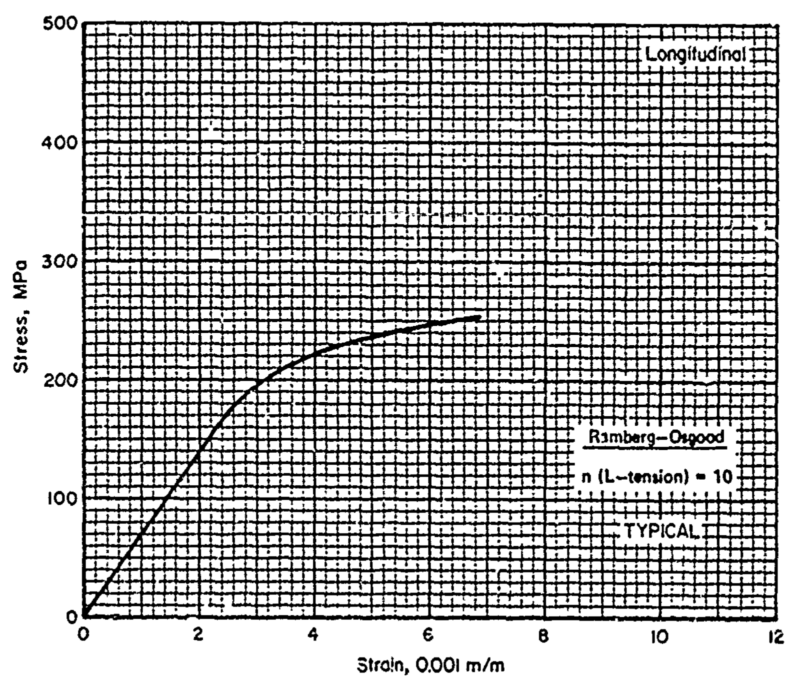


FIGURE 3.5.4.3.6(b). Typical tensile stress-strain curve for 5454-H34 aluminum alloy (plate) at room temperature.

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 373 K 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.

TABLE 3.5.5.0(a). *Material Specifications for 5456 Aluminum Alloy*

Specification	Form
QQ-A-250/9	Sheet and plate
QQ-A-200/7	Extruded bar, rod and shapes

The temper index for 5456 is as follows:

Section	Temper
3.5.5.1	0
3.5.5.2	H111
3.5.5.3	H112
3.5.5.4	H321
3.5.5.5	H323
3.5.5.6	H343

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 Table 3.5.5.0(b), (c), and (d). The effect of temperature on physical properties is shown in Figure 3.5.5.0.

3.5.5.1 *0 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(c). *Percent Elongation Values for 5456 Aluminum Alloy*

Material condition	Thickness range, mm	Elongation, percent
H323 and H343 ..	1.30–3.18	6
	3.19–6.32	8

TABLE 3.5.5.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 5456 ALUMINUM ALLOY (SHEET AND PLATE)

SPECIFICATION	QQ-A-250/9												
FORM	SHEET AND PLATE												
TEMPER	O					H112		H321				H323	H343
THICKNESS, MM	1.30-38.11	38.12-76.21	76.22-127.01	127.02-177.81	177.82-203.20	6.35-38.11	38.12-76.20	4.78-15.86	15.87-31.75	31.40-38.11	38.12-76.20	1.30-6.32	1.30-6.32
BASIS	S	S	S	S	S	S	S	S	S	S	S	S	S
MECHANICAL PROPERTIES:													
FTU, MPA:													
L	290	283	276	269	262	290	283	317	317	303	283	331	365
LT	290	...	...	...	...	...	...	317	310	296	...	331	365
FTY, MPA:													
L	131	124	117	110	103	131	124	228	228	214	200	248	283
LT	131	...	...	...	...	...	...	207	200	193	...	234	269
FCY, MPA:													
L	131	...	...	...	...	...	...	186	179	165	...	234	269
LT	131	...	...	...	...	...	...	228	214	200	...	248	283
FSU, MPA	179	...	...	...	...	...	...	186	186	172	...	193	214
FBRU, MPA:													
(E/D=1.5)	434	...	...	...	...	...	...	462	462	441	483	531	
(E/D=2.0)	579	...	...	...	...	...	...	579	579	552	...	627	696
FBRY, MPA:													
(E/D=1.5)	221	...	...	...	...	...	...	317	317	296	...	352	400
(E/D=2.0)	262	...	...	...	...	...	...	365	365	345	...	400	455
EL, PERCENT:													
L	16	16	14	14	12	12	12	12	12	12	12	a	a
E, GPA	70.3												
EC, GPA	71.7												
G, GPA	26.5												
MU	0.33												
PHYSICAL PROPERTIES:													
OMEGA, MG/M3	2.66												
C, J/(G*K)	0.96 (AT 373 K)												
K, W/(M*K)	118 (AT 298 K)												
ALPHA, 10-6 M/(M*K)	23.9 (293-373 K)												

[a] SEE TABLE 3.5.5.0(C).

TABLE 3.5.5.0(D). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 5456 ALUMINUM ALLOY (EXTRUSION)

SPECIFICATION	QQ-A-200/7		
FORM	EXTRUDED BAR, ROD, AND SHAPES		
TEMPER	O	H111	H112
THICKNESS, MM	<127.00[a]	<127.00[a]	≤127.00[a]
BASIS	S	S	S
MECHANICAL PROPERTIES:			
FTU, MPA:			
L	283	290	283
LT	...	...	283
FTY, MPA:			
L	131	179	131
LT	...	...	131
FCY, MPA:			
L	131	...	131
LT	...	...	131
FSU, MPA	...	...	159
FBRU, MPA:			
(E/D=1.5)	...	...	393
(E/D=2.0)	...	...	510
FBRY, MPA:			
(E/D=1.5)	...	...	234
(E/D=2.0)	...	...	262
EL, PERCENT:			
L	14	12	12
LT	...	...	...
E, GPA	70.3		
EC, GPA	71.7		
G, GPA	26.5		
MU	0.33		
PHYSICAL PROPERTIES:			
OMEGA, MG/M3	2.66		
C, J/(G*K)	0.96 (AT 373 K)		
K, W/(M*K)	118 (AT 298 K)		
ALPHA, 10-6 M/(M*K)	23.9 (293-373 K)		

[a] CROSS SECTIONAL AREA ≤ 2,064.5 SQ. CM.

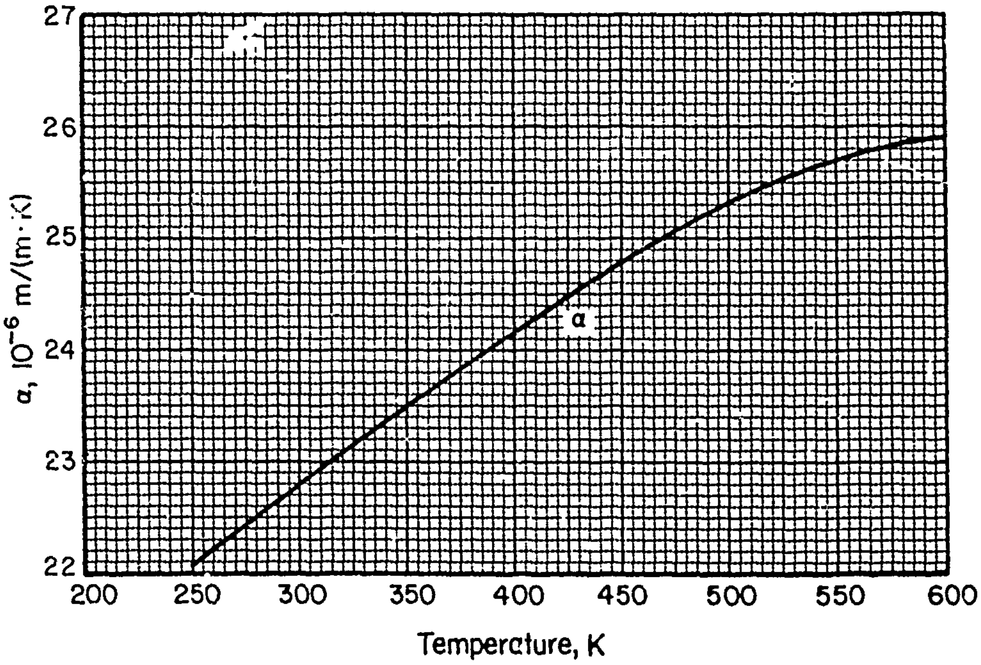


FIGURE 3.5.5.0. Effect of temperature on the physical properties of 5456 aluminum alloy.

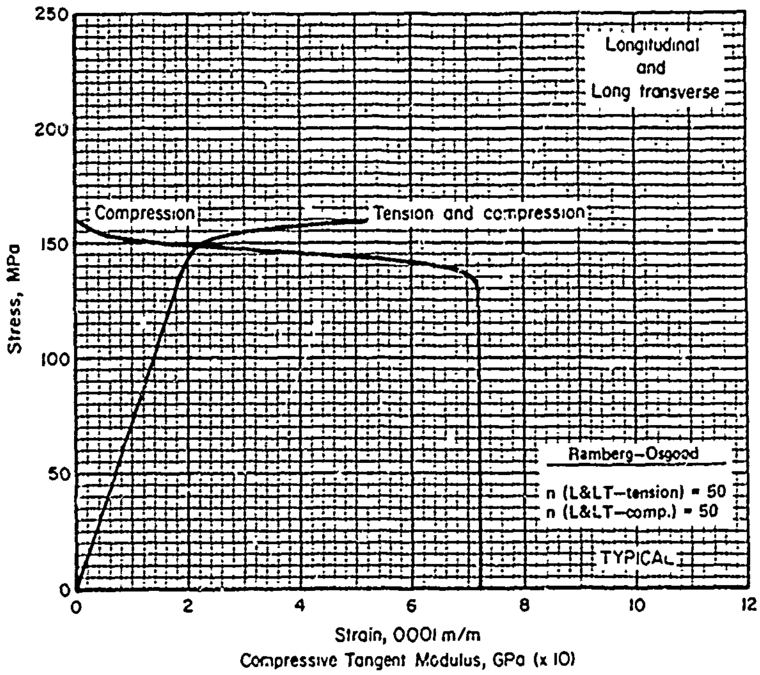


FIGURE 3.5.5.1.6(a). Typical tensile stress-strain and compressive stress-strain and tangent modulus curves for 5456-0 aluminum alloy (sheet and plate) at room temperature.

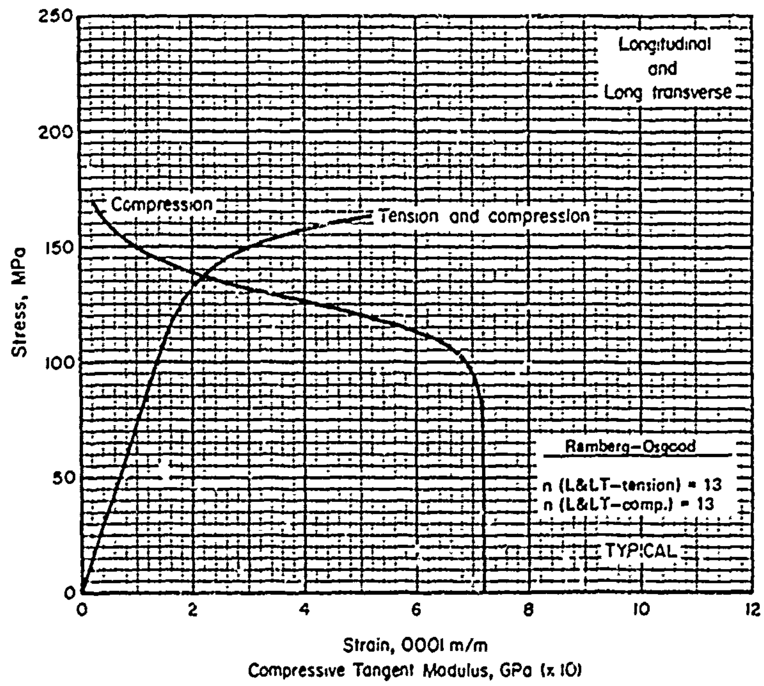


FIGURE 3.5.5 1.6(b). Typical tensile stress-strain and compressive stress-strain and tangent-modulus curves for 5456-0 aluminum alloy (extrusion) at room temperature.

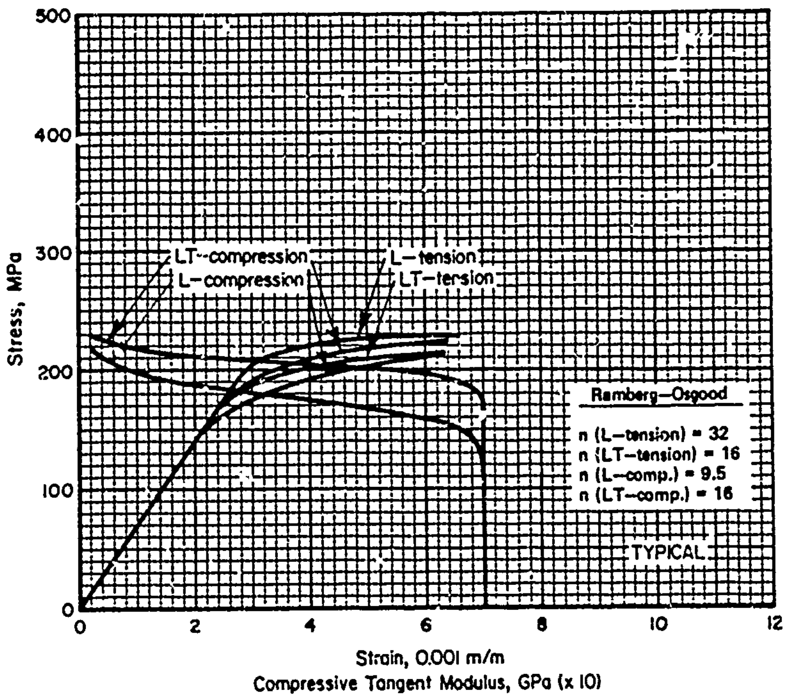


FIGURE 3.5.5.2.6. Typical tensile stress-strain and compressive stress-strain and tangent modulus curves for 5456-H111 aluminum alloy (extrusion) at room temperature.

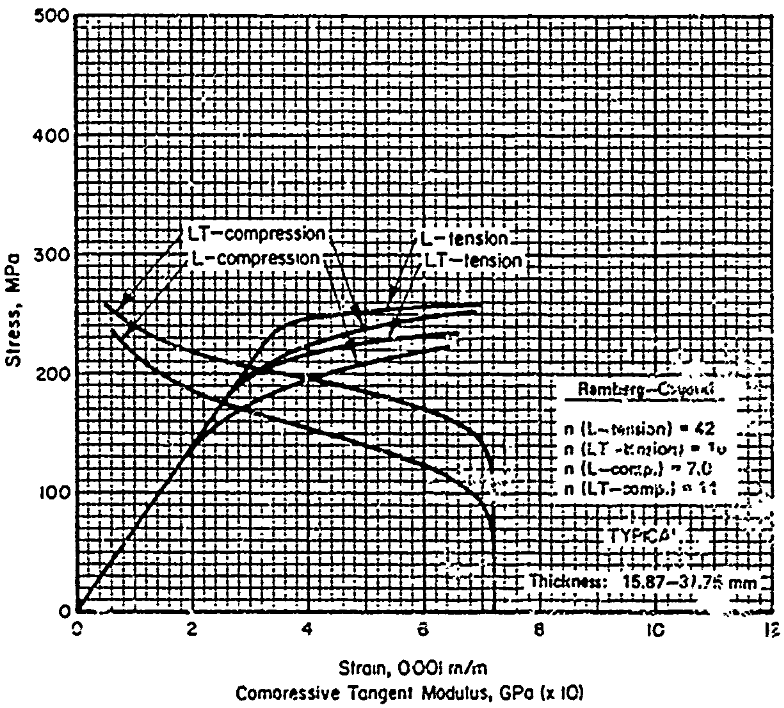


FIGURE 3.5.5.4.6. Typical tensile stress-strain and compressive stress-strain and tangent modulus curves for 5456-H321 aluminum alloy (plate) at room temperature.

TABLE 3.6.1.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 6061 ALUMINUM ALLOY (SHEET AND PLATE)

SPECIFICATION	QQ-A-250/11									QQ-A-250/11							
FORM	SHEET									PLATE							
TEMPER	T4		T6 AND T62[a,b]		T42[b]	T451				T651 AND T62[a,b]						T42[b]	
THICKNESS, MM	0.25-6.32		0.25-6.32		0.25-6.32	6.35-50.81		50.82-76.20		12.70-50.81		50.82-76.21		76.22-101.61	101.62-152.40[d]	5.59-25.41	25.42-76.20
BASIS	A	B	A	B	S	A	B	A	B	A	B	A	B	S	S	S	S
MECHANICAL PROPERTIES:																	
FTU, MPA:																	
L	...	...	290	296	...	...	...	...	...	290	296	...	...	...	...	...	...
LT	207	221	290	296	207	207	221	207	221	290	296	290	296	290	276	207	207
FTY, MPA:																	
L	...	...	248	262	...	...	...	...	...	248	262	...	...	...	...	...	...
LT	110	124	241	255	97	110	124	110	124	241	255	241	255	241	241	97	97
FCY, MPA:																	
L	...	...	241	255	...	...	...	...	...	241	255	...	...	...	...	...	...
LT	110	124	248	262	...	110	124	...	...	248	262	...	...	...	...	...	...
FSU, MPA	138	145	186	193	...	138	145	...	...	186	193	...	...	...	...	...	...
FBRU, MPA:																	
(E/D=1.5)	331	352	462	476	...	331	352	...	...	462	476	...	...	...	...	...	...
(E/D=2.0)	434	462	607	621	...	434	462	...	...	607	621	...	...	...	...	...	...
FBRY, MPA:																	
(E/D=1.5)	152	172	345	365	...	152	172	...	...	345	365	...	...	...	...	...	...
(E/D=2.0)	179	200	400	421	...	179	200	...	...	400	421	...	...	...	...	...	...
EL, PERCENT:																	
L	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
LT	c	...	c	...	c	c	...	16	c	...	6	6	6	18	16	...	...
E, GPA	68.3					68.3											
EC, GPA	69.6					69.6											
G, GPA	26.2					26.2											
MU	0.33					0.33											
PHYSICAL PROPERTIES:																	
OMEGA, MG/M3	2.71																
C, J/(G*K)	0.96 (AT 373 K)																
K, W/(M*K)	156 (AT 298 K) FOR T4XX; 166 (AT 298 K) FOR T6XX																
ALPHA, 10-6 M/(M*K)	23.4 (293-373 K)																

[a] THE ALLOWABLES SHOWN FOR THESE TEMPERS ARE BASED ON AND HAVE BEEN DETEPMINED FROM THE RESULTS OBTAINED ON TESTING OF T6 AND T651 TEMPER MATERIAL AND ON THE TESTING OF T62 TEMPER SAMPLES FOR SPECIFICATION CONFORMANCE.

[b] THESE PROPERTIES APPLY WHEN SAMPLES OF MATERIAL SUPPLIED IN THE O OR F TEM.ER 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] SEE TABLE 3.6.1.0(C).

[d] THE PROPERTIES FOR THIS THICKNESS APPLY ONLY TO T651 TEMPER PLATE.

TABLE 3.6.1.0(c). Percent Elongation Values for 6061 Aluminum Alloys (Sheet, Plate, and Tubing)

Temper	Thickness range, mm	Elongation, percent	
T4 or T451 (sheet and plate) ..	0.25-0.51	14	
	0.52-6.33	16	
	6.34-25.40	18	
	25.41-50.80	16	
T6 or T651 (sheet and plate) ..	0.25-0.51	8	
	0.52-12.69	10	
	12.70-25.40	9	
	25.41-50.80	8	
		Full-section specimen	Cut out specimen
T4 or T42 tubing	0.64-1.26	16	14
	1.27-6.59	18	16
	6.60-12.70	20	18
T6 or T62 tubing	0.64-1.26	10	8
	1.27-6.59	12	10
	6.60-12.70	14	12

TABLE 3.6.1.0(O). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 6061 ALUMINUM ALLOY(WIRE, BAR, ROD AND SHAPES DRAWN TUBE; PIPE)

SPECIFICATION	QQ-A-225/8						WW-T-700/6			MIL-P-25995	
FORM	BAR, ROD, WIRE AND SPECIAL SHAPES						DRAWN TUBE			PIPE	
TEMPER	T4	T451	T42[a]	T6	T651	T62[a]	T4	T42[a]	T6 AND T62[a,b]	T6	
THICKNESS, MM	≤ 203.20	12.70-203.20	≤203.20	-203.20	12.70-203.20	≤203.20	0.63-12.70	0.63-12.70	0.63-12.70	1.24-3.91	1.65-17.45
DIAMETER, MM OR CROSS-SECTIONAL AREA, MM2			≤ 32260				...			3.17-19.05	25.40-304.80
BASIS	S	S	S	S	S	S	S	S	S	S	S
MECHANICAL PROPERTIES:											
FTU, MPA:											
L	207	207	207	290	290	290	207	207	290	290	262
LT	...	...	...	...	...	...	...	...	...	...	...
FTY, MPA:											
L	110	110	97	241	241	241	110	97	241	241	241
LT	...	...	...	...	...	...	...	...	...	...	...
FCY, MPA:											
L	97	97	...	234	234	...	97	...	234	234	234
LT	...	...	...	...	...	...	...	...	...	...	...
FSU, MPA	138	. 38	...	186	186	...	138	...	186	186	165
FBRU, MPA:											
(E/D=1.5)	331	331	...	462	462	...	331	...	462	462	421
(E/D=2.0)	434	434	...	469	469	...	434	...	607	607	552
FBRY, MPA:											
(E/D=1.5)	152	152	...	338	338	...	152	...	338	338	338
(E/D=2.0)	179	179	...	386	386	...	179	...	386	386	386
EL, PERCENT:											
L	18	18	18	10	10	10	c	c	c	12	10
LT	...	...	...	...	...	...	...	...	...	...	...
E, GPA	68.3										
EC, GPA	69.6										
G, GPA	26.2										
MU	0.33										
PHYSICAL PROPERTIES:											
OMEGA, MG/M3	2.71										
C, J/(G*K)	0.96 (AT 373 K)										
K, W/(M*K)	156 (AT 298 K) FOR T4XX; 166 (AT 298 K) FOR T6XX										
ALPHA, 10-6 M/(M*K)	23.4 (293-373 K)										

[a] 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 OROTHERWISE COLD OR HOT WORKED, PARTICULARLY IN THE ANNEALED TEMPER, PRIOR TO SOLUTION HEAT TREATMENT.

[b] THE ALLOWABLES SHOWN FOR THESE TEMPERS ARE BASED ON AND HAVE BEEN DETERMINED FROM THE RESULTS OBTAINED ON TESTING OF T6 TEMPER MATERIAL AND ON THE TESTING OF T62 TEMPER SAMPLES FOR SPECIFICATION CONFORMANCE.

[c] ELONGATION VALUES ARE IN TABLE 3.6.1.0(C).

TABLE 3.6.1.0(E). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 6061 ALUMINUM ALLOY (DIE FORGING)

SPECIFICATION..........	MIL-A-22771
FORM..................	DIE FORGING
CONDITION..............	T6 AND T652
THICKNESS[b], MM..........	< 101.60
BASIS.................	S
MECHANICAL PROPERTIES:	
FTU, MPA:	
L[a]................	262
T................	262
FTY, MPA:	
L................	241
T................	241
FCY, MPA:	
L................	248
T................	248
FSU, MPA............	172
FBRU, MPA:	
(E/D=1.5)..........	421
(E/D=2.0)..........	524
FBRY, MPA:	
(E/D=1.5)..........	372
(E/D=2.0)..........	421
EL, PERCENT:	
L................	7
T................	5
E, GPA..............	68.3
EC, GPA.............	69.6
G, GPA..............	26.2
MU..................	0.33
PHYSICAL PROPERTIES:	
OMEGA, MG/M3..........	2.71
C, J/(G*K)...........	0.96 (AT 373 K)
K, W/(M*K)...........	166 (AT 298 K)
ALPHA, 10-6 M/(M*K)..	23.4 (293-373 K)

[a]FOR DIE FORGINGS. T INDICATES ANY GRAIN DIRECTION NOT WITHIN ± 15 DEGREES OF BEING PARALLEL TO THE FORGING FLOW LINES. SPECIMENS TO TEST TRANSVERSE PROPERTIES SHOULD BE LOCATED AS CLOSE TO THE SHORT TRANSVERSE DIRECTION AS POSSIBLE.

[b]THE THICKNESS COLUMNS ARE FOR THE AS-HEAT-TREATED THICKNESS. TO ENTER THE TABLE USE THE HIGHER OF THE HEAT-TREAT THICKNESS OR ONE-HALF OF THE AS FORGED THICKNESS.

TABLE 3.6.1.0(F). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 6061 ALUMINUM ALLOY (HAND FORGING)

SPECIFICATION..........	MIL-A-22771	
FORM..................	HAND FORGING	
CONDITION.............	T6 AND T652	
THICKNESS,[a] MM..........	<101.61	101.62-203.20
BASIS.................	S	S
MECHANICAL PROPERTIES:		
FTU, MPA:		
L.................	262	255
LT................	262	255
ST................	255	241
FTY, MPA:		
L.................	241	234
LT................	241	234
ST................	228	221
FCY, MPA:		
L.................	248	241
LT................	248	241
ST................	234	228
FSU, MPA.............	172	165
FBRU, MPA:		
(E/D=1.5).........	421	407
(E/D=2.0).........	524	510
FBRY, MPA:		
(E/D=1.5).........	372	434
(E/D=2.0).........	421	407
EL, PERCENT:		
L.................	10	8
LT................	8	6
ST................	5	4
E, GPA.............	68.3	
EC, GPA............	69.6	
G, GPA.............	26.2	
MU.................	0.33	
PHYSICAL PROPERTIES:		
OMEGA, MG/M3.........	2.71	
C, J/(G*K)...........	0.96 (AT 373 K)	
K, W/(M*K)...........	156 (AT 298 K)	
ALPHA, 10-6 M/(M*K)..	23.4 (293-373 K)	

[a] WHEN HAND FORGINGS ARE MACHINED BEFORE HEAT TREATMENT, THE SECTION THICKNESS AT TIME OF HEAT TREATMENT SHALL 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 16,516 SQ.CM.

... PROPERTIES OF
6061 ALUMINUM ALLOY (EXTRUDED ROD, BAR AND SHAPES)

SPECIFICATION	QQ-A-200/8											
FORM	EXTRUDED ROD, BAR AND SHAPES											
TEMPER	T4, T4510, AND T4511	T42[b]	T6, T6510, T6511, AND T62[b,c]									
CROSS-SECTIONAL AREA, MM2	...	...	≤20650									
THICKNESS, MM	≤ 76.20	≤ 76.20	≤ 6.33		6.34-12.68		12.69-25.41		25.42-76.18		76.19-165.10	
BASIS	S	S	A	B	A	B	A	B	A	B	A	B
MECHANICAL PROPERTIES:												
FTU, MPA:												
L	179	179	262	283	262	283	262	283	262	283	262	283
LT	...	...	255	276	255	276	255	276	228	241	228	241
FTY, MPA:												
L	110	83	241	262	241	262	241	262	241	262	241	262
LT	...	...	223	248	228	248	228	248	193	214	193	214
FCY, MPA:												
L	97	...	241	262	241	262	241	262	241	262	241	262
LT	...	...	241	262	241	262	241	262	207	228	207	228
FSU, MPA	110	...	186	200	186	200	186	200	131	145	131	145
FBRU,[a] MPA:												
(E/D=1.5)	290	...	441	476	441	476	441	476	338	469	338	469
(E/D=2.0)	379	...	565	614	565	614	565	614	476	510	476	510
FBRY,[a] MPA:												
(E/D=1.5)	152	...	372	400	372	400	372	400	290	317	290	317
(E/D=2.0)	179	...	414	448	414	448	414	448	352	379	352	379
EL, PERCENT:												
L	16	16	8	...	10	...	10	...	10	...	10	...
LT	...	...	...	...	...	...	...	...	...	...	...	...
E, GPA	68.3											
EC, GPA	69.6											
G, GPA	2.3											
MU	0.33											
PHYSICAL PROPERTIES:												
OMEGA, MG/M3	2.71											
C, J/(G*K)	0.96 (AT 373 K)											
K, W/(M*K)	156 (AT 298 K) FOR T4XX; 166 (AT 298 K) FOR T6XXX											
ALPHA, 10-6 M/(M*K)	23.4 (293-373 K)											

[a] BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

[b] THE ALLOWABLES SHOWN FOR THESE TEMPERS ARE BASED ON AND HAVE BEEN DETERMINED FROM THE RESULTS OBTAINED ON TESTING OF T4 AND T6 TEMPER MATERIAL AND ON THE TESTING OF T42 AND T62 TEMPER SAMPLES FOR SPECIFICATION CONFORMANCE.

[c] THESE PROPERTIES APPLY WHEN SAMPLES OF MATERIAL SUPPLIED IS THE O TO 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.

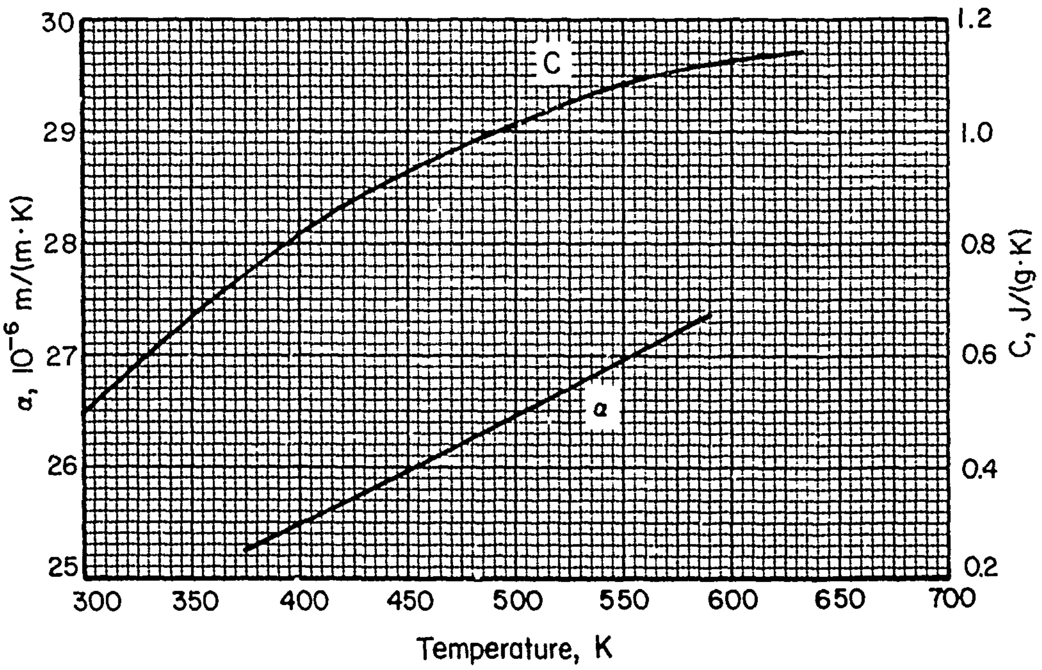


FIGURE 3.6.1.0. Effect of temperature on the physical properties of 6061 aluminum alloy.

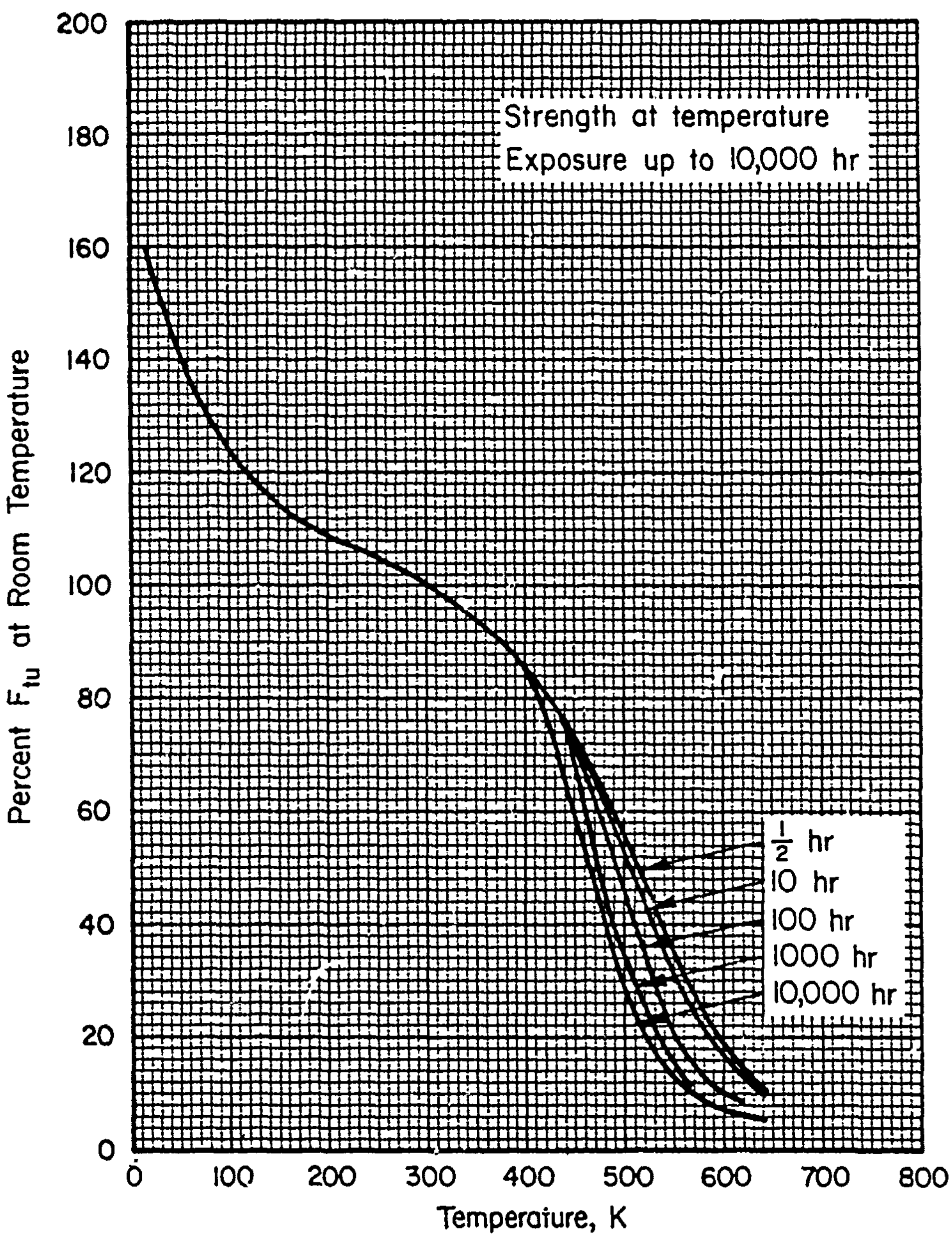


FIGURE 3.6.1.2.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of 6061-T6 aluminum alloy (all products).

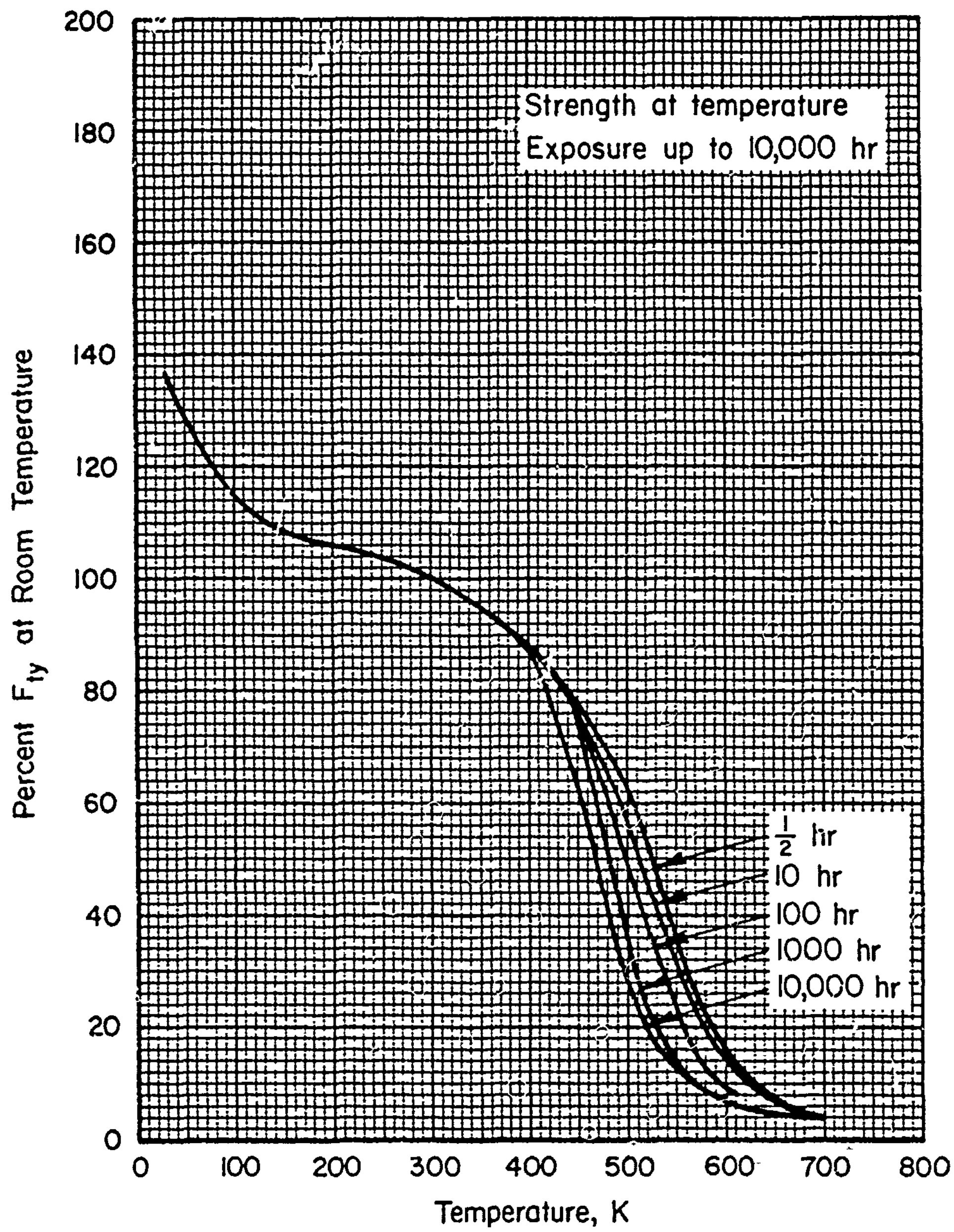


FIGURE 3.6.1.2.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of 6061-T6 aluminum alloy (all products).

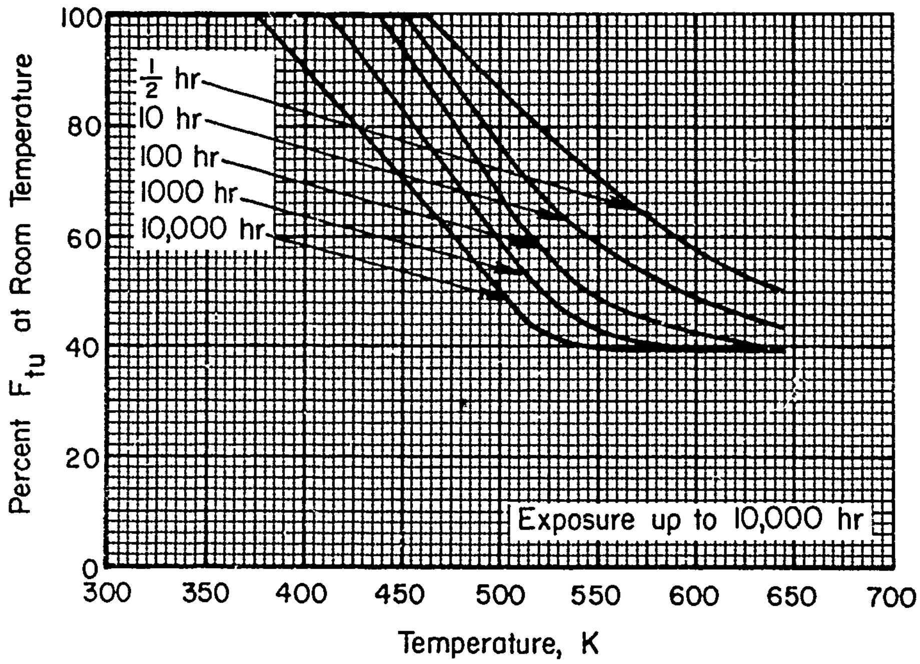


FIGURE 3.6.1.2.1(c). Effect of exposure at elevated temperatures on the room-temperature ultimate tensile strength (F_{tu}) of 6061-T6 aluminum alloy (all products).

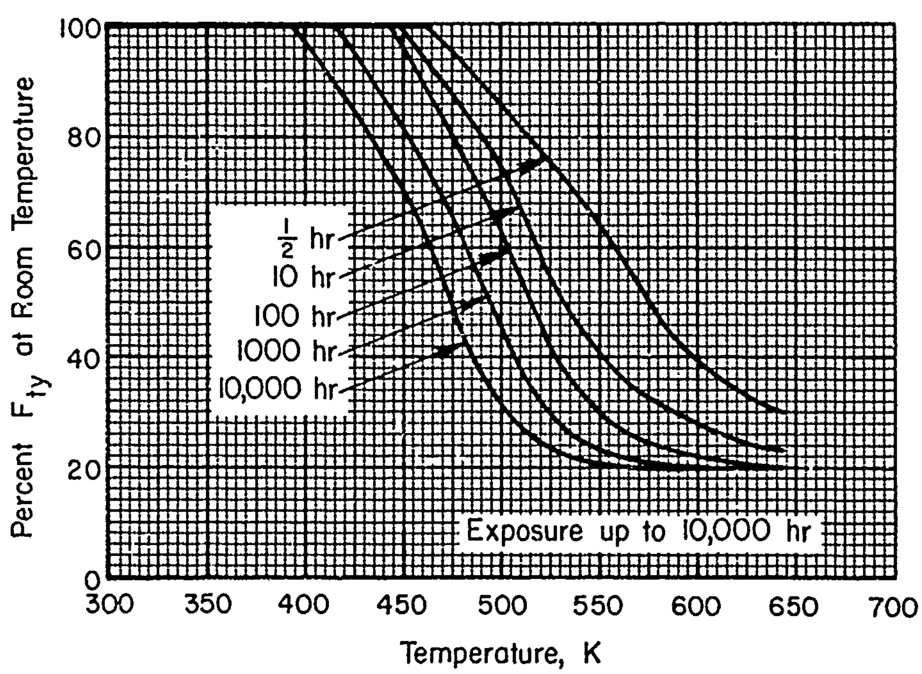


FIGURE 3.6.1.2.1(d). Effect of exposure at elevated temperatures on the room-temperature tensile yield strength (F_{ty}) of 6061-T6 aluminum alloy (all products).

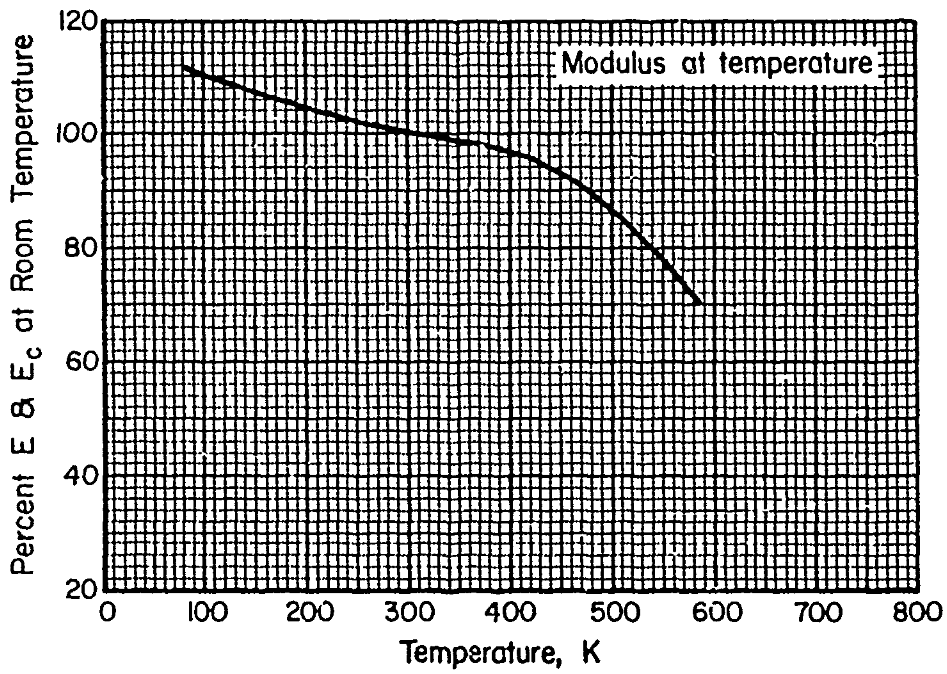


FIGURE 3.6.1.2.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of 6061 aluminum alloy.

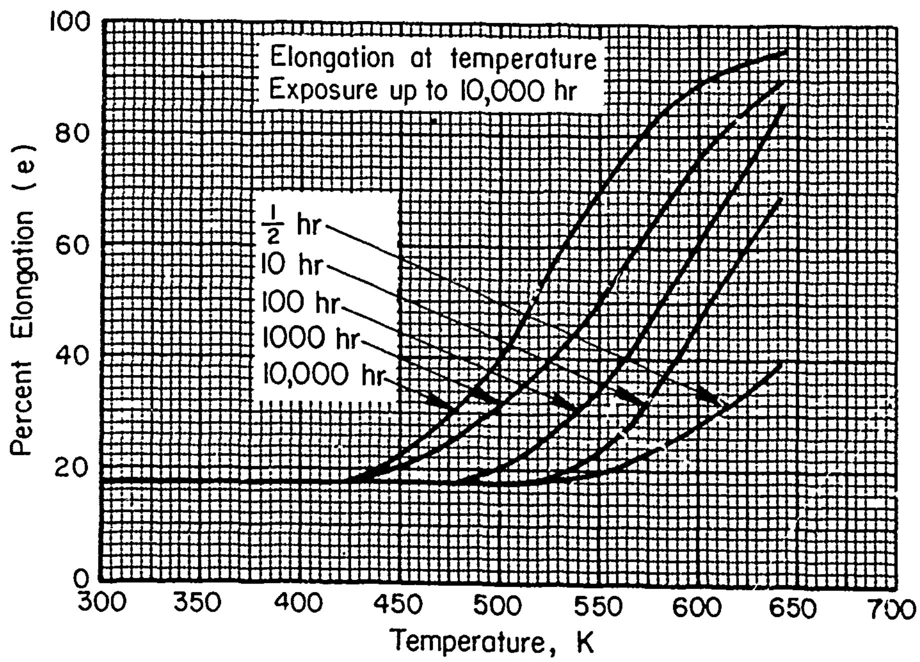


FIGURE 3.6.1.2.5(a). Effect of temperature on the elongation of 6061-T6 aluminum alloy (all products).

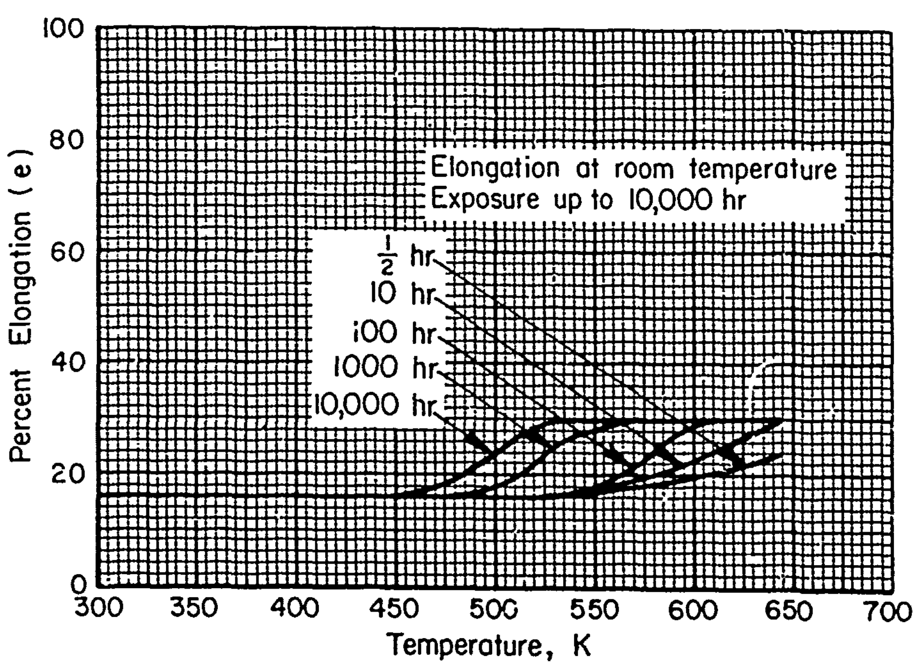


FIGURE 3.6.1.2.5(b). Effect of exposure at elevated temperatures on the elongation of 6061-T6 aluminum alloy (all products).

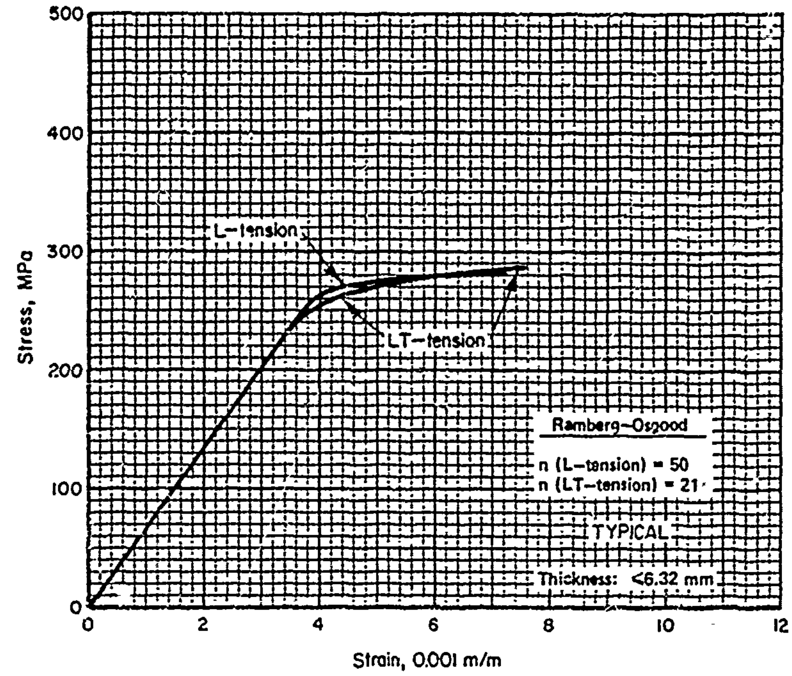


FIGURE 3.6.1.2.6(a). Typical tensile stress-strain curves for 6061-T6 aluminum alloy (sheet) at room temperature.

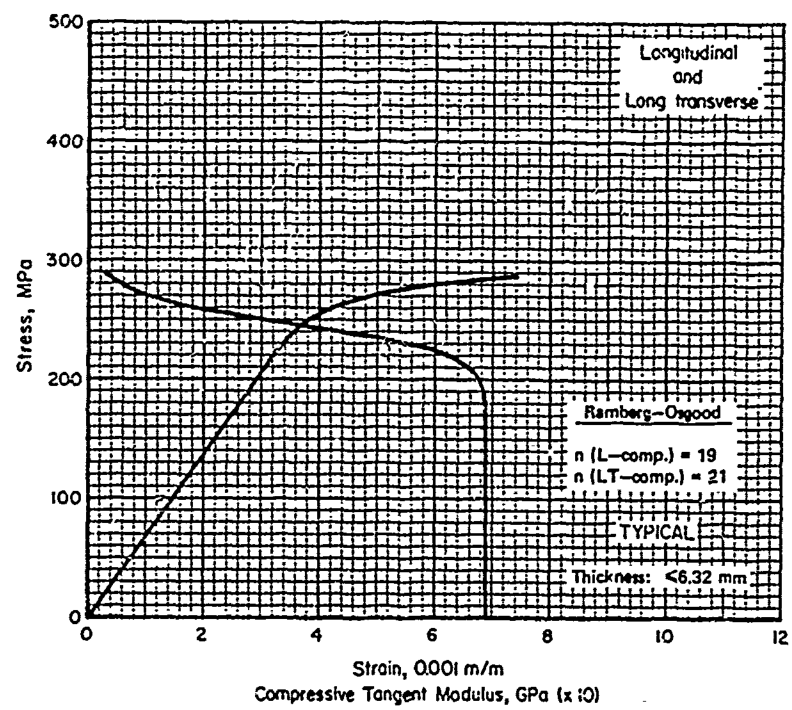


FIGURE 3.6.1.2.6(b). Typical compressive stress-strain and tangent-modulus curves for 6061-T6 aluminum alloy (sheet) at room temperature.

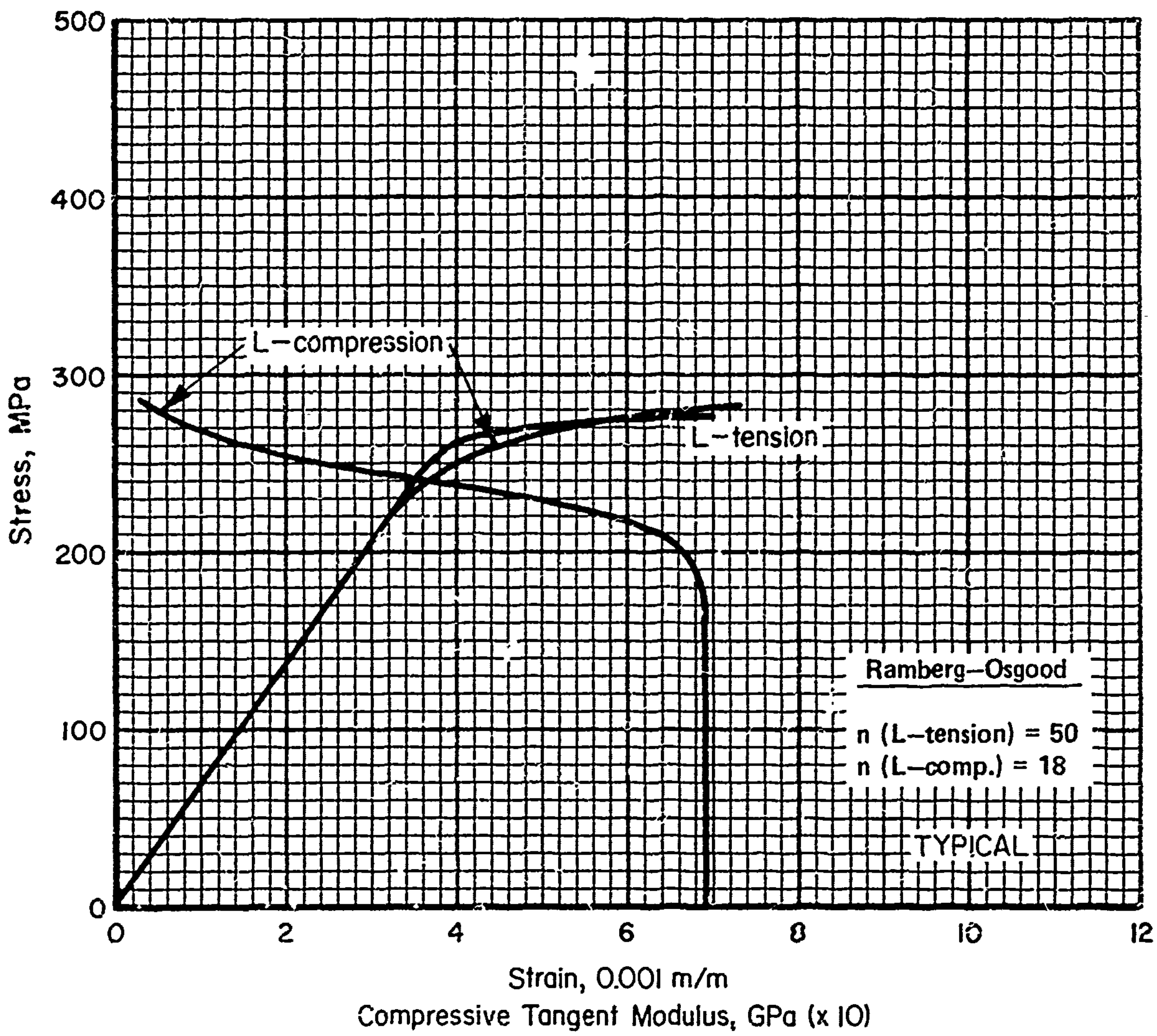


FIGURE 3.6.1.2.6(c). Typical tensile stress-strain and compressive stress-strain curves for 6061-T6 aluminum alloy (extrusion) at room temperature.

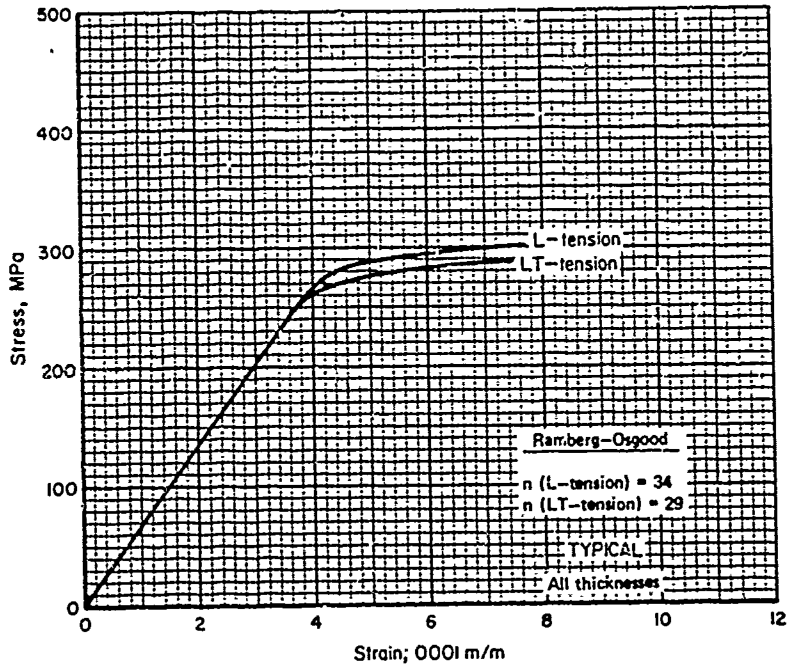


FIGURE 3.6.1.2.6(d). Typical tensile stress-strain curves for 6061-T62 aluminum alloy (extrusion) at room temperature.

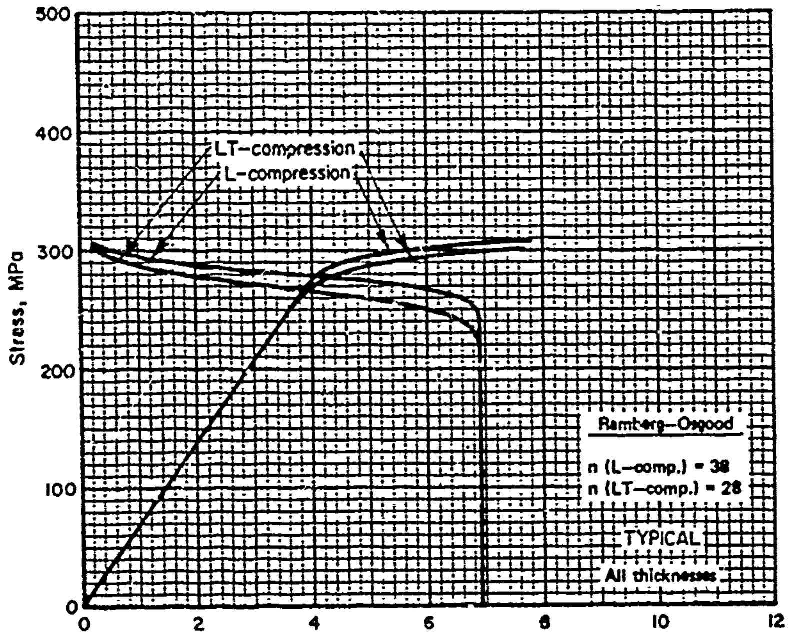


FIGURE 3.6.1.2.6(e). Typical compressive stress-strain and tangent-modulus curves for 6061-T62 aluminum alloy (extrusion) at room temperature.

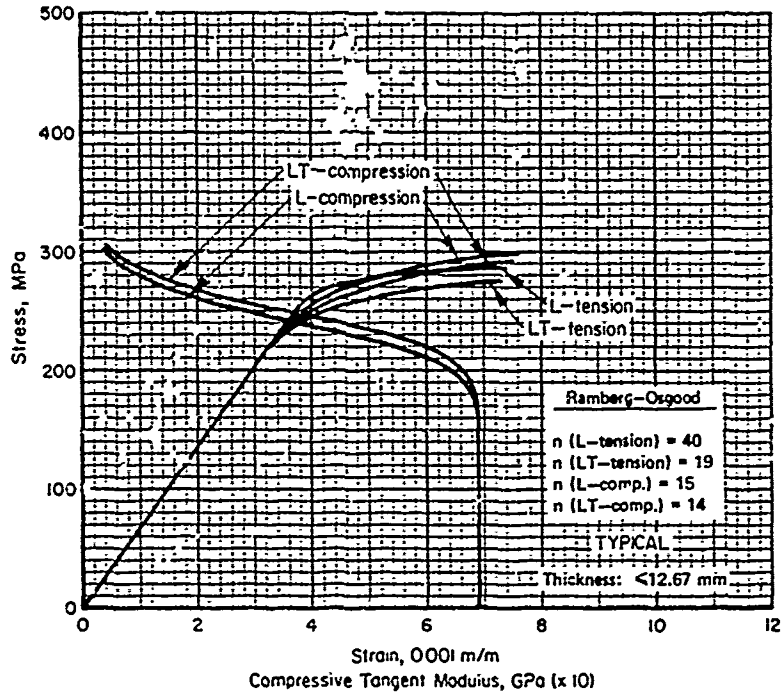


FIGURE 3.6.1.2.6(f). Typical tensile stress-strain and compressive stress-strain and tangent modulus curves for 6061-T651X aluminum alloy (extrusion) at room temperature.

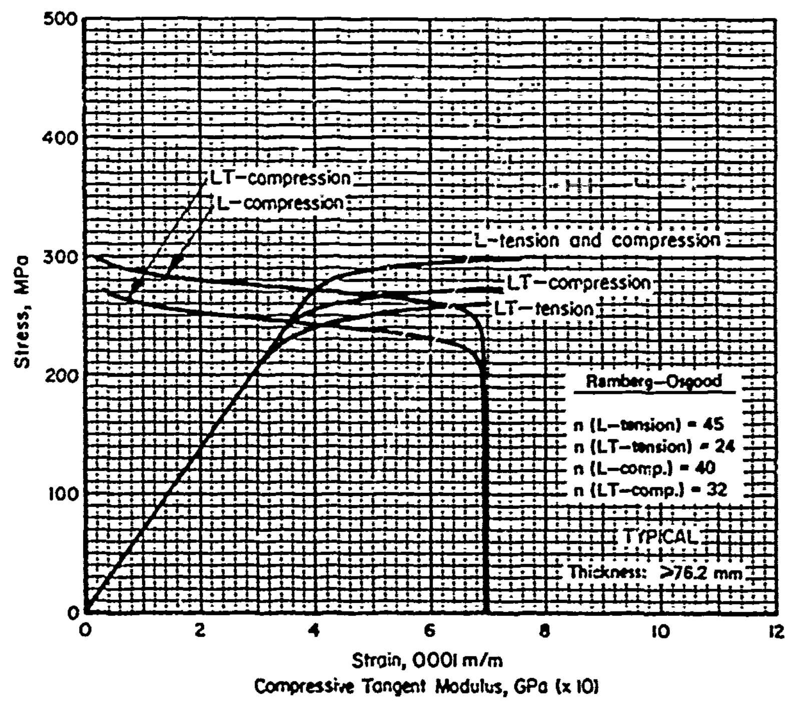


FIGURE 3.6.1.2.6(g). Typical tensile stress-strain and compressive stress-strain and tangent-modulus curves for 6061-T651X aluminum (extrusion) at room temperature.

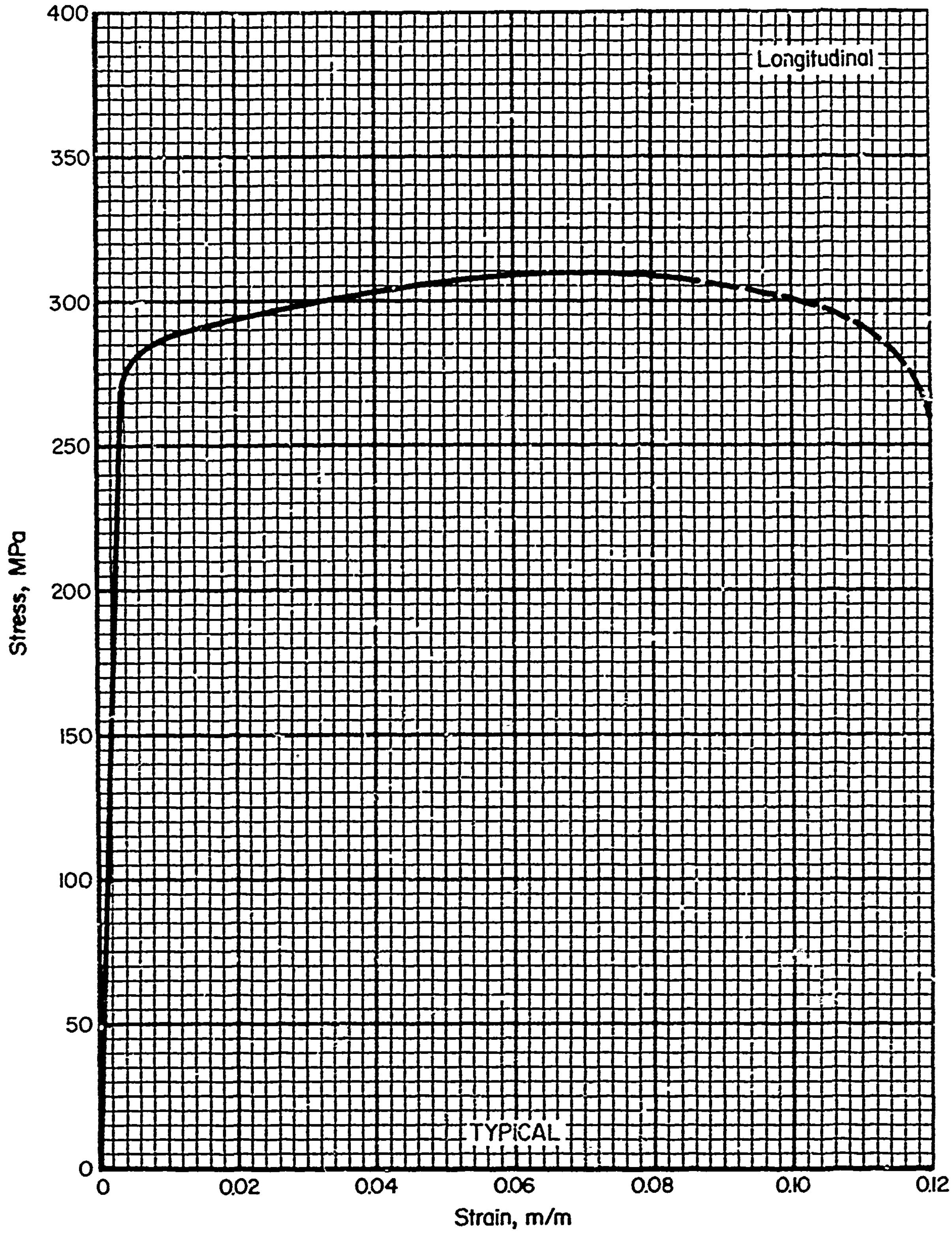


FIGURE 3.6.1.2.6(h). Typical tensile stress-strain curve (full range) for 6061-T6 aluminum alloy (sheet) at room temperature.

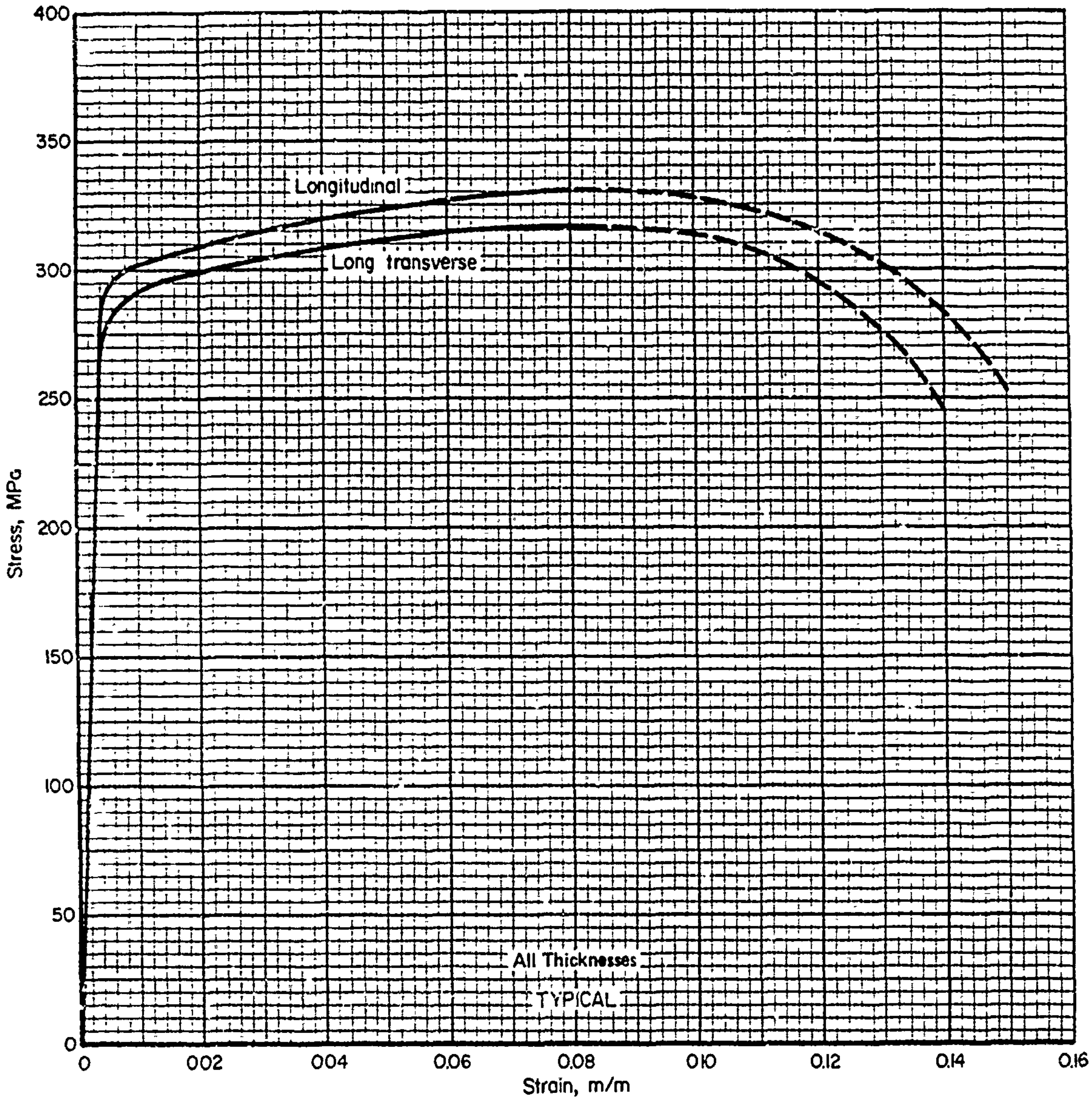


FIGURE 3.6.1.2.6(i). Typical tensile stress-strain curves (full range) for 6061-T62 aluminum alloy (extrusion) at room temperature.

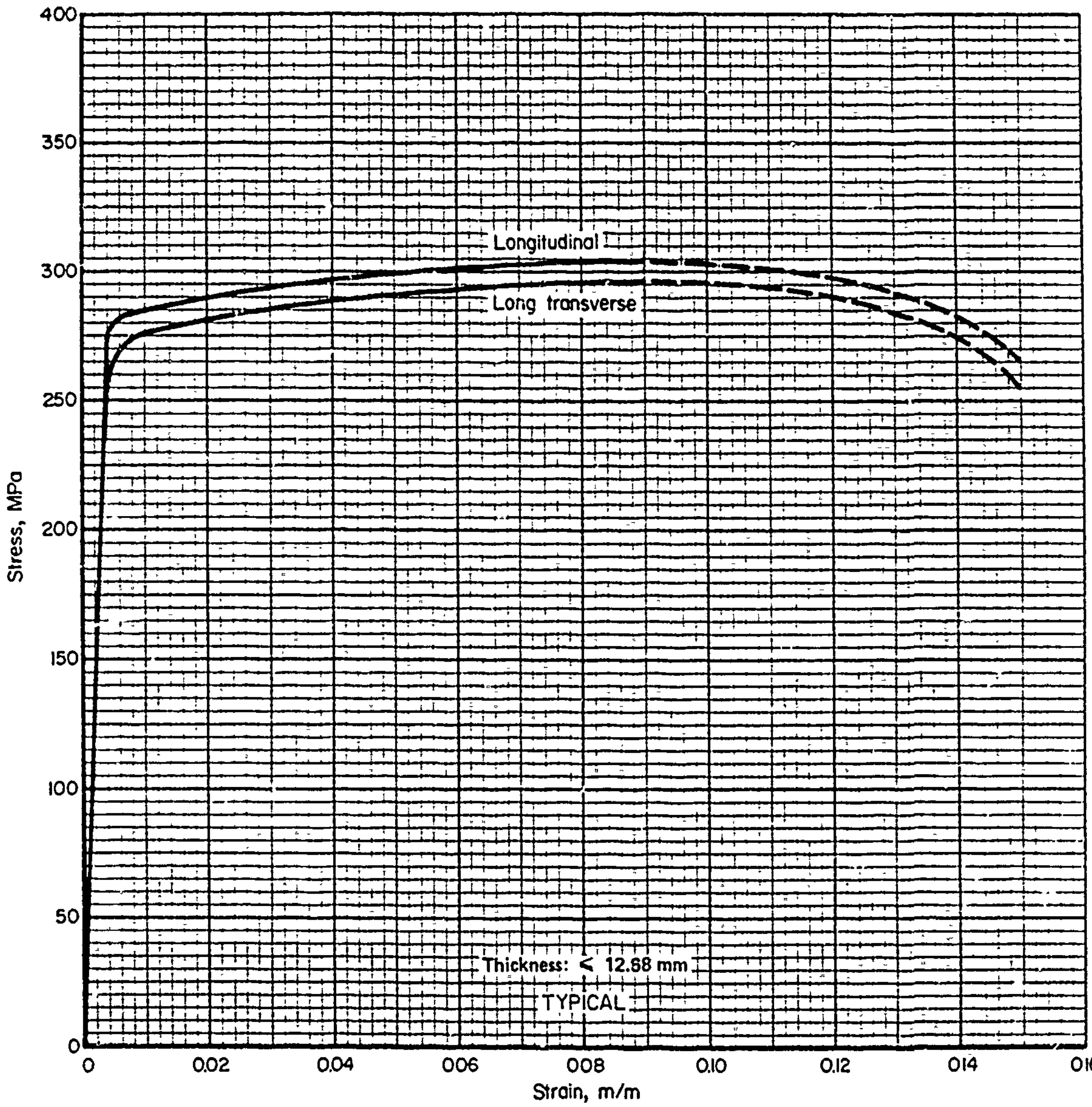


FIGURE 3.6.1.2.6(j). Typical tensile stress-strain curves (full range) for 6061-T651X aluminum alloy (extrusion) at room temperature.

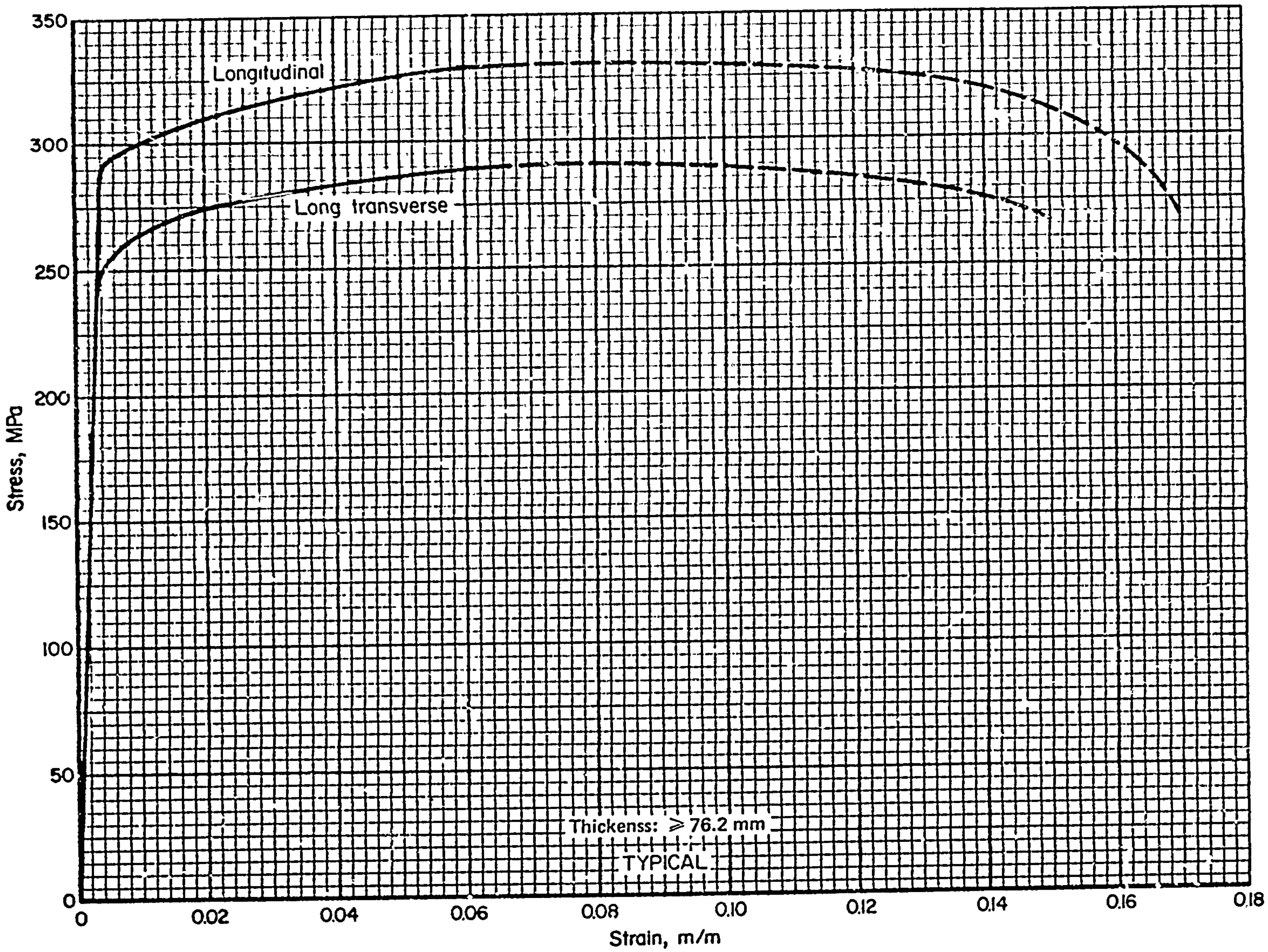


FIGURE 3.6.1.2.6(k). Typical tensile stress-strain curves (full range) for 6061-T651X aluminum alloy (extrusion) at room temperature.

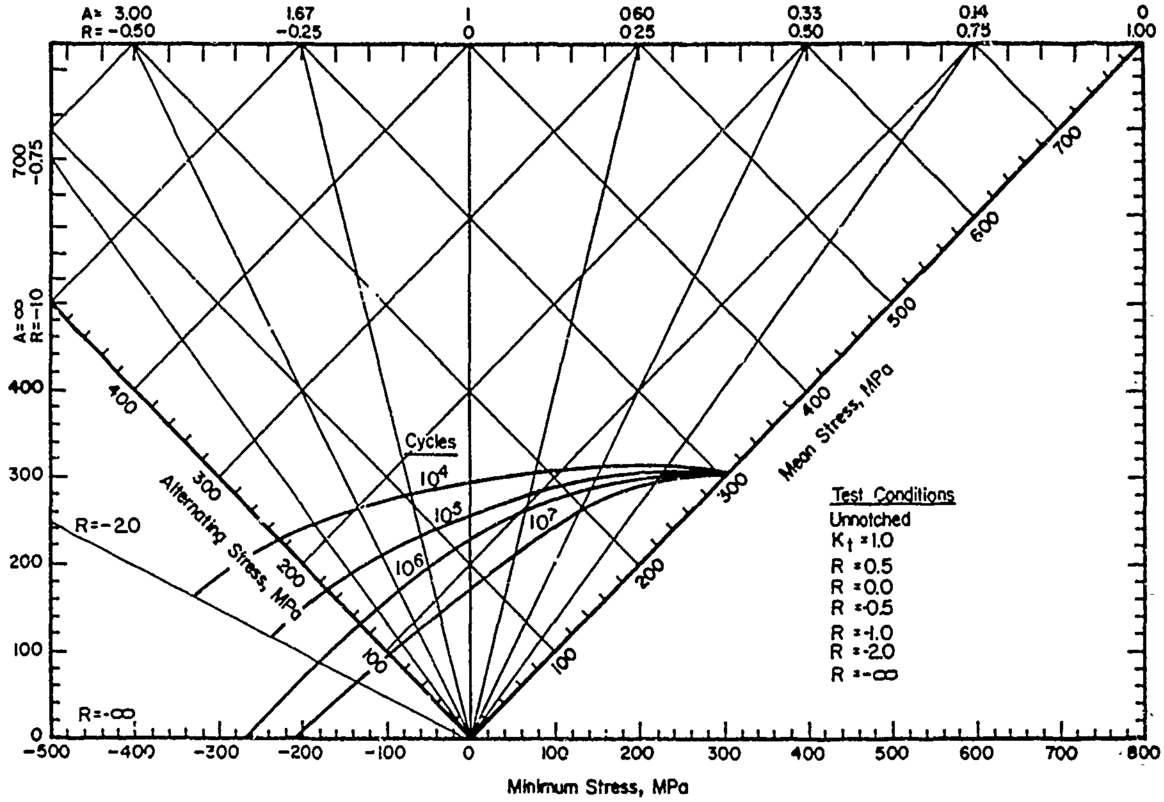


FIGURE 3.6.1.2.8. Typical constant-life diagram for fatigue behavior of various wrought products of 6061-T6 aluminum alloy

Correlative Information for Figure 3.6.1.2.8

Product Form: Drawn rod, 19.1 mm diameter
Rolled bar, 25 x 190 mm

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

Properties:

TUS, MPa	TYS, MPa	Temp, K
305	272	RT

Specimen Details: Unnotched:
5.08 mm diameter

Surface Condition: Unnotched: not known

3.6.2 6151 ALLOY

3.6.2.0 *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.

A material specification for 6151 alloy aluminum is presented in Table 3.6.2.0(a). Room-temperature mechanical and physical properties are shown in Table 3.6.2.0(b). The effect of temperature on physical properties is shown in Figure 3.6.2.0.

TABLE 3.6.2.0(a). *Material Specification for 6151 Aluminum Alloy*

Specification	Form
MIL-A-22771	Forgings

The temper index for 6151 is as follows:

Section	Temper
3.6.2.1	T6

3.6.2.1 *T6 Temper.*—Modulus data from Figure 3.6.1.2.4 can be used for this alloy.

TABLE 3.6.2.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 6151 ALUMINUM ALLOY (DIE FORGING)

SPECIFICATION..........	MIL-A-22771
FORM....................	DIE FORGING
CONDITION..............	T6
THICKNESS,[b] MM..........	< 101.60
BASIS..................	S
MECHANICAL PROPERTIES:	
FTU, MPA:	
L................	303
T[a]................	303
FTY, MPA:	
L................	255
T................	255
FCY, MPA:	
L................	269
T................	241
FSU, MPA............	193
FBRU, MPA:	
(E/D=1.5).........	...
(E/D=2.0).........	...
FBRY, MPA:	
(E/D=1.5).........	...
(E/D=2.0).........	...
EL, PERCENT:	
L................	10
T................	6
E, GPA..............	69.6
EC, GPA.............	71.0
G, GPA..............	26.5
MU..................	0.33
PHYSICAL PROPERTIES:	
OMEGA, MG/M3.........	2.71
C, J/(G*K)...........	0.96 (AT 373 K)
K, W/(M*K)...........	173 (AT 298 K)
ALPHA, 10-6 M/(M*K)..	21.6 (293-373 K)

[a] FOR DIE FORGINGS, T INDICATES ANY GRAIN DIRECTION NOT WITHIN ± 15 DEGREES OF BEING PARALLEL TO THE FORGING FLOW LINES. SPECIMENS TO TEST TRANSVERSE PROPERTIES SHOULD BE LOCATED AS CLOSE TO THE SHORT TRANSVERSE DIRECTION AS POSSIBLE.

[b] THE THICKNESS COLUMNS ARE FOR THE AS-HEAT-TREATED THICKNESS. TO ENTER THE TABLE USE THE HIGHER OF THE HEAT-TREAT THICKNESS OR ONE-HALF OF THE AS-FORGED THICKNESS.

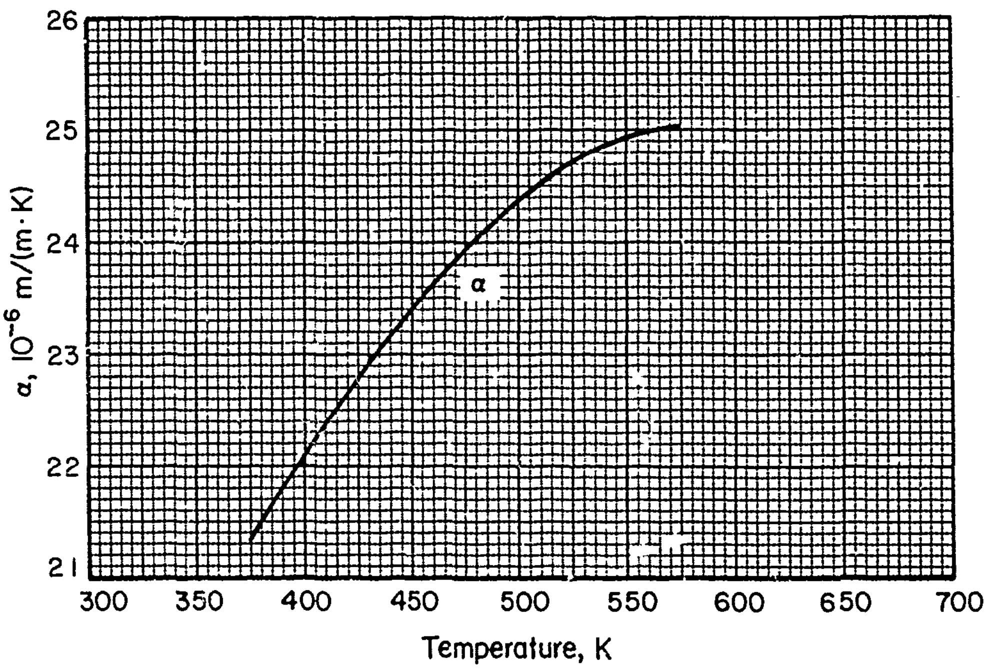


FIGURE 3.6.2.0. Effect of temperature on the physical properties of 6151 aluminum alloy.

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 the light of Sections 3.1.2.3 and 3.1.3.

3.7.1 7049 ALLOY

3.7.1.0 *Comments and Properties.*—7049 is available only in the form of die and hand forgings. The T73 temper provides static strengths about equivalent to those of forged 7079-T6, with high resistance to stress-corrosion cracking. The fatigue characteristics are about equal to those of 7075-T6 and 7079-T6 products, while the toughness is somewhat higher. 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 7049 aluminum alloy are presented in Table 3.7.1.0(a). Room temperature mechanical and physical properties are shown in Tables 3.7.1.0(b), (c) and (d).

TABLE 3.7.1.0(a). *Material Specification for 7049 Aluminum Alloy*

Specification	Form
QQ-A-367	Forgings
AMS 4157	Extrusions

The temper index for 7049 is as follows:

Section	Temper or condition
3.7.1.1	T73, T73511

3.7.1.1 *T73 Temper.*—Figures 3.7.1.1.6(a) through 3.7.1.1.6(d) present tensile and compressive stress-strain and tangent-modulus curves for die and hand forgings at room temperature.

TABLE 3.7.1.0(B). [illegible] MECHANICAL AND PHYSICAL PROPERTIES OF [illegible] ALUMINUM ALLOY (DIE FORGING)

SPECIFICATION	QQ-A-367				
FORM	DIE FORGING				
CONDITION	T73				
THICKNESS, MM	< 25.40	25.42-50.81	50.82-76.21	76.22-101.61	101.62-127.00
BASIS	S	S	S	S	S
MECHANICAL PROPERTIES:					
FTU, MPA:					
L	496	496	490	490	483
T[a]	490	483	483	483	469
FTY, MPA:					
L	427	427	421	421	414
T	421	414	414	414	400
FCY, MPA:					
L	441	441	434	434	427
T	434	427	427	427	414
FSU, MPA	283	283	276	276	269
FBRU,[b] MPA:					
(E/D=1.5)	696	696	683	683	676
(E/D=2.0)	917	917	903	889	889
FBRY,[b] MPA:					
(E/D=1.5)	552	552	545	538	538
(E/D=2.0)	562	662	655	641	641
EL, PERCENT:					
L	7	7	7	7	7
T	3	3	3	2	2
E, GPA	70.3				
EC, GPA	73.8				
G, GPA	26.9				
MU	0.33				
PHYSICAL PROPERTIES:					
OMEGA, MG/M3	2.82				
C, J/(G*K)	0.96 (AT 373 K)				
K, W/(M*K)	154 (AT 298 K)				
ALPHA, 10-6 M/(M*K)	23.4 (RT-373 K)				

[a] FOR DIE FORGINGS, T INDICATES ANY GRAIN DIRECTION NOT WITH ± 15 DEGREE OF BEING PARALLEL TO THE FORGING FLOW LINES. SPECIMENS TO TEST TRANSVERSE PROPERTIES SHOULD BE LOCATED AS CLOSE TO THE SHORT TRANSVERSE DIRECTION AS POSSIBLE.

[b] BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

TABLE 3.7.1.0(C). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 7049 ALUMINUM ALLOY (HAND FORGING)

SPECIFICATION..........	QQ-A-367		
FORM..................	HAND FORGING		
CONDITION..............	T73		
THICKNESS,[a] MM..........	50.83-76.21	76.22-101.61	101.62-127.00
BASIS..................	S	S	S
MECHANICAL PROPERTIES:			
FTU, MPA:			
L..................	490	476	462
LT.................	490	476	462
ST.................	476	462	455
FTY, MPA:			
L..................	421	407	386
LT.................	407	393	386
ST.................	400	386	379
FCY, MPA:			
L..................	421	407	386
LT.................	414	400	393
ST.................	427	414	407
FSU, MPA............	276	269	262
FBRU,[b] MPA:			
(E/D=1.5)...........	683	662	648
(E/D=2.0)...........	903	876	855
FBRY,[b] MPA:			
(E/D=1.5)...........	565	552	538
(E/D=2.0)...........	669	648	634
EL, PERCENT:			
L..................	9	8	7
LT.................	4	3	3
ST.................	3	2	2
E, GPA................	70.3		
EC, GPA...............	73.1		
G, GPA................	26.9		
NU....................	0.33		
PHYSICAL PROPERTIES:			
OMEGA, MG/M3..........	2.82		
C, J/(G*K)............	0.96 (AT 373 K)		
K, W/(M*K)............	154 (AT 298 K)		
ALPHA, 10-6 M/(M*K)..	23.4 (RT-373 K)		

[a] WHEN HAND FORGINGS ARE MACHINED BEFORE HEAT TREATMENT, THE SECTION THICKNESS AT TIME OF HEAT TREATMENT SHALL 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 16,516 SQ. CM.

[b] BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

TABLE 3.7.1.0(D). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 7049 ALUMINUM ALLOY (EXTRUSION)

SPECIFICATION	AMS 4157	
FORM	EXTRUSION	
CONDITION	T73511	
THICKNESS, MM	≤76.18	76.19-127.00
BASIS	S	S
MECHANICAL PROPERTIES:		
FTU, MPA:		
L	510	496
LT	483	469
FTY, MPA:		
L	441	427
LT	414	400
FCY, MPA:		
L	448	434
LT	421	407
FSU, MPA	262	255
FBRU[a], MPA:		
(E/D=1.5)	717	696
(E/D=2.0)	938	910
FBRY[a], MPA:		
(E/D=1.5)	552	531
(E/D=2.0)	676	655
EL, PERCENT:		
L	7	7
LT	5	5
E, GPA	72.4	
EC, GPA	...	
G, GPA	27.6	
MU	0.31	
PHYSICAL PROPERTIES:		
OMEGA, MG/M3	2.82	
C, J/(G*K)	0.96 (AT 373 K)	
K, W/(M*K)	...	
ALPHA, 10-6 M/(M*K)	23.4 (RT TO 373 K)	

[a]BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

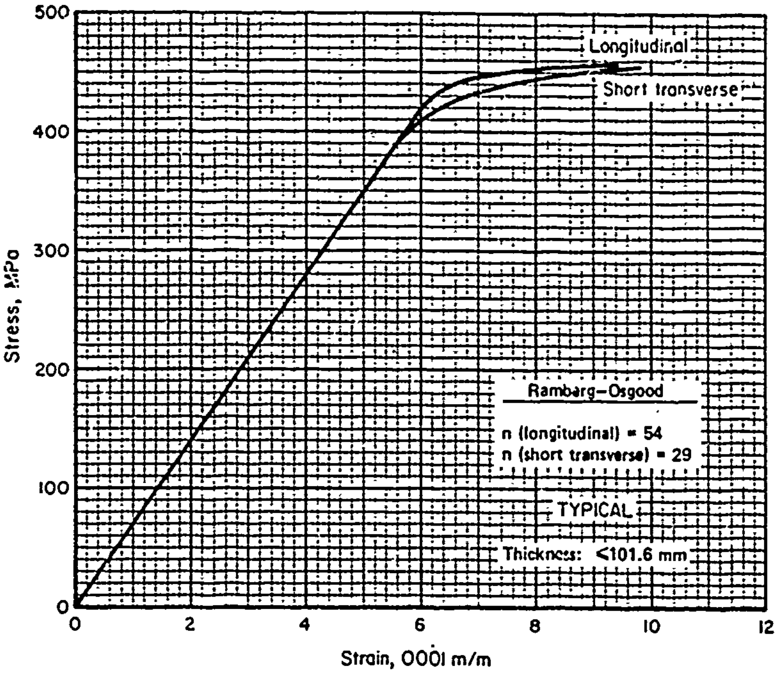


FIGURE 3.7.1.1.6(a). Typical tensile stress-strain curves for 7049-T73 aluminum alloy (die forgings) at room temperature.

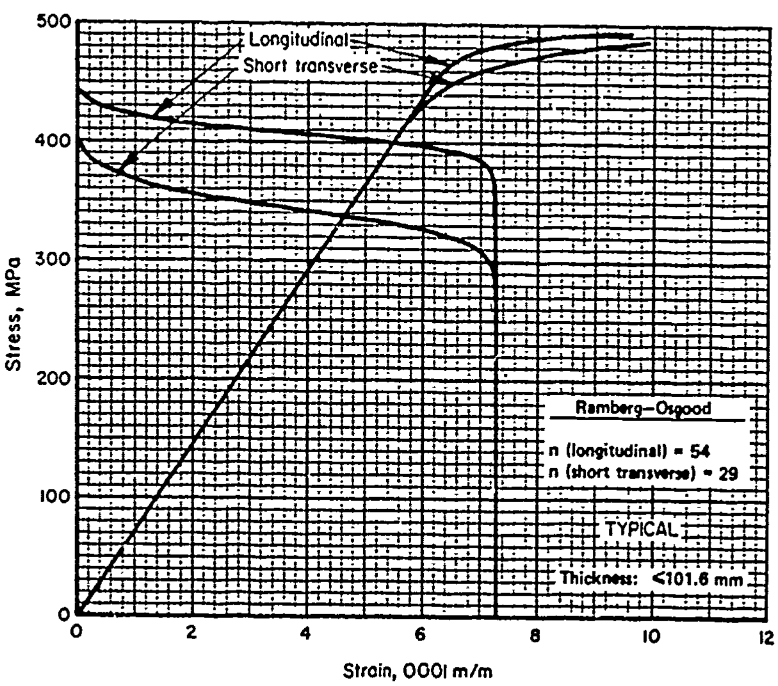


FIGURE 3.7.1.1.6(b). Typical compressive stress-strain and tangent-modulus curves for 7049-T73 aluminum alloy (die forgings) at room temperature.

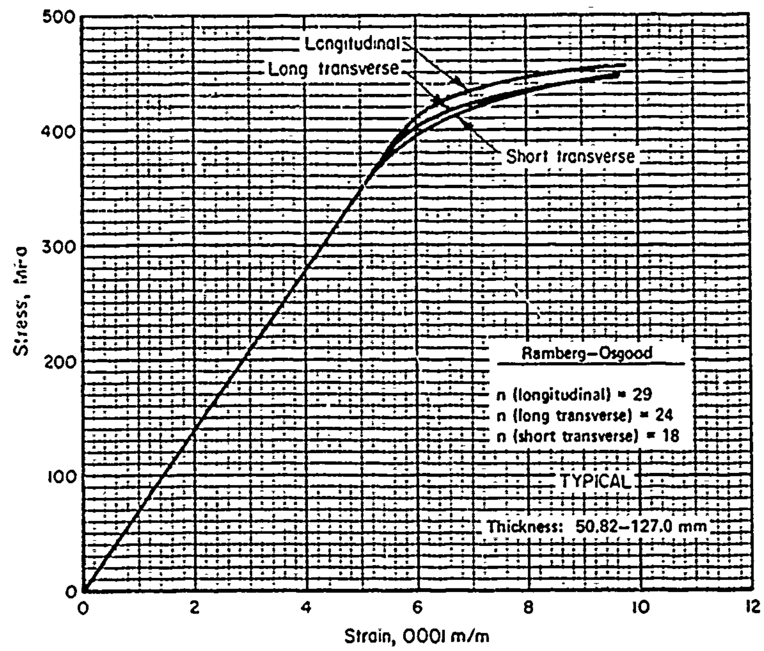


FIGURE 3.7.1.1.6(c). Typical tensile stress-strain curves for 7049-T73 aluminum alloy (hand forgings) at room temperature.

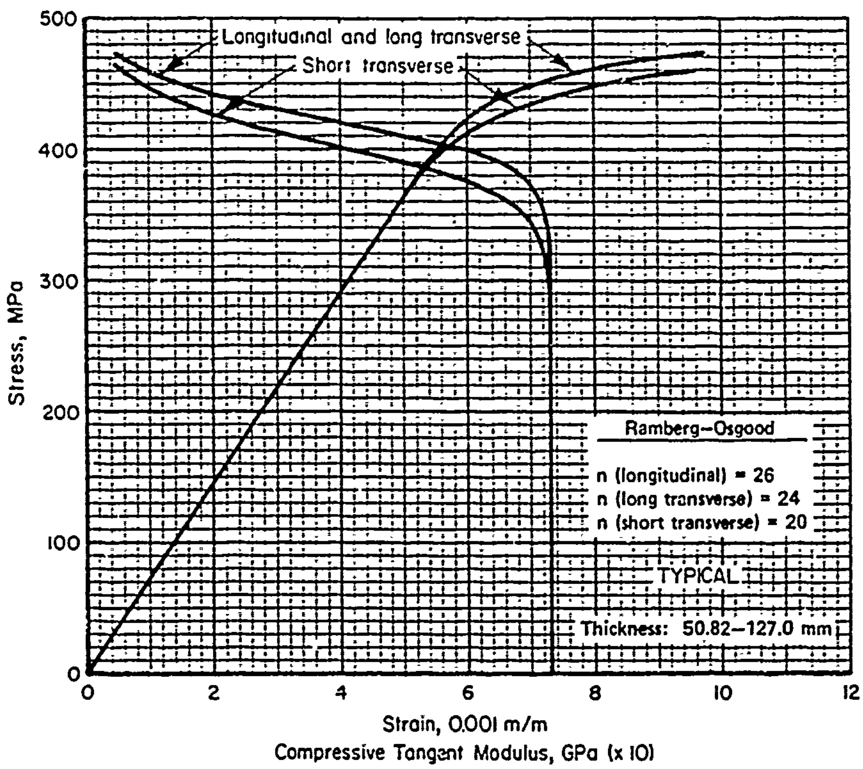


FIGURE 3.7.1.1.6(d). Typical compressive stress-strain and tangent-modulus curves for 7049-T73 aluminum alloy (hand forgings) at room temperature.

3.7.2 7050 ALLOY

3.7.2.0 *Comments and Properties.* — 7050 is an Al-Zn-Mg-Cu-Zr alloy developed to have a combination of high strengths, 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. Plate, hand and die forgings in the T736-type temper have static strengths about equivalent to those of corresponding products of 7079 in the T6-type tempers and toughness levels equal to or higher than other conventional high-strength alloys. Plate in the T73651 temper has stress-corrosion resistances higher than 7075-T7651 and hand and die forgings in the T73652 and T736 tempers, respectively, have stress-corrosion resistance equivalent to 7175-T736 forgings.

Material specifications for 7050 plate hand forgings and die forgings are shown in Table 3.7.2.0(a). Room-temperature mechanical properties are shown in Tables 3.7.2.0(b) through (d).

TABLE 3.7.2.0(a). *Material Specifications for 7050 Aluminum Alloy*

Specification	Form
AMS 4050	Bare plate
AMS 4108	Hand forgings
AMS 4107	Die forgings

The temper index for 7050 is as follows:

Section	Temper
3.7.2.1	T736, T73651, T73652

3.7.2.1 *T736, T73651, and T73652 Tempers.* — Figures 3.7.2.1.6(a) through (f) present stress-strain and tangent-modulus curves for various products and tempers.

TABLE 3.7.2.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 7050 ALUMINUM ALLOY (PLATE)

SPECIFICATION	AMS 4050							
FORM	PLATE							
CONDITION	T73651							
THICKNESS, MM	6.35-12.68	12.69-25.41	25.42-38.11	38.12-50.81	50.82-76.21	76.22-101.61	101.62-127.01	127.02-152.40
BASIS	S	S	S	S	S	S	S	S
MECHANICAL PROPERTIES:								
FTU, MPA:								
L	490	490	490	490	490	476	462	455
LT	496	496	496	496	496	483	469	462
ST	...	...	...	...	469	455	441	434
FTY, MPA:								
L	434	434	434	434	434	414	400	386
LT	434	434	434	434	434	414	400	386
ST	...	...	...	...	407	386	372	365
FCY, MPA:								
L	427	427	421	421	414	393	372	359
LT	448	448	448	448	455	434	421	407
ST	...	...	...	...	427	414	400	393
FSU, MPA	283	283	276	296	296	290	290	290
FBRU[a], MPA:								
(E/D=1.5)	717	717	717	756	758	738	717	710
(E/D=2.0)	945	945	945	979	979	952	924	910
FBRY[a], MPA:								
(E/D=1.5)	586	586	586	627	627	614	600	586
(E/D=2.0)	696	696	696	710	710	703	689	676
EL, PERCENT:								
L	9	9	9	9	9	9	9	8
LT	6	6	6	6	6	6	5	5
ST	...	...	...	...	2	2	2	2
E, GPA	71.0							
EC, GPA	73.1							
G, GPA	26.9							
MU	0.33							
PHYSICAL PROPERTIES:								
OMEGA, MG/M3	2.82							
C, J/(G*K)	0.96 (AT 373 K)							
K, W/(M*K)	161 (AT 298 K)							
ALPHA, 10-6 M/(M*K)	23.0 (293 TO 373 K)							

[a]BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

TABLE 3.7.2.0(C). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 7050 ALUMINUM ALLOY (DIE FORGING)

SPECIFICATION............	AMS 4107					
FORM.....................	DIE FORGING[a]					
CONDITION................	T736					
THICKNESS[c], MM...........	≤25.41	25.42-50.81	50.82-76.21	76.22-101.61	101.62-127.01	127.02-152.40
BASIS....................	S	S	S	S	S	S
MECHANICAL PROPERTIES:						
FTU, MPA:						
L................	496	496	490	490	483	483
T................	469	469	462	462	455	455
FTY, MPA:						
L................	427	427	421	421	414	407
T................	386	386	379	379	372	372
FCY, MPA:						
L................	434	434	434	434	434	427
T................	400	400	393	386	379	372
FSU, MPA.............	290	290	283	283	283	283
FBRU[b], MPA:						
(E/D=1.5).........	683	683	676	676	669	669
(E/D=2.0).........	903	903	889	889	876	876
FBRY[b], MPA:						
(E/D=1.5).........	565	565	558	558	545	538
(E/D=2.0).........	662	662	655	655	641	634
EL, PERCENT:						
L................	7	7	7	7	7	7
T................	5	5	4	4	3	3
E, GPA...............	70.3					
EC, GPA..............	73.8					
G, GPA...............	26.9					
MU...................	0.33					
PHYSICAL PROPERTIES:						
OMEGA, MG/M3.........	2.82					
C, J/(G*K)...........	0.96 (AT 373 K)					
K, W/(M*K)...........	161 (AT 298 K)					
ALPHA, 10-6 M/(M*K)..	23.0 (293 TO 373 K)					

[a] FOR DIE FORGINGS, T INDICATES ANY GRAIN DIRECTION NOT WITHIN ± 15 DEGREE OF BEING PARALLEL TO THE FORGING FLOW LINE, WITH THE AXIS OF THE SPECIMEN LOCATED AS CLOSE TO THE SHORT TRANSVERSE DIRECTION AS POSSIBLE

[b] BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

[c] THE THICKNESS COLUMNS ARE FOR THE AS-HEAT-TREATED THICKNESS. TO ENTER THE TABLE USE THE HIGHER OF THE HEAT-TREAT THICKNESS OR ONE-HALF OF THE AS-FORGED THICKNESS.

TABLE ..7.2.0(D). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 7050 ALUMINUM ALLOY (HAND FORGINGS)

SPECIFICATION	AMS 4108						
FORM	HAND FORGINGS						
CONDITION	T73652						
THICKNESS,[a] MM	≤50.81	50.82-76.21	76.22-101.61	101.62-127.01	127.02-152.41	152.42-177.81	177.82-203.20
BASIS	S	S	S	S	S	S	S
MECHANICAL PROPERTIES:							
FTU, MPA:							
L	496	496	490	483	476	469	462
LT	490	483	463	476	469	462	455
ST	...	462	462	455	455	448	441
FTY, MPA:							
L	434	427	421	414	407	400	393
LT	421	414	407	400	386	372	359
ST	...	379	379	372	365	352	345
FCY, MPA:							
L	441	434	427	421	414	407	400
LT	448	441	434	427	414	400	386
ST	...	421	421	414	407	393	379
FSU, MPA	290	283	283	283	276	259	269
FBRU[b], MPA:							
(E/D=1.5)	689	683	683	669	662	655	641
(E/D=2.0)	903	896	896	883	869	855	641
FBRY[b], MPA:							
(E/D=1.5)	593	586	572	565	545	524	503
(E/D=2.0)	696	689	676	662	641	621	593
EL, PERCENT:							
L	9	9	9	9	9	9	9
LT	5	5	5	4	4	4	4
ST	...	4	4	3	3	3	3
E, GPA	70.3						
EC, GPA	73.1						
G, GPA	26.9						
MU	0.33						
PHYSICAL PROPERTIES:							
OMEGA, MG/M3	2.82						
C, J/(G*K)	0.96 (AT 373 K)						
K, W/(M*K)	161(AT 298 K)						
ALPHA, 10-6 M/(M*K)	23.0 (293 TO 373 K)						

[a] WHEN HAND FORGINGS ARE MACHINED BEFORE HEAT TREATMENT, THE SECTION THICKNESS AT TIME OF HEAT TREATMENT SHALL 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.

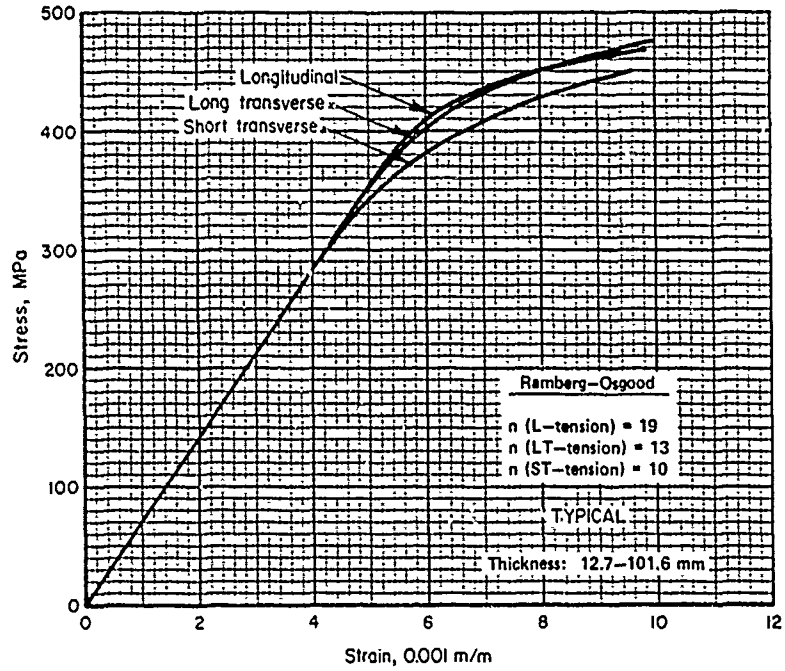


FIGURE 3.7.2.1.6(a). Typical tensile stress-strain curves for 7050-T73651 aluminum alloy (plate) at room temperature.

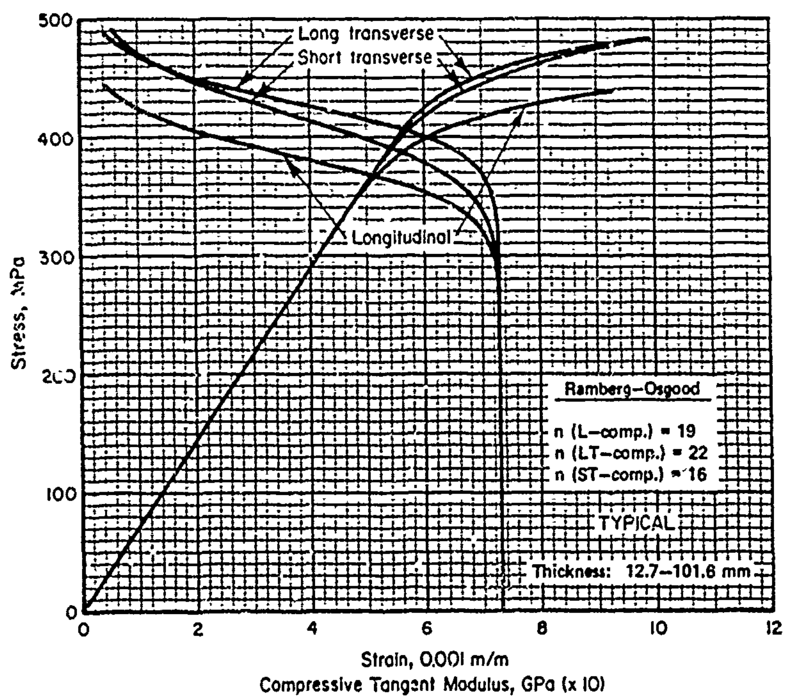


FIGURE 3.7.2.1.6(b). Typical compressive stress-strain and tangent-modulus curves for 7050-T73651 aluminum alloy (plate) at room temperature.

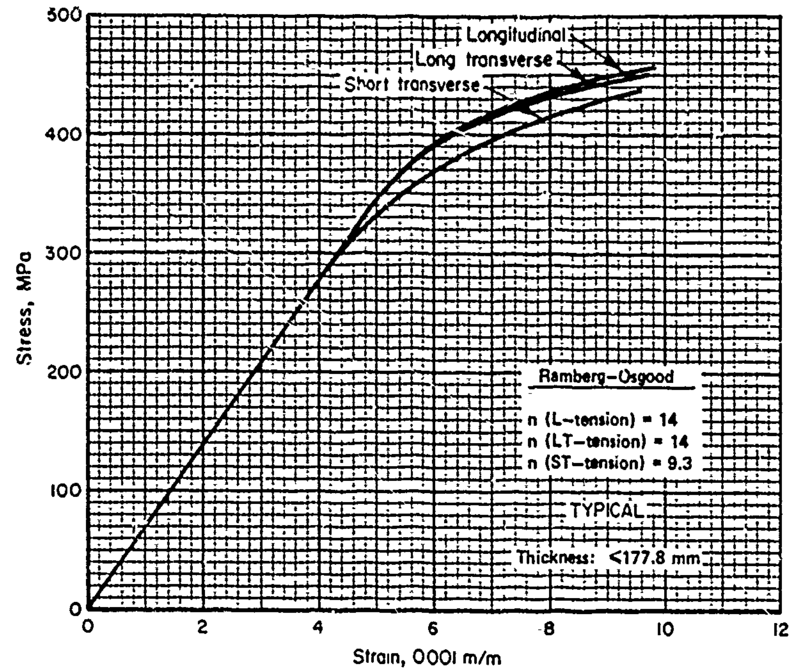


FIGURE 3.7.2.1.6(c). Typical tensile stress-strain curves for 7050-T73652 aluminum alloy (hand forgings) at room temperature.

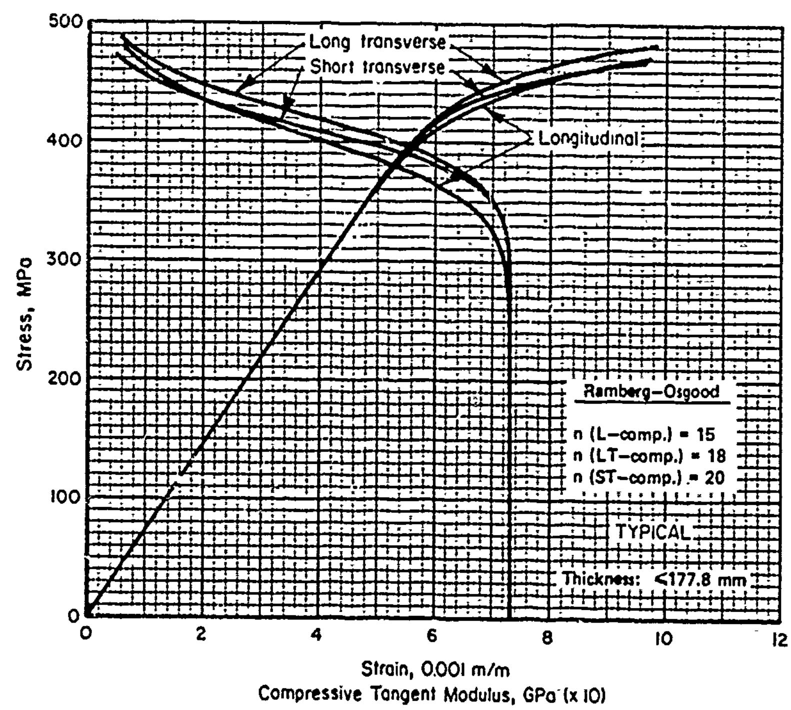


FIGURE 3.7.2.1.6(d). Typical compressive stress-strain and tangent-modulus curves for 7050-T73652 aluminum alloy (hand forgings) at room temperature.

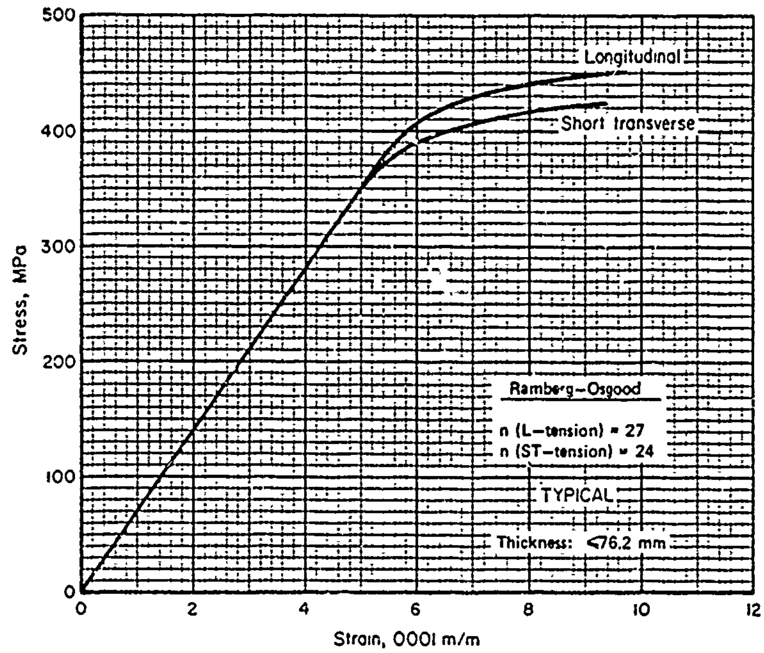


FIGURE 3.7.2.1.6(e). Typical tensile stress-strain curves for 7050-T736 aluminum alloy (die forgings) at room temperature.

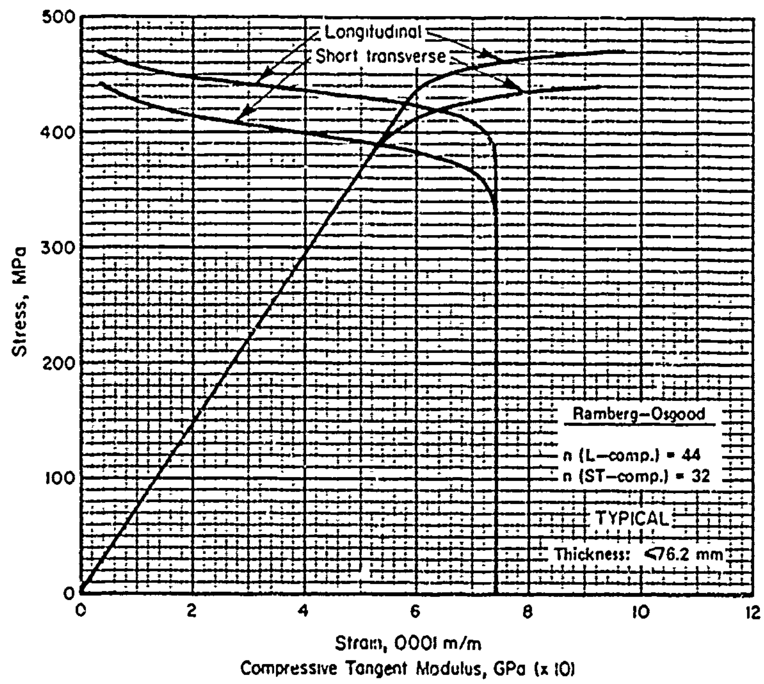


FIGURE 3.7.2.1.6(f). Typical compressive stress-strain and tangent-modulus curves for 7050-T736 aluminum alloy (die forgings) at room temperature.

3.7.3 7075 ALLOY

3.7.3.0 *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 and lowest toughness, and is susceptible to stress-corrosion cracking. Since toughness decreases with a decrease in temperature, the T6 temper is not generally recommended for cryogenic applications. The T73 temper has the lowest strength, but is relatively tough and very resistant to stress-corrosion cracking and exfoliation attack. The T76 temper is a compromise providing higher strength than the T73 temper and higher resistance to corrosion than the T6 temper. 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 7075 aluminum alloy are presented in Table 3.7.3.0 (a). Room-temperature mechanical and physical properties are shown in Table 3.7.3.0(b) through (L) .The effect of temperature on the physical properties of this alloy is presented in Figure 3.7.3.0.

TABLE 3.7.3.0(a). *Material Specifications for 7075 Aluminum Alloy*

Specification	Form
QQ-A-250/12, 24	Bare sheet and plate
QQ-A-250/13, 25, 26	Clad sheet and plate
QQ-A-225/9	Roiled or drawn bars, rods and wire
QQ-A-200/11, 15	Extruded bar, rod, and shapes
MIL-A-22771	Forgings

The temper index for 7075 is as follows:

Section	Temper
3.7.3.1	T6, T651, T652, T6510, T6511
3.7.3.2	T73, T7351, T7352, T73510, T73511
3.7.3.3	T76, T7651, T76510, T76511

3.7.3.1 *T6, T651, T652, T6510, T6511 Temper.*—Room and elevated temperature data for this condition are presented in Figures 3.7.3.1.1(a) through 3.7.3.1.8(f) as follows:

Figures 3.7.3.1.1(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 394 K following a complex exposure of 422 K, 8 hours plus 450 K, 1 hour.

1. Reduce given complex exposure by converting 450 K exposure to equivalent exposure time at 422 K.*
   a. On the 450 K single exposure temperature line find 450 K, 1 hour.
   b. From this point move vertically to the 422 K exposure temperature line and then read right, 12 hours exposure.
   c. Total equivalent exposure time at 422 K is therefore 8 hours + 12 hours or 20 hours.
2. Find F_{tu} at 394 K following 422 K, 20 hours exposure:
   a. On the 422 K exposure temperature line find 422 K, 20 hours.
   b. From this point move vertically to the 394 K 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 3.7.3.1.

Stressed Thermal Exposure—Stress applied during simple and complex thermal exposure of 7075-T6 can have an additional effect in reducing material strength. However, the effect becomes significant only when exposure strains exceed 0.2 percent. For specific data, see Reference 3.7.3.1.

Figures 3.7.3.1.1(c) through 3.7.3.1.5(b) present effect of temperature curves for various mechanical properties.

*Choice of reference temperature is optional as long as it permits computation within the bounds of the figures.

Figures 3.7.3.1.6(a) through (m) present tensile and compressive stress-strain curves and tangent-modulus curves for various tempers and at a number of temperatures.

Figures 3.7.3.1.6(n) through (q) are full-range stress-strain curves for various tempers.

Figures 3.7.3.1.7(a) through (h) are creep and stress-rupture curves for T6 temper at several temperatures.

Figures 3.7.3.1.8(a) through (f) provide room temperature fatigue curves for T6 temper products.

3.7.3.2 *T73, T7351, T7352, T73510, T73511 Tempers.* — Figures 3.7.3.2.6(a) through (d) present stress-strain and tangent-modulus curves for various products and tempers.

Figures 3.7.3.2.6(e) and (f) are full-range stress-strain curves at room temperature for extrusion.

3.7.3.3 *T76, T7651, T76510, T76511 Tempers.*

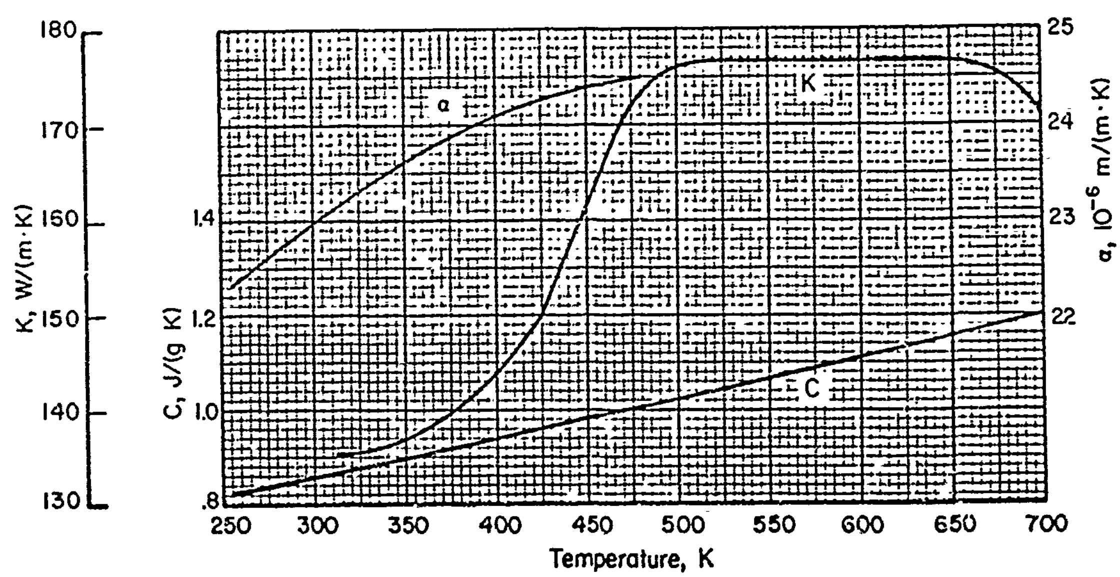


FIGURE 3.7.3.0. Effect of temperature on the physical properties of 7075 aluminum alloy.

TABLE 3.7.3.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 7075 ALUMINUM ALLOY (SHEET)

SPECIFICATION	QQ-A-250/12						
FORM	SHEET						
TEMPER	T6 AND T62[a]						
THICKNESS, MM	0.20-0.29	0.30-1.00		1.01-3.18		3.19-6.33	
BASIS	S	A	B	A	B	A	B
MECHANICAL PROPERTIES:							
FTU, MPA:							
L	...	524	538	538	552	538	552
LT	510	524	538	538	552	538	552
ST	...	...	...	...	...	...	...
FTY, MPA:							
L	...	476	496	483	496	490	503
LT	434	462	483	469	483	476	490
ST	...	...	...	...	...	...	...
FCY, MPA:							
L	...	469	490	476	490	483	496
LT	...	490	510	496	510	503	517
ST	...	...	...	...	...	...	...
FSU, MPA	...	317	324	324	331	324	331
FBRU[b], MPA:							
(E/D=1.5)	...	814	834	834	855	834	855
(E/D=2.0)	...	1050	1080	1080	1100	1080	1100
FBRY[b], MPA:							
(E/D=1.5)	...	689	724	703	724	710	731
(E/D=2.0)	...	807	841	821	841	834	855
EL, PERCENT:							
L	...	7	...	8	...	8	...
LT	5	7	...	8	...	8	...
ST	...	...	...	...	...	...	...
E, GPA	71.0						
EC, GPA	72.4						
G, GPA	26.9						
MU	0.33						
PHYSICAL PROPERTIES:							
OMEGA, MG/M3	2.80						
C, J/(G*K)	0.96 (AT 373 K)						
K, W/(M*K)	132 (AT 298 K)						
ALPHA, 10-6 M/(M*K)	23.2 (293-373 K)						

[a] THE ALLOWABLES SHOWN FOR THESE TEMPERS ARE BASED ON AND HAVE BEEN DETERMINED FROM THE RESULTS OBTAINED ON TESTING OF T6 AND T651 TEMPER MATERIAL ON THE TESTING OF T62 TEMPER SAMPLES FOR SPECIFICATION CONFORMANCE.; THESE ALLOWABLES ALSO 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.

[b] SEE TABLE 3.1.2.1.1. BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

TABLE 3.7.3.0(C). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 7075 ALUMINUM ALLOY (PLATE)

SPECIFICATION	QQ-A-250/12													
FORM	PLATE													
TEMPER	T651 AND T62[a]													
THICKNESS, MM	6.34-12.68		12.69-25.41		25.42-50.81		50.82-63.51		63.52-76.21		76.22-88.91		88.92-101.60	
BASIS	A	B	A	B	A	B	A	B	A	B	A	B	A	B
MECHANICAL PROPERTIES:														
FTU, MPA:														
L	531	545	531	545	524	538	517	531	490	503	483	496	455	469
LT	538	552	538	552	531	545	524	538	496	510	490	503	462	476
ST	...	...	...	...	...	...	469	483	448	462	441	455	414	427
FTY, MPA:														
L	476	490	483	496	476	490	455	469	434	448	414	427	386	400
LT	462	476	469	483	462	476	441	455	421	434	400	414	372	386
ST	...	...	...	...	...	...	393	407	372	386	359	372	331	345
FCY, MPA:														
L	469	483	469	483	455	469	427	441	407	421	386	393	352	365
LT	490	503	496	510	490	503	469	483	448	462	421	441	393	407
FSU, MPA	303	310	303	310	310	317	310	317	296	303	296	303	283	290
FBRU[b], MPA:														
(E/D=1.5)	814	834	814	834	807	827	793	814	752	772	745	765	703	724
(E/D=2.0)	1010	1030	1010	1030	993	1020	979	1010	931	952	917	938	862	889
FBRY[b], MPA:														
(E/D=1.5)	576	696	696	717	703	724	683	703	662	683	634	662	600	621
(E/D=2.0)	793	821	814	841	821	841	800	821	772	793	738	765	696	724
EL, PERCENT:														
L	9	...	7	...	6	...	5	...	5	...	5	...	...	...
LT	9	...	7	...	6	...	5	...	5	...	5	...	3	...
ST	...	...	...	...	...	...	...	...	...	...	...	...	...	...
E, GPA	71.0													
EC, GPA	73.1													
G, GPA	26.9													
MU	0.33													
PHYSICAL PROPERTIES:														
OMEGA, MG/M3	2.80													
C, J/(G*K)	0.96 (AT 373 K)													
K, W/(M*K)	132 (AT 298 K)													
ALPHA, 10-6 M/(M*K)	23.2 (293-373 K)													

[a] THE ALLOWABLES SHOWN FOR THESE TEMPERS ARE BASED ON AND HAVE BEEN DETERMINED FROM THE RESULTS OBTAINED ON TESTING OF T6 AND T651 TEMPER MATERIAL ON THE TESTING OF T62 TEMPER SAMPLES FOR SPECIFICATION CONFORMANCE; THESE ALLOWABLES ALSO 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.

[b] SEE TABLE 3.1.2.1.1. BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

TABLE 3.7.3.0(D). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 7075 ALUMINUM ALLOY (SHEET AND PLATE)

SPECIFICATION	QQ-A-250/12												QQ-A-250/24			
FORM	SHEET	PLATE											SHEET	PLATE		
TEMPER	T73	T7351											T76	T7651		
THICKNESS, MM	1.02-6.33	6.34-12.68	12.69-25.41		25.42-38.11		38.12-50.81		50.82-63.51		63.52-76.20		3.17-6.33	6.34-12.68	12.69-25.41	25.42-50.80
BASIS	S	S	A	B	A	B	A	B	A	B	A	B	S	S	S	S
MECHANICAL PROPERTIES:																
FTU, MPA:																
L	462	469	469	483	462	475	455	469	448	462	434	448	496	493	490	490
LT	462	476	476	490	469	483	462	476	455	469	441[c]	455	503	496	490	490
ST	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
FTY, MPA:																
L	386	393	393	407	393	407	379	393	359[b]	379	338[c]	365	427	421	414	414
LT	386	393	393	407	393	407	379	393	359[b]	379	338[c]	365	427	421	414	414
ST	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
FCY, MPA:																
L	379	386	386	400	386	400	372	386	352	372	324	352	421	414	407	437
LT	400	407	407	421	407	421	393	407	372	393	352	379	448	434	427	427
ST	...	...	...	...	...	...	...	...	...	...	...		...	...	...	...
FSU, MPA	262	276	269	276	262	269	276	283	276	283	262	269	303	283	283	293
FBRU[a], MPA:																
(E/D=1.5)	724	738	738	758	703	724	717	738	703	724	683	703	779	758	745	745
(E/D=2.0)	924	952	931	952	917	938	924	952	910	938	883	910	986	958	945	945
FBRY[a], MPA:																
(E/D=1.5)	579	586	572	593	572	593	586	607	552	586	524	565	614	634	627	627
(E/D=2.0)	703	689	669	689	669	689	683	710	641	683	607	655	724	752	745	745
EL, PERCENT:																
L	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
LT	8	7	7	...	6	...	6	...	6	...	6		8	8	6	5
ST	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
E, GPA	71.0	71.6											71.8	71.8		
EC, GPA	72.4	73.1											72.4	73.1		
G, GPA	26.9	26.9											26.9	26.9		
MU	0.33	0.33											0.33	0.33		
PHYSICAL PROPERTIES:																
OMEGA, MG/M3	2.80												2.80			
C, J/(G*K)	0.96 (AT 373 K)												0.96 (AT 373 K)			
K, W/(M*K)	156 (AT 298 K)												151 (AT 298 K)			
ALPHA, 10-6 M/(M*K)	23.2 (293-373 K)												23.2 (293-373 K)			

[a] SEE TABLE 3.1.2.1.1. BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.
[b] THE A VALUE IS HIGHER THAN SPECIFICATION VALUE AS FOLLOWS FTY(LT)= 365 MPA.
[c] A VALUES ARE HIGHER THAN SPECIFICATION VALUES AS FOLLOWS: FTU(LT)=448 MPA AND FTY(LT)=359 MPA.

TABLE 3.7.3.0(E). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF CLAD 7075 ALUMINUM ALLOY (SHEET)

SPECIFICATION	QQ-A-250/13								
FORM	SHEET								
TEMPER	T6 AND T62[a]								
THICKNESS, MM	0.20-0.29	0.30-1.00		1.01-1.58		1.59-4.76		4.77-6.33	
BASIS	S	A	B	A	B	A	B	A	B
MECHANICAL PROPERTIES:									
FTU, MPA:									
L	...	483	503	496	510	503	517	517	531
LT	469	483	503	496	510	503	517	517	531
ST	...	...	...	...	...	...	...	...	...
FTY, MPA:									
L	...	427	448	441	455	448	462	455	469
LT	400	414	434	427	441	434	448	441	455
ST	...	...	...	...	...	...	...	...	...
FCY, MPA:									
L	...	421	441	434	448	441	455	448	462
LT	...	441	462	455	469	462	476	469	483
FSU, MPA	...	290	303	296	303	303	310	310	317
FBRU, MPA:									
(E/D=1.5)	...	745	779	772	793	779	800	800	821
(E/D=2.0)	965	1010	993	1020	1010	1030	1030	1060	
FBRY, MPA:									
(E/D=1.5)	...	621	648	641	662	648	669	662	683
(E/D=2.0)	...	724	758	745	772	758	786	772	793
EL, PERCENT:									
L	...	7	...	8	...	8	...	8	...
LT	5	7	...	8	...	8	...	8	...
ST	...	...	...	...	...	...	...	...	...
E, GPA:									
PRIMARY			71.0			71.0		71.0	
SECONDARY			65.5			67.6		68.9	
EC, GPA:									
PRIMARY			72.4			72.4		72.4	
SECONDARY			66.9			68.9		70.3	
G, GPA			...			...		...	
MU			0.33			0.33		0.33	
PHYSICAL PROPERTIES:									
OMEGA, MG/M3	2.80								
C, J/(G*K)	...								
K, W/(M*K)	...								
ALPHA, 10-6 M/(M*K)	...								

[a] THE ALLOWABLES SHOWN FOR THESE TEMPERS ARE BASED ON AND HAVE BEEN DETERMINED FROM THE RESULTS OBTAINED ON TESTING OF T6 AND T651 TEMPER MATERIAL AND ON THE TESTING OF T62 TEMPER SAMPLES FOR SPECIFICATION CONFORMANCE. THESE ALLOWABLES ALSO 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.

[b] SEE TABLE 3.1.2.1.1. BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

TABLE 3.7.3.0(F). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF CLAD 7075 ALUMINUM ALLOY (PLATE)

SPECIFICATION	QQ-A-250/13													
FORM	PLATE													
TEMPER	T651 AND T62[a]													
THICKNESS, MM	6.34-12.68		12.69-25.41[b]		25.42-50.81[b]		50.82-63.51[b]		63.52-76.21[b]		76.22-88.91[b]		88.92-101.60[b]	
BASIS	A	B	A	B	A	B	A	B	A	B	A	B	A	B
MECHANICAL PROPERTIES:														
FTU, MPA:														
L	510	524	517	531	510	524	503	517	476	490	469	483	441	455
LT	517	531	524	538	517	531	510	524	483	496	476	490	448	462
ST	...	...	...	...	...	...	469	483	448	462	441	455	414	427
FTY, MPA:														
L	462	476	469	483	462	476	441	455	421	434	400	414	372	386
LT	448	462	455	469	448	462	427	441	407	421	386	400	359	372
ST	...	...	...	...	...	...	393	407	372	386	359	372	331	345
FCY, MPA:														
L	455	469	455	469	441	455	414	427	393	407	372	385	338	352
LT	476	490	483	496	476	490	455	469	434	448	407	421	379	393
ST	...	...	...	...	...	...	448	462	427	441	407	421	379	393
FSU, MPA	290	295	296	303	296	310	303	310	290	296	290	296	276	283
FBRU, MPA:														
(E/D=1.5)	785	807	793	814	786	807	772	793	731	752	724	745	683	703
(E/D=2.0)	965	993	979	1010	965	993	952	979	903	931	889	917	834	862
FBRY, MPA:														
(E/D=1.5)	655	676	676	696	683	703	662	683	641	662	614	634	579	600
(E/D=2.0)	772	793	793	814	793	821	772	800	745	772	717	738	669	696
EL, PERCENT:														
L	9	...	7	...	6	...	5	...	5	...	5	...	...	...
LT	9	...	7	...	6	...	5	...	5	...	5	...	3	...
ST	...	...	...	...	...	...	...	...	...	...	...	...	...	...
E, GPA:														
PRIMARY	71.0													
SECONDARY	68.9													
EC, GPA:														
PRIMARY	73.1													
SECONDARY	71.0													
G, GPA	...													
MU	0.33													
PHYSICAL PROPERTIES:														
OMEGA, MG/M3	2.80													
C, J/(G*K)	...													
K, W/(M*K)	...													
ALPHA, 10-6 M/(M*K)	...													

[a] THE ALLOWABLES SHOWN FOR THESE TEMPERS ARE BASED ON AND HAVE BEEN DETERMINED FROM THE RESULTS OBTAINED ON TESTING OF T6 AND T651 TEMPER MATERIAL AND ON THE TESTING OF T62 TEMPER SAMPLES FOR SPECIFICATION CONFORMANCE. THESE ALLOWABLES ALSO 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.

[b] 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.

[c] SEE TABLE 3.1.2.1.1. BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

TABLE 3.7.3.0(G). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF CLAD 7075 ALUMINUM ALLOY (SHEET AND PLATE)

SPECIFICATION	QQ-A-250/25			
FORM	SHEET		PLATE	
TEMPER	T76		T7651	
THICKNESS, MM	3.17-4.76	4.77-6.33	6.34-12.68	12.69-25.40[a]
BASIS	S	S	S	S
MECHANICAL PROPERTIES:				
FTU, MPA:				
L	462	476	469	469
LT	469	483	476	469
ST	...	...	...	...
FTY, MPA:				
L	393	407	400	393
LT	393	407	400	393
ST	...	...	...	...
FCY, MPA:				
L	345	400	393	386
LT	414	421	414	...
ST	...	...	...	...
FSU, MPA	283	283	276	276
FBRU[b], MPA:				
(E/D=1.5)	724	745	724	710
(E/D=2.0)	917	945	917	903
FBRY[b], MPA:				
(E/D=1.5)	565	579	600	600
(E/D=2.0)	669	689	717	710
EL, PERCENT:				
L	...	...	...	...
LT	8	8	8	6
ST	...	...	...	...
E, GPA:				
PRIMARY	71.0	71.0	71.0	
SECONDARY	67.6	68.9	68.9	
EC, GPA:				
PRIMARY	72.4	72.4	73.1	
SECONDARY	68.9	70.3	71.0	
G, GPA	...	...	...	
MU	0.33	0.33	0.33	
PHYSICAL PROPERTIES:				
OMEGA, MG/M3	2.80			
C, J/(G*K)	0.96 (AT 373 K)			
K, W/(M*K)	151 (AT 298 K)			
ALPHA, 10-6 M/(M*K)	23.2 (293-373 K)			

[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]SEE TABLE 3.1.2.1. BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

TABLE 3.7.3.0(H). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 7011 CLAD 7075 ALUMINUM ALLOY (SHEET AND PLATE)

SPECIFICATION	QQ-A-00250/26														
FORM	SHEET			PLATE							SHEET			PLATE	
TEMPER	T6 AND T62[a]			T651 AND T62[a]							T76			T7651	
THICKNESS, MM	0.38-1.00	1.01-4.76	4.77-6.33	6.34-12.68	12.69-25.41[b]	25.42-50.81[b]	50.82-63.51[b]	63.52-76.21[b]	76.22-88.91[b]	88.92-101.60[b]	1.02-1.58	1.59-4.76	4.77-6.33	6.34-12.68	12.69-25.40[b]
BASIS	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
MECHANICAL PROPERTIES:															
FTU, MPA:															
L	503	517	524	517	524	517	510	483	476	448	476	483	490	483	476
LT	503	517	524	524	531	524	517	490	483	455	483	490	496	490	483
ST	...	...	...	...	...	...	448	434	434	414	...	...	...	...	...
FTY, MPA:															
L	441	455	462	469	469	462	441	427	407	379	407	414	421	414	407
LT	434	448	455	455	462	455	434	414	393	365	407	414	421	414	407
ST	...	...	...	...	...	...	379	365	352	324	...	...	...	...	...
FCY, MPA:															
L	448	462	469	462	455	441	414	400	379	345	400	407	414	407	400
LT	462	476	483	483	490	483	462	441	414	386	427	434	441	427	421
ST	...	...	...	...	...	...	434	421	400	372	...	...	...	...	...
FSU, MPA	296	303	310	296	310	303	303	290	290	283	290	296	296	290	276
FBRU[c], MPA:															
(E/D=1.5)	752	772	779	793	807	793	786	745	731	689	752	758	772	758	752
(E/D=2.0)	952	979	993	979	993	979	965	917	903	848	938	952	965	952	938
FBRY[c], MPA:															
(E/D=1.5)	607	627	634	669	683	683	676	648	627	593	593	600	607	621	607
(E/D=2.0)	596	717	731	786	807	807	786	758	731	689	600	683	696	703	689
EL, PERCENT:															
L	7	8	8	9	7	6	6	6	6	...	8	8	8	8	6
LT	7	8	8	9	7	6	5	5	5	3	8	8	8	8	6
ST	...	...	...	...	...	...	1	1	1	...	...	...	...	...	...
E, GPA	71.0			71.0							71.0			71.0	
EC, GPA	72.4			73.1							72.4			73.1	
G, GPA	26.9			26.9							26.9			26.9	
MU	0.33			0.33							0.33			0.33	
PHYSICAL PROPERTIES:															
OMEGA, MG/M3	2.80														
C, J/(G*K)	...														
K, W/(M*K)	...														
ALPHA, 10-6 M/(M*K)	...														

[a] THE ALLOWABLES SHOWN FOR THESE TEMPERS ARE BASED ON AND HAVE BEEN DETERMINED FROM THE RESULTS OBTAINED ON TESTING OF T6 AND T651 TEMPER MATERIAL AND ON THE TESTING OF T62 TEMPER SAMPLES FOR SPECIFICATION CONFORMANCE. THESE ALLOWABLES ALSO 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.

[b] 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.

[c] SEE TABLE 3.1.2.1.1. BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

TABLE 3.7.3.0(I). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 7075 ALUMINUM ALLOY (BAR, ROD, WIRE AND SHAPES)

SPECIFICATION	QQ-A-225/9										
FORM	BAR, ROD, WIRE AND SHAPES (ROLLED, DRAWN, OR COLD FINISHED)										
CONDITION	T6, T6518 AND T62[c]								T73 OR T7351[d]		
THICKNESS, MM	≤25.41[b]		25.42-50.81		50.82-76.21		76.22-101.60		9.52-25.41	25.42-50.81	50.82-76.20
BASIS	A	B	A	B	A	B	A	B	S	S	S
MECHANICAL PROPERTIES:											
FTU, MPA:											
L	531	545	531	545	531	545	531	545	469	469	469
LT	531	545	517	531	496	510	476	490	...	...	448
FTY, MPA:											
L	455	469	455	469	455	469	455	469	386	386	386
LT	455	469	455	469	434	448	414	427	...	...	359
FCY, MPA:											
L	441	455	441	455	441	455	441	455	359	365	379
LT	...	...	...	...	...	...	...	...	...	379	
FSU, MPA	317	324	317	324	317	324	317	324	290	283	283
FBRU, MPA:											
(E/D=1.5)	589	710	689	710	689	710	689	710	703	703	703
(E/D=2.0)	848	869	848	869	848	869	848	869	917	917	917
FBRY, MPA:											
(E/D=1.5)	593	607	593	607	593	607	593	607	565	565	565
(E/D=2.0)	634	655	634	655	634	655	634	655	696	696	696
EL, PERCENT:											
L	7[c]	...	7	...	7	...	7	...	10	10	10
LT	4	...	3	...	2	...	1	...	...	...	...
E, GPA	71.0								71.0		
EC, GPA	72.4								72.4		
G, GPA	26.9								26.9		
MU	0.33								0.33		
PHYSICAL PROPERTIES:											
OMEGA, MG/M3	2.80								2.80		
C, J/(G*K)	0.96 (AT 393 K)								0.96 (AT 393 K)		
K, W/(M*K)	132 (AT 298 K)								156 (AT 298 K)		
ALPHA, 10-6 M/(M*K)	23.2 (293-393 K)								23.2 (293-393 K)		

[a]BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

[b]FOR ROUNDS (ROD) MAXIMUM DIAMETER IS 101.6 MM.; FOR SQUARE BAR, MAXIMUM SIZE IS 88.9 MM.; FOR RECTANGULAR BAR, MAXIMUM THICKNESS IS 76.2 MM. WITH CORRESPONDING WIDTH OF 152.4 MM.; FOR RECTANGULAR BAR LESS THAN 76.2 MM. IN THICKNESS, MAXIMUM WIDTH IS 254.0.

[c]EXCEPT FOR WIRE LESS THAN 3.2 MM. IN DIAMETER.

[d]THE ALLOWABLES SHOWN FOR THESE TEMPERS ARE BASED ON AND HAVE BEEN DETERMINED FROM THE RESULTS OBTAINED ON TESTING OF T6 AND T651 TEMPER MATERIAL AND ON THE TESTING OF T62 TEMPER SAMPLES FOR SPECIFICATION CONFORMANCE. THESE ALLOWABLES ALSO 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.

TABLE 3.7.3.0(J1). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 7075 ALUMINUM ALLOY (DIE FORGING)

SPECIFICATION	MIL-A-22771													
FORM	DIE FORGING													
CONDITION	T6							T652						
THICKNESS, MM	≤ 25.41		25.42-50.81		50.82-76.21		76.22-101.60	≤ 25.41		25.42-50.81		50.82-76.21		76.22-101.60
BASIS	A	B	A	B	A	B	S	A	B	A	B	A	B	S
MECHANICAL PROPERTIES:														
FTU, MPA:														
L	517	538	510	531	510	524	503	517	538	510	531	510	524	503
T[a]	490	517	490	510	483	503	483	490	517	490	510	483	503	483
FTY, MPA:														
L	441	462	434	455	434	448	427	441	462	434	455	434	448	427
T	421	448	421	441	414	434	414	414	441	414	434	407	427	407
FCY, MPA:														
L	462	483	455	476	455	469	448	441	462	434	455	434	448	427
T	441	469	441	462	434	455	434	448	476	448	469	441	462	441
FSU, MPA	296	310	296	303	290	296	290	296	310	296	303	290	296	290
FBRU[c], MPA:														
(E/D=1.5)	724	752	717	745	717	731	703	724	752	717	745	717	731	703
(E/D=2.0)	931	965	917	952	917	938	903	931	965	917	952	917	938	903
FBRY[c], MPA:														
(E/D=1.5)	572	600	565	593	565	579	558	572	600	565	593	565	579	558
(E/D=2.0)	662	689	648	683	648	669	641	662	689	648	683	648	669	641
EL, PERCENT:														
L	7	...	7	...	7	...	7	7	...	7	...	7	...	7
T	3	...	3	...	3	...	2	2	...	2	...	2	...	1
E, GPA	68.9													
EC, GPA	71.7													
G, GPA	26.2													
MU	0.33													
PHYSICAL PROPERTIES:														
OMEGA, MG/M3	2.80													
C, J/(G*K)	0.96 (AT 393 K)													
K, W/(M*K)	132 (AT 298 K)													
ALPHA, 10-6 M/(M*K)	23.2 (293-393 K)													

[a]FOR DIE FORGINGS, T INDICATES ANY GRAIN DIRECTION NOT WITHIN ± 15 DEGREES OF BEING PARALLEL TO THE FORGING FLOW LINES. SPECIMENS TO TEST TRANSVERSE PROPERTIES SHOULD BE LOCATED AS CLOSE TO THE SHORT TRANSVERSE DIRECTION AS POSSIBLE.

[b]THE THICKNESS COLUMNS ARE FOR THE AS-HEAT-TREATED THICKNESS. TO ENTER THE TABLE USE THE HIGHER OF THE HEAT-TREAT THICKNESS OR ONE-HALF OF THE AS-FORGED THICKNESS.

[c]BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

TABLE 3.7.3.0(J2). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 7075 ALUMINUM ALLOY (DIE FORGING)

SPECIFICATION	MIL-A-22771										
FORM	DIE FORGING										
CONDITION	T73								T7352		
THICKNESS,[b] MM	≤ 25.41		25.42-50.81		50.82-76.21		76.22-101.60		≤ 76.21		76.22-101.60
BASIS	A	B	A	B	A	B	A	B	A	B	S
MECHANICAL PROPERTIES:[c]											
FTU, MPA:											
L	455	490	455	490	455	476	441	476	455	476	441
T[a]	427	476	427	462	427	455	421	455	427	462	421
FTY, MPA:											
L	386	421	386	407	386	407	379	407	386	407	365
T	365	400	365	393	365	393	359	386	352	386	338
FCY, MPA:											
L	400	434	400	421	400	421	393	421	386	407	365
T	379	414	379	407	379	407	372	400	379	414	365
FSU, MPA	269	290	269	290	269	283	262	283	269	283	262
FBRU,[d] MPA:											
(E/D=1.5)	662	710	662	710	662	689	641	689	662	689	641
(E/D=2.0)	862	931	862	931	862	903	841	903	862	903	841
FBRY,[d] MPA:											
(E/D=1.5)	538	586	538	572	538	572	531	572	538	572	510
(E/D=2.0)	621	676	621	648	621	648	607	648	621	648	586
EL, PERCENT:											
L	7	...	7	...	7	...	7	...	7	...	7
T	3	...	3	...	3	...	2	...	3	...	2
E, GPA	68.9										
EC, GPA	71.7										
G, GPA	26.2										
MU	0.33										
PHYSICAL PROPERTIES:											
OMEGA, MG/M3	2.80										
C, J/(G*K)	0.96 (AT 393 K)										
K, W/(M*K)	156 (AT 298 K)										
ALPHA, 10-6 M/(M*K)	23.2 (293-393 K)										

[a] FOR DIE FORGINGS, T INDICATES ANY GRAIN DIRECTION NOT WITHIN ± 15 DEGREE OF BEING PARALLEL TO THE FORGING FLOW LINES. SPECIMENS TO TEST TRANSVERSE PROPERTIES SHOULD BE LOCATED AS CLOSE TO THE SHORT TRANSVERSE DIRECTION AS POSSIBLE.

[b] THE THICKNESS COLUMNS ARE FOR THE AS-HEAT-TREATED THICKNESS. TO ENTER THE TABLE USE THE HIGHER OF THE HEAT-TREAT THICKNESS OR ONE-HALF OF THE AS-FORGED THICKNESS.

[c] MOST OF THE ACTUAL A TENSILE VALUES ARE HIGHER THAN SPECIFICATION VALUES. CONSEQUENTLY, THE A VALUES SHOWN ARE SPECIFICATION VALUES PER THE GUIDELINES.

[d] BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

SPECIFICATION	MIL-A-22771									
FORM	HAND FORGING[a]									
TEMPER	T6					T652				
THICKNESS,[b] MM	≤50.81	50.82-76.21	76.22-101.61	101.62-127.01	127.02-152.40	≤50.81	50.82-76.21	76.22-101.61	101.62-127.01	127.02-152.40
BASIS	S	S	S	S	S	S	S	S	S	S
MECHANICAL PROPERTIES:										
FTU, MPA:										
L	510	503	490	476	469	510	503	490	476	469
LT	503	490	483	469	455	503	490	483	469	455
ST	...	476	469	455	448	...	476	469	455	448
FTY, MPA:										
L	434	421	414	400	386	434	421	414	400	386
LT	421	407	400	386	379	421	407	400	386	379
ST	...	400	393	386	379	...	393	386	379	372
FCY, MPA:										
L	434	421	...	...	...	434	421	...	...	...
LT	421	407	...	...	...	421	407	...	...	...
ST	...	...	...	...	...	...	...	...	...	...
FSU, MPA	303	303	296	283	283	303	303	296	283	283
FBRU,[c] MPA:										
(E/D=1.5)	...	...	...	...	...	...	...	...	...	...
(E/D=2.0)	...	...	...	...	...	...	...	...	...	...
FBRY,[c] MPA:										
(E/D=1.5)	...	...	...	...	...	...	...	...	...	...
(E/D=2.0)	...	...	...	...	...	...	...	...	...	...
EL, 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, GPA	68.9									
EC, GPA	71.7									
G, GPA	26.2									
MU	0.33									
PHYSICAL PROPERTIES:										
OMEGA, MG/M3	2.80									
C, J/(G*K)	0.96 (AT 393 K)									
K, W/(M*K)	132 (AT 298 K)									
ALPHA, 10-6 M/(M*K)	23.2 (293-393 K)									

[a] WHEN HAND FORGINGS ARE MACHINED BEFORE HEAT TREATMENT, THE SECTION THICKNESS AT TIME OF HEAT TREATMENT SHALL 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 16,516 SQ. CM.

[b] THE THICKNESS COLUMNS ARE FOR THE AS-HEAT-TREATED THICKNESS. TO ENTER THE TABLE USE THE HIGHER OF THE HEAT-TREAT THICKNESS OR ONE-HALF OF THE AS-FORGED THICKNESS.

[c] BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

TABLE 3.7.3.0(K2). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 7075 ALUMINUM ALLOY (HAND FORGING)

SPECIFICATION	MIL-A-22771									
FORM	HAND FORGING[a]									
TEMPER	T73				T7352					
THICKNESS,[b] MM	≤76.21	76.22-101.61	101.62-127.01	127.02-152.40	≤50.81	50.82-76.21	76.22-101.61		101.62-127.01	127.02-152.40
BASIS	S	S	S	S	S	S	A	B	S	S
MECHANICAL PROPERTIES:										
FTU, MPA:										
L	455	441	427	421	455	455	441	462	427	421
LT	441	434	421	407	441	441	434	455	421	407
ST	421	414	400	393	...	421	414	434	400	393
FTY, MPA:										
L	386	379	365	352	372	372	365	379	352	338
LT	372	365	352	345	359	359	345	365	331	317
ST	359	352	345	338	...	345	331	352	317	303
FCY, MPA:										
L	386	...	...	...	365	365	359	372	345	331
LT	359	...	...	...	372	372	359	379	345	331
ST	...	...	...	...	...	379	365	386	352	338
FSU, MPA	269	...	...	...	262	262	255	269	248	241
FBRU,[c] MPA:										
(E/D=1.5)	...	...	...	...	641	641	634	662	614	593
(E/D=2.0)	...	...	...	...	834	834	821	862	800	772
FBRY,[c] MPA:										
(E/D=1.5)	...	...	...	...	538	538	517	545	496	476
(E/D=2.0)	...	...	...	...	607	607	579	621	558	538
EL, PERCENT:										
L	7	7	7	6	7	7	7	...	7	6
LT	4	3	3	3	4	4	3	...	3	3
ST	3	2	2	2	...	3	2	...	2	2
E, GPA	68.9									
EC, GPA	71.7									
G, GPA	26.2									
MU	0.33									
PHYSICAL PROPERTIES:										
OMEGA, MG/M3	2.80									
C, J/(G*K)	0.96 (AT 393 K)									
K, W/(M*K)	156 (AT 298 K)									
ALPHA, 10-6 M/(M*K)	23.2 (293-393 K)									

[a]WHEN HAND FORGINGS ARE MACHINED BEFORE HEAT TREATMENT, THE SECTION THICKNESS AT TIME OF HEAT TREATMENT SHALL 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 16,516 SQ. CM.

[b]THE THICKNESS COLUMNS ARE FOR THE AS-HEAT-TREATED THICKNESS. TO ENTER THE TABLE USE THE HIGHER OF THE HEAT-TREAT THICKNESS OR ONE-HALF OF THE AS-FORGED THICKNESS.

[c][illegible] VALUES SEE SECTION 1.4.7.1.

TABLE 3.7.3.0(L1). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 7075 ALUMINUM ALLOY (EXTRUSION)

SPECIFICATION	QQ-A-200/11														
FORM	EXTRUSION (ROD, BARS, AND SHAPES)														
TEMPER	T6, T6510, T6511, AND T62[c]														
CROSS-SECTIONAL AREA, MM2	<12900												>12900 <20650	<20650	
THICKNESS[a] MM	≤ 6.33		6.34-12.68		12.69-19.03		19.04-38.08		38.09-76.18		76.19-114.28			114.29-127.00	
BASIS	A	B	A	B	A	B	A	B	A	B	A	B	S	A	B
MECHANICAL PROPERTIES:															
FTU, MPA:															
L	538	565	558	586	558	586	558	585	558	586	559	579	538	538	558
LT	524	552	538	558	524	552	510	538	483	510	462	483	448	448	462
FTY, MPA:															
L	483	510	503	531	496	524	496	524	496	524	490	510	483	469	490
LT	455	483	469	496	455	483	448	469	421	448	386	400	379	345	365
FCY, MPA:															
L	483	510	503	531	496	524	496	524	495	524	490	510	483	469	490
LT	496	524	510	578	496	524	490	510	462	490	421	441	414	386	400
FSU, MPA	290	303	296	310	296	310	290	303	283	296	276	283	262	255	269
FBRU[b], MPA:															
(E/D=1.5)	772	814	807	841	807	841	800	841	793	827	752	779	724	689	717
(E/D=2.0)	972	1020	1010	1050	1010	1050	1000	1050	993	1040	979	1010	938	931	965
FBRY[b], MPA:															
(E/D=1.5)	648	683	669	710	662	696	655	689	641	676	614	634	600	572	600
(E/D=2.0)	758	807	793	834	779	821	772	814	758	800	724	758	717	683	710
EL, PERCENT:															
L	7	8	7	8	7	8	7	8	7	8	7	8	6	6	...
LT	5	...	5	...	4	...	3	...	1	...	1	...	1	1	...
E, GPA	71.7														
EC, GPA	73.8														
G, GPA	27.6														
MU	0.33														
PHYSICAL PROPERTIES:															
OMEGA, MG/M3	2.80														
C, J/(G*K)	0.96 (AT 393 K)														
K, W/(M*K)	132 (AT 298 K)														
ALPHA, 10-6 M/(M*K)	23.2 (293-393 K)														

[a] FOR EXTRUSIONS WITH OUTSTANDING LEGS, THE LOAD-CARRYING ABILITY OF SUCH LEGS SHALL BE DETERMINED ON THE BASIS OF THE PROPERTIES IN THE APPROPRIATE COLUMN CORRESPONDING TO THE LEG THICKNESS.

[b] BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

[c] THE ALLOWABLES SHOWN FOR THESE TEMPERS ARE BASED ON AND HAVE BEEN DETERMINED FROM THE RESULTS OBTAINED ON TESTING OF T6, T6510, AND T6511 TEMPER MATERIAL AND ON THE TESTING OF T62 TEMPER SAMPLES FOR SPECIFICATION CONFORMANCE. THESE ALLOWABLES ALSO 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.

TABLE 3.7.3.0(L2). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 7075 ALUMINUM ALLOY (EXTRUSION)

SPECIFICATION	QQ-A-200/11													
FORM	EXTRUSION (ROD, BARS, AND SHAPES)													
TEMPER	T73, T73510, T73511													
CROSS-SECTIONAL AREA, MM2	≤12900		≤16130								≤12900		>12900 ≤20650	
THICKNESS,[a] MM	1.57-6.33		6.34-12.68		12.69-19.03		19.04-38.08		38.09-76.18		76.19-114.27		76.19-114.27	
BASIS	A	B	A	B	A	B	A	B	A	B	A	B	A	B
MECHANICAL PROPERTIES														
FTU, MPA:														
L	469[c]	496	483[c]	510	483[c]	503	483[c]	503	476[c]	510	469[c]	490	448[c]	483
LT	448	476	462	483	455	476	448	469	434	462	414	427	393	421
FTY, MPA:														
L	400	421	414	434	414	434	414	434	407[c]	448	393[c]	427	379[c]	414
LT	379	400	386	407	386	407	379	400	221	393	324	352	317	345
FCY, MPA:														
L	400	421	414	434	414	434	414	434	407	448	393	427	379	414
LT	407	427	414	434	414	434	407	427	386	421	352	379	338	372
FSU, MPA	248	262	255	276	255	269	255	269	255	276	248	262	241	255
FBRU,[b] MPA:														
(E/D=1.5)	696	738	710	752	710	738	703	738	689	738	662	696	634	683
(E/D=2.0)	896	952	924	972	917	958	917	958	896	958	869	910	834	896
FBRY,[b] MPA:														
(E/D=1.5)	558	586	572	607	572	600	565	593	545	600	510	552	490	538
(E/D=2.0)	669	703	689	724	683	717	676	710	648	717	607	655	586	634
EL, PERCENT:														
L	7	...	8	...	8	...	8	...	8	...	7	...	7	...
LT	...	...	...	...	...	...	...	...	...	...	...	...	...	...
E, GPA	71.7													
EC, GPA	73.8													
G, GPA	27.6													
MU	0.33													
PHYSICAL PROPERTIES:														
OMEGA, MG/M3	2.80													
C, J/(G*K)	0.96 (AT 393 K)													
K, W/(M*K)	156 (AT 298 K)													
ALPHA, 10-6 M/(M*K)	23.2 (293-393 K)													

[a] FOR EXTRUSIONS WITH OUTSTANDING LEGS, THE LOAD-CARRYING ABILITY OF SUCH LEGS SHALL BE DETERMINED ON THE BASIS OF THE PROPERTIES IN THE APPROPRIATE COLUMN CORRESPONDING TO THE LEG THICKNESS.

[b] BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

[c] THE A VALUES ARE HIGHER THAN S VALUES AS FOLLOWS:

CROSS-SECTIONAL AREA, MM2	≤ 12900	≤ 16130	≤ 16130	≤ 12900	> 12900
THICKNESS, MM	1.57-6.33	12.69-19.03	38.09-76.18	76.20-114.28	76.20-114.28
	FTU(L) = 476 MPA	FTU(L) = 490 MPA	FTU(L) = 496 MPA	FTU(L) = 476 MPA	FTU(L) = 469 MPA
			FTY(L) = 427 MPA	FTY(L) = 407 MPA	FTY(L) = 393 MPA

TABLE 3.7.3.0(L3). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 7075 ALUMINUM ALLOY (EXTRUSION)

SPECIFICATION..........	QQ-A-200/15						
FORM..................	EXTRUSION (ROD, BAR, AND SHAPES)						
TEMPER.................	T76, T76510, T76511						
CROSS-SECTIONAL AREA, MM2	≤ 12900						
THICKNESS,[a] MM...........	1.57-6.33		6.34-12.68	12.69-19.03		19.04-25.40	
BASIS..................	A	B	S	A	B	A	B
MECHANICAL PROPERTIES:							
FTU, MPA:							
L..................	490	510	517	517	524	517	524
LT.................	469	490	496	490	503	483	490
FTY, MPA:							
L..................	421	448	448	448	462	448	462
LT.................	393	214	421	414	427	407	421
FCY, MPA:							
L..................	421	448	448	448	462	462	
LT.................	427	455	455	448	462	441	455
FSU, MPA............	262	276	283	283	290	276	283
FBRU[b], MPA:							
(E/D=1.5).........	710	738	752	752	758	752	758
(E/D=2.0).........	903	945	958	958	972	958	972
FBRY[b], MPA:							
(E/D=1.5).........	565	607	607	607	621	607	621
(E/D=2.0).........	676	717	717	717	738	717	736
EL, PERCENT:							
L..................	7	...	7	7	...	7	...
LT.................	...	...	...	...	...	...	...
E, GPA...............	71.7						
EC, GPA..............	73.8						
G, GPA...............	27.6						
MU..................	0.33						
PHYSICAL PROPERTIES:							
OMEGA, MG/M3..........	2.80						
C, J/(G*K)...........	0.96 (AT 393 K)						
K, W/(M*K)...........	151 (AT 298 K)						
ALPHA, 10-6 M/(M*K)..	23.2 (293-393 K)						

[a] FOR EXTRUSIONS WITH OUTSTANDING LEGS, THE LOAD-CARRYING ABILITY OF SUCH LEGS SHALL BE DETERMINED ON THE BASIS OF THE PROPERTIES IN THE APPROPRIATE COLUMN CORRESPONDING TO THE LEG THICKNESS.

[b] BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

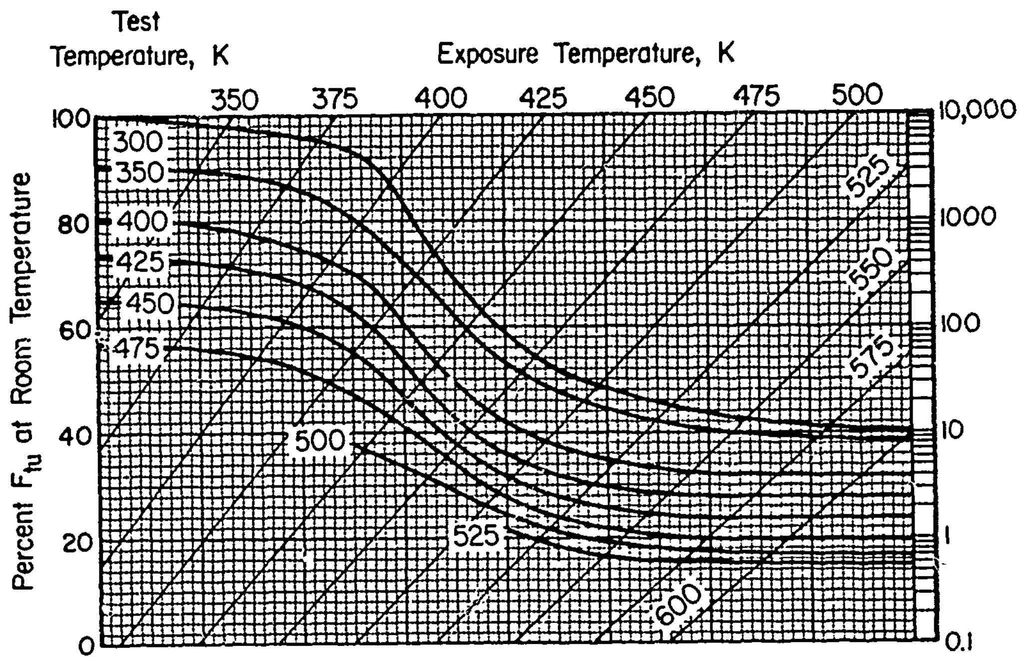


FIGURE 3.7.3.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of 7075-T6, T651, T6510, and T6511 aluminum alloy (all products).

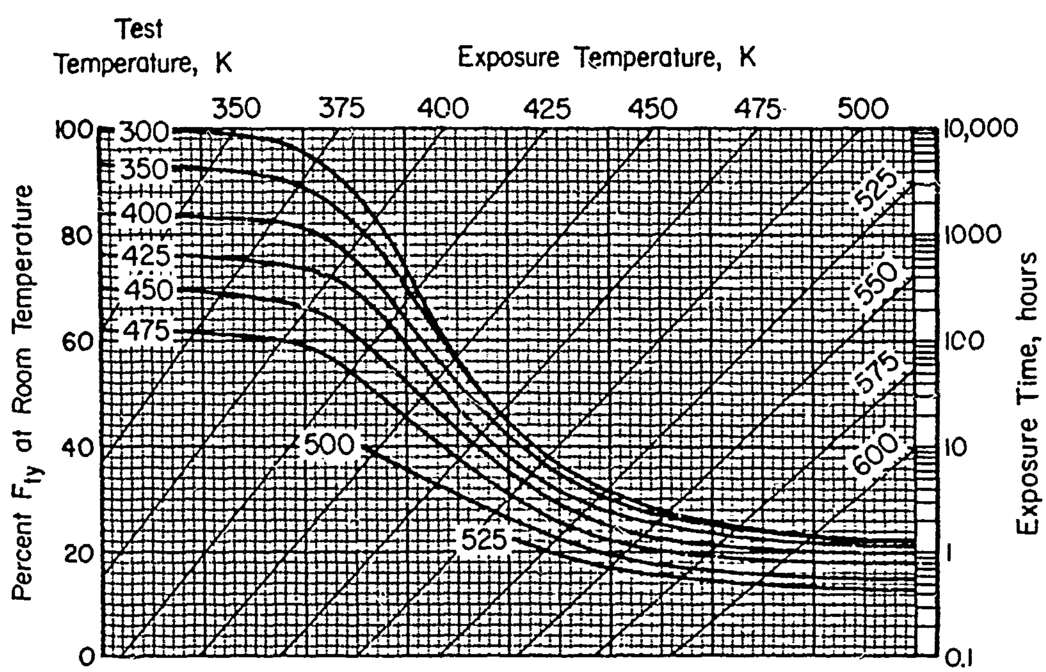


FIGURE 3.7.3.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of 7075-T6, T651, T6510, and T6511 aluminum alloy (all products).

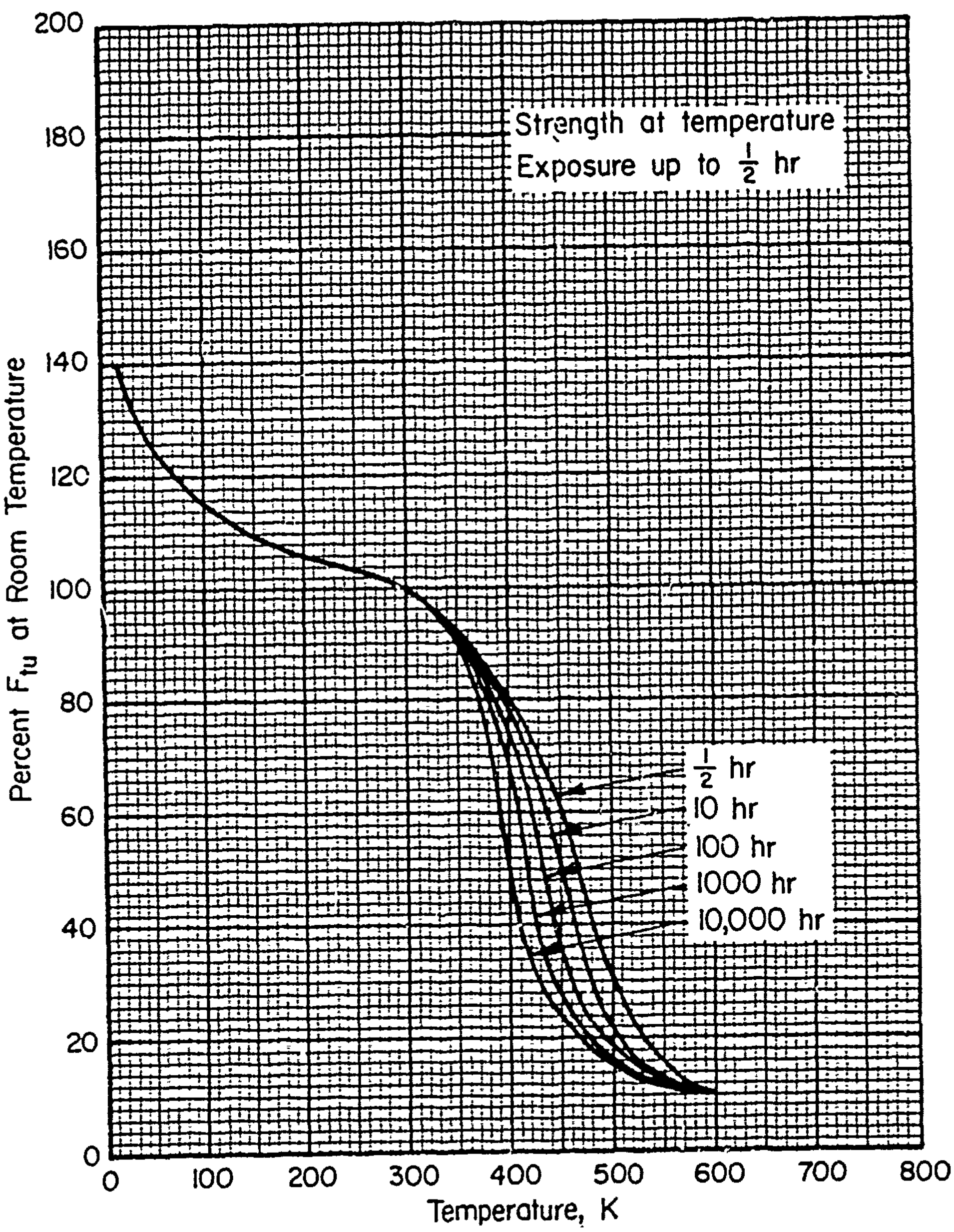


FIGURE 3.7.3.1.1(c). Effect of temperature on the ultimate tensile strength (F_{tu}) of 7075-T6, T651, T6510, and T6511 aluminum alloy (all products).

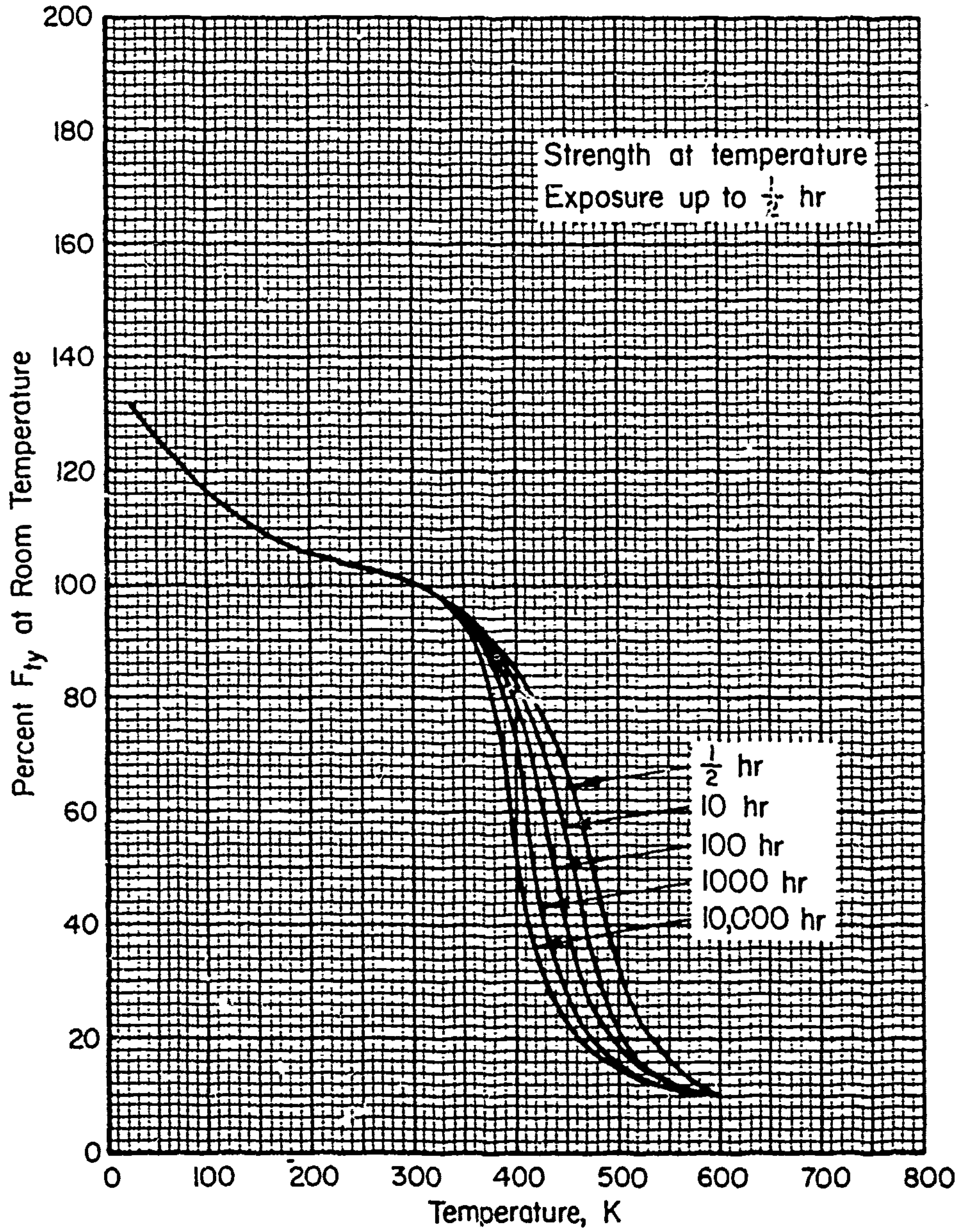


FIGURE 3.7.3.1.1(d). Effect of temperature on the tensile yield strength (F_{ty}) of 7075-T6, T651, T6510, and T6511 aluminum alloy (all products).

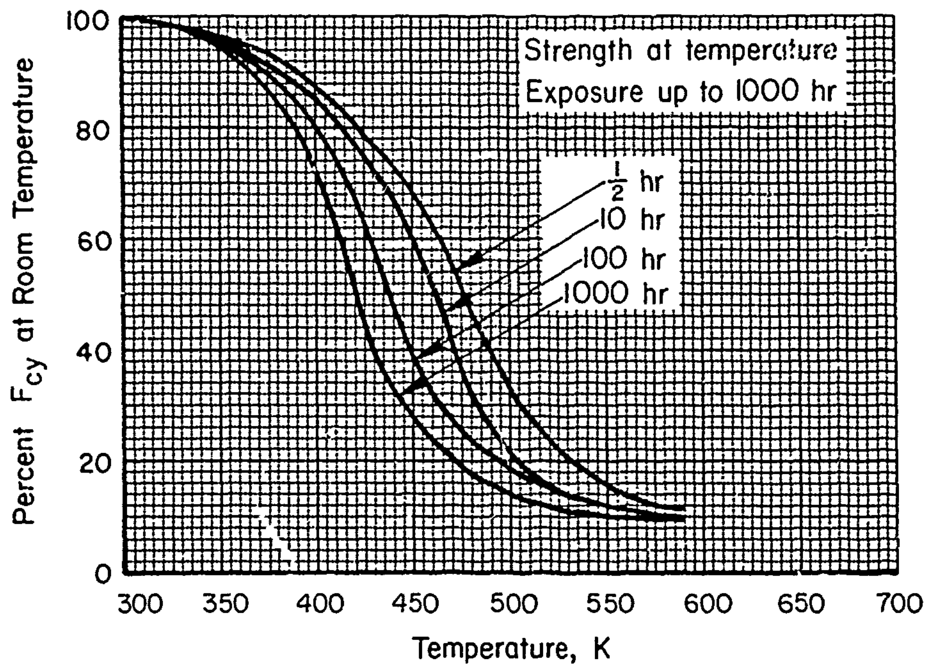


FIGURE 3.7.3.1.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of 7075-T6, T651, T6510, and T6511 aluminum alloy (all products).

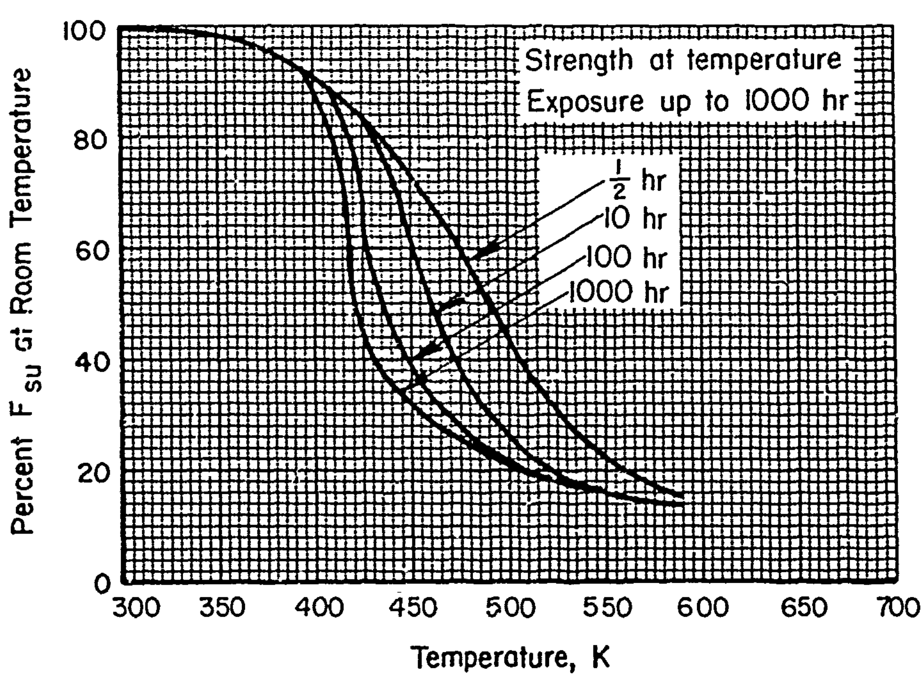


FIGURE 3.7.3.1.2(b). Effect of temperature on the ultimate shear strength (F_{su}) of 7075-T6, T651, T6510, and T6511 aluminum alloy (all products).

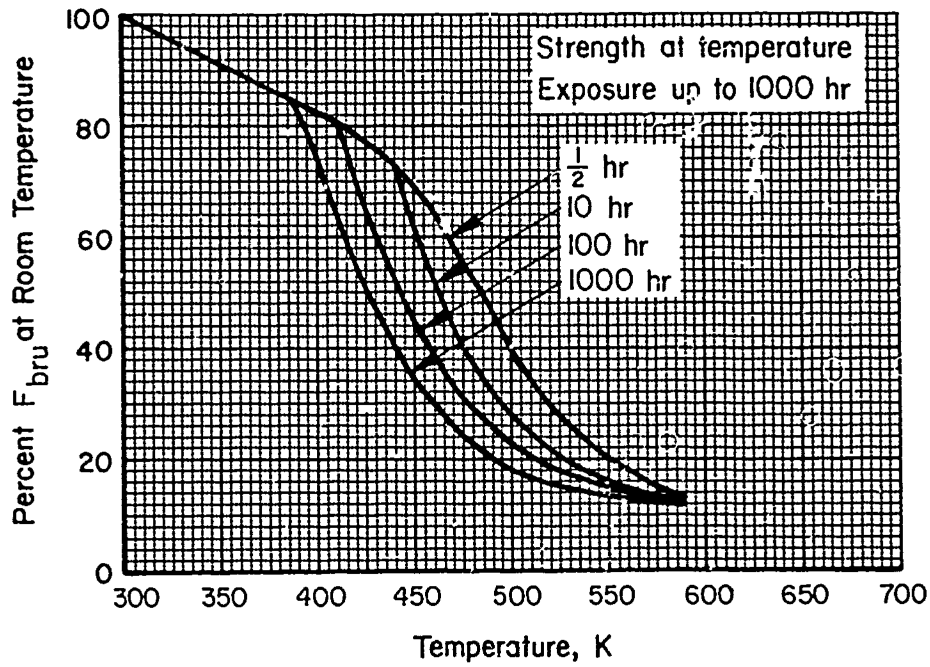


FIGURE 3.7.3.1.3(a). Effect of temperature on the ultimate bearing strength (F_{bru}) of 7075-T6, T651, T6510, and T6511 aluminum alloy (all products).

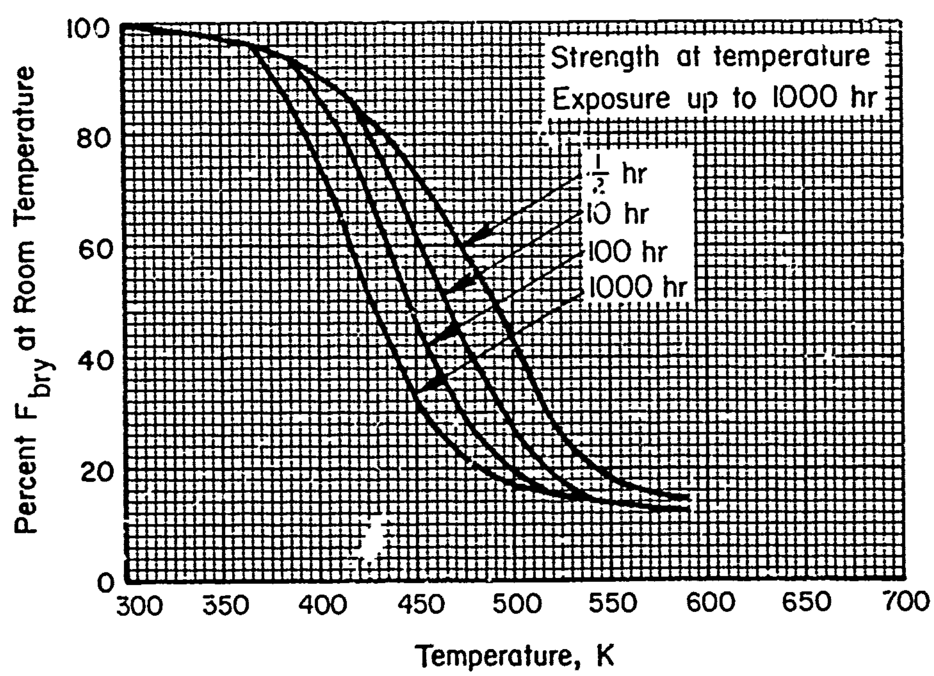


FIGURE 3.7.3.1.3(b). Effect of temperature on the bearing yield strength (F_{bry}) of 7075-T6, T651, T6510, and T6511 aluminum alloy (all products).

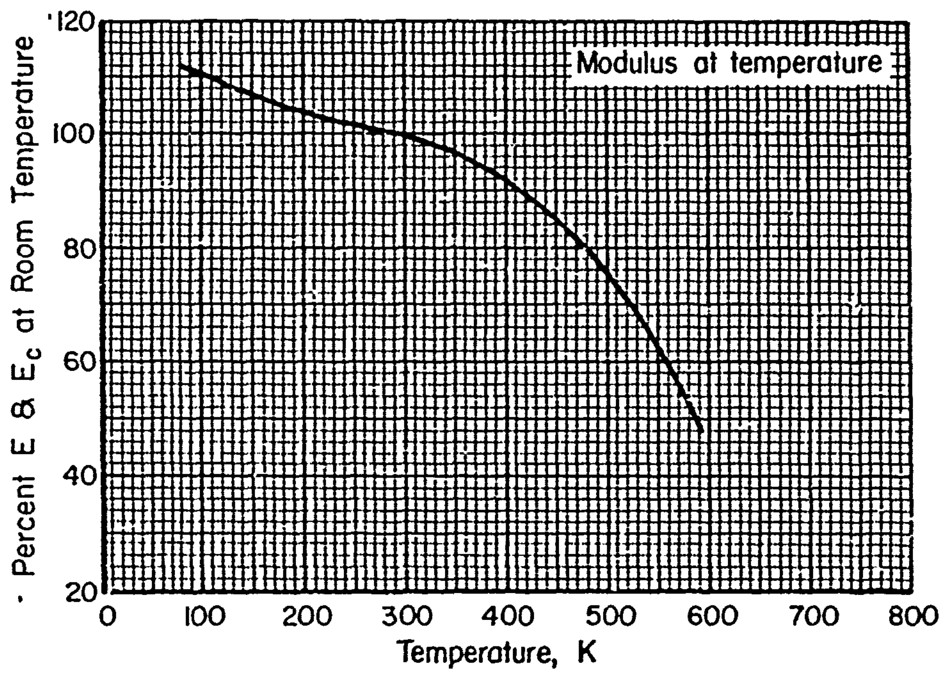


FIGURE 3.7.3.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of 7075 aluminum alloy.

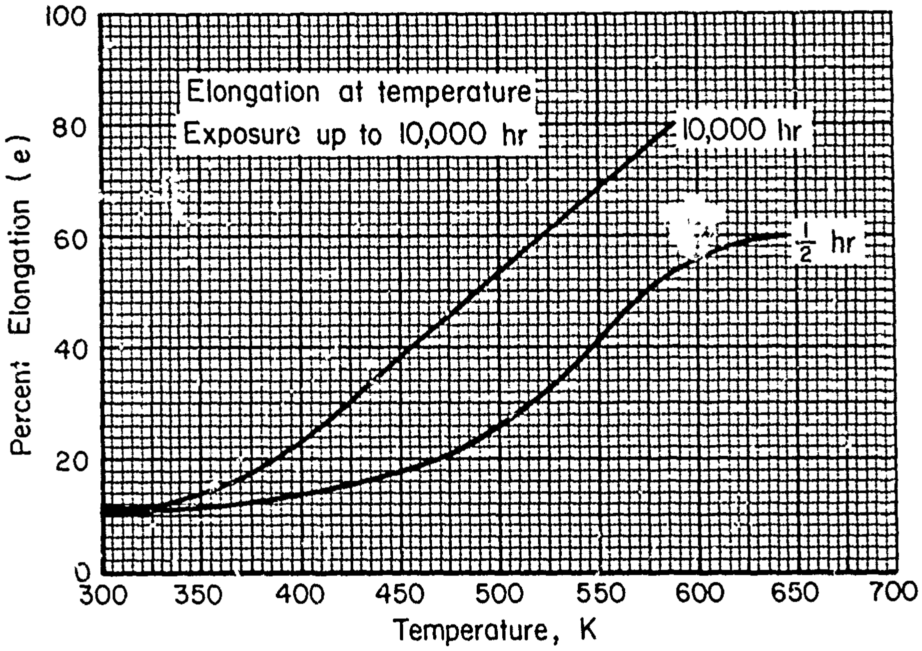


FIGURE 3.7.3.1.5(a). Effect of temperature on the elongation of 7075-T6, T651, T6510, and T6511 aluminum alloy (all products except thick extrusions).

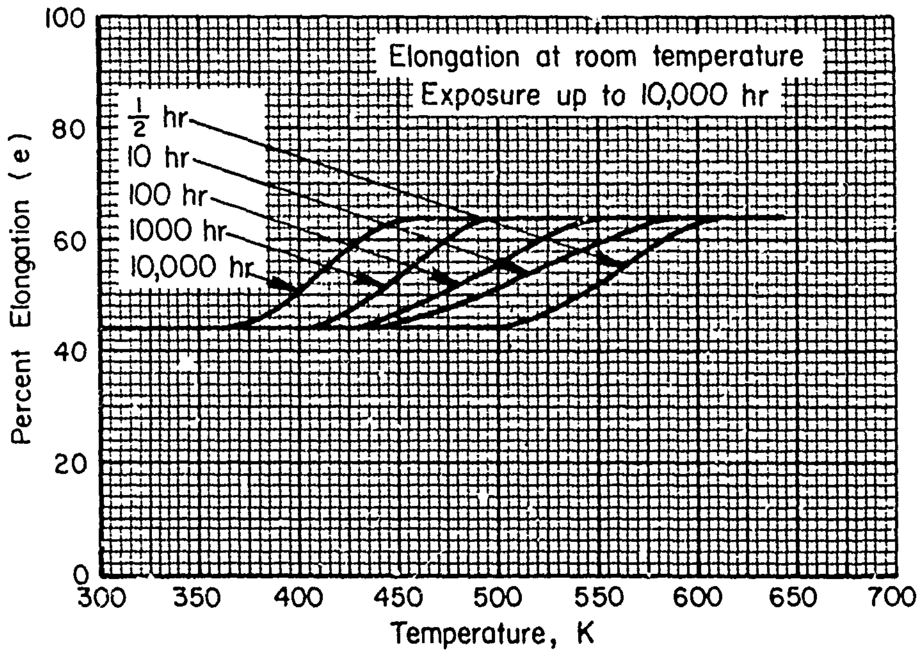


FIGURE 3.7.3.1.5(b). Effect of exposure at elevated temperatures on the elongation of 7075-T6, T651, T6510, and T6511 aluminum alloy (all products except thick extrusions).

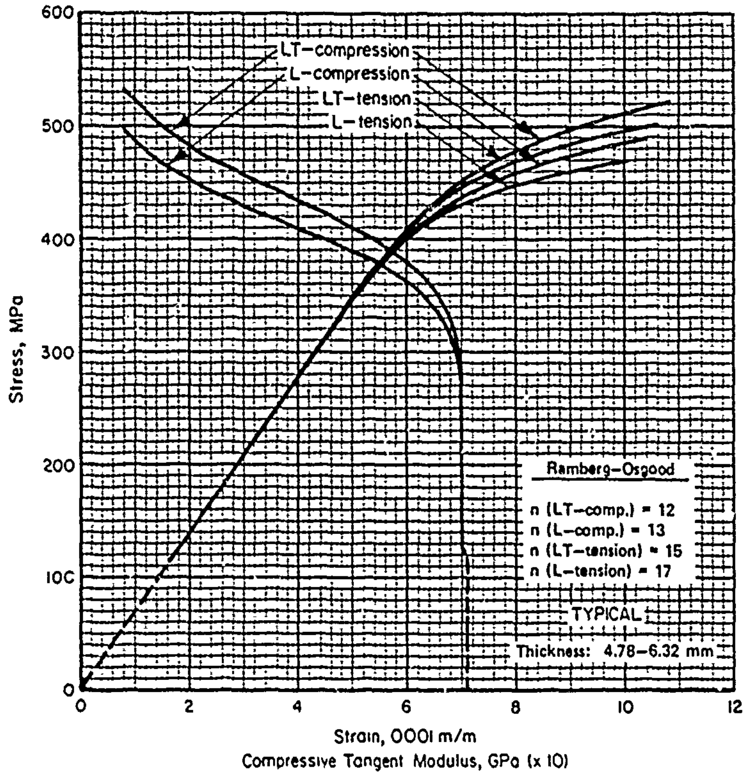


FIGURE 3.7.3.1.6(a). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for clad 7075-T6 and T651 aluminum alloy (sheet and plate) at room temperature.

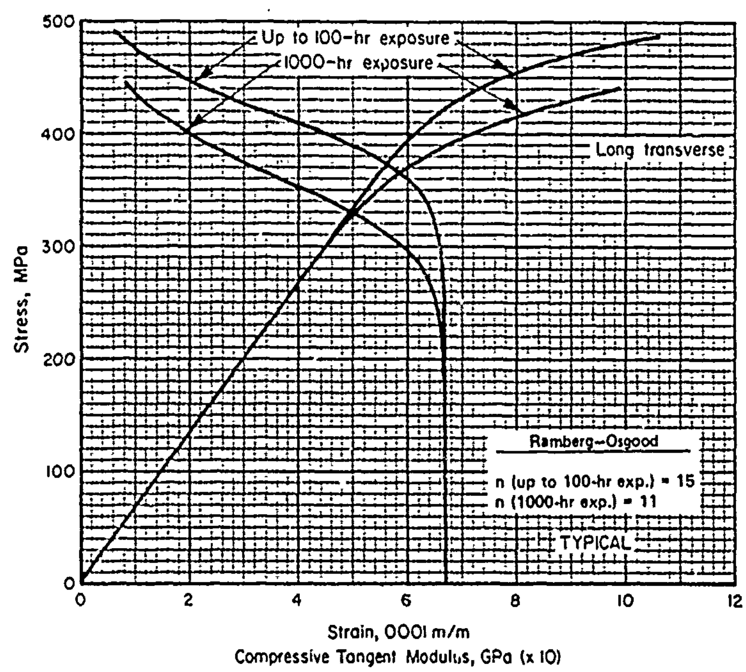


FIGURE 3.7.3.1.6(b). Typical compressive stress-strain and tangent-modulus curves for clad 7075-T6 aluminum alloy (sheet) at 93 K.

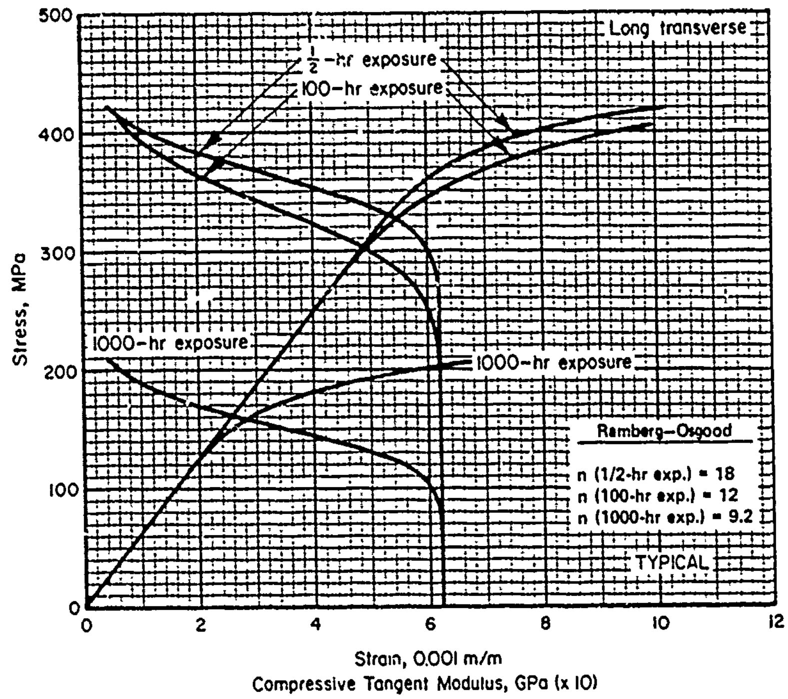


FIGURE 3.7.3.1.6(c). Typical compressive stress-strain and tangent-modulus curves for clad 7075-T6 aluminum alloy (sheet) at 149 K.

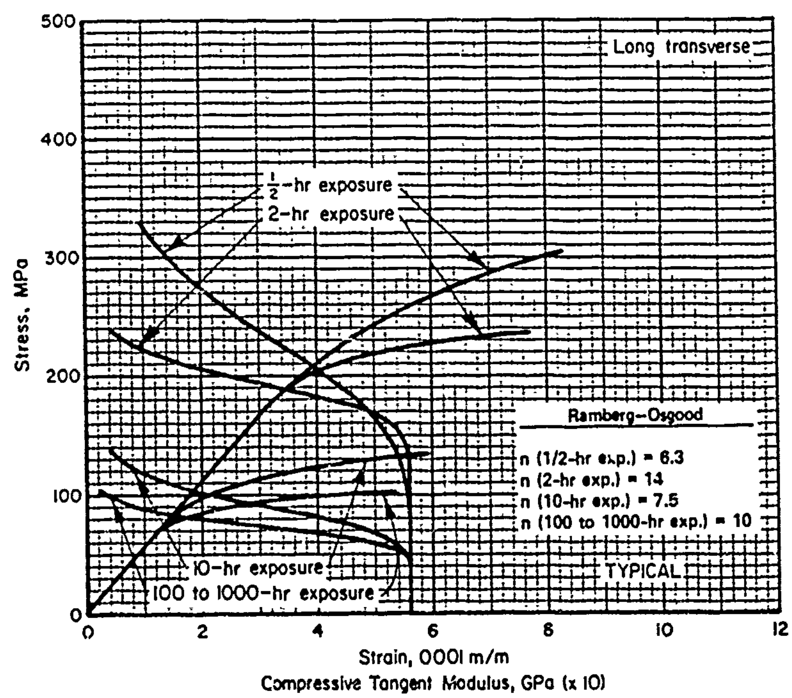


FIGURE 3.7.3.1.6(d). Typical compressive stress-strain and tangent-modulus curves for clad 7075-T6 aluminum alloy (sheet) at 204 K.

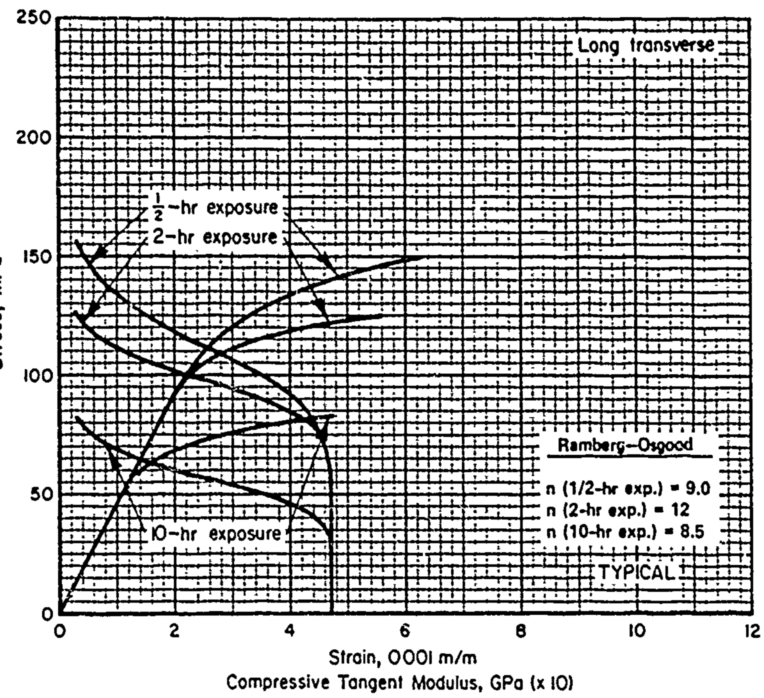


FIGURE 3.7.3.1.6(e). Typical compressive stress-strain and tangent-modulus curves for clad 7075-T6 aluminum alloy (sheet) at 260 K.

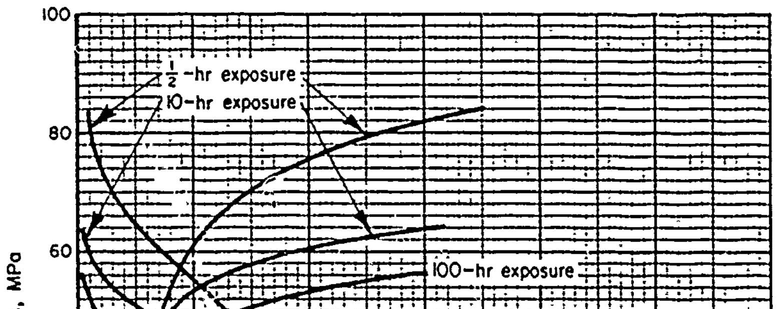


FIGURE 3.7.3.1.6(f). Typical compressive stress-strain and tangent-modulus curves for clad 7075-T6 aluminum alloy (sheet) at 316 K.

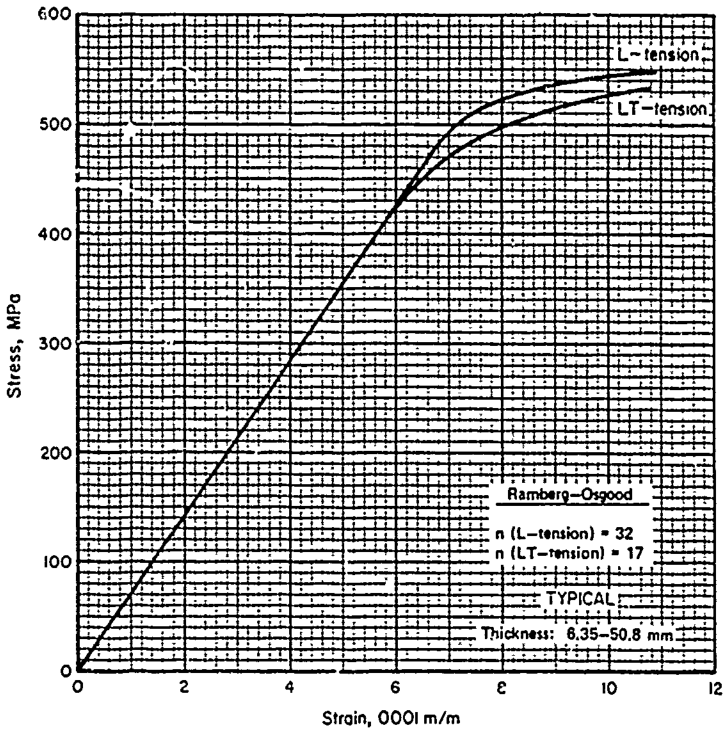


FIGURE 3.7.3.1 ɔ(8). Typical tensile stress-strain curves for 7075-T651 aluminum alloy (plate) at room temperature.

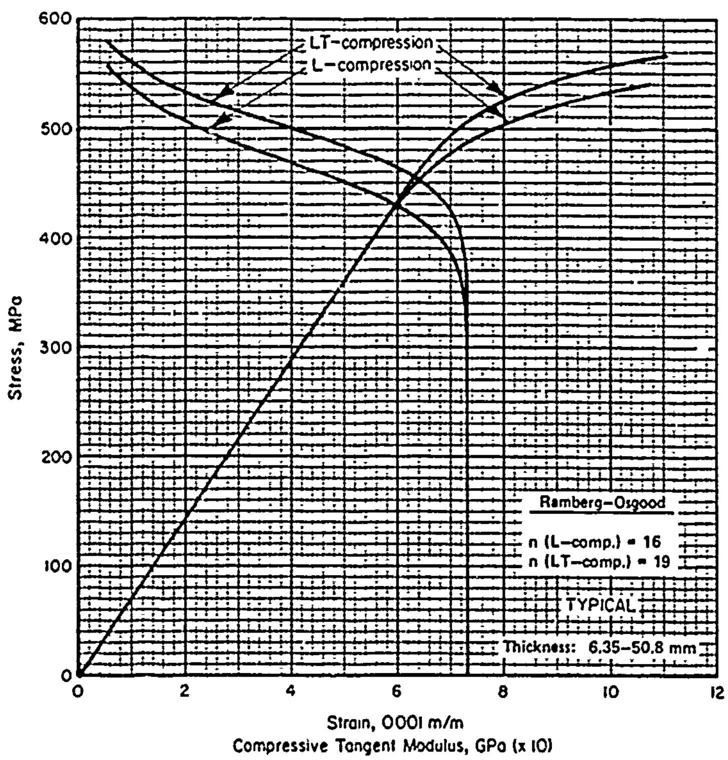


FIGURE 3.7.3.1.6(h). Typical compressive stress-strain and tangent-modulus curves for 7075-T651 aluminum alloy (plate) at room temperature.

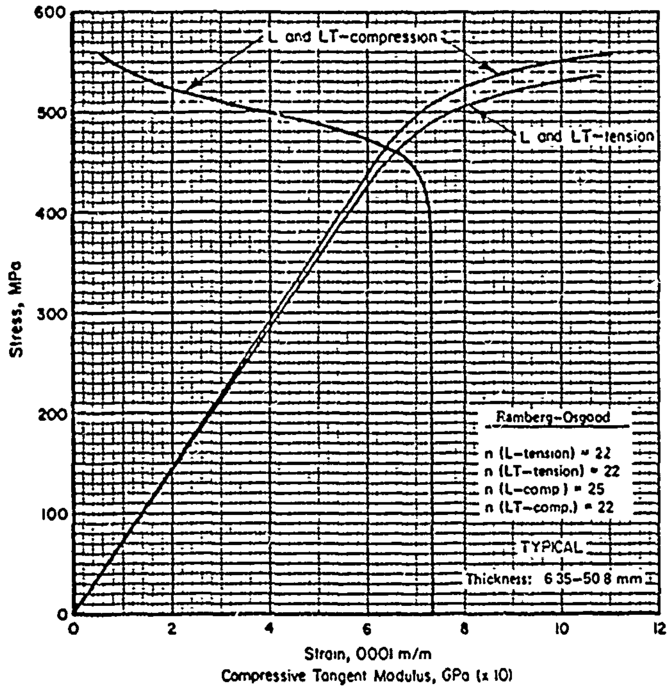


FIGURE 3.7.3.1.6(i). Typical tensile and compressive stress-strain and tangent-modulus curves for 7075-T62 aluminum alloy (plate) at room temperature.

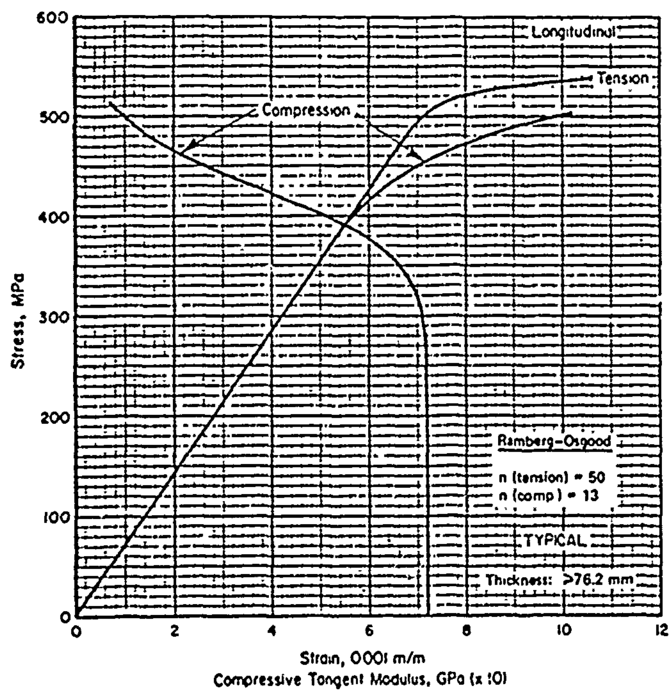


FIGURE 3.7.3.1.6(j). Typical tensile stress-strain and compressive stress-strain and tangent-modulus curves for 7075-T6 and T651 aluminum alloy (rolled-bar, rod,

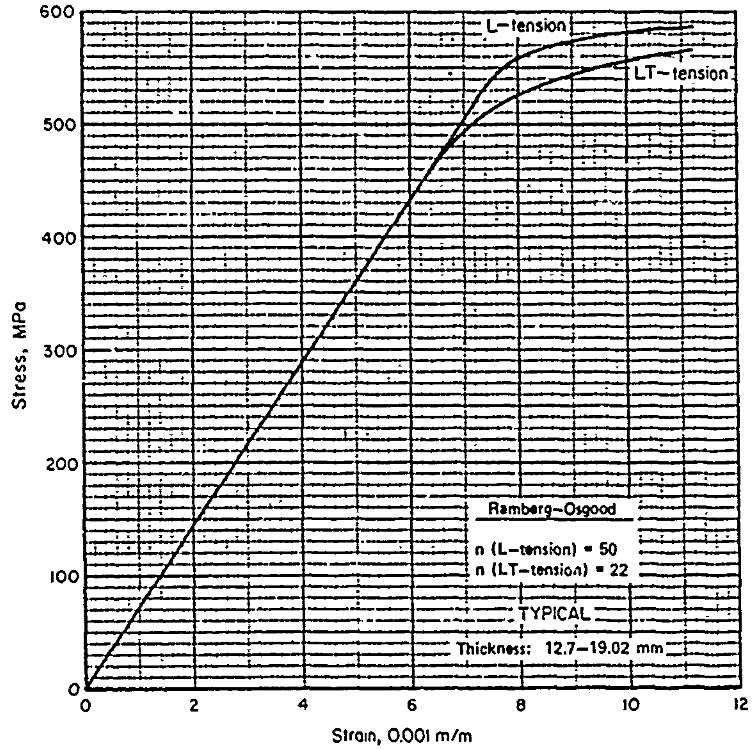


FIGURE 3.7.3.1.6(k). Typical tensile stress-strain curves for 7075-T651X aluminum alloy (extrusion) at room temperature.

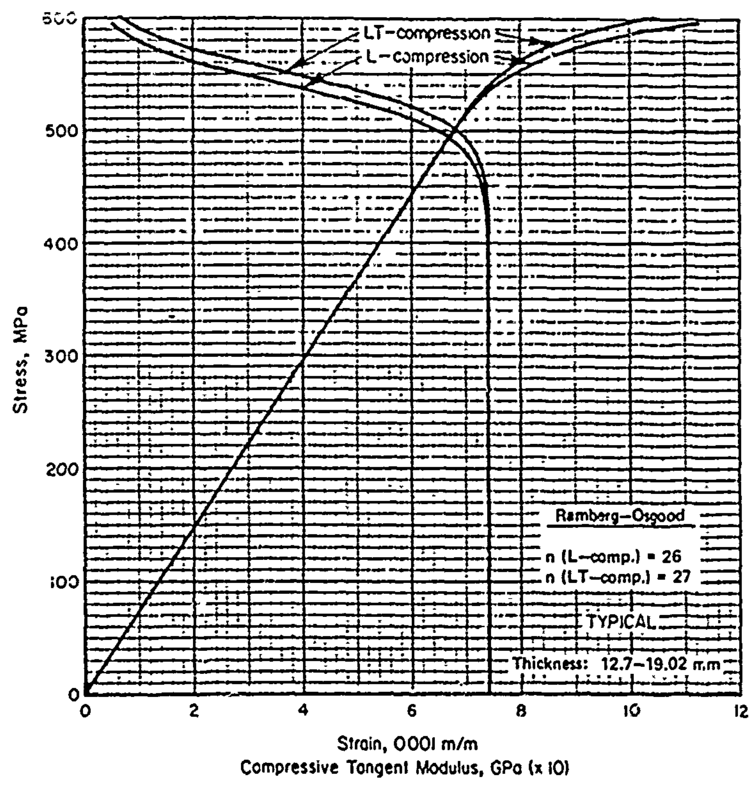


FIGURE 3.7.3.1.6(l). Typical compressive stress-strain and tangent-modulus curves for 7075-T651X aluminum alloy (extrusion) at room temperature.

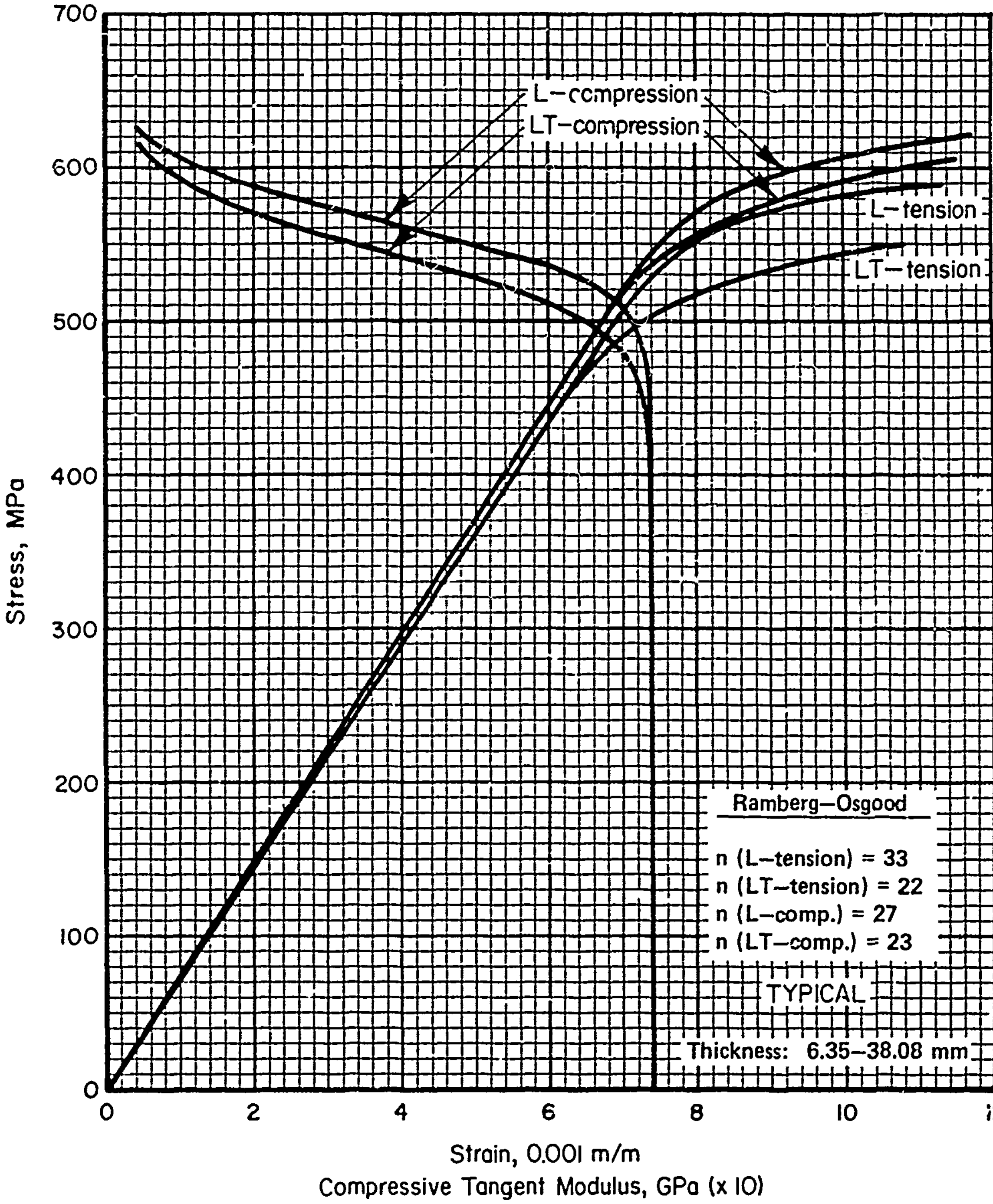


FIGURE 3.7.3.1.6(m). Typical tensile stress-strain and compressive stress-strain and tangent-modulus curves for 7075-T62 aluminum alloy (extrusion) at room temperature.

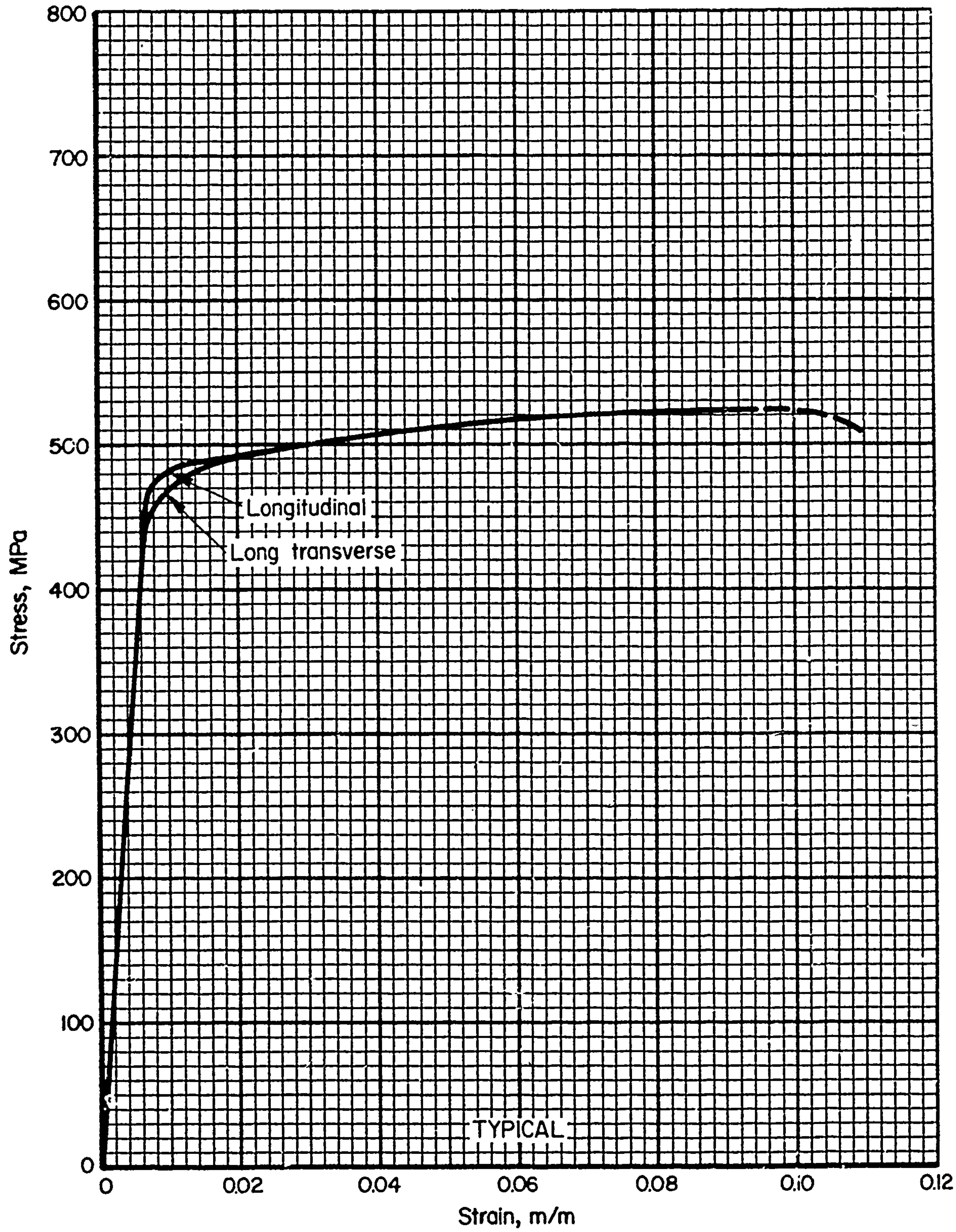


FIGURE 3.7.3.1.6(n). Typical tensile stress-strain curve (full range) for clad 7075-T6 aluminum alloy (sheet) at room temperature.

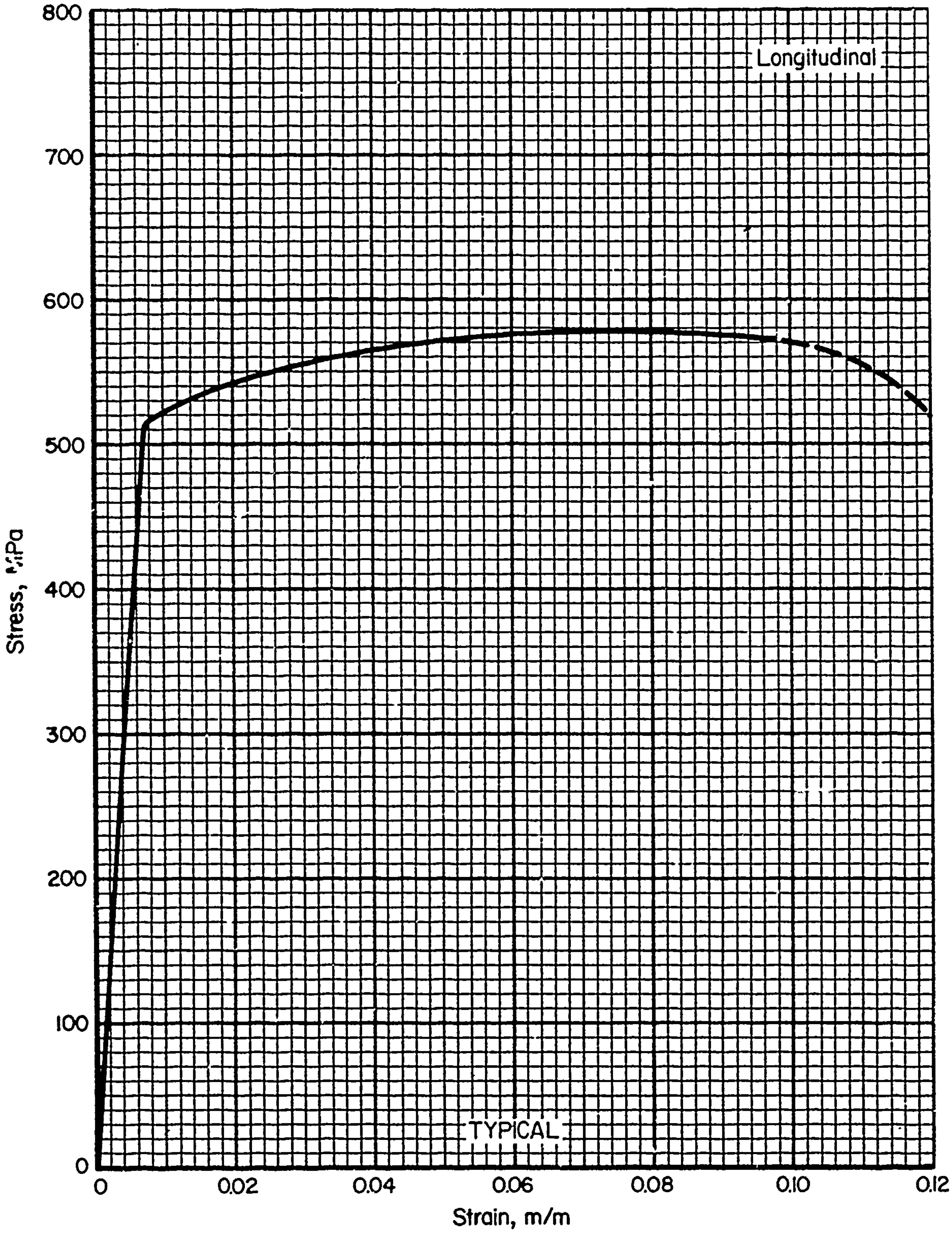


FIGURE 3.7.3.1.6(o). Typical tensile stress-strain curve (full range) for 7075-T6 and T651 aluminum alloy (rolled or cold-finished bar) at room temperature.

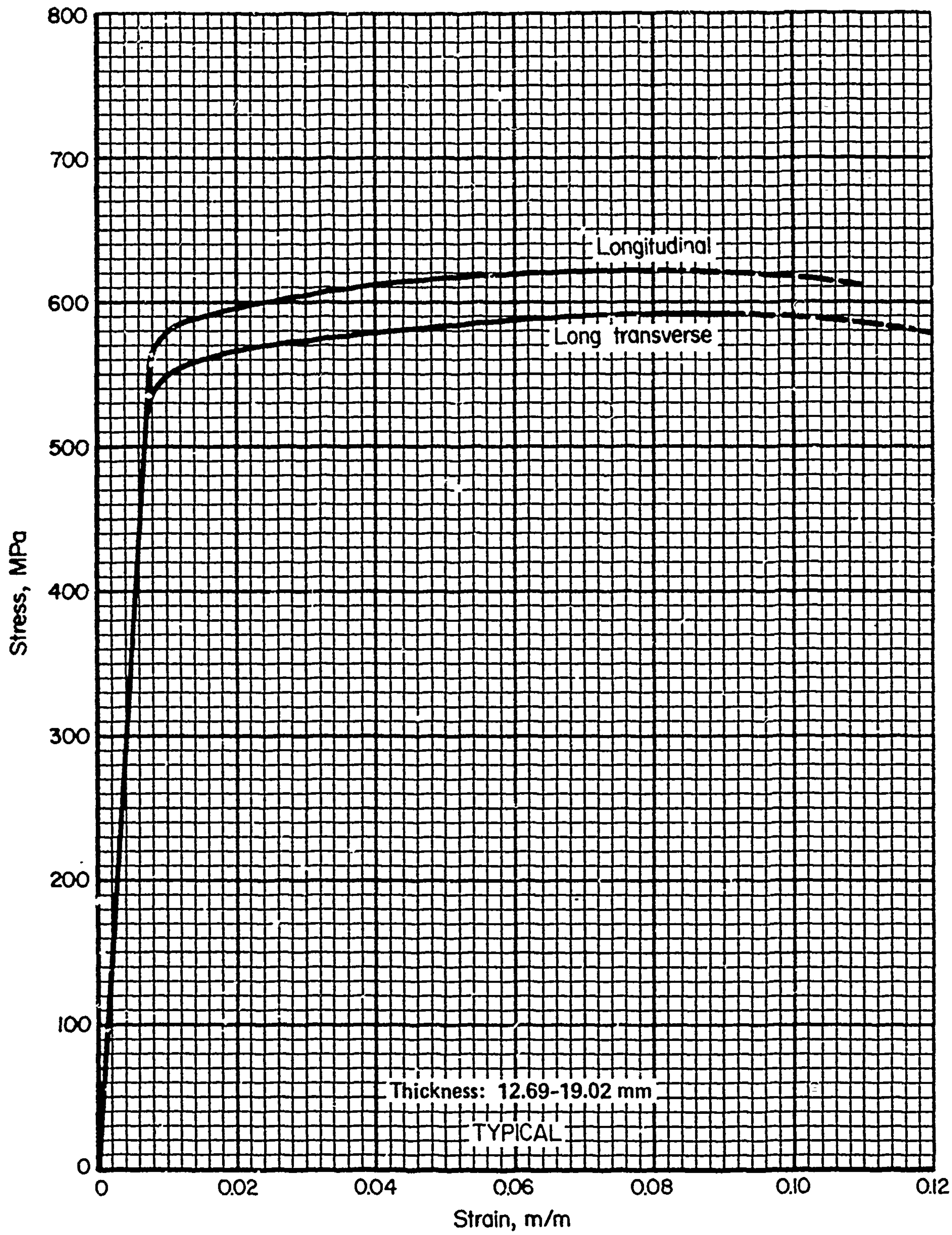


FIGURE 3.7.3.1.6(p). Typical tensile stress-strain curves (full range) for 7075-T651 X aluminum alloy (extrusion) at room temperature.

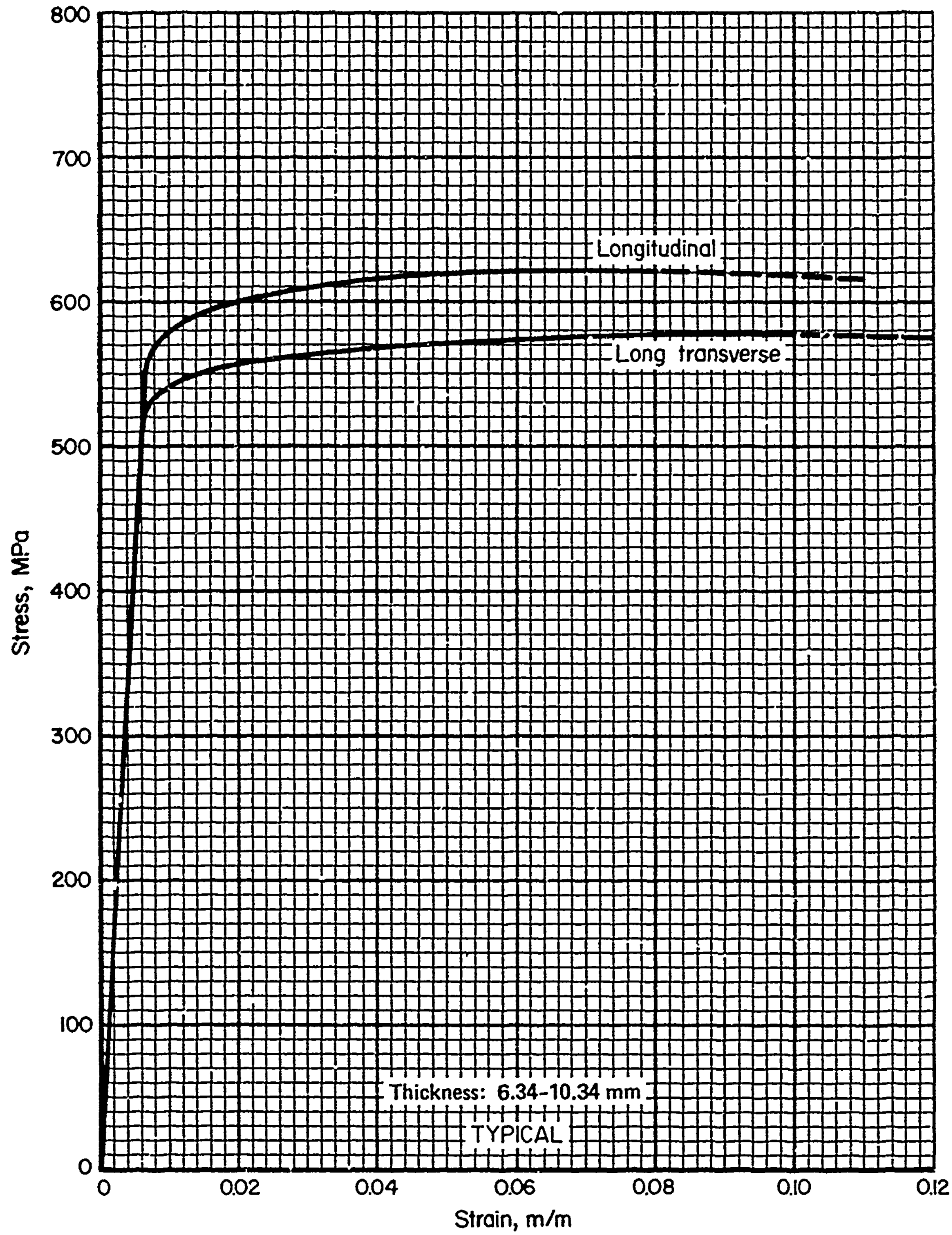


FIGURE 3.7.3.1.6(q). Typical tensile stress-strain curves (full range) for 7075-T62 aluminum alloy (extrusion) at room temperature.

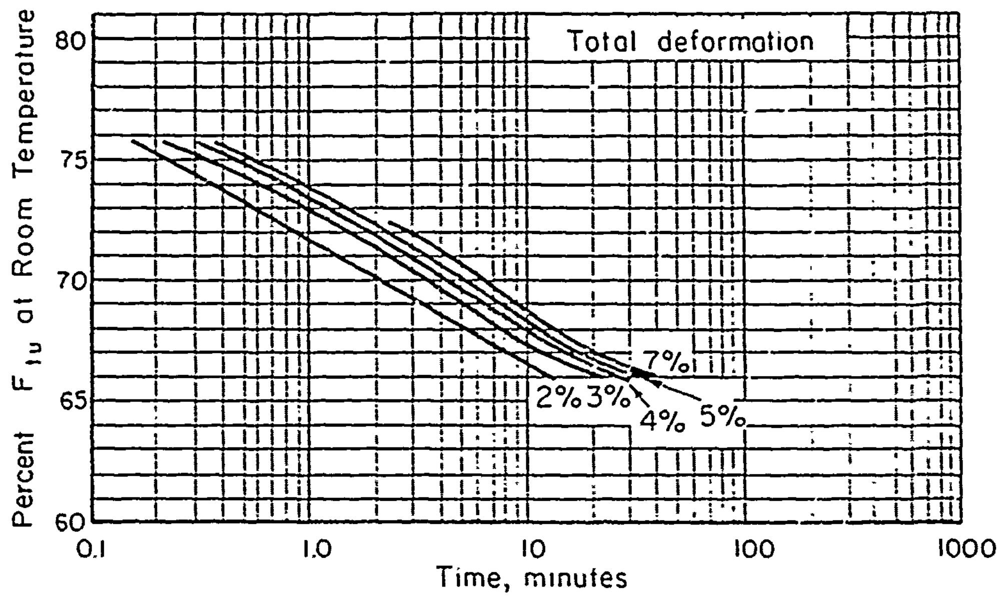


FIGURE 3.7.3 1.7(a). Creep data for 7075-T6 aluminum alloy (clad sheet) at 422 K.

Deformation includes thermal expansion of 0.30 percent. Heating rate 294 K per second.

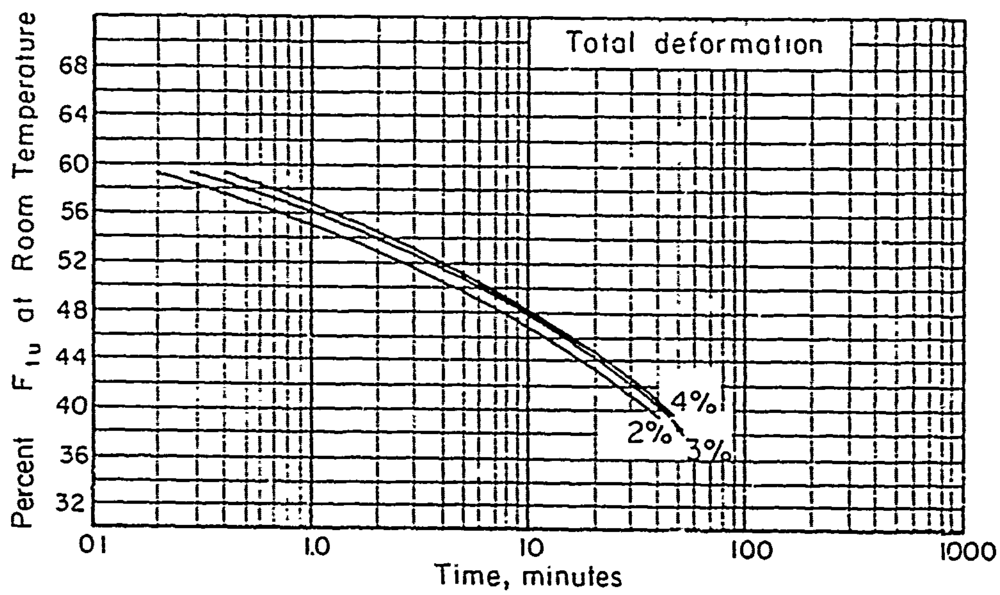


FIGURE 3.7.3.1.7(b). Creep data for 7075-T6 aluminum alloy (clad sheet) at 478 K.

Deformation includes thermal expansion of 0.43 percent. Heating rate 297 K per second.

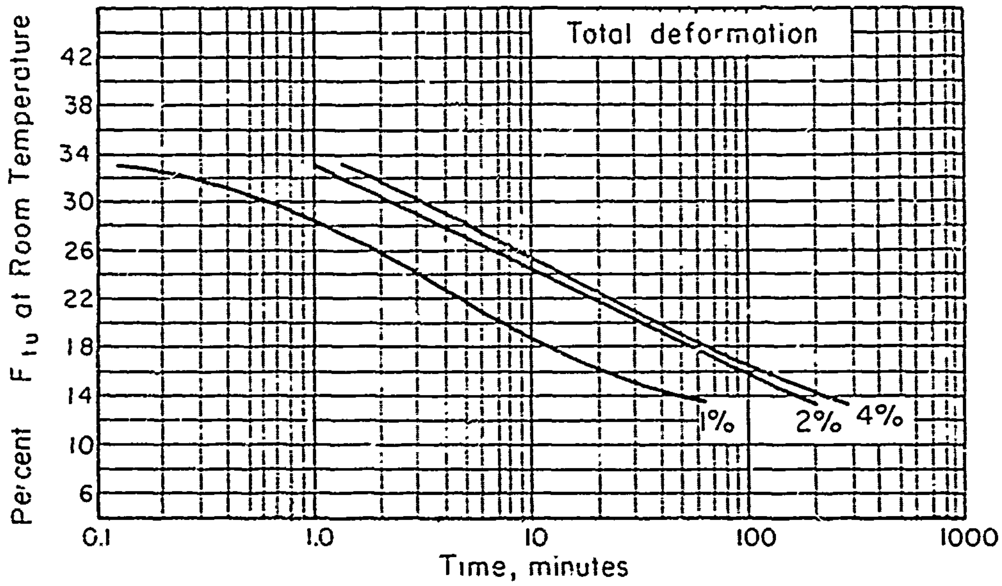


FIGURE 3.7.3.1.7(c). Creep data for 7075-T6 aluminum alloy (clad sheet) at 533 K.

Deformation includes thermal expansion of 0.63 percent. Heating rate 297 to 311 K per second.

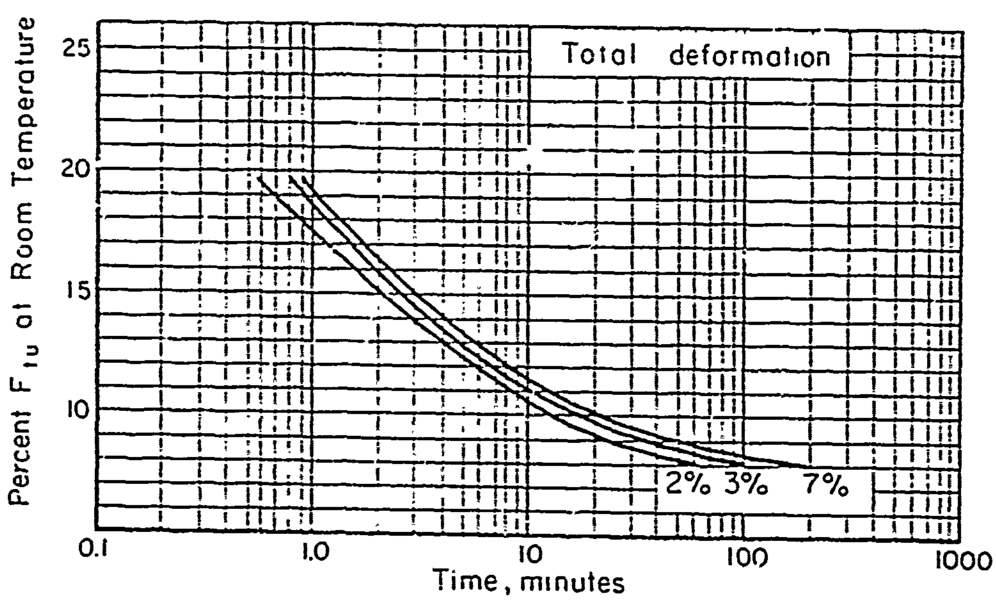


FIGURE 3.7.3.1.7(d). Creep data for 7075-T6 aluminum alloy (clad sheet) at 589 K.

Deformation includes thermal expansion of 0.74 percent. Heating rate 300 to 305 K per second.

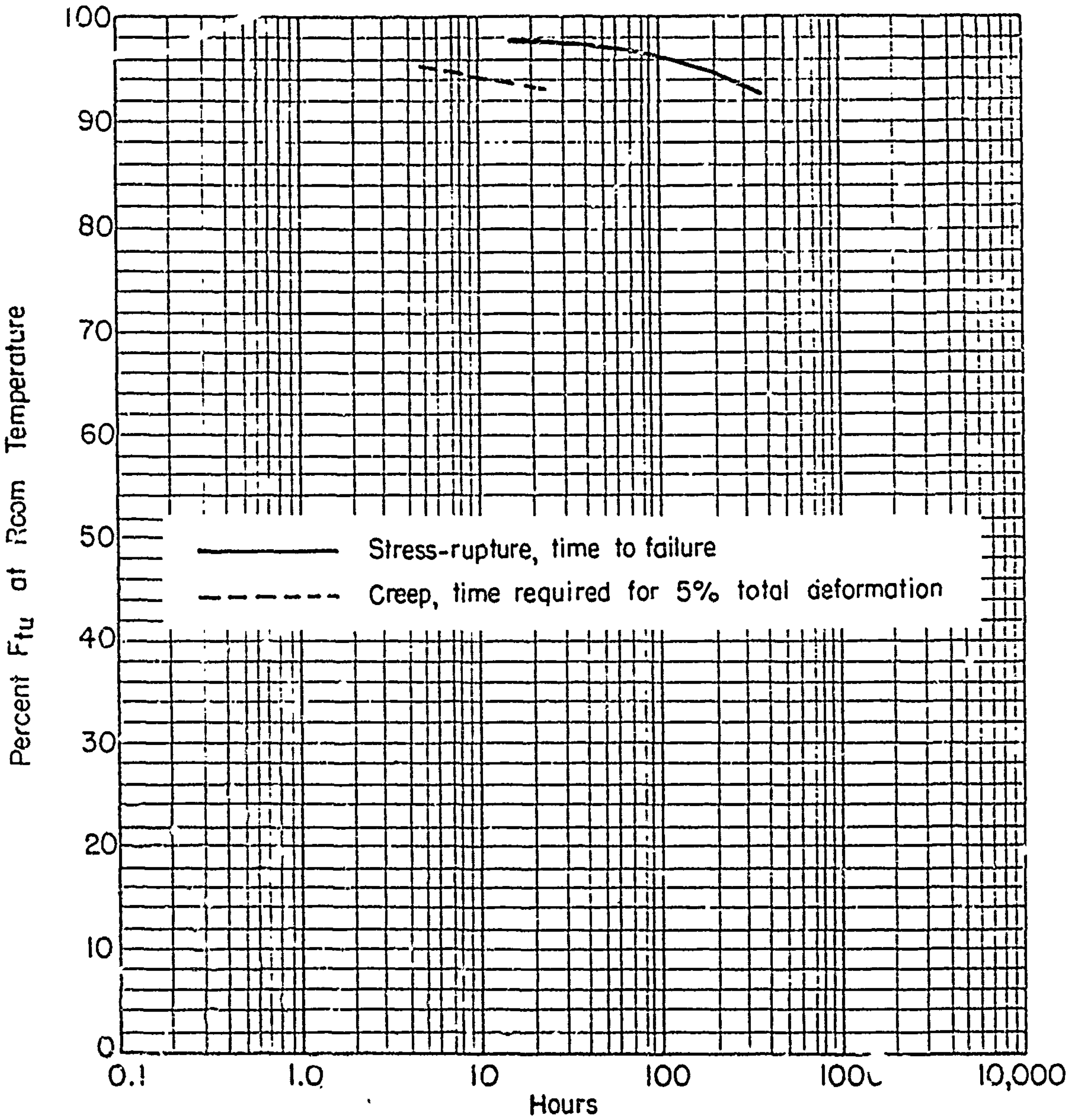


FIGURE 3.7.3.1.7(e) Creep and stress-rupture properties of wrought 7075-T6 aluminum alloy at 308 K.

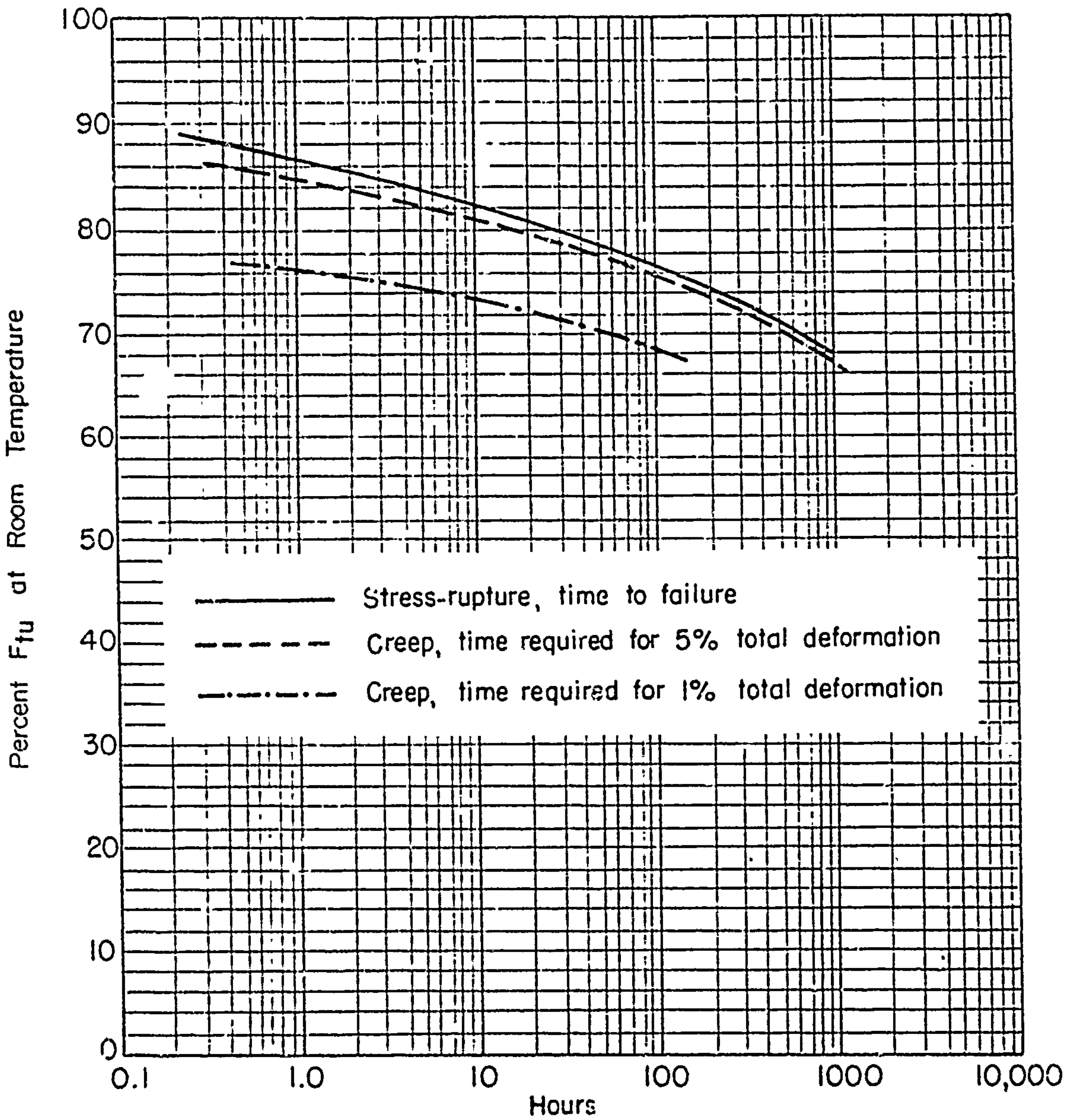


FIGURE 3.7.3.1.7 (f) Creep and stress-rupture properties of wrought 7075-T6 aluminum alloy at 373 K.

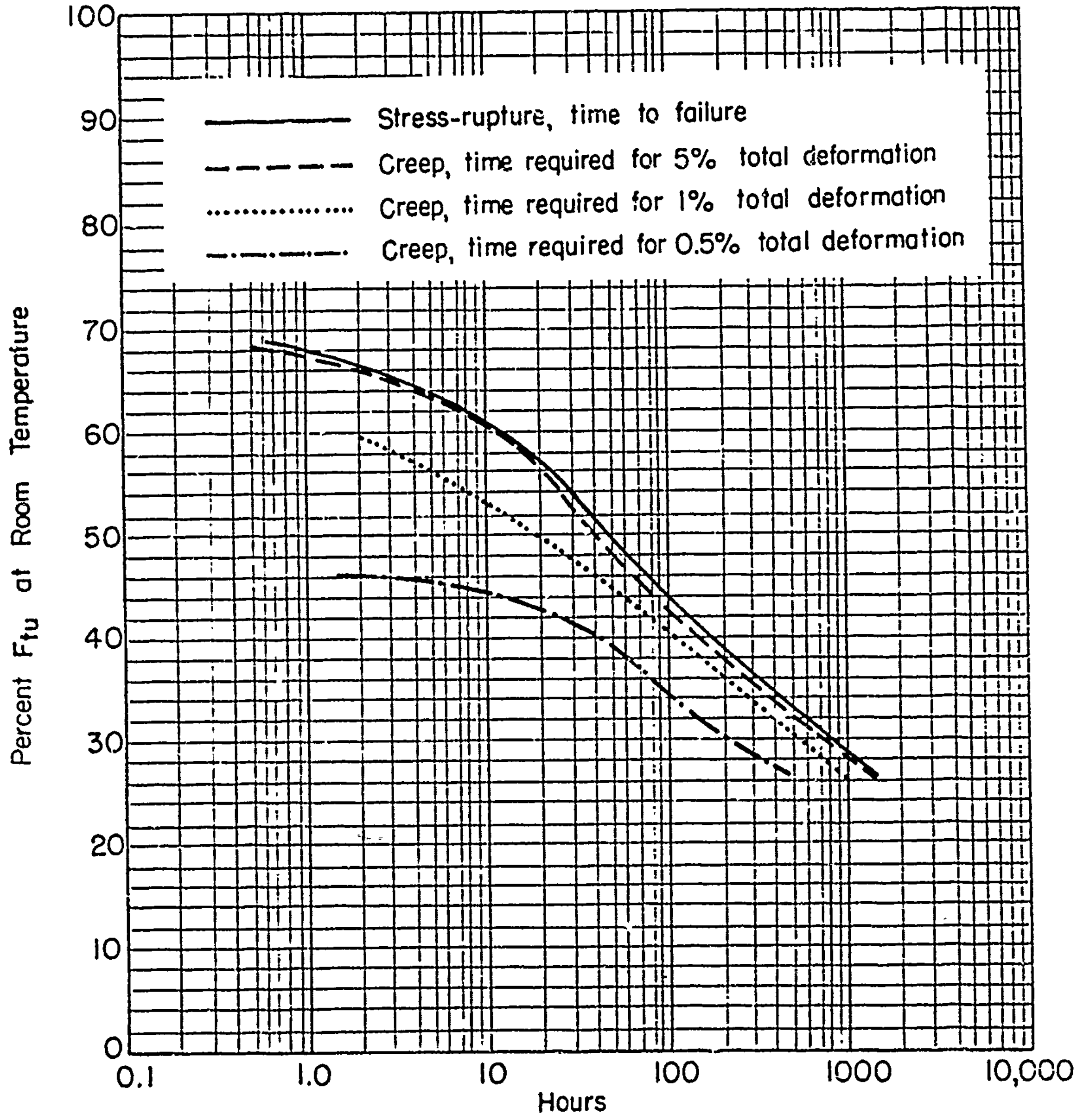


FIGURE 3.7.3.1.7 (g) Creep and stress-rupture properties of wrought 7075-T6 aluminum alloy at 422 K.

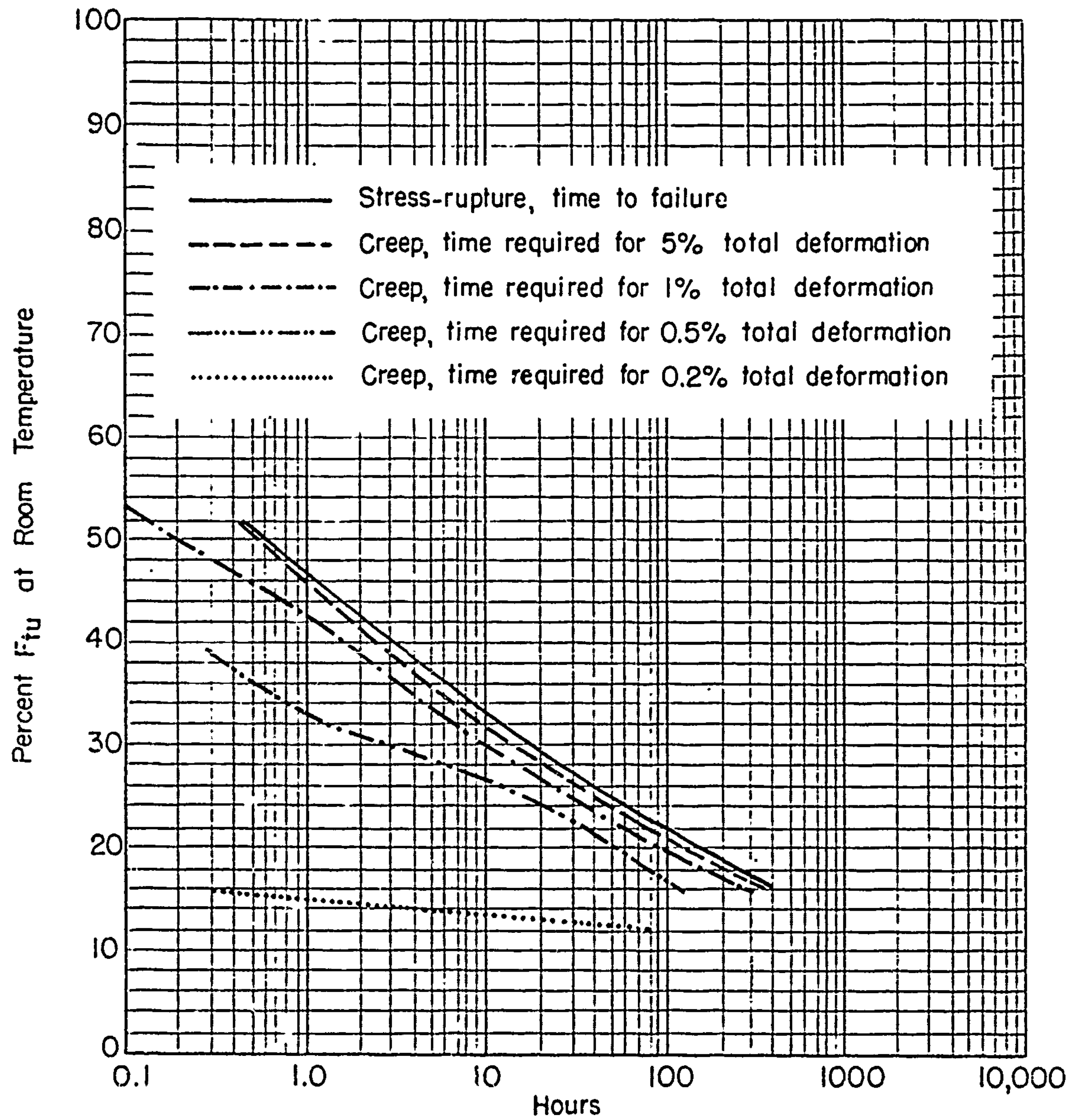


FIGURE 3.7.3.1.7 (h). Creep and stress-rupture properties of wrought 7075-T76 aluminum alloy at 464 K.

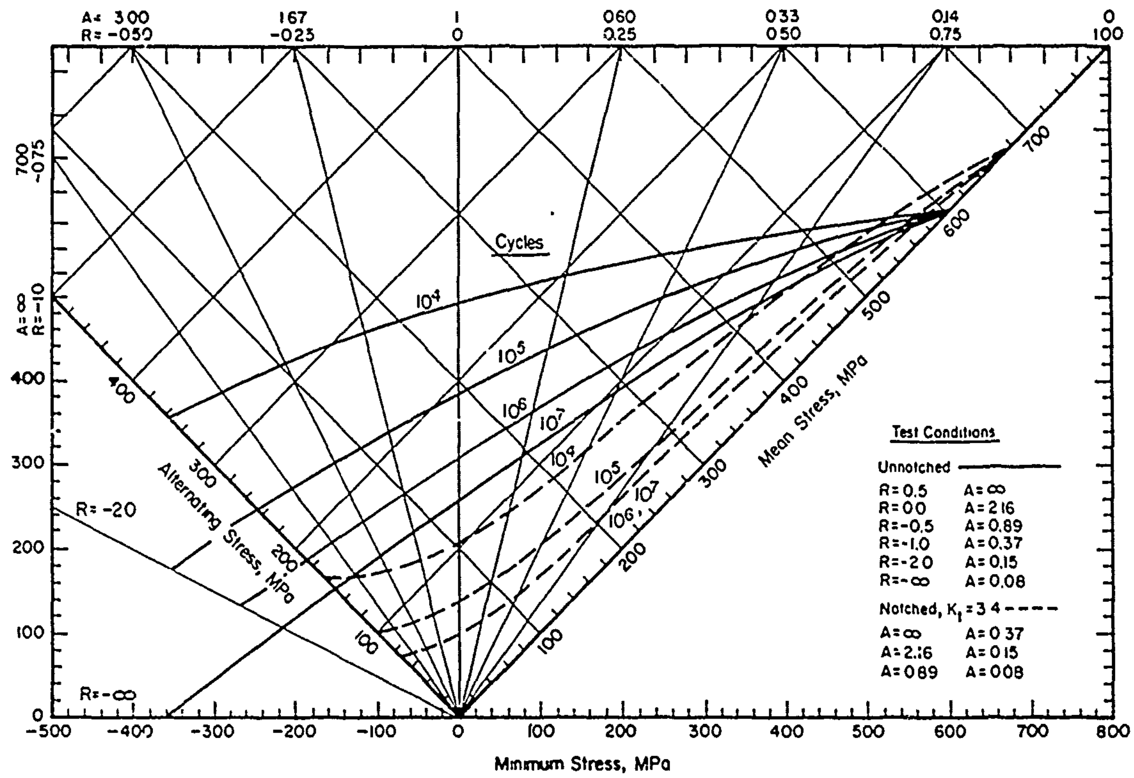


FIGURE 3.7.3.1.8(a). Typical constant-life diagram for fatigue behavior of various wrought products of 7075-T6 aluminum alloy

Correlative Information for Figure 3.7.3.1.8(a)

Product Form: Drawn Rod, 19.1 mm diameter
Rolled bar and rod, 31.8 mm diameter
25 x 190 mm and 28.6 mm diameter
Extruded rod and bar, 31.8 mm diameter
31.8 x 31.8 mm, 31.8 x 102 mm

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

Properties:

TUS, MPa	TYS, MPa	Temp, K
601	535	RT (Unnotched)
679	—	RT (Notched)

Specimen Details:

Unnotched:
10.2 mm diameter

Notched, V-Groove, $K_t = 3.4$
11.4 mm gross diameter
10.2 mm net diameter
0.25 mm root radius, r
60° flank angle, ω

$$K_N = 1.99,\ \rho = 0.356\text{ mm, where } K_N = 1 + \frac{K_t - 1}{1 + \frac{\pi}{\pi - \omega}\sqrt{\frac{\rho}{r}}}$$

Surface Condition: Unnotched: longitudinal polish, 900 grit
Notched: as machined.

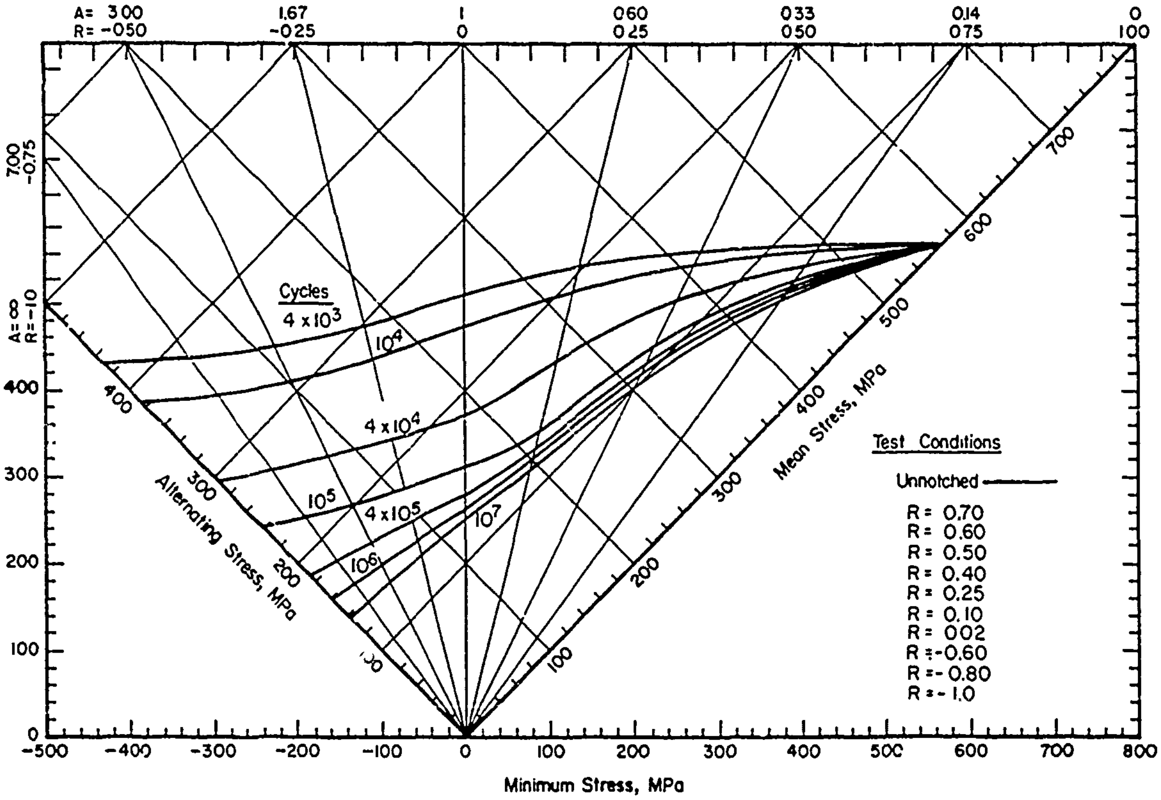


FIGURE 3.7.3.1.8(b). *Typical constant-life diagram for unnotched fatigue behavior of 7075-T6 aluminum alloy.*

Correlative Information for Figure 3.7.3.1.8(b)

Product Form: 2.29 mm bare sheet

Test Parameters:
Loading — Axial
Frequency — 1100 to 1200 cpm
Temperature — RT
Atmosphere — Air

Properties:	TUS, MPa	TYS, MPa	Temp, K
	569	524	RT

Specimen Details: Unnotched:
25.4 metres wide

Surface Condition: Electropolished.

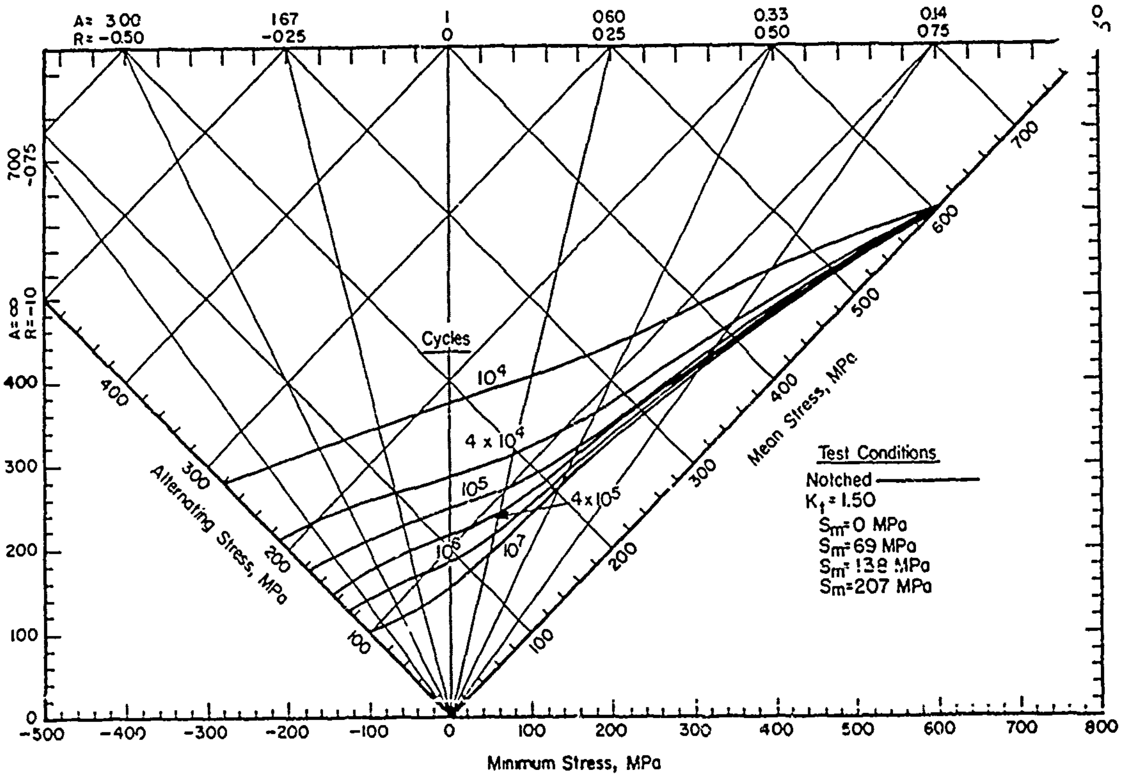


FIGURE 3.7.3.1.8(c). *Typical constant-life diagram for notched fatigue behavior of 7075-T6 aluminum alloy.*

Correlative Information for Figure 3.7.3.1.8(c)

Product Form: 2.29 mm bare sheet

Test Parameters:
Loading — Axial
Frequency — 1100 to 1500 cpm
Temperature — RT
Atmosphere — Air

Properties:	TUS, MPa	TYS, MPa	Temp, K
	569	524	RT (Unnotched)
	598	—	RT (Notched)

Specimen Details: Notched, Edge, $K_t = 1.5$
76.2 mm gross width
38.1 mm net width
19.3 mm root radius, r
0° flank angle, ω

$$K_N = 1.44,\ \rho = 0.432 \text{ mm, where } K_N = 1 + \frac{K_t - 1}{1 + \frac{\pi}{\pi - \omega}\sqrt{\frac{\rho}{r}}}$$

Surface Condition: Electropolished.

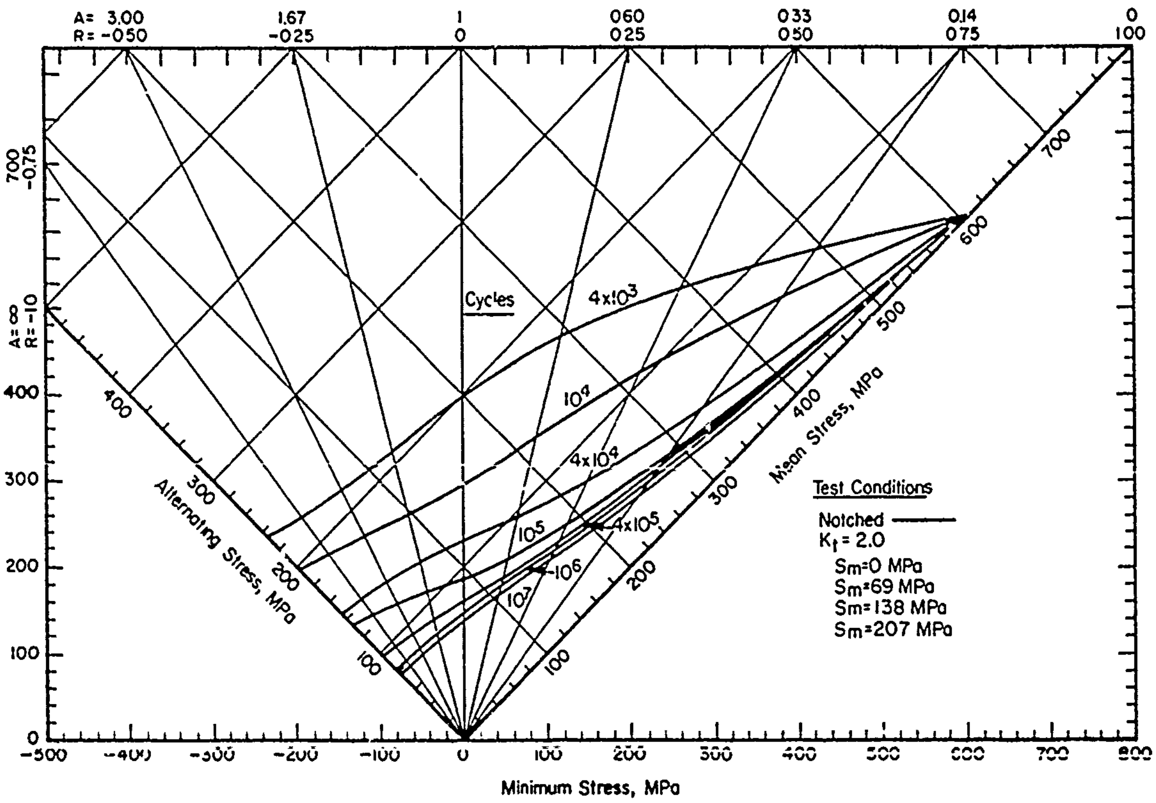


FIGURE 3.7.3.1.8(d). *Typical constant-life diagram for notched fatigue behavior of 7075-T6 aluminum alloy.*

Correlative Information for Figure 3.7.3.1.8(d)

Product Form: 2.29 mm bare sheet

Test Parameters:
- Loading — Axial
- Frequency — 1100 to 1500 cpm
- Temperature — RT
- Atmosphere — Air

Properties:

TUS, MPa	TYS, MPa	Temp, K
569	524	RT (Unnotched)
603	—	RT (Notched)

Specimen Details: Notched, Edge, $K_t = 2.0$
- 57.2 mm gross width
- 38.1 mm net width
- 8.06 mm root radius, r
- 0° flank angle, ω

$$K_N = 1.81,\ \rho = 0.432 \text{ mm where } K_N = 1 + \frac{K_t - 1}{1 + \frac{\pi}{\pi - \omega}\sqrt{\frac{\rho}{r}}}$$

Surface Condition: Electropolished.

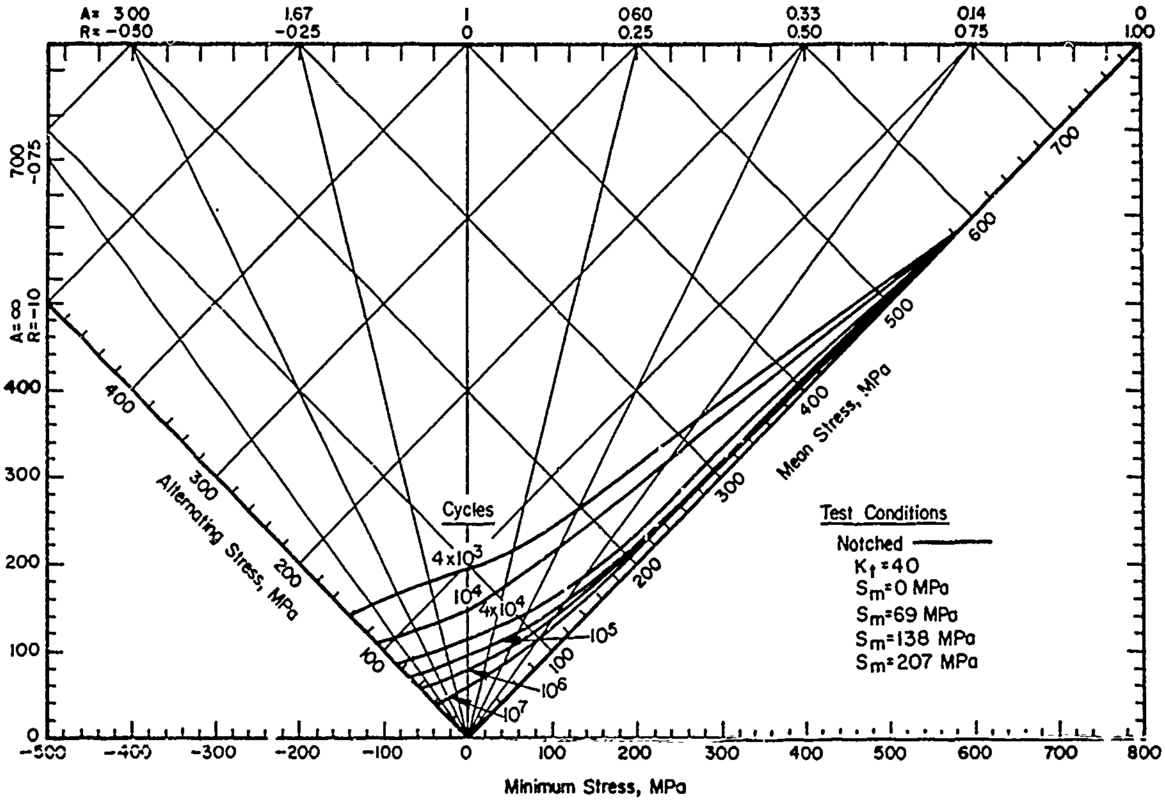


FIGURE 3.7.3.1.8(e). *Typical constant-life diagram for notched fatigue behavior of 7075-T6 aluminum alloy.*

Correlative Information for Figure 3.7.3.1.8(e)

Product Form: 2.29 mm bare sheet

Test Parameters:
Loading — Axial
Frequency — 1100 to 1500 cpm
Temperature — RT
Atmosphere — Air

Properties:	TUS, MPa	TYS, MPa	Temp, K
	569	524	RT (Unnotched)
	569	—	RT (Notched)

Specimen Details: Notched, Edge, $K_t = 4.0$
57.2 mm gross width
38.1 mm net width
1.45 mm root radius, r
0° flank angle, ω

$$K_N = 2.94,\ \rho = 0.432 \text{ mm, where } K_N = 1 + \frac{K_t - 1}{1 + \frac{\pi}{\pi - \omega}\sqrt{\frac{\rho}{r}}}$$

Surface Condition: Electropolished.

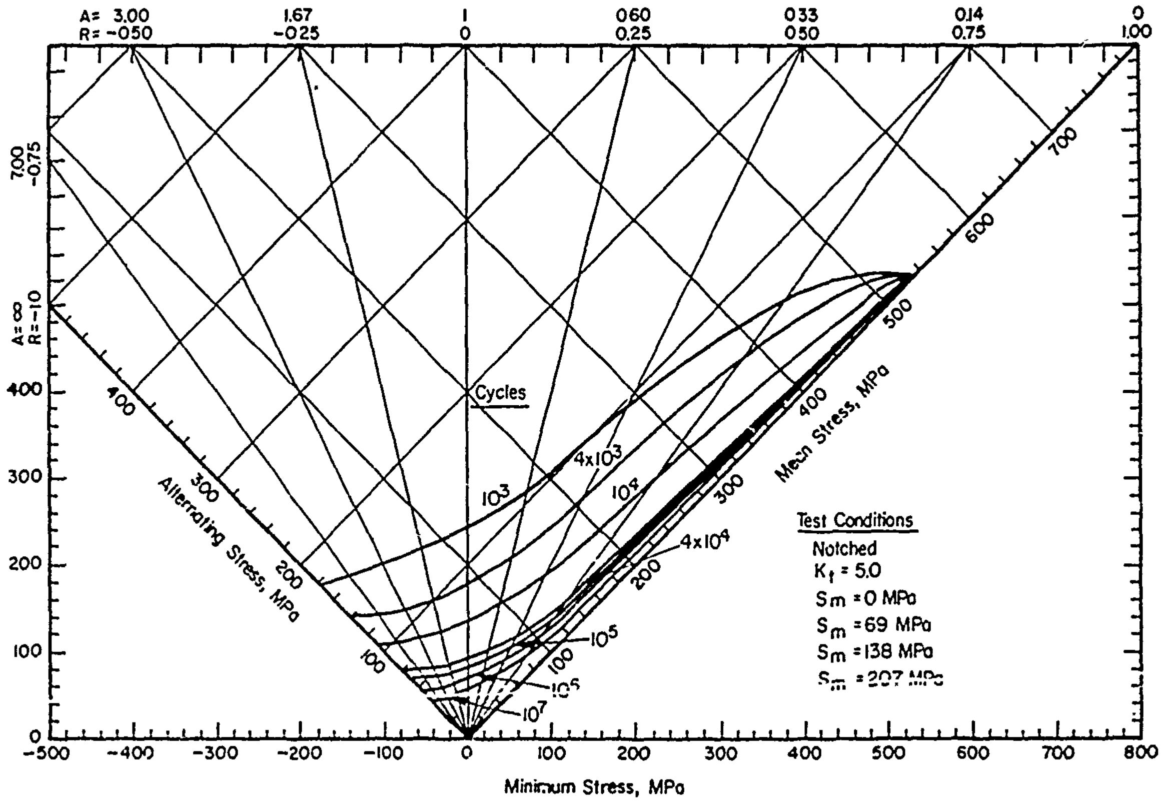


FIGURE 3.7.3.1.8(f). *Typical constant-life diagram for notched fatigue behavior of 7075-T6 aluminum alloy.*

Correlative Information for Figure 3.7.3.1.8(f)

Product Form: 2.29 mm bare sheet

Test Parameters:
Loading — Axial
Frequency — 1100 to 1500 cpm
Temperature — RT
Atmosphere — Air

Properties:

TUS, MPa	TYS, MPa	Temp, K
569	524	RT (Unnotched)
534	—	RT (Notched)

Specimen Details: Notched, Edge, $K_t = 5.0$
57.2 mm gross width
38.1 mm net width
0.79 mm root radius, r
0° flank angle, ω

$$K_N = 3.31,\ \rho = 0.432 \text{ mm} \quad \text{where } K_N = 1 + \frac{K_t - 1}{1 + \frac{\pi}{\pi - \omega}\sqrt{\frac{\rho}{r}}}$$

Surface Condition: Electropolished.

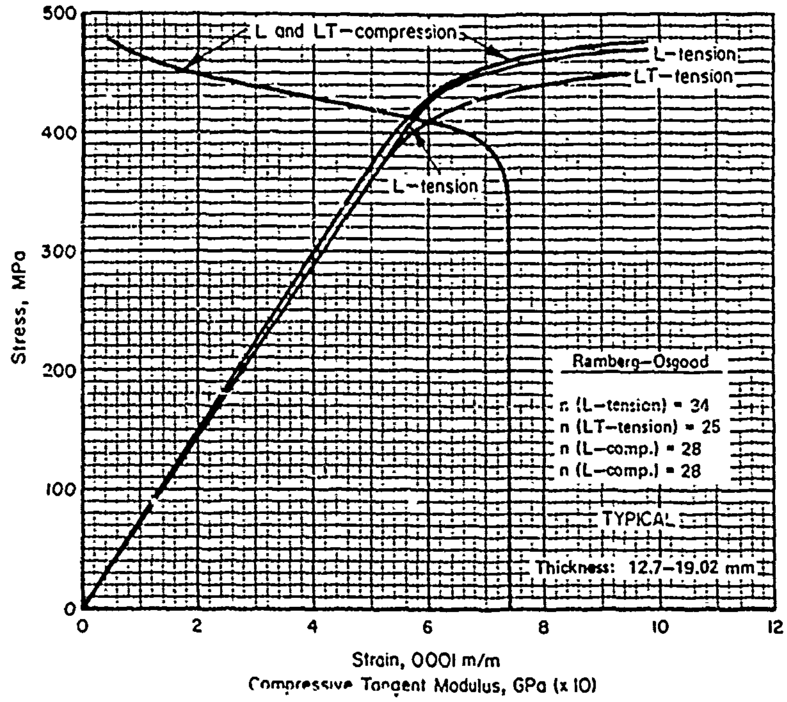


FIGURE 3.7.3.2.6(a). Typical tensile stress-strain and compressive stress-strain and tangent-modulus curves for 7075-T7351X aluminum alloy (extrusion) at room temperature.

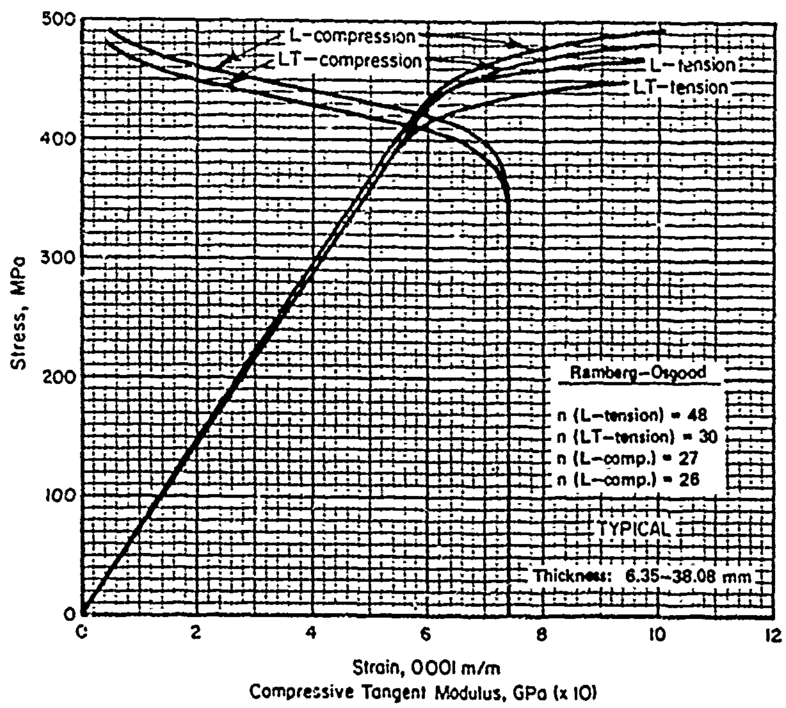


FIGURE 3.7.3.2.6(b). Typical tensile stress-strain and compressive stress-strain and tangent-modulus curves for 7075-T73 aluminum alloy (extrusion) at room temperature.

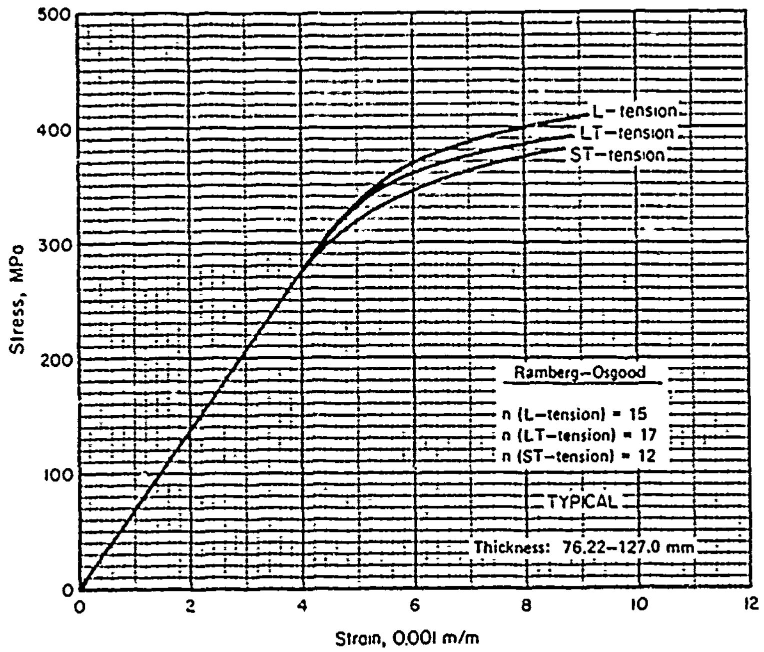


FIGURE 3.7.3.2.6(c). Typical tensile stress-strain curves for 7075-T7352 aluminum alloy (hand forging) at room temperature.

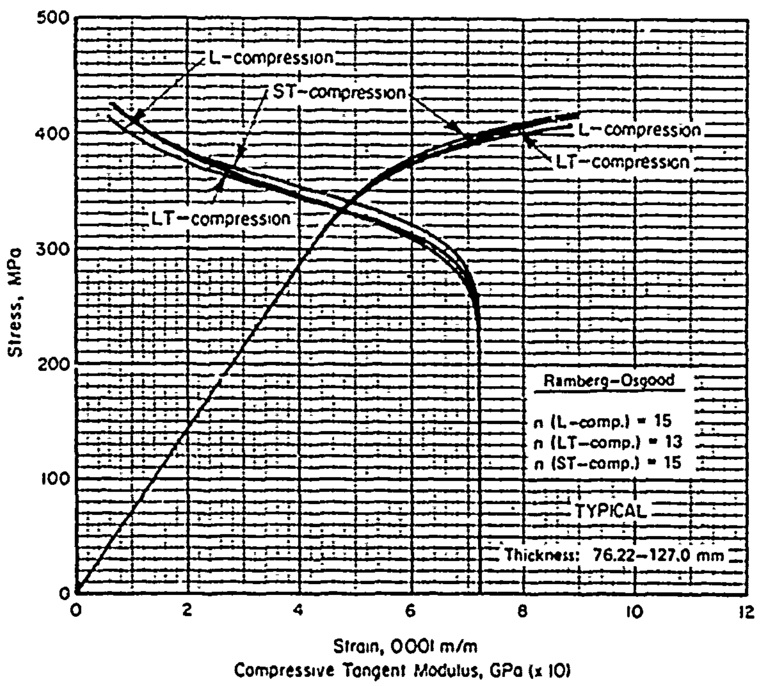


FIGURE 3.7.3.2.6(d). Typical compressive stress-strain and tangent-modulus curves for 7075-T7352 aluminum alloy (hand forging) at room temperature.

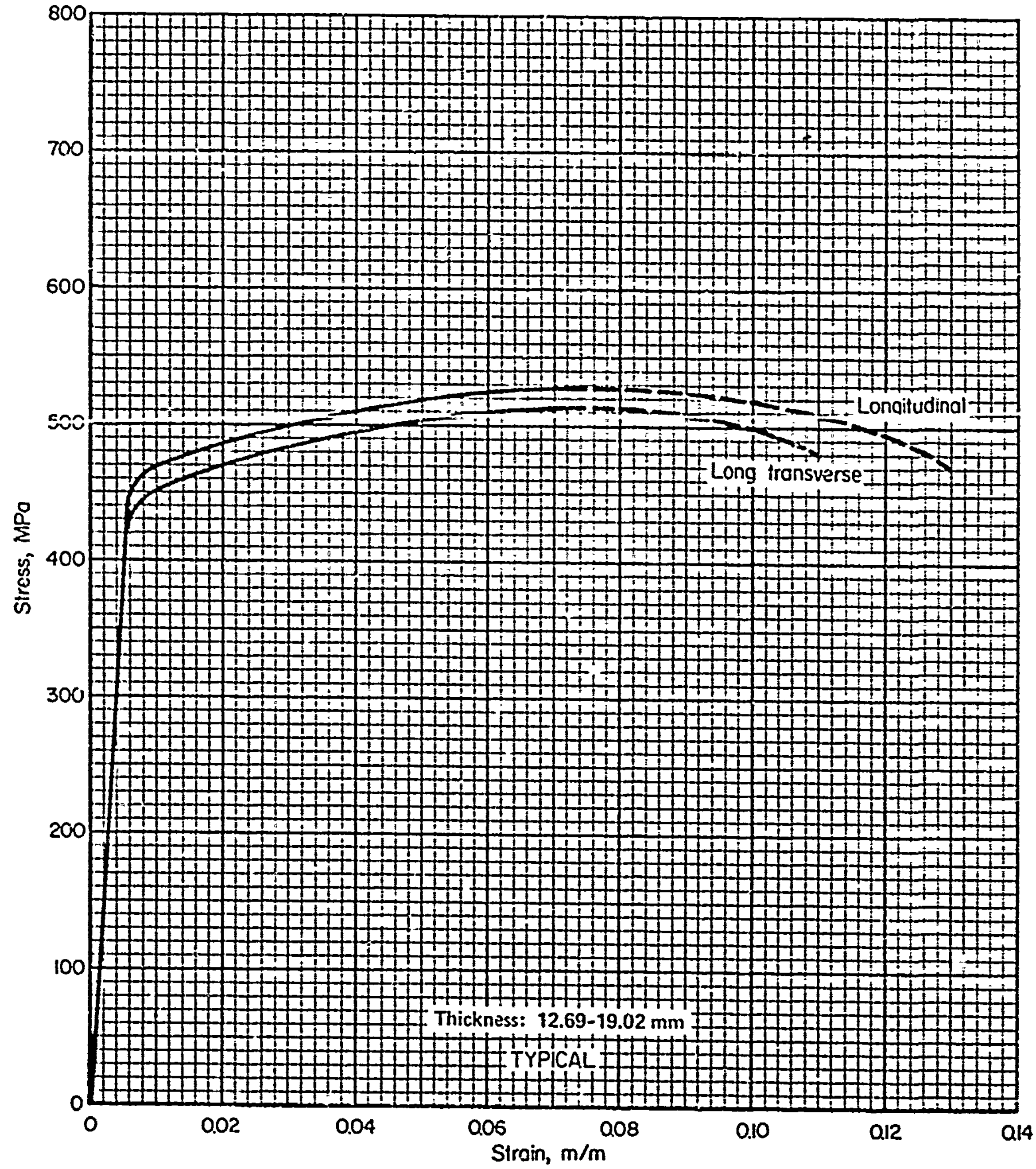


FIGURE 3.7.3.2.6(e). Typical tensile stress-strain curves (full range) for 7075-T7351X aluminum alloy (extrusion) at room temperature.

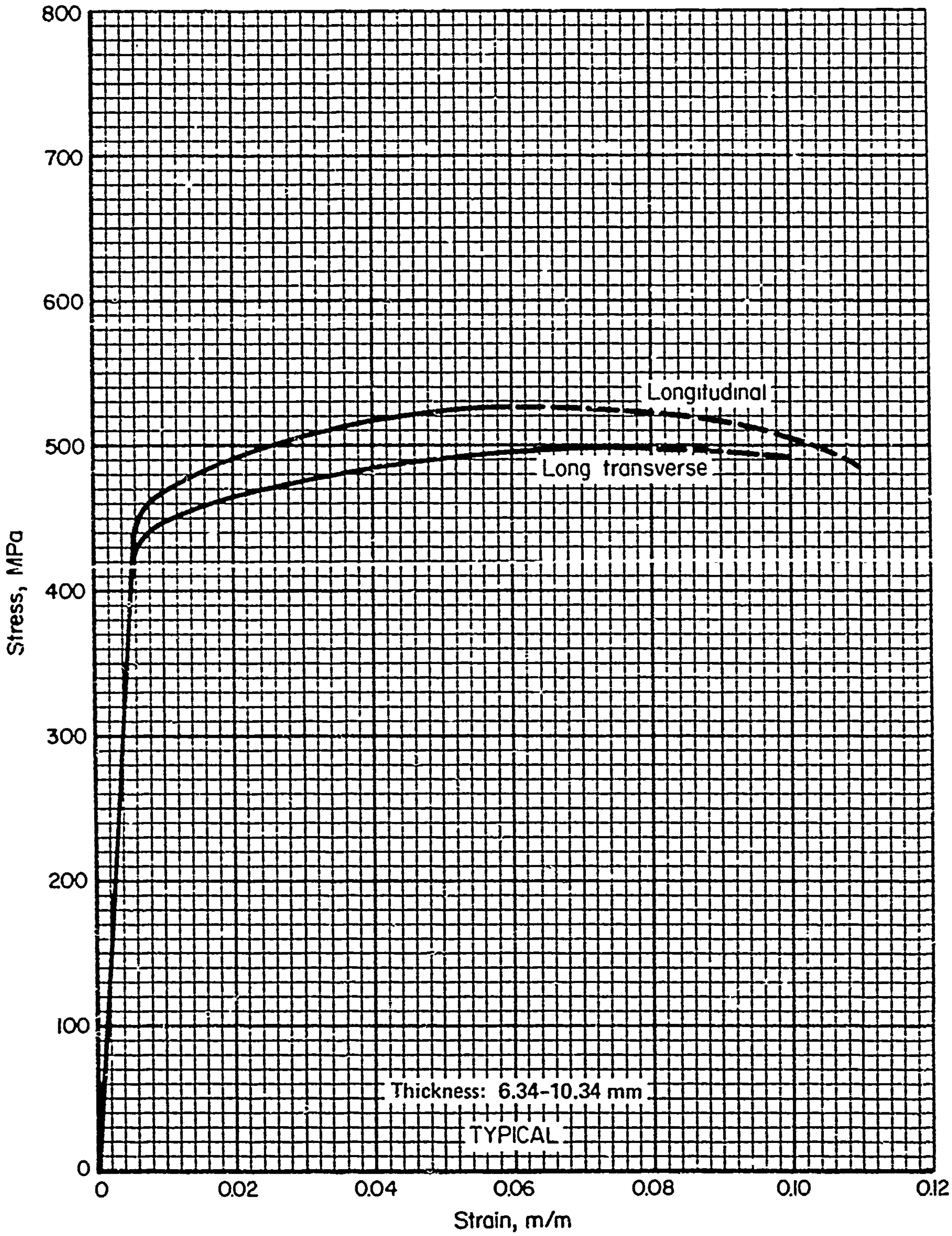


FIGURE 3.7.3.2.6(f). Typical tensile stress-strain curves (full range) for 7075-T73 aluminum alloy (extrusion) at room temperature.

3.7.4 7079 ALLOY

3.7.4.0 *Comments and Properties.*—7079 is a high-strength Al-Zn alloy available in a wide range of product forms. 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 7079 are presented in Table 3.7.4.1(a). Room temperature mechanical and physical properties are shown in Table 3.7.4.0(b) through (h). The effect of temperature on physical properties is shown in Figure 3.7.4.0.

TABLE 3.7.4.0(a). *Material Specifications for 7079 Aluminum Alloy*

Specification	Form
QQ-A-200/12	Extrusions
QQ-A-250/17	Bare sheet and plate
QQ-A-250/27	7011 clad sheet and plate
QQ-A-250/23	One-side clad sheet
MIL-A-8923	Clad sheet and plate
MIL-A-22771	Forgings

The temper index for 7079 is as follows:

Section	Temper
3.7.4.1	T6, T651, T652, T6510, T6511

3.7.4.1 *T6, T651, T652, T6510, and T6511 Tempers.*—Effect-of-temperature curves are presented in Figures 3.7.4.1.1(a) through 3.7.4.1.5(b) for various mechanical properties.

Figures 3.7.4.1.6(a) through (g) present tensile and compressive stress-strain curves and tangent modulus curves at room temperature. Figures 3.7.4.1.6(h) through (j) are full-range stress-strain curves at room temperature.

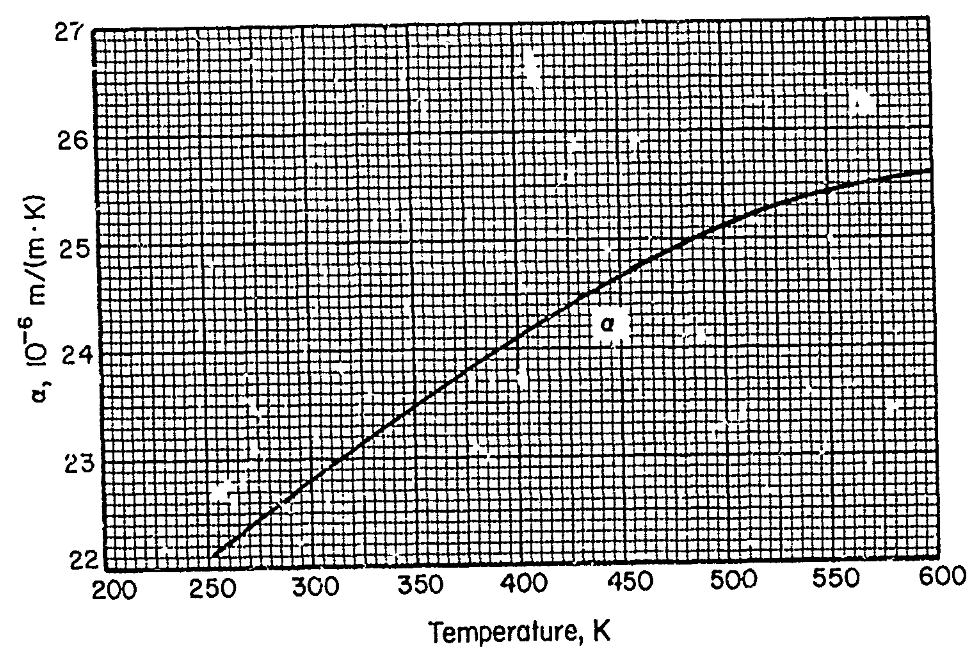


FIGURE 3.7.4.0. Effect of temperature on the physical properties of 7079 aluminum alloy.

TABLE 3.7.4.0(B1). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 7079 ALUMINUM ALLOY (SHEET AND PLATE)

SPECIFICATION	QQ-A-250/17												
FORM	SHEET			PLATE									
TEMPER	T6			T651									
THICKNESS, MM	0.38-1.00	1.01-6.33		6.34-25.41		25.42-38.11		38.12-50.81		50.82-63.51		63.52-76.20	
BASIS	S	A	B	A	B	A	B	A	B	A	B	A	B
MECHANICAL PROPERTIES:													
FTU, MPA:													
L	503	510	524	517	524	490	496	490	496	490	496	490	496
LT	503	510	524	510	517	503	510	503	510	503	510	496	503
ST	...	...	...	...	...	...	...	...	...	469	476	455	462
FTY, MPA:													
L	441	455	469	455	462	448	455	448	455	441	448	434	441
LT	441	448	462	448	455	441	448	441	448	434	441	427	434
ST	...	...	...	...	...	...	...	...	...	407	414	400	407
FCY, MPA:													
L	448	455	469	448	455	441	448	434	441	427	434	421	427
LT	462	476	490	476	483	469	476	469	476	455	462	448	455
ST	...	...	...	...	...	...	...	...	...	448	455	441	448
FSU, MPA	310	310	317	290	296	290	296	296	303	296	303	296	296
FBRU[a], MPA:													
(E/D=1.5)	779	793	814	800	827	786	800	786	800	786	800	779	786
(E/D=2.0)	1010	1020	1050	1010	1020	993	1010	993	1010	993	1010	979	993
FBRY[a], MPA:													
(E/D=1.5)	662	669	689	676	683	676	683	683	689	676	689	669	683
(E/D=2.0)	772	786	807	786	800	786	800	786	800	786	793	779	786
EL, PERCENT:													
L	...	8	...	...	...	...	...	...	...	6	...	6	...
LT	7	8	...	8	...	8	...	7	...	6	...	6	...
ST	...	...	...	...	...	...	...	...	...	2	...	2	...
E, GPA	71.0			71.0									
EC, GPA	72.4			73.1									
G, GPA	26.9			26.9									
MU	0.33			0.33									
PHYSICAL PROPERTIES:													
OMEGA, MG/M3	2.74												
C, J/(G*K)	0.96 (AT 373 K)												
K, W/(M*K)	126(AT 298 K)												
ALPHA, 10-6 M/(M*K)	23.6 (293 TO 373 K)												

[a]SEE TABLE 3.1.2.1.1. BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

[illegible] DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF
7079 ALUMINUM ALLOY (PLATE)

SPECIFICATION	QQ-A-250/17									
FORM	PLATE									
TEMPER	T651									
THICKNESS, MM	76.22-101.61		101.62-114.31		114.32-127.01		127.02-139.71		139.72-152.40	
BASIS	A	B	A	B	A	B	A	B	A	B
MECHANICAL PROPERTIES:										
FTU, MPA:										
L	483	490	469	476	469	476	462	469	455	462
LT	483	490	469	476	469	476	462	469	455	462
ST	448	455	434	441	434	441	427	434	421	427
FTY, MPA:										
L	414	421	400	407	400	407	393	400	386	393
LT	414	421	400	407	400	407	393	400	386	393
ST	386	393	372	379	372	379	365	372	359	365
FCY, MPA:										
L	407	414	393	400	393	400	386	393	372	379
LT	434	441	421	427	421	427	414	421	407	41[illegible]
ST	427	434	414	421	414	421	407	414	400	407
FSU, MPA	296	296	290	296	290	296	290	296	290	296
FBRU[a], MPA:										
(E/D=1.5)	752	765	731	745	731	745	724	738	710	724
(E/D=2.0)	952	965	924	938	924	938	910	924	896	910
FBRY[a], MPA:										
(E/D=1.5)	662	669	648	655	648	662	646	662	641	655
(E/D=2.0)	758	772	738	752	738	758	738	752	731	745
EL, PERCENT:										
L	6	...	6	...	5	...	4	...	4	...
LT	5	...	5	...	5	...	4	...	4	...
ST	2	...	2	...	2	...	2	...	2	...
E, GPA	71.0									
EC, GPA	73.1									
G, GPA	26.9									
MU	0.33									
PHYSICAL PROPERTIES:										
OMEGA, MG/M3	2.74									
C, J/(G*K)	0.96(AT 373 K)									
K, W/(M*K)	128 (AT 298 K)									
ALPHA, 10-6 M/(M*K)	23.6(293 TO 373 K)									

[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(B3). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 7079 ALUMINUM ALLOY (SHEET AND PLATE)

SPECIFICATION	QQ-A-250/17										
FORM	SHEET AND PLATE										
TEMPER	T62[a]										
THICKNESS, MM	1.02-6.33	6.34-25.41	25.42-36.11	38.12-50.81	50.82-63.51	63.52-76.21	76.22-101.61	101.62-114.31	114.32-127.01	127.02-139.71	139.72-152.40
BASIS	S	S	S	S	S	S	S	S	S	S	S
MECHANICAL PROPERTIES:											
FTU, MPA:											
L	...	...	...	...	...	...	483	469	469	462	455
LT	496	503	503	503	503	490	483	465	469	462	455
ST	...	...	...	...	...	...	448	434	434	427	421
FTY, MPA:											
L	...	...	...	...	...	...	414	400	400	393	386
LT	427	434	434	434	434	427	414	400	400	393	386
ST	...	...	...	...	...	...	386	372	372	365	359
FCY, MPA:											
L	...	...	...	...	...	...	...	...	...	...	...
LT	...	...	...	...	...	...	...	...	...	...	...
ST	...	...	...	...	...	...	...	...	...	...	...
FSU, MPA	...	...	...	...	...	...	...	...	...	...	...
FBRU, MPA:											
(E/D=1.5)	...	...	...	...	...	...	...	...	...	...	...
(E/D=2.0)	...	...	...	...	...	...	...	...	...	...	...
FBRY, MPA:											
(E/D=1.5)	...	...	...	...	...	...	...	...	...	...	...
(E/D=2.0)	...	...	...	...	...	...	...	...	...	...	...
EL, PERCENT:											
L	...	...	...	...	...	...	6	6	5	4	4
LT	8	8	8	7	6	6	5	5	5	4	4
ST	...	...	...	...	...	...	2	2	2	2	2
E, GPA	71.0										
EC, GPA	73.1										
G, GPA	26.9										
MU	0.33										
PHYSICAL PROPERTIES:											
OMEGA, MG/M3	2.74										
C, J/(G*K)	0.96 (AT 373K)										
K, W/(M*K)	128(AT 298 K)										
ALPHA, 10-6 M/(M*K)	23.6 (293 TO 373 K)										

[a]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.

TABLE 3.7.4.0(C). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF CLAD 7079 ALUMINUM ALLOY (SHEET)

SPECIFICATION	MIL-A-8923											
FORM	SHEET											
TEMPER	T6								T62[b]			
THICKNESS, MM	0.38-1.00		1.01-1.58		1.59-4.76		4.77-6.32		0.38-1.00	1.01-1.58	1.59-4.76	4.77-6.32
BASIS	A	B	A	B	A	B	A	B	S	S	S	S
MECHANICAL PROPERTIES:												
FTU, MPA:												
L	455	469	476	490	483	496	490	503	...	...	...	...
LT	455	469	476	490	483	496	490	503	448	462	469	483
FTY, MPA:												
L	386	400	421	434	427	441	434	448	...	...	...	...
LT	386	400	414	427	421	434	427	441	386	400	407	414
FCY, MPA:												
L	393	407	421	434	427	441	434	448	...	...	...	...
LT	407	421	441	455	448	462	455	469	...	...	...	...
FSU, MPA	269	276	283	290	290	296	290	303	...	...	...	...
FBRU[a] MPA:												
(E/D=1.5)	703	724	736	758	745	772	758	779	...	...	...	...
(E/D=2.0)	910	938	952	979	965	993	979	1010	...	...	...	...
FBRY[a] MPA:												
(E/D=1.5)	579	600	621	641	627	648	641	662	...	...	...	...
(E/D=2.0)	676	696	724	745	738	758	745	772	...	...	...	...
EL, PERCENT:												
L	7	...	8	...	8	...	8	...	...	...	...	...
LT	7	...	8	...	8	...	8	...	7	8	6	6
E, GPA:												
PRIMARY	71.0				71.0		71.0		71.0		71.0	71.0
SECONDARY	65.5				67.6		68.9		65.5		67.6	68.9
EC, GPA:												
PRIMARY	72.4				72.4		72.4		72.4		72.4	72.4
SECONDARY	66.9				68.9		70.3		66.9		68.9	70.3
G, GPA	26.9				26.9		26.9		26.9		26.9	26.9
MU	0.33				0.33		0.33		0.33		0.33	0.33
PHYSICAL PROPERTIES:												
OMEGA, MG/M3	2.74											
C, J/(G*K)	0.96 (AT 273 K)											
K, W/(M*K)	128 (AT 298 K)											
ALPHA, 10-6 M/(M*K)	23.6 (293 TO 373 K)											

[a]BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

[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.

TABLE 3.7.4.0(D). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF ONE-SIDE CLAD 7079 ALUMINUM ALLOY (SHEET)

SPECIFICATION	QQ-A-250/23								
FORM	SHEET								
TEMPER	T6					T62[b]			
THICKNESS, MM	0.51-1.00	1.01-1.58	1.59-4.76		4.77-6.32	0.51-1.00	1.01-1.58	1.59-4.76	4.77-6.32
BASIS	S	S	A	B	S	S	S	S	S
MECHANICAL PROPERTIES:									
FTU, MPA:									
L	476	[illegible]	496	510	496	...	...	...	...
LT	476	490	496	510	496	469	476	433	490
FTY, MPA:									
L	414	434	441	455	441	...	...	...	...
LT	414	427	434	448	434	400	414	414	421
FCY, MPA:									
L	421	434	441	455	441	...	...	...	...
LT	434	455	462	476	462	...	...	...	...
FSU, MPA	283	290	296	303	296	...	...	...	...
FBRU[a], MPA:									
(E/D=1.5)	710	731	745	765	745	...	...	...	...
(E/D=2.0)	903	931	945	972	945	...	...	...	...
FBRY[a], MPA:									
(E/D=1.5)	579	600	607	627	607	...	...	...	...
(E/D=2.0)	662	683	696	717	696	...	...	...	...
EL, PERCENT:									
L	7	8	8	...	8	...	...	...	...
LT	7	8	8	...	8	7	8	6	8
E, GPA:									
PRIMARY	71.0		71.0		71.0	71.0		71.0	71.0
SECONDARY	68.9		69.6		70.3	68.9		69.6	70.3
EC, GPA:									
PRIMARY	72.4		72.4		72.4	72.4		72.4	72.4
SECONDARY	70.3		71.0		71.7	70.3		71.0	71.7
G, GPA	26.9		26.9		26.9	26.9		26.9	26.9
MU	0.33		0.33		0.33	0.33		0.33	0.33
PHYSICAL PROPERTIES:									
OMEGA, MG/M3	2.74								
C, J/(G*K)	0.96 (AT 373 K)								
K, W/(M*K)	128 (AT 298 K)								
ALPHA, 10-6 M/(M*K)	23.6 (293 TO 373 K)								

[a] BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.
[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.

TABLE 3.7.4.0(E). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 7011 CLAD 7079 ALUMINUM ALLOY (SHEET AND PLATE)

SPECIFICATION	QQ-A-00250/27									
FORM	SHEET		PLATE		SHEET AND PLATE					
TEMPER	T6		T651		T62[a]					
THICKNESS, MM	0.38-1.00	1.01-6.33	6.34-12.68	12.69-25.40[b]	0.38 1.00-	1.01-1.58	1.59-4.76	4.77-6.33	6.34 12.68	12.69-25.40[b]
BASIS	S	S	S	S	S	S	S	S	S	S
MECHANICAL PROPERTIES:										
FTU, MPA:										
L	476	496	490	490	...	...	...	...	...	...
LT	476	496	503	503	469	476	483	490	496	496
FTY, MPA:										
L	414	441	448	448	...	...	...	...	...	...
LT	414	434	441	441	407	414	421	421	427	421
FCY, MPA:										
L	421	441	441	434	...	...	...	...	...	...
LT	441	462	462	462	...	...	...	...	...	...
FSU, MPA	283	296	299	290	...	...	...	...	...	...
FBRU[c] MPA:										
(E/D=1.5)	710	745	786	786	...	...	...	...	...	...
(E/D=2.0)	903	945	993	993	...	...	...	...	...	...
FBRY[c] MPA:										
(E/D=1.5)	579	607	669	669	...	...	...	...	...	...
(E/D=2.0)	662	696	779	779	...	...	...	...	...	...
EL, PERCENT:										
L	7	8	...	...	...	...	...	...	...	...
LT	7	8	8	8	7	8	8	8	8	8
E, GPA	71.0		71.0		71.0				71.0	
EC, GPA	72.4		73.1		72.4				73.1	
G, GPA	26.9		26.9		26.9				26.9	
MU	0.33		0.33		0.33				0.33	
PHYSICAL PROPERTIES:										
OMEGA, MG/M3	2.74									
C, J/(G*K)	0.96 (AT 373 K)									
K, W/(M*K)	128 (AT 298 K)									
ALPHA, 10-6 M/(M*K)	23.6 (293 TO 373 K)									

[a]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.

[b]THESE VALUES HAVE BEEN ADJUSTED TO REPRESENT THE AVERAGE PROPERTIES ACROSS THE WHOLE SECTION, INCLUDING 1-1/2 PERCENT PER SIDE NOMINAL CLADDING THICKNESS.

[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(F). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 7079 ALUMINUM ALLOY (DIE FORGINGS)

SPECIFICATION	MIL-A-22771											
FORM	DIE FORGINGS											
CONDITION	T6						T652					
THICKNESS,[c] MM	≤ 25.41	25.42-50.81	50.82-76.21	76.22-101.61	101.62-127.01	127.02-152.40	≤25.41	25.42-50.81	50.82-76.21	76.22-101.61	101.62-127.01	127.02-152.40
BASIS	S	S	S	S	S	S	S	S	S	S	S	S
MECHANICAL PROPERTIES:												
FTU, MPA:												
L	496	496	490	490	483	483	496	496	490	490	463	483
T[a]	490	483	483	483	469	469	490	463	483	483	469	469
FTY, MPA:												
L	427	427	421	421	414	407	427	427	421	421	414	407
T	421	414	414	414	400	400	421	414	414	414	400	400
FCY, MPA:												
L	448	448	441	441	434	421	434	434	427	427	421	407
T	441	434	434	434	421	421	448	441	441	441	427	427
FSU, MPA	290	290	290	290	263	263	290	290	290	290	263	283
FBRU,[b] MPA:												
(E/D=1.5)	696	696	683	683	676	676	696	696	683	683	676	676
(E/D=2.0)	896	896	883	883	869	869	896	896	883	883	869	869
FBRY,[b] MPA:												
(E/D=1.5)	558	558	545	545	536	531	558	558	545	545	538	531
(E/D=2.0)	641	641	627	627	621	607	641	641	627	627	621	607
EL, PERCENT:												
L	7	7	7	7	7	7	7	7	7	7	7	7
T	5	5	4	4	3	3	5	5	4	4	3	3
E, GPA	68.9											
EC, GPA	71.7											
G, GPA	26.2											
MU	0.33											
PHYSICAL PROPERTIES	0.099											
OMEGA, MG/M3	2.74											
C, J/(G*K)	0.96 (AT 373 K)											
K, W/(M*K)	128 (AT 298 K)											
ALPHA, 10-6 M/(M*K)	23.6 (293 TO 373 K)											

[a]FOR DIE FORGINGS, T INDICATES ANY GRAIN DIRECTION NOT WITHIN ± 15 DEGREES OF BEING PARALLEL TO THE FORGING FLOW LINES. SPECIMENS TO TEST TRANSVERSE PROPERTIES SHOULD BE LOCATED AS CLOSE TO THE SHORT TRANSVERSE DIRECTION AS POSSIBLE.

[b]BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

[c]THE THICKNESS COLUMNS ARE FOR THE AS-HEAT-TREATED THICKNESS. TO ENTER THE TABLE USE THE HIGHER OF THE HEAT-TREAT THICKNESS OR ONE-HALF OF THE AS-FORGED THICKNESS.

TABLE 3.7.4.0(G). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 7079 ALUMINUM ALLOY (HAND FORGINGS)

SPECIFICATION	MIL-A-22771													
FORM	HAND FORGINGS[a]													
TEMPER	T6							T652						
THICKNESS, MM	≤50.81	50.82-76.21	76.22-101.61	101.62-127.01	127.02-152.41	152.42-177.81	177.82-203.20	<50.81	50.82-76.21	76.22-101.61	101.62-127.01	127.02-152.41	152.42-177.81	177.82-203.20
BASIS	S	S	S	S	S	S	S	S	S	S	S	S	S	S
MECHANICAL PROPERTIES:														
FTU, MPA:														
L	496	496	490	483	476	469	462	496	496	490	483	476	469	462
LT	490	483	483	476	469	462	455	490	483	483	476	469	462	455
ST	...	462	462	455	455	448	441	...	462	462	455	455	448	441
FTY, MPA:														
L	434	427	421	414	407	400	393	434	427	421	414	407	400	393
LT	421	414	407	400	386	372	365	421	414	407	400	386	372	359
ST	...	386	386	379	372	365	359	...	379	379	372	365	352	345
FCY, MPA:														
L	455	448	441	434	427	...	...	441	434	427	421	414	...	...
LT	...	...	...	...	...	...	...	448	441	434	427	414	...	...
ST	...	...	...	...	...	...	...	...	427	427	421	414	...	...
FSU, MPA	296	296	296	290	283	...	...	296	290	290	283	283	...	...
FBRU[b], MPA:														
(E/D=1.5)	648	648	634	627	621	...	...	703	689	689	683	676	...	...
(E/D=2.0)	841	841	834	821	807	...	...	931	917	917	910	896	...	...
FBRY[b], MPA:														
(E/D=1.5)	565	558	545	538	531	...	...	621	614	600	593	572	...	...
(E/D=2.0)	648	641	627	621	607	...	...	724	710	696	683	662	...	...
EL, PERCENT:														
L	9	9	9	9	9	9	9	9	9	9	9	9	9	9
LT	5	5	5	4	4	4	4	5	5	5	4	4	4	4
ST	...	4	4	4	4	4	4	...	3	3	3	3	3	3
E, GPA	68.9													
EC, GPA	71.7													
G, GPA	26.2													
MU	0.33													
PHYSICAL PROPERTIES:														
OMEGA, MG/M3	2.74													
C, J/(G*K)	0.96 (AT 373 K)													
K, W/(M*K)	128 (AT 298 K)													
ALPHA, 10-6 M/(M*K)	23.6 (293 TO 373 K)													

[a]WHEN HAND FORGINGS ARE MACHINED BEFORE HEAT TREATMENT, THE SECTION THICKNESS AT TIME OF HEAT TREATMENT SHALL 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 1650 SQ CM.

[b]BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

TABLE 3.7 4.0(H). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 7079 ALUMINUM ALLOY (EXTRUSIONS)

SPECIFICATION..........	QQ-A-200/12													
FORM..................	EXTRUDED BAR, ROD, AND SHAPES													
TEMPER................	T6, T6510[a], T6511[a], AND T62[c]													
THICKNESS, MM..........	≤6.33	6.34-12.68	12.69-38.08	38.09-76.18	76.19-114.28			114.29-127.01			127.02-152.38		152.39-177.77	
CROSS-SECTIONAL AREA, MM2	<12900				<12900	>12900 <20650	>20650 <32260	<20650	>20650 <24520	>24520 <38710	<24520	>24520 <38710	<32260	>32260 <38710
BASIS..................	S	S	S	S	S	S	S	S	S	S	S	S	S	S
MECHANICAL PROPERTIES:														
FTU, MPA:														
L..................	517	531	538	545	545	531	524	538	538	524	538	524	524	510
LT.................	462	476	483	483	483	469	469	462	455	448	440	448	443	434
FTY, MPA:														
L..................	462	469	483	483	483	483	469	469	469	469	469	469	455	441
LT.................	407	414	421	427	427	414	414	400	393	386	366	386	372	359
FCY, MPA:														
L..................	455	462	476	490	490	490	476	476	476	476	476	476	455	441
LT.................	441	448	462	455	455	441	441	427	427	421	427	421	460	386
FSU, MPA.............	276	283	283	296	296	290	290	296	296	290	296	290	290	283
FBRU[b], MPA:														
(E/D=1.5)..........	745	758	772	655	655	634	627	648	648	627	648	627	627	614
(E/D=2.0)..........	938	965	972	869	869	848	841	862	862	841	862	841	841	814
FBRY[b], MPA:														
(E/D=1.5)..........	621	600	586	531	531	531	517	517	517	517	517	517	503	483
(E/D=2.0)..........	710	689	669	676	676	676	655	655	655	655	655	655	634	621
EL, PERCENT:														
L..................	7	7	7	7	7	7	7	6	6	6	6	6	6	4
LT.................	5	6	5	4	3	3	3	3	3	3	3	2	2	2
E, GPA................	71.7													
EC, GPA...............	73.8													
G, GPA................	27.6													
MU....................	0.33													
PHYSICAL PROPERTIES:														
OMEGA, MG/M3..........	2.74													
C, J/(G*K)............	0.96 (AT 374 K)													
K, W/(M*K)............	128 (AT 298 K)													
ALPHA, 10-6 M/(M*K)...	23.4 (293 TO 373 K)													

[a] FOR THICKNESSES GREATER THAN 38.07 ALL VALUES ARE APPLICABLE TO THE T6510 AND T6511 TEMPERS EXCEPT FCY (L), WHICH MAY BE LOWER THAN THE VALUES INDICATED.

[b] BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

[c] THE ALLOWABLES SHOWN FOR THESE TEMPERS ARE BASED ON AND HAVE BEEN DETERMINED FROM THE RESULTS OBTAINED ON TESTING OF T6, T6510, AND T6511 TEMPER MATERIAL AND ON THE TESTING OF T62 TEMPER SAMPLES FOR SPECIFICATION CONFORMANCE. THESE ALLOWABLES ALSO APPLY WHEN SAMPLES OF MATERIAL SUPPLIED IN THE O OF 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 OF OTHERWISE COLD OR HOT WORKED, PARTICULARLY IN THE ANNEALED TEMPER, PRIOR TO SOLUTION HEAT TREATMENT.

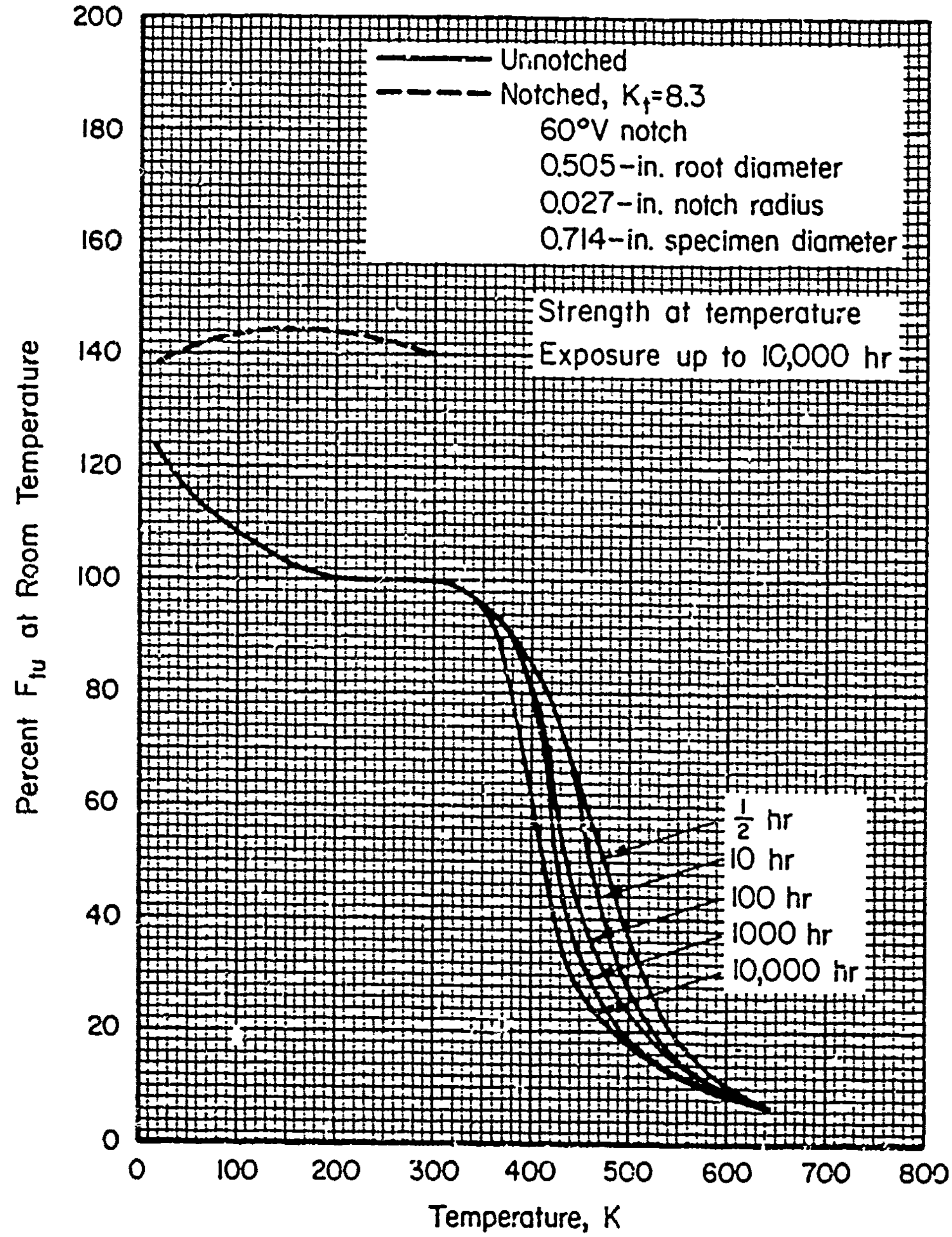


FIGURE 3.7.4.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of 7079 aluminum alloy.

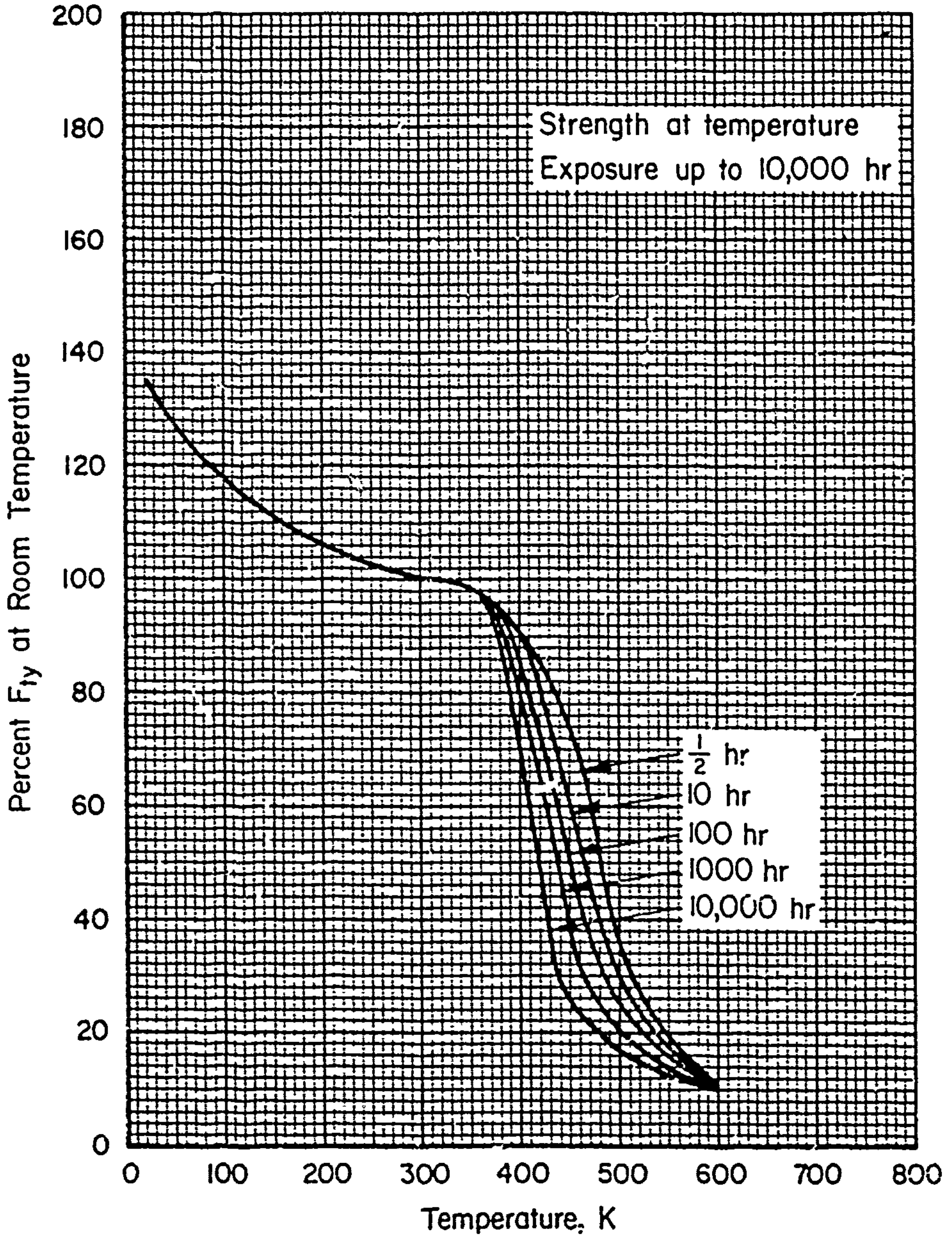


FIGURE 3.7.4.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of 7079 aluminum alloy.

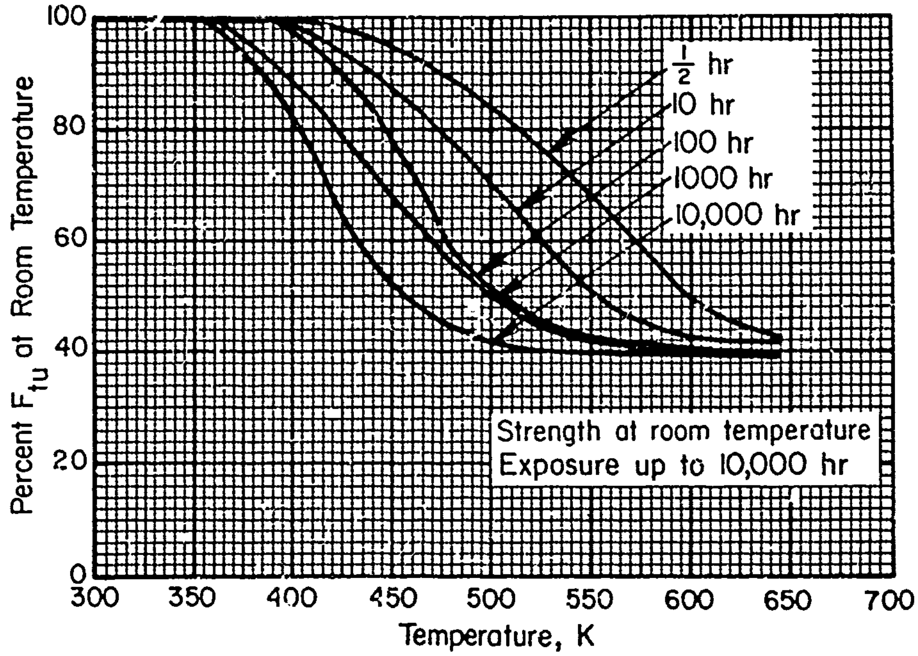


FIGURE 3.7.4.1.1(c). Effect of exposure at elevated temperatures on the room-temperature ultimate tensile strength (F_{tu}) of 7079-T6 aluminum alloy (hand forgings).

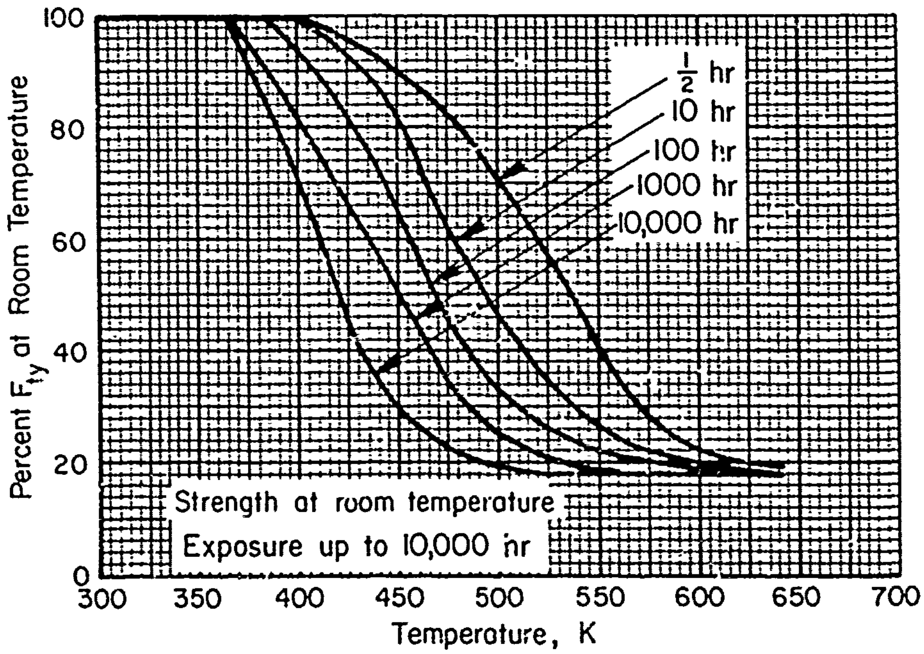


FIGURE 3.7.4.1.1(d). Effect of exposure at elevated temperatures on the room-temperature tensile yield strength (F_{ty}) of 7079-T6 aluminum alloy (hand forgings).

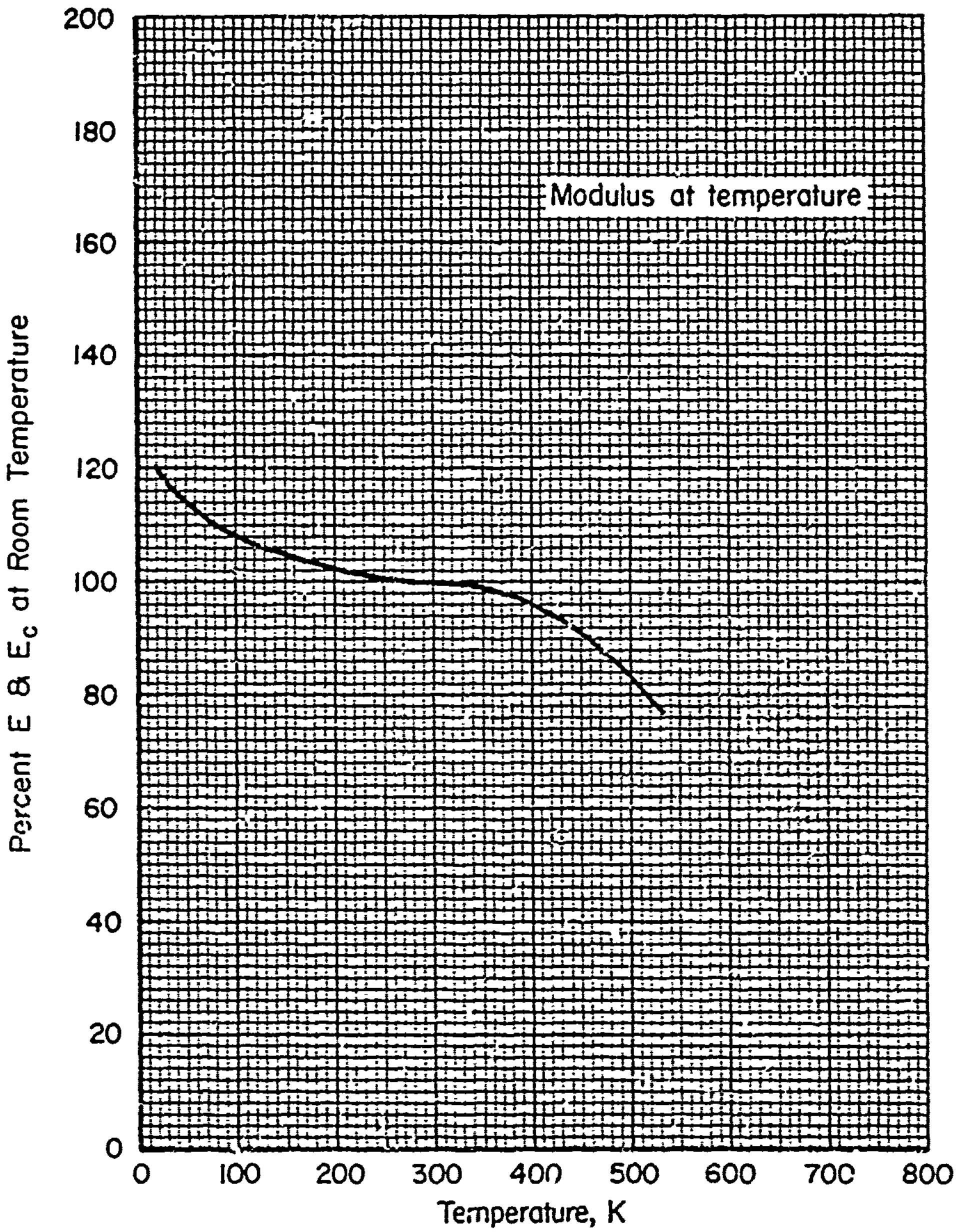


FIGURE 3.7.4.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of 7079 aluminum alloy.

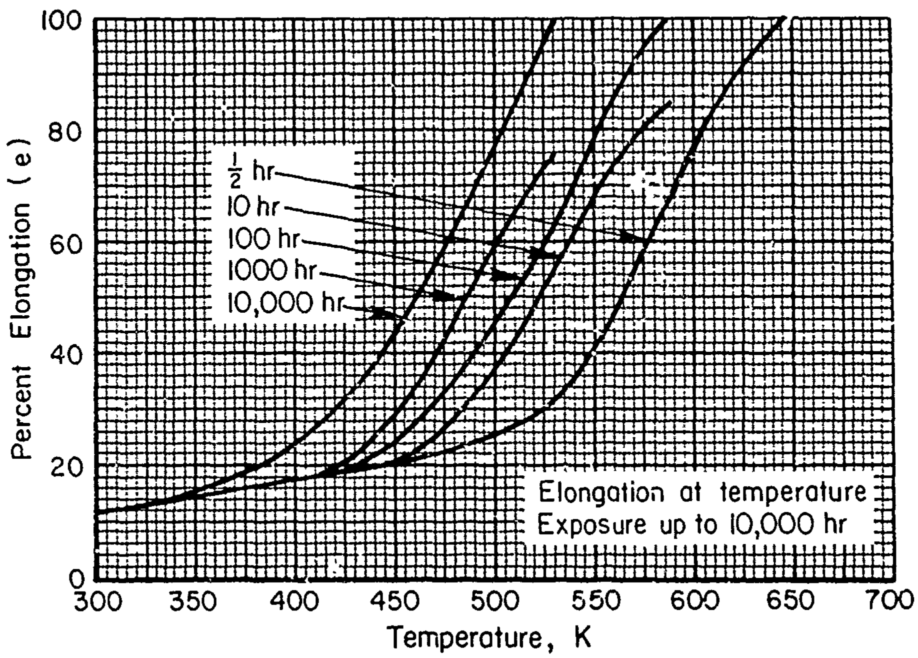


FIGURE 3.7.4.1.5(a). Effect of temperature on the elongation of 7079-T6 aluminum alloy (hand forgings).

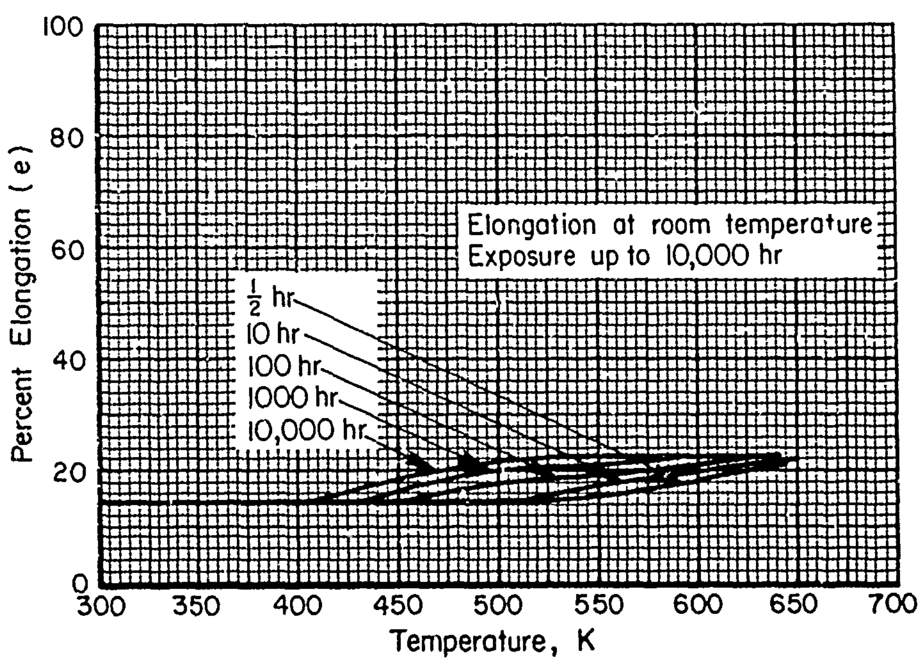


FIGURE 3.7.4.1.5(b). Effect of exposure at elevated temperatures on the elongation of 7079-T6 aluminum alloy (hand forgings).

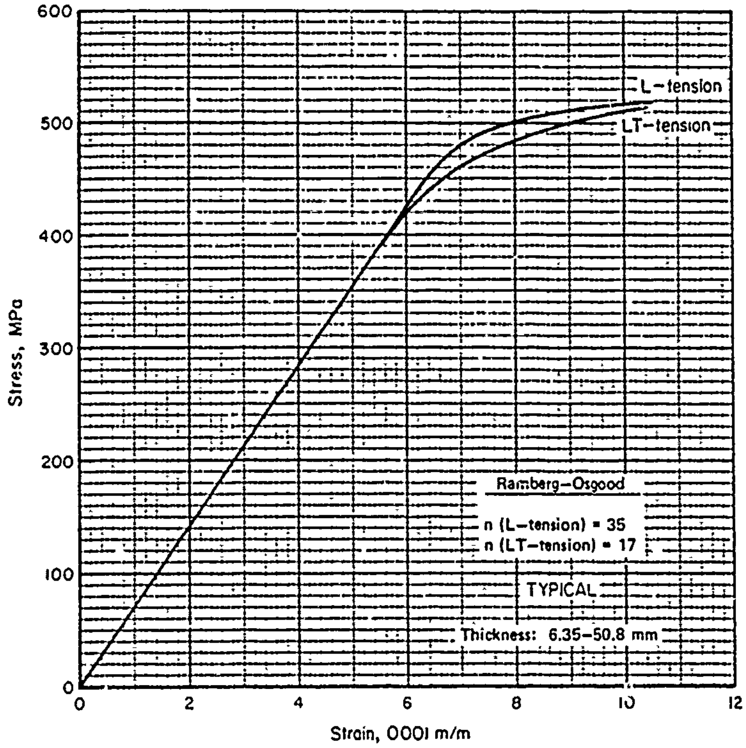


FIGURE 3.7.4.1.6(a). Typical tensile stress-strain curves for 7079-T651 aluminum alloy (plate) at room temperature.

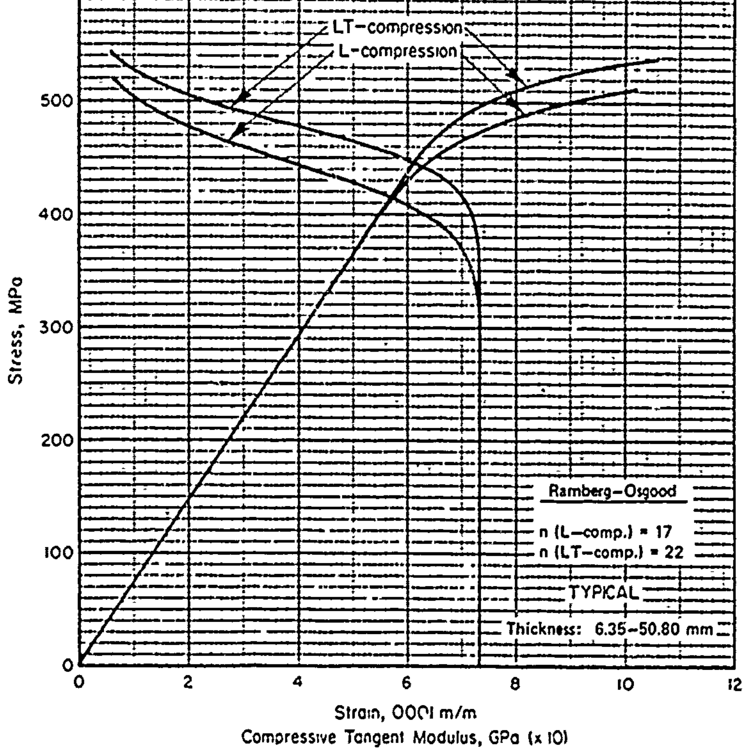


FIGURE 3.7.4.1.6(b). Typical compressive stress-strain and tangent-modulus curves for 7079-T651 aluminum alloy (plate) at room temperature.

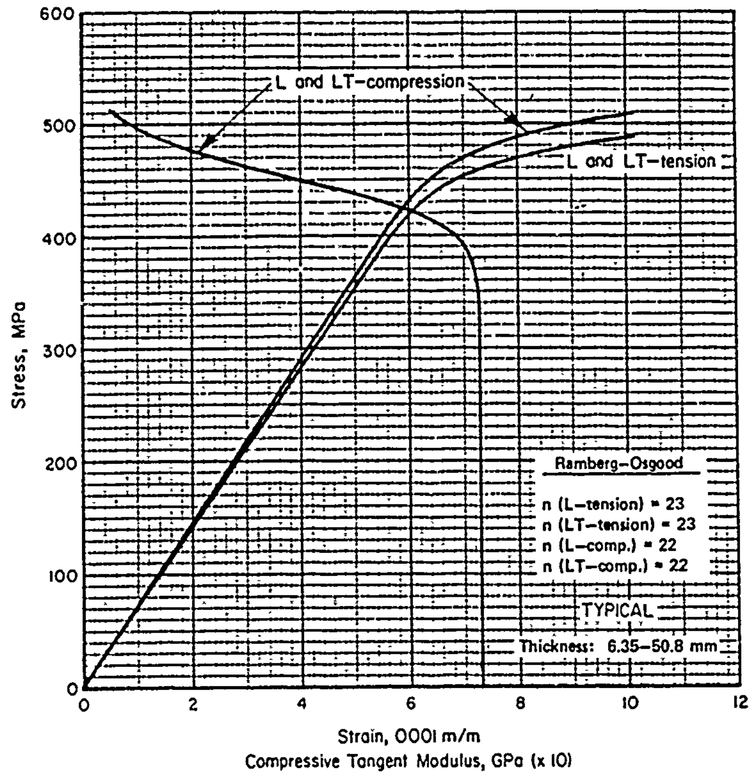


FIGURE 3.7.4.1.6(c). Typical tensile stress-strain and compressive stress-strain and tangent-modulus curves for 7079-T62 aluminum alloy (plate) at room temperature.

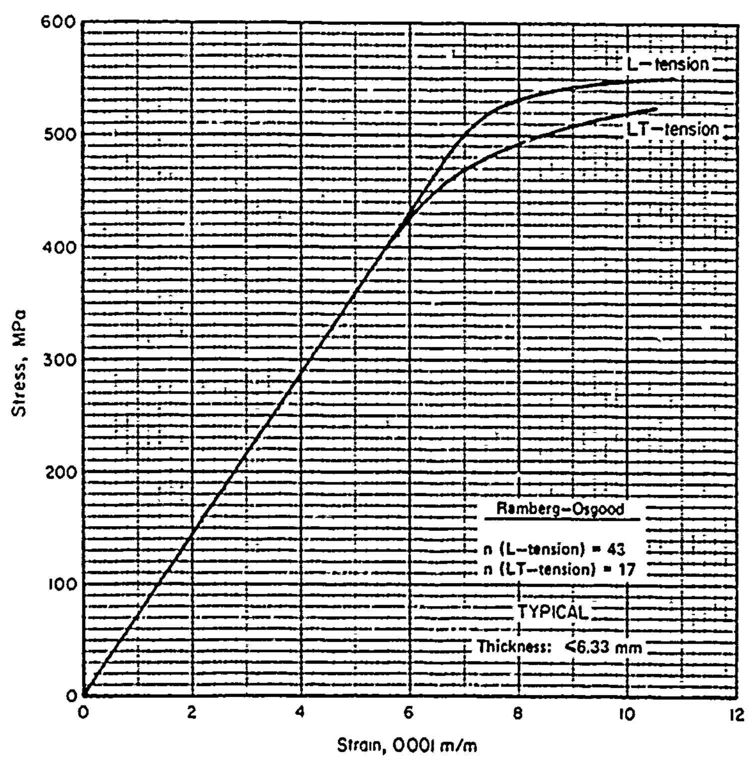


FIGURE 3.7.4.1.6(d). Typical tensile stress-strain curves for 7079-T6511X aluminum alloy (extrusion) at room temperature.

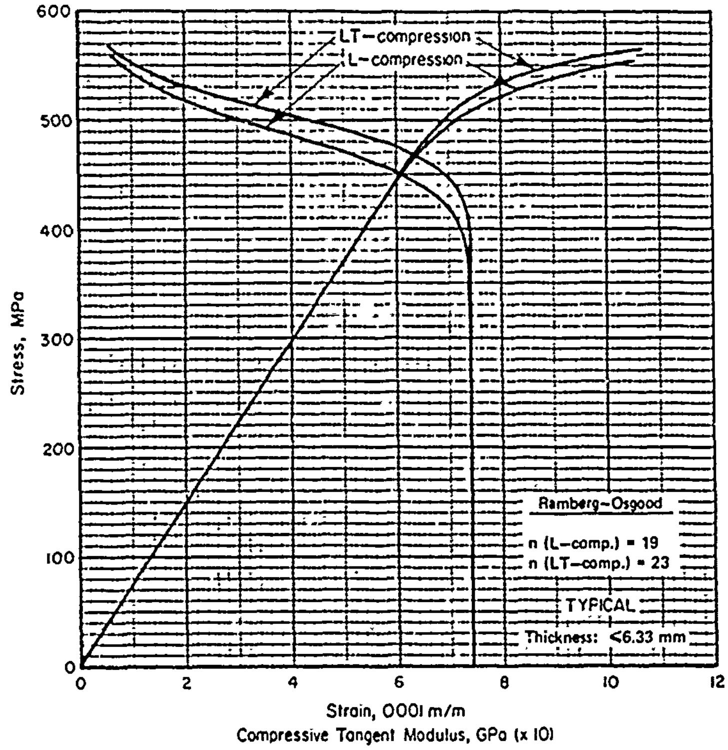


FIGURE 3.7.4.1.6(e). Typical compressive stress-strain and tangent-modulus curves for 7079-T651X aluminum alloy (extrusion) at room temperature.

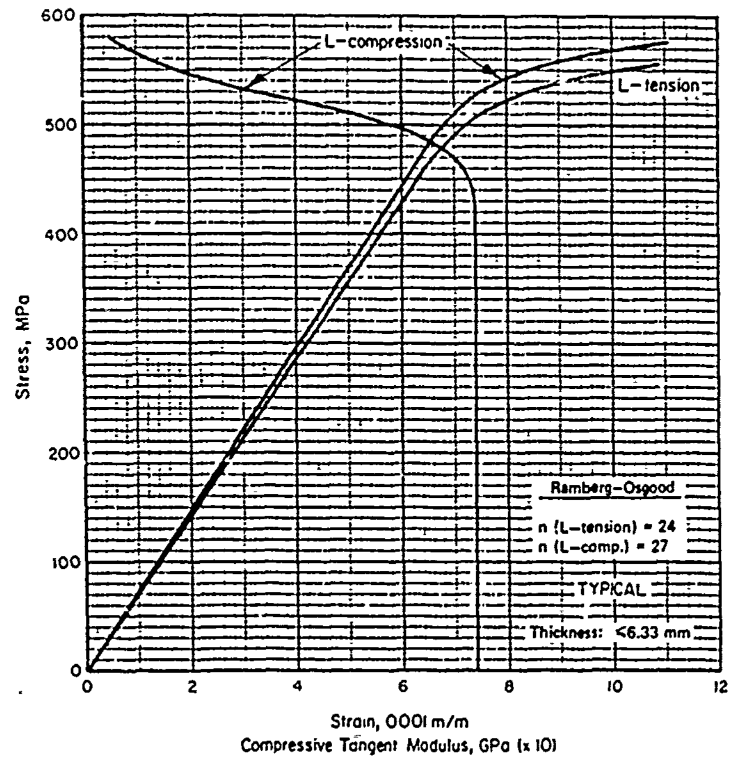


FIGURE 3.7.4.1.6(f). Typical tensile stress-strain and compressive stress-strain and tangent-modulus curves for 7079-T652 aluminum alloy (extrusion) at room temperature

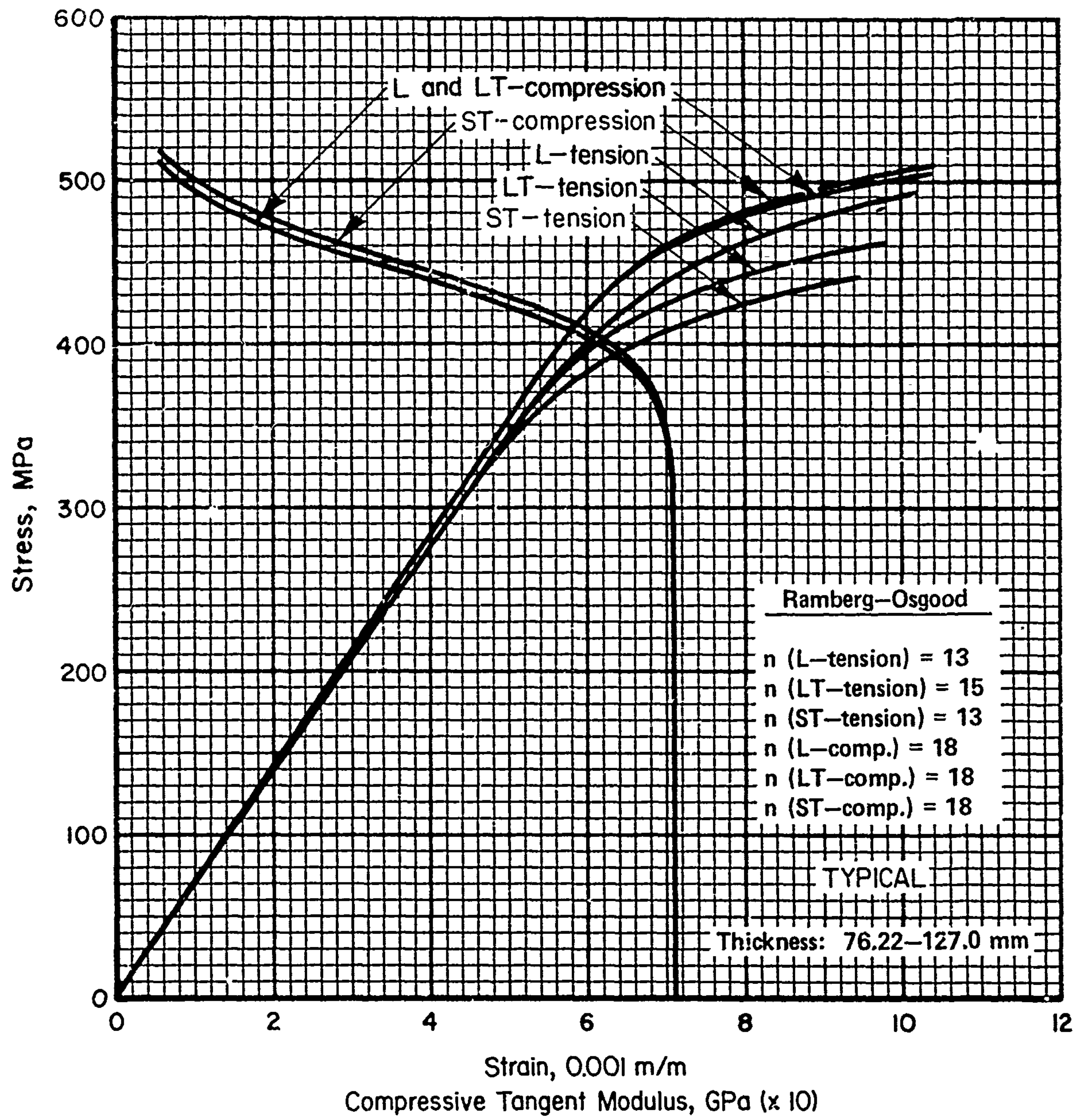


FIGURE 3.7.4.1.6(g). Typical tensile stress-strain and compressive stress-strain and tangent-modulus curves for 7079-T652 aluminum alloy (hand forging) at room temperature.

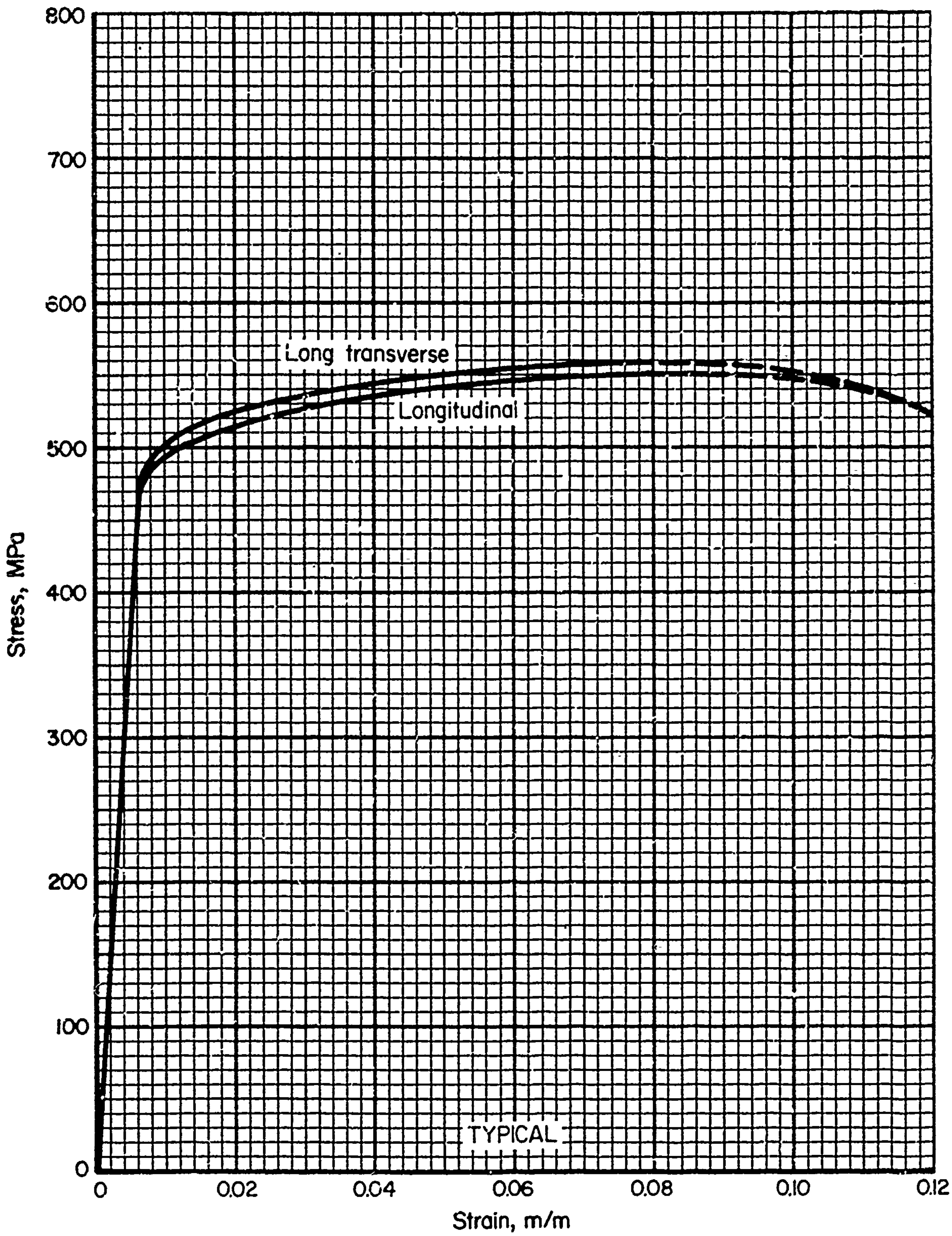


FIGURE 3.7.4.1.6(h). Typical tensile stress-strain curves (full range) for 7079-T651 aluminum alloy (plate) at room temperature.

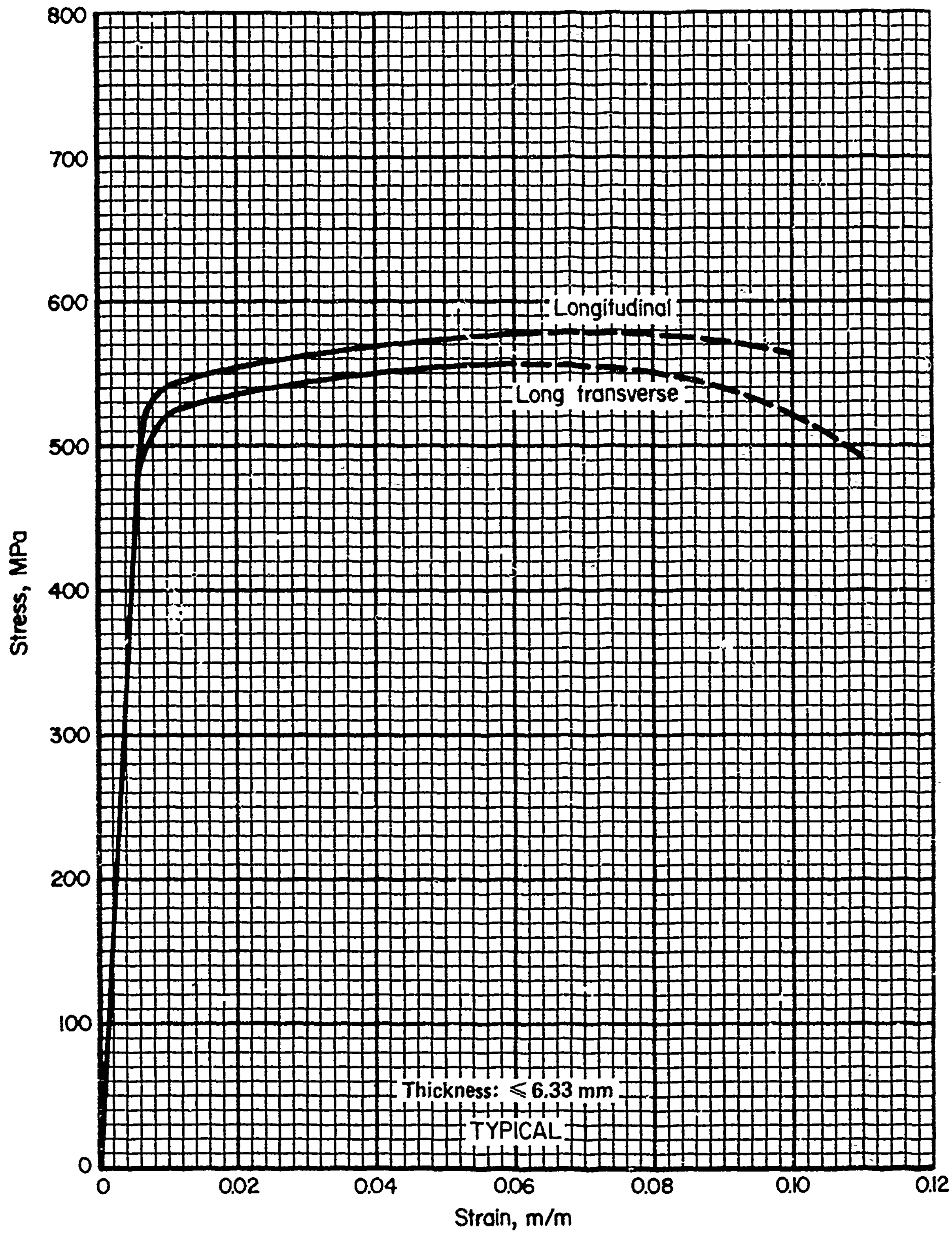


FIGURE 3.7.4.1.6(i). Typical tensile stress-strain curves (full range) for 7079-T651X aluminum alloy (extrusion) at room temperature.

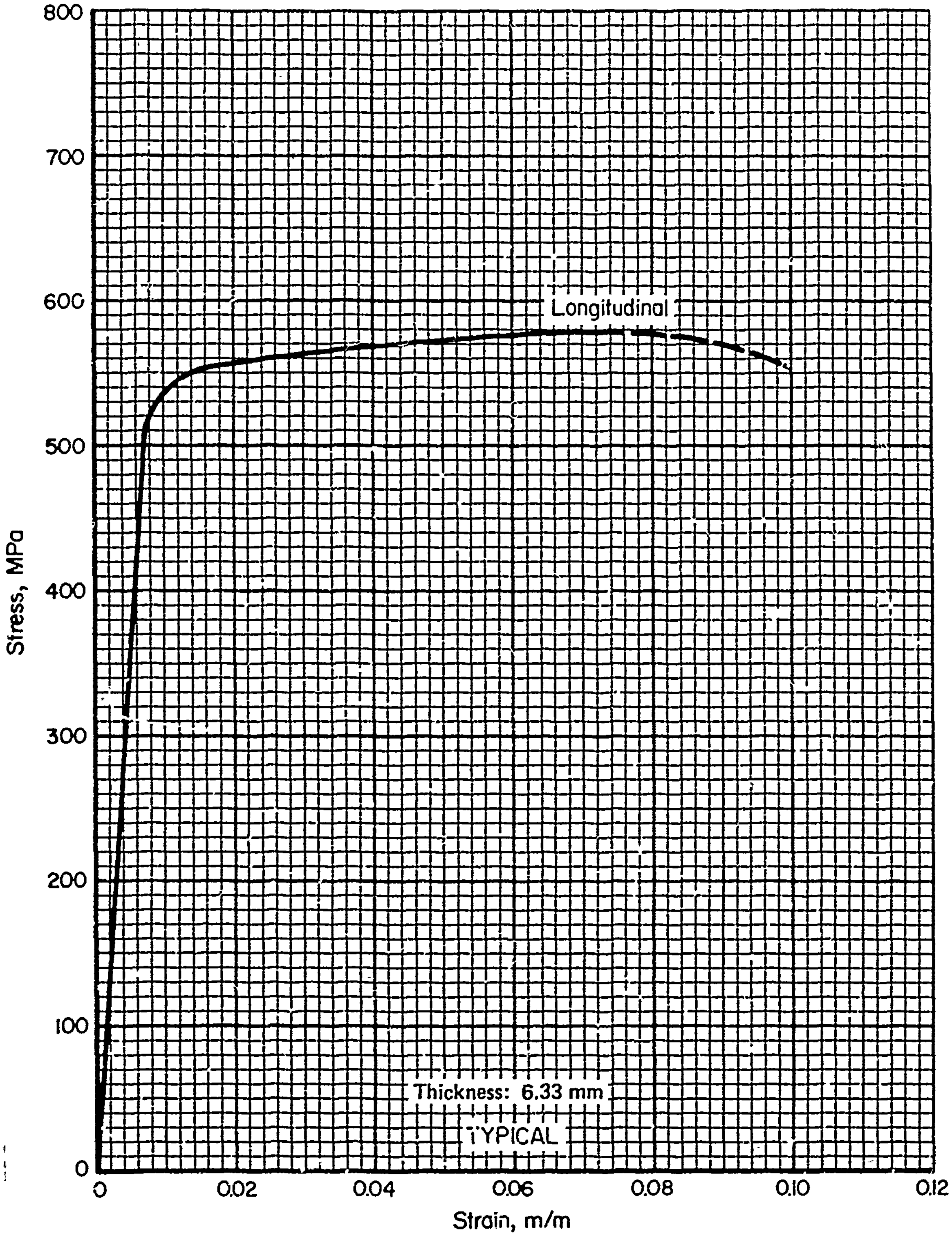


FIGURE 3.7.4.1.6(j). Typical tensile stress-strain curve (full range) for 7079-T62 aluminum alloy (extrusion) at room temperature.

3.7.5 7175 ALLOY

3.7.5.0 *Comments and Properties.*—7175 is a high-strength Al-Zn-Mg-Cu alloy available only in the form of die and hand forgings. Die forgings are available in the T66 and T736 tempers, while hand forgings are available in the T736 and T73652 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-T736-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 plus high resistance 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 7175 die and hand forgings are presented in Table 3.7.5.0(a). Room-temperature mechanical and physical properties for 7175-T66 and T736 die forgings and 7175-T736 and T73652 hand forgings are shown in Tables 3.7.5.0(b) and (c).

TABLE 3.7.5.0(a). *Material Specifications for 7175 Aluminum Alloy*

Specification	Form
AMS 4148 (T66)	Die forgings
AMS 4149 (T736)	Die forgings
AMS 4109 (T736)	Hand forgings
AMS 4179 (T73652)	Hand forgings

The temper index for 7175 is as follows:

Section	Temper
3.7.5.1	T66
3.7.5.2	T736, T73652

3.7.5.1 *T66 Temper*

3.7.5.2 *T736 and T73652 Tempers.*—Figures 3.7.5.2.6(a) through (d) present tensile and compressive stress-strain and tangent-modulus curves for die and hand forgings.

TABLE 3.7.5.0(8). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 7175 ALUMINUM ALLOY (DIE FORGINGS)

SPECIFICATION	AMS 4148	AMS 4149		
FORM	DIE FORGINGS			
CONDITION	T66	T736		
THICKNESS, MM	≤76.20	≤25.41	25.42–50.81	50.82–76.20
BASIS	S	S	S	S
MECHANICAL PROPERTIES:				
FTU, MPA:				
L	593	524	524	524
T	531	490	490	490
FTY, MPA:				
L	524	455	455	455
T	455	427	427	427
FCY, MPA:				
L	...	462	462	462
T	...	448	441	434
FSU, MPA	...	296	296	296
FBRU, MPA:				
(E/D=1.5)	...	731	731	731
(E/D=2.0)	...	965	965	965
FBRY, MPA:				
(E/D=1.5)	...	593	593	593
(E/D=2.0)	...	703	703	703
EL, PERCENT:				
L	7	7	7	7
T	4	4	4	4
E, GPA	70.3			
EC, GPA	73.8			
G, GPA	26.9			
MU	0.33			
PHYSICAL PROPERTIES:				
OMEGA, MG/M3	2.80			
C, J/(G*K)	0.96 (AT 373 K)			
K, W/(M*K)	132 (AT 298 K FOR T66); 156 (AT 298 K FOR T36)			
ALPHA, 10-6 M/(M*K)	23.2 (293 TO 373 K)			

[a] FOR DIE FORGINGS, T INDICATES ANY GRAIN DIRECTION NOT WITHIN ± 15 DEGREES OF BEING PARALLEL TO THE FORGING FLOW LINES. SPECIMENS TO TEST TRANSVERSE PROPERTIES SHOULD BE LOCATED AS CLOSE TO THE SHORT TRANSVERSE DIRECTION AS POSSIBLE.

[b] BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

TABLE 3.7.5.0(C). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 7175 ALUMINUM ALLOY (HAND FORGINGS)

SPECIFICATION	AMS 4109				AMS 4179			
FORM	HAND FORGINGS[a]							
CONDITION	T736				T73652			
THICKNESS, MM	≤76.21	76.22-101.61	101.62-127.01	127.02-152.40	≤76.21	76.22-101.61	101.62-127.01	127.02-152.40
BASIS	S	S	S	S	S	S	S	S
MECHANICAL PROPERTIES:								
FTU, MPA:								
L	503	490	469	448	490	469	448	434
LT	490	483	462	441	476	462	441	421
ST	476	469	455	434	462	448	434	414
FTY, MPA:								
L	434	421	393	372	421	393	372	352
LT	414	400	386	359	400	379	359	338
ST	414	393	379	359	372	352	338	317
FCY, MPA:								
L	441	427	400	...	...	...	...	...
LT	434	421	407	...	...	...	...	...
ST	434	414	400	...	...	...	...	...
FSU, MPA	290	283	269	...	...	...	...	...
FBRU,[b] MPA:								
(E/D=1.5)	710	696	689	...	...	...	..	...
(E/D=2.0)	931	917	876	...	...	...	...	...
FBRY,[b] MPA:								
(E/D=1.5)	579	558	538	...	...	...	...	...
(E/D=2.0)	683	662	634	...	...	...	...	...
EL, PERCENT:								
L	9	9	8	8	9	9	8	8
LT	5	5	5	5	5	5	5	5
ST	4	4	4	4	4	4	4	4
E, GPA	70.3							
EC, GPA	73.1							
G, GPA	26.9							
MU	0.33							
PHYSICAL PROPERTIES:								
OMEGA, MG/M3	2.80							
C, J/(G*K)	0.96 (AT 373 K)							
K, W/(M*K)	156 (AT 298 K)							
ALPHA, 10-6 M/(M*K)	23.2 (293 TO 373 K)							

[a]WHEN HAND FORGINGS ARE MACHINED BEFORE HEAT TREATMENT, THE SECTION THICKNESS AT TIME OF HEAT TREATMENT SHALL 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 1910 SQ. CM.

[b]BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

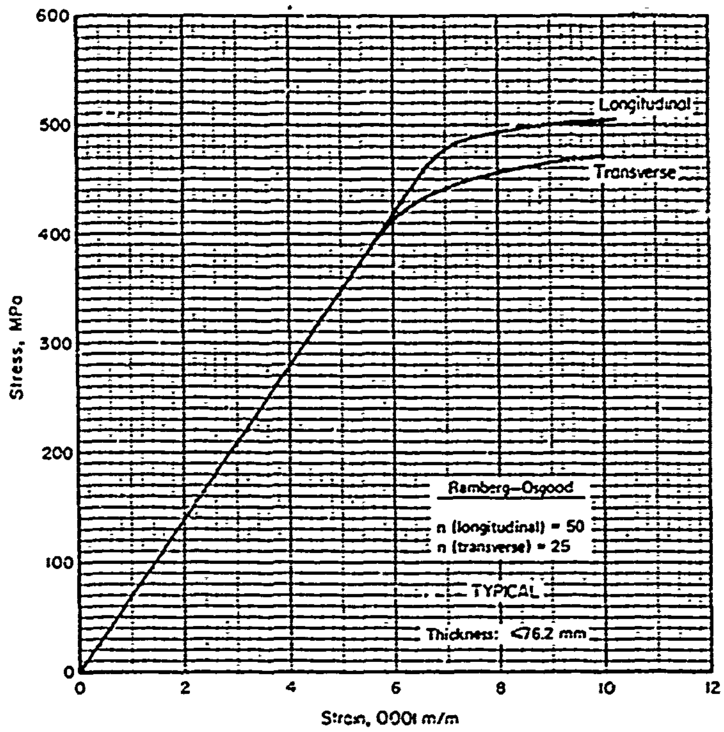


FIGURE 3.7.5.2.6(a). Typical tensile stress-strain curves for 7175-T736 aluminum alloy (die forgings) at room temperature.

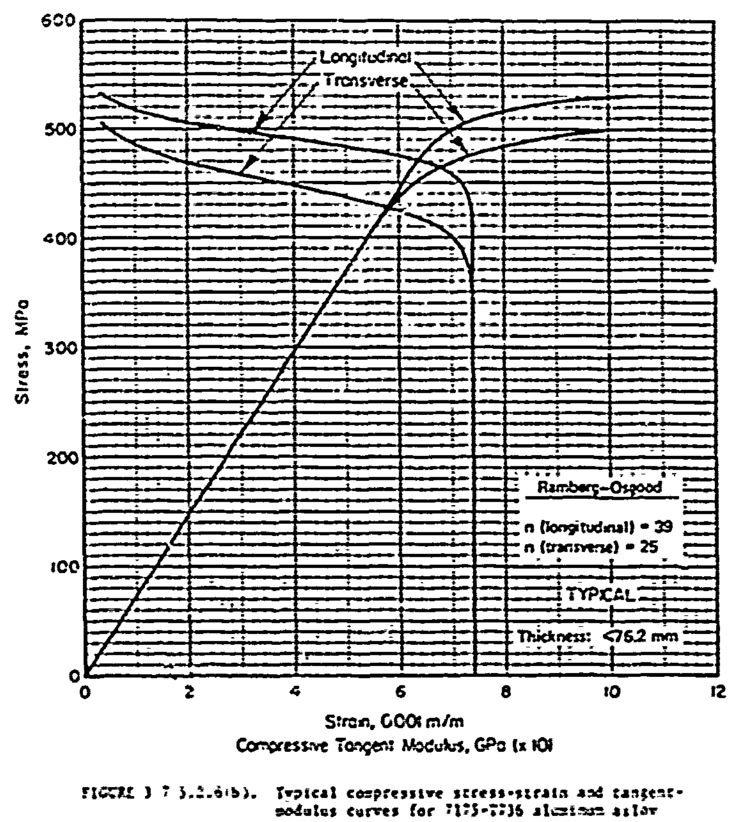


FIGURE 3.7.5.2.6(b). Typical compressive stress-strain and tangent-modulus curves for 7175-T736 aluminum alloy (die forgings) at room temperature.

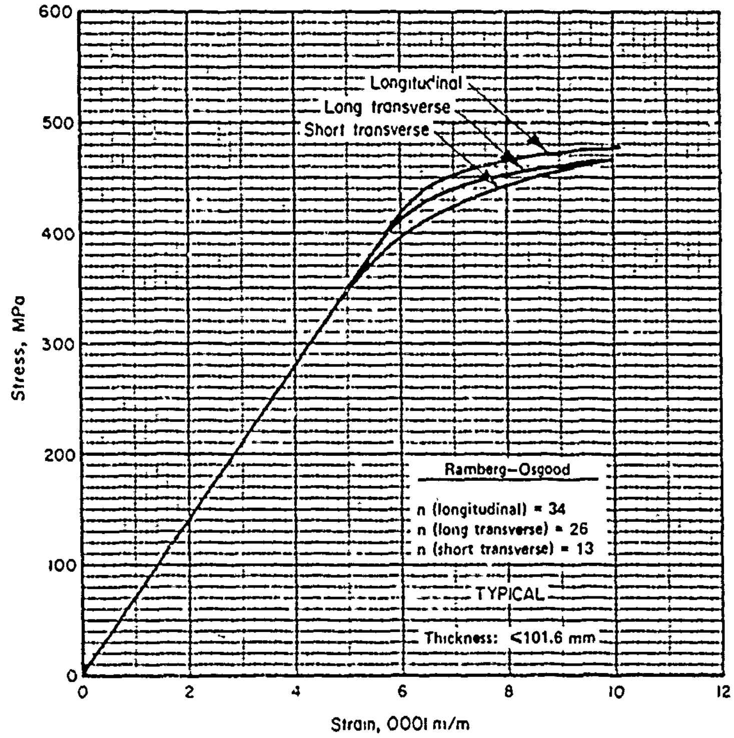


FIGURE 3.7.5.2.5(c). Typical tensile stress-strain curves for 7175-T736 aluminum alloy (hand forgings) at room temperature.

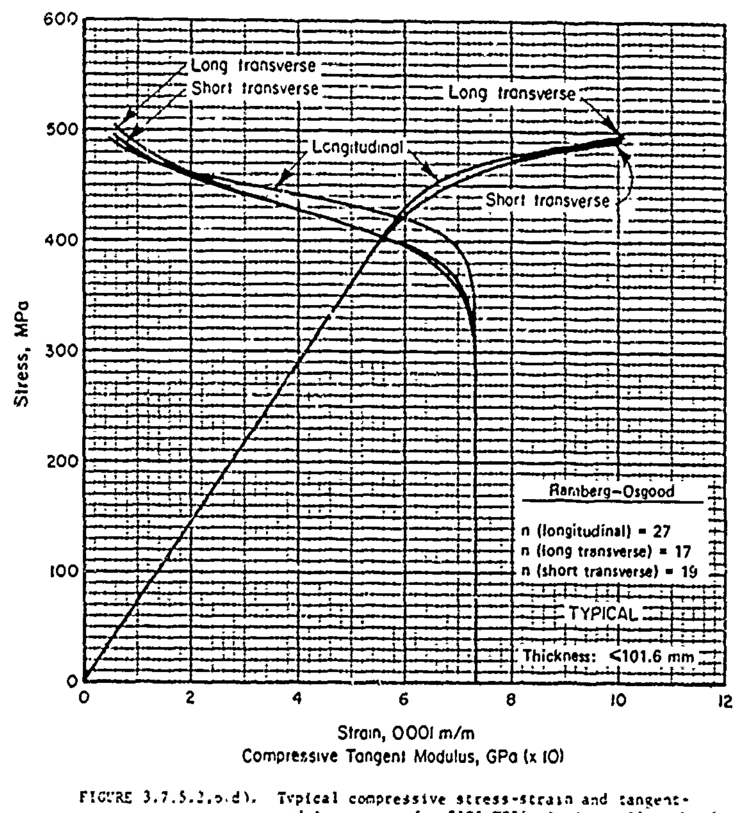


FIGURE 3.7.5.2.5(d). Typical compressive stress-strain and tangent-modulus curves for 7175-T736 aluminum alloy (hand forgings) at room temperature.

3.7.6 7178 ALLOY

3.7.6.0 *Comments and Properties.*—7178 is the highest-strength Al-Zn-Mg-Cu alloy available in a variety of product forms.

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 7178 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) through (c). The effect of temperature on thermal expansion is shown in Figure 3.7.6.0.

TABLE 3.7.6.0(a). *Material Specifications for 7178 Aluminum Alloy*

Specification	Form
QQ-A-250/14, 21	Bare sheet and plate
QQ-A-250/15, 22	Clad sheet and plate
QQ-A-200/13, 14	Extrusions
QQ-A-250/28	7011 clad sheet and plate

The temper index for 7178 is as follows:

Section	Temper
3.7.6.1	T6, T62, T651, T652, T6510, T6511
3.7.6.2	T76, T7651, T76510, T76511

3.7.6.1 *T6, T62, T651, T652, T6510, T6511 Tempers.*—Effect-of-temperature curves are presented for various mechanical properties in Figures 3.7.6.1.1(a) through 3.7.6.1.5.

Figures 3.7.6.1.6(a) through (l) present tensile and compressive stress-strain curves and tangent-modulus curves at room temperature for various products and tempers.

Figures 3.7.6.1.6(m) and (n) are full-range stress-strain curves for extrusions at room temperature.

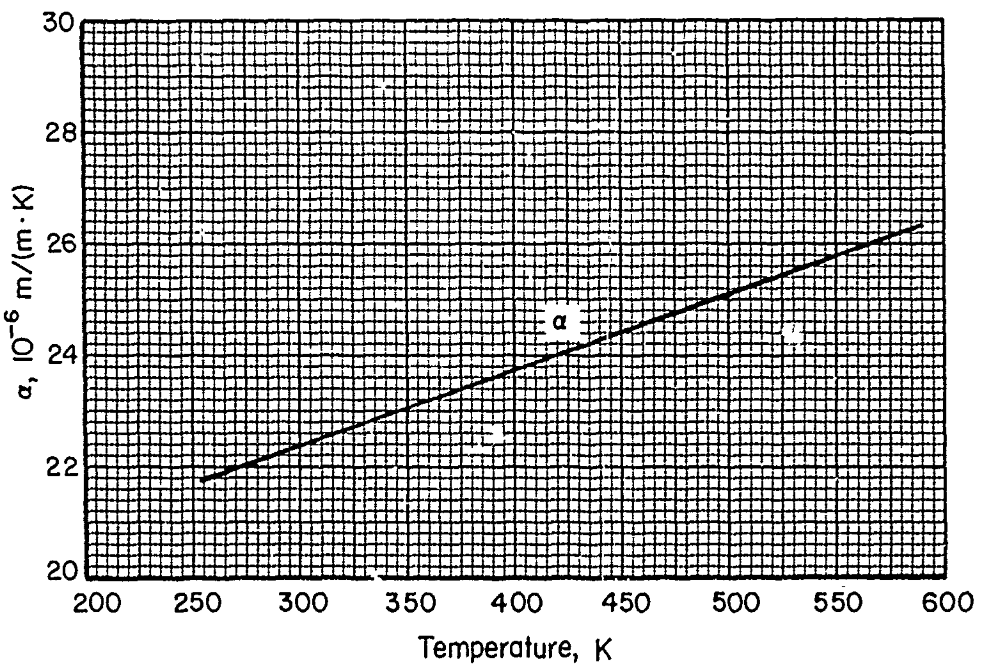


FIGURE 3.7.6.0. *Effect of temperature on the physical properties of 7178 aluminum alloy.*

TABLE 3.7.6.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 7178 ALUMINUM ALLOY (SHEET AND PLATE)

SPECIFICATION	QQ-A-250/14 AND QQ-A250/21														
FORM	SHEET AND PLATE														
TEMPER	T6 AND T62[b]				T651[a] AND T62[b]								T76	T7651	
THICKNESS, MM	0.38-1.13		1.14-6.33		6.34-12.68		12.69-25.41		25.42-38.11		38.12-50.80		1.14-6.33	6.34-12.68	12.69-25.40
BASIS	A	B	A	B	A	B	A	B	A	B	A	B	S	S	S
MECHANICAL PROPERTIES:															
FTU, MPA:															
L	572	586	579	593	572	586	572	586	572	586	545	552	510	503	496
LT	572	586	579	593	579	593	579	593	573	593	552	558	517	510	503
FTY, MPA:															
L	503	517	510	524	517	531	510	524	503	517	463	490	448	434	427
LT	496	510	503	517	503	517	503	517	503	517	483	490	441	434	427
FCY, MPA:															
L	503	517	510	524	503	517	503	517	503	517	483	490	448	434	427
LT	531	545	538	552	538	552	531	545	517	531	490	496	469	462	455
FSU, MPA	345	352	345	359	338	345	317	324	296	303	262	262	303	303	296
FBRU[c], MPA:															
(E/D=1.5)	855	876	869	869	883	903	855	876	814	834	731	745	814	800	793
(E/D=2.0)	1090	1110	1100	1120	1090	1110	1050	1070	986	1010	869	896	1030	1020	1010
FBRY[c], MPA:															
(E/D=1.5)	703	724	717	731	758	779	731	752	696	717	634	641	696	683	662
(E/D=2.0)	807	827	814	841	896	917	869	889	821	848	752	756	807	793	779
EL, PERCENT:															
L	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
LT	7	...	8	...	8	...	6	...	4	...	3	...	8	6	6
E, GPA	71.0				71.0								71.0	71.0	
EC, GPA	72.4				73.1								72.4	73.1	
G, GPA	26.9				26.9								26.9	26.3	
MU	0.33				0.33								0.33	0.33	
PHYSICAL PROPERTIES:															
OMEGA, MG/M3	2.82												2.82		
C, J/(G*K)	0.96 (AT 373 K)												0.96 (AT 373 K)		
K, W/(M*K)	125 (AT 298 K)												149 (AT 298 K)		
ALPHA, 10-6 M/(M*K)	23.4 (293 TO 373 K)												23.4 (293 TO 373 K)		

[a]BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.
[b]THE ALLOWABLES SHOWN FOR THESE TEMPERS ARE BASED ON AND HAVE BEEN DETERMINED FROM THE RESULTS OBTAINED ON TESTING OF T6 AND T651 TEMPER MATERIAL AND ON THE TESTING OF T62 TEMPER SAMPLES FOR SPECIFICATION CONFORMANCE. THESE ALLOWABLES ALSO 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]SEE TABLE 3.1.2.1.1.

TABLE 3.7.6.C(C1). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF CLAD 7178 ALUMINUM ALLOY (SHEET AND PLATE)

SPECIFICATION	QQ-A-250/15														
FORM	SHEET AND PLATE														
TEMPER	T6 AND T62[c]								T651 AND T62[c]						
THICKNESS, MM	0.38-1.13		1.14-1.58		1.59-4.76		4.77-6.33		6.34-12.68		12.69-25.41[a]		25.42-38.11[a]		38.12-50.80[a]
BASIS	A	B	A	B	A	B	A	B	A	B	A	B	A	B	S
MECHANICAL PROPERTIES:															
FTU, MPA:															
L	524	538	538	552	552	565	565	579	558	572	558	572	558	572	531
LT	524	538	538	552	552	565	565	579	565	579	565	579	565	579	536
FTY, MPA:															
L	462	476	476	490	490	503	496	510	503	517	496	510	490	503	462
LT	455	469	469	483	483	496	490	503	490	503	490	503	490	503	469
FCY, MPA:															
L	462	476	476	490	490	503	496	510	490	503	490	503	490	503	469
LT	490	503	503	517	517	531	524	538	524	538	510	524	503	517	476
FSU, MPA	310	324	324	331	331	338	338	345	324	331	310	317	290	296	255
FBRU,[b] MPA:															
(E/D=1.5)	834	834	834	855	855	876	876	896	862	883	834	855	793	814	717
(E/D=2.0)	1050	1060	1080	1100	1100	1130	1130	1160	1060	1090	1020	1050	965	986	669
FBRY,[b] MPA:															
(E/D=1.5)	683	703	703	724	724	745	731	752	738	758	717	731	676	696	614
(E/D=2.0)	793	821	821	841	841	869	855	883	876	896	841	869	800	827	731
EL, PERCENT:															
L	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
LT	7	...	8	...	8	...	8	...	6	...	6	...	4	...	3
E, GPA:															
PRIMARY	71.0				71.0		71.0		71.0						
SECONDARY	65.5				67.6		66.9		68.9						
EC, GPA:															
PRIMARY	72.4				72.4		72.4		73.1						
SECONDARY	66.9				68.9		70.3		71.0						
G, GPA	...				...		...		...						
MU	0.33				0.33		0.33		0.33						
PHYSICAL PROPERTIES:															
OMEGA, MG/M3	2.82														
C, J/(G*K)	0.96 (AT 373 K)														
K, W/(M*K)	125 (AT 298 K)														
ALPHA, 10-6 M/(M*K)	23.4 (293 TO 373 K)														

[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] SEE TABLE 3.1.2.1.1. BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

[c] THE ALLOWABLES SHOWN FOR THESE TEMPERS ARE BASED ON AND HAVE BEEN DETERMINED FROM THE RESULTS OBTAINED ON TESTING OF T6 AND T651 TEMPER MATERIAL AND ON THE TESTING OF T62 TEMPER SAMPLES FOR SPECIFICATION CONFORMANCE. THESE ALLOWABLES ALSO 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.

TABLE 3.7.6.0(C2). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF CLAD 7178 ALUMINUM ALLOY (SHEET AND PLATE)

SPECIFICATION	QQ-A-250/22				
FORM	SHEET AND PLATE				
TEMPER	T76			T7651	
THICKNESS, MM	1.14-1.58	1.59-4.76	4.77-6.33	6.34-12.68	12.69-25.40
BASIS	S	S	S	S	S
MECHANICAL PROPERTIES:					
FTU, MPA:					
L	476	483	496	490	483
LT	483	490	503	496	490
FTY, MPA:					
L	414	421	427	414	407
LT	407	414	421	414	407
FCY, MPA:					
L	414	421	427	414	407
LT	434	441	448	434	427
FSU, MPA	283	290	296	290	290
FBRU, MPA:					
(E/D=1.5)	745	756	779	772	731
(E/D=2.0)	965	979	1010	993	952
FBRY, MPA:					
(E/D=1.5)	627	641	655	641	593
(E/D=2.0)	731	745	758	745	689
EL, PERCENT:					
L	...	...	...	...	...
LT	8	8	8	8	6
E, GPA:					
PRIMARY	71.0	71.0	71.0	71.0	
SECONDARY	65.5	67.6	68.9	68.9	
EC, GPA:					
PRIMARY	72.4	72.4	72.4	73.1	
SECONDARY	66.9	68.9	70.3	71.0	
G, GPA	...	...	...	...	
MU	0.33	0.33	0.33	0.33	
PHYSICAL PROPERTIES:					
OMEGA, MG/M3	2.82				
C, J/(G*K)	0.96 (AT 373 K)				
K, W/(M*K)	149 (AT 298 K)				
ALPHA, 10-6 M/(M*K)	23.4 (293 TO 373 K)				

[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] SEE TABLE 3.1.2.1.1. BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

TABLE 3.7.6.0(D). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 7011 CLAD 7178 ALUMINUM ALLOY (SHEET AND PLATE)

SPECIFICATION	QQ-A-00250/28													
FORM	SHEET				PLATE				SHEET			PLATE	
TEMPER	T6 AND T62[a]				T651 AND T62[a]				T76			T7651	
THICKNESS, MM	0.38-1.13	1.14-1.58	1.59-4.76	4.77-6.33	6.34-12.68	12.69-25.41[b]	25.42-38.11[b]	38.12-50.80[b]	1.14-1.58	1.59-4.76	4.77-6.33	6.34-12.68	12.69-25.41
BASIS	S	S	S	S	S	S	S	S	S	S	S	S	S
MECHANICAL PROPERTIES:													
FTU, MPA:													
L	545	558	565	572	565	565	565	538	...	...	...	...	...
LT	545	558	565	572	572	572	572	545	503	503	510	503	496
FTY, MPA:													
L	483	490	496	503	503	496	496	476	...	...	...	...	...
LT	476	463	490	496	496	496	496	476	427	427	434	421	421
FCY, MPA:													
L	483	490	496	503	496	490	490	469	...	...	...	...	...
LT	510	517	524	531	524	517	510	453	...	...	...	...	...
FSU, MPA	324	331	338	345	331	317	290	255	...	...	...	...	...
FBRU, MPA:													
(E/D=1.5)	814	834	848	855	876	841	800	724	...	...	...	...	...
(E/D=2.0)	1030	1060	1080	1090	1080	1030	972	876	...	...	...	...	...
FBRY, MPA:													
(E/D=1.5)	669	676	683	696	752	745	683	627	...	...	...	...	...
(E/D=2.0)	758	772	786	793	883	855	814	738	...	...	...	...	...
EL, PERCENT:													
L	...	...	...	...	...	...	...	...	...	...	...	...	...
LT	7	8	8	8	8	6	4	3	8	8	8	6	6
E, GPA	71.0				71.0				71.0			71.0	
EC, GPA	72.4				73.1				72.4			73.1	
G, GPA	26.9				26.9				26.9			26.9	
MU	0.33				0.33				0.33			0.33	
OMEGA, MG/M3	2.82				2.82				2.82			2.82	

[a] THE ALLOWABLES SHOWN FOR THESE TEMPERS ARE BASED ON AND HAVE BEEN DETERMINED FROM THE RESULTS OBTAINED ON TESTING OF T6 AND T651 TEMPER MATERIAL AND ON THE TESTING OF T62 TEMPER SAMPLES FOR SPECIFICATION CONFORMANCE. THESE ALLOWABLES ALSO 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.

[b] THESE VALUES HAVE BEEN ADJUSTED TO REPRESENT THE AVERAGE PROPERTIES ACROSS TH WHOLE SECTION, INCLUDING THE 1-1/2 PERCENT PER SIDE NOMINAL CLADDING THICKNESS.

[c] SEE TABLE 3.1.2.1.1. BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

TABLE 3.7.6.0(E1) DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 7178 ALUMINUM ALLOY (EXTRUSIONS)

SPECIFICATION	QQ-A-200/13												
FORM	EXTRUDED ROD, BAR, AND SHAPES												
TEMPER	T6, T6510 AND T6511												
CROSS-SECTIONAL AREA, MM2	≤12900						≤16130					>16130 ≤20650	≤20650
THICKNESS,[a] MM	≤1.56		1.57-6.33		6.34-12.68		12.69-19.03		19.04-38.08-		38.09-63.48	38.09-63.48	63.49-75.95
BASIS	A	B	A	B	A	B	A	B	A	B	S	S	S
MECHANICAL PROPERTIES:													
FTU, MPA:													
L	565	593	579	607	600	621	600	621	609	621	593	579	565
LT	545	572	552	579	[illegible]	[illegible]	558	579	545	565	510	...	...
FTY, MPA:													
L	524	552	524	552	538	558	538	558	538	558	531	517	490
LT	490	517	490	517	496	517	493	510	476	490	441	...	...
FCY, MPA:													
L	524	552	517	538	531	545	531	545	531	545	524	...	...
LT	524	552	538	565	545	565	538	556	531	552	496	...	...
FSU, MPA	303	317	290	303	303	310	303	310	303	310	296	...	...
FBRU,[b] MPA:													
(E/D=1.5)	738	772	827	869	655	883	848	876	834	869	667	...	...
(E/D=2.0)	903	952	1030	1080	1060	1100	1060	1100	1050	1080	1010	...	...
FBRY,[b] MPA:													
(E/D=1.5)	683	717	683	717	703	731	703	731	703	731	696	...	...
(E/D=2.0)	731	772	800	841	821	848	821	848	821	848	807	...	...
EL, PERCENT:													
L	5	...	5	...	5	...	5	...	5	...	5	5	5
LT	...	...	...	...	...	...	...	...	...	...	...	...	...
E, GPA	71.7												
EC, GPA	73.8												
G, GPA	27.6												
MU	0.33												
PHYSICAL PROPERTIES:													
OMEGA, MG/M3	2.82												
C, J/(G*K)	0.96 (AT 373 K)												
K, W/(M*K)	125 (AT 298 K)												
ALPHA, 10-6 M/(M*K)	23.4 (293 TO 373 K)												

[a] FOR EXTRUSIONS WITH OUTSTANDING LEGS, THE LOAD CARRYING ABILITY OF SUCH LEGS SHALL BE DETERMINED ON THE BASIS OF THE PROPERTIES IN THE APPROPRIATE COLUMN CORRESPONDING TO THE LEG THICKNESS.

[b] BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

TABLE 3.7.6.0(E2). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 7178 ALUMINUM ALLOY (EXTRUSIONS)

SPECIFICATION............	QQ-A-200/13					
FORM.....................	EXTRUDED ROD, BAR, AND SHAPES					
TEMPER...................	T62[a]					
CROSS-SECTIONAL AREA, MM2	≤12900	≤16130			>16130 ≤20650	≤20650
THICKNESS,[b] MM...........	≤1.55	[illegible]- 6.33	6.34- 38.08	38.09- 63.47	38.09- 63.48	63.49- 76.17
BASIS....................	S	S	S	S	S	S
MECHANICAL PROPERTIES:						
FTU, MPA:						
L.................	545	565	593	593	579	565
LT................	...	...	...	...	...	...
FTY, MPA:						
L.................	503	510	531	531	517	490
LT................	...	...	...	...	...	...
FCY, MPA:						
L.................	...	...	...	...	...	...
LT................	...	...	...	...	...	...
FSU, MPA.............	...	...	...	...	...	...
FBRU[c] MPA:						
(E/D=1.5).........	...	...	...	...	...	...
(E/D=2.0).........	...	...	...	...	...	...
FBRY, MPA:						
(E/D=1.5).........	...	...	...	...	...	...
(E/D=2.0).........	...	...	...	...	...	...
EL, PERCENT:						
L.................	5	5	5	5	5	5
LT................	...	...	...	...	...	...
E, GPA...............	71.7					
EC, GPA..............	73.8					
G, GPA...............	27.6					
MU...................	0.33					
PHYSICAL PROPERTIES:						
OMEGA, MG/M3..........	2.82					
C, J/(G*K)............	0.96 (AT 373 K)					
K, W/(M*K)............	125 (AT 298 K)					
ALPHA, 10-6 M/(M*K)..	23.4 (293 TO 373 K)					

[a] 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.

[b] FOR EXTRUSIONS WITH OUTSTANDING LEGS, THE LOAD CARRYING ABILITY OF SUCH LEGS SHALL BE DETERMINED ON THE BASIS OF THE PROPERTIES IN THE APPROPRIATE COLUMN CORRESPONDING TO THE LEG THICKNESS.

[c] BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

TABLE 3.7.6.0(E3). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 7178 ALUMINUM ALLOY (EXTRUSION)

SPECIFICATION...........	QQ-A-00200/14			
FORM....................	EXTRUDED BAR, ROD, AND SHAPES			
TEMPER..................	T76, T76510, T76511			
CROSS-SECTIONAL AREA, MM2	≤12900			
THICKNESS,[a] MM..........	3.17-6.33	6.34-12.68	12.69-19.03	19.04-25.40
BASIS...................	S	S	S	S
MECHANICAL PROPERTIES:				
FTU, MPA:				
L..................	524	531	531	531
LT.................	510	510	496	490
FTY, MPA:				
L..................	455	462	462	462
LT.................	434	434	427	421
FCY, MPA:				
L..................	462	469	462	462
LT.................	476	476	469	462
FSU, MPA............	290	296	296	296
FBRU,[b] MPA:				
(E/D=1.5).........	779	786	779	772
(E/D=2.0).........	965	972	965	956
FBRY,[b] MPA:				
(E/D=1.5).........	621	634	634	634
(E/D=2.0).........	731	738	738	738
EL, PERCENT:				
L..................	7	7	7	7
LT.................	...	...	...	...
E, GPA...............	71.7			
EC, GPA..............	73.8			
G, GPA...............	27.6			
MU...................	0.33			
PHYSICAL PROPERTIES:				
OMEGA, MG/M3.........	2.82			
C, J/(G*K)...........	0.96 (AT 373 K)			
K, W/(M*K)...........	149 (AT 298 K)			
ALPHA, 10-6 M/(M*K)..	23.4 (293 TO 373 K)			

[a] FOR EXTRUSIONS WITH OUTSTANDING LEGS, THE LOAD CARRYING ABILITY OF SUCH LEGS SHALL BE DETERMINED ON THE BASIS OF THE PROPERTIES IN THE APPROPRIATE COLUMN CORRESPONDING TO THE LEG THICKNESS.

[b] BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

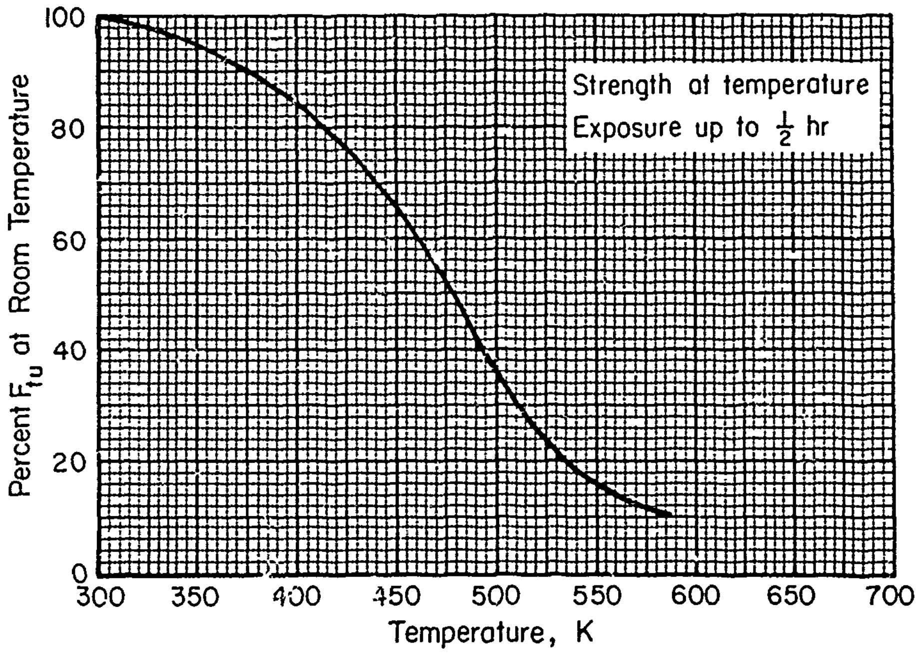


FIGURE 3.7.6.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of 7178-T6 aluminum alloy.

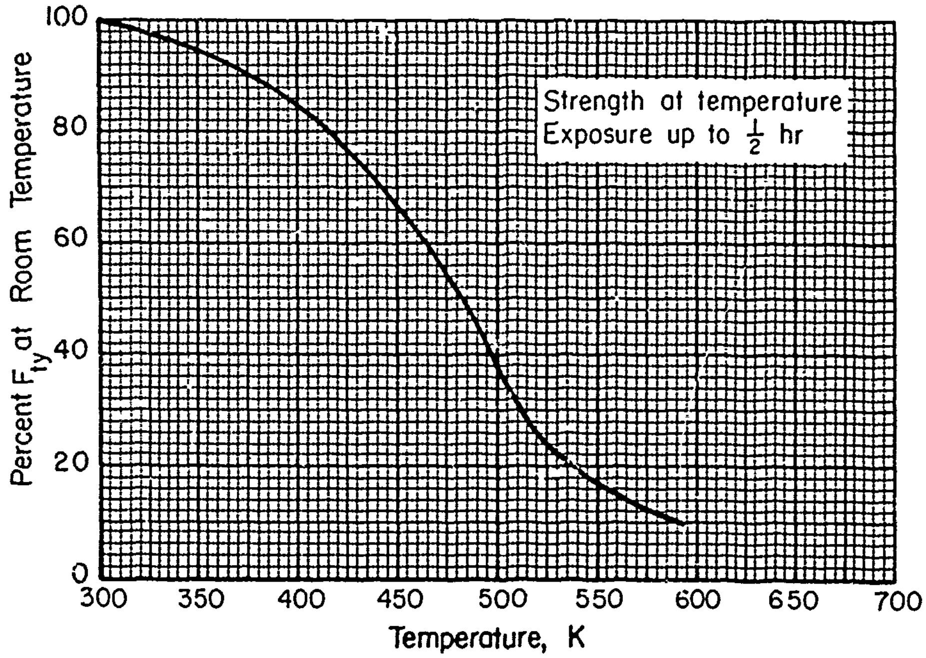


FIGURE 3.7.6.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of 7178-T6 aluminum alloy.

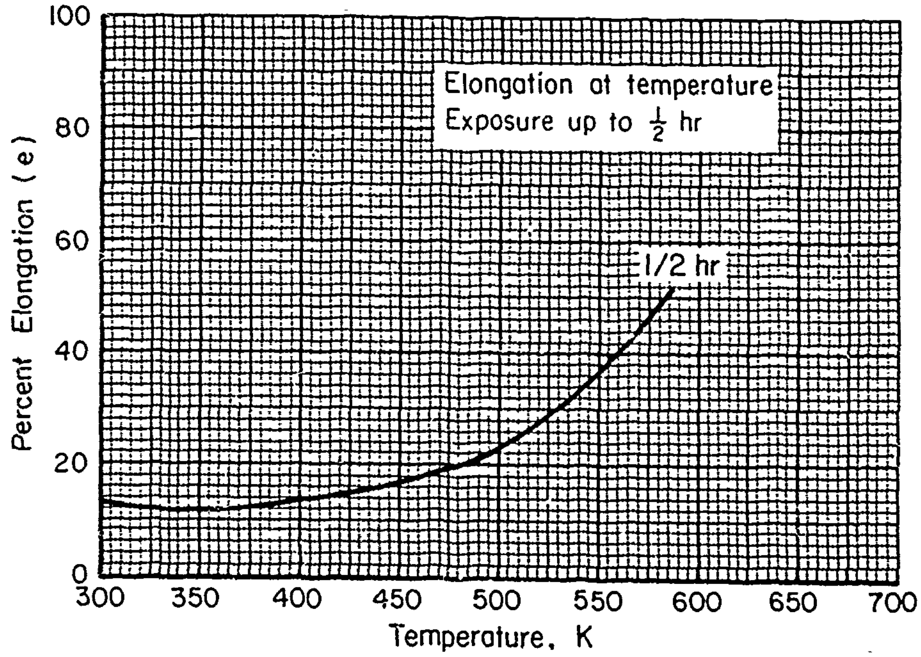


FIGURE 3.7.6.1.5. Effect of temperature on the elongation of 7178-T6 aluminum alloy.

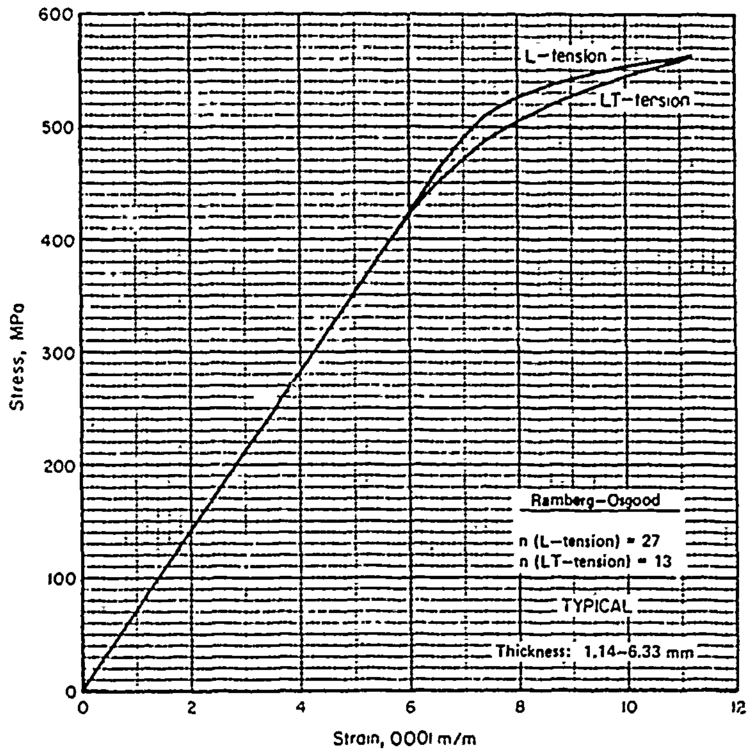


FIGURE 3.7.6.1.6(a). Typical tensile stress-strain curves for 7178-T6 aluminum alloy (sheet) at room temperature.

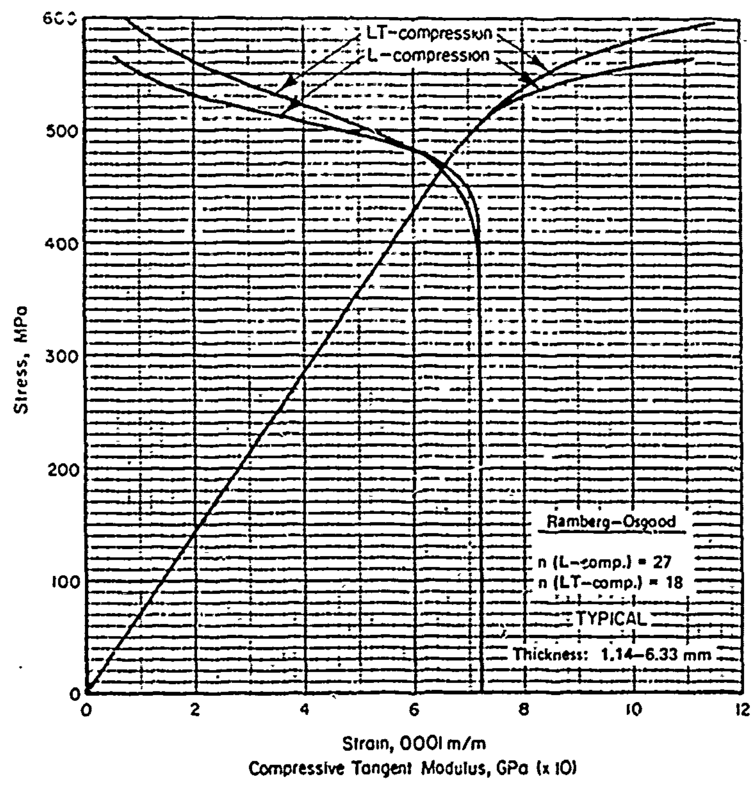


FIGURE 3.7.5.1.6(b). Typical compressive stress-strain and tangent-modulus curves for 7178-T6 aluminum alloy (sheet) at room temperature.

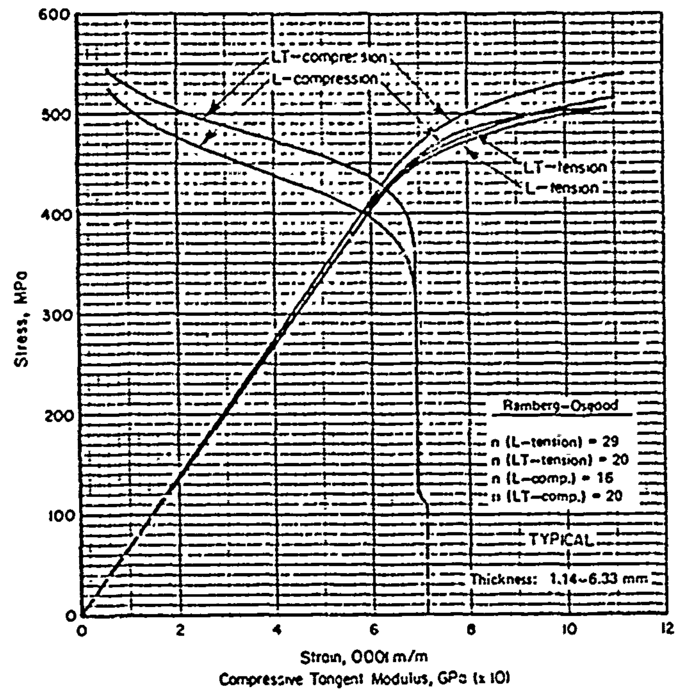


FIGURE 3.7.6.1.6(c). Typical tensile stress-strain and compressive stress-strain and tangent-modulus curves for clad 7178-T6 aluminum alloy (sheet) at room temperature.

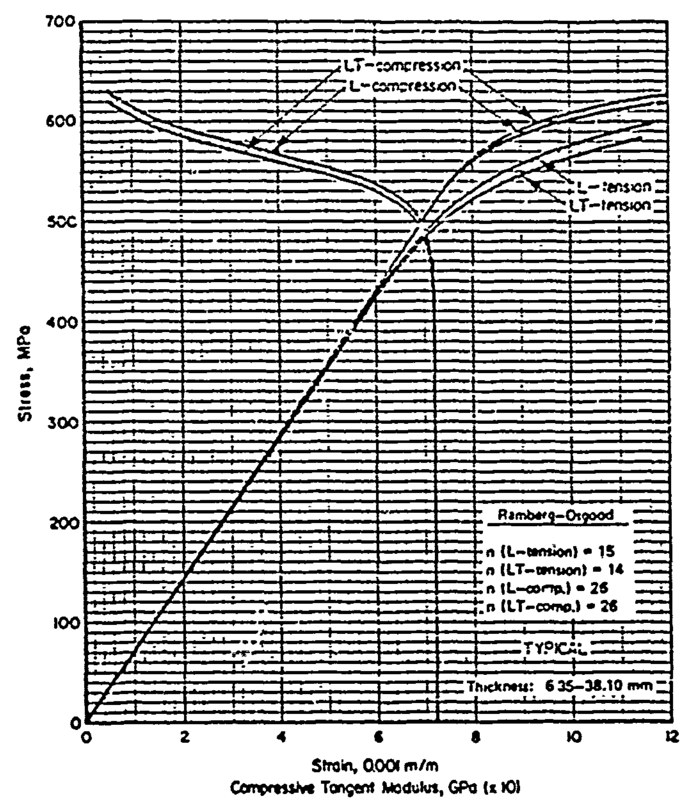


FIGURE 3.7.6.1.6(d). Typical tensile stress-strain and compressive stress-strain and tangent-modulus curves for 7178-T62 aluminum alloy (plate) at room temperature.

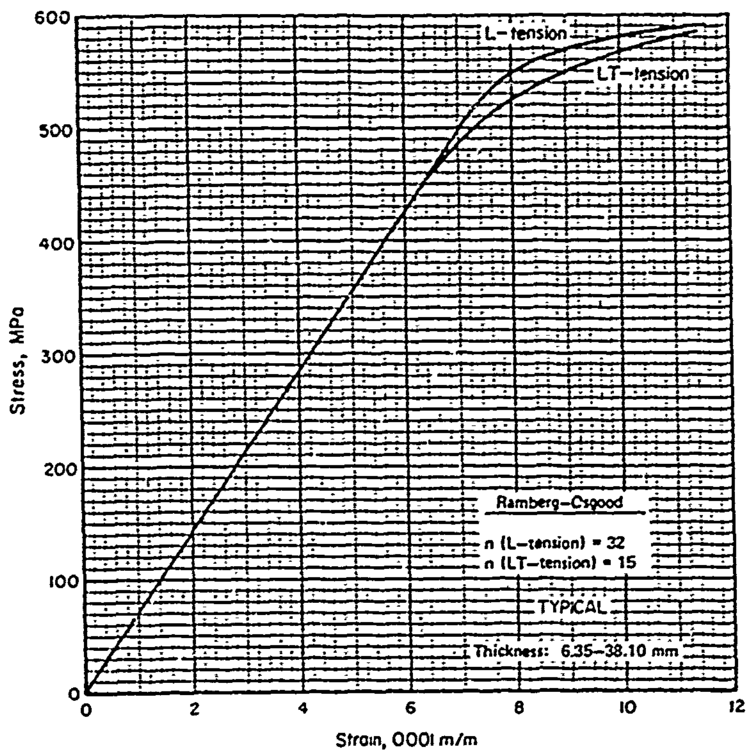


FIGURE 3.7.6.1.6(e). Typical tensile stress-strain curves for 7178-T651 aluminum alloy (plate) at room temperature.

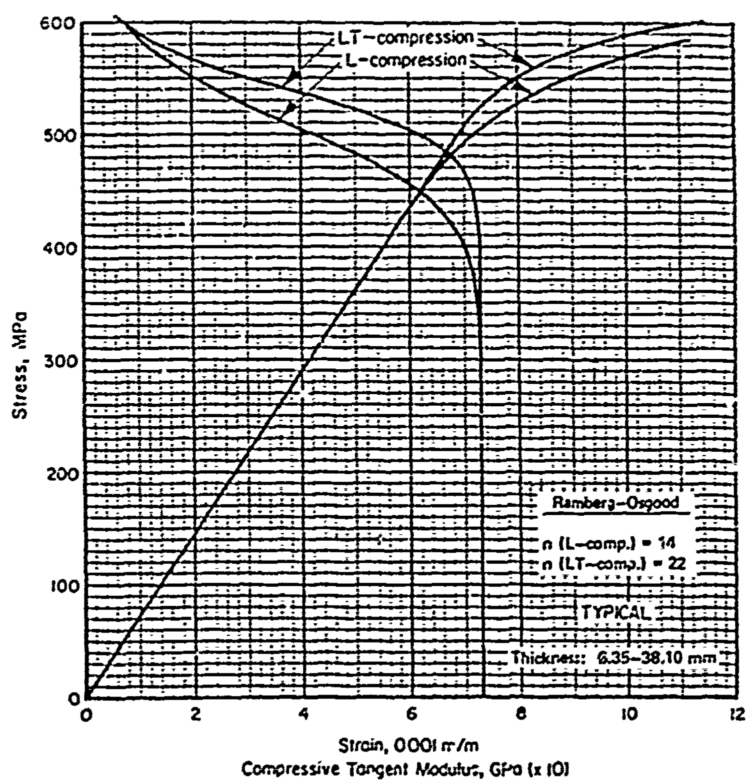


FIGURE 3.7.6.1.6(f). Typical compressive stress-strain curves for 7178-T651 aluminum alloy (plate) at room temperature.

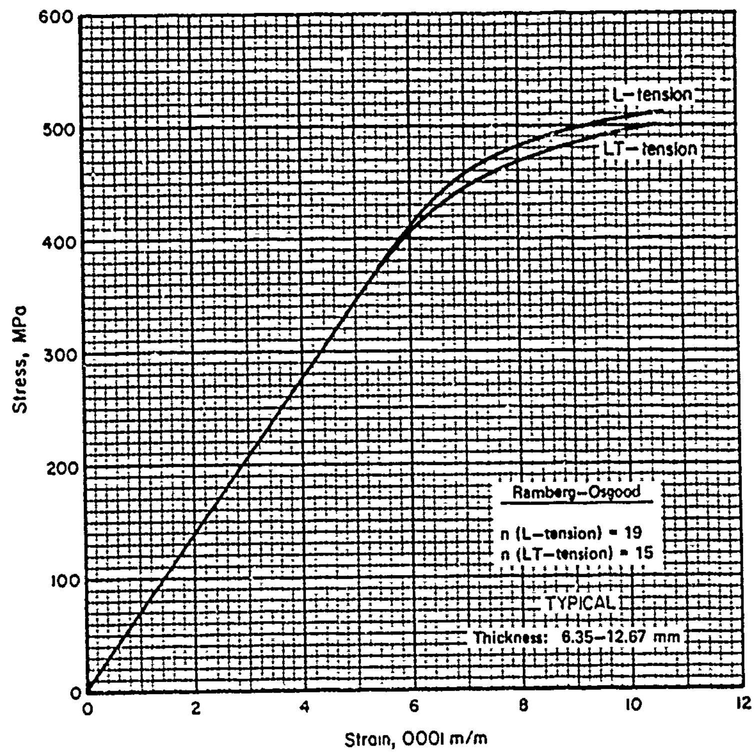


FIGURE 3.7.6.1.6(g). Typical tensile stress-strain curves for clad 7178-T6 aluminum alloy (plate) at room temperature.

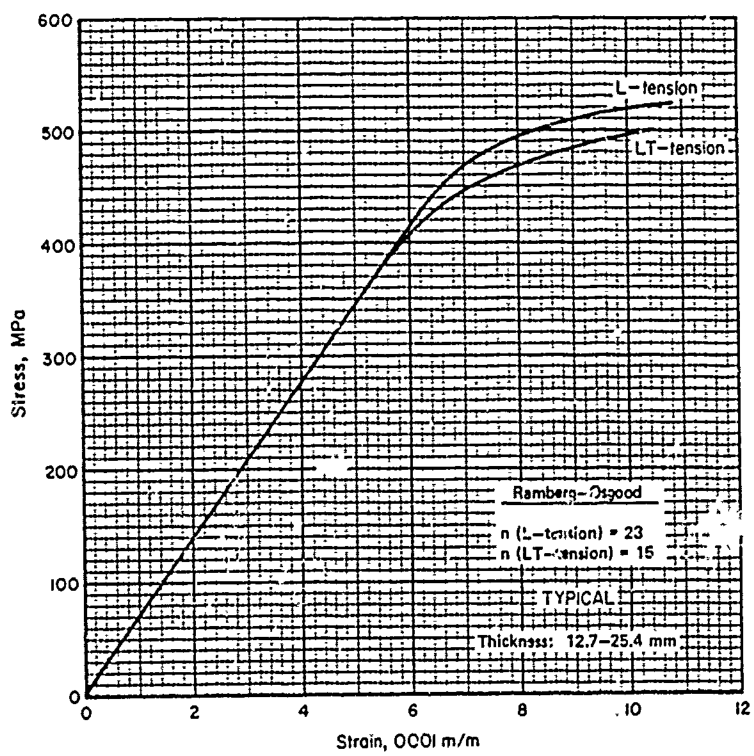


FIGURE 3.7.6.1.6(h). Typical tensile stress-strain curves for clad 7178-T6 aluminum alloy (plate) at room temperature.

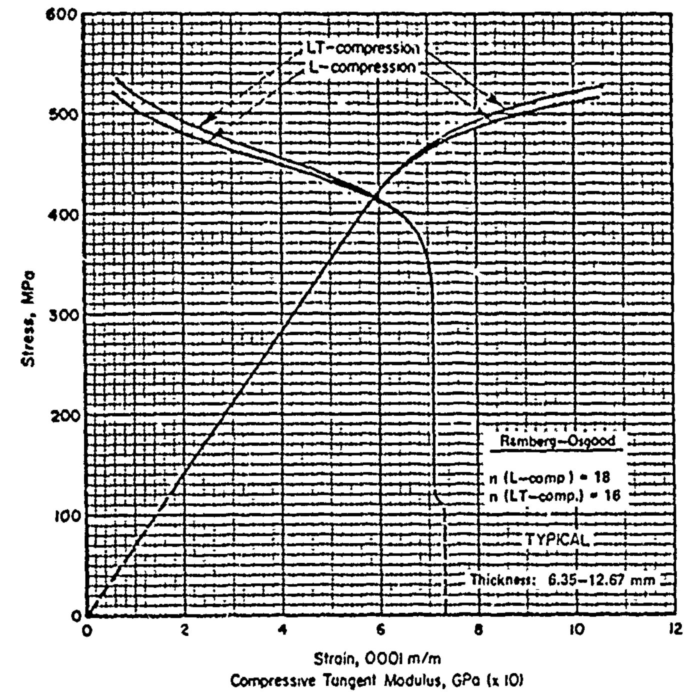


FIGURE 3.7.6.1.6(i). Typical compressive stress-strain and tangent-modulus curves for clad 7178-T6 aluminum alloy (plate) at room temperature.

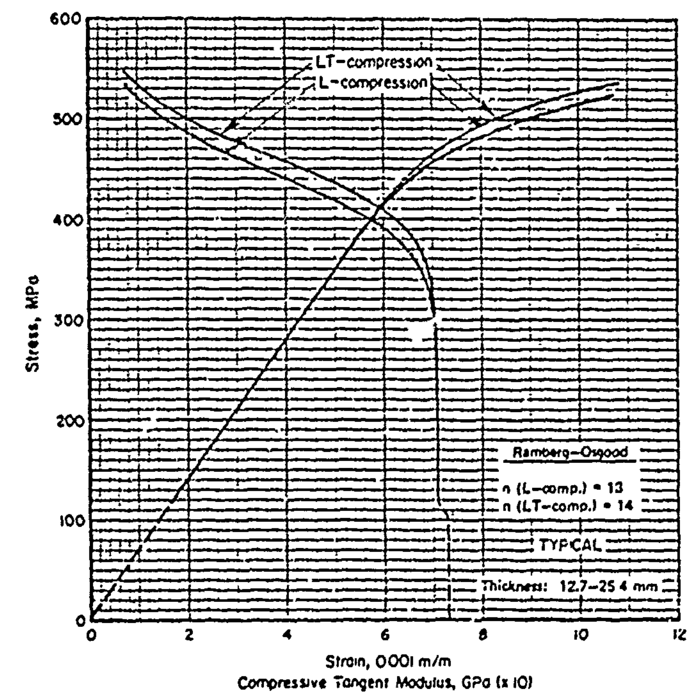


FIGURE 3.7.6.1.6(j). Typical compressive stress-strain and tangent-modulus curves for clad 7178-T6 aluminum alloy (plate) at room temperature.

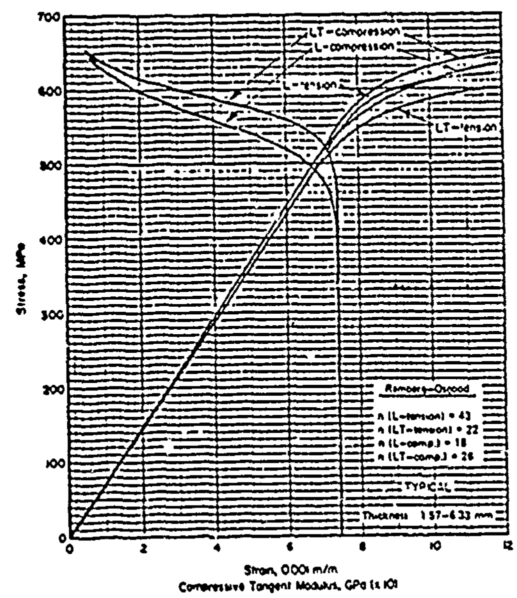


FIGURE 3.7.6.1.6(k). Typical tensile stress-strain and compressive stress-strain and tangent-modulus curves for 7178-T651X aluminum alloy (extrusion) at room temperature.

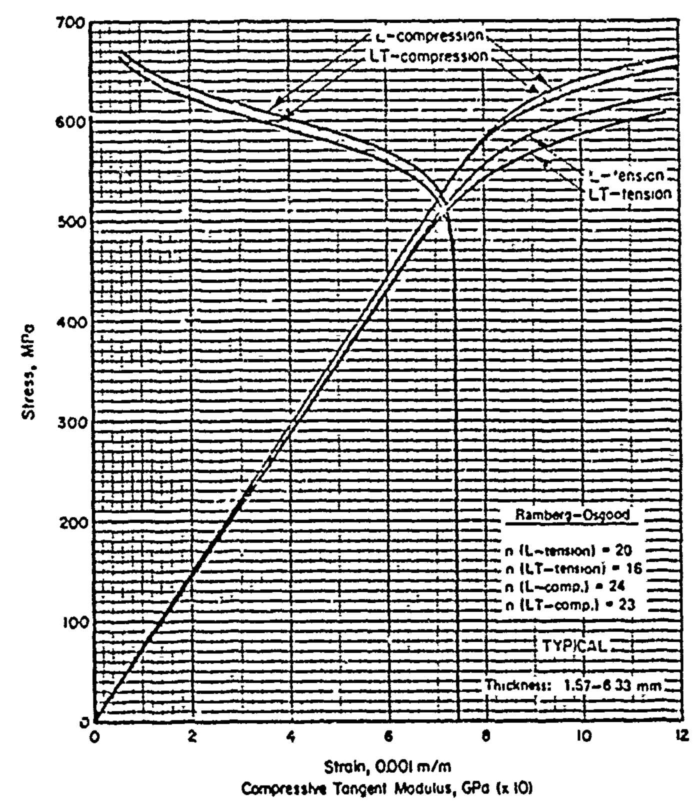


FIGURE 3.7.6.1.6(l). Typical tensile stress-strain and compressive stress-strain and tangent-modulus curves for 7178-T6 aluminum alloy (extrusion) at room temperature.

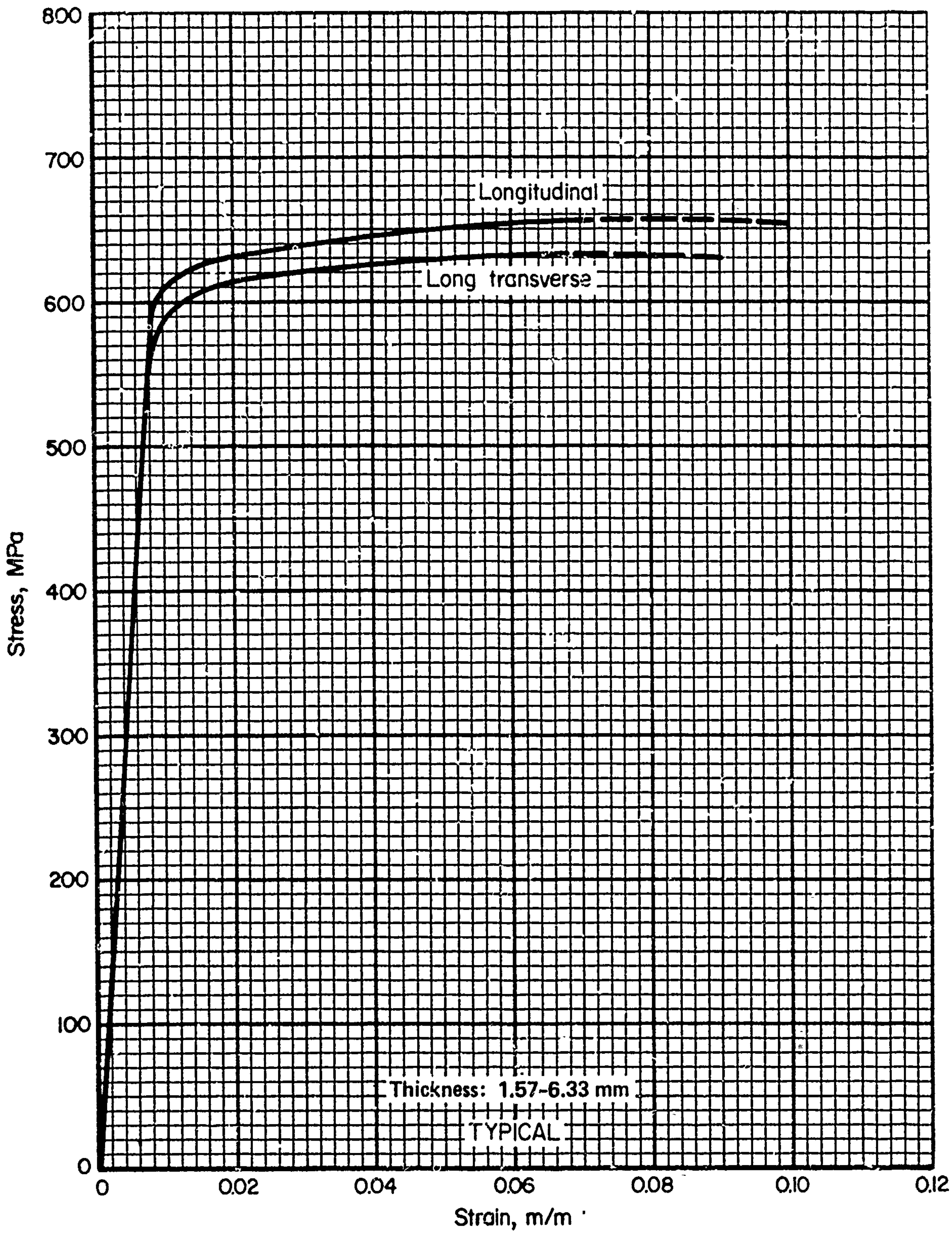


FIGURE 3.7.6.1.6(m). Typical tensile stress-strain curves (full range) for 7178-T651X aluminum alloy (extrusion) at room temperature.

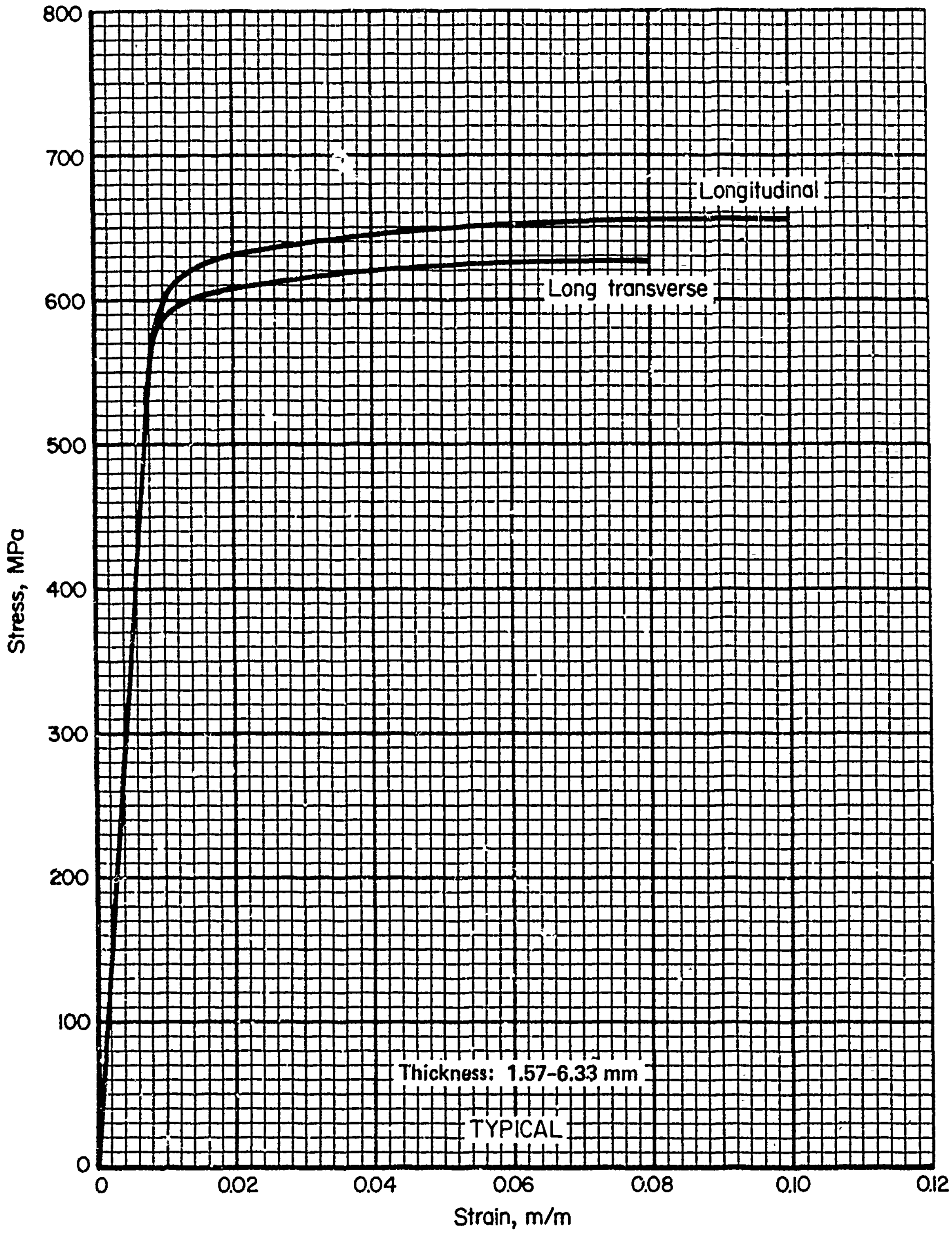


FIGURE 3.7.6.1.6(n). Typical tensile stress-strain curves (full range) for 7178-T62 aluminum alloy (extrusion) at room temperature.

3.7.7 7475 ALLOY

3.7.7.0 *Comments and Properties.*—7475 is a 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 strengths equivalent to that of 7075 combined with the toughness of 2024-T3. Plate has strengths similar to those of corresponding tempers of 7075; the toughness of 7475-T651 equals or exceeds that of 7075-T7351 and for 7475-T7651 plate the toughness exceeds that of 2024-T351. Resistance to stress-corrosion cracking and exfoliation are comparable to that of 7075; exfoliation resistance of 7475-T61 sheet is slightly better than that of 7075-T6 sheet.

Material specifications for 7475 sheet and plate are shown in Table 3.7.7.0(a). Room-temperature mechanical properties for 7475-T61 and T761 sheet and 7475-T651 and T7651 plate are shown in Table 3.7.7.0(b).

TABLE 3.7.7.0(a). *Material Specifications for 7475 Aluminum Alloy*

Specification	Form
AMS 4084 (T61)	Sheet
AMS 4085 (T761)	Sheet
AMS 4090 (T651)	Plate
AMS 4089 (T7651)	Plate

The temper index for 7475 is as follows:

Section	Temper
3.7.7.1	T61,T651
3.7.7.2	T761, T7651

3.7.7.1 *T61 and T651 Tempers.*—Figures 3.7.7.1.6(a) through (d) present tensile and compressive stress-strain curves and tangent-modulus curves for T61 sheet and T651 plate. Figure 3.7.7.1.6(e) contains full-range tensile curves for T61 sheet.

3.7.7.2 *T761 and T7651 Tempers.*—Figures 3.7.7.2.6(a) through (d) present tensile and compressive stress-strain curves and tangent-modulus curves for T761 sheet and T7651 plate. Figure 3.7.7.2.6(e) contains full-range tensile curves for T761 sheet.

TABLE 3.7.7.0(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		
CONDITION	T61	T651			T761	T7651		
THICKNESS, MM	1.02-6.33	6.34-12.68	12.69-25.41	25.42-38.07	1.02-6.33	6.34-12.68	12.69-25.41	25.42-38.07
BASIS	S	S	S	S	S	S	S	S
MECHANICAL PROPERTIES:								
FTU, MPA:								
L	517	531	531	524	490	483	476	476
LT	517	538	538	531	490	490	483	483
FTY, MPA:								
L	455	462	469	462	421	414	407	437
LT	441	462	469	462	414	414	407	407
FCY, MPA:								
L	448	448	455	448	414	414	407	437
LT	469	483	490	483	434	434	427	427
FSU, MPA	310	303	296	276	296	263	269	255
FBRU,[a] MPA:								
(E/D=1.5)	627	779	779	765	779	717	710	710
(E/D=2.0)	1060	993	993	979	1000	938	924	924
FBRY,[a] MPA:								
(E/D=1.5)	662	634	641	634	621	565	558	558
(E/D=2.0)	772	689	738	731	724	669	655	655
EL, PERCENT:								
L	9	9	8	6	9	9	8	6
LT	9	9	8	6	9	9	8	6
E, GPA	68.9	70.3			68.9	70.3		
EC, GPA	72.4	73.1			72.4	73.1		
G, GPA	26.2	26.9			26.2	26.9		
MU	0.33	0.33			0.33	0.33		
PHYSICAL PROPERTIES:								
OMEGA, MG/M3	2.80							
C, J/(G*K)	0.96 (AT 373 K)							
K, W/(M*K)	...							
ALPHA, 10-6 M/(M*K)	23.2 (293 TO 373 K)							

[a] BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

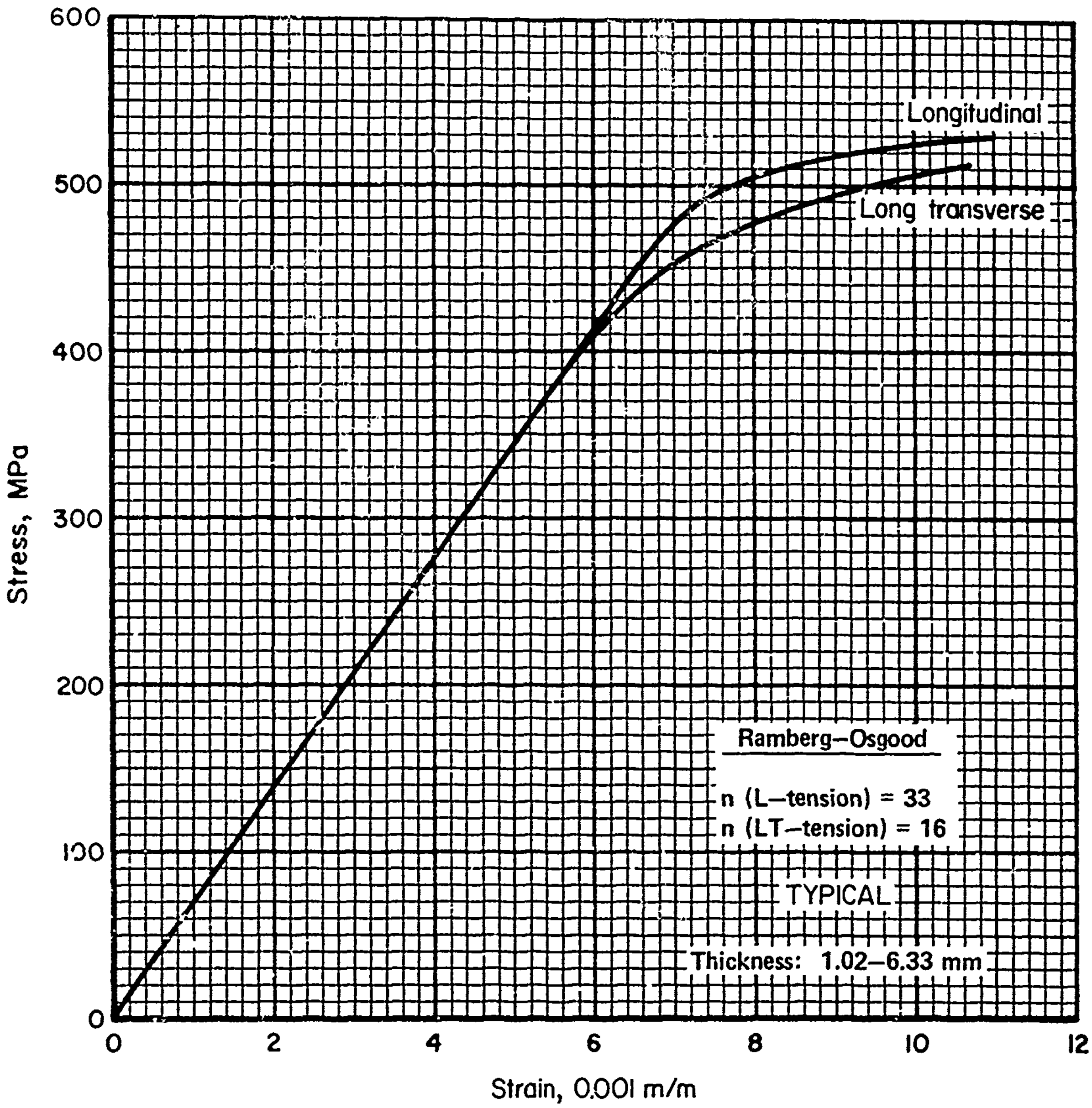


FIGURE 3.7.7.1.6(a). Typical tensile stress-strain curves for 7475-T61 aluminum alloy (sheet) at room temperature.

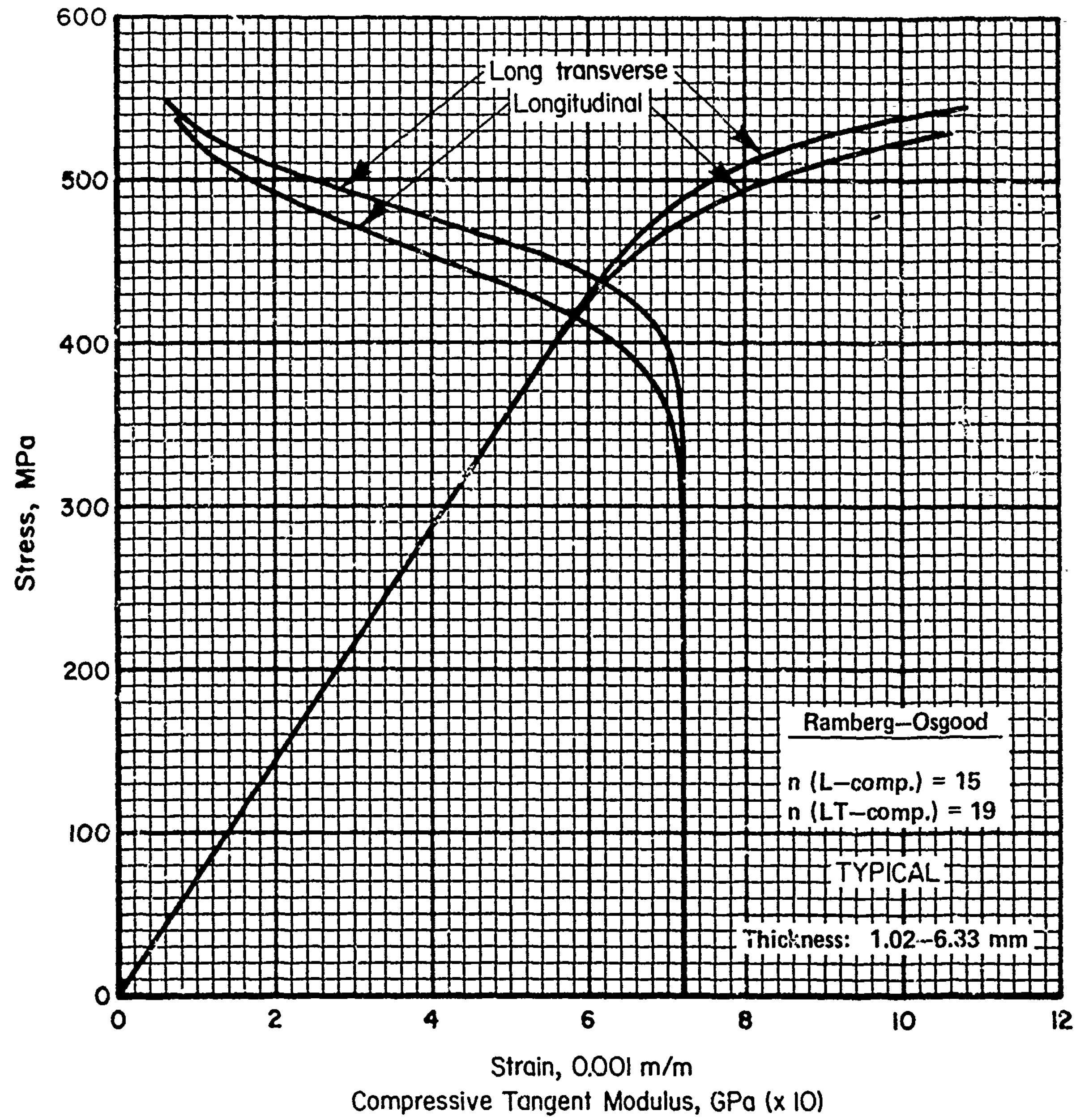


FIGURE 3.7.7.1.6(b). Typical compressive stress-strain and tangent-modulus curves for 7475-T61 aluminum alloy (sheet) at room temperature.

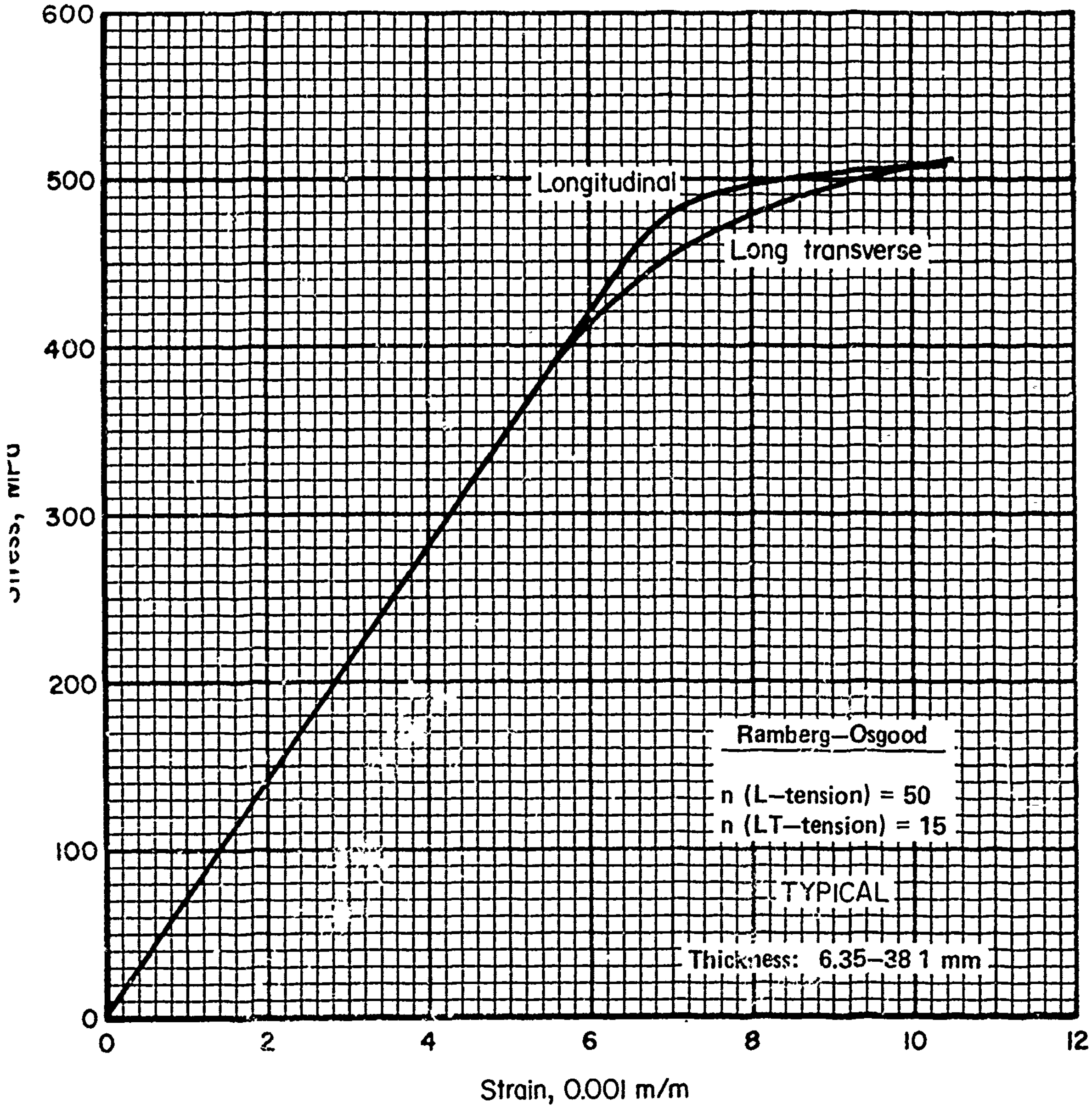


FIGURE 3.7.7.1.6(c). Typical tensile stress-strain curves for 7475-T651 aluminum alloy (plate) at room temperature.

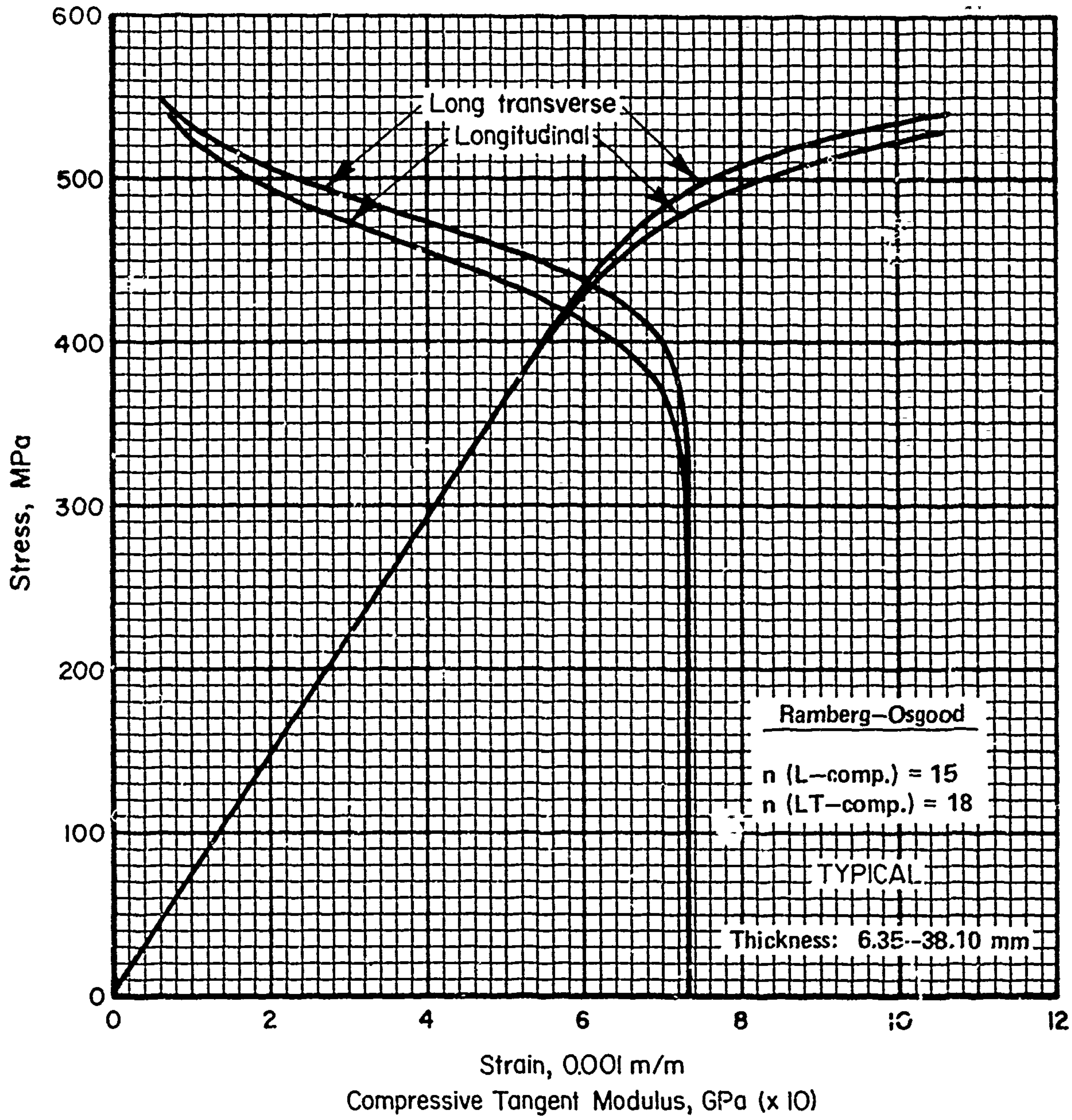


FIGURE 3.7.7.1.6(d). Typical compressive stress-strain and tangent-modulus curves for 7475-T651 aluminum alloy (plate) at room temperature.

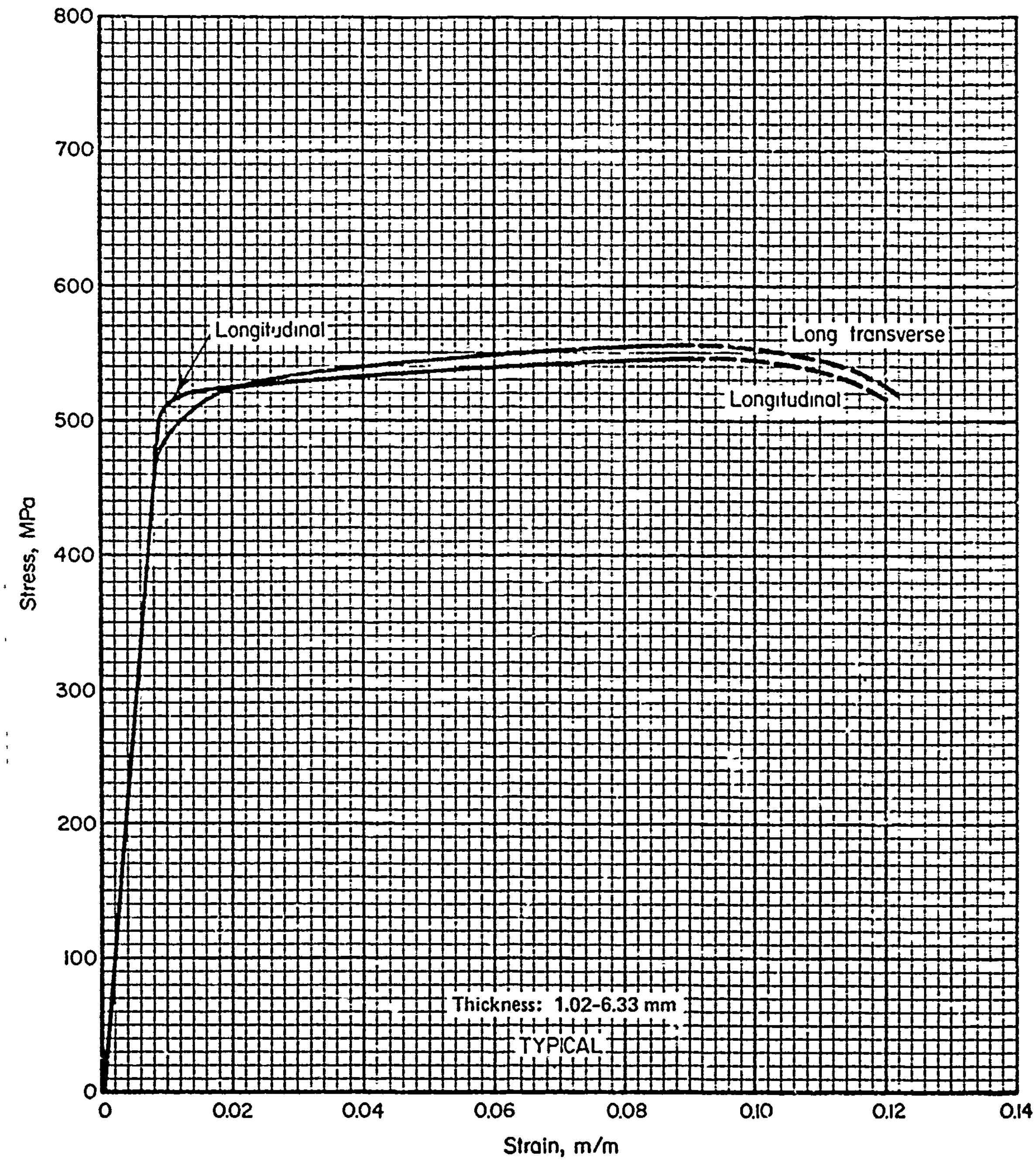


FIGURE 3.7.7.1.6(e). Typical tensile stress-strain curves (full range) for 7475-T651 aluminum alloy (sheet) at room temperature.

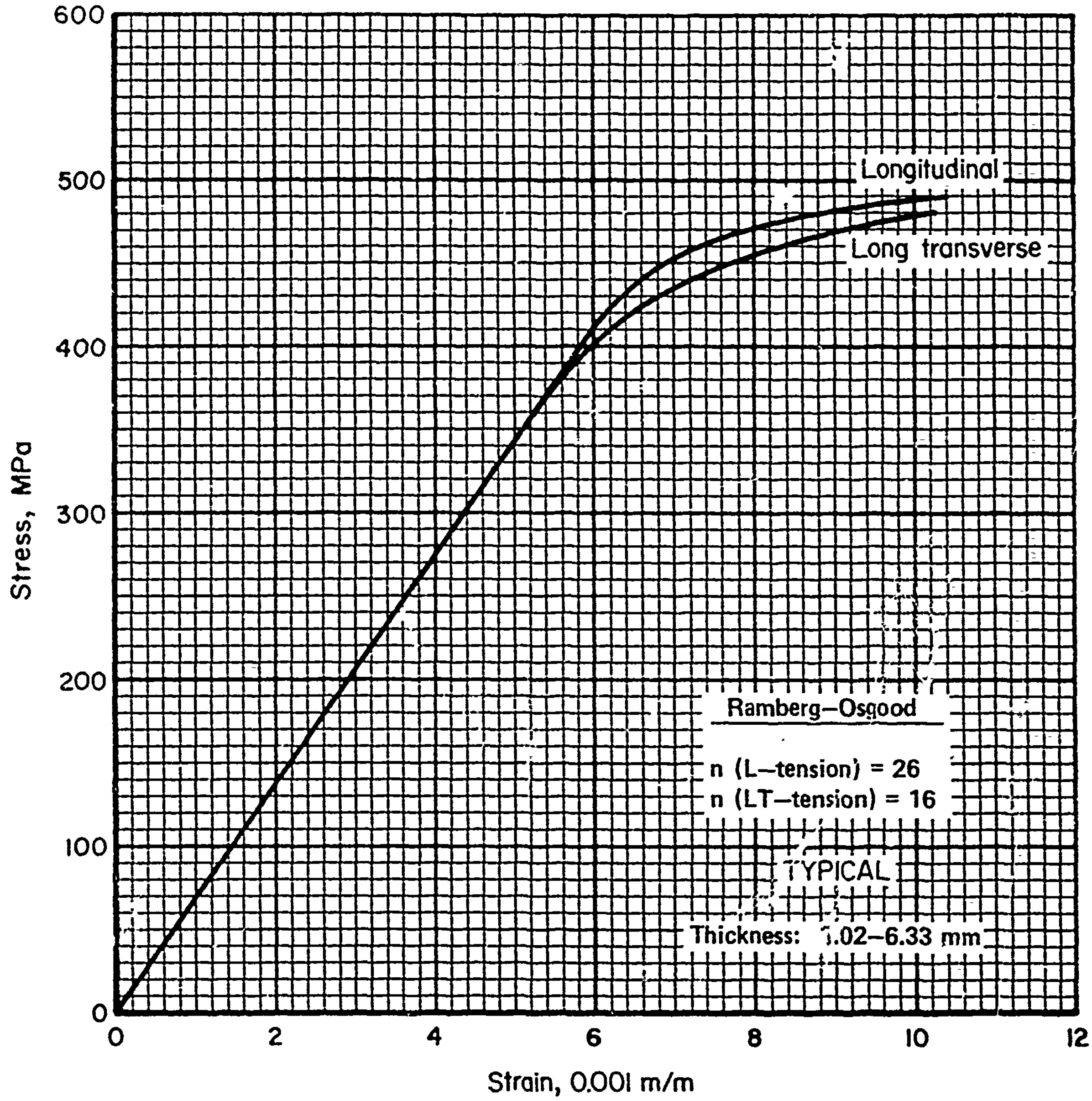


FIGURE 3.7.7.2.6(a). Typical tensile stress-strain curves for 7475-T761 aluminum alloy (sheet) at room temperature.

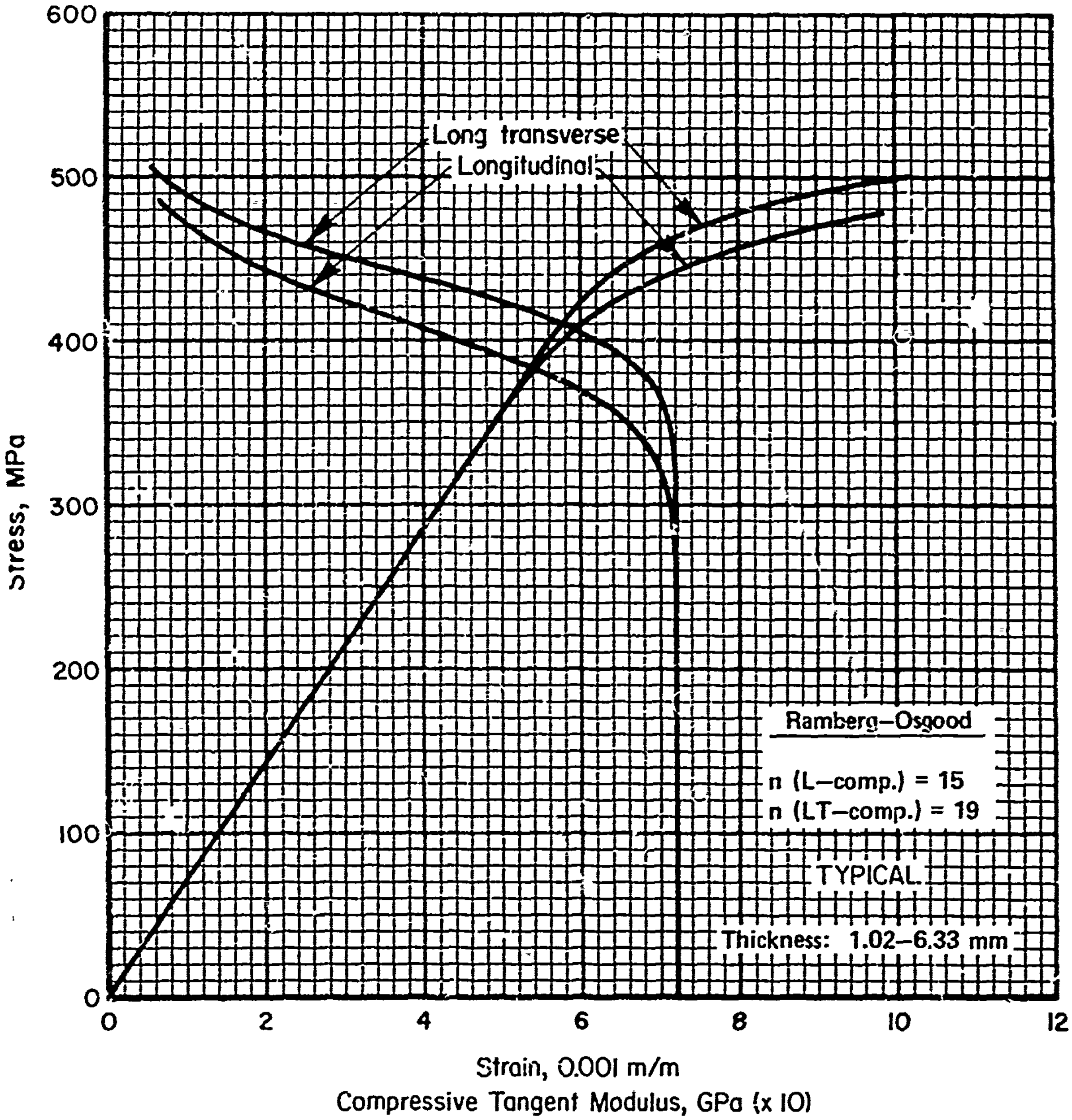


FIGURE 3.7.7.2.6(b). Typical compressive stress-strain and tangent-modulus curves for 7475-T761 aluminum alloy (sheet) at room temperature.

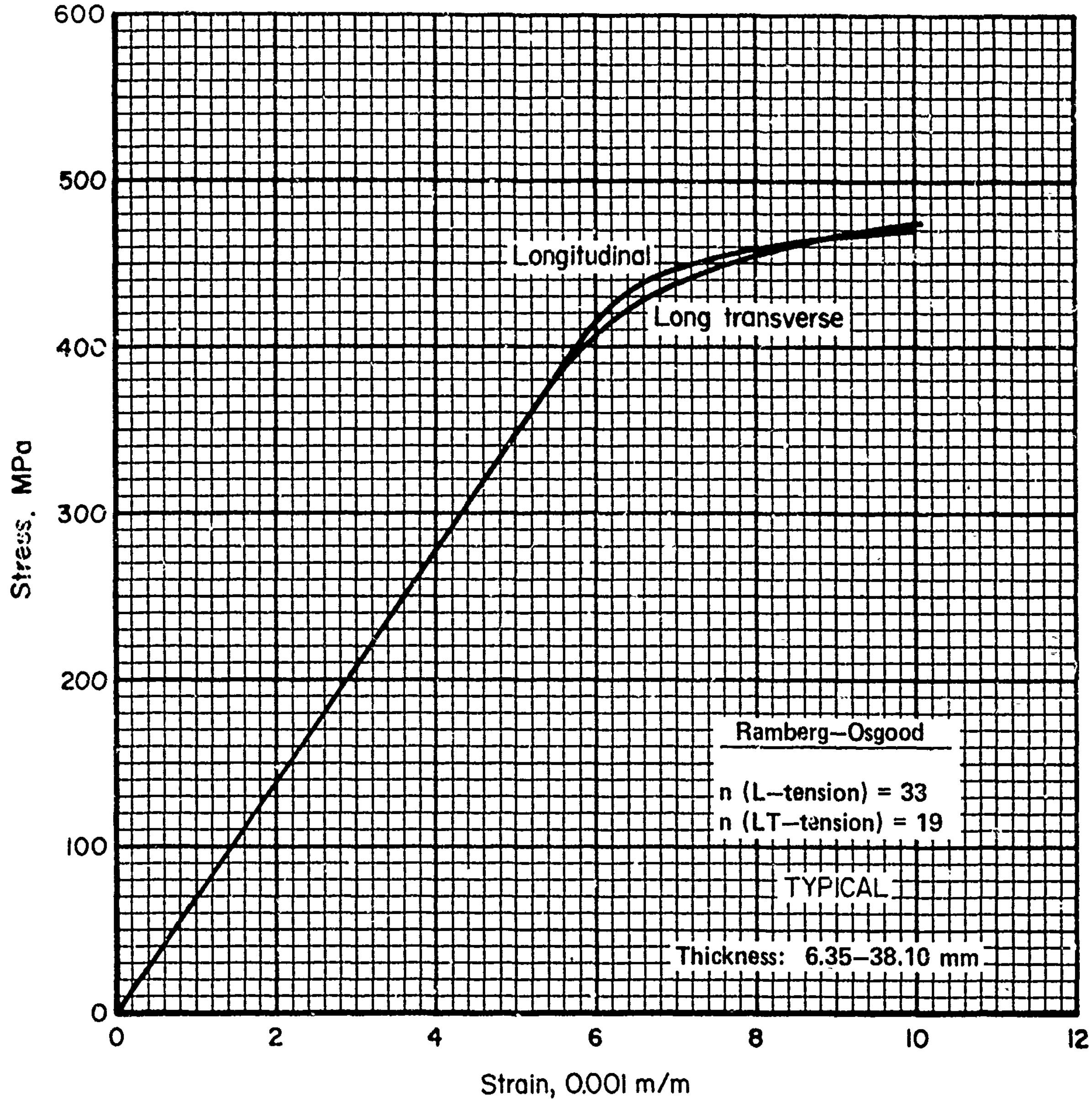


FIGURE 3.7.7.2.6(c). Typical tensile stress-strain curves for 7475-T651 aluminum alloy (plate) at room temperature.

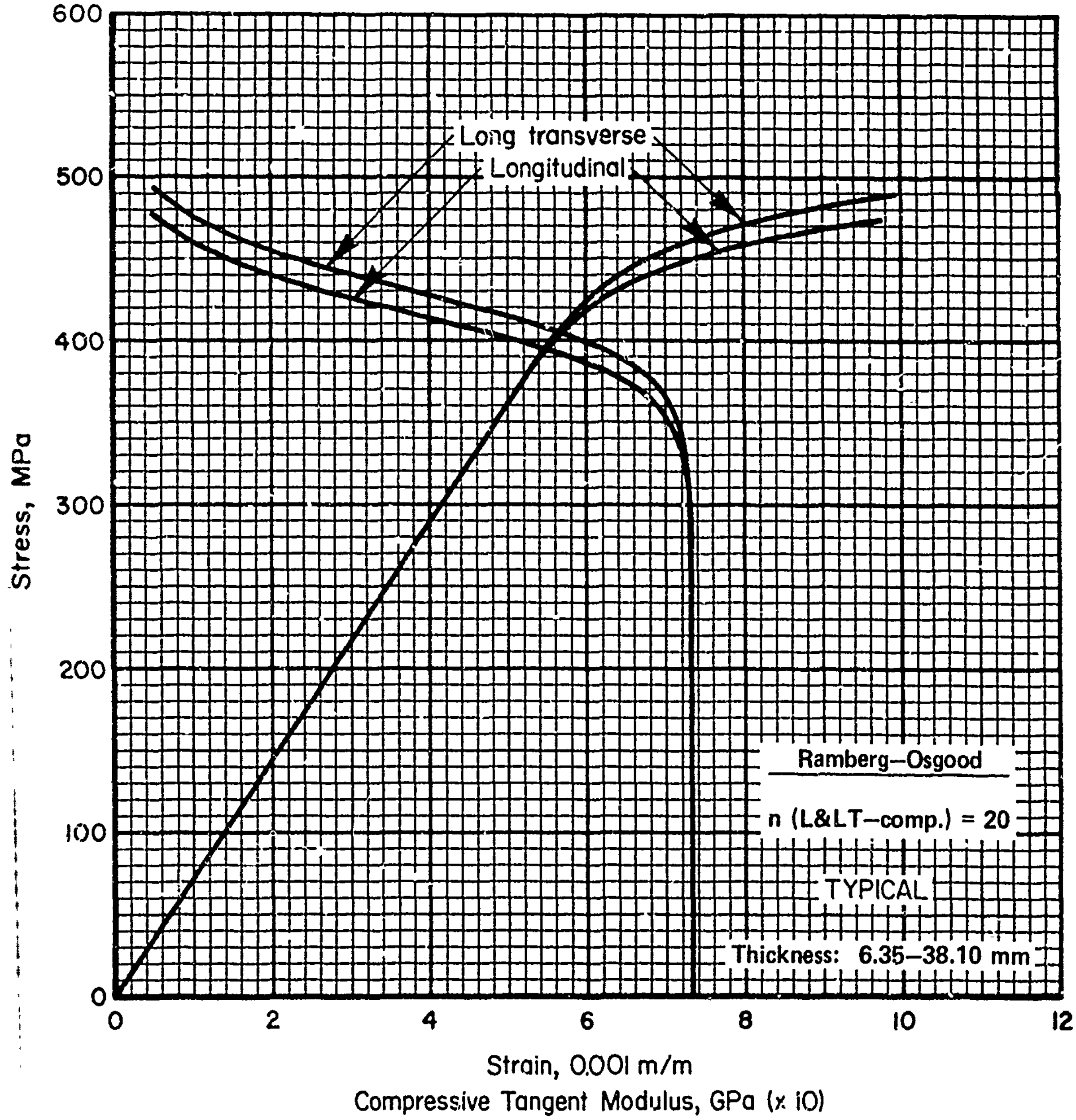


FIGURE 3.7.7.2.6(d). Typical compressive stress-strain and tangent-modulus curves for 7475-T651 aluminum alloy (plate) at room temperature.

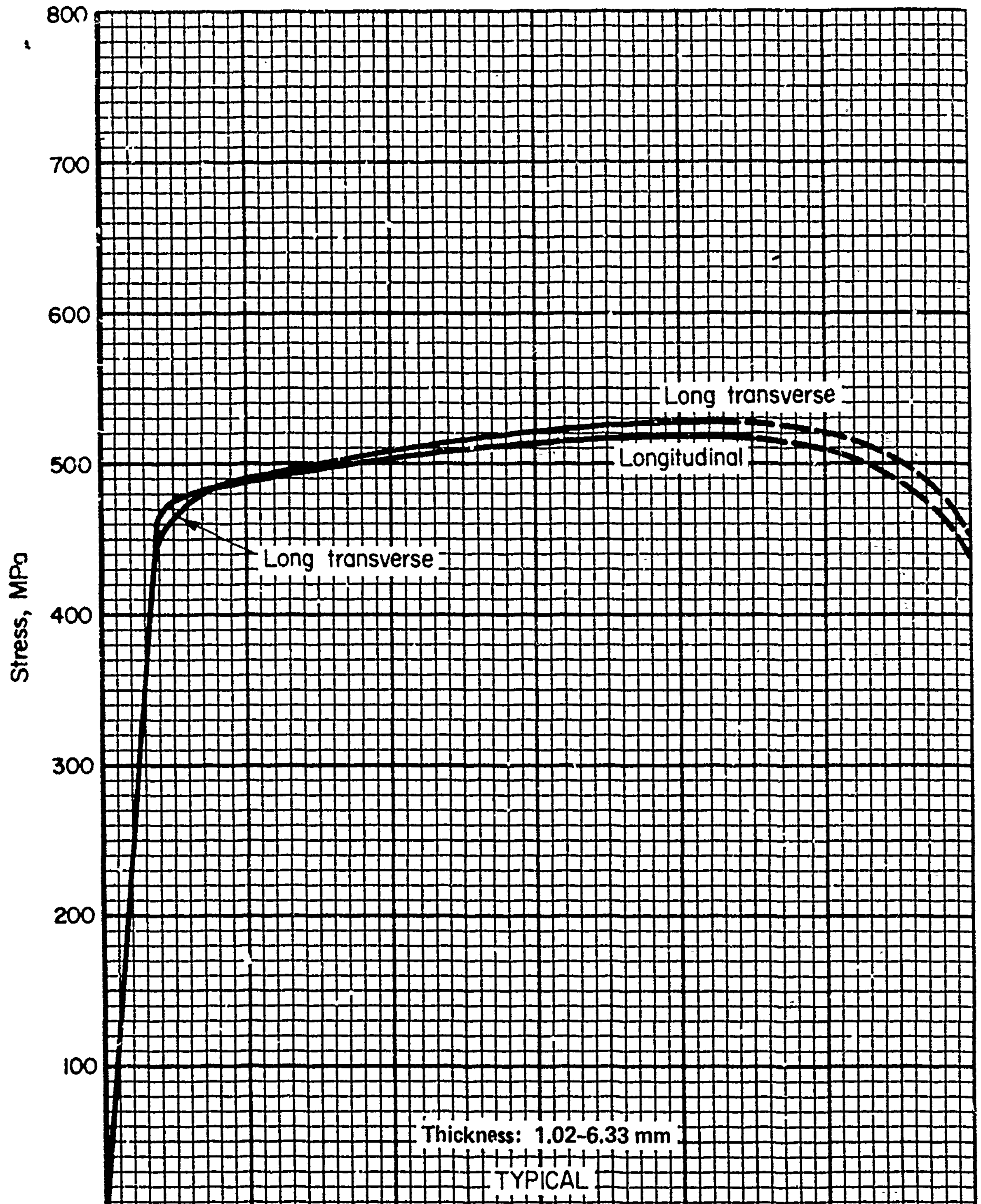


FIGURE 3.7.7.2.6(e). Typical tensile stress-strain (full range) for 7475-T761 (sheet) at room temperature.

3.8 800 Series Wrought Alloys
3.9)
3.10) Unused numbers
3.11)
3.12 200.0 Series Cast Alloys

Alloys of the 200 series contain copper as the principal alloying element, and are particularly useful for elevated temperature applications.

3.12.1 201.0 ALLOY

3.12.1.0 *Comments and Properties.*—201.0 is a high-strength, heat-treatable Al-Cu-Ag casting alloy. In the T6 (aged) temper, it possesses high strength and good ductility, but is not recommended for use in environments conducive to stress-corrosion cracking. In the T7 (overaged) temper, it possesses high strength and moderate ductility and optimum resistance to stress-corrosion cracking. Refer to Section 3.1.3.4 for comments regarding the weldability of the alloy.

Material specifications covering this alloy are presented in Table 3.12.1.0(a). Room-temperature mechanical and physical properties are presented in Table 3.12.1.0(b). The effect of temperature on physical properties is shown in Figure 3.12.1.0.

TABLE 3.12.1.0(a). *Material Specifications for 201.0 Aluminum Alloy*

Specification	Form
AMS 4228	Castings (T6 temper)
AMS 4229	Castings (T7 temper)

The temper index for 201.0 is as follows:

Section	Temper
3.12.1.1	T6
3.12.1.2	T7

3.12.1.1 *T6 Temper.*—A full-range tensile stress-strain curve for this temper is presented in Figure 3.12.1.1.6.

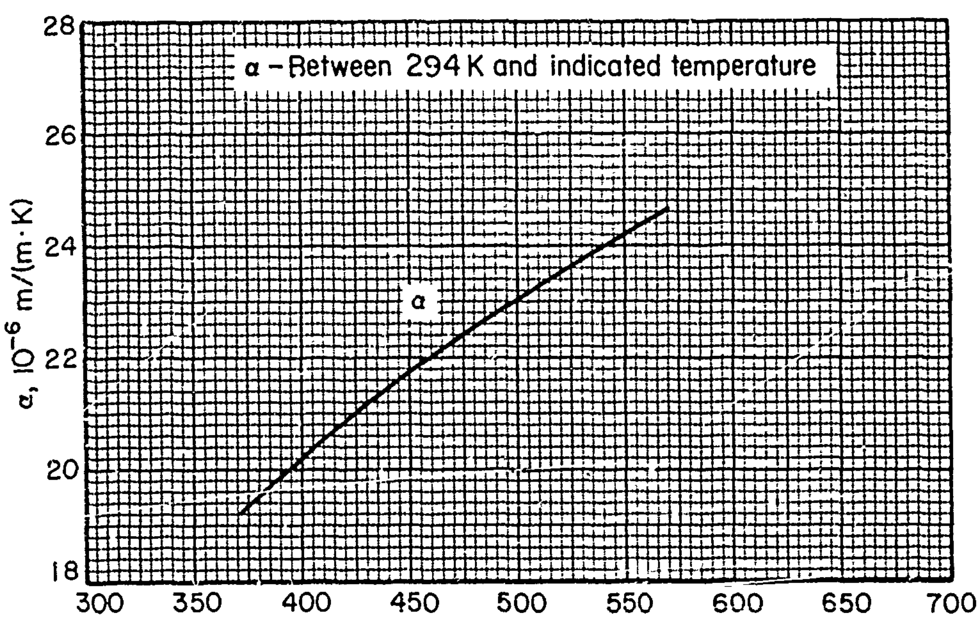


FIGURE 3.12.1.0. Effect of temperature on the physical properties of 201.0 aluminum alloy (castings).

TABLE 3.12.1.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 201.0 ALUMINUM ALLOY (CASTINGS)

SPECIFICATION............	AMS 4228		AMS 4229	
FORM......................	CASTINGS		CASTINGS	
TEMPER....................	T6		T7	
CLASS[a]	1[b]	10[c]	2[b]	11[c]
BASIS.....................	S	S	S	S
MECHANICAL PROPERTIES[d]:				
FTU, MPA..............	414	386	414	386
FTY, MPA..............	345	331	345	331
FCY, MPA..............	352	338	...	...
FSU, MPA..............	255	241	...	...
FBRU, MPA:				
(E/D=1.5)..........	621	579	...	...
(E/D=2.0)..........	793	738	...	...
FBRY, MPA:				
(E/D=1.5)..........	531	510	...	...
(E/D=2.0)..........	621	593	...	...
EL, PERCENT...........	5	3	3	1.5
E, GPA................	71.0			
EC, GPA...............	73.8			
G, GPA................	27.6			
MU....................	0.33			
PHYSICAL PROPERTIES:				
OMEGA, MG/M3..........	2.80			
C, J/(G*K)............	0.92 (373 K)			
K, W/(M*K)............	121 (AT 298 K)			
ALPHA, 10-6 M/(M*K)..	SEE FIGURE 3.12.1.0			

[a] CLASS DESIGNATIONS ARE DEFINED IN MIL-A-21180.

[b] PROPERTIES IN CLASSES 1 AND 2 ARE OBTAINABLE ONLY IN DESIGNATED AREAS WITHIN CASTING.

[c] PROPERTIES IN CLASSES 10 AND 11 APPLY TO UNSPECIFIED LOCATIONS WITHIN CASTING.

[d] THE MECHANICAL PROPERTIES SHOWN ARE RELIABLY OBTAINABLE IN CASTINGS OF THIS ALLOY AND HEAT-TREAT CONDITION WHEN PRODUCED UNDER THE QUALITY ASSURANCE PROVISIONS OF MIL-A-21180. THESE PROVISIONS REQUIRE PRE-PRODUCTION 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 ARE MANDATORY IF THESE PROPERTIES ARE TO BE RELIABLY ASSURED IN EACH CASTING.

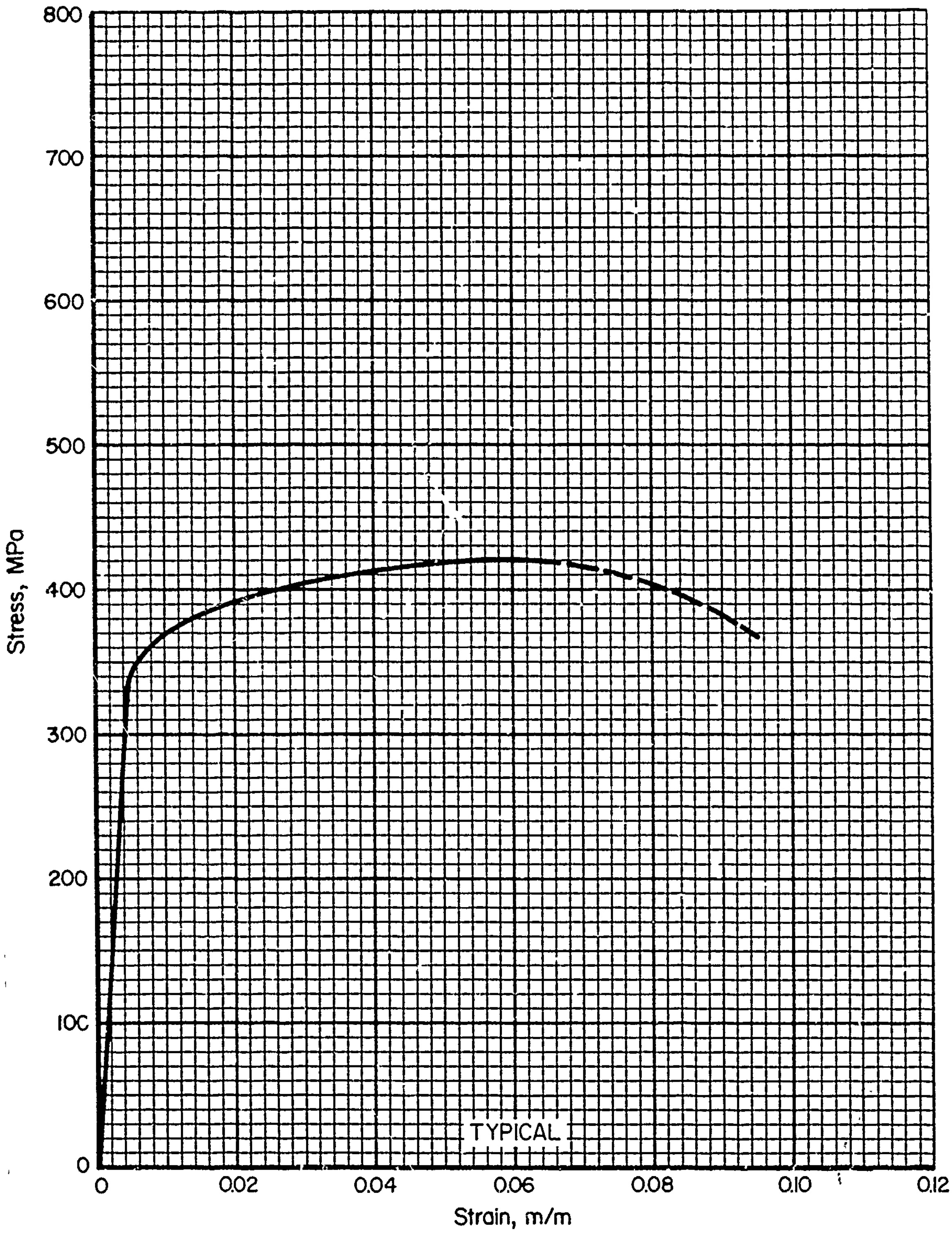


FIGURE 3.12.1.1.6. Typical full-range tensile stress-strain curve for 201.0-T6 aluminum alloy (castings).

3.12.2 224.0 ALLOY

3.12.2.0 *Comments and Properties.*—Alloy 224.0 is a heat treatable Al-Cu-Zr casting alloy. When solution heat treated and overaged, it possesses excellent mechanical properties at elevated temperatures, good fatigue properties and toughness. A material specification covering this alloy is presented in Table 3.12.2.0(a). Room-temperature mechanical and physical properties are presented in Table 3.12.2.0(b).

TABLE 3.12.2.0(a). *Material Specification for 224.0 Aluminum Alloy*

Specification	Form
AMS 4226	Castings

The temper index for 224.0 is as follows:

Section	Temper
3.12.2.1	Solution and Precipitation Heat Treated (Overaged)

A typical room-temperature tensile stress-strain curve is presented in Figure 3.12.2.1.6(a). Typical room-temperature compressive stress-strain and tangent-modulus curves are shown in Figure 3.12.2.1.6(b). A typical full-range tensile stress-strain curve is presented in Figure 3.12.2.1.6(c).

TABLE 3.12.2.0(b). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF ALUMINUM ALLOY 224.0 (CASTINGS)

SPECIFICATION	AMS 4226			
FORM	CASTINGS			
TEMPER	SOLUTION AND PRECIPITATION HEAT TREATED (OVERAGED)			
CLASS	1	2	10	11
BASIS	S	S	S	S
MECHANICAL PROPERTIES:				
FTU, MPA	345	379	310	345
FTY, MPA	255	255	241	255
FCY, MPA	262	262	248	262
FSU, MPA	221	248	200	221
FBRU[a], MPA:				
(E/D=1.5)	552	607	496	552
(E/D=2.0)	689	758	621	689
FBRY[a], MPA:				
(E/D=1.5)	407	407	386	407
(E/D=2.0)	510	510	483	510
EL, PERCENT	3	5	2	3
E, GPA	71.0			
EC, GPA	72.4			
G, GPA	26.9			
MU	0.33			
PHYSICAL PROPERTIES:				
OMEGA, MG/M3	2.82			
C, J/(G*K)	...			
K, W/(M*K)	121 (AT 298 K)			
ALPHA, 10-6 M/(M*K)	...			

[a] BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

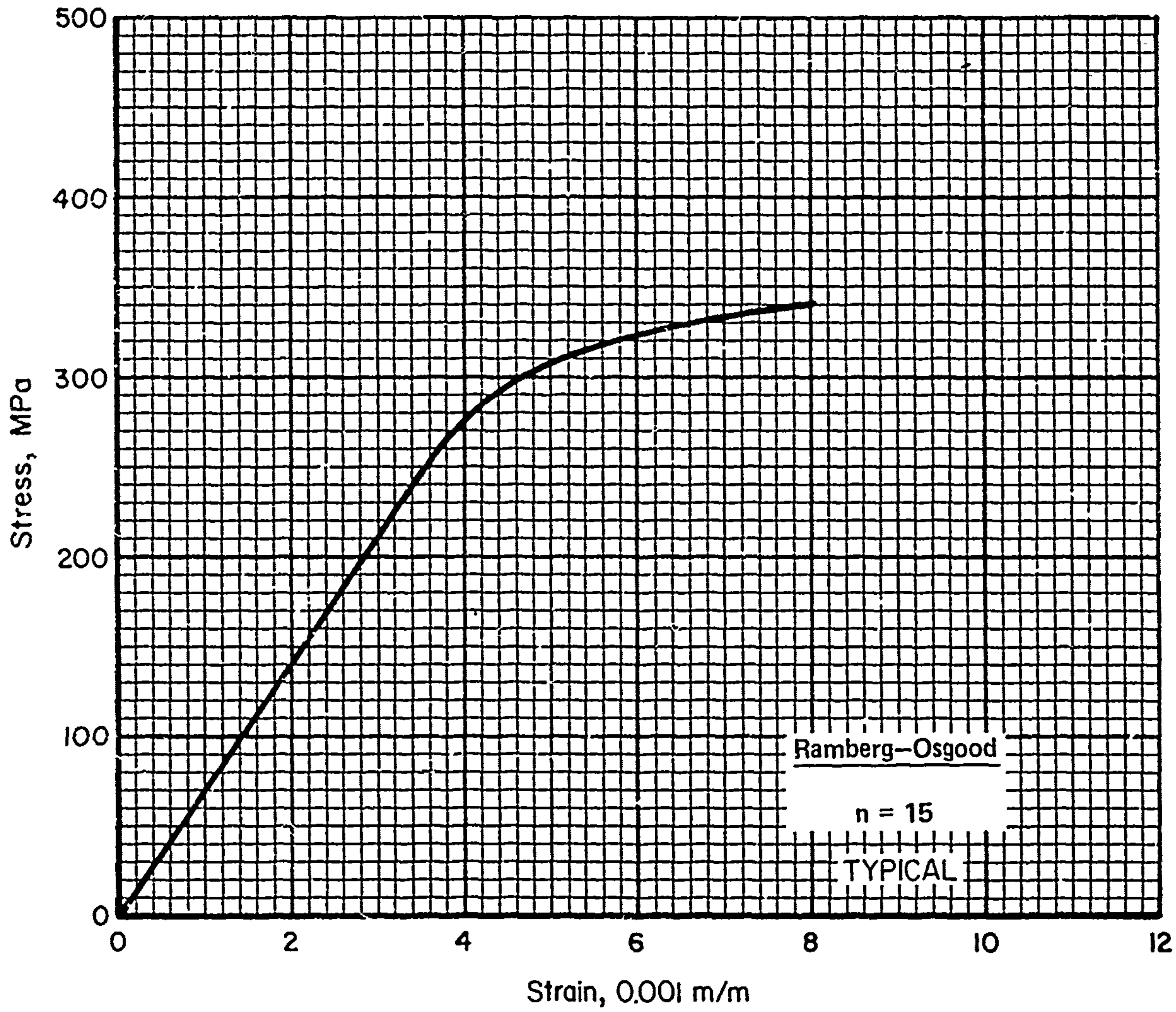


FIGURE 3.12.2.1.6(a). Typical tensile stress-strain curve for 224.0 aluminum alloy (casting) at room temperature.

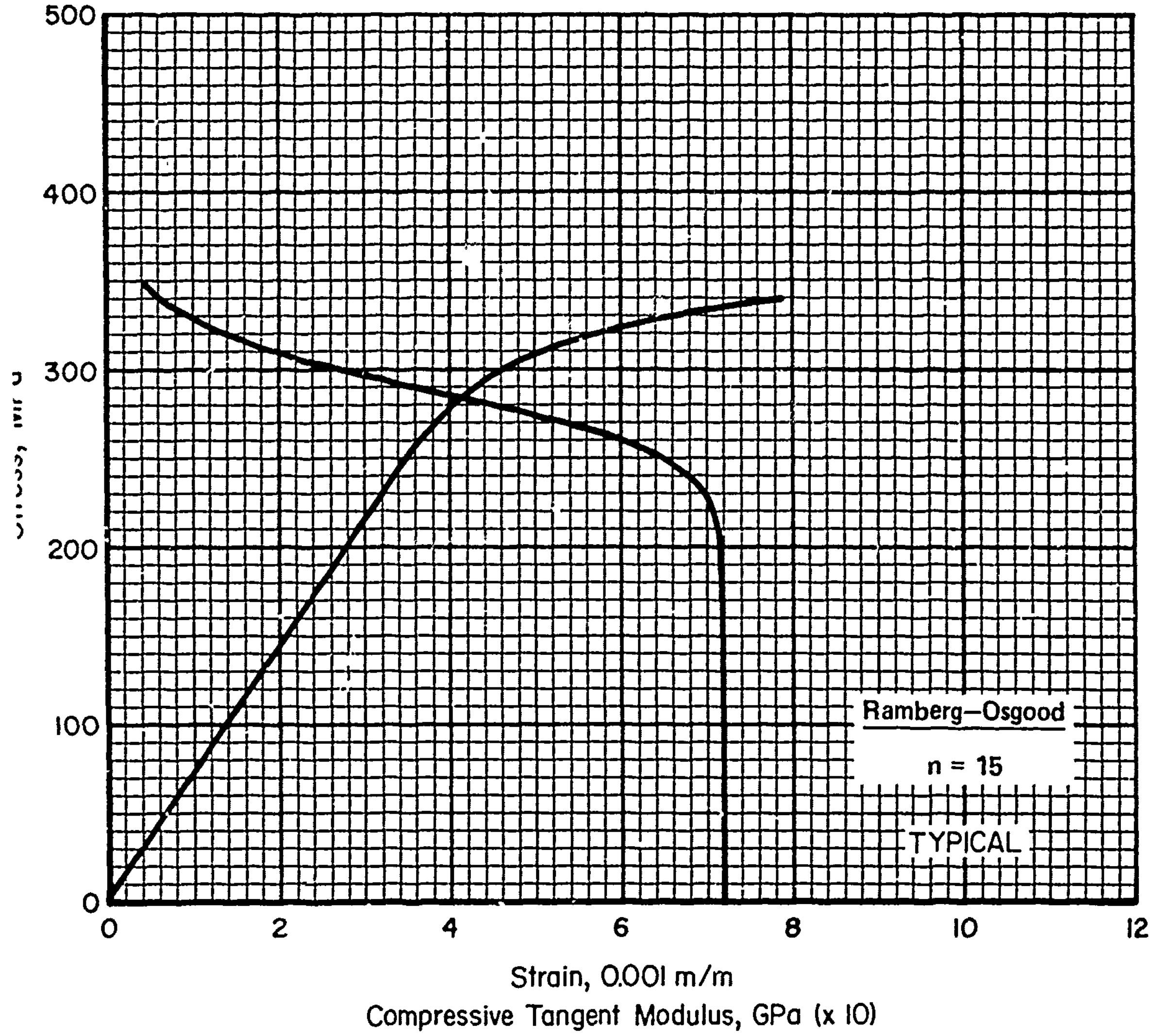


FIGURE 3.12.2.1.6(b). Typical compressive stress-strain and tangent-modulus curves for 224.0 aluminum alloy (casting) at room temperature.

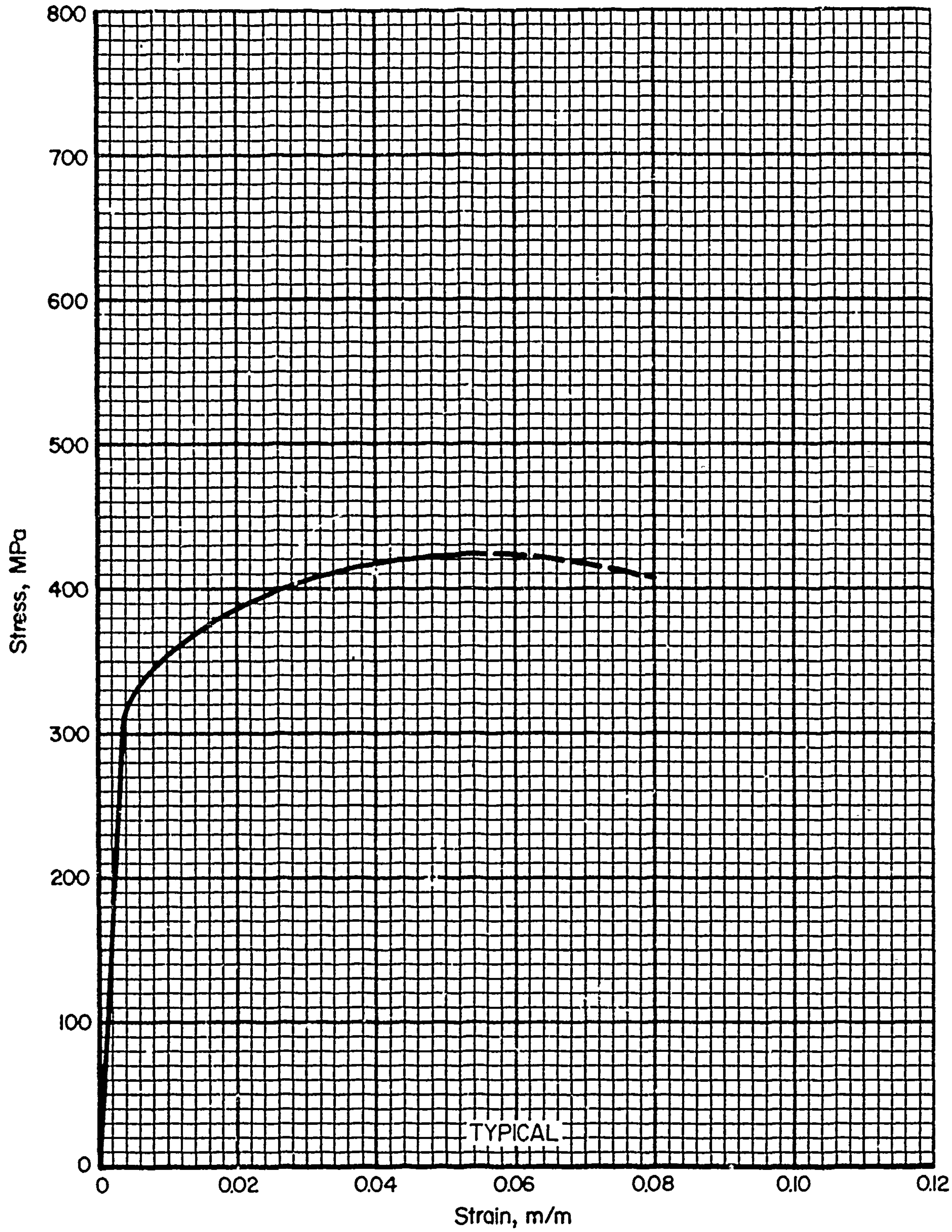


FIGURE 3.12.2.1.6(c). Typical tensile stress-strain curve (full range) for 224.0 aluminum alloy (casting) at room temperature.

3.12.3 295.0(195) ALLOY

3.12.3.0 *Comments and Properties.*—295.0 is a heat-treatable Al-Cu alloy with high strength at elevated temperatures. Casting characteristics are only fair. Refer to Section 3.1.3.4 for comments regarding the weldability of the alloy.

A material specification for 295.0 aluminum alloy is presented in Table 3.12.3.0(a). Room-temperature mechanical and physical properties are shown in Table 3.12.3.0(b). The effect of temperature on physical properties is shown in Figure 3.12.3.0.

TABLE 3.12.3.0(a). *Material Specification for 295.0 Aluminum Alloy*

Specification	Form
QQ-A-601	Sand castings

The temper index for 295.0 is as follows:

Section	Temper
3.12.3.1	T4
3.12.3.2	T6

TABLE 3.12.3.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 295.0 ALUMINUM ALLOY (CASTINGS)[a]

SPECIFICATION	QQ-A-601	
FORM	SAND CASTING	
CONDITION	T4	T6
CLASS	...	...
BASIS	S[b]	S[b]
MECHANICAL PROPERTIES:		
FTU, MPA	200	221
FTY, MPA	93	138
FCY, MPA	97	145
FSU, MPA	152	165
FBRU, MPA:		
(E/D=1.5)	317	352
(E/D=2.0)	421	462
FBRY, MPA:		
(E/D=1.5)	152	234
(E/D=2.0)	179	276
EL, PERCENT	6	3
E, GPA	68.3	
EC, GPA	69.6	
G, GPA	26.5	
MU	0.33	
PHYSICAL PROPERTIES:		
OMEGA, MG/M3	2.82[c]	
C, J/(G*K)	0.96 (AT 373 K)	
K, W/(M*K)	138 (AT 298 K)	
ALPHA, 10-6 M/(M*K)	22.9 (293 TO 373 K)	

a REFERENCE SHOULD BE MADE TO THE SPECIFIC REQUIREMENTS OF THE PROCURING OR CERTIFICATING AGENCY IN REGARD TO THE USE OF THE ABOVE VALUES IN THE DESIGN OF CASTINGS.

b MECHANICAL PROPERTIES IN THIS COLUMN ARE BASED UPON THE MINIMUM GUARANTEED TENSILE PROPERTIES FROM SEPARATELY CAST TEST BARS. THE STRENGTH OF PRODUCTION CASTINGS MAY BE AS LOW AS 75 PERCENT, AND ELONGATION AS LOW AS 25 PERCENT, OF THE TABULATED VALUES.

c THIS VALUE OF DENSITY ASSUMES SOLID (VOID-FREE) METAL. SINCE SOME POROSITY CANNOT BE AVOIDED IN COMMERCIAL CASTINGS, THE DENSITY WILL BE SLIGHTLY LESS THAN THE THEORETICAL VALUE.

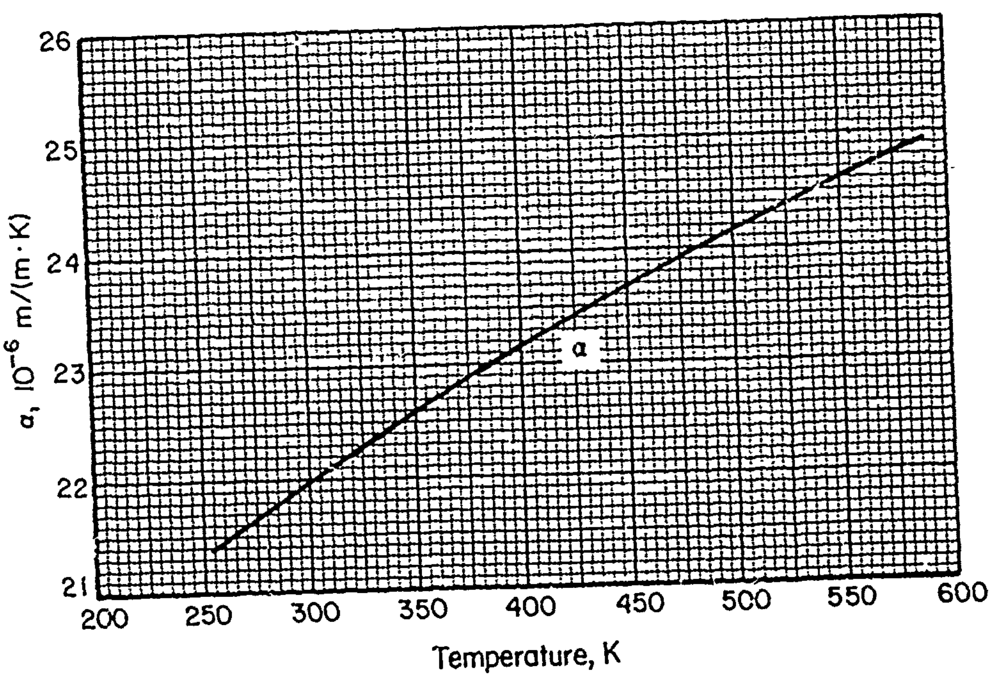


FIGURE 3.12.3.0. Effect of temperature on the physical properties of 295.0 aluminum alloy.

3.13 300.0 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.

3.13.1 354.0 ALLOY

3.13.1.0 *Comments and Properties.*—354.0 is a heat-treatable Al-Si-Mg alloy having 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 of the alloy.

A material specification for 354.0 aluminum alloy is presented in Table 3.13.1.0(a). Room-temperature mechanical and physical properties are shown in Table 3.13.1.0(b).

TABLE 3.13.1.0(a). *Material Specification for 354.0 Aluminum Alloy*

Specification	Form
MIL-A-21180	Castings

The temper index for 354.0 is as follows:

Section	Temper
3.13.11	T61

TABLE 3.13.1.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 354.0 ALUMINUM ALLOY (CASTINGS)

SPECIFICATION	MIL-A-21180			
FORM	CASTINGS			
CONDITION	T61			
CLASS	1[a,b]	2[a,b]	10	11
BASIS	S	S	S	S
MECHANICAL PROPERTIES[c]				
FTU, MPA	324	345	324	296
FTY, MPA	248	290	248	228
FCY, MPA	248	290	248	228
FSU, MPA	228	241	228	207
FBRU, MPA:				
(E/D=1.5)	455	483	455	414
(E/D=2.0)	586	621	586	531
FBRY, MPA:				
(E/D=1.5)	400	462	400	365
(E/D=2.0)	448	524	448	407
EL, PERCENT	3	2	3	2
E, GPA	73.1			
EC, GPA	74.5			
G, GPA	27.6			
MU	0.33			
PHYSICAL PROPERTIES:				
OMEGA, MG/M3	2.71			
C, J/(G*K)	0.96 (AT 373 K)			
K, W/(M*K)	...			
ALPHA, 10-6 M/(M*K)	20.9 (293 TO 373 K)			

[a] PROPERTIES LISTED FOR THIS CLASS ARE APPLICABLE TO DESIGNATED AREAS OF THE CASTING.

[b] THIS CLASS IS OBTAINABLE IN FAVORABLE CASTING CONFIGURATIONS AND MUST BE NEGOTIATED WITH THE FOUNDRY FOR THE PARTICULAR CONFIGURATION DESIRED.

[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 MIL-A-21180. THESE PROVISIONS REQUIRE PRE-PRODUCTION 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.

3.13.2 355.0 ALLOY

3.13.2.0 *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 3.13.2.0(a). Room-temperature mechanical and physical properties are shown in Table 3.13.2.0(b). The effect of temperature on α is shown in Figure 3.13.2.0.

TABLE 3.13.2.0(a). *Material Specification for 355.0 Aluminum Alloy*

Specification	Form
QQ-A-596	Permanent mold castings

The temper index for 355.0 is as follows:

Section	Temper
3.13.2.1	T6

TABLE 3.13.2.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 355.0 ALUMINUM ALLOY (CASTINGS)[a]

SPECIFICATION..........	QQ-A-596
FORM....................	PERMANENT MOLD
FORM....................	CASTINGS
CONDITION...............	T6
CLASS...................	...
BASIS...................	S[b]
MECHANICAL PROPERTIES:	
FTU, MPA..............	255
FTY, MPA..............	159
FCY, MPA..............	159
FSU, MPA..............	179
FBRU, MPA:	
(E/D=1.5).........	...
(E/D=2.0).........	...
FBRY, MPA:	
(E/D=1.5).........	...
(E/D=2.0).........	...
EL, PERCENT..........	1
E, GPA................	71.0
EC, GPA...............	71.0
G, GPA................	26.2
MU....................	0.33
PHYSICAL PROPERTIES:	
OMEGA, MG/M3.........	2.71
C, J/(G*K)...........	0.96
K, W/(M*K)...........	152
ALPHA, 10-6 M/(M*K)..	22.3

[a]REFERENCE SHOULD BE MADE TO THE SPECIFIC REQUIREMENTS OF THE PROCURING OR CERTIFICATING AGENCY IN REGARD TO THE USE OF THE ABOVE VALUES IN THE DESIGN OF CASTINGS.

[b]MECHANICAL PROPERTIES IN THIS COLUMN ARE BASED UPON THE MINIMUM GUARANTEED TENSILE PROPERTIES FROM SEPARATELY CAST TEST BARS. THE STRENGTH OF PRODUCTION CASTINGS MAY BE AS LOW AS 75 PERCENT, AND ELONGATION AS LOW AS 25 PERCENT, OF THE TABULATED VALUES.

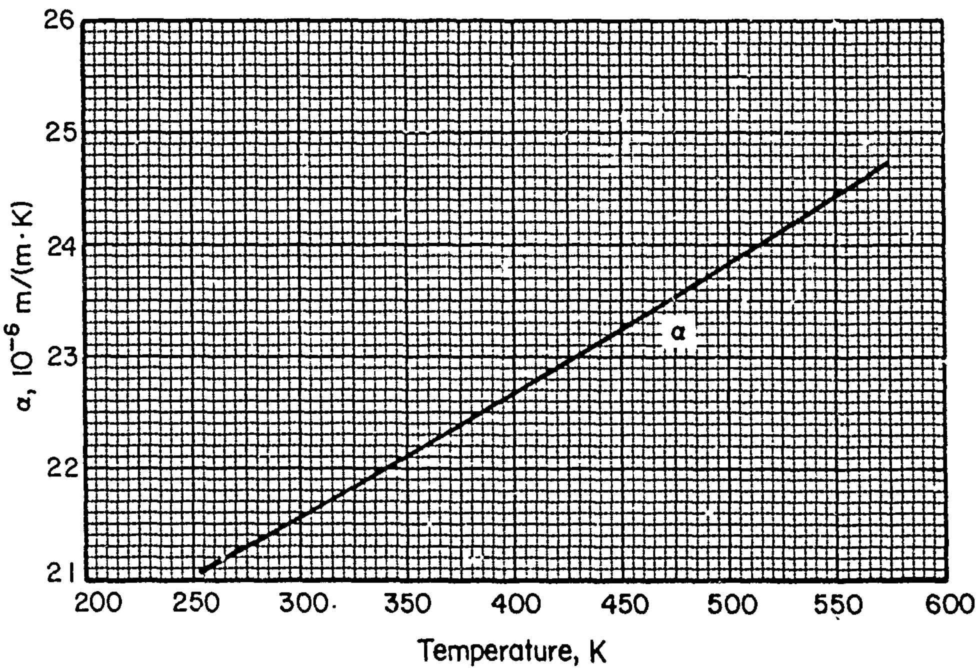


FIGURE 3.13.2.0. Effect of temperature on the physical properties of 355.0 aluminum alloy.

3.13.3 C355.0 ALLOY

3.13.3.0 *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 3.13.3.0(a). Room-temperature mechanical and physical properties are shown in Table 3.13.3.0(b).

TABLE 3.13.3.0(a). *Material Specification for C355.0 Aluminum Alloy*

Specification	Form
MIL-A-21180	Castings

The temper index for C355.0 is as follows:

Section	Temper
3.13.1.1	T61

TABLE 3.13.3.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF C355.0 ALUMINUM ALLOY (CASTINGS)

SPECIFICATION..........	MIL-A-21180					
FORM..................	CASTINGS					
CONDITION..............	T61					
CLASS..................	1[a]	2	3[a,b]	10	11	12
BASIS..................	S	S	S	S	S	S
MECHANICAL PROPERTIES[c]:						
FTU, MPA.............	283	303	345	283	255	241
FTY, MPA.............	214	228	276	214	207	193
FCY, MPA.............	214	228	276	214	207	193
FSU, MPA.............	200	214	241	200	179	165
FBRU, MPA:						
(E/D=1.5).........	393	427	483	393	359	336
(E/D=2.0).........	510	545	621	510	462	434
FBRY, MPA:						
(E/D=1.5).........	345	365	441	345	331	310
(E/D=2.0).........	386	407	496	386	372	345
EL, PERCENT..........	3	3	2	3	1	1
E, GPA...............	69.6					
EC, GPA..............	71.0					
G, GPA...............	26.5					
MU...................	0.33					
PHYSICAL PROPERTIES:						
OMEGA, MG/M3.........	2.71					
C, J/(G*K)...........	0.96 (373 K)					
K, W/(M*K)...........	152 (AT 298 K)					
ALPHA, 10-6 M/(M*K)..	22.3 (293 TO 373 K)					

[a] PROPERTIES LISTED FOR THIS CLASS ARE APPLICABLE TO DESIGNATED AREAS OF THE CASTING.

[b] THIS CLASS IS OBTAINABLE IN FAVORABLE CASTING CONFIGURATIONS AND MUST BE NEGOTIATED WITH THE FOUNDRY FOR THE PARTICULAR CONFIGURATION DESIRED.

[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 MIL-A-21180. THESE PROVISIONS REQUIRE PRE-PRODUCTION 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.

3.13.4 356.0 ALLOY

3.13.4.0 *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 3.13.4.0(a). Room-temperature mechanical and physical properties are shown in Table 3.13.4.0(b). The effect of temperature on physical properties is given in Figure 3.13.4.0.

TABLE 3.13.4.0(a). *Material Specifications for 356.0 Aluminum Alloy*

Specification	Form
QQ-A-596	Permanent mold castings
QQ-A-601	Sand castings
AMS 4260	Investment castings

The temper index for 356.0 is as follows:

Section	Temper
3.13.4.1	T6

TABLE 3.13.4.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 356.0 ALUMINUM ALLOY (CASTINGS)

SPECIFICATION..........	QQ-A-601	QQ-A-596, AMS 4260
FORM..................	SAND CASTINGS	INVESTMENT AND PERMANENT MOLD CASTINGS
CONDITION..............	T6	
BASIS..................	S^b	S^b
MECHANICAL PROPERTIES:		
FTU, MPA...............	207	228
FTY, MPA...............	138	152
FCY, MPA...............	138	152
FSU, MPA...............	172	172
FBRU, MPA:		
(E/D=1.5)..........	331	317
(E/D=2.0)..........	434	407
FBRY, MPA:		
(E/D=1.5)..........	234	241
(E/D=2.0)..........	276	276
EL, PERCENT...........	3	3
E, GPA................	71.0	
EC, GPA...............	71.0	
G, GPA................	26.5	
MU....................	0.33	
PHYSICAL PROPERTIES:		
OMEGA, MG/M3..........	2.68	
C, J/(G*K)............	0.96 (AT 373 K)	
K, W/(M*K)............	152 (AT 298 K)	
ALPHA, 10-6 M/(M*K)..	21.4 (293 TO 373 K)	

[a] REFERENCE SHOULD BE MADE TO THE SPECIFIC REQUIREMENTS OF THE PROCURING OR CERTIFICATING AGENCY IN REGARD TO THE USE OF THE ABOVE VALUES IN THE DESIGN OF CASTINGS.

[b] MECHANICAL PROPERTIES IN THIS COLUMN ARE BASED UPON THE MINIMUM GUARANTEED TENSILE PROPERTIES FROM SEPARATELY CAST TEST BARS. THE STRENGTH OF PRODUCTION CASTINGS MAY BE AS LOW AS 75 PERCENT, AND ELONGATION AS LOW AS 25 PERCENT OF THE TABULATED VALUES.

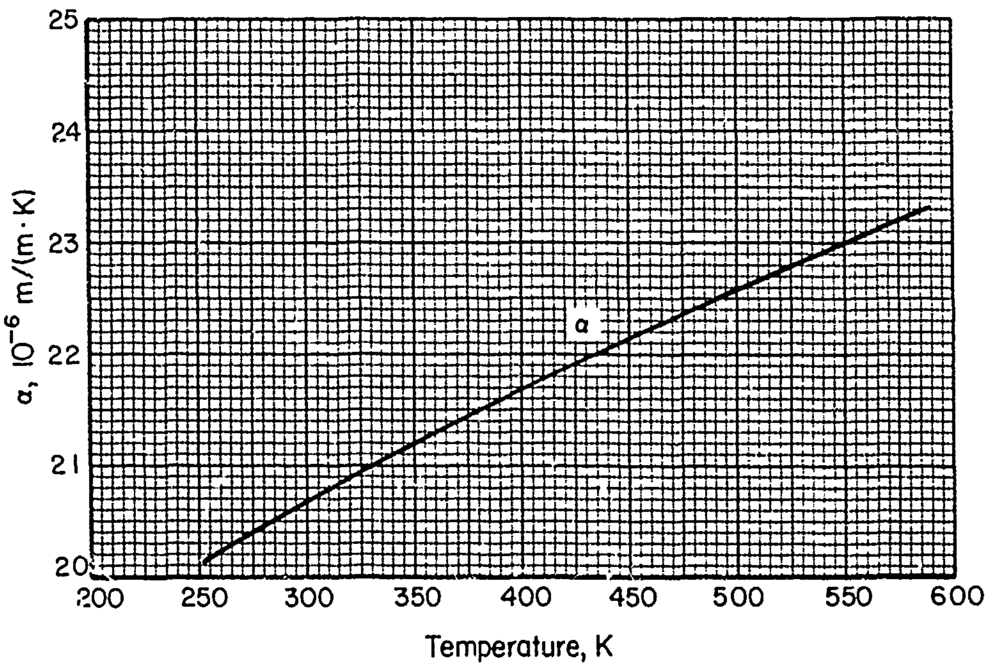


FIGURE 3.13.4.0. Effect of temperature on the physical properties of 356.0 aluminum.

3.13.5 A356.0 ALLOY

3.13.5.0 *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 Section 3.1.3.4 for comments regarding the weldability of the alloy.

A material specification for A356.0 aluminum alloy is presented in Table 3.13.5.0(a). Room-temperature mechanical and physical properties are shown in Table 3.13.5.0(b).

TABLE 3.13.5.0(a). *Material Specification for A356.0 Aluminum Alloy*

Specification	Form
MIL-A-21180	Casting

The temper index for A356.0 is as follows:

Section	Temper
3.13.5.1	T61

TABLE 3.13.5.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF A356.0 ALUMINUM ALLOY (CASTINGS)

SPECIFICATION............	MIL-A-21180					
FORM.....................	CASTINGS					
CONDITION................	T61					
CLASS.	1[a]	2[a,b]	3[a,b]	10	11	12
BASIS....................	S	S	S	S	S	S
MECHANICAL PROPERTIES[c]:						
FTU, MPA..............	262	276	310	262	228	221
FTY, MPA..............	193	207	234	193	186	152
FCY, MPA..............	193	207	234	193	186	152
FSU, MPA..............	186	193	214	186	159	152
FBRU, MPA:						
(E/D=1.5).........	365	386	434	365	317	310
(E/D=2.0).........	469	496	550	469	407	400
FBRY, MPA:						
(E/D=1.5).........	310	331	372	310	296	241
(E/D=2.0).........	345	372	421	345	338	276
EL, PERCENT..........	5	3	3	5	3	2
E, GPA................	71.7					
EC, GPA...............	72.4					
G, GPA................	26.9					
MU....................	0.33					
PHYSICAL PROPERTIES:						
OMEGA, MG/M3.........	2.68					
C, J/(G*K)...........	0.96 (AT 373 K)					
K, W/(M*K)...........	152 (AT 298 K)					
ALPHA, 10-6 M/(M*K)..	21.4 (298 TO 373 K)					

[a]PROPERTIES LISTED FOR THIS CLASS ARE APPLICABLE TO DESIGNATED AREAS OF THE CASTING.

[b]THIS CLASS IS OBTAINABLE IN FAVORABLE CASTING CONFIGURATIONS AND MUST BE NEGOTIATED WITH THE FOUNDRY FOR THE PARTICULAR CONFIGURATION DESIRED.

[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 MIL-A-21180. THESE PROVISIONS REQUIRE PRE-PRODUCTION 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.

3.13.6 A357.0 ALLOY

3.13.6.0 *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 the highest strengths available in commercial castings, 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 3.13.6.0(a). Room-temperature mechanical and physical properties are shown in Table 3.13.6.0(b).

TABLE 3.13.6.0(a). *Material Specification for A357.0 Aluminum Alloy*

Specification	Form
MIL-A-21180	Castings

The temper index for A357.0 is as follows:

Section	Temper
3.13.6.1	T61

TABLE 3.13.6.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF A357.0 ALUMINUM ALLOY (CASTINGS)

PECIFICATION...........	MIL-A-21180			
ORM....................	CASTINGS			
NDITION................	T61			
ASS.	1[a,b]	2[a,b]	10	11
SIS....................	S	S	S	S
CHANICAL PROPERTIES[c]:				
FTU, MPA...............	310	345	262	283
FTY, MPA...............	241	276	193	214
FCY, MPA...............	241	276	193	214
FSU, MPA...............	214	241	166	200
FBRU, MPA:				
(E/D=1.5)..........	434	483	365	393
(E/D=2.0)..........	558	621	469	510
FBRY, MPA:				
(E/D=1.5)..........	386	441	310	345
(E/D=2.0)..........	434	496	345	386
EL, PERCENT............	3	5	5	3
E, GPA.................	71.7			
EC, GPA................	72.4			
G, GPA.................	26.9			
MU.....................	0.33			
YSICAL PROPERTIES:				
OMEGA, MG/M3...........	2.68			
C, J/(G*K).............	0.96 (AT 373 K)			
K, W/(M*K).............	152 (AT 298 K)			
ALPHA, 10-6 M/(M*K)..	21.6 (293 TO 373 K)			

[a]PROPERTIES LISTED FOR THIS CLASS ARE APPLICABLE TO DESIGNATED AREAS OF THE CASTING.

[b]THIS CLASS IS OBTAINABLE IN FAVORABLE CASTING CONFIGURATIONS AND MUST BE NEGOTIATED WITH THE FOUNDRY FOR THE PARTICULAR CONFIGURATION DESIRED.

[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 MIL-A-21180. THESE PROVISIONS REQUIRE PRE-PRODUCTION 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.

3.13.7 359.0 ALLOY

3.13.7.0 *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 is presented in Table 3.13.7.0(a). Room-temperature mechanical and physical properties are shown in Table 3.13.7.0(b).

TABLE 3.13.7.0(a). *Material Specification for 359.0 Aluminum Alloy*

Specification	Form
MIL-A-21180	Castings

The temper index for 359.0 is as follows:

Section	Temper
3.13.7.1	T61

TABLE 3.13.7.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 359.0 ALUMINUM ALLOY (CASTINGS)

ECIFICATION............	MIL-A-21180			
RM.....................	CASTINGS			
NDITION................	T61			
ASS.	1[a,b]	2[a,b]	10	11
SIS....................	S	S	S	S
CHANICAL PROPERTIES[c]				
FTU, MPA..............	310	324	310	276
FTY, MPA..............	241	262	234	207
FCY, MPA..............	241	262	234	207
FSU, MPA..............	214	228	214	193
FBRU, MPA:				
(E/D=1.5)..........	434	455	434	386
(E/D=2.0)..........	558	586	558	496
FBRY, MPA:				
(E/D=1.5)..........	386	421	372	331
(E/D=2.0)..........	434	469	421	372
EL, PERCENT...........	4	3	4	3
E, GPA................	72.4			
EC, GPA...............	73.8			
G, GPA................	27.6			
MU....................	0.33			
SICAL PROPERTIES:				
OMEGA, MG/M3.........	2.68			
C, J/(G*K)............	0.96 (AT 373 K)			
K, W/(M*K)............	138 (AT 298 K)			
ALPHA, 10-6 M/(M*K)..	19.8 (293 TO 373 K)			

[a]PROPERTIES LISTED FOR THIS CLASS ARE APPLICABLE TO DESIGNATED AREAS OF THE CASTING.

[b]THIS CLASS IS OBTAINABLE IN FAVORABLE CASTING CONFIGURATIONS AND MUST BE NEGOTIATED WITH THE FOUNDRY FOR THE PARTICULAR CONFIGURATION DESIRED.

[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 MIL-A-21180. THESE PROVISIONS REQUIRE PRE-PRODUCTION 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 ARE MANDATORY IF THESE PROPERTIES ARE TO BE RELIABLY ASSURED IN EACH CASTING.

3.14 400.00 Series Cast Alloys

3.15 500.00 Series Cast Alloys

The 500.0 series of casting alloys contain magnesium as the principal alloying element, and are used primarily for sand castings.

3.15.1 520.0 (220) ALLOY

3.15.1.0 *Comments and Properties.*—520.0 is a relatively high strength, heat treatable sand casting alloy with excellent machinability and resistance to corrosion. It requires special foundry practices for casting. Refer to Section 3.1.3.4 for comments regarding the weldability of the alloy.

A material specification for 520.0 aluminum alloy is presented in Table 3.15.1.0(a). Room-temperature mechanical and physical properties are shown in Table 3.15.1.0(b). The effect of temperature on α is shown in Figure 3.15.1.0.

TABLE 3.15.1.0(a). *Material Specification for 520.0 Aluminum Alloy*

Specification	Form
QQ-A-601	Castings

The temper index for 520.0 is as follows:

Section	Temper
3.15.1.1	T4

TABLE 3.15.1.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 520.0 ALUMINUM ALLOY (CASTINGS)[a]

SPECIFICATION...........	QQ-A-601	
FORM....................	SAND CASTING	
CONDITION...............	T4[b]	
CLASS.	...	
BASIS...................	S[c]	
MECHANICAL PROPERTIES:		
FTU, MPA..............	290	
FTY, MPA..............	152	
FCY, MPA..............	159	
FSU, MPA..............	207	
FBRU, MPA:		
(E/D=1.5).........	462	
(E/D=2.0).........	607	
FBRY, MPA:		
(E/D=1.5).........	255	
(E/D=2.0).........	303	
EL, PERCENT...........	12	
E, GPA................	71.0	
EC, GPA...............	71.0	
G, GPA................	26.5	
MU....................	0.33	
PHYSICAL PROPERTIES:		
OMEGA, MG/M3..........	2.57	
C, J/(G*K)............	0.96	(AT 373 K)
K, W/(M*K)............	88	(AT 298 K)
ALPHA, 10-6 M/(M*K)..	24.7	(293 TO 373 K)

[a] REFERENCE SHOULD BE MADE TO THE SPECIFIC REQUIREMENTS OF THE PROCURING OR CERTIFICATING AGENCY IN REGARD TO THE USE OF THE ABOVE VALUES IN THE DESIGN OF CASTINGS.

[b] THIS ALLOY IS HIGHLY SUSCEPTIBLE TO STRESS CORROSION FAILURE. SPECIAL HEAT TREATMENT IS REQUIRED.

[c] MECHANICAL PROPERTIES IN THIS COLUMN ARE BASED UPON THE MINIMUM GUARANTEED TENSILE PROPERTIES FROM SEPARATELY CAST TEST BARS. THE STRENGTH OF PRODUCTION CASTINGS MAY BE AS LOW AS 75 PERCENT, AND ELONGATION OF AS LOW AS 25 PERCENT OF THE TABULATED VALUES.

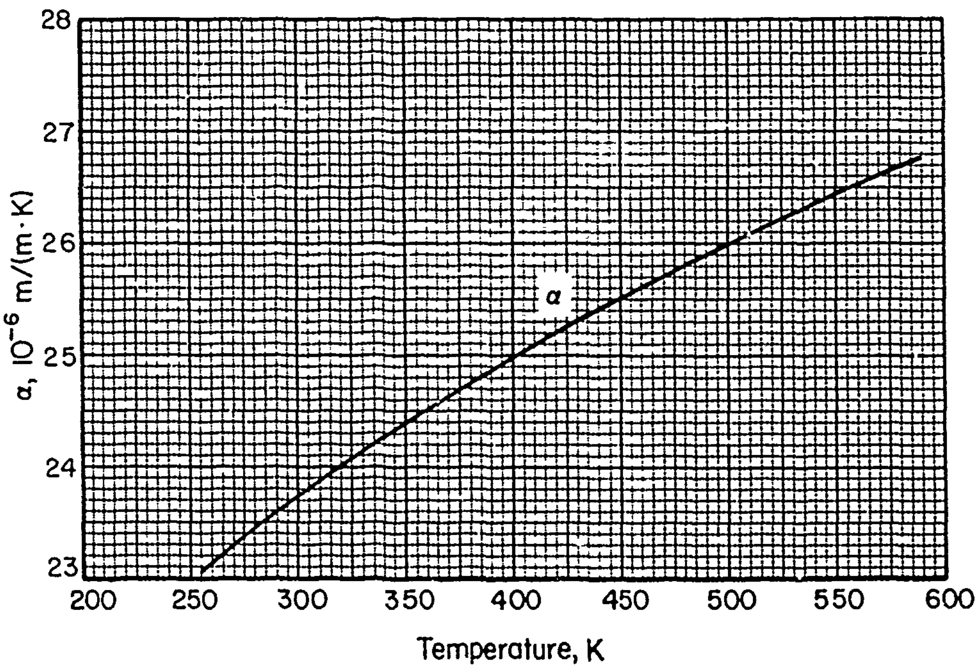


FIGURE 3.15.1.0. Effect of temperature on the physical properties of 520.0 aluminum alloy.

3.15.2 535.0 (ALMAG 35) ALLOY

3.15.2.0 *Comments and Properties.*—535.0 is a medium strength sand casting alloy used in the as cast condition. Refer to Section 3.1.3.4 for comments regarding the weldability of the alloy.

A material specification for 535.0 is presented in Table 3.15.2.0(a). Room-temperature mechanical and physical properties are shown in Table 3.15.2.0(b).

TABLE 3.15.2.0(a). *Material Specification for 535.0 Aluminum Alloy*

Specification	Form
QQ-A-601	Sand castings

The temper index for 535.0 is as follows.

Section	Temper
3.15.2.1	F

TABLE 3.15.2.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 535.0 ALUMINUM ALLOY (CASTINGS)[a]

ECIFICATION...........	QQ-A-601
RM.....................	SAND CASTINGS
NDITION................	F
ASS....................	...
SIS....................	S[b]
CHANICAL PROPERTIES:	
FTU, MPA..............	241
FTY, MPA..............	124
FCY, MPA..............	...
FSU, MPA..............	...
FBRU, MPA:	
(E/D=1.5)..........	...
(E/D=2.0)..........	...
FBRY, MPA:	
(E/D=1.5)..........	...
(E/D=2.0)..........	...
EL, PERCENT...........	9
E, GPA................	...
EC, GPA...............	...
G, GPA................	...
MU....................	0.33
SICAL PROPERTIES:	
OMEGA, MG/M3..........	2.63
C, J/(G*K)............	...
K, W/(M*K)............	...
ALPHA, 10-6 M/(M*K)..	...

[a]REFERENCE SHOULD BE MADE TO THE SPECIFIC REQUIREMENTS OF THE PROCURING OR CERTIFICATING AGENCY IN REGARD TO THE USE OF THE ABOVE VALUES IN THE DESIGN OF CASTINGS.

[b]MECHANICAL PROPERTIES IN THIS COLUMN ARE BASED UPON THE MINIMUM GUARANTEED TENSILE PROPERTIES FROM SEPARATELY CAST TEST BARS. THE STRENGTH OF PRODUCTION CASTINGS MAY BE AS LOW AS 75 PERCENT, AND ELONGATION OF AS LOW AS 25 PERCENT OF THE TABULATED VALUES.

3.16 Unassigned

3.17 700.0 Series Cast Alloys

3.17.1 D712.0 (40-E) ALLOY

3.17.1.0 *Comments and Properties.*—D712.0 is an Al-Zn-Mg sand casting alloy which develops high strength without solution heat treatment. Refer to Section 3.1.3.4 for comments regarding the weldability of the alloy.

A material specification for D712.0 aluminum alloy is presented in Table 3.17.1.0(a). Room-temperature mechanical and physical properties are shown in Table 3.17.1.0(b).

TABLE 3.17.1.0(a). *Material Specification for D712.0 Aluminum Alloy*

Specification	Form
QQ-A-601	Sand castings

The temper index for D712.0 is as follows:

Section	Temper
3.17.1.1	T5

TABLE 3.17.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF D712.0 ALUMINUM ALLOY (CASTINGS)

SPECIFICATION..........	QQ-A-601
FORM..................	SAND CASTING
CONDITION..............	T5
CLASS.	17M
BASIS..................	S[b]
MECHANICAL PROPERTIES:	
FTU, MPA..............	221
FTY, MPA..............	138
FCY, MPA..............	...
FSU, MPA..............	186
FBRU, MPA:	
(E/D=1.5).........	...
(E/D=2.0).........	...
FBRY, MPA:	
(E/D=1.5).........	...
(E/D=2.0).........	...
EL, PERCENT..........	3
E, GPA................	71.0
EC, GPA...............	71.0
G, GPA................	26.2
MU....................	0.33
PHYSICAL PROPERTIES:	
OMEGA, MG/M3.........	2.80
C, J/(G*K)...........	0.96 (AT 373 K)
K, W/(M*K)...........	138 (AT 298 K)
ALPHA, 10-6 M/(M*K)..	24.7 (294 TO 364 K)

[a]REFERENCE SHOULD BE MADE TO THE SPECIFIC REQUIREMENTS OF THE PROCURING OR CERTIFICATING AGENCY IN REGARD TO THE USE OF THE ABOVE VALUES IN THE DESIGN OF CASTINGS.

[b]MECHANICAL PROPERTIES IN THIS COLUMN ARE BASED UPON THE MINIMUM GUARANTEED TENSILE PROPERTIES FROM SEPARATELY CAST TEST BARS. THE STRENGTH OF PRODUCTION CASTINGS MAY BE AS LOW AS 75 PERCENT, AND ELONGATION AS LOW AS 25 PERCENT, OF THE TABULATED VALUES.

3.20 Element Properties

3.20.1 BEAMS. See Equation 1 3.2.3, Section 1.5.2.5, and Reference 1.7.1 for general information on stress analysis of beams.

3.20 1.1 *Simple Beams.*—Beams of solid, tubular, or similar cross sections can be aussumed 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.

3.20.1.1.1 *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 3.20.1.1.1. It should be noted that these values apply only when the tubes are restrained against local buckling at the loading points.

3.20.1.1.2 *Unconventional Cross Section.*—Sections other than solid or tubular should be tested to determine the allowable bending stress.

3.20.1.2 *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 3.20.1.2).

3.20 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.

3.20.2 COLUMNS

3.20.2.1 *Primary Failure.*—The general formula for primary instability is given in Section 1.3.8.

3.20.2.2 *Local Failure.*—The local stability of aluminum alloy column sections may be determined using the methods outlined in References 3.20.2.2(a) through (e).

3.20.2.3 *Column Properties.*—Curves of the allowable column stresses for round and streamline tubing are given in Figure 3.20.2.3. The allowable stress is plotted against the effective slenderness ratio, defined by the formula:

$$\frac{L'}{\rho} = \frac{L}{\rho\sqrt{c}} \qquad (3.20.2.3)$$

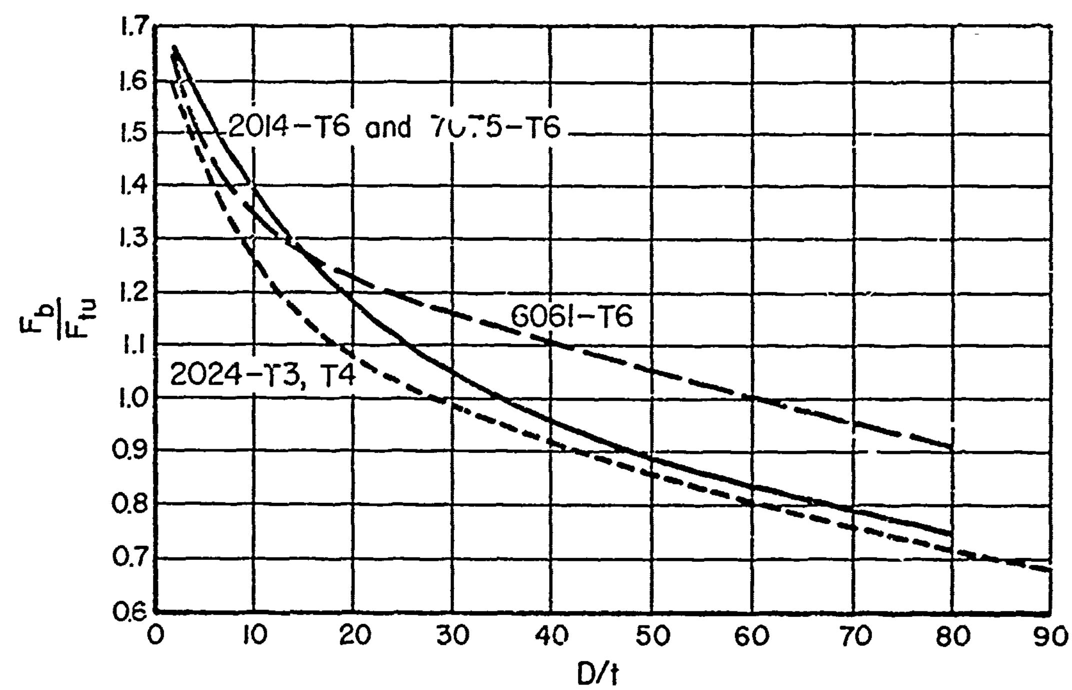
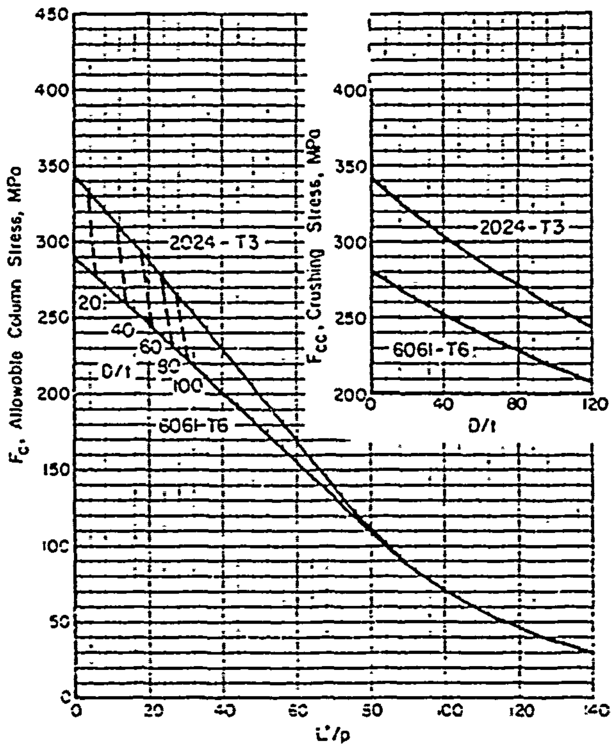
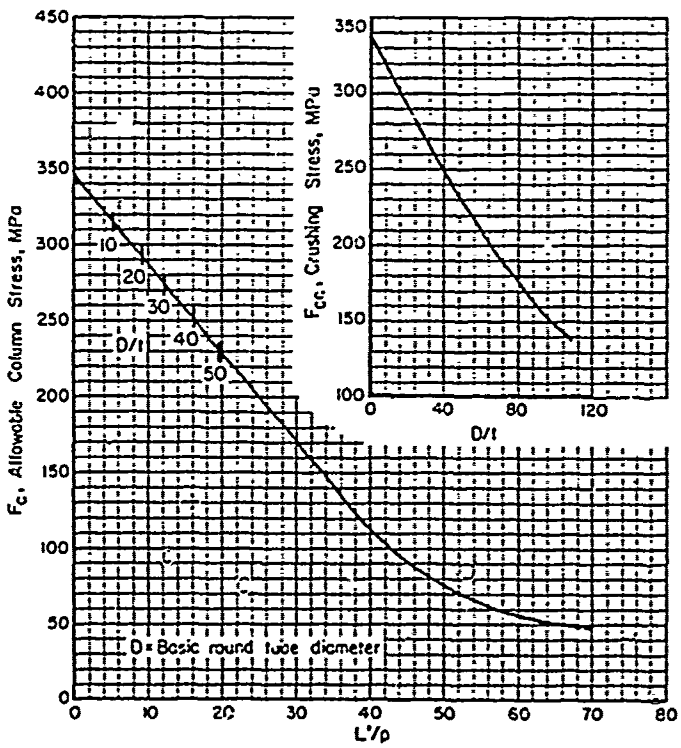


FIGURE 3.20.1.1.1. *Bending modulus of rupture for aluminum alloy round tubing.*



(a) Round 2024 and 6061 Tubing



(b) Streamline 2024-T3 Tubing

FIGURE 3.20.2.3. Allowable column and crushing stresses for 2024 and 6061 aluminum alloy tubing.

3.20.3 TORSION

3.20.3.1 *General.* The torsional failure of aluminum-alloy tubes may be due to plastic failure of the metal, plastic 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.

3.20.3.2 *Torsion Properties.*—The curves of Figures 3.20.3.2(a) through (g) are derived from the method outlined in Reference 2.7.3.2 and take into account the parameter L/D. The theoretical results set forth in Reference 2.7.3.2 have been found to be in good agreement with the experimental results.

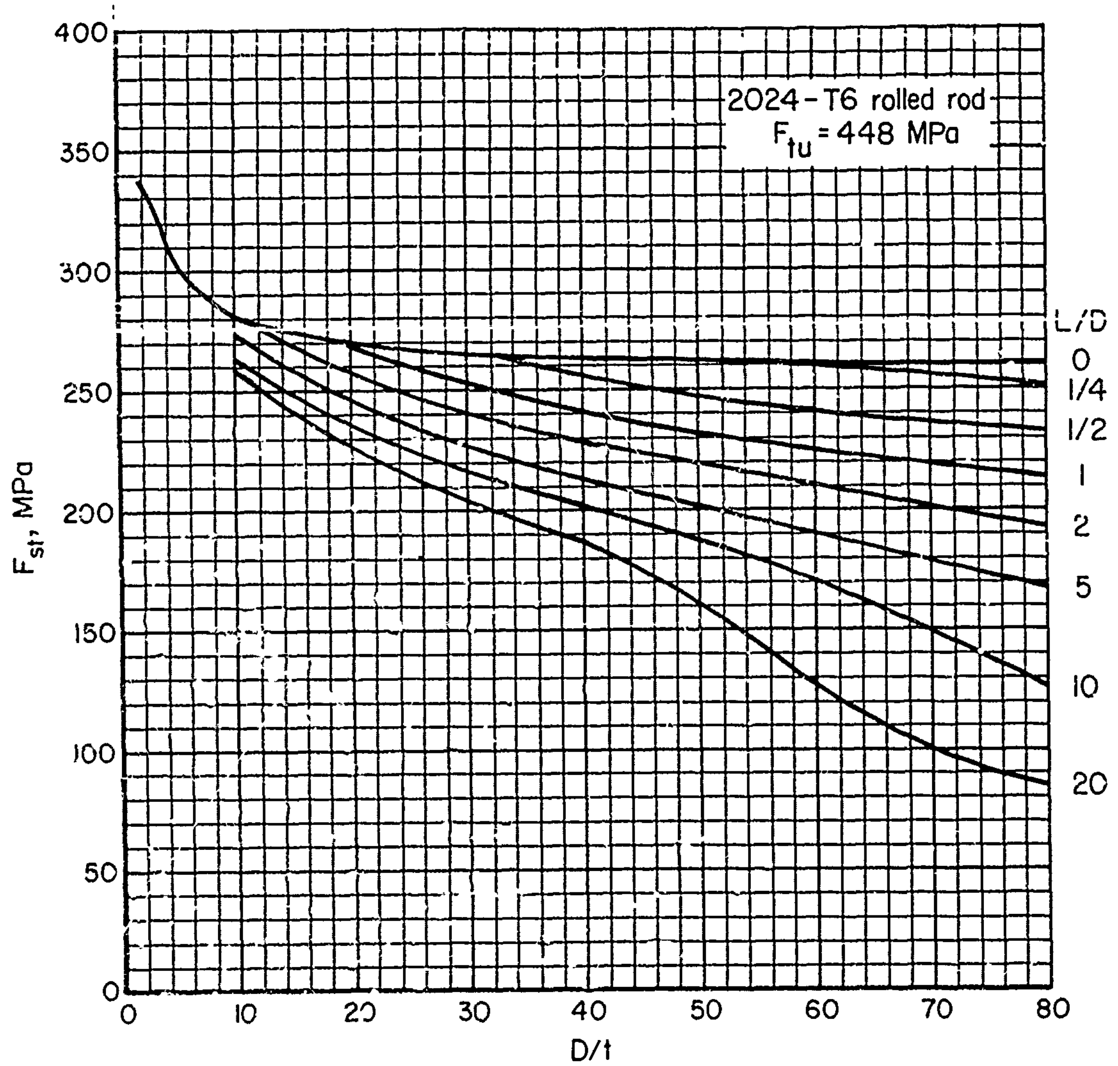


FIGURE 3.20.3.2(a). Torsional modulus of rupture--
2014-T6 aluminum alloy rolled rod.

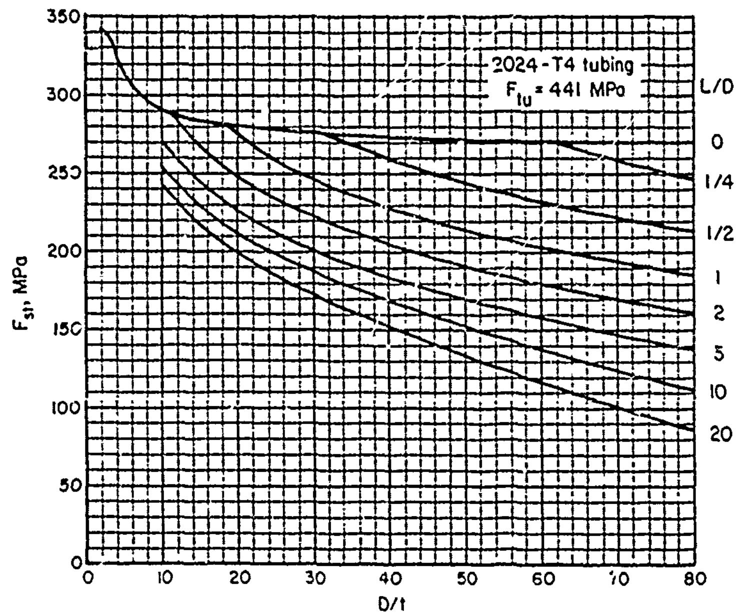


FIGURE 3.20.3.2(c). Torsional modulus of rupture--2024-T3 aluminum alloy tubing.

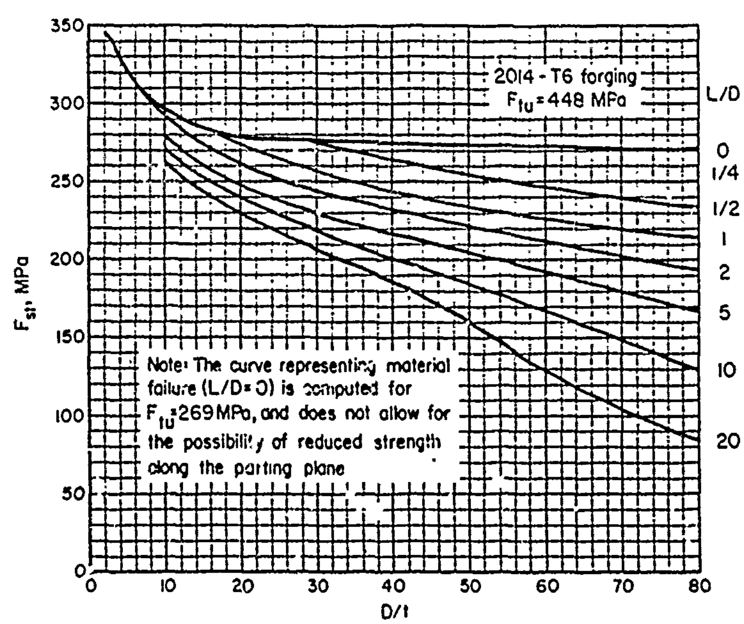


FIGURE 3.20.3.2(b). Torsional modulus of rupture--2014-T6 aluminum alloy forging.

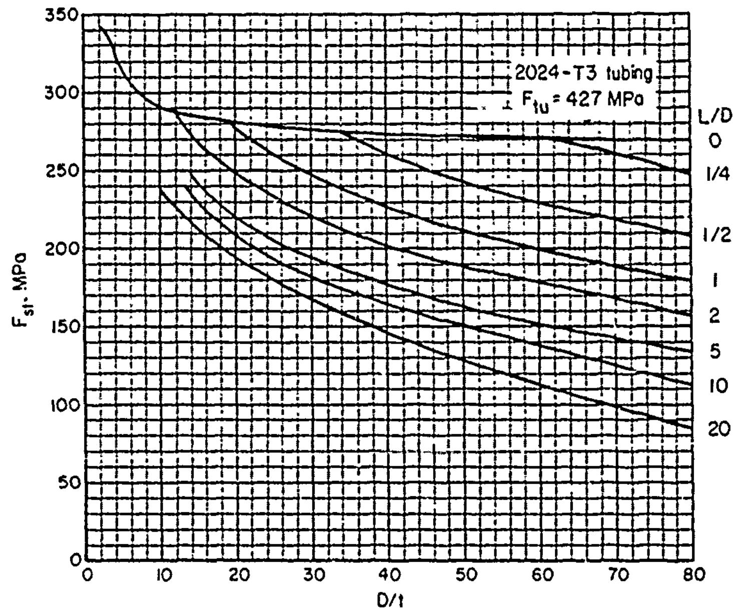


FIGURE 3.20.3.2(d). Torsional modulus of rupture—2024-T4 aluminum alloy tubing.

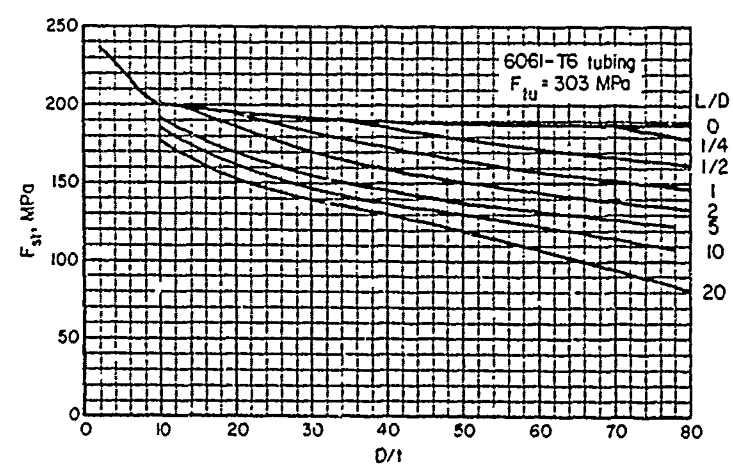


FIGURE 3.20.3.2(e). Torsional modulus of rupture—6061-T6 aluminum alloy tubing.

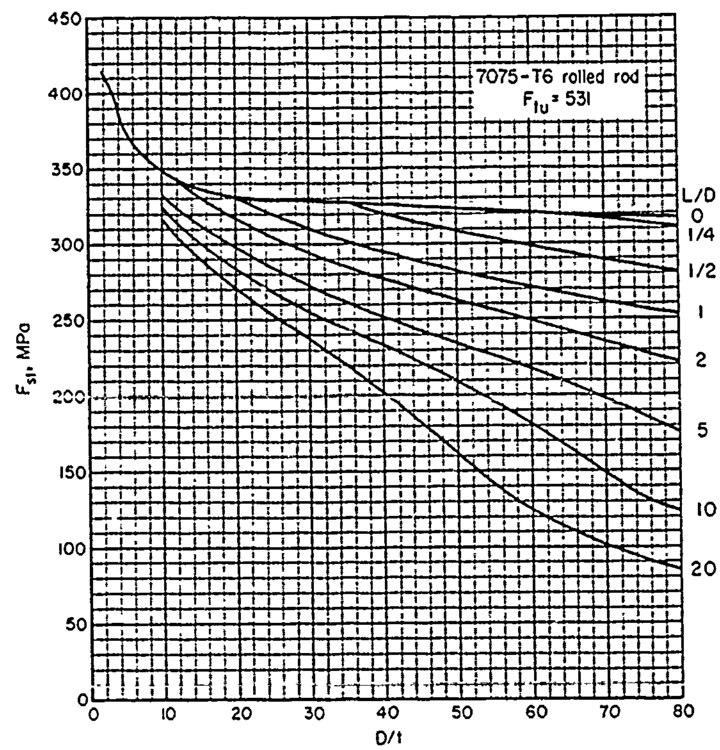


FIGURE 3.20.3.2(f). Torsional modulus of rupture—7075-T6 aluminum alloy rolled rod.

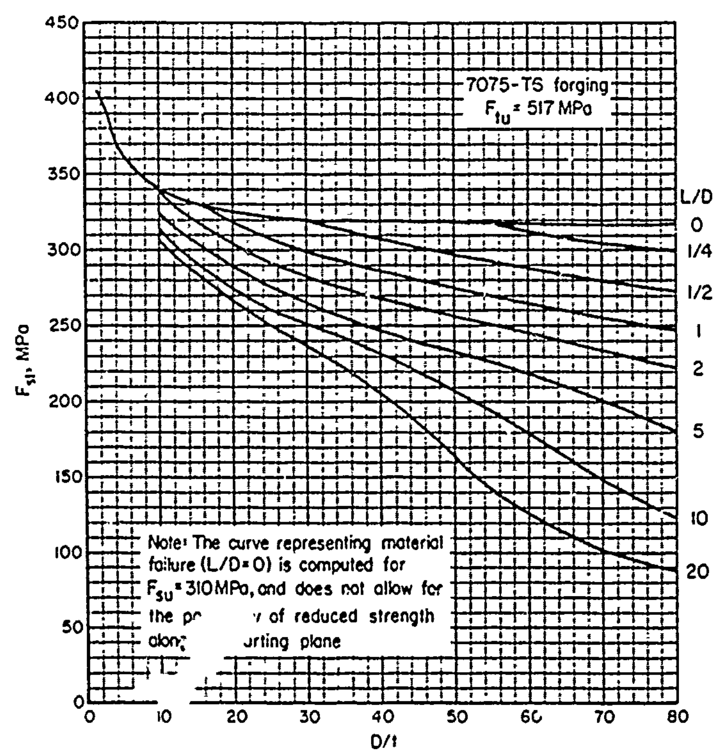


FIGURE 3.20.3.2(g). Torsional modulus of rupture--7075-T6 aluminum alloy forging.

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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 alpha-numeric 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 as follows:

4.2	Magnesium Alloy Wrought Products
4.2.1	AZ31B
4.2.2	AZ61A
4.2.3	AZ80A
4.2.4	HK31A
4.2.5	HM21A
4.2.6	HM31A
4.2.7	LA141A
4.2.8	ZK60A
4.3	Magnesium Alloy Cast Products
4.3.1	AM100A
4.3.2	AZ81A
4.3.3	AZ91C
4.3.4	AZ92A
4.3.5	EZ33A
4.3.6	HK31A
4.3.7	HZ32A
4.3.8	QE22A
4.3.9	ZH62A
4.3.10	ZK51A

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 E8, Tension Testing of Metallic Materials. The yield strength (F_{ty}) is obtained by the "offset method" using an offset of 0.2 percent. The elongation (e) is not a design allowable but is of some use in comparing materials where large changes of ductility may be of concern. The elongation values are given as percent and are based on a gage length of 51 mm or 4 times the diameters. 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 690 MPa per minute and the rate of straining from the yield strength to fracture is less than 0.5. One exception is for LA141A where the product specification covering this alloy specifies a closely controlled rate of straining for room-temperature tension tests. For the other alloys 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 E21, Short-Time Elevated-Temperature Tension Tests of Materials; Recommended Practice For. The speed of testing has a considerable effect on the results obtained and no one standard rate of straining is given in E21. The strain rates most commonly used on magnesium are 0.005 m/m/min to the yield and 0.10 m/m/min from yield to fracture [see References 4.1.2.1.1(a) to (d)].

4.1.2.1.2 *Compression Testing.*—The compression test methods used for magnesium are those in

ASTM E9, Compression Testing of Metallic Materials at Room Temperature. 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 E238, Pin-Type Bearing Test of Metallic Materials. The size of pin used has a significant effect on the values obtained, especially the bearing strength (F_{bru}). On tests made to obtain the data on magnesium alloys shown in this document, pin diameters of 4.75 mm and 6.35 mm were used. For pin diameters significantly larger than 6.35 mm 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.*—No standard methods for shear testing have been written. The 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 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 effects 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 effects of notches, holes, and stress raisers on the static properties of magnesium alloys are given in References 4.1.2.1.5(a) through (c). Additional data on the strength properties of magnesium alloys are given in References 4.1.2.1.5(d) through (i).

4.1.2.1.6 *Stress-Strain Relationships.*—The stress-strain relationships presented, which include elastic and tangent moduli, are typical curves based on one or more groups of test data. Being typical, these curves will not correspond to yield-stress and modulus-of-elasticity data presented as design allowables. 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 affine to the typical curve or by using Ramberg-Osgood parameters obtained from the typical curves. [See References 4.1.2.1.6(a) and (b).] If discrepancies exist between the modulus or yield stress of the stress-strain curve and the modulus or yield stress of the tables or elevated-temperature-property curves, the latter values should be used. Other information can be found in Reference 4.1.2.1.6(c).

4.1.2.1.7 *Creep.*—Curves for computing the approximate reduction in ultimate tensile strength under long-time loads, and for predicting corresponding deformation, when available, are shown in the appropriate alloy sections. See ASTM E139, Conducting Creep and Time-for-Rupture Tension Tests of Materials for testing procedures. Some creep data on magnesium alloys are summarized in Reference 4.1.2.1.7. See Section 1.4.8.2.1 for definitions of terms used in figures containing creep data in the individual alloy sections.

4.1.2.1.8 *Fatigue.*—Room-temperature axial load fatigue data for several magnesium alloys are given in appropriate sections of the chapter for specific materials. Since the test conditions were limited, only S-N curves are shown for individual load ratios, R. In using these data, it should be remembered that they have been obtained from specimens in which stress concentrations are purposely minimized, and that suitable allowance should be made for reentrant corners, notches, holes, joints, and all other conditions which may produce localized high stresses. These localized high stresses, which have almost no effect on the static strength of the members, are of importance in fatigue. The curves given in the alloy sections were obtained by testing 1.63 mm by 25 mm sheet specimens and 0.8 mm diameter machined and polished specimens in Krouse direct tension-compression fatigue machines. The data represent uniformly distributed stresses which such specimens will withstand under repeated axial loads. Reference 4.1.2.1.8 provides data on fatigue of magnesium alloys.

4.1.3 PHYSICAL PROPERTIES. — Selected experimental data from the literature were used in determining values of the physical properties where possible. In other cases, enough information was available to calculate the constants. Estimated values of some of the remaining constants were also included. Calculated and estimated values are indicated in the tables. All of the physical constants listed may be considered as design values in the absence of more reliable data.

4.1.4 ENVIRONMENTAL CONSIDERATIONS. — Corrosion protection must be considered in all magnesium designs. 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. The temper designations used are those given in ASTM B296, Temper Designations of Magnesium Alloys, Cast and Wrought. A summary of the temper designations used in this document is given in Table 4.1.5.

4.1.6 JOINING METHODS. — Most magnesium alloys may be welded, refer to "Comments and Properties" Sections in individual alloy listings. Adhesive bonding and brazing may be used to join magnesium to itself or other alloys. All types of mechanical fasteners are readily applicable to magnesium. Refer to Section 4.1.4 when using mechanical fasteners or joining of dissimilar materials with magnesium alloys.

TABLE 4.1.5. *Temper Designations for Magnesium Alloys*

Temper	Definition
F	As fabricated
O	Annealed, recrystallized (Wrought products only)
H	Strain hardened (Wrought products only)
H2, plus one or more digits	Strain hardened and then partially annealed
T	Treated to produce stable tempers other than F, O, or H
T4	Solution heat-treated
T5	Cooled from an elevated-temperature shaping process and then artificially aged
T6, T61	Solution heat-treated (T4) and then artificially aged
T7	Solution heat-treated (T4) and then stabilized
T8, T81	Solution heat-treated (T4) cold worked, and then artificially aged

4.2 Magnesium Alloy Wrought Products

4.2.1 AZ31B

4.2.0 *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 422 K. 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).

TABLE 4.2.1.0(a). *Material Specifications for AZ31B Magnesium Alloy*

Specification	Form
QQ-M-31	Extrusions
QQ-M-40	Forgings
QQ-M-44	Sheet and plate
WW-T-285	Tubes

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

Room-Temperature Properties

Room-temperature mechanical and physical properties are shown in Tables 4.2.1.0(b) and (c). The effect of temperature on physical properties is shown in Figure 4.2.1.0.

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 curves and tangent-modulus curves are presented in Figure 4.2.1.1.6. A typical axial-load fatigue curve for AZ31B-O sheet is shown in Figure 4.2.1.1.8.

4.2.1.2 *AZ31B-H24 Temper.*—Effect of temperature on the mechanical properties of sheet and plate in this temper is shown in Figures 4.2.1.2.1(a) through 4.2.1.4.

Typical room-temperature tension and compression stress-strain curves and tangent-modulus curves for sheet in this temper are shown in Figure 4.2.1.2.6.

Creep data at room temperatures from 422 K to 589 K are shown in Figures 4.2.1.2.7(a) through (d) for this temper.

Figure 4.2.1.1.8 also contains fatigue data on unnotched sheet at room temperature for AZ31B-H24.

4.2.1.3 *AZ31B-H25 Temper.*

4.2.1.4 *AZ31B-F Temper.*—Figure 4.2.1.1.8 contains fatigue data on unnotched extrusions at room temperature for AZ31B-F.

TABLE 4.2.1.0(B1). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF AZ31B MAGNESIUM ALLOY (SHEET AND PLATE)

SPECIFICATION	QQ-M-44													
FORM	SHEET AND PLATE													
TEMPER	O							H24						
THICKNESS, MM	0.41-1.53		1.54-6.33		6.34-12.71	12.72-50.81	50.82-76.20	0.41-6.33		6.34-9.51	9.52-12.71	12.72-25.41	25.42-50.81	52.82-76.20
BASIS	A	B	A	B	S	S	S	A	B	S	S	S	S	S
MECHANICAL PROPERTIES:														
FTU, MPA:														
L	221	248	221	248	221	221	221	269	276	262	255	248	234	234
LT	...	...	...	...	...	...	...	276	...	269	262	255	241	...
FTY, MPA:														
L	124	131	103	131	103	103	103	200	207	179	165	152	138	124
LT	...	...	...	...	...	...	...	221	...	200	186	172	159	...
FCY, MPA:														
L	83	90	83	97	69	69	55	165	172	138	110	90	69	62
LT[a]	...	...	...	...	...	...	...	...	...	...	...	...	...	...
FSU, MPA	117	159	117	159	117	...	...	124	179	124	124	...	...	...
FBRU[b] MPA:														
(E/D=1.5)	345	359	345	359	345	...	...	403	414	386	372	...	...	...
(E/D=2.0)	414	421	414	421	414	...	...	463	483	448	434	...	...	...
FBRY[b] MPA:														
(E/D=1.5)	200	207	200	214	186	...	...	296	303	262	234	...	...	...
(E/D=2.0)	200	207	200	214	186	...	...	296	303	262	234	...	...	...
EL, PERCENT:														
L	12	18	12	19	12	10	9	6	8	8	8	8	8	8
LT	...	...	...	...	...	...	...	5	...	10	10	10	10	...
E, GPA	44.8													
EC, GPA	44.8													
G, GPA	16.5													
MU	0.35													
PHYSICAL PROPERTIES:														
OMEGA, MG/M3	1.77													
C, J/(G*K)	SEE FIGURE 4.2.1.0													
K, W/(M*K)	SEE FIGURE 4.2.1.0													
ALPHA, 10-6 M/(M*K)	SEE FIGURE 4.2.1.0													

[a] LONG TRANSVERSE FCY ALLOWABLES ARE EQUAL TO OR GREATER THAN THE LONGITUDINAL FCY ALLOWABLES.

[b] BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

TABLE 4.2.1.0(B2). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF AZ31B MAGNESIUM ALLOY (SHEET AND PLATE)

SPECIFICATION	QQ-M-44						
FORM	SHEET AND PLATE						
TEMPER	H26						
THICKNESS, MM	6.35-9.51	9.52-11.14	11.15-12.71	12.72-19.06	19.07-25.41	25.42-38.11	38.12-50.80
BASIS	S	S	S	S	S	S	S
MECHANICAL PROPERTIES:							
FTU, MPA:							
L	269	262	262	255	255	241	241
LT	276	269	269	262	262	248	248
FTY, MPA:							
L	186	179	179	172	159	152	145
LT	207	200	200	193	179	172	165
FCY, MPA:							
L	152	145	124	117	110	103	97
LT[a]	...	...	...	...	...	...	...
FSU, MPA	124	124	124	...	...	...	...
FBRU, MPA:							
(E/D=1.5)	400	386	386	...	...	...	...
(E/D=2.0)	469	448	448	...	...	...	...
FBRY[b], MPA:							
(E/D=1.5)	276	269	248	...	...	...	...
(E/D=2.0)	276	269	248	...	...	...	...
EL, PERCENT:							
L	5	6	6	6	6	6	6
LT	3	8	8	8	8	8	8
E, GPA	44.8						
EC, GPA	44.8						
G, GPA	16.5						
MU	0.35						
PHYSICAL PROPERTIES:							
OMEGA, MG/M3	1.77						
C, J/(G*K)	SEE FIGURE 4.2.1.0						
K, W/(M*K)	SEE FIGURE 4.2.1.0						
ALPHA, 10-6 M/(M*K)	SEE FIGURE 4.2.1.0						

[a] LONG TRANSVERSE FCY ALLOWABLES ARE EQUAL TO OR GREATER THAN THE LONGITUDINAL FCY 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 (EXTRUSIONS AND FORGINGS)

SPECIFICATION	QQ-M-31					WW-T-825		QQ-M-40
FORM	EXTRUDED BARS, ROD, AND SOLID SHAPES				HOLLOW SHAPES	EXTRUDED TUBES		FORGING
CONDITION	F							
THICKNESS, MM	≤ 6.33	6.34-38.08	38.09-63.48	63.49-126.97	...	0.71-6.36	6.37-19.05	...
BASIS	S	S	S	S	S	S	S	S
MECHANICAL PROPERTIES:								
FTU, MPA:								
L	241	241	234	221	221	221	221	234
LT	...	...	...	...	...	...	...	...
FTY, MPA:								
L	145	152	152	138	110	110	110	131
LT	...	...	...	...	...	...	...	...
FCY, MPA:								
L	...	83	83	69	69	69	69	...
LT	...	...	...	...	...	...	...	...
FSU, MPA	117	117	117	...	...	...	...	...
FBRU[a], MPA:								
(E/D=1.5)	248	248	248	...	...	...	...	...
(E/D=2.0)	310	310	310	...	...	...	...	...
FBRY[a], MPA:								
(E/D=1.5)	159	159	159	...	...	...	...	...
(E/D=2.0)	159	159	159	...	...	...	...	...
EL, PERCENT:								
L	7	7	7	7	8	8	4	6
LT	...	...	...	...	...	...	...	...
E, GPA	44.8							
EC, GPA	44.8							
G, GPA	16.5							
MU	0.35							
PHYSICAL PROPERTIES:								
OMEGA, MG/M3	1.77							
C, J/(G*K)	SEE FIGURE 4.2.1.0							
K, W/(M*K)	SEE FIGURE 4.2.1.0							
ALPHA, 10-6 M/(M*K)	SEE FIGURE 4.2.1.0							

[a] BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

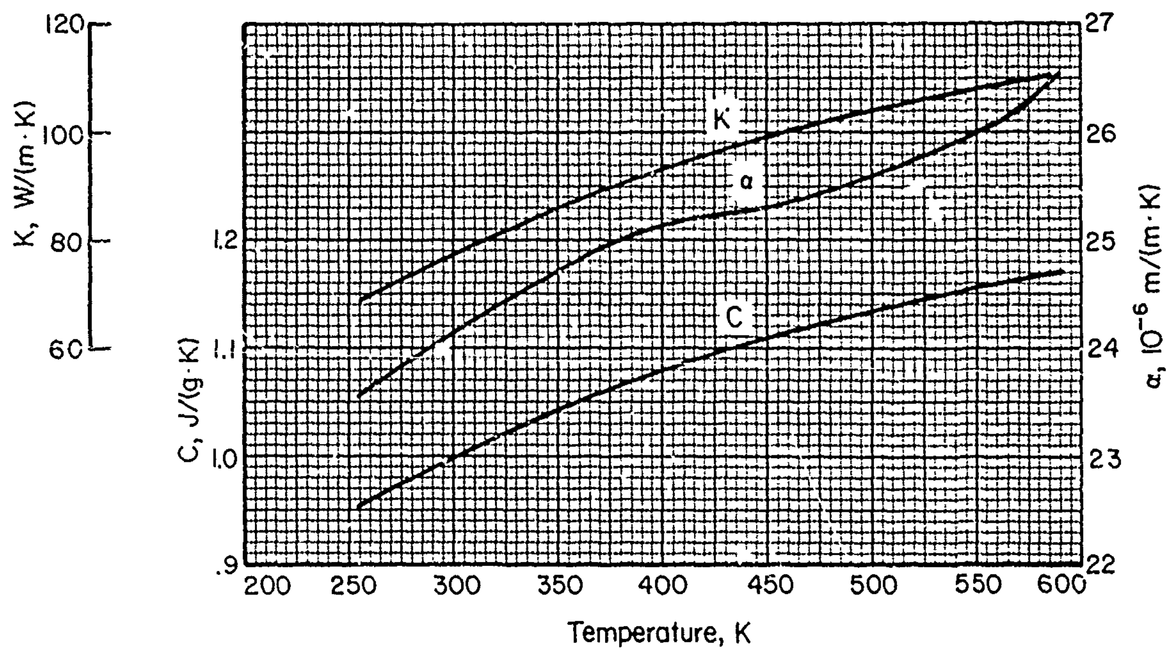

FIGURE 4.2.1.0. Effect of temperature on the physical properties of wrought AZ31B.

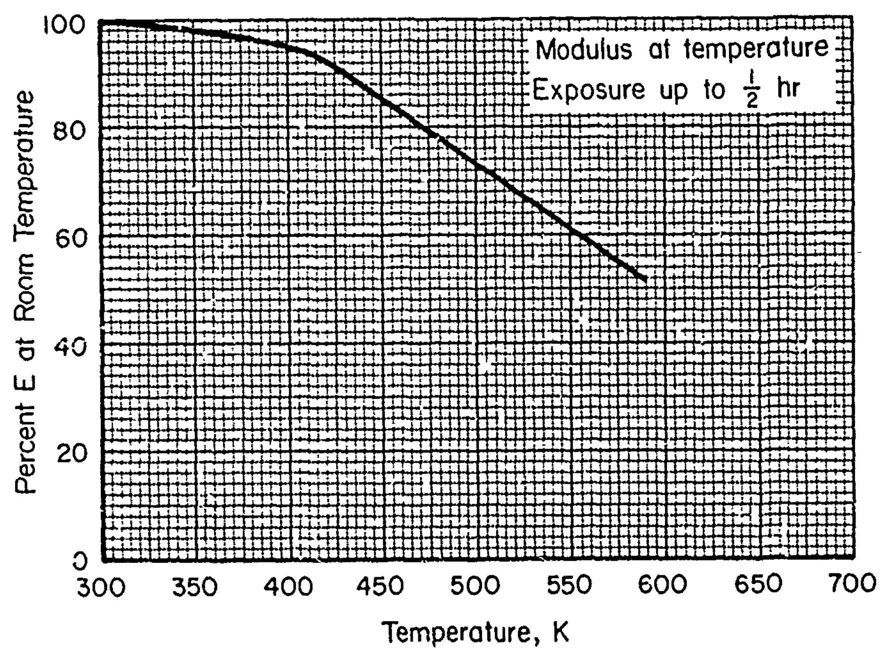

FIGURE 4.2.1.1.4. Effect of temperature on the tensile modulus (E) of AZ31B-O (sheet and plate).

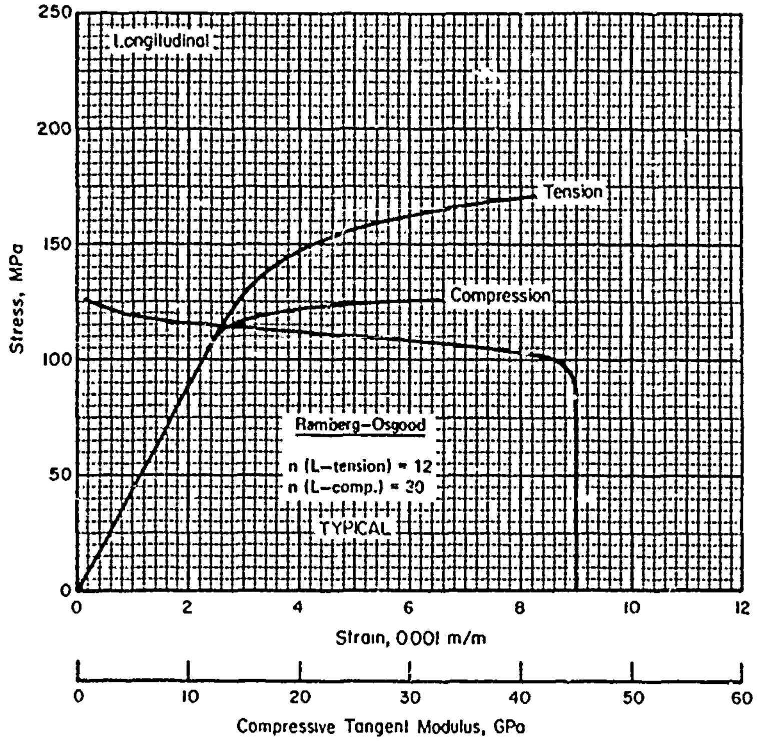

FIGURE 4.2.1.1.6. Typical tensile and compressive stress-strain and compressive tangent-modulus curves for AZ31B-O (sheet and plate) at room temperature.

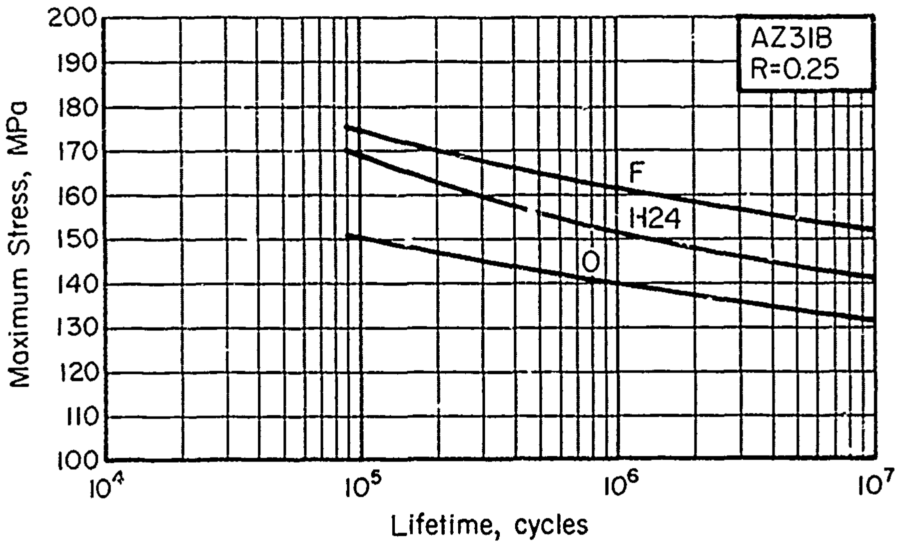

FIGURE 4.2.1.1.8. Typical fatigue curves for AZ31B-0 and AZ318-H24 sheet, and AZ31B - F extrusions at room temperature.

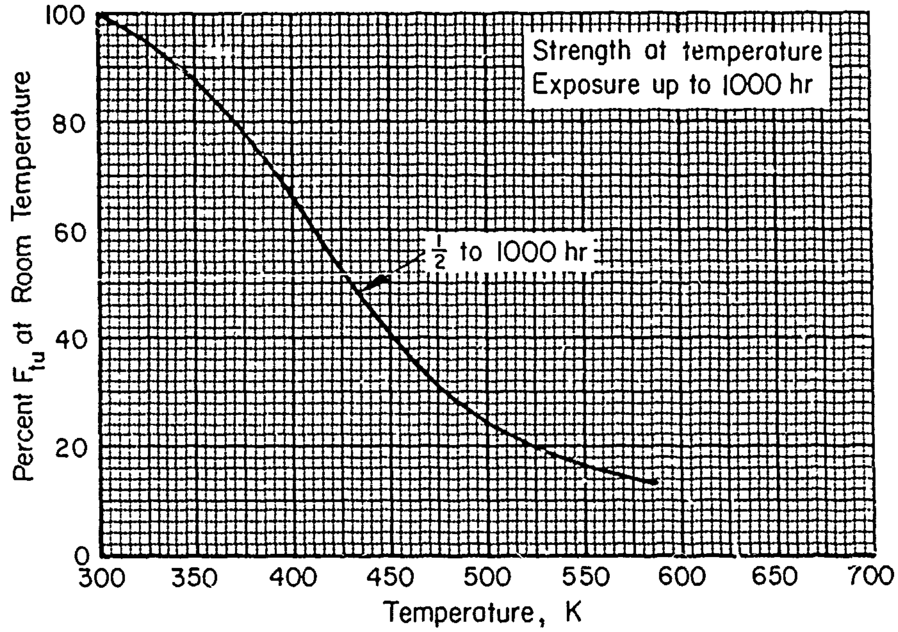

FIGURE 4.2.1.2.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of AZ31B-H24 (sheet and plate).

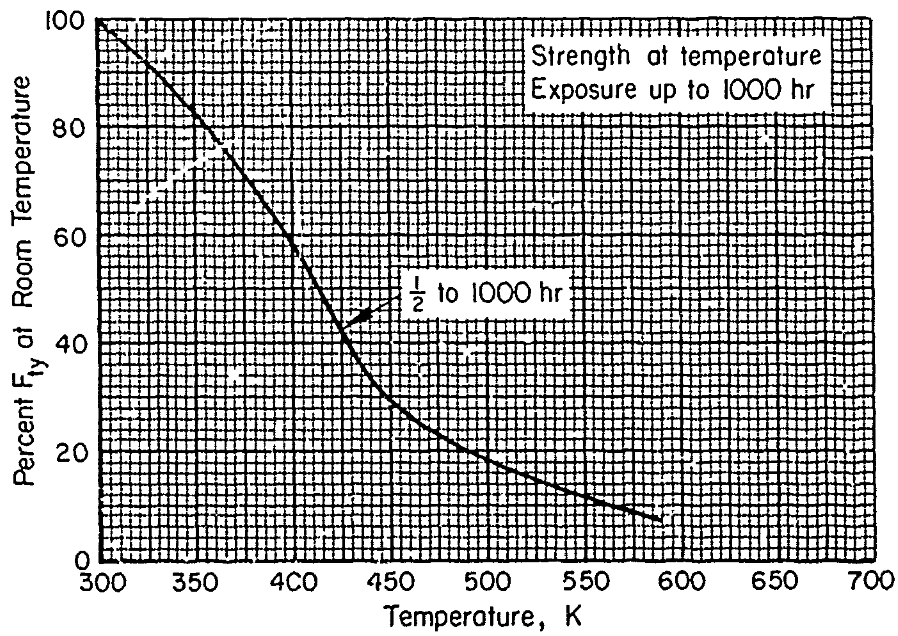

FIGURE 4.2.1.2.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of AZ31B-H24 (sheet and plate).

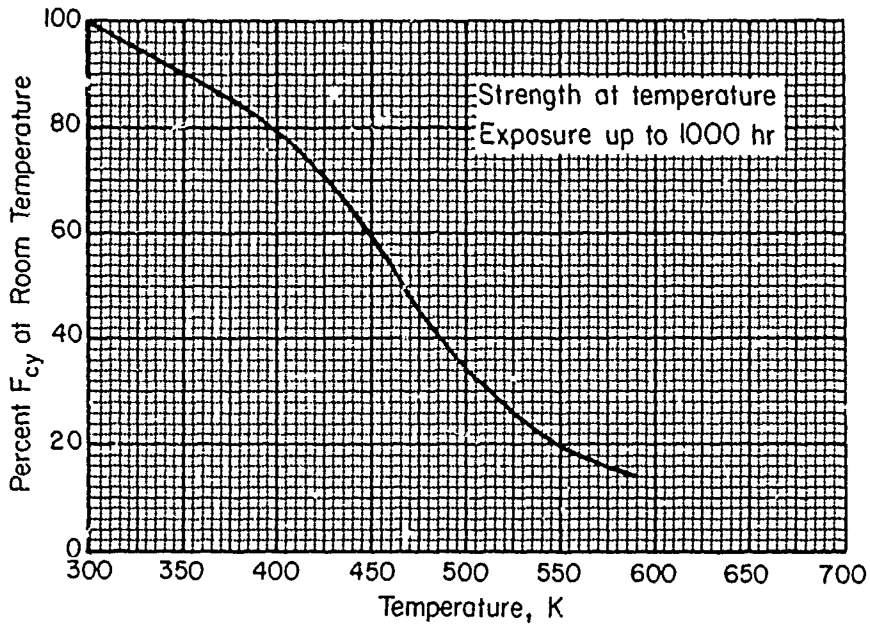

FIGURE 4.2 1.2.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of AZ231B-H24 (sheet and plate).

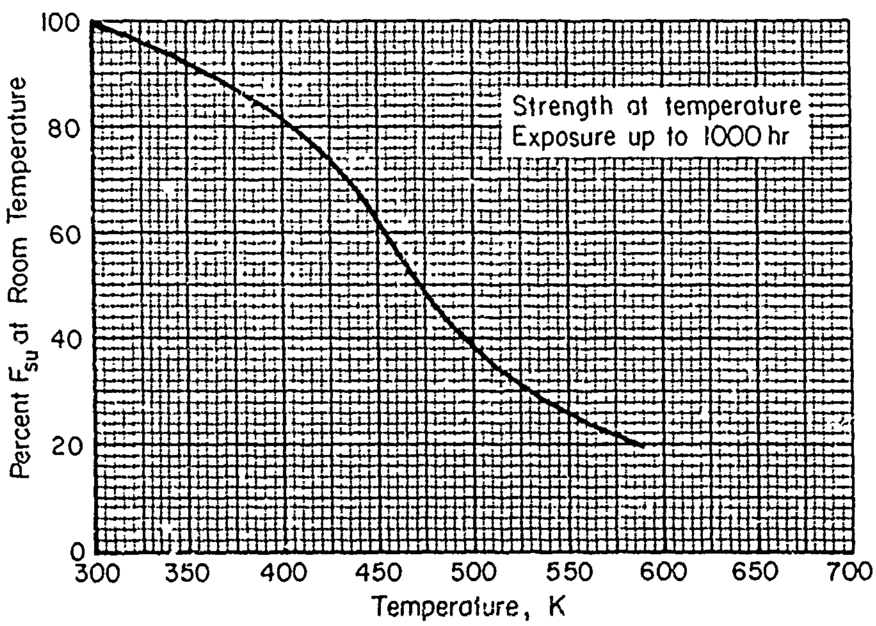

FIGURE 4.2.1.2.2(b). Effect of temperature on the ultimate shear strength (F_{su}) of AZ231B-H24 (sheet and plate).

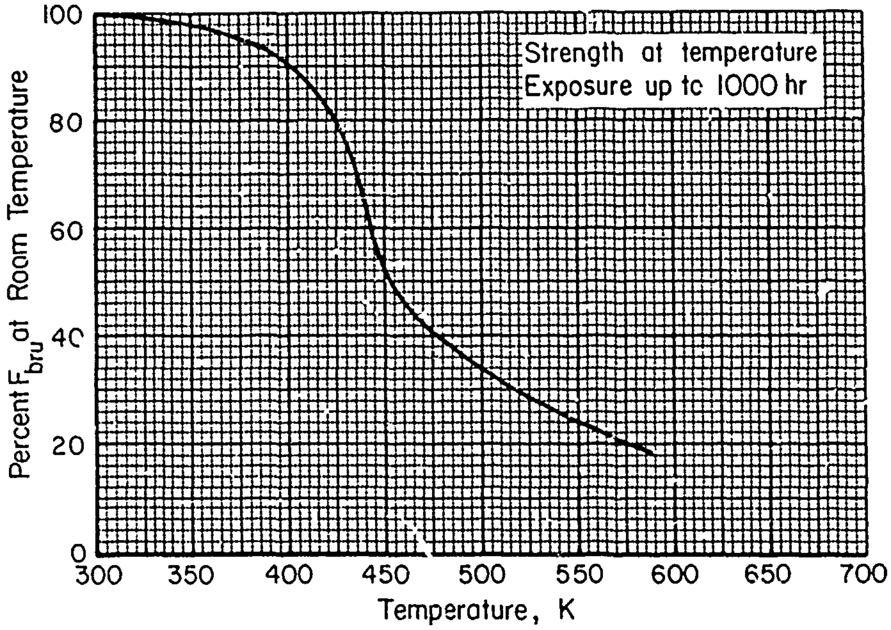

FIGURE 4.2.1.2.3(a). Effect of temperature on the ultimate bearing strength (F_{bru}) of AZ31B-H24 (sheet and plate).

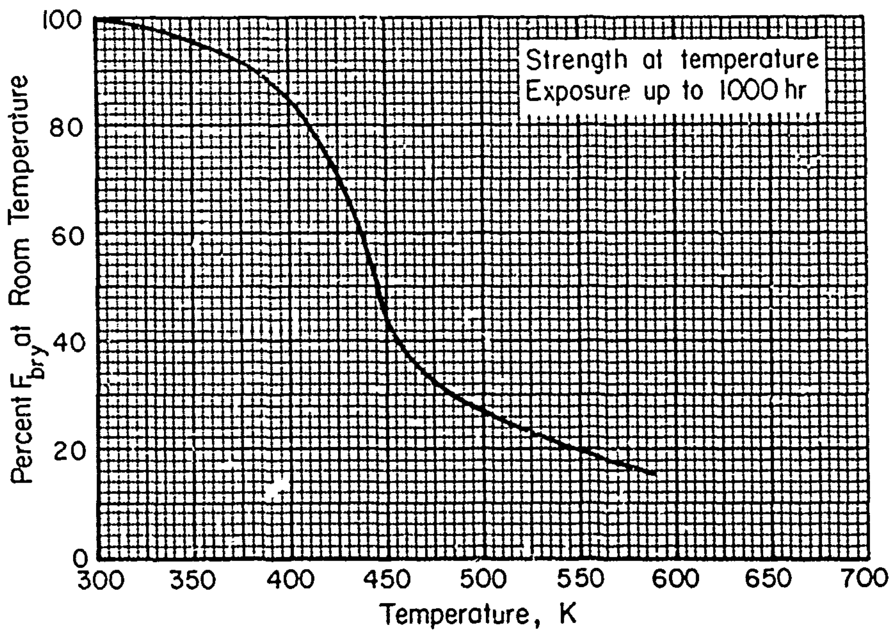

FIGURE 4.2.1.2.3(b). Effect of temperature on the bearing yield strength (F_{bry}) of AZ31B-H24 (sheet and plate).

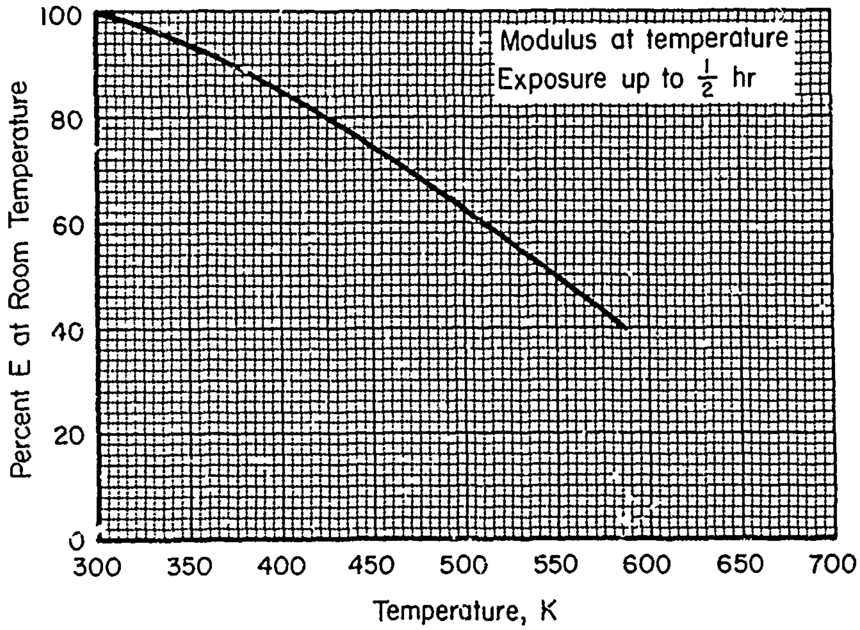

FIGURE 4.2.1.2.4. Effect of temperature on the tensile modulus (E) of AZ31B-H24 (sheet and plate).

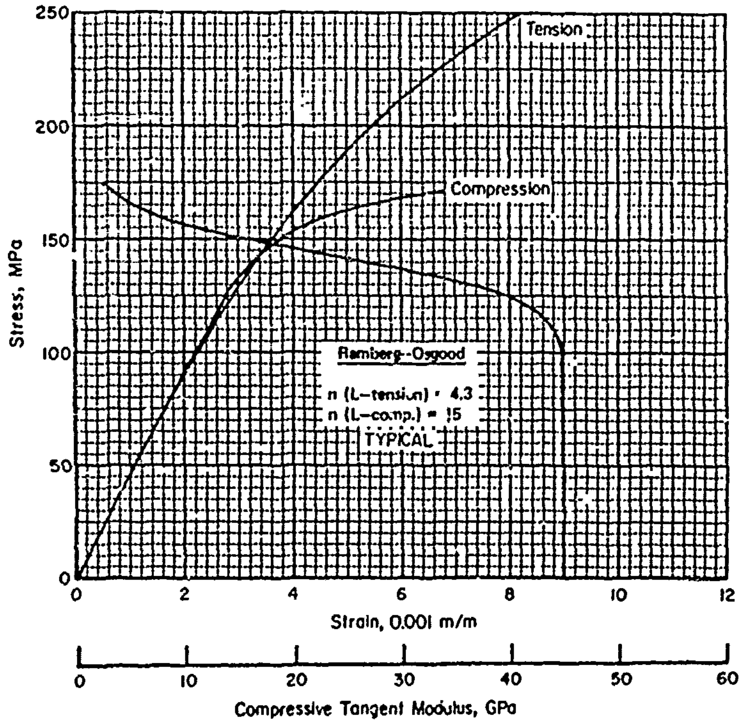

FIGURE 4.2.1.2.6. Typical tensile and compression stress-strain and compressive tangent-modulus curve for AZ31B-H24 (sheet) at room temperature.

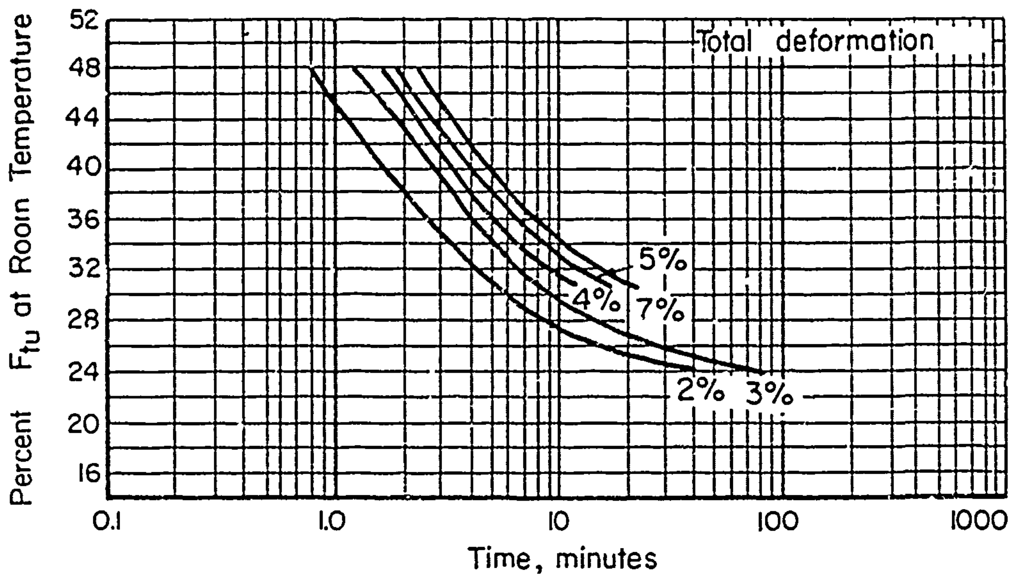

FIGURE 4.2.1.2.7(a). *Creep data for AZ31B-H24 magnesium alloy (sheet) at 422 K.*

Deformation includes thermal expansion of 0.29 percent. Heating rate 283 to 289 K per second.

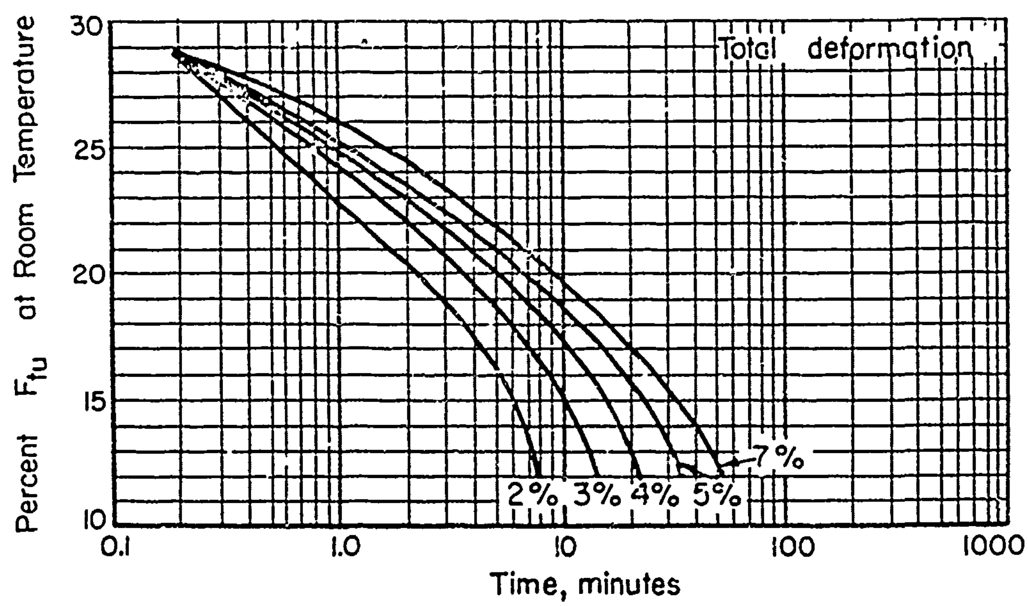

FIGURE 4.2.1.2.7(b). *Creep data for AZ31B-H24 magnesium alloy (sheet) at 478 K.*

Deformation includes thermal expansion of 0.47 percent. Heating rate 283 to 289 K per second.

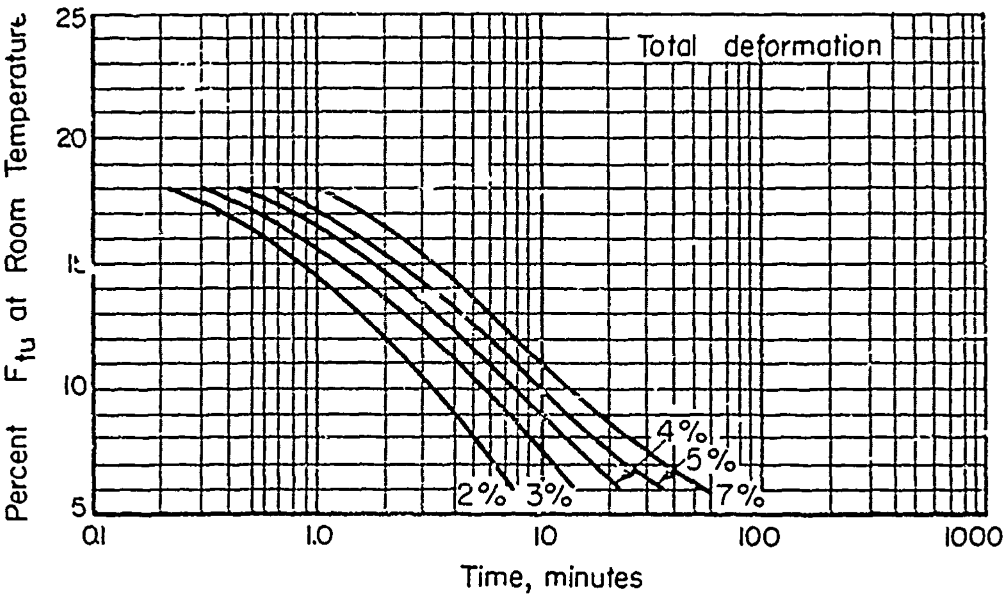

FIGURE 4.2.1.2.7(c). *Creep data for AZ31B-H24 magnesium alloy (sheet) at* 533 K.

Deformation includes thermal expansion of 0.71 percent. Heating rate 294 K per second.

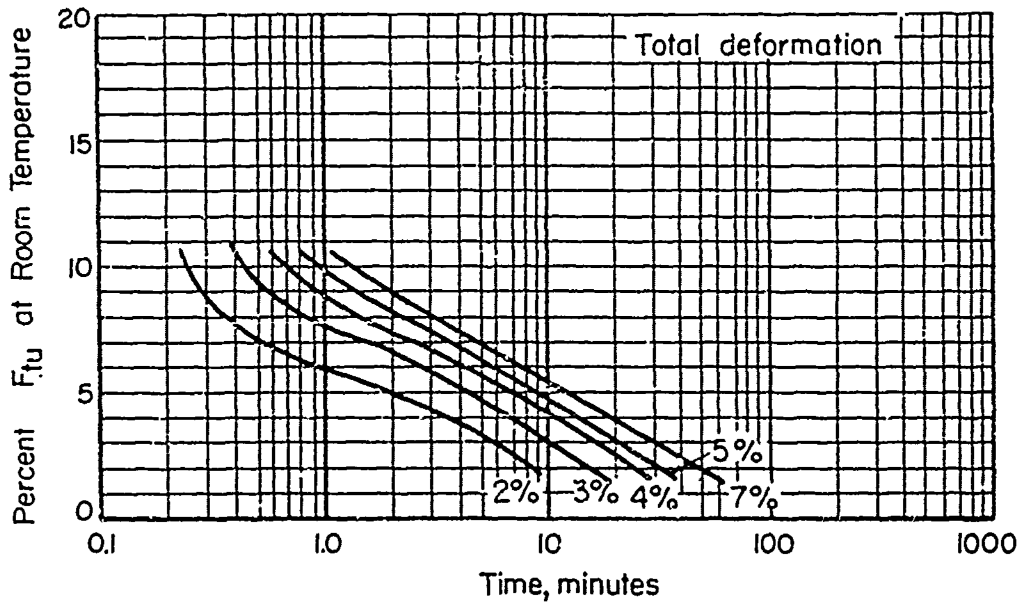

FIGURE 4.2.1.2.7(d). *Creep data for AZ31B-H24 magnesium alloy (sheet) at* 589 K.

Deformation includes thermal expansion of 0.90 percent. Heating rate 294 K per second.

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).

TABLE 4.2.2.0(a). *Material Specifications for AZ61A Magnesium Alloy*

Specification	Form
QQ-M-31	Extrusions
QQ-M-40	Forgings
WW-T-825	Tubes

The temper index for AZ61A is as follows:

Section	Temper
4.2.2.1	F

Room-Temperature Properties

Room-temperature mechanical and physical properties are shown in Table 4.2.2.0(b).

4.2.2.1 *AZ61A-F Temper.*—A typical fatigue curve is shown in Figure 4.2.2.1.8 for extrusions in this temper.

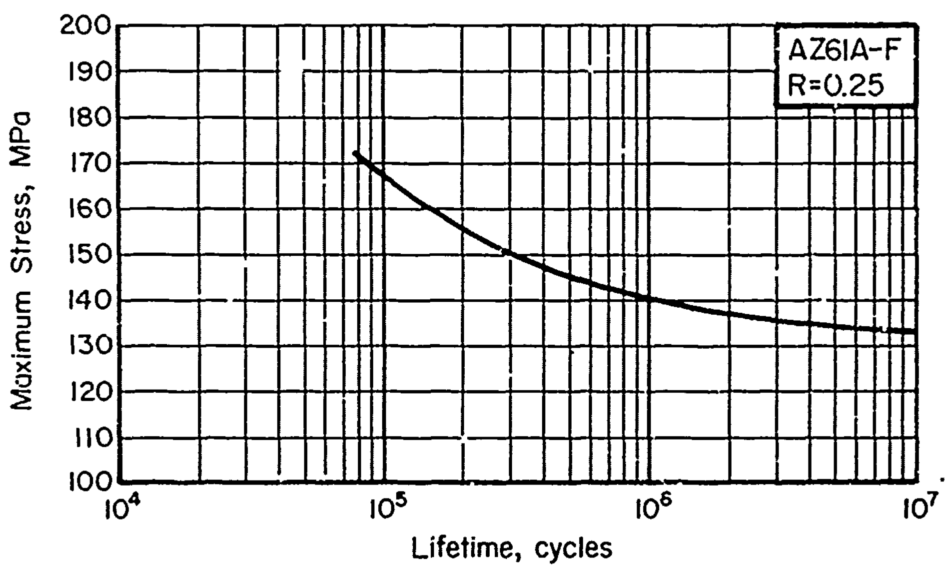

FIGURE 4.2.2.1.8. Typical fatigue curve for AZ91A-F (extrusions) at room temperature.

TABLE 4.2.2.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF AZ61A MAGNESIUM ALLOY (EXTRUSIONS AND FORGINGS)

SPECIFICATION	QQ-M-31				WW-T-825	QQ-M-40
FORM	EXTRUDED BAR, ROD, AND SOLID SHAPES			HOLLOW SHAPES	EXTRUDED TUBES	FORGING
TEMPER	F					
THICKNESS, MM	≤ 6.33	6.34-63.48	63.49-126.97	...	0.71-19.05	...
BASIS	S	S	S	S	S	S
MECHANICAL PROPERTIES:						
FTU, MPA:						
L	262	276	276	248	248	262
LT	...	...	...	...	...	...
FTY, MPA:						
L	145	165	152	110	110	152
LT	...	...	...	...	...	...
FCY, MPA:						
L	97	97	97	76	76	97
LT	...	...	...	...	...	...
FSU, MPA	131	131	...	...	...	131
FBRU[a], MPA:						
(E/D=1.5)	310	310	...	...	...	345
(E/D=2.0)	379	379	...	...	...	414
FBRY[a], MPA:						
(E/D=1.5)	193	193	...	...	...	193
(E/D=2.0)	221	221	...	...	...	221
EL, PERCENT:						
L	8	9	7	7	7	6
LT	...	...	...	...	...	...
E, GPA	43.4					
EC, GPA	43.4					
G, GPA	16.5					
MU	0.31					
PHYSICAL PROPERTIES:						
OMEGA, MG/M3	1.79					
C, J/(G*K)	1.05 (AT 299 K)[b]					
K, W/(M*K)	80 (373 TO 573 K)					
ALPHA, 10-6 M/(M*K)	25.2 (291 TO 373 K)					

[a] BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.
[b] ESTIMATED.

4.2.3 AZ80A

4.2.3.0 *Comments and Properties.*—AZ80A is a wrought-magnesium-base alloy with the highest aluminum content of the wrought magnesium alloys containing aluminum and zinc. It is available in the form of solid extruded shapes and forgings. AZ80A is much like AZ16A in general characteristics except that it has greater strength and less ductility and better resistance to stress corrosion cracking. It is available in the F and T5 tempers; the T5 temper material having higher strength with some loss in ductility.

Most bending and forming must be done at elevated temperatures. This alloy is not commonly welded. It requires stress relief after welding to prevent stress corrosion cracking.

Material specifications covering AZ80A are given in Table 4.2.3.0(a).

TABLE 4.2.3.0(a). *Material Specifications for AZ80A Magnesium Alloy*

Specification	Form
QQ-M-31	Extrusions
QQ-M-40	Forgings

The temper index for AZ80A is as follows:

Section	Temper
4.2.3.1	F
4.2.3.2	T5

Room-Temperature Properties

Room-temperature mechanical and physical properties are shown in Table 4.2.3.0(b).

4.2.3.1 *AZ80A-F Temper*

4.2.3.2 *AZ80A-T5 Temper.*—Effect of temperature on tensile properties is shown on Figure 4.2.3.2.1(a) and (b).

Figure 4.2.3.2.6 contains typical stress-strain and tangent-modulus curves for extrusions.

Creep properties for AZ80A-T5 forgings at various temperatures are shown in Figures 4.2.3.2.7(a) and (b).

TABLE 4.2.3.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF AZ80A MAGNESIUM ALLOY (EXTRUSIONS AND FORGINGS)

SPECIFICATION	QQ-M-31								QQ-M-40	
FORM	EXTRUDED BARS, RODS, AND SOLID SHAPES								FORGINGS	
TEMPER	F				T5				F	T5
THICKNESS, MM	≤ 6.33	6.34-38.08	38.09-63.48	63.49-126.97	≤ 6.33	6.34-38.08	38.09-63.48	63.49-126.97	...	...
BASIS	S	S	S	S	S	S	S	S	S	S
MECHANICAL PROPERTIES:										
FTU, MPA:										
L	296	296	296	290	324	331	331	310	290	290
LT	...	...	...	...	...	...	...	...	...	...
FTY, MPA:										
L	193	193	193	186	207	228	228	207	179	193
LT	...	...	...	...	...	...	...	...	...	...
FCY, MPA:										
L	...	117	117	117	...	193	186	179	124	172
LT	...	...	...	...	...	...	...	...	...	...
FSU, MPA	131	131	131	...	138	138	138	...	138	138
FBRU[a], MPA:										
(E/D=1.5)	331	331	331	...	...	...	...	...	...	345
(E/D=2.0)	386	386	386	...	...	...	...	...	...	483
FBRY[a], MPA:										
(E/D=1.5)	248	248	248	...	...	...	...	...	...	290
(E/D=2.0)	276	276	276	...	...	...	...	...	...	...
EL, PERCENT:										
L	9	8	6	4	4	4	4	2	5	
LT	...	...	...	...	...	...	...	...	...	...
E, GPA	44.8									
EC, GPA	44.8									
G, GPA	16.5									
MU	0.35									
PHYSICAL PROPERTIES:										
OMEGA, MG/M3	1.80									
C, J/(G*K)	1.05[b] (AT 299 K)									
K, W/(M*K)	76 (373 TO 573 K)									
ALPHA, 10-6 M/(M*K)	25.2 (291 TO 373 K)									

[a] BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.
[b] ESTIMATED.

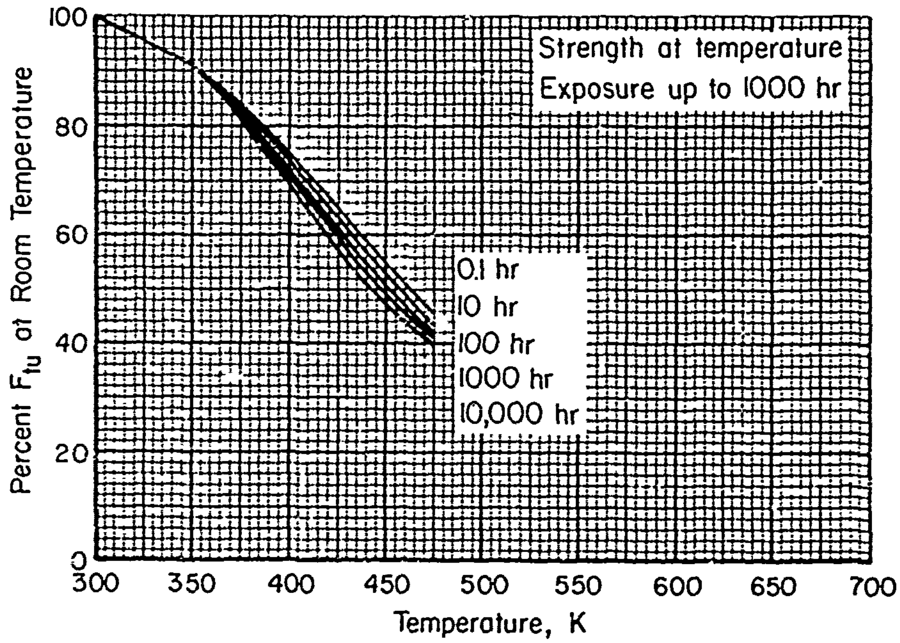

FIGURE 4.2.3.2.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of AZ80A-T5 forgings.

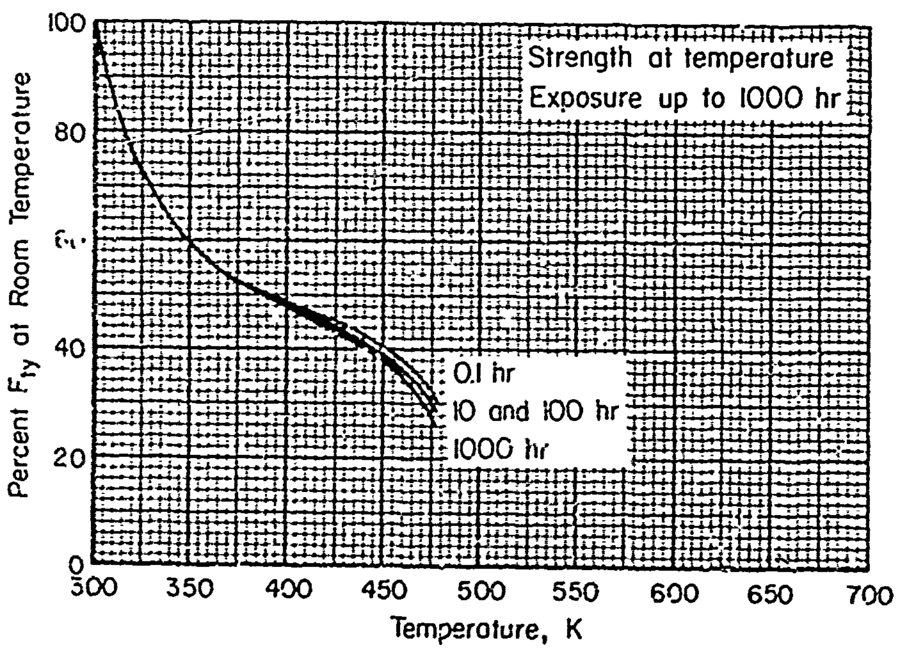

FIGURE 4.2.3.2.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of AZ80A-T5 forgings.

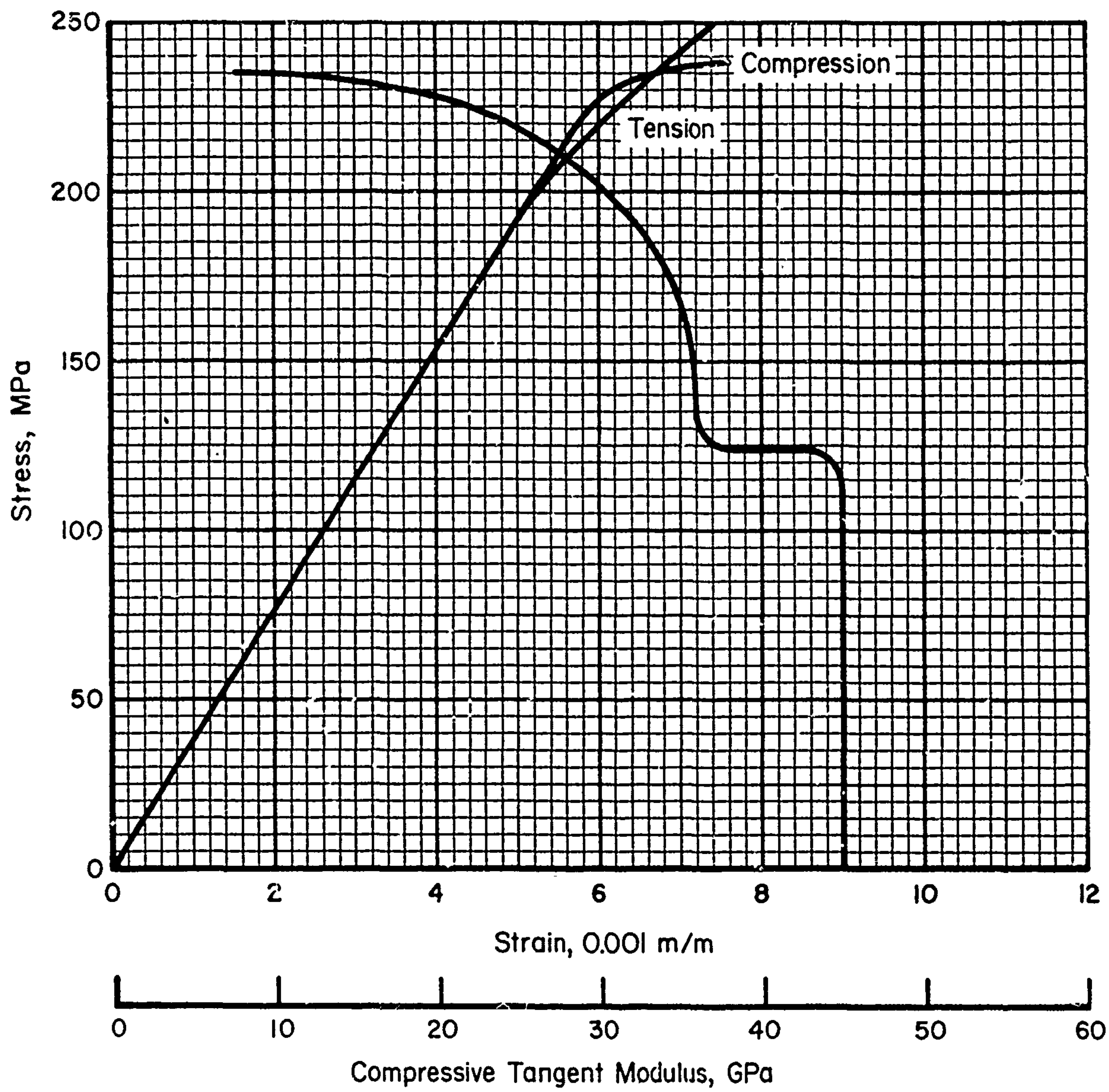

FIGURE 4.2.3.2.6. Typical stress-strain and tangent-modulus curves for AZ80A-T5 (extrusions) at room temperature.

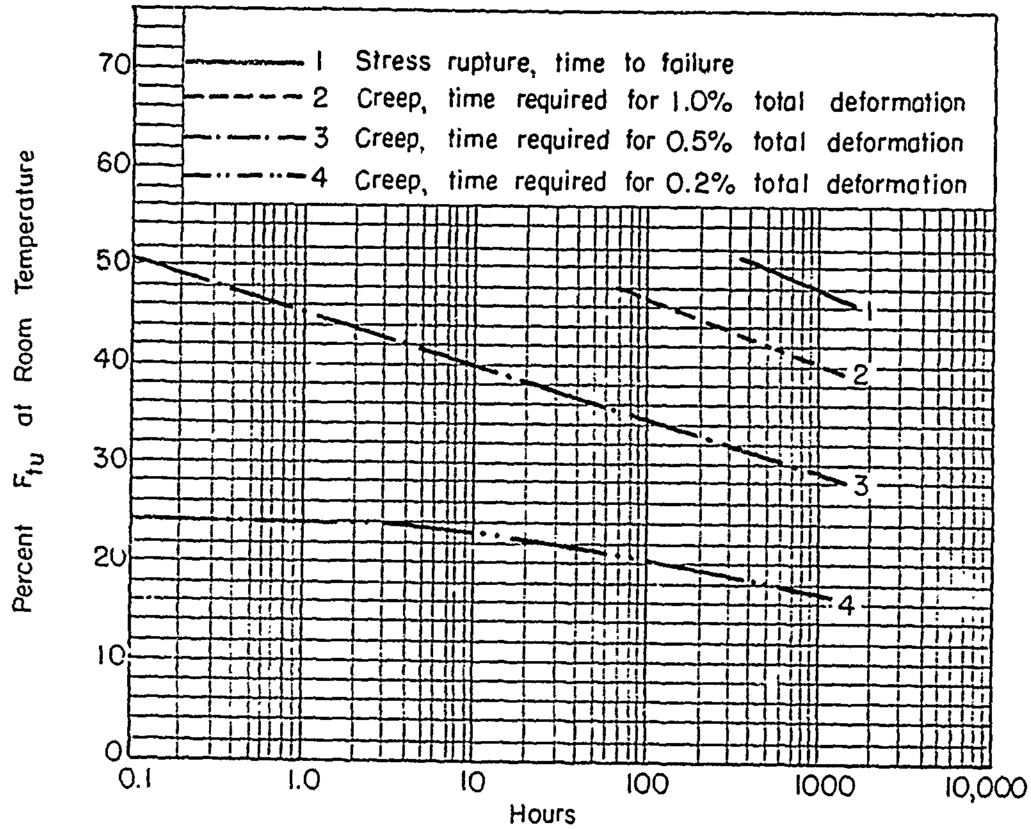

FIGURE 4.2.3.2.7(a). Properties of AZ80A-T5 forgings at 366 K.

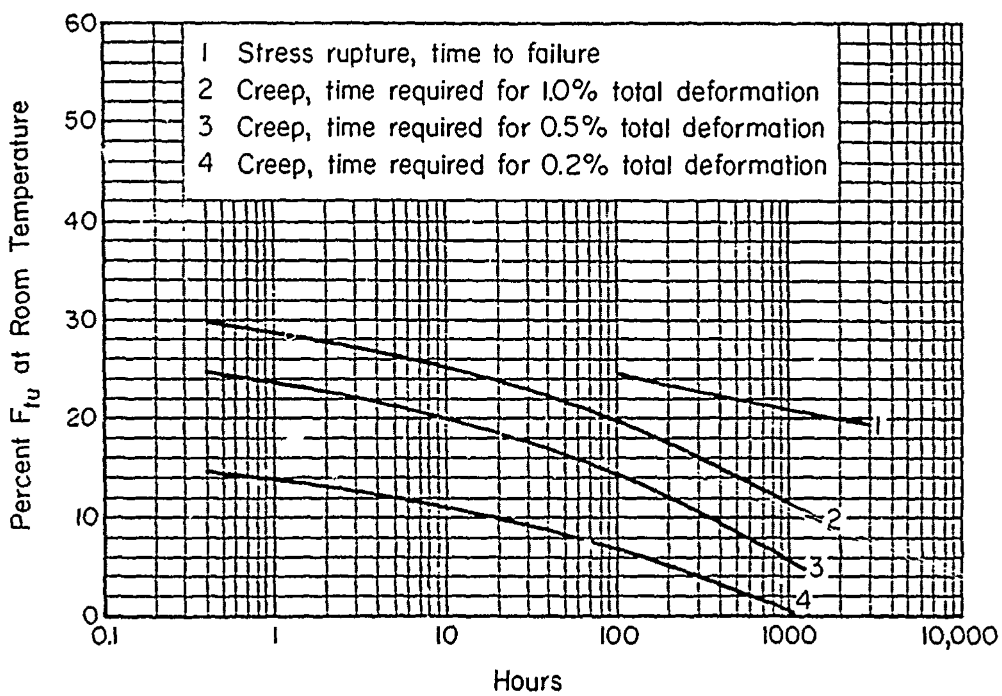

FIGURE 4.2.3.2.7(b). Properties of AZ80A-T5 forgings at 422 K.

4.2.4 HK31A

4.2.4.0 *Comments and Properties.*—HK31A is a magnesium-base alloy containing thorium and zirconium that is available in both wrought and cast forms. Casting properties are given in Section 4.3.6. It has relatively high strength in the temperature range of 422 to 644 K and is used primarily for components requiring a good strength-to-weight ratio in this temperature range. Increased strength is obtained in sheet and plate by strain hardening with a subsequent partial anneal (H24 temper).

The forming must be done at higher temperatures than for the magnesium-base alloys containing aluminum and zinc to get equivalent formability. HK31A arc-welds readily and weld samples have joint efficiencies of about 85 percent at room temperature. At 478 to 589 K the weld strength is not significantly different from the base sheet properties. Stress relieving is not required after welding to prevent stress corrosion.

A material specification covering HK31A is given in Table 4.2.4.0(a).

TABLE 4.2.4.0(a). *Material Specification for HK31A Magnesium Alloy*

Specification	Form
MIL-M-26075	Sheet and plate

The temper index for HK31A is as follows:

Section	Temper
4.2.4.1	0
4.2.4.2	H24

Room-Temperature Properties

Room-temperature mechanical and physical properties are shown in Table 4.2.4.0(b). The effect of temperature on physical properties is shown in Figure 4.2.4.0.

4.2.4.1 *HK31A-O Temper*

4.2.4.2 *HK31A-H24 Temper.*—Effect of temperature on curves for various mechanical properties is shown in Figures 4.2.4.2.1(a) through 4.2.4.2.4.

Typical tension and compression stress-strain curves from room temperature through 644 K are given in Figures 4.2.4.2.6(a) and (b).

Fatigue curves for unnotched sheet samples at room temperature and 478 K are shown in Figure 4.2.4.2.8.

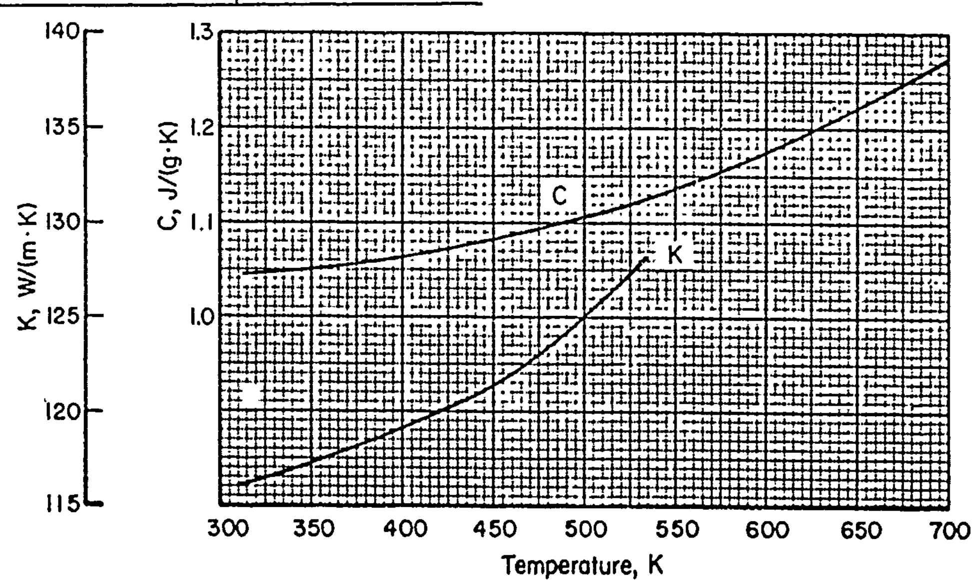

FIGURE 4.2.4.0. Effect of temperature on the physical properties of HK31A.

TABLE 4.2.4.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF HK31A(SHEET AND PLATE)

SPECIFICATION	MIL-M-26075											
FORM	SHEET AND PLATE											
TEMPER	O					H24						
THICKNESS, MM	0.41-6.36		6.37-12.71	12.72-25.41	25.42-76.20	0.41-3.18		3.19-6.36		6.37-25.41		25.42-76.20
BASIS	A	B	S	S	S	A	B	A	B	A	B	S
MECHANICAL PROPERTIES:												
FTU, MPA:												
L	207	221	207	207	200	234	248	234	241	234	248	228
LT[a]	...	...	...	...	...	...	...	...	...	...	...	...
FTY, MPA:												
L	124	131	110	103	97	179	193	165	193	172	186	172
LT[a]	...	...	...	...	...	...	...	...	...	...	...	...
FCY, MPA:												
L	83	90	69	69	69	138	145	152	165	138	152	117
LT[a]	...	...	...	...	...	...	...	...	...	...	...	...
FSU, MPA	152	152	152	152	...	159	159	159	159	159	159	...
FBRU[b] MPA:												
(E/D=1.5)	296	317	296	...	...	338	359	378	352	338	359	...
(E/D=2.0)	352	372	352	...	...	393	414	393	400	393	414	...
FBRY[b] MPA:												
(E/D=1.5)	165	172	145	...	...	234	241	248	269	234	248	...
(E/D=2.0)	165	172	145	...	...	234	241	248	269	234	248	...
EL, PERCENT:												
L	12	20	12	12	12	4	4	4	8	4	7	4
LT	...	...	...	...	...	...	...	...	...	...	...	...
E, GPA	44.8											
EC, GPA	44.8											
G, GPA	16.5											
MU	0.35											
PHYSICAL PROPERTIES:												
OMEGA, MG/M3	1.79											
C, J/(G*K)	SEE FIGURE 4.2.4.0											
K, W/(M*K)	SEE FIGURE 4.2.4.0											
ALPHA, 10-6 M/(M*K)	27.0 (293 TO 473 K)											

[a] TRANSVERSE PROPERTIES ARE EQUAL TO OR GREATER THAN THE LONGITUDINAL PROPERTIES.

[b] BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

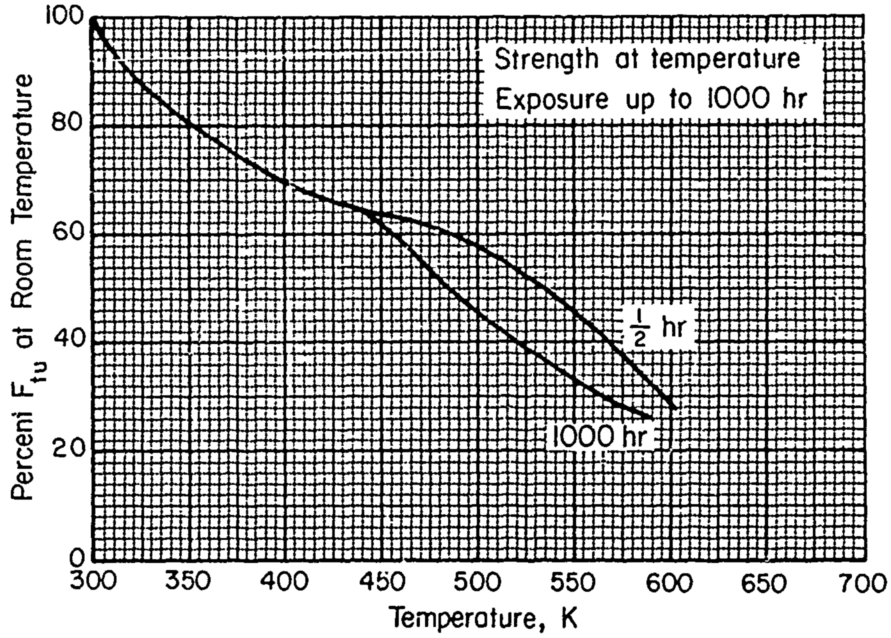

FIGURE 4.2.4.2.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of HK31A-H24 (sheet).

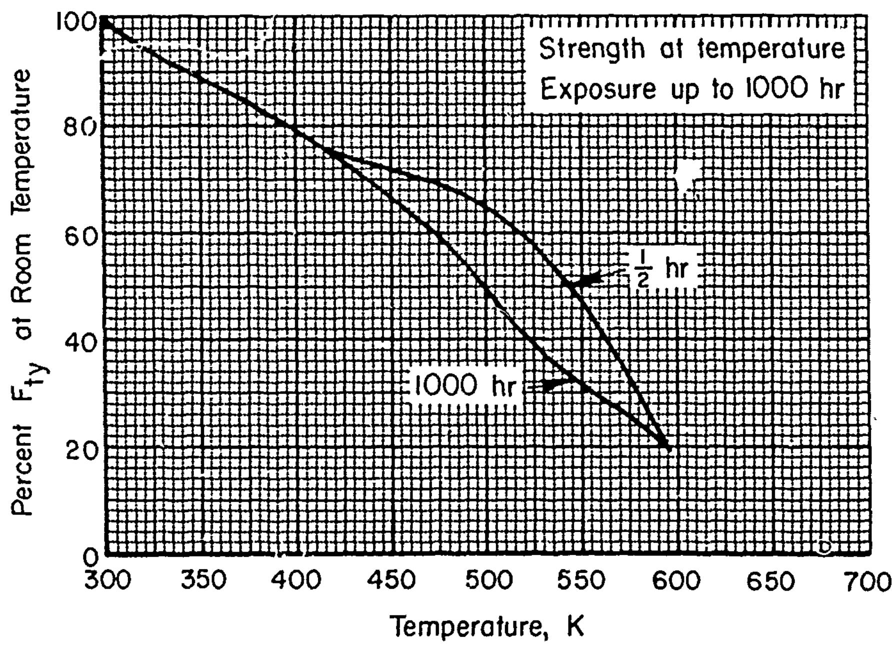

FIGURE 4.2.4.2.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of HK31A-H24 (sheet).

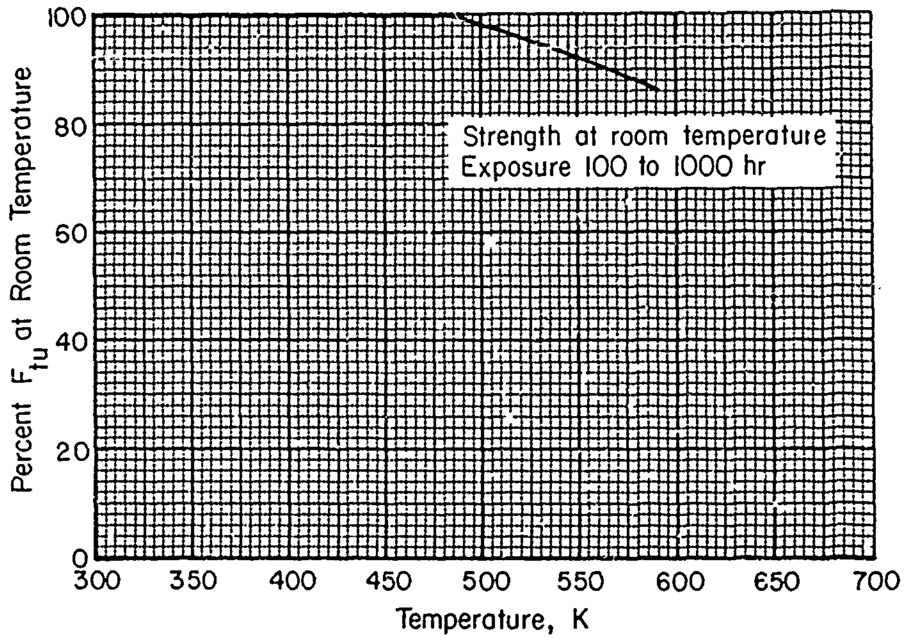

FIGURE 4.2.4.2.1(c). Effect of exposure at elevated temperature on the room-temperature ultimate tensile strength (F_{tu}) of HK31A-H24 (sheet).

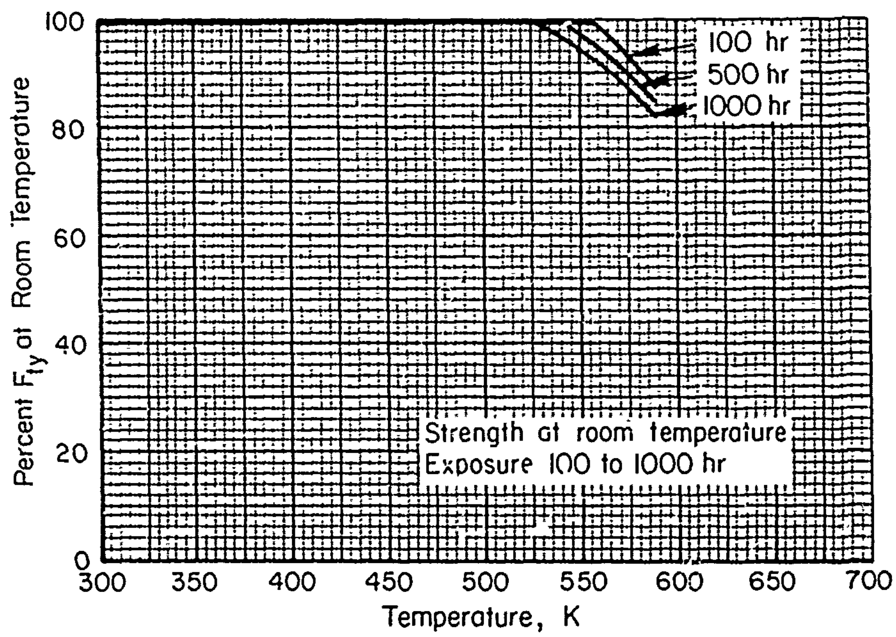

FIGURE 4.2.4.2.1(d). Effect of exposure at elevated temperatures on the room-temperature tensile yield strength (F_{ty}) of HK31A-H24 (sheet).

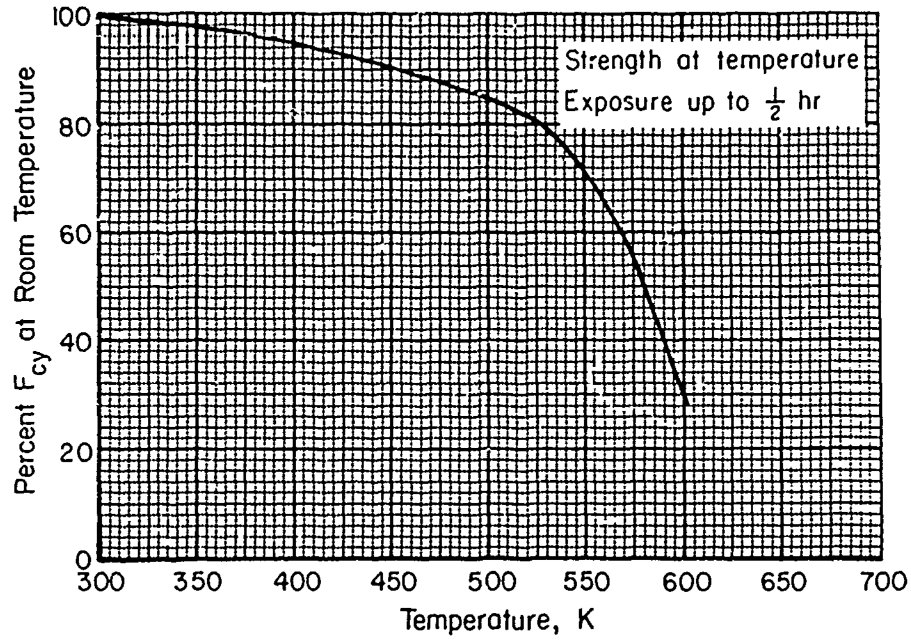

FIGURE 4.2.4.2.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of HK31A-H24 (sheet).

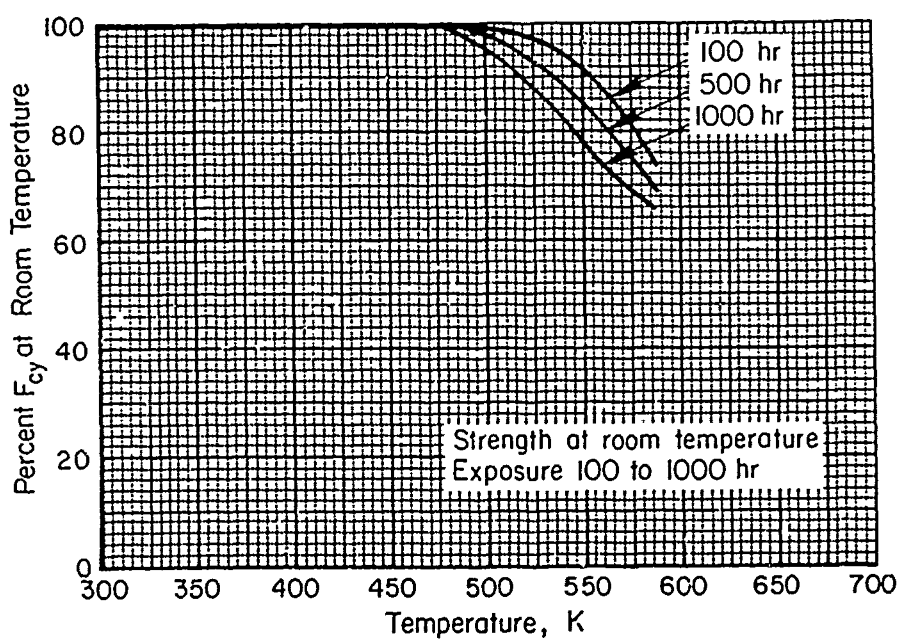

FIGURE 4.2.4.2.2(b). Effect of exposure at elevated temperatures on the room-temperature compressive yield strength (F_{cy}) of HK31A-H24 (sheet).

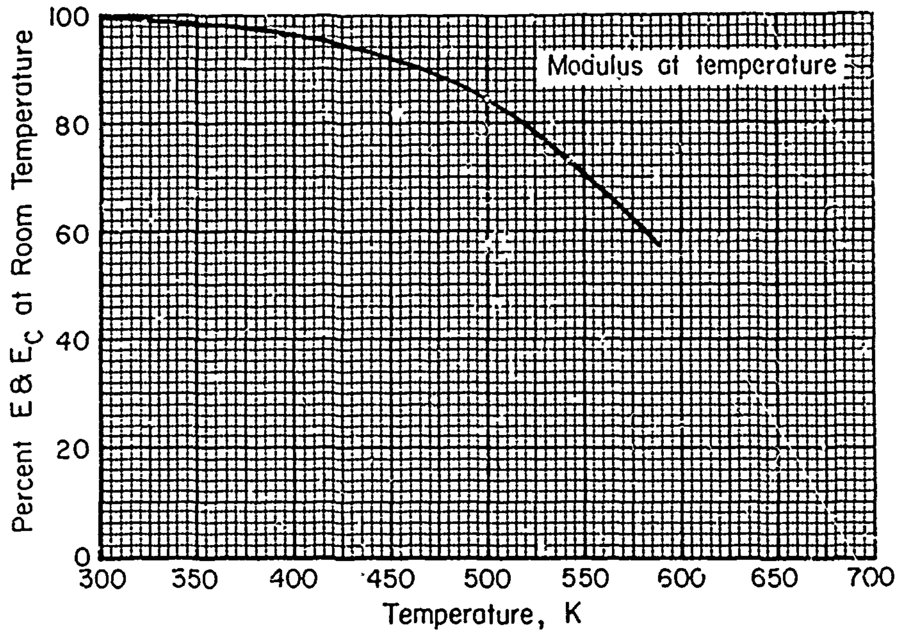

FIGURE 4.2.4.2.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of HK31A-H24 (sheet and plate).

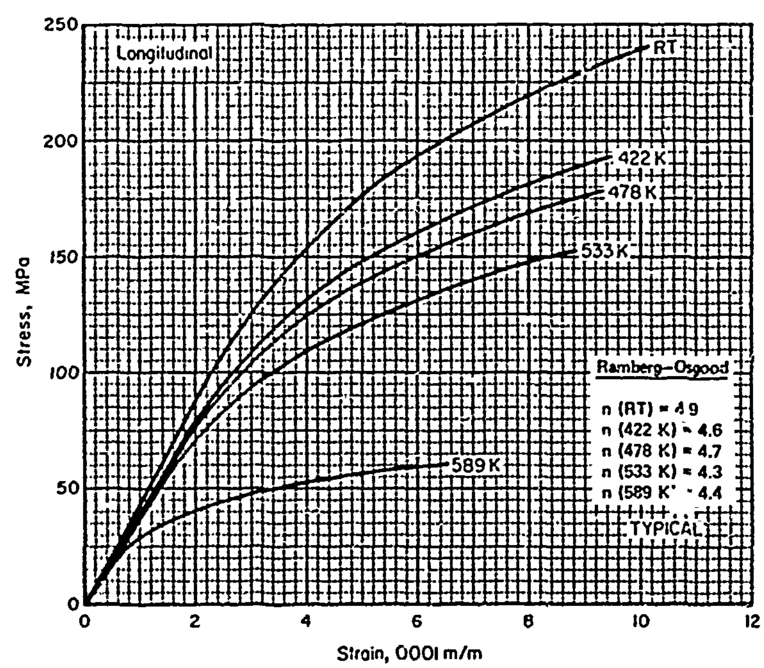

FIGURE 4.2.4.2.6(a). Typical tensile stress-strain curves for HK31A-H24 (sheet) at room and elevated temperatures.

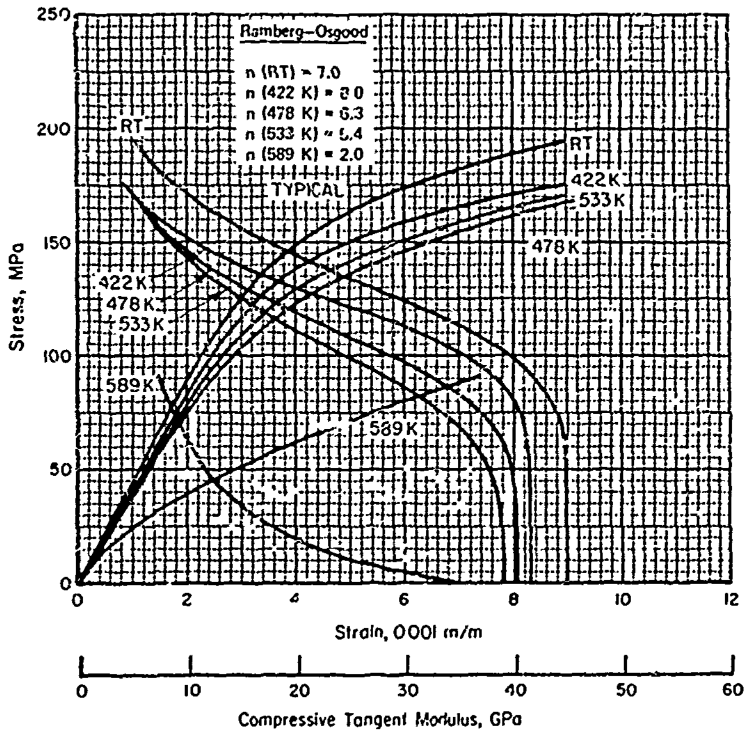

FIGURE 4.2.4.2.7(b). Typical compressive stress-strain and tangent-modulus curves for HK31A-H24 (sheet) at room and elevated temperatures.

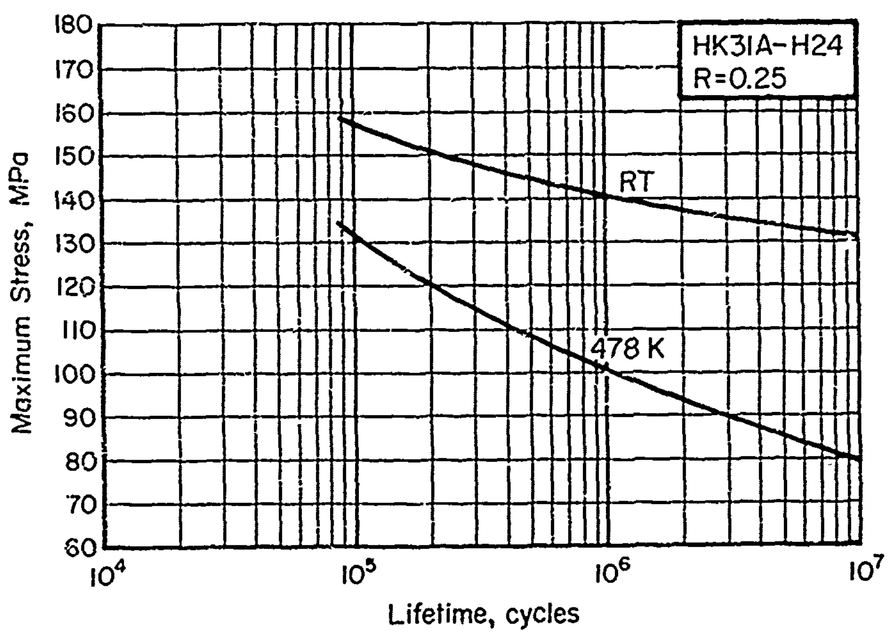

FIGURE 4.2.4.2.8. Typical fatigue curves for HK31A-H24 (sheet) at room temperature and 478 K.

4.2.5 HM21A

4.2.5.0 *Comments and Properties.*—HM21A is a magnesium-base alloy containing thorium and manganese. It is available in the form of sheet and plate usually in the solution heat-treated, cold-worked, and artificially aged (T8) and (T81) tempers. Forgings are available in the artificially aged (T5) temper. It is used primarily in the temperature range of 533 to 700 K where it is superior from a strength standpoint to the other magnesium alloys available in the form of sheet, plate and forgings.

Forming must be done at higher temperatures than for the magnesium-base alloys containing aluminum and zinc. Arc-welded samples of HM21A-T8 sheet have joint efficiencies of 85 percent at room temperature. At 478 K and above the weld strength is not significantly different from the base sheet properties. Stress relieving is not required to prevent stress corrosion.

Material specifications are given in Table 4.2.5.0(a). AMS 4363 is listed for forgings in addition to QQ-M-40 because it covers ring forgings as well as the die and hand forgings covered by QQ-M-40.

TABLE 4.2.5.0(a). *Material Specifications for HM21A Magnesium Alloy*

Specification	Form
QQ-M-40	Forgings
MIL-M-8917	Sheet and plate
AMS 4363	Forgings

The temper index for HM21A is as follows.

Section	Temper
4.2.5.1	T8
4.2.5.2	T81
4.2.5.3	T5

Room-Temperature Properties

Room-temperature mechanical and physical properties are shown in Table 4.2.5.0(b).

4.2.5.1 *HM21A-T8 Temper.*—Effect-of-temperature curves for various mechanical properties are shown in Figures 4.2.5.1.1(a) through 4.2.5.1.4 for sheet and plate with this temper.

Typical tension and compression stress-strain curves and compression tangent-modulus curves for sheet at several temperatures between room temperature and 644 K are presented in Figures 4.2.5.1.6(a) through (c).

4.2.5.2 *HM21A-T81 Temper.*—The effect of temperature on tensile strength and elongation of sheet material in this temper are shown in Figures 4.2.5.2.1 and 4.2.5.2.5.

TABLE 4.2.5.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF HM21A MAGNESIUM ALLOY (SHEET, PLATE AND FORGINGS)

SPECIFICATION..........	MIL-M-8917						QQ-M-40	AMS4363
FORM..................	SHEET AND PLATE						FORGINGS	ROLLED RINGS
FORM..................								AND FORGINGS
TEMPER................	T6					T81	T5	T5
THICKNESS, MM.........	0.41-6.36	6.37-12.71	12.72-25.41	25.42-50.81	50.82-76.20	5.46-7.92	≤ 101.60	...
BASIS.................	S	S	S	S	S	S	S	S
MECHANICAL PROPERTIES:								
FTU, MPA:								
L.....................	228	221	207	207	207	234[a]	228	221
LT....................	228	221	207	207	207	234[a]	...	...
FTY, MPA:								
L.....................	124	145	145	145	145	172[a]	172	179
LT....................	124	145	145	145	145	172[a]	...	...
FCY, MPA:								
L.....................	103	138	117	103	97	152[a]	...	...
LT....................	103	138	117	103	97	152[a]	...	...
FSU, MPA..............	145	135	131	131	131	...	...	...
FBRU[b], MPA:								
(E/D=1.5).............	324	310	296	296	296	...	...	...
(E/D=2.0).............	386	372	359	359	359	...	...	...
FBRY[b], MPA:								
(E/D=1.5).............	200	241	214	200	186	...	...	...
(E/D=2.0).............	200	241	214	200	186	...	...	...
EL, PERCENT:								
L.....................	6	6	6	6	6	4[a]	3	4
LT....................	6	6	6	6	6	4[a]	...	...
E, GPA................	44.8							
EC, GPA...............	44.8							
G, GPA................	16.5							
MU....................	0.35							
PHYSICAL PROPERTIES:								
OMEGA, MG/M3..........	1.77							
C, J/(G*K)............	1.05 (AT 299 K)[c]							
K, W/(M*K)............	138 (373 TO 573 K)[c]							
ALPHA, 10-6 M/(M*K)...	25.2 (291 TO 373 K)							

[a] THESE VALUES MAY NOT BE OBTAINED USING STRAIN RATES LOWER THAN 0.010 MM/MM/MIN TO THE YIELD STRENGTH AND APPROXIMATELY 0.3 MM/MM/MIN FROM THE YIELD STRENGTH TO FRACTURE.

[b] BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

[c] ESTIMATED.

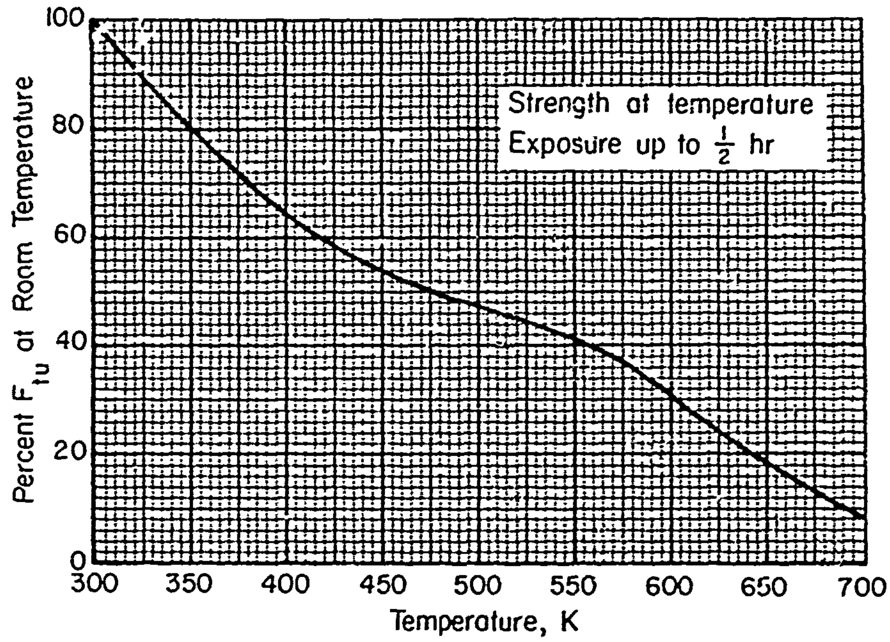

FIGURE 4.2.5.1.1(a). Effect of temperature on the ultimate strength (F_{tu}) of HM21A-T8 (sheet).

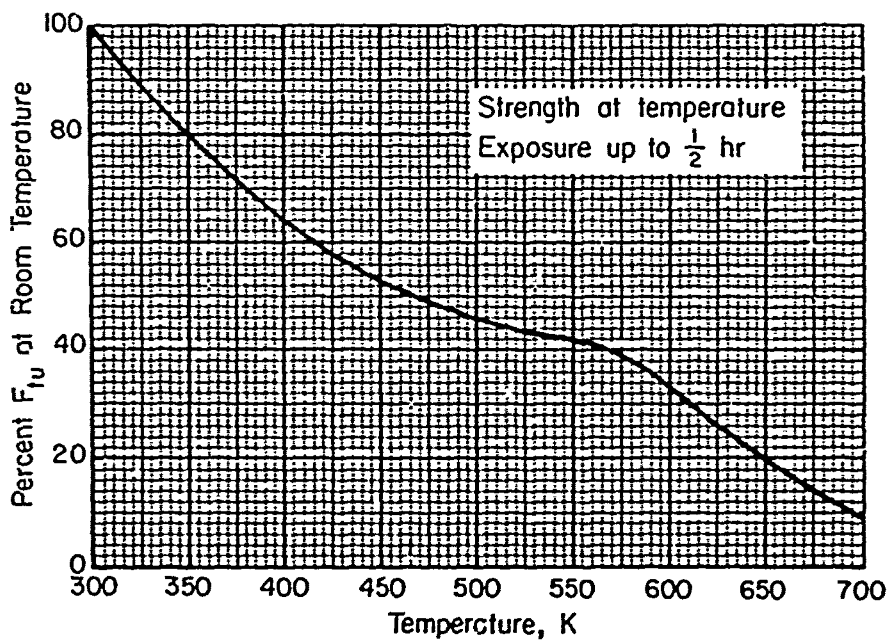

FIGURE 4.2.5.1.1(b). Effect of temperature on the ultimate tensile strength (F_{tu}) of HM21A-T8 (plate).

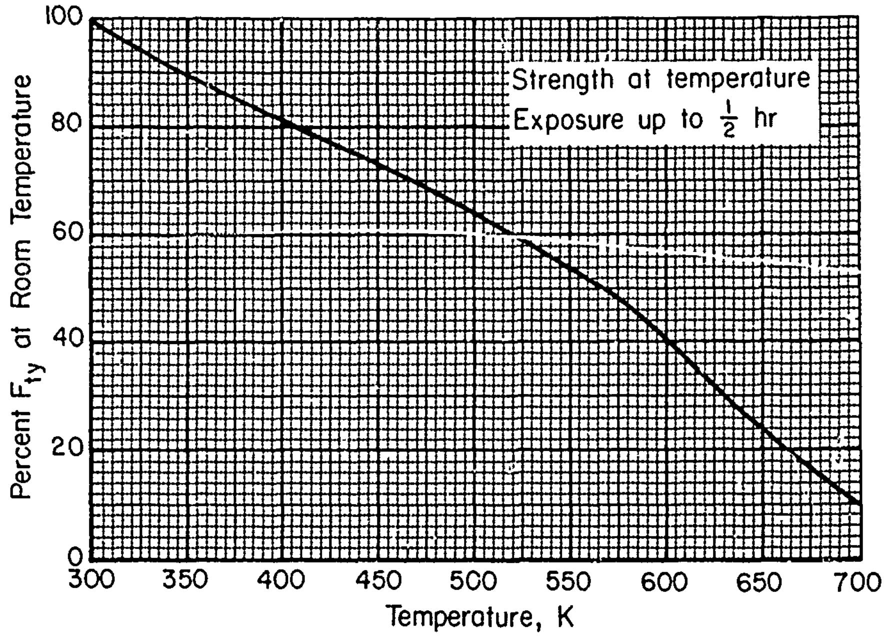

FIGURE 4.2.5.1.1(c). Effect of temperature on the tensile yield strength (F_{ty}) of HM21A-T8 (sheet).

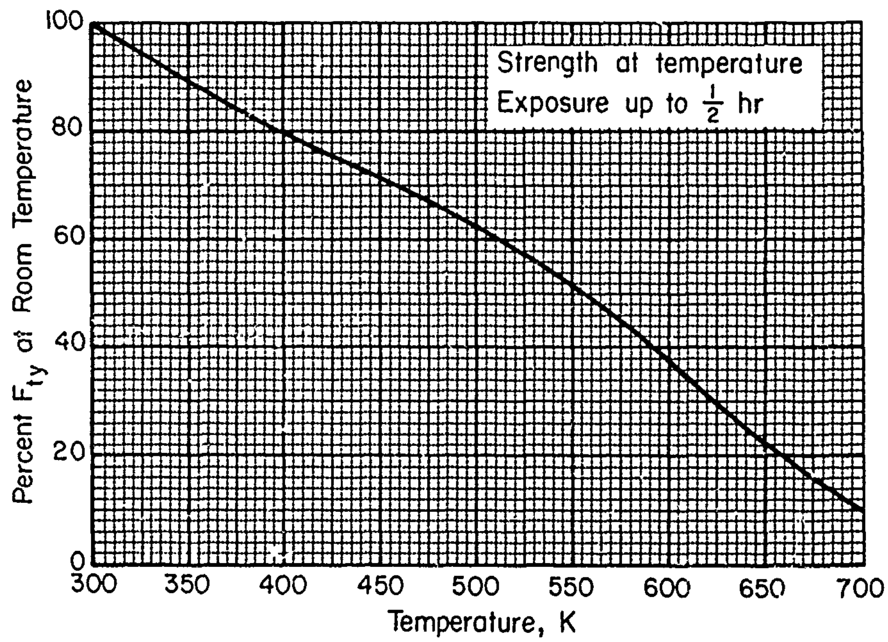

FIGURE 4.2.5.1.1(d). Effect of temperature on the tensile yield strength (F_{ty}) of HM21A-T8 (plate).

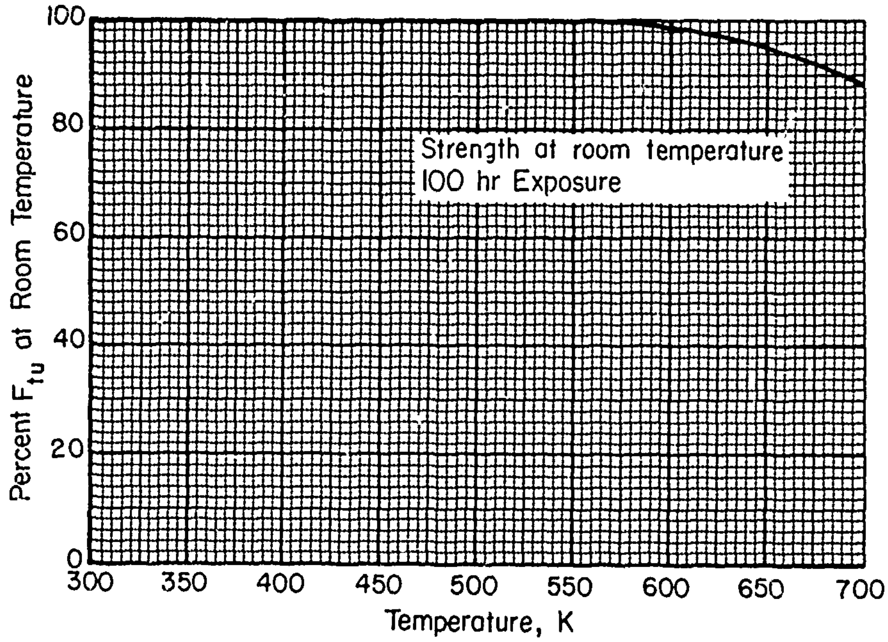

FIGURE 4.2.5.1.1(e). Effect of exposure at elevated temperature on the room-temperature ultimate tensile strength (F_{tu}) of HM21A-T8 (sheet and plate).

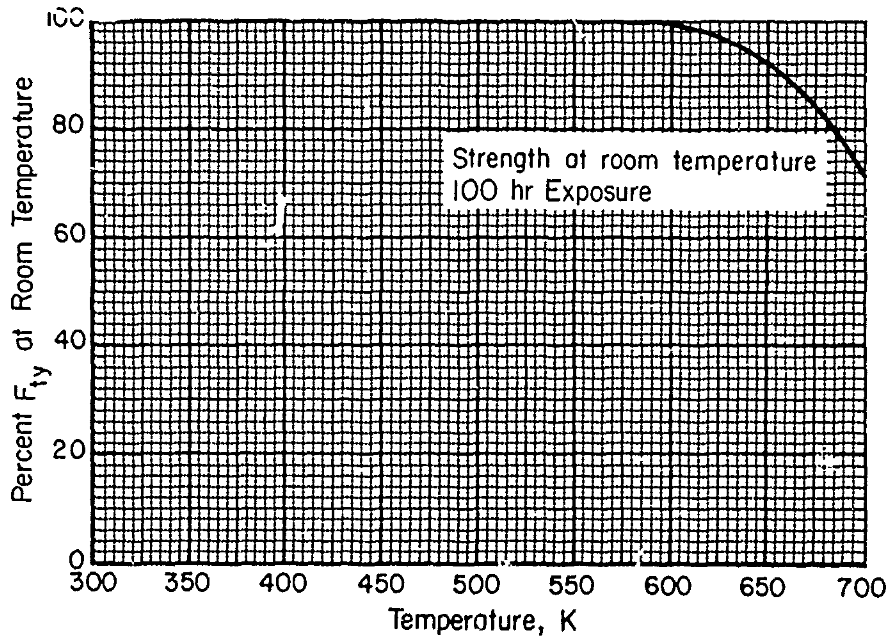

FIGURE 4.2.5.1.1(f). Effect of exposure at elevated temperature on the room-temperature tensile yield strength (F_{ty}) of HM21A-T8 (sheet and plate).

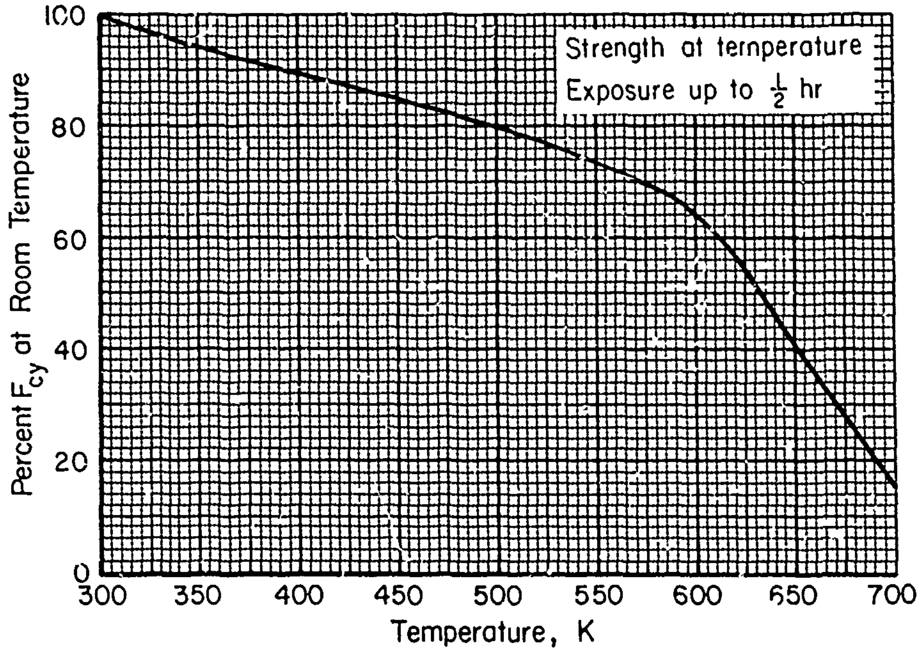

FIGURE 4.2.5.1.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of HM21A-T8 (sheet and plate).

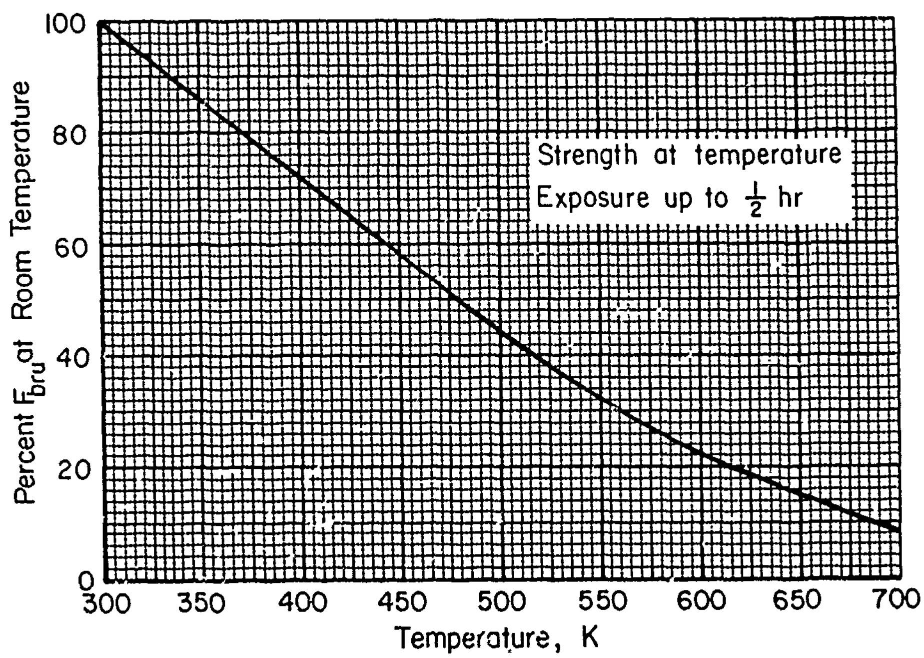

FIGURE 4.2.5.1.3(a). Effect of temperature on the ultimate bearing strength (F_{bru}) of HM21A-T8 (sheet and plate).

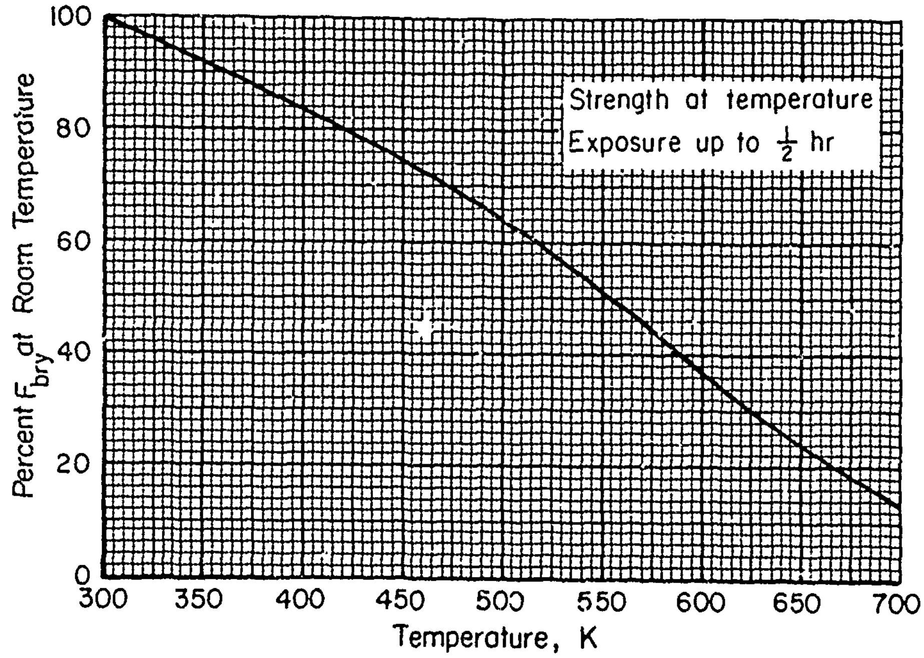

FIGURE 4.2.5.1.3(b). Effect of temperature on the bearing yield strength (F_{bry}) of HM21A-T8 (sheet and plate).

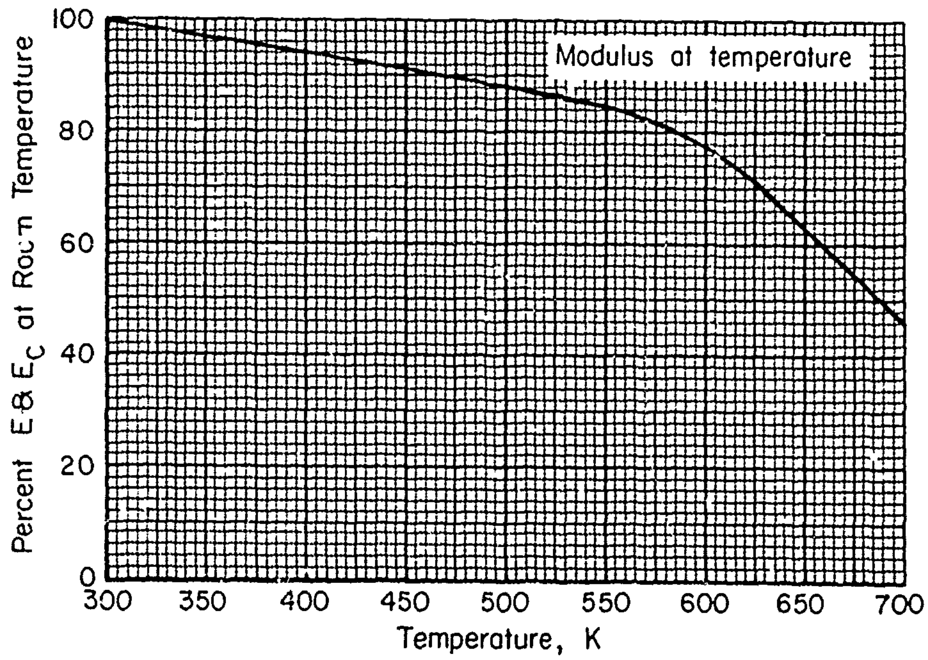

FIGURE 4.2.5.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of HM21A-T8 (sheet and plate).

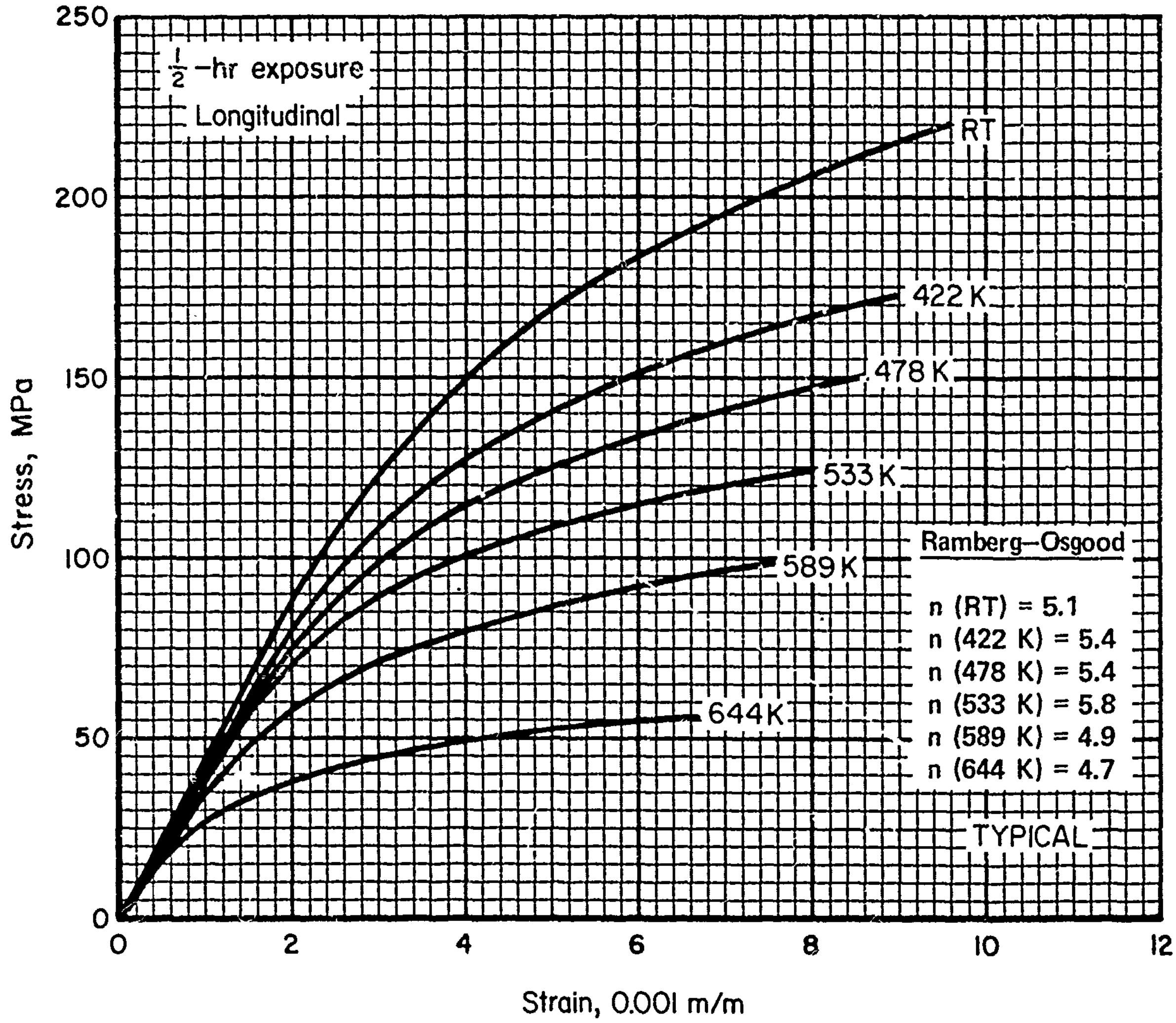

FIGURE 4.2.5.1.6(a). Typical tensile stress-strain curves for HM21A-T8 (sheet) at room and elevated temperatures.

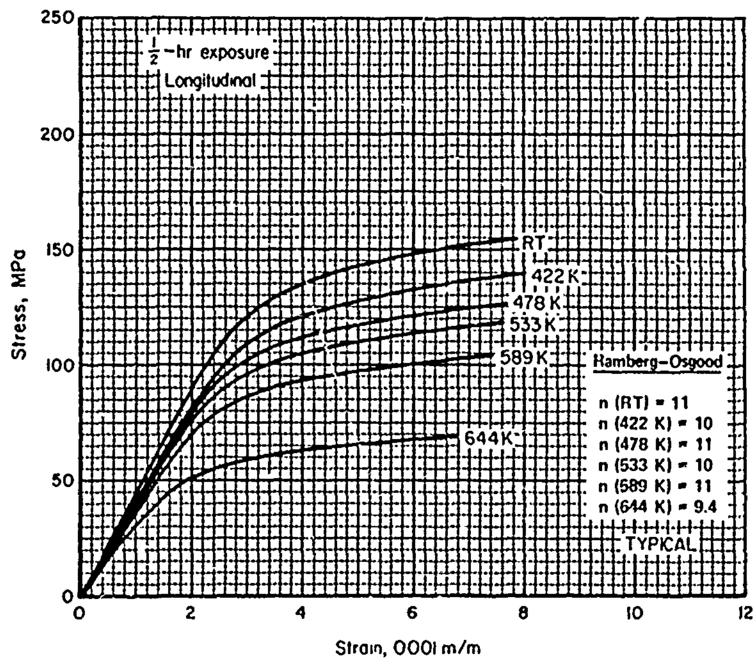

FIGURE 4.2.5.1.6(b). Typical compressive stress-strain curves for HM21A-T8 (sheet) at room and elevated temperatures.

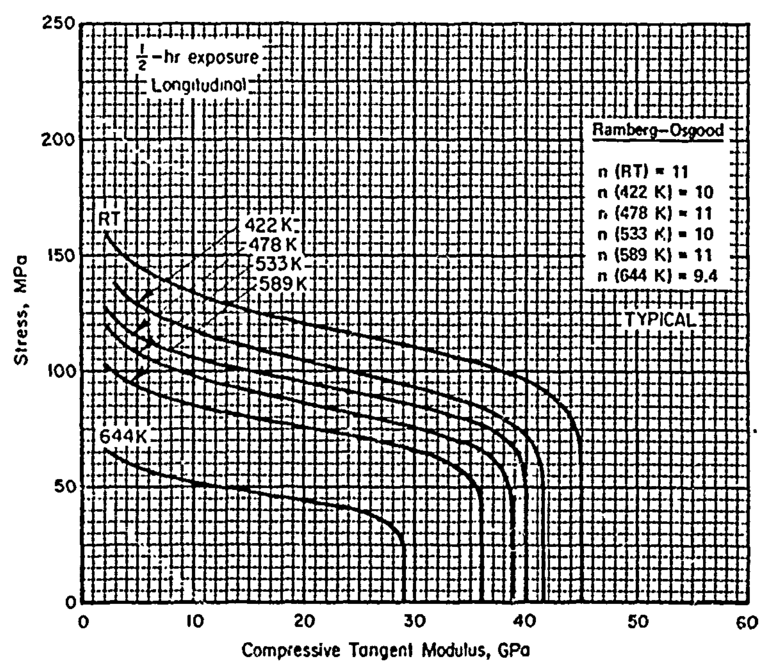

FIGURE 4.2.5.1.6(c). Typical compressive tangent-modulus curves for HM21A-T8 (sheet) at room and elevated temperatures.

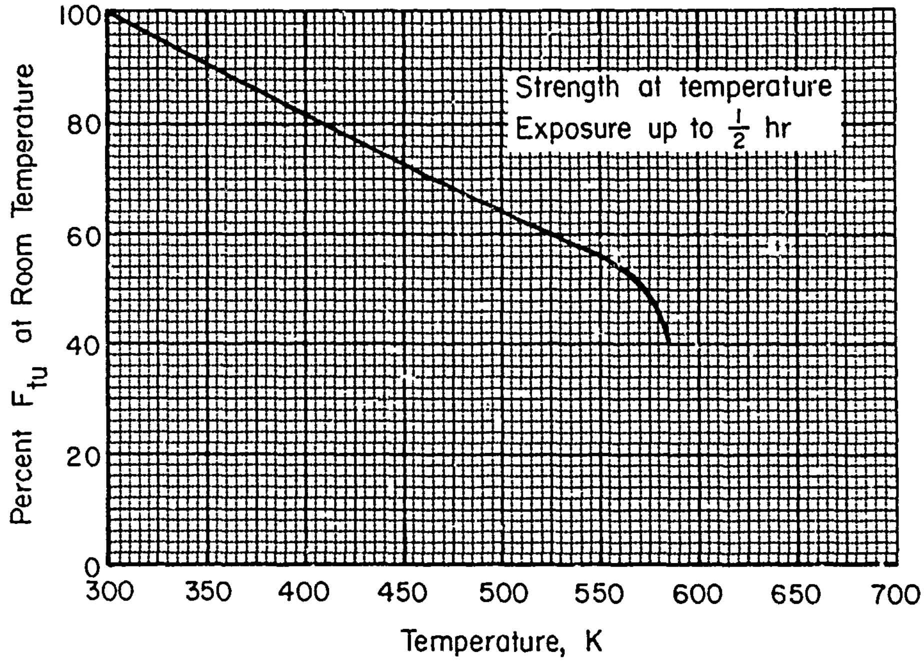

FIGURE 4.2.5.2.1. Effect of temperature on the ultimate tensile strength (F_{tu}) of HM21A-T81 (sheet).

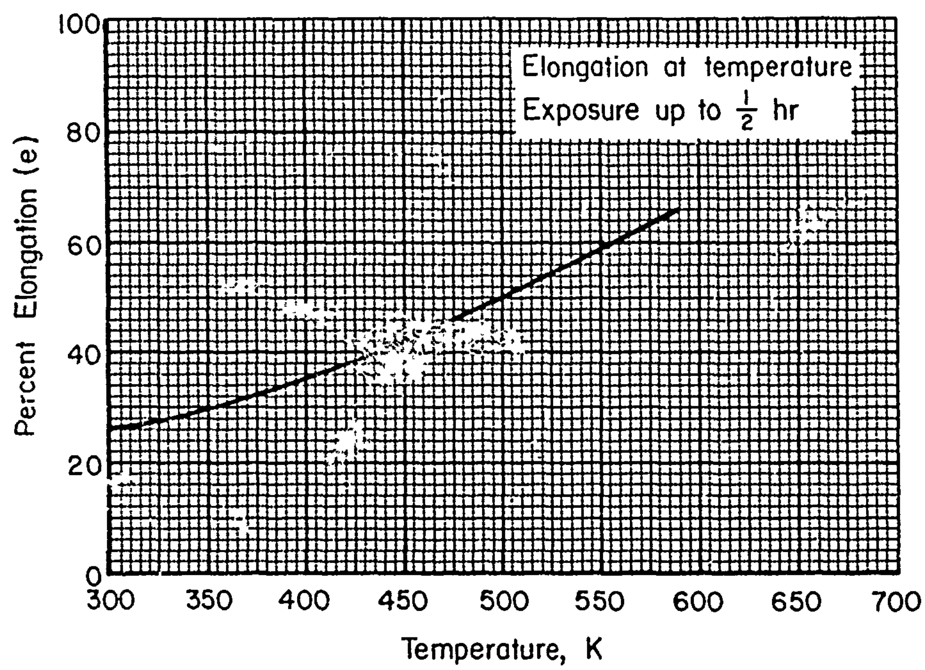

FIGURE 4.2.5.2.5. Effect of temperature on the elongation (e) of HM21A-T81 (sheet).

4.2.6 HM31A

4.2.6.0 *Comments and Properties.*—HM31A is a magnesium-base alloy containing thorium and manganese. It is available in the form of solid extruded shapes in the artificially aged (T5) temper. It is used primarily in the temperature range of 478 to 700 K.

Forming must be done at higher temperatures than for the magnesium-base alloys containing aluminum and zinc. Arc-welded samples of HM31A-T5 have joint efficiencies of about [illegible] percent at room temperature and about 85 percent at 478 K. Stress relieving after welding is not required to prevent stress corrosion.

A material specification is given in Table 4.2.6.0(a).

TABLE 4.2.6.0(a). *Material Specification for HM31A Magnesium Alloy*

Specification	Form
MIL-M-8916	Extrusions

A temper index for HM31A is as follows:

Section	Temper
4.2.6.1	T5

Room-Temperature Properties

Room-temperature mechanical and physical properties are shown in Table 4.2.6.0(b).

4.2.6.1 *HM31A-T5 Temper.*—Effect-of-temperature curves for various mechanical properties are presented for this temper in Figures 4.2.6.1.1(a) through 4.2.6.1.4.

Typical tension and compression stress-strain curves at various temperatures between room temperature and 700 K are presented in Figures 4.2.6.1(a) and (b).

TABLE 4.2.6.0(9). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF HM31A MAGNESIUM ALLOY (EXTRUSIONS)

SPECIFICATION..........	MIL-M8916
FORM..................	EXTRUDED BAR, ROD,
FORM..................	AND SOLID SHAPES
TEMPER................	T5
CROSS-SECTIONAL AREA, CM2	< 2580
BASIS.................	S
MECHANICAL PROPERTIES:	
FTU, MPA:	
L.................	255
LT................	...
FTY, MPA:	
L.................	179
LT................	...
FCY, MPA:	
L.................	131
LT................	...
FSU, MPA............	...
FBRU, MPA:	
(E/D=1.5).........	...
(E/D=2.0).........	...
FBRY, MPA:	
(E/D=1.5)	...
(E/D=2.0)	...
EL, PERCENT:	
L.................	4
LT................	...
E, GPA..............	44.8
EC, GPA.............	44.8
G, GPA..............	16.5
MU..................	0.35
PHYSICAL PROPERTIES:	
OMEGA, MG/M3..........	1.80
C, J/(G*K)............	1.05 (AT 299 K)[a]
K, W/(M*K)............	106 (373 TO 573 K)[a]
ALPHA, 10-6 M/(M*K)..	25.2 (291 TO 373 K)

[a]ESTIMATED.

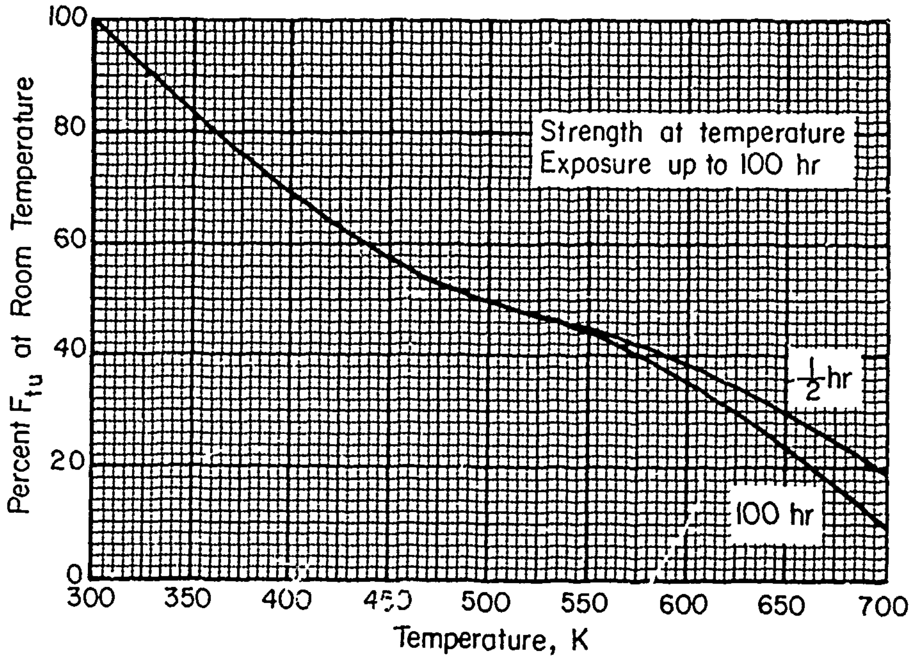

FIGURE 4.2.6.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of HM31A-T5 (extrusion).

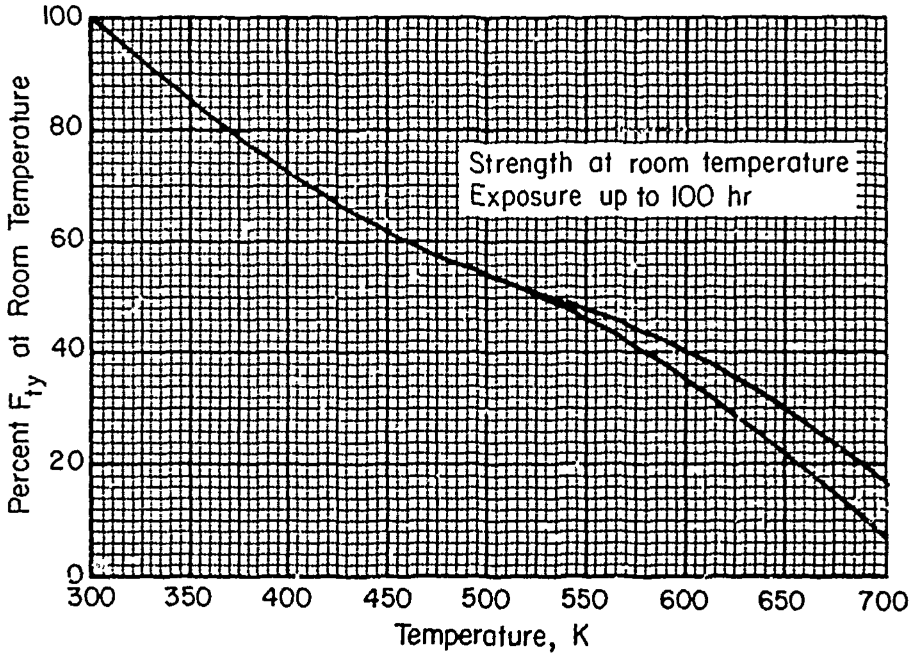

FIGURE 4.2.6.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of HM31A-T5 (extrusion).

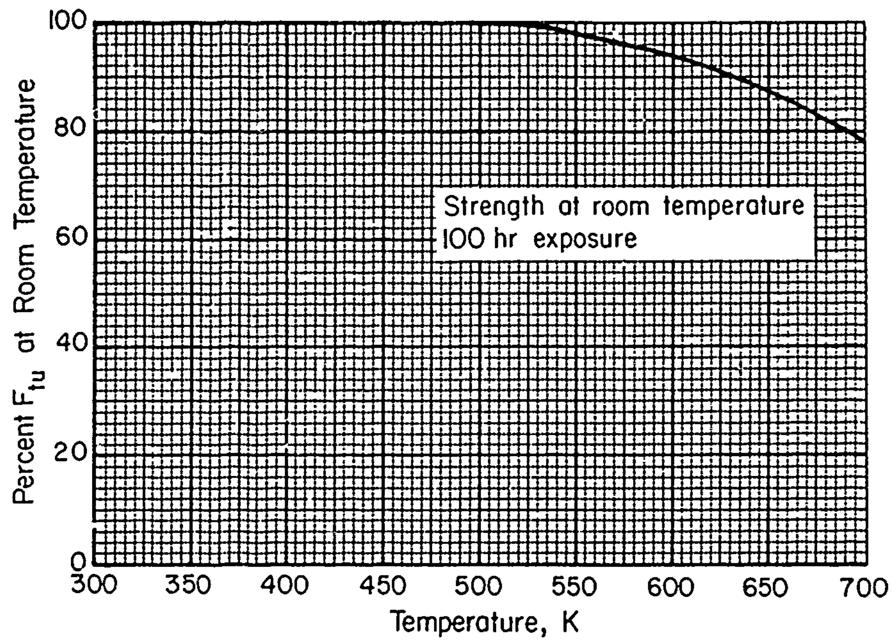

FIGURE 4.2.6.1.1(c). Effect of exposure at elevated temperatures on the room-temperature ultimate tensile strength (F_{tu}) of HM31A-T5 (extrusion).

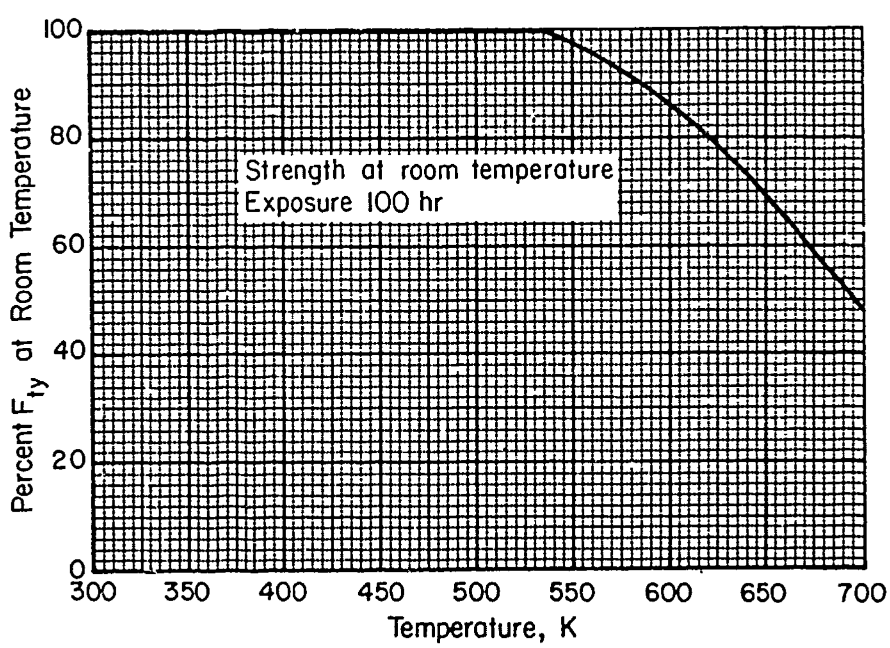

FIGURE 4.2.6.1.1(d). Effect of exposure at elevated temperature on the room-temperature tensile yield strength (F_{ty}) of HM31A-T5 (extrusion).

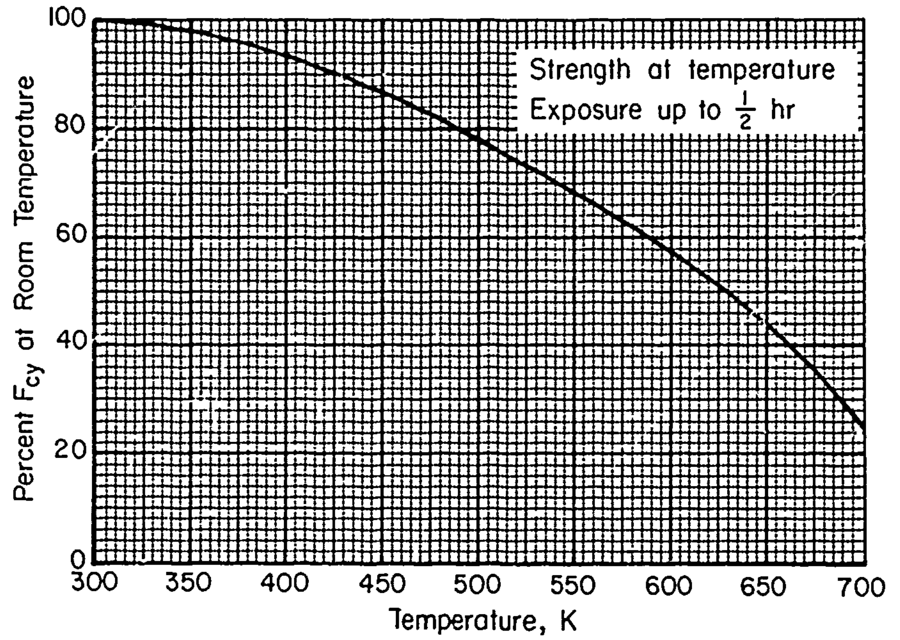

FIGURE 4.2.6.1.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of HM31A-T5 (extrusions).

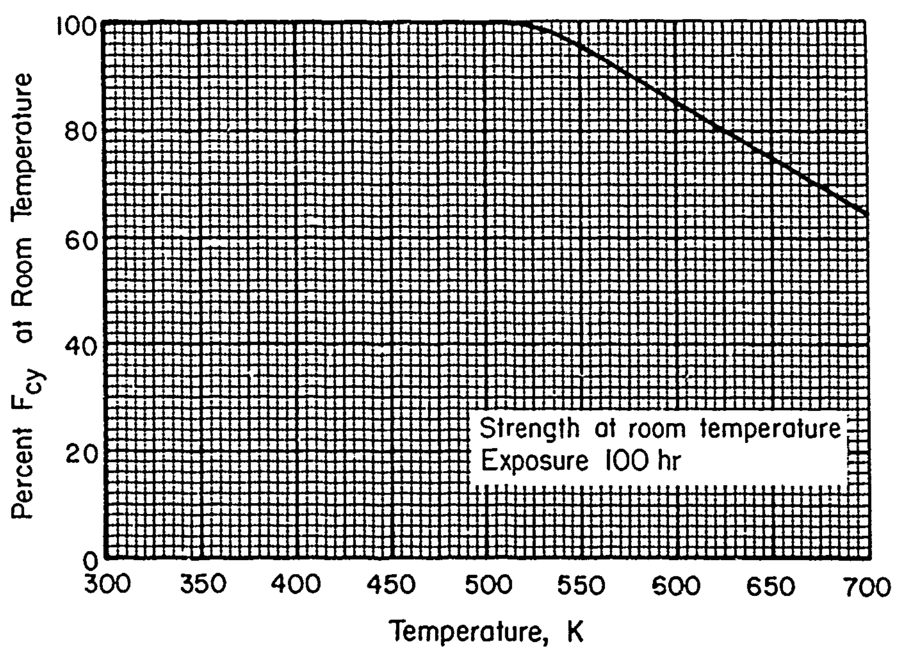

FIGURE 4.2.6.1.2(b). Effect of exposure at elevated temperatures on the room-temperature compressive yield strength (F_{cy}) of HM31A-T5 (extrusion).

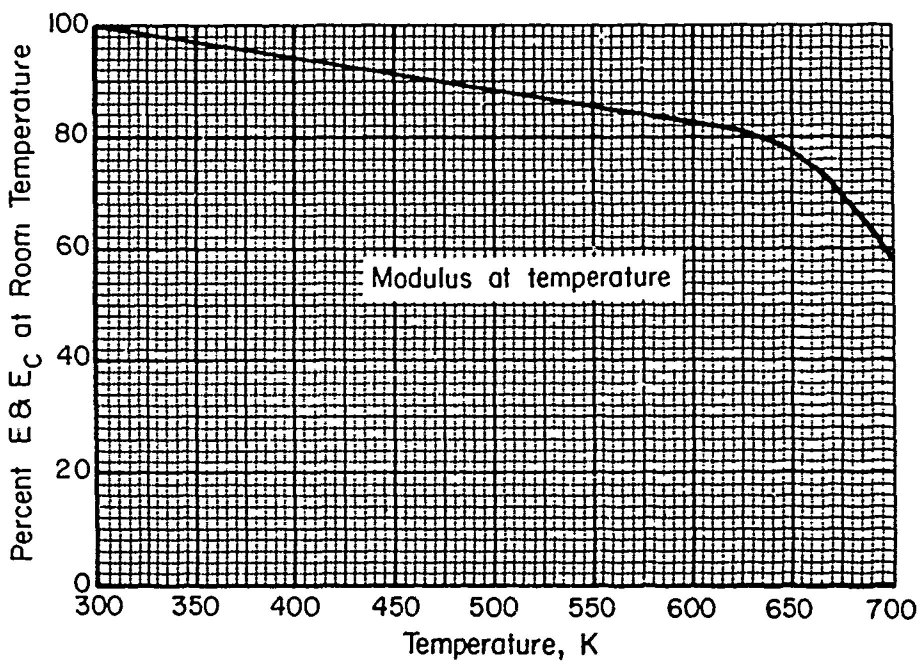

FIGURE 4.2.6.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of HM31A-T5 (extrusions).

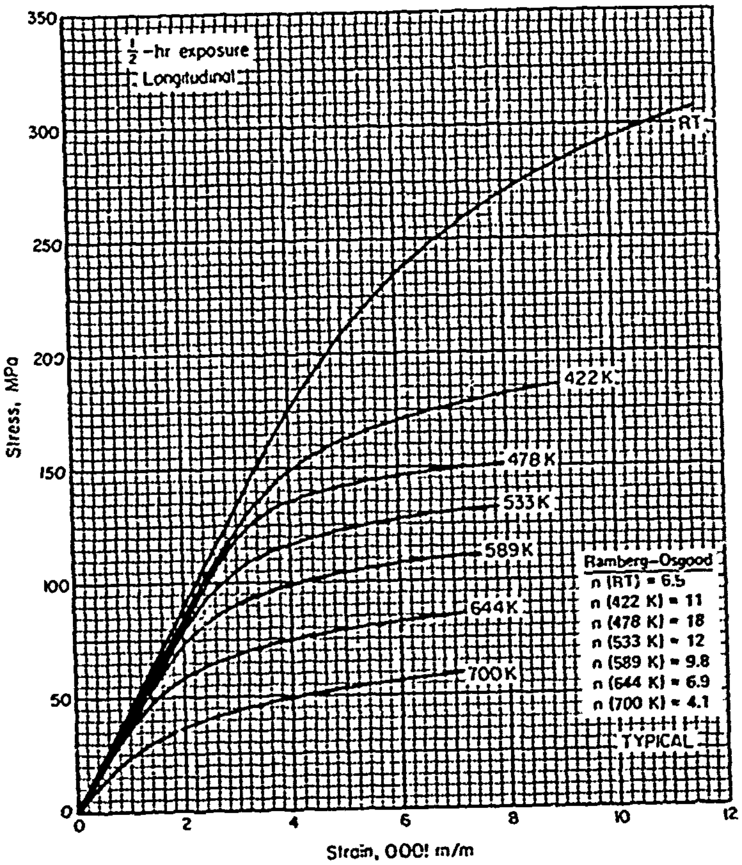

FIGURE 4.2.6.1.6(a). Typical tensile stress-strain curves for HM31A-T5 (extrusions) at room and elevated temperatures.

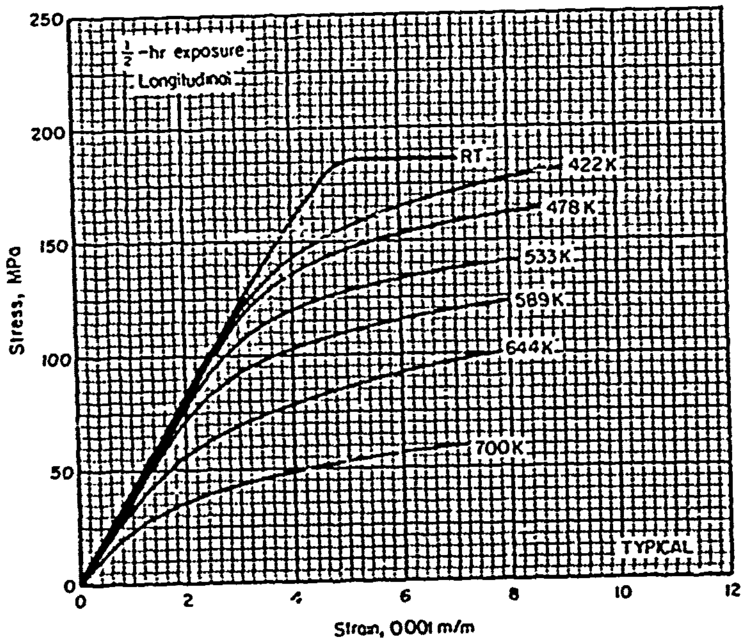

FIGURE 4.2.6.1.6(b). Typical compressive stress-strain curves for HM31A-T5 (extrusions) at room and elevated temperatures.

4.2.7 LA141A

4.2.7.0 *Comments and Properties*—LA141A is a low-density magnesium-base alloy containing lithium and aluminum. It is available as sheet, plate and extrusions, usually in the stabilized (T7) temper. The strength of LA141A decreases rapidly above room temperature so applications are limited to those requiring low density, good formability and weldability, and moderate strength at room temperature and below.

At temperatures at least down to room temperature, creep deformation of LA141A-T7 magnesium alloy can be expected at stresses below the yield strength. Limited data indicate that room-temperature creep can approach 0.2 percent total strain in 10 hours at approximately 58 percent of the yield strength, or in 100 hours at approximately 48 percent F_{ty}. LA141A has excellent formability at room temperature and good weldability but must be stress relieved after welding.

A material specification for LA141A-T7 sheet and plate is given in Table 4.2.7.0(a). No specification has been written for LA141A extrusions.

TABLE 4.2.7.0(a). *Material Specification for LA141A Magnesium Alloy*

Specification	Form
AMS 4386	Sheet and plate

The temper index for LA141A is as follows:

Section	Temper
4.2.7.1	T7

Room-Temperature Properties

Room-temperature mechanical and physical properties are shown in Table 4.2.7.0(b).

4.2.7.1 *LA141A-T7.*—Effect-of-temperature curves for this temper are presented in Figures 4.2.7.1.1(a) through 4.2.7.1.5.

TABLE 4.2.7.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF LA141A MAGNESIUM ALLOY (SHEET AND PLATE)

SPECIFICATION	AMS 4386					
FORM	SHEET AND PLATE					
CONDITION	T7					
THICKNESS, MM	0.51–2.30		2.31–6.36		6.37–50.80	
BASIS	A	B	A	B	A	B
MECHANICAL PROPERTIES:						
FTU, MPA:						
L	124	131	124	131	124	131
LT	...	...	...	...	...	...
FTY, MPA:						
L	83	97	83	90	76	90
LT	...	...	...	...	...	...
FCY, MPA:						
L	90	103	...	...	...	...
LT	...	...	...	...	...	...
FSU, MPA	90	97	...	...	...	...
FBRU[a] MPA:						
(E/D=1.5)	...	...	...	...	...	...
(E/D=2.0)	290	303	...	...	...	...
FBRY[a] MPA:						
(E/D=1.5)	...	...	...	...	...	...
(E/D=2.0)	152	172	...	...	...	...
EL, PERCENT:						
L	10	...	10	...	10	...
LT	...	...	...	...	...	...
E, GPA	42.1					
EC, GPA	...					
G, GPA	...					
MU	...					
PHYSICAL PROPERTIES:						
OMEGA, MG/M3	1.34					
C, J/(G*K)	1.47 (AT 297 K)					
K, W/(M*K)	43 (AT 297 K)					
ALPHA, 10-6 M/(M*K)	39.6 (297 TO 366 K)					

[a]BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

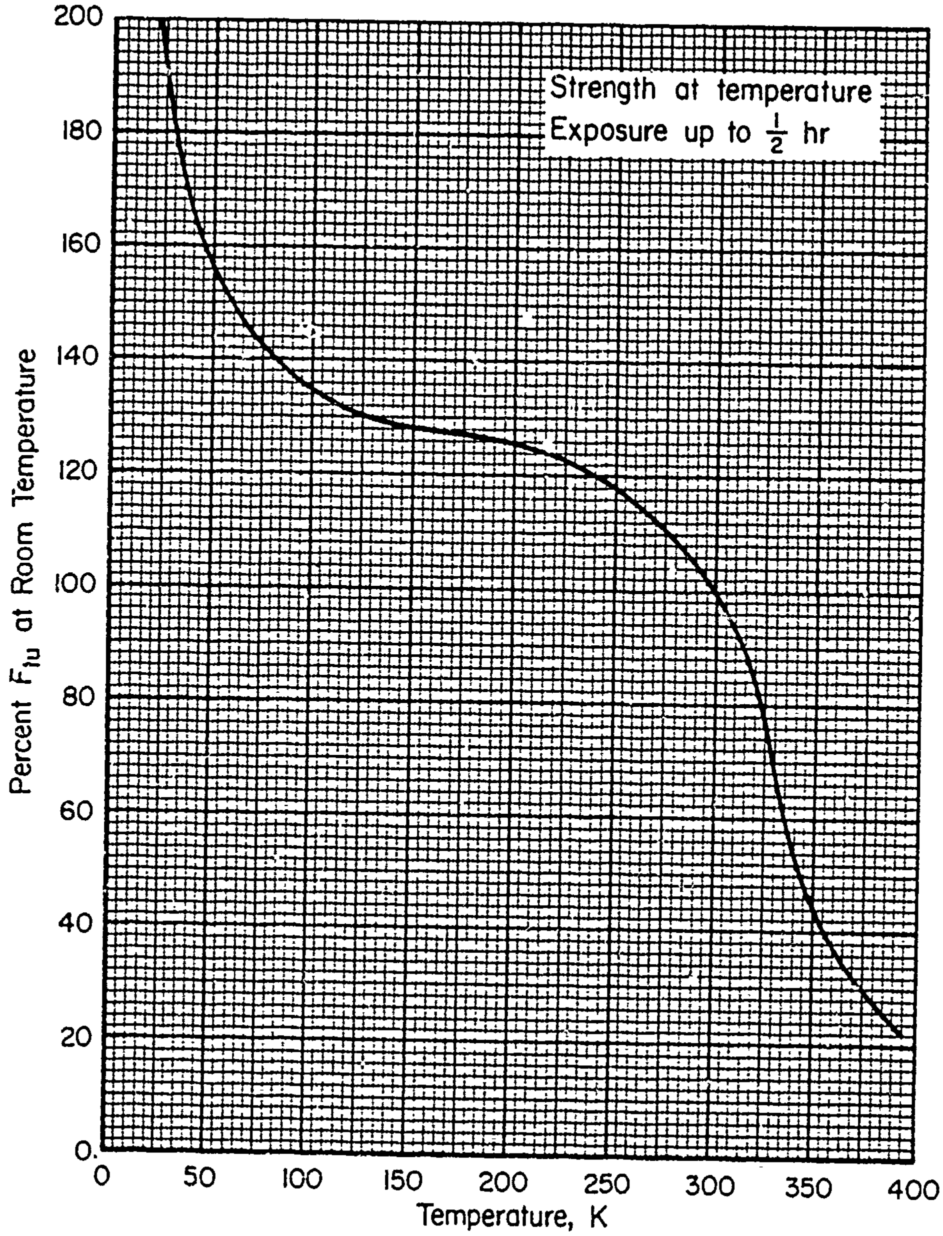

FIGURE 4.2.7.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of LA 141A-T7 sheet 0.508-2.286mm thick.

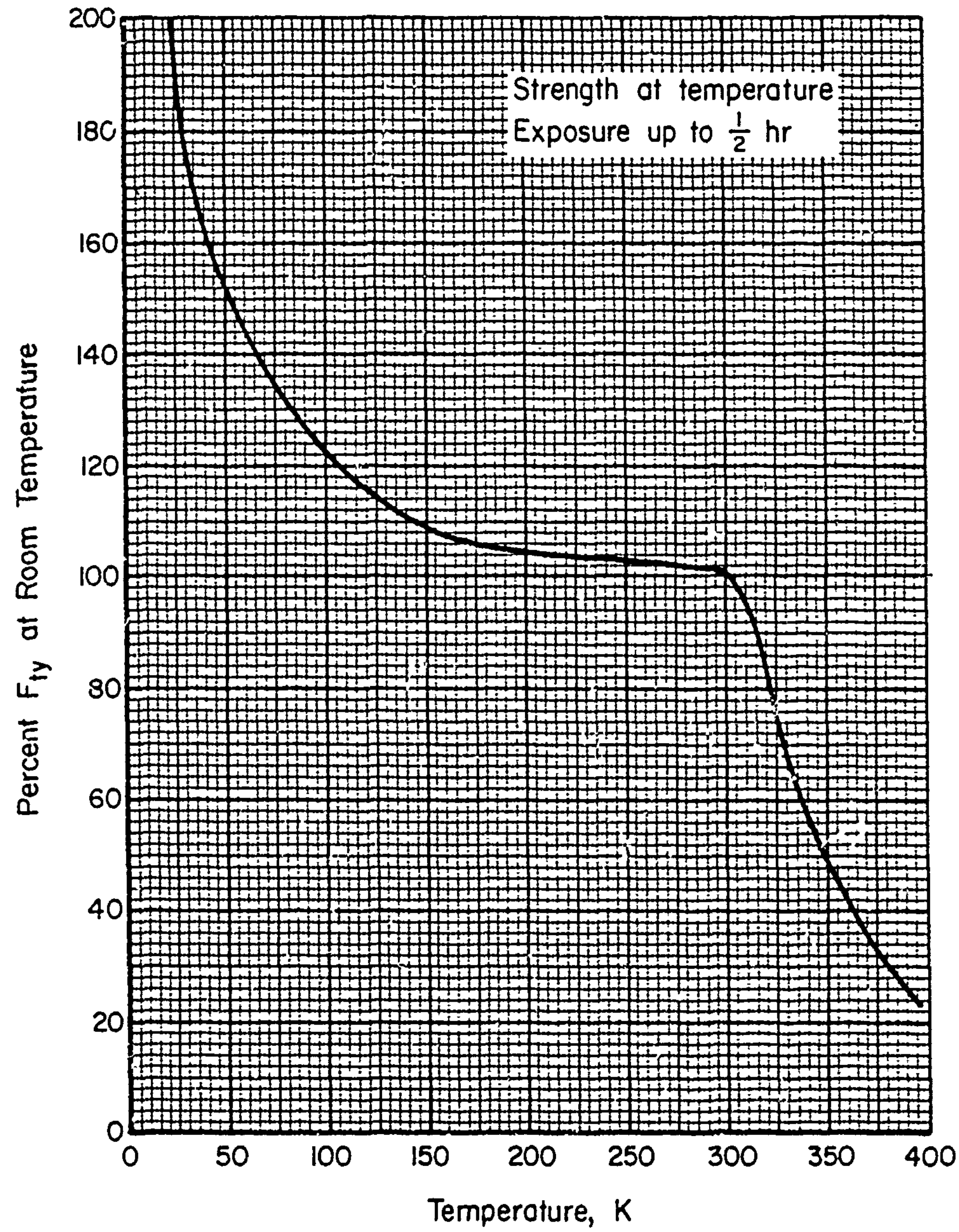

FIGURE 4.2.7.1.(b). Effect of temperature on the tensile yield strength (F_{ty}) of LA 141A-T7 sheet 0.508-2.286 mm thick.

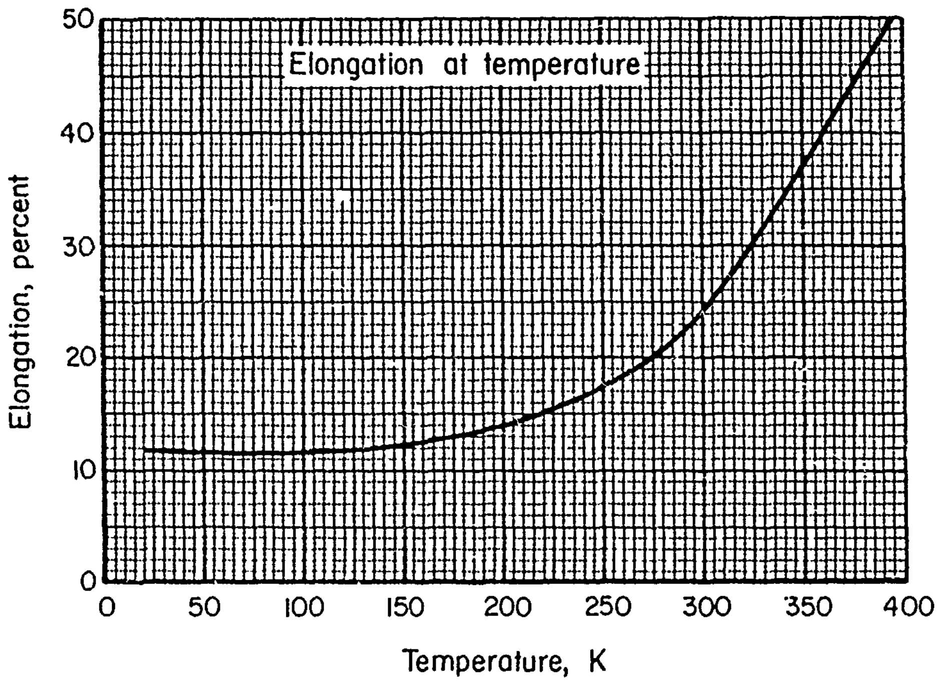

FIGURE 4.2.7.1.5. Effect of temperature on the elongation of LA141A-T7 sheet 0.508-2.286 mm thick.

4.2.8 ZK60A

4.2.8.0 *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. Increased strength for forgings of 2 inches thick or less is obtained by solution heat treating and artificially aging to the T6 condition. 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 422 K.

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 4.2.8.0(a).

TABLE 4.2.8.0(a). *Material Specifications for ZK60A Magnesium Alloy*

Specification	Form
QQ-M-31	Extrusions
WW-T-825	Tubes
QQ-M-40	Forgings

The temper index for ZK60A is as follows:

Section	Temper
4.2.8.1	F
4.2.8.2	T5
4.2.8.3	T6

Room-Temperature Properties

Room-temperature mechanical and physical properties are shown in Table 4.2.8.0(b). Effect-of-temperature curves for physical properties are shown in Figure 4.2.8.0.

4.2.8.1 *ZK60A-F Temper.*—A typical fatigue curve for this temper is presented in Figure 4.2.8.1.8.

4.2.8.2. *ZK60A-T5 Temper.*—Typical room-temperature tension and compression stress-strain curves for extrusions in this temper are shown in Figures 4.2.8.2.6(a) and (b).

A typical fatigue curve for this temper is presented in Figure 4.2.8.1.8.

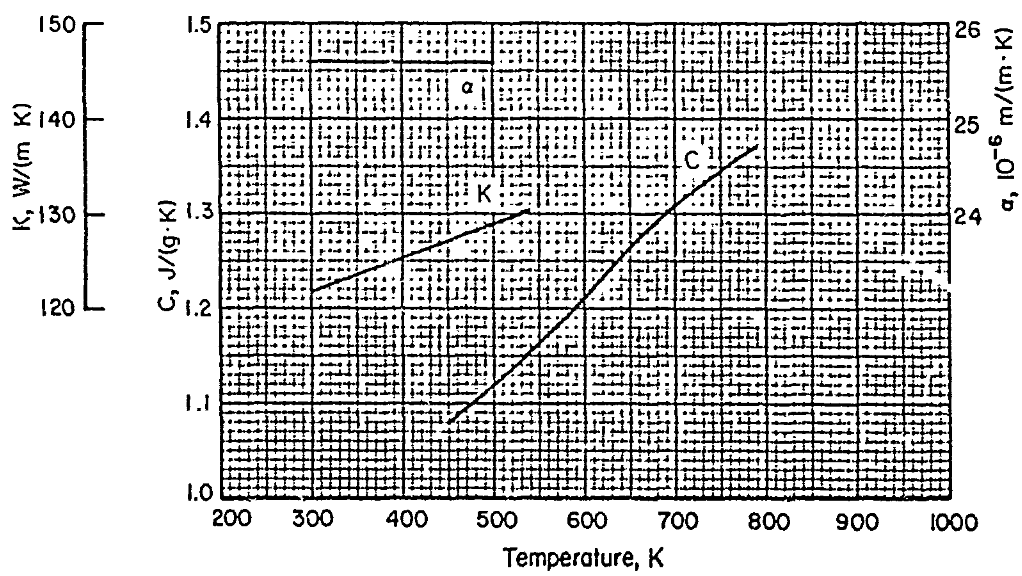

FIGURE 4.2.8.0. Effect of temperature on the physical properties of ZK60A magnesium alloy.

TABLE 4.2.8.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF ZK60A MAGNESIUM ALLOY (EXTRUSIONS AND FORGINGS)

SPECIFICATION	QQ-M-31												MM-T-325			QQ-M-40	
FORM	EXTRUDED RODS, BARS, AND SOLID SHAPES										EXTRUDED HOLLOW SHAPES		EXTRUDED TUBES			FORGINGS	
TEMPER	F				T5						F	T5	F	T5	T5	T5	T6
CROSS-SECTIONAL AREA, MM2	<1290	1290-1939	1940-3229	3230-25800	<1290-	1290-1939	1940-3229	3230-6449	6450-16129	16130-25800	ALL	ALL	1940 IN. DIA.		1940-5460 IN. DIA.	...	...
THICKNESS, MM													0.71-6.35 WALL		2.39-25.40 WALL	<76.20	<50.80
BASIS	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	... S	... S
MECHANICAL PROPERTIES:																	
FTU, MPA:																	
L	296	296	296	296	310	310	310	310	310	296	276	317	276	317	303	290	296
LT[a]	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
FTY, MPA:																	
L	214	214	214	214	248	248	248	234	234	214	193	262	193	262	225	179	221
LT[a]	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
FCY, MPA:																	
L	186	179	172	138	207	193	172	159	152	138	138	179	138	179	145	...	...
LT[a]	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
FSU, MPA	152	152	152	...	152	152	152	...	...	...	...	...	...	...	...	...	...
FBRU,[b] MPA:																	
(E/D=1.5)	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
(E/D=2.0)	483	483	483	...	490	490	490	...	...	...	...	...	...	...	...	...	...
FBRY,[b] MPA:																	
(E/D=1.5)	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
(E/D=2.0)	310	310	310	...	324	324	324	...	...	...	...	...	...	...	...	...	...
EL, PERCENT:																	
L	5	5	5	6	4	4	4	6	6	6	5	4	5	4	4	7	4
LT[a]	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
E, GPA	44.8																
EC, GPA	44.8																
G, GPA	16.5																
MU	0.35																
PHYSICAL PROPERTIES:																	
OMEGA, MG/M3	1.82																
C, J/(G*K)	SEE FIGURE 4.2.8.0																
K, W/(M*K)	SEE FIGURE 4.2.8.0																
ALPHA, 10-6 M/(M*K)	SEE FIGURE 4.2.8.0																

[a] THE TRANSVERSE PROPERTIES FOR EXTRUDED ZK60A ARE LOWER THAN THE LONGITUDINAL PROPERTIES.

[b] BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

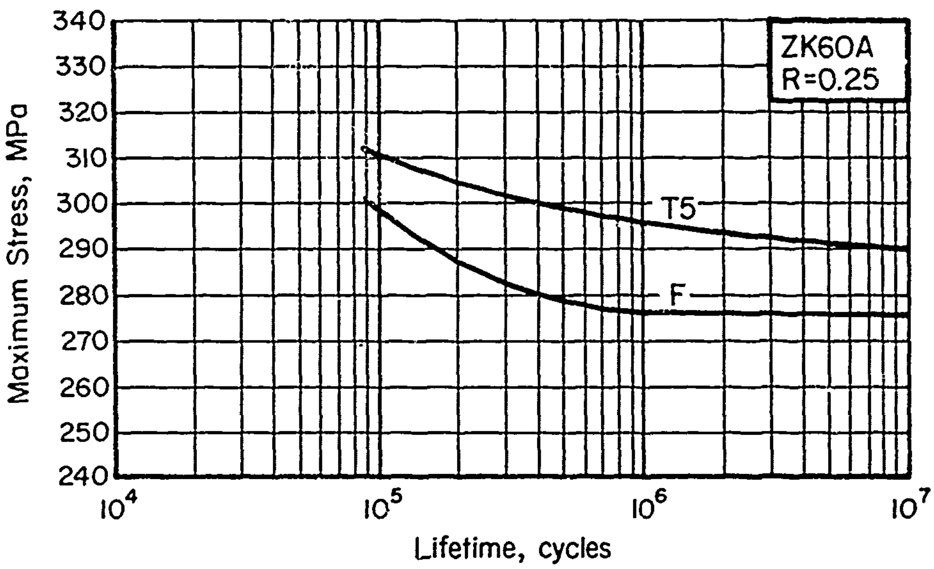

FIGURE 4.2.8.1.8. Typical fatigue curves for ZK60A-F and ZK60A-T5 (extrusions) at room temperature.

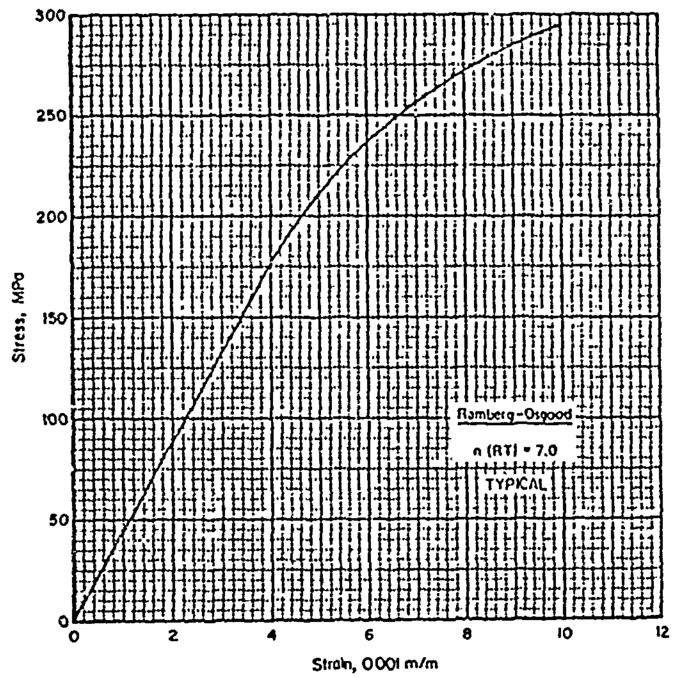

FIGURE 4.2.8.2.6(a). Typical tensile stress-strain curve for ZK60A-T5 (extrusions) at room temperature.

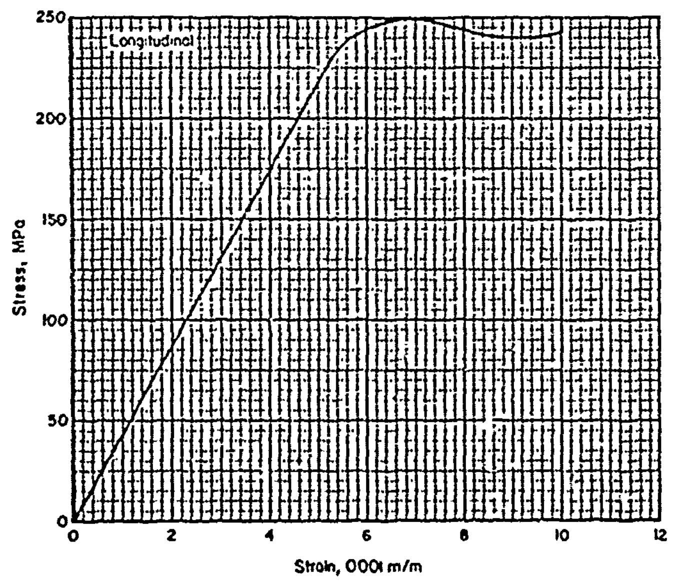

FIGURE 4.2.8.2.6(b). Typical compressive stress-strain curves for ZK60A-T5 (extrusions < 12.9 sq. cm. cross section) at room temperature.

4.3 Magnesium Alloy Cast Products

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 is available in the as-cast (F), solution heat-treated (T4), and solution heat-treated and artificially aged (T6 and T61) tempers.

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).

TABLE 4.3.1.0(a). *Material Specifications for AM100A Magnesium Alloy*

Specification	Form
QQ-M-55	Permanent mold castings
MIL-M-46062	Castings

The temper index for AM100A is as follows:

Section	Temper
4.3.1.1	F
4.3.1.2	T4
4.3.1.3	T6
4.3.1.4	T61

Room-Temperature Properties

Room-temperature mechanical and physical properties are shown in Table 4.3.1.0(b).

TABLE 4.3.1.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF AM100A MAGNESIUM ALLOY (CASTINGS)[a]

SPECIFICATION	QQ-M-55							MIL-M-46062		
FORM	PERMANENT MOLD CASTINGS									
TEMPER	F	T4	T6	T61	T4	T6	T61	T6		
LOCATION WITHIN CASTING	SEPARATE TEST BARS				UNSPECIFIED LOCATIONS			SPECIFIED LOCATIONS ONL		
								CLASS 1	CLASS 2	CLASS
BASIS	S	S	S	S	S	S	S	S	S	S
MECHANICAL PROPERTIES:										
FTU, MPA	138	234	234	234	117	117	117	262	241	20[illegible]
FTY, MPA	69	69	103	117	62	69	79	138	124	11[illegible]
FCY, MPA	69	69	103	117	62	69	79	138	124	11[illegible]
FSU, MPA	...	...	...	...	...	...	...	...	...	..
FBRU, MPA:										
(E/D=1.5)	...	...	...	...	...	...	...	...	...	..
(E/D=2.0)	...	...	...	...	...	...	...	...	...	..
FBRY, MPA:										
(E/D=1.5)	...	...	...	...	...	...	...	...	...	..
(E/D=2.0)	...	...	...	...	...	...	...	...	...	..
EL, PERCENT	...	6	2	...	1.5	1.5	...	3	1.5	
E, GPA	44.8									
EC, GPA	44.8									
G, GPA	16.5									
MU	0.35									
PHYSICAL PROPERTIES:										
OMEGA, MG/M3	1.80									
C, J/(G*K)	...									
K, W/(M*K)	...									
ALPHA, 10-6 M/(M*K)	...									

[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]CLASS OF PROPERTIES ATTAINABLE DEPENDS ON LOCATION SPECIFIED AND CASTING DESIGN AND SHOULD BE COORDINATED WITH THE PRODUCER.

4.3.2 AZ81A

4.3.2.0 *Comments and Properties.*—AZ81A is a magnesium-base alloy containing aluminum and zinc. In general characteristics it is much like AZ91C. It is used for both sand and permanent mold castings generally in the solution heat-treated (T4) temper.

AZ81A has good weldability and fair pressure tightness. When used in the T4 temper it has less tendency for natural aging to the T6 temper than the magnesium-base alloys with higher aluminum content.

Material specifications for AZ81A are presented in Table 4.3.2.0(a).

TABLE 4.3.2.0(a). *Material Specifications for AZ81A Magnesium Alloy*

Specification	Form
QQ-M-56	Sand castings
QQ-M-55	Permanent-mold castings

The temper index for AZ81A is as follows:

Section	Temper
4.3.2.1	T4

Room-Temperature Properties

Room-temperature mechanical and physical properties are shown in Table 4.3.2.0(b). The effect of temperature on physical properties is shown in Figure 4.3.2.0.

4.3.2.1 *AZ81A-Temper.*—Typical tensile stress-strain curves for cast AZ81A-T4 at various temperatures between room temperature and 644 K are shown in Figure 4.3.2.1.6.

TABLE 4.3.2.0(8). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF AZ81A MAGNESIUM ALLOY (CASTINGS)[a]

SPECIFICATION..........	QQ-M-55 AND QQ-M-56	
FORM..................	SAND CASTINGS AND PERMANENT-MOLD CASTINGS	
TEMPER................	T4	
LOCATION WITHIN CASTING	SEPARATE TEST BARS	UNSPECIFIED LOCATIONS
BASIS.................	S	S
MECHANICAL PROPERTIES:		
FTU, MPA.............	234	117
FTY, MPA.............	76	62
FCY, MPA.............	76	62
FSU, MPA.............	117	...
FBRU[b], MPA:		
(E/D=1.5).........	248	...
(E/D=2.0).........	345	...
FBRY[b], MPA:		
(E/D=1.5).........	241	...
(E/D=2.0).........	276	...
EL, PERCENT..........	7	1.75
E, GPA...............	44.8	
EC, GPA..............	44.8	
G, GPA...............	16.5	
MU...................	0.35	
PHYSICAL PROPERTIES:		
OMEGA, MG/M3.........	1.80	
C, J/(G*K)...........	1.05[c]	
K, W/(M*K)...........	76 (373 TO 573 K)[c]	
ALPHA, 10-6 M/(M*K)..	SEE FIGURE 4.3.2.0	

[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]BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

[c]ESTIMATED.

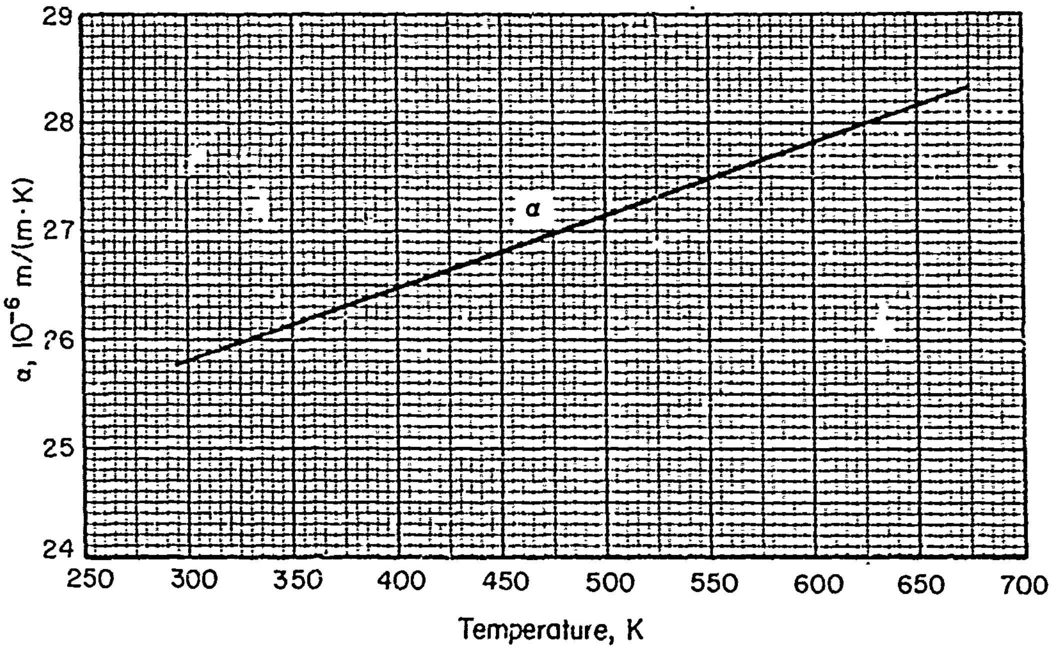

FIGURE 4.3.2.0. Effect of temperature on the physical properties of AZ81A magnesium alloy.

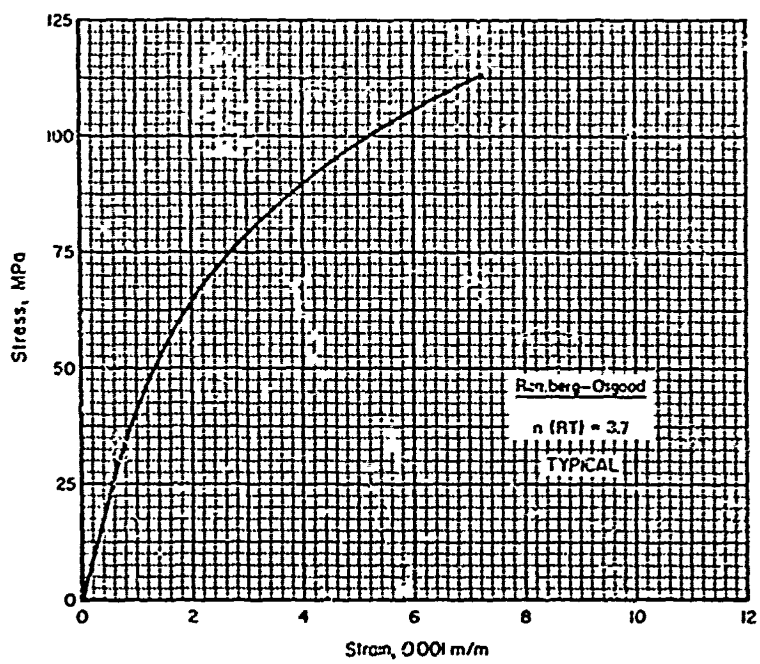

FIGURE 4.3.2.1.6. Typical tensile stress-strain curve for cast AZ81A-T4 at room temperature (1/2 hour exposure).

4.3.3 AZ91C

4.3.3.0 *Comments and Properties.* AZ91C is a magnesium-base casting alloy containing aluminum and zinc. It has good castability with a good combination of ductility and strength. It is the magnesium alloy most commonly used for sand castings at temperatures under 422 K. AZ91C is available as sand and permanent mold castings in the as-cast (F), as-cast and artificially aged (T5), solution heat-treated (T4) and solution heat-treated and artificially aged (T6) tempers.

AZ91C has fair weldability and pressure tightness. Castings that have been welded and subsequently heat treated to the T6 temper show no degradation of static or fatigue properties.

Some material specifications covering AZ91C are presented in Table 4.3.3.0(a).

TABLE 4.3.3.0(a). *Material Specifications for AZ91C Magnesium Alloy*

Specification	Form
QQ-M-56	Sand castings
QQ-M-55	Permanent- mold castings
MIL-M-46062 ...	Castings

The temper index for AZ91C is as follows:

Section	Temper
4.3.3.1	F
4.3.3.2	T4
4.3.3.3	T5
4.3.3.4	T6

Room-Temperature Properties

Room-temperature mechanical and physical properties are shown in Table 4.3.3.0(b).

4.3.3.1 *AZ91C-F Temper*

4.3.3.2 *AZ91C-T4 Temper.*—Typical tensile stress-strain curves for cast AZ91C-T4 at room temperature and several elevated temperatures are presented in Figure 4.3.3.2.6.

4.3.3.3 *AZ91C-T5 Temper*

4.3.3.4 *AZ91C-T6 Temper.*—Figure 4.3.3.4.4 contains an effect of temperature curve on tension and compression modulus for this temper.

Typical tensile stress-strain curves at room temperature and several elevated temperatures are presented in Figure 4.3.3.4.6.

TABLE 4.3.3.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF AZ91C MAGNESIUM ALLOY (CASTINGS)[a]

SPECIFICATION	QQ-M-55 AND QQ-M-56						MIL-M-46062		
FORM	SAND CASTINGS AND PERMANENT-MOLD CASTINGS								
TEMPER	F	T4	T5	T6	T4	T6	T6		
LOCATION WITHIN CASTING	SEPARATE TEST BARS				UNSPECIFIED LOCATIONS		SPECIFIED LOCATIONS ONLY[b]		
							CLASS 1	CLASS 2	CLASS 3
BASIS	S	S	S	S	S	S	S	S	S
MECHANICAL PROPERTIES:									
FTU, MPA	159	234	159	234	117	117	241	200	186
FTY, MPA	76	76	83	110	62	83	124	110	97
FCY, MPA	76	76	83	110	62	83	124	110	97
FSU, MPA	...	117	...	131	...	...	...	...	...
FBRU[c] MPA:									
(E/D=1.5)	...	248	...	345	...	...	...	...	...
(E/D=2.0)	...	345	...	448	...	...	...	...	...
FBRY[c] MPA:									
(E/D=1.5)	...	241	...	248	...	...	...	...	...
(E/D=2.0)	...	276	...	310	...	...	...	...	...
EL, PERCENT	...	7	2	3	1.75	0.75	4	3	2
E, GPA	44.8								
EC, GPA	44.8								
G, GPA	16.5								
MU	0.35								
PHYSICAL PROPERTIES:									
OMEGA, MG/M3	1.80								
C, J/(G*K)	1.05[d]								
K, W/(M*K)	71 (373 TO 573 K)								
ALPHA, 10-6 M/(M*K)	25.2 (291 TO 373 K)								

[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]CLASS OF PROPERTIES ATTAINABLE DEPENDS ON LOCATION SPECIFIED AND CASTING DESIGN AND SHOULD BE COORDINATED WITH THE PRODUCER.
[c]BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.
[d]ESTIMATED.

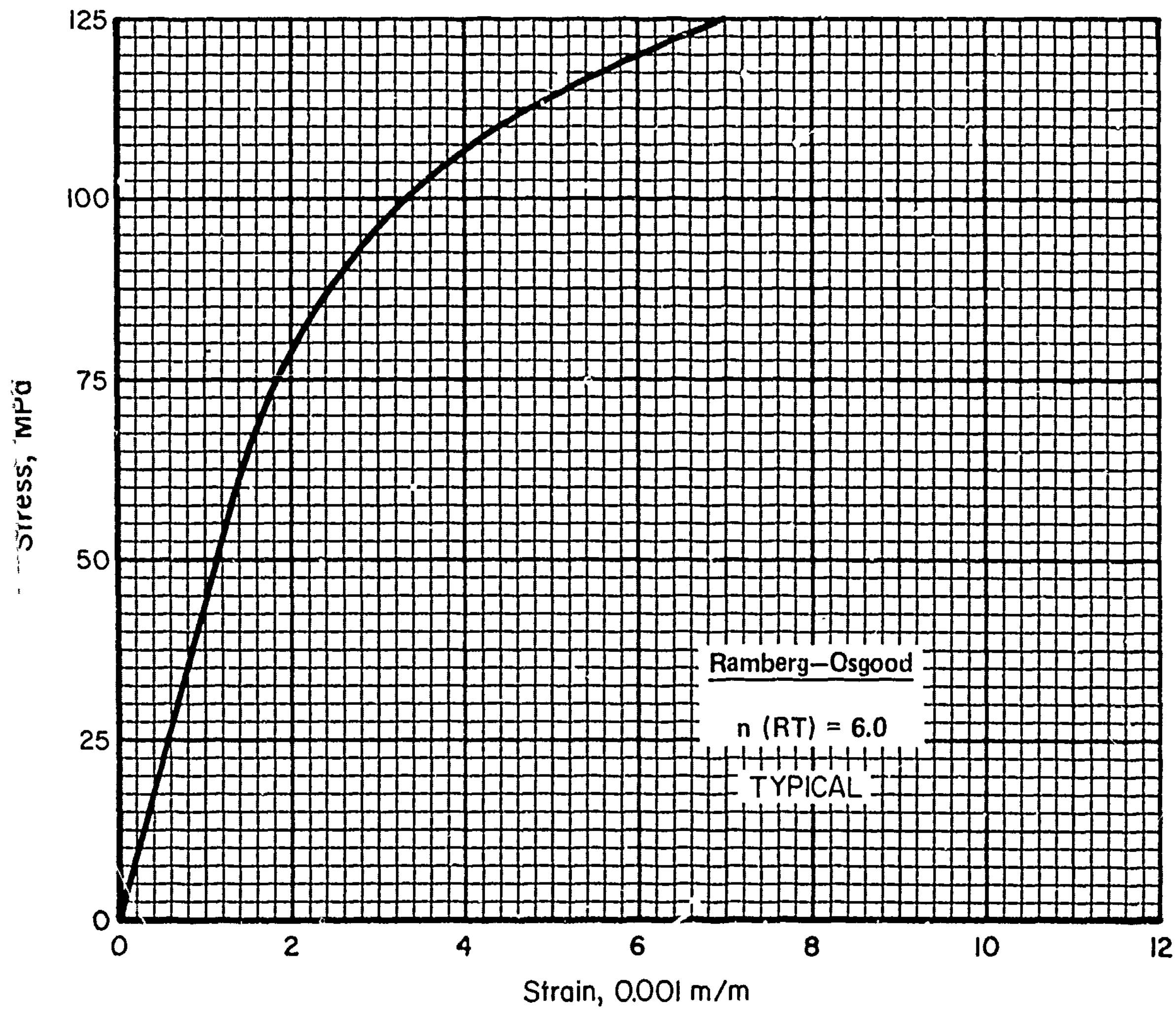

FIGURE 4.3.3.2.6. Typical tensile stress-strain curve for cast AZ91C-T4 at room temperature (1/2 hour exposure).

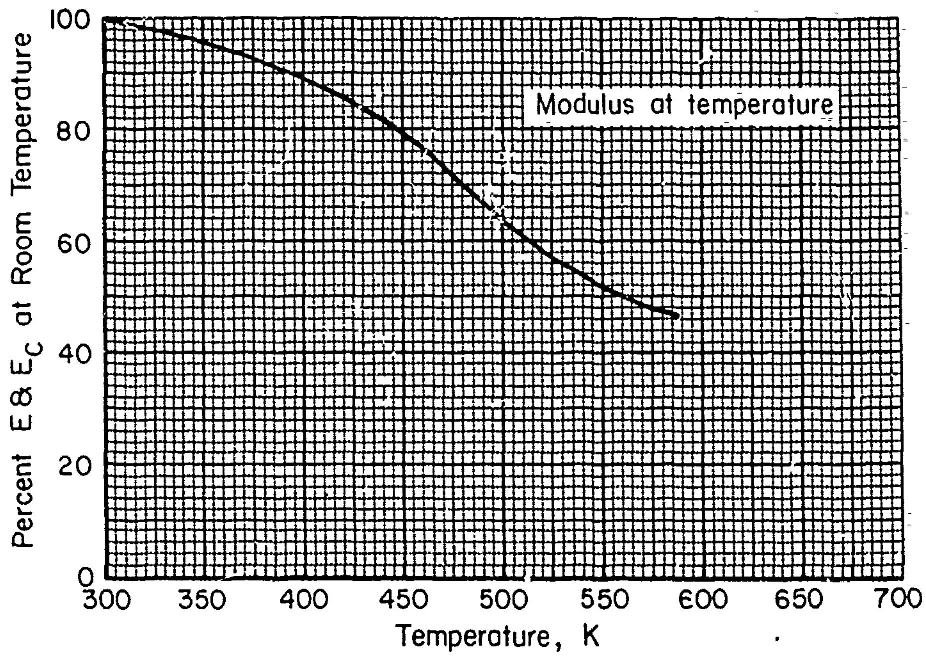

FIGURE 4.3.3.4.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of cast AZ91C-T6.

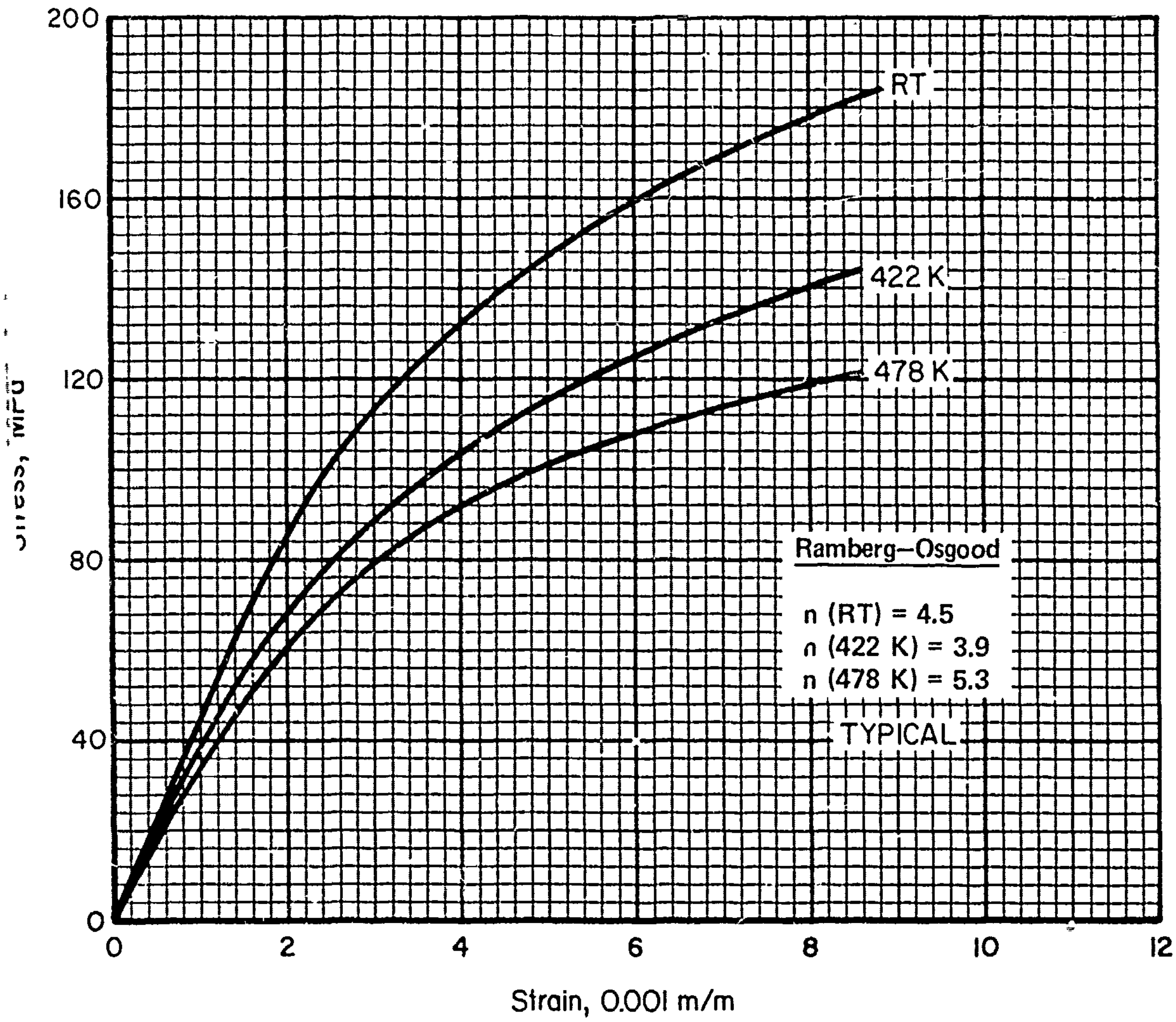

FIGURE 4.3.3.4.6. Typical tensile stress-strain curves for cast AZ91C-T6 at room and elevated temperatures (1/2 hour exposure).

4.3.4. AZ92A

4.3.4.0 *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 castings in the as-cast (F), as-cast and artificially aged (T5), solution heat treated (T4) and solution heat treated and artificially aged (T6) tempers. AZ92A has fair weldability and pressure tightness.

Material specifications for AZ92A are presented in Table 4.3.4.0(a).

TABLE 4.3.4.0(a) *Material Specifications for AZ92A Magnesium Alloy*

Specification	Form
QQ-M-56	Sand castings
QQ-M-55	Permanent-mold castings
MIL-M-46062	Castings

The temper index for AZ92A is as follows:

Section	Temper
4.3.4.1	F
4.3.4.2	T4
4.3.4.3	T5
4.3.4.4	T6

Room-Temperature Properties

Room-temperature mechanical and physical properties are shown in Table 4.3.4.0(b). Effect-of-temperature curves on physical properties are shown in Figure 4.3.4.0.

4.3.4.1 *AZ92A-F Temper.*—Typical stress-strain and tangent-modulus curves in tension and compression at room temperature are presented in Figure 4.3.4.1.6.

A fatigue curve for unnotched specimens with this temper is shown on Figure 4.3.4.1.8.

4.3.4.2 *AZ92A-T4 Temper.*—Typical stress-strain and tangent-modulus curves in tension and compression at room temperature are presented in Figure 4.3.4.2.6.

A fatigue curve for unnotched specimens with this temper is shown on Figure 4.3.4.1.8.

4.3.4.3 *AZ92A-T5 Temper*

4.3.4.4 *AZ92A-T6 Temper.*—Effect of temperature on various mechanical properties is presented in Figure 4.3.4.4.1(a) through 4.3.4.4.4 for this temper.

Typical stress-strain and tangent-modulus curves at room temperature and several elevated temperatures are shown in Figures 4.3.4.4.6(a) and (b).

A fatigue curve for unnotched specimens with this temper is shown on Figure 4.3.4.1.8

TABLE 4.3.4.0(3). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF AZ92A MAGNESIUM ALLOY (CASTINGS)[a]

SPECIFICATION	QQ-M-55 AND QQ-M-56						MIL-M-46062		
FORM	SAND CASTINGS AND PERMANENT-MOLD CASTINGS								
TEMPER	F	T4	T5	T6	T4	T6	T6		
FORM	SEPARATE TEST BARS				UNSPECIFIED LOCATIONS		SPECIFIED LOCATIONS ONLY[b]		
							CLASS 1	CLASS 2	CLASS 3
BASIS	S	S	S	S	S	S	S	S	S
MECHANICAL PROPERTIES:									
FTU, MPA	159	234	159	234	117	117	276	234	207
FTY, MPA	76	76	83	124	62	93	172	138	124
FCY, MPA	76	76	83	124	62	93	172	138	124
FSU, MPA	124	117	...	138	...	...	...	...	...
FBRU[c], MPA:									
(E/D=1.5)	255	331	...	359	...	...	...	...	...
(E/D=2.0)	331	400	...	483	...	...	...	...	...
FBRY[c], MPA:									
(E/D=1.5)	228	241	...	310	...	...	...	...	...
(E/D=2.0)	303	303	...	379	...	...	...	...	...
EL, PERCENT	...	6	...	1	...	...	3	1	...
E, GPA	44.8								
EC, GPA	44.8								
G, GPA	16.5								
MU	0.35								
PHYSICAL PROPERTIES:									
OMEGA, MG/M3	1.82								
C, J/(G*K)	1.05[d]								
K, W/(M*K)	SEE FIGURE 4.3.4.0								
ALPHA, 10-6 M/(M*K)	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]CLASS OF PROPERTIES ATTAINABLE DEPENDS ON LOCATION SPECIFIED AND CASTING DESIGN AND SHOULD BE COORDINATED WITH THE PRODUCER.

[c]BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

[d]ESTIMATED.

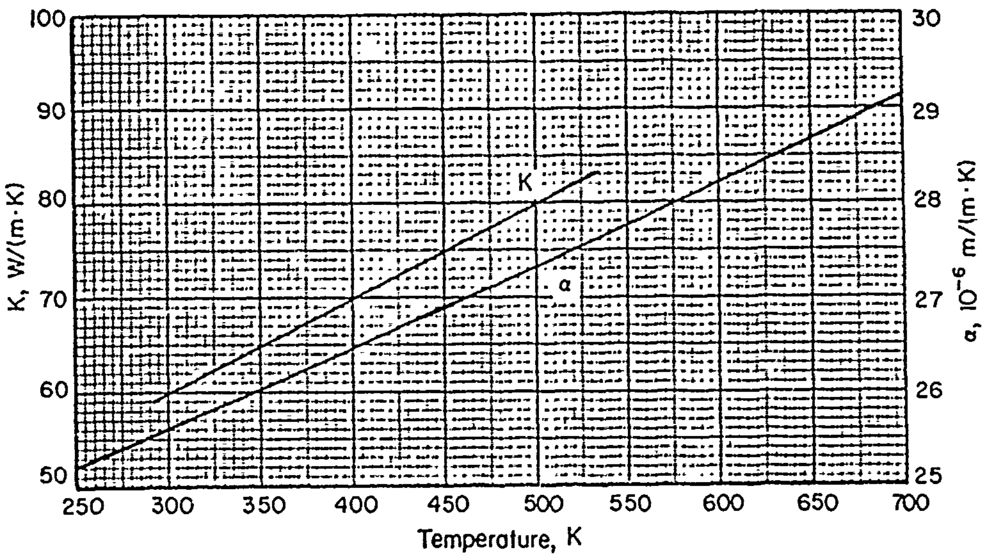

FIGURE 4.3.4.0. Effect of temperature on the physical properties of AZ92A.

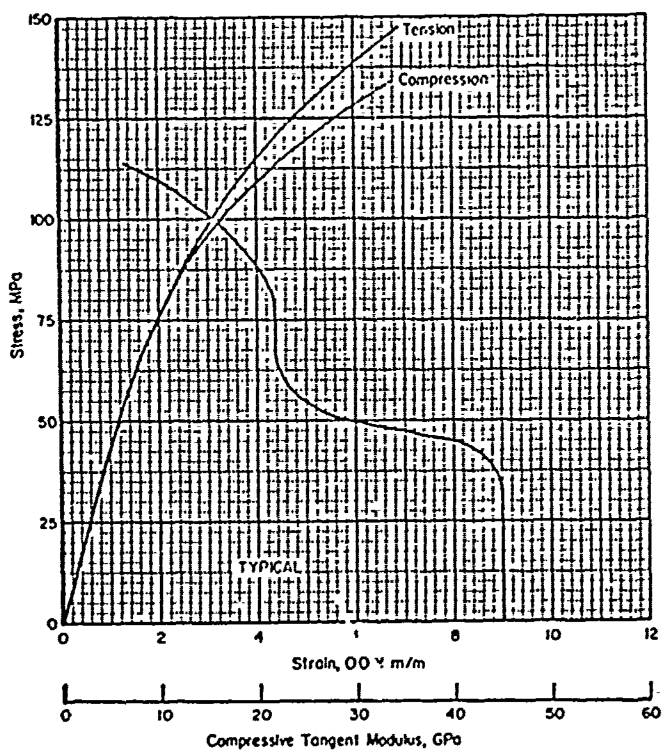

FIGURE 4.3.4.1.6. Typical tensile and compressive stress-strain and tangent-modulus curves for cast AZ92A-F at room temperature.

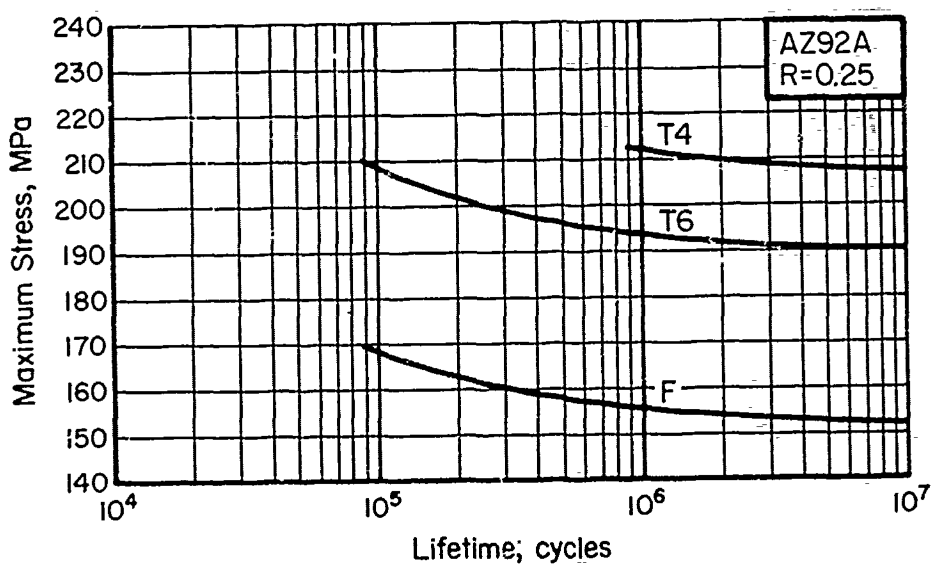

FIGURE 4.3.4.1.8. Typical fatigue curves for AZ92A-F, AZ92A-T4 and AZ92A-T6 sand castings at room temperature.

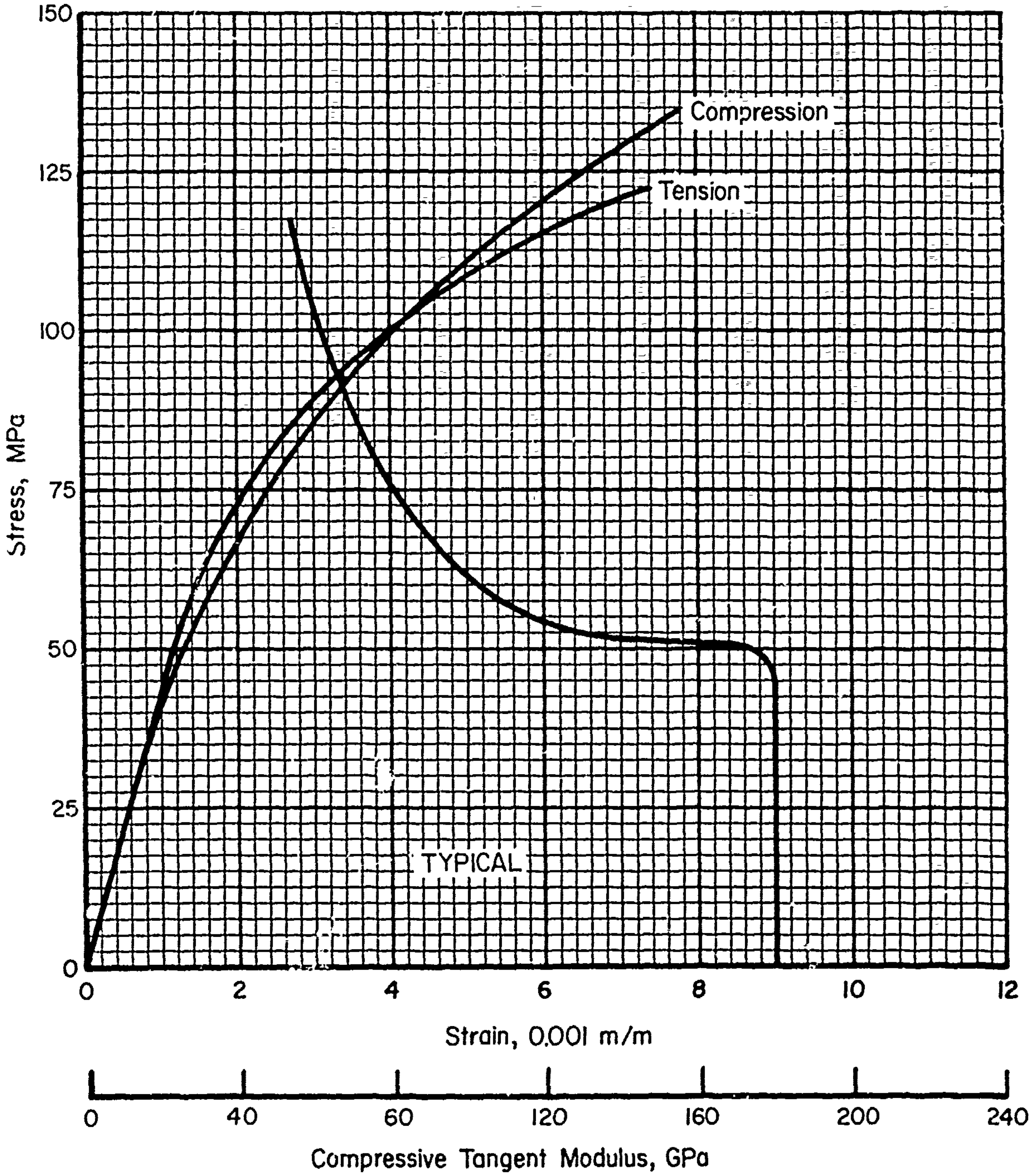

FIGURE 4.3.4.2.6. Typical tensile and compressive stress-strain and compressive tangent-modulus curves for cast AZ92A-T4 at room temperature.

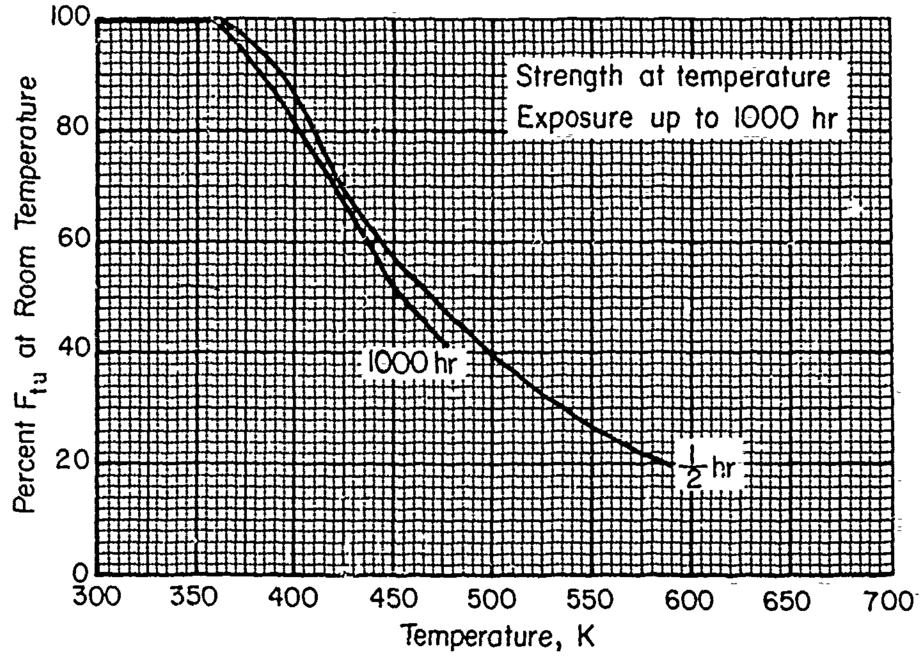

FIGURE 4.3.4.4.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of cast AZ92A-T6.

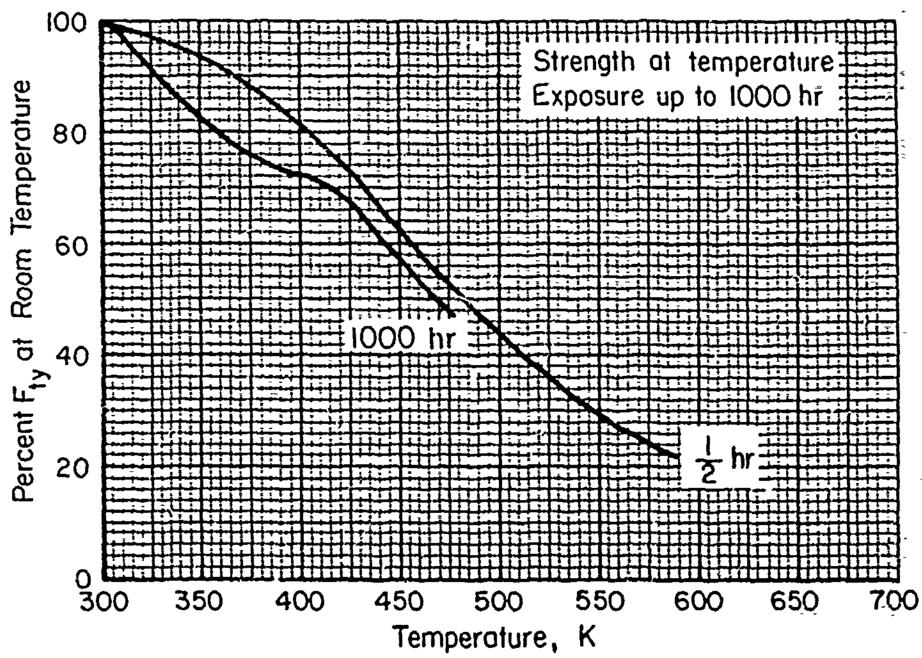

FIGURE 4.3.4.4.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of cast AZ92A-T6.

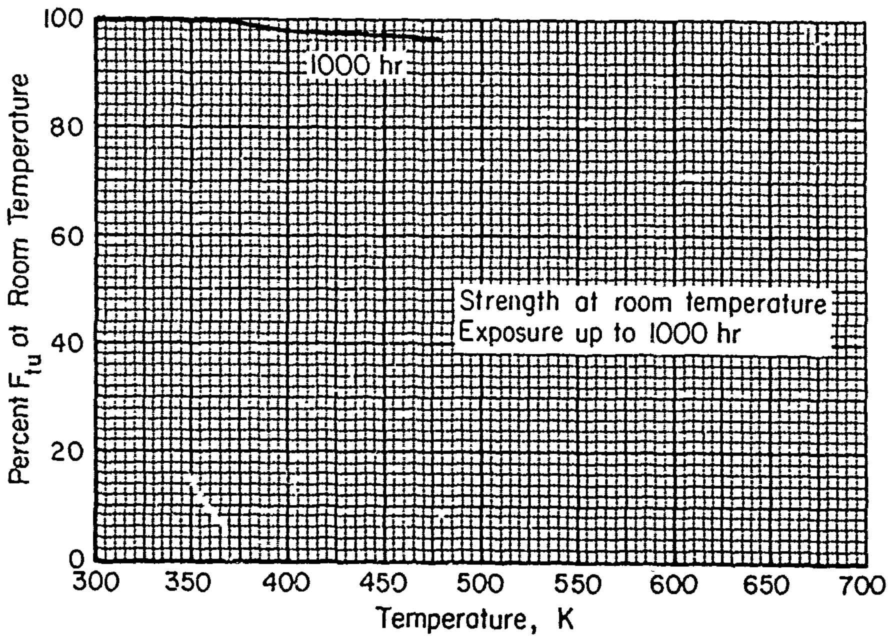

FIGURE 4.3.4.4.1(c). Effect of exposure at elevated temperatures on the room-temperature ultimate tensile strength (F_{tu}) of cast AZ92A-T6.

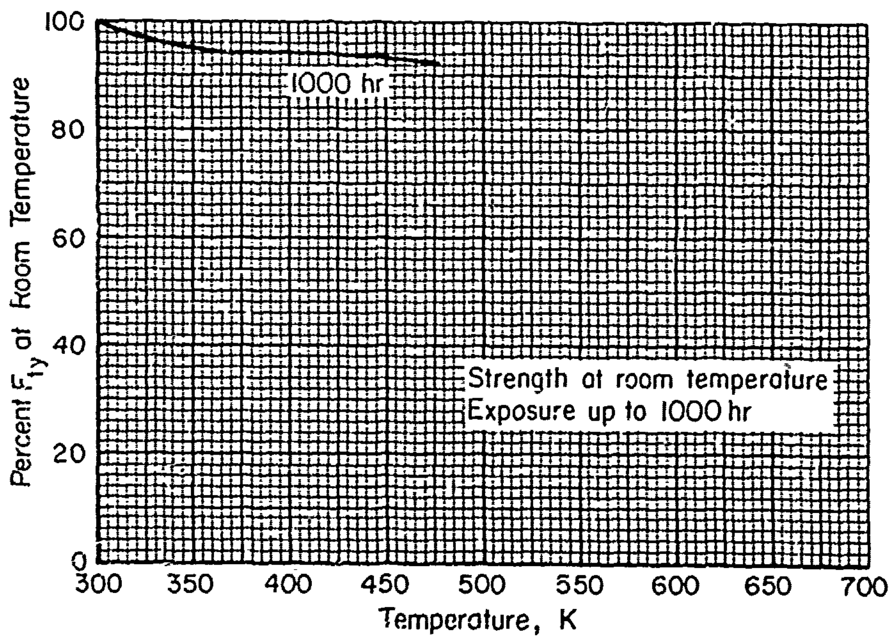

FIGURE 4.3.4.4.1(d). Effect of exposure at elevated temperatures on the room-temperature tensile yield strength (F_{ty}) of cast AZ92A-T6.

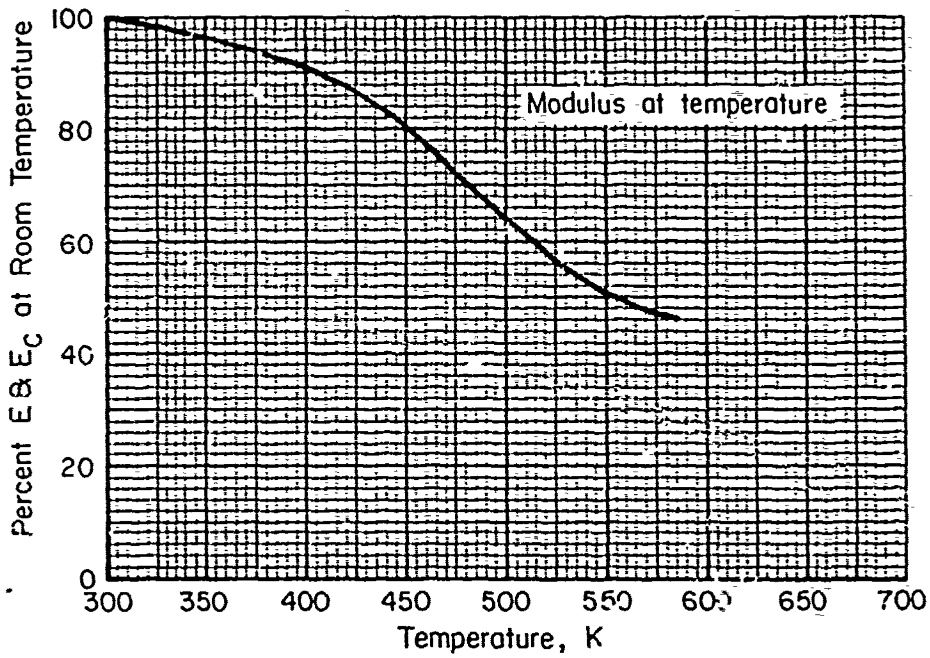

FIGURE 4.3.4.4.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of cast AZ92A-T6.

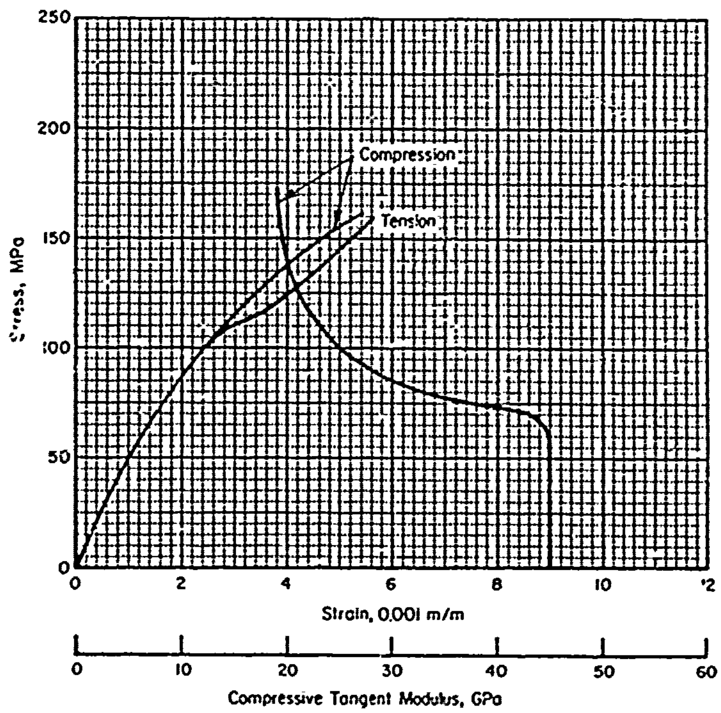

FIGURE 4.3.4.4.6(a). Typical stress-strain and tangent-modulus curves for cast AZ92A-T6 at room temperature.

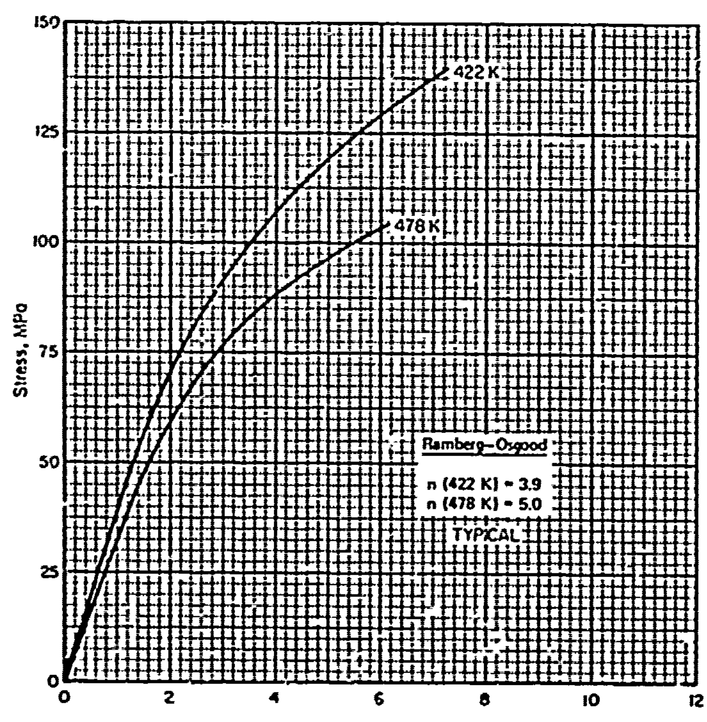

FIGURE 4.3.4.4.6(b). Typical tensile stress-strain curves for cast AZ92A-T6 at elevated temperatures (1/2 hour exposure).

4.3.5 EZ33A

4.3.5.0 *Comments and Properties.*—EZ33A is a magnesium-base casting alloy containing rare earths, zinc and zirconium. It is available as sand and permanent mold castings generally 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 422 to 533 K.

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.

Material specifications for EZ33A are presented in Table 4.3.5.0(a).

TABLE 4.3.5.0(a). *Material Specifications for EZ33A Magnesium Alloy*

Specification	Form
QQ-M-56	Sand castings
QQ-M-55	Permanent-mold castings

The temper index for EZ33A is as follows:

Section	Temper
4.3.5.1	T5

Room-Temperature Properties

Room-temperature mechanical and physical properties are shown in Table 4.3.5.0(b).

4.3.5.1 *EZ33A-T5 Temper.*—Effect of temperature on tensile properties is presented in Figures 4.3.5.1.1(a) through (d).

Typical tensile stress-strain curves at various temperatures from room temperature at 700K are given in Figure 4.3.5.1.6.

TABLE 4.3.5.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF EZ33A MAGNESIUM ALLOY (CASTINGS)[a]

SPECIFICATION	QQ-M-55 AND QQ-M-56	
FORM	SAND CASTINGS AND PERMANENT-MOLD CASTINGS	
TEMPER	T5	
LOCATION WITHIN CASTING	SEPARATE TEST BARS	UNSPECIFIED LOCATIONS
BASIS	S	S
MECHANICAL PROPERTIES:		
FTU, MPA	138	90
FTY, MPA	97	76
FCY, MPA	97	76
FSU, MPA	...	...
FBRU, MPA:		
(E/D=1.5)	...	...
(E/D=2.0)	...	...
FBRY, MPA:		
(E/D=1.5)	...	...
(E/D=2.0)	...	...
EL, PERCENT	2	0.5
E, GPA	44.8	
EC, GPA	44.8	
G, GPA	16.5	
MU	0.35	
PHYSICAL PROPERTIES:		
OMEGA, MG/M3	1.82	
C, J/(G*K)	1.05	
K, W/(M*K)	100	
ALPHA, 10-6 M/(M*K)	27.0 (293 TO 373 K)	

[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.

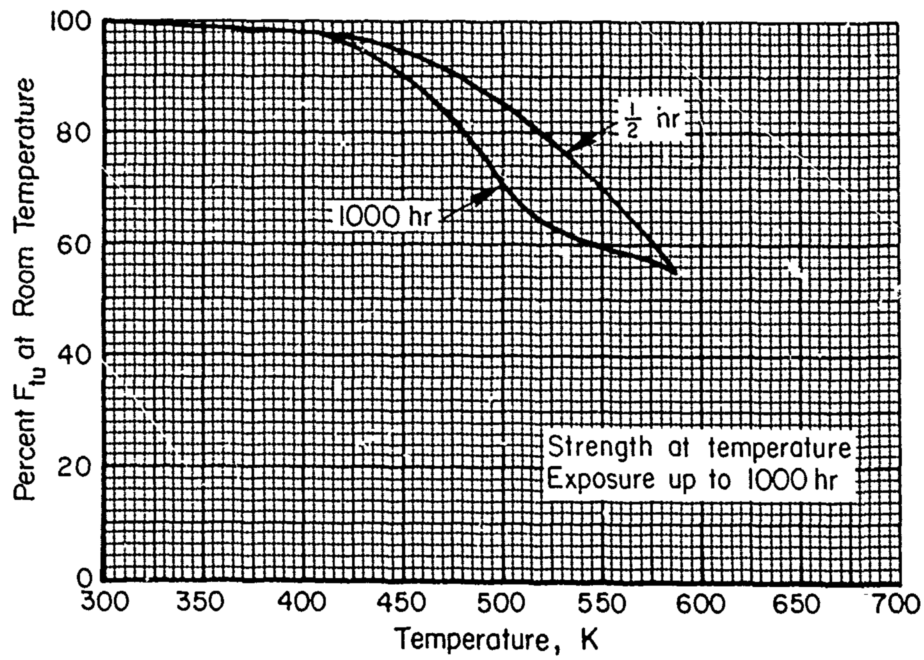

FIGURE 4.3.5.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of cast EZ33A-T5.

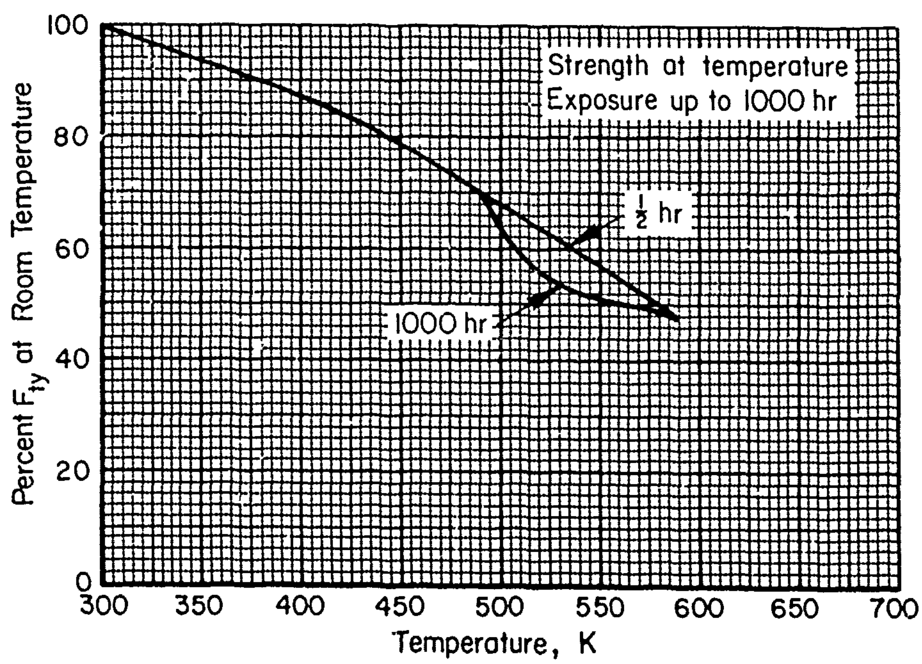

FIGURE 4.3.5.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of cast EZ33A-T5.

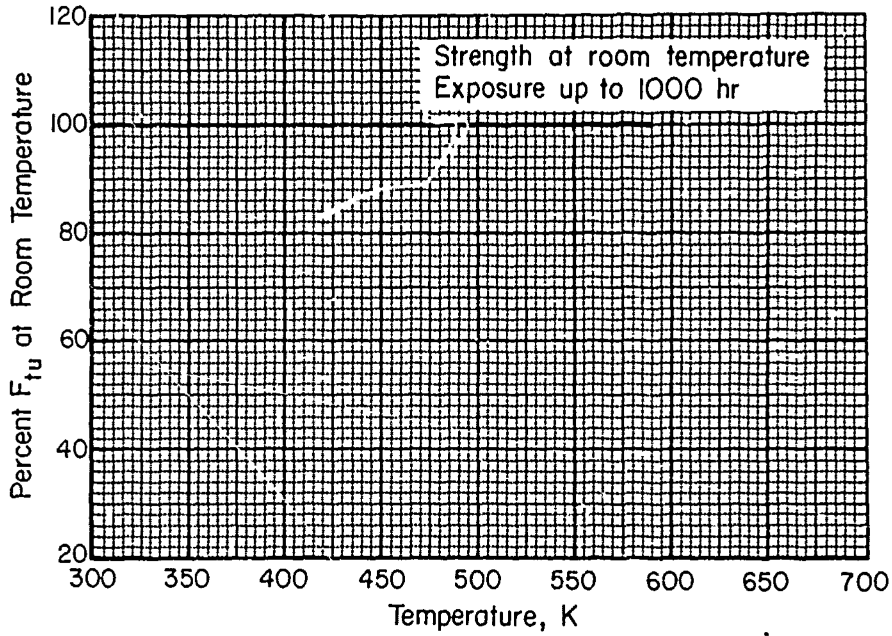

FIGURE 4.3.5.1.1(c). Effect of exposure at elevated temperatures on the room-temperature ultimate tensile strength (F_{tu}) of cast EZ33A-T5.

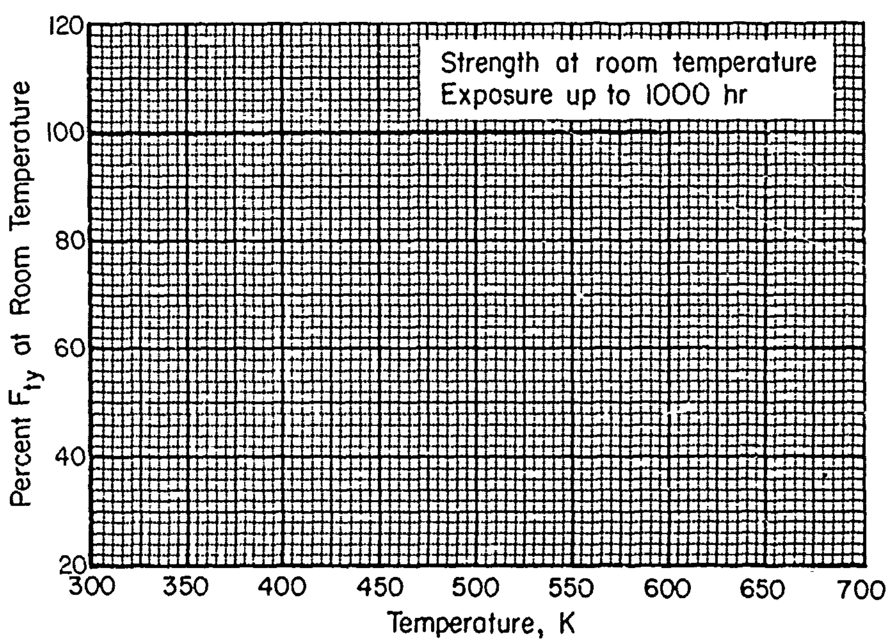

FIGURE 4.3.5.1.1(d). Effect of exposure at elevated temperatures on the room-temperature tensile yield strength (F_{ty}) of cast EZ33A-T5.

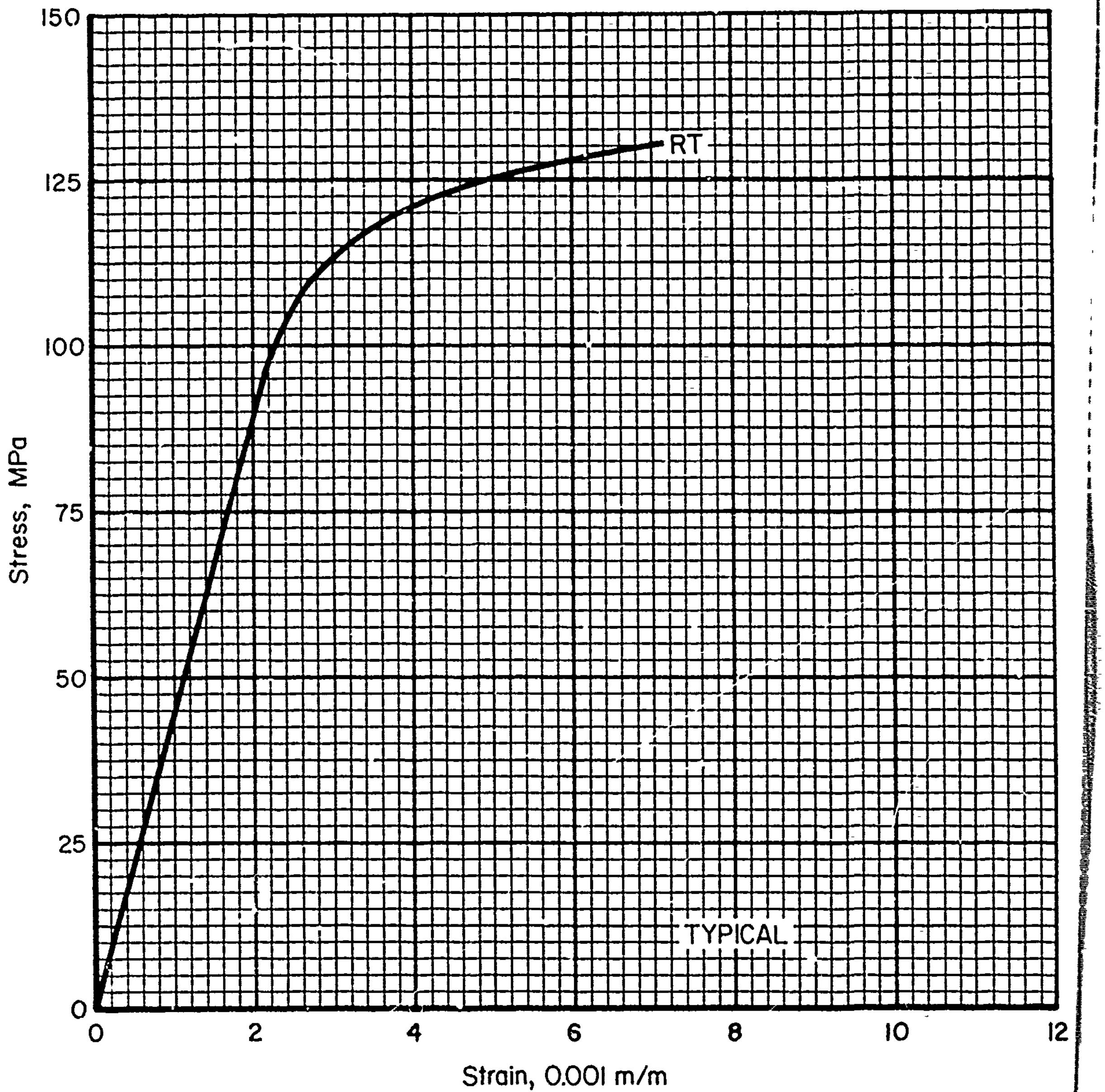

FIGURE 4.3.5.1.6. Typical tensile stress-strain curves for cast EZ33A-T5 at room temperature (1/2 hour exposure).

4.3.6 HK31A

4.3.6.0 *Comments and Properties.*—HK31A is a magnesium-base alloy containing thorium and zirconium available in both cast and wrought forms. Wrought product properties are given in Section 4.2.4. It has relatively high strength in short-time static and creep tests in the temperature range of 422 to 644 K and is used primarily for components requiring a good strength-weight ratio in this temperature range. HK31A is available as sand and permanent mold castings in the solution heat-treated and artificially aged (T6) temper.

HK31A has excellent weldability and pressure tightness. The weld strength at 478 to 589 K is not significantly different from the properties of the base material.

Material specifications for HK31A are presented in Table 4.3.6.0(a).

TABLE 4.3.6.0(a). *Material Specifications for HK31A Magnesium Alloy*

Specification	Form
QQ-M-56	Sand castings
QQ-M-55	Permanent-mold castings
MIL-M-46062	Castings

The temper index for HK31A is as follows:

Section	Temper
4.3.6.1	T6

Room-Temperature Properties

Room-temperature mechanical and physical properties are shown in Table 4.3.6.0(b). Effect-of-temperature curves for physical properties are shown in Figure 4.3.6.0.

4.3.6.1 *HK31A-T6 Temper.*—Effect of temperature on tensile properties and on modulus of elasticity are presented in Figures 4.3.6.1.1(a) through 4.3.6.1.4.

Typical tensile stress-strain curves at various temperatures from room temperature to 700 K are shown in Figure 4.3.6.1.6.

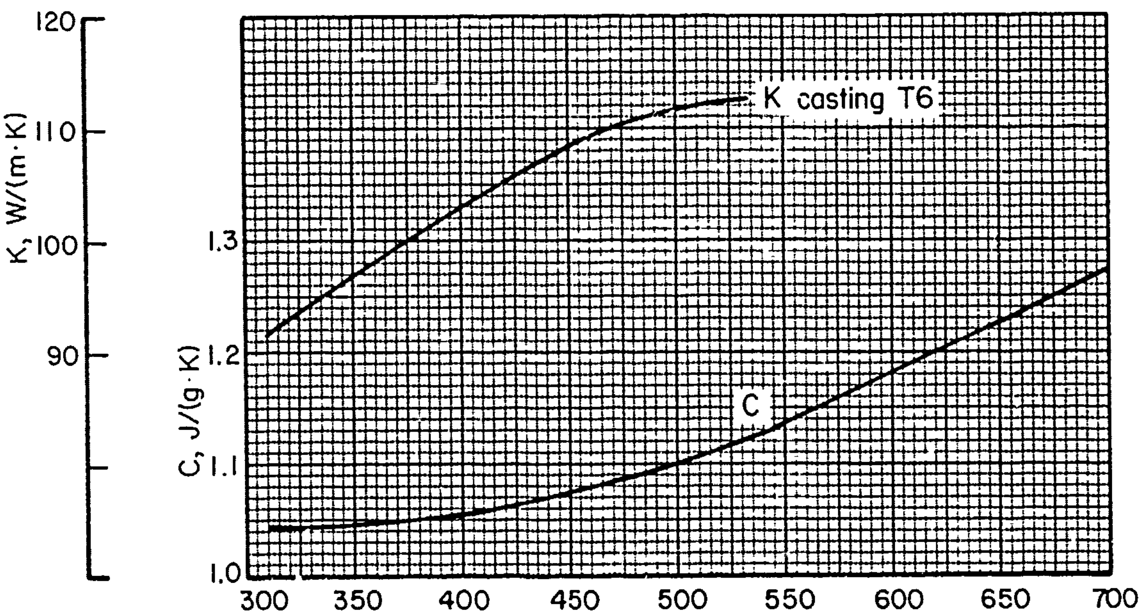

FIGURE 4.3.6.0. Effect of temperature on the physical properties of HK31A.

TABLE 4.3.6.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF HK31A MAGNESIUM ALLOY (CASTINGS)[a]

SPECIFICATION	QQ-M-55 AND QQ-M-56		MIL-M-46062		
FORM	CASTINGS (ANY METHOD)				
TEMPER	T6				
	SEPARATE TEST BARS	UNSPECIFIED LOCATIONS	SPECIFIED LOCATIONS ONLY[b] CLASS 1	CLASS 2	CLASS 3
BASIS	S	S	S	S	S
MECHANICAL PROPERTIES:					
FTU, MPA	186	131	228	200	172
FTY, MPA	90	72	110	97	83
FCY, MPA	90	72	110	97	83
FSU, MPA	...	...	...	...	...
FBRU, MPA:					
(E/D=1.5)	...	...	...	...	...
(E/D=2.0)	...	...	...	...	...
FBRY, MPA:					
(E/D=1.5)	...	...	...	...	...
(E/D=2.0)	...	...	...	...	...
EL, PERCENT	4	1	6	3	1
E, GPA	44.8				
EC, GPA	44.8				
G, GPA	16.5				
MU	0.35				
PHYSICAL PROPERTIES:					
OMEGA, MG/M3	1.79				
C, J/(G*K)	SEE FIGURE 4.3.6.0				
K, W/(M*K)	SEE FIGURE 4.3.6.0				
ALPHA, 10-6 M/(M*K)	27.0 (293 TO 473 K)				

[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] CLASS OF PROPERTIES ATTAINABLE DEPENDS ON LOCATION SPECIFIED AND CASTING DESIGN AND SHOULD BE COORDINATED WITH THE PRODUCER.

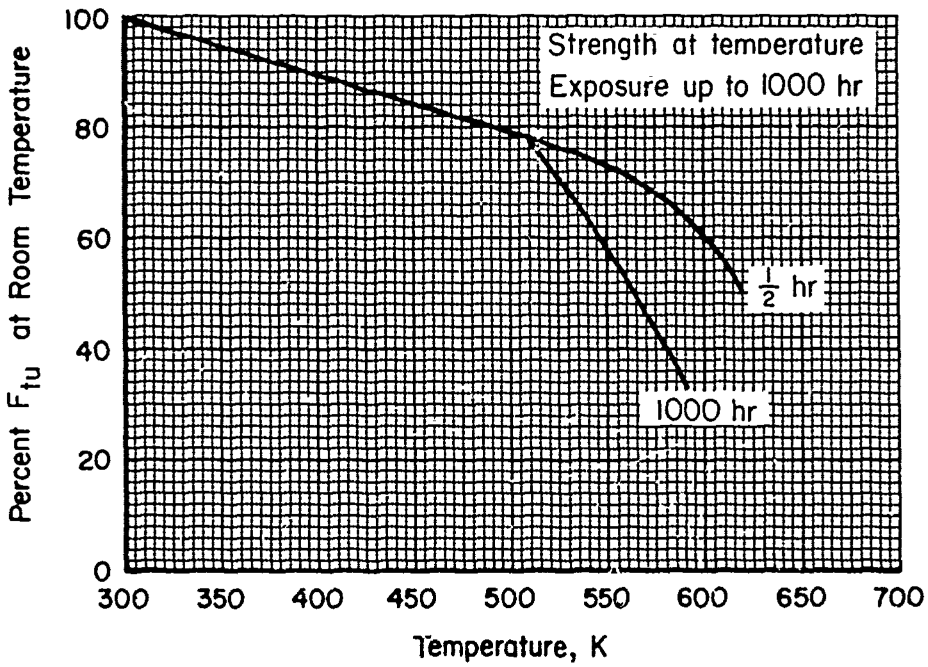

FIGURE 4.3.6.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of cast HK31A-T6.

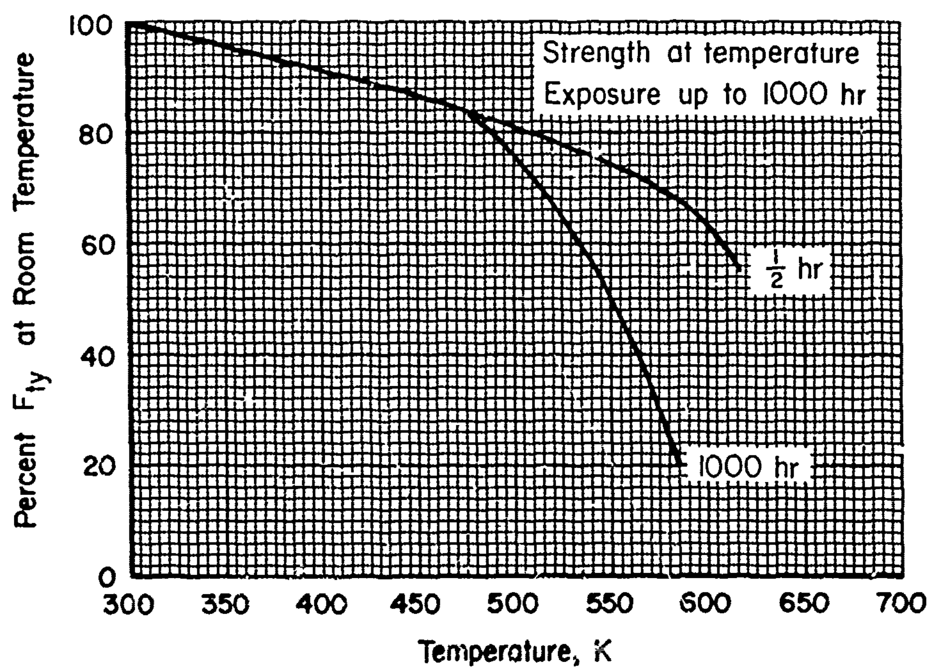

FIGURE 4.3.6.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of cast HK31A-T6.

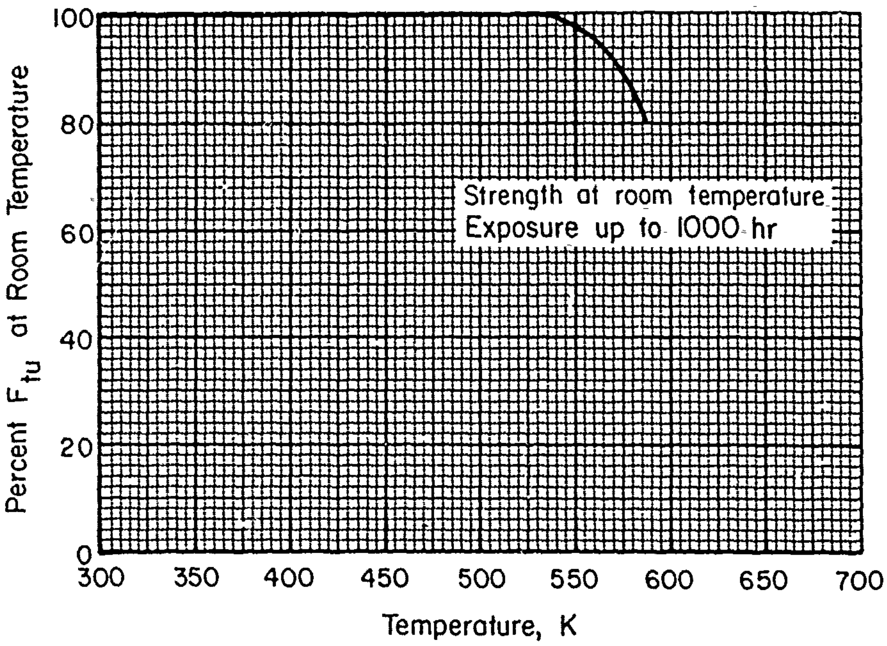

FIGURE 4.3.6.1.1(c). Effect of exposure at elevated temperatures on the room-temperature ultimate tensile strength (F_{tu}) of cast HK31A-T6.

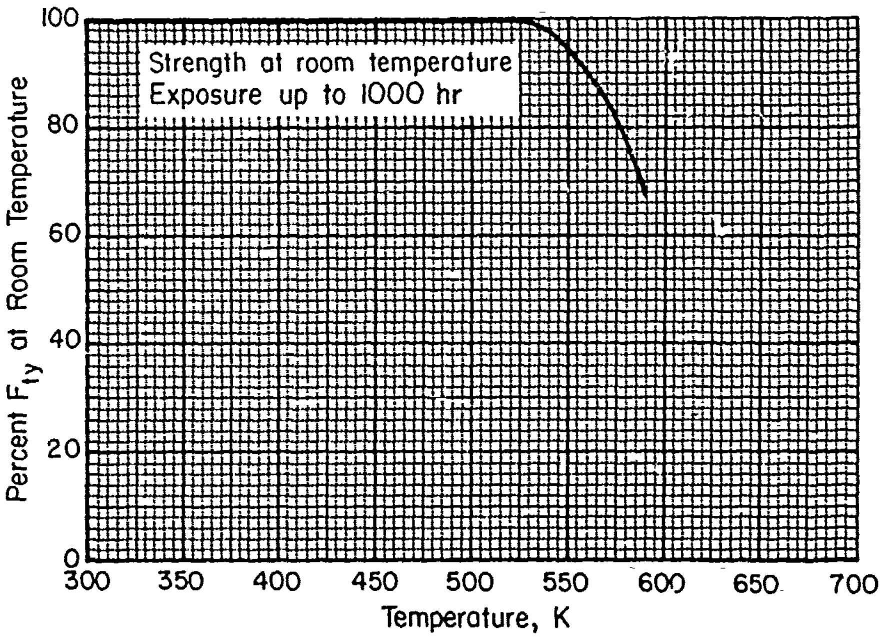

FIGURE 4.3.6.1.1(d). Effect of exposure at elevated temperatures on the room-temperature tensile yield strength (F_{ty}) of cast HK31A-T6.

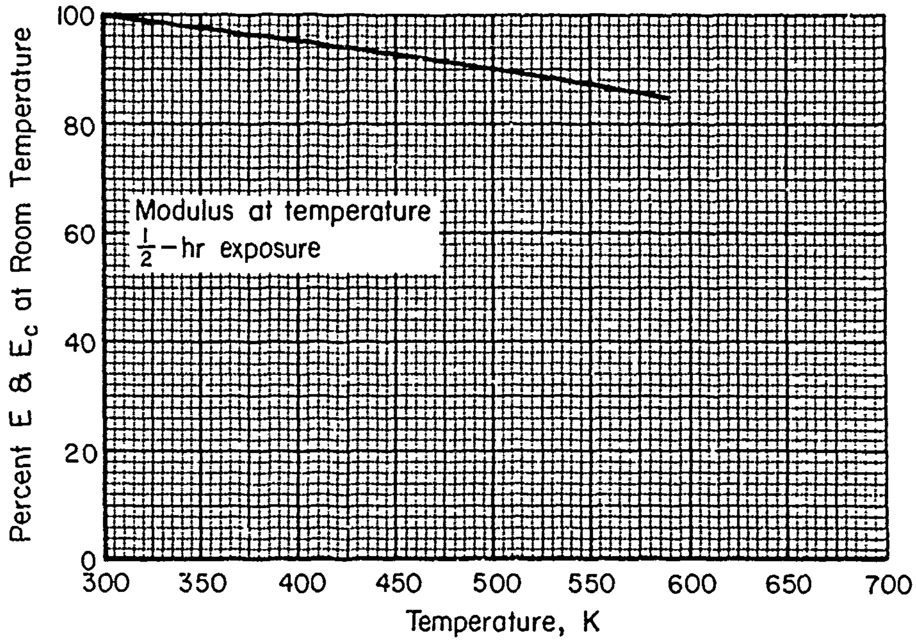

FIGURE 4.3.6.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of cast HK31A-T6.

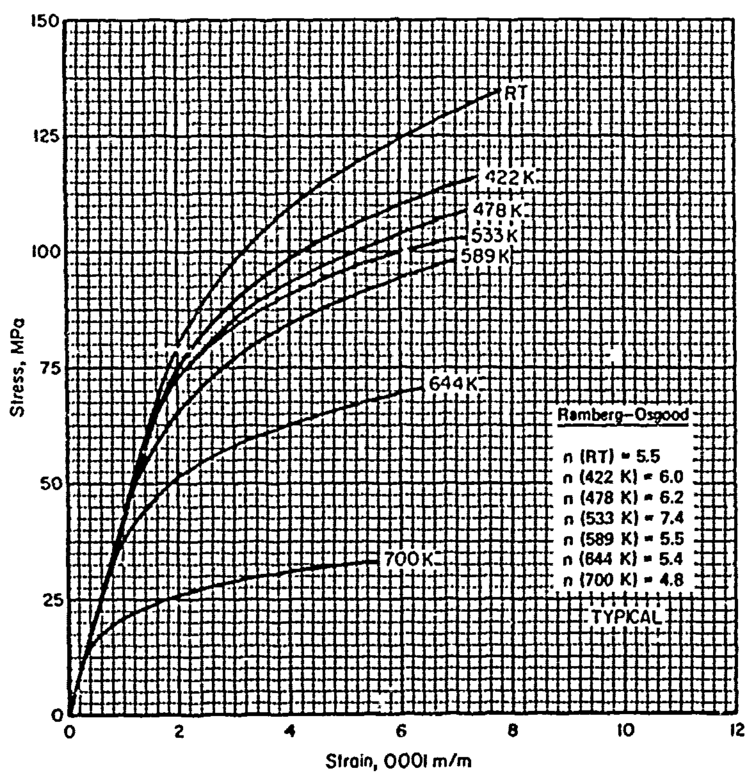

FIGURE 4.3.6.1.6. Typical tensile stress-strain curves for cast HK31A-T6 at room and elevated temperatures (1/2 hour exposure).

4.3.7 HZ32A

4.3.7.0 *Comments and Properties.*—HZ32A is a magnesium-base casting alloy containing zinc, thorium and zirconium. It is available in the form of sand castings. Its general characteristics are similar to those of HK31A. HK31A has better short-time tensile strength up to 644 K. Above 533 K HZ32A-T5 has better creep strength than HK31A-T6. HZ32A-T5 has somewhat better strength stability than HK31A-T6. HZ32A-T5 has somewhat better strength stability than HK31A-T6. HZ32A is available only in the artifically aged (T5) temper. HZ32A has fair weldability and good pressure tightness.

A material specification for HZ32A is given in Table 4.3.7.0(a).

TABLE 4.3.7.0(a). *Material Specifications for HZ32A Magnesium Alloy*

Specification	Form
QQ-M-56	Sand castings

The temper index for HZ32A is as follows:

Section	Temper
4.3.7.1	T5

Room-Temperature Properties

Room-temperature mechanical and physical properties are shown in Table 4.3.7.0(b).

4.3.7.1 *HZ32A-T5.*—Effect of temperature on tensile properties and modulus of elasticity are presented in Figures 4.3.7.1.1(a) through 4.3.7.1.4.

Typical tensile stress-strain curves at various temperatures from room temperature to 700 Kare shown in Figure 4.3.7.1.6.

TABLE 4.3.7.0(b). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF HZ32A MAGNESIUM ALLOY (SAND CASTINGS)[a]

SPECIFICATION	QQ-M-56	
FORM	SAND CASTINGS	
TEMPER	T5	
LOCATION WITHIN CASTING	SEPARATE TEST BARS	UNSPECIFIED LOCATIONS
BASIS	S	S
MECHANICAL PROPERTIES:		
FTU, MPA	186	131
FTY, MPA	90	72
FCY, MPA	90	72
FSU, MPA	...	...
FBRU, MPA:		
(E/D=1.5)	...	...
(E/D=2.0)	...	...
FBRY, MPA:		
(E/D=1.5)	...	...
(E/D=2.0)	...	...
EL, PERCENT	4	1
E, GPA	44.8	
EC, GPA	44.8	
G, GPA	16.5	
MU	0.35	
PHYSICAL PROPERTIES:		
OMEGA, MG/M3	1.82	
C, J/(G*K)	1.05[b]	
K, W/(M*K)	116	
ALPHA, 10-6 M/(M*K)	25.2 (291 TO 373 K)[b]	

[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]ESTIMATED.

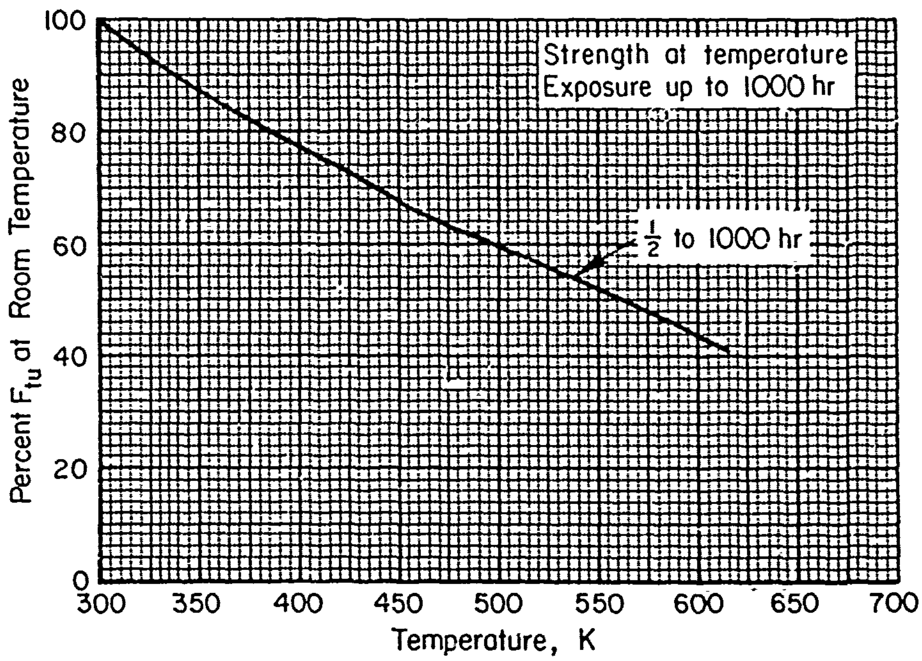

FIGURE 4.3.7.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of cast HZ32A-T5.

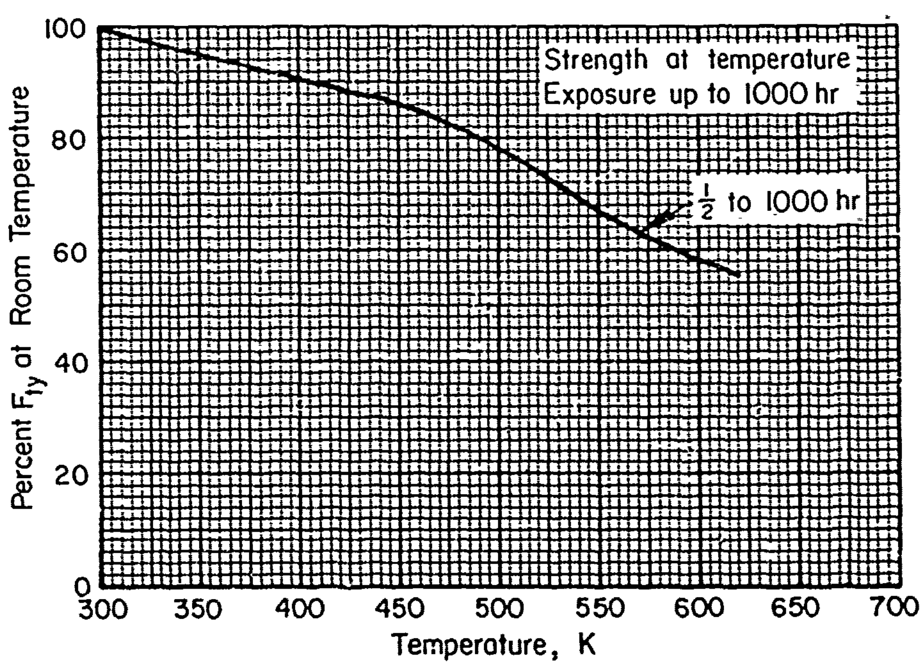

FIGURE 4.3.7.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of cast HZ32A-T5.

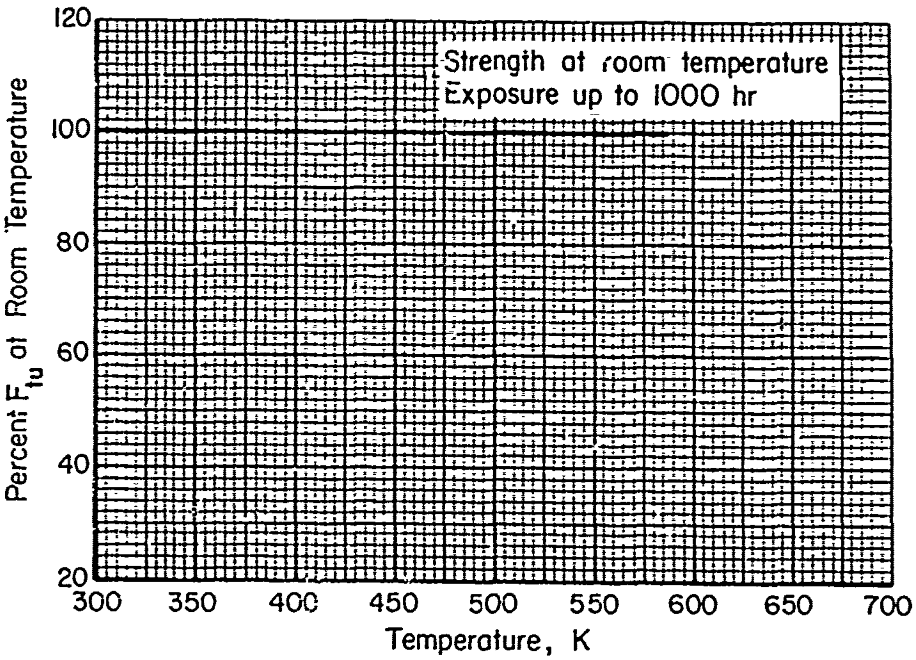

FIGURE 4.3.7.1.1(c). Effect of exposure at elevated temperatures on the room-temperature ultimate tensile strength (F_{tu}) of cast HZ32A-T5.

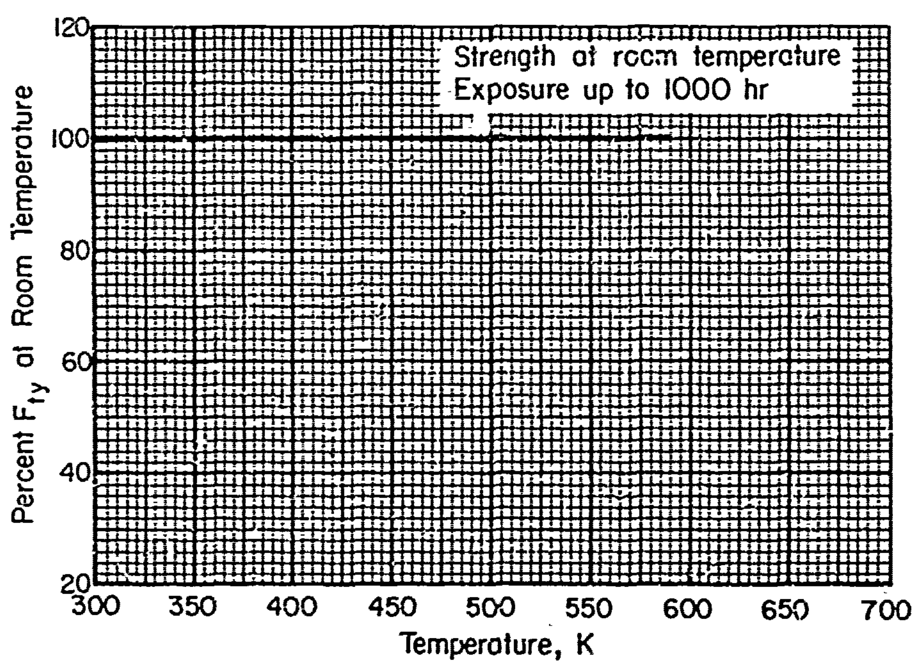

FIGURE 4.3.7.1.1(d). Effect of exposure at elevated temperatures on the room-temperature tensile yield strength (F_{ty}) of cast HZ32A-T5.

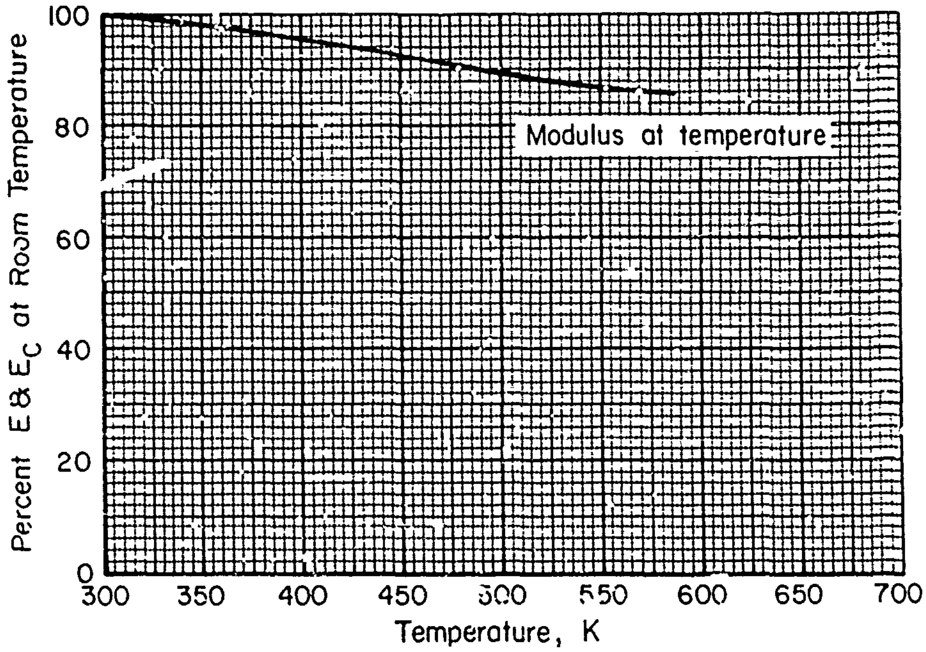

FIGURE 4.3.7.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of cast HZ32A-T5.

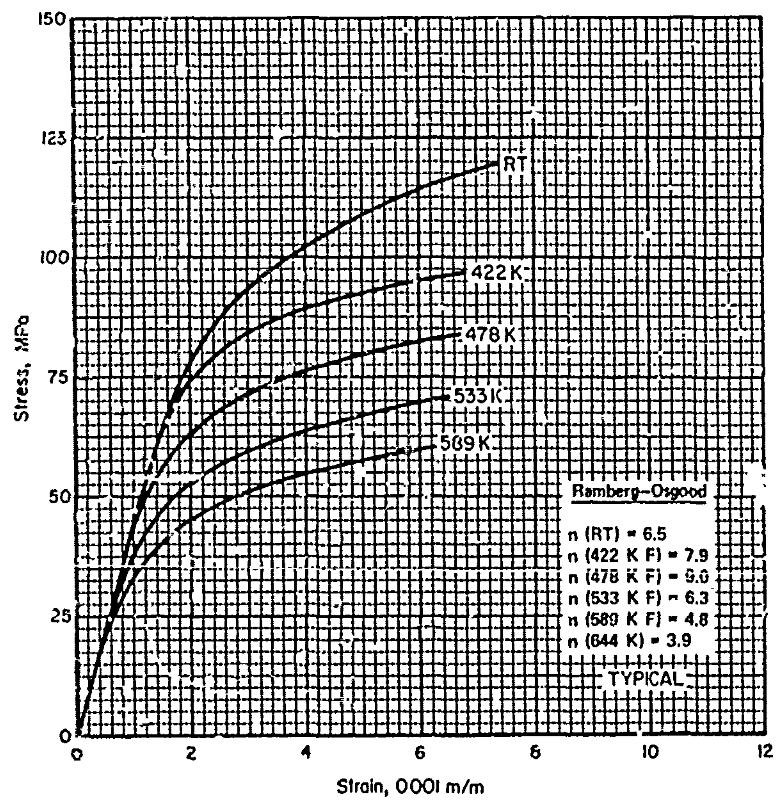

FIGURE 4.3 7.1.6. Typical tensile stress-strain curves for cast HZ32A-T5 at room and elevated temperatures (1/2 hour exposure).

4.3.8 QE22A

4.3.8.0 *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 589 K. QE22A has good weldability and fair pressure tightness.

Material specifications for QE22A are presented in Table 4.3.8.0(a).

TABLE 4.3.8.0(a). *Material Specifications for QE22A Magnesium Alloy*

Specification	Form
QQ-M-56	Sand castings
QQ-M-55	Permanent-mold castings
MIL-M-46062	Castings

The temper index for QE22A is as follows:

Section	Temper
4.3.8.1	T6

Room-Temperature Properties

Room-temperature mechanical and physical properties are shown in Table 4.3.8.0(b).

4.3.8.1 *QE22A-T6 Temper.*—Effect of temperature on tensile properties and modulus of elasticity are presented in Figures 4.3.8.1.1(a) through 4.3.8.1.4.

Typical tensile stress-strain curves at various temperatures from room temperature to 644 K are shown in Figure 4.3.8.1.6.

TABLE 4.3.8.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF QE22A MAGNESIUM ALLOY (CASTINGS)[a]

SPECIFICATION...........	QQ-M-55 AND QQ-M-56		MIL-M-46062		
FORM....................	CASTINGS (ANY METHOD)				
TEMPER..................	T6				
LOCATION WITHIN CASTING.....	SEPARATE TEST BARS	UNSPECIFIED LOCATIONS	SPECIFIED LOCATIONS ONLY[b] CLASS 1	CLASS 2	CLASS 3
BASIS...................	S	S	S	S	S
MECHANICAL PROPERTIES:					
FTU, MPA..............	241	193	276	255	228
FTY, MPA..............	172	138	193	179	159
FCY, MPA..............	172	138	193	179	159
FSU, MPA..............	138	...	...	...	...
FBRU, MPA:					
(E/D=1.5)..........	...	...	...	...	...
(E/D=2.0)..........	...	...	...	...	...
FBRY, MPA:					
(E/D=1.5)..........	...	...	...	...	...
(E/D=2.0)..........	...	...	...	...	...
EL, PERCENT..........	2	1	4	2	2
E, GPA...............	44.8				
EC, GPA..............	44.8				
G, GPA...............	16.5				
MU...................	0.35				
PHYSICAL PROPERTIES:					
OMEGA, MG/M3.........	1.81				
C, J/(G*K)...........	1.05[c]				
K, W/(M*K)...........	102				
ALPHA, 10-6 M/(M*K)..	25.2 (293 TO 473 K)				

[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]CLASS OF PROPERTIES ATTAINABLE DEPENDS ON LOCATION SPECIFIED AND CASTING DESIGN AND SHOULD BE COORDINATED WITH THE PRODUCER.

[c]ESTIMATED.

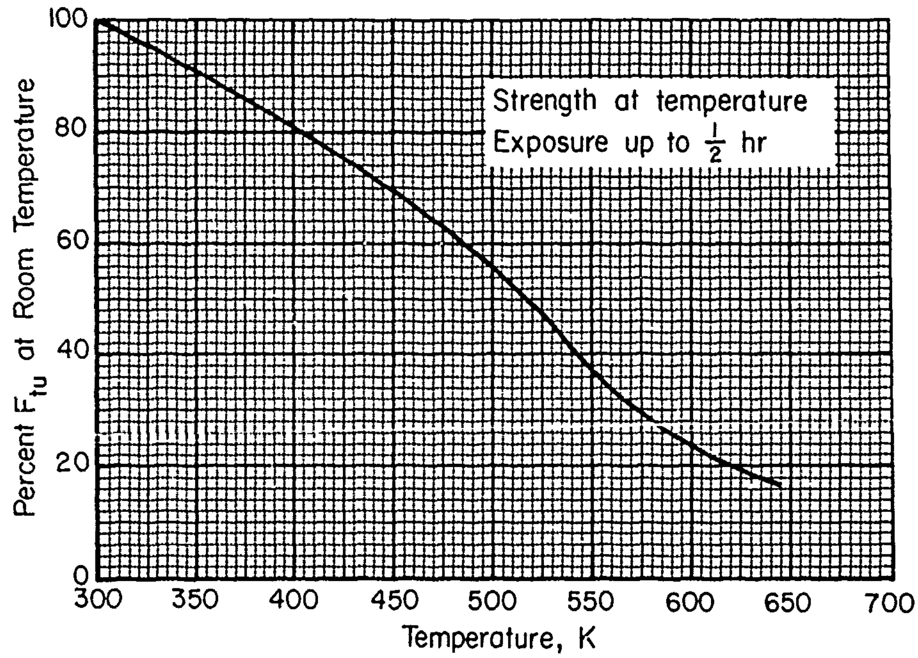

FIGURE 4.3.8.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of cast QE22A-T6.

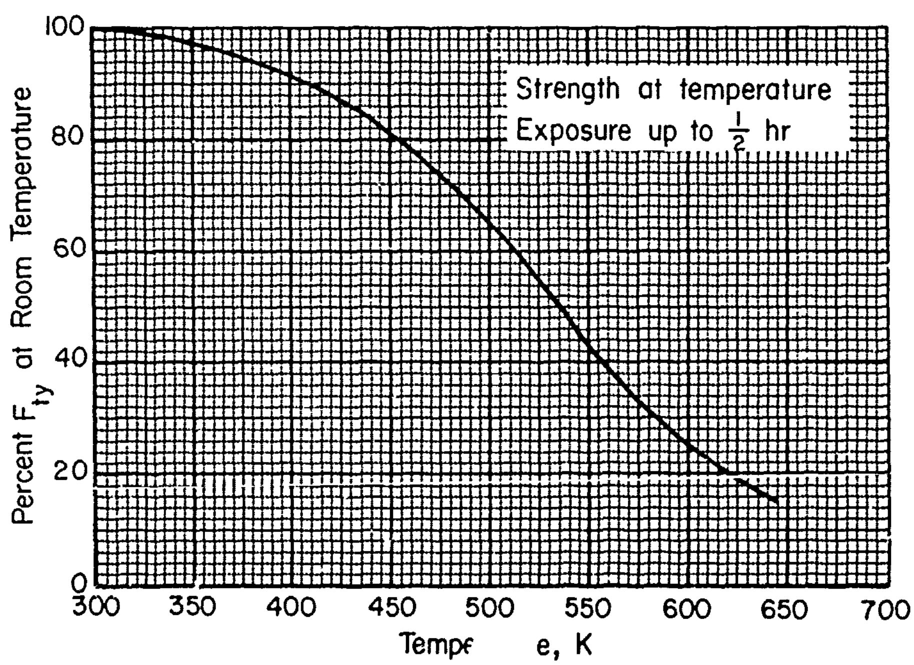

FIGURE 4.3.8.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of cast QE22A-T6.

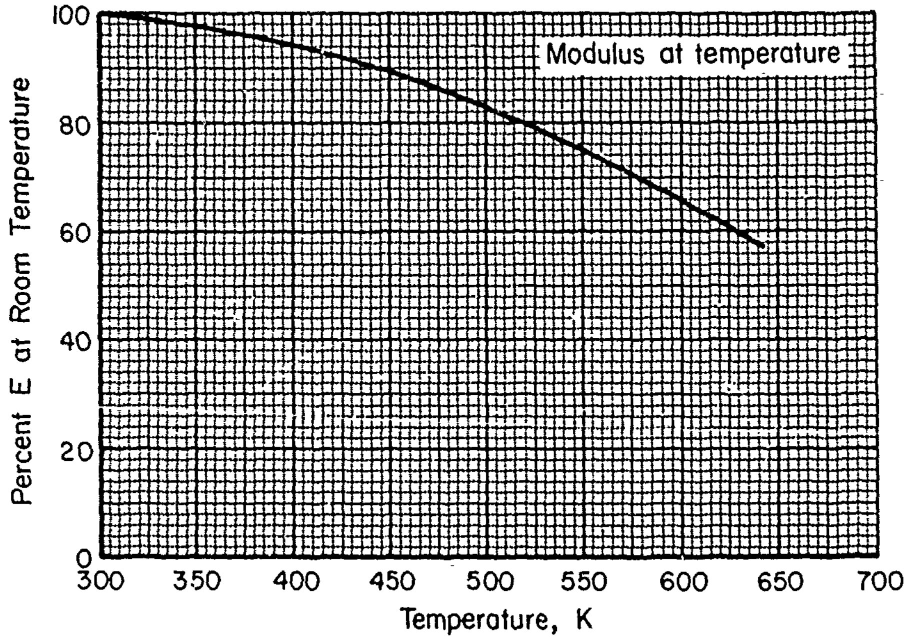

FIGURE 4.3.8.1.4. Effect of temperature on the tensile modulus (E) of cast QE22A-T6.

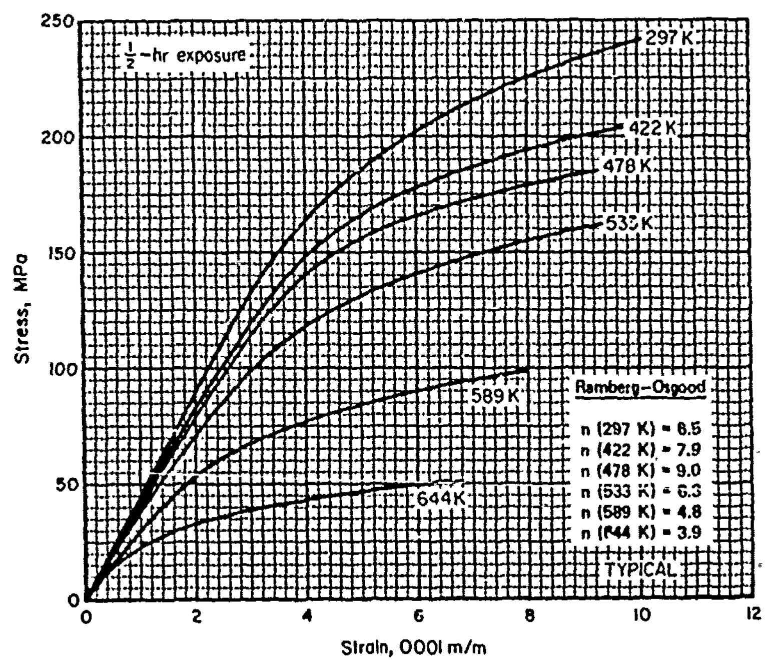

FIGURE 4.3.8.1.6. Typical tensile stress-strain curves for cast QE22A-T6 at room and elevated temperatures.

4.3.9 ZH62A

4.3.9.0 *Comments and Properties.*—ZH62A is a magnesium-base casting alloy containing zinc, thorium, and zirconium. It is available as sand castings and is generally not used for permanent-mold castings. ZH62A has a high room-temperature yield strength and excellent ductility. It is used for applications where the Mg-Al-Zn alloys are suitable but better strength is needed. ZH62A castings are available in the artificially aged (T5) temper.

ZH62A has less tendency to microshrinkage and hot cracking than ZK51A so is used as an alternate when the part cannot be cast satisfactorily in ZK51A. The welding characteristics of ZH62A are better than ZK51A. ZH62A castings have fair pressure tightness.

Material specifications for ZH62A are presented in Table 4.3.9.0(a).

TABLE 4.3.9.0(a). *Material Specifications for ZH62A Magnesium Alloy*

Specification	Form
QQ-M-56	Sand casting
MIL-M-46062	Castings

The temper index for ZH62A is as follows:

Section	Temper
4.3.9.1	T5

Room-Temperature Properties

Room-temperature mechanical and physical properties are shown in Table 4.3.9.0(b).

TABLE 4.3.9.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF ZH62A MAGNESIUM ALLOY (CASTINGS)[a]

SPECIFICATION	QQ-M-56		MIL-M-46062		
FORM	SAND CASTINGS		CASTINGS (ANY METHOD)		
TEMPER	T5				
LOCATION WITHIN CASTING	SEPARATE TEST BARS	UNSPECIFIED LOCATIONS	SPECIFIED LOCATIONS ONLY[b] CLASS 1	CLASS 2	CLASS 3
BASIS	S	S	S	S	S
MECHANICAL PROPERTIES:					
FTU, MPA	241	197	262	234	217
FTY, MPA	152	121	159	145	131
FCY, MPA	152	121	159	145	131
FSU, MPA	...	...	...	...	...
FBRU, MPA:					
(E/D=1.5)	...	...	...	...	...
(E/D=2.0)	...	...	...	...	...
FBRY, MPA:					
(E/D=1.5)	...	...	...	...	...
(E/D=2.0)	...	...	...	...	...
EL, PERCENT	5	1.25	5	3	2
E, GPA	44.8				
EC, GPA	44.8				
G, GPA	16.5				
MU	0.35				
PHYSICAL PROPERTIES:					
OMEGA, MG/M3	1.85				
C, J/(G*K)	1.05[c]				
K, W/(M*K)	109				
ALPHA, 10-6 M/(M*K)	25.2 (291 TO 373 K)[c]				

[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] CLASS OF PROPERTIES ATTAINABLE DEPENDS ON LOCATION SPECIFIED AND CASTING DESIGN AND SHOULD BE COORDINATED WITH THE PRODUCER.

[c] ESTIMATED.

4.3.10 ZK51A

4.3.10.0 *Comments and Properties.*—ZK51A is a magnesium-base casting alloy containing zinc and zirconium. It is available in the form of sand castings. The properties and general characteristics are similar to ZH62A. A tendency to hot cracking prevents using it for intricate shapes where ZH62A may be satisfactory. ZK51A castings are generally available in the artificially aged (T5) temper.

ZK51A is not considered a weldable alloy. The pressure tightness is rated poor in comparison with other magnesium casting alloys.

Material specifications for ZK51A are presented in Table 4.3.10.0(a).

TABLE 4.3.10.0(a). *Material Specifications for ZK51A Magnesium Alloy*

Specification	Form
QQ-M-56	Sand castings
MIL-M-46062	Castings

The temper index for ZK51A is as follows:

Section	Temper
4.3.10.1	T5

Room-Temperature Properties

Room-temperature mechanical and physical properties are shown in Table 4.3.10.0(b). Effect-of-temperature curves for physical properties are shown in Figure 4.3.10.0.

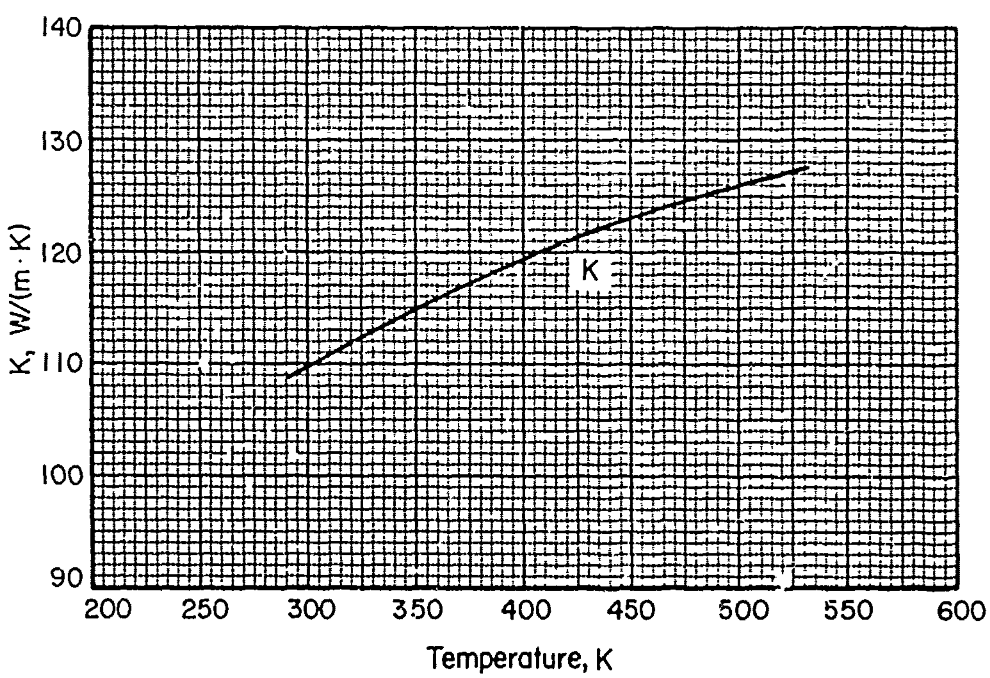

FIGURE 4.3.10.0. Effect of temperature on the physical properties of cast ZK51A.

TABLE 4.3.10.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF ZK51A MAGNESIUM ALLOY (CASTINGS)[a]

SPECIFICATION	QQ-M-56		MIL-M-46062		
FORM	SAND CASTINGS		CASTINGS (ANY METHOD)		
TEMPER	T5				
LOCATION WITHIN CASTING	SEPARATE TEST BARS	UNSPECIFIED LOCATIONS	SPECIFIED LOCATIONS ONLY[b] CLASS 1	CLASS 2	CLASS 3
BASIS	S	S	S	S	S
MECHANICAL PROPERTIES:					
FTU, MPA	234	165	248	221	200
FTY, MPA	138	97	145	131	117
FCY, MPA	138	97	145	131	117
FSU, MPA	...	...	...	...	...
FBRU, MPA:					
(E/D=1.5)	...	...	...	...	...
(E/D=2.0)	...	...	...	...	...
FBRY, MPA:					
(E/D=1.5)	...	...	...	...	...
(E/D=2.0)	...	...	...	...	...
EL, PERCENT	5	1.25	6	4	3
E, GPA	44.8				
EC, GPA	44.8				
G, GPA	16.5				
MU	0.35				
PHYSICAL PROPERTIES:					
OMEGA, MG/M3	1.81				
C, J/(G*K)	0.96				
K, W/(M*K)	SEE FIGURE 4.3.10.0				
ALPHA, 10-6 M/(M*K)	27.0 (293 TO 473 K)				

[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]CLASS OF PROPERTIES ATTAINABLE DEPENDS ON LOCATION SPECIFIED AND CASTING DESIGN AND SHOULD BE COORDINATED WITH THE PRODUCER.

4.4.1 BEAMS.—See Equation 1.3.2.1, Section 1.5.2.5, 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 the allowable bending stress.

4.4.1.2 *Builtup Beams.*—Builtup beams will usually fail because of local failure of the component parts.

4.4.1.3 *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 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).

TABLE 4.4.2.1(a). *Column Formulas for Magnesium-Alloy Extruded Open Shapes*[a]

General Formula

$$\frac{P}{A} = \frac{K(F_{cy})^n}{(L'/\rho)^m}$$

(Stress values are in ksi)

Alloy	K	n	M	Max.P/A
AZ31B,AZ61A,AZ80A	2,900	1/4	1.5	F_y
AZ80A-T6, ZK60A-T5	3,300	1/4	1.5	$0.96 F_y$

[a]Formulas given above are 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).

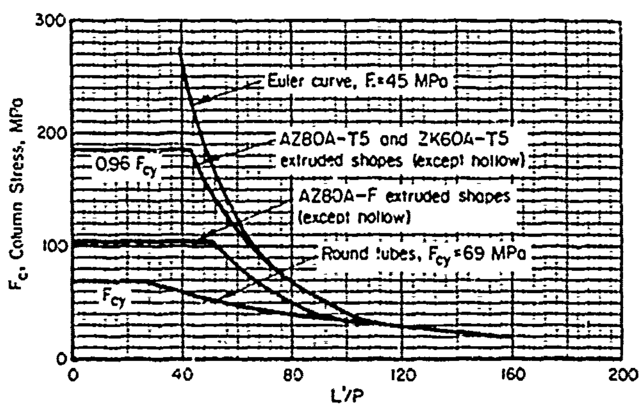

Figure 4.4.2.3(a). Allowable column stresses for magnesium-alloy columns.

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 3.20.2.3.

4.4.3 TORSION

4.4.3.2 *General.*—The general statements relating to aluminum-alloy tubing, Section 3.20.3, are applicable to magnesium tubing.

4.4.3.2 *Torsion Properties.*—An empirical curve of the allowable torsional modulus of rupture for magnesium-alloy round tubing (specification WW-T-825) is given in Figure 4.4.3.2.

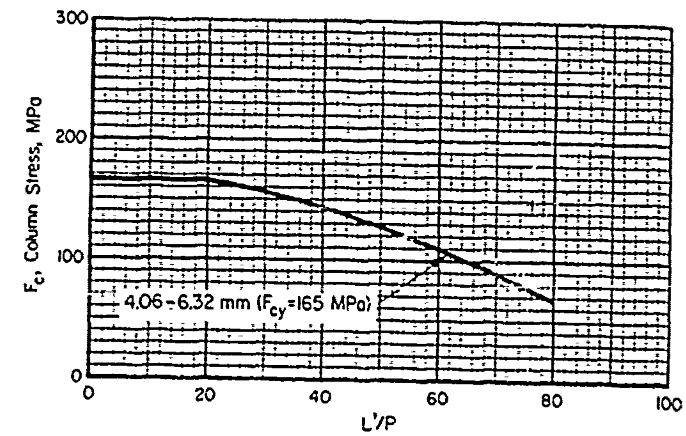

FIGURE 4.4.2.3(b). Allowable column stresses for AZ31B-H24 magnesium-alloy sheet.

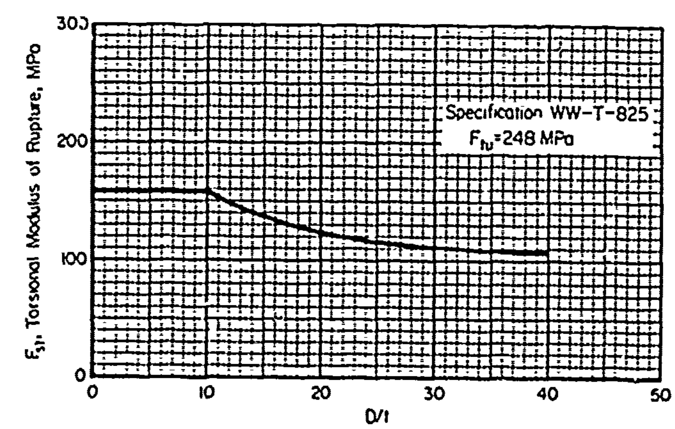

FIGURE 4.4.3.2. Torsional modulus of rupture for magnesium-alloy round tubing.

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Chapter 5

TITANIUM

5.1 General

This chapter contains the engineering properties and related characteristics of wrought 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 notch toughness, 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 as follows:

5.2 Unalloyed Titanium

5.2.1 Commercially Pure Titanium

5.3 Alpha and Near-Alpha Titanium Alloys

5.3.1 Ti-5Al-2.5Sn (Alpha)
5.3.2 Ti-8Al-1Mo-lV (Near-Alpha)
5.3.3 Ti-6Al-2Sn-4Zr-2Mo (Near-Alpha)
5.3 4 Ti-11Sn-5Zr-2Al-1Mo (Near-Alpha)

5.4 Alpha-Beta Titanium Alloys

5.4.1 Ti-8Mn
5.4.2 Ti-6Al-2Sn-4Zr-6Mo
5.4.3 Ti-6Al-4V
5.4.4 Ti-6Al-6V-2Sn
5.4.5 Ti-7Al-4Mo

5.5 Beta Titanium Alloys

5.5.1 Ti-13V-11Cr-3Al

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 found. Under equilibrium conditions, pure titanium has an "alpha" structure up to 1155 K, 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 directions of prior working. The presence of textures in these materials leads to anisotropy with respect to many of the 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 effects 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 specification materials or 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 several titanium alloys are presented in Table 5.1.2.1.1 for information only. These are average values for which valid data are available and are representative of the various alloys and products, but they do not have the statistical reliability of the room-temperature mechanical properties.

5.1.3 MANUFACTURING CONSIDERATIONS.

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 with the material. 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 422 K, as well as above about 644 K, 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-5Al-2.5Sn 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(b) and (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 14 joules. In gaseous oxygen, a partial pressure of about 345 kPa is sufficient to ignite a fresh titanium surface over the temperature range from 116 K to room temperature or higher.

Titanium is susceptible to stress-corrosion cracking in certain anhydrous chemicals including methyl alcohol and nitrogen textroxide. 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 0.4-0.8 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.

TABLE 5.1.2.1.1. *Typical Values of Room Temperature Plane-Strain Fracture Toughness of Titanium Alloys*[a]

Alloy	Product	Heat Treat Condition	TUS, MPa	Product Thickness[b] Range, mm	K_{Ic}, MPa-$mm^{1/2}$									
					L-T[c]					T-L[c]				
					No. of Lots	Specimen Thickness[b], mm	Minimum	Average	Maximum	No. of Lots	Specimen Thickness[b], inch	Minimum	Average	Maximum
Ti-6Al-6V-2Sn	Bar	ANN	1069	95	1	25	63	65	68	..	...	...	...	...
Ti-6Al-6V-2Sn	Bar	STA	1323	95	1	25	33	34	35	...	...	...	...	...

[a]These values are for information only.
[b]Minimum thickness of specimen on which values were obtained.
[c]Refer to Figure 1.4.12.3 for definition of symbols.

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 505–533K 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 non-chlorinated solvent (to remove salt deposits, including fingerprints) of parts used above 505 K is recommended.

In laboratory tests, with a fatigue crack present in the specimen, certain titanium alloys show an increased rate of crack propagation 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.

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.*—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 (422 to 755 K) 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 839 K. 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.

Specifications.—Some material specifications for commercially pure titanium are presented in Table 5.2.1.0(a).

TABLE 5.2.1.0(a). *Material Specifications for Commercially Pure Titanium*

Specification	Form
MIL-T-9046....	Sheet, strip, and plate
MIL-T-9047....	Bars
MIL-T-81556...	Extruded bars, rods, and special shaped sections

Heat Treatment.—Commercially pure titanium is full annealed by heating to 811 to 978 K for 10 to 30 minutes. It is stress relieved by heating to 755 to 811 K for 30 minutes. Commercially pure titanium cannot be hardened by heat treatment.

Room-Temperature Properties

Room-temperature mechanical properties for commercially pure titanium are shown in Tables 5.2.1.0(b) (c) and (d). 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 276 and 480 MPa yield strength commercially pure titanium are shown in Figures 5.2.1.1.6(a) and 5.2.1.1.6(b).

TABLE 5.2.1.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF COMMERCIALLY PURE TITANIUM

SPECIFICATION	MIL-T-9046, TYPE I			MIL-T-9047
	COMP. A	COMP. B	COMP. C	COMP. 1
FORM	SHEET, STRIP, PLATE			BARS
CONDITION	ANNEALED			ANNEALED
THICKNESS, MM	≤ 2.54			<76.20[b]
BASIS	S	S	S	S
MECHANICAL PROPERTIES:				
FTU, MPA:				
L	345	552	448	552
LT	345	552	448	552
ST	...	...	...	552
FTY, MPA:				
L	276	483	379	483
LT	276	483	379	483
ST	...	...	...	483
FCY, MPA:				
L	...	483	...	...
LT	...	483	...	...
ST	...	...	...	...
FSU, MPA	...	290	...	...
FBRU, MPA:				
(E/D=1.5)	...	827	...	...
(E/D=2.0)	...	...	...	...
FBRY, MPA:				
(E/D=1.5)	...	696	...	...
(E/D=2.0)	...	...	...	...
EL, PERCENT:				
L	20[a]	15[a]	18[a]	15
LT	20[a]	15[a]	18[a]	15
ST	...	...	...	15
E, GPA	106.9			
EC, GPA	110.3			
G, GPA	44.0			
MU	...			
PHYSICAL PROPERTIES:				
OMEGA, MG/M3	4.51			
C, J/(G*K)	SEE FIGURE 5.2.1.0			
K, W/(M*K)	SEE FIGURE 5.2.1.0			
ALPHA, 10-6 M/(M*K)	SEE FIGURE 5.2.1.0			

[a] THICKNESS OF 0.635 MM AND ABOVE.
[b] MAXIMUM OF 64.5 SQ CM CROSS-SECTIONAL AREA.

TABLE 5.2.1.0(C). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF COMMERCIALLY PURE TITANIUM (EXTRUSIONS)

SPECIFICATION..........	MIL-T-81556, TYPE I			
	COMP. A	COMP. B	COMP. C	COMP. D
FORM....................	EXTRUDED BARS, RODS, AND SPECIAL SHAPED SECTIONS			
CONDITION...............	ANNEALED			
THICKNESS, MM...........	<76.20			
BASIS...................	S	S	S	S
MECHANICAL PROPERTIES:				
FTU, MPA:				
L.................	276	345	448	552
LT................	...	...	...	...
FTY, MPA:				
L.................	207	276	379	483
LT................	...	...	...	...
FCY, MPA:				
L.................	...	...	...	...
LT................	...	...	...	...
FSU, MPA.............	...	...	...	...
FBRU, MPA:				
(E/D=1.5).........	...	...	...	...
(E/D=2.0).........	...	...	...	...
FBRY, MPA:				
(E/D=1.5).........	...	...	...	...
(E/D=2.0).........	...	...	...	...
EL, PERCENT:				
L.................	a	a	a	a
LT................	...	...	...	...
E, GPA...............	106.9			
EC, GPA..............	110.3			
G, GPA...............	44.8			
MU...................	...			
PHYSICAL PROPERTIES:				
OMEGA, MG/M3.........	4.51			
C, J/(G*K)...........	SEE FIGURE 5.2.1.0			
K, W/(M*K)...........	SEE FIGURE 5.2.1.0			
ALPHA, 10-6 M/(M*K)..	SEE FIGURE 5.2.1.0			

[a] SEE TABLE 5.2.1.0(D).

TABLE 5.2.1.0(d). *Percent Elongation Values for Commercially Pure Titanium Extruded Bars, Rods, Special Shaped Sections*

Thickness, mm	Elongation, percent			
	Comp. A	Comp. B	Comp. C	Comp. D
⩽ 25.40	25	20	18	15
25.41-50.80	20	18	15	12
50.81-76.20	18	15	12	10

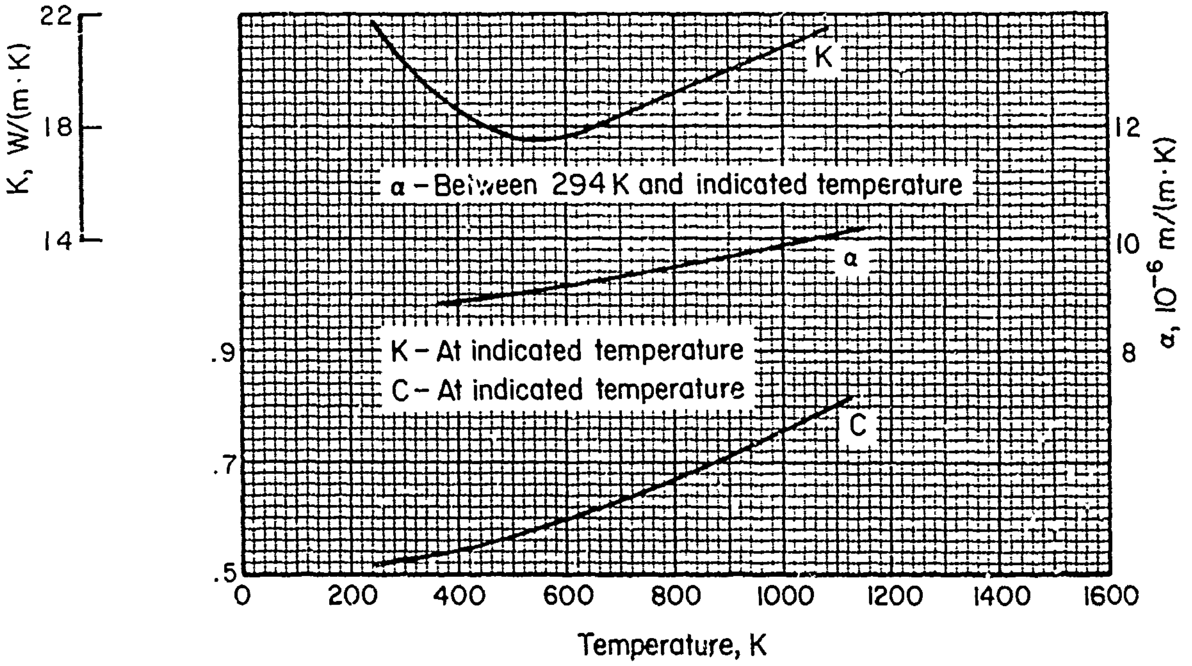


FIGURE 5.2.1.0. Effect of temperature on the physical properties of commercially pure titanium.

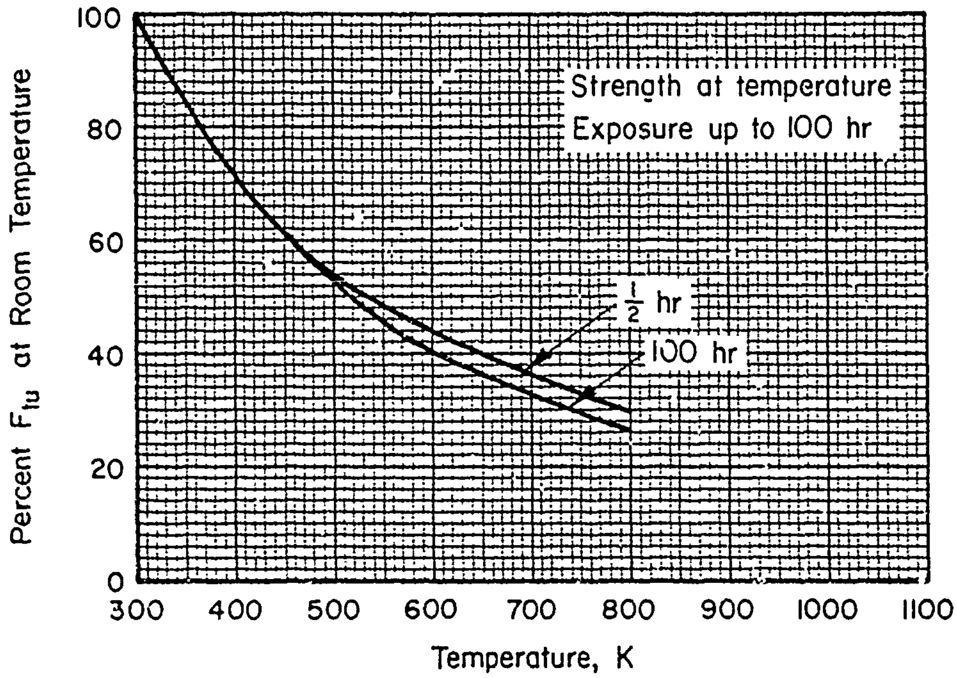


FIGURE 5.2.1.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of annealed commercially pure titanium.

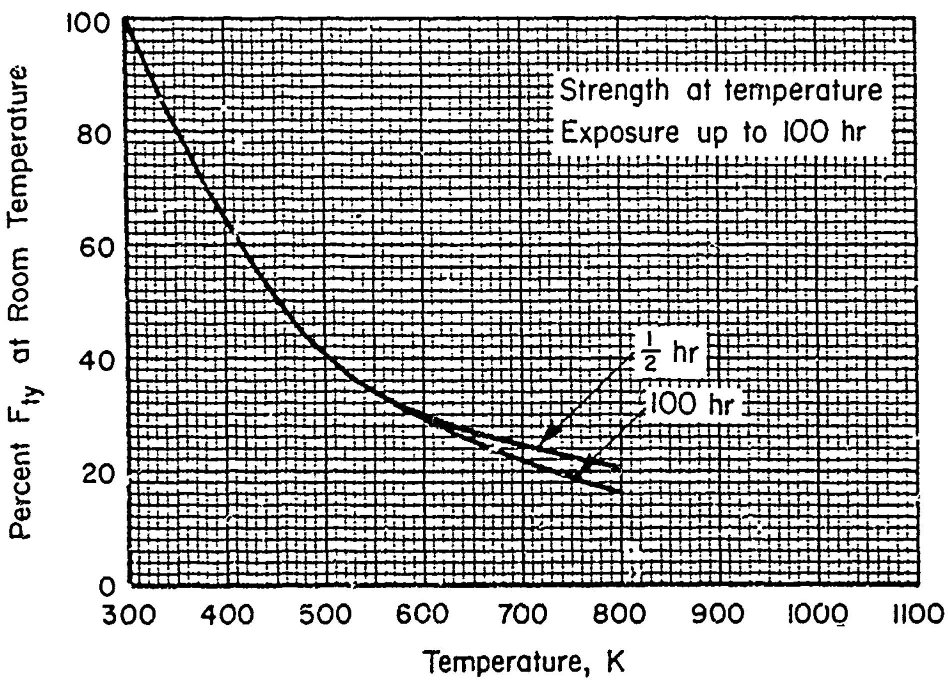


FIGURE 5.2.1.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of annealed commercially pure titanium.

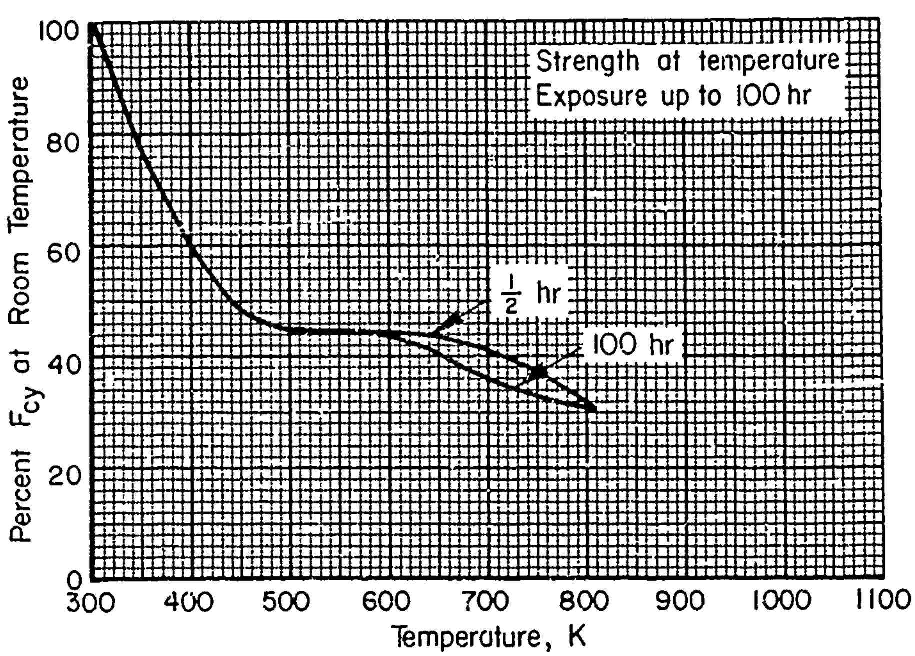


FIGURE 5.2.1.1.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of annealed commercially pure titanium.

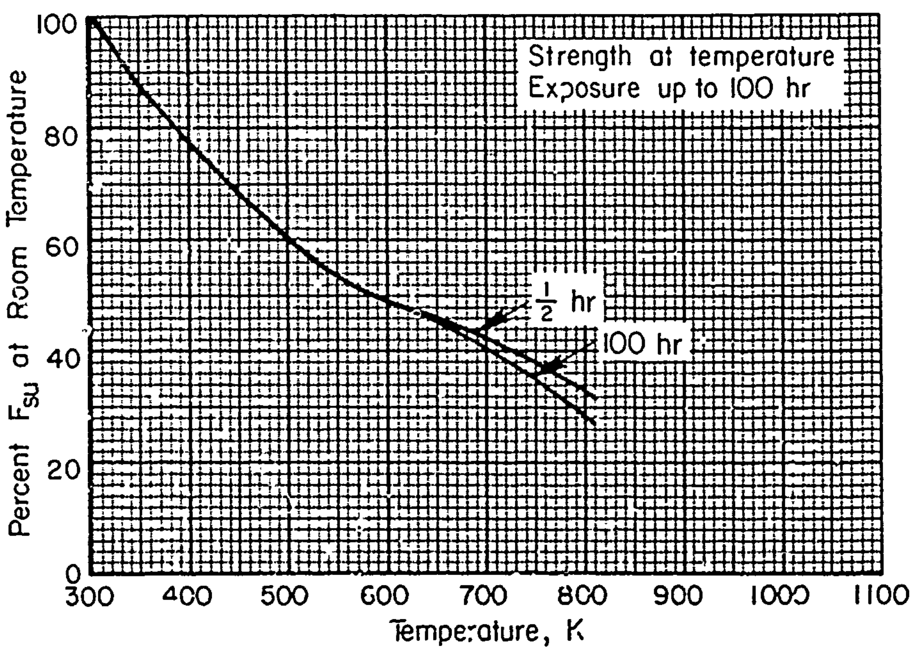


FIGURE 5.2.1.1.2(b). Effect of temperature on the ultimate shear strength (F_{su}) of annealed commercially pure titanium.

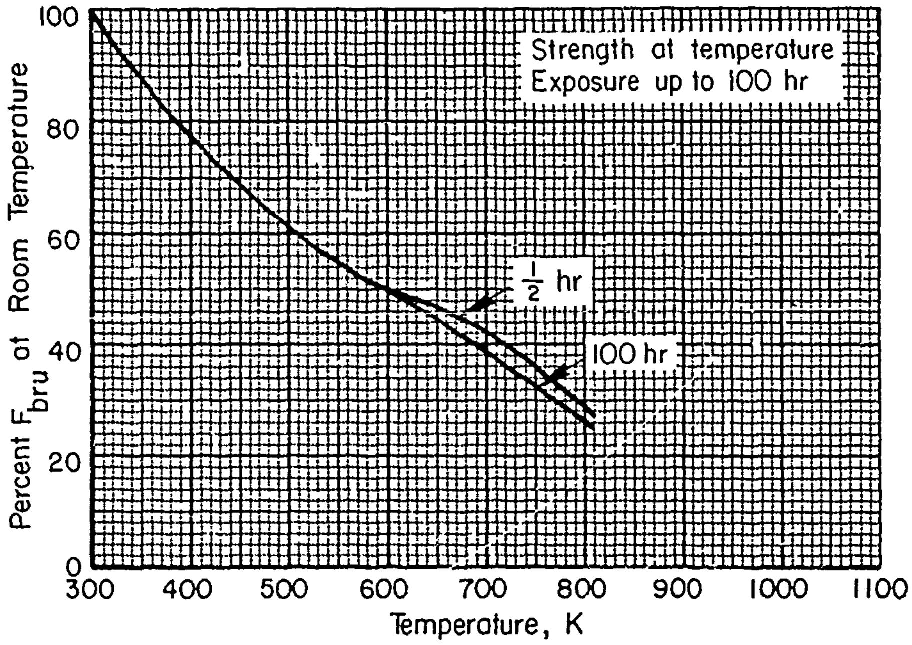


FIGURE 5.2.1.1.3(a). Effect of temperature on the ultimate bearing strength (F_{bru}) of annealed commercially pure titanium.

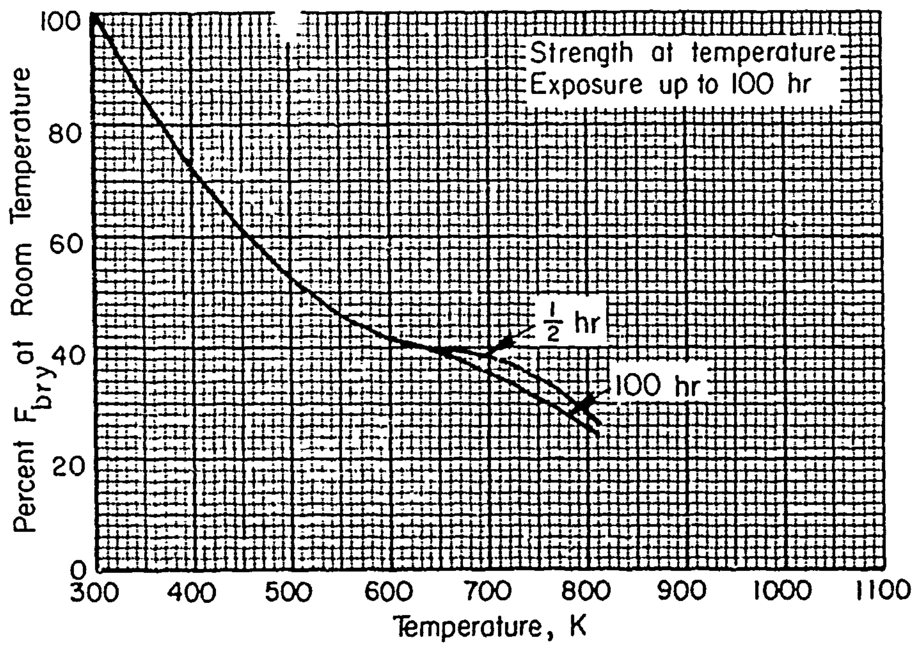


FIGURE 5.2.1.1.3(b). Effect of temperature on the bearing yield strength (F_{bry}) of annealed commercially pure titanium.

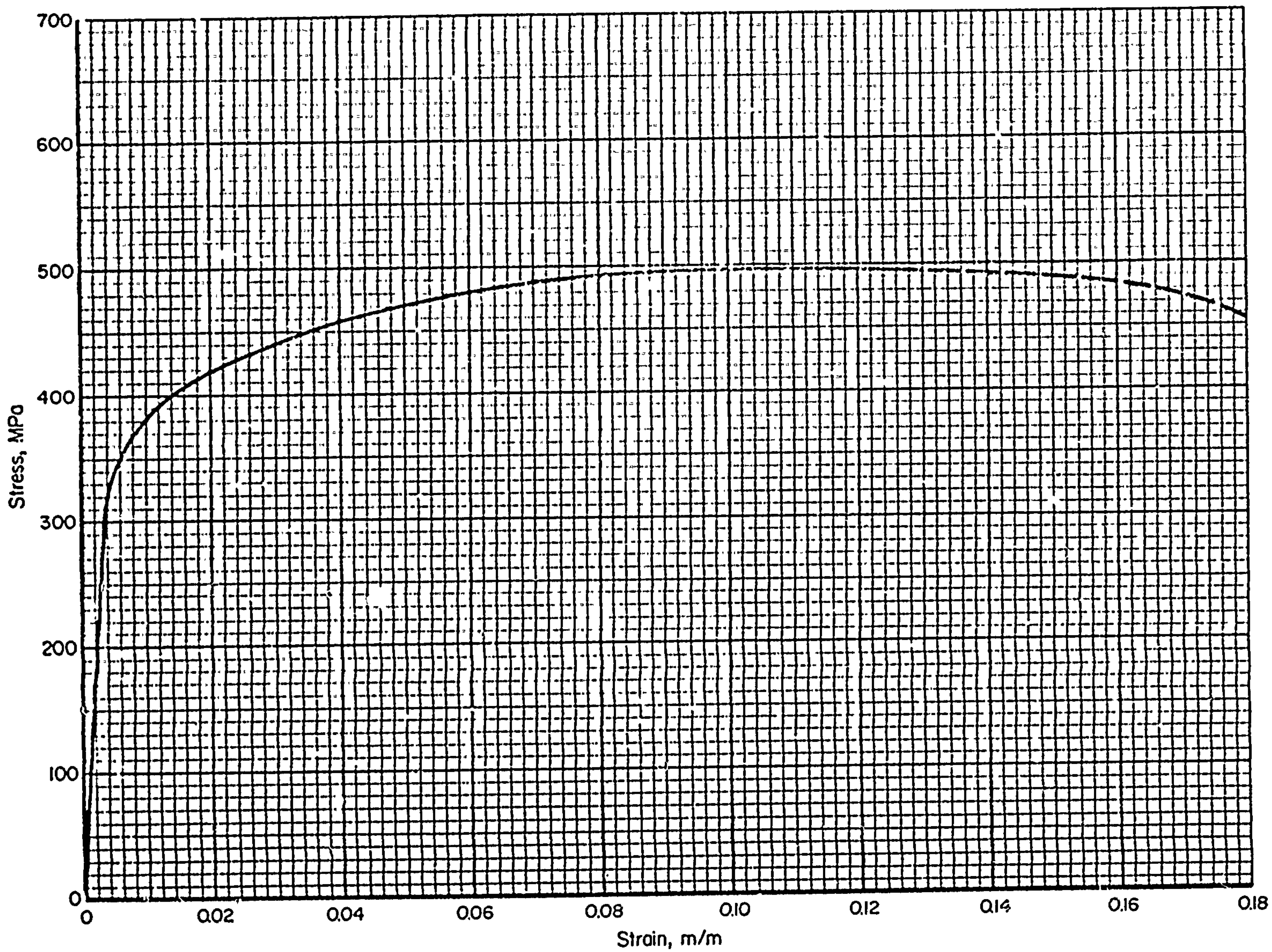


FIGURE 5.2.1.1.6(a). Typical full range stress-strain curve for commercially pure titanium sheet (276MPa yield) at room temperature.

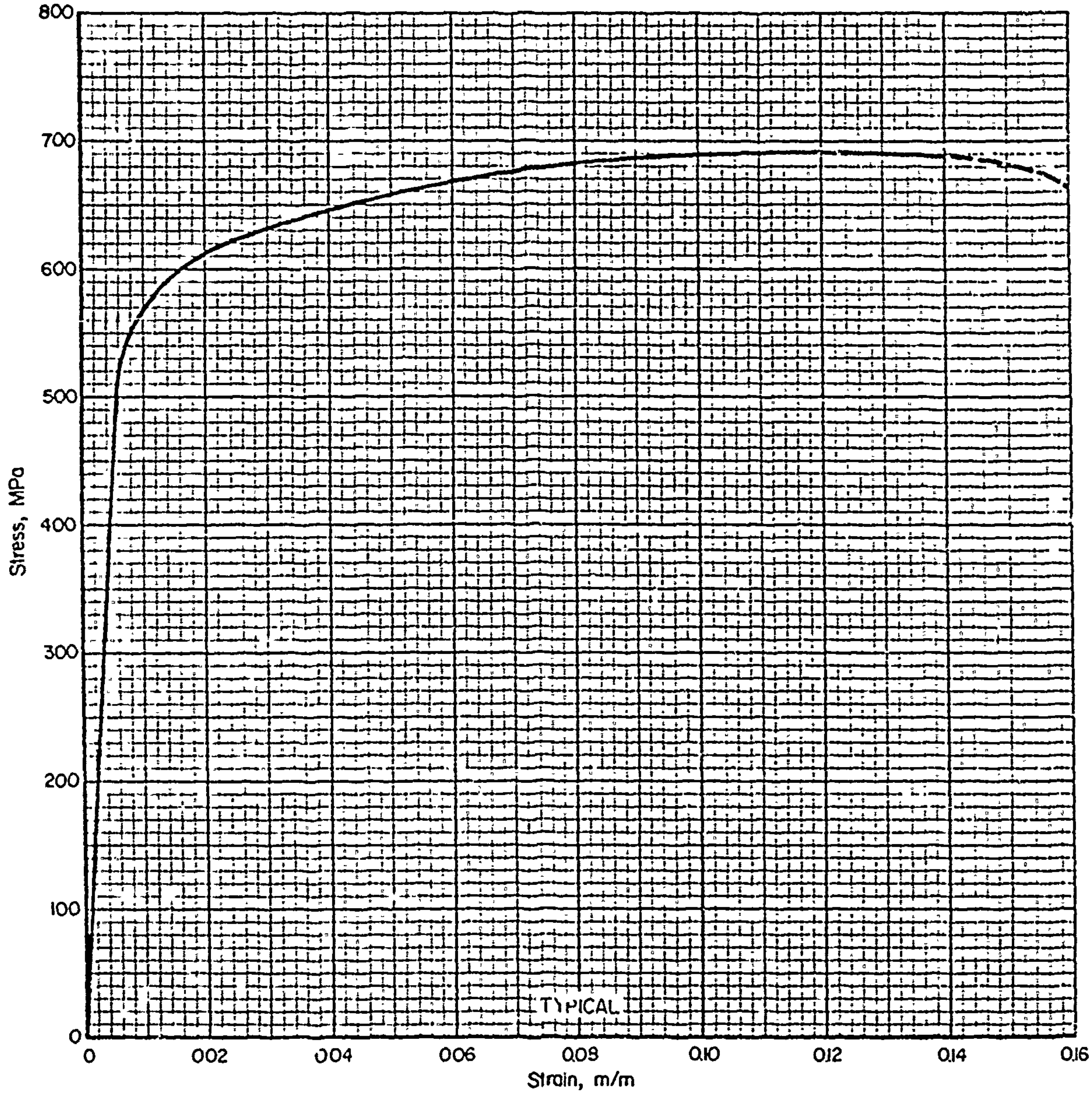


FIGURE 5.2.1.1.6(b). Typical full range stress-strain curve for commercially pure titanium sheet (483 MPa yield) at room temperature.

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.*—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 755 K or to 866 K 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 922 K. Moderately severe forming can be done at 422 to 589 K 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-2Sn can be welded readily by the inert-gas or vacuum-shielded arc methods or by spot or seam welding without atmospheric shielding. Brazing requires protection from the atmosphere, however, this may be 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 and care should be exercised in applications involving such environments. The alloy has good oxidation resistance up to 839 K. 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 20 K.

Specifications.—Some material specifications for Ti-5Al-2.5Sn are presented in Table 5.3.1.0(a).

TABLE 5.3.1.0(a). *Material Specifications for Ti-5Al-2.5Sn*

Specification	Form
MIL-T-9046....	Sheet, strip, and plate
MIL-T-9047....	Bars
MIL-T-81556...	Extruded bars, rods, and special shaped sections
AMS 4966	Forgings

Heat Treatment.—This alloy is annealed by heating to between 1033 K for 60 minutes and 1144 K for 10 minutes and cooling in air. Stress relieving requires 1 or 2 hours at 811 to 922 K. Ti-5Al-2.5Sn cannot be hardened by heat treatment.

Room-Temperature Properties

Room-temperature mechanical properties for Ti-5Al-2.5Sn are shown in Tables 5.3.1.0(b) and (c). The effect of temperature on physical properties is shown in Figure 5.3.1.0.

5.3.1.1 *Annealed Condition.*—Effect of temperature curves for annealed Ti-5Al-2.5Sn are presented in Figures 5.3.1.1.1(a) through 5.3.1.1.5. Tensile properties cover the range 20 K to 811 K; whereas other properties are for the range room temperature to 811 K.

TABLE 5.3.1.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF
TI-5AL-2.5SN

SPECIFICATION	MIL-T-9046, TYPE II, COMP. A						MIL-T-9047		AMS 4966
FORM	SHEET + STRIP		PLATE				BARS		FORGINGS
CONDITION	ANNEALED						ANNEALED		ANNEALED
THICKNESS, MM	<4.76		4.76-6.35		6.36-38.11	38.12-101.60	≤76.20[b]		...
BASIS	A	B	A	B	S	S	A	B	S
MECHANICAL PROPERTIES:									
FTU, MPA:									
L	827	862	827	862	827	793	793[c]	869	793[d]
LT	827	862	827	862	827	793	...	...	...
FTY, MPA:									
L	779	814	779	814	779	758	758[c]	827	758[d]
LT	779	814	779	814	779	758	...	...	...
FCY, MPA:									
L	814	848	814	848	814	...	...	...	...
LT	814	848	814	848	814	...	...	...	...
FSU, MPA	517	538	517	538	517	...	...	...	...
FBRU, MPA:									
(E/D=1.5)	1150	1200	1150	1200	1150	...	...	...	...
(E/D=2.0)	1720	1800	1720	1800	1720	...	...	...	...
FBRY, MPA:									
(E/D=1.5)	917	958	917	958	917	...	...	...	...
(E/D=2.0)	1310	1370	1310	1370	1310	...	...	...	...
EL, PERCENT:									
L	10[a]	...	10	...	10	10	10[c]	...	10[d]
LT	10[a]	...	10	...	10	10	...	...	...
E, GPA	106.9								
EC, GPA	106.9								
G, GPA	...								
MU	...								
PHYSICAL PROPERTIES:									
OMEGA, MG/M3	4.48								
C, J/(G*K)	SEE FIGURE 5.3.1.0								
K, W/(M*K)	SEE FIGURE 5.3.1.0								
ALPHA, 10-6 M/(M*K)	SEE FIGURE 5.3.1.0								

[a] THICKNESS 0.635 MM AND ABOVE.
[b] MAXIMUM OF 64.5 SQ CM CROSS-SECTIONAL AREA.
[c] THE A VALUES ARE HIGHER THAN S VALUES AS FOLLOWS: FTU = 807 MPA, FTY = 779 MPA, EL=11%.
[d] GRAIN DIRECTION NOT SPECIFIED.

TABLE 5.3.1.0(C). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF TI-5AL-2.5SN (EXTRUSIONS)

SPECIFICATION............	MIL-T-81556, TYPE II, COMP. A			
FORM....................	EXTRUDED BARS, RODS, AND SPECIAL SHAPED SECTIONS			
CONDITION...............	ANNEALED			
THICKNESS, MM...........	≤25.41	25.42-50.8[1]	50.82-76.21	76.22-101.60
BASIS...................	S	S	S	S
MECHANICAL PROPERTIES:				
FTU, MPA:				
L................	827	793	793	793
LT...............	...	...	...	...
FTY, MPA:				
L................	793	758	758	...
LT...............	...	...	...	...
FCY, MPA:				
L................	...	...	...	...
LT...............	...	...	...	...
FSU, MPA.............	...	...	...	...
FBRU, MPA:				
(E/D=1.5)..........	...	...	...	...
(E/D=2.0)..........	...	...	...	...
FBRY, MPA:				
(E/D=1.5)..........	...	...	...	...
(E/D=2.0)..........	...	...	...	...
EL, PERCENT:				
L................	10[a]	10	8	6
LT...............	...	...	...	...
E, GPA...............	106.9			
EC, GPA..............	106.9			
G, GPA...............	...			
MU...................	...			
PHYSICAL PROPERTIES:				
OMEGA, MG/M3.........	4.48			
C, J/(G*K)...........	SEE FIGURE 5.3.1.0			
K, W/(M*K)...........	SEE FIGURE 5.3.1.0			
ALPHA, 10-6 M/(M*K)..	SEE FIGURE 5.3.1.0			

[a]THICKNESS 1.575 MM AND ABOVE.

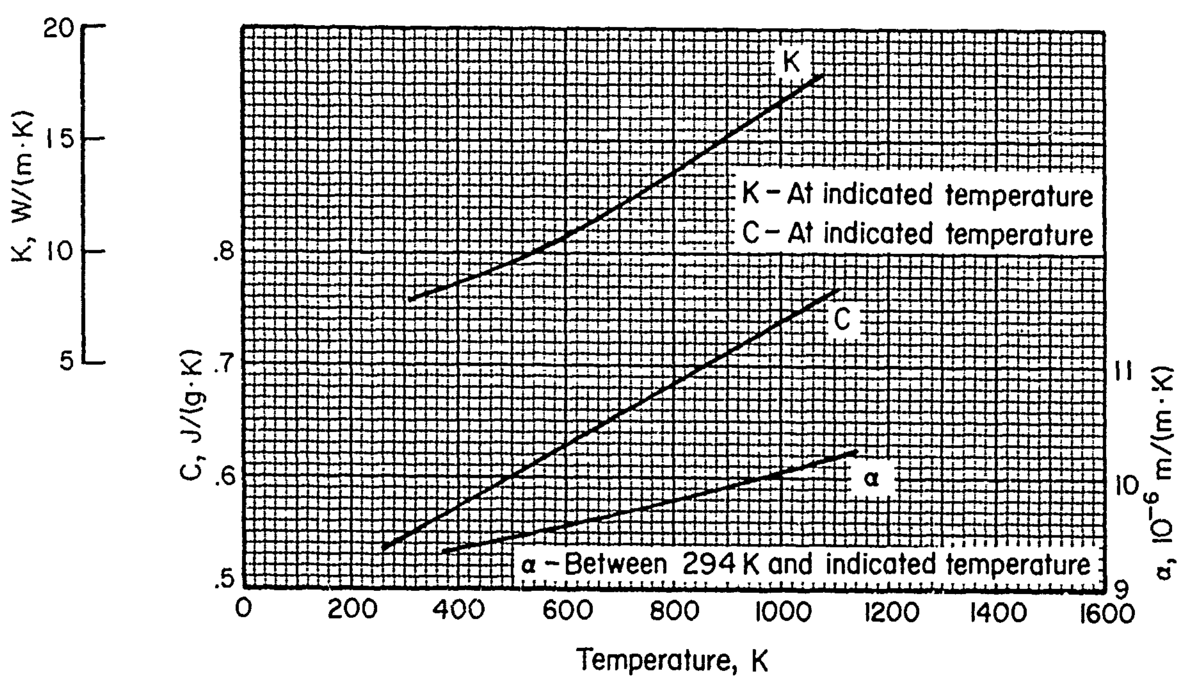


FIGURE 5.3.1.0. Effect of temperature on the physical properties of Ti-5Al-2.5Sn alloy.

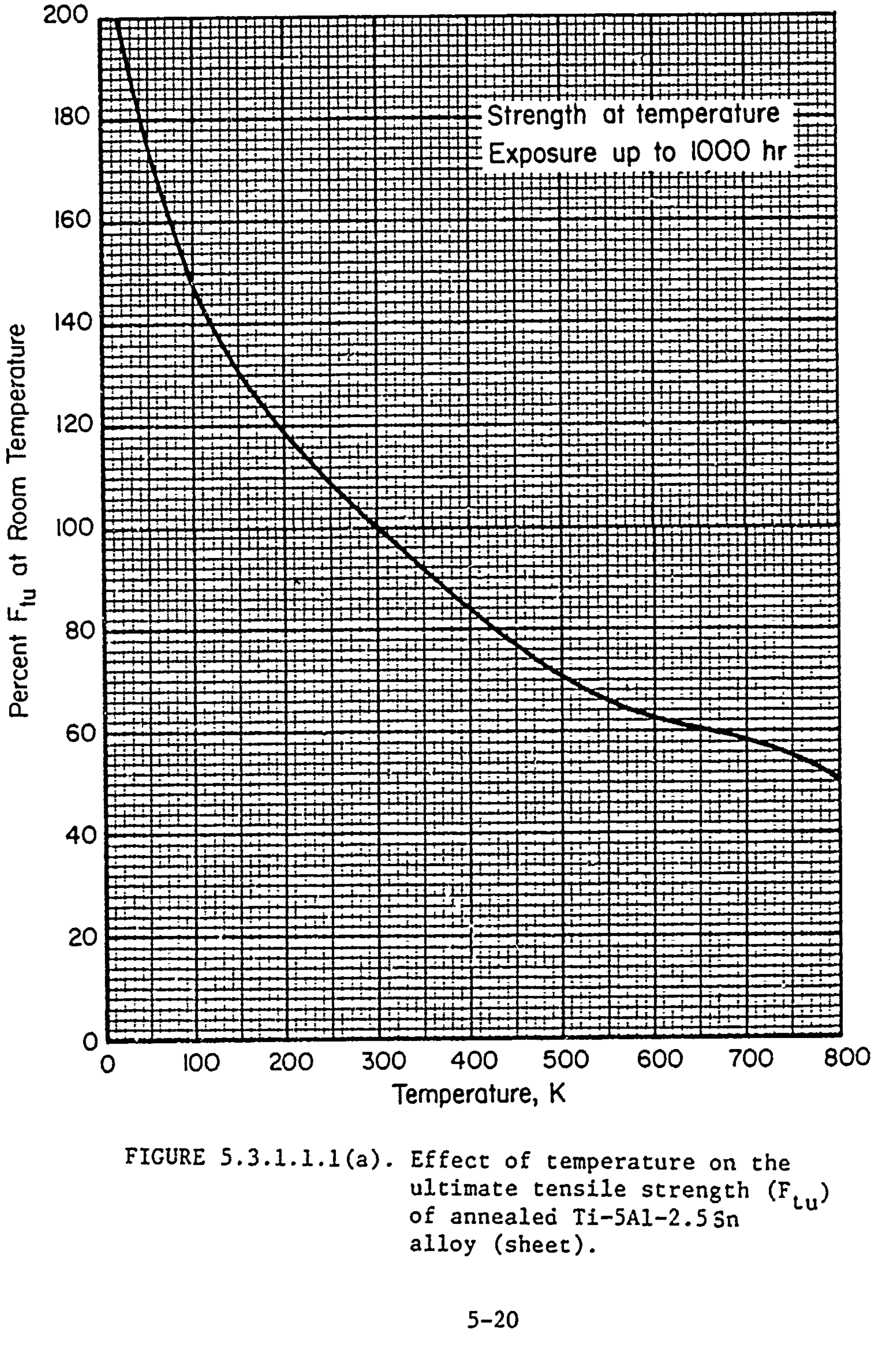


FIGURE 5.3.1.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of annealed Ti-5Al-2.5Sn alloy (sheet).

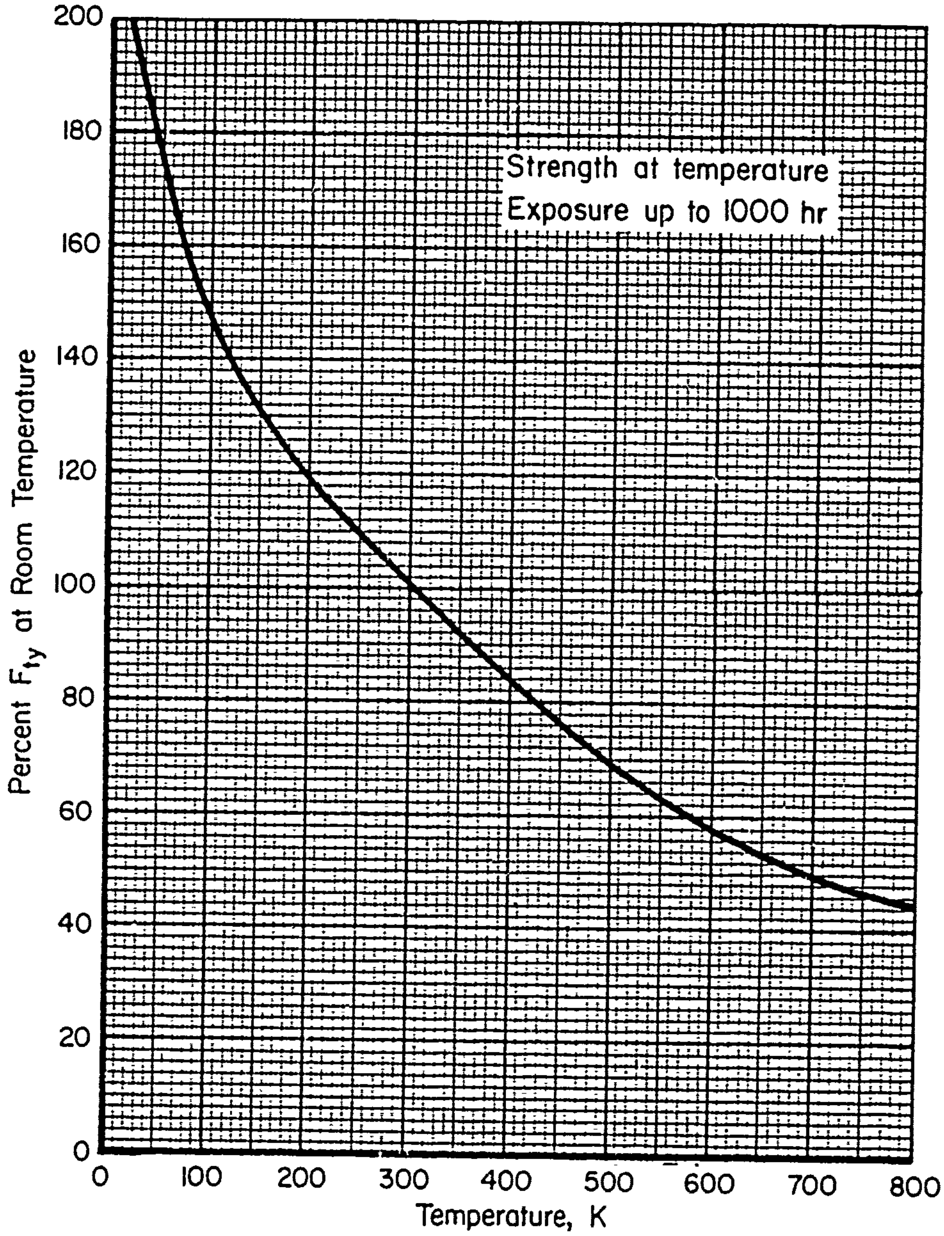


FIGURE 5.3.1.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of annealed Ti-5Al-2.5Sn alloy (sheet).

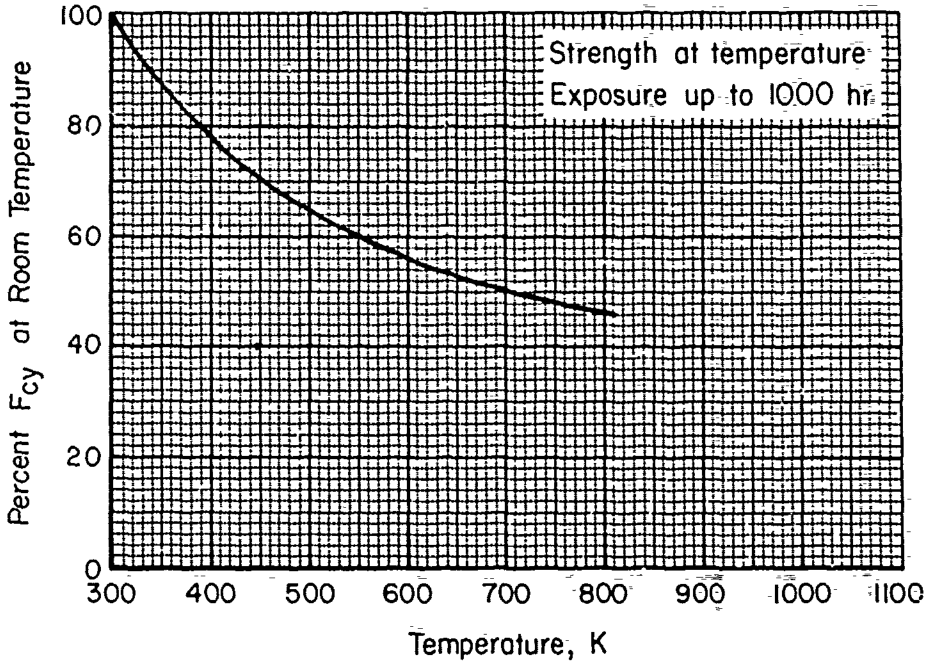


FIGURE 5.3.1.1.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of annealed Ti-5Al-2.5Sn alloy (sheet).

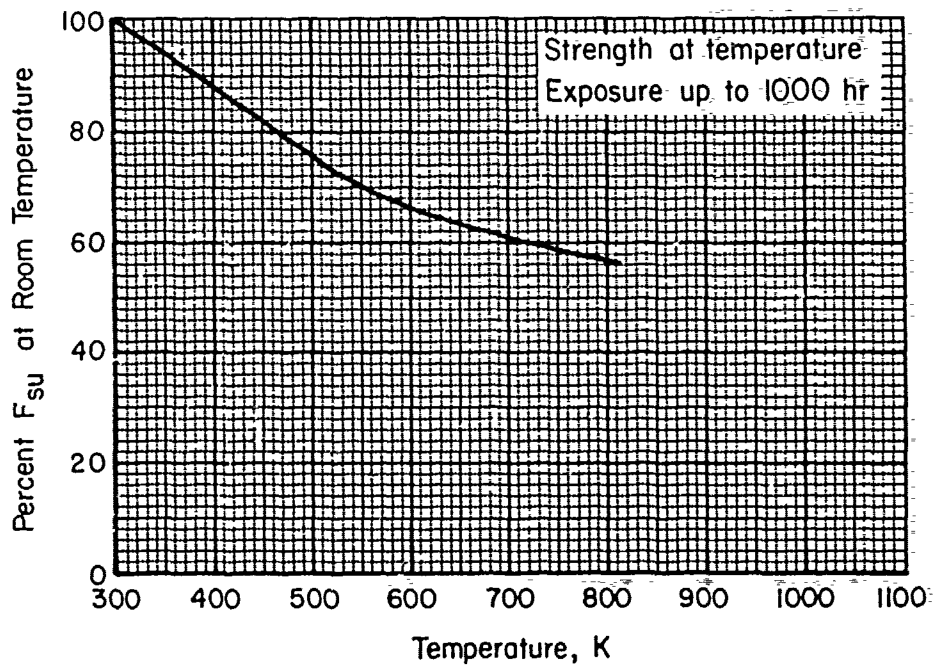


FIGURE 5.3.1.1.2(b). Effect of temperature on the ultimate shear strength (F_{su}) of annealed Ti-5Al-2.5Sn alloy (sheet).

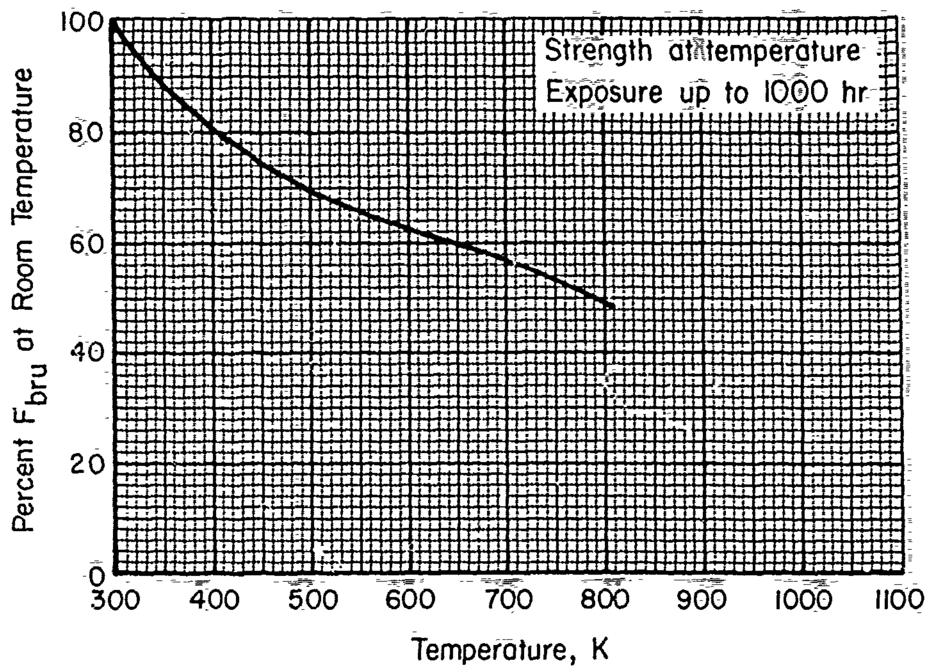


FIGURE 5.3.1.1.3(a). Effect of temperature on the ultimate bearing strength (F_{bru}) of annealed Ti-5Al-2.5Sn alloy (sheet).

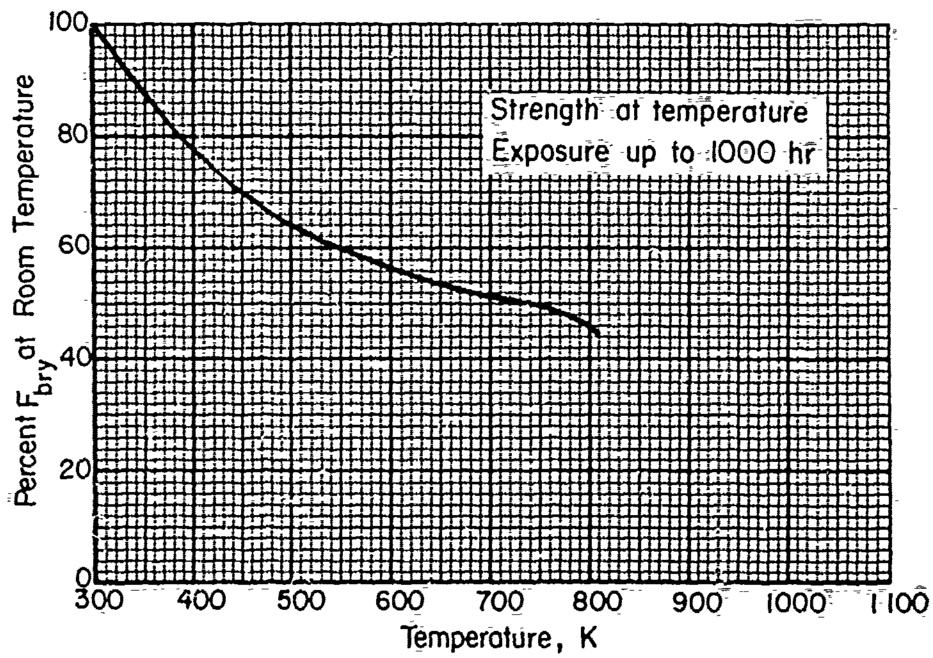


FIGURE 5.3.1.1.3(b). Effect of temperature on the bearing yield strength (F_{bry}) of annealed Ti-5Al-2.5Sn alloy (sheet).

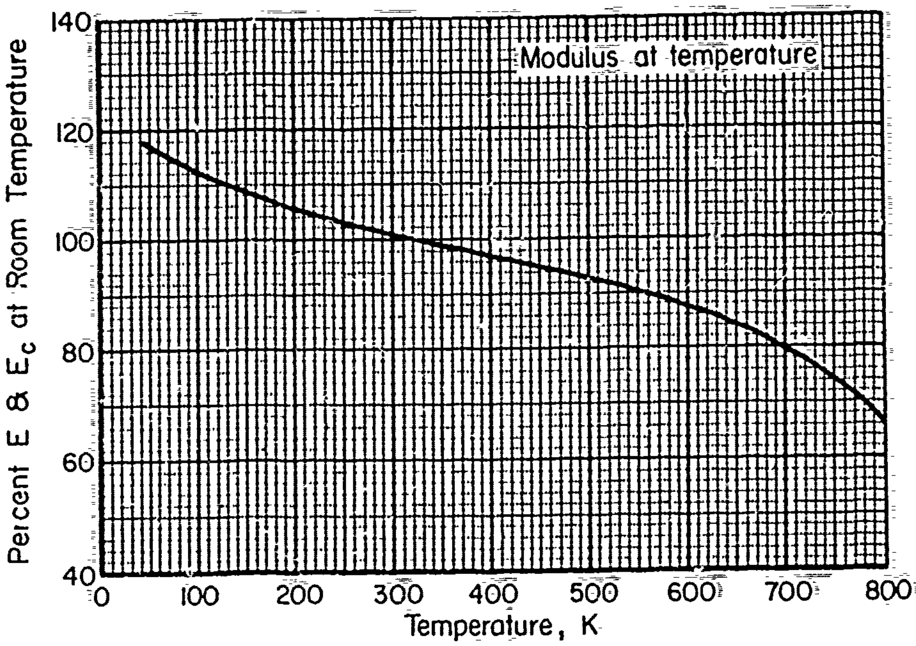


Figure 5.3.1.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of annealed Ti-5Al-2.5Sn alloy (sheet).

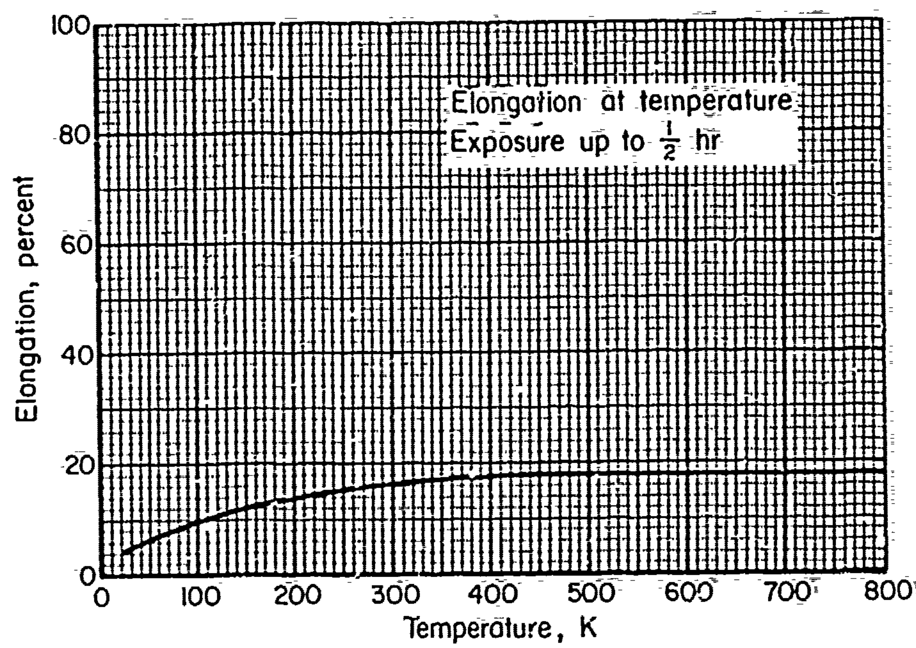


FIGURE 5.3.1.1.5. Effect of temperature on the elongation of annealed Ti-5Al-2.5Sn alloy (sheet).

5.3.2 Ti-8Al-1Mo-1V

5.3.2.0 *Comments.*—Ti-8Al-1Mo-1V alloy is a near-alpha composition developed in the late 1950's for improved creep resistance and thermal stability up to about 728K. The alloy is available as billet, bar, plate, sheet, strip, and extrusions, and is usually used in one of two annealed conditions.

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 728 K. A decrease in tensile elongation has been reported for single-annealed sheet following 150 hours stressed exposure at 811 K. Extended exposure to temperatures exceeding 589 K adversely affects room-temperature spot-weld tension strength. This alloy is not recommended for structural applications at liquid-hydrogen temperatures (20 K). 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.

Specifications.—Material specifications for Ti-8Al-1Mo-1V are presented in Table 5.3.2.0(a).

TABLE 5.3.2.0(a). *Material Specifications for Ti-8Al-1Mo-1V*

Specification	Form
MIL-T-9046	Sheet, strip, and plate
MIL-T-9047	Bars
AMS 4973	Forgings

Heat Treatment.—Two different annealing treatments are used with Ti-8Al-1Mo-1V. These are:

Single Anneal: 1061 K for 8 hours, furnace cool.

Duplex Anneal: 1061 K for 8 hours furnace cool, followed by 1061 K for 15 to 20 minutes, 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.

Room-Temperature Properties

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.

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(a) through 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 property curves for this condition are shown in Figures 5.3.2.2.1(a) and (b).

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.

Constant-life fatigue diagrams for unnotched and notched specimens at room temperature and several elevated temperatures are shown in Figures 5.3.2.2.8(a) through (f).

TABLE 5.3.2.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF TI-8AL-1MO-1V

SPECIFICATION	MIL-T-9046, TYPE II, COMP. F					MIL-T-9047, COMP. 5		AMS 4973	
FORM	SHEET	PLATE				BAR		FORGINGS	
CONDITION	SINGLE ANNEALED					SINGLE ANNEALED		DUPLEX ANNEALED	
THICKNESS, MM	≤4.76	4.77-12.71	12.72-25.41	25.42-63.51	63.52-101.60	63.52	63.52-101.60[b]	≤63.50	63.50-101.60
BASIS	S	S	S	S	S	S	S	S	S
MECHANICAL PROPERTIES:									
FTU, MPA:									
L	1000	1000	965	896	827	896	827	896	827[d]
LT	1000	1000	965	896	827	896	827	...	...
ST	...	...	...	...	827	896	827	...	...
FTY, MPA:									
L	931	931	896	827	758	827	758	827	758[d]
LT	931	931	896	827	758	827	758	...	...
ST	...	...	...	...	758	827	758	...	...
FCY, MPA:									
L	985	...	...	...	...	...	...	...	...
LT	986	...	...	...	...	...	...	...	...
ST	...	...	...	...	...	...	...	...	...
FSU, MPA	627	...	...	...	...	...	...	...	...
FBRU, MPA:									
(E/D=1.5)	...	...	...	...	...	...	...	...	...
(E/D=2.0)	2000	...	...	...	...	...	...	...	...
FBRY, MPA:									
(E/D=1.5)	...	...	...	...	...	...	...	...	...
(E/D=2.0)	1490	...	...	...	...	...	...	...	...
EL, PERCENT:									
L	a	10	10	10	8	10	10	10[d]	10
LT	a	10	10	10	8	10	10	...	...
ST	...	...	...	...	8	10	10	...	...
E, GPA	120.7[c]								
EC, GPA	124.1[c]								
G, GPA	46.2								
MU	0.32								
PHYSICAL PROPERTIES:									
OMEGA, MG/M3	4.37								
C, J/(G*K)	0.50								
K, W/(M*K)	SEE FIGURE 5.3.2.0								
ALPHA, 10-6 M/(M*K)	SEE FIGURE 5.3.2.0								

[a] 0.203-0.358 MM THICKNESS, 6 PERCENT; 0.369-0.610 MM THICKNESS, 8 PERCENT; > 0.635 MM THICKNESS, 10 PERCENT.
[b] MAXIMUM OF 64.5 SQ CM CROSS-SECTIONAL AREA.
[c] AVERAGE VALUES MAY VARY WITH TEST DIRECTION.
[d] GRAIN DIRECTION NOT SPECIFIED.

TABLE 5.3.2.0(c). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF TI-8AL-1MO-1V (SHEET, STRIP, AND PLATE)

SPECIFICATION..........	MIL-T-9046, TYPE II, COMP. F					
FORM..................	SHEET, STRIP AND PLATE					
CONDITION.............	DUPLEX ANNEALED					
THICKNESS, MM.........	<0.51	0.51-4.76	4.77-12.71	12.72-25.41	25.42-50.81	50.82-101.60
BASIS.................	S	S	S	S	S	S
MECHANICAL PROPERTIES:						
FTU, MPA:						
L..................	931	931	896	896	862	827
LT.................	931	931	896	896	862	827
FTY, MPA:						
L..................	827	827	827	827	793	758
LT.................	827	827	827	827	793	758
FCY, MPA:						
L..................	876	876	...	...	...	...
LT.................	876	876	...	...	...	...
FSU, MPA..............	...	...	...	...	...	...
FBRU, MPA:						
(E/D=1.5)..........	...	...	...	...	...	...
(E/D=2.0)..........	1790	1790	...	...	...	...
FBRY, MPA:						
(E/D=1.5)..........	...	...	...	...	...	...
(E/D=2.0)..........	1320	1320	...	...	...	...
EL, PERCENT:						
L..................	...	10[a]	10	10	10	8
LT.................	...	...	...	...	...	...
E, GPA................	120.7[b]					
EC, GPA...............	124.1[b]					
G, GPA................	46.2					
MU....................	0.32					
PHYSICAL PROPERTIES:						
OMEGA, MG/M3..........	4.37					
C, J/(G*K)............	0.50					
K, W/(M*K)............	SEE FIGURE 5.3.2.0					
ALPHA, 10-6 M/(M*K)..	SEE FIGURE 5.3.2.0					

[a] THICKNESS > 0.635 MM.
[b] AVERAGE, L AND LT: VALUES MAY VARY WITH TEST DIRECTION.

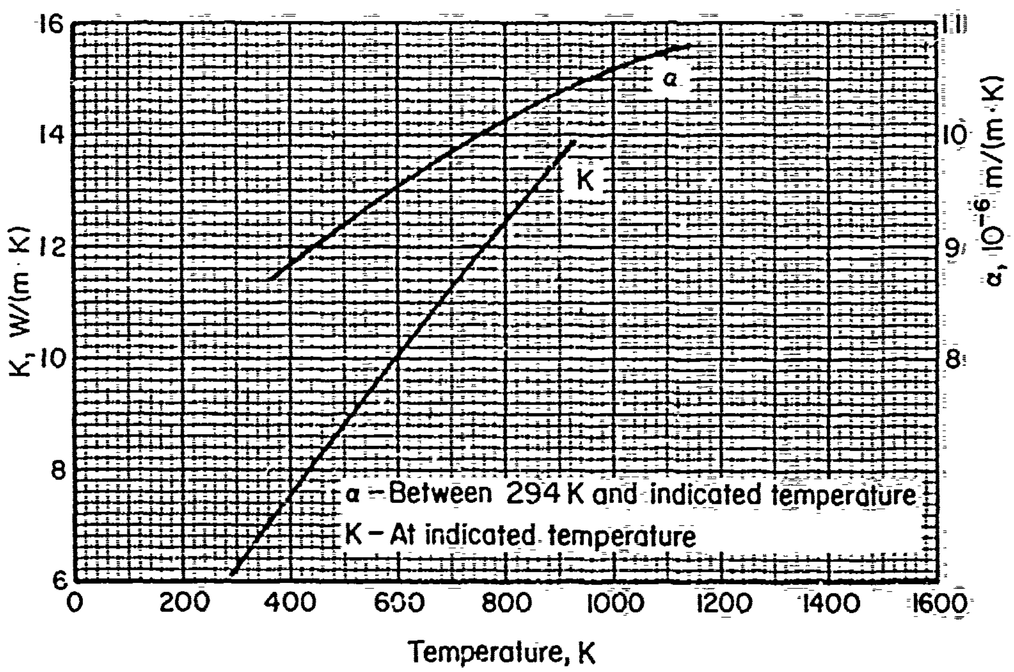


FIGURE 5.3.2.6. Effect of temperature on the physical properties of Ti-8Al-1Mo-1V alloy.

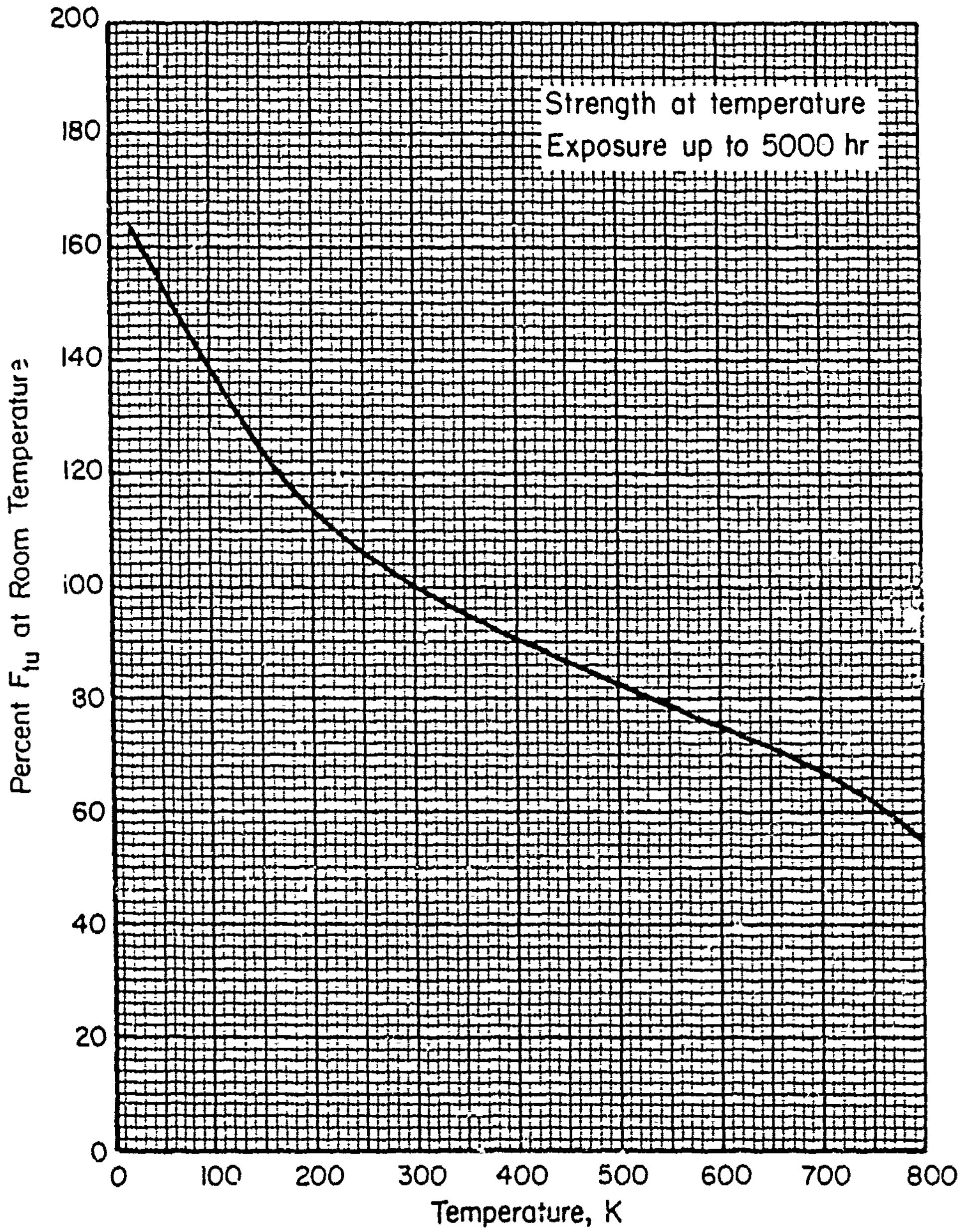


FIGURE 5.3.2.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of single annealed Ti-8Al-1Mo-1V alloy (sheet).

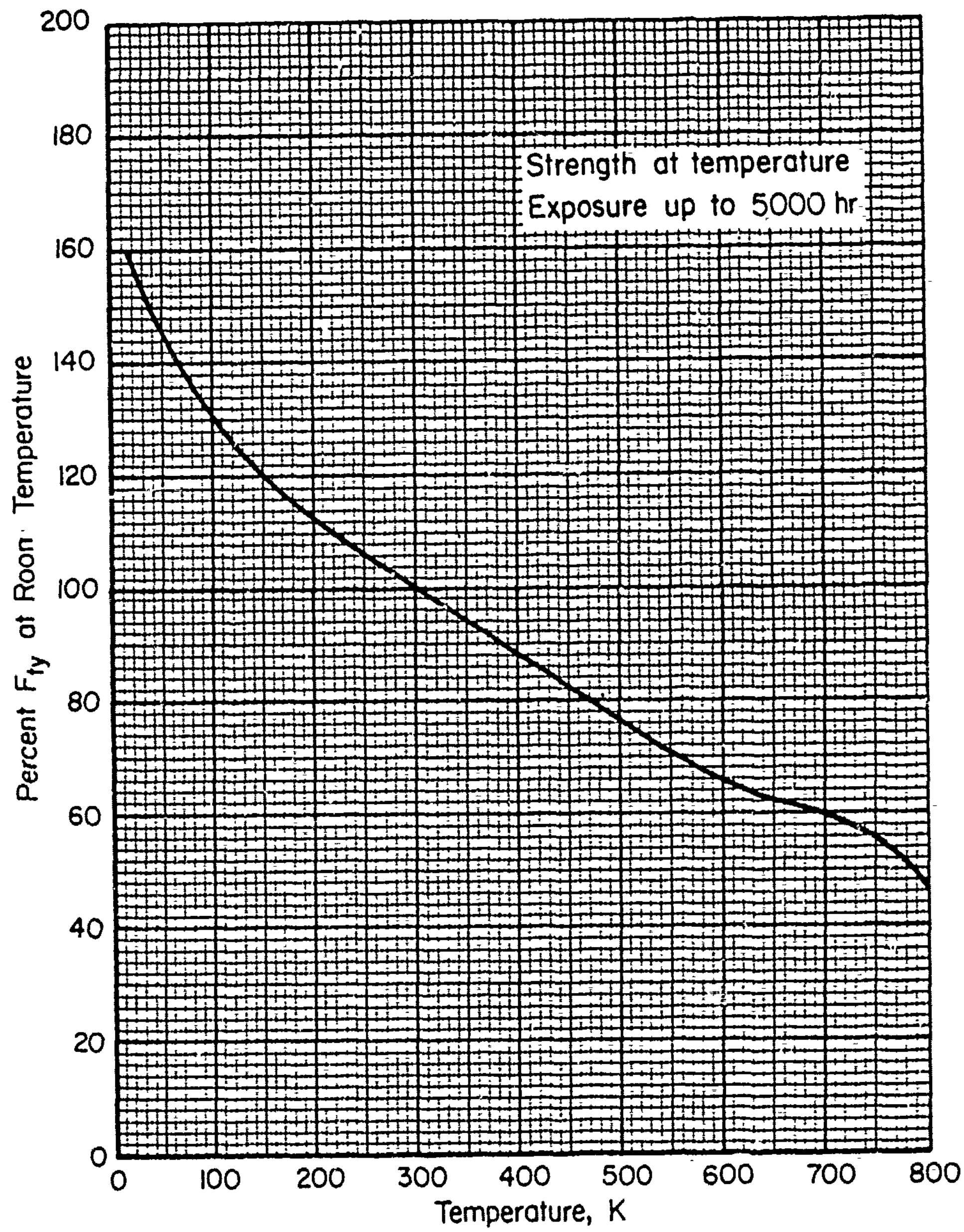


FIGURE 5.3.2.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of single annealed TI-8A1-1Mo-1V alloy (sheet).

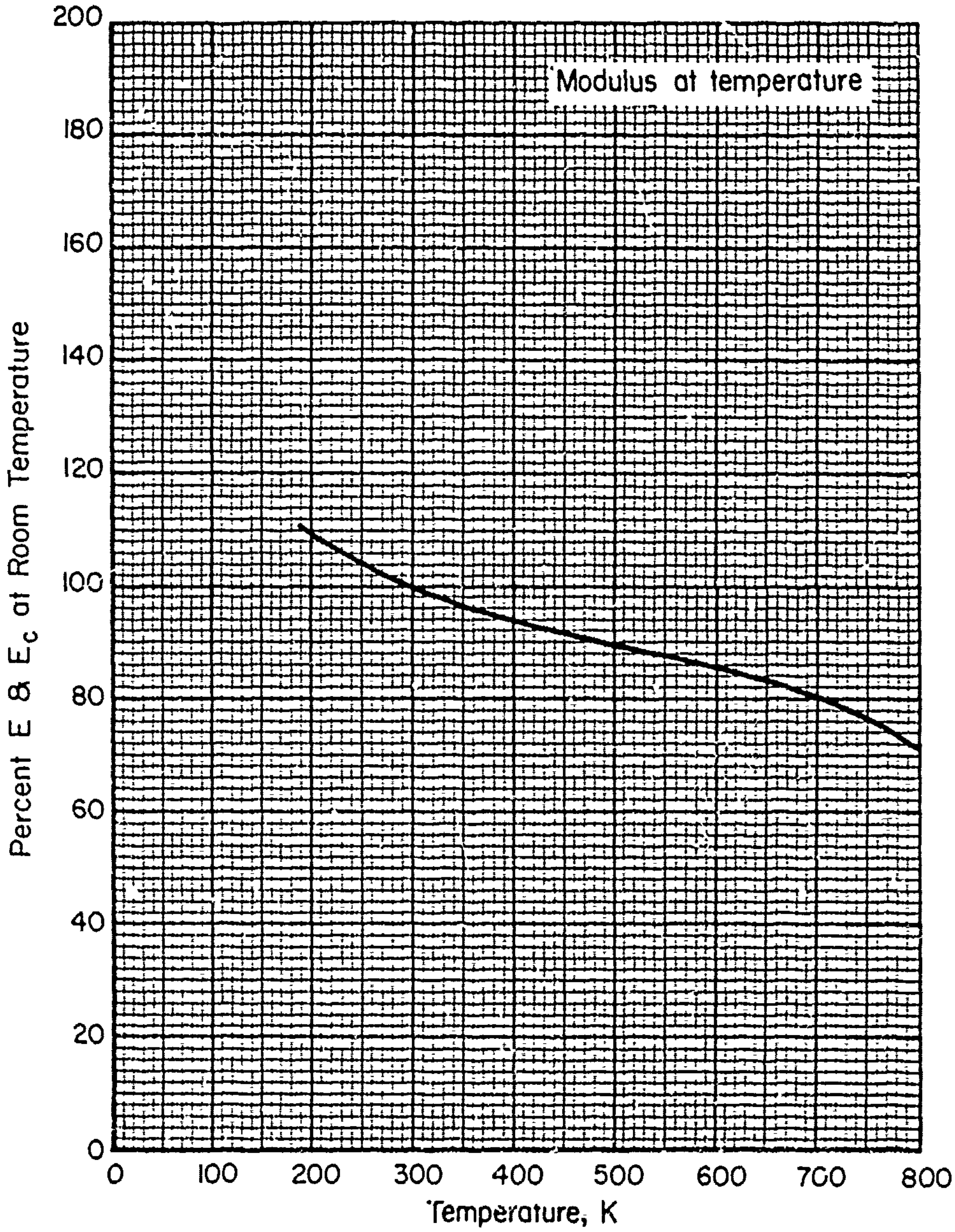


FIGURE 5.3.2.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of Ti-8Al-1Mo-1V alloy (sheet).

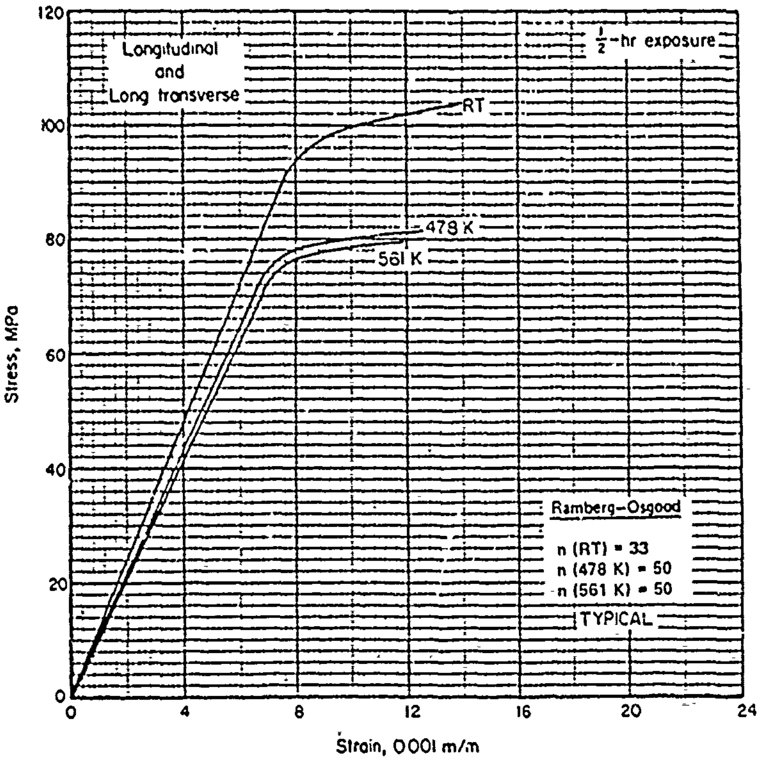


FIGURE 5.3.2.1.6(a). Typical tensile stress-strain curves for single-annealed Ti-8Al-1Mo-1V alloy (sheet) at room and elevated temperatures.

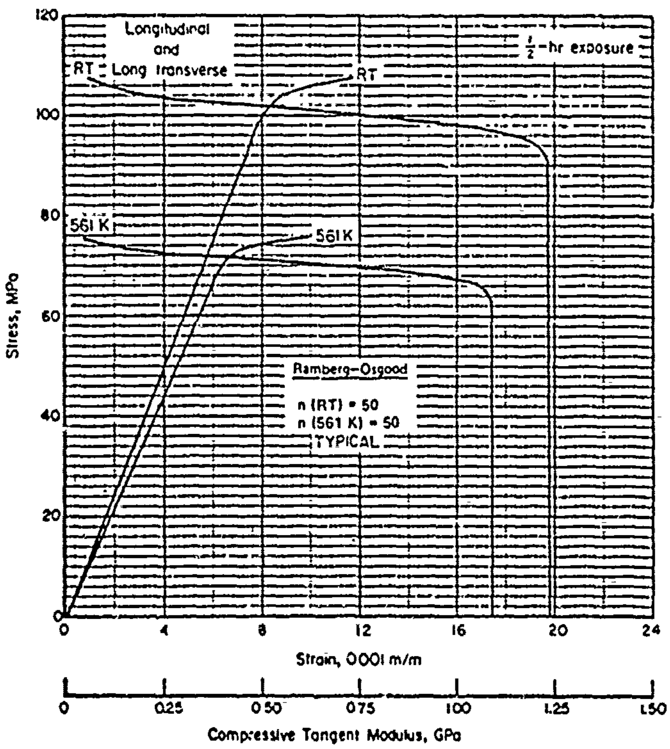


FIGURE 5.3.2.1.6(b). Typical compressive stress-strain curves for single-annealed Ti-8Al-1Mo-1V alloy (sheet) at room and elevated temperatures.

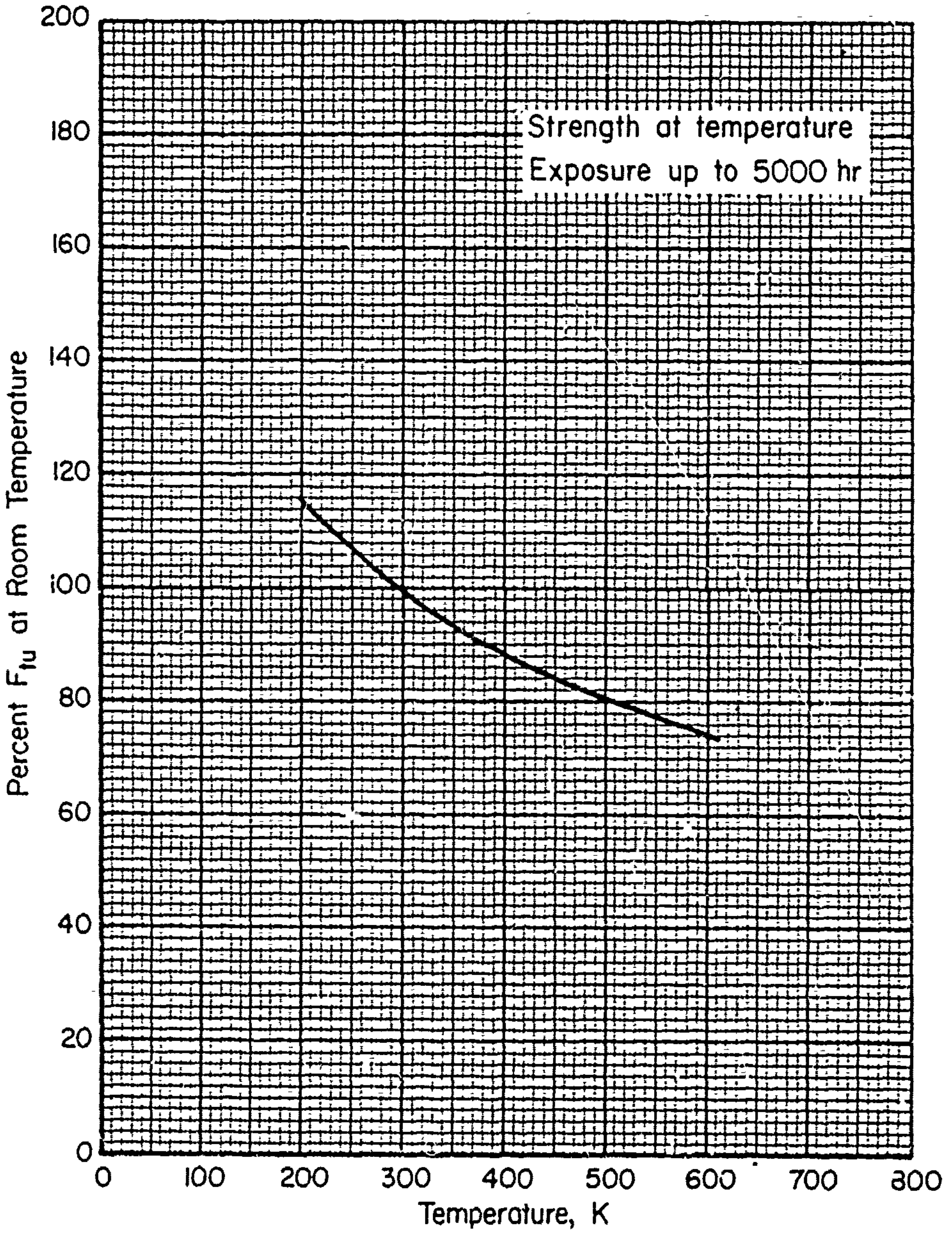


FIGURE 5.3.2.2.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of duplex-annealed Ti-8Al-1Mo-1V alloy (sheet).

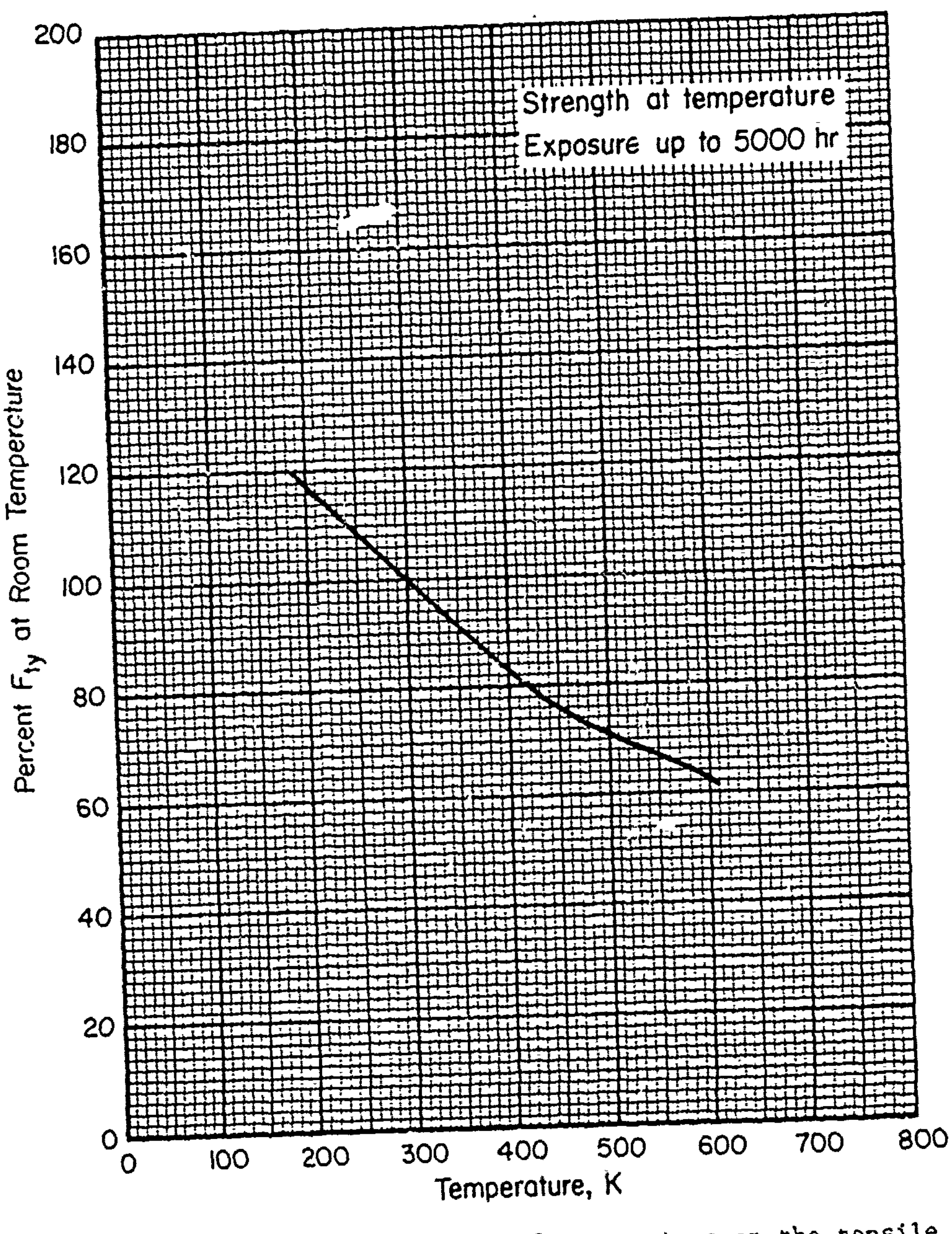


FIGURE 5.3.2.2.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of duplex-annealed Ti-8Al-1Mo-1V alloy (sheet).

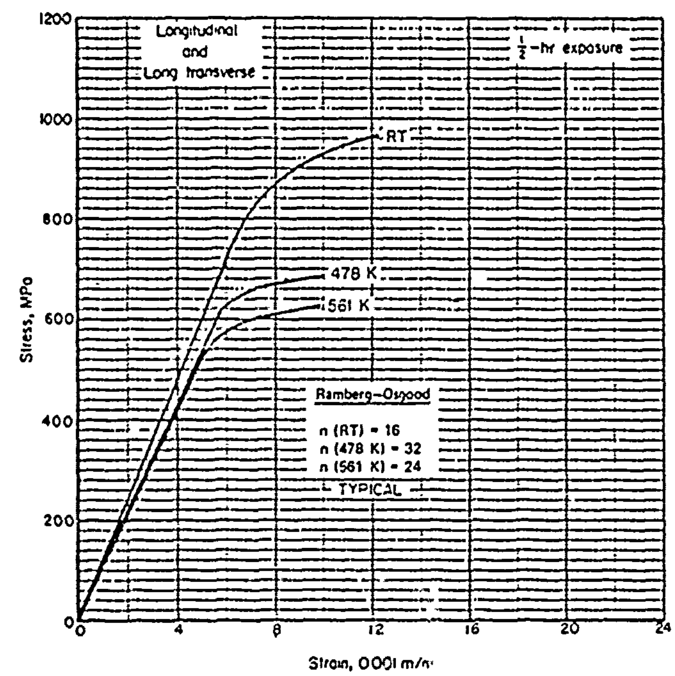


FIGURE 5.3.2.2.6(a). Typical tensile stress-strain curves for duplex-annealed Ti-8Al-1Mo-1V alloy (sheet) at room and elevated temperatures.

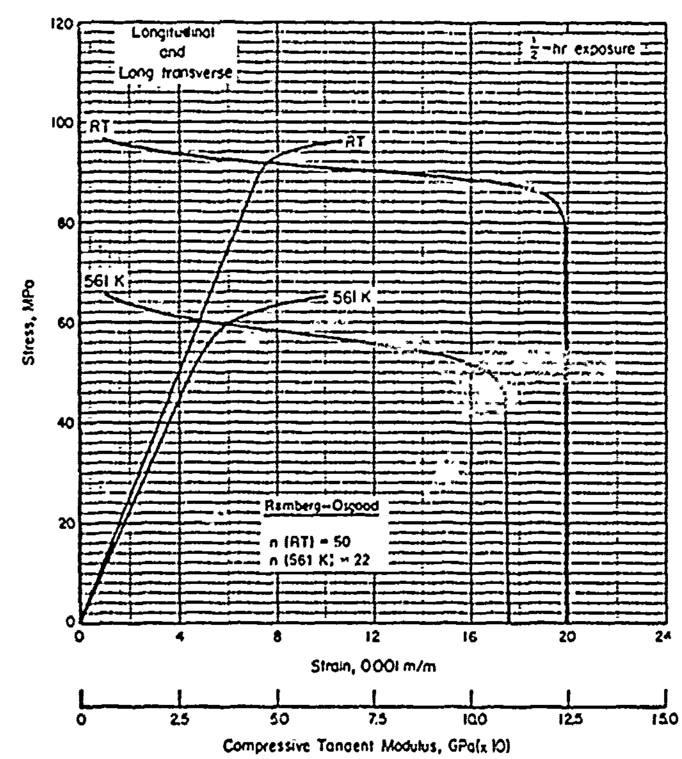


FIGURE 5.3.2.2.6(b). Typical compressive stress-strain and tangent-modulus curves for duplex-annealed Ti-8Al-1Mo-1V alloy (sheet) at room and elevated temperatures.

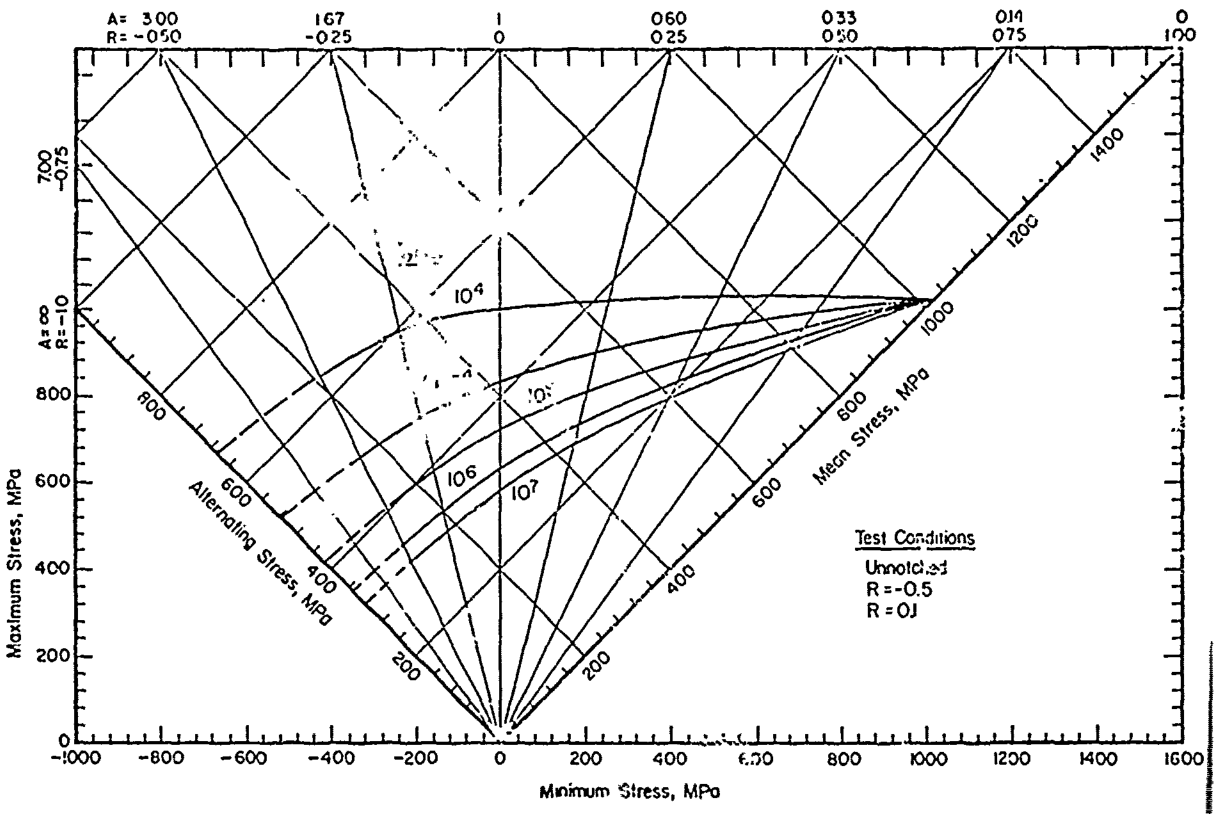


FIGURE 5.3.2. ·:(a). *Constant-life fatigue diagram for unnotched Ti-8Al-1Mo-1V alloy (sheet) at room temperature.*

Correlative Information for Figure 5.3.2.2.8(a)

Product Form: Sheet, 1.27 mm thick

Properties:

TUS, MPa	TYS, MPa	Temp, K
1020	938	RT (Unexposed)
1048	958	RT (Exposed)*

Test Parameters:
Loading—Axial
Frequency—1800 cpm
Temperature—RT
Atmosphere—Air

Specimen Details: Unnotched:
19.05 mm width

Surface Condition: HNO_3 pickled.

*Exposure: 172 MPa at 478 K, up to 5000 hours
172 MPa at 616 K, up to 5000 hours

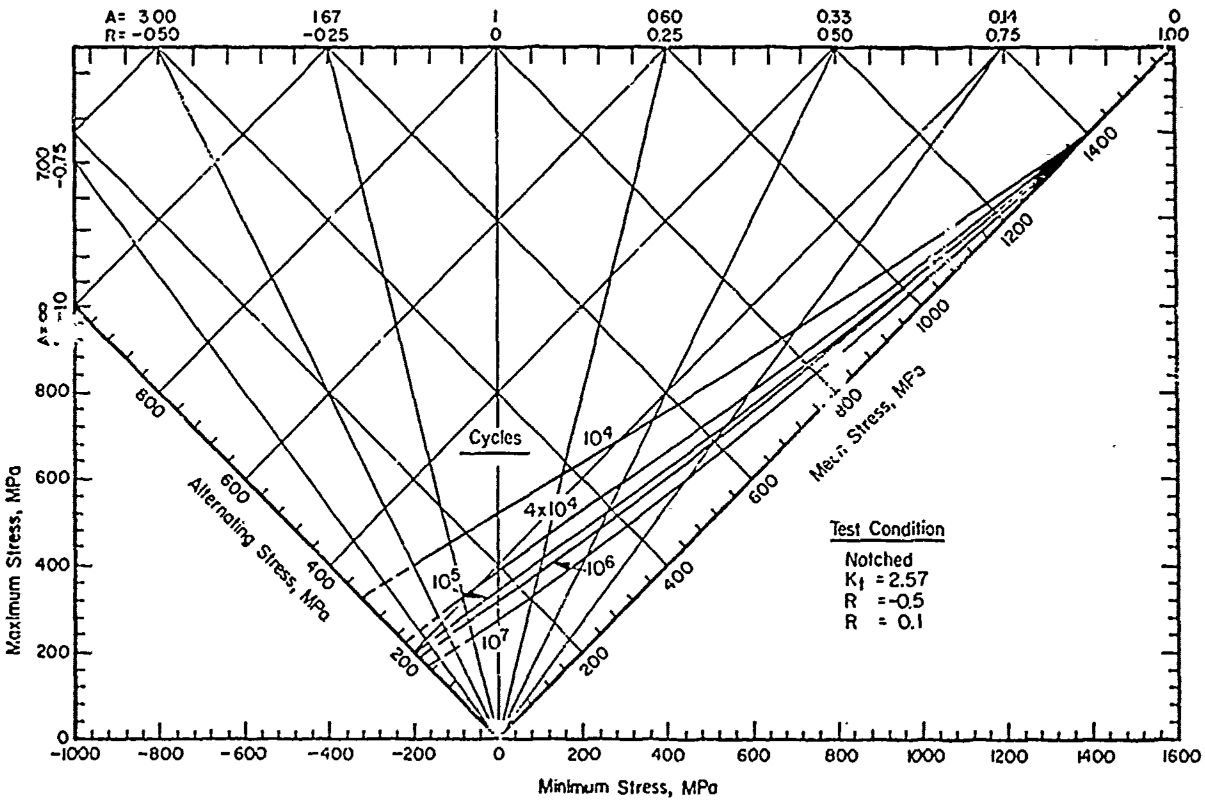


FIGURE 5.3.2.2.8(b). Constant-life fatigue diagram for notched Ti-6Al-1Mo-1V alloy (sheet) at room temperature

Correlative Information for Figure 5.3.2.2.8(b)

Product Form: Sheet, 1.27 mm thick

Test Parameters:
Loading—Axial
Frequency—1800 cpm
Temperature—RT
Atmosphere—Air

Properties:

TUS, MPa	TYS, MPa	Temp, K
1020	938	RT (Unnotched, unexposed)
1379 (est.)	—	RT (Notched, unexposed)
1048	958	RT (Exposed)*

Specimen Details:

Unnotched:
19.05 mm width

Notched, Hole type, $K_t = 2.57$
38.10 mm, gross width
31.75 mm, net width
6.35 mm - diameter hole

$K_N = 1.91$, $\rho = 1.702$ mm; where $K_N = 1 + \dfrac{K_t - 1}{1 + \frac{\pi}{\pi - \omega}\sqrt{\frac{\rho}{r}}}$

Surface Condition: HNO_3 pickled.

*Exposure: 172 MPa at 478 K, up to 5000 hours
172 MPa at 616 K, up to 5000 hours

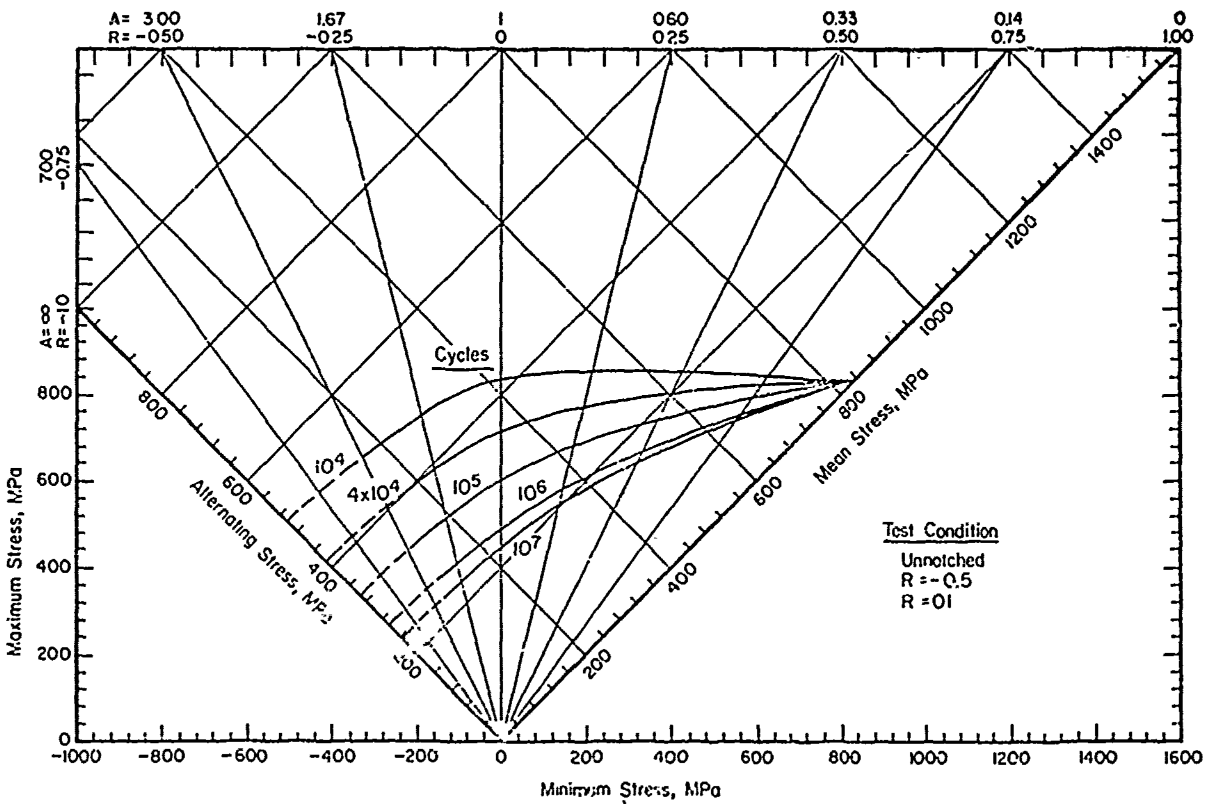


FIGURE 5.3.2.2.8(c). Constant-life fatigue diagram for unnotched Ti-8Al-1Mo-1V alloy (sheet) at 478 K

Correlative Information for Figure 5.3.2.2.8(c)

Product Form: Sheet, 1.27 mm thick

Properties:

TUS, MPa	TYS, MPa	Temp., K	
827	696	478	(Unexposed)
876	731	478	(Exposed)*

Specimen Details: Unnotched:
19.05 mm width

Surface Condition: HNO_3 pickled.

Test Parameters:
Loading—Axial
Frequency—1800 cpm
Temperature—478 K
Atmosphere—Air

*Exposure: 172 MPa at 478 K, up to 5000 hours
172 MPa at 533 K, up to 5000 hours

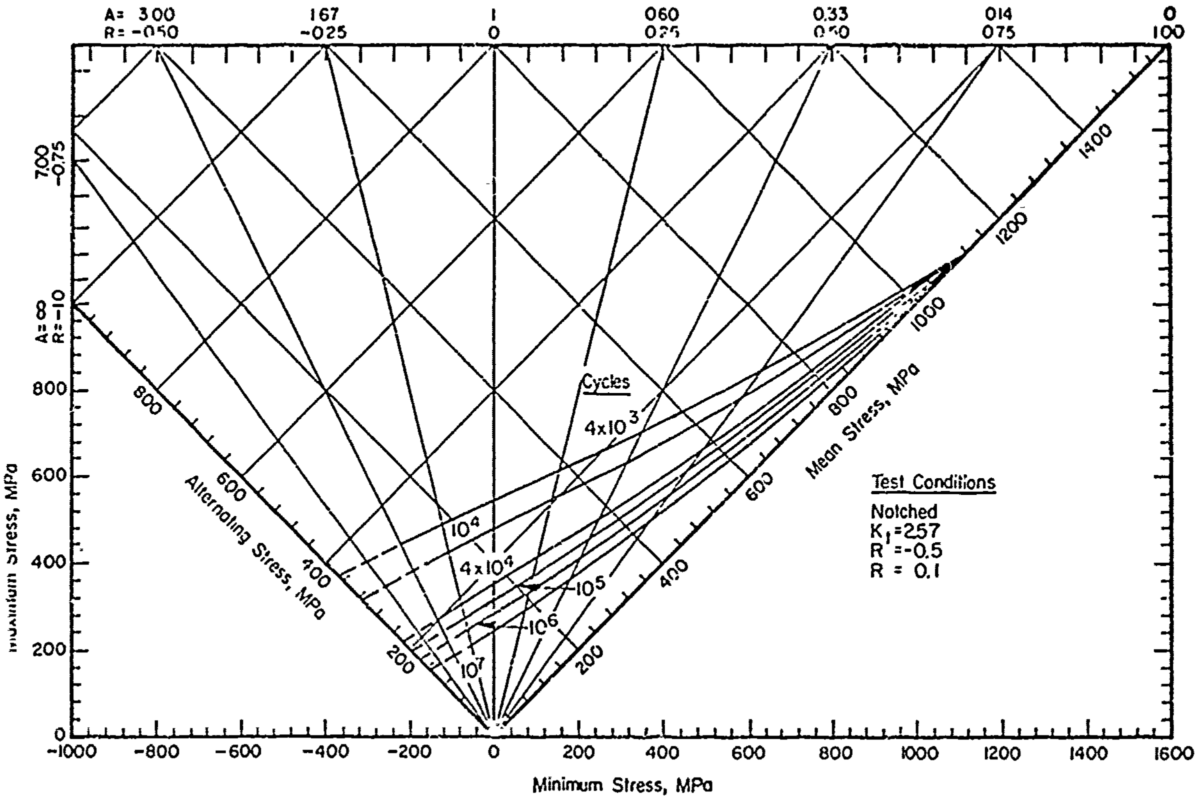


FIGURE 5.3.2.2.8(d). Constant-life fatigue diagram for notched Ti-8Al-1Mo-1V alloy (sheet) at 478 K

Correlative Information for Figure 5.3.2.2.8(d)

Product Form: Sheet, 1.27 mm thick

Properties:

TUS, MPa	TYS, MPa	Temp, K
827	696	478 (Unnotched, unexposed)
1103	--	478 (Exposed)*

Specimen Details: Unnotched: 19.05 mm width

Notched, Hole type, $K_t = 2.57$
38.10 mm, gross width
31.75 mm, net width
6.35 mm - diameter hole

$$K_N = 1.62, \rho = 7.62 \text{ mm, where } K_N = 1 + \frac{K_t - 1}{1 + \frac{\pi}{\pi - \omega}\sqrt{\frac{\rho}{r}}}$$

Surface Condition: HNO_3 pickled.

Test Parameters:
Loading—Axial
Frequency—1800 cpm
Temperature— 478 K
Atmosphere--Air

*Exposure: 172 MPa at 478 K, up to 5000 hours
172 MPa at 533 K, up to 5000 hours

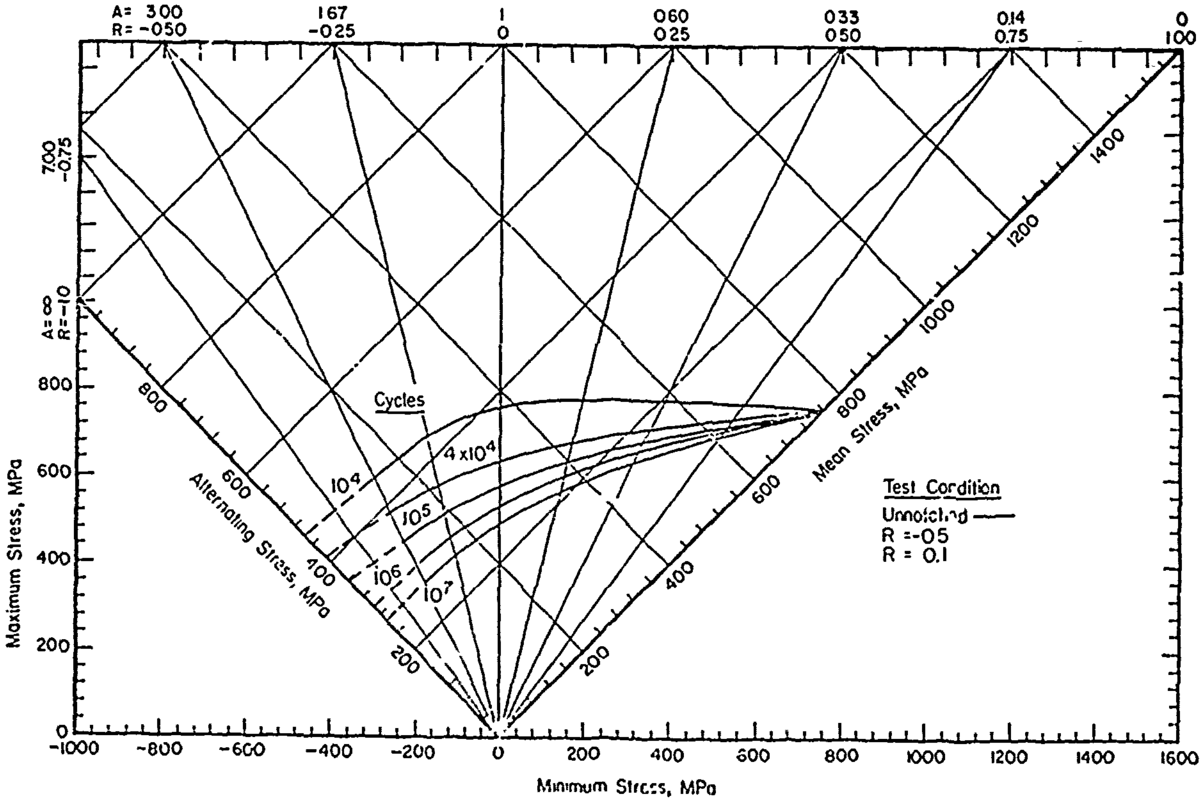


FIGURE 5.3.2.2.8(e). Constant-life fatigue diagram for unnotched Ti-8Al-1Mo-1V alloy (sheet) at 616 K

Correlative Information for Figure 5.3.2.2.8(e)

Product Form: Sheet, 1.27 mm thick

Properties:

TUS, MPa	TYS, MPa	Temp, K	
758	600	616	(Unexposed)
793	633	616	(Exposed)*

Specimen Details: Unnotched:
19.05 mm width

Surface Condition: HNO_3 pickled.

Test Parameters:
Loading—Axial
Frequency—1800 cpm
Temperature- 616 K
Atmosphere—Air

*Exposure: 172 MPa at 478 K, up to 5000 hours
172 MPa at 533 K, up to 5000 hours

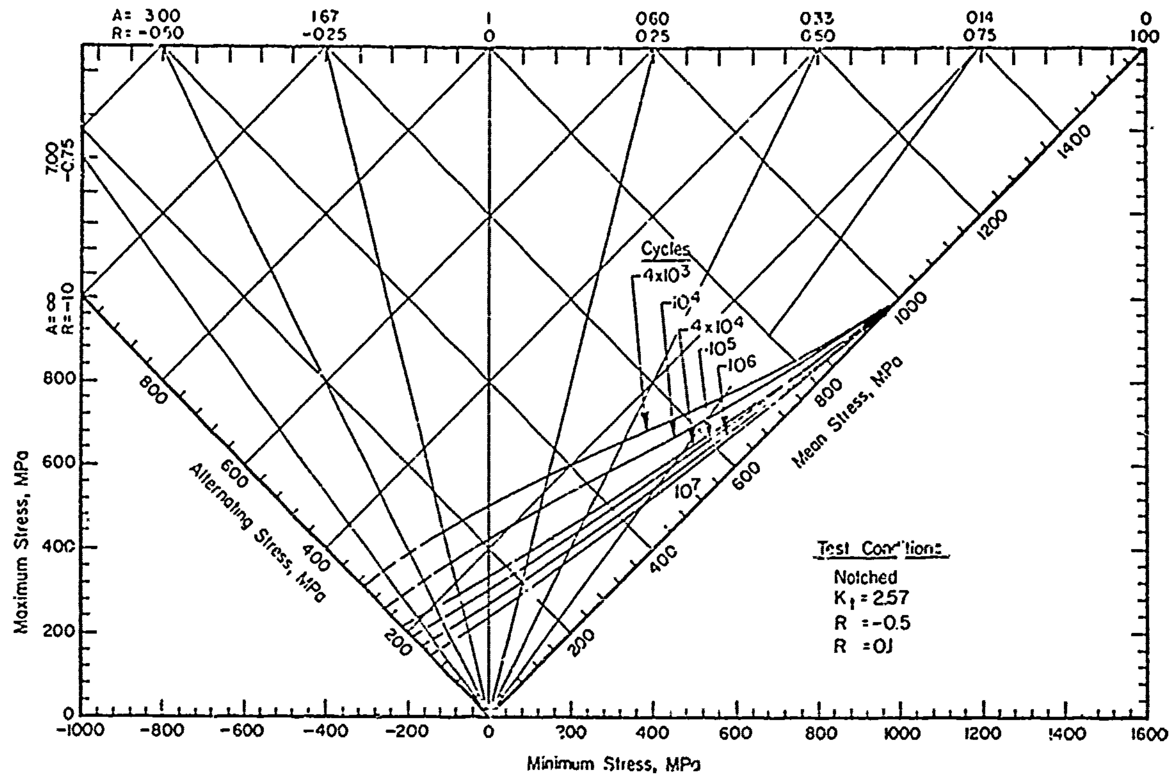


FIGURE 5.3.2.2.8(f). Constant-life fatigue diagram for notched Ti-8Al-1Mo-1V alloy (sheet) at 616 K

Correlative Information for Figure 5.3.2.2.8(f)

Product Form: Sheet, 1.27 mm thick

Properties:

TUS, MPa	TYS, MPa	Temp, K
758	600	616 (Unnotched, unexposed)
965	—	616 (Notched, unexposed)
793	621	616 (Unnotched, exposed)*

Test Parameters:
Loading—Axial
Frequency—1800 cpm
Temperature— 616 K
Atmosphere—Air

Specimen Details:

Unnotched:
19.05 mm width

Notched, Hole type, $K_t = 2.57$
38.10 mm, gross width
31.75 mm, net width
6.35 mm - diameter hole

$K_N = 1.85$, $\rho = 2.29$ mm, where $K_N = 1 + \frac{K_t - 1}{1 + \frac{\pi}{\pi - \omega}\sqrt{\frac{\rho}{r}}}$

Surface Condition: HNO_3 pickled.

*Exposure: 172 MPa at 478 K, up to 5000 hours
172 MPa at 533 K, up to 5000 hours

5.3.3 Ti-6Al-2Sn-4Zr-2Mo

5.3.3.0 *Comments.*—Ti-6Al-2Sn-4Zr-2Mo is a near-alpha titanium composition developed for improved elevated-temperature performance. It is creep resistant and relatively stable to about 839 K. The material is available in billet, bar, plate, sheet, strip, and extrusions.

Manufacturing Considerations.—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 other 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 (~780 K) do not adversely affect properties.

Specifications.—Material specifications for Ti-6Al-2Sn-4Zr-2Mo are given in Table 5.3.3.0(a).

TABLE 5.3.3.0(a). *Material Specifications for Ti-6Al-2Sn-4Zr-2Mo*

Specification	Form
MIL-T-9046	Sheet and strip
MIL-T-9047	Bars
AMS 4976	Forgings

Heat Treatment.—Several different annealing treatments, which are described below, are available for Ti-6Al-2Sn-4Zr-2Mo.

For sheet:

Single Anneal. 978–1089 K for 1 to 8 hours, slow cool to 839 K and air cool.

Duplex Anneal. 1172 K for 1/2 hour, air cool, followed by 1061 K for 1/4 hour, and air cool.

Triplex Anneal. 1172 K for 1/2 hour, air cool, followed by 1061 K for 1/4 hour, air cool, followed by 866 K for 2 hours and air cool.

For bars and forgings less than 64 mm in thickness:

Duplex Anneal. 1228 K for 1 hour, air cool, followed by 866 K for 8 hours and air cool.

For bars and forgings less than 64 mm in thickness:

Duplex Anneal: 1172 K (or 1228 K) for 1 hour, air cool, followed by 866 K for 8 hours and air cool.

For sheet, the triplex anneal offers higher uniaxial strength at room temperature. For bar and forging, the 1172 K treatment, along with the 866 K provides somewhat higher tensile strengths at room and elevated temperatures while the 1228 K treatment combined with 866 K results in superior creep resistance and improved elevated temperature stability.

Room-Temperature Properties

Room-temperature mechanical and physical properties for Ti-6Al-2Sn-4Zr-2Mo are presented in Table 5.3.3.0(b). The effect of temperature on physical properties is shown in Figure 5.3.3.0.

5.3.3.1 *Single, Duplex, and Triplex Annealed Condition.*—Room and elevated temperature property curves for these conditions are shown in Figures 5.3.3.1.1(a) through 5.3.3.1.4.

Typical stress-strain curves at room and elevated temperatures are shown in Figures 5.3.3.1.6(a) through (c).

TABLE 5.3.3.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF TI-6AL-2SN-4ZR-2MO

SPECIFICATION............	MIL-T-9046, TYPE III, COMP. G				MIL-T-9047 COMP. 11	AMS 4976
FORM....................	SHEET AND STRIP				BARS	FORGINGS
CONDITION...............	DUPLEX ANNEALED		TRIPLEX ANNEALED		ANNEALED	DUPLEX ANNEALED
THICKNESS, MM...........	≤4.76		≤4.76		≤76.20[a]	...
BASIS...................	A	B	A	B	S	S[f]
MECHANICAL PROPERTIES:						
FTU, MPA:						
L................	931[b]	986	993	1020	896	896
LT...............	931[b]	986	993	1020	896	...
ST...............	...	...	...	...	896	...
FTY, MPA:						
L................	862[c]	938	931	965	827	827
LT...............	862[c]	924	917	945	827	...
ST...............	...	...	...	...	827	...
FCY, MPA:						
L................	...	...	...	...	...	...
LT...............	...	...	...	...	...	...
ST...............	...	...	...	...	...	...
FSU, MPA.............	...	...	...	...	...	...
FBRU, MPA:						
(E/D=1.5).........	...	...	...	...	...	...
(E/D=2.0).........	...	...	...	...	...	...
FBRY, MPA:						
(E/D=1.5).........	...	...	...	...	...	...
(E/D=2.0).........	...	...	...	...	...	...
EL, PERCENT:						
L................	8[d]	...	9[e]	...	10	10
LT...............	8[d]	...	9[e]	...	10	...
ST...............	...	...	...	...	...	...
E, GPA...............	113.8					
EC, GPA..............	...					
G, GPA...............	42.7					
MU...................	0.32					
PHYSICAL PROPERTIES:						
OMEGA, MG/M3..........	4.54					
C, J/(G*K)............	...					
K, W/(M*K)............	...					
ALPHA, 10-6 M/(M*K)..	7.74 (473K); 8.1.0 (590-811K)					

[a] MAXIMUM OF 64.5 SQ CM CROSS-SECTIONAL AREA.

[b] THE A VALUES ARE HIGHER THAN SPECIFICATION VALUES AS FOLLOWS: FTU(L+LT) = 958 MPA.

[c] THE A VALUES ARE HIGHER THAN SPECIFICATION VALUES AS FOLLOWS: FTY(L) = 903 MPA, FTY(LT) = 889 MPA.

[d] A VALUE BASED ON ≥ 0.406 MM THICKNESS; SPECIFICATION VALUE IS 8% FOR < 0.508 MM THICKNESS.

[e] A VALUE BASED ON ≥ 0.660 MM THICKNESS; SPECIFICATION VALUE IS 8% FOR <0.508 MM THICKNESS.

[f] GRAIN DIRECTION NOT SPECIFIED.

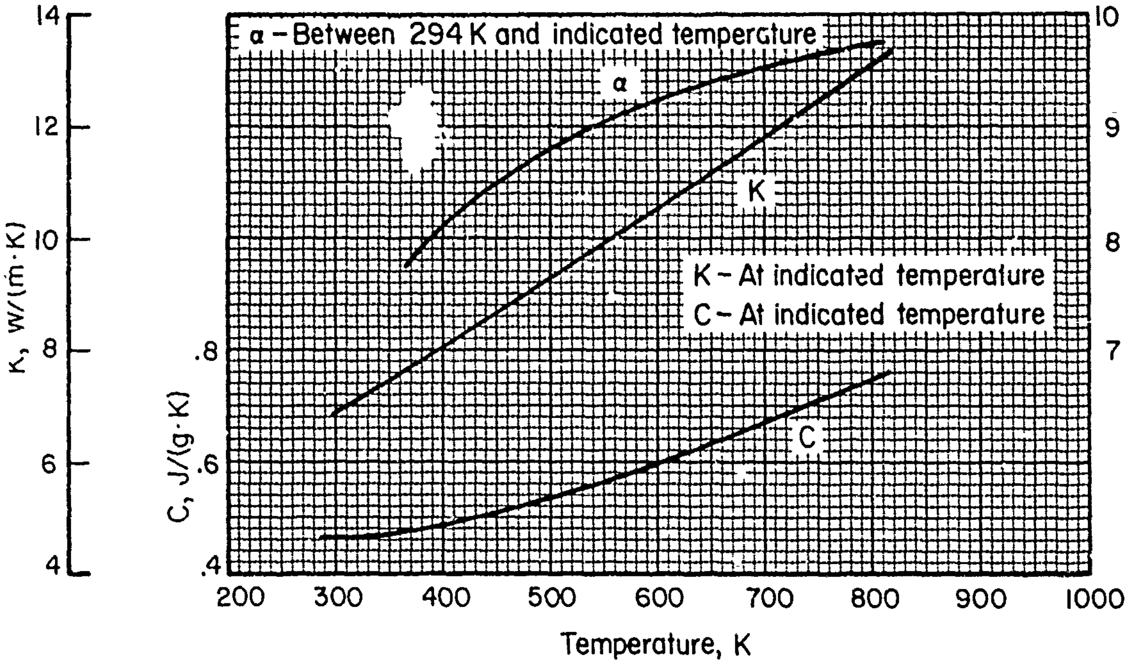


FIGURE 5.3.3.0. Effect of temperature on the physical properties of Ti-6Al-2Sn-4Zr-2Mo alloy.

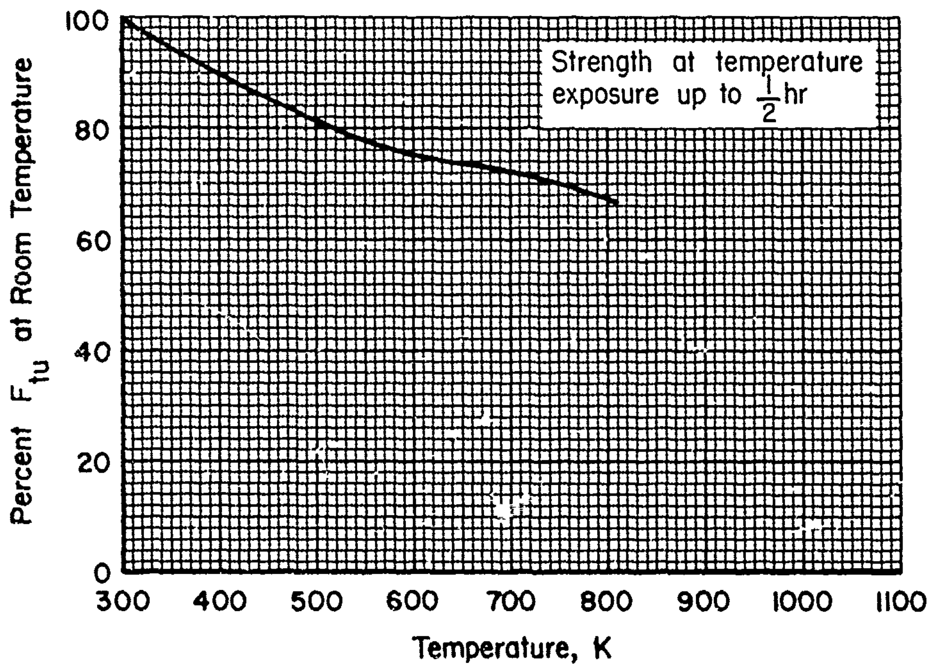


FIGURE 5.3.3.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of single, duplex, and triplex annealed Ti-6Al-2Sn-4Zr-2Mo alloy.

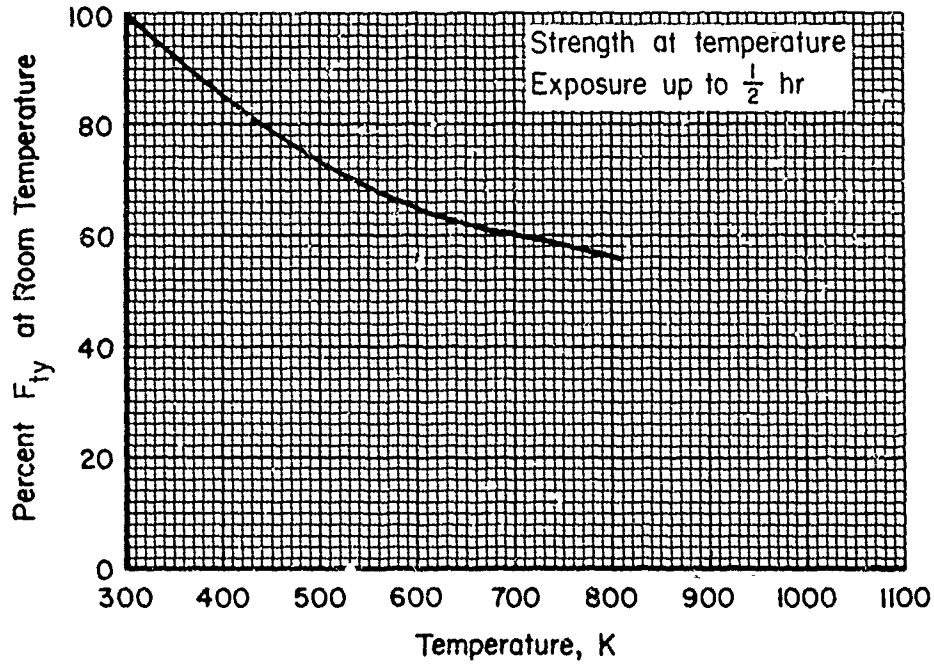


FIGURE 5.3.3.1.1(b). Effect of temperature in the tensile yield strength (F_{ty}) of single, duplex, and triplex annealed Ti-6Al-3Sn-4Zr-2Mo alloy.

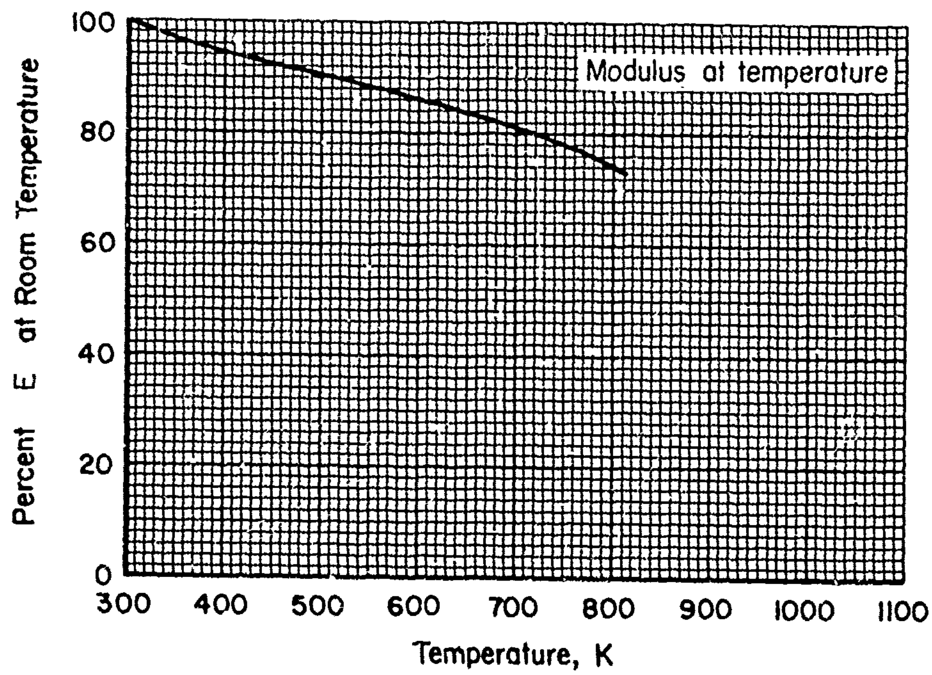


FIGURE 5.3.3.1.4. Effect of temperature on the tensile modulus (E) of single, duplex, and triplex annealed Ti-6Al-2Sn-4Zr-2Mo alloy.

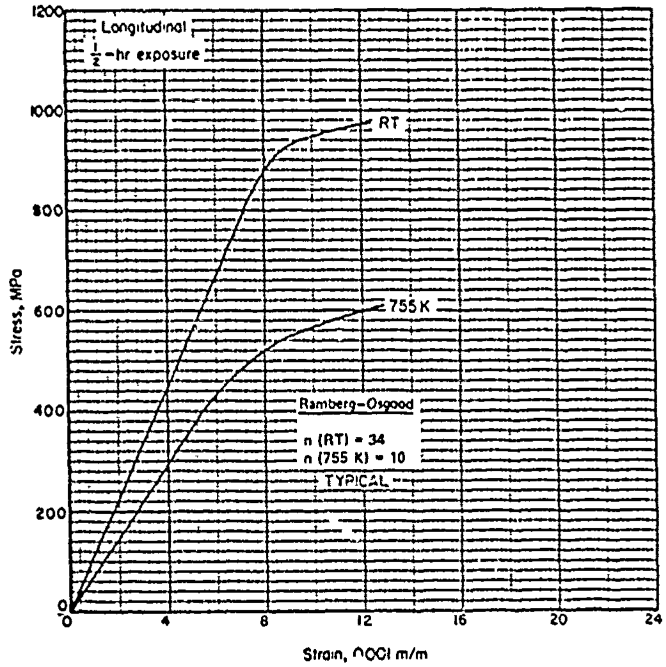


FIGURE 5.3.3.1.6(a). Typical tensile stress-strain curves for duplex-annealed Ti-6Al-2Sn-4Zr-2Mo alloy (bar) at various temperatures.

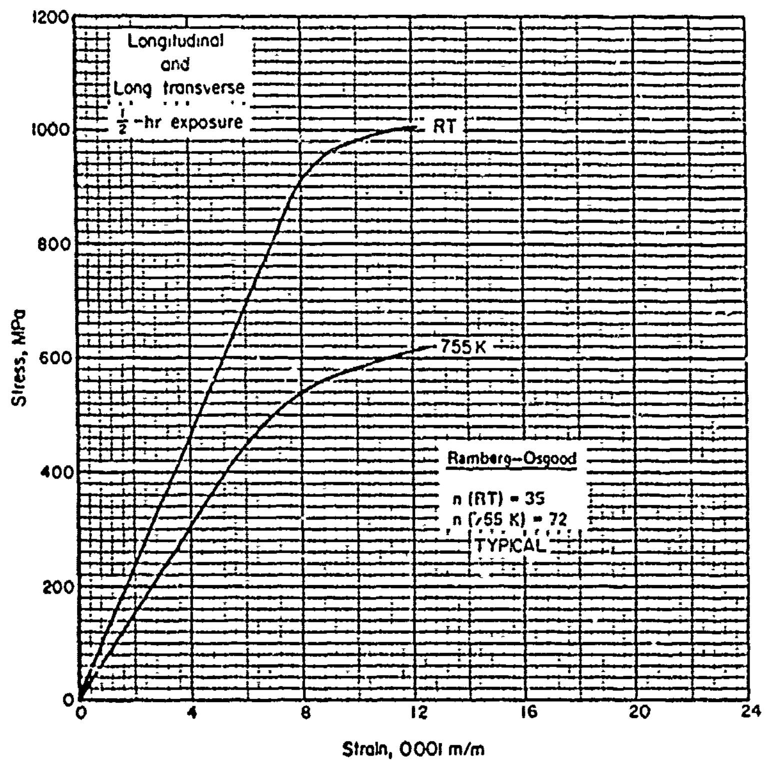


FIGURE 5.3.3.1.6(b). Typical tensile stress-strain curves for duplex and triplex annealed Ti-6Al-2Sn-4Zr-2Mo alloy (sheet) at various temperatures.

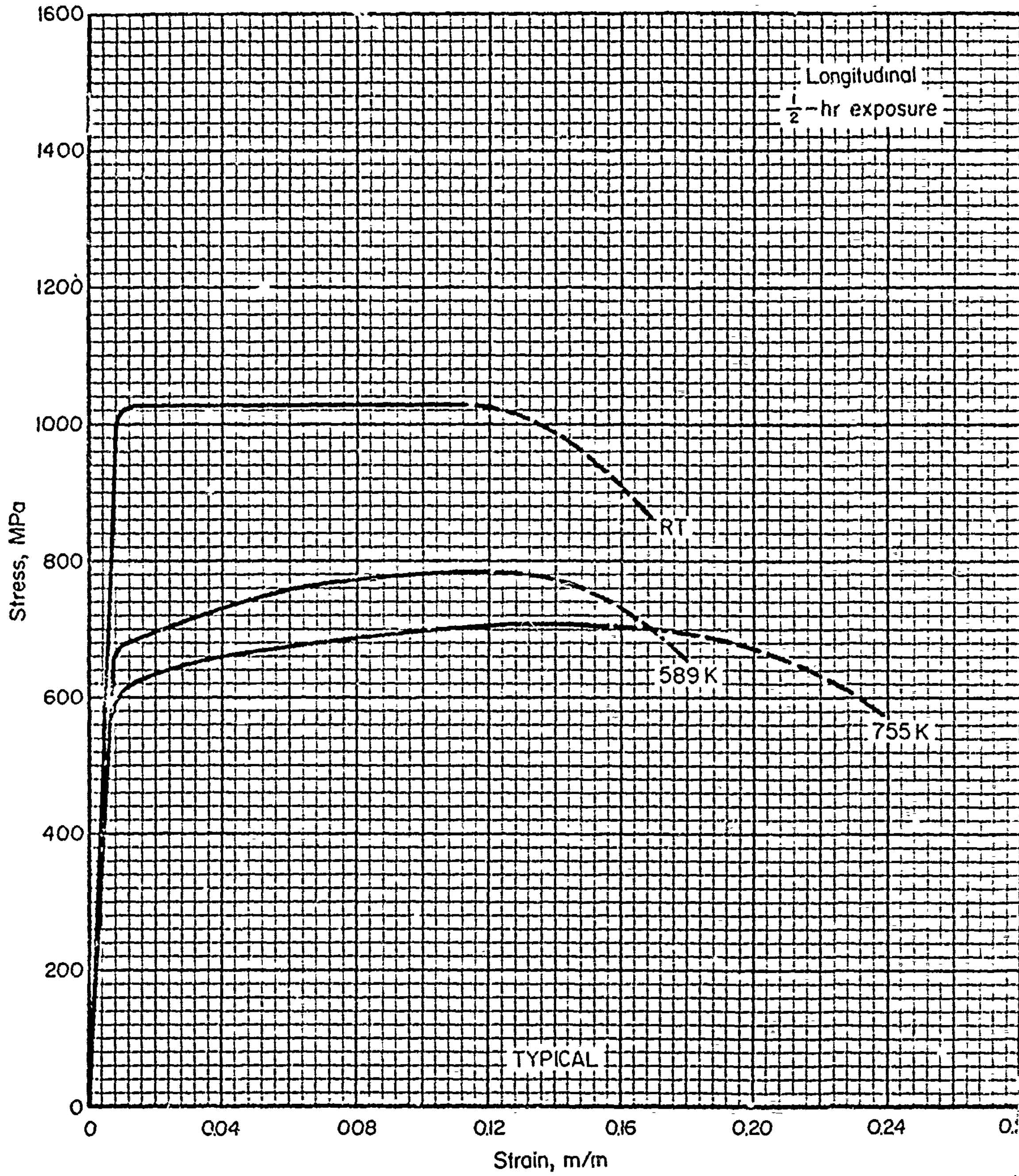


FIGURE 5.3.3.1.6(c). Typica. tensile stress-strain curves (full range) for duplex annealed Ti-6Al-2Sn-4Zr-2Mo alloy (sheet) at room and elevated temperatures.

5.3.4 Ti-11Sn-5Zr-2Al-1Mo

5.3.4.0 *Comments.*—Ti-11Sn-5Zr-2Al-1Mo alloy, commonly called Ti-679, is near-alpha titanium composition which is distinct from other near-alpha alloys because of the low aluminum and high tin contents and because of the intentional silicon addition (~0.2 percent). The alloy is available in the form of billet and bar. The alloy is intended for applications requiring high-temperature creep strength, stability and short-time strength properties to 755 K. The alloy is noted for its creep resistance but not for its weldability.

Manufacturing Considerations.—Initial forging of Ti-11Sn-5Zr-2Al-1Mo alloy may be done at temperatures as high as 1269 K, although finish forging should be accomplished below 1186 K. Since a range of mechanical properties are available from this alloy depending upon processing and heat treatment, it is desirable to follow producer recommendations carefully.

Environmental Considerations.—Ti-11Sn-5Zr-2Al-1Mo is unstable in stressed exposure at temperatures above 755 K in times as short as 100 hours. However, good stability exists at temperatures up to 755 K. The threshold stress for hot-salt stress-corrosion at 755 K is 276 MPa (2500 hours) which is superior to some other titanium alloys (e.g., Ti-8Al-1Mo-1V). The material is marginally susceptible to aqueous chloride solution stress corrosion.

Specifications.—A material specification for Ti-11Sn-5Zr-2Al-1Mo is presented in Table 5.3.4.0(a).

TABLE 5.3.4.0(a). *Material Specification for Ti-11Sn-5Zr-2Al-1Mo*

Specification	Form
MIL-T-9047	Bars

Room-Temperature Properties

Room-temperature mechanical and physical properties for Ti-11Sn-5Zr-2Al-1Mo are presented in Table 5.3.4.0(b). The effect of temperature on physical properties is shown in Figure 5.3.4.0.

5.3.4.1 *Annealed Condition.*—Effect of temperature curves for annealed Ti-11Sn-5Zr-2Al-1Mo are presented in Figures 5.3.4.1.1(a) through 5.3.4.1.5.

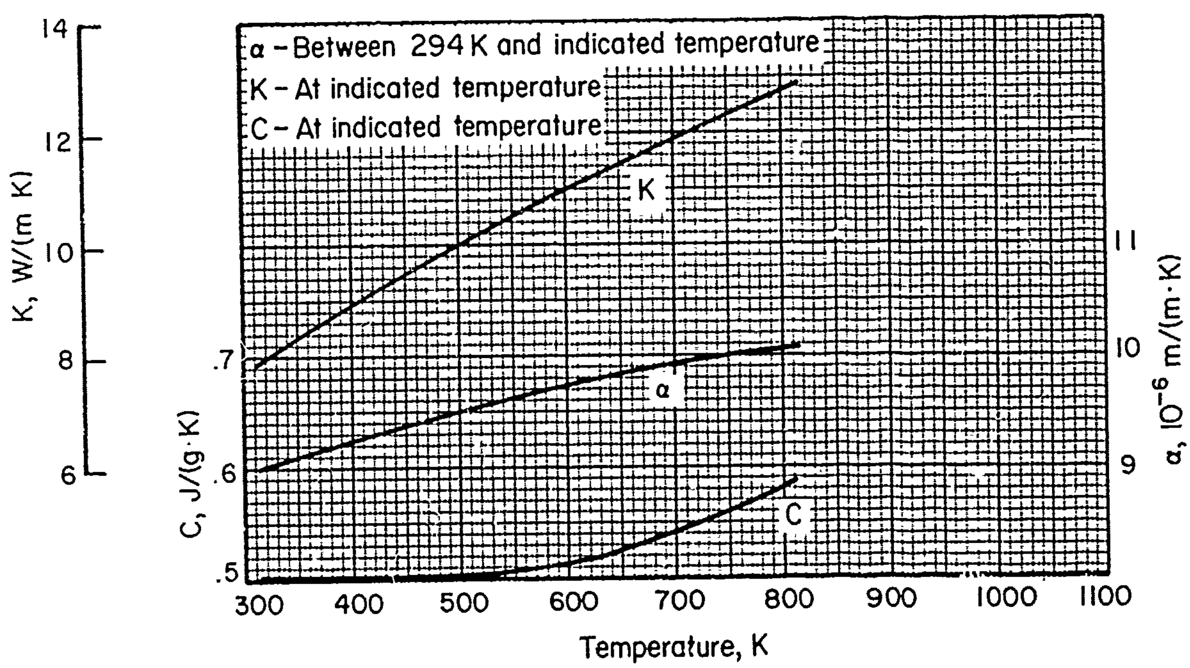


FIGURE 5.3.4.0. Effect of temperature on the physical properties of Ti-11Sn-5Zr-2Al-1Mo alloy.

TABLE 5.3.4.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF TI-11SN-5ZR-2AL-1MO (BARS)

SPECIFICATION...........	MIL-T-9047, COMP. 10
FORM....................	BARS
CONDITION...............	ANNEALED
THICKNESS, MM...........	≤57.15[a]
BASIS...................	S
MECHANICAL PROPERTIES:	
FTU, MPA:	
L................	965
LT...............	965
ST...............	965
FTY, MPA:	
L................	896
LT...............	896
ST...............	896
FCY, MPA:	
L................	...
LT...............	...
ST...............	...
FSU, MPA............	...
FBRU, MPA:	
(E/D=1.5).........	...
(E/D=2.0).........	...
FBRY, MPA:	
(E/D=1.5).........	...
(E/D=2.0).........	...
EL, PERCENT:	
L................	10
LT...............	10
ST...............	10
E, GPA..............	113.8
EC, GPA.............	...
G, GPA..............	...
MU..................	...
PHYSICAL PROPERTIES:	
OMEGA, MG/M3.........	4.82
C, J/(G*K)...........	SEE FIGURE 5.3.4.0
K, W/(M*K)...........	SEE FIGURE 5.3.4.0
ALPHA, 10-6 M/(M*K)..	SEE FIGURE 5.3.4.0

[a] MAXIMUM OF 32.2 SQ CM CROSS-SECTIONAL AREA.

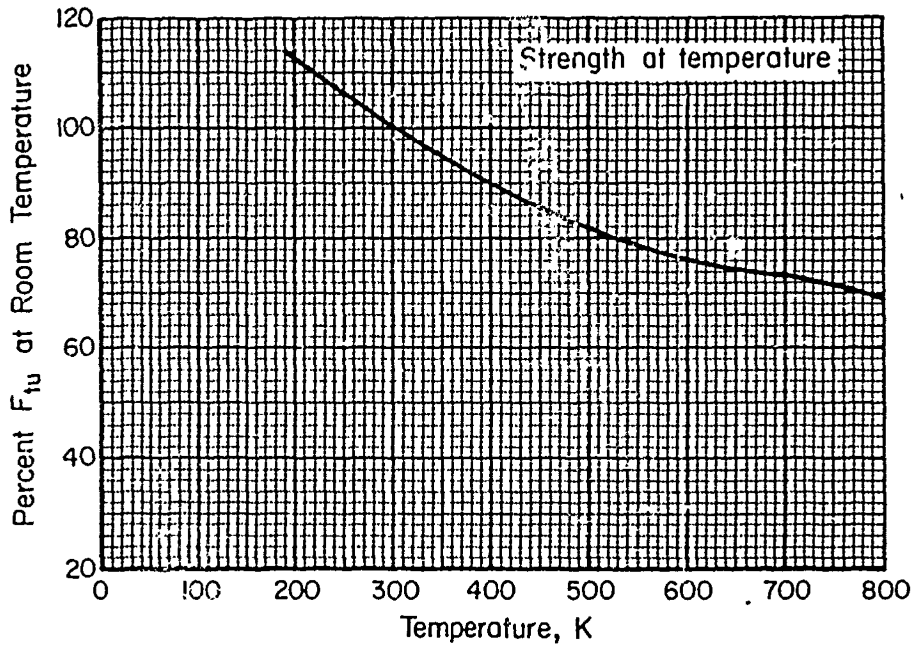


FIGURE 5.3.4.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of annealed Ti-2Al-11Sn-5Zr-1Mo (bars and forgings).

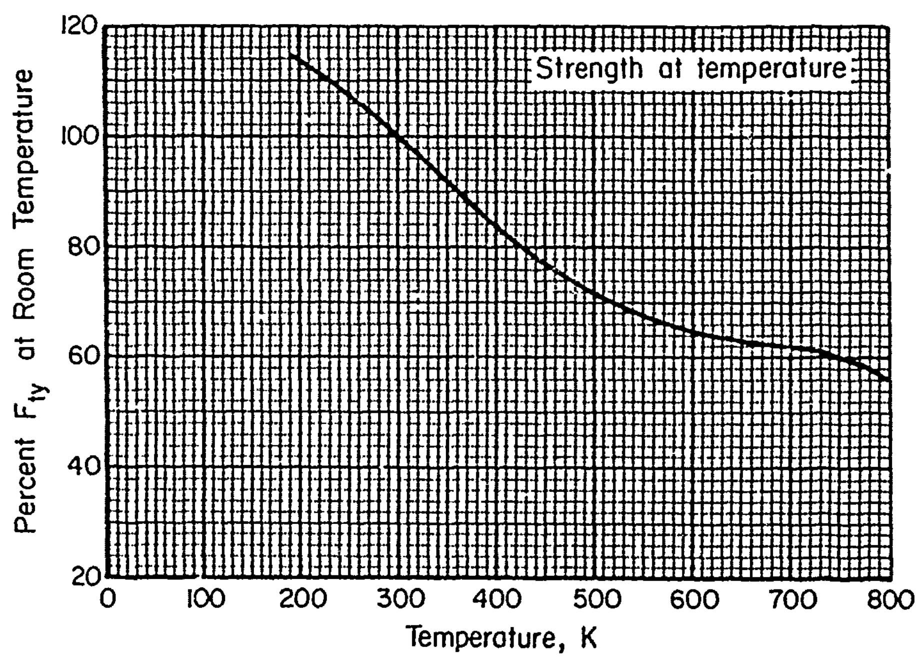


FIGURE 5.3.4.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of annealed Ti-2Al-11Sn-5Zr-1Mo (bars and forgings).

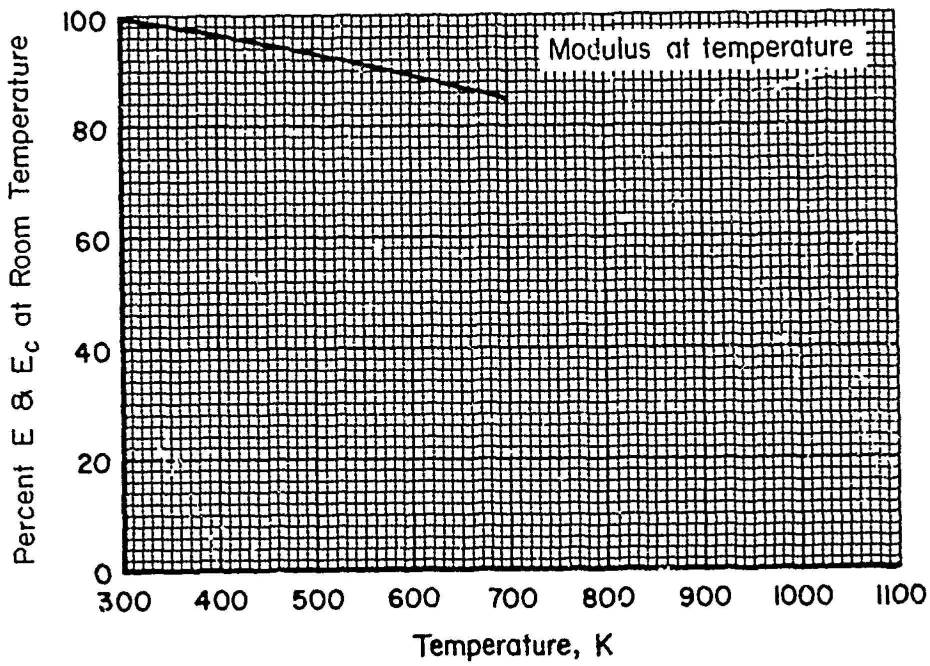


FIGURE 5.3.4.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of annealed Ti-11Sn-5Zr-1Mo (bars).

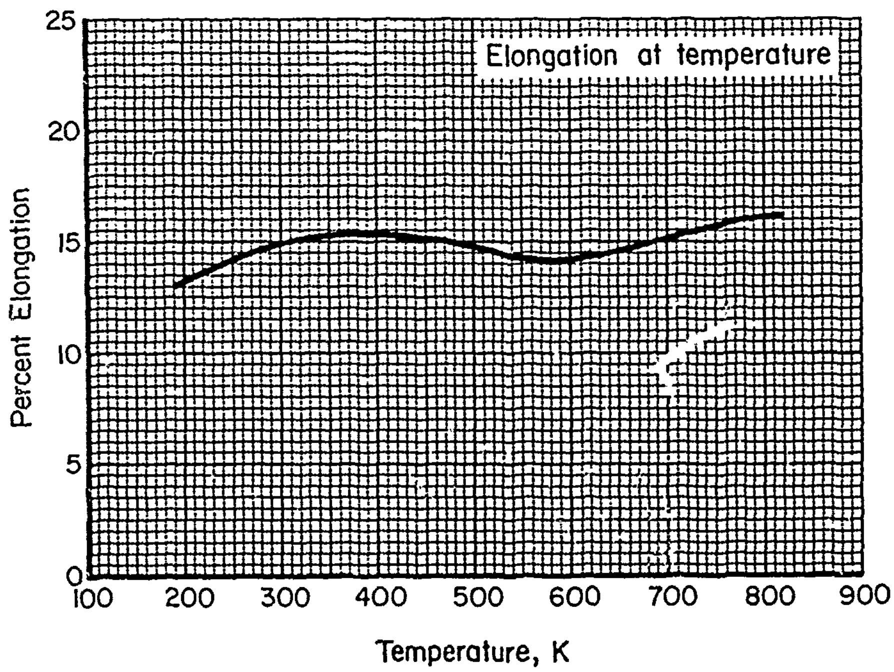


FIGURE 5.3.4.1.5. Effect of temperature on the elongation of annealed Ti-11Sn-5Zr-2Al-1Mo (bars).

5.4 Alpha-Beta Titanium Alloys

The alpha-beta titanium alloys contain both the alpha and beta phases at room temperature. The alpha phase is similar to that of unalloyed titanium but is strengthened by the alpha stabilizing additions (e g., aluminum). The beta phase is the high-temperature phase of titanium but it is stabilized to room temperature by sufficient quantities of such beta stabilizing elements 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 very 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 are being welded successfully with special precautions.

5.4.1 Ti-8Mn

5.4.1.0 *Comments.*—Ti-8Mn alloy is a sheet and plate alloy developed for its excellent formability combined with an intermediate strength level. The material has good elevated-temperature strength and stability up to about 589 K. Ti-8Mn is used in the annealed condition only. Heat treatment is not recommended.

Manufacturing Considerations. — Ti-8Mn can be formed severely without difficulty. Recommended forming temperatures are 755 to 811 K for severe forming, and room temperature for simple forming. Welding of this alloy is not recommended because of brittleness in the weld joint. However, spot welding has been used extensively in design applications where joint strength was not a factor.

Environmental Considerations. — Ti-8Mn is stable under stress at temperatures up to 616 K for times up to 1000 hours without loss of ductility. This alloy is not recommended for cryogenic applications. The material is sensitive to chloride containing environments showing susceptibility to aqueous chloride solution stress corrosion as well as hot-salt stress-corrosion attack. Ti8Mn is resistant to oxidation up to the service temperature limit (589 K).

Specifications. — A material specification for Ti-8Mn is presented in Table 5.4.1.0(a).

TABLE 5.4.1.0(a). *Material Specification for Ti-8Mn*

Specification	Form
AMS 4908	Sheet, strip, and plate

Heat Treatment. — This alloy is annealed by heating to 950 to 978 K for 1 hour, furnace cooling at 422 K per hour maximum to 839 K maximum. Stress relieving requires approximately 20 min. at 811 K.

Room-Temperature Properties

Room-temperature mechanical properties for Ti-8Mn are shown in Table 5.4.1.0(b). The effect of temperature on physical properties is shown in Figure 5.4.1.0.

5.4.1.1 *Annealed Condition.* — Elevated-temperature data for annealed Ti-8Mn are presented in Figures 5.4.1.1.1(a) through 5.4.1.1.4.

Compression stress-strain and tangent-modulus curves at various temperatures are shown in Figures 5.4.1.1.6(a) through (c).

TABLE 5.4.1.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF TI-8MN (SHEET AND STRIP).

SPECIFICATION..........	AMS 4908	
FORM...................	SHEET AND STRIP	
CONDITION..............	ANNEALED	
THICKNESS, MM..........	≤4.76	
BASIS..................	A	B
MECHANICAL PROPERTIES:		
FTU, MPA:		
L..................	862	896
LT.................	862	896
FTY, MPA:		
L..................	758	793
LT.................	758	793
FCY, MPA:		
L..................	758	793
LT.................	758	793
FSU, MPA............	600	627
FBRU, MPA:		
(E/D=1.5).........	1220	1270
(E/D=2.0).........	...	...
FBRY, MPA:		
(E/D=1.5).........	896	938
(E/D=2.0).........	...	...
EL, PERCENT:		
L..................	10[a]	...
LT.................	10[a]	...
E, GPA..............	106.9	
EC, GPA.............	110.3	
G, GPA..............	...	
MU..................	...	
PHYSICAL PROPERTIES:		
OMEGA, MG/M3.........	4.73	
C, J/(G*K)...........	SEE FIGURE 5.4.1.0	
K, W/(M*K)...........	SEE FIGURE 5.4.1.0	
ALPHA, 10-6 M/(M*K)..	SEE FIGURE 5.4.1.0	

a THICKNESS 0.635 MM AND ABOVE.

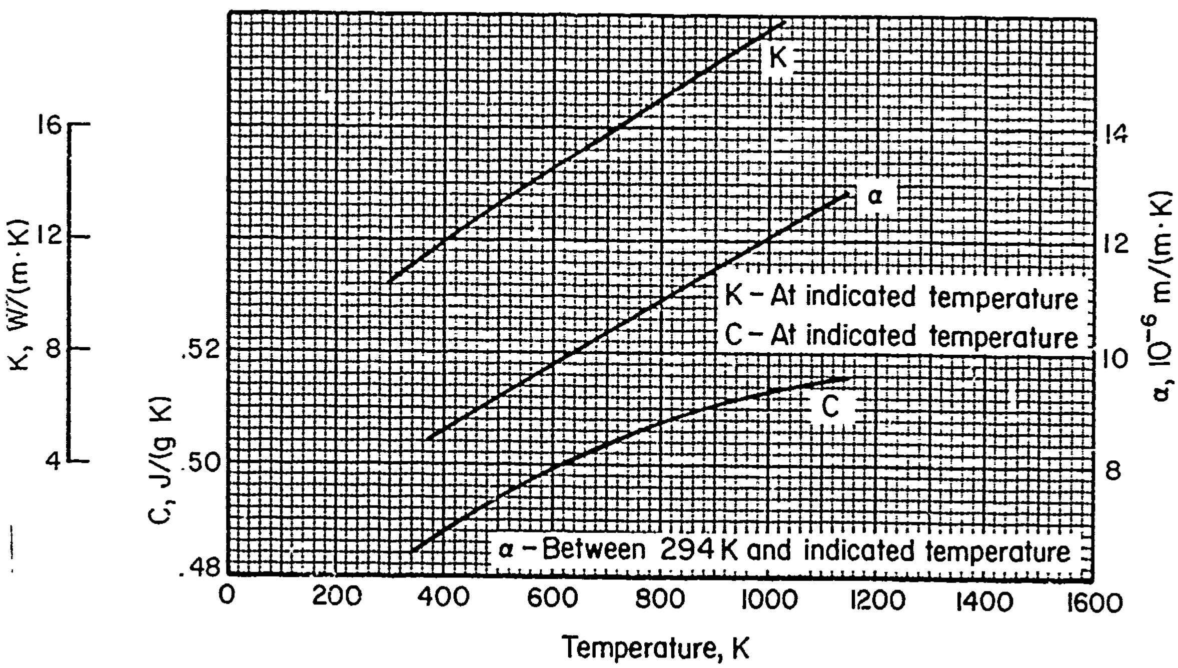


FIGURE 5.4.1.0. Effect of temperature on the physical properties of Ti-8Mn alloy.

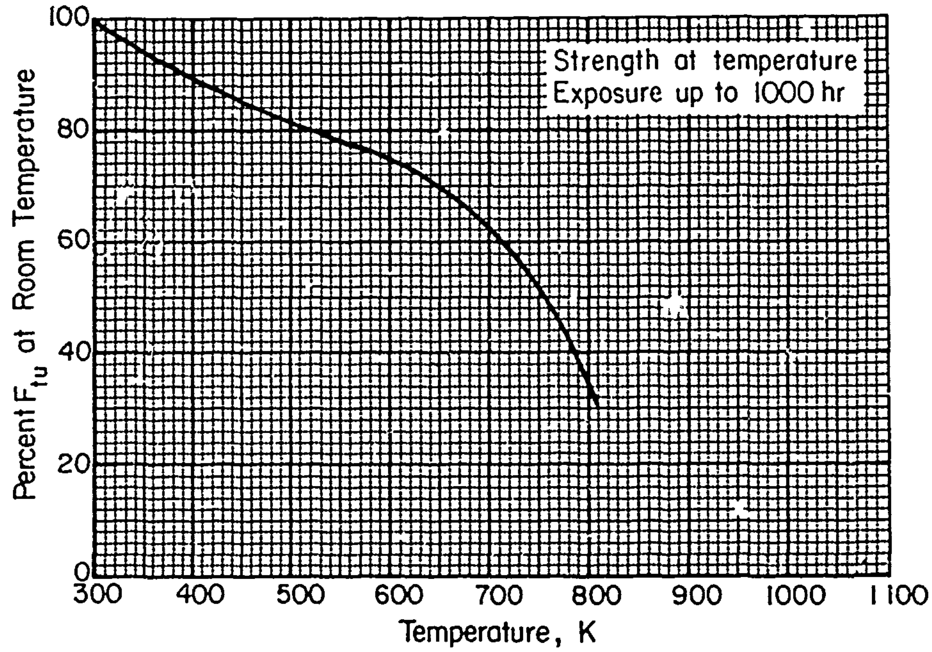


FIGURE 5.4.1.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of annealed Ti-8Mn alloy.

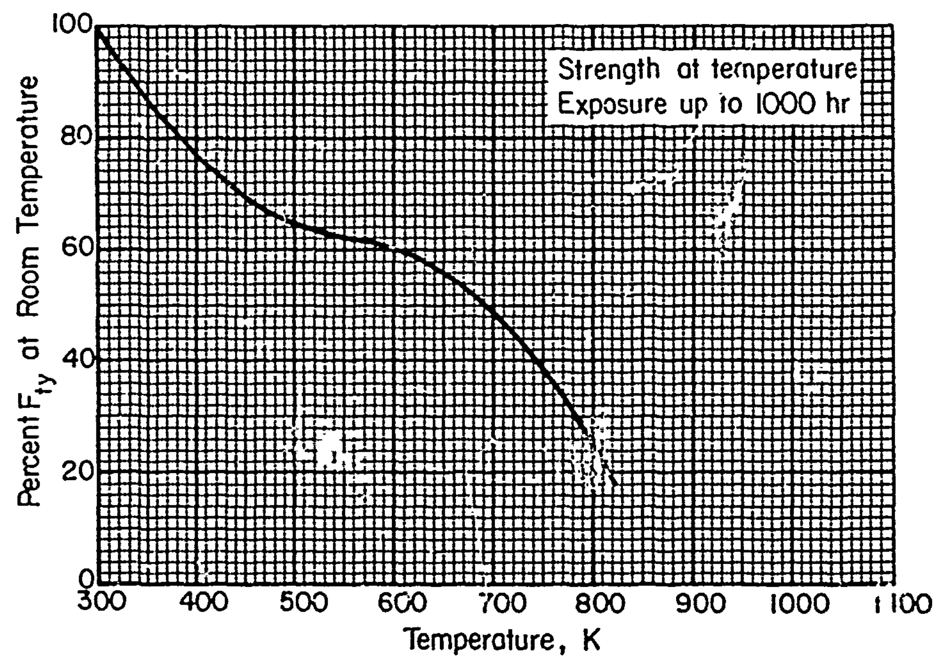


FIGURE 5.4.1.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of annealed Ti-8Mn alloy.

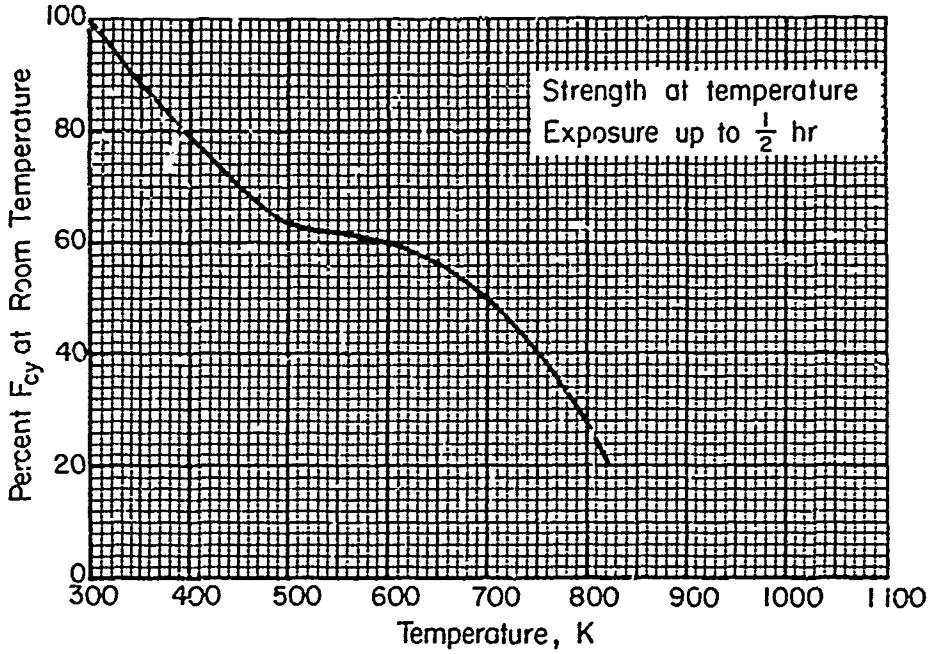


FIGURE 5.4.1.1.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of annealed Ti-8Mn alloy.

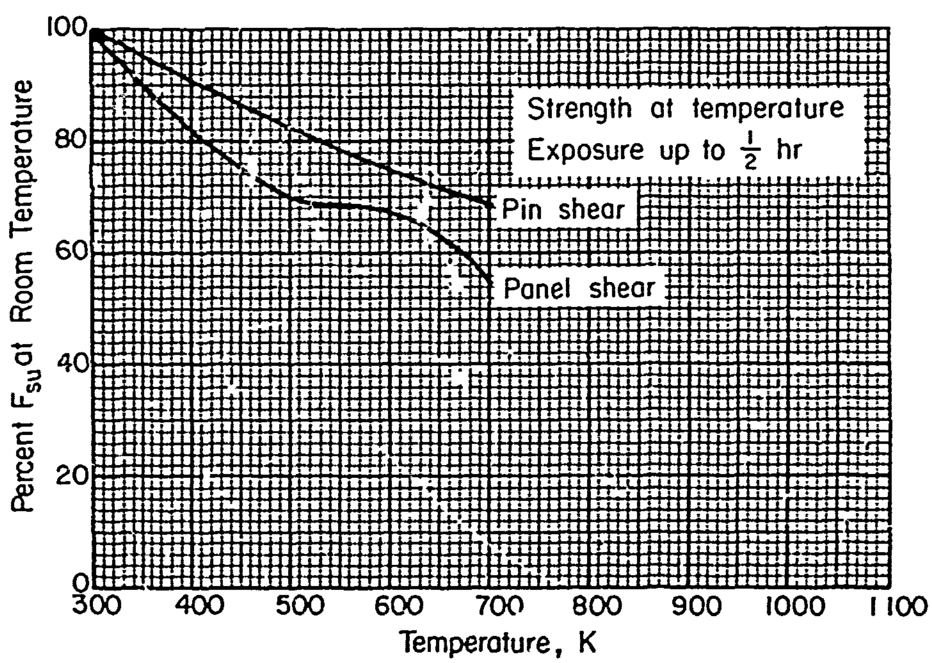


FIGURE 5.4.1.1.2(b). Effect of temperature on the ultimate shear strength (F_{su}) of annealed Ti-8Mn alloy.

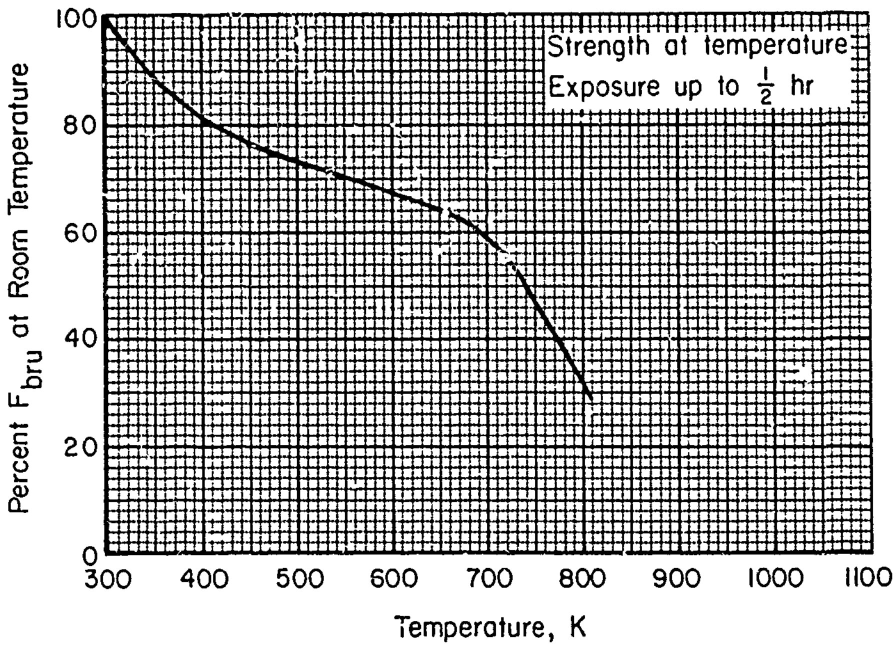


FIGURE 5.4.1.1.3(a). Effect of temperature on the ultimate bearing strength (F_{bru}) of annealed Ti-8Mn alloy.

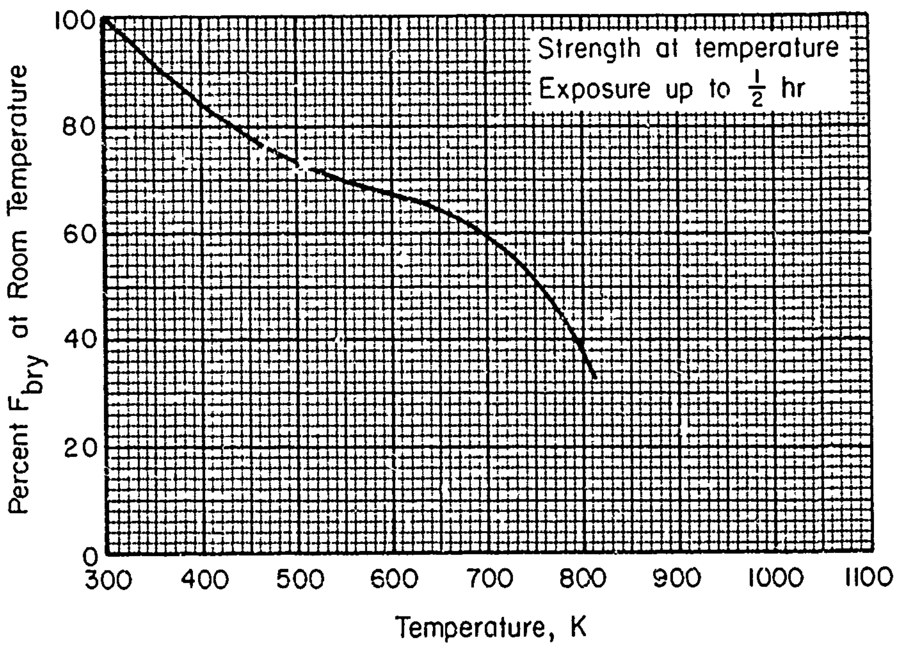


FIGURE 5.4.1.1.3(b). Effect of temperature on the bearing yield strength (F_{bry}) of annealed Ti-8Mn alloy.

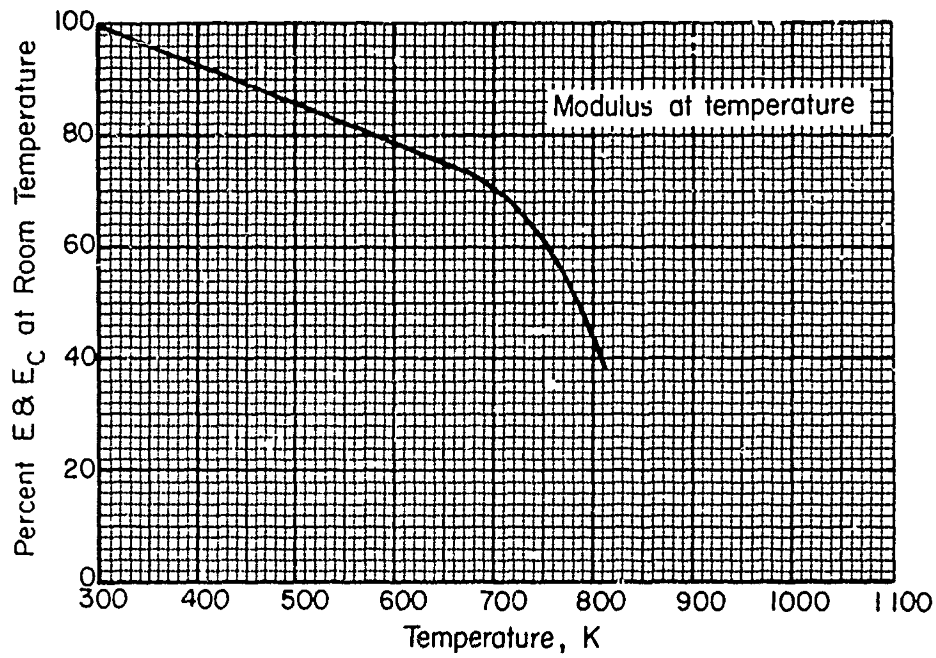


FIGURE 5.4.1.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of annealed Ti-8Mn alloy.

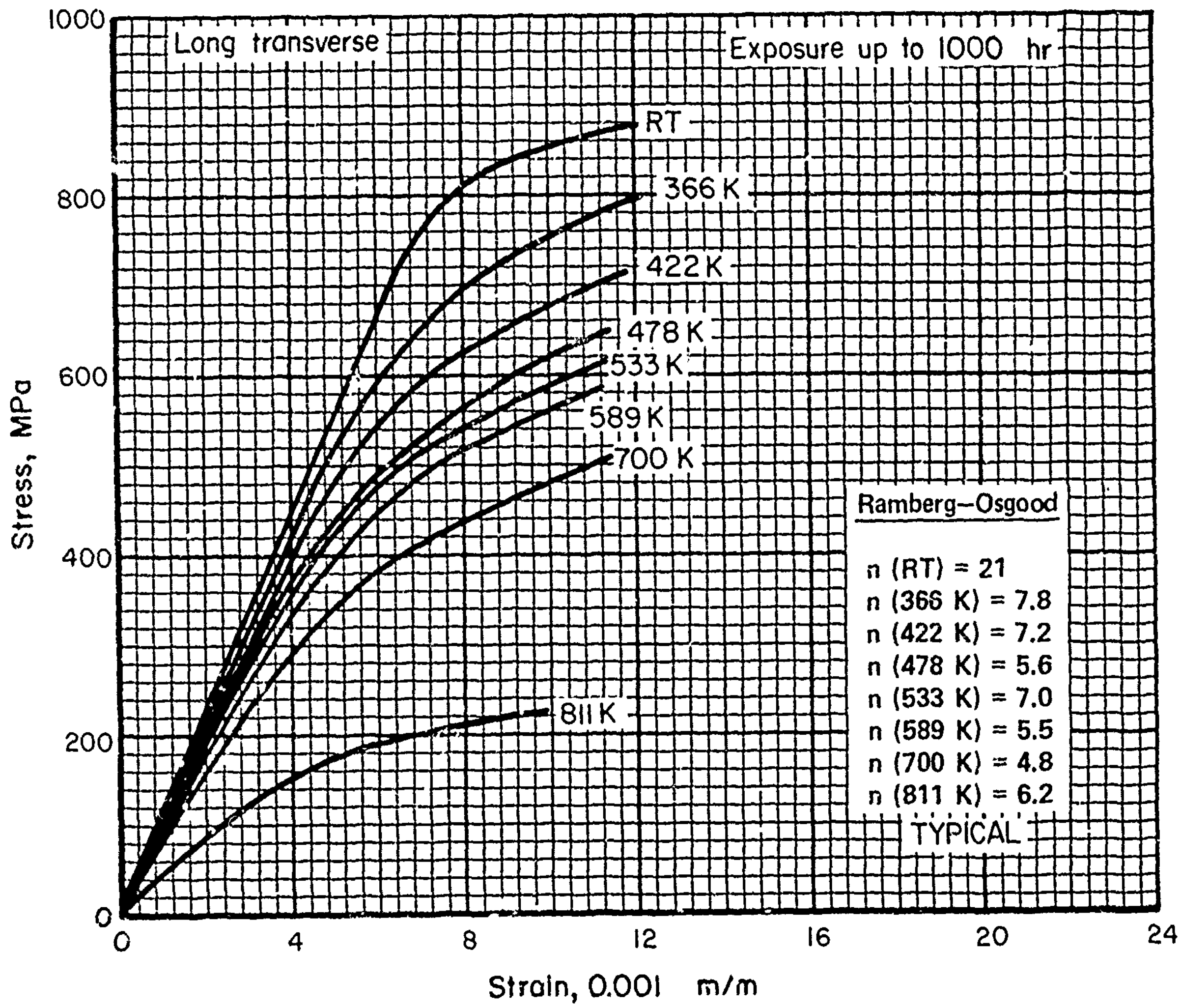


FIGURE 5.4.1.1.6(a). Typical compressive stress-strain curves for annealed Ti-8Mn alloy (sheet) at various temperatures.

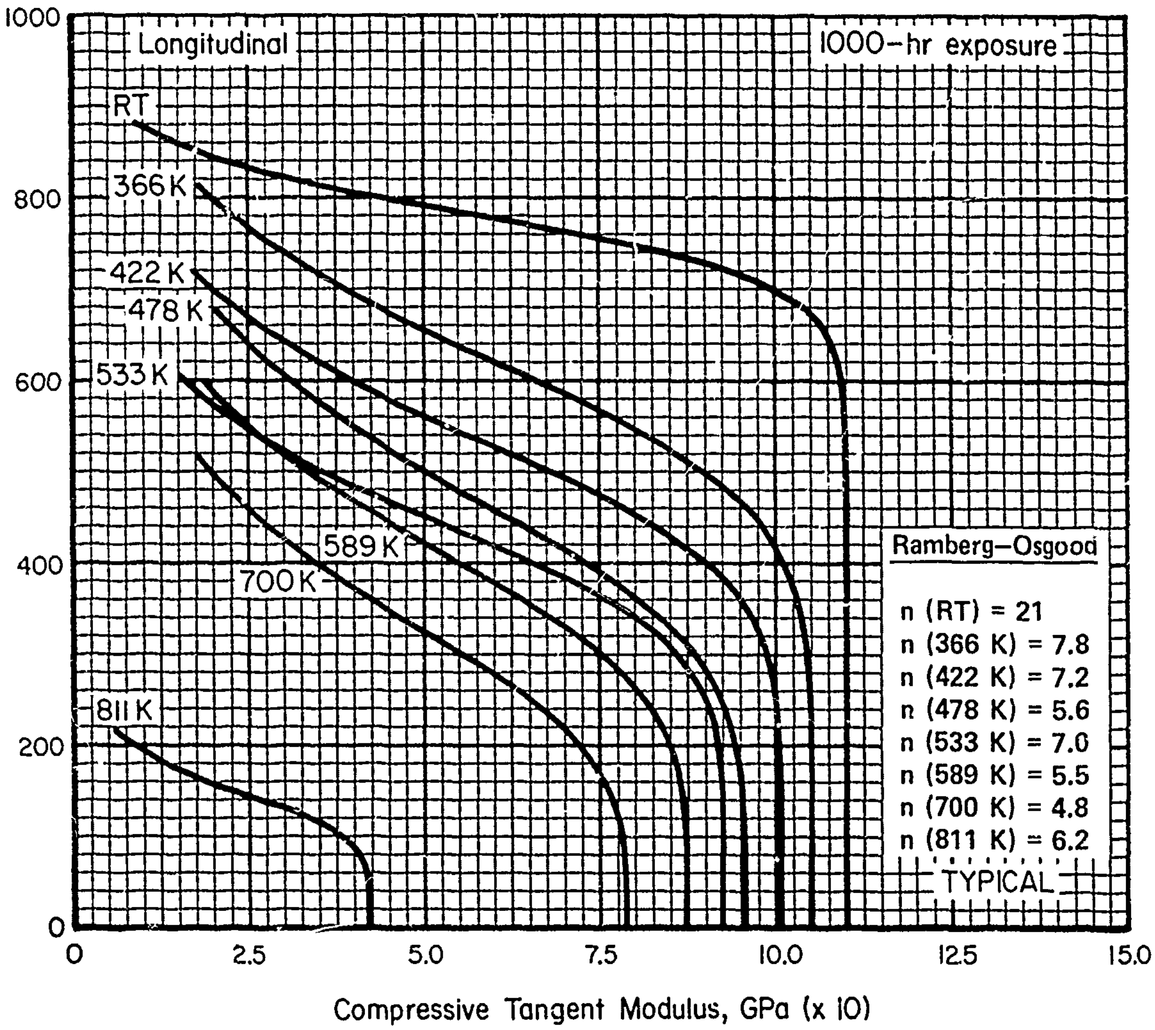


FIGURE 5.4.1.1.6(b). Typical compressive tangent-modulus curves for annealed Ti-8Mn alloy (sheet) at various temperatures.

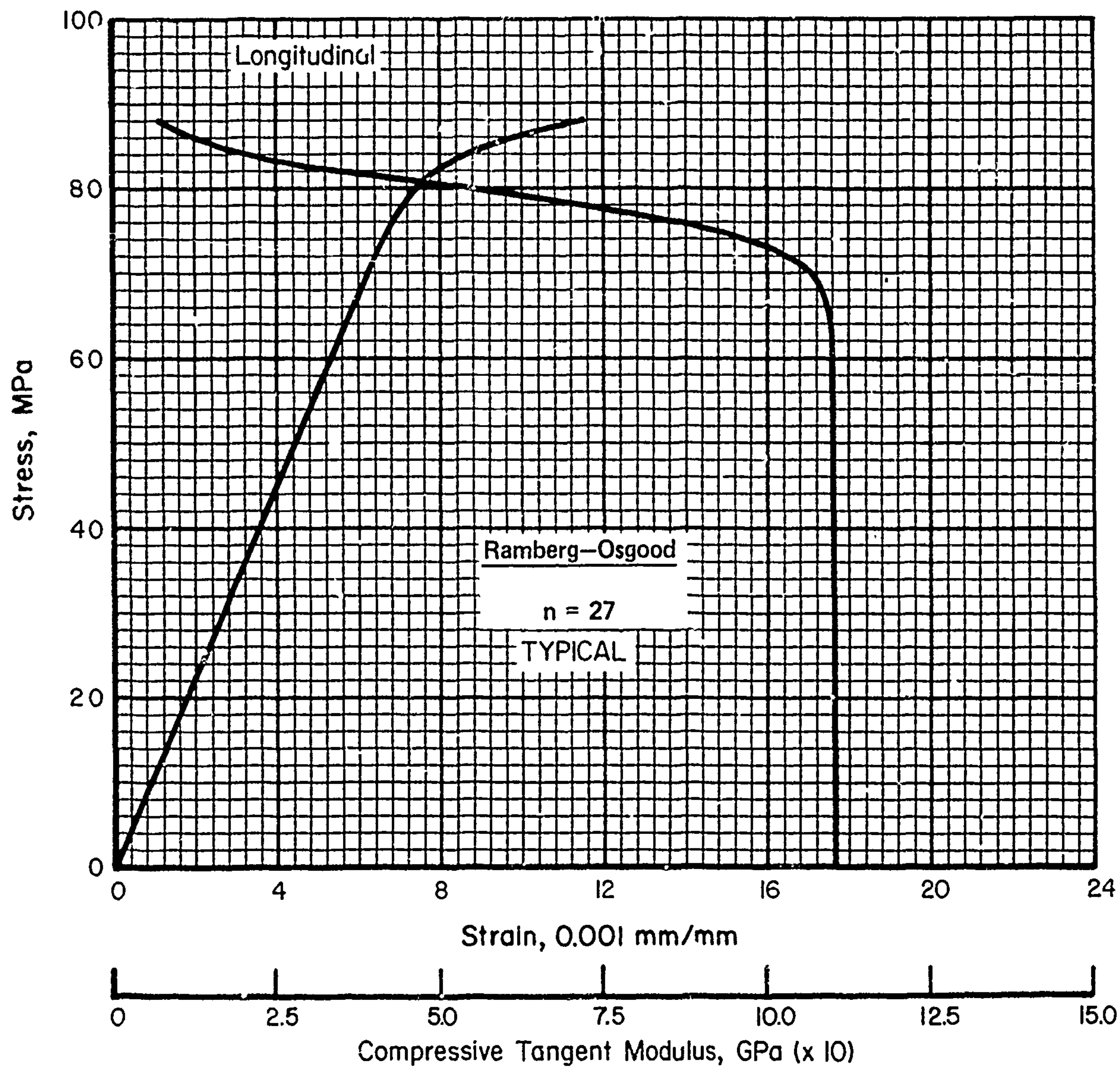


FIGURE 5.4.1.1.6(c). Typical compressive stress-strain and tangent-modulus curve for annealed Ti-8Mn alloy (sheet) at room temperature.

5.4.2. Ti-6Al-2Sn-4Zr-6Mo

5.4.3 Ti-6Al-4V

5.4.3.0 *Comments.*—Ti-6Al-4V is available in all mill product forms as well as in castings and powder metallurgy forms. It can be used in either the annealed or solution treated plus aged (STA) conditions and is weldable. Temperature use range is from 78 to 672 K. For maximum toughness, Ti-6Al-4V should be used in the annealed or duplex annealed condition whereas for maximum strength, the STA condition is used. The full strength potential for this alloy is not available in sections greater than about 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 the beta transus temperature for good combinations of fabricability, strength, ductility, and toughness. Elevated temperatures are usually used to form flat-rolled products although extensive forming also 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 it 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 672 K without loss of ductility. Its toughness in the annealed condition is adequate at temperatures down to 78 K. (A special low interstitial grade may be used down to 20 K.) Ti-6Al-4V is resistant to oxidation at least to 811 K and 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.

Specification.—Some material specifications for Ti-6Al-4V are presented in Table 5.4.3.0(a).

TABLE 5.4.3.0(a). *Material Specifications for Ti-6Al-4V*

Specification	Form
MIL-T-9046	Sheet, strip, and plate
AMS 4906	Continuously rolled sheet
MIL-T-9047	Bars
MIL-T-81556	Extruded bars, rods, and special shaped sections
AMS 4928	Forgings

Heat Treatment.—This alloy is commonly specified in either the annealed condition or in the fully heat-treated condition. Annealing requires 1 hour at 978 K, 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 1200 K for 5 to 25 minutes, quench in water.

Age at 797 K for 4 to 6 hours, air cool.

For bars and forgings:

Solution treat at 1200 K for 1 hour, quench in water.

Age at 811 K for 3 hours, air cool.

Room-Temperature Properties

Room-temperature mechanical properties for Ti-6Al-4V are shown in Tables 5.4.3.0(b) through (f). The effect of temperature on physical properties is shown in Figure 5.4.3.0.

5.4.3.1. *Annealed Condition.*—Effect of temperature curves for annealed Ti-6Al-4V are presented in Figures 5.4.3.1.1(a) through 5.4.3.1.5. Typical stress-strain curves at several temperatures are presented in Figures 5.4.3.1.6(a) through (c). Typical full-range stress-strain curves at room temperature for this condition are shown in Figure 5.4.3.1.6(d).

Typical unnotched and notched fatigue data at room temperature are shown in Figures 5.4.3.1.8(a) through (d).

5.4.3.2 *Solution-Treated and Aged Condition.*— Effect of temperature curves for solution-treated and aged Ti-6Al-4V are presented in Figures 5.4.3.2.1(a) through 5.4.3.2.4. Typical tensile and compressive stress-strain curves for sheet material at several temperatures between room temperature and 811 K are shown in Figures 5.4.3.2.6(a) through (e). Typical full-range stress-strain curves at several temperatures between room temperature and 811 K are shown in Figure 5.4.3.2.6(f).

A nomograph of typical creep properties of solution-treated and aged sheet for the temperature range 587 K through 700 K is presented in Figure 5.4.3.2.7.

Typical unnotched and notched fatigue data at room temperature and elevated temperatures are shown in the constant-life fatigue diagrams of Figures 5.4.3.2.8(a) through (c).

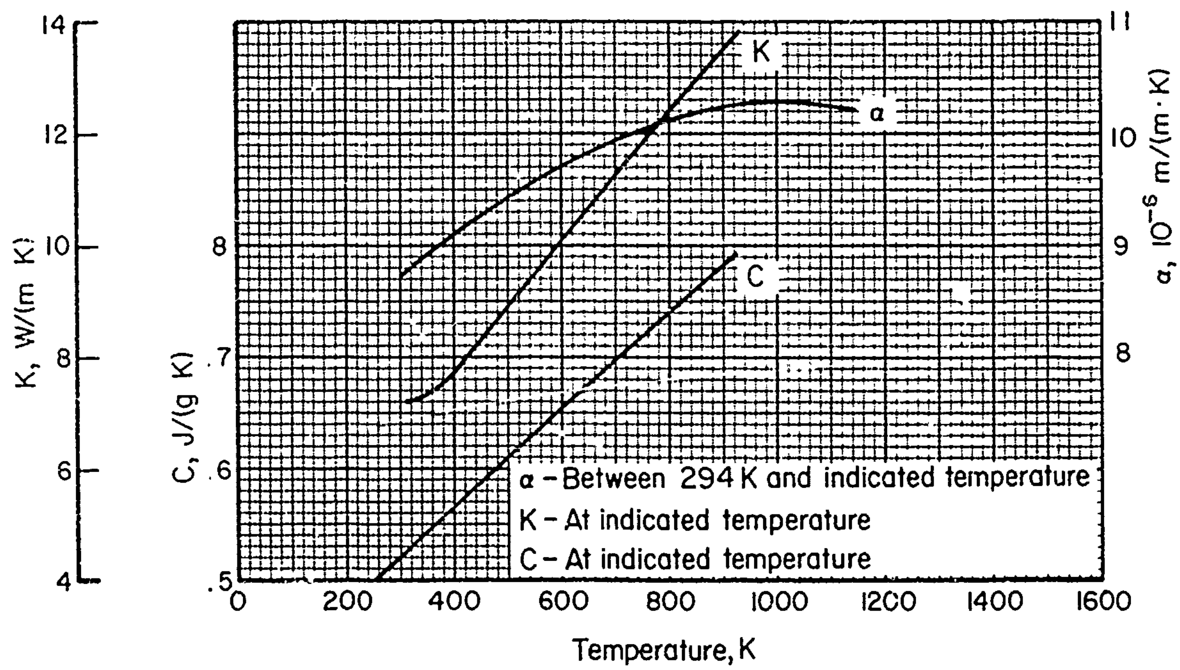


FIGURE 5.4.3.0. Effect of temperature on the physical properties of Ti-6Al-4V alloy.

TABLE 5.4.3.0(8). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF TI-6AL-4V (SHEET, STRIP, AND PLATE)

SPECIFICATION	MIL-T-9046, TYPE III, COMP. C									
FORM	SHEET, STRIP, AND PLATE									
CONDITION	ANNEALED					SOLUTION TREATED AND AGED				
THICKNESS, MM	≤4.76		4.77-50.81		50.82-101.60	≤4.76	4.77-19.06	19.07-25.41	25.42-50.81	50.82-101.60
BASIS	A	B	A	B	S	S	S	S	S	S
MECHANICAL PROPERTIES:										
FTU, MPA:										
L	924	958	896[c]	931	896	1100	1100	1030	1000	896
LT	924	958	896[c]	952	895	1100	1100	1030	1000	896
FTY, MPA:										
L	869	903	827[c]	862	827	1000	1000	965	931	827
LT	869	903	827[c]	903	827	1000	1000	965	931	827
FCY, MPA:										
L	910	952	869	903	869	1060	...	...	...	...
LT	910	952	869	952	869	1120	...	...	...	...
FSU, MPA	545	558	524	545	524	689	...	...	...	...
FBRU, MPA:										
(E/D=1.5)	1360	1410	1320	1370	1320	1630	...	...	...	...
(E/D=2.0)	1740	1800	1690	1750	1690	1970	...	...	...	...
FBRY, MPA:										
(E/D=1.5)	1180	1230	1120	1170	1120	1450	...	...	...	...
(E/D=2.0)	1430	1490	1370	1420	1370	1600	...	...	...	...
EL, PERCENT:										
L	8[a]	...	10	...	10	5[b]	8	6	6	6
LT	8[a]	...	10	...	10	5[b]	8	6	6	6
E, GPA	110.3									
EC, GPA	113.1									
G, GPA	42.7									
MU	0.31									
PHYSICAL PROPERTIES:										
OMEGA, MG/M3	4.43									
C, J/(G*K)	SEE FIGURE 5.4.3.0									
K, W/(M*K)	SEE FIGURE 5.4.3.0									
ALPHA, 10-6 M/(M*K)	SEE FIGURE 5.4.3.0									

[a] 8 - 0.635 TO 1.588 MM
10 - 1.587 MM AND ABOVE

[b] 5 - 1.256 MM AND ABOVE
4 - 0.826 TO 1.257 MM
3 - 0.825 MM AND BELOW

[c] THE A VALUES ARE HIGHER THAN SPECIFICATION VALUES AS FOLLOWS: FTU(L) = 903 MPA, FTJ(LT) = 910 MPA, AND FTY(LT) = 848 MPA.

TABLE 5.4.3.0(C). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF TI-6AL-4V (SHEET AND STRIP)

SPECIFICATION	AMS 4906				
FORM	CONTINUOUSLY ROLLED SHEET AND STRIP[a]				
CONDITION	ANNEALED				
THICKNESS, MM	0.20	≤0.20-0.63		0.64-1.52	
BASIS	S	A	B	A	B
MECHANICAL PROPERTIES:					
FTU, MPA:					
L	...	965[b]	1030	965[c]	1000
LT	965	965[b]	1020	965[c]	1010
FTY, MPA:					
L	...	841[b]	896	841[d]	883
LT	869	869[b]	965	869[c]	931
FCY, MPA:					
L	...	862	924	862	910
LT	889	889	993	889	958
FSU, MPA	621	621	655	621	641
FBRU[e], MPA:					
(E/D=1.5)	1490	1490	1570	1490	1540
(E/D=2.0)	1930	1930	2030	1930	2000
FBRY[e], MPA:					
(E/D=1.5)	...	1140	1210	1140	1200
(E/D=2.0)	...	1400	1490	1400	1480
EL, PERCENT:					
L	4	7	...	8	...
LT	4	5	...	8	...
E, GPA	110.3				
EC, GPA	113.1				
G, GPA	42.7				
MU	0.31				
PHYSICAL PROPERTIES:					
OMEGA, MG/M3	4.43				
C, J/(G*K)	SEE FIGURE 5.4.3.0				
K, W/(M*K)	SEE FIGURE 5.4.3.0				
ALPHA, 10-6 M/(M*K)	SEE FIGURE 5.4.3.0				

[a] WIDTH GREATER THAN 229 MM.
[b] THE A VALUES ARE HIGHER THAN SPECIFICATION VALUES AS FOLLOWS: FTU(L) = 1000 MPA, FTU(LT) = 993 MPA, FTY(LT) = 924 MPA.
[c] THE A VALUES ARE HIGHER THAN SPECIFICATION VALUES AS FOLLOWS: FTU(L) = 972 MPA, FTU(LT) = 986 MPA, FTY(LT) = 903 MPA.
[d] ESTIMATED VALUE BASED ON LIMITED DATA.
[e] BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

... PHYSICAL PROPERTIES OF

TI-6AL-4V (ROLLED AND FORGED BAR)

SPECIFICATION	MIL-T-9047, COMP. 6											
FORM	ROLLED AND FORGED BAR											
CONDITION	ANNEALED			SOLUTION TREATED AND AGED								
WIDTH	a			≤203.20	≤101.60	101.60-203.20	101.60	101.61-203.20	≤101.60	101.61-203.20	≤203.20	≤203.20
THICKNESS, MM	<12.71	12.71-76.21		≤12.71	12.72-25.41		25.42-38.11		38.12-50.81		50.82-76.21	76.22-101.60
BASIS	S	A	B	S	S	S	S	S	S	S	S	S
MECHANICAL PROPERTIES:												
FTU, MPA:												
L	896	896[b]	952	1100	1070	1030	1030	1000	1000	965	931	896
LT	896	896[b]	965	1100	1070	1030	1030	1000	1000	965	931	896
FTY, MPA:												
L	827	827[c]	889	1030	1000	965	965	931	931	896	862	827
LT	827	827[c]	889	1030	1000	965	965	931	931	896	862	827
FCY, MPA:												
L	869	869	931	...	...	...	...	...	...	...	...	...
LT	869	869	931	...	...	...	...	...	...	...	...	...
FSU, MPA	552	552	579	634	...	...	...	...	...	...	...	...
FBRU, MPA:												
(E/D=1.5)	1350	1350	1420	...	...	...	...	...	...	...	...	...
(E/D=2.0)	1710	1710	1800	...	...	...	...	...	...	...	...	...
FBRY, MPA:												
(E/D=1.5)	1200	1200	1290	...	...	...	...	...	...	...	...	...
(E/D=2.0)	1410	1410	1520	...	...	...	...	...	...	...	...	...
EL, PERCENT:												
L	10	10[d]	...	10	10	10	10	10	10	10	5	6
LT	...	7	...	10	10	10	10	10	10	10	8	6
E, GPA	110.3											
EC, GPA	113.1											
G, GPA	42.7											
MU	0.31											
PHYSICAL PROPERTIES:												
OMEGA, MG/M3	4.43											
C, J/(G*K)	...											
K, W/(M*K)	...											
ALPHA, 10-6 M/(M*K)	...											

[a] VALUES APPLY TO SECTIONS WITH A MAXIMUM CROSS-SECTIONAL AREA OF 64.5 SQ CM.
[b] THE A VALUES ARE HIGHER THAN SPECIFICATION VALUES AS FOLLOWS: FTU(L) = 910 MPA AND FTU(LT) = 924 MPA.
[c] THE A VALUES ARE HIGHER THAN SPECIFICATION VALUES AS FOLLOWS: FTY(L) AND (LT) = 848 MPA.
[d] THE A VALUE IS HIGHER THAN SPECIFICATION VALUE AS FOLLOWS: EL(L) = 11 PERCENT.

TABLE 5.4.3.0(E). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF TI-6AL-4V (FORGINGS)

SPECIFICATION............	AMS 4928	
FORM......................	FORGINGS	
CONDITION................	ANNEALED	
THICKNESS, MM............	≤101.61	101.62-152.40
BASIS....................	S	S
MECHANICAL PROPERTIES:		
FTU, MPA:		
L................	896	896
LT...............	896	896
ST...............	896	896
FTY, MPA:		
L................	827	827
LT...............	827	827
ST...............	827	827
FCY, MPA:		
L................	...	...
LT...............	...	...
ST...............	...	...
FSU, MPA.............	...	...
FBRU, MPA:		
(E/D=1.5).........	...	...
(E/D=2.0).........	...	...
FBRY, MPA:		
(E/D=1.5).........	...	...
(E/D=2.0).........	...	...
EL, PERCENT:		
L................	10	10
LT...............	10	10
ST...............	10	8
E, GPA...............	110.3	
EC, GPA..............	113.1	
G, GPA...............	42.7	
MU...................	0.31	
PHYSICAL PROPERTIES:		
OMEGA, MG/M3.........	4.43	
C, J/(G*K)...........	SEE FIGURE 5.4.3.0	
K, W/(M*K)...........	SEE FIGURE 5.4.3.0	
ALPHA, 10-6 M/(M*K)..	SEE FIGURE 5.4.3.0	

[illegible] DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF TI-6AL-4V (EXTRUSIONS)

SPECIFICATION	MIL-T-81556, TYPE III, COMP. A												
FORM	EXTRUDED BARS, RODS, AND SPECIAL SHAPED SECTIONS												
CONDITION	ANNEALED					SOLUTION TREATED AND AGED							
THICKNESS, MM	<50.80		50.80 - 76.20		76.21- 101.60	<12.70		12.70 19.05		19.06- 25.40		25.41- 50.80	50.81- 101.60
BASIS	A	B	A	B	S	A	B	A	B	A	B	S	S
MECHANICAL PROPERTIES:													
FTU, MPA:													
L	896 [a]	945	896 [b]	931	896	1070	1120	1040	1080	1010	1050	965	896
LT	895 [a]	958	896 [b]	958	...	1070	1120	1040	1080	1010	1070	...	...
FTY, MPA:													
L	827	855	814	841	827	952	1010	952	986	917	965	896	827
LT	827 [c]	883	827	862	...	952	1010	952	1000	917	979	...	...
FCY, MPA:													
L	883	910	855	883	869	1010	1080	1010	1050	979	1030	958	883
LT	863	945	869	903	869	1010	1080	1010	1070	958	1050	958	883
FSU, MPA	579	614	579	607	579	648	683	634	662	614	641	586	545
FBRU[c], MPA:													
(E/D=1.5)	1490	1570	1490	1540	1490	1680	1770	1630	1700	1590	1650	1520	1410
(E/D=2.0)	1850	1940	1850	1920	1850	2140	2250	2090	2170	2030	2120	1940	1800
FBRY[c], MPA:													
(E/D=1.5)	1250	1300	1230	1280	1250	1430	1530	1430	1490	1390	1460	1350	1250
(E/D=2.0)	1430	1540	1460	1520	1490	1670	1770	1670	1720	1610	1690	1570	1450
EL, PERCENT:													
L	10	...	10	...	10	6	...	6	...	6	...	6	6
LT	...	...	...	...	...	...	...	...	...	...	...	...	...
E, GPA	110.3												
EC, GPA	113.1												
G, GPA	42.7												
MU	0.31												
PHYSICAL PROPERTIES:													
OMEGA, MG/M3	4.43												
C, J/(G*K)	SEE FIGURE 5.4.3.0												
K, W/(M*K)	SEE FIGURE 5.4.3.0												
ALPHA, 10-6 M/(M*K)	SEE FIGURE 5.4.3.0												

[a] THE A VALUES ARE HIGHER THAN SPECIFICATION VALUES AS FOLLOWS: FTU(L) AND (LT) = 910 MPA AND FTY(LT) = 834 MPA.

[b] THE A VALUES ARE HIGHER THAN SPECIFICATION VALUES AS FOLLOWS: FTU(L) = 910 MPA AND FTU(LT) = 938 MPA.

[c] BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

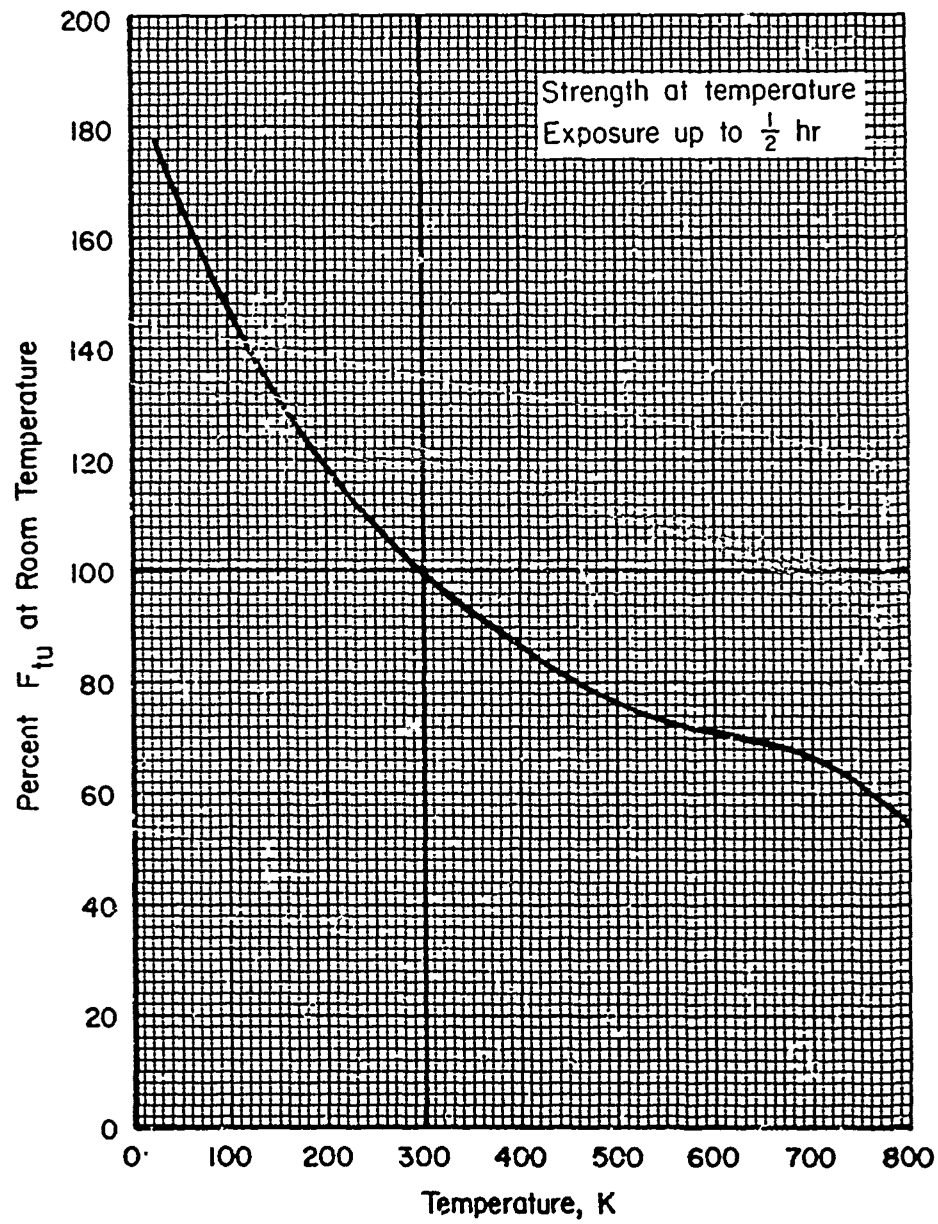


FIGURE 5.4.3.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of annealed Ti-6Al-4V alloy.

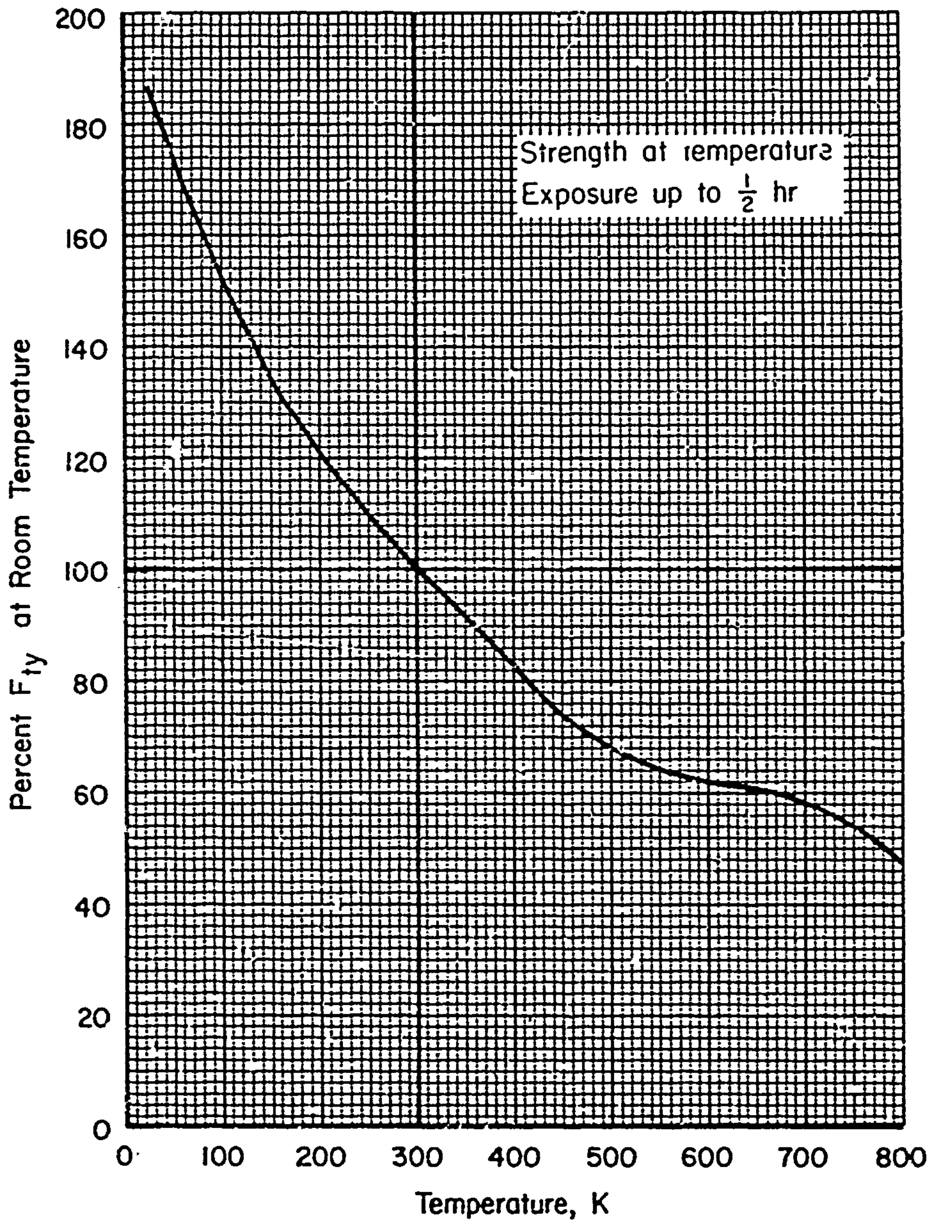


FIGURE 5.4 3.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of annealed Ti-6Al-4V alloy.

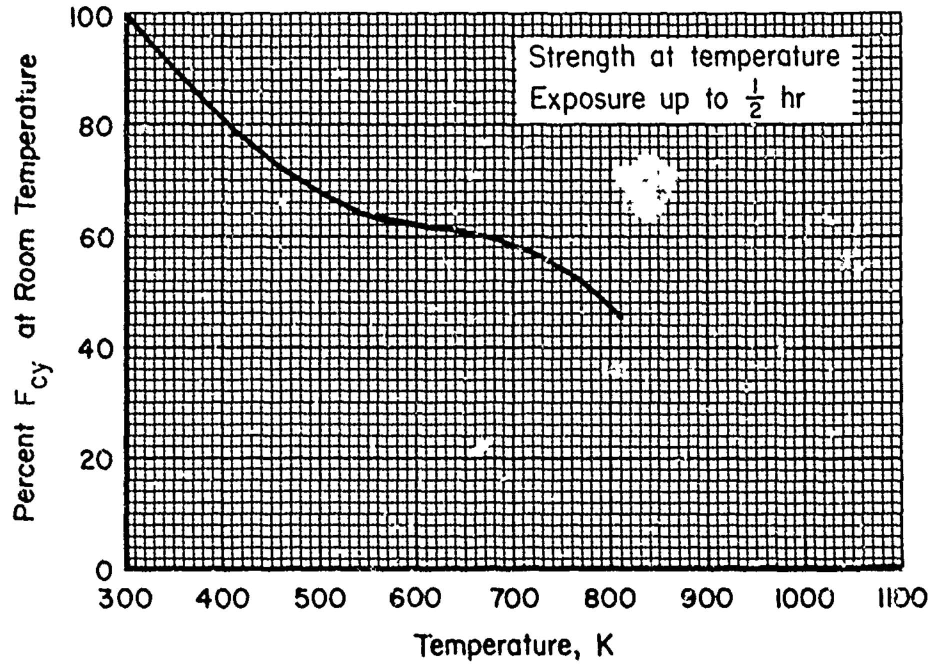


FIGURE 5.4.3.1.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of annealed Ti-6Al-4V alloy.

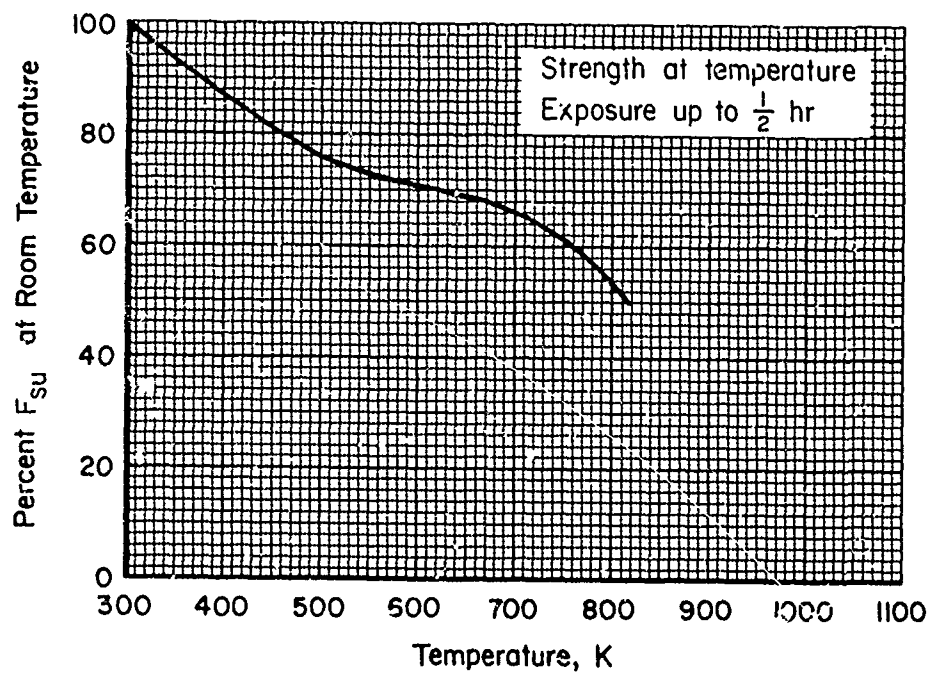


FIGURE 5.4.3.1.2(b). Effect of temperature on the ultimate shear strength (F_{su}) of annealed Ti-6Al-4V alloy.

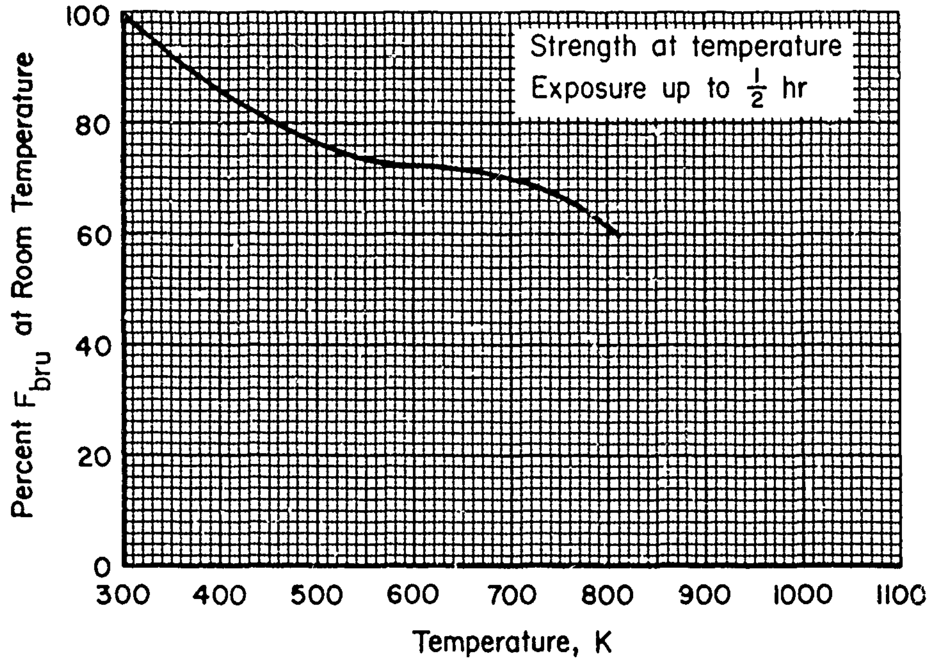


FIGURE 5.4.3.1.3(a). Effect of temperature on the ultimate bearing strength (F_{bru}) of annealed Ti-6Al-4V alloy.

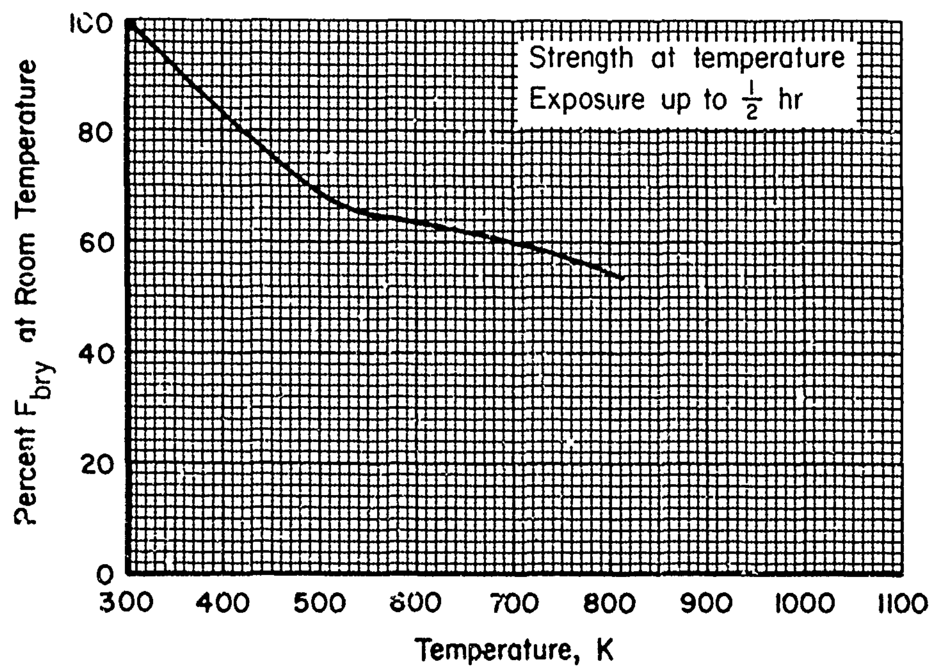


FIGURE 5.4.3.1.3(b). Effect of temperature on the bearing yield strength (F_{bry}) of annealed Ti-6Al-4V alloy.

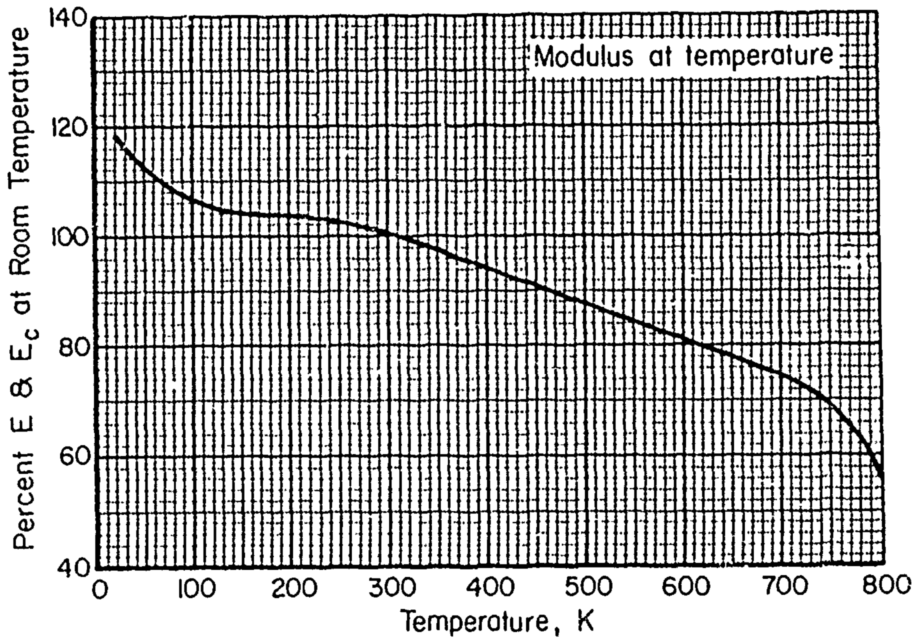


FIGURE 5.4.3.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of 6Al-4V annealed titanium alloy (sheet and bar).

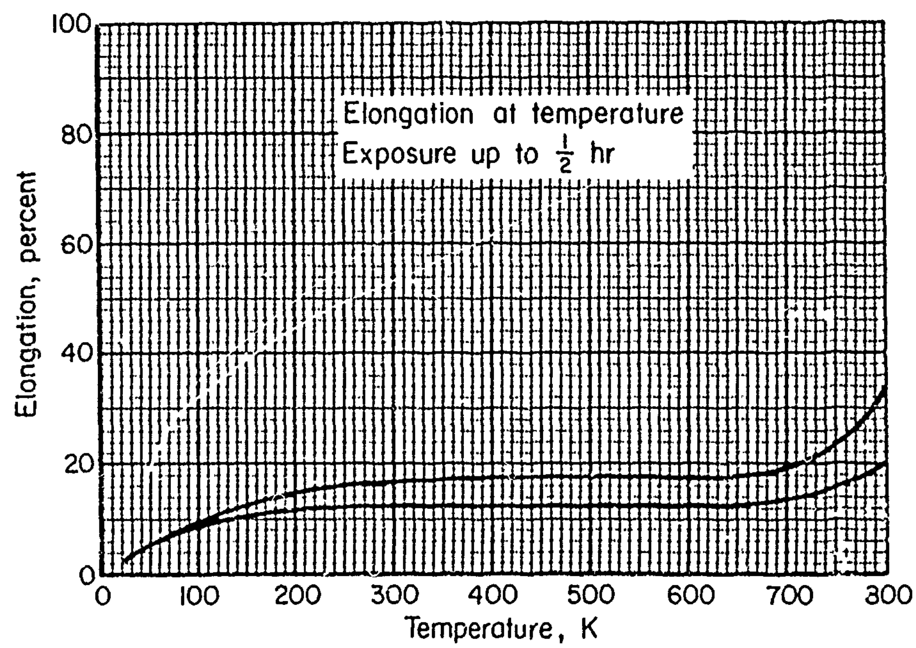


FIGURE 5.4.3.1.5. Effect of temperature on the elongation of annealed Ti-6Al-4V (sheet and bar).

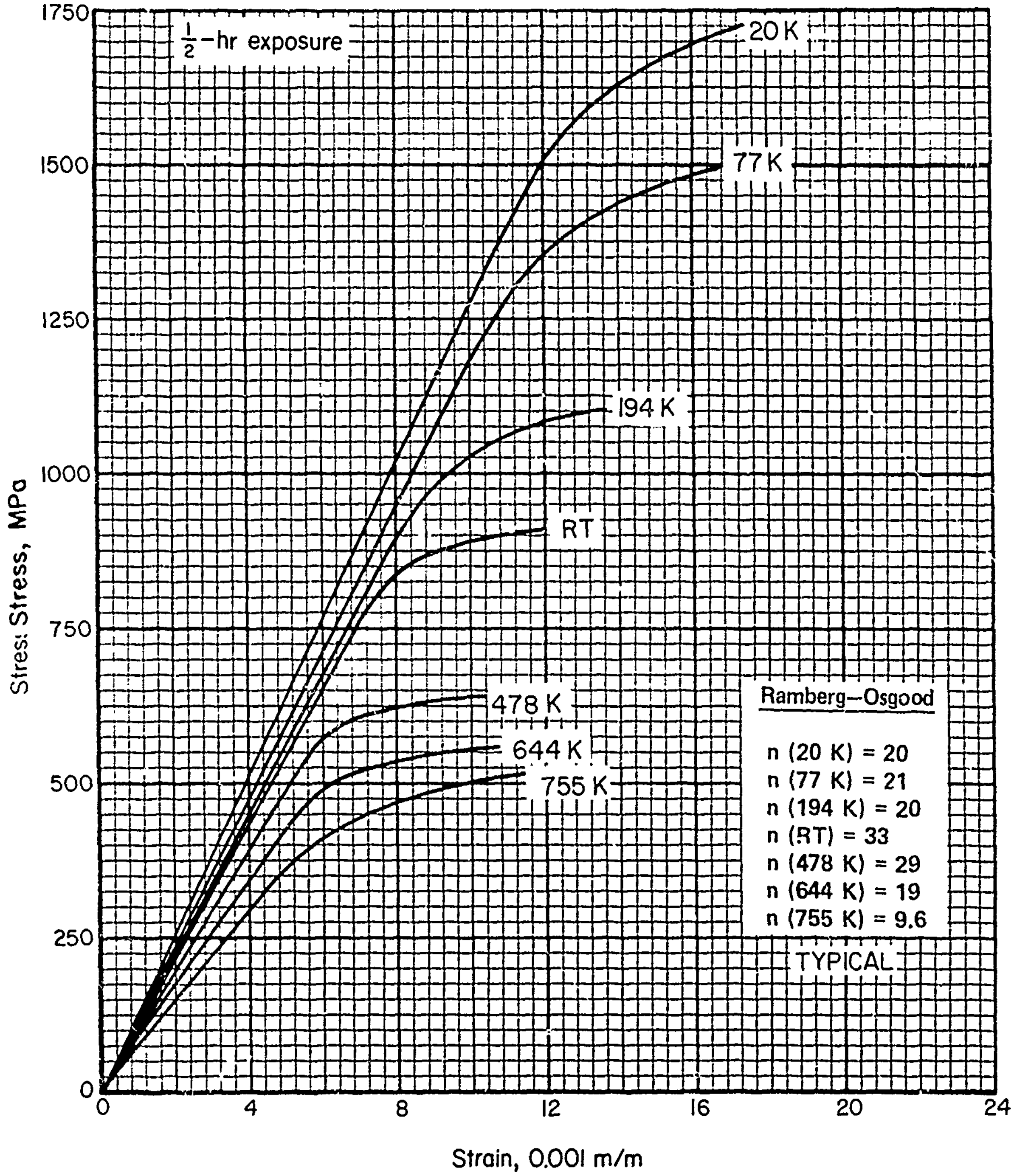


FIGURE 5.4.3.1.6(a). Typical tensile stress-strain curves at cryogenic, room and elevated temperatures for annealed Ti-6Al-4V alloy.

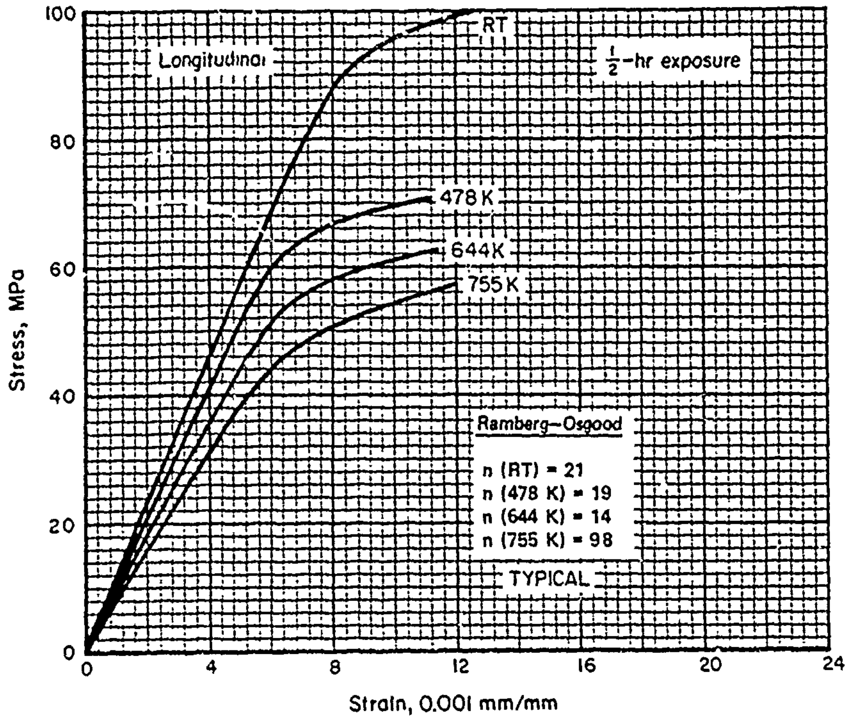


FIGURE 5.4.3.1.6(b). Typical compressive stress-strain curves at room and elevated temperatures for annealed Ti-6Al-4V alloy (extrusions).

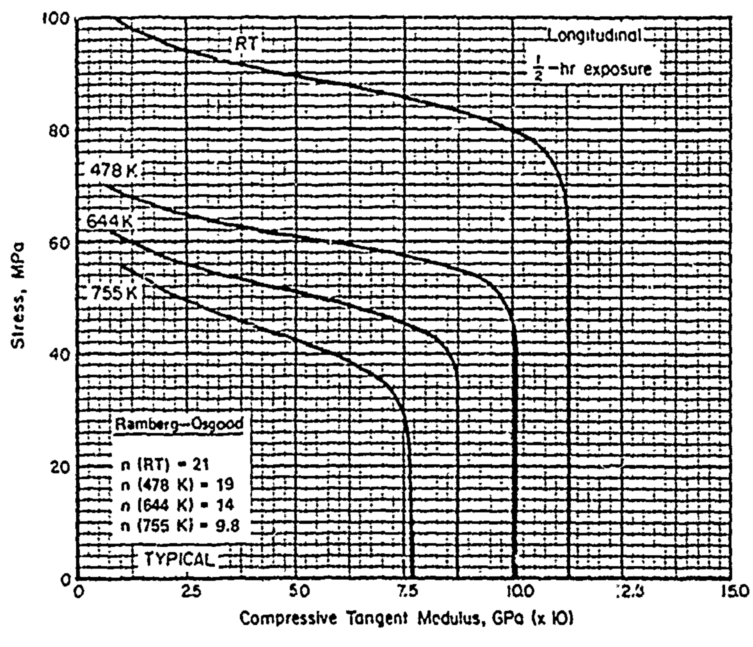
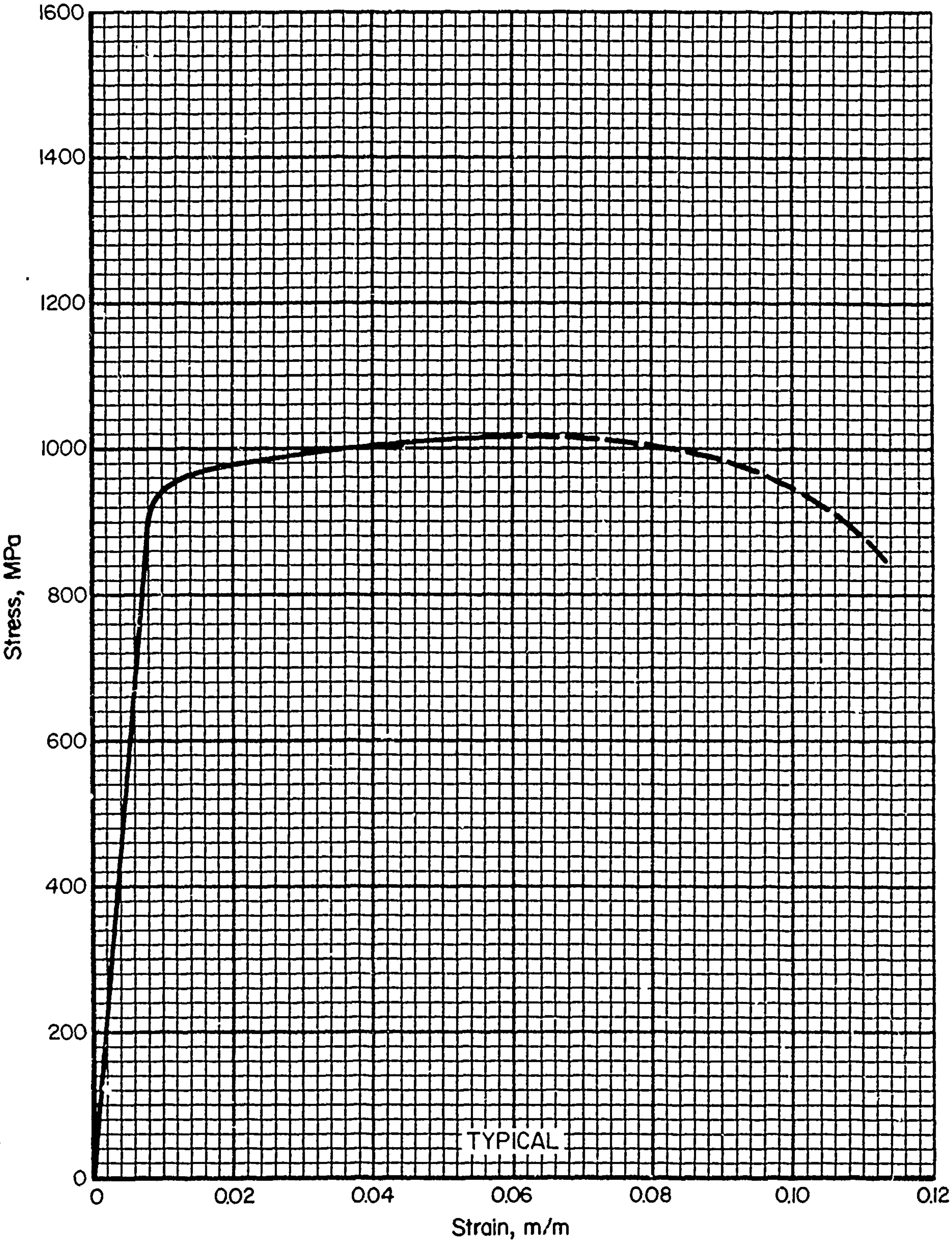


FIGURE 5.4.3.1.6(c). Typical compressive tangent-modulus curves at room and elevated temperatured for annealed Ti-6Al-4V alloy (extrusions).



IGURE 5.4.3.1.6(d). Typical tensile full range stress-strain curves for annealed Ti-6Al-4V sheet at room temperature.

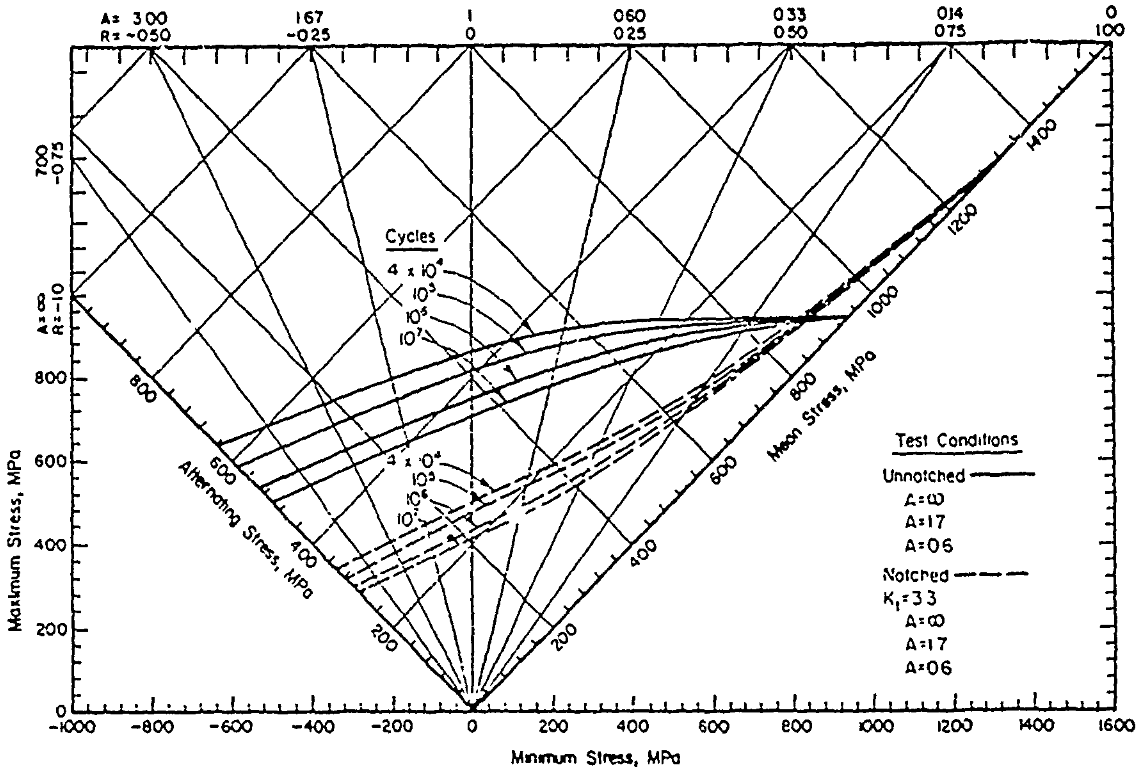


FIGURE 5.4.3.1.8(a). Typical constant-life fatigue diagram for annealed Ti-6Al-4V alloy(bar) at room temperature.

Correlative Information for Figure 5.4.3.1.8(a)

Product Form: Roller Bar, 31.75 mm diameter

Properties	TUS, MPa	TYS, MPa	Temp, K
	941	886	RT (Unnotched)
	1303	—	RT (Notched)

Test Parameters:
- Loading - Axial
- Frequency - 1750 cpm
- Temperature - RT
- Atmosphere - Air

Specimen Details:

Unnotched
- 5.16 mm diameter

Notched, V-Groove, $K_t = 3.3$
- 8.41 mm, gross diameter
- 6.40 mm, net diameter
- 0.25 mm, root radius, r
- 60° flank angle, ω

$$K_N = 1.74, \ \rho = 1.118 \text{ mm, where } K_N = 1 + \frac{K_t - 1}{1 + \frac{\pi}{\pi - \omega}\sqrt{\frac{\rho}{r}}}$$

Surface Condition: Unnotched: Polished longitudinally with 240, 400 and 600 emery belts.
Notched: Machined V-groove followed by polishing notch root with 600-grit slurry and rotating copper wire.

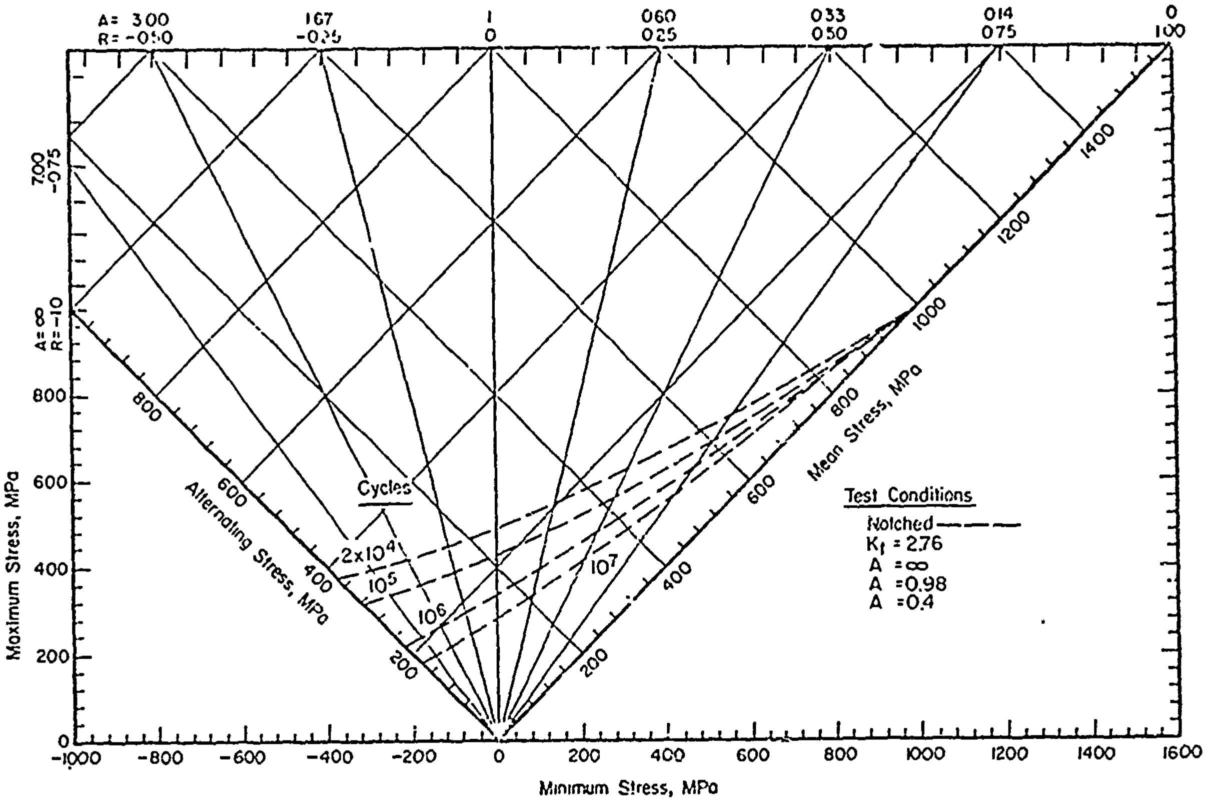


FIGURE 5.4.3.1.8(b). Typical constant-life fatigue diagram for notched annealed Ti-6Al-4V alloy (extrusions) at room temperature, longitudinal direction

Correlative Information for Figure 5.4.3.1.8(b)

Product Form: Extrusion, 7.62 and 14.22 mm thick

Grain Direction: Longitudinal

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

Properties:	TUS, MPa	TYS, MPa	Temperature, K
	986	876	RT (Unnotched)
	...	...	RT (Notched)

Specimen Details: Notched, Hole type, K_t = 2.76
38.10 mm, gross width
31.75 mm, net width
6.35 mm, hole diameter

Surface Condition: Notched: Machined to RMS 63.

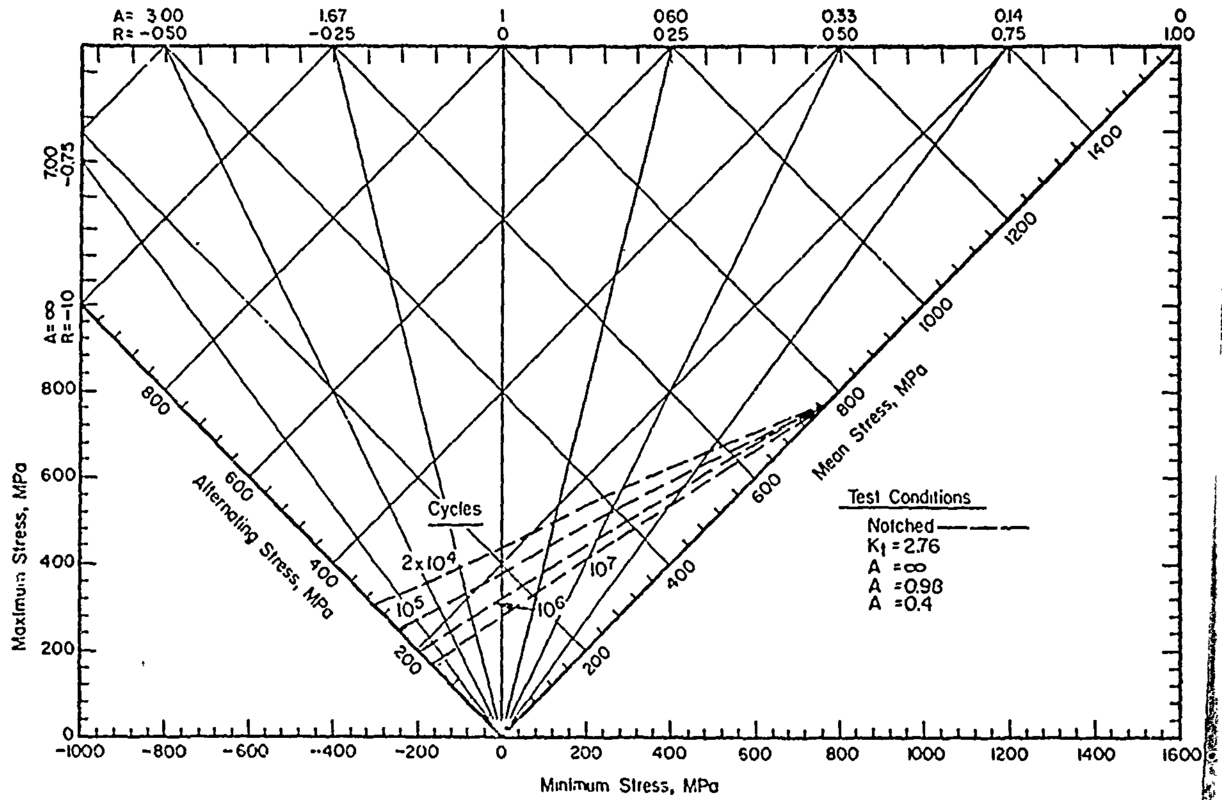


FIGURE 5.4.3.1.8(c). Typical constant-life fatigue diagram for notched annealed Ti-6Al-4V (extrusion) at 478 K, longitudinal direction

Correlative Information for Figure 5.4.3.1.8(c)

Product Form: Extrusion, 7.62 and 14.22 mm thick

Grain Direction: Longitudinal

Test Parameters:
- Loading: Axial
- Frequency: 1800 cpm
- Temperature: 478 K
- Atmosphere: Air

Properties:

TUS, MPa	TYS, MPa	Temperature, K
772	634	478 (Unnotched)
...	...	478 (Notched)

Specimen Details: Notched, Hole type, $K_t = 2.76$

38.10 mm, gross width
31.75 mm, net width
6.35 mm, hole diameter

Surface Condition: Notched: Machined to RMS 63.

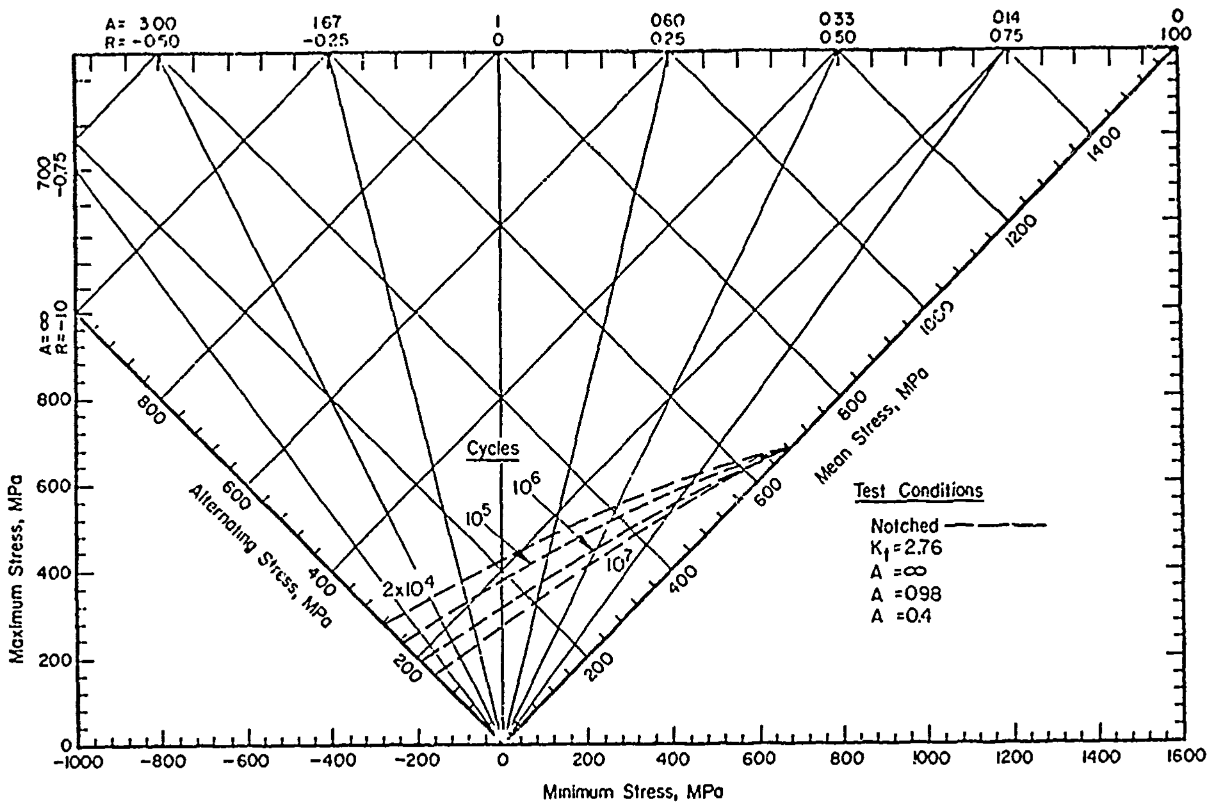


FIGURE 5.4.3.1.8(d). Typical constant-life fatigue diagram for notched annealed Ti-6Al-4V (extrusions) at 589 K, longitudinal direction

Correlative Information for Figure 5.4.3.1.8(d)

Product Form: Extrusion, 7.62 and 14.22 mm thick

Grain Direction: Longitudinal

Test Parameters:
Loading: Axial
Frequency: 1800 cpm
Temperature: 589 K
Atmosphere: Air

Properties:

TUS, MPa	TYS, MPa	Temperature, K
696	531	589 (Unnotched)
...	...	589 (Notched)

Specimen Details: Notched, Hole type, K_t = 2.76

38.10 mm, gross width
31.75 mm, net width
6.35 mm, hole diameter

Surface Condition: Notched: Machined to RMS 63.

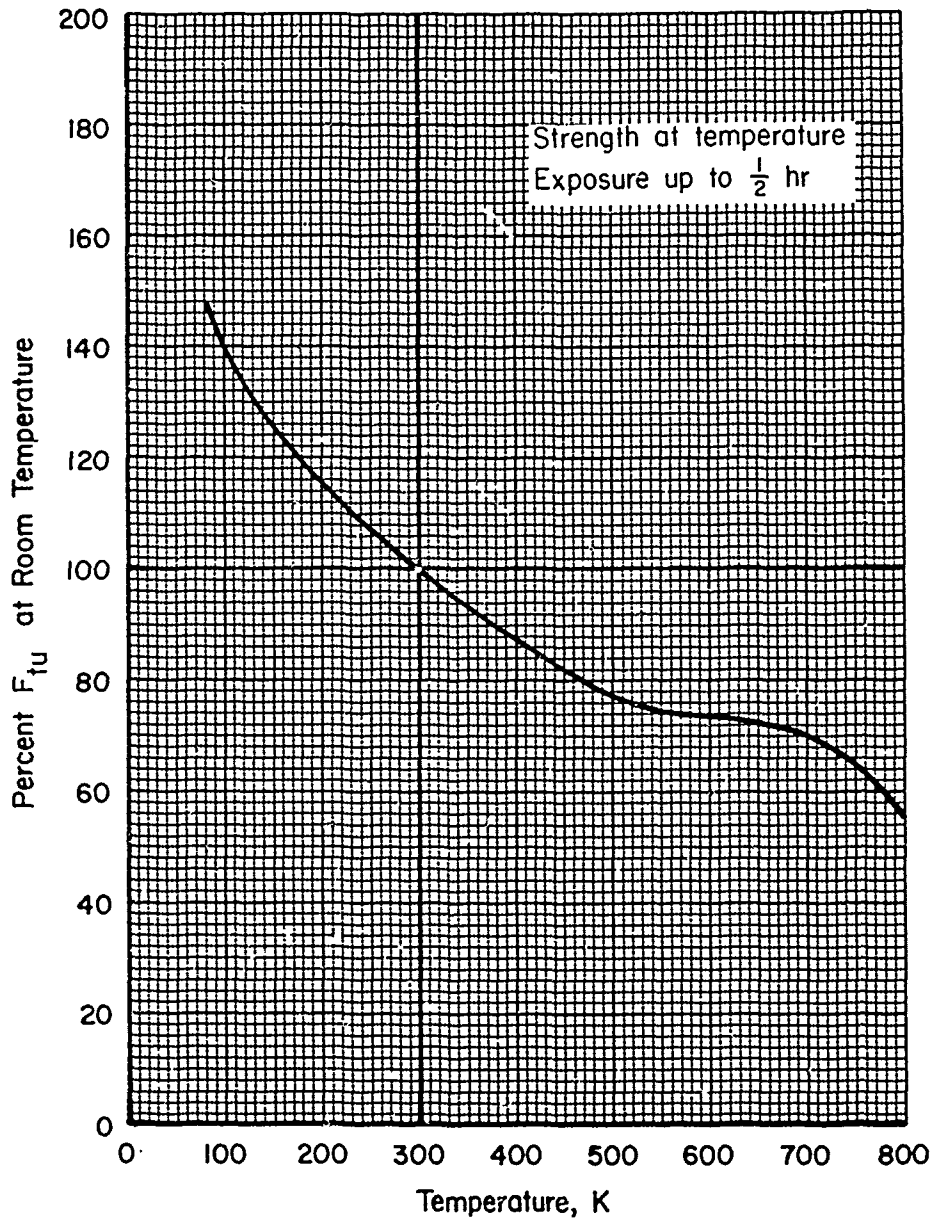


FIGURE 5.4.3.2.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of solution-treated and aged Ti-6Al-4V alloy.

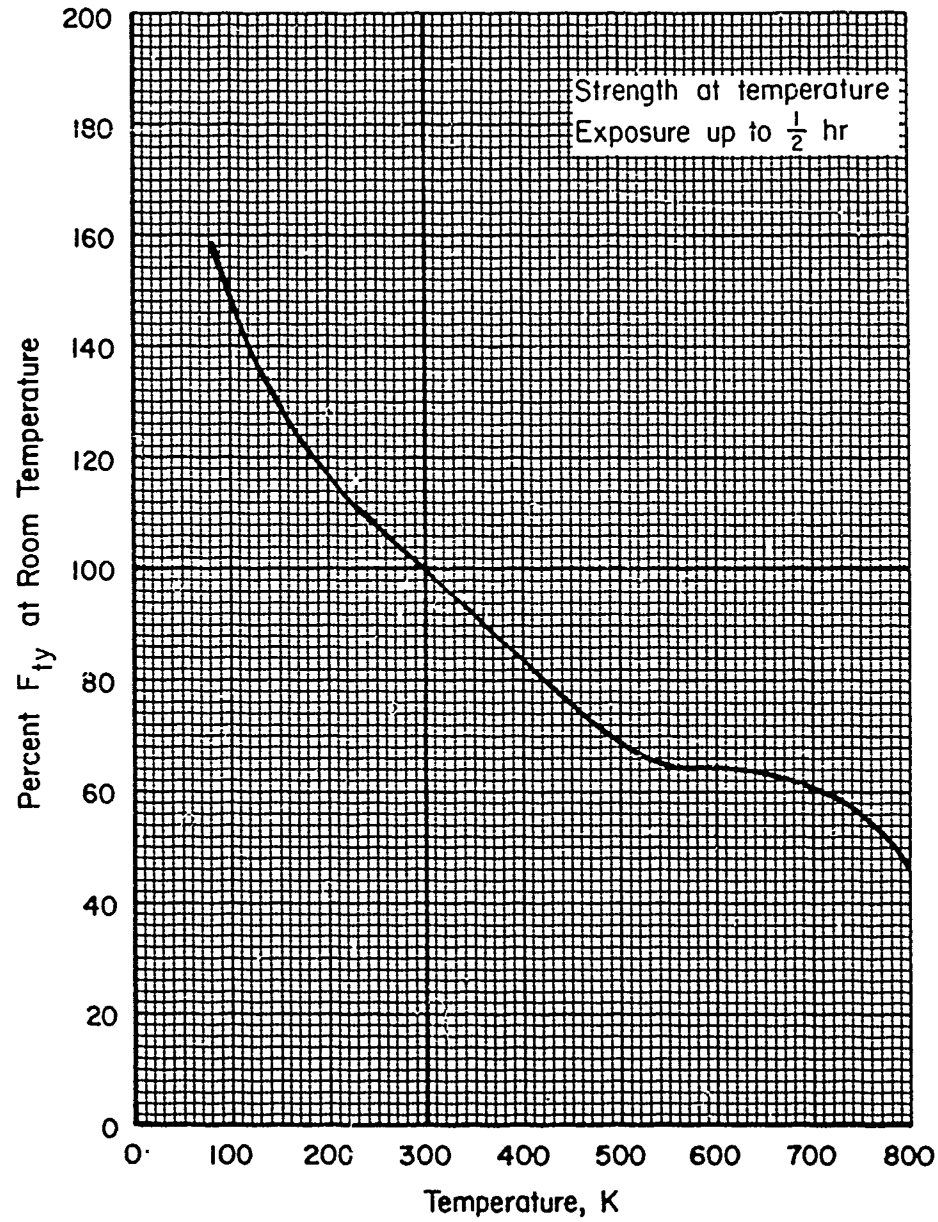


FIGURE 5.4.3.2.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of solution-treated and aged Ti-6Al-4V alloy.

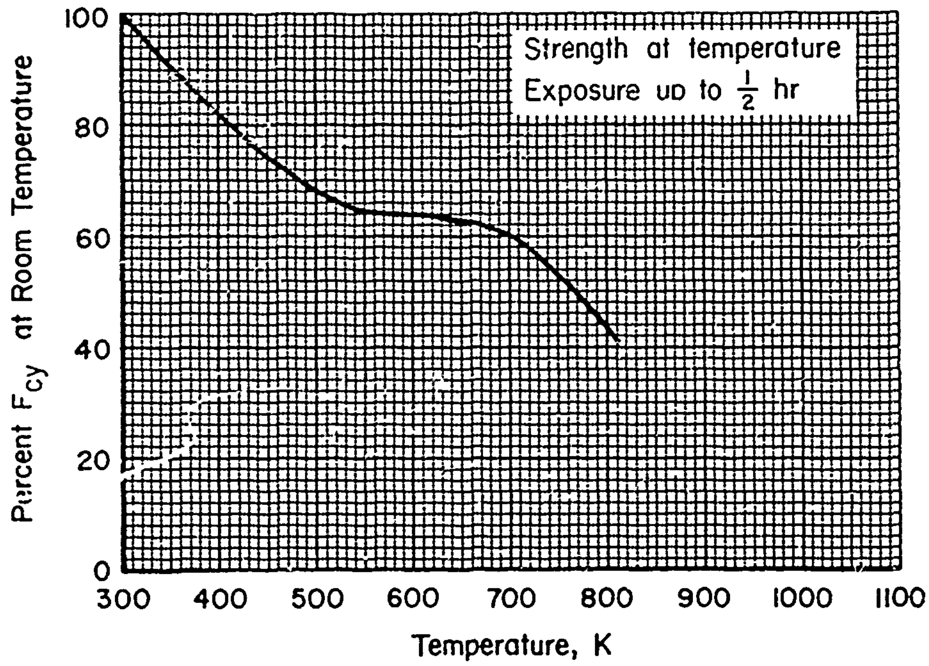


FIGURE 5.4.3.2.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of solution-treated and aged Ti-6Al-4V alloy.

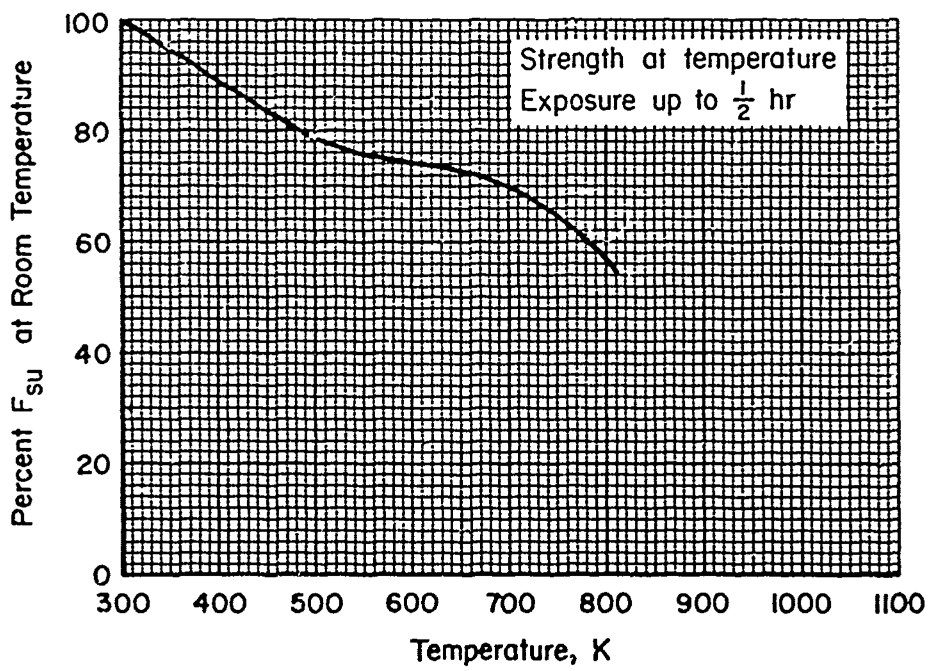


FIGURE 5.4.3.2.2(b). Effect of temperature on the ultimate shear strength (F_{su}) of solution-treated and aged Ti-6Al-4V alloy.

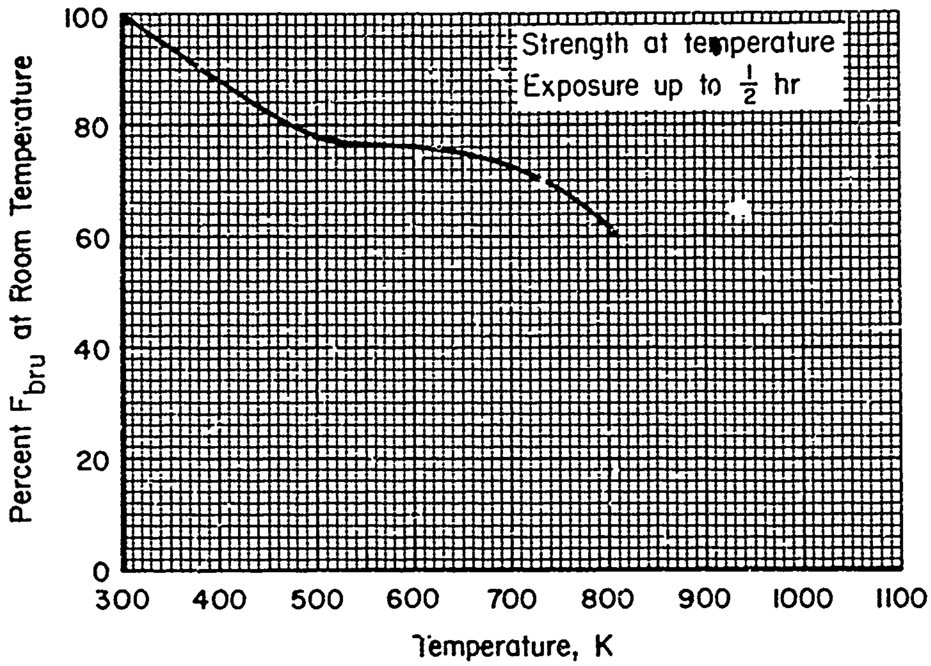


FIGURE 5.4.3.2.3(a). Effect of temperature on the ultimate bearing strength (F_{bru}) of solution-treated and aged Ti-6Al-4V alloy.

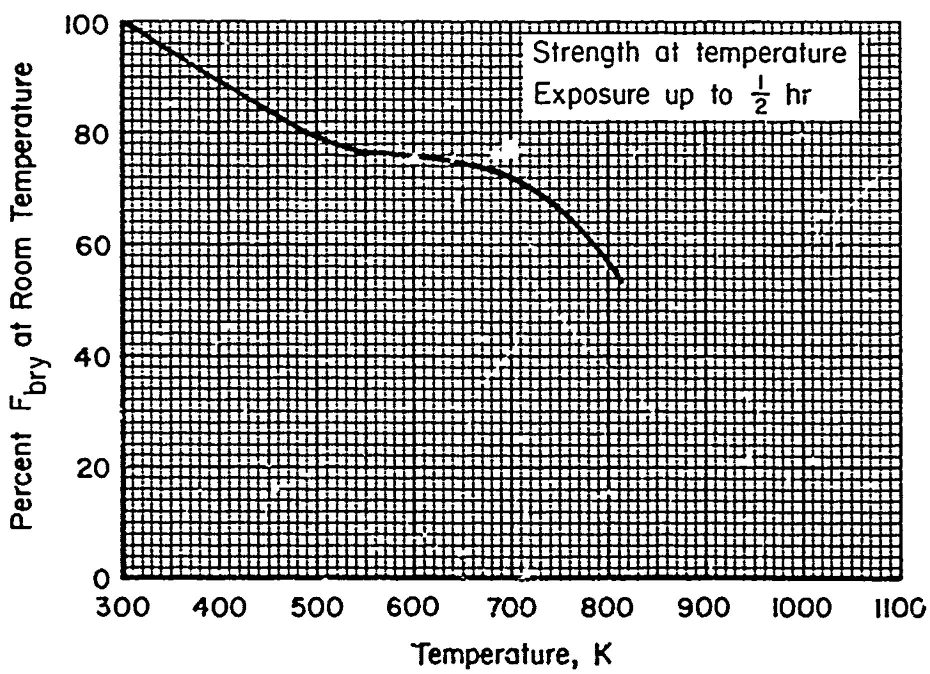


FIGURE 5.4.3.2.3(b). Effect of temperature on the bearing yield strength (F_{bry}) of solution-treated and aged Ti-6Al-4V alloy.

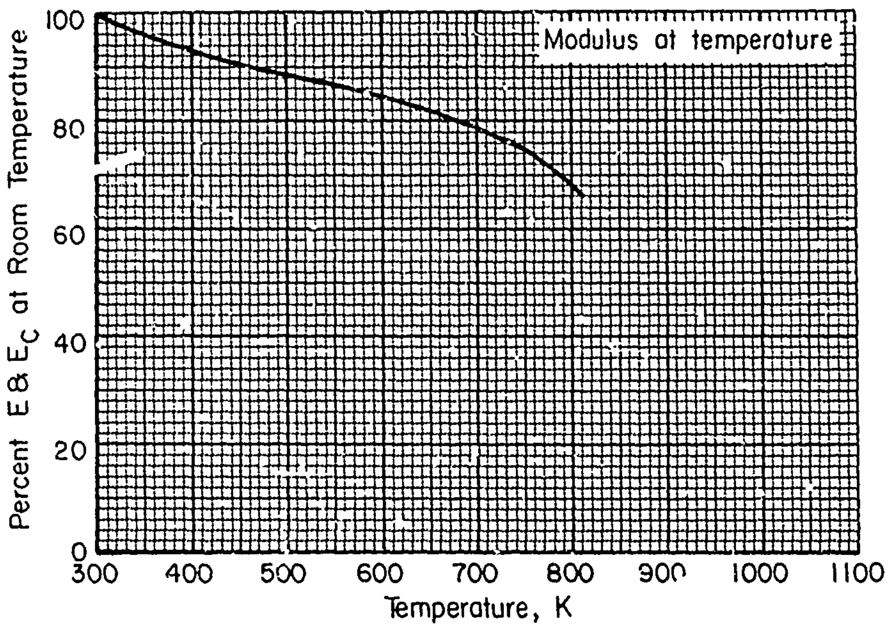


FIGURE 5.4.3.2.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of solution-treated and aged Ti-6Al-4V alloy.

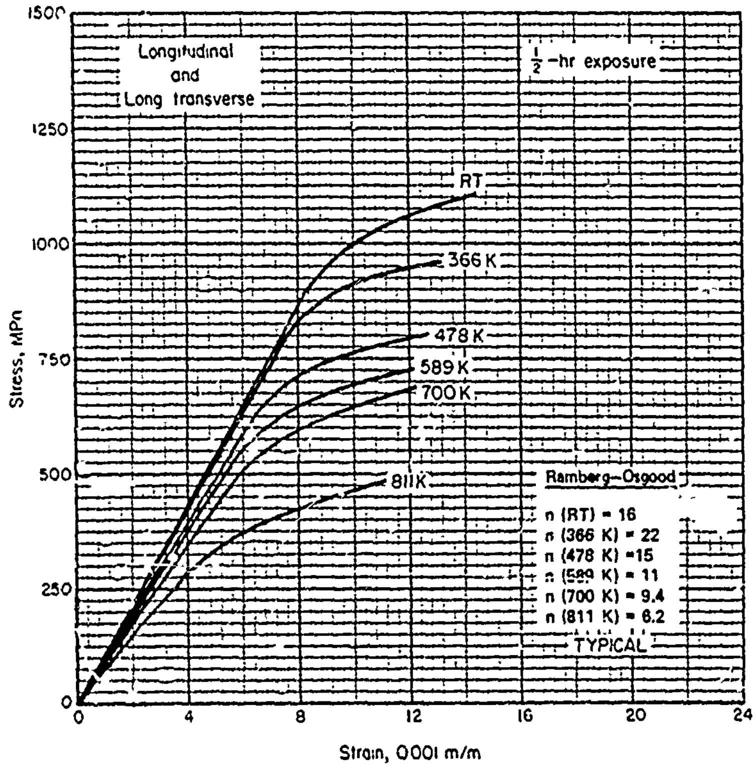


FIGURE 5.4.3.2.6(a). Typical tensile stress-strain curves for solution-treatment and aged Ti-6AL-4V alloy (sheet) at room and elevated temperatures.

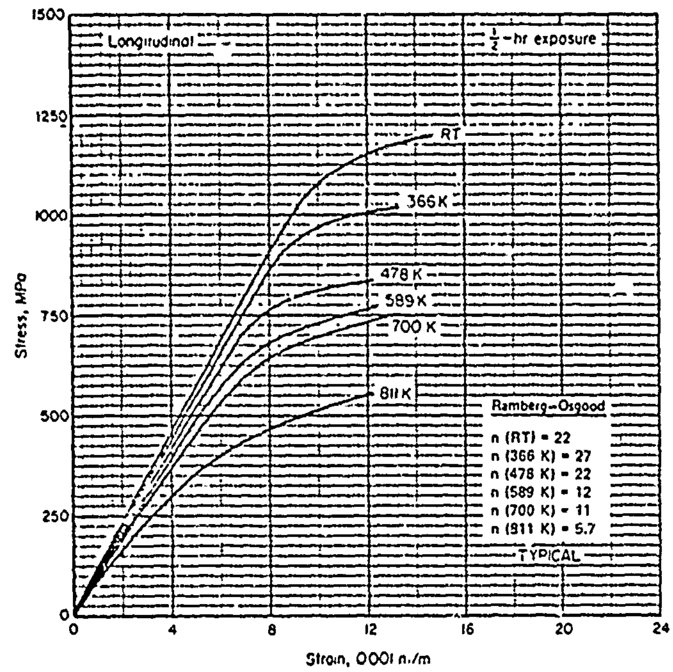


FIGURE 5.4.3.2.6(b). Typical compressive stress-strain curves for solution-treated and aged Ti-6Al-4V alloy (sheet) at room and elevated temperatures.

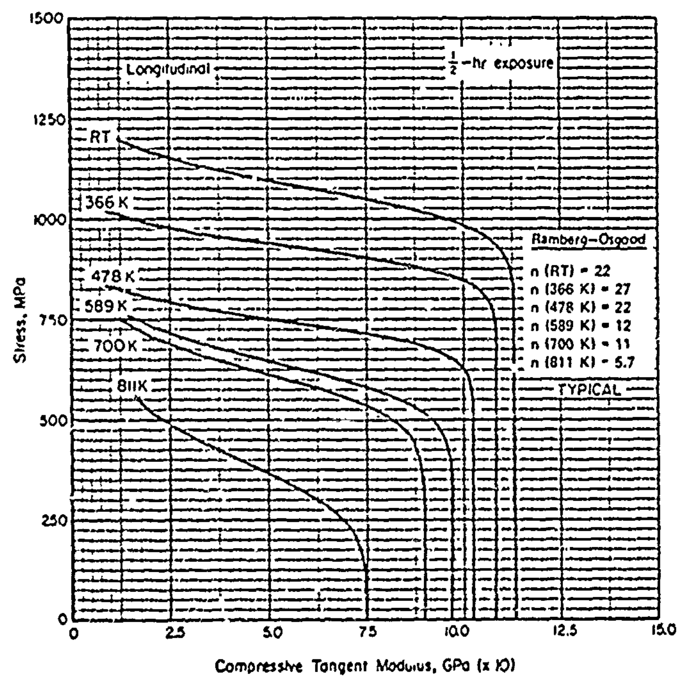


FIGURE 5.4.3.2.6(c). Typical compressive tangent-modulus curves for solution-treated and aged Ti-6Al-4V alloy (sheet) at room and elevated temperatures.

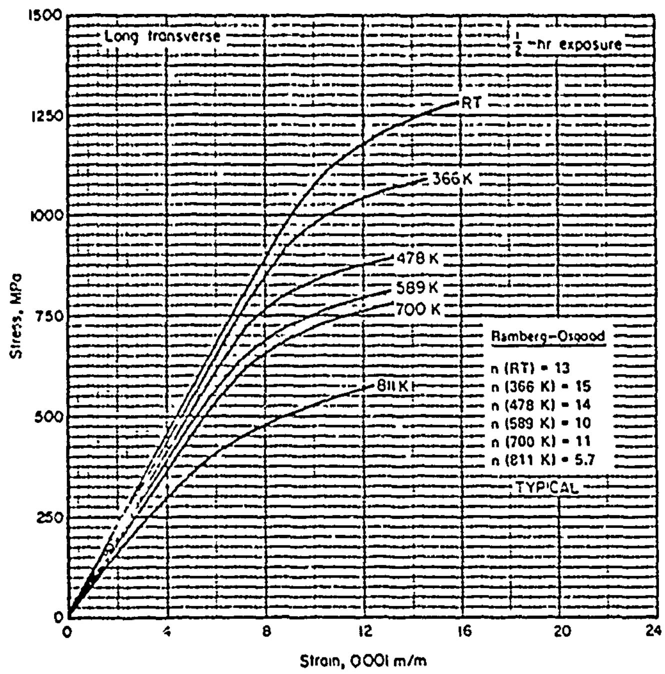


FIGURE 5.4.3.2.6(d). Typical compressive stress-strain curves for solution-treated and aged Ti-6Al-4V alloy (sheet) at room and elevated temperatures.

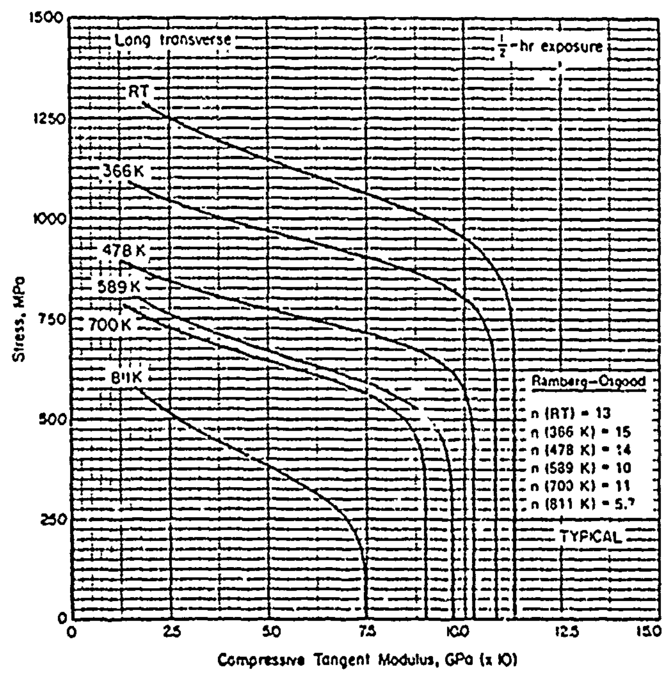


FIGURE 5.4.3.2.6(e). Typical compressive tangent-modulus curves for solution-treated and aged Ti-6Al-4V alloy (sheet) at room and elevated temperatures.

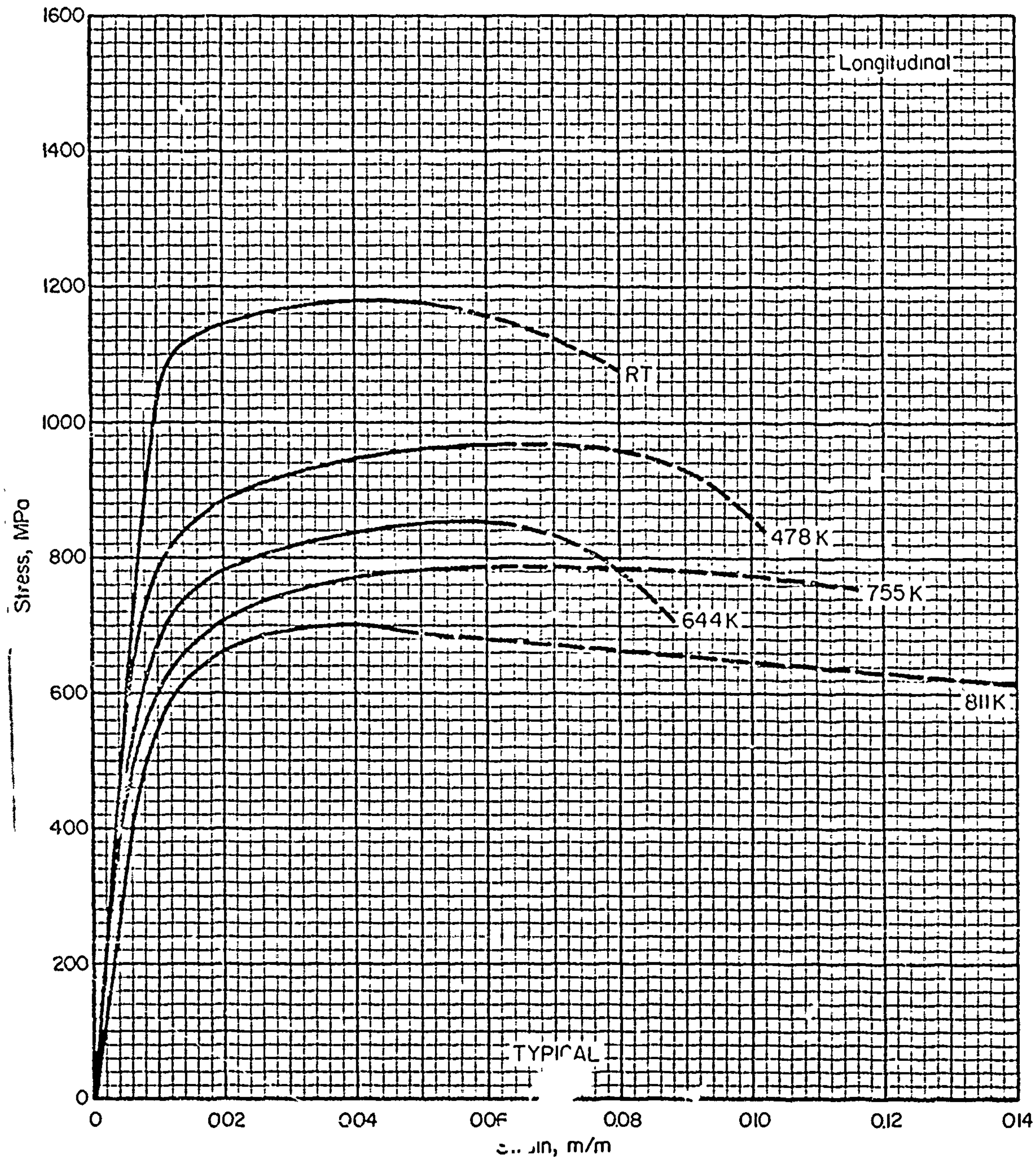


FIGURE 5.4.3.2.6(f) Typical full range stress-strain curves for solution-treated and aged Ti-6Al-4V alloy at room and elevated temperatures.

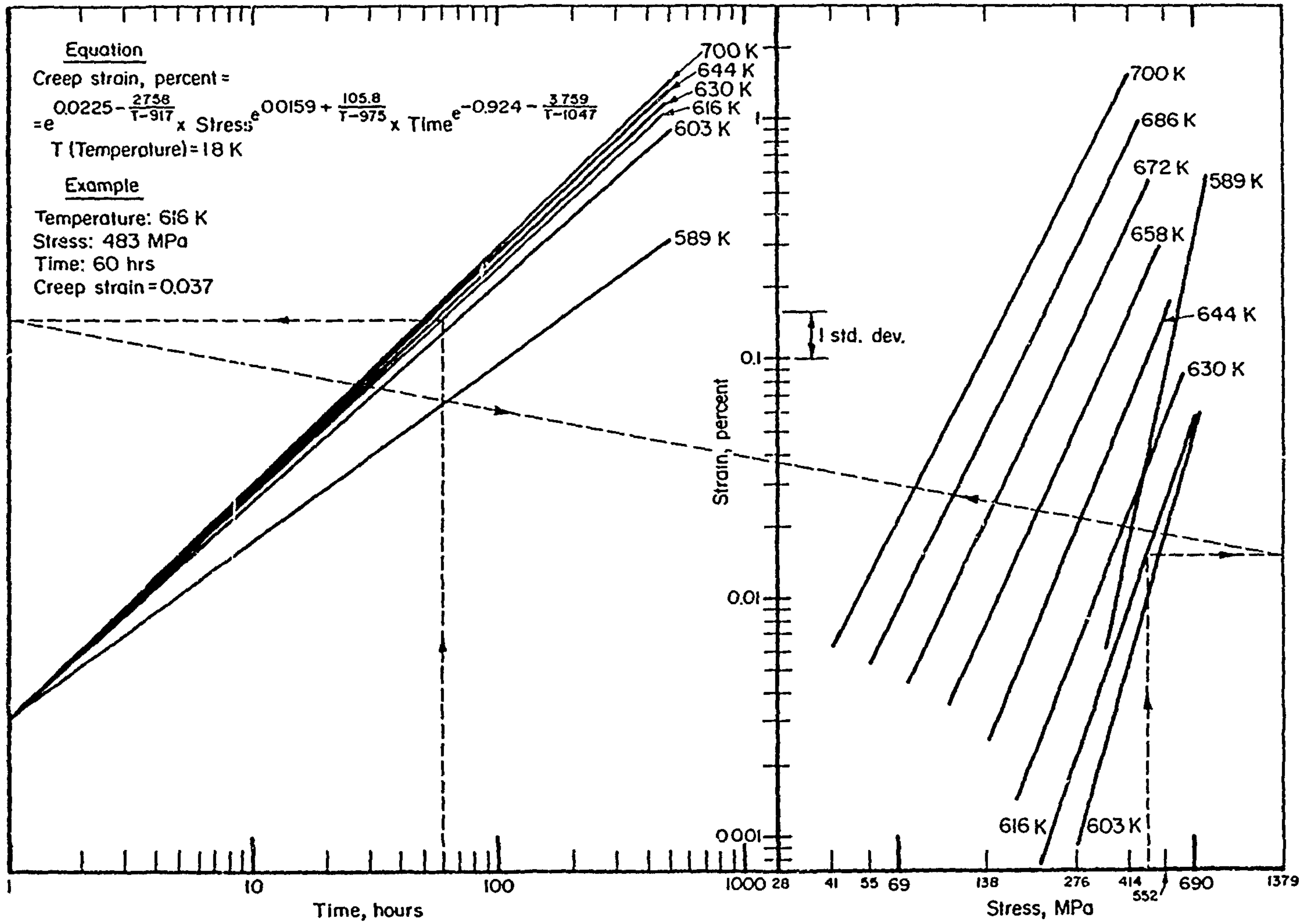


FIGURE 5.4.3.2.7. Typical creep properties of solution-treated and aged Ti-6Al·4V alloy sheet for temperature range 589K through 700K.

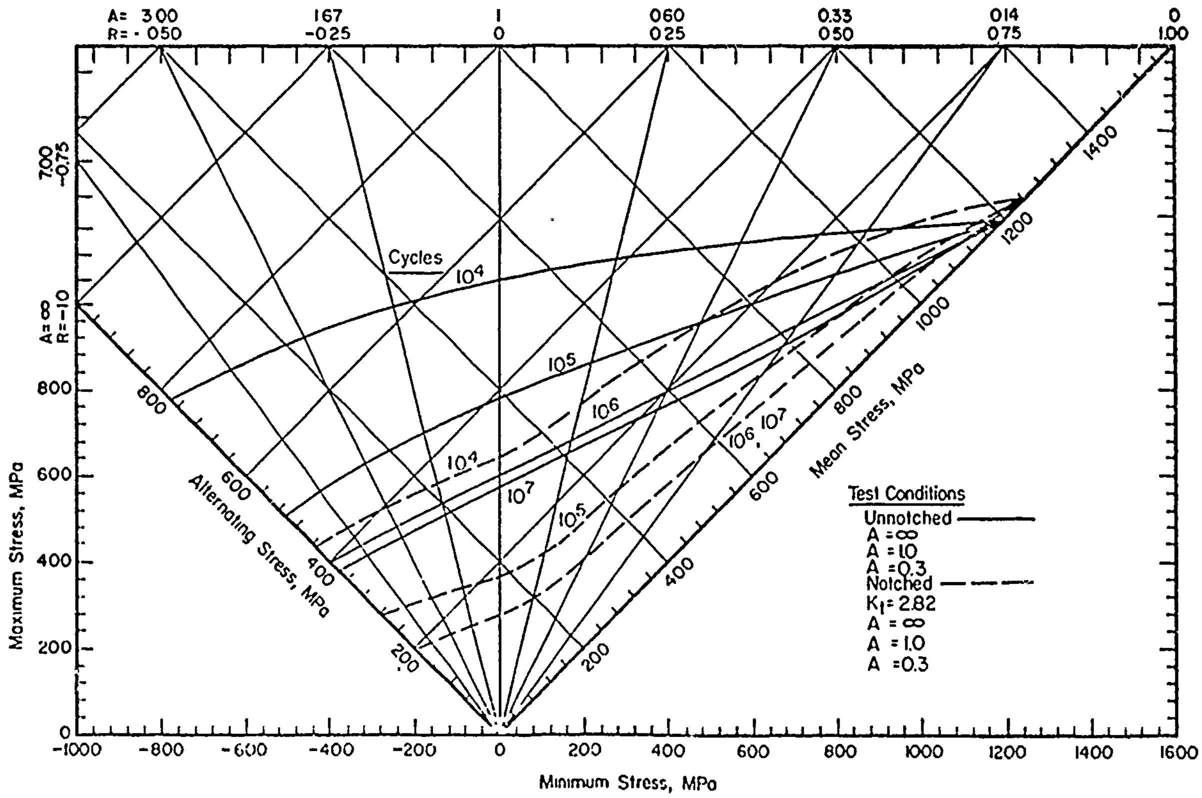


FIGURE 5.4.3.2.8(a). Typical constant-life fatigue diagram for solution-treated and aged Ti-6Al-4V alloy (sheet) at room temperature

Correlative Information for Figure 5.4.3.2.8(a)

Product Form: Sheet, 1.60 mm and 3.18 mm thick

Properties:

TUS, MPa	TYS, MPa	Temp, K
1186	1089	RT (Unnotched)
1241	—	RT (Notched)

Test Parameters:
Loading - Axial
Frequency - 1500 to 2200 cpm
Temperature - RT
Atmosphere - Air

Specimen Details:

Unnotched
25.4 mm width

Notched, V-Groove, $K_t = 2.82$
25.4 mm, gross width
23.81 mm, net width
1.588 mm, hole diameter

$$K_N = 1.72,\ \rho = 1.803\ \text{mm},\quad \text{where } K_N = 1 + \frac{K_t - 1}{1 + \frac{\pi}{\pi - \omega}\sqrt{\frac{\rho}{r}}}$$

Surface Condition: Unnotched. As rolled surface but edges machined and hand polished with Numbers 1 and 00 grit emery paper, cleaned with methyl ethyl ketone.
Notched: Surface and edges were prepared as above, 1.5875 mm-diameter hole was drilled and reamed.

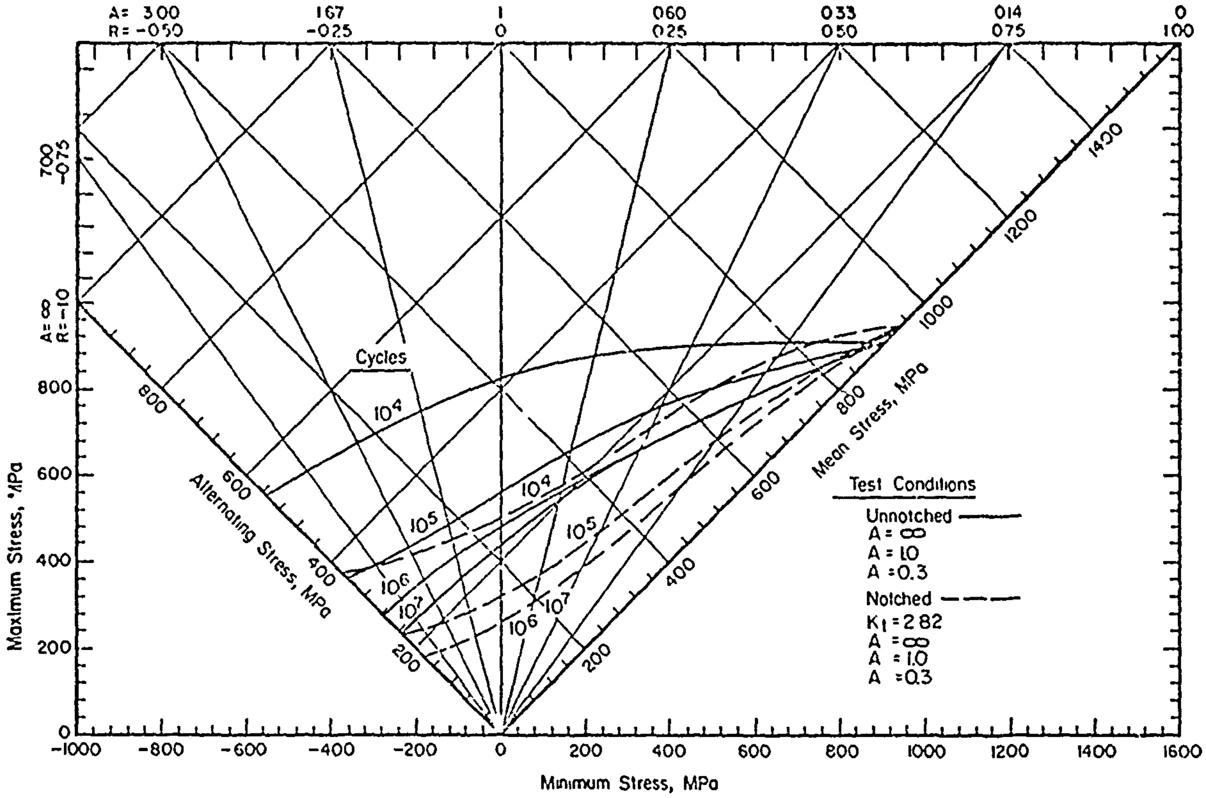


FIGURE 5.4.3.2.8(b). Typical constant-life fatigue diagram for solution-treated and aged Ti-6Al-4V alloy (sheet) at 589 K

Correlative Information for Figure 5.4.3.2.8(b)

Product Form: Sheet, 1.60 mm and 3.18 mm thick

Properties:

TUS, MPa	TYS, MPa	Temp, K
910	724	589 (Unnotched)
938	—	589 (Notched)

Test Parameters:
Loading - Axial
Frequency - 1500 to 2200 cpm
Temperature - 589 K
Atmosphere - Air

Specimen Details:

Unnotched: 25.4 mm width

Notched, Hole type, $K_t = 2.82$:
25.40 mm, gross width
23.81 mm, net width
1.588 mm, hole diameter

$$K_N = 1.29,\ \rho = 22.1\ \text{mm, where}\ K_N = 1 + \frac{K_t - 1}{1 + \frac{\pi}{\pi - \omega}\sqrt{\frac{\rho}{r}}}$$

Surface Condition: Unnotched: As rolled surface but edges machined and hand polished with Numbers 1 and 00 grit emery paper, cleaned with methyl ethyl ketone.
Notched: Surface and edges were prepared as above, 1.58785 mm-diameter hole was drilled and reamed.

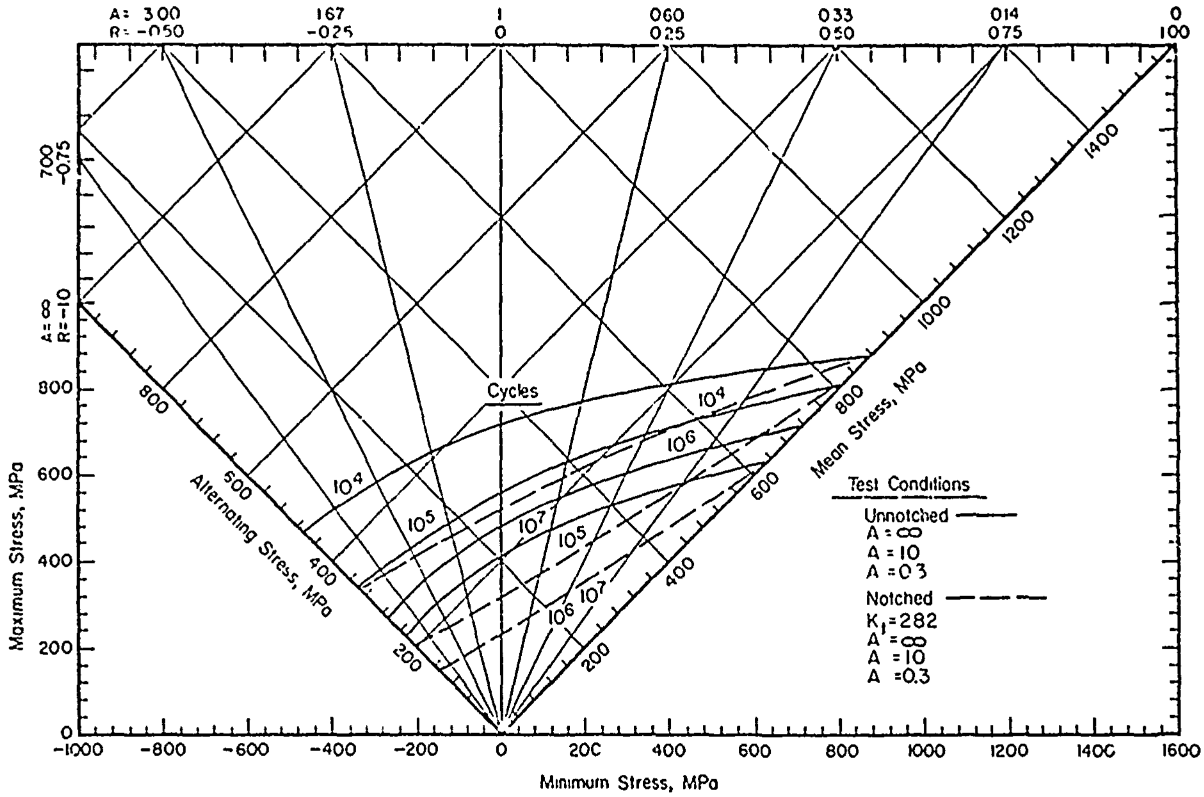


FIGURE 5.4.3.2.8(c). Typical constant-life fatigue diagram for solution-treated aged Ti-6Al-4V alloy (sheet) at 700 K

Correlative Information for Figure 5.4.3.2.8(c)

Product Form: Sheet, 1.60 mm and 3.18 mm thick

Properties:	TUS, MPa	TYS, MPa	Temp, K
	855	669	700 (Unnotched)
	876	—	700 (Notched)

Test Parameters:
- Loading - Axial
- Frequency - 1500 to 2200 cpm
- Temperature - 700 K
- Atmosphere - Air

Specimen Details:

Unnotched
- 25.40 mm width

Notched, Hole type, $K_t = 2.82$
- 25.40 inch, gross width
- 23.81 inch, net width
- 1.588 inch, hole diameter

$$K_N = 1.50,\ \rho = 5.33 \text{ mm, where } K_N = 1 + \frac{K_t - 1}{1 + \frac{\pi}{\pi - \omega}\sqrt{\frac{\rho}{r}}}$$

Surface Condition. Unnotched. As rolled surface but edges machined and hand polished with Numbers 1 and 00 grit emery paper, cleaned with methyl ethyl ketone.
Notched: Surface and edges were prepared as above, 1.5875 mm-diameter hole was drilled and reamed.

5.4.4 Ti-6Al-6V-2Sn

5.4.4.0 *Comments.* —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 51 mm in thickness.

Manufacturing Considerations. — To insure 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., < 1219K). 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 is hot formed at any temperature over 811 K and air cooled, the material should be stabilized by reheating to 811 K 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 616 Kand long-term stability at temperatures above 700 Kare not. The material ages during prolonged exposures around 700 K and above, particularly when under stress. Oxidation resistance of Ti-6Al-6V-2Sn is satisfactory in short term exposures to 811 K. The material is nearly equivalent to the Ti-6Al 4V alloy in terms of hot-salt and aqueous chloride solution stress-corrosion resistance.

Specifications. — Material specifications for Ti-6Al-6V-2Sn are presented in Table 5.4.4.0(a).

TABLE 5.4.4.0(a). *Material Specifications for Ti-6Al-6V-2Sn*

Specifications	Form
MIL-T-9046....	Sheet, strip and plate
MIL-T-9047....	Bars
MIL-T-81556...	Extruded bars, rods, and special shaped sections
AMS 4978	Forgings

Heat Treatment. — This alloy is commonly specified in either the annealed condition or the fully heat-treated condition. The specified fully heat-treated, or solution-treated and aged condition is as follows:

Solution treat at 1158 K for 1/2 to 1 hour, quench in water.

Age at 811 ± 15 K for 4 to 8 hours, air cool.

Room-Temperature Properties

Room-temperature mechanical and physical properties for Ti-6Al-6V-2Sn are presented in Tables 5.4.4.0(b) through (e). The effect of temperature on physical properties is shown in Figure 5.4.4.0.

5.4.4.1 *Annealed Condition* — Effect of temperature curves for annealed condition are shown in Figures 5.4.4.1.1(a) through 5.4.4.1.3(b). Typical stress-strain curves for this condition are presented in Figures 5.4.4.1.6(a) through (c).

5.4.4.2 *Solution-Treated and Aged Condition.* — Effect of temperature curves for this condition are presented in Figures 5.4.4.2.1(a) and (b).

TABLE 5.4.4.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF TI-6AL-6V-2SN (SHEET, STRIP AND PLATE)

SPECIFICATION	MIL-T-9046, TYPE III, COMP. E							
FORM	SHEET, STRIP AND PLATE							
CONDITION	ANNEALED				SOLUTION TREATED AND AGED			
THICKNESS, MM	≤4.76		4.77-50.8[1]	50.82-101.60	≤4.76	4.77-38.1[1]	38.12-63.5[1]	63.52-101.60
BASIS	A	B	S	S	S	S	S	S
MECHANICAL PROPERTIES:								
FTU, MPA:								
L	1070	1100	1030	1000	1170	1170	1100	1030
LT	1070	1100	1030	1000	1170	1170	1100	1030
FTY, MPA:								
L	1000[a]	1050	965	931	1100	1100	1030	965
LT	1000[a]	1060	965	931	1100	1100	1030	965
FCY, MPA:								
L	...	...	...	...	...	...	...	...
LT	...	...	...	...	...	...	...	...
FSU, MPA	...	...	...	...	...	...	...	...
FBRU, MPA:								
(E/D=1.5)	...	...	...	...	...	...	...	...
(E/D=2.0)	...	...	...	...	...	...	...	...
FBRY, MPA:								
(E/D=1.5)	...	...	...	...	...	...	...	...
(E/D=2.0)	...	...	...	...	...	...	...	...
EL, PERCENT:								
L	b	...	10	8	8	8	6	6
LT	b	...	8	6	6	8	6	6
E, GPA	117.2							
EC, GPA	120.7							
G, GPA	44.8							
MU	0.32							
PHYSICAL PROPERTIES:								
OMEGA, MG/M3	4.54							
C, J/(G*K)	SEE FIGURE 5.4.4.0							
K, W/(M*K)	SEE FIGURE 5.4.4.0							
ALPHA, 10-6 M/(M*K)	SEE FIGURE 5.4.4.0							

[a] THE A VALUES ARE HIGHER THAN THE SPECIFICATION VALUES AS FOLLOWS: FTY(L) = 10 MPA, FTY(LT) = 1027 MPA, EL(LT) = 9 PERCENT.

[b] LONGITUDINAL ≥ 0.635 THICK = 10
LONG TRANSVERSE ≥ 0.635 THICK = 8
LONGITUDINAL < 0.635 THICK = 8
LONG TRANSVERSE < 0.635 THICK = 6.

TABLE 5.4.4.0(C). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF TI-5AL-6V-2SN (BARS)

SPECIFICATION	MIL-T-9047, COMP. 8									
FORM	ROLLED AND FORGED BAR									
CONDITION	FURNACE-COOL ANNEALED[a]						SOLUTION TREATED AND AGED			
THICKNESS, MM	≤38.11		38.12-76.21		76.22-101.60		≤25.41	25.42-50.81	50.82-76.21	76.22-101.60
BASIS	A	B	A	B	A	B	S	S	S	S
MECHANICAL PROPERTIES:										
FTU, MPA:										
L	965	1010	924	972	924	972	1210	1170	1070	1030
LT	953	1010	...	...	...	...	1210	1170	1070	1030
ST	...	...	...	...	...	...	1210	1170	1070	1030
FTY, MPA:										
L	924	979	889	931	889	931	1100	1070	1000	965
LT	889	938	...	...	...	...	1100	1070	1000	965
ST	...	...	...	...	...	...	1100	1070	1000	965
FCY, MPA:										
L	...	...	...	...	...	...	...	...	...	...
LT	...	...	...	...	...	...	...	...	...	...
ST	...	...	...	...	...	...	...	...	...	...
FSU, MPA	...	...	...	...	...	...	...	...	...	...
FBRU, MPA:										
(E/D=1.5)	...	...	...	...	...	...	...	...	...	...
(E/D=2.0)	...	...	...	...	...	...	...	...	...	...
FBRY, MPA:										
(E/D=1.5)	...	...	...	...	...	...	...	...	...	...
(E/D=2.0)	...	...	...	...	...	...	...	...	...	...
EL, PERCENT:										
L	8	...	8	...	8	...	6	6	6	6
LT	8	...	...	...	...	6	6	6	6	6
ST	...	...	...	...	...	...	6	6	6	6
E, GPA	117.2									
EC, GPA	120.7									
G, GPA	44.8									
MU	0.32									
PHYSICAL PROPERTIES:										
OMEGA, MG/M3	4.54									
C, J/(G*K)	SEE FIGURE 5.4.4.0									
K, W/(M*K)	7									
ALPHA, 10-6 M/(M*K)	SEE FIGURE 5.4.4.0									

[a] 478 TO 1005K FOR 2 HOURS, FURNACE COOL TO 811K, AIR COOL TO ROOM TEMPERATURE.

TABLE 5.4.4.0(D). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF TI-6AL-6V-2SN (FORGINGS)

SPECIFICATION	AMS 4979	
FORM	FORGINGS	
CONDITION	ANNEALED	
THICKNESS, MM	≤50.81	50.82-101.60
BASIS	S	S
MECHANICAL PROPERTIES:		
FTU, MPA:		
L	1030	1000
T	1030	1000
FTY, MPA:		
L	965	931
T	965	931
FCY, MPA:		
L	...	...
T	...	...
FSU, MPA	...	...
FBRU, MPA:		
(E/D=1.5)	...	...
(E/D=2.0)	...	...
FBRY, MPA:		
(E/D=1.5)	...	...
(E/D=2.0)	...	...
EL, PERCENT:		
L	10	10
T	8	8
E, GPA	117.2	
EC, GPA	120.7	
G, GPA	44.8	
MU	0.32	
PHYSICAL PROPERTIES:		
OMEGA, MG/M3	4.54	
C, J/(G*K)	SEE FIGURE 5.4.4.0	
K, W/(M*K)	7	
ALPHA, 10-6 M/(M*K)	SEE FIGURE 5.4.4.0	

TABLE 5.4.4.0(E). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF TI-6A1-6V-2SN (EXTRUSIONS)

SPECIFICATION	MIL-T-81556, TYPE III, COMP. C						
FORM	EXTRUDED BARS, RODS, AND SPECIAL SHAPED SECTIONS						
CONDITION	ANNEALED			SOLUTION TREATED AND AGED			
THICKNESS, MM	<50.81		50.82-101.60	≤12.70	12.71-38.10	38.11-63.50	63.51-101.60
BASIS	A	B	S	S	S	S	S
MECHANICAL PROPERTIES:							
FTU, MPA:							
L	979	1020	1000	1170	1140	1100	1030
LT	972	1020	...	...	...	...	...
FTY, MPA:							
L	889	931	931	1100	1070	1030	965
LT	883	917	...	...	...	...	...
FCY, MPA:							
L	945	993	...	...	...	...	...
LT	933	979	...	...	...	...	...
FSU, MPA	641	669	...	...	...	...	...
FBRU[a], MPA:							
(E/D=1.5)	1500	1580	...	...	...	...	...
(E/D=2.0)	1850	1940	...	...	...	...	...
FBRY[a], MPA:							
(E/D=1.5)	1350	1400	...	...	...	...	...
(E/D=2.0)	1570	1620	...	...	...	...	...
EL, PERCENT:							
L	8	...	8	6	6	6	6
LT	...	...	...	...	...	...	...
E, GPA	117.2						
EC, GPA	120.7						
G, GPA	44.8						
MU	0.32						
PHYSICAL PROPERTIES:							
OMEGA, MG/M3	4.54						
C, J/(G*K)	SEE FIGURE 5.4.4.0						
K, W/(M*K)	SEE FIGURE 5.4.4.0						
ALPHA, 10-6 M/(M*K)	SEE FIGURE 5.4.4.0						

[a] BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

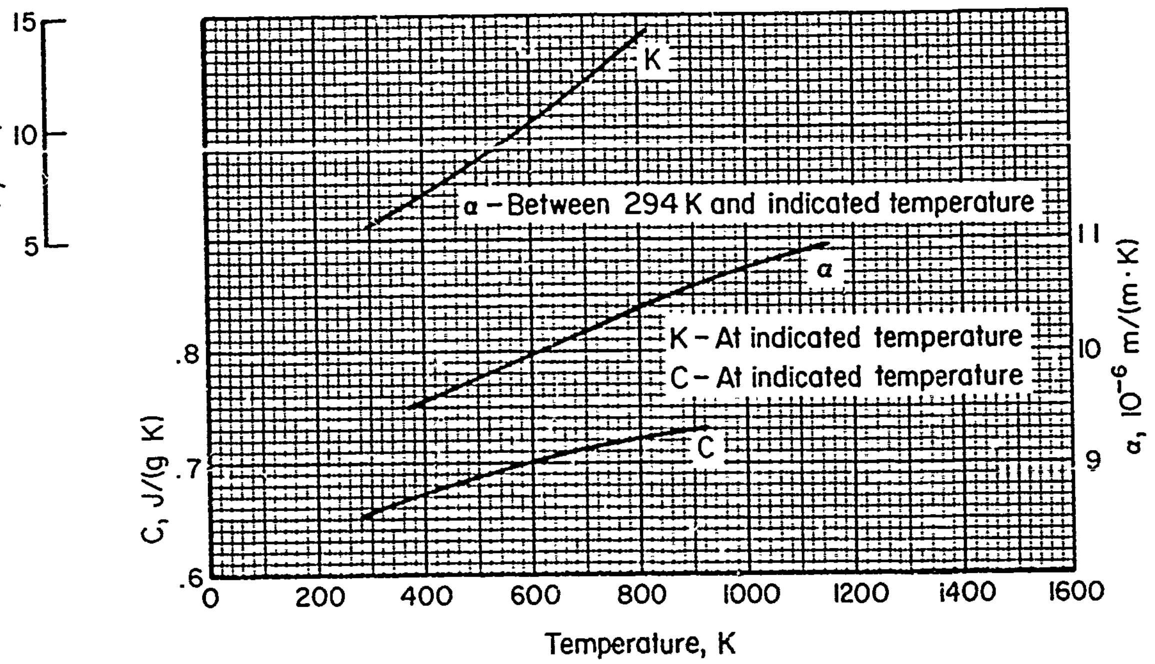


FIGURE 5.4.4.0. Effect of temperatures on the physical properties of Ti-6Al-6V-2Sn alloy.

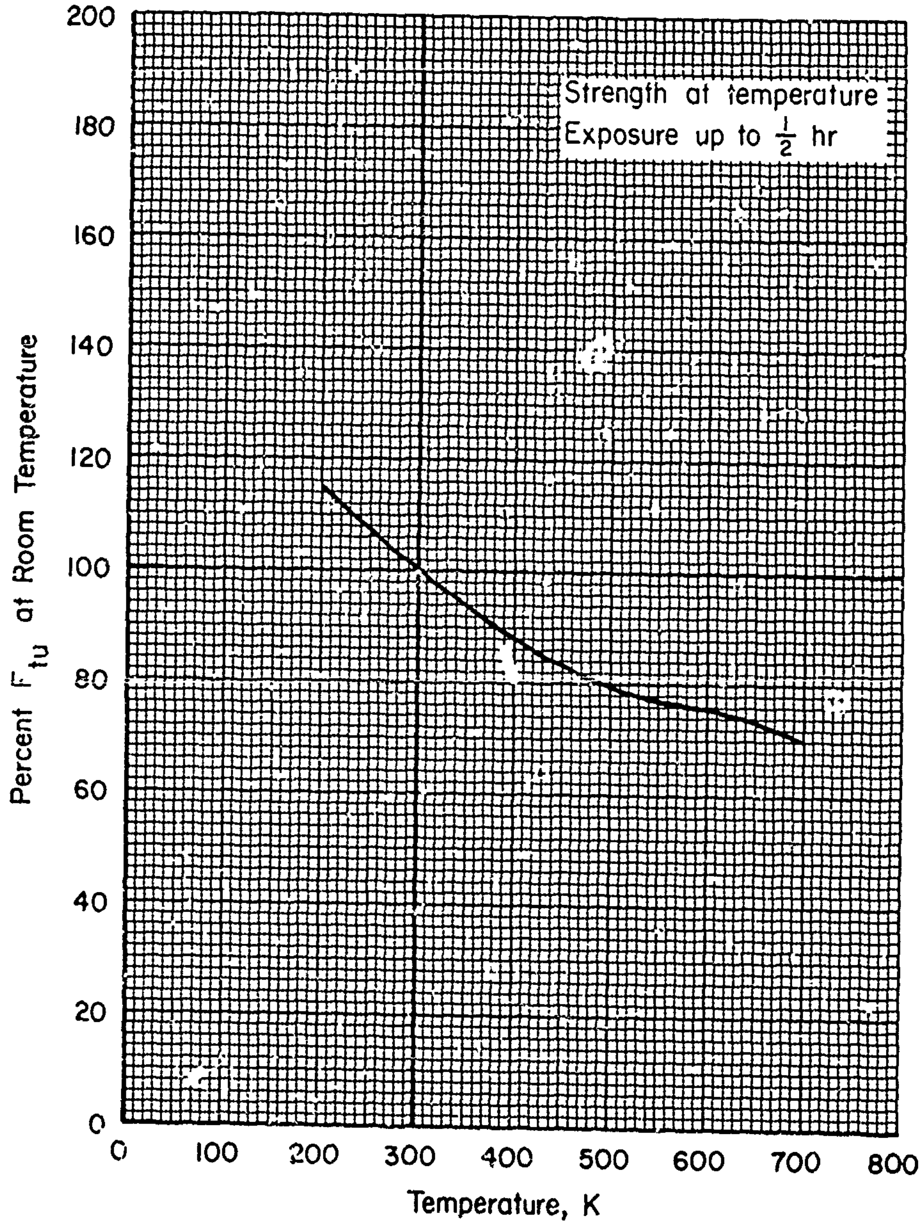


FIGURE 5.4.4.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of annealed Ti-6Al-6V-2Sn extrusions.

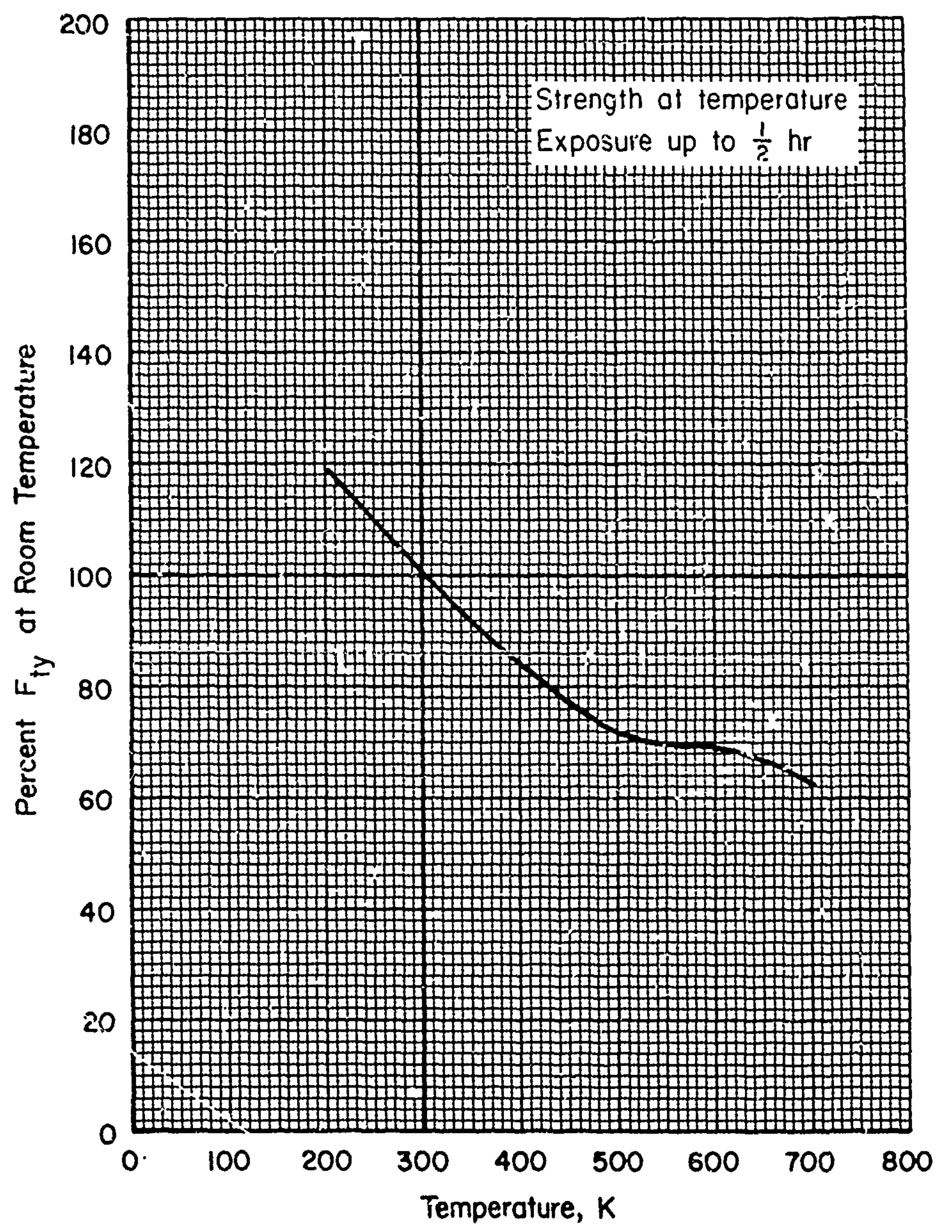


FIGURE 5.4.4.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of annealed Ti-6Al-6V-2Sn extrusions.

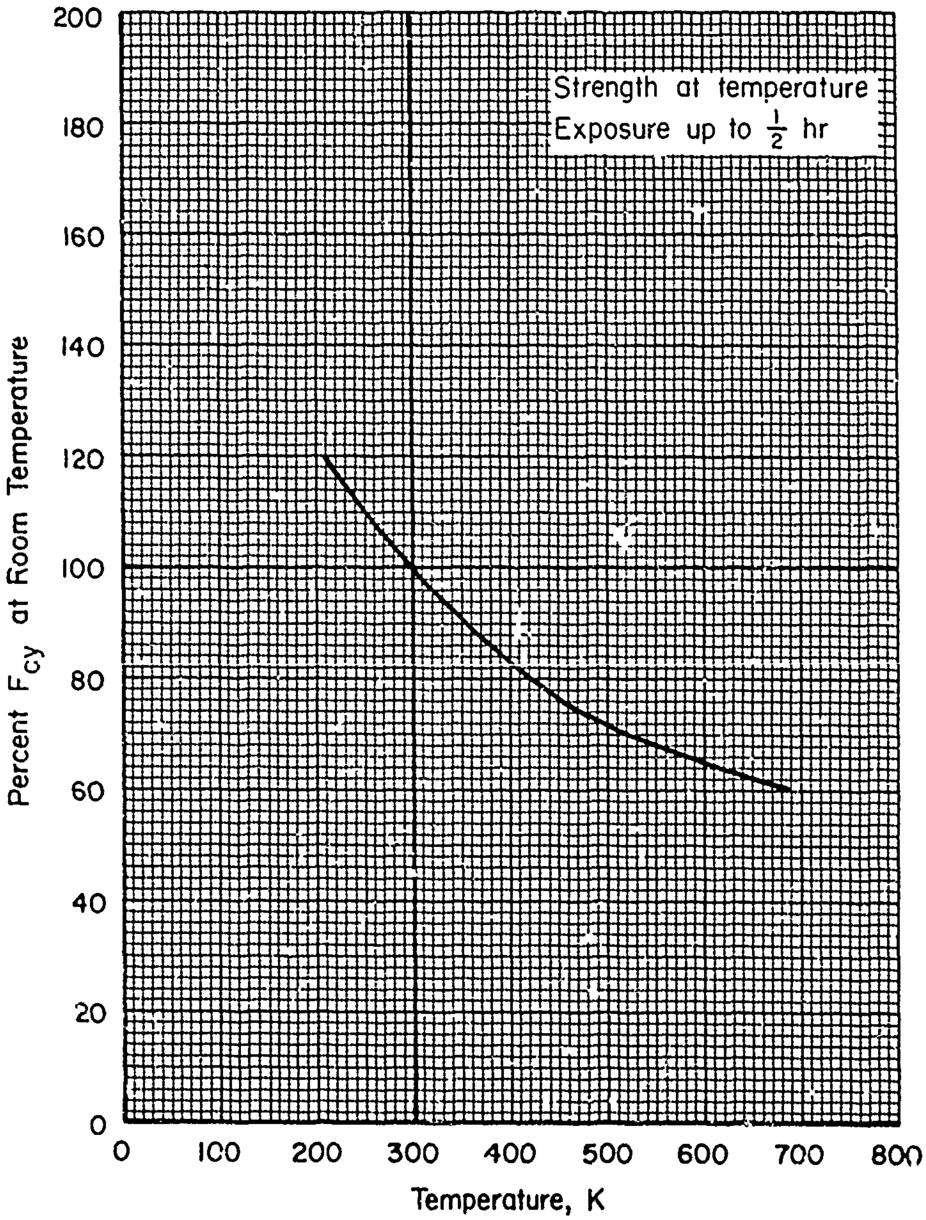


FIGURE 5.4.4.1.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of annealed Ti-6Al-6V-2Sn extrusions.

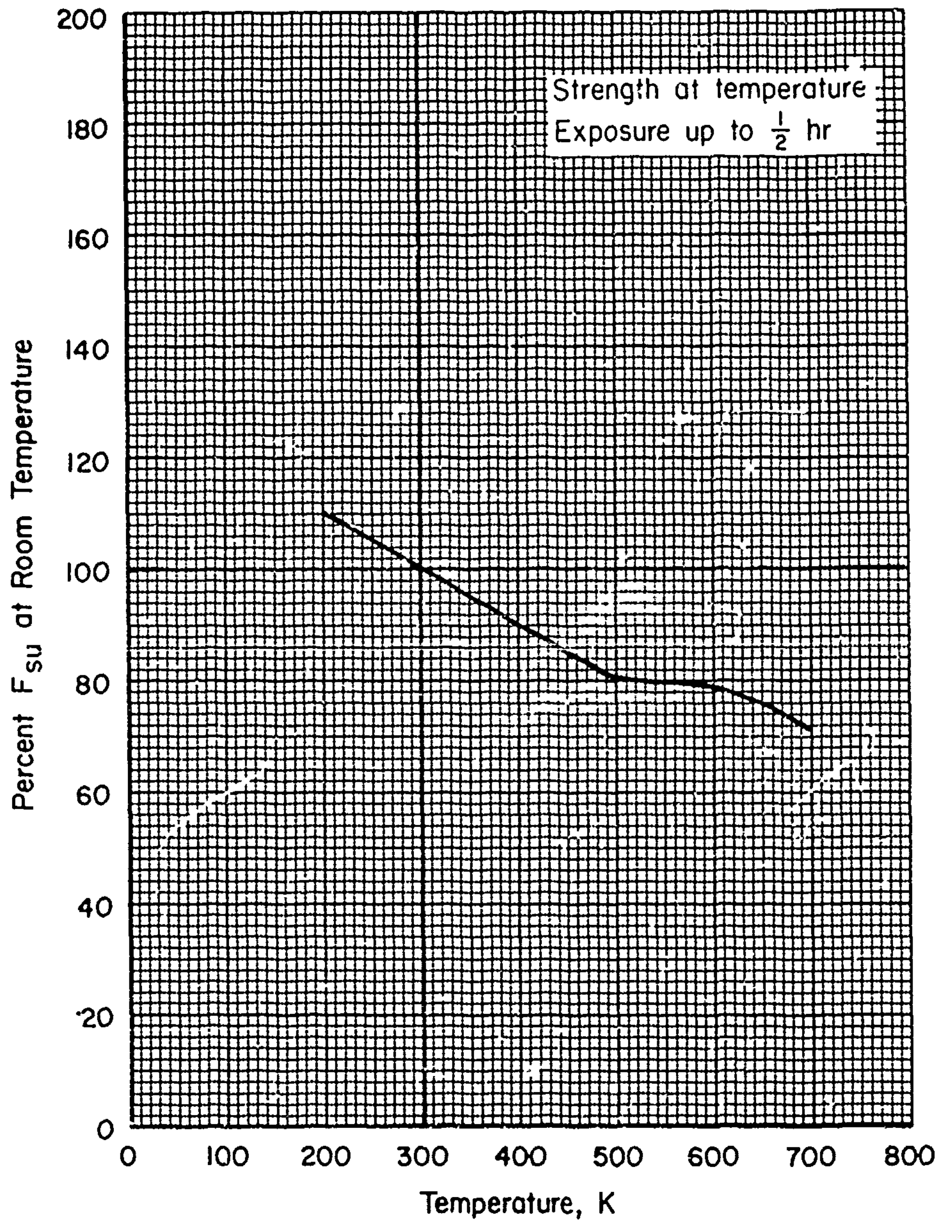


FIGURE 5.4.4.1.2(b). Effect of temperature on the ultimate shear strength (F_{su}) of annealed Ti-6Al-6V-2Sn extrusions.

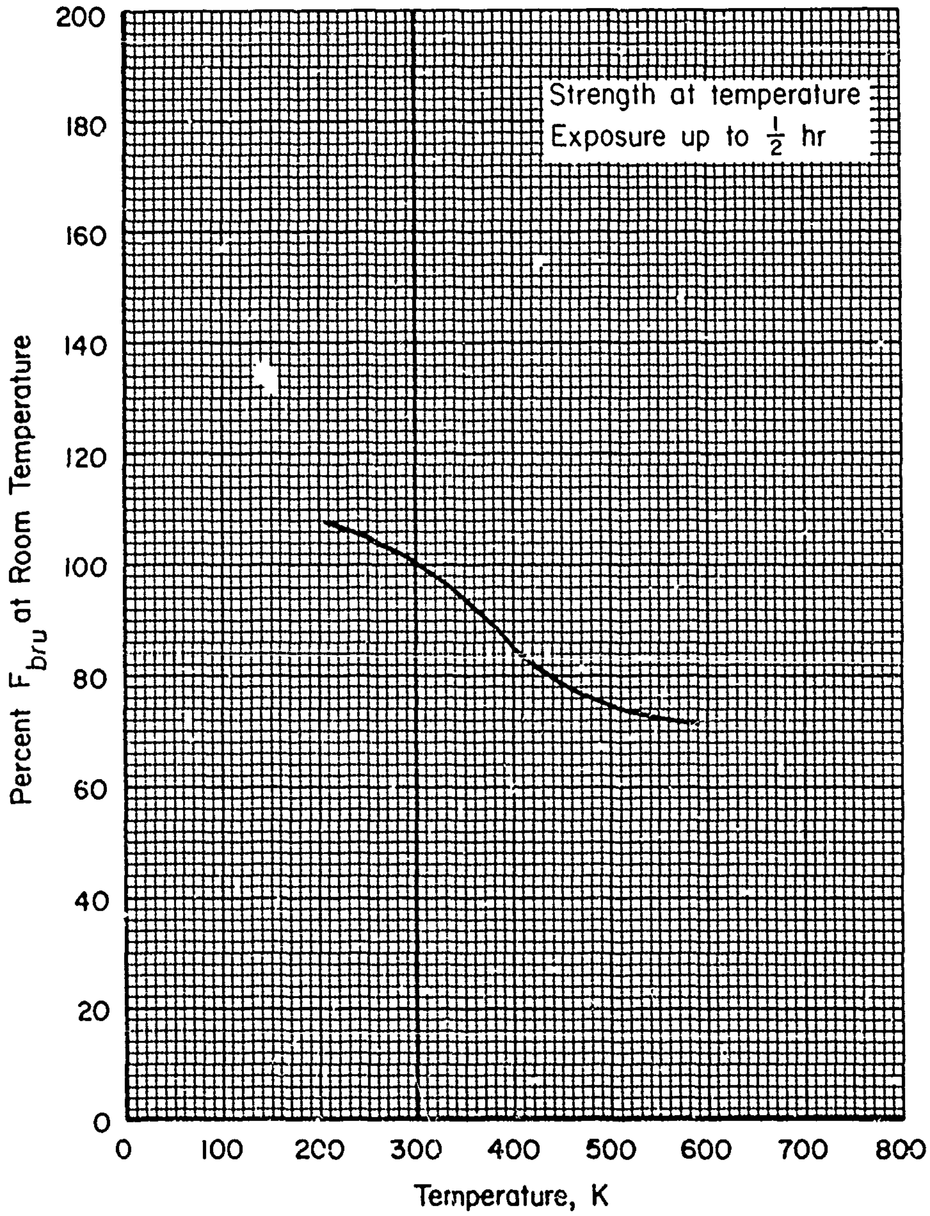


FIGURE 5.4.4.1.3(a). Effect of temperature on the ultimate bearing strength (F_{bru}) of annealed Ti-6Al-6V-2Sn extrusions.

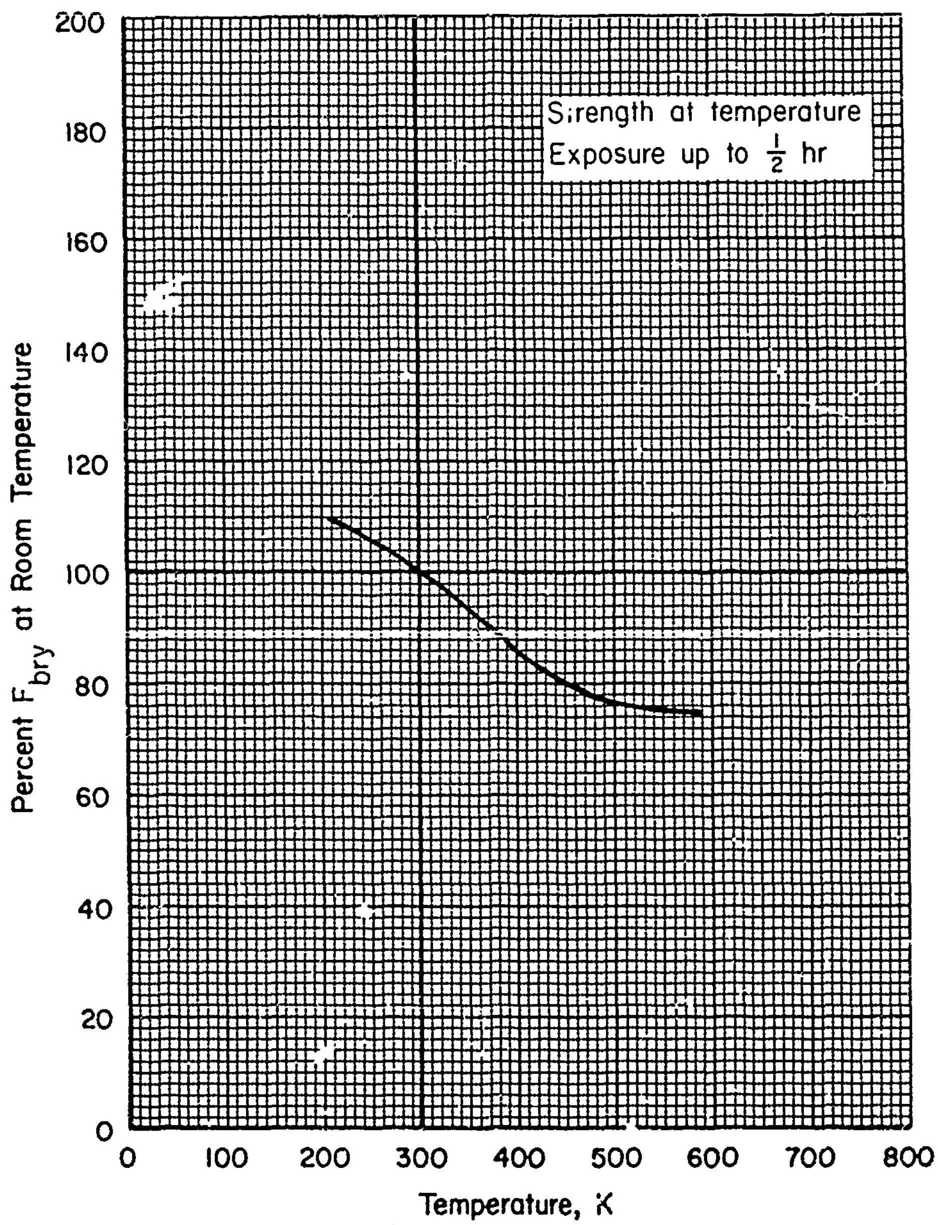


FIGURE 5.4.4.1.3(b). Effect of temperature on the bearing yield strength (F_{bry}) of annealed Ti-6Al-6V-2Sn extrusions.

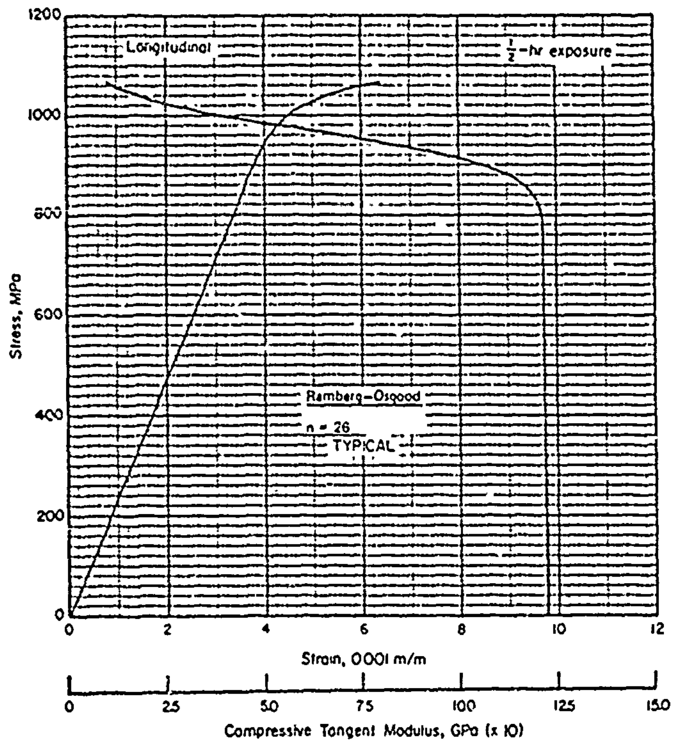


FIGURE 5.4.4.1.6(a). Typical compressive stress-strain and tangent-modulus curves at room temperature for annealed Ti-6Al-6V-2Sn (extrusions).

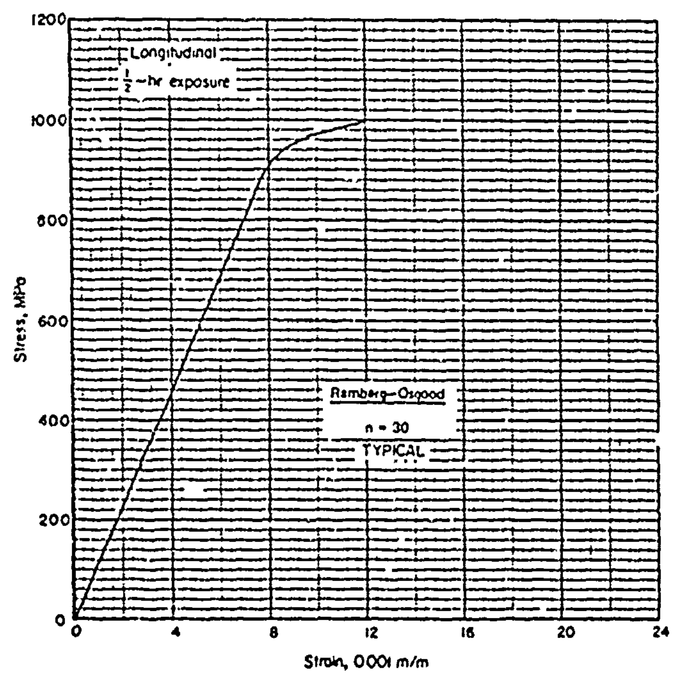


FIGURE 5.4.4.1.6(b). Typical tensile stress-strain curve at room temperature for annealed Ti-6Al-6V-2Sn (extrusions).

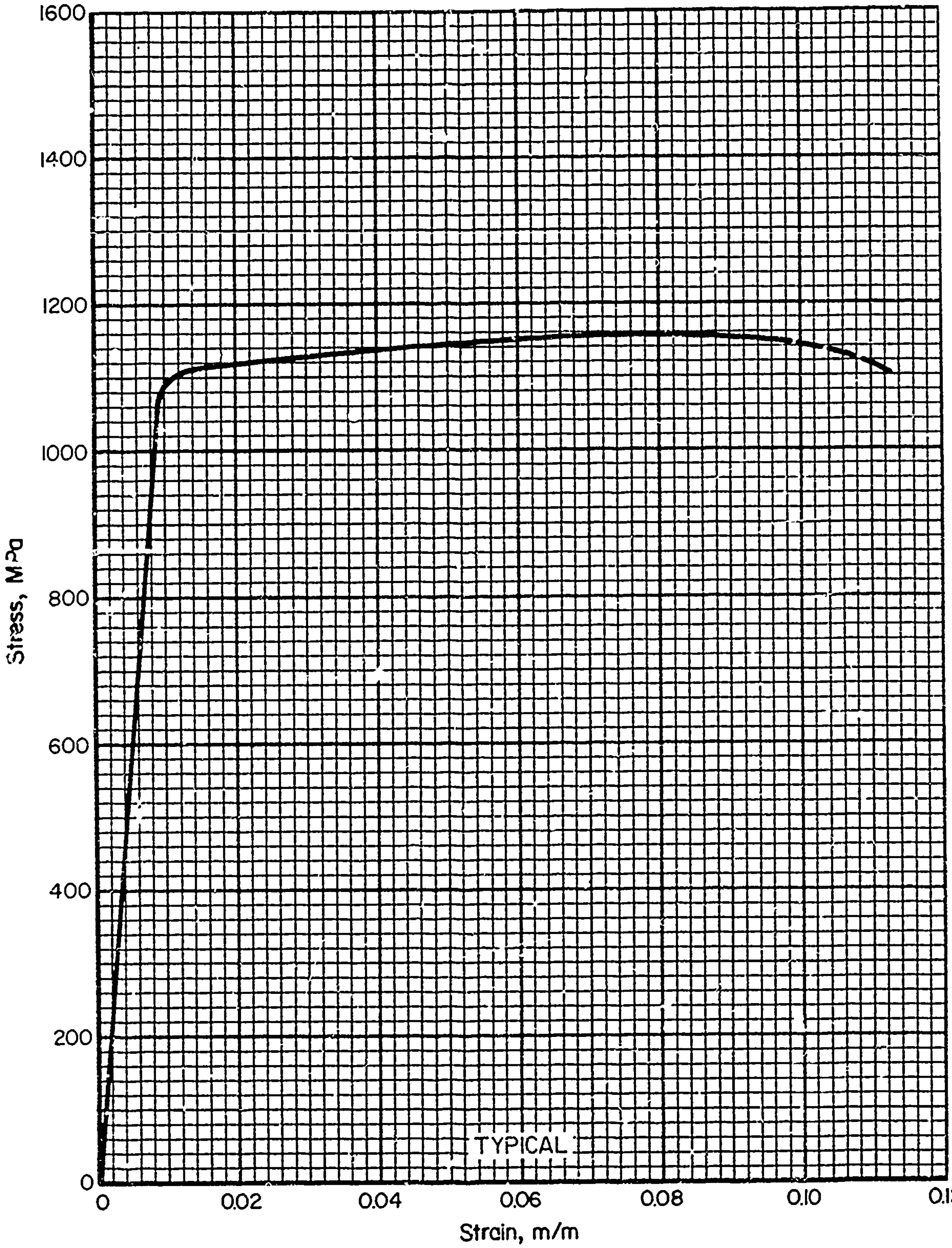


FIGURE 5.4.4.1.6(c). Typical full range tensile stress-strain curve for annealed Ti-6Al-6V-2Sn (sheet) at room temperature.

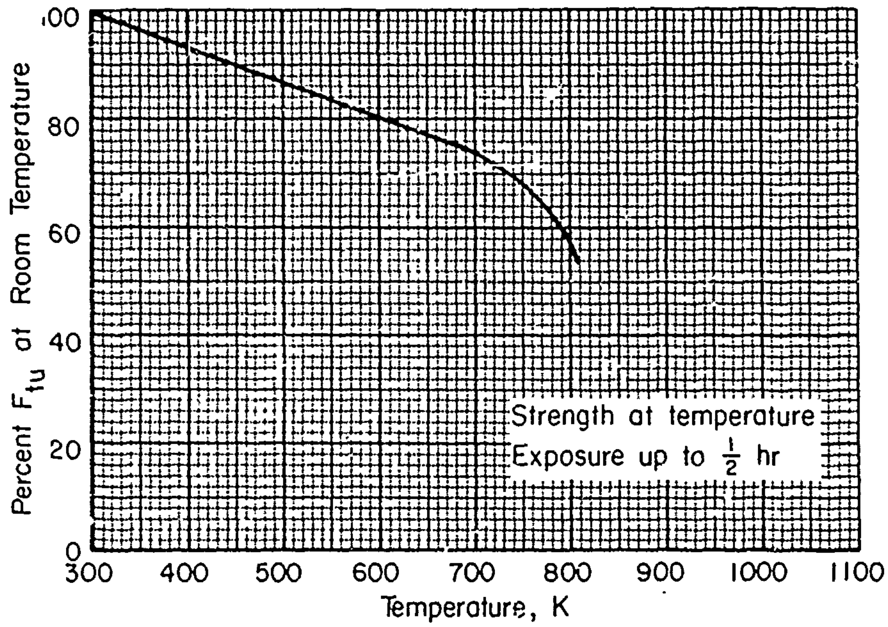


FIGURE 5.4.4.2.1(a). Effect of temperature on ultimate tensile strength (F_{tu}) of solution-treated and aged Ti-6Al-6V-2Sn (plate).

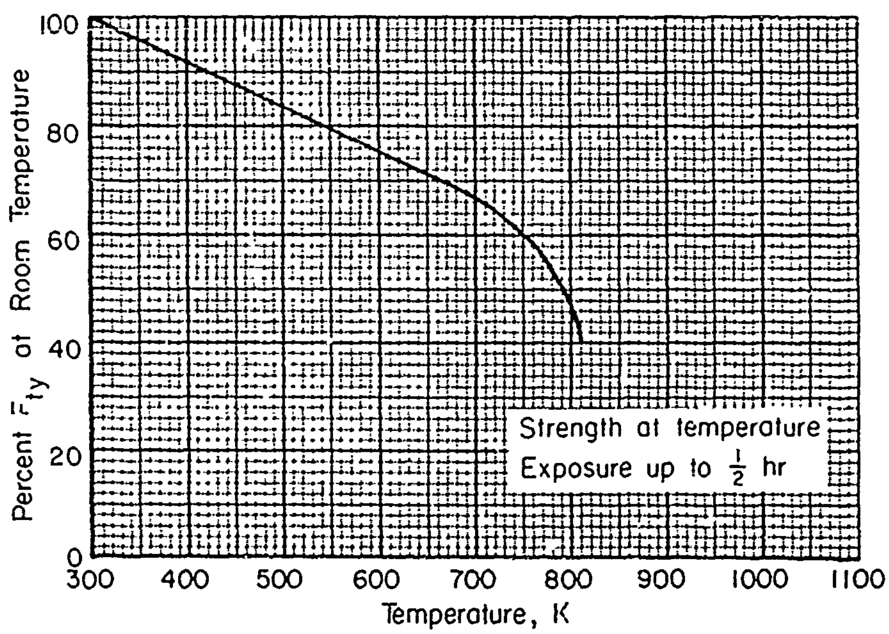


FIGURE 5.4.4.2.1(b). Effect of temperature on tensile yield strength (F_{ty}) of solution-treated and aged Ti-6Al-6V-2Sn (plate).

5.4.5 Ti-7Al-4Mo

5.4.5.0 *Comments.*—Ti-7Al-4Mo was developed principally as a forging alloy, although plate and extrusions have been used on a limited basis. The alloy is age hardenable to high strength levels although it also may be used in the lower strength but more ductile and tough annealed condition.

Manufacturing Considerations.—Elevated temperature forging, rolling, and extrusion operations are used to form part blanks from Ti-7Al-4Mo alloy. Forging is usually accomplished by finishing below 1278 K while extrusions are usually produced from above this temperature Almost without exception, parts are finished by relief annealing. Although the material is generally considered non-weldable, pressure welding (e.g., hemisphere to hemisphere joining) has been utilized successfully.

Environmental Considerations.—Ti-7Al-4Mo alloy is stable to at least 728 K if the annealing treatment includes sufficient annealing time and slow cooling to the stabilization temperature or if the aging treatment selected is just above the proposed service temperature. The material exhibits good oxidation resistance. Resistance to both hot-salt and aqueous chloride solution stress corrosion is marginal.

Specifications.—Material specifications for Ti-7Al-4Mo are presented in Table 5.4.5.0(a).

TABLE 5.4.5.0(a). *Material Specifications for Ti-7Al-4Mo*

Specification	Form
MIL-T-9047	Bars
MIL-T-81556	Extruded bars, rods, and special shaped sections

Heat Treatment.—The recommended annealing treatment for the Ti-7Al-4Mo alloy is 1 hour at 1061 K, furnace cool to about 839 K, then air cool to room temperature. Solution heat treatment times between 1/2 to 1-1/2 hours at temperatures between 1186 and 1242 are recommended. The solution treatment is terminated by water quenching and is followed by aging at temperatures between 783 and 922 K for times from 2 to 8 hours (terminated by air cooling).

Room-temperature mechanical and physical properties for Ti-7Al-4Mo are presented in Tables 5.4.5.0(b) and (c). The effect of temperature on physical properties is shown in Figure 5.4.5.0.

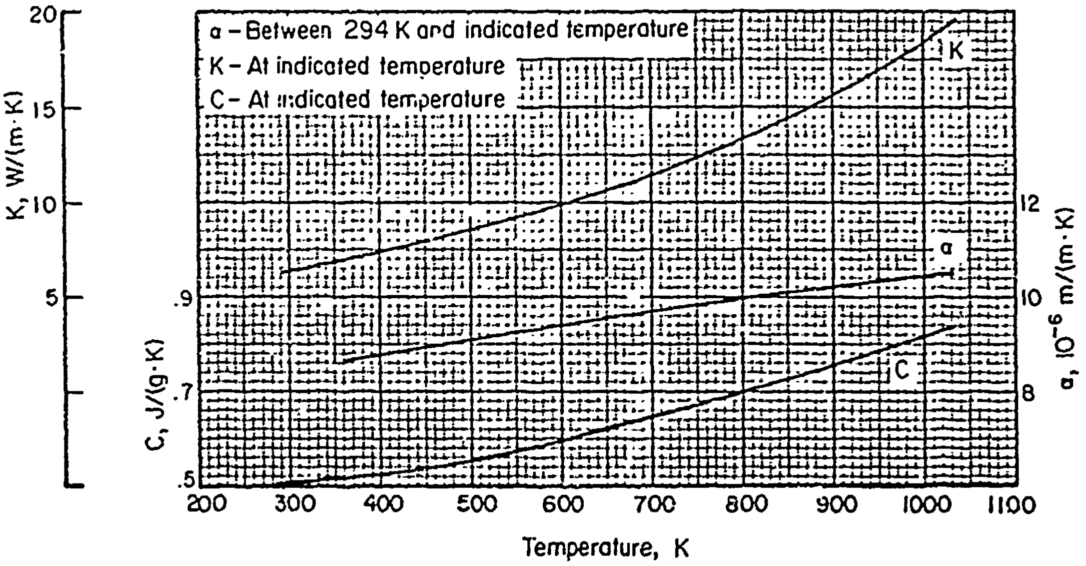


FIGURE 5.4.5.0. Effect of temperature on the physical properties of Ti-7Al-4Mo alloy.

TABLE 5.4.5.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF TI-7AL-4MO (BARS)

SPECIFICATION	MIL-T-9047, COMP. 9				
FORM	BARS				
CONDITION	ANNEALED		SOLUTION-TREATED AND AGED		
THICKNESS, MM	≤50.81[a]	50.82-76.20	25.41-	25.42-50.80	50.82-101.60
BASIS	S	S	S	S	S
MECHANICAL PROPERTIES:					
FTU, MPA:					
L	1000	965	1170	1100	1030
LT	1000	965	1170	1100	1030
ST	...	965	...	...	1030
FTY, MPA:					
L	931	896	1100	1030	965
LT	931	896	1100	1030	965
ST	...	896	...	...	965
FCY, MPA:					
L	...	...	...	...	...
LT	...	...	...	...	...
ST	...	...	...	...	...
FSU, MPA	...	...	...	...	...
FBRU, MPA:					
(E/D=1.5)	...	...	...	...	...
(E/D=2.0)	...	...	...	...	...
FBRY, MPA:					
(E/D=1.5)	...	...	...	...	...
(E/D=2.0)	...	...	...	...	...
EL, PERCENT:					
L	10	10	8	8	8
LT	10	10	8	8	8
ST	...	10	...	...	8
E, GPA	111.7		116.5		
EC, GPA	111.7		116.5		
G, GPA	42.1		44.1		
MU	0.32		0.32		
PHYSICAL PROPERTIES:					
OMEGA, MG/M3	4.48				
C, J/(G*K)	SEE FIGURE 5.4.5.0				
K, W/(M*K)	SEE FIGURE 5.4.5.0				
ALPHA, 10-6 M/(M*K)	SEE FIGURE 5.4.5.0				

[a] MAXIMUM OF 64.5 SQ CM CROSS-SECTIONAL AREA.

TABLE 5.4.5.0(C). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF TI-7AL-4MO (EXTRUSIONS)

SPECIFICATION	MIL-T-81556, TYPE III, COMP. D						
FORM	EXTRUDED BARS, RODS, AND SPECIAL SHAPED SECTIONS						
CONDITION	ANNEALED			SOLUTION TREATED AND AGED			
THICKNESS, MM	<50.81	50.82-101.60	12.71	12.72-25.40	25.41-50.80	50.81-63.50	63.51-101.60
BASIS	S	S	S	S	S	S	S
MECHANICAL PROPERTIES:							
FTU, MPA:							
L	1000	965	1170	1100	1030	1000	965
LT	...	...	...	...	...	...	...
FTY, MPA:							
L	931	896	1100	1030	965	931	896
LT	...	...	...	...	...	...	...
FCY, MPA:							
L	...	...	...	...	...	...	...
LT	...	...	...	...	...	...	...
FSU, MPA	...	...	...	...	...	...	...
FBRU, MPA:							
(E/D=1.5)	...	...	...	...	...	...	...
(E/D=2.0)	...	...	...	...	...	...	...
FBRY, MPA:							
(E/D=1.5)	...	...	...	...	...	...	...
(E/D=2.0)	...	...	...	...	...	...	...
EL, PERCENT:							
L	10	10	6	6	6	6	6
LT	...	...	...	...	...	...	...
E, GPA	111.7			116.5			
EC, GPA	111.7			116.5			
G, GPA	42.1			44.1			
MU	0.32			0.32			
PHYSICAL PROPERTIES:							
OMEGA, MG/M3	4.48						
C, J/(G*K)	SEE FIGURE 5.4.5.0						
K, W/(M*K)	SEE FIGURE 5.4.5.0						
ALPHA, 10-6 M/(M*K)	SEE FIGURE 5.4.5.0						

5.5 Beta Titanium Alloys

The beta titanium alloys are essentially single-phase beta at room temperature because of the predominance of beta-stabilizing elements such as chromium, iron, molybdenum, and vanadium. They are capable of being age hardened to high strength levels. These alloys will probably be selected for use in the annealed condition where good formability, moderate strength, and high fracture toughness are required; or in the aged condition where high strength up to 561 K is required and lower fracture toughness can be tolerated.

5.5.1 Ti-13V-11Cr-3Al

5.5.1.0 *Comments*.—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 150 mm diameter or greater) at intermediate strength levels (around) 1170 MPa 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 561 K and in the solution treated and aged condition up to 589 K. 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 922 K 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 beta alloy at temperatures as low as 533 K 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.

Specifications.—Material specifications for Ti-13V-11Cr-3Al are presented in Table 5.5.1.0(a).

TABLE 5.5.1.0(a). *Material Specifications For Ti-13V-11Cr-3Al*

Specification	Form
MIL-T-9046	Sheet, strip, and plate
MIL-T-9047	Bars

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 1061 K for 15 to 60 minutes, air cool (water quench if material is over 51 mm thick).

Age at 755 K for 2 to 60 hours dependent on strength level. (Note: typical aging time to achieve F_{tu} = 1170 MPa is 24 to 36 hours.)

Room-Temperature Properties

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.

5.5.1.1 *Annealed Condition*.—Effect of temperature curves for annealed Ti-13V-11Cr-3Al are presented in Figures 5.5.1.1.1(a) through 5.5.1.1.4.

Typical tensile stress-strain curves for annealed material at temperatures ranging from room temperature to 811 K 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 the constant-life fatigue diagrams of Figures 5.5.1.1.8(a) through (c).

5.5.1.2 *Solution-Treated and Aged Condition*.—Effect of temperature curves for solution-treated and aged Ti-13V-11Cr-3Al are presented in Figures 5.5.1.2.1(a) through 5.5.2.1.4.

Typical tensile stress-strain curves at various temperatures are shown in Figure 5.5.1.2.6.

Unnotched and notched fatigue data at room and elevated temperatures for solution-treated and aged sheet are shown in the constant-life fatigue diagrams of 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	MIL-T-9046B TYPE IV, COMP. A			MIL-T-9047, COMP. 12		
FORM	SHEET, STRIP, AND PLATE			BARS		
CONDITION	ANNEALED		SOLUTION TREATED AND AGED	ANNEALED	SOLUTION TREATED AND AGED	
THICKNESS, MM	<1.27	1.27-101.60	≤101.60	≤76.20[b]	≤50.81	50.82-177.80
BASIS	S	S	S	S	S	S
MECHANICAL PROPERTIES:						
FTU, MPA:						
L	910	862	1170	862	1170	1170
LT	910	862	1170	862	1170	1170
ST	...	862	1170	862	...	1170
FTY, MPA:						
L	869	827	1100	827	1100	1100
LT	869	827	1100	827	1100	1100
ST	...	827	1100	827	...	1100
FCY, MPA:						
L	...	827	1120	...	...	...
LT	...	827	1120	...	...	...
ST	...	827	1120	...	...	...
FSU, MPA	...	634	724	...	...	...
FBRU, MPA:						
(E/D=1.5)	...	1430	1710	...	...	...
(E/D=2.0)	...	1860	2160	...	...	...
FBRY, MPA:						
(E/D=1.5)	...	1170	1500	...	...	...
(E/D=2.0)	...	1380	1700	...	...	...
EL, PERCENT:						
L	8	10	4[a]	10	4	2
LT	8	10	4[a]	10	4	2
ST	...	10	4[a]	10	4	2
E, GPA	100.0		106.9	100.0	106.9	
EC, GPA	...		...	...	...	
G, GPA	...		...	...	...	
MU	...		...	...	...	
PHYSICAL PROPERTIES:						
OMEGA, MG/M3	4.82					
C, J/(G*K)	SEE FIGURE 5.5.1.0					
K, W/(M*K)	SEE FIGURE 5.5.1.0					
ALPHA, 10-6 M/(M*K)	SEE FIGURE 5.5.1.0					

[a]THICKNESS 0.635 MM AND ABOVE; 3 PERCENT BELOW 0.635 MM.
[b]MAXIMUM OF 64.5 SQ CM CROSS-SECTIONAL AREA.

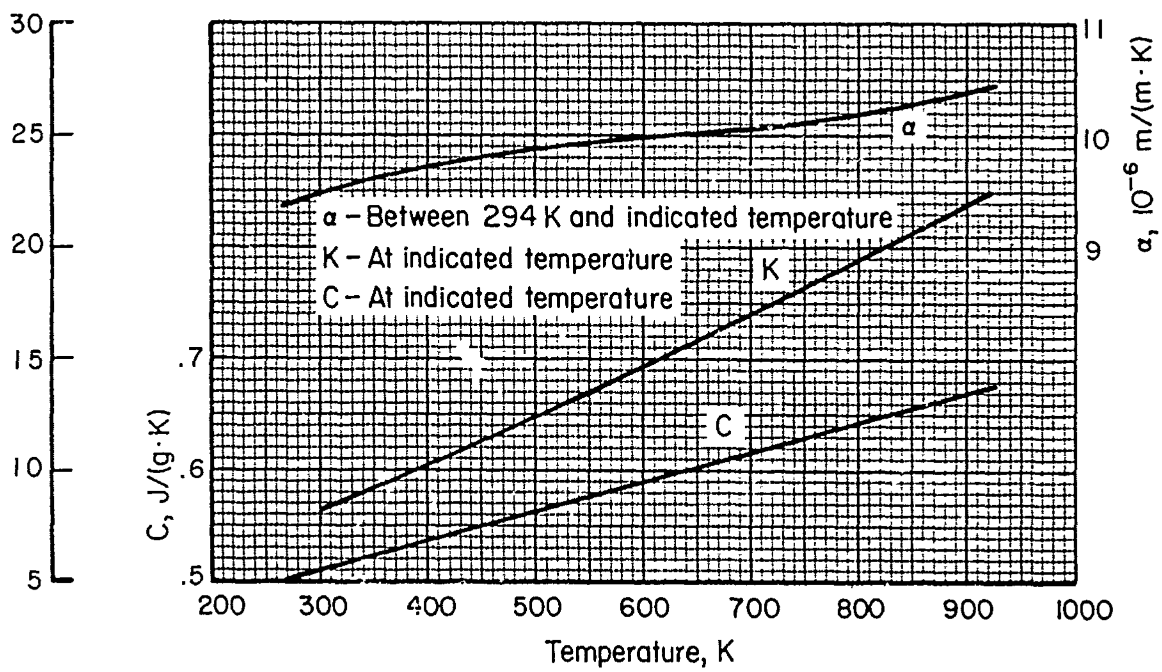


FIGURE 5.5.1.0. Effect of temperature on the physical properties of Ti-13V-11Cr-3Al alloy.

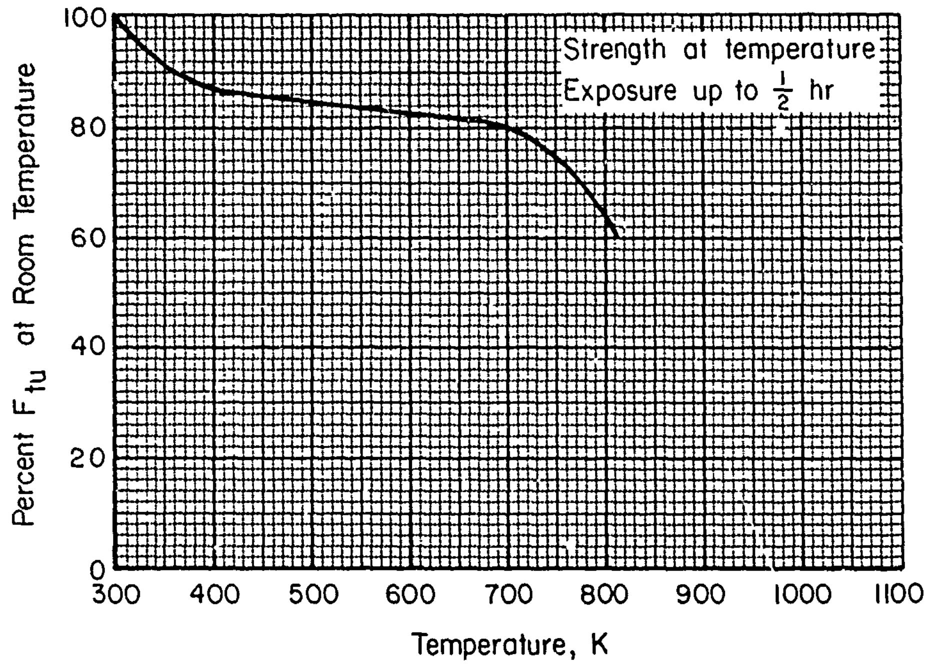


FIGURE 5.5.1.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of annealed Ti-13V-11Cr-3Al alloy (sheet).

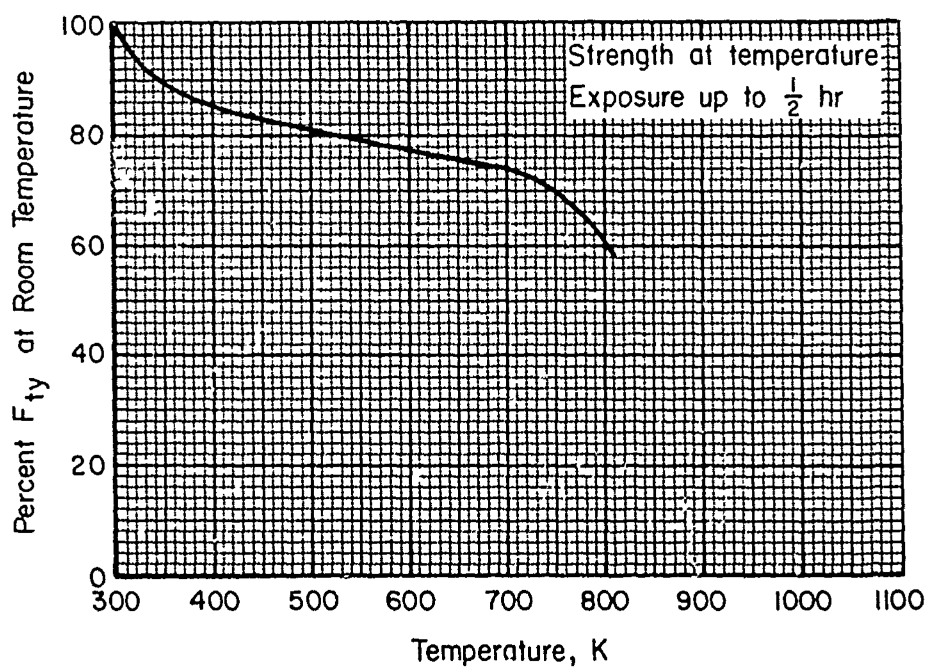


FIGURE 5.5.1.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of annealed Ti-13V-11Cr-3Al alloy (sheet).

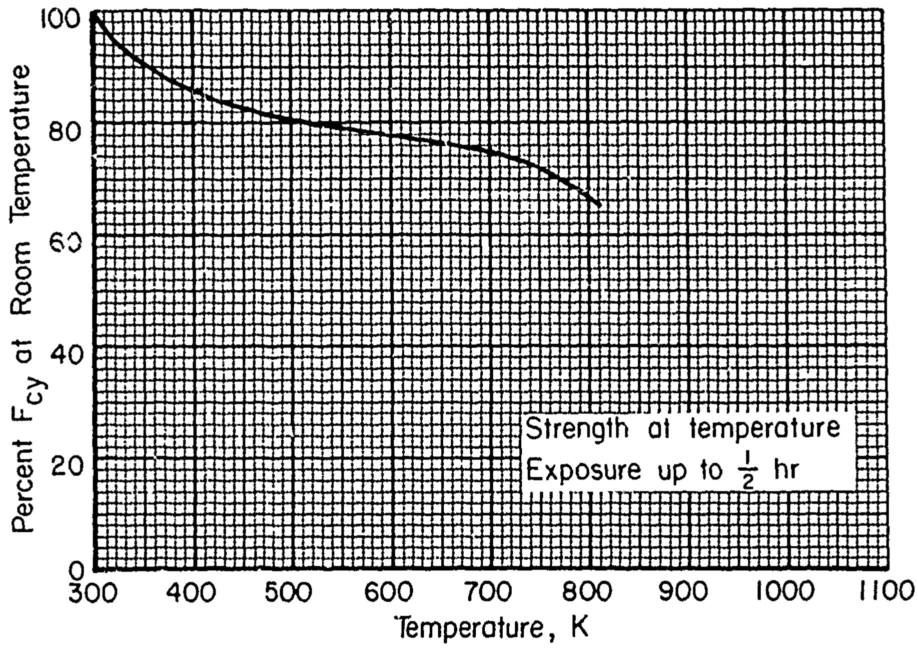


FIGURE 5.5.1.1.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of annealed Ti-13V-11Cr-3Al alloy (sheet).

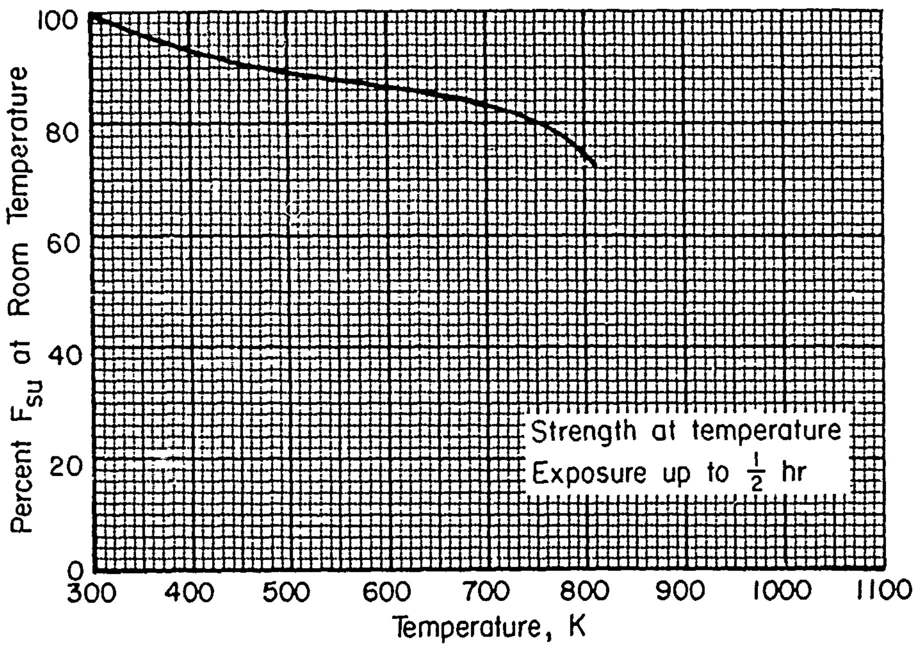


FIGURE 5.5.1.1.2(b). Effect of temperature on the ultimate shear strength (F_{su}) of annealed Ti-13V-11Cr-3Al alloy (sheet).

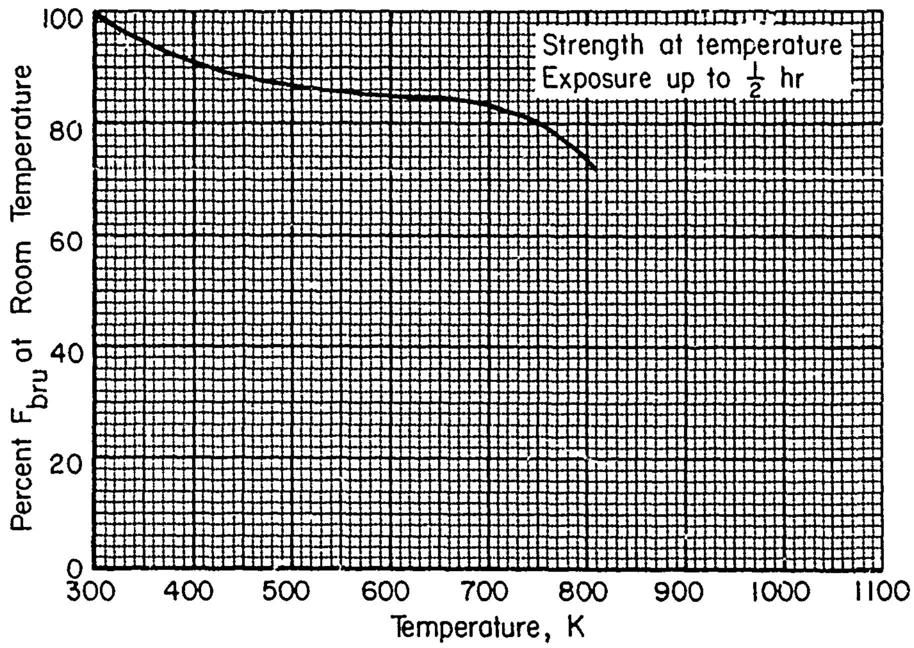


FIGURE 5.5.1.1.3(a). Effect of temperature on the ultimate bearing strength (F_{bru}) of annealed Ti-13V-11Cr-3Al alloy (sheet).

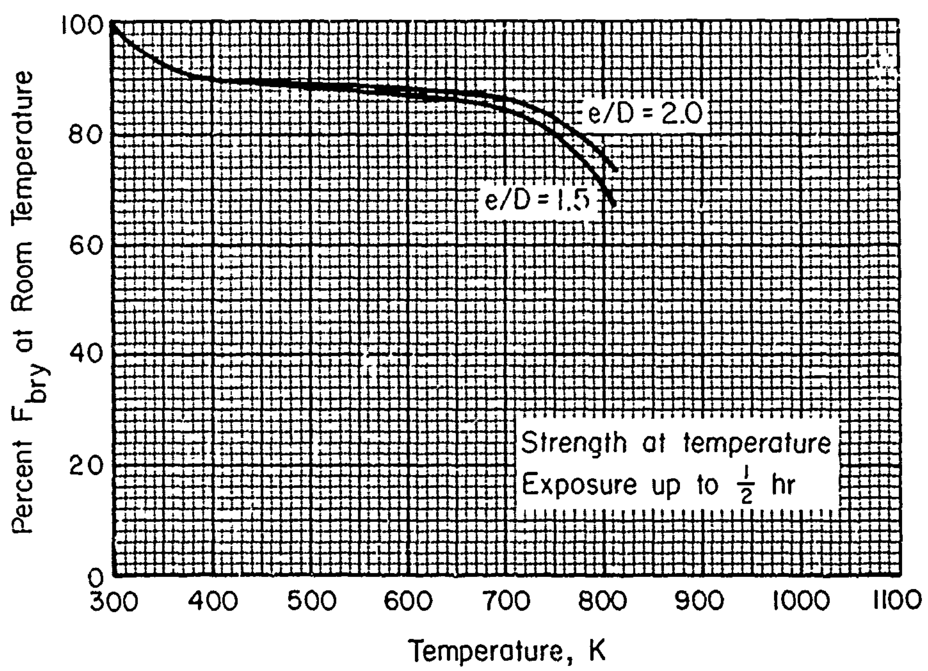


FIGURE 5.5.1.1.3(b). Effect of temperature on the bearing yield strength (F_{bry}) of annealed Ti-13V-11Cr-3Al alloy (sheet).

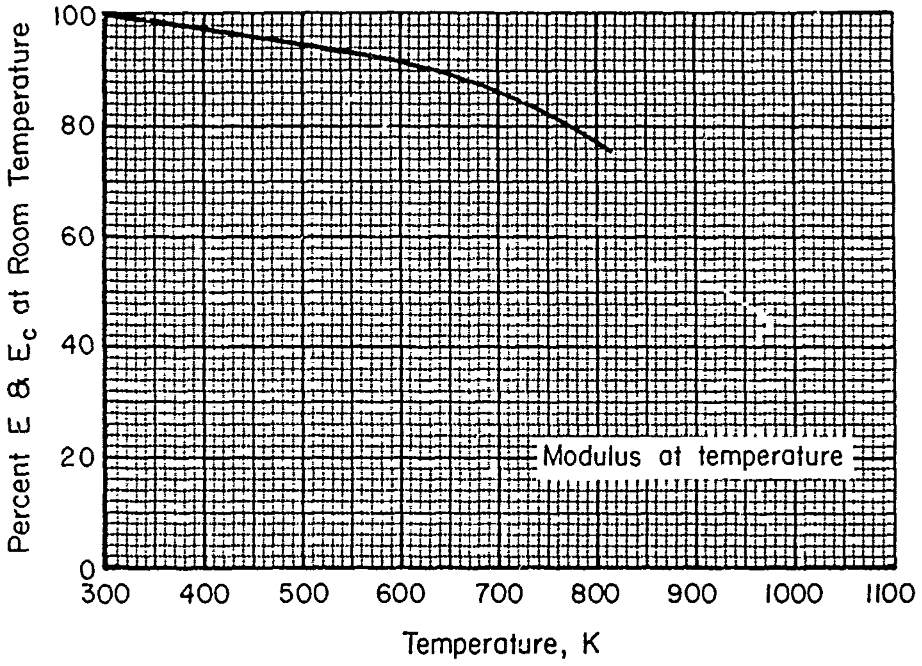


FIGURE 5.5.1.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of annealed Ti-13V-11Cr-3Al alloy (sheet).

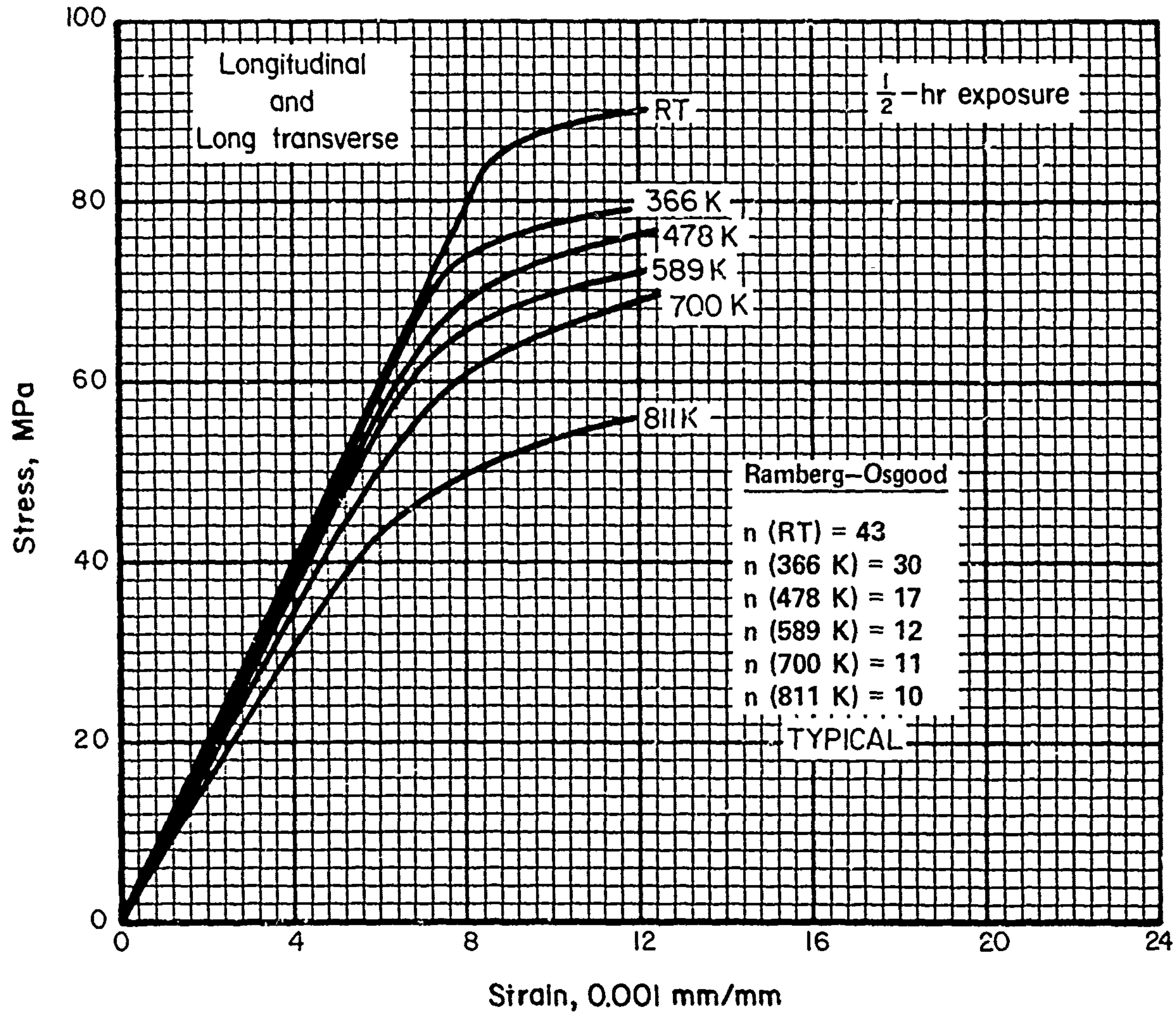


FIGURE 5.5.1.1.6. Typical tensile stress-strain curves for annealed Ti-13V-11Cr-3Al alloy (sheet) at room and elevated temperatu

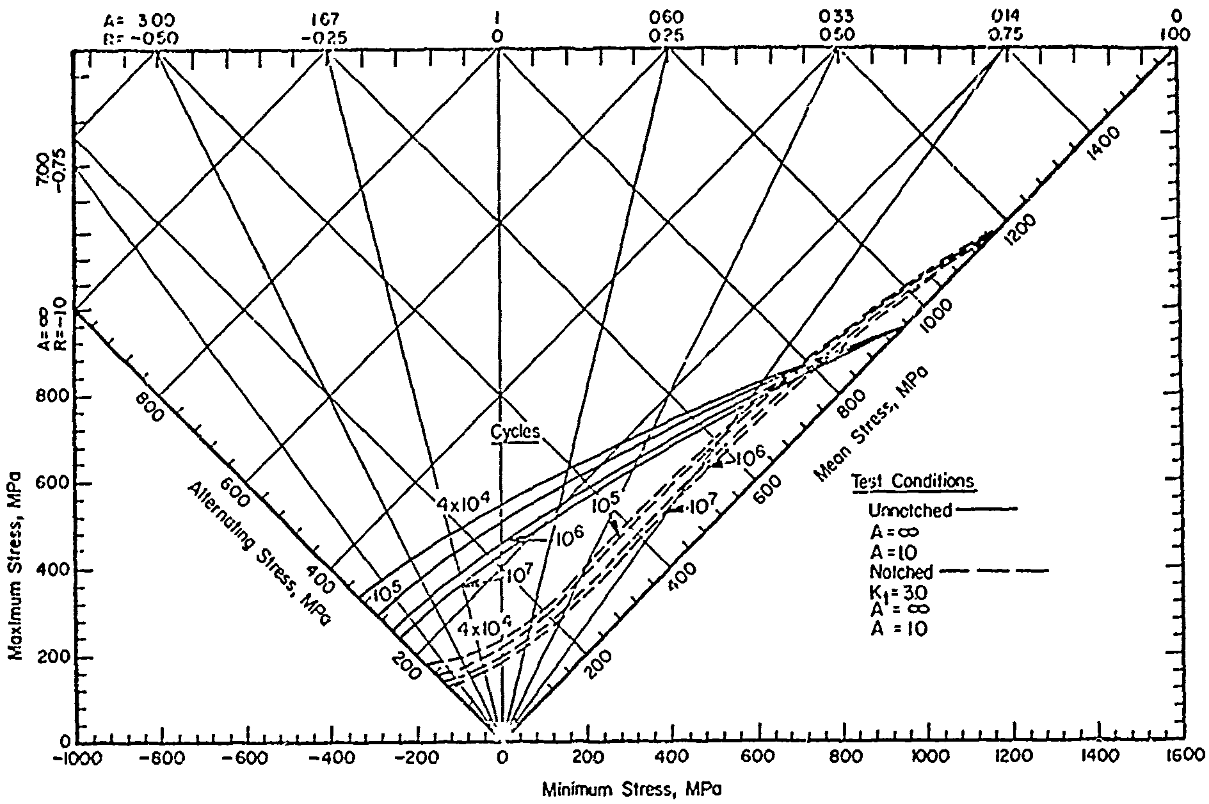


FIGURE 5.5.1.1.8(a). Typical constant-life fatigue diagram for annealed Ti-13V-11Cr-3Al alloy (sheet) at room temperature

Correlative Information for Figure 5.5.1.1.8(a)

Product Form: Sheet, 1.09 mm thick

Properties:

TUS, MPa	TYS, MPa	Temp, K
955	916	RT (Unnotched)
1172 (est.)	—	RT (Notched)

Test Parameters:
- Loading - Axial
- Frequency - 3600 cpm
- Temperature - RT
- Atmosphere - Air

Specimen Details:

Unnotched
7.62 mm width

Notched, Edge, $K_t = 3.0$
11.38 mm, gross width
7.62 mm, net width
0.56 mm, root radius, r
60° flank angle, ω

$$K_N = 1.77,\ \rho = 0.635 \text{ mm, where } K_N = 1 + \frac{K_t - 1}{1 + \frac{\pi}{\pi - \omega}\sqrt{\frac{\rho}{r}}}$$

Surface Condition: Unnotched: Surface as finished at the mill, edges polished with emery paper.
Notched: Same as above.

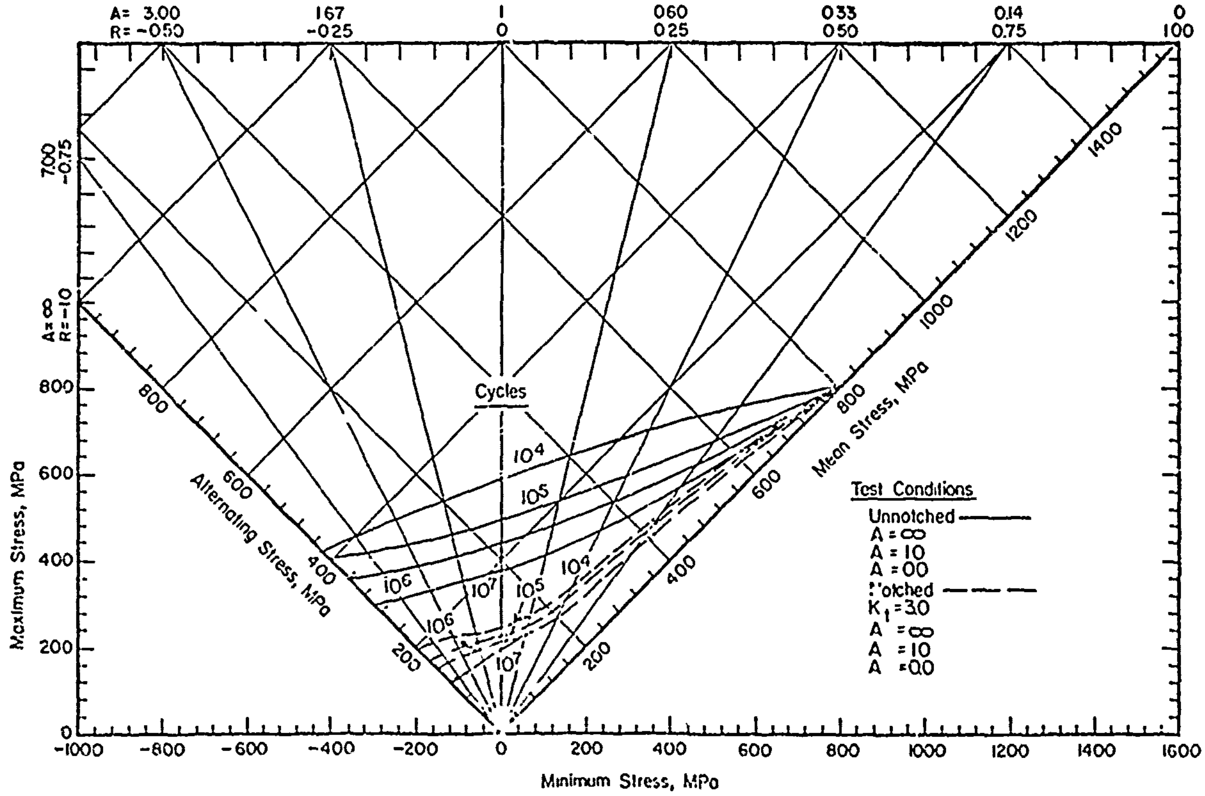


FIGURE 5.5.1.1.8(b). Typical constant-life fatigue diagram for annealed Ti-13V-11Cr-3Al alloy (sheet) at 589 K

Correlative Information for Figure 5.5.1.1.8(b)

Product Form: Sheet, 1.09 mm thick

Test Parameters:
Loading - Axial
Frequency - 3600 cpm
Temperature - 589K
Atmosphere - Air

Properties:

TUS, MPa	TYS, MPa	Temp, K
800	707	589 (Unnotched)
841	—	589 (Notched)

Specimen Details:

Unnotched: 7.62 mm width

Notched, Edge, $K_t = 3.0$:
11.38 mm, gross width
7.62 mm, net width
0.56 mm, root radius, r
60° flank angle, ω

$$K_N = 1.81,\ \rho = 0.559 \text{ mm, where } K_N = 1 + \frac{K_t - 1}{1 + \frac{\pi}{\pi - \omega}\sqrt{\frac{\rho}{r}}}$$

Surface Condition. Unnotched. Surface as finished at the mill, edges polished with emery paper
Notched: Same as above.

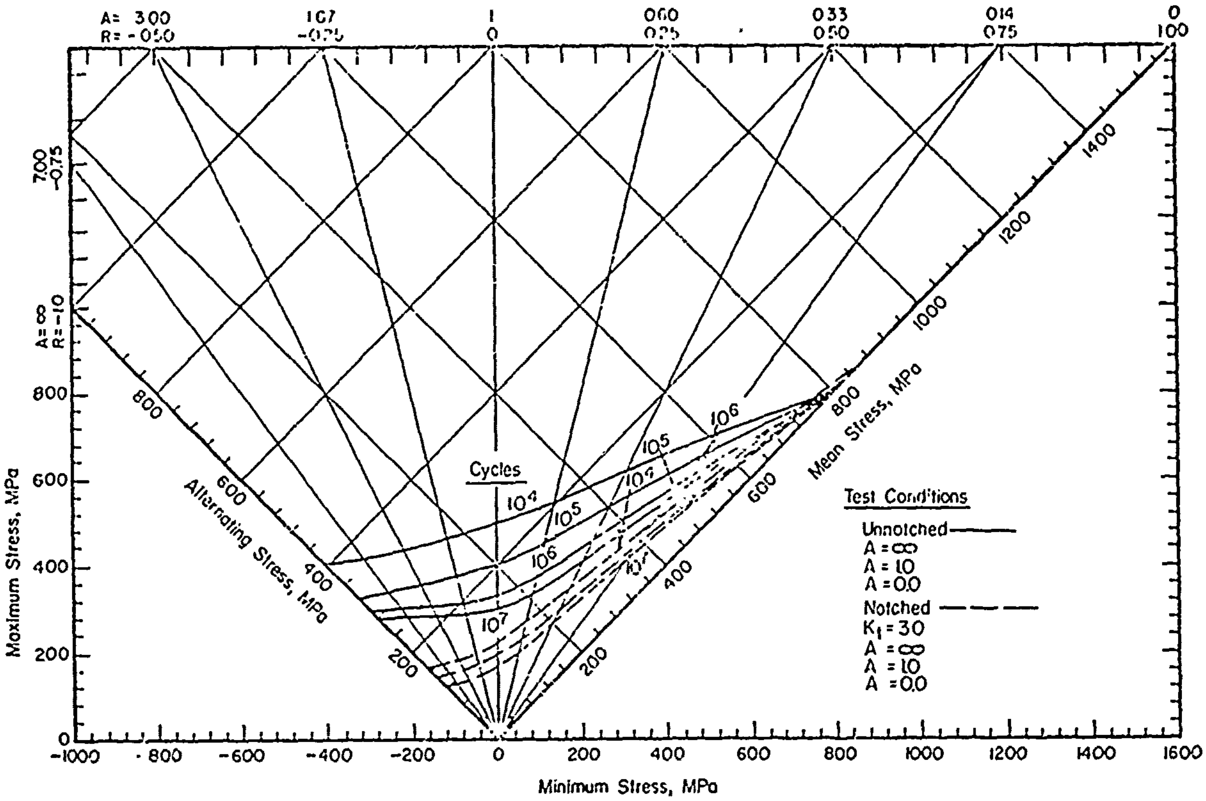


FIGURE 5.5.1.1.8(c). Typical constant-life fatigue diagram for annealed Ti-13V-11Cr-3Al alloy (sheet) at 700 K

Correlative Information for Figure 5.5.1.1.8(c)

Product Form: Sheet, 1.09 mm thick

Properties:

TUS, MPa	TYS, MPa	Temp, K
800	680	700 (Unnotched)
855	—	700 (Notched)

Test Parameters:
Loading - Axial
Frequency - 3600 cpm
Temperature - 700K
Atmosphere - Air

Specimen Details:

Unnotched: 7.62 mm width

Notched, Edge, K_t = 3.0: 11.38 mm, gross width; 7.62 mm, net width; 0.56 mm, root radius, r; 60° flank angle, ω

K_N = 2.0, p = 0.254 mm, where $K_N = 1 + \dfrac{K_t - 1}{1 + \dfrac{\pi}{\pi-\omega}\sqrt{\dfrac{p}{r}}}$

Surface Condition: Unnotched: Surface as finished at the mill, edges polished with emery paper.
Notched: Same as above.

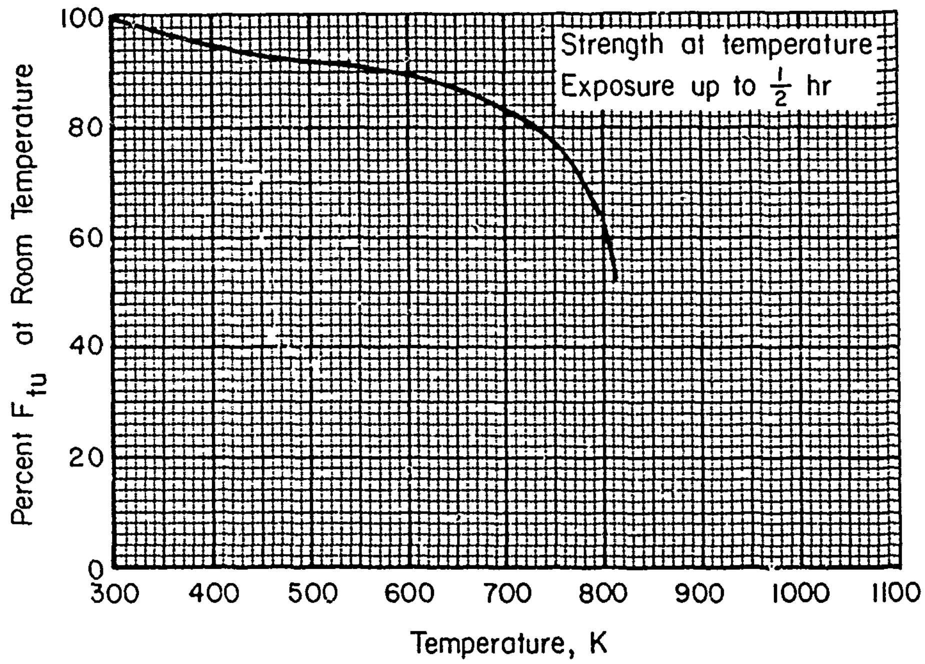


FIGURE 5.5.1.2.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of solution-treated and aged Ti-13V-11Cr-3Al alloy (sheet).

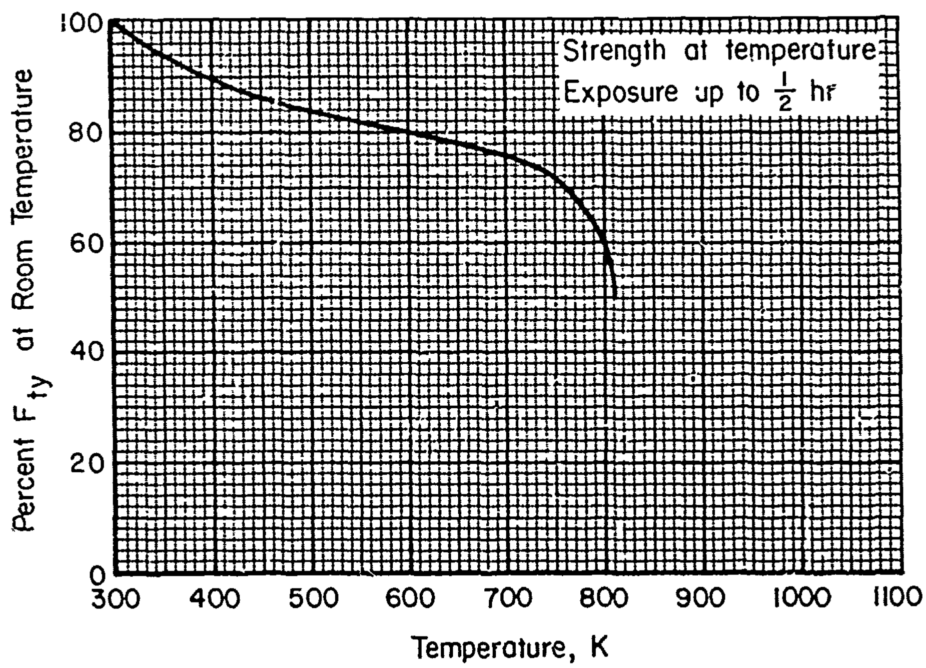


FIGURE 5.5.1.2.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of solution-treated and aged Ti-13V-11Cr-3Al alloy (sheet).

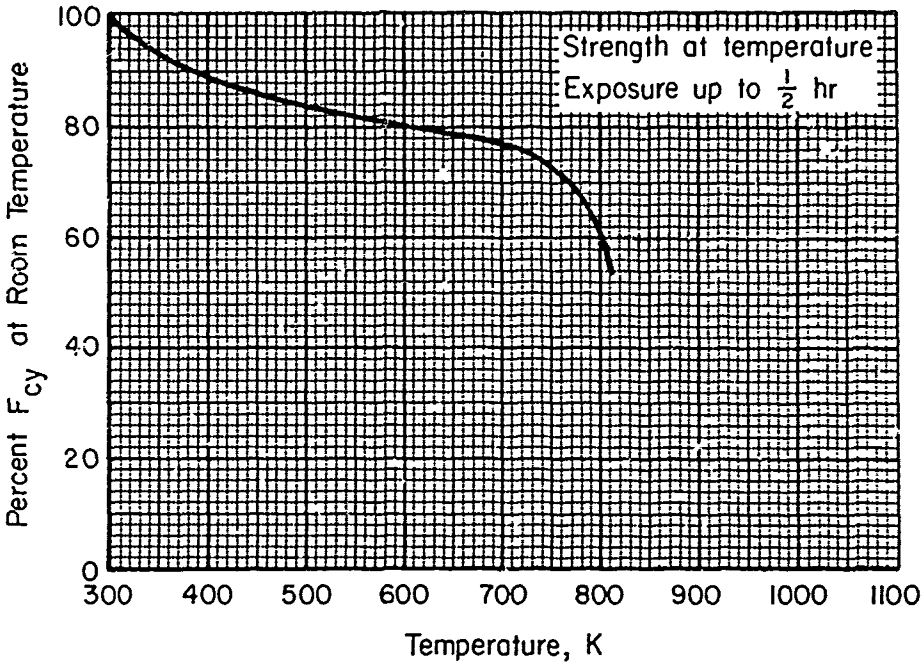


FIGURE 5.5.1.2.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of solution-treated and aged Ti-13V-11Cr-3Al alloy (sheet).

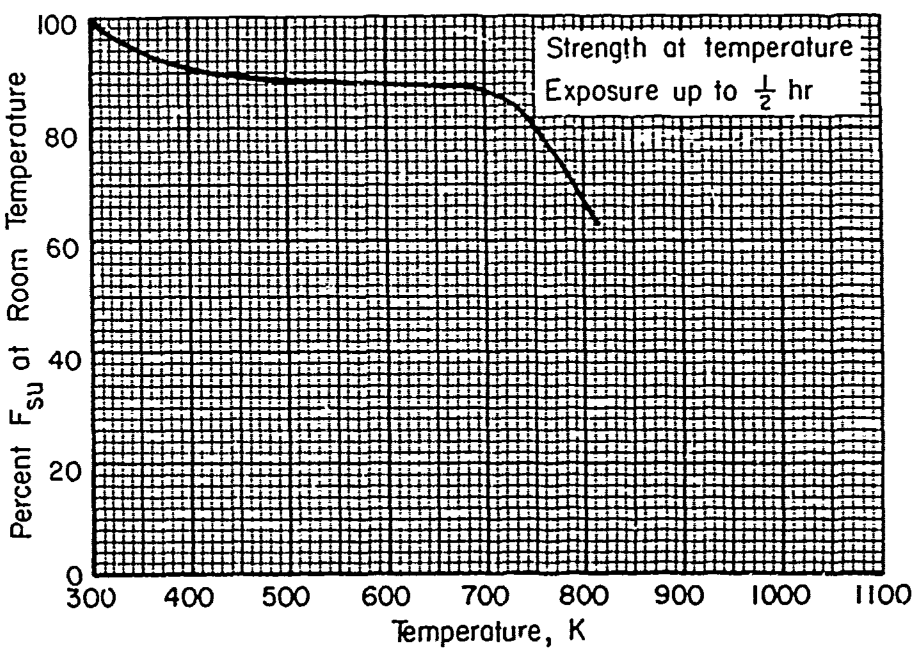


FIGURE 5.5.1.2.2(b). Effect of temperature on the ultimate shear strength (F_{su}) of solution-treated and aged Ti-13V-11Cr-3Al alloy (sheet).

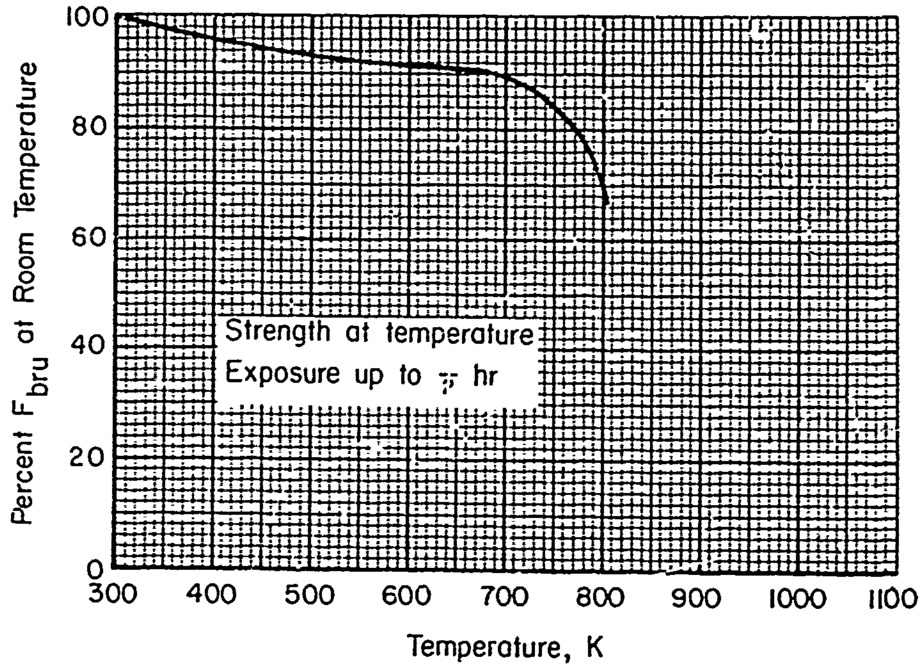


FIGURE 5.5.1.2.3(a). Effect of temperature on the ultimate bearing strength (F_{bru}) of solution-treated and aged Ti-13V-11Cr-3Al alloy (sheet).

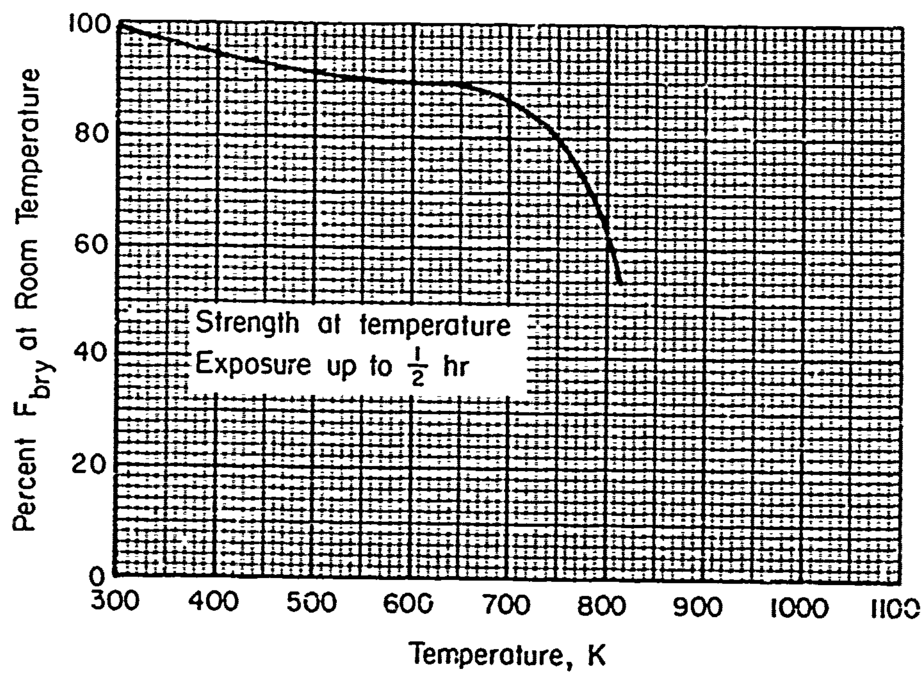


FIGURE 5.5.1.2.3(b). Effect of temperature on the bearing yield strength (F_{bry}) of solution-treated and aged Ti-13V-11Cr-3Al alloy (sheet).

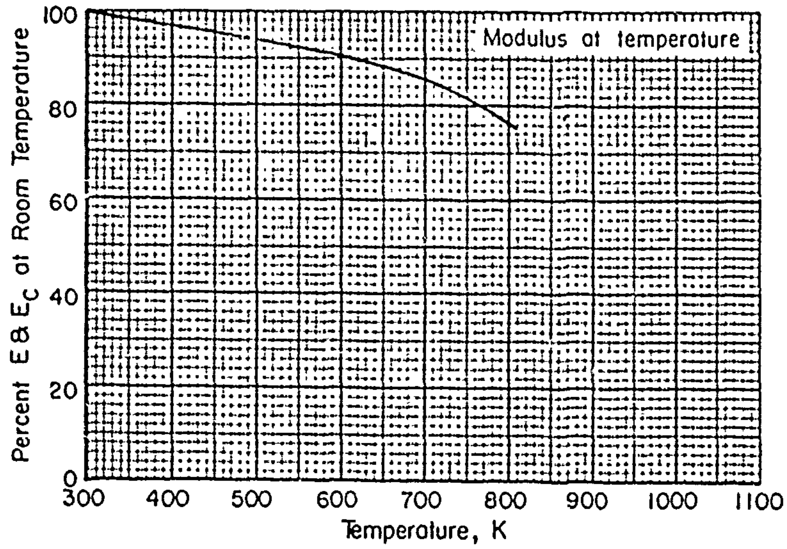


FIGURE 5.5.1.2.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of solution-treated and aged Ti-13V-11Cr-3Al alloy (sheet).

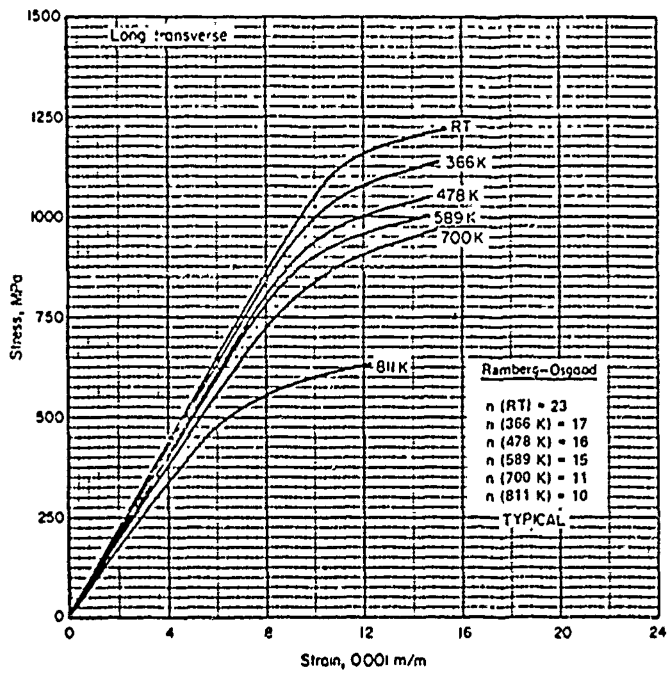


FIGURE 5.5.1.2.6. Typical tensile stress-strain curves for solution-treated and aged Ti-13V-11Cr-3Al alloy (sheet) at room and elevated temperatures.

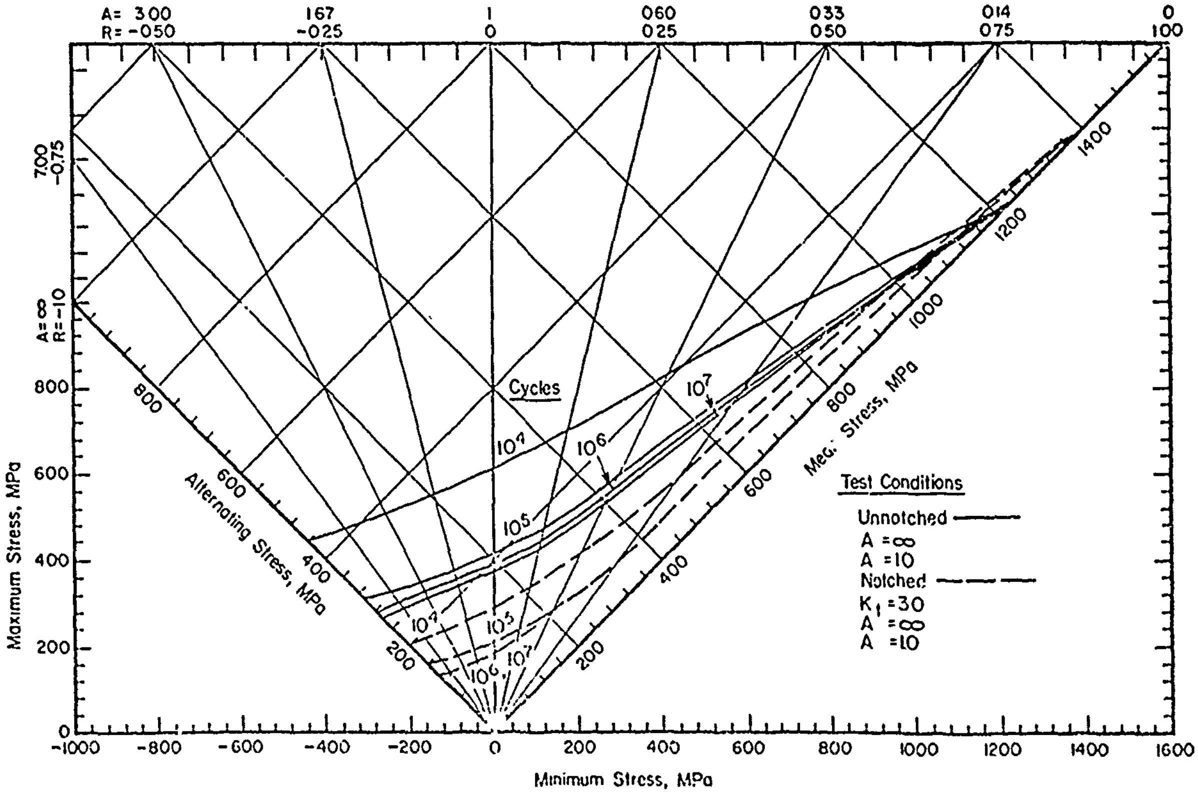


FIGURE 5.5.1.2.8(a). Typical constant-life fatigue diagram for solution-treated and aged Ti-13V-11Cr-3Al alloy (sheet) at room temperature

Correlative Information for Figure 5.5.1.2.8(a)

Product Form: Sheet, 1.09 mm thick

Properties:

TUS, MPa	TYS, MPa	Temp, K
1203	1080	RT (Unnotched)
1379	—	RT (Notched)

Test Parameters:
Loading - Axial
Frequency - 3600 cpm
Temperature - RT
Atmosphere - Air

Specimen Details:

Unnotched	Notched, Edge, $K_t = 3.0$
7.62 mm width	11.38 mm, gross width
	7.62 mm, net width
	0.56 mm, root radius, r
	60° flank angle, ω

$$K_N = 2.11,\ \rho = 1.60\ \text{mm}, \quad \text{where } K_N = 1 + \frac{K_t - 1}{1 + \frac{\pi}{\pi - \omega}\sqrt{\frac{\rho}{r}}}$$

Surface Condition: Unnotched: Surface as finished at the mill, edges polished with emery paper.
Notched: Same as above.

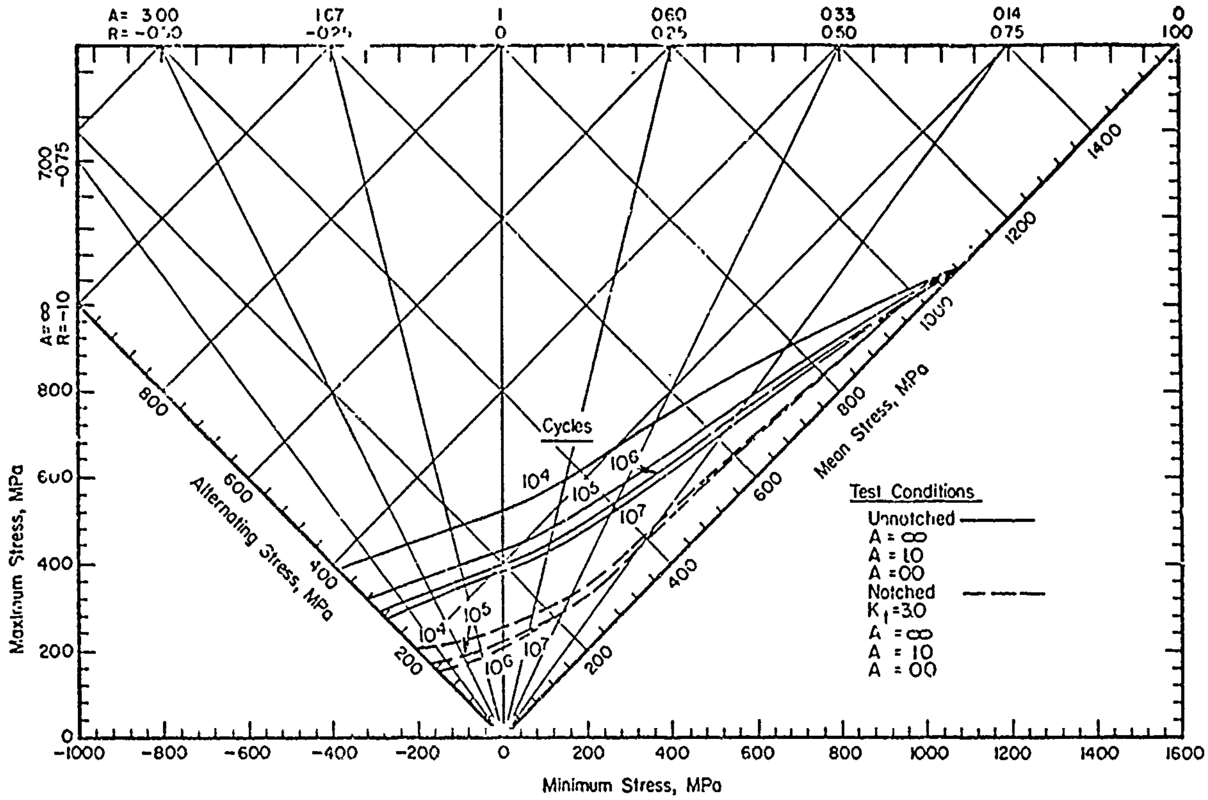


FIGURE 5.5.1.2.8(b). Typical constant-life fatigue diagram for solution-treated and aged Ti-13V-11Cr-3Al alloy (sheet) at 589 K

Correlative Information for Figure 5.5.1.2.8(b)

Product Form: Sheet, 1.09 mm thick

Test Parameters:
- Loading - Axial
- Frequency - 3600 cpm
- Temperature - 589 K
- Atmosphere - Air

Properties:

TUS, MPa	TYS, MPa	Temp, K
1076	876	589 (Unnotched)
1131	...	589 (Notched)

Specimen Details:

Unnotched: 7.62 mm width

Notched, Edge, $K_t = 3.0$:
- 11.38 mm, gross width
- 7.62 mm, net width
- 0.56 mm, root radius, r
- 60° flank angle, ω

$$K_N = 1.86,\ \rho = 0.432\ \text{mm, where } K_N = 1 + \frac{K_t - 1}{1 + \frac{\pi}{\pi - \omega}\sqrt{\frac{\rho}{r}}}$$

Surface Condition: Unnotched. Surface as finished at the mill, edges polished with emery paper. Notched: Same as above.

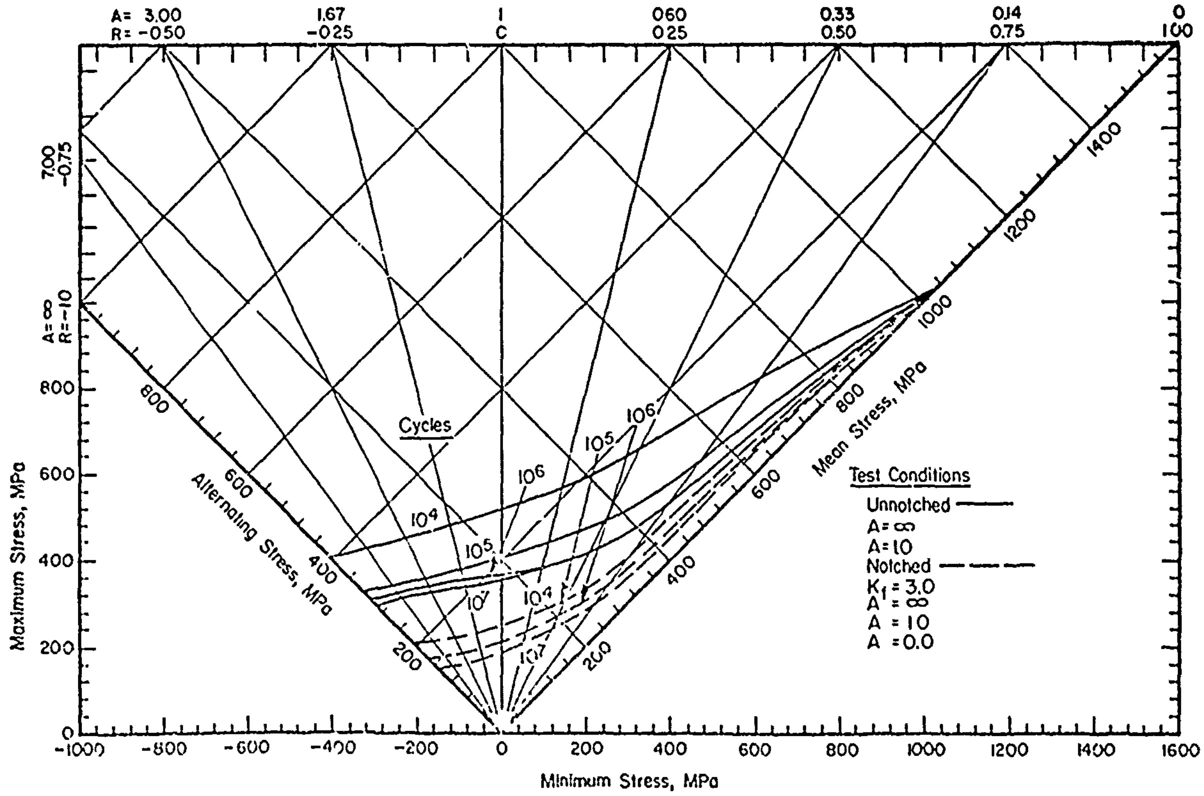


FIGURE 5.5.1.2.8(c). Typical constant-life fatigue diagram for solution-treated and aged Ti-13V-11Cr-3Al alloy (sheet) at 700 K

Correlative Information for Figure 5.5.1.2.8(c)

Product Form: Sheet, 1.09 mm thick

Properties:

TUS, MPa	TYS, MPa	Temp, K
1027	841	700 (Unnotched)
1076	—	700 (Notched)

Specimen Details:

Unnotched: 7.62 mm width

Notched, Edge, $K_t = 3.0$: 11.38 mm, gross width; 7.62 mm, net width; 0.56 mm, root radius, r; 60° flank angle, ω

$K_N = 2.05, \rho = 0.203$ mm, where $K_N = 1 + \frac{K_t - 1}{1 + \frac{\pi}{\pi - \omega}\sqrt{\frac{\rho}{r}}}$

Surface Condition: Unnotched. Surface as finished at the mill, edges polished with emery paper. Notched: Same as above.

Test Parameters:
- Loading - Axial
- Frequency - 3600 cpm
- Temperature - 700 K
- Atmosphere - Air

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 for 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.

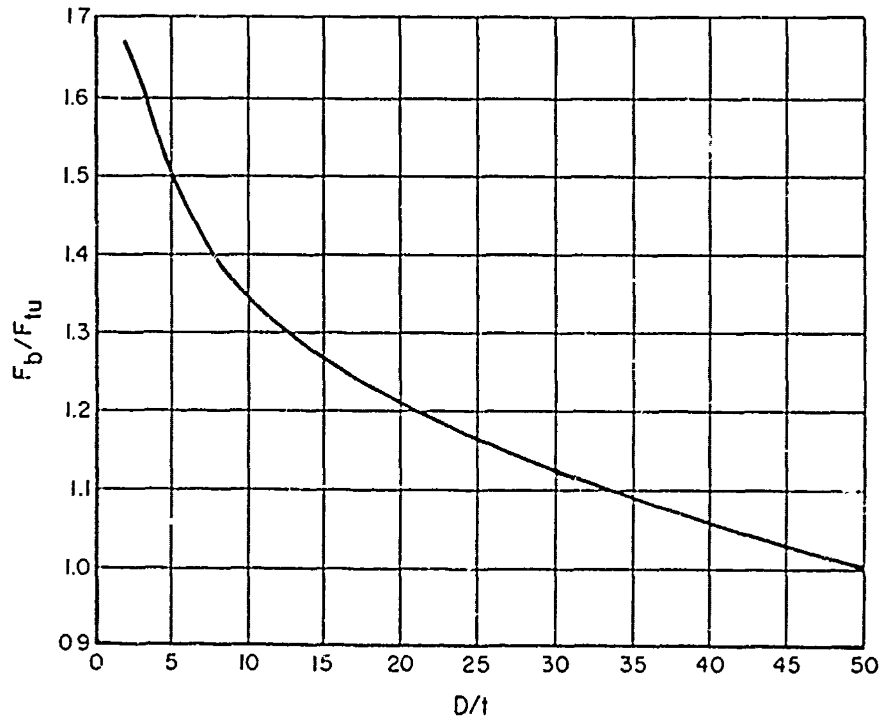


FIGURE 5.6.1.1.1. *Bending modulus of rupture for solution-treated and aged Ti-6Al-4V alloy round tubing manufactured from bar material.*

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5 1.4(e) Jackson, J. D., Boyd, W. K., "Corrosion of Titanium", DMIC Memorandum 218, Defense Metals Information Center, Battelle Memorial Institute, Columbus, Ohio, September 1, 1966.

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5.3.2(a) Christian, J. L., "Mechanical Properties of Ti-8Al-1Mo-1V Alloy at Room and Cryogenic Temperatures", General Dynamics/Report MRG 246, August 1961.

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5.4.3.1.9 Brockett, R. M., Gottbrath, J. A., "Development of Engineering Data on Titanium Extrusion for use in Aerospace Design", Lockheed-California Company, Report AFML-TR-67-189, July 1967.

5.4.3.2(a) Hickey, C. F., Jr., "Mechanical Properties of Titanium and Aluminum Alloys at Cryogenic Temperatures", Watertown Arsenal Report WAL TR 340.2/1, March 1962.

5.4.3.2(b) "Elevated Temperature Design Data Confirmation, Ti-6Al-4V", North American Aviation Report TFD-60-677, September 1960.

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5.6(b) Cozzone, F. P., "Bending Strength in the Plastic Range", Journal of the Aeronautical Sciences, May 1943.

5.6(c) Ades, C. S., "Bending Strength of Tubing in the Plastic Range", Journal of Aeronautical Sciences, August 1957.

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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 aircraft fabrication. 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, fatigue, and element properties will be added as information becomes available.

The alloys in this chapter have not been coded in a recognized numbering system such as that used for steels or aluminum alloys. 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 in this Handbook are as follows:

6.2 Iron-Chromium-Nickel-Base Alloys
- 6.2.1 A-286
- 6.2.2 N-155
- 6.2.3 W-545

6.3 Nickel-Base Alloys
- 6.3.1 Hastelloy B
- 6.3.2 Hastelloy X
- 6.3.3 Inconel Alloy 600 (Inconel)
- 6.3.4 Inconel 625
- 6.3.5 Inconel 702
- 6.3.6 Inconel 706
- 6.3.7 Inconel 718
- 6.3.8 Inconel Alloy X-750 (Inconel X)
- 6.3.9 M-252 Alloy
- 6.3.10 René 41
- 6.3.11 Udimet 500
- 6.3.12 Waspaloy

6.4 Cobalt-Base Alloys
- **6.4.1 L-605**

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, as used in this chapter, may be 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.

Other terminology in this chapter is used in the same manner as elsewhere in this handbook and as defined or described in Chapter 1, or in other recognized sources.

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 requirements of recognized specifications. Values for non-specification strength properties are derived from published test data and are adjusted to the strength level of the specified strength properties. 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 the property-data tables and curves in this chapter 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 (OTS PB 161093), 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 922 to 1033 K, 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.—Where well substantiated data are available, covering the temperatures and times of exposure and the creep deformations of interest, these 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 or as creep nomograph such as discussed in Chapter 9.

Fatigue.—Fatigue data for unnotched and notched specimens at room temperature and elevated temperatures are shown in each alloy section, for those alloys where sufficiently well documented data exist. These graphical displays are considered typical values and may include S-N curves or constant-life diagrams.

6.1.1.2 *Physical Properties.*—Selected physical-property data from the literature 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 generally fall between the austenitic stainless steels and the nickel- and cobalt-base alloys, both in cost and in maximum service temperature. They are used in airframes, principally in the temperature range 811 to 922 K, 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 retain 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 in these alloys. Nickel and cobalt strengthen and toughen them. Molybdenum, tungsten, and columbium contribute to hardness and strength, particularly at elevated temperatures. Titanium and aluminum are added to many of these alloys to permit age-hardening.

Heat Treatment.—The complex-base alloys are heat treated with conventional equipment and fixtures such as would be used with 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 often 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 978 K and oxidation resistance up to 1089K. 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 all the usual mill forms.

A-286 is somewhat harder to hot or cold work than the austenitic stainless steels. Its forging range is 1450 to 1255 K; when finishing below 1255K, 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 metre per metre is experienced during aging.

Oxidation resistance of A-286 is equivalent to that of Type 310 stainless steel up to 1255 K.

Some material specifications for A-286 alloy are presented in Table 6.2.1.0(a).

Room-Temperature Properties

Room-temperature mechanical properties are shown in Table 6.2.1.0(b). Tensile properties are minimum AMS values, and compressive, shear, and bearing values are derived from published test data for A-286 and similar alloys. Physical properties are shown in Figure 6.2.1.0.

6.2.1.1 *Solution-Treated and Aged Condition.*—Elevated-temperature data for this condition are presented in Figures 6.2.1.1.1(a) through 6.2.1.14(b). In addition, stress rupture properties are specified at 922 K. The appropriate specifications should be consulted for detailed requirements. Figures 6.2.1.1.8(a) and (b) are constant-life diagrams showing unnotched fatigue and dynamic creep of this alloy and condition at 1005 K.

TABLE 6.2.1.0(a). *Material Specifications for A-286 Alloy*

Specification	Form	Condition
AMS5525	Sheet, strip, and plate	Solution treated
AMS 5735	Bars, forgings, and mechanical tubing	Solution treated and aged
AMS 5737	Bars, forgings and mechanical tubing	Consumable-electrode melted; solution treated and aged

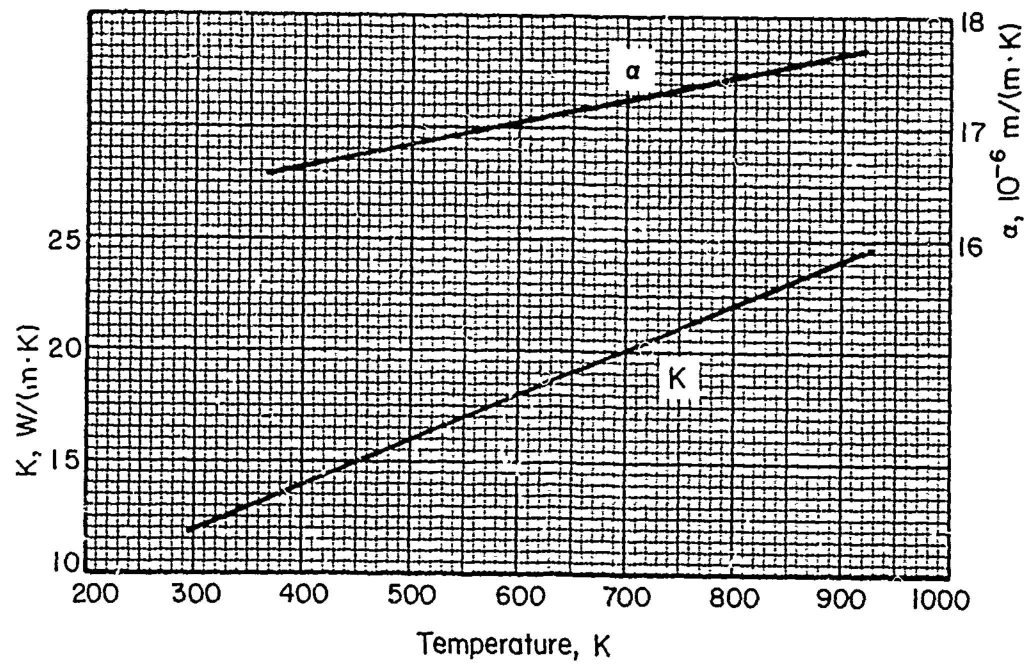


FIGURE 6.2.1.0. Effect of temperature on the physical properties of A-286 alloy.

TABLE 6.2.1.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF A-286 ALLOY

SPECIFICATION	AMS 5525	AMS 5735	AMS 5737
FORM	SHEET, STRIP AND PLATE	BARS, FORGINGS AND MECHANICAL TUBING	
CONDITION	SOLUTION TREATED AND AGED		
THICKNESS, MM	THICKNESS OVER 0.102 MM	...	CONSUMABLE-ELECTRODE MELTED
BASIS	S	S	S
MECHANICAL PROPERTIES:			
FTU, MPA	965	896	965
FTY, MPA	655	586	655
FCY, MPA	655	586	655
FSU, MPA	627	586	627
FBRU, MPA:			
(E/D=1.5)	1450	1340	1450
(E/D=2.0)	1830	1700	1830
FBRY, MPA:			
(E/D=1.5)	979	876	979
(E/D=2.0)	1180	1050	1180
EL, PERCENT	15	15	12
E, GPA		200.6	
EC, GPA		200.6	
G, GPA		71.7	
MU		0.29	

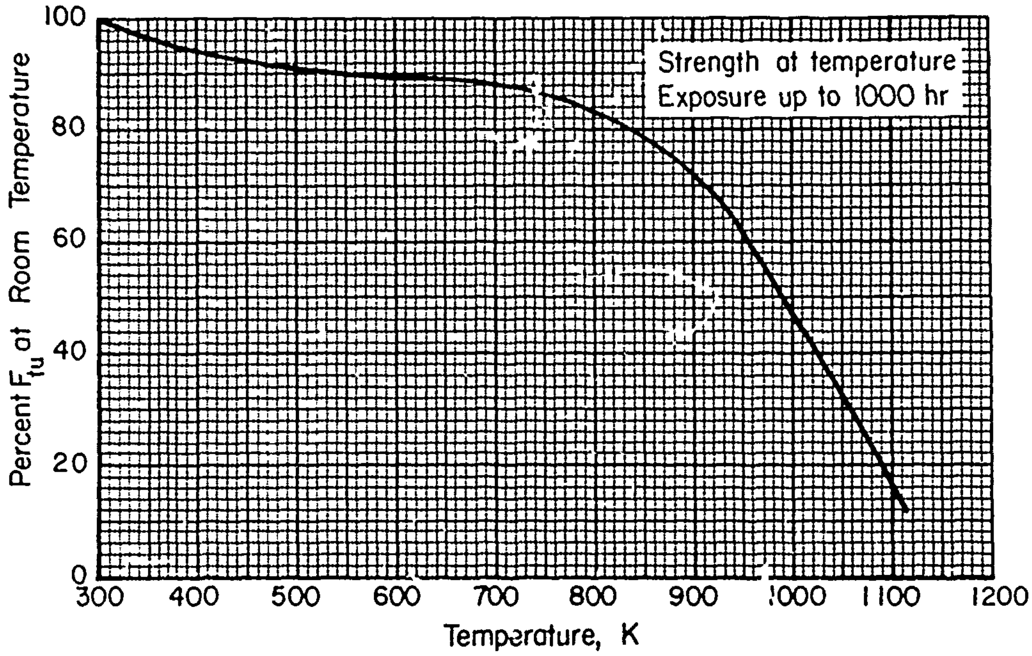


FIGURE 6.2.1.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of A-286 alloy.

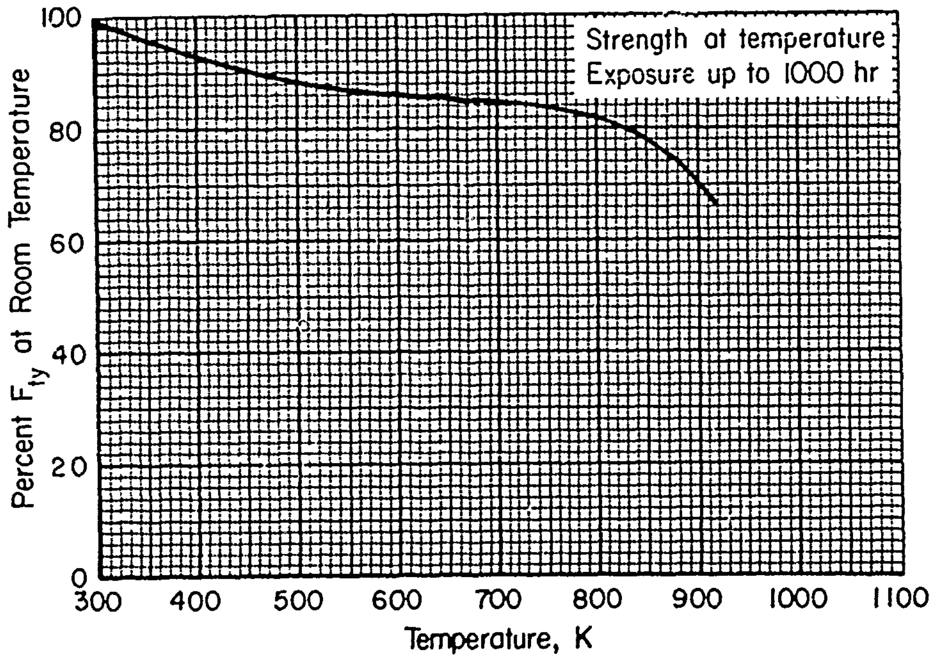


FIGURE 6.2.1.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of A-286 alloy.

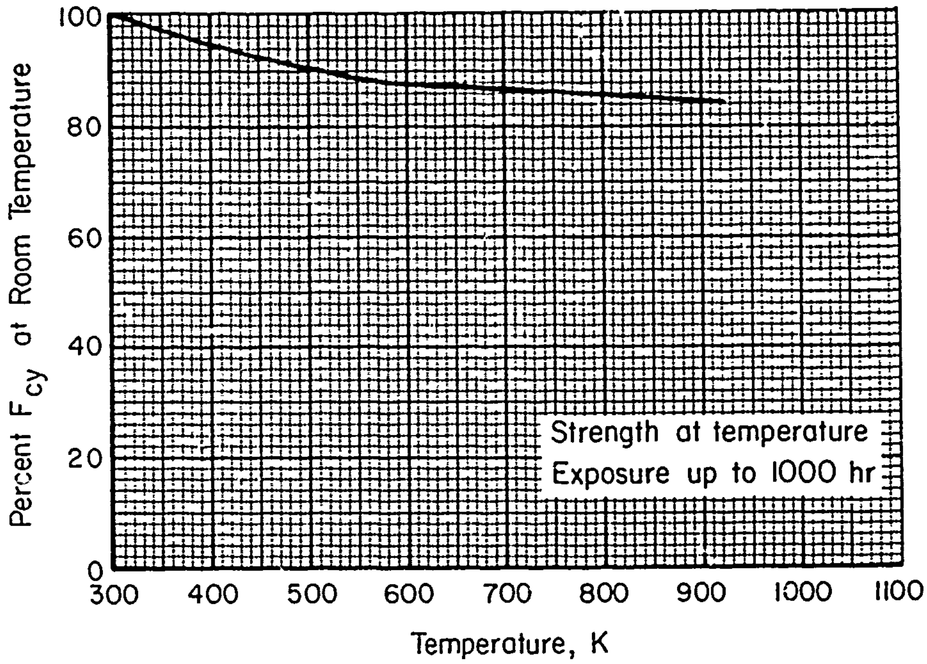


FIGURE 6.2.1.1.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of A-286 alloy.

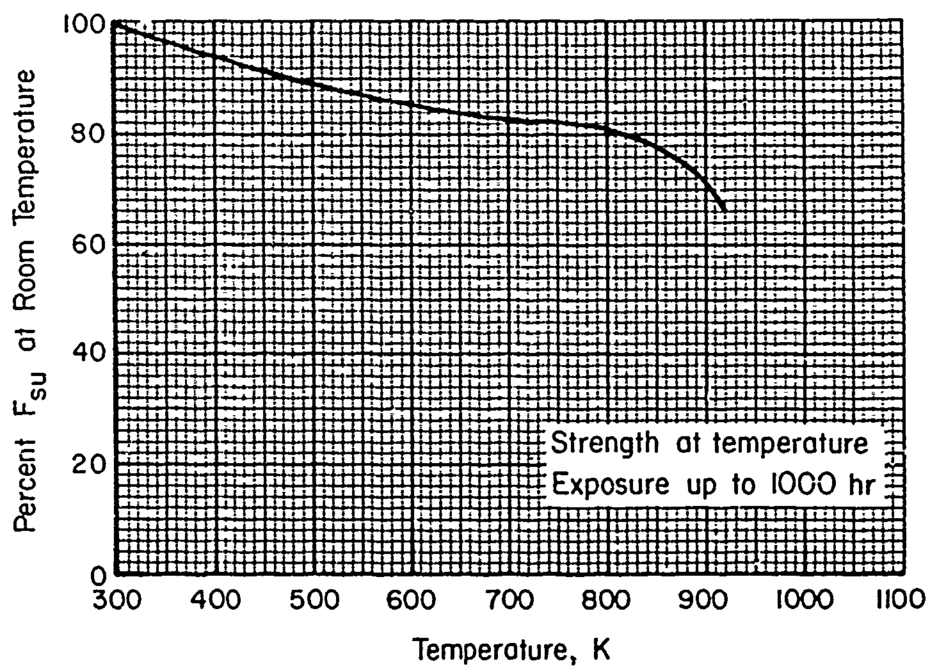


FIGURE 6.2.1.1.2(b). Effect of temperature on the ultimate shear strength (F_{su}) of A-286 alloy.

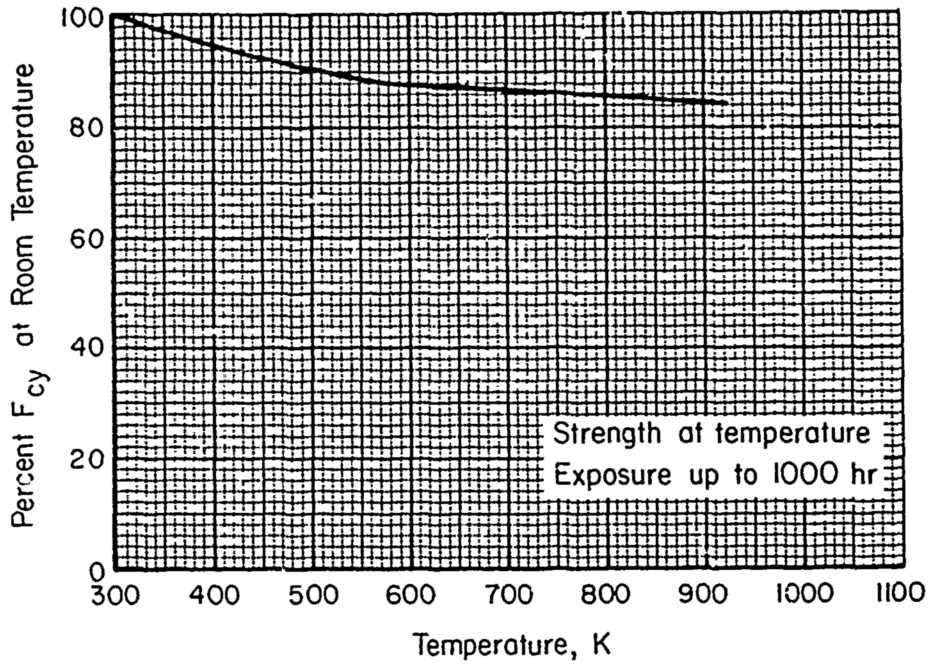


FIGURE 6.2.1.1.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of A-286 alloy.

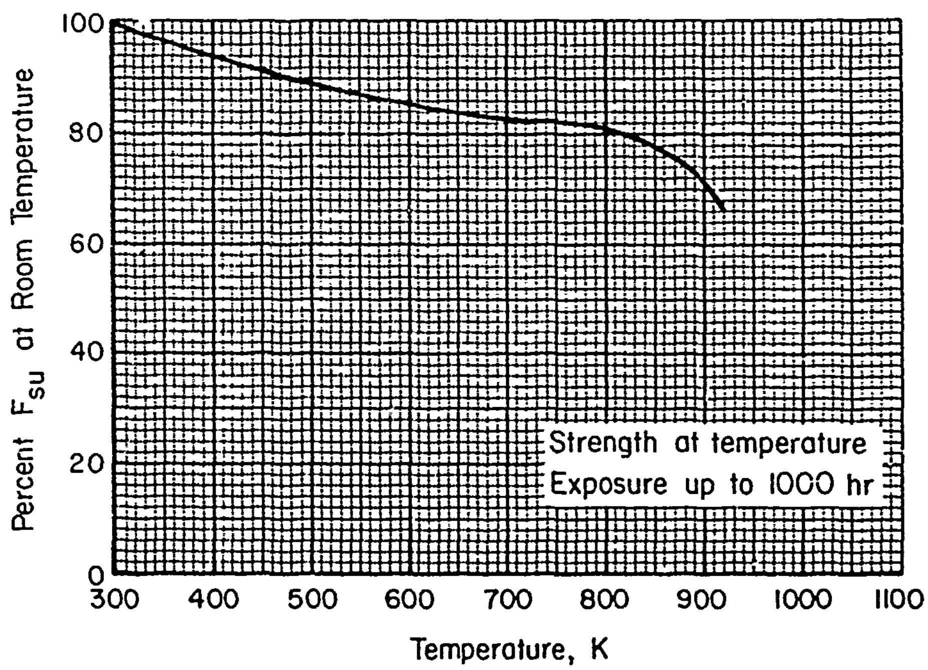


FIGURE 6.2.1.1.2(b). Effect of temperature on the ultimate shear strength (F_{su}) of A-286 alloy.

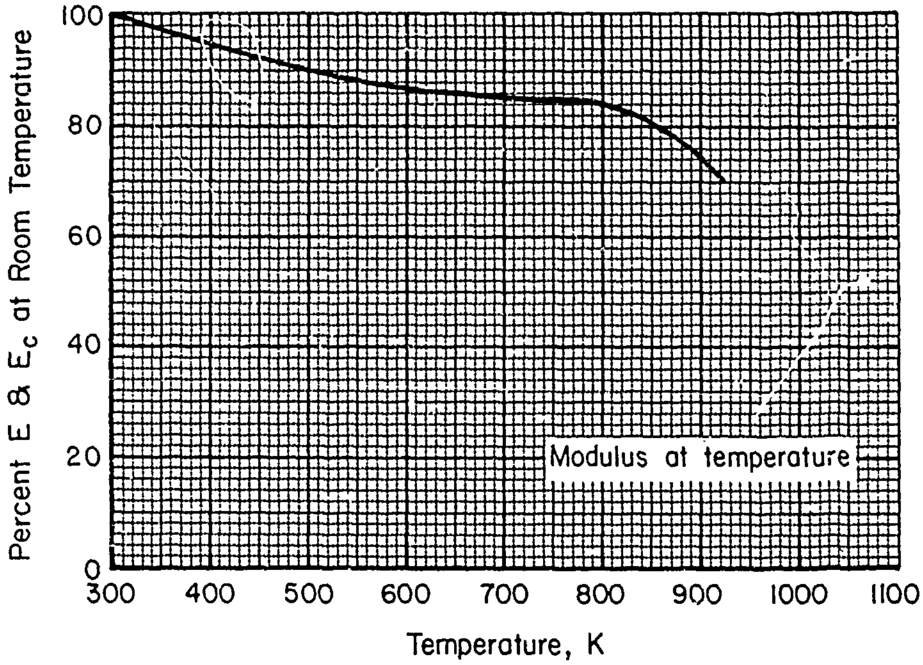


FIGURE 6.2.1.1.4(a). Effect of temperature on the tensile and compressive moduli (E and E_c) of A-286 alloy.

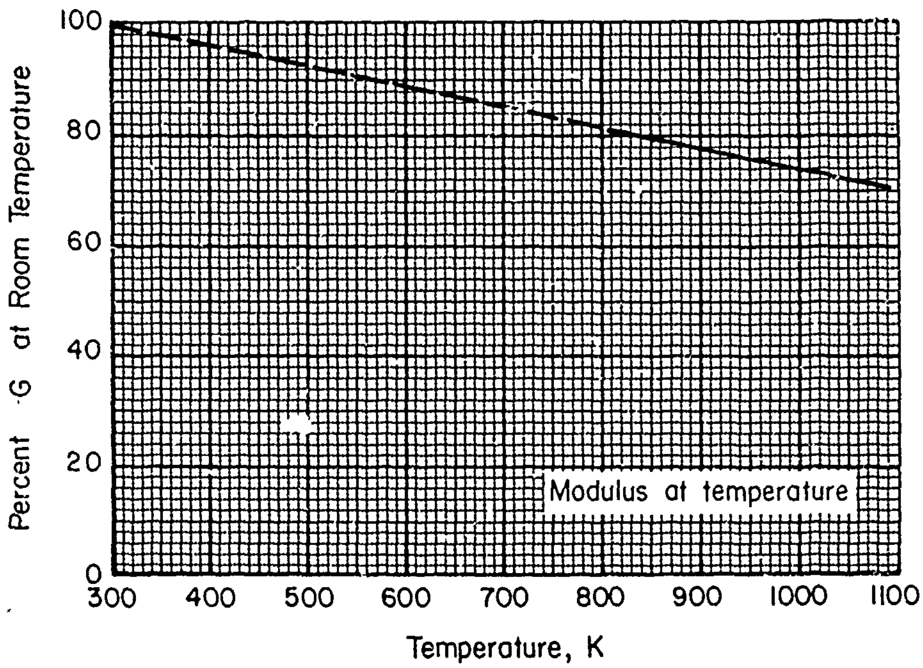


FIGURE 6.2.1.1.4(b). Effect of temperature on the shear modulus (G) of A-286 alloy.

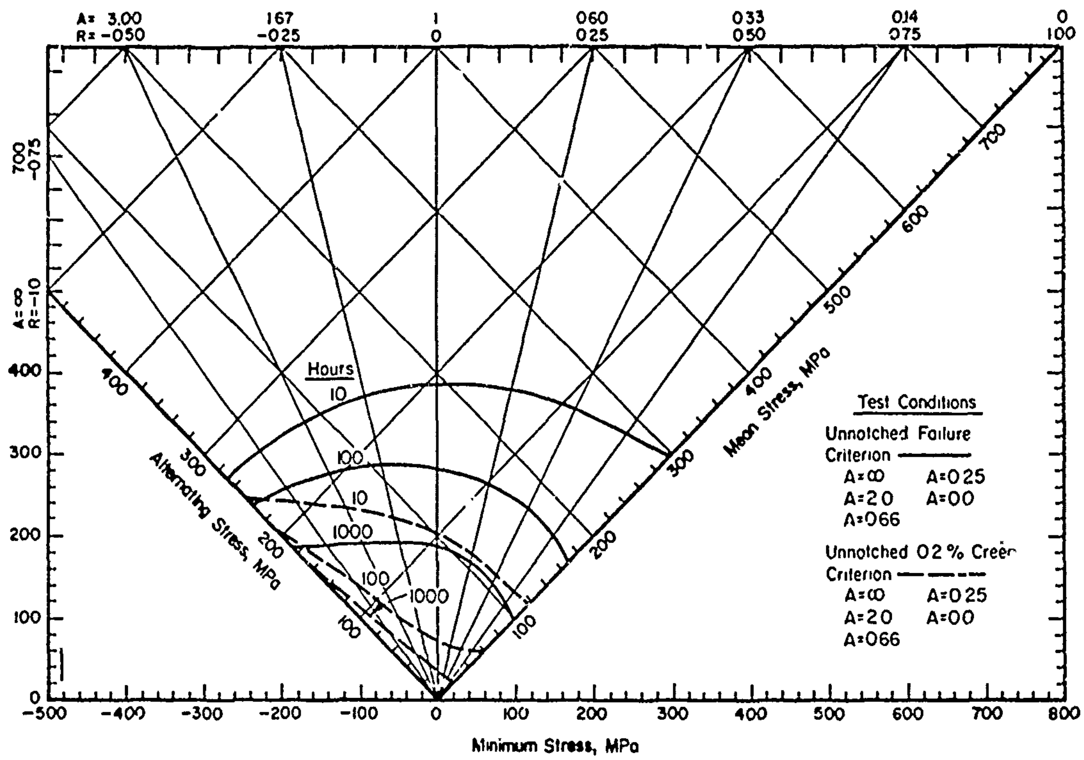


FIGURE 6.2.1.1.8(a). Typical constant-life diagram for fatigue and dynamic creep behavior of solution treated and aged A-286 alloy (bar) at 1005K.

Correlative Information for Figure 6.2.1.1.8(a)

Product Form: Roller Bar, 30.2 mm diameter

Properties:	TUS, MPa	TYS, MPa	Temp, K
	1014	607	RT
	—	—	1005

Test Parameters:
Loading — Axial
Frequency — 1800 cpm
Temperature — 1005 K
Atmosphere — Air

Specimen Details: Unnotched
6.35 mm diameter

Surface Condition Longitudinally polished with 240, 400 and 600 grit paper to 5-8 RMS surface finish. Heat treatment consisted of solution treat at 1172 K for 1 hour, water quenched; aged at 992 K for 16 hours (packed in cast iron chips), air cooled.

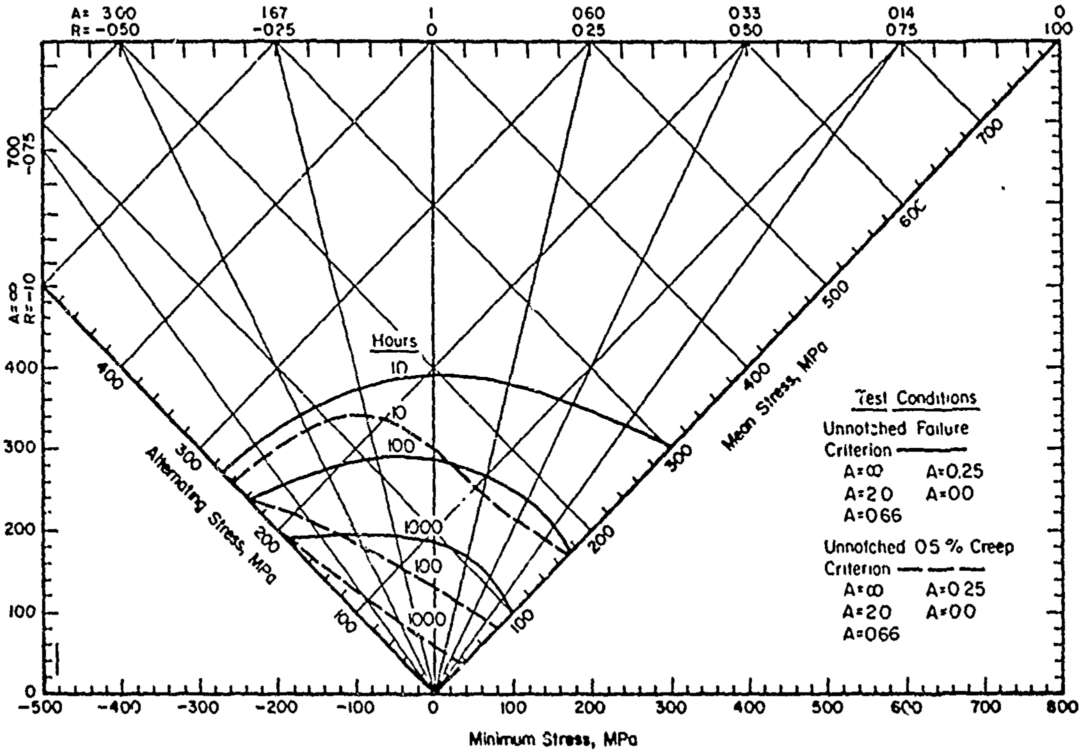


FIGURE 6.2.1.1.8(b). Typical constant-life diagram for fatigue and dynamic creep behavior of solution treated and aged A-286 alloy (bar) at 1005 K.

Correlative Information for Figure 6.2.1.1.8(b)

Product Form: Roller Bar, 30.2 mm diameter

Properties:

TUS, MPa	TYS, MPa	Temp, K
1014	607	RT
—	—	1005

Test Parameters:
- Loading — Axial
- Frequency — 1800 cpm
- Temperature — 1005 K
- Atmosphere — Air

Specimen Details: Unnotched
6.25 mm diameter

Surface Condition: Longitudinally polished with 240, 400 and 600 grit paper to 5-8 RMS surface finish. Heat treatment consisted of solution treat at 1172 K for 1 hour, water quenched; aged at 992 K for 16 hours (packed in cast iron chips), air cooled.

6.2.2. N-155 ALLOY

6.2.2.0 *Comments and Properties.*—N-155 alloy, also known as Multimet, is designed for applications involving high stress up to 1089 K. 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 1478 and 1172 K. It is easily cold 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 is good up to 1089 K.

Some material specifications for N-155 are presented in Table 6.2.2.0(a).

Room-Temperature Properties

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.

6.2.2.1 *Solution-Treated Conditions.*—Elevated-temperature mechanical properties for N-155 in the solution-treated condition are presented in Figures 6.2.2.1.1(a) through 6.2.2.1.8(c). In addition, stress-rupture properties are specified at 1089 K for sheet material and at 1005 K for bars and forgings of this alloy. The appropriate specifications should be consulted for detailed requirements.

TABLE 6.2.2.0(a). *Material Specifications for N-155 Alloy*

Specification	Form	Condition
AMS 5531	Sheet (low Cb + Ta)	Solution treated
AMS 5532	Sheet	Solution treated
AMS 5585	Tubing (welded)	Solution treated
AMS 5768	Bars and forgings	Solution treated and aged
AMS 5769	Bars and forgings	Solution treated

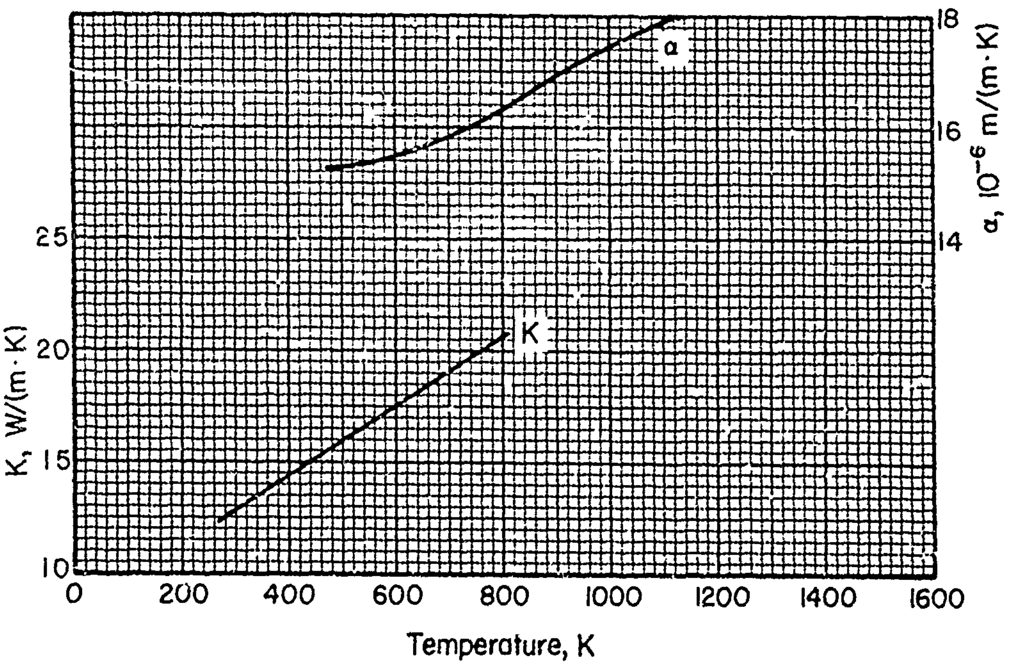


FIGURE 6.2.2.0. Effect of temperature on the physical properties of N-155 alloy.

TABLE 6.2.2.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF N-155 ALLOY

SPECIFICATION	AMS 5531 AND AMS 5532	AMS 5585
FORM	SHEET	TUBING
CONDITION	SOLUTION TREATED	
THICKNESS, MM	...	...
BASIS	S[a]	S
MECHANICAL PROPERTIES:		
FTU, MPA:		
L	...	689
LT	689	...
FTY, MPA:		
L	...	338[b]
LT	338[b]	...
FCY, MPA:		
L	...	...
LT	...	...
FSU, MPA	...	...
FBRU, MPA:		
(E/D=1.5)	...	...
(E/D=2.0)	...	...
FBRY, MPA:		
(E/D=1.5)	...	...
(E/D=2.0)	...	...
EL, PERCENT:		
L	...	c
LT	40	...
E, GPA	201.3	
EC, GPA	201.3	
G, GPA	...	
MU	...	
PHYSICAL PROPERTIES:		
OMEGA, MG/M3	8.30	
C, J/(G*K)	0.43 (294-373 K)	
K, W/(M*K)	12.25 (at 294K); 18.86 (at 700K); 22.15 (at 922K)	
ALPHA, 10-6 M/(M*K)	15.30 (294-589K); 16.38 (294-811K)	

[a] TEST DIRECTION LONGITUDINAL FOR WIDTHS LESS THAN 229 MM; TRANSVERSE FOR WIDTHS 229 MM AND OVER.
[b] TYPICAL VALUE REDUCED TO MINIMUM.
[c] STRIP = 35.
FULL SECTION ≥ 15.875 MM THICK = 40
FULL SECTION A 15.875 MM THICK = 30.

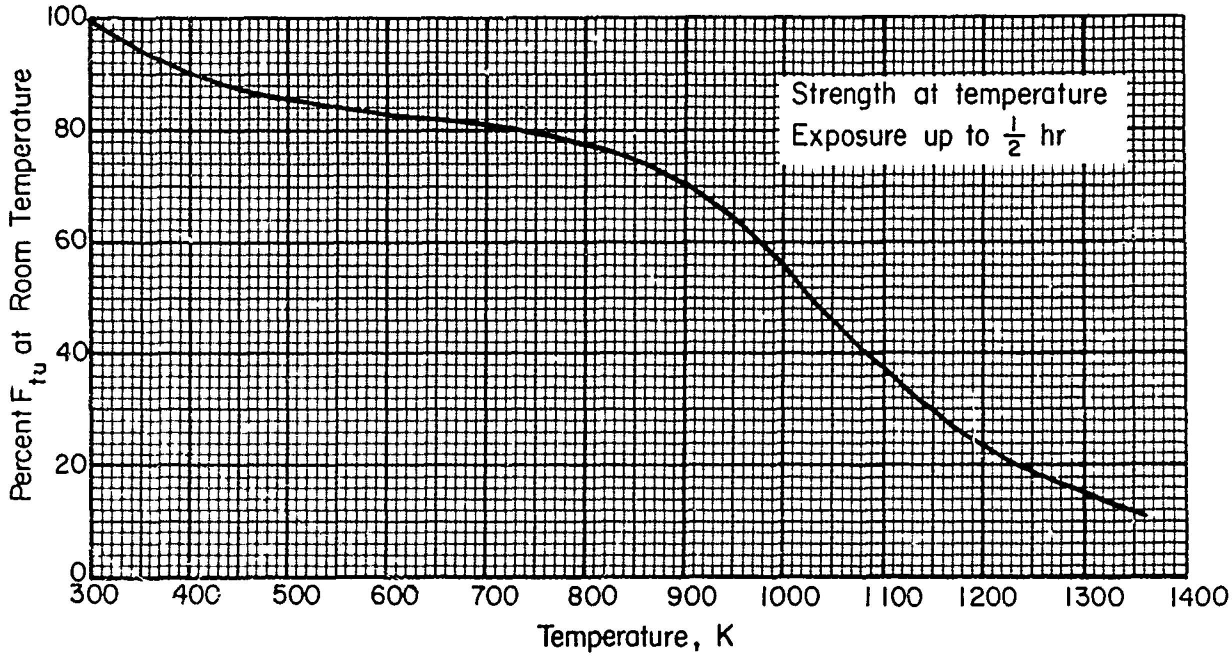


FIGURE 6.2.2.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of N-155 alloy.

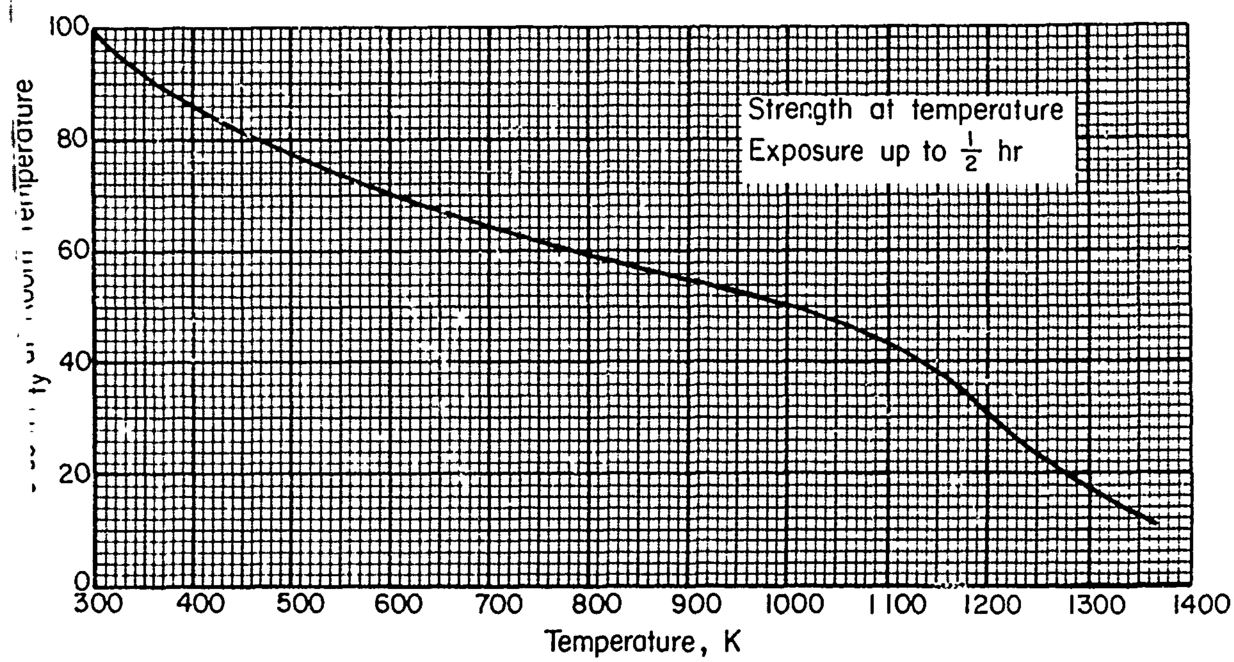


FIGURE 6.2.2.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of N-155 alloy.

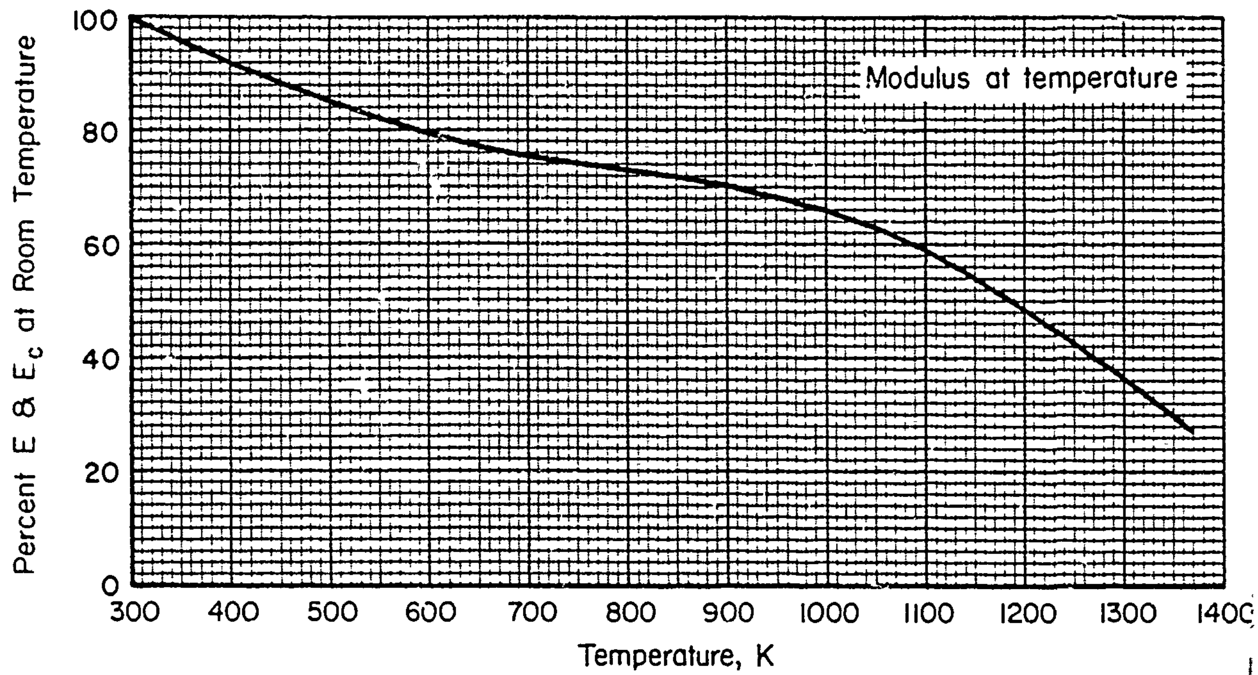


FIGURE 6.2.2.1.4(a). Effect of temperature on the tensile and compressive moduli (E and E_c) of N-155 alloy.

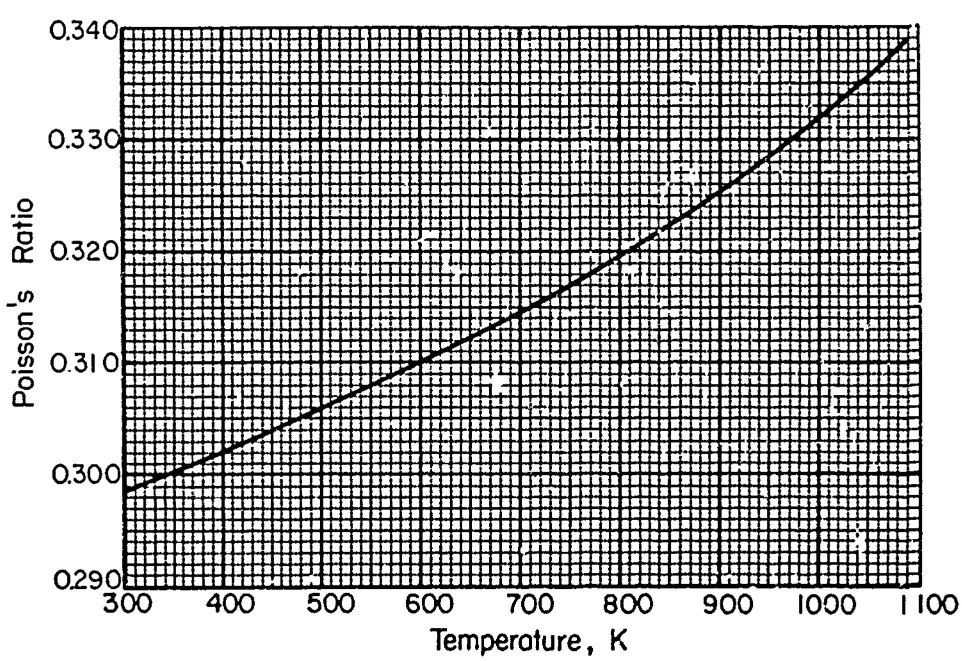


FIGURE 6.2.2.1.4(b). Effect of temperature on Poisson's ratio (μ) for N-155 alloy.

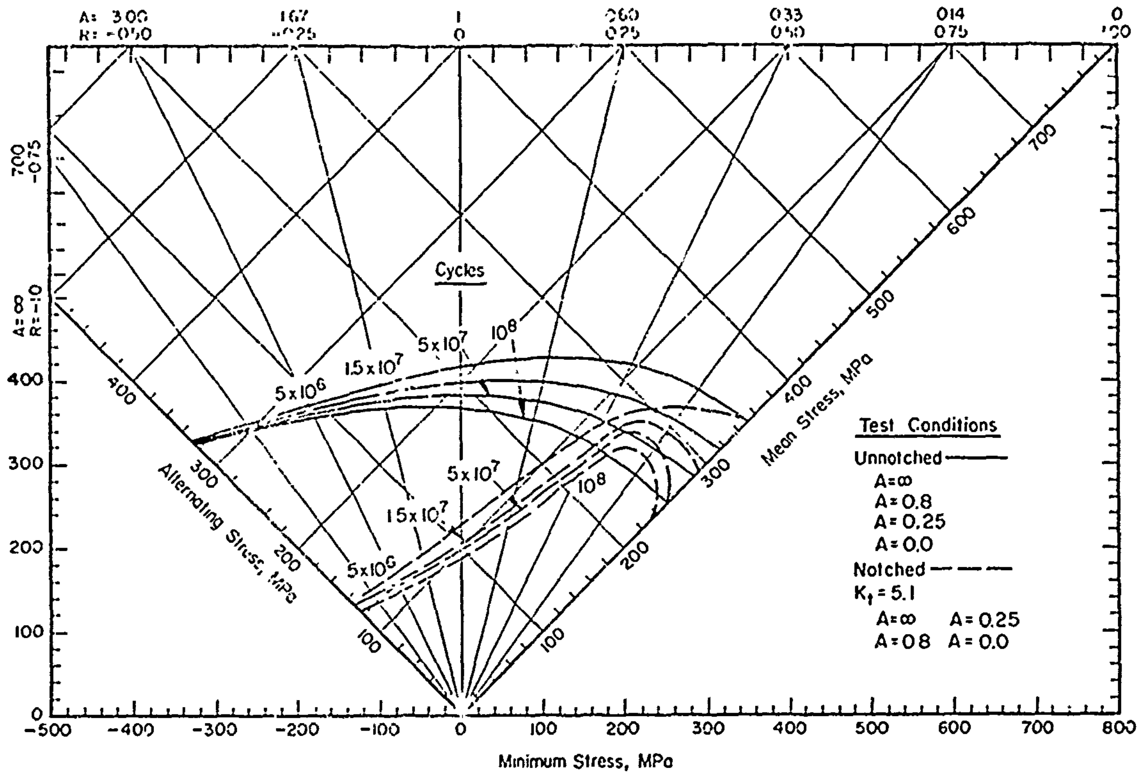


FIGURE 6.2.2.1.8(a). Typical constant-life fatigue diagram for solution-treated and aged N-155 bar at 922 K

Correlative Information for Figure 6.2.2.1.8(a)

Product Form: Roller bar, 25.4 mm diameter

Test Parameters:
- Loading - Axial
- Frequency - 1500 cpm
- Temperature - 922 K
- Atmosphere - Air

Properties:

TUS, MPa	TYS, MPa	Temp, K
552	—	922

Specimen Details:

Unnotched	Notched, V-Groove, $K_t = 5.1$
5.72 mm diameter	8.10 mm, gross diameter
	5.72 mm, net diameter
	0.13 mm, root radius, r
	60° flank angle, ω

$K_N = 3.37$, $\rho = 0.0305$ mm, where $K_N = 1 + \dfrac{K_t - 1}{1 + \dfrac{\pi}{\pi - \omega}\sqrt{\dfrac{\rho}{r}}}$

Surface Conditions: Unnotched specimens were longitudinally polished with 400 grit paper. Notched specimens were lathe turned in the notch with a carbide tool. Heat treatment involved solution treatment at 1478K for 1 hour, water quench; aging treatment at 1033 K for 16 hours.

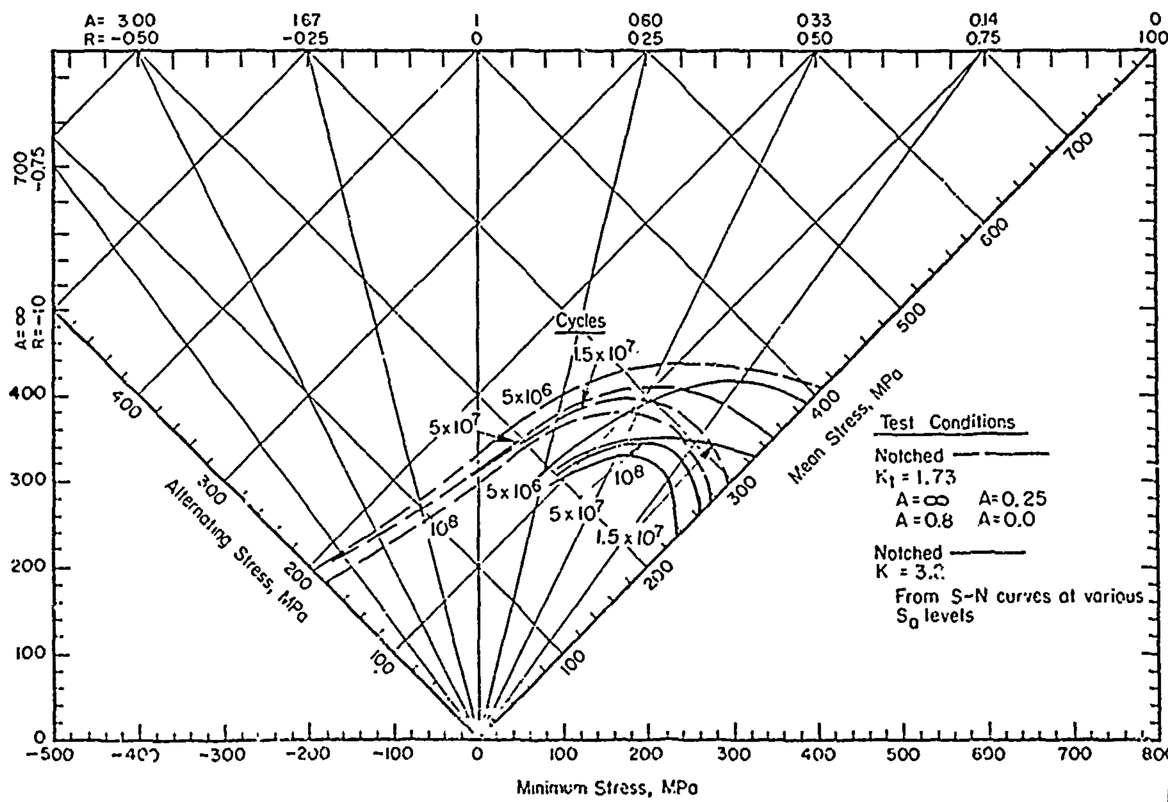


Fig. 6.2.2.1.8(b). Typical constant-life fatigue diagram for solution-treated and aged N-155 bar at 922 K.

Correlative Information for Figure 6.2.2.1.8(b)

Product Form: Roller bar, 25.4 mm diameter

Test Parameters:
Loading — Axial
Frequency — 1500 cpm
Temperature — 922 K
Atmosphere — Air

Properties:

TUS, MPa	TYS, MPa	Temp, K
552	—	922

Specimen Details:

Unnotched
5.72 mm diameter

Notched, V-Groove, $K_t = 1.73$
8.10 mm, gross diameter
5.72 mm, net diameter
1.27 mm, root radius, r
60° flank angle, ω

Notched, V-Groove, $K_t = 3.2$
0.25 mm, root radius, r
other dimensions are as given above

Surface Condition. Unnotched specimens were longitudinally polished with 400 grit paper. Notched specimens were lathe turned in the notch with a carbide tool.
Heat treatment involved solution treatment at 1478 K for 1 hour, water quench; aging treatment at 1033 K for 16 hours.

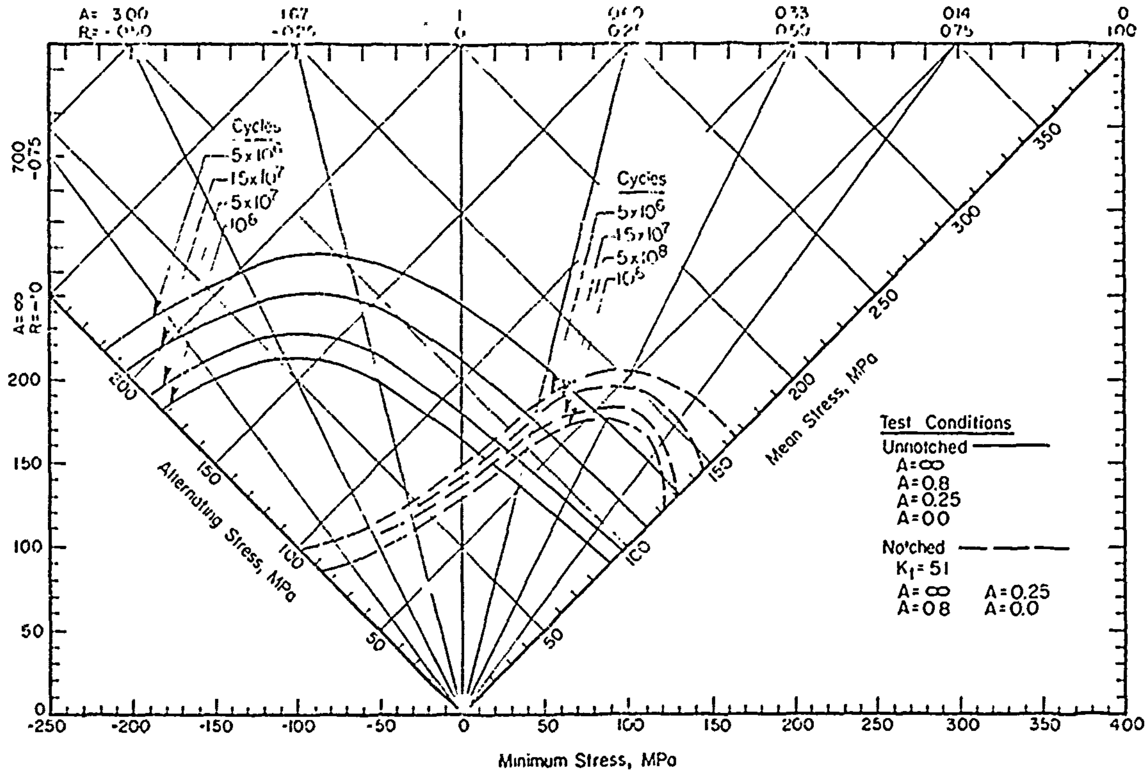


FIGURE 6.2.2.1.8(c). Typical constant-life fatigue diagram for solution-treated and aged I-155 bar at 1089 K

Correlative Information for Figure 6.2.2.1.8(c)

Product Form: Roller bar, 25.4 mm diameter

Test Parameters:
Loading - Axial
Frequency - 1500 cpm
Temperature - 1089 K
Atmosphere - Air

Properties:

TUS, MPa	TYS, MPa	Temp, K
345	—	1089 (Unnotched)
—	—	1089 (Notched)

Specimen Details:

Unnotched	Notched, V-Groove, $K_t = 5.1$
5.72 mm diameter	8.10 mm, gross diameter
	5.72 mm, net diameter
	0.13 mm, root radius, r
	60° flank angle, ω

$$K_N = 2.16, \rho = 0.406 \text{ mm, where } K_N = 1 + \frac{K_t - 1}{1 + \frac{\pi}{\pi - \omega}\sqrt{\frac{\rho}{r}}}$$

Surface Condition: Unnotched specimens were longitudinally polished with 400 grit paper. Notched specimens were lathe turned in the notch with a carbide tool. Heat treatment involved solution treatment at 1478 K for one hour, water quench; aging treatment at 1033K for 16 hours.

6.2.3. W-545 ALLOY

6.2.3.0 *Comments and Properties.*—W-545 is a vacuum-melted, age-hardening iron-base alloy designed for high-stress applications up to 1005 K. Its excellent notch toughness and good oxidation resistance make it especially suited for use in turbine discs, rotors, bolts, and fasteners. W-545 is available in most wrought mill forms.

W-545 has much higher strength than the austenitic stainless steels at forging temperatures; however, it is forged or rolled readily in the range, 1366 to 1255 K. W-545 has good cold-forming properties in the solution-treated condition. W-545 is machinable in all conditions, using high-speed steel cutting tools; finish machining should be done in the age-hardened condition. Inert arc welding is recommended for W-545; the alloy should be welded in the solution-treated condition and should be solution-treated again after welding.

W-545 is resistant to attack by turbine-engine gases up to 978 K; its service at higher temperatures is limited by strength considerations.

Some material specifications for W-545 alloy are presented in Table 6.2.3.0(a).

TABLE 6.2.3.0(a). *Material Specifications for W-545 Alloy*

Specification	Form	Condition
AMS 5543	Sheet, strip, and plate	Solution treated
AMS 5741	Bars and forgings	Solution treated and aged

Room-Temperature Properties

Room-temperature mechanical and physical properties of W-545 alloy are presented in Table 6.2.3.0(b). The effect of temperature on physical properties is shown in Figure 6.2.3.0.

6.2.3.1 *Solution-Treated and Aged Condition.*—Elevated-temperature properties for this condition are presented in Figures 6.2.3.1.1(a) through 6.2.3.1.6. In addition, stress-rupture properties at 978 K are specified for this alloy; the appropriate material specification should be consulted for detailed requirements.

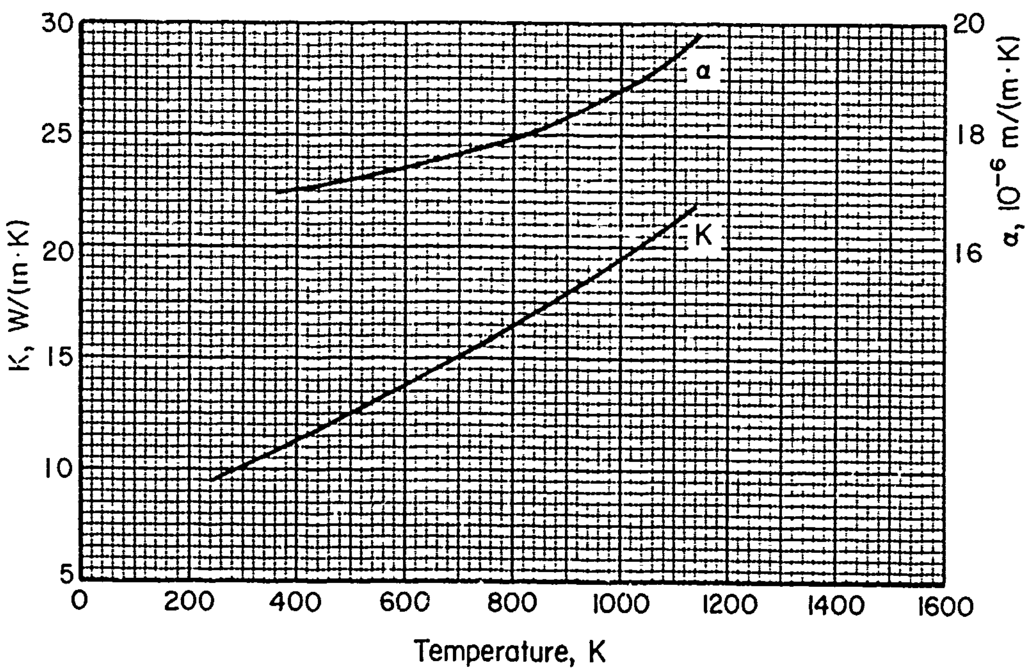


FIGURE 6.2.3.0. Effect of temperature on the physical properties of W-545 alloy.

TABLE 6.2.3.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF W-545 ALLOY

SPECIFICATION	AMS 5543	AMS5741
FORM	SHEET AND STRIP	BARS AND FORGINGS
CONDITION	SOLUTION TREATED AND AGED	
THICKNESS, MM	...	...
BASIS	S[a]	S[b]
MECHANICAL PROPERTIES:		
FTU, MPA:		
L	...	1070
LT	1070	...
FTY, MPA:		
L	...	827
LT	827	...
FCY, MPA:		
L	...	...
LT	...	...
FSU, MPA	...	...
FBRU, MPA:		
(E/D=1.5)	...	...
(E/D=2.0)	...	...
FBRY, MPA:		
(E/D=1.5)	...	...
(E/D=2.0)	...	...
EL, PERCENT:		
L	...	12
LT	12	...
EL, PERCENT:		
L	...	15
LT	...	...
E, GPA	200.6	
EC, GPA	200.6	
G, GPA	79.3	
MU	...	
PHYSICAL PROPERTIES:		
OMEGA, MG/M3	7.89	
C, J/(G*K)	0.48	
K, W/(M*K)	SEE FIGURE 6.2.3.0	
ALPHA, 10-6 M/(M*K)	SEE FIGURE 6.2.3.0	

[a] TEST DIRECTION LONGITUDINAL FOR WIDTHS LESS THAN 229 MM; TRANSVERSE FOR WIDTHS 229 MM AND OVER.

[b] GRAIN DIRECTION NOT SPECIFIED.

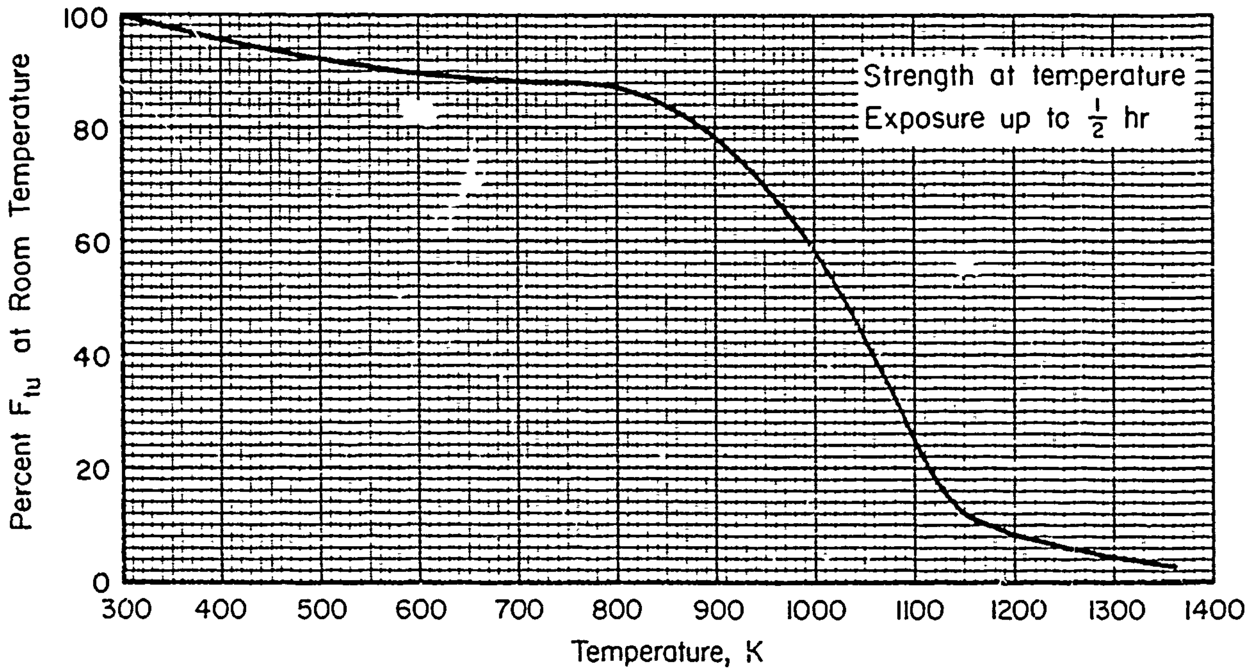


FIGURE 6.2.3.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of W-545 alloy.

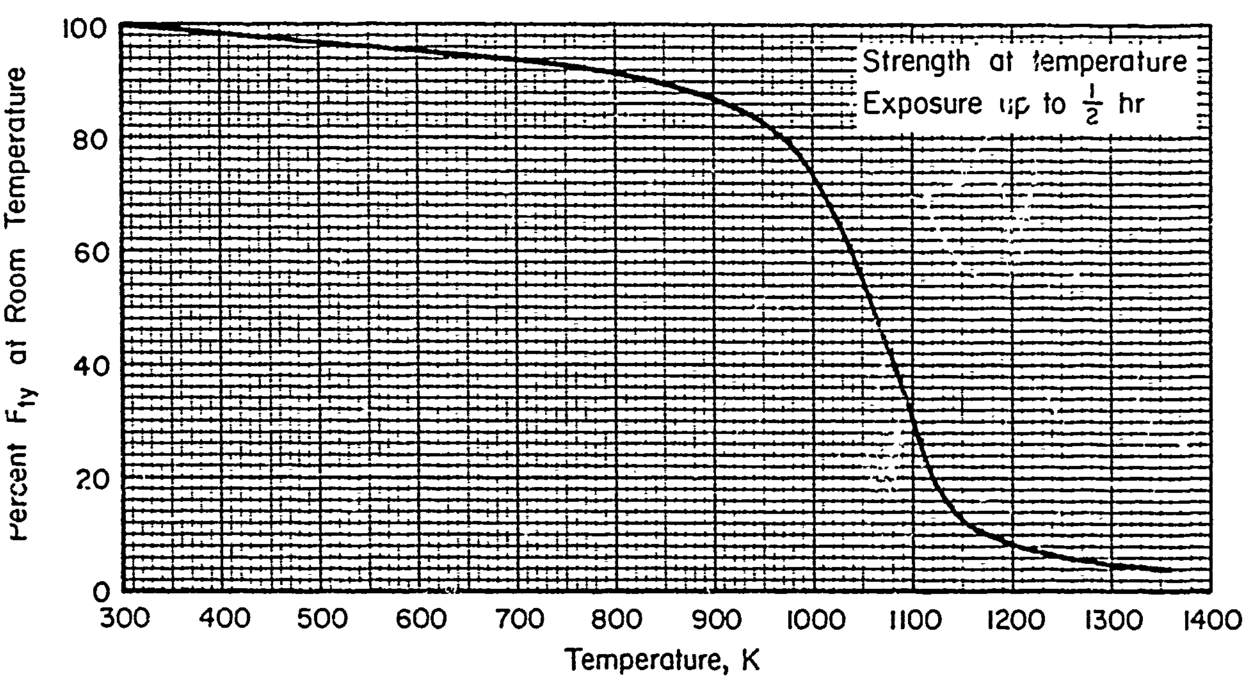


FIGURE 6.2.3.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of W-545 alloy.

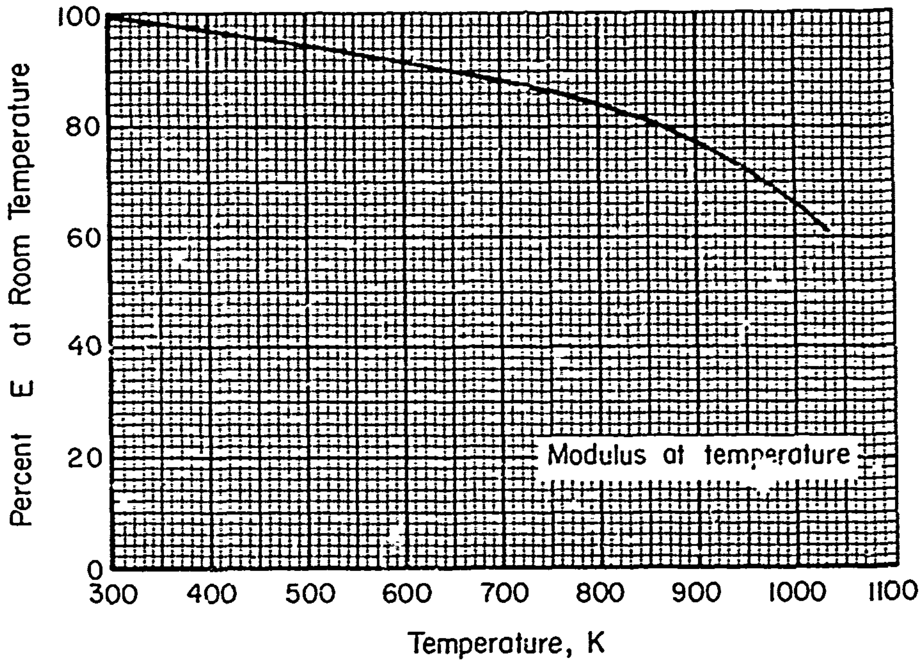


FIGURE 6.2.3.1.4(a). Effect of temperature on the tensile modulus (E) of W-545 alloy.

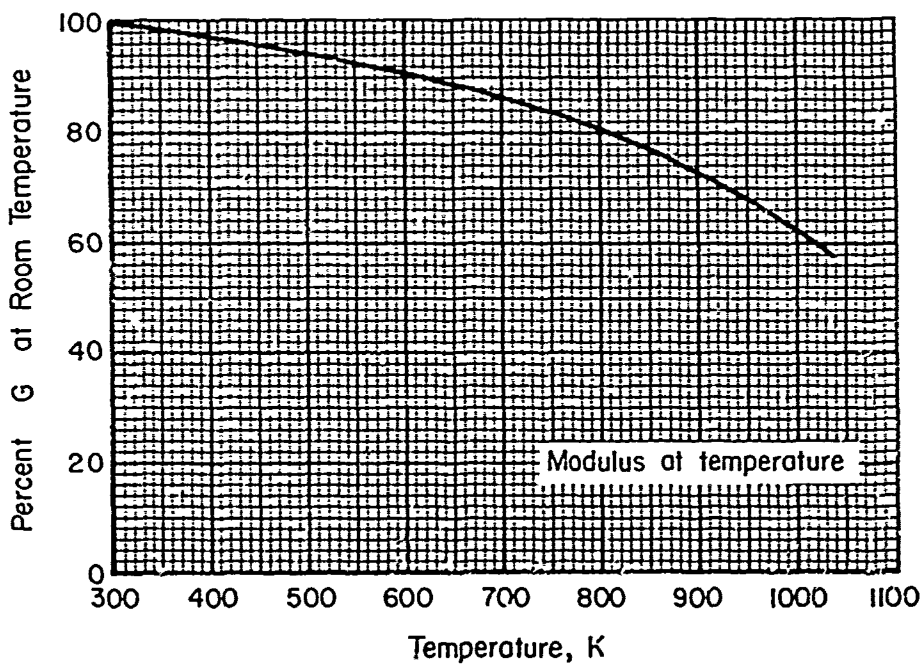


FIGURE 6.2.3.1.4(b). Effect of temperature on the shear modulus (G) of W-545 alloy.

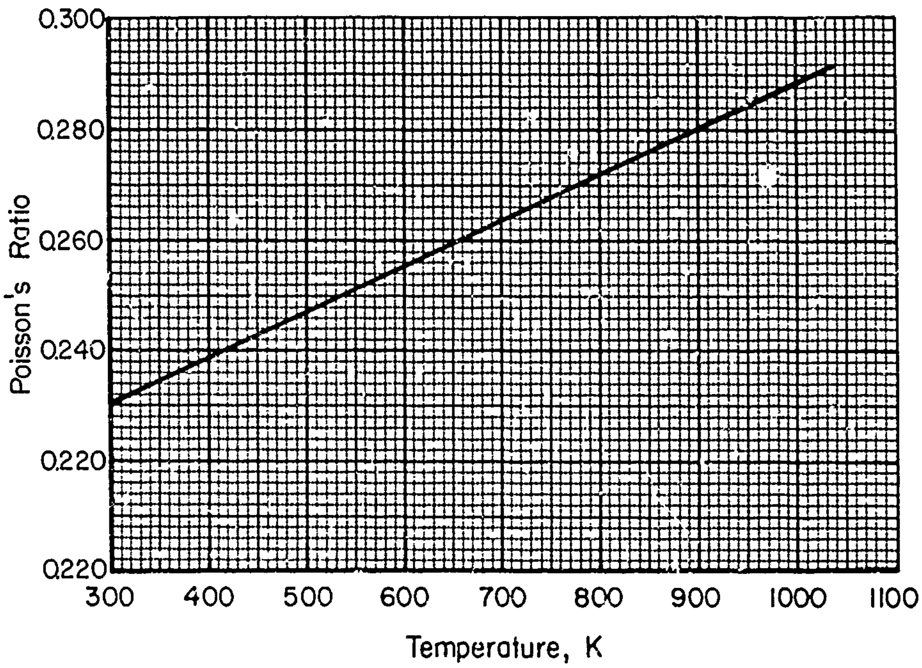


FIGURE 6.2.3.1.4(c). Effect of temperature on Poisson's ratio (μ) for W-545 alloy.

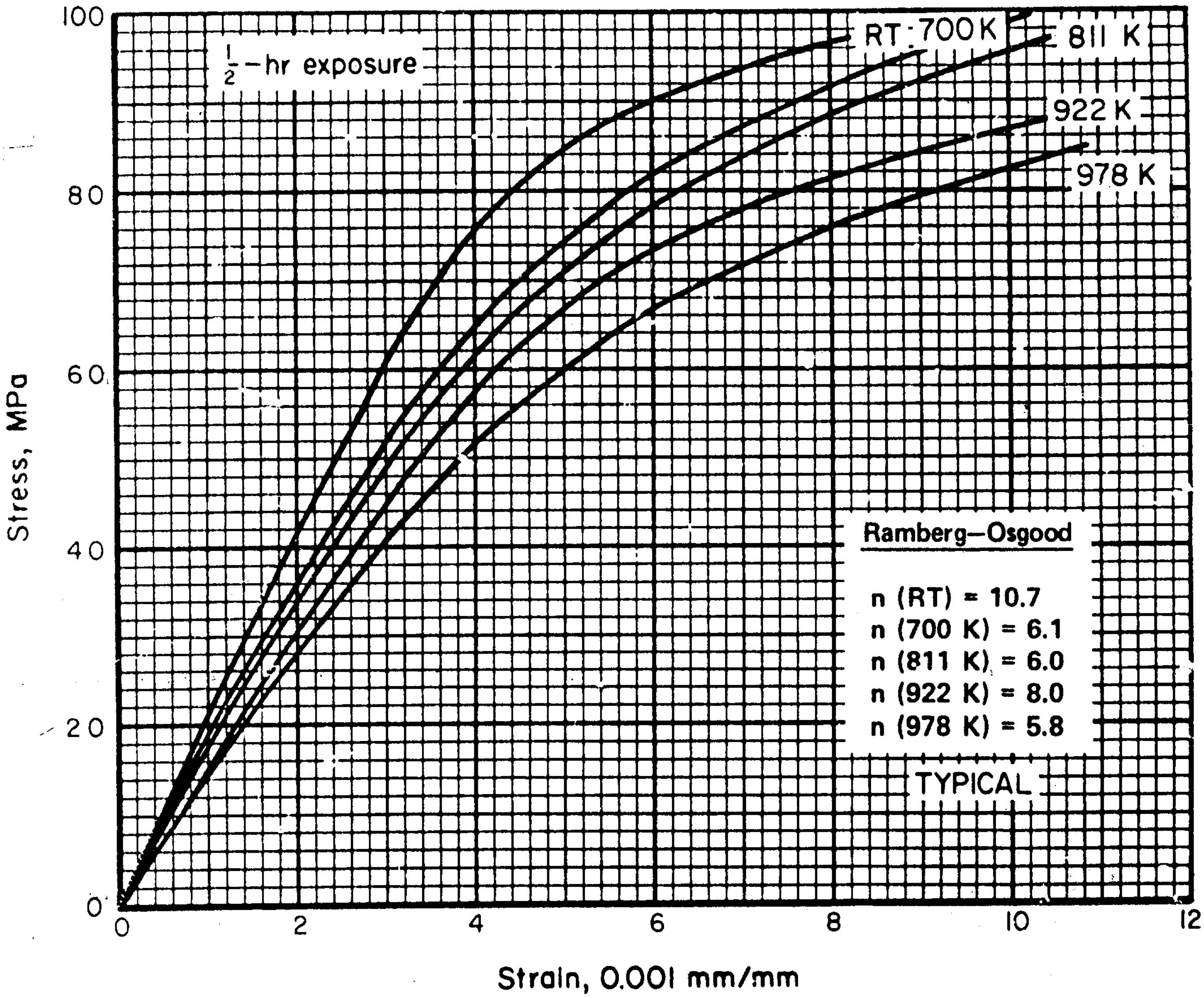


FIGURE 6.2.3.1.6. Typical tensile stress-strain curves at room and elevated temperatures for W-545 alloy.

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 much 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 275 K 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, 922 to 1033 K (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 weld and/or 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 speaking, it is desirable to braze annealed (stress-free) material to avoid embrittlement. As with the stainless steels, dry hydrogen, argon, or helium atmospheres (211 Kdew 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 1/2 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 palladium-base brazing alloys may be useful under some circumstances in intermediate-temperature applications.

6.3.1 HASTELLOY B

6.3.1.0 *Comments and Properties.*—Hastelloy B is a corrosion-resistant nickel-base alloy that has found application in the gas-turbine engine and in high-temperature bolting and shafting because of its good high-temperature properties. It is not hardenable by heat treatment and is used in the hot-rolled and annealed condition. Hastelloy B is available in the usual mill forms.

Hastelloy B is somewhat more difficult to hot work than austenitic stainless steels; its hot-working range is 1478 to 1311 K. It is preferably formed cold and requires frequent anneals. It is somewhat more difficult to machine than the austenic stainless steels because of its work-hardening capacity. Hastelloy B can be welded in the same manner as the austenitic stainless steels, but oxyacetylene welding is not recommended for corrosion applications.

Hastelloy B is resistant to both oxidizing and reducing atmospheres up to 1033K.

Two ASTM specifications are available for this alloy in its wrought form, and these are presented in Table 6.3.1.0(a). No aeronautical specifications are presently available for this alloy.

TABLE 6.3.1.0(a). *Materials Specifications for Hastelloy B*

Specification	Form	Condition
ASTM B333	Sheet and plate	Hot-rolled and annealed
ASTM B335	Rod	Hot-rolled and annealed

Room-Temperature Properties

Room-temperature mechanical and physical properties for this alloy are presented in Table 6.3.1.0(b). The tensile properties are ASTM specification minimums and the physical properties were taken from the literature. Figure 6.3.1.0 shows the effect of temperature on the physical properties of Hastelloy B.

6.3.1.1 *Annealed Condition.*—Elevated temperature properties for this alloy are presented in Figures 6.3.1.1.1(a) through 6.3.1.1.4.

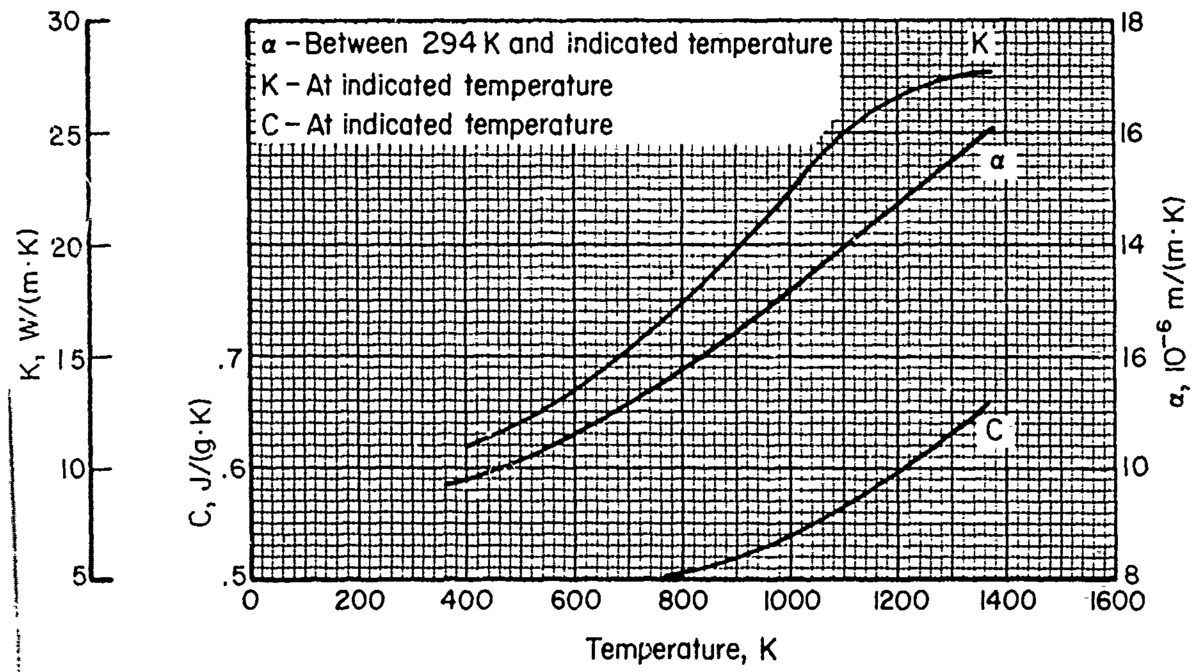


FIGURE 6.3.1.0. Effect of temperature on the physical properties of Hastelloy B.

TABLE 6.3.1.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF HASTELLOY B

SPECIFICATION	ASTM B333			ASTM B335	
FORM	SHEET	PLATE		ROD	
CONDITION	ANNEALED				
THICKNESS, MM	≤4.76	4.77–19.06	19.07–63.50	7.92–38.11	38.12–88.90
BASIS	S[a]	S[a]	S[a]	S	S
MECHANICAL PROPERTIES:					
FTU, MPA:					
L	793	689	621	793	689
LT	...	...	...	...	...
FTY, MPA:					
L	345	310	310	317	317
LT	...	...	...	...	...
FCY, MPA:					
L	...	...	...	...	...
LT	...	...	...	...	...
FSU, MPA	...	...	...	...	...
FBRU, MPA:					
(E/D=1.5)	...	...	...	...	...
(E/D=2.0)	...	...	...	...	...
FBRY, MPA:					
(E/D=1.5)	...	...	...	...	...
(E/D=2.0)	...	...	...	...	...
EL, PERCENT:					
L	45	40	35	35	30
LT	...	...	...	...	...
E, GPA	212.4				
EC, GPA	...				
G, GPA	...				
MU	...				
PHYSICAL PROPERTIES:					
OMEGA, MG/M3	9.25				
C, J/(G*K)	SEE FIGURE 6.3.1.0				
K, W/(M*K)	SEE FIGURE 6.3.1.0				
ALPHA, 10-6 M/(M*K)	SEE FIGURE 6.3.1.0				

[a] GRAIN DIRECTION NOT SPECIFIED.

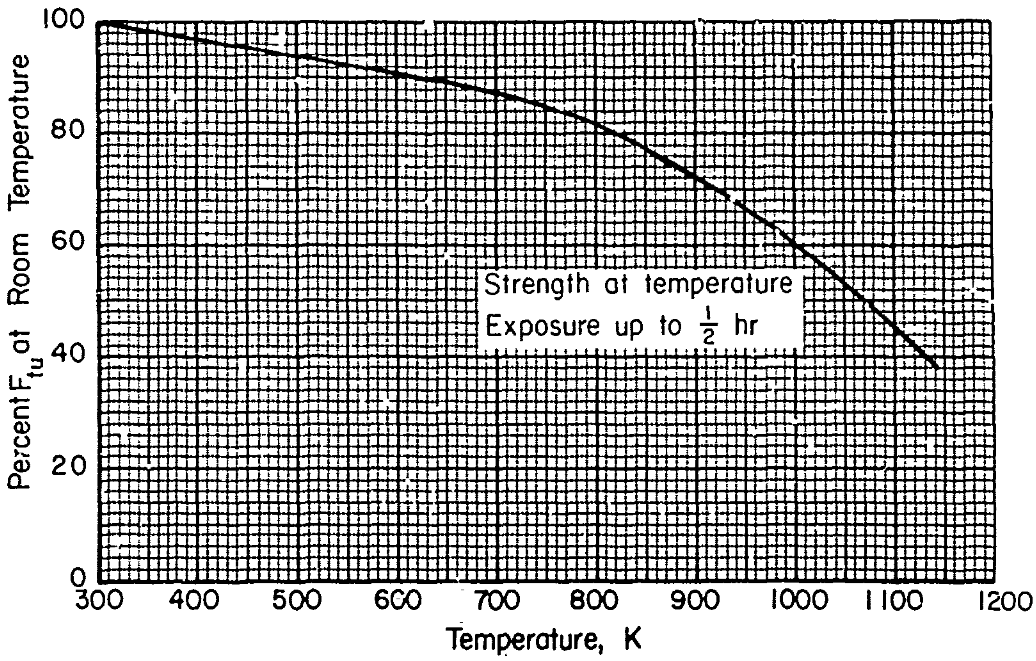


FIGURE 6.3.1.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of Hastelloy B.

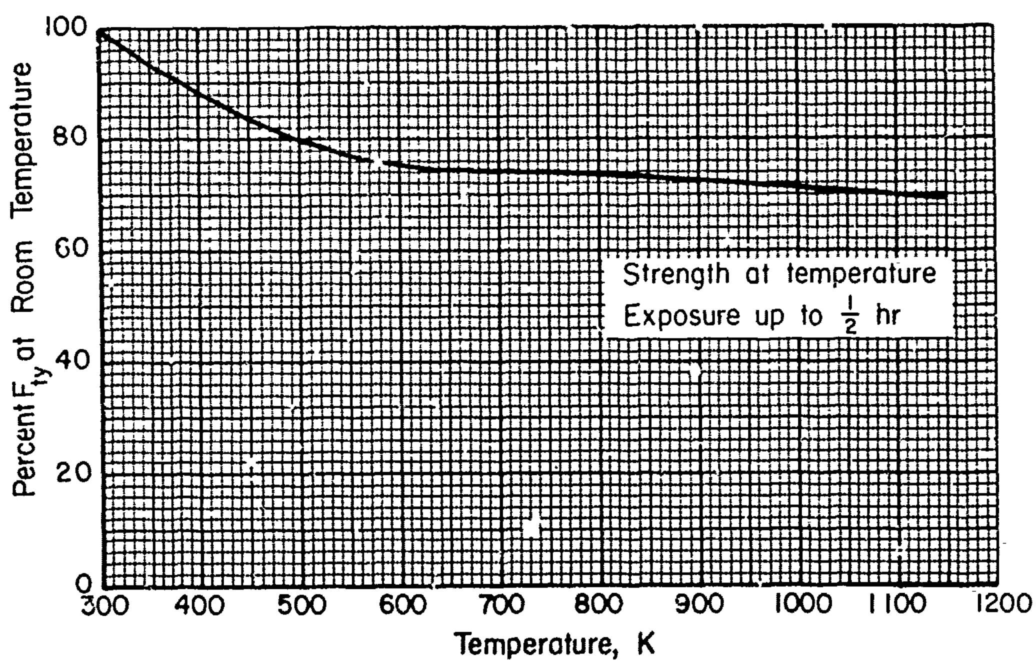


FIGURE 6.3.1.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of Hastelloy B.

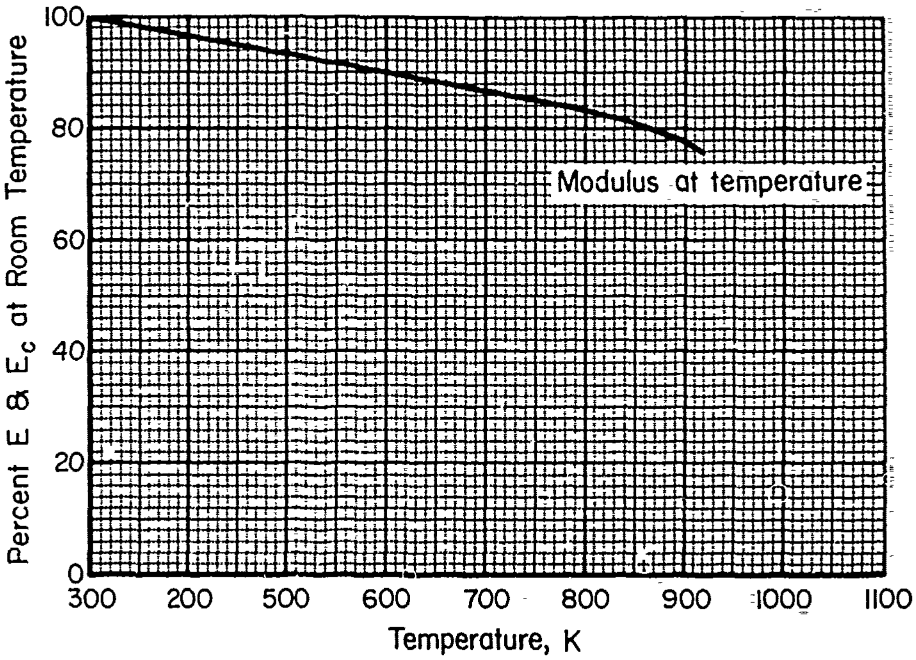


FIGURE 6.3.1.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of Hastelloy B.

6.3.2 HASTELLOY X

6.3.2.0 *Comments and Properties.*—Hastelloy X is a nickel-base alloy used for burner-liner parts, turbine-exhaust weldments, afterburner parts, and other parts requiring oxidation resistance and moderately high strength above 1061 K. 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 1450 to 1478 K 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 1450 K 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 1144 K for 1 hour.

Hastelloy X has good oxidation resistance up to 1422 K. It age hardens somewhat during long exposure between 922 and 1255 K, but this is not a serious problem.

Some material specifications for Hastelloy X are presented in Table 6.3.2.0(a).

TABLE 6.3.2.0(a). *Material Specifications for Hastelloy X*

Specification	Form	Condition
AMS 5536	Sheet and plate	Solution heat treated (annealed)
AMS 5754	Bars and forgings	Solution heat treated (annealed)

Room-Temperature Properties

Room-temperature mechanical and physical properties for Hastelloy X sheet are presented in Table 6.3.2.0(b). AMS 5754 does not specify tensile properties for bars and forgings. Figure 6.3.2.0 shows the effect of temperature on physical properties.

6.3.2.1 *Annealed Condition.*—The effect of temperature on various mechanical properties is presented in Figures 6.3.2.1.1(a) through 6.3.2.1.4. These properties are based primarily on data for sheet, but are satisfactory for application to bars and forgings. In addition, certain stress-rupture requirements at 1089 K are specified in AMS 5536 and 5754 for Hastelloy X.

Typical tensile stress-strain curves at room and elevated temperatures are presented in Figure 6.3.2.1.6(a). Typical compressive stress-strain and tangent-modulus curves at room and elevated temperatures are presented in Figure 6.3.2.1.6(b).

TABLE 6.3.2.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF HASTELLOY X

SPECIFICATION	AMS 5536						
FORM	SHEET[a] AND PLATE[a]						
CONDITION	SOLUTION TREATED (ANNEALED)						
THICKNESS, MM	<0.25	0.25-0.49	0.50-2.55		2.56-4.76	4.77-50.80	>50.80
BASIS	S	S	A	B	S	S	S
MECHANICAL PROPERTIES:							
FTU, MPA:							
L	...	...	...	...	...	...	...
LT	724	724	703	731	724	689	655
FTY, MPA:							
L	...	...	...	...	...	...	...
LT	310	310	303	324	310	276	276
FCY, MPA:							
L	...	...	...	...	...	...	...
LT	...	...	...	...	...	...	...
FSU, MPA	...	...	...	...	...	...	...
FBRU, MPA:							
(E/D=1.5)	...	...	...	...	...	...	...
(E/D=2.0)	...	...	...	...	...	...	...
FBRY, MPA:							
(E/D=1.5)	...	...	...	...	...	...	...
(E/D=2.0)	...	...	...	...	...	...	...
EL, PERCENT:							
L	...	...	...	...	...	...	...
LT	...	29	35	...	35	35	35
E, GPA	200.0						
EC, GPA	200.0						
G, GPA	75.8						
MU	0.32						
PHYSICAL PROPERTIES:							
OMEGA, MG/M3	8.22						
C, J/(G*K)	SEE FIGURE 6.3.2.0						
K, W/(M*K)	SEE FIGURE 6.3.2.0						
ALPHA, 10-6 M/(M*K)	SEE FIGURE 6.3.2.0						

[a] TEST DIRECTION LONGITUDINAL FOR WIDTHS LESS THAN 229 MM; TRANSVERSE FOR WIDTHS 229 MM AND OVER.

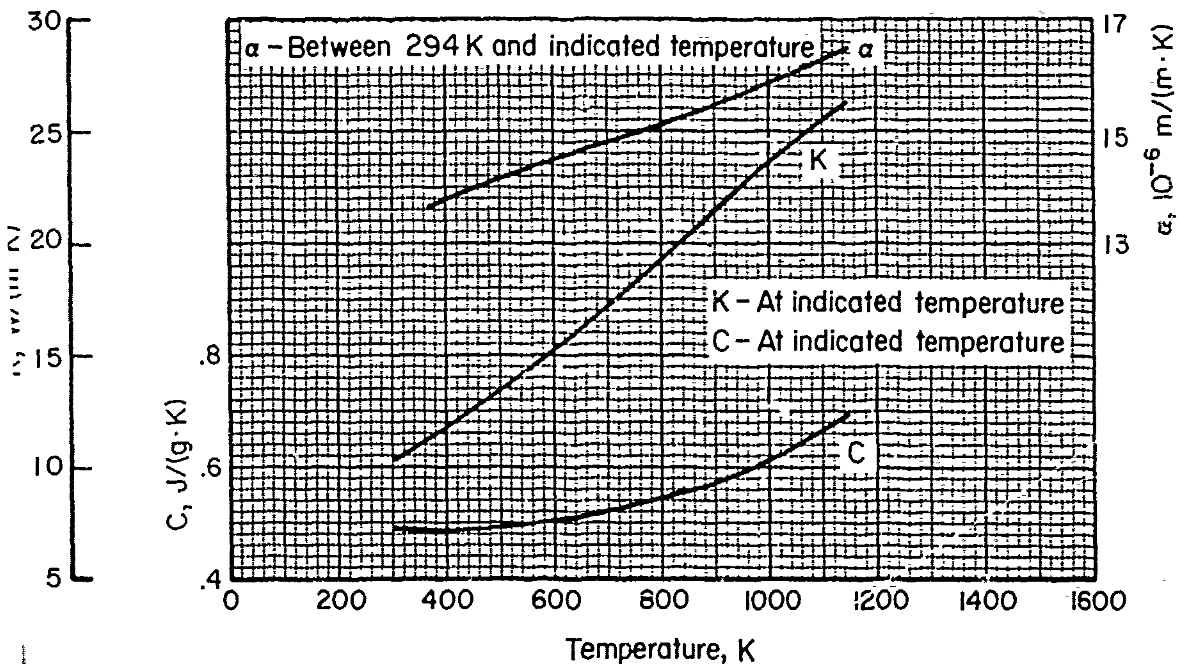


FIGURE 6.3.2.0. Effect of temperature on the physical properties of Hastelloy X.

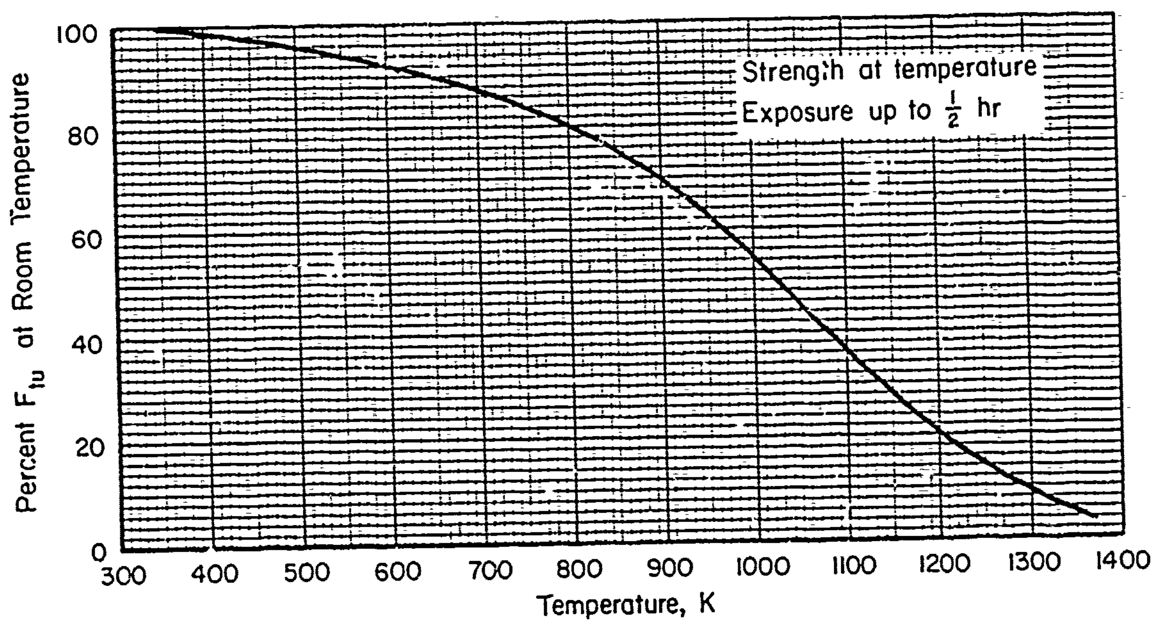


FIGURE 6.3.2.1.1(a). Effect of temperature on ultimate tensile strength (F_{tu}) of Hastelloy X.

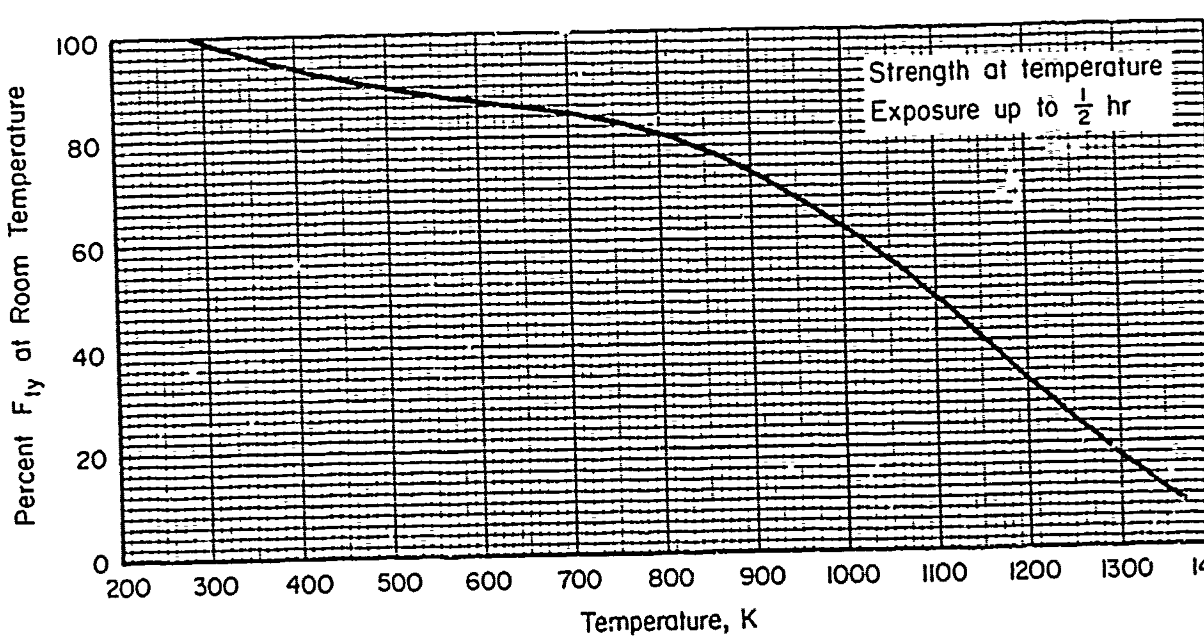


FIGURE 6.3.2.1.1(b). Effect of temperature on tensile yield strength (F_{ty}) of Hastell

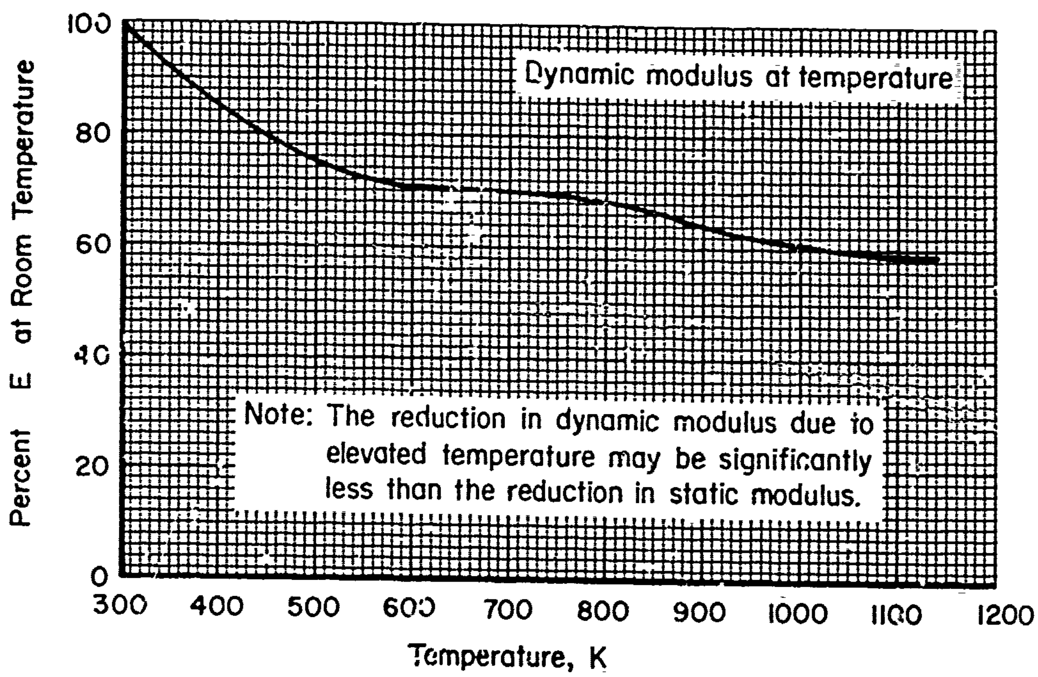


FIGURE 6.3.2.1.4. Effect of temperature on dynamic modulus (E) of Hastelloy X (sheet).

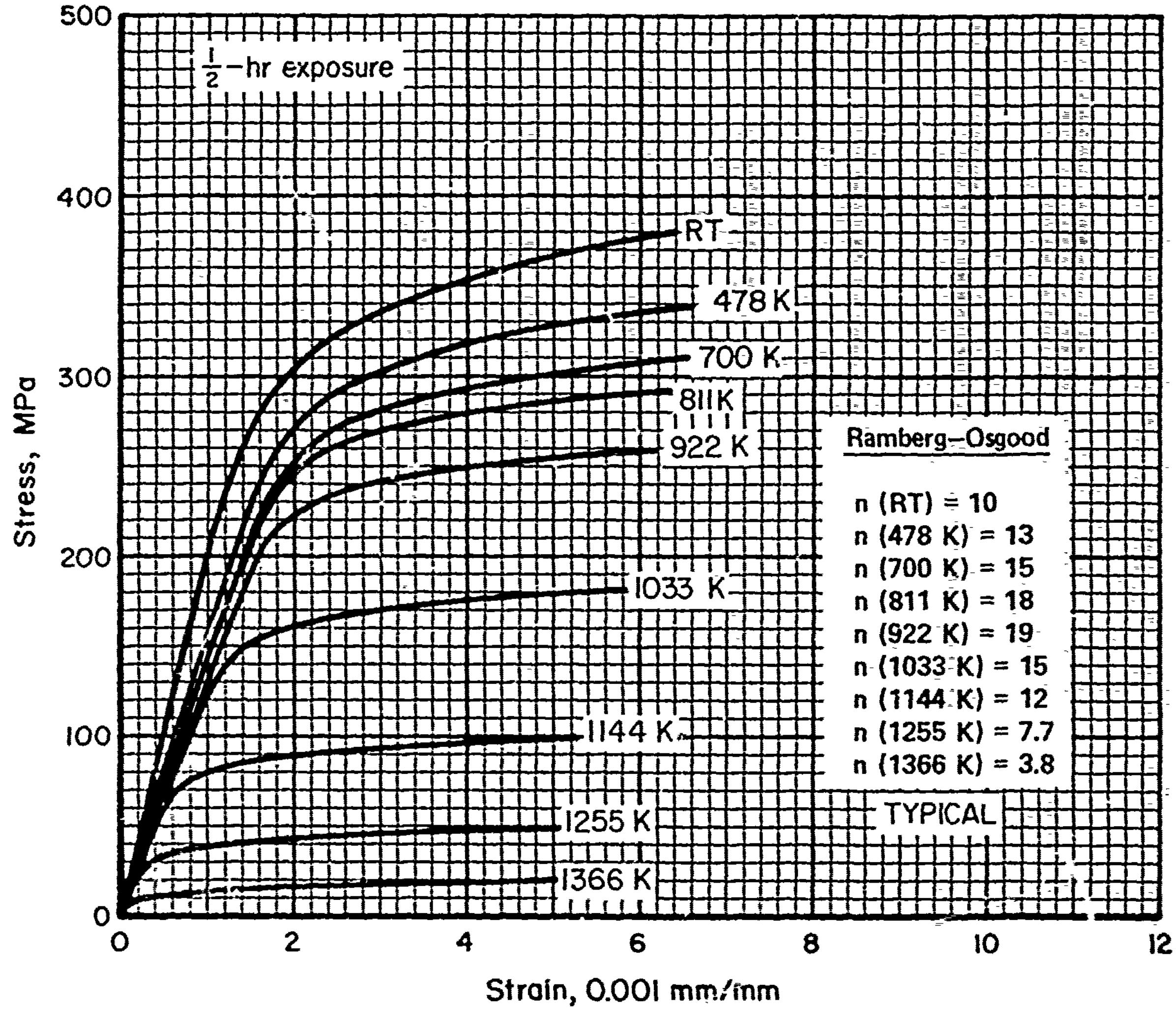
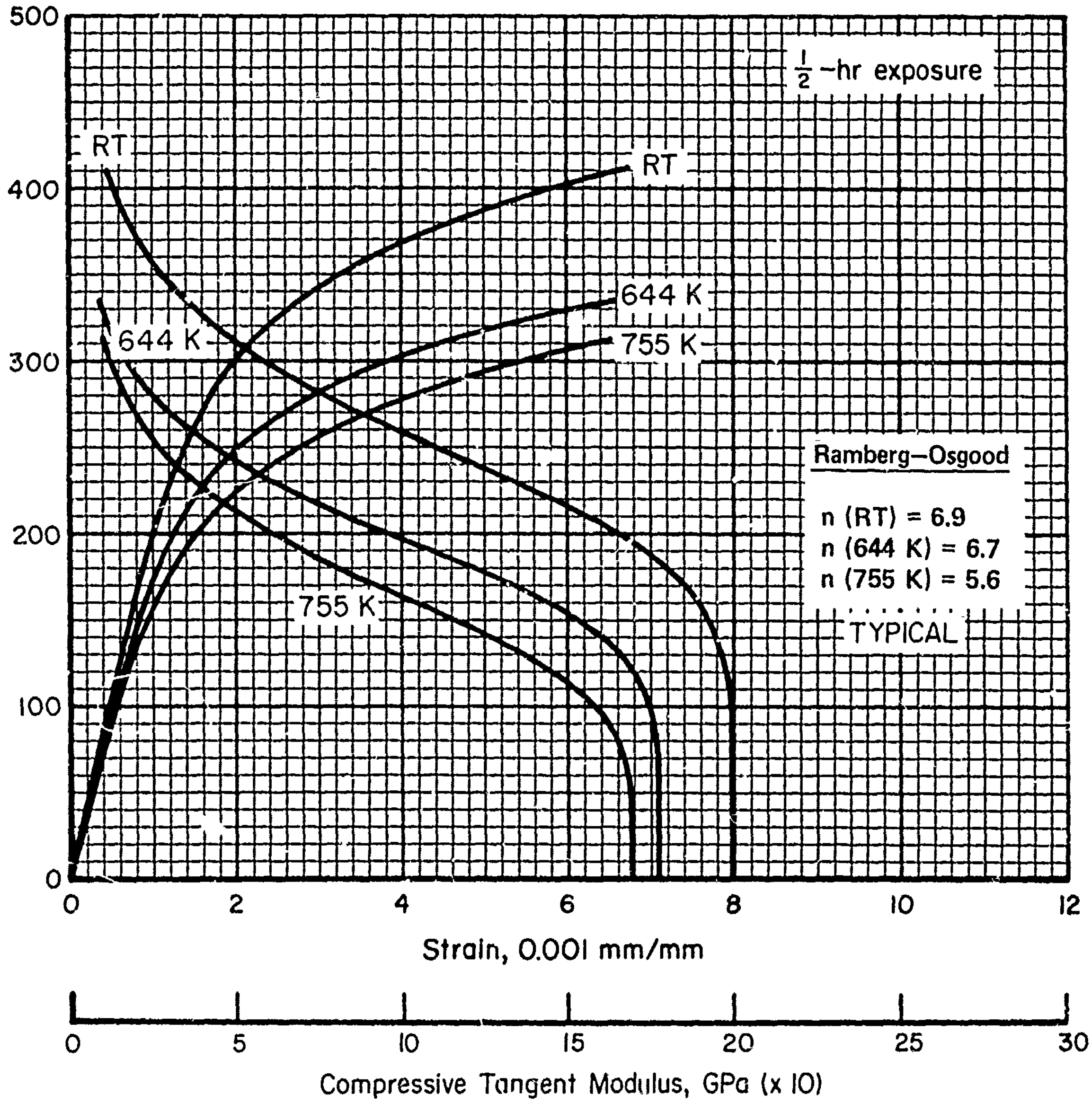


FIGURE 6.3.2.1.6(a). Typical tensile stress-strain curves for Hastelloy X (sheet) at room and elevated temperatures.



IGURE 6.3.2.1.6(b). Typical compressive stress-strain and tangent-modulus curves for Hastelloy X (bar) at room and elevated temperatures.

6.3.3 INCONEL ALLOY 600

6.3.3.0 *Comments and Properties.*—Inconel Alloy 600 is a corrosion- and heat-resistant nickel-base alloy used for low-stressed parts operating up to 1366 K. It is not hardenable except by cold working and is usually used in the annealed condition. Inconel is available in all the usual mill forms.

Inconel Alloy 600 is readily forged between 1505 and 1311 K; "hot-cold" working between 1144 and 922 K is harmful and should be avoided; cold working below 922 K results in improved properties. This alloy is readily formed but should be annealed after severe forming operations. The maximum annealing temperature is 1255 K if minimum yield-strength requirements are to be met consistently. Inconel Alloy 600 is susceptible to rapid grain growth at 1255 K or higher, and exposures at these temperatures are necessarily brief if large grain size is objectionable.

Inconel Alloy 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; large or complex fusion weldments should be stress relieved at 1144 K for 1 hour.

Oxidation resistance of Inconel Alloy 600 is excellent up to 1366 K in sulfur-free atmospheres. This alloy is subject to attack in sulfur-containing atmospheres.

Some material specifications for Inconel Alloy 600 are presented in Table 6.3.3.0(a).

TABLE 6.3.3.0(a). *Material Specifications for Inconel Alloy 600*

Specification	Form	Condition
MIL-N-6840	Plate, sheet, and strip	Annealed
MIL-N-6710	Bars, rods, and forgings	Various
MIL-T-7840	Tubing, seamless, and welded	Annealed

Room-Temperature Properties

Room-temperature mechanical and physical properties are shown in Tables 6.3.3.0(b), (c), and (d). Figure 6.3.3.0 shows the effect of temperature on the physical properties.

6.3.3.1 *Annealed Condition.*—Elevated-temperature data for this condition are shown in Figures 6.3.3.1.1(a) through 6.3.3.1.4.

TABLE 6.3.3.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF INCONEL ALLOY 600

SPECIFICATION	MIL-N-6840		MIL-T-7840	MIL-N-6710	
FORM	SHEET AND STRIP	PLATE	TUBING	FORGINGS	
CONDITION	ANNEALED			AS FORGED	ANNEALED
THICKNESS, MM	0.51-4.76	≥4.77	...	...	...
BASIS	S[a]	S[a]	S[a]	S[a]	S[a]
MECHANICAL PROPERTIES:					
FTU, MPA:					
L	552	552	552	586	586
LT	...	...	...	...	...
FTY, MPA:					
L	207	207	207	241	207
LT	...	...	...	...	...
FCY, MPA:					
L	207	207	207	...	...
LT	...	...	...	...	...
FSU, MPA	352	352	352	...	...
FBRU, MPA:					
(E/D=1.5)	...	...	...	...	...
(E/D=2.0)	1050	1050	1050	...	...
FBRY, MPA:					
(E/D=1.5)	...	...	...	...	...
(E/D=2.0)	...	...	...	...	...
EL, PERCENT:					
L	40	35	35	30	35
LT	...	...	...	...	...
E, GPA	213.7				
EC, GPA	213.7				
G, GPA	75.8				
MU	...				
PHYSICAL PROPERTIES:					
OMEGA, MG/M3	8.50				
C, J/(G*K)	SEE FIGURE 6.3.3.0				
K, W/(M*K)	SEE FIGURE 6.3.3.0				
ALPHA, 10-6 M/(M*K)	SEE FIGURE 6.3.3.0				

[a]GRAIN DIRECTION NOT SPECIFIED.

TABLE 6.3.3.0(C). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF INCONEL 600 (BARS AND RODS)

SPECIFICATION............	MIL-N-6710				
FORM.....................	ROUNDS			SQUARES, FLATS HEXAGONS	
CONDITION................	COLD - DRAWN				
THICKNESS, MM............	6.35-12.68	12.69-25.41	25.42-63.50	≤6.36	6.37-11.10
BASIS....................	S	S	S	S	S
MECHANICAL PROPERTIES:					
FTU, MPA:					
L................	827	758	724	689	655
LT...............	...	...	...	...	...
FTY, MPA:					
L................	621	586	552	552	483
LT...............	...	...	...	...	...
FCY, MPA:					
L................	...	...	...	...	...
LT...............	...	...	...	...	...
FSU, MPA.............	...	...	...	...	...
FBRU, MPA:					
(E/D=1.5).........	...	...	...	...	...
(E/D=2.0).........	...	...	...	...	...
FBRY, MPA:					
(E/D=1.5).........	...	...	...	...	...
(E/D=2.0).........	...	...	...	...	...
EL, PERCENT:					
L................	7	10	12	5	7
LT...............	...	...	...	...	...
E, GPA...............	213.7				
EC, GPA..............	213.7				
G, GPA...............	75.8				
MU...................	...				
PHYSICAL PROPERTIES:					
OMEGA, MG/M3.........	8.50				
C, J/(G*K)...........	SEE FIGURE 6.3.3.0				
K, W/(M*K)...........	SEE FIGURE 6.3.3.0				
ALPHA, 10-6 M/(M*K)..	SEE FIGURE 6.3.3.0				

TABLE 6.3.3.0(D). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF INCONEL ALLOY 600

SPECIFICATION............	MIL-N-6710				
FORM.....................	ROUNDS			SQUARES, FLATS HEXAGONS,	BARS, RODS, FORGINGS
CONDITION................	HOT ROLLED				ANNEALED
THICKNESS, MM............	6.35-12.71	12.72-76.21	76.22-114.30	ALL	ALL
BASIS....................	S[a]	S[a]	S[a]	S[a]	S[a]
MECHANICAL PROPERTIES:					
FTU, MPA:					
L................	655	621	586	586	552
LT...............	...	...	...	...	...
FTY, MPA:					
L................	310	276	241	241	207
LT...............	...	...	...	...	...
FCY, MPA:					
L................	...	...	...	...	207
LT...............	...	...	...	...	...
FSU, MPA.............	...	...	...	...	352
FBRU, MPA:					
(E/D=1.5)..........	...	...	...	...	...
(E/D=2.0)..........	...	...	...	...	1050
FBRY, MPA:					
(E/D=1.5)..........	...	...	...	...	...
(E/D=2.0)..........	...	...	...	...	...
EL, PERCENT:					
L................	30	30	30	30	35
LT...............	...	...	...	...	...
E, GPA...............	213.7				
EC, GPA..............	213.7				
G, GPA...............	75.8				
MU...................	...				
PHYSICAL PROPERTIES:					
OMEGA, MG/M3..........	8.50				
C, J/(G*K)............	SEE FIGURE 6.3.3.0				
K, W/(M*K)............	SEE FIGURE 6.3.3.0				
ALPHA, 10-6 M/(M*K)..	SEE FIGURE 6.3.3.0				

[a] GRAIN DIRECTION NOT SPECIFIED.

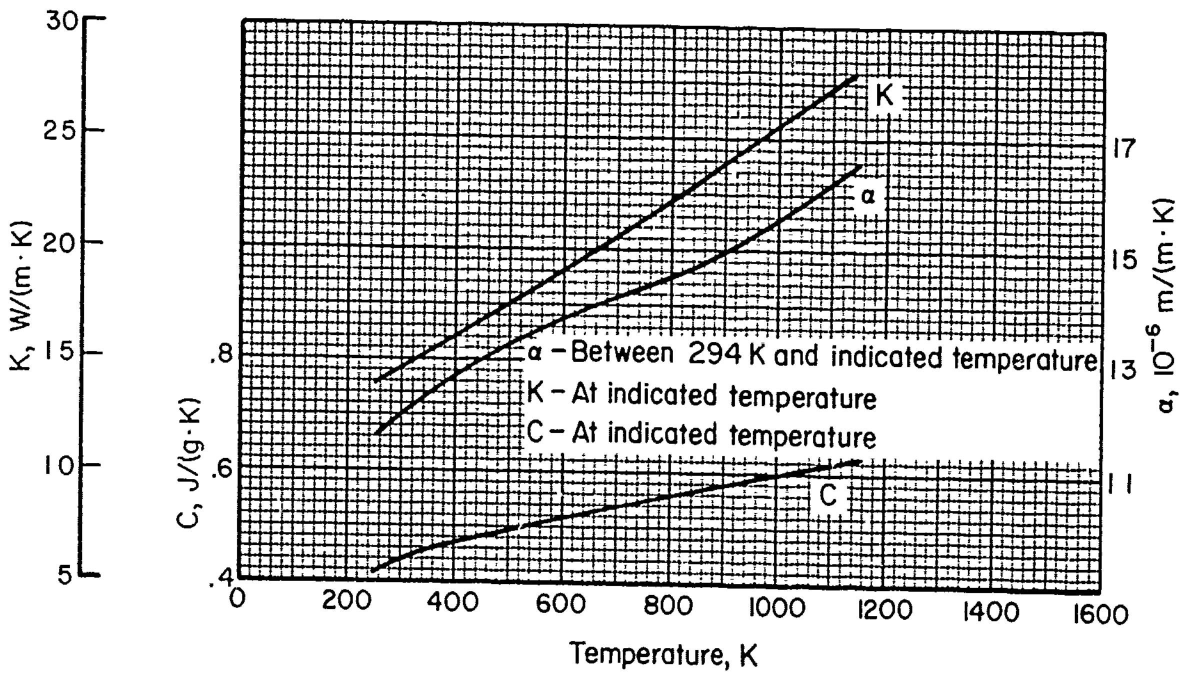


FIGURE 6.3.3.0. Effect of temperature on the physical properties of Inconel 600.

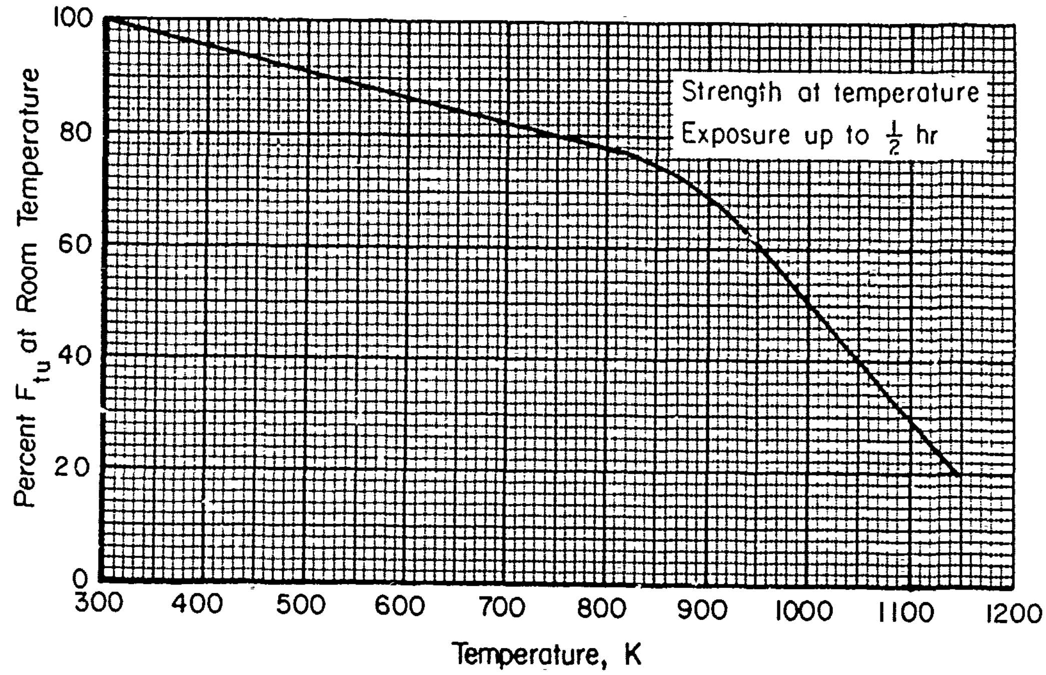


FIGURE 6.3.3.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of Inconel Alloy 600.

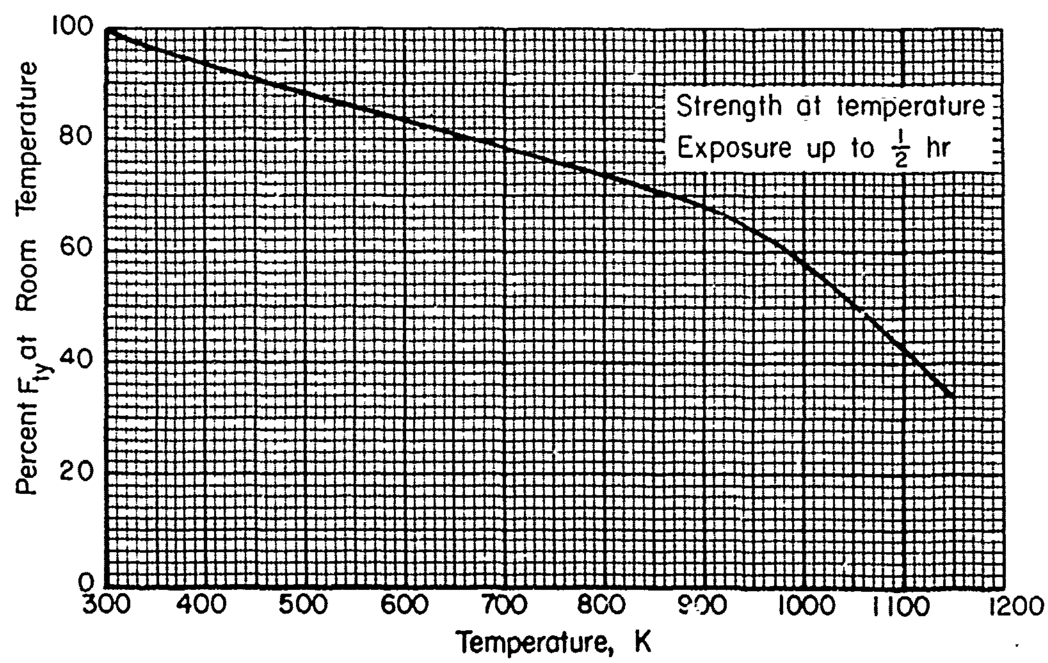


FIGURE 6.3.3.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of Inconel Alloy 600.

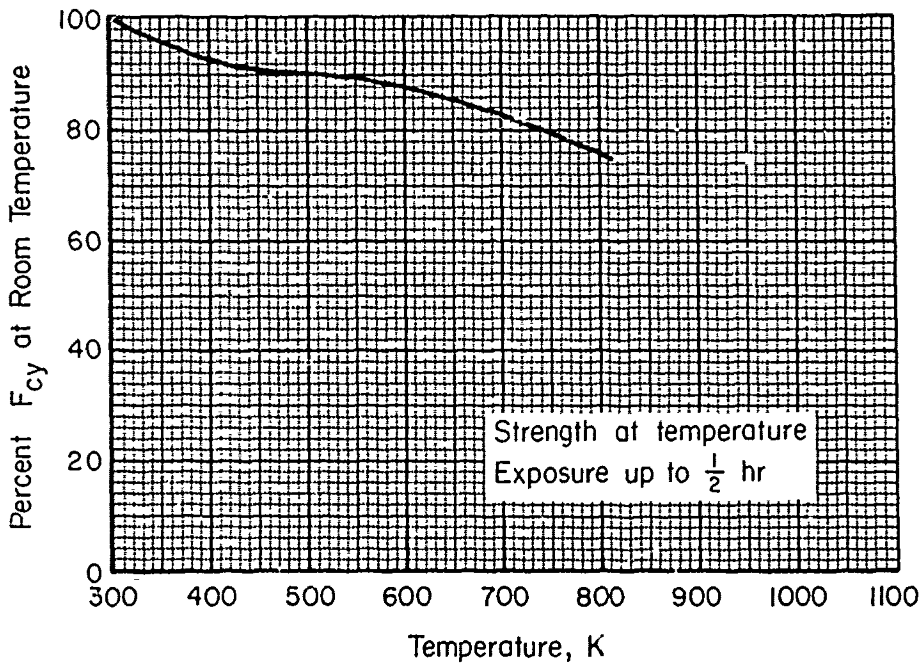


FIGURE 6.3.3.1.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of Inconel Alloy 600.

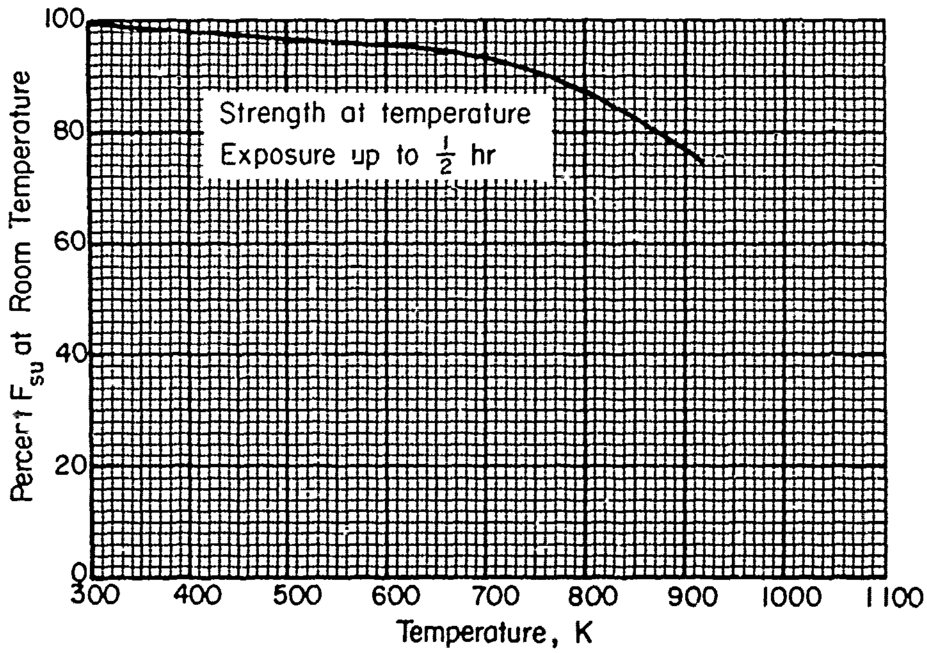


FIGURE 6.3.3.1.2(b). Effect of temperature on the ultimate shear strength (F_{su}) of Inconel Alloy 600.

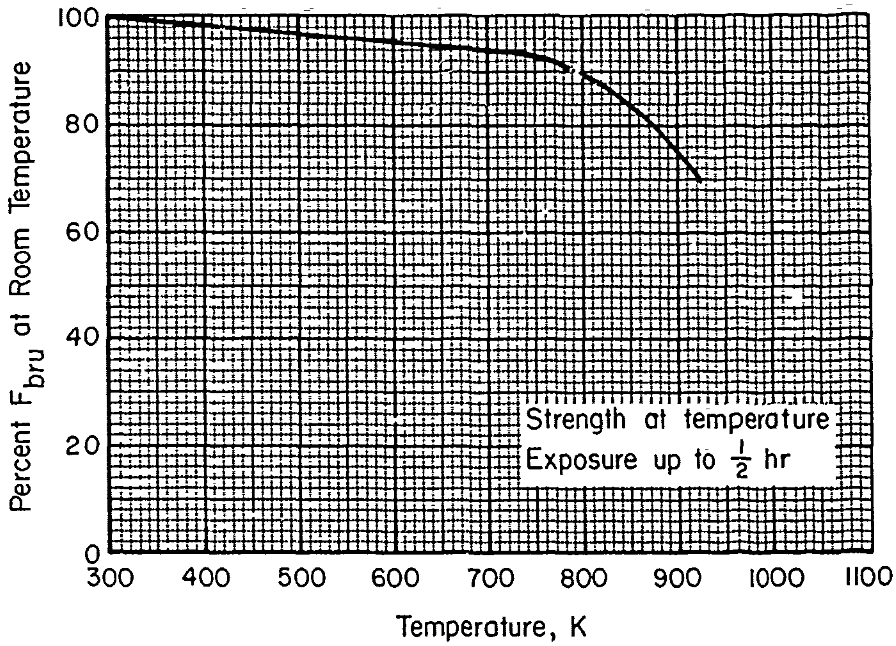
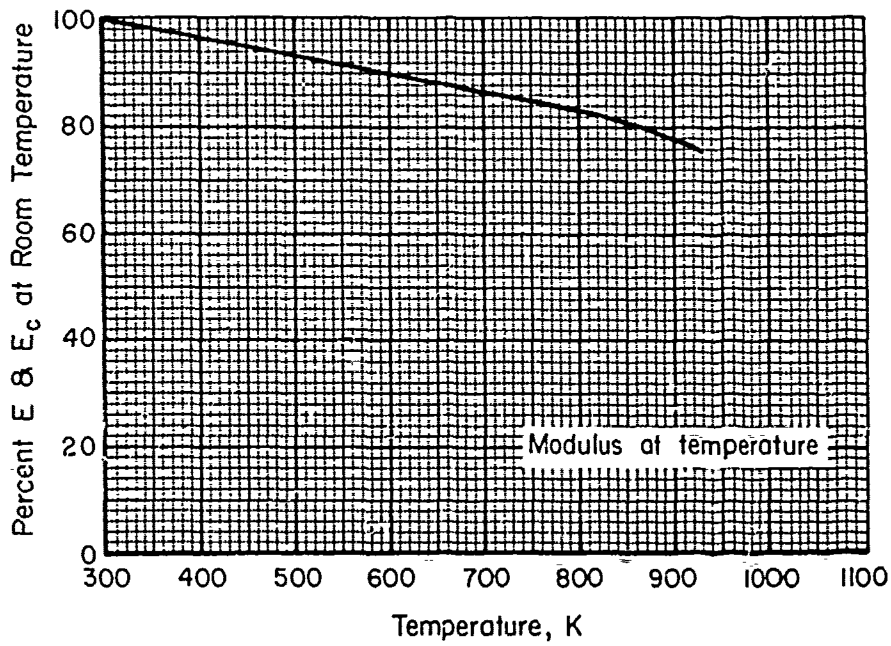


FIGURE 6.3.3.1.3(a). Effect of temperature on the ultimate bearing strength (F_{bru}) of Inconel Alloy 600.



IGURE 6.3.3.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of Inconel Alloy 600.

6.3.4 INCONEL ALLOY 625

6.3.4.0 *Comments and Properties.*—Inconel Alloy 625 is a solid-solution, matrix strengthened nickel-base alloy primarily for applications requiring good corrosion and oxidation resistance at temperatures up to approximately 1255 K 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 1200–1311K for times 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.

The material specifications for Inconel Alloy 625 are listed in Table 6.3.4.0(a).

TABLE 6.3.4.0(a). *Material Specifications for Inconel Alloy 625*

Specification	Form	Condition
AMS 5599	Sheet, strip, and plate	Annealed
AMS 5666	Bars, forgings, and rings	Annealed

Room-Temperature Properties

Room-temperature mechanical and physical properties for Inconel Alloy 625 are listed in Table 6.3.4.0(b). Figure 6.3.4.0 shows the effect of temperature on the physical properties.

6.3.4.1 *Annealed Condition.*—Effect-of-temperature curves for tensile ultimate strength, tensile yield strength, and tensile and compressive moduli are presented in Figures 6.3.4.1.1(a) through 6.3.4.1.4.

Typical tensile stress-strain curves are shown in Figures 6.3.4.1.6(a) and (c). Typical compressive stress-strain and tangent-modulus curves are presented in Figures 6.3.4.1.6(b) and (d).

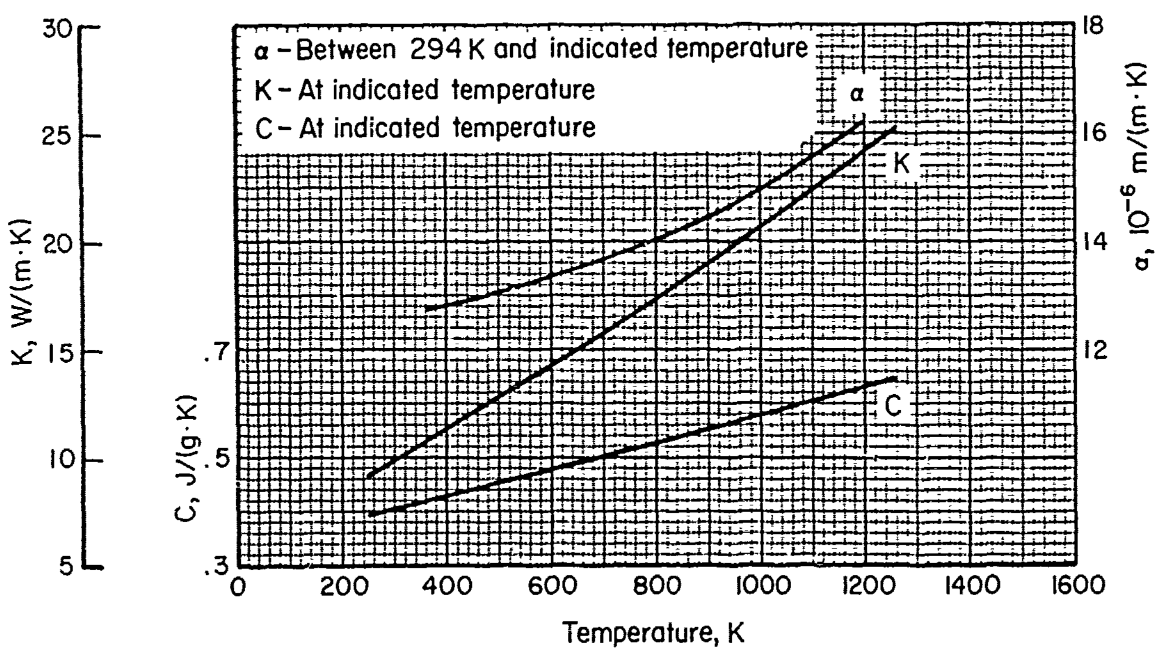


FIGURE 6.3.4.0. Effect of temperature on the physical properties of Inconel Alloy 625.

TABLE 6.3.4.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF INCONEL ALLOY 625

SPECIFICATION	AMS 5599[a]									AMS 5666
FORM	SHEET AND STRIP								PLATE	BARS, FORGINGS, RINGS
CONDITION	ANNEALED AT 1200 - 1311K									ANNEALED
THICKNESS, MM	<1.58		1.59-2.78		2.79-3.57		3.58-4.76		≥4.77	<101.60
BASIS	A	B	A	B	A	B	A	B	S	S[b]
MECHANICAL PROPERTIES:										
FTU, MPA:										
L	...	...	...	...	...	...	...	...	...	827
LT	827[c]	883	827[c]	876	827[c]	869	821	855	827	...
FTY, MPA:										
L	...	...	...	...	...	...	...	...	...	414
LT	393	434	386	427	379	421	372	414	414	...
FCY, MPA:										
L	...	...	...	...	...	...	...	...	...	...
LT	379	421	372	414	365	407	359	400	400	...
FSU, MPA	...	...	...	...	...	...	...	...	...	...
FBRU, MPA:										
(E/D=1.5)	...	...	...	...	...	...	...	...	...	...
(E/D=2.0)	...	...	...	...	...	...	...	...	...	...
FBRY, MPA:										
(E/D=1.5)	...	...	...	...	...	...	...	...	...	...
(E/D=2.0)	...	...	...	...	...	...	...	...	...	...
EL, PERCENT:										
L	...	...	...	...	...	...	...	...	...	30
LT	30	...	30	...	30	...	30	...	30	...
E, GPA	205.5									
EC, GPA	205.5									
G, GPA	81.4									
MU	0.28									
PHYSICAL PROPERTIES:										
OMEGA, MG/M3	8.44									
C, J/(G*K)	SEE FIGURE 6.3.4.0									
K, W/(M*K)	SEE FIGURE 6.3.4.0									
ALPHA, 10-6 M/(M*K)	SEE FIGURE 6.3.4.0									

[a] SEE SPECIFICATION FOR APPLICABLE ELEVATED TEMPERATURE REQUIREMENTS.
[b] GRAIN DIRECTION NOT SPECIFIED.
[c] THE A VALUES ARE HIGHER THAN SPECIFICATION VALUES AS FOLLOWS: FTU(≤1.58) = 848 MPA, FTU (1.59 - 2.78) = 841 MPA, FTU (2.79 - 3.57) = 834 MPA.

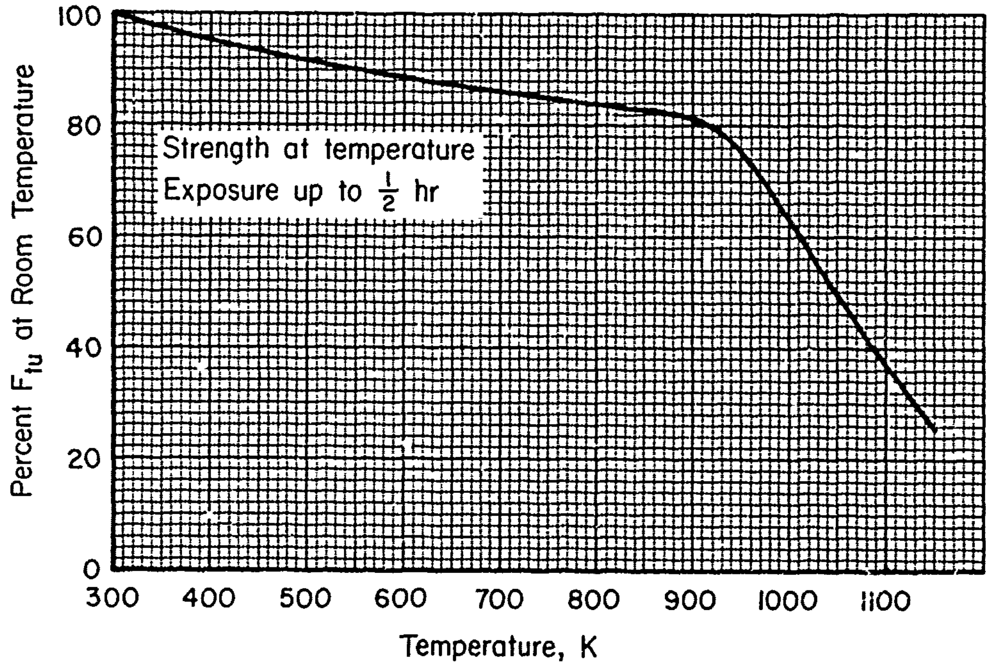


FIGURE 6.3.4.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of annealed Inconel Alloy 625 (sheet and bar).

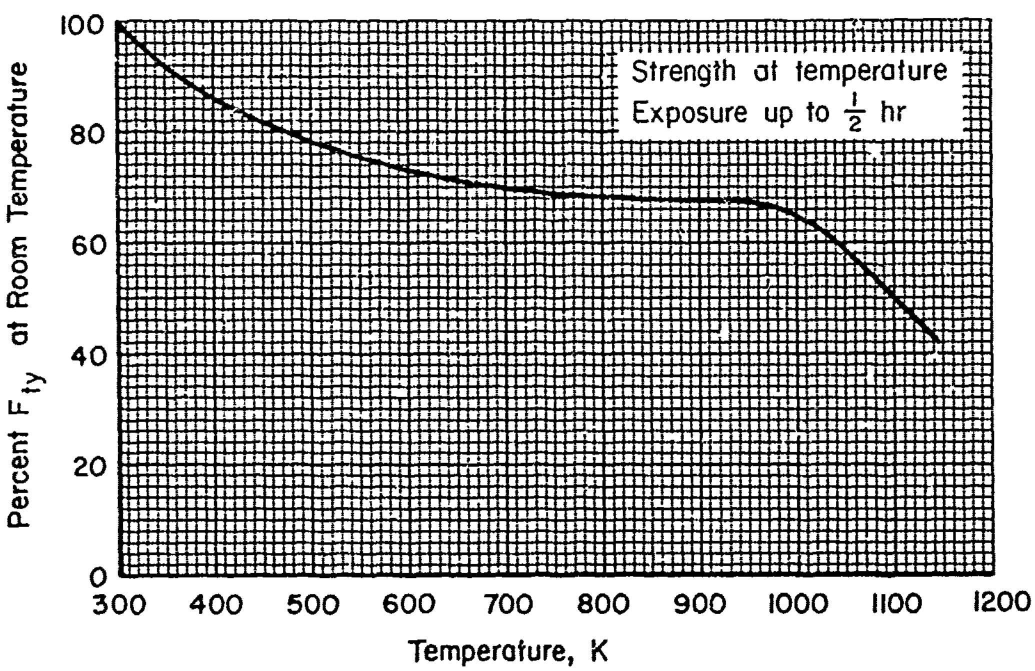


FIGURE 6.3.4.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of annealed Inconel Alloy 625 (sheet and bar).

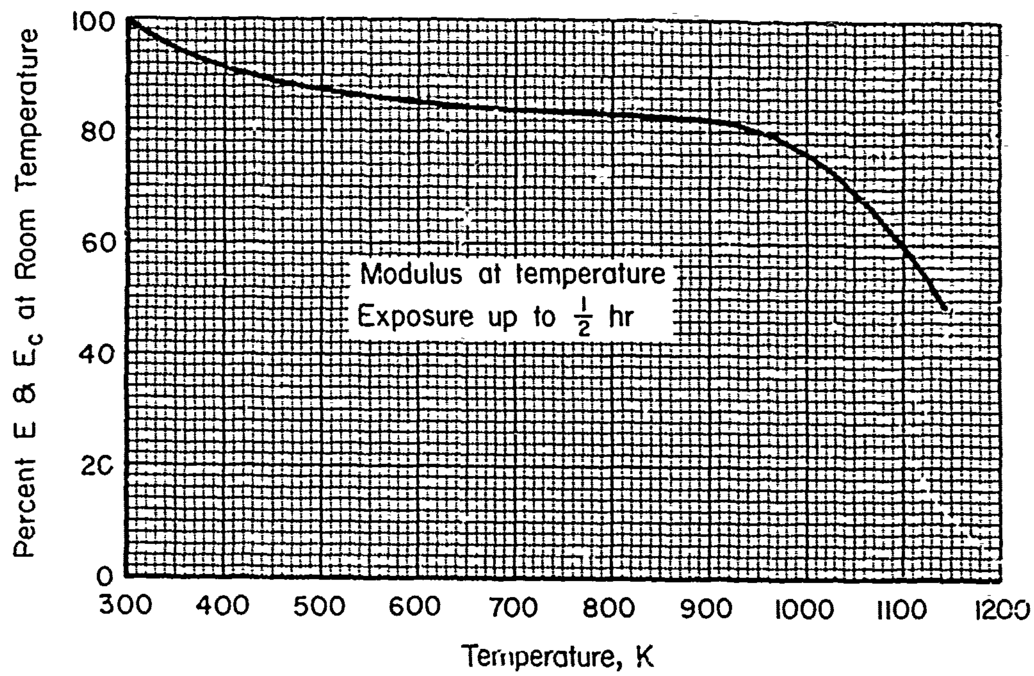


FIGURE 6.3.4.1.4 Effect of temperature on the tensile and compressive moduli (E and E_c) of Inconel Alloy 625.

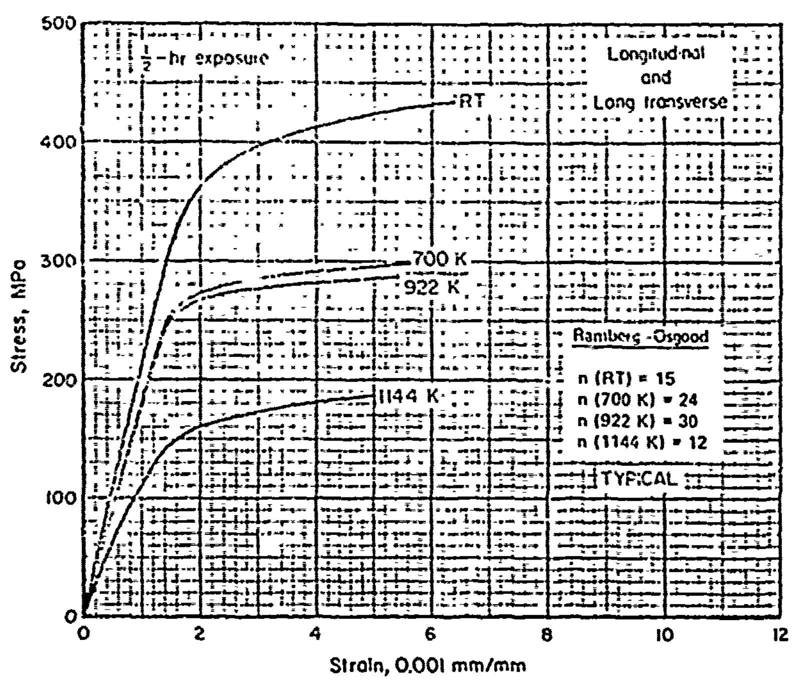


FIGURE 6.3.4.1.6(a). Typical tensile stress-strain curves for annealed Inconel Alloy 625 (sheet) at room and elevated temperatures.

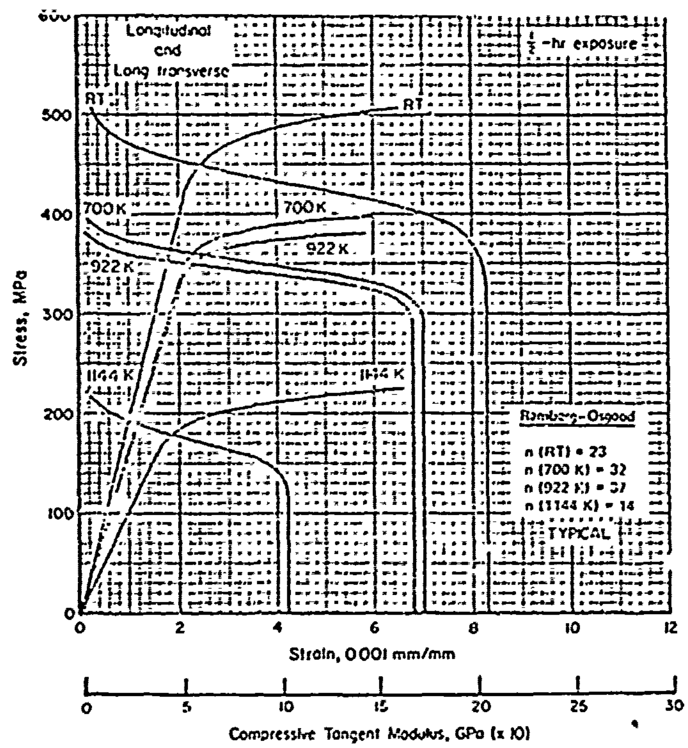


FIGURE 6.3.4.1.6(b). Typical compressive stress-strain and tangent-modulus curves for annealed Inconel Alloy 625 (sheet) at room and elevated temperatures.

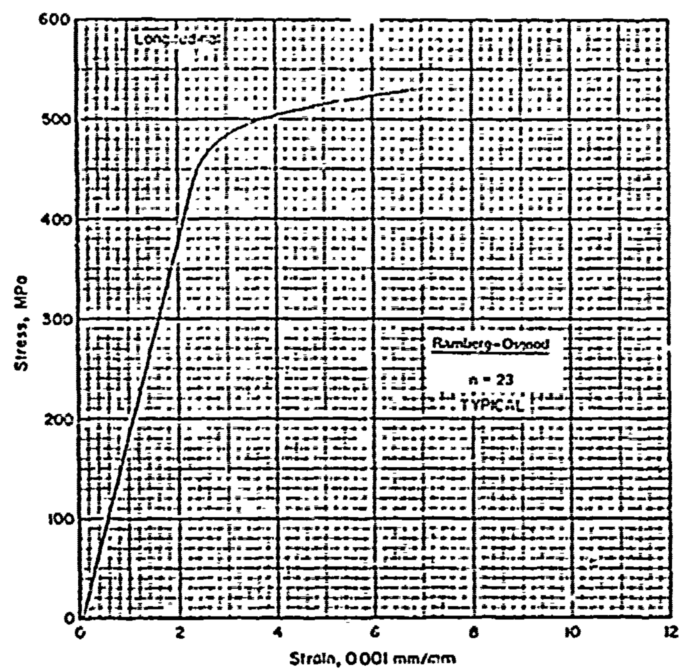


FIGURE 6.3.4.1.6(c). Typical tensile stress-strain curve at room temperature for annealed Inconel Alloy 625 (bar).

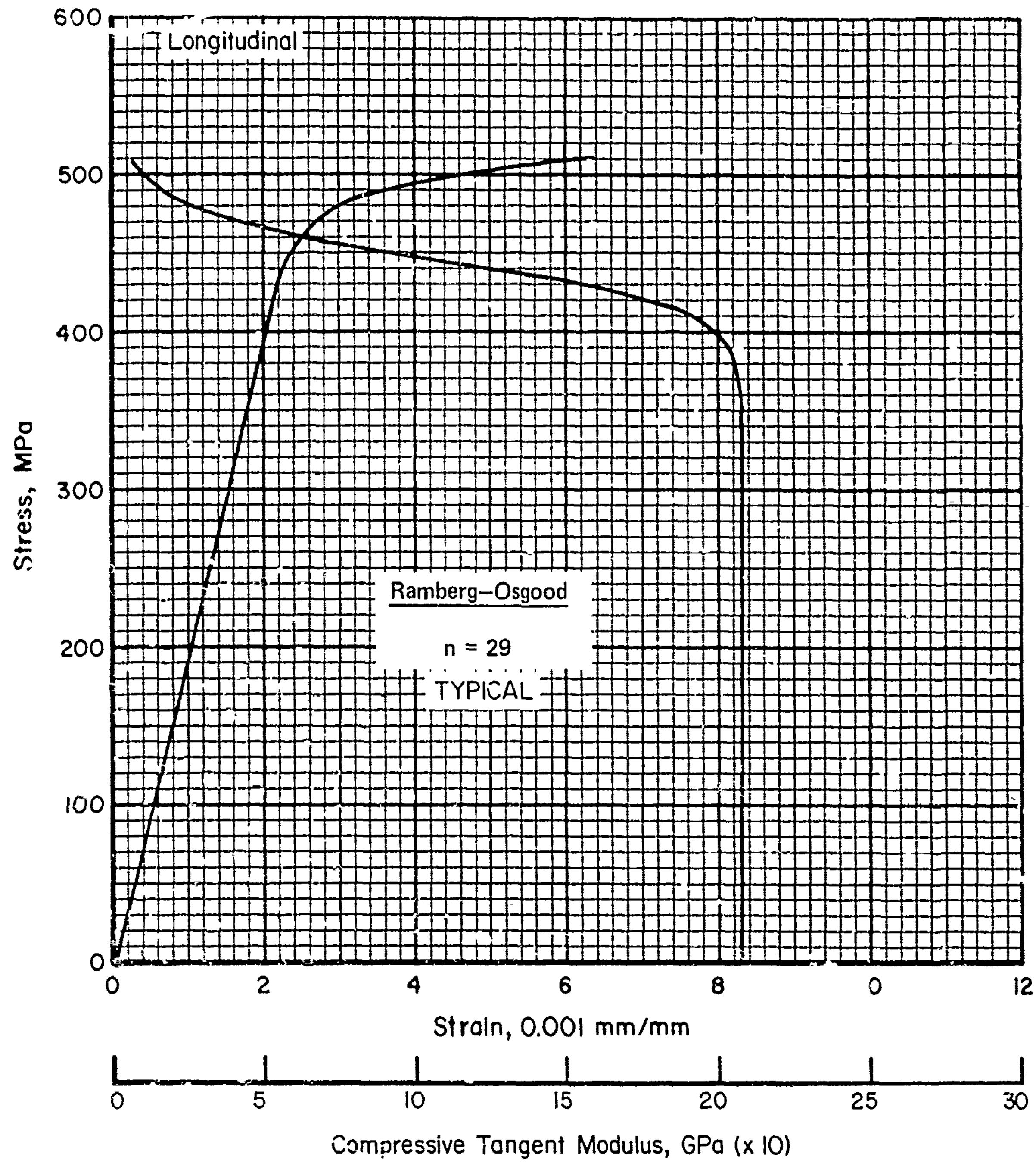


FIGURE 6.3.4.1.6(d). Typical compressive stress-strain and tangent-modulus curves at room temperature for annealed Inconel Alloy 625 (bar).

6.3.5 INCONEL 702

6.3.5.1 *Comments and Properties.*—Inconel 702 is a heat-treatable nickel-base alloy containing chromium and aluminum for oxidation resistance, and aluminum and titanium as hardeners. It is used primarily for parts and assemblies requiring oxidation resistance to about 1366 K (and under some conditions to 1589 K) rather than high strength, and where parts may require welding during fabrication. It is available as strip, sheet, hot finished bars, and seamless tubing, although it is used primarily in sheet form.

For welding this alloy, the inert gas tungsten arc process is preferred, using filler metal of matching composition. The alloy also can be metal arc welded or joined by brazing and resistance welding.

The alloy is preferably machined in the annealed or hot-worked condition, although aged material can be machined.

Contact with sulfur containing atmospheres at high temperatures should be avoided.

A material specification for Inconel 702 is presented in Table 6.3.5.0(a).

TABLE 6.3.5.0(a). *Material Specification for Inconel 702*

Specification	Form
AMS 5550	Sheet and strip

Room-Temperature Properties

Room-temperature mechanical and physical properties are presented in Table 6.3.5.0(b). The effect of temperature on physical properties is shown in Figure 6.3.5.0.

6.3.5.1 *Aged Condition.*—Effect-of-temperature curves for aged Inconel 702 sheet are presented in Figures 6.3.5.1.1(a) through 6.3.5.1.5.

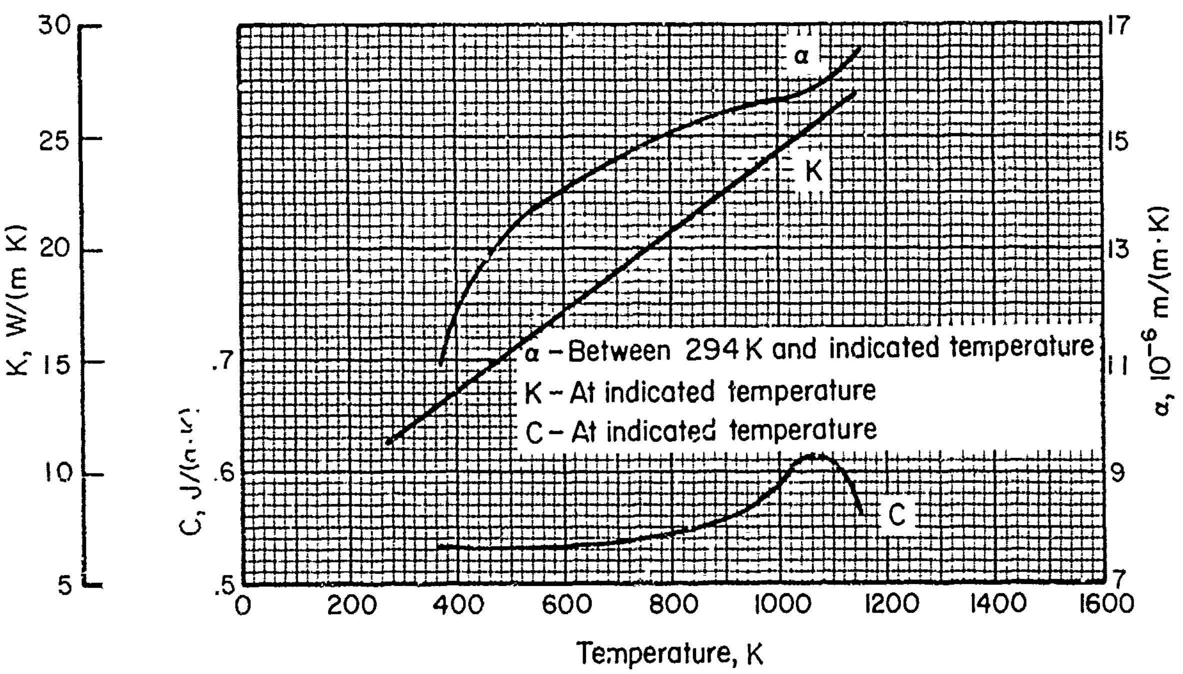


FIGURE 6.3.5.0. Effect of temperature on the physical properties of Inconel 702.

TABLE 6.3.5.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF INCONEL 702 (SHEET AND STRIP)

SPECIFICATION	AMS 5550[a]		
FORM	SHEET		STRIP
CONDITION	PRECIPITATION HEAT TREATED		
THICKNESS, MM	0.25-0.62	0.63-6.35	0.25-3.17
BASIS	S	S	S
MECHANICAL PROPERTIES:			
FTU, MPA:			
L	...	...	862
LT	862	862	...
FTY, MPA:			
L	...	...	...
LT	414	414	...
FCY, MPA:			
L	...	...	...
LT	...	...	...
FSU, MPA	...	...	...
FBRU, MPA:			
(E/D=1.5)	...	...	...
(E/D=2.0)	...	...	...
FBRY, MPA:			
(E/D=1.5)	...	...	...
(E/D=2.0)	...	...	...
EL, PERCENT:			
L	...	...	15
LT	17	25	...
E, GPA	217.2		
EC, GPA	...		
G, GPA	...		
MU	...		
PHYSICAL PROPERTIES:			
OMEGA, MG/M3	8.41		
C, J/(G*K)	SEE FIGURE 6.3.4.0		
K, W/(M*K)	SEE FIGURE 6.3.4.0		
ALPHA, 10-6 M/(M*K)	SEE FIGURE 6.3.4.0		

[a] TEST DIRECTION LONGTIUDINAL FOR WIDTHS LESS THAN 229 MM; TRANSVERSE FOR WIDTHS 229 MM AND OVER.

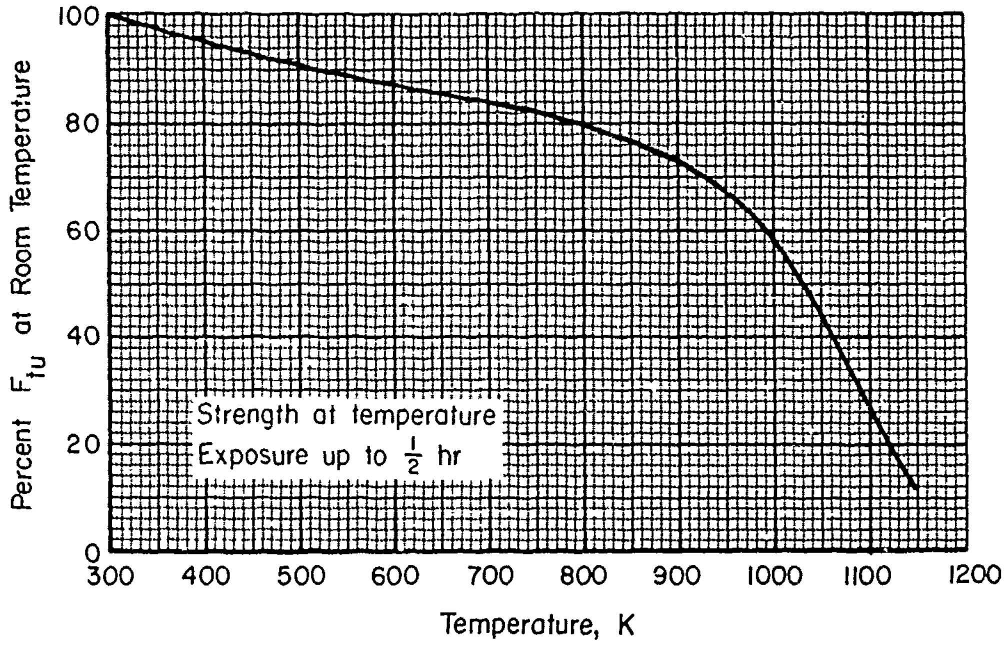


FIGURE 6.3.5.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of Inconel 702 alloy.

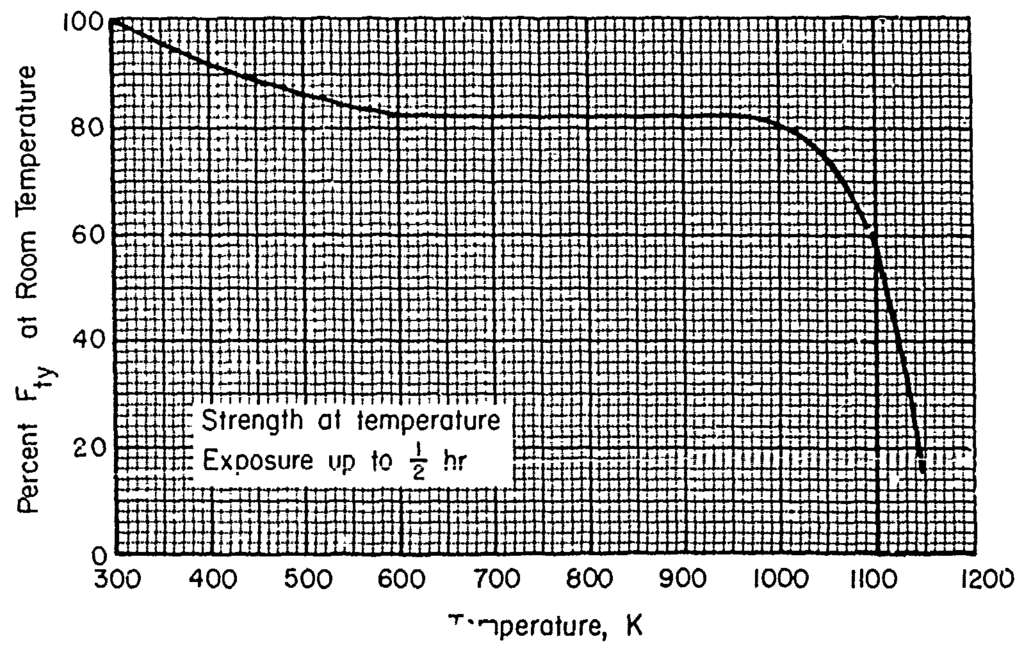


FIGURE 6.3.5.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of Inconel 702 alloy.

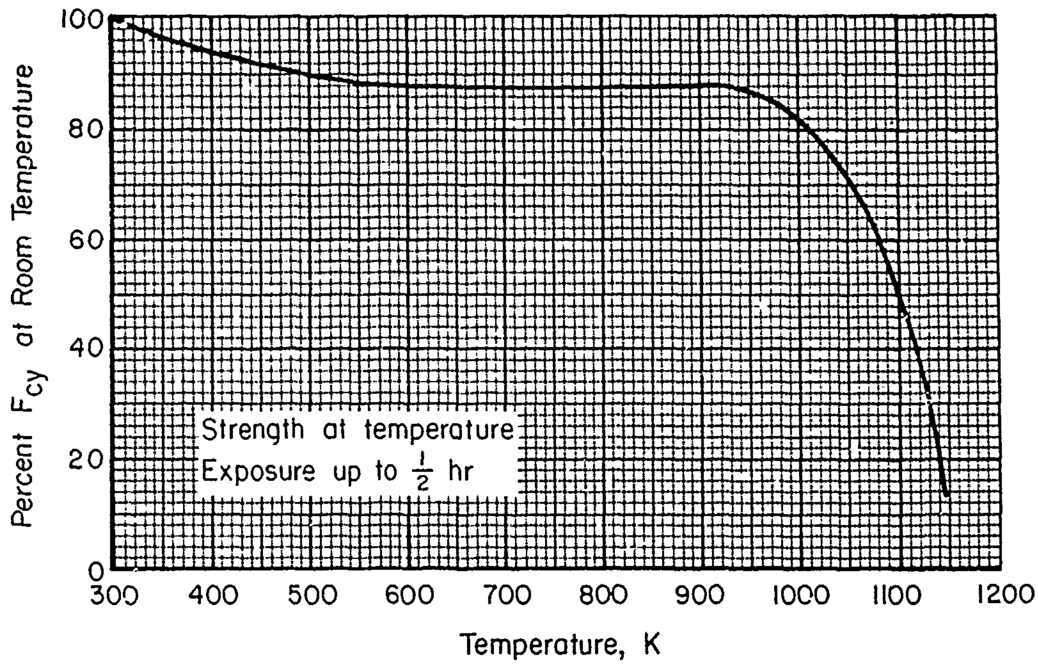


FIGURE 6.3.5.1.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of Inconel 702 alloy.

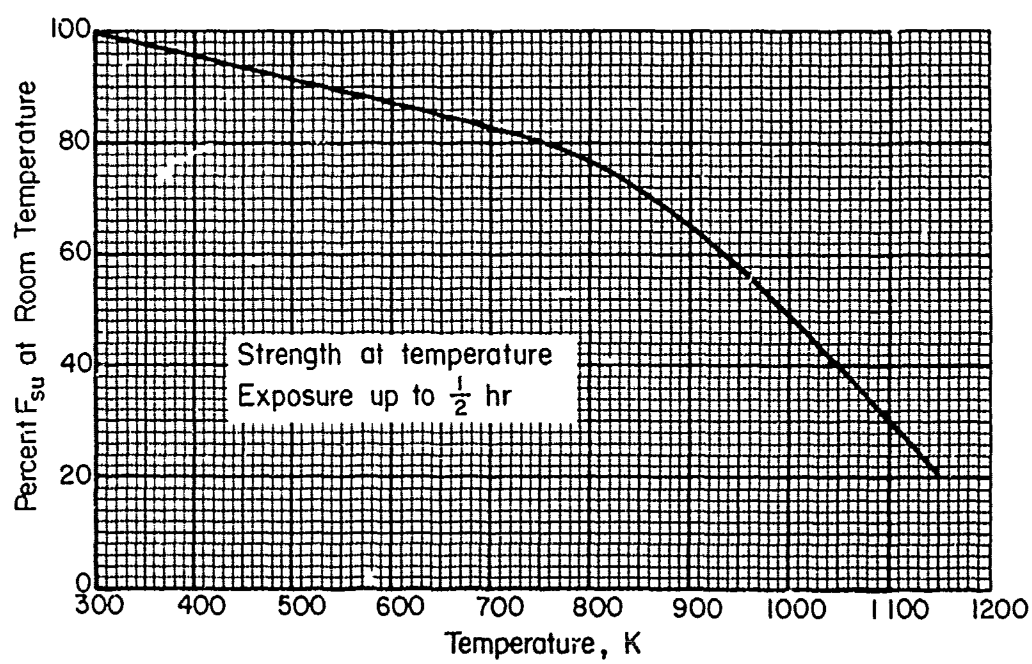


FIGURE 6.3.5.1.2(b). Effect of temperature on the ultimate shear strength (F_{su}) of Inconel 702 alloy.

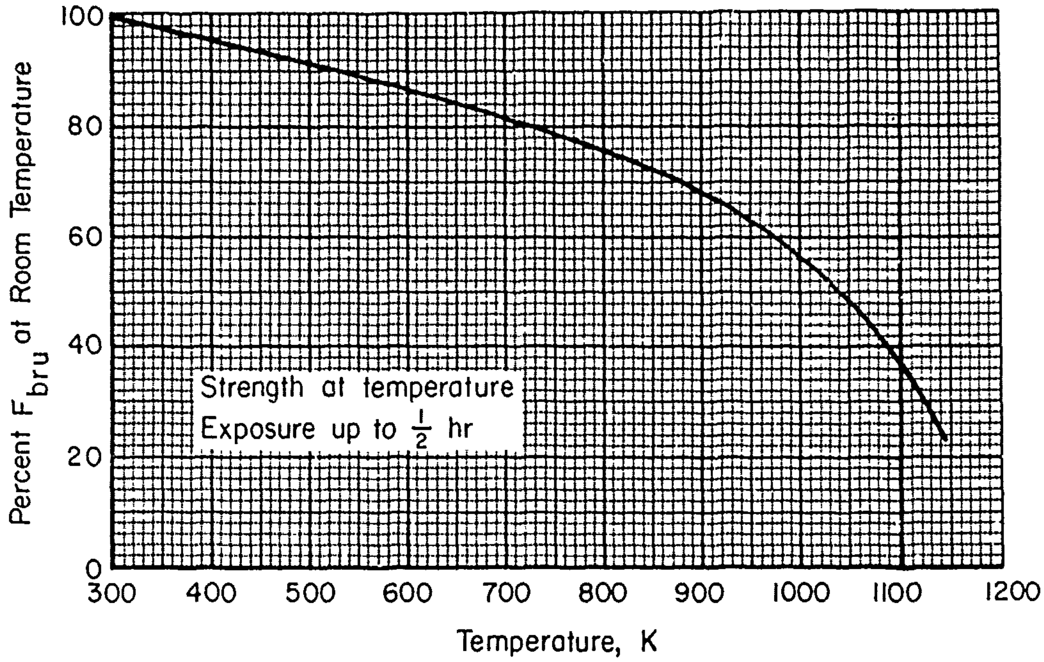


FIGURE 6.3.5.1.3(a). Effect of temperature on the ultimate bearing strength (F_{bru}) of Inconel 702 alloy.

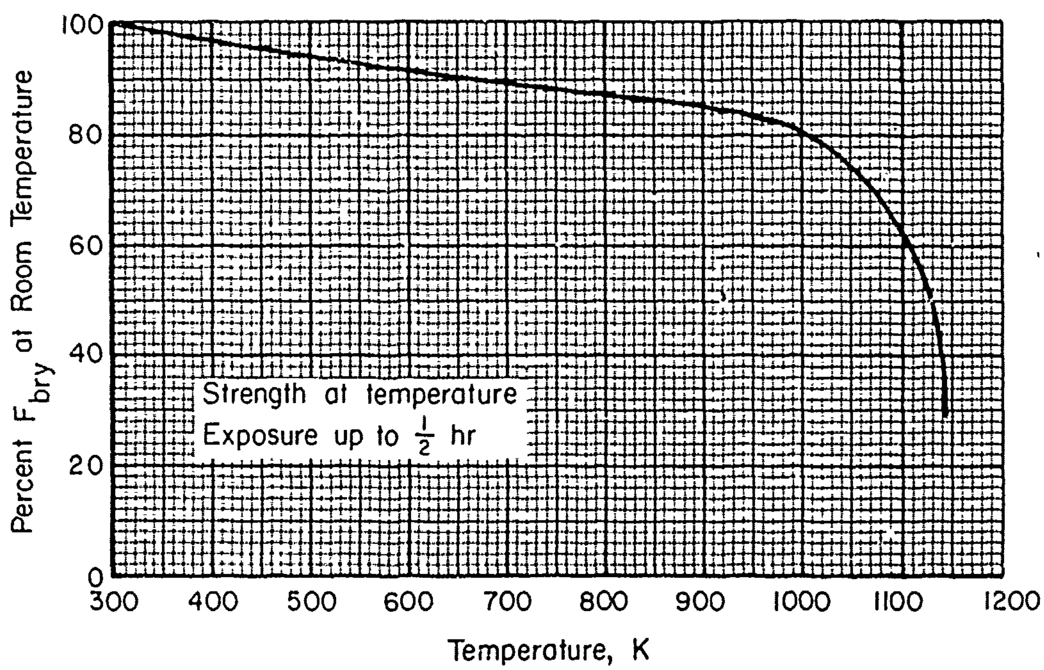


FIGURE 6.3.5.1.3(b). Effect of temperature on the bearing yield strength (F_{bry}) of Inconel 702 alloy.

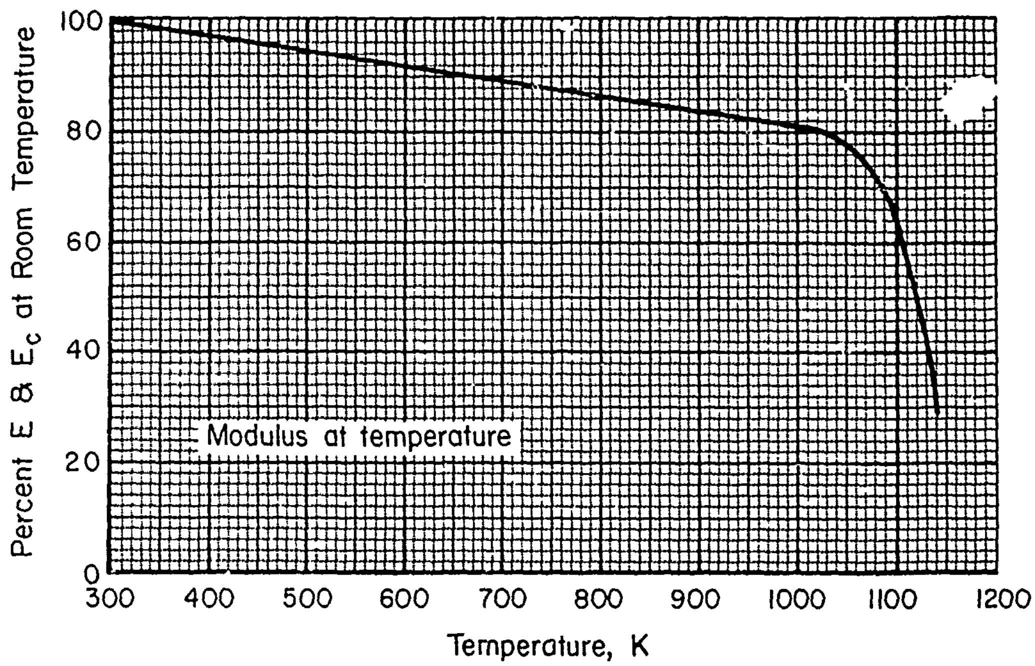


FIGURE 6.3.5.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of Inconel 702 alloy.

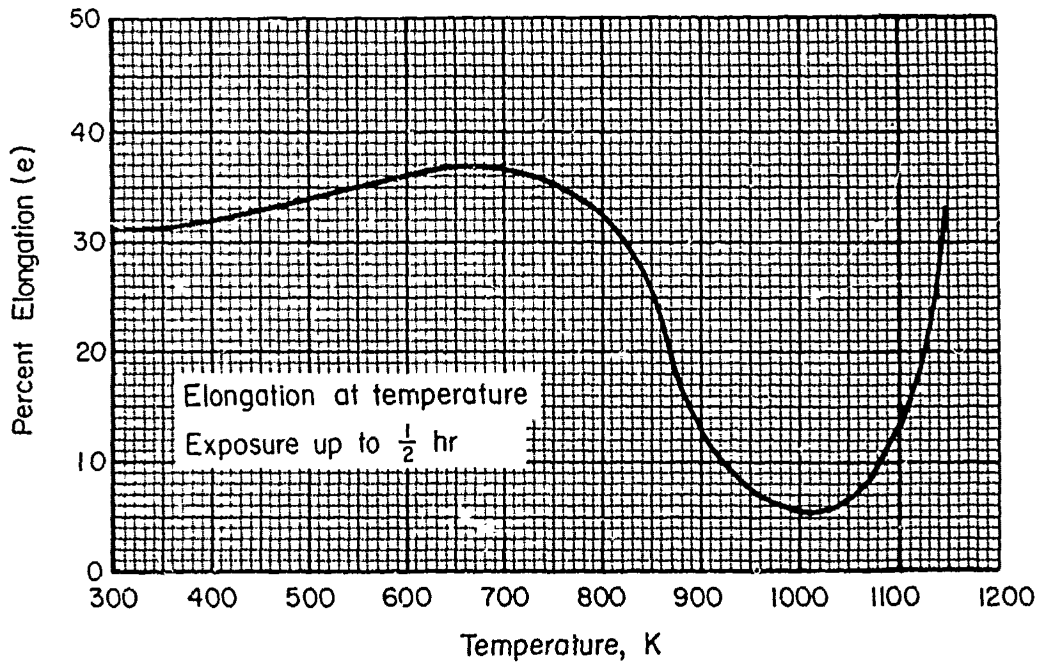


FIGURE 6.3.5.1.5. Effect of temperature on the elongation (e) of Inconel 702 alloy (sheet).

6.3.6 INCONEL ALLOY 706

6.3.6.0 *Comments and Properties.*—Inconel Alloy 706 is a vacuum-melted precipitation-hardened, nickel-base alloy with characteristics similar to Inconel Alloy 718 except that Inconel Alloy 706 has greatly improved machineability. The alloy has good formability and weldability. Like Inconel Alloy 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 978 K 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 Alloy 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 applications, both the product form and application are listed with the specifications in Table 6.3.6.0(a).

Room-Temperature Properties

Room-temperature mechanical and physical properties are shown in Table 6.3.6.0(b). The effect of temperature on physical properties is shown in Figure 6.3.6.0.

6.3.6.1 *Solution Treated and Aged Conditions (Creep Rupture Heat Treatment).*—The effect of temperature on the tensile ultimate strength and tensile yield strength of Alloy 706 is presented in Figures 6.3.6.1.1(a) and (b), and the effect on the tensile and compressive moduli in Figure 6.3.6.1.4. The effect of temperature on elongation is shown in Figure 6.3.6.1.5. Typical tensile stress-strain curves are shown in Figure 6.3.6.1.6(a) and typical compressive stress-strain and tangent-modulus curves in Figure 6.3.6.1.6(b). A typical full-range tensile stress-strain curve is shown in Figure 6.3.6.1.6(c). The stress-rupture properties are specified at 1200 F; the appropriate specification should be consulted for detailed requirements.

TABLE 6.3.6.0(a). *Material Specifications for Inconel Alloy 706*

Specification	Form	Application
AMS 5605	Sheet, strip, and plate	Tensile 1255 K solution treated
AMS 5606	Sheet, strip, and plate	Creep-Rupture 1228 K solution treated
AMS 5701	Bars, forgings, and rings	Tensile 1255 K solution treated
AMS 5702	Bars, forgings, and rings	Creep-Rupture 1228 K solution treated
AMS 5703	Bars, forgings, and rings	Creep-Rupture 1228 K solution treated, stabilized and precipitation treated

TABLE 6.3.6.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF INCONEL ALLOY 706

SPECIFICATION	AMS 5605		AMS 5606	AMS 5701		AMS 5702 AND AMS 5703	
FORM	SHEET, STRIP, AND PLATE			BARS, FORGINGS, AND RINGS			
CONDITION	HEAT TREATED PER INDICATED SPECIFICATION						
THICKNESS, MM	≤4.75	> 4.75	ALL	<63.50	63.50-101.60	<63.50	63.50-101.60
BASIS	S[a]	S[a]	S[a]	S[a]	S[a]	S[a]	S
MECHANICAL PROPERTIES:							
FTU, MPA:							
L	...	...	...	1170	1170	1170	1140
LT	1210	1170	1170	...	...	...	...
FTY, MPA:							
L	...	...	...	965	931	896	896
LT	1000	965	931	...	...	...	...
FCY, MPA:							
L	...	...	...	1010	972	938	938
LT	1050	1010	972	...	...	...	...
FSU, MPA	752	731	731	731	731	731	710
FBRU[b], MPA:							
(E/D=1.5)	1870	1810	1810	1810	1810	1810	1770
(E/D=2.0)	2370	2300	2300	2300	2300	2300	2240
FBRY[b], MPA:							
(E/D=1.5)	1390	1340	1300	1340	1300	1250	1250
(E/D=2.0)	1680	1610	1560	1610	1560	1500	1500
EL, PERCENT:							
L	...	...	...	12	12	12	12
LT	12	12	12	...	...	...	...
EL, PERCENT:							
L	...	...	...	15	15	15	15
LT	...	...	...	...	...	...	...
E, GPA	209.6						
EC, GPA	209.6						
G, GPA	75.8						
MU	0.38						
PHYSICAL PROPERTIES:							
OMEGA, MG/M3	8.08						
C, J/(G*K)	SEE FIGURE 6.3.6.0						
K, W/(M*K)	SEE FIGURE 6.3.6.0						
ALPHA, 10-6 M/(M*K)	SEE FIGURE 6.3.6.0						

[a] GRAIN DIRECTION NOT SPECIFIED.
[b] BEARING VALUES ARE DRY PIN VALUES PER SECTION 1.4.7.1.

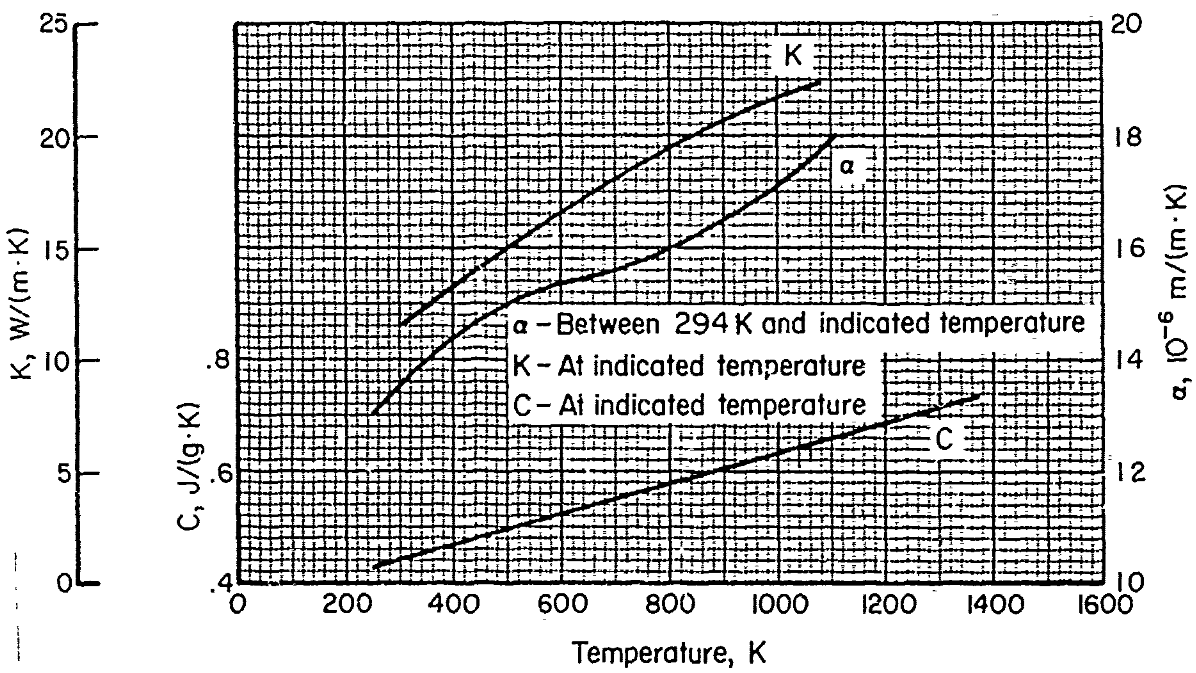


FIGURE 6.3.6.0. Effect of temperature on the physical properties of solution-treated and aged Inconel Alloy 706.

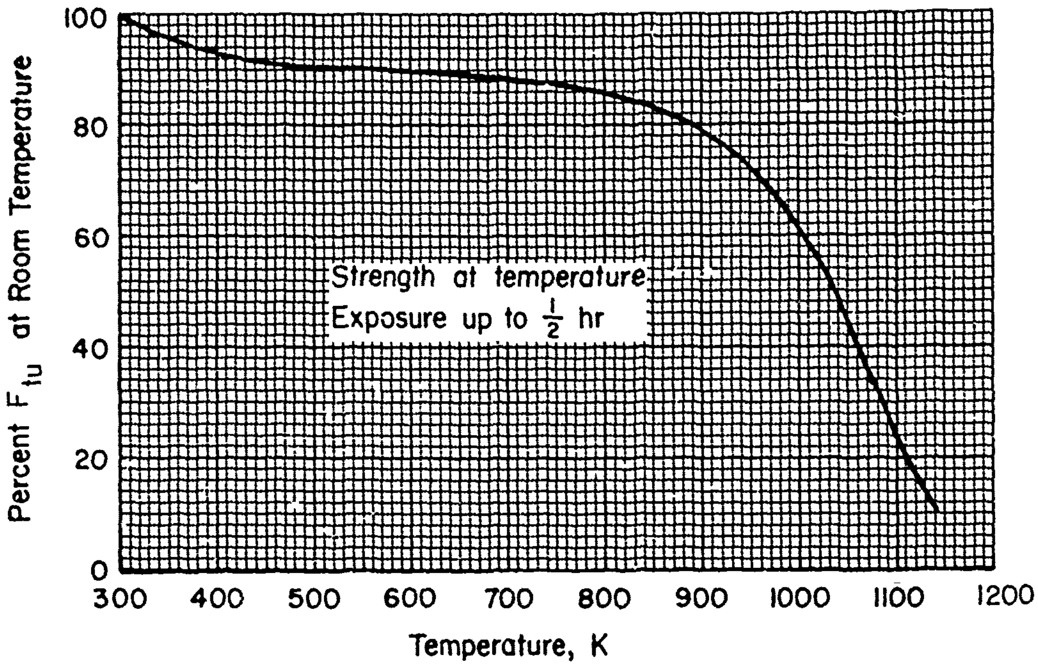


FIGURE 6.3.6.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of solution-treated and aged Inconel Alloy 706 (creep rupture heat treatment).

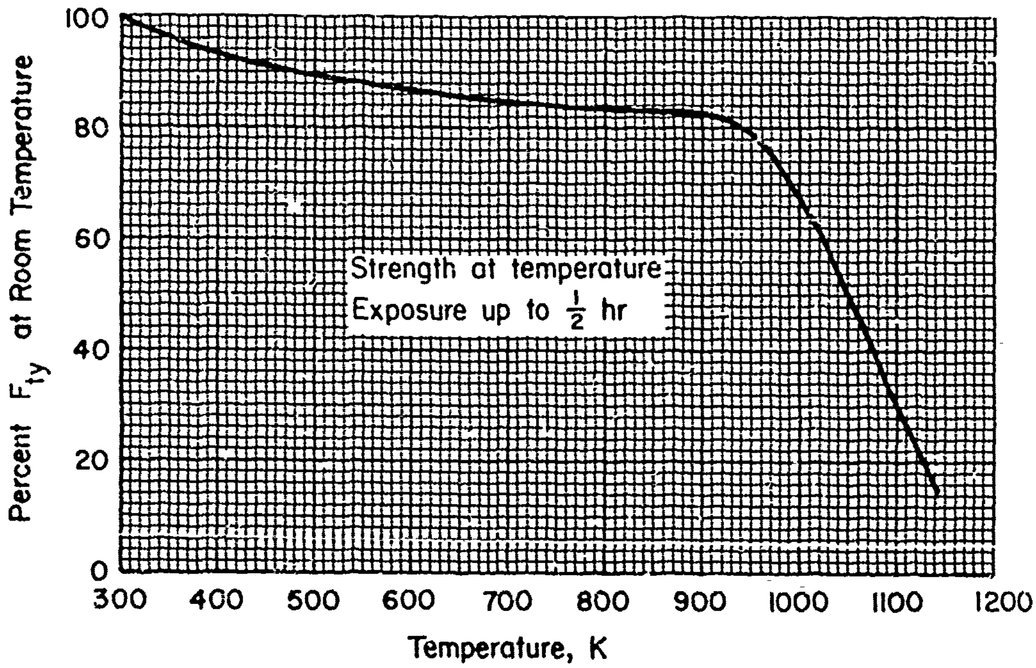


FIGURE 6.3.6.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of solution-treated and aged Inconel Alloy 706 (creep rupture heat treatment).

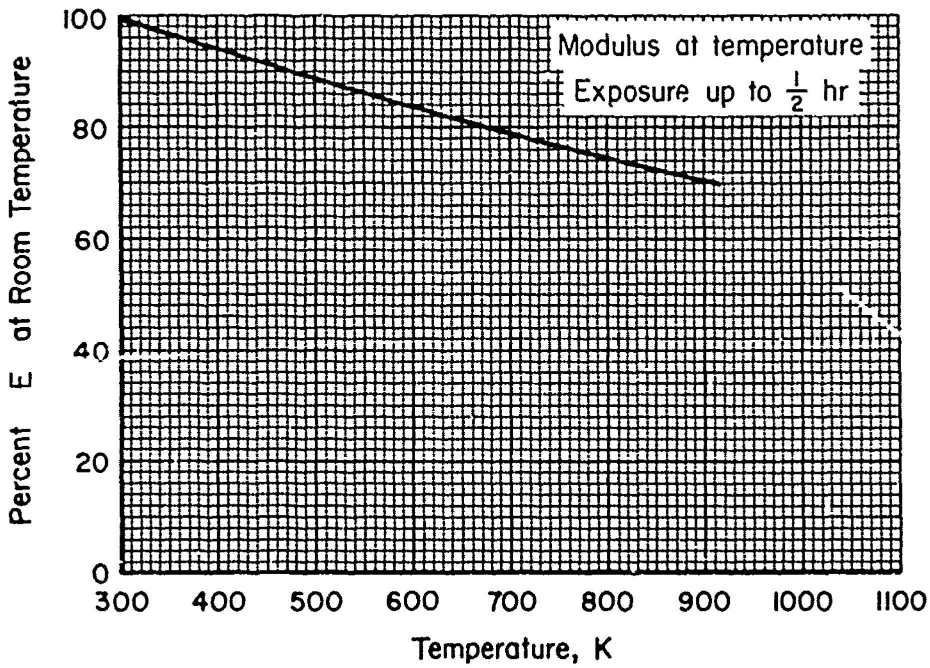


FIGURE 6.3.6.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of Inconel Alloy 706.

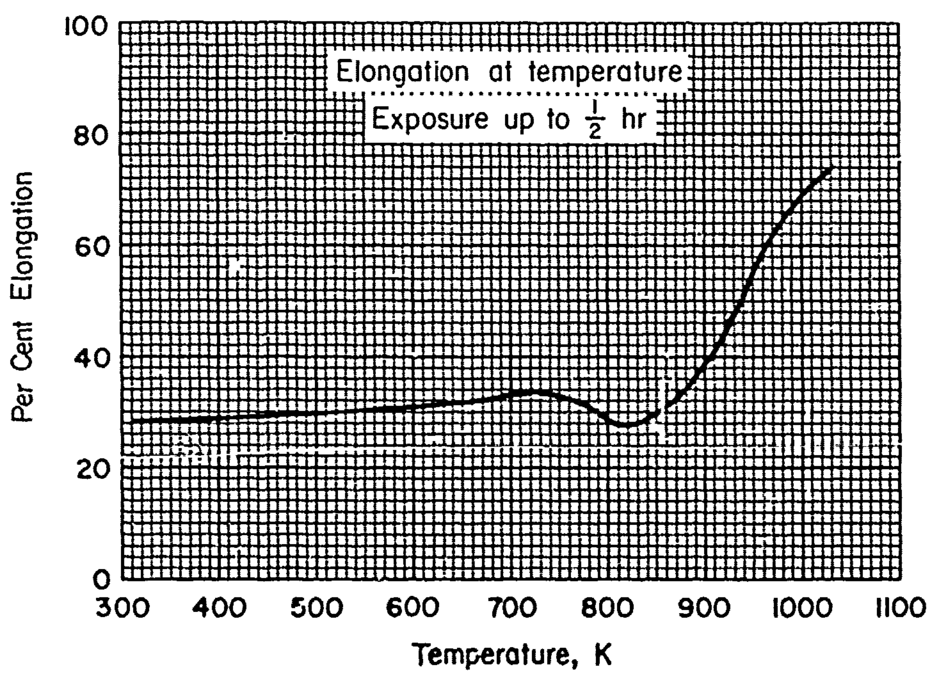


FIGURE 6.3.6.1.5. Effect of temperature on the elongation of solution-treated and aged Inconel Alloy 706 (creep rupture heat treatment).

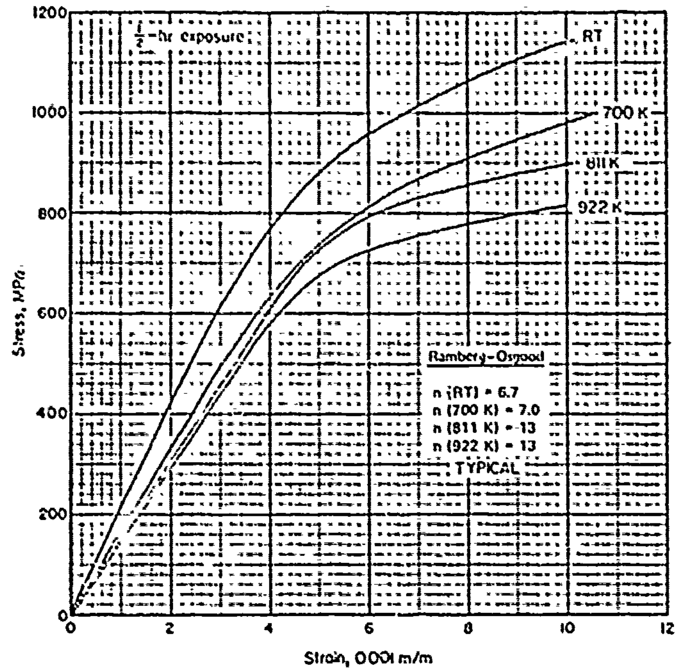


FIGURE 6.3.6.1.6(a). Typical tensile stress-strain curves for solution-treated and aged Inconel Alloy 706 (creep rupture heat treatment).

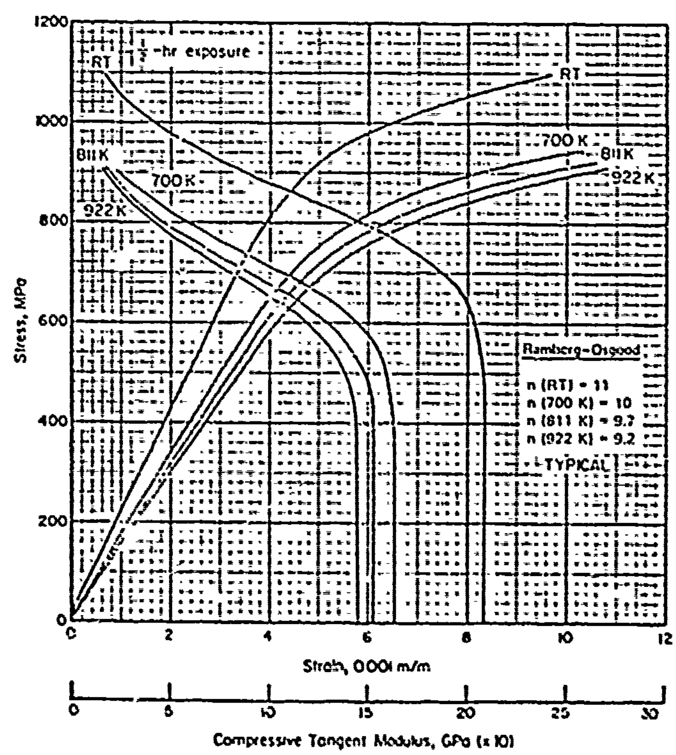
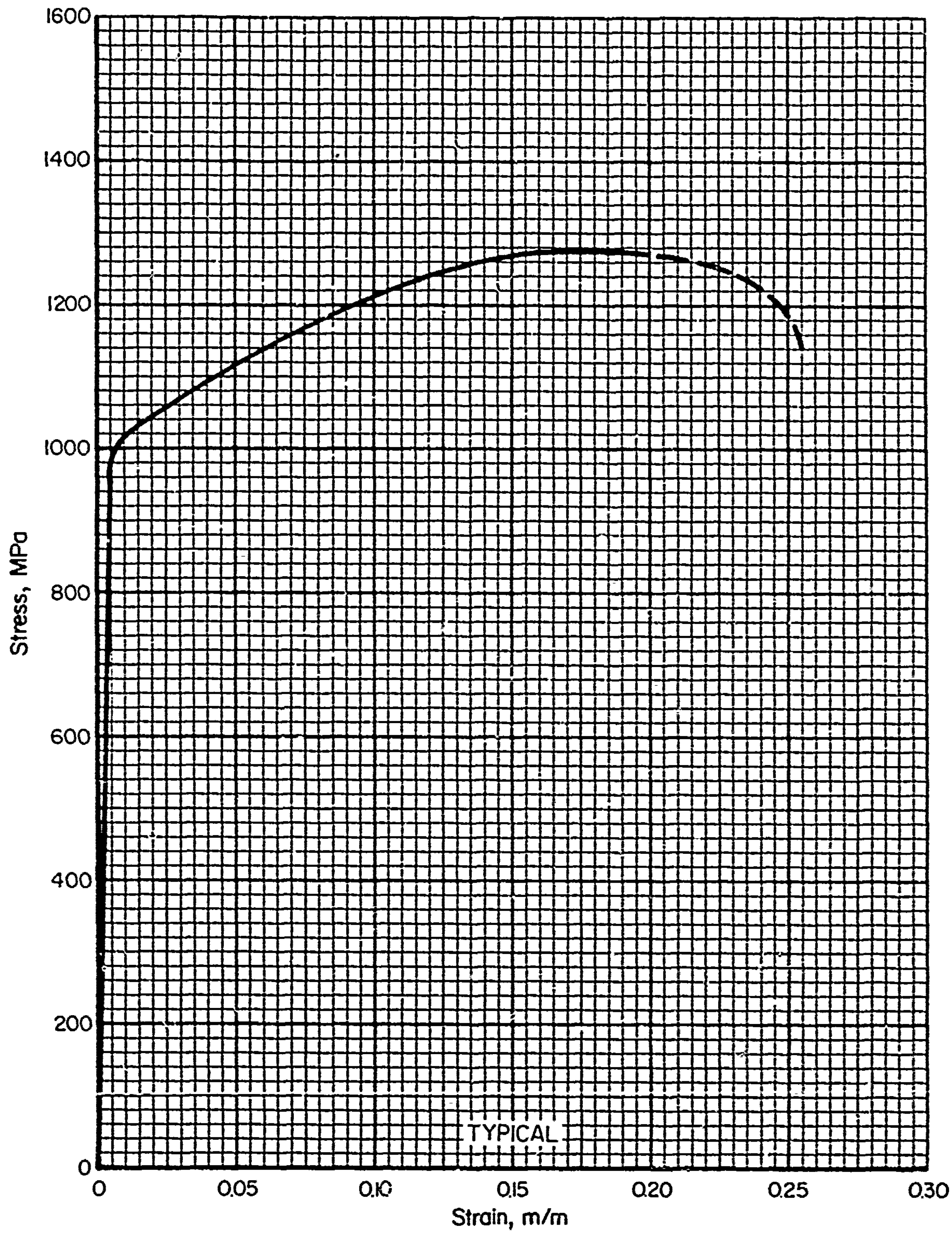


FIGURE 6.3.6.1.6(b). Typical compressive stress-strain and tangent-modulus curves for solution-treated and aged Inconel Alloy 706



JRE 6.3.6.1.6(c). Typical tensile stress-strain curve (Full range) for Inconel Alloy 706 (bar and sheet) at room temperature (creep rupture heat treatment).

6.3.7 INCONEL 718

6.3.7.0 *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 up to 978 K or (2) high strength at cryogenic temperatures and for short-time use up to 811 K. It also has good oxidation resistance up to 1255 K. Inconel 718 is available in all wrought forms and as 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 6.3.7.0(a).

Room-Temperature Properties

Room-temperature mechanical and physical properties are presented in Tables 6.3.7.0(b) and (c). Other physical properties as a function of temperature are presented in Figure 6.3.7.0.

6.3.7.1 *Solution Treated and Aged Condition.*—Effect-of-temperature curves for solution treated and aged Inconel 718 are presented in Figures 6.3.7.1.1(a) through 6.3.7.1.4. Typical constant life fatigue diagrams are presented in Figures 6.3.7.1.8(a) through 6.3.7.1.8(d).

TABLE 6.3.7.0(a). *Material Specifications for Inconel 718 Alloy*

Specification	Form	Application
AMS 5383	Investment castings	Creep-rupture
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	Bars, forgings	Creep-rupture
AMS 5664	Bars, forgings	Short-time

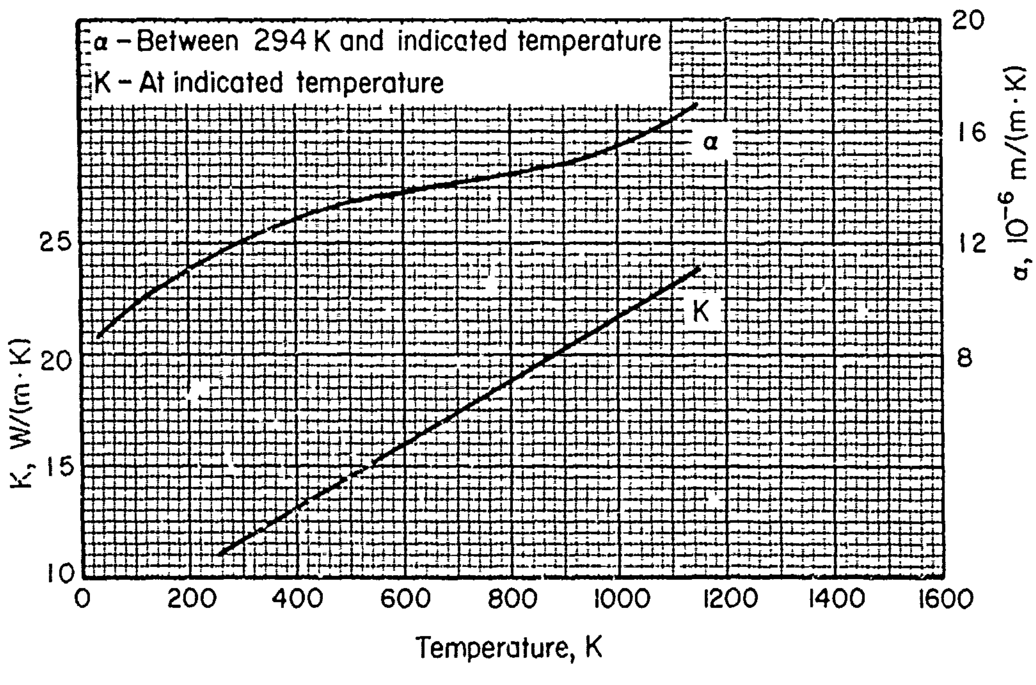


FIGURE 6.3.7.0. Effect of temperature on the physical properties of Inconel 718 alloy.

TABLE 6.3.7.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF INCONEL 718 ALLOY

SPECIFICATION	AMS 5596	AMS 5597	AMS 5589	AMS 5590	AMS 5383
FORM	SHEET AND PLATE		TUBING		CASTINGS
CONDITION	SOLUTION TREATED AND AGED PER INDICATED SPECIFICATION				
THICKNESS, MM	...	...	O.D. ≥3.17 WALL ≥0.38		...
BASIS	S[a]	S[a]	S	S	S[b,c]
MECHANICAL PROPERTIES:					
FTU, MPA:					
L	...	...	1280	1170	862
LT	1240	1240	...	...	...
FTY, MPA:					
L	...	...	1030	1000	758
LT	1030	1030	...	...	...
FCY, MPA:					
L	...	...	...	...	...
LT	...	...	...	...	...
FSU, MPA	...	...	...	...	...
FBRU, MPA:					
(E/D=1.5)	...	...	...	...	...
(E/D=2.0)	...	...	...	...	...
FBRY, MPA:					
(E/D=1.5)	...	...	...	...	...
(E/D=2.0)	...	...	...	...	...
EL, PERCENT:					
L	...	...	12	15	5
LT	12	15	...	...	...
E, GPA	204.1				
EC, GPA	...				
G, GPA	...				
MU	...				
PHYSICAL PROPERTIES:					
OMEGA, MG/M3	8.22				
C, J/(G*K)	0.46 (AT 225 K)				
K, W/(M*K)	SEE FIGURE 6.3.5.0				
ALPHA, 10-6 M/(M*K)	SEE FIGURE 6.3.5.0				

[a] TEST DIRECTION LONGITUDINAL FOR WIDTHS LESS THAN 229 MM; TRANSVERSE FOR WIDTHS 229 MM AND OVER.
[b] GRAIN DIRECTION NOT APPLICABLE.
[c] FOR CAST TEST BARS. SPECIMENS MACHINED FROM LARGER CASTINGS MAY HAVE LOWER PROPERTIES.

TABLE 6.3.7.0 (C). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF INCONEL 718 ALLOY (BARS AND FORGINGS)

SPECIFICATION..........	AMS 5662 AND AMS 5663		AMS 5664	
FORM..................	BARS	FORGINGS	BARS	FORGINGS
CONDITION.............	SOLUTION-TREATED AND AGED PER INDICATED SPECIFICATION			
THICKNESS, MM.........	...		...	
BASIS.................	S	S	S	S
MECHANICAL PROPERTIES:				
FTU, MPA:				
L..................	1280	1280	1240	1240[a]
LT.................	1240	1240	1240	1240
ST.................	1240	...	1240	...
FTY, MPA:				
L..................	1030	1030	1030	1030[a]
LT.................	1030	1030	1030	1030
ST.................	1030	...	1030	...
FCY, MPA:				
L..................	...	...	...	...
LT.................	...	...	...	...
ST.................	...	...	...	...
FSU, MPA.............	...	...	...	...
FBRU, MPA:				
(E/D=1.5)..........	...	...	...	...
(E/D=2.0)..........	...	...	...	...
FBRY, MPA:				
(E/D=1.5)..........	...	...	...	...
(E/D=2.0)..........	...	...	...	...
EL, PERCENT:				
L..................	12	12	10	12
LT.................	6	10	10	12
ST.................	6	...	10	...
EL, PERCENT:				
L..................	15	15	12	15
LT.................	8	12	12	1[illegible]
ST.................	8	...	12	...
E, GPA...............	204.1[b]			
EC, GPA..............	...			
G, GPA...............	...			
MU...................	...			
PHYSICAL PROPERTIES:				
OMEGA, MG/M3.........	8.22			
C, J/(G*K)...........	0.46(AT 255K)			
K, W/(M*K)...........	SEE FIGURE 6.3.5.0			
ALPHA, 10-6 M/(M*K)..	SEE FIGURE 6.3.5.0			

[a] TRANSVERSE GRAIN DIRECTION.
[b] DYNAMIC MODULUS.

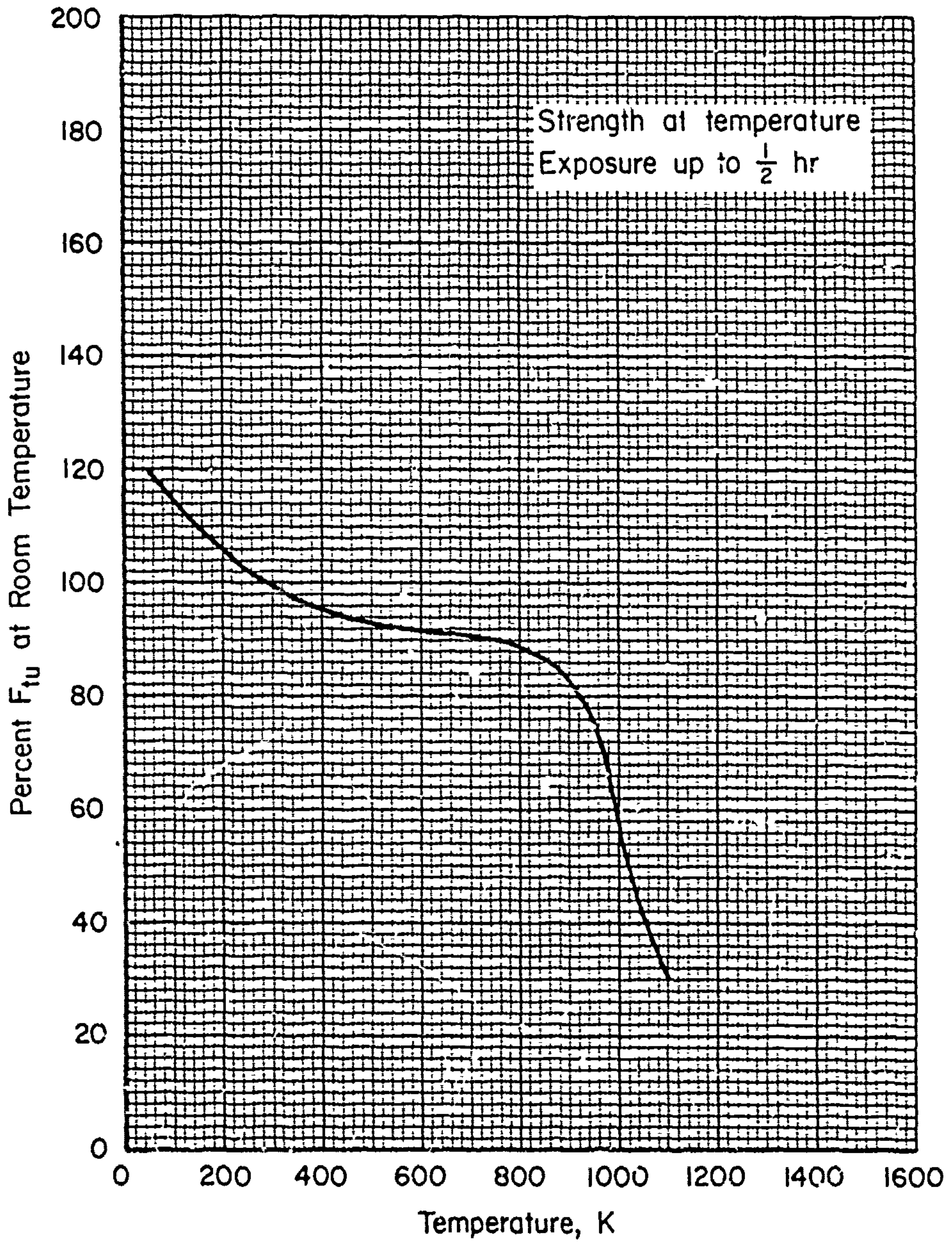


FIGURE 6.3.7.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of solution-treated and aged Inconel 718 alloy.

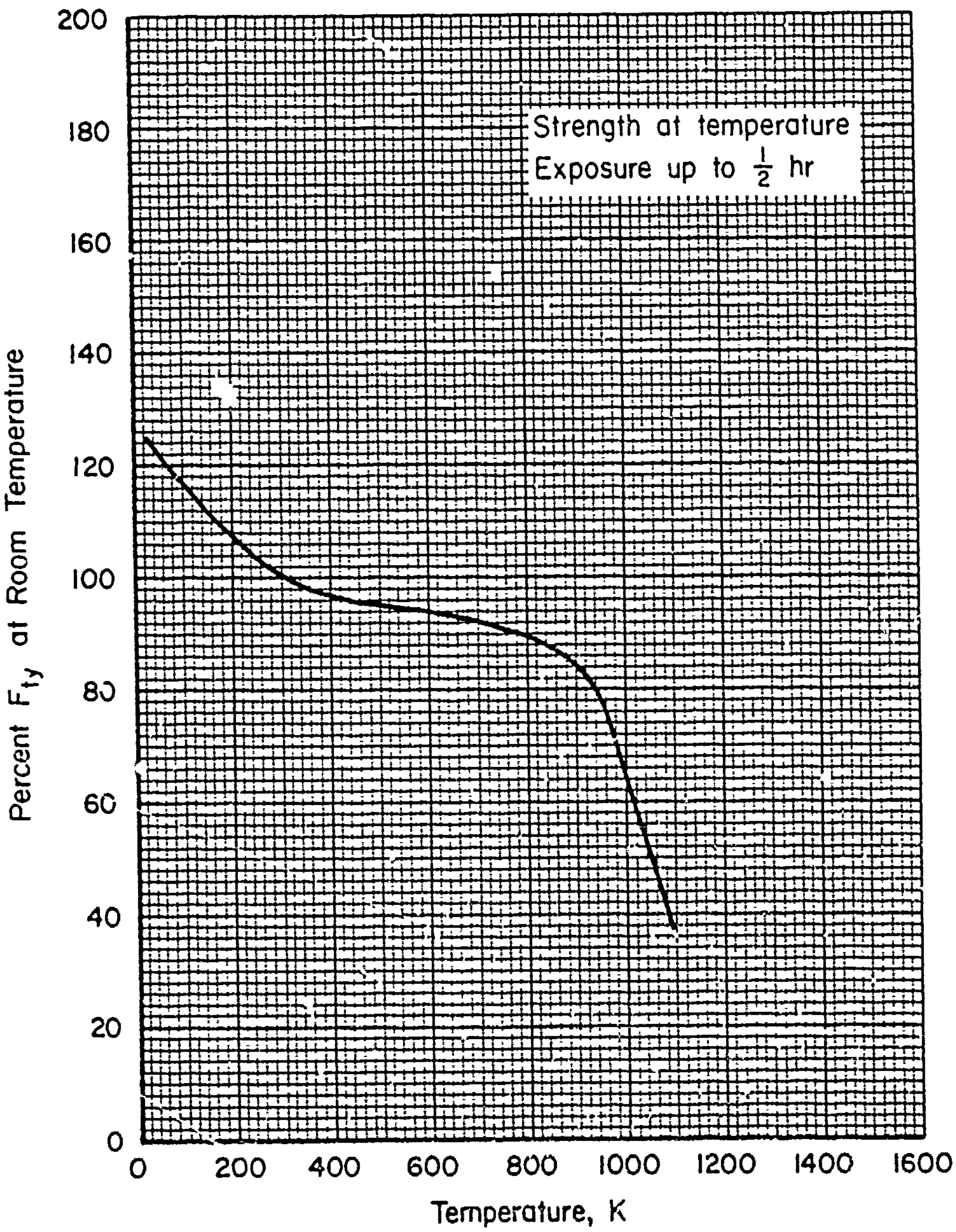


FIGURE 6.3.7.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of solution-treated and aged Inconel 718 alloy.

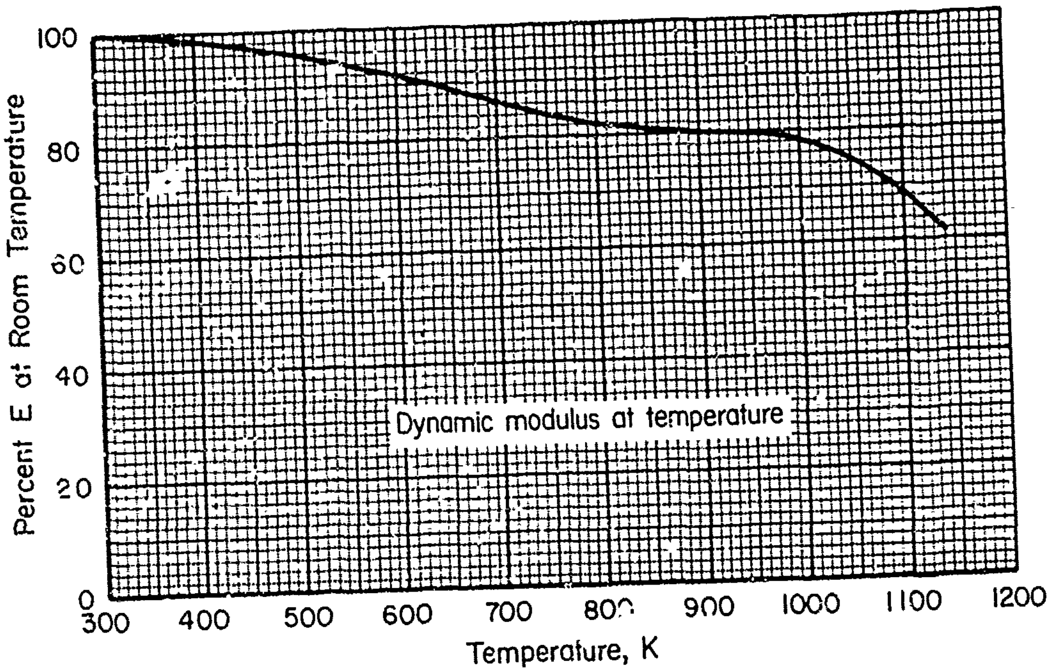


FIGURE 6.3.7.1.4. Effect of temperature on the tensile modulus (E) of solution-treated and aged Inconel 718 Alloy.

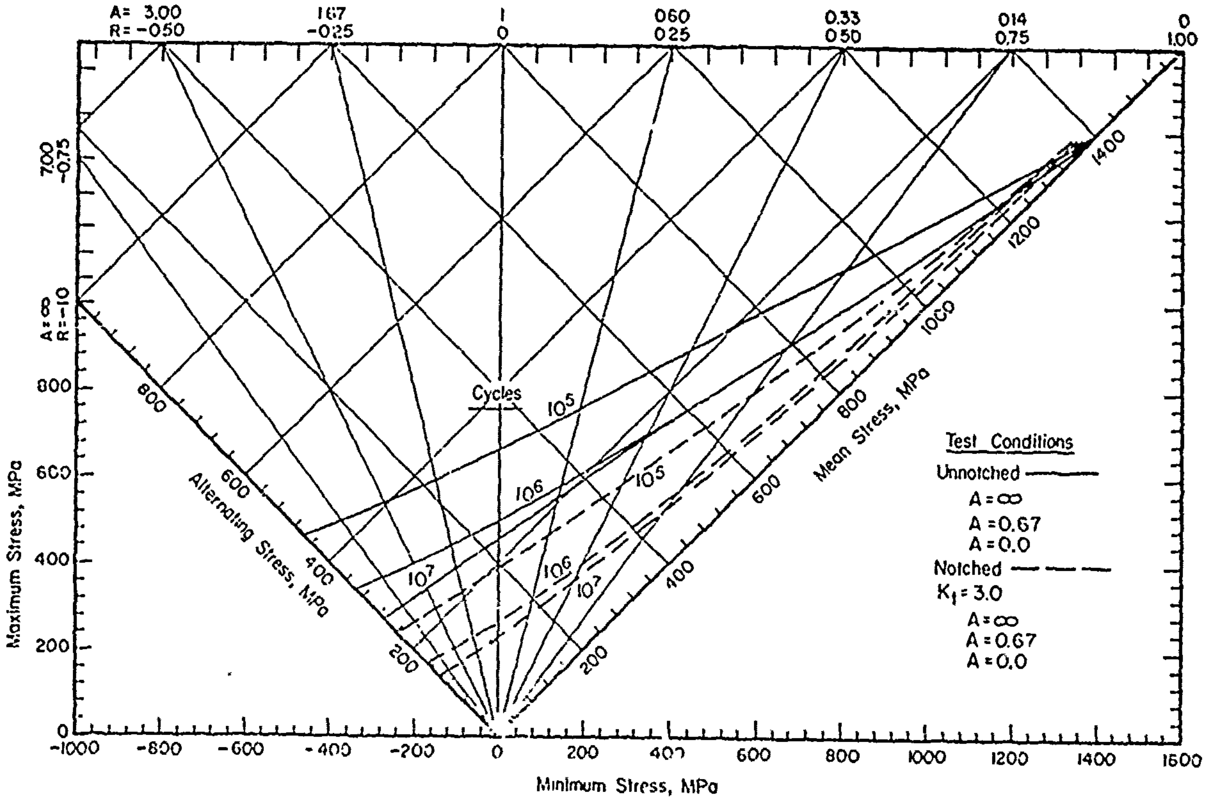


FIGURE 6.3.7.1.8(a). *Typical constant-life fatigue diagram for Inconel 718 (sheet) at room temperature, long transverse direction.*

Correlative Information for Figure 6.3.7.1.8(a)

Product Form: Aged Sheet, 1.70 mm thick

Properties:

TUS, MPa	TYS, MPa	Temp, K
1358	1131	RT (Unnotched)
1517	—	RT (Notched)

Test Parameters:
Loading - Axial
Frequency - 3600 cpm
Temperature - RT
Atmosphere - Air

Specimen Details:

Unnotched:
7.62 mm width

Notched, V-Groove, $K_t = 3.0$
11.32 mm, gross width
7.62 mm, net width
0.56 mm, root radius, r
60° flank angle, ω

$K_N = 2.79, \rho = 0.00356$ mm, where $K_N = 1 + \dfrac{K_t - 1}{1 + \dfrac{\pi}{\pi - \omega}\sqrt{\dfrac{\rho}{r}}}$

Surface Condition: Unnotched: Specimen edges were finished by belt grinding with 400 grit belts and vapor mist cooling.
Notched: Notch contours were finished with a combination of milling and grinding. Both types of specimens were double aged after machining: 992 K for 8 hours, furnace cooled to 894 K holding at 894 K to complete a total of 18 hours in the furnace.

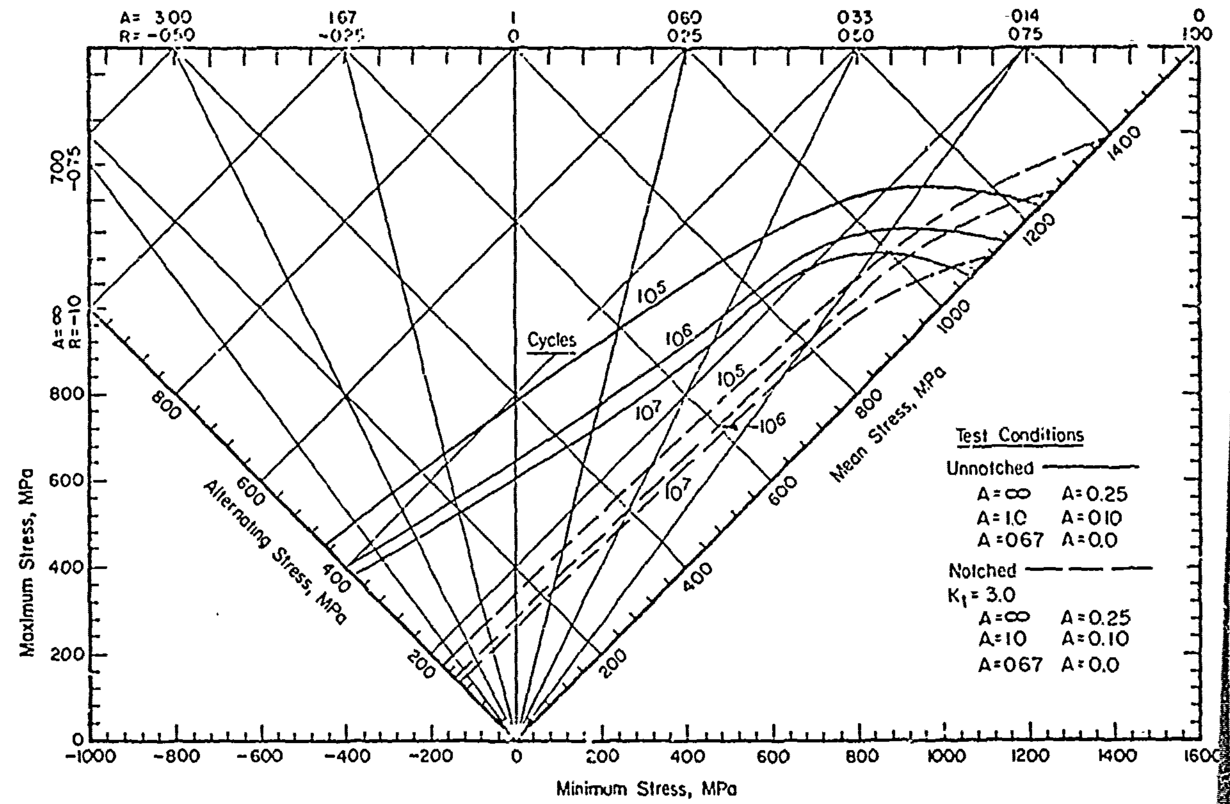


FIGURE 6.3.7.1.8(b). *Typical constant-life fatigue diagram for Inconel 718 (sheet) at* 811 K, *long transverse direction.*

Correlative Information for Figure 6.3.7.1.8(b)

Product Form: Aged Sheet, 1.70 mm thick

Properties:

TUS, MPa	TYS, MPa	Temp, K	
1138	979	811	(Unnotched)
1276	--	—	(Notched)

Test Parameters:
- Loading — Axial
- Frequency — 3600 cpm
- Temperature — 811 K
- Atmosphere — Air

Specimen Details:

Unnotched: 7.62 mm width

Notched, Edge Type, $K_t = 3.0$:
- 11.38 mm, gross width
- 7.62 mm, net width
- 0.56 mm, root radius, r
- 60° flank angle, ω

$$K_N = 2.84,\ \rho = 0.00203 \text{ mm, where } K_N = 1 + \frac{K_t - 1}{1 + \frac{\pi}{\pi - \omega}\sqrt{\frac{\rho}{r}}}$$

Surface Condition: Unnotched: Specimen edges were finished by belt grinding with 400 grit belts and vapor mist cooling.
Notched: Notch contours were finished with a combination of milling and grinding. Both types of specimens were double aged after machining: 992 K for 8 hours, furnace cooled to 894 K holding at 894 K to complete a total of 18 hours in the furnace.

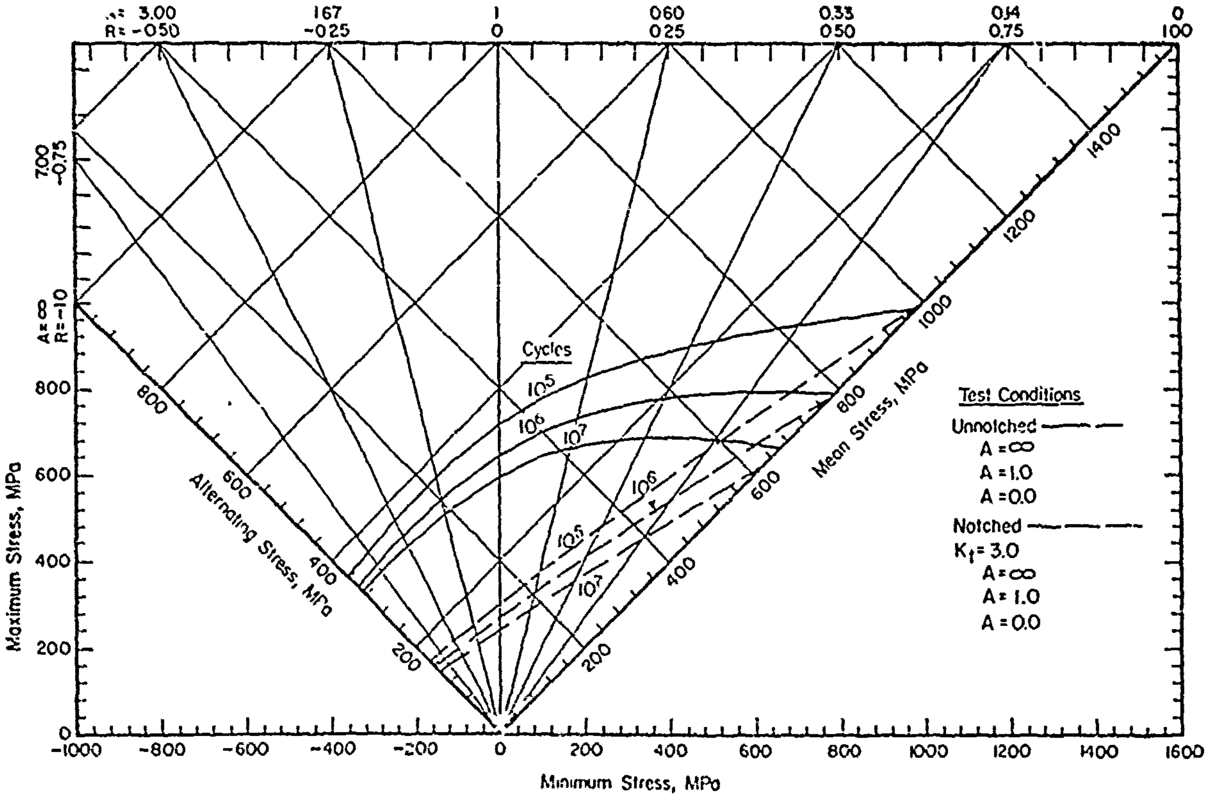


FIGURE 6.3.7.1.8(c). *Typical constant-life fatigue diagram for Inconel 718 (sheet) at 922 K, long transverse direction.*

Correlative Information for Figure 6.3.7.1.8(c)

Product Form: Aged Sheet, 1.70 mm thick

Properties:

TUS, MPa	TYS, MPa	Temp, K
1103	924	922 (Unnotched)
965 (est)	—	922 (Notched)

Test Parameters:
- Loading - Axial
- Frequency - 3600 cpm
- Temperature - 922 K
- Atmosphere - Air

Specimen Details:

Unnotched
7.62 mm width

Notched, V-Groove, K_t = 3.0
11.38 mm, gross width
7.62 mm, net width
0.56 mm, root radius, r
60° flank angle, ω.

$$K_N = 2.35,\ \rho = 0.0584\text{mm}, \quad \text{where } K_N = 1 + \frac{K_t - 1}{1 + \frac{\pi}{\pi - \omega}\sqrt{\frac{\rho}{r}}}$$

Surface Condition: Unnotched: Specimen edges were finished belt grinding with 400 grit belts and vapor mist cooling.

Notched: Notch contours were finished with a combination of milling and grinding

Both types of specimens were double aged after machining: 992 K for 8 hours, furnace cooled to 894 K holding at 894 K to complete a total of 18 hours in the furnace.

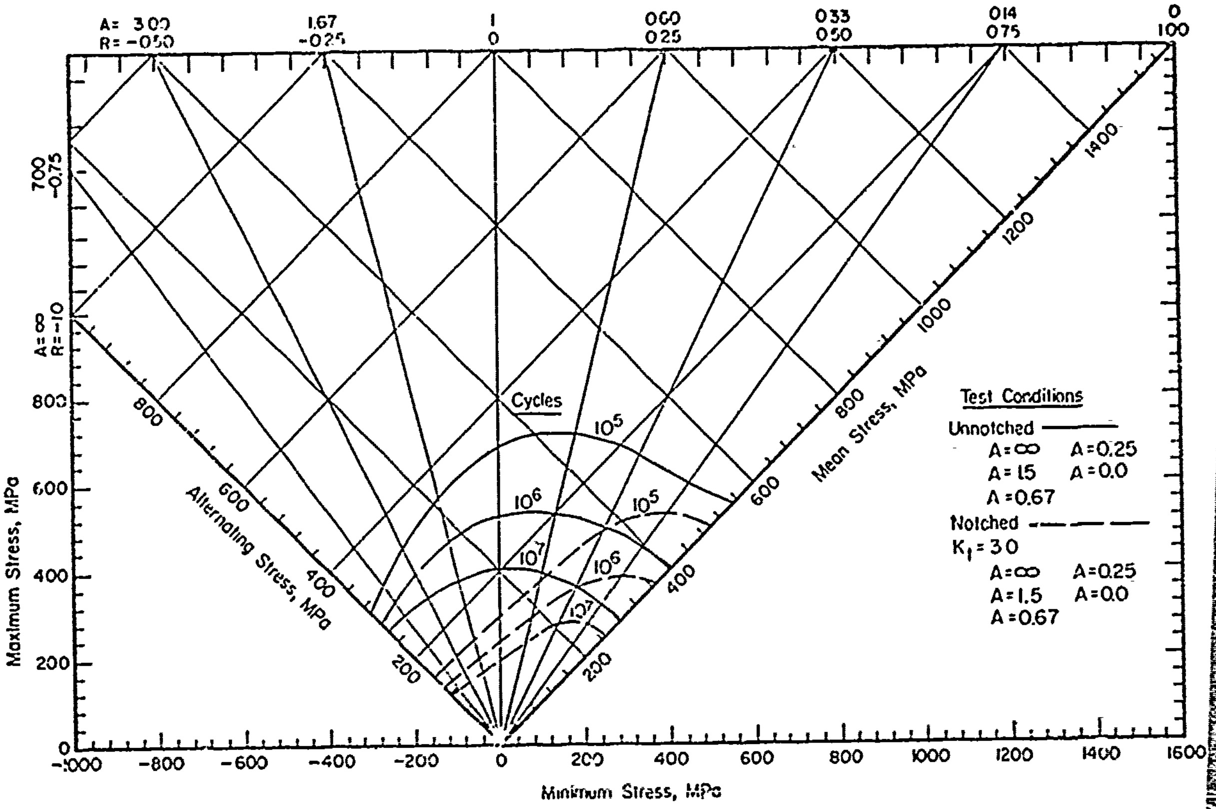


FIGURE 6.3.7.1.8(d). *Typical constant-life fatigue diagram for Inconel 718 (sheet) at* 1033 K, *long transverse direction.*

Correlative Information for Figure 6.3.7.1.8(d)

Product Form: Aged Sheet, 1.70 mm thick

Properties:

TUS, MPa	TYS, MPa	Temp, K
779	696	1033 (Unnotched)
		1033 (Notched)

Test Parameters:
Loading — Axial
Frequency — 3600 cpm
Temperature — 1033 K
Atmosphere — Air

Specimen Details:

Unnotched
7.62 mm width

Notched, Edge Type, $K_t = 3.0$
11.38 mm, gross width
7.62 mm , net width
0.56 mm , root radius, r
60° flank angle, ω

$K_N = 2.3$, $\rho = 0.0711$ mm, where $K_N = 1 + \dfrac{K_t - 1}{1 + \frac{\pi}{\pi - \omega}\sqrt{\frac{\rho}{r}}}$

Surface Condition. Unnotched. Specimen edges where finished by belt grinding with 400 grit belts and vapor mist cooling.
Notched. Notch contours were finished with a combination of milling and grinding. Both types of specimens were doubled aged after machining: 992 K for 8 hours, furnace cooled to 894 K holding at 894 K to complete a total of 18 hours in the furnace.

6.3.8 INCONEL ALLOY X-750 (Inconel X)

6.3.8.0 *Comments and Properties.*—Inconel Alloy X-750 is a high-strength oxidation-resistant nickel-base alloy. It is used for parts requiring high strength up to 811 K or high creep strength up to 1089 K and for low-stressed parts operating up to 1311 K. It is hardenable by various combinations of solution treatment and aging, depending on its form and intended application. Inconel Alloy X-750 is available in all the usual wrought mill forms.

Inconel Alloy X-750 can be readily forged between 1492 and 1311 K; "hot-cold" working between 1144 and 922 K is harmful and should be avoided. This alloy is readily formed but should be solution treated at 1325 K for 7 to 10 minutes after severe forming operations. It is somewhat more difficult to machine than the 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 1172 K for 2 hours, then aged. Nickel brazing, followed by precipitation heat treatment of the brazed assembly will result in strength nearly equal to that of fully heat-treated material.

Oxidation resistance of Inconel Alloy X-750 is good to 1311 K, but the beneficial effects of aging are lost above 1089 K. This alloy is subject to attack in sulfur-containing atmospheres.

Some material specifications for Inconel Alloy X-750 are presented in Table 6.3.8.0(a).

TABLE 6.3.8.0(a). *Material Specifications for Inconel Alloy X-750*

Specification	Form	Condition
MIL-N-7786	Sheet and strip	Annealed
MIL-N-8550	Bars and forgings	Solution treated and double aged
AMS 5667	Bars and forgings	Equalized

Three slightly different heat-treated conditions are specified for Inconel Alloy X-750. Sheet and strip are generally supplied in the mill annealed condition and, after fabrication, are aged at 978 K for 20 hours and air cooled. An alternative aging treatment, aging at 1033 K for 1 hour, produces substantially the same tensile properties as aging at 978 K for 20 hours.

The solution-treated and double-aged condition (MIL-N-8550) is specified for bars and forgings for maximum creep strength above 866 K. This condition is obtained for this material in three steps: solution treatment at 1422 K for 2 to 4 hours and cooling in air; high-temperature aging at 1116 K for 24 hours; then low-temperature aging at 978 K for 24 hours and air cooling. Cooling to room temperature between the two aging treatments is optional.

The equalized and aged condition (AMS 5667) is specified for bars and forgings for maximum tensile strength up to 866 K. This condition is obtained by equalizing at 1158 K for 24 hours and air cooling, followed by aging at 978 K for 20 hours and air cooling.

Room-Temperature Properties

Room-temperature mechanical and physical properties are shown in Table 6.3.8.0(b). Tensile properties for sheet are minimum value from MIL-N-7786. Tensile properties for bars and forgings in the equalized and aged condition are from AMS 5667. MIL-N-8550 does not specify tensile properties for bars and forgings in the full heat-treated condition. Compressive, shear, and bearing values are derived from published test data for Inconel Alloy X-750 and similar alloys. The effect of temperature on the physical properties of this alloy is shown in Figure 6.3.8.0.

6.3.8.1 *Annealed-Aged, Equalized-Aged Conditions.*—The effect-of-temperature curves for these conditions are shown in Figures 6.3.8.1.1(a) through 6.3.8.1.4.

TABLE 6.3.8.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF INCONEL ALLOY X-750

SPECIFICATION..........	MIL-N-7786	AMS 5667	
FORM..................	SHEET AND STRIP	BARS AND FORGINGS	
CONDITION..............	ANNEALED AND AGED	EQUALIZED AND AGED	
THICKNESS, MM..........	≥ 0.25	<101.60	≥ 101.60
BASIS..................	S	S[a]	S[a]
MECHANICAL PROPERTIES:			
FTU, MPA:			
L................	...	1140	1100
LT...............	1070	...	...
FTY, MPA:			
L................	...	724	689
LT...............	689	...	...
FCY, MPA:			
L................	...	724	689
LT...............	689	...	...
FSU, MPA............	696	738	717
FBRU, MPA:			
(E/D=1.5).........	1600	1650	1630
(E/D=2.0).........	2030	2100	2160
FBRY, MPA:			
(E/D=1.5).........	1030	1080	1030
(E/D=2.0).........	1240	1300	1240
EL, PERCENT:			
L................	...	20	15
LT...............	20	...	...
EL, PERCENT:			
L................	...	25	17
LT...............	...	...	...
E, GPA.............	213.7		
EC, GPA............	213.7		
G, GPA.............	75.8		
MU.................	...		
PHYSICAL PROPERTIES:			
OMEGA, MG/M3.........	8.30		
C, J/(G*K)...........	SEE FIGURE 6.3.8.0		
K, W/(M*K)...........	SEE FIGURE 6.3.8.0		
ALPHA, 10-6 M/(M*K)..	SEE FIGURE 6.3.8.0		

[a]GRAIN DIRECTION NOT SPECIFIED.

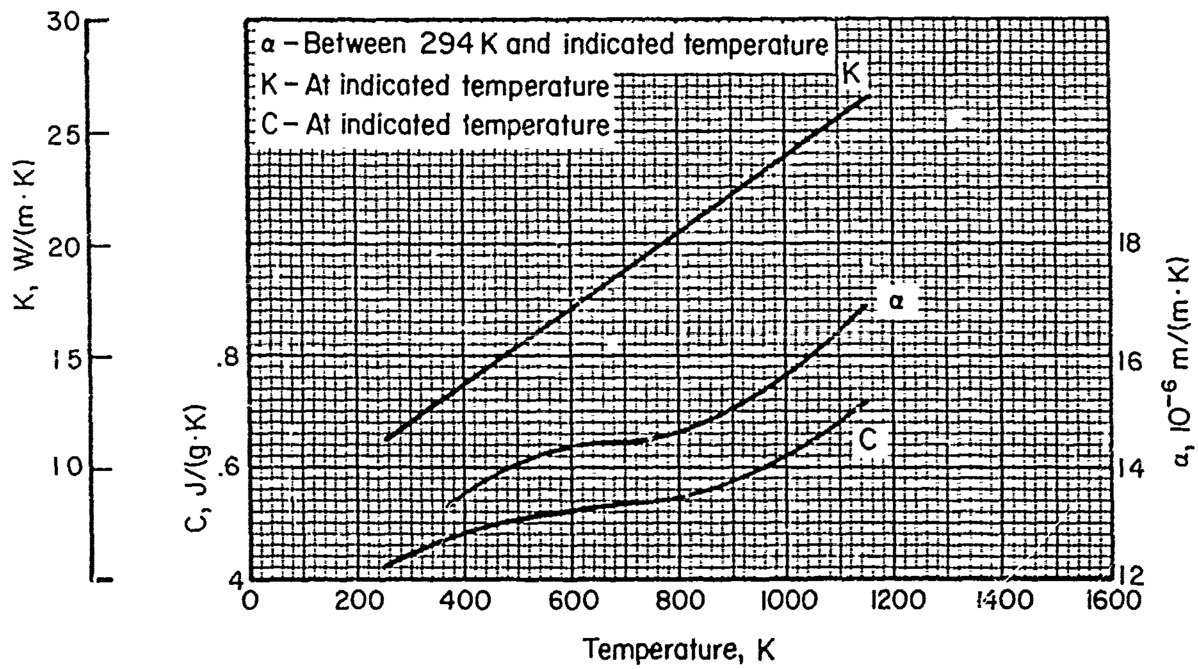


FIGURE 6.3.8.0. Effect of temperature on the physical properties of Inconel Alloy X-750.

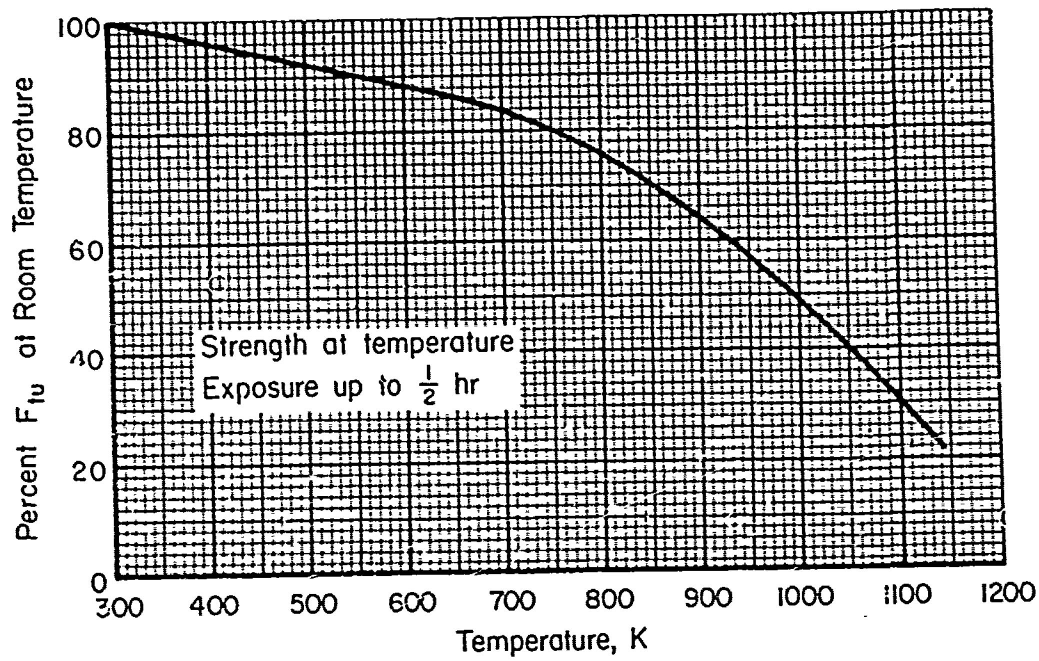


FIGURE 6.3.8.1.1.(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of Inconel X-750 Alloy.

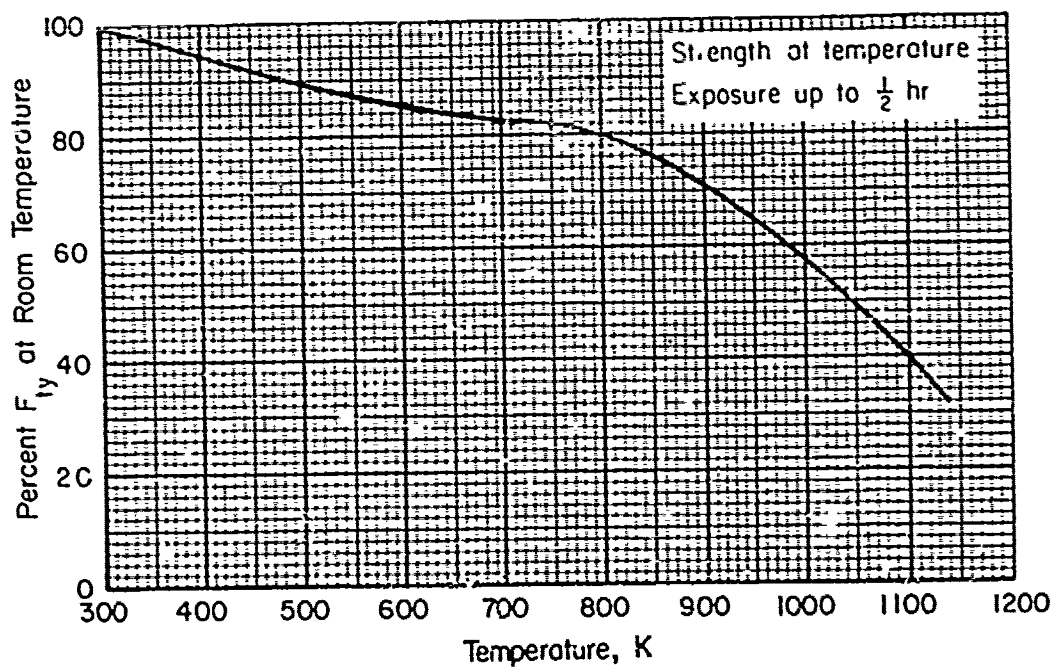


FIGURE 6.3.8.1 1(b). Effect of temperature on the tensile yield strength (F_{ty}) of Inconel Alloy X-750.

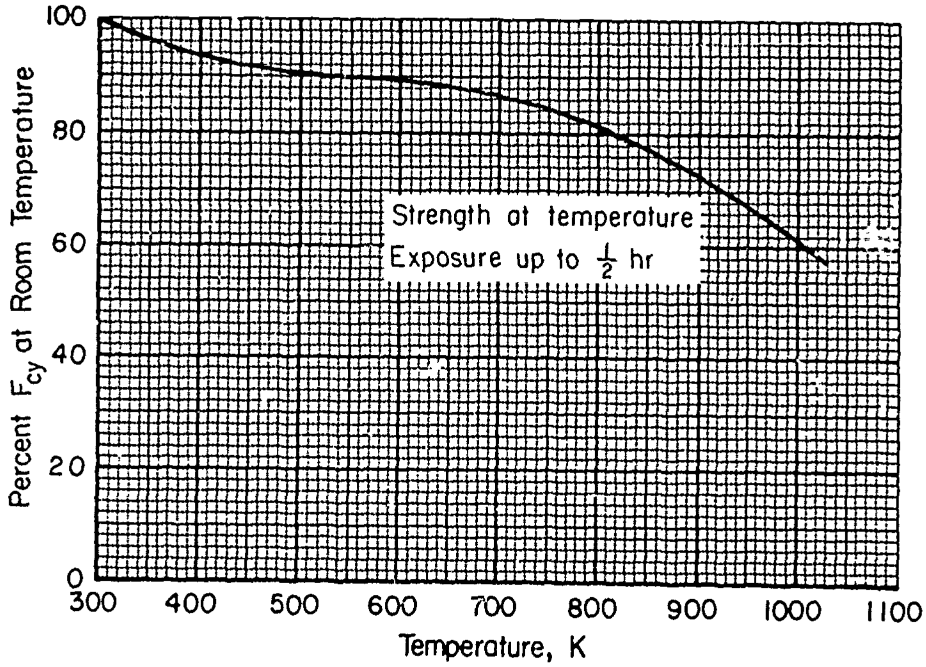


FIGURE 6.3.8.1.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of Inconel Alloy X-750.

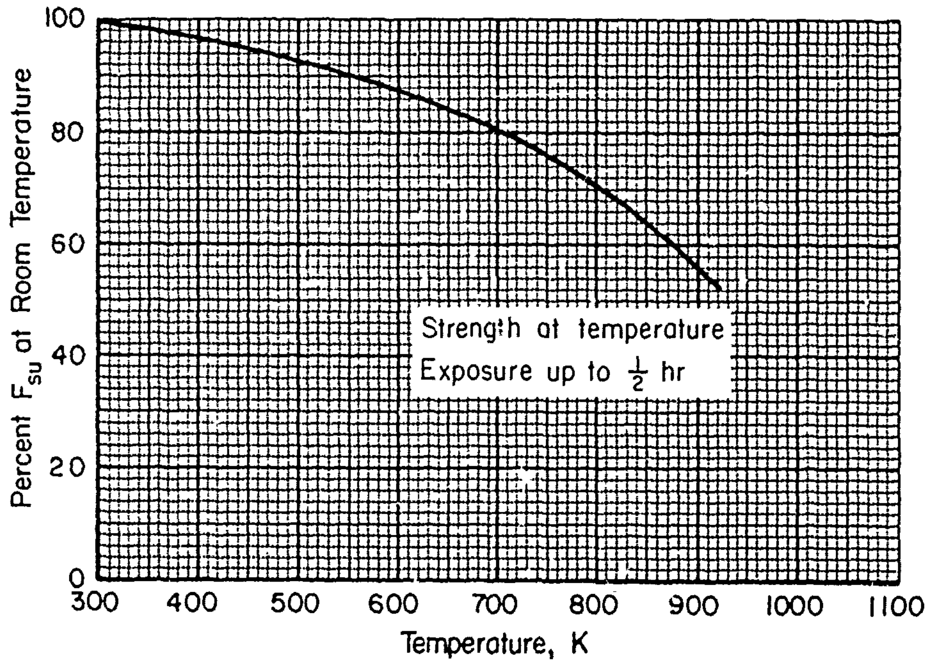


FIGURE 6.3.8.1.2(b). Effect of temperature on the ultimate shear strength (F_{su}) of Inconel Alloy X-750.

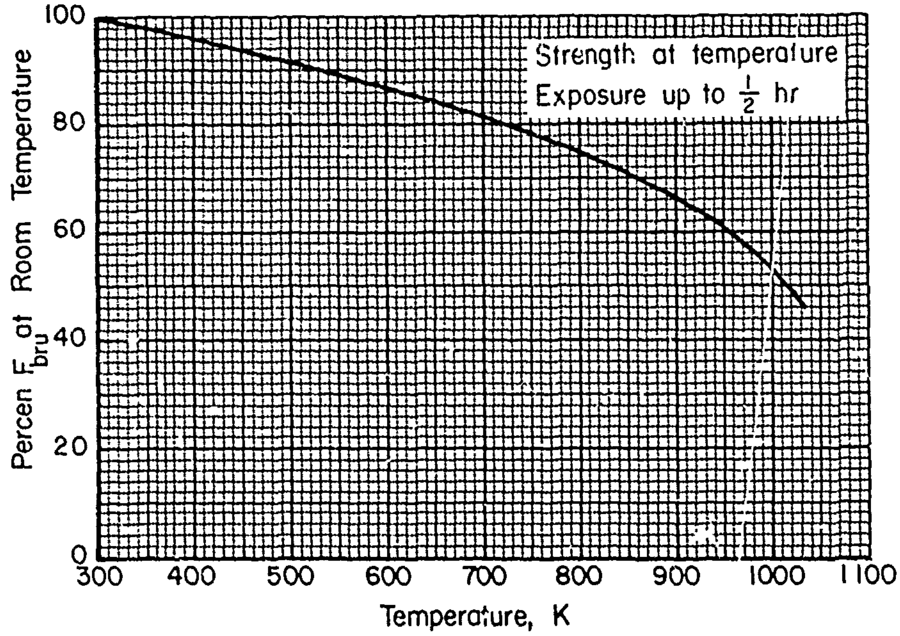


FIGURE 6.3.8.1.3(a). Effect of temperature on the ultimate bearing strength (F_{bru}) of Inconel Alloy X-750.

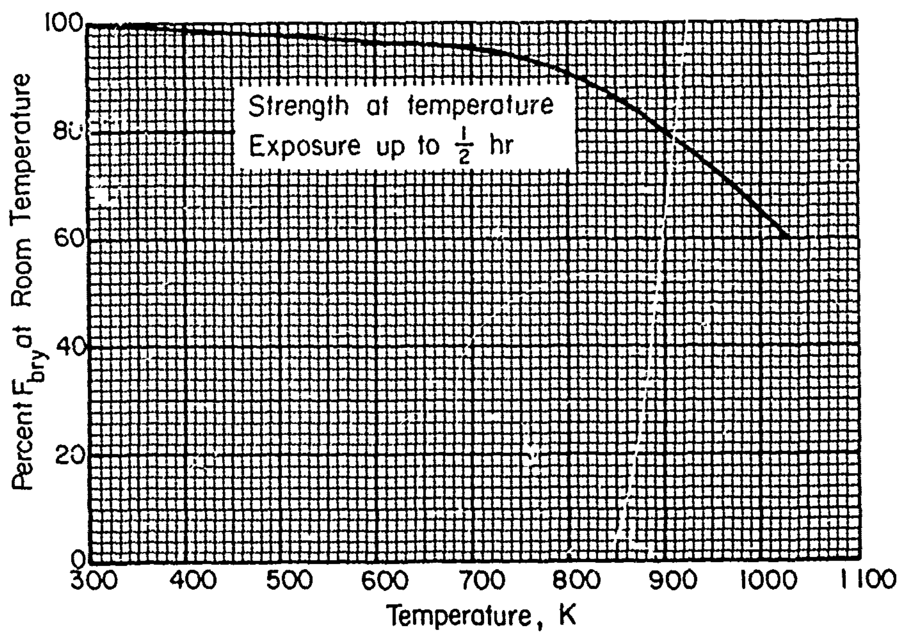


FIGURE 6.3.8.1.3(b). Effect of temperature on the bearing yield strength (F_{bry}) of Inconel Alloy X-750.

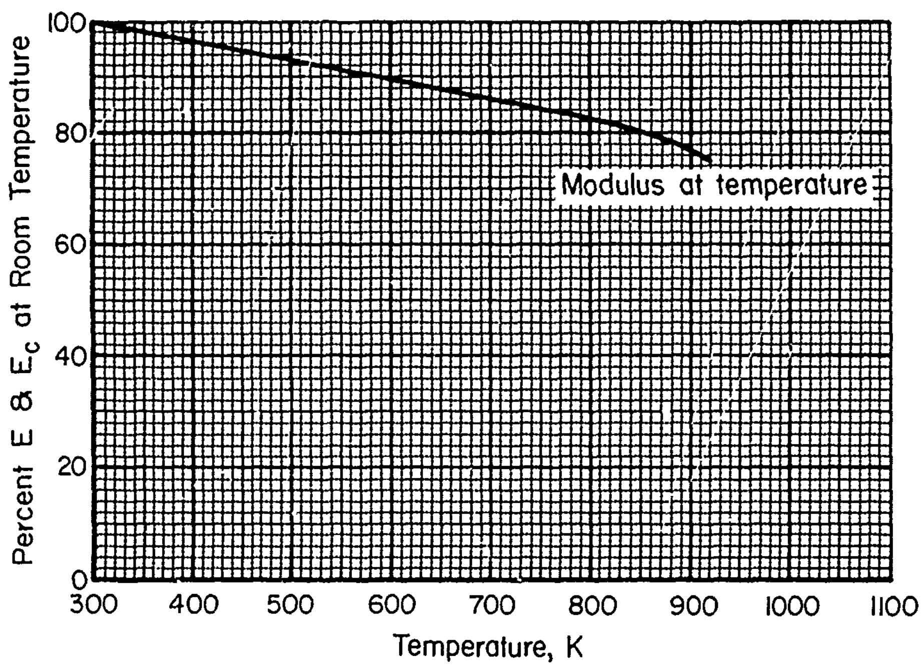


FIGURE 6.3.8.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of Inconel Alloy X-750.

6.3.9 M-252 ALLOY

6.3.9.0 *Comments and Properties.*—M-252 is a vacuum-melted precipitation-hardening nickel-base alloy designed for highly stressed parts operating up to 1089 K. It is used for jet-engine and gas-turbine buckets and for high-temperature bolting. M-252 is primarily a forging alloy but is available in all wrought mill forms.

M-252 is difficult to forge. Its forging range is 1450 to 1255 K; its hot short (brittle) just above the forging range; light reductions (1 to 10 percent) below about 1255 K cause excessive gain growth in the subsequent heat treatment and should be avoided. M-252 is seldom formed cold; it work hardens very rapidly, and frequent anneals are required. This alloy is very difficult to machine; heavy machine tools and sharp tungsten carbide cutting tools should be used; for drilling and tapping operations, the alloy should be in the solution-treated condition. Weldability of M-252 is comparable with that of the austenitic stainless steels and it should be welded in the solution-treated condition. The alloy may display hot-shortness and be sensitive to strain cracking.

M-252 exhibits very good resistance to jet-engine gases up to 1144 K.

Some material specifications for M-252 are presented in Table 6.3.9.0(a).

TABLE 6.3.9.0(a). *Material Specifications for M-252 Alloy*

Specification	Form	Condition
AMS 5551	Sheet and strip	Solution treated
AMS 5757	Bars and forgings	Solution treated and aged

Room-Temperature Properties

Room-temperature mechanical and physical properties are presented in Table 6.3.9.0(b). Figure 6.3.9.0 presents effect-of-temperature curves for physical properties.

6.3.9.1 *Solution Treated at* 1353 K *and Aged at* 1172 K *Condition.*—Tensile properties at 1089 K are specified for M-252 sheet. The appropriate specification should be consulted for detailed requirements.

6.3.9.2 *Solution Treated at* 1339 K *and Aged at* 1033 K *Condition.*—Stress-rupture properties at 1089 K are specified for bars and forgings; the appropriate specifications should be consulted for detailed requirements. Other elevated-temperature data for this condition are presented in Figures 6.3.9.2.1(a) through 6.3.9.2.8(b). These figures are derived from data for both sheet and bars in this condition.

TABLE 6.3.9.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF M-252 ALLOY

SPECIFICATION	AMS 5551	AMS 5757
FORM	SHEET AND STRIP	BARS AND FORGINGS
CONDITION	SOLUTION TREATED AND AGED	
THICKNESS, MM	...	...
BASIS	S[a]	S[b]
MECHANICAL PROPERTIES:		
FTU, MPA:		
L	...	1140
LT	1100	...
FTY, MPA:		
L	...	758
LT	689	...
FCY, MPA:		
L	...	...
LT	...	...
FSU, MPA	...	...
FBRU, MPA:		
(E/D=1.5)	...	...
(E/D=2.0)	...	...
FBRY, MPA:		
(E/D=1.5)	...	...
(E/D=2.0)	...	...
EL, PERCENT:		
L	...	15
LT	10	...
EL, PERCENT:		
L	...	18
LT	...	...
E, GPA	217.2	
EC, GPA	...	
G, GPA	...	
MU	...	
PHYSICAL PROPERTIES:		
OMEGA, MG/M3	8.25	
C, J/(G*K)	SEE FIGURE 6.3.9.0	
K, W/(M*K)	SEE FIGURE 6.3.9.0	
ALPHA, 10-6 M/(M*K)	SEE FIGURE 6.3.9.0	

[a] TEST DIRECTION LONGITUDINAL FOR WIDTHS LESS THAN 229 MM; TRANSVERSE FOR WIDTHS 229 MM AND OVER.
[b] GRAIN DIRECTION NOT SPECIFIED.

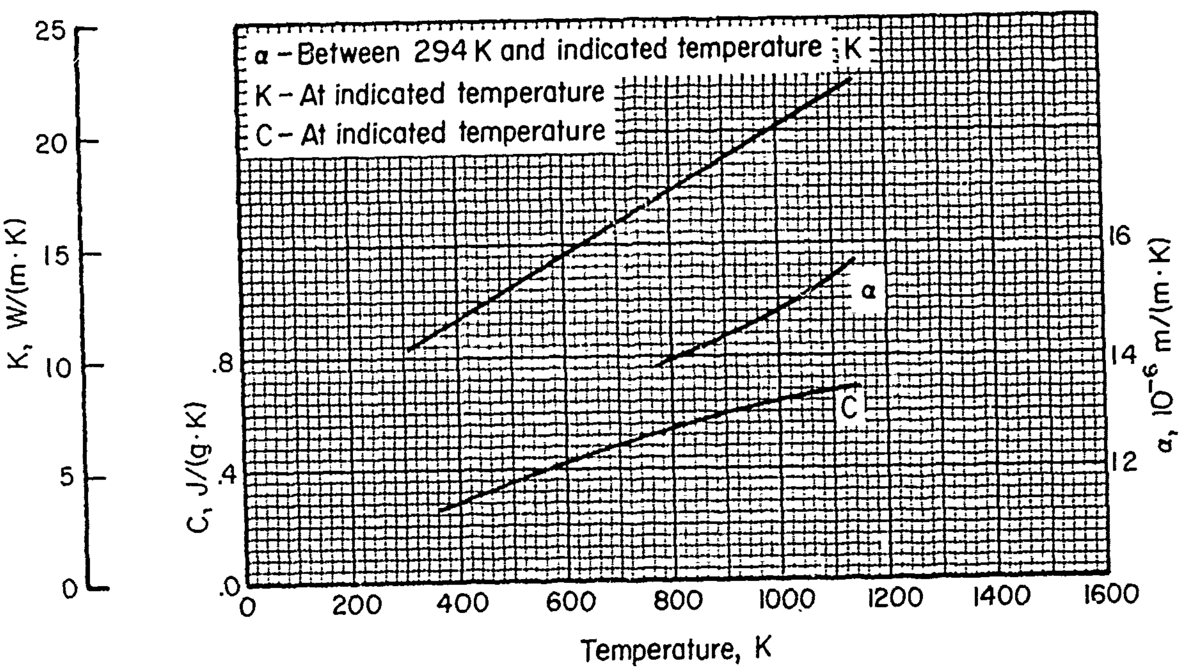


FIGURE 6.3.9.0. Effect of temperature on the physical properties of M-252 alloy.

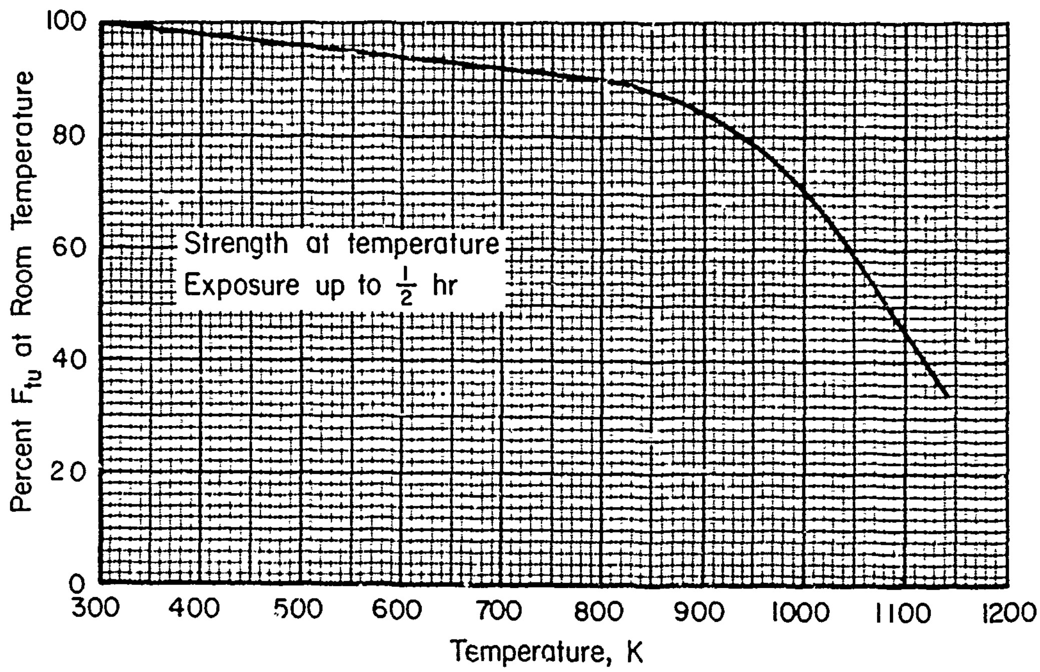


FIGURE 6.3.9.2.1.(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of M-252 Alloy.

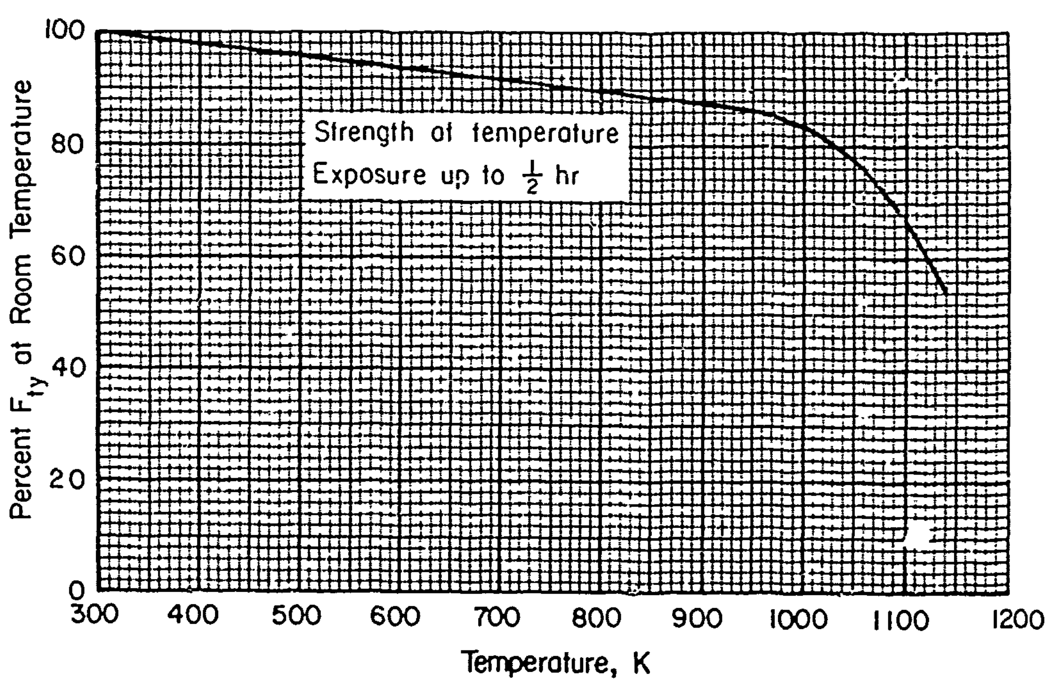


FIGURE 6.3.9.2.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of M-252 alloy.

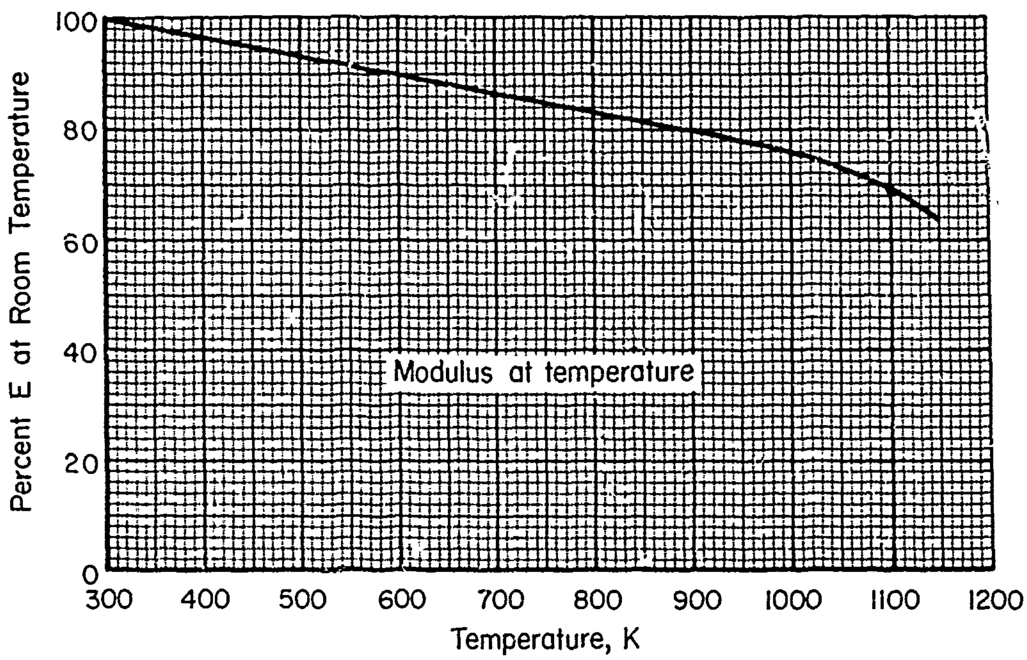


FIGURE 6.3.9.2.4. Effect of temperature on the tensile modulus (E) of M-252 Alloy.

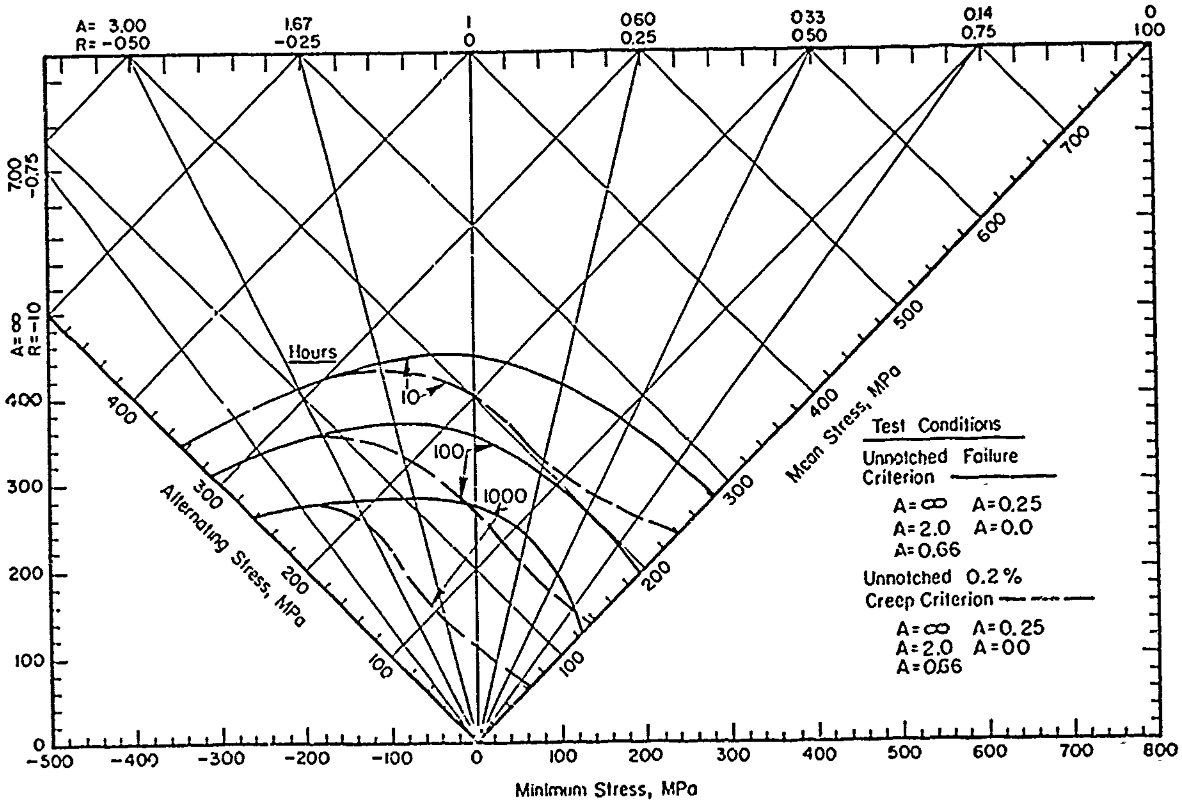


FIGURE 6.3.9.2.8(a). Typical constant-life diagram for fatigue and dynamic creep behavior of solution treated and aged M-252 forgings at 1089 K

Correlative Information for Figure 6.3.9.2.8(a)

Product Form: Forged bar, 44.5 mm diameter

Properties:

TUS, MPa	TYS, MPa	Temp, K
1214	690	RT
690	503	1089

Specimen Details: Unnotched
6.35 mm diameter

Surface Condition. Longitudinally polished with 240,000 and 600 grit belts to provide surface finish of 5-8 RMS.
Heat treatment included solution treatment at 1339 K for 4 hours, air cooled; aging at 1033 K for 15 hours (packed in cast iron chips), air cooled.

Test Parameters:
- Loading — Axial
- Frequency — 1800 cpm
- Temperature — 1089 K
- Atmosphere — Air

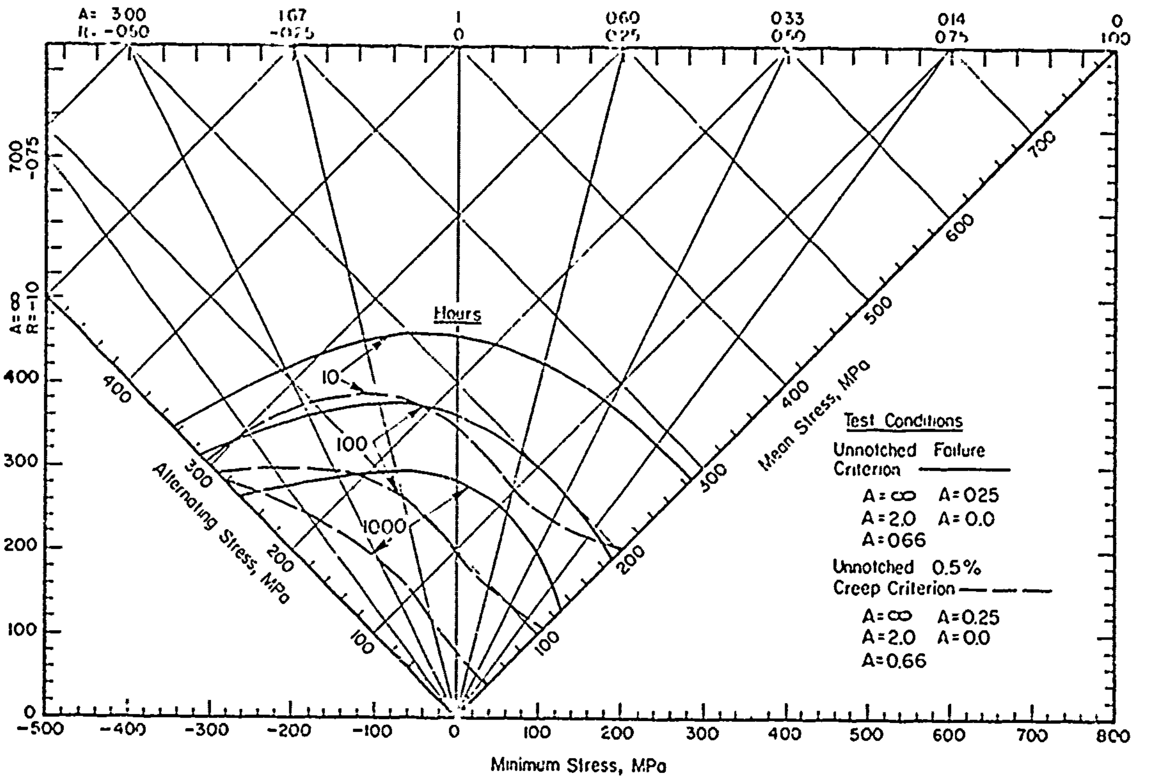


FIGURE 6.3.9.2.8(b). Typical constant-life diagram for fatigue and dynamic creep behavior of solution treated and aged M-252 forgings at 1089 K

Correlative Information for Figure 6.3.9.2.8(b)

roduct Form: Forged bar, 44.5 mm diameter

Test Parameters:
Loading — Axial
Frequency — 1800 cpm
Temperature — 1089 K
Atmosphere — Air

operties:

TUS, MPa	TYS, MPa	Temp, K
1214	690	RT
690	503	1089

:cimen Details: Unnotched
6.35 mm diameter

'face Condition Longitudinally polished with 240, 400 and 600 grit belts to provide surface finish of 5-8 RMS.
Heat treatment included solution treatment at 1339K for 4 hours, air cooled: aging at 1033K for 15 hours (packed in cast iron chips), air cooled.

6.3.10 RENÉ 41

6.3.10.0 *Comments and Properties.*—René 41 is a vacuum-melted precipitation-hardening nickel-base alloy designed for highly stressed parts operating between 922 and 1255K. 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 1450 and 1311K; small reductions must be made when breaking up an as-cast structure; cracking may be encountered in finishing below 1283 K. René 41 works hardens very rapidly, and frequent anneals are required; to anneal, heat rapidly to 1339 K 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 1394 K during the latter stages of hot working or during subsequent operations, otherwise, severe intergranular cracking may be encountered.

The oxidation resistance of René 41 is good up to 1255 K. Lengthy exposure above the aging temperature (1033 to 1172K) will result in substantial loss of strength and room-temperature ductility.

Some material specifications for René 41 are presented in Table 6.3.10.0(a).

TABLE 6.3.10.0(a). *Material Specifications for René 41 Alloy*

Specification	Form	Condition
AMS 5545	Plate, sheet, and strip	Vacuum melted, solution treated
AMS 5713	Bars and forgings	Vacuum melted, solution treated and aged

Two different heat treatments are commonly recommended for René 41.

(1) Solution treating at 1339 K for 2/2 hour and air cooling*; then again at 1033 K for 16 hours and air cooling.

(2) Solution treating at 1394 K for 1/2 hour and air cooling; then aging at 1172 K for 4 hours and air cooling.

The first heat treatment (1033 K age) is used to produce optimum strength properties at 1033 K and below. The second heat treatment (1172 K age) is preferred for application above 1033 K because it provides better dimensional stability at these temperatures.

Room-Temperature Properties

Room-temperature mechanical and physical properties are shown in Table 6.3.10.0(b). The effect of temperature on physical properties is shown in Figure 6.3.10.0. Compressive, shear, and bearing values are derived from published data for René 1 and similar alloys.

6.3.10.1 *Aged at* 1033 K *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 6.3.10.1.1(a) through 6.3.10.1.5. A creep nomograph for René 41 alloy sheet is shown in Figure 6.3.10.1.7.

* Current AMS specifications require solution treating at 1353 K for at least 60 minutes per 25 mm of thickness and rapid cooling in air blast or quenching in oil or water.

TABLE 6.3.10.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF RENÉ 41 ALLOY.

SPECIFICATION............	AMS 5545				AMS 5713	
FORM....................	SHEET AND STRIP			PLATE	BARS, FORGINGS	
CONDITION...............	SOLUTION TREATED AND AGED (1033 K)					
THICKNESS, MM...........	0.13 0.49	0.50- 4.75		> 4.75	...	
BASIS...................	S	A	B	S	A	B
MECHANICAL PROPERTIES:						
FTU, MPA:						
L.................	1170	1170[a]	1280	1170	1170	1250
LT................	1170	1170[a]	1280	1170	...	...
FTY, MPA:						
L.................	896	848	910	896	736	862
LT................	696	848	910	896	...	...
FCY, MPA:						
L.................	...	903	972	779	738	862
LT................	...	945	1010	807	...	...
FSU, MPA..............	...	745	814	814	758	807
FBRU, MPA:						
(E/D=1.5).........	...	1680	1830	1740	...	...
(E/D=2.0).........	...	2060	2240	2190	2230	2380
FBRY, MPA:						
(E/D=1.5).........	...	1320	1410	1440	...	...
(E/D=2.0).........	...	1600	1720	1740	1320	1550
EL, PERCENT:						
L.................	...	10	...	10	...	...
LT................	...	...	...	...	8	...
E, GPA................	217.9					
EC, GPA...............	217.9					
G, GPA................	83.4					
MU....................	0.31					
PHYSICAL PROPERTIES:						
OMEGA, MG/M3..........	8.25					
C, J/(G*K)............	SEE FIGURE 6.3.10.0					
K, W/(M*K)............	SEE FIGURE 6.3.10.0					
ALPHA, 10-6 M/(M*K)..	SEE FIGURE 6.3.10.0					

[a] THE A VALUE IS HIGHER THAN SPECIFICATION AS FOLLOWS: FTU = 1227 MPA.

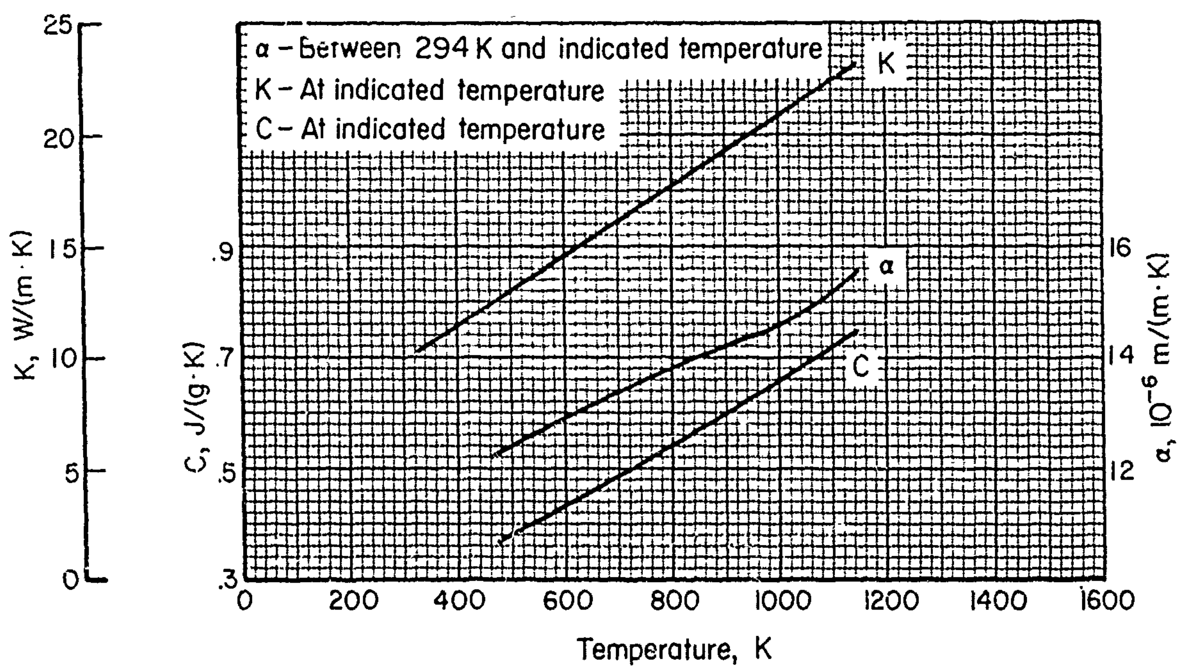


FIGURE 6.3.10.0. Effect of temperature on the physical properties of René 41 alloy.

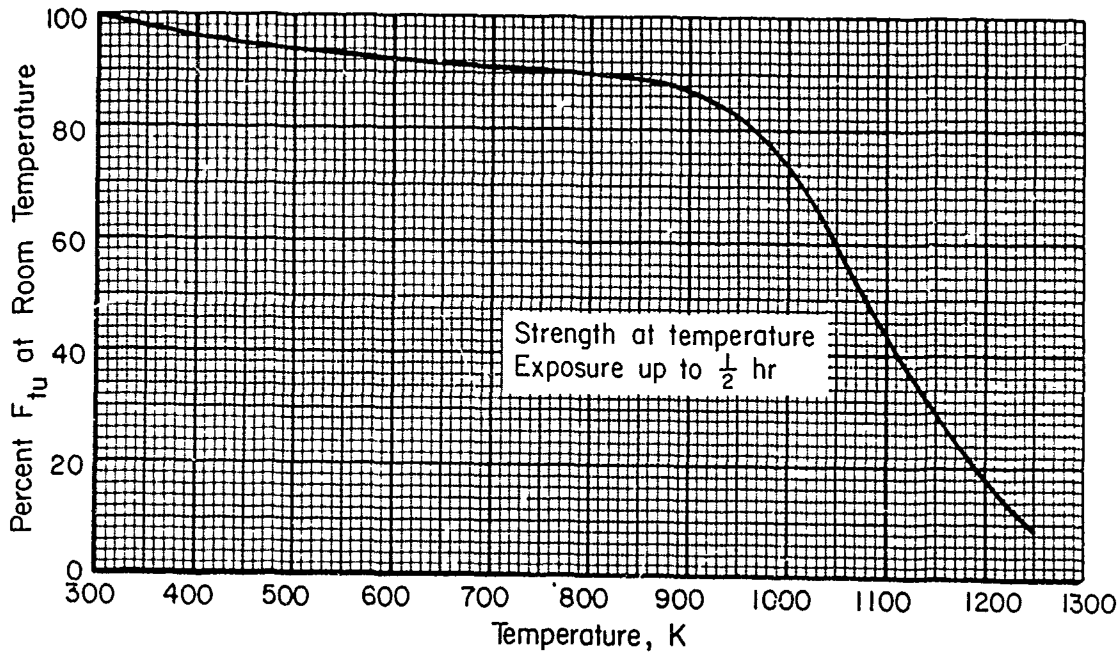


FIGURE 6.3.10.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of René 41 alloy.

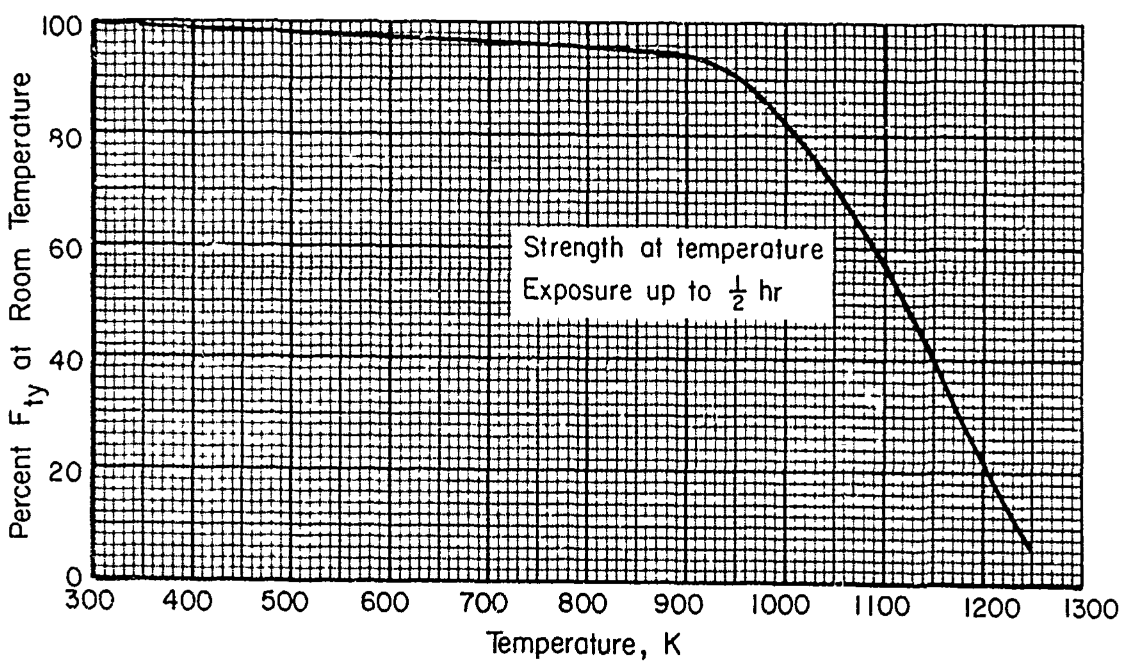


FIGURE 6.3.10.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of René 41 alloy.

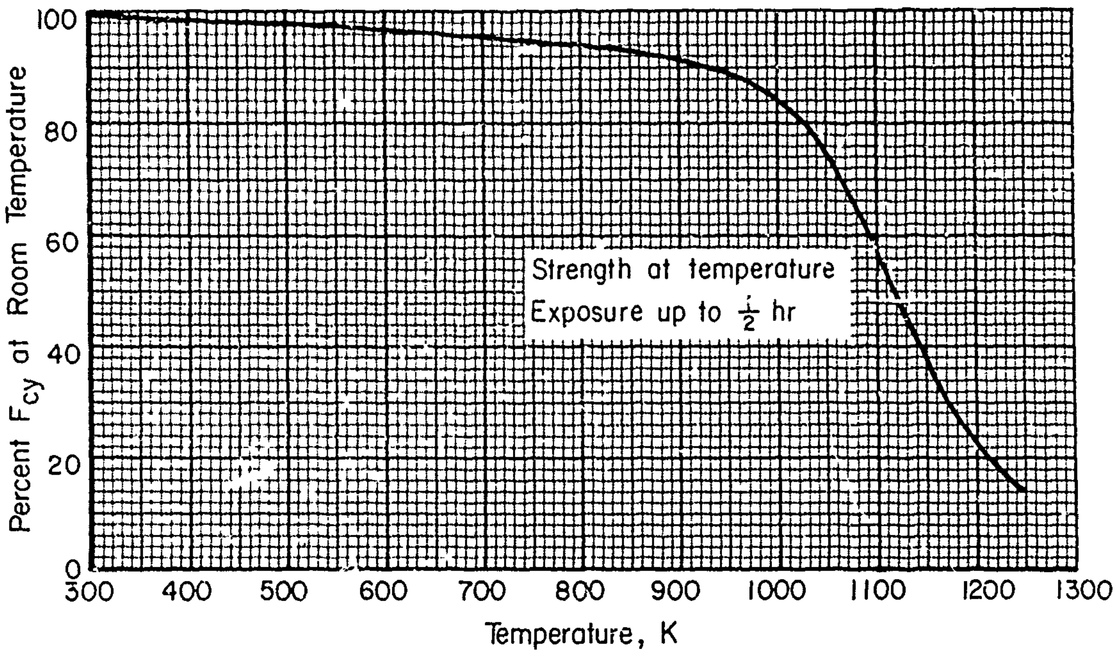


FIGURE 6.3.10.1.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of René 41 alloy.

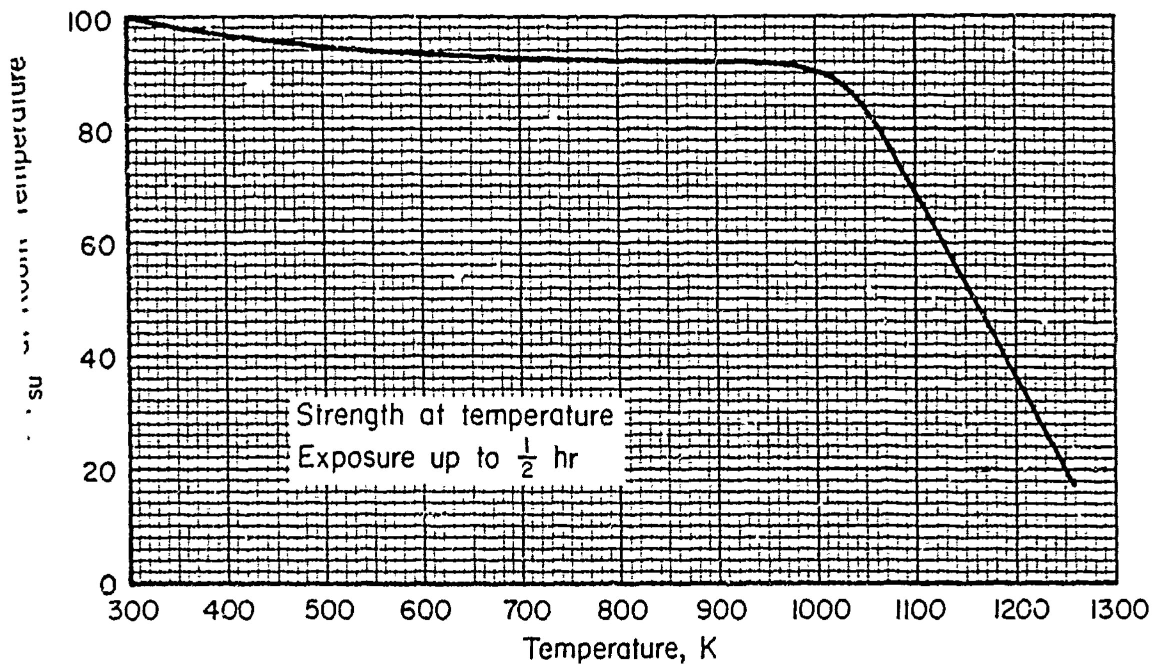


FIGURE 6.3.10.1.2(b). Effect of temperature on the ultimate shear strength (F_{su}) of René 41 alloy.

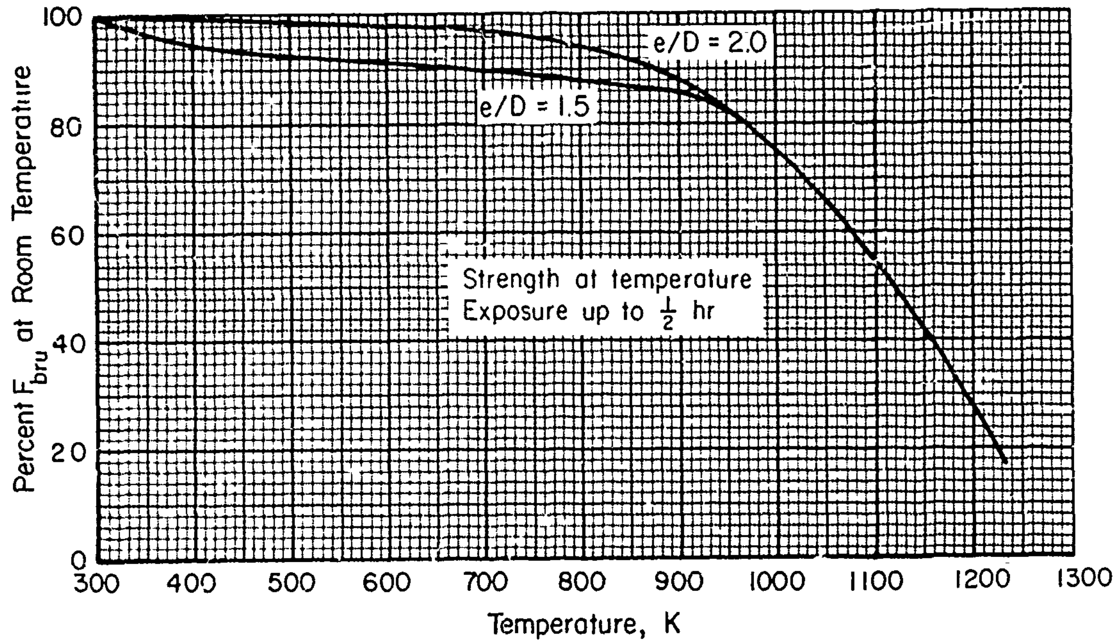


FIGURE 6.3.10.1.3(a). Effect of temperature on the ultimate bearing strength (F_{bru}) of René 41 alloy.

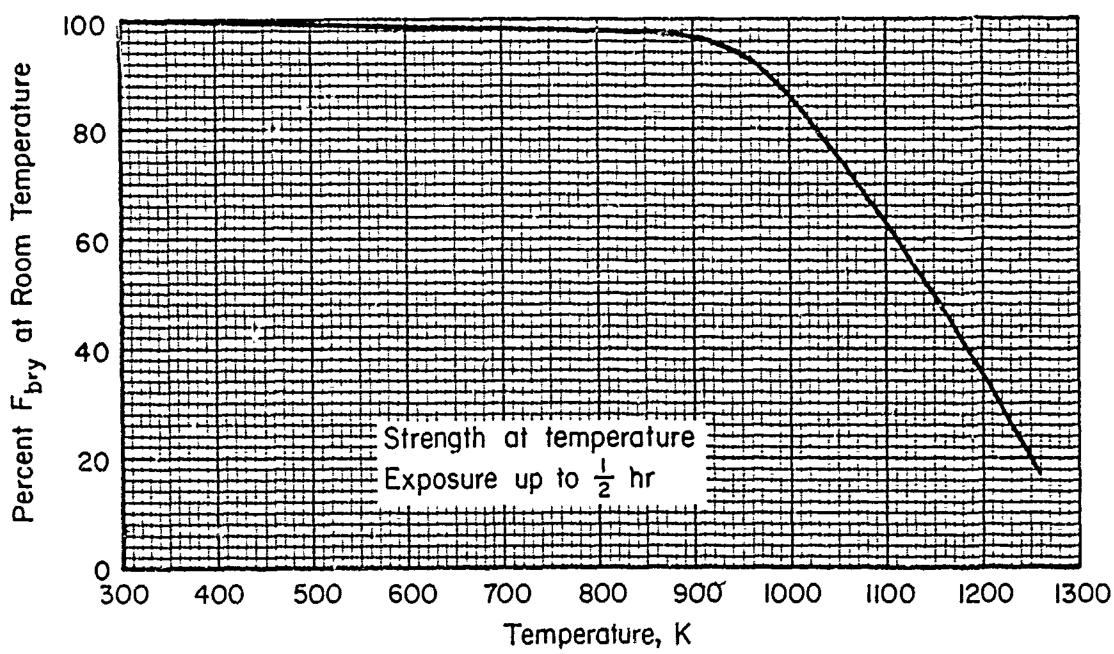


FIGURE 6.3.10.1.3(b) Effect of temperature on the bearing yield strength (F_{bry}) of René 41 alloy.

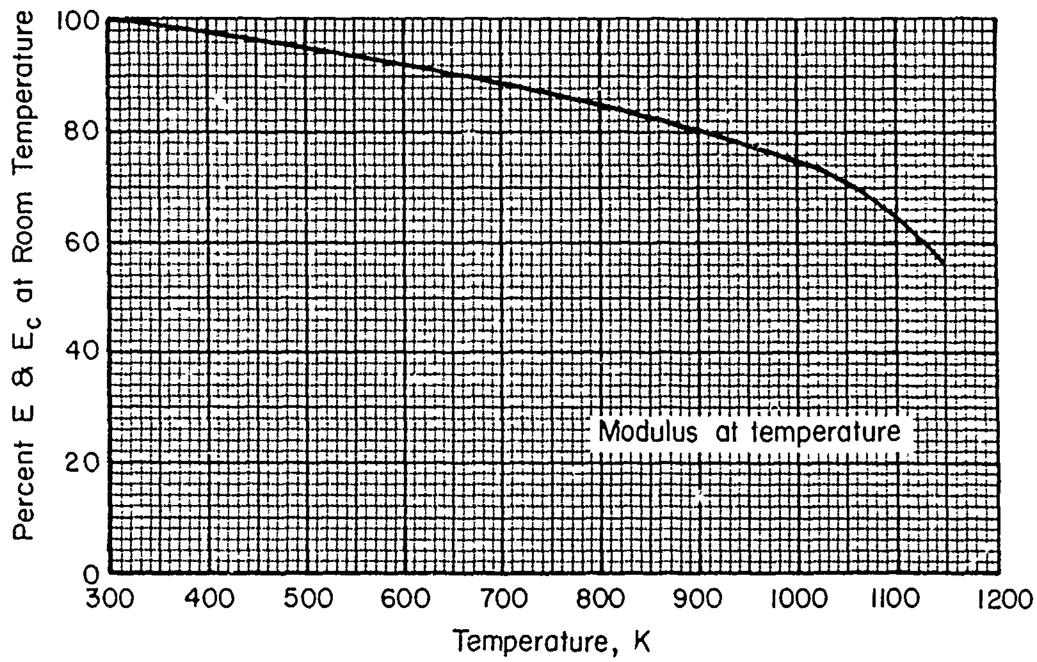


FIGURE 6.3.10.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of René 41 alloy.

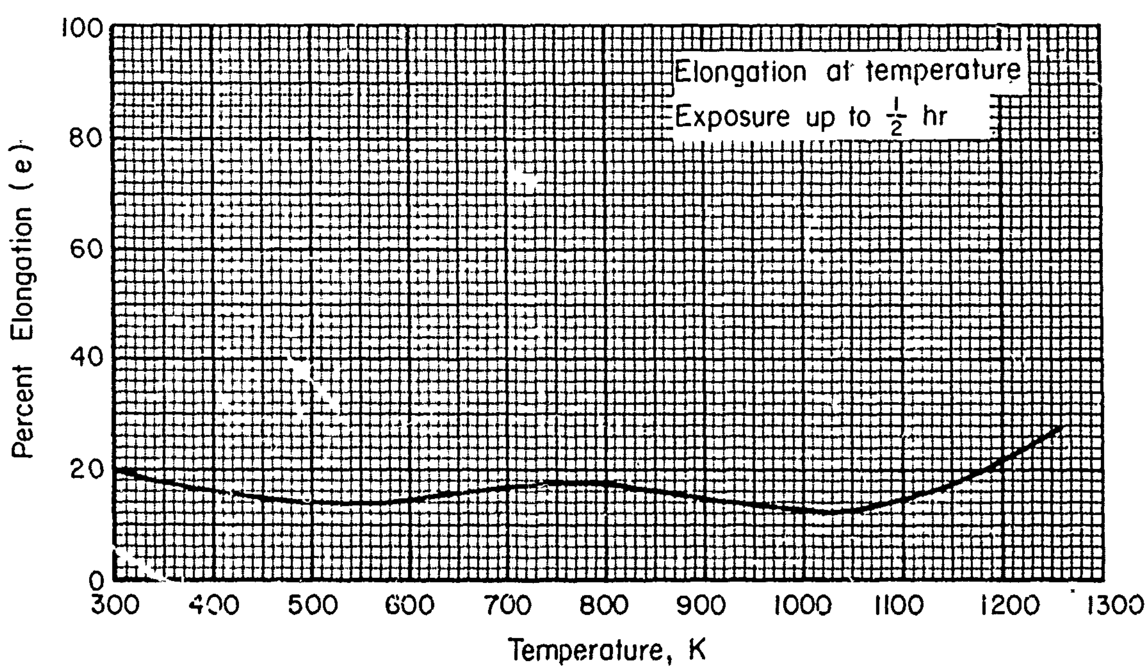


FIGURE 6.3.10.1.5. Effect of temperature on the elongation (e) of René 41 alloy (>.508 thickness).

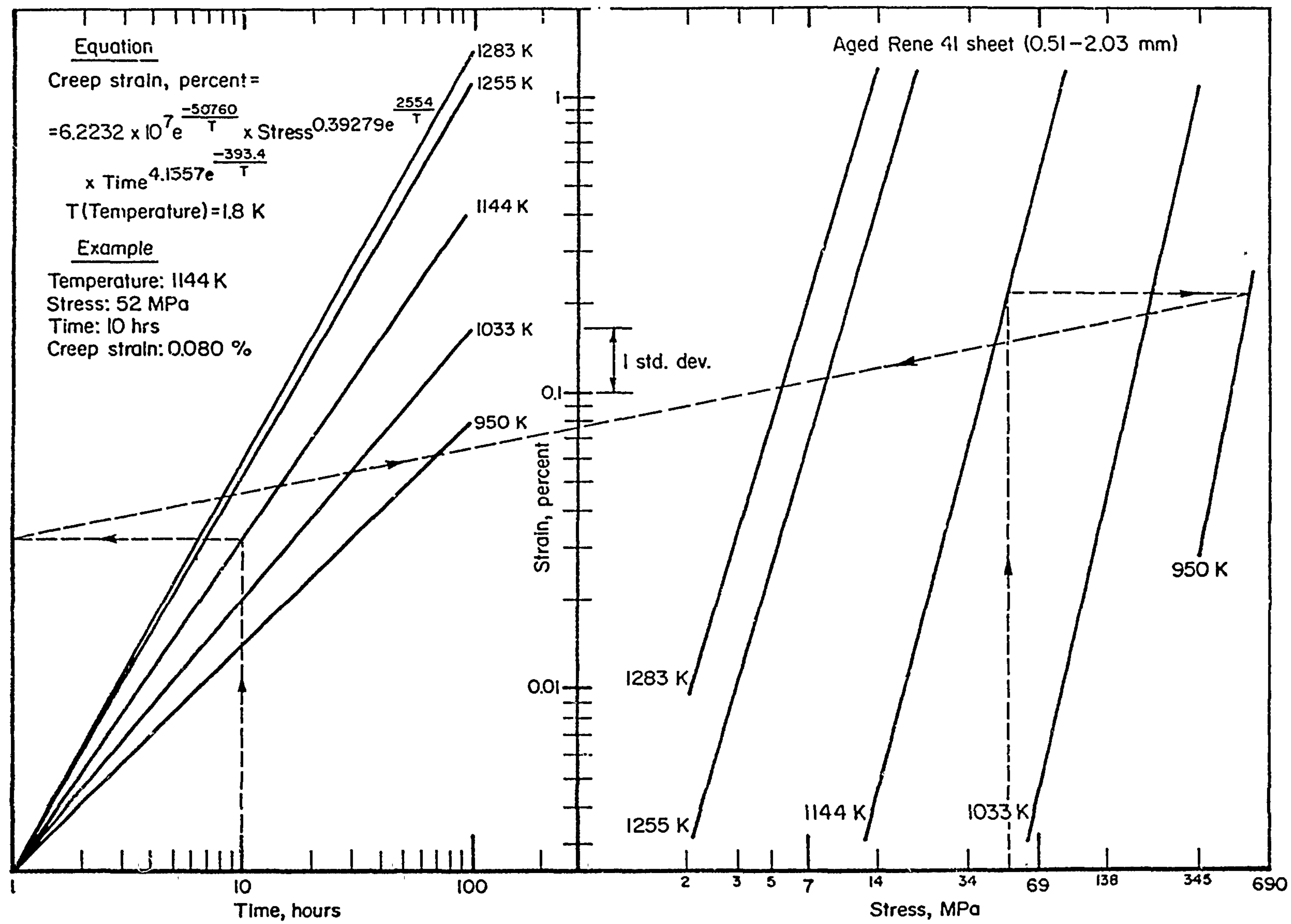


FIGURE 6.3.10.1.7. Typical creep properties of René 41 alloy (sheet).

6.3.11 UDIMET 500

6.3.11.0 *Comments and Properties.*— Udimet 500 is a vacuum-melted age-hardenable nickel-base alloy possessing high strength up to 1144 K and oxidation resistance up to 1255 K. It is designed primarily for gas-turbine applications, such as blades, bolts, and other highly stressed parts. It is available in all the usual mill forms.

Udimet 500 must be handled very carefully during forging operations because of its tendency to crack. It has a narrow hot-working range extending from 1450 to 1311 K. Cold forming is usually not considered for this alloy; it has limited formability in the solution-treated condition and requires frequent anneals. Because of its strength and work-hardening characteristics, Udimet 500 is very difficult to machine, and grinding is usually required for finish machining. Optimum machinability is obtained in the solution-treated condition, although the aged condition may be required in finish machining; heavy machine tools and sharp carbide cutting tools are required. Welding should be done only in the solution-treated condition. This alloy may exhibit hot-shortness and be sensitive to strain cracking. Weldments will have lower strength than the heat-treated material and should be located in low-stress areas.

Udimet 500 possesses excellent resistance to attack by jet-engine gases up to 1172 K. It forms a strong, closely adherent oxide film which protects it from progressive attack.

Some material specifications for Udimet 500 are presented in Table 6.3.11.0(a).

TABLE 6.3.11.0(a). *Material Specifications for Udimet 500 Alloy*

Specification	Form	Condition
AMS 5751	Bars and forgings	Solution treated, stabilized and aged
AMS 5753	Bars and forgings	Solution treated

Room-Temperature Properties

Mechanical properties at room temperature are not specified for this alloy. Consequently, values were derived for room-temperature properties from such considerations as specified minimum tensile properties at 922 K, ratios of tensile ultimate and yield strengths at 922 K to those at room temperature, and producers' typical and guaranteed minimum tensile properties. These values are presented in Table 6.3.11.0(b). Compression, shear, and bearing values were derived from published data for Udimet 500 and similar alloys. The effect of temperature on physical properties is shown in Figure 6.3.11.0.

6.3.11.1 *Solution-Treated, Stabilized, and Aged Condition.*—Elevated-temperature tensile and stress-rupture requirements are specified for this alloy. The appropriate AMS specification should be consulted for detailed requirements. Other elevated-temperature property data for Udimet 500 are presented in Figures 6.3.11.1.1(a) through 6.3.11.1.8(b).

TABLE 6.3.11.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF UDIMET 500 ALLOY

SPECIFICATION	AMS 5751
FORM	BARS AND FORGINGS
CONDITION	SOLUTION TREATED, STABILIZED, AND AGED
BASIS	DERIVED VALUES (SEE TEXT)
MECHANICAL PROPERTIES:	
FTU, MPA	1280
FTY, MPA	827
FCY, MPA	827
FSU, MPA	827
FBRU, MPA:	
(E/D=1.5)	...
(E/D=2.0)	2420
FBRY, MPA:	
(E/D=1.5)	...
(E/D=2.0)	1490
EL, PERCENT	10
E, GPA	213.7
EC, GPA	...
G, GPA	...
MU	...
PHYSICAL PROPERTIES:	
OMEGA, MG/M3	8.03
C, J/(G*K)	SEE FIGURE 6.3.11.0
K, W/(M*K)	SEE FIGURE 6.3.11.0
ALPHA, 10-6 M/(M*K)	SEE FIGURE 6.3.11.0

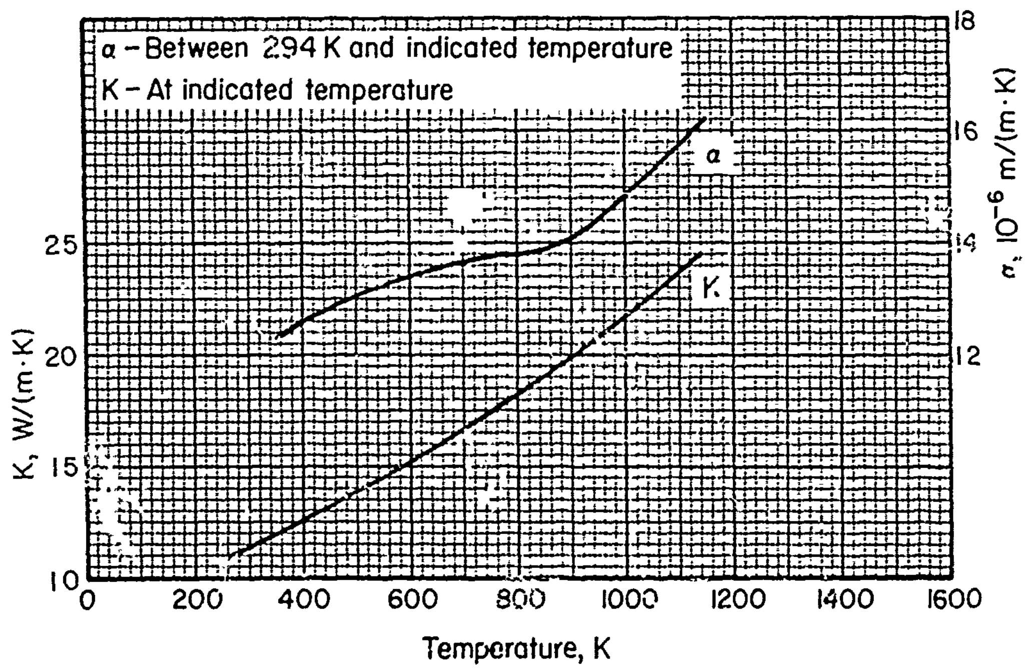


FIGURE 6.3.11.0. Effect of temperature on the physical properties of Udimet 500 alloy.

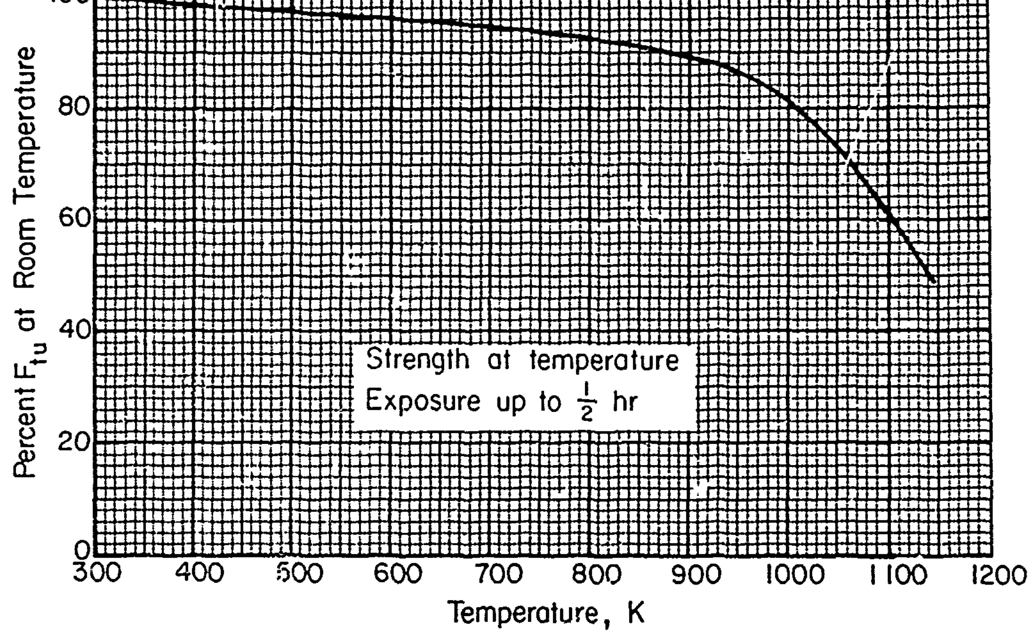


FIGURE 6.3.11.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of Udimet 500 alloy.

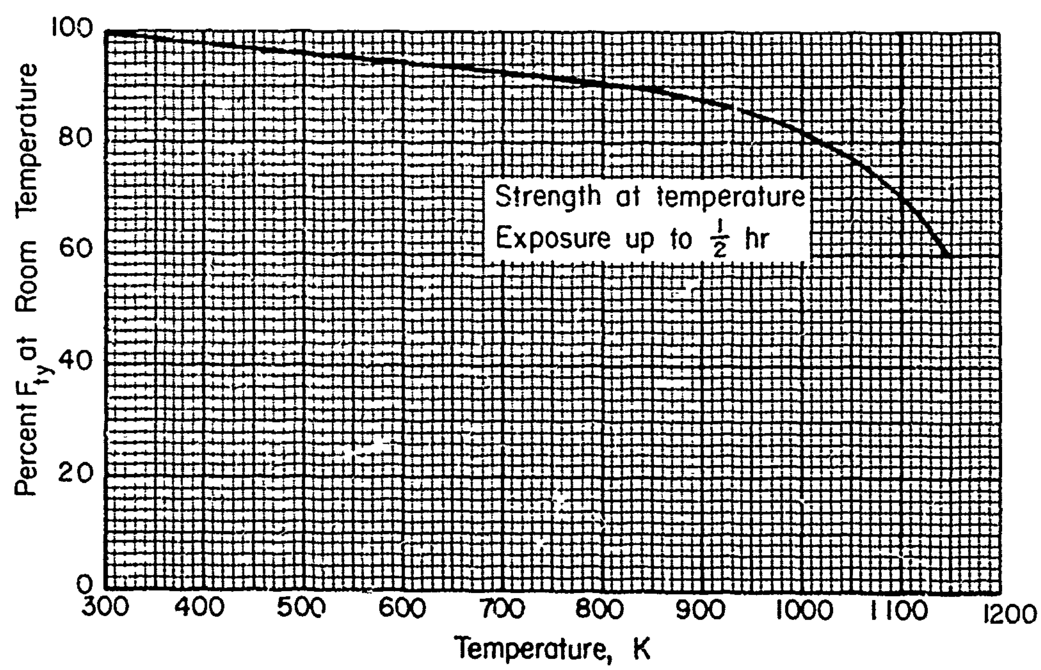


FIGURE 6.3.11.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of Udimet 500 alloy.

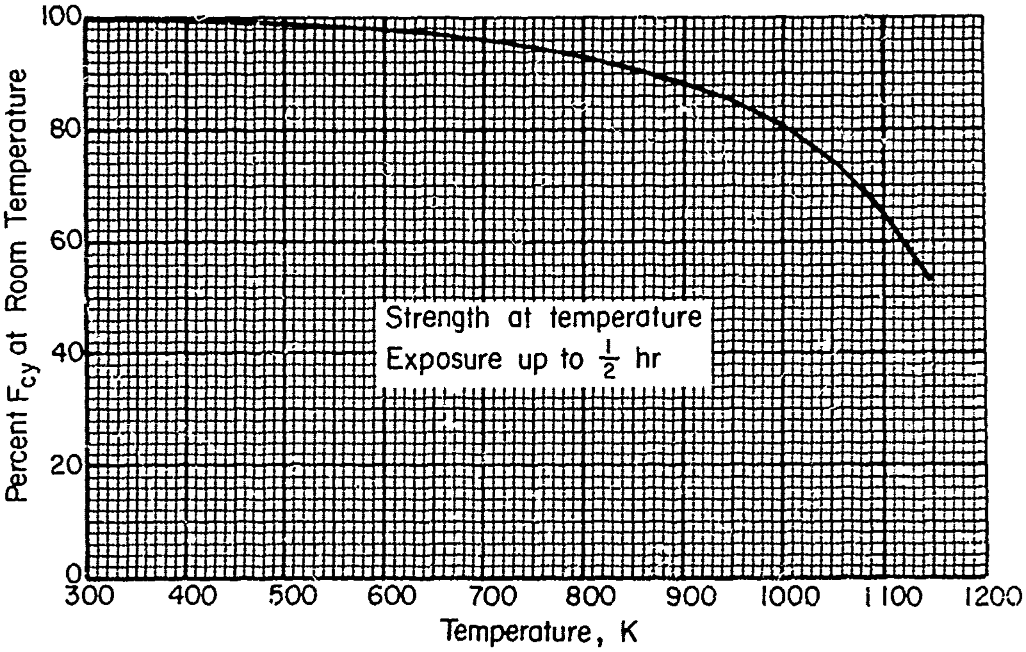


FIGURE 6.3.11.1.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of Udimet 500 alloy.

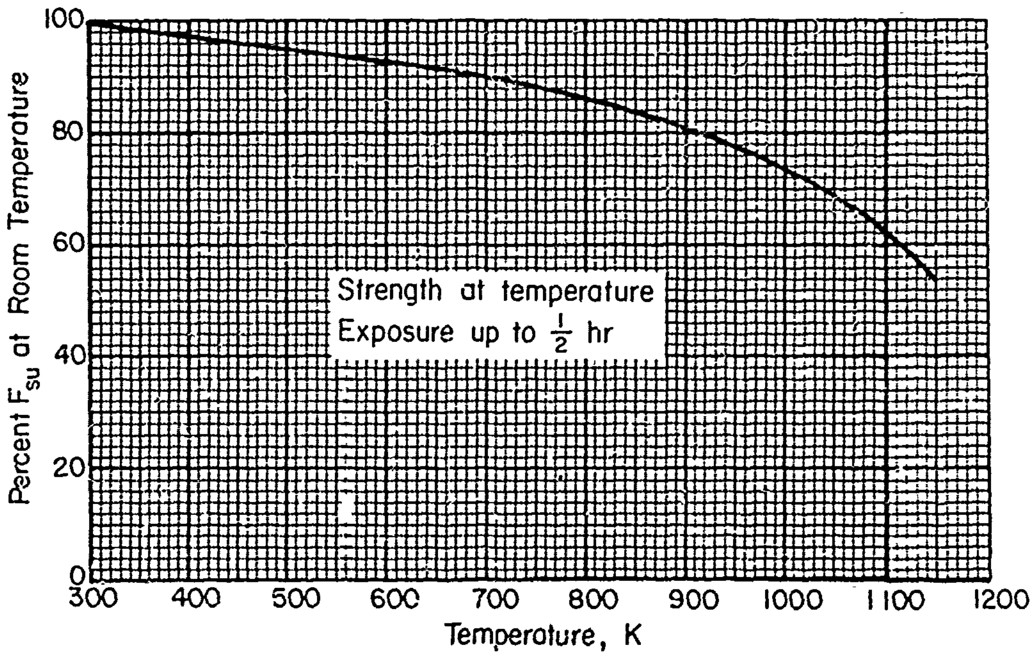


FIGURE 6.3.11.1.2(b). Effect of temperature on the ultimate shear strength (F_{su}) of Udimet 500 alloy.

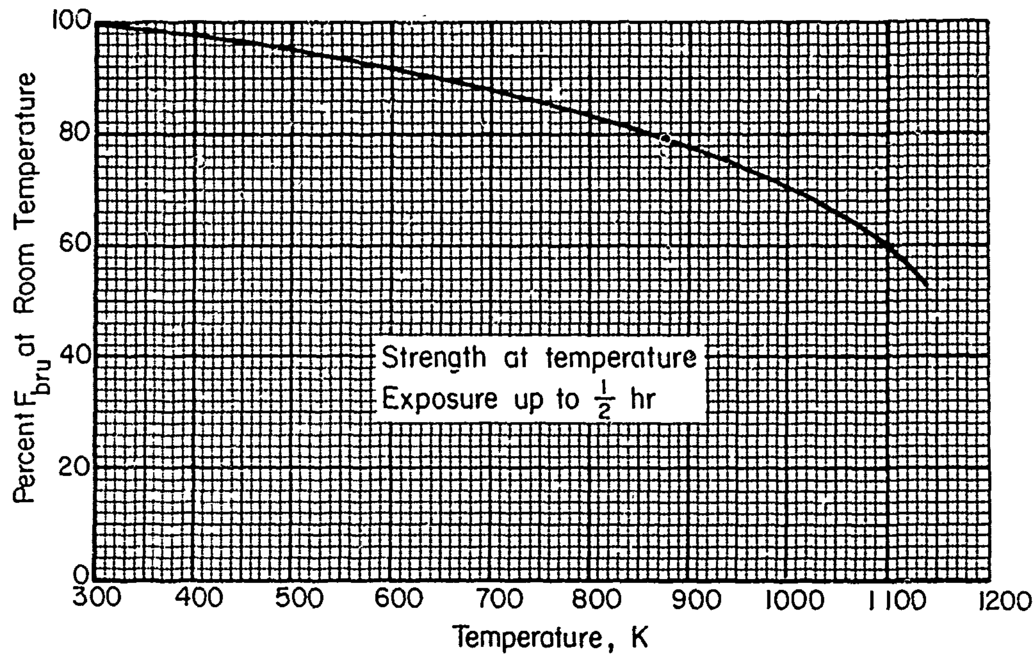


FIGURE 6.3.11.1.3(a). Effect of temperature on the ultimate bearing strength (F_{bru}) of Udimet 500 alloy.

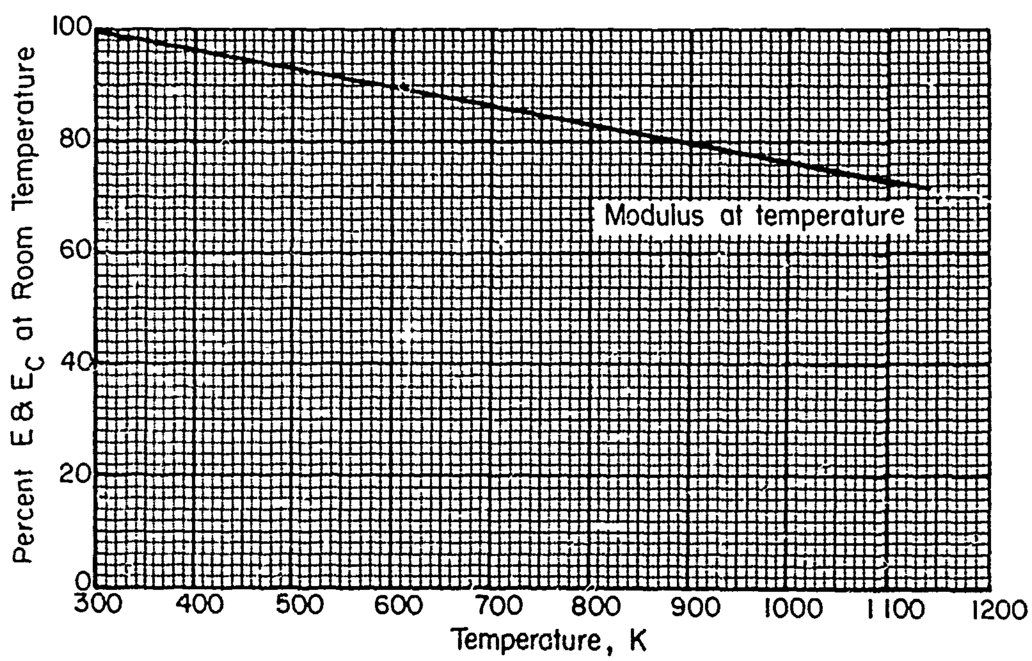


FIGURE 6.3.11.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of Udimet 500 alloy.

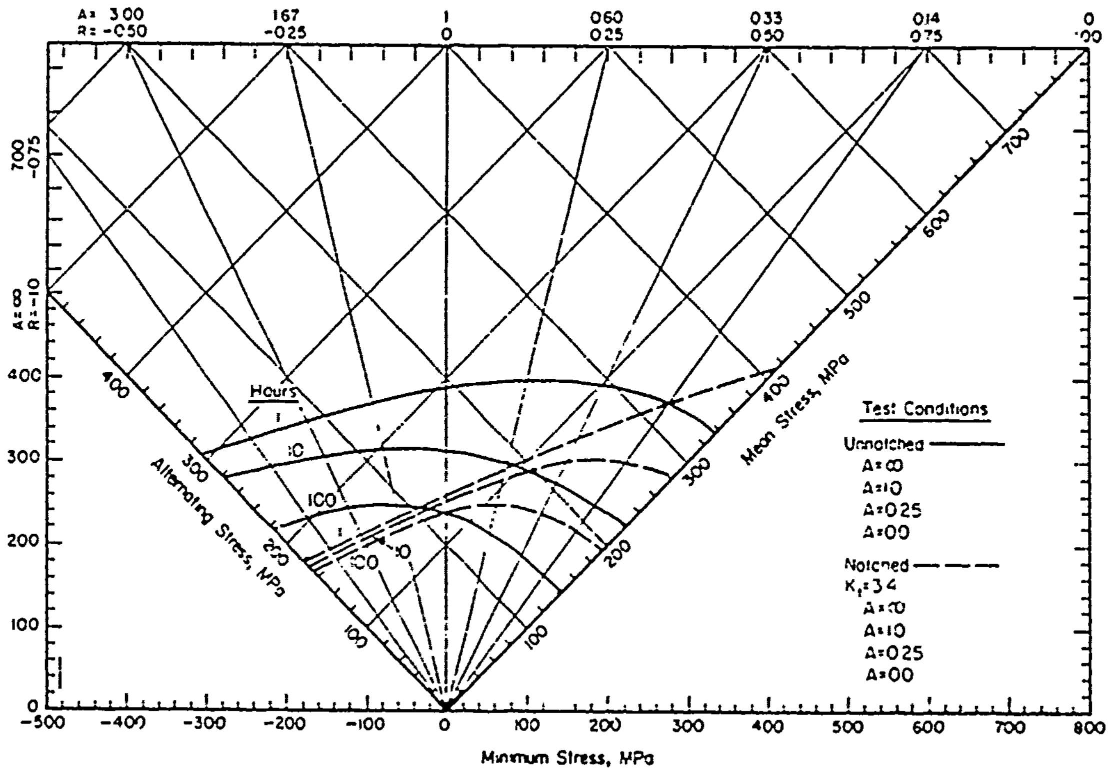


FIGURE 6.3.11.1.8(a). Typical constant-life diagram for fatigue behavior of solution-treated and aged Udimet 500 alloy (bar) at 922 K.

Correlative Information for Figure 6.3.11.1.8(a)

Product Form: Roller bar, 19.1 mm diameter

Properties: TUS, MPa TYS, MPa Temp, K
(no properties given)

Specimen Details: Unnotched — 5.08 mm diameter

Notched, V-Groove, $K_t = 3.4$
9.53 mm, gross diameter
6.35 mm, net diameter
0.25 mm, root radius, r
60° flank angle, ω

$$K_N = 2.41, \rho = 0.0559 \text{ mm, where } K_N = 1 + \frac{K_t - 1}{1 + \frac{\pi}{\pi - \omega}\sqrt{\frac{\rho}{r}}}$$

Surface Condition: Unnotched: Longitudinal polish with 400 grit.
Notched: Notched polish with 600 grit.

Test Parameters:
Loading — Axial
Frequency — 3600 cpm
Temperature — 922 K
Atmosphere — Air

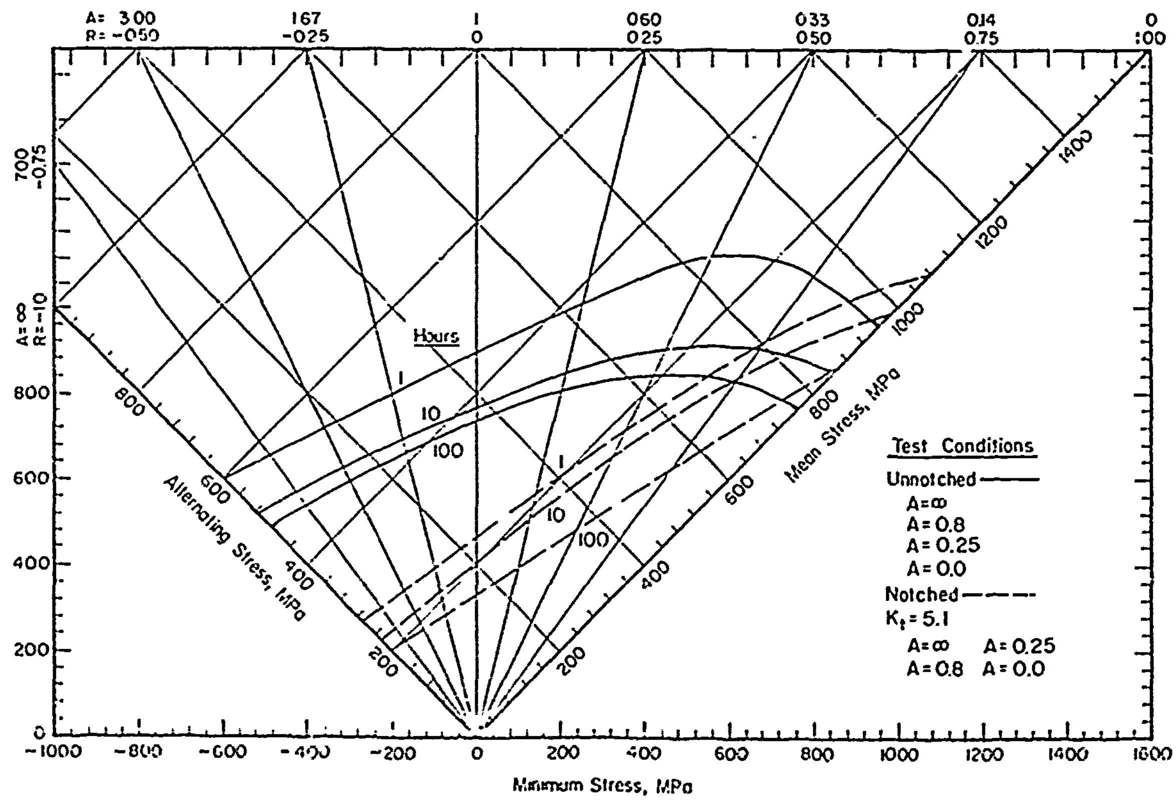


FIGURE 6.3.11.1.8(b). [illegible] constant-life diagram for fatigue behavior of solution-treated and [illegible] bar at 1172 K.

<u>Correlative Information for Figure 6.3.11.1.8(b)</u>

Product Form: Rolled bar, 19.1 mm diameter

Test Parameters:
Loading — Axial
Frequency — 3600 cpm
Temperature — 1172 K
Atmosphere — Air

Properties:

TUS, MPa	TYS, MPa	Temp, K
579	—	1172 (Unnotched)
—	—	1172 (Notched)

Specimen Detail:

Unnotched
5.08 mm diameter

Notched, V-Groove, K_t = 3.4
9.53 mm, gross diameter
6.35 mm, net diameter
0.25 mm, root radius, r
60° flank angle, ω

Surface Condition:
Unnotched: Longitudinal polish with 400 grit.
Notched: Notch polish with 600 grit.

6.3.12 WASPALOY

6.3.12.0 *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 1116 K, 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 1394 to 1311 K. Avoid working the alloy below 1311 K due to danger of cracking and also decreasing the stress-rupture life. Sufficient soaking time between heating is necessary to insure complete recrystalization; 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 the solution-treated and partially aged condition. Generally, carbide 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 1450 K, 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 1228 K and to combustion products encountered in aircraft gas turbines.

Some material specifications for Waspaloy are presented in Table 6.3.12.0(a).

TABLE 6.3.12.0(a). *Material Specifications for Waspaloy*

Specification	Type of Product
AMS 5544	Plate, sheet, strip
AMS 5704	Forgings
AMS 5706	Bars, forgings, rings
AMS 5707	Bars, forgings, rings
AMS 5708	Bars, forgings, rings[a]
AMS 5709	Bars, forgings, rings[a]

[a] Primarily for applications requiring high stress-rupture strength.

Two heat treatments are listed for this material. One is for optimum tensile strength (solution treated 1269–1311K, stabilize 1116 K, 24 hours air cool, and age 16 hours at 1033 K air cool), and the other for stress-rupture properties (solution treated 1353 K, stabilize 1116 K, 24 hours air cool, age 1033 K 16 hours air cool).

Room-Temperature Properties

Room-temperature mechanical properties are shown in Table 6.3.12.0(b). Physical properties at room and elevated temperatures are shown in Figure 6.3.12.0.

6.3.12.1 *Aged Condition.*—The effect of temperature on tensile properties and modulus of elasticity are presented in Figures 6.3.12.1.1(a) through 6.3.12.1.5(b). Typical tensile stress-strain curves (computed) are presented in Figure 6.3.12.1.6(a). The effect of temperature on the Ramberg-Osgood parameter n (tension) is presented in Figure 6.3.12.1.6(b).

TABLE 6.3.12.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF WASPALOY

SPECIFICATION...........	AMS 5544		AMS 5704	AMS 5706 AND AMS 5707
FORM....................	SHEET, STRIP, AND PLATE		FORGINGS	BARS, FORGINGS AND RINGS
CONDITION...............	SOLUTION, STABILIZATION, AND PRECIPITATION HEAT TREATED			
THICKNESS, MM...........	≤ 0.51	> 0.51	...	...
BASIS...................	S[a]	S[a]	S[a]	S[a]
MECHANICAL PROPERTIES:				
FTU, MPA:				
L................	...	...	1210	1100
LT...............	1170	1210	...	...
FTY, MPA:				
L................	...	...	827	758
LT...............	758	793	...	...
FCY, MPA:				
L................	...	...	...	...
LT...............	...	...	...	...
FSU, MPA.............	...	...	...	...
FBRU, MPA:				
(E/D=1.5)..........	...	...	...	...
(E/D=2.0)..........	...	...	...	...
FBRY, MPA:				
(E/D=1.5)..........	...	...	...	...
(E/D=2.0)..........	...	...	...	...
EL, PERCENT:				
L................	...	...	15	15
LT...............	15	20	...	...
EL, PERCENT:				
L................	...	...	18	18
LT...............	...	...	...	...
E, GPA...............	211.0			
EC, GPA..............	...			
EC, GPA..............	...			
G, GPA...............	...			
MU...................	...			
PHYSICAL PROPERTIES:				
OMEGA, MG/M3.........	8.19			
C, J/(G*K)...........	SEE FIGURE 6.3.12.0			
K, W/(M*K)...........	SEE FIGURE 6.3.12.0			
ALPHA, 10-6 M/(M*K)..	SEE FIGURE 6.3.12.0			

[a] GRAIN DIRECTION NOT SPECIFIED.

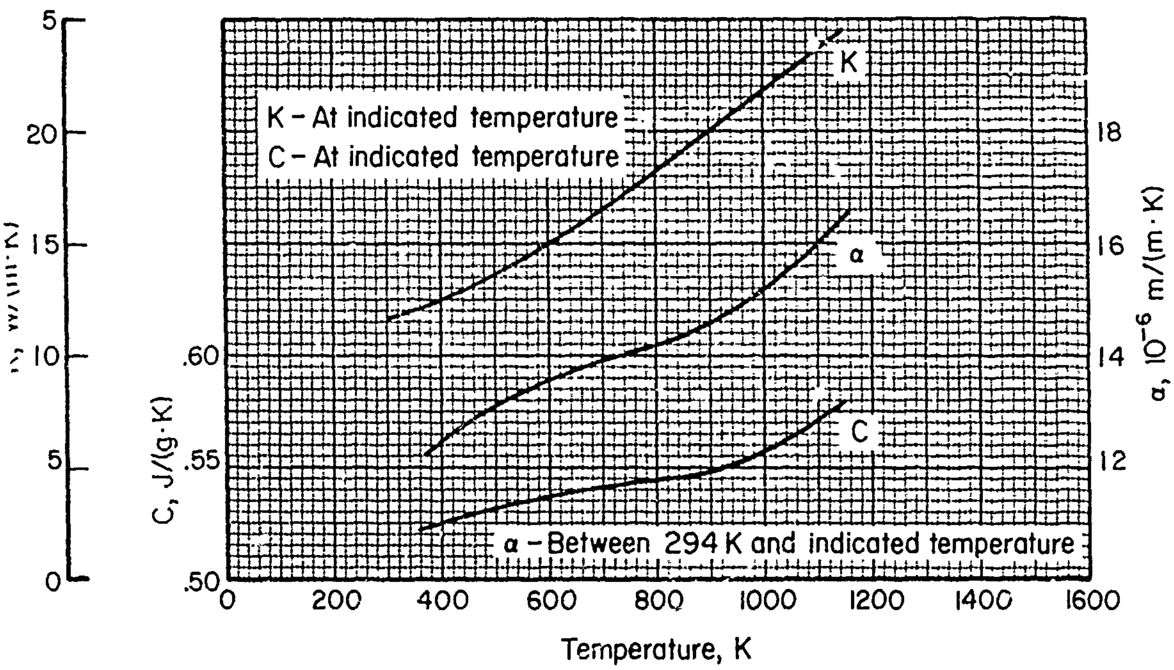


FIGURE 6.3.12.0. Effect of temperature on the physical properties of Waspaloy.

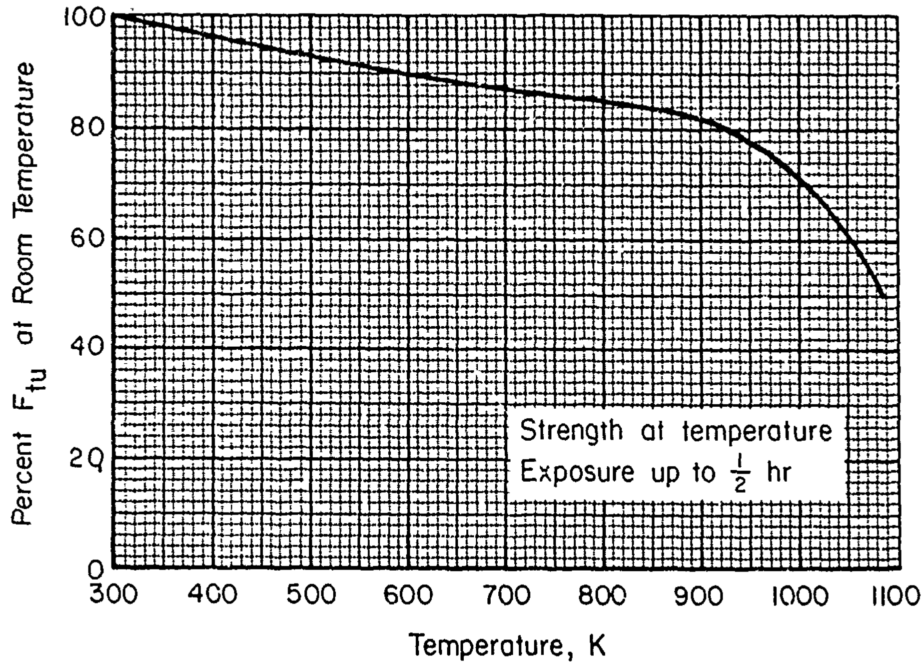


FIGURE 6.3.12.1.1(a). Effect of temperature on ultimate tensile strength (F_{tu}) of Waspaloy.

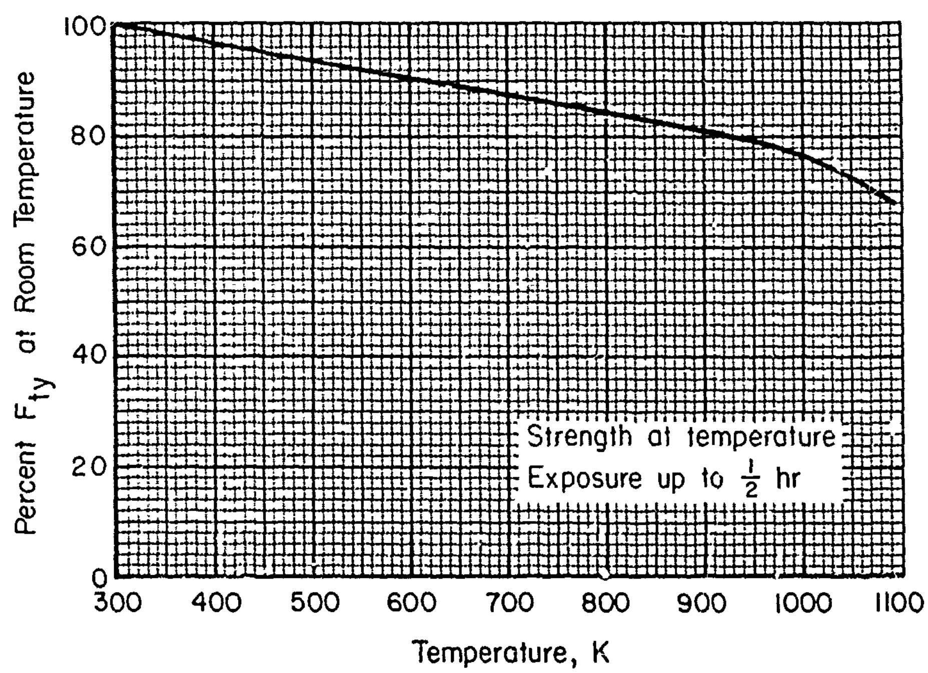


FIGURE 6.3.12.1.1(b). Effect of temperature on tensile yield strength (F_{ty}) of Waspaloy.

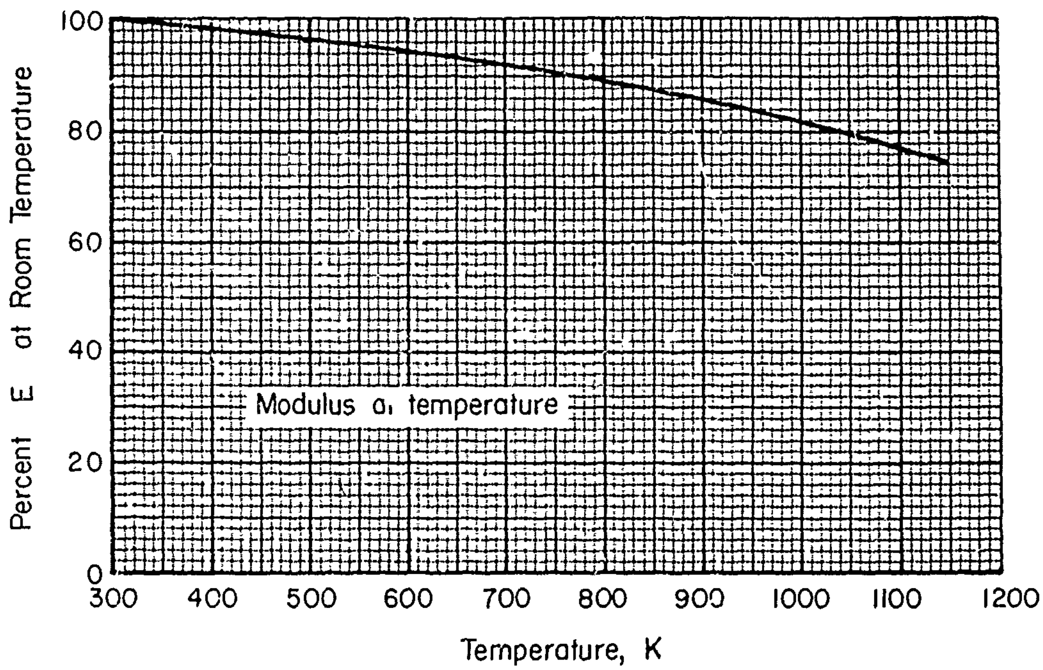


FIGURE 6.3.12.1.4. Effect of temperature on the modulus of elasticity (E) of Waspaloy.

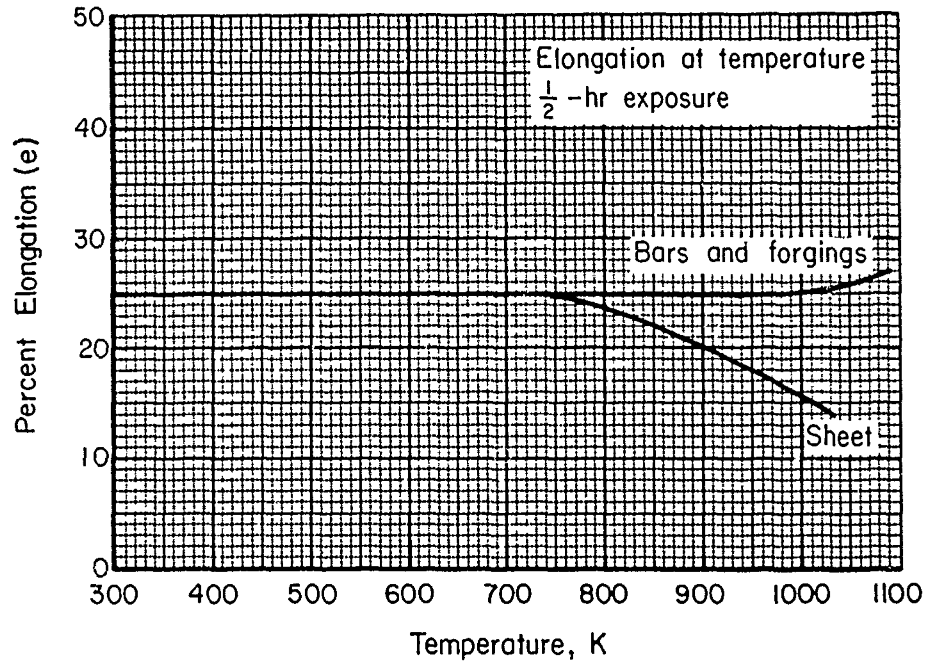


FIGURE 6.3.12.1.5(a). Effect of temperature on elongation (e) of Waspaloy.

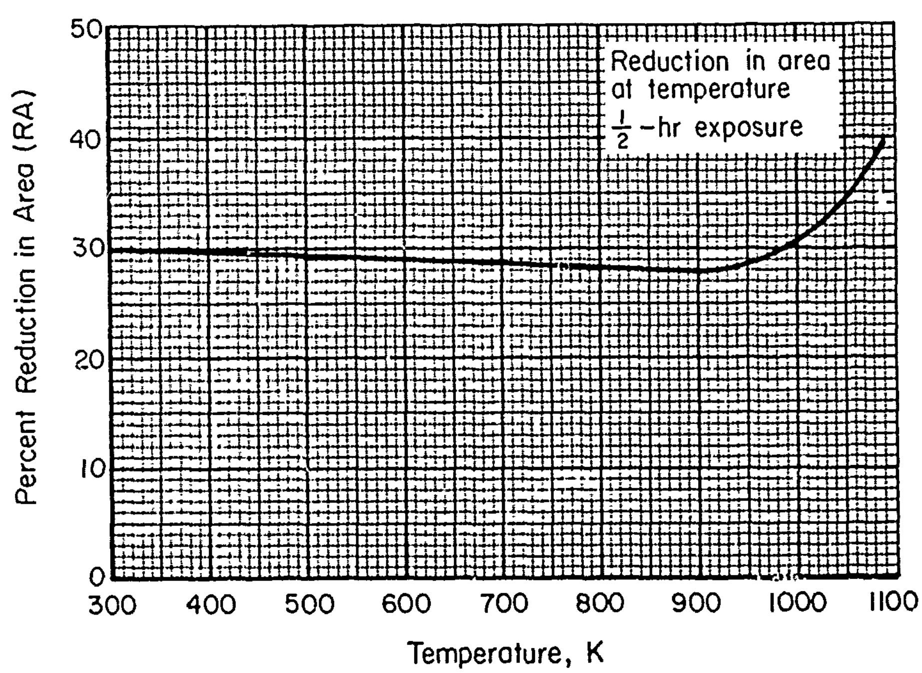


FIGURE 6.3.12.1.5(b). Effect of temperature on reduction in area (RA) of Waspaloy (bars and forgings).

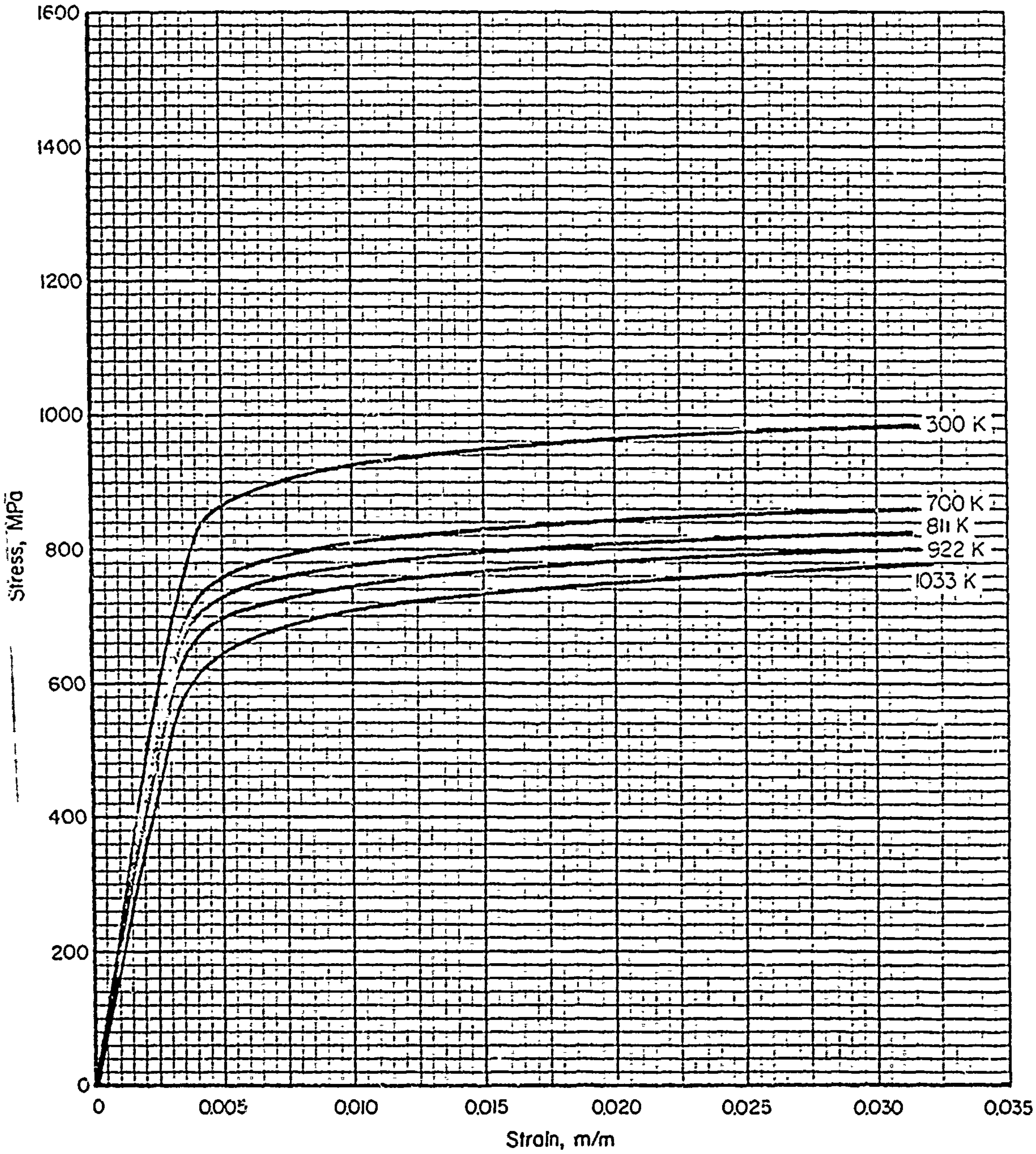


FIGURE 6.3.12.1.6(a). Typical tensile stress-strain curves for aged Waspaloy (all products) at room and elevated temperatures.

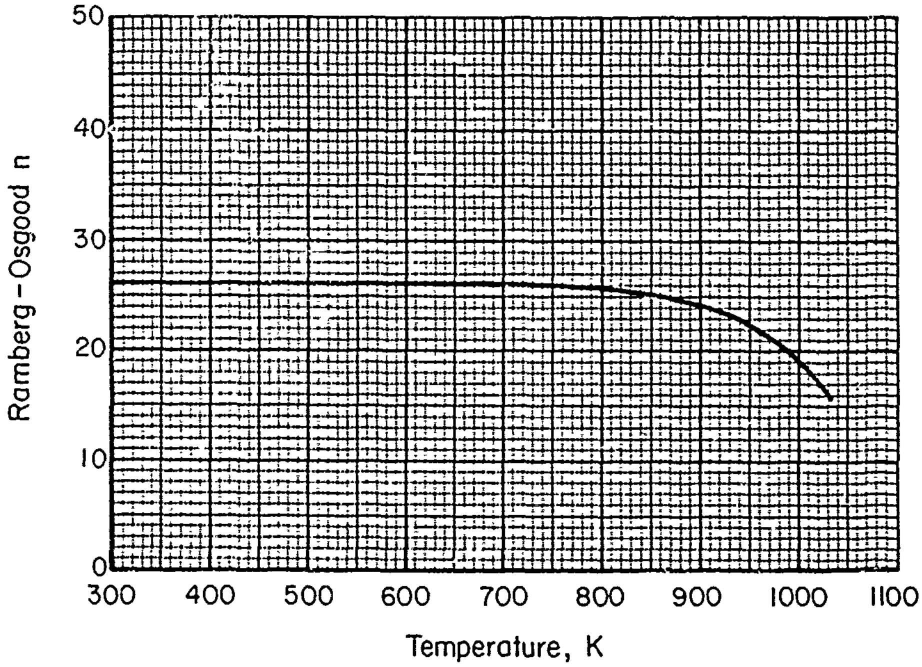


FIGURE 6.3.12.1.6(b). Effect of temperature on the Ramberg-Osgood parameter (n) of Waspaloy.

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 presently 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 is added to increase toughness; carbon is added to increase the hardness and strength, expecially 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 would be 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 without subsequent stress relief.

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 811 and 1311 K. Its applications include gas-turbine blades and rotors, combusion chambers, and after-burner 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 1505 and 1311 K. In the annealed condition, it has excellent formability at room temperature; severely formed parts should be annealed at 1491 K 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 978 K for 2 hours.

This alloy has excellent oxidation resistance up to 1311 K.

Some material specifications for L-605 are presented in Table 6.4.1.0(a).

TABLE 6.4.1.0(a). *Material Specifications for L-605 Alloy*

Specification	Form	Condition
AMS 5537	Sheet	Solution treated (annealed)
AMS 5759	Bars and forgings	Solution treated (annealed)

Room-Temperature Properties

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.

6.4.1.1 *Solution Treated Condition.*—Elevated temperature properties for this condition are presented in Figures 6.4.1.1.1(a) through 6.4.1.1.5. A creep nomograph is shown in Figure 6.4.1.1.7.

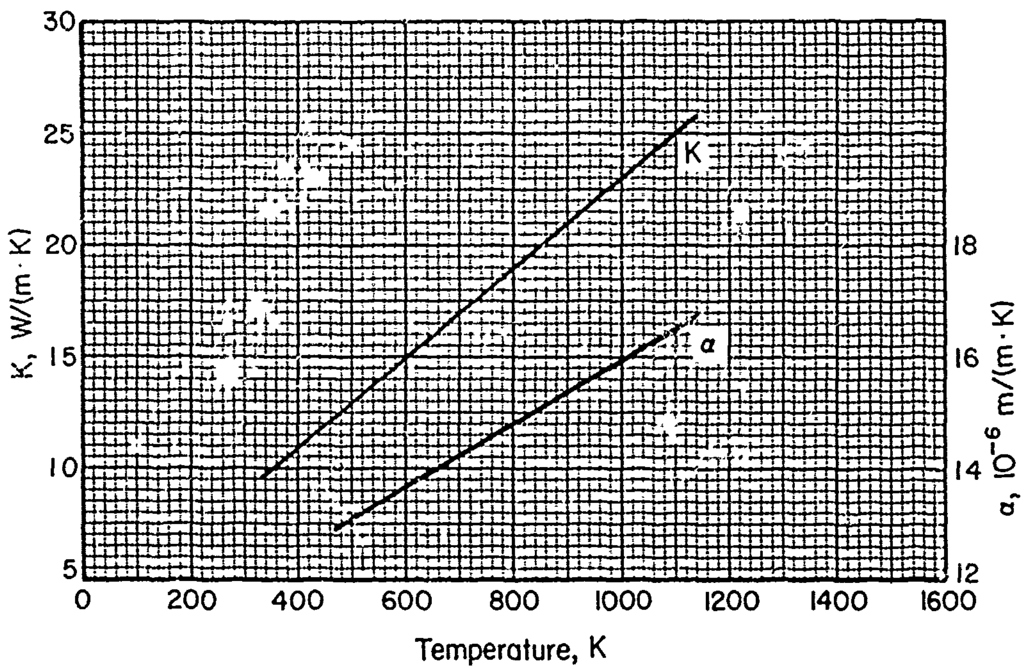


FIGURE 6.4.1.0. Effect of temperature on the physical properties of L-605 alloy.

TABLE 6.4.1.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF L-605 ALLOY

SPECIFICATION	AMS 5537			AMS 5759
FORM	SHEET		PLATE	BARS AND FORGINGS
CONDITION	SOLUTION TREATED			
THICKNESS, MM	0.25 - 4.75		> 4.75	...
BASIS	A	B	S	S[a]
MECHANICAL PROPERTIES:				
FTU, MPA:				
L	...	...	...	862
LT	896	931	896	827
FTY, MPA:				
L	...[b]	...	...	310
LT	379	414	379	...
FCY, MPA:				
L	283	310	359	303
LT	421	455	359	...
FSU, MPA	758	786	648	621
FBRU, MPA:				
(E/D=1.5)	1280	1330	1260	...
(E/D=2.0)	1610	1670	1510	...
FBRY, MPA:				
(E/D=1.5)				
L	565	614	...	...
LT	655	710	648	...
(E/D=2.0)				
L	695	758	...	...
LT	736	862	655	...
EL, PERCENT:				
L	...	...	...	30
LT	c	...	45	...
E, GPA	235.8			
EC, GPA	...			
G, GPA	...			
MU	...			
PHYSICAL PROPERTIES:				
OMEGA, MG/M3	9.13			
C, J/(G*K)	0.38 (294 - 373K)			
K, W/(M*K)	...			
ALPHA, 10-6 M/(M*K)	...			

[a] GRAIN DIRECTION NOT INDICATED.
[b] THE A VALUE IS HIGHER THAN SPECIFICATION VALUE AS FOLLOWS: FTY = 386 MP
[c] 30-≤ 0.520;35-0.521 TO 0.925 MM; 40=0.826 TO 1.092;45->1.092.

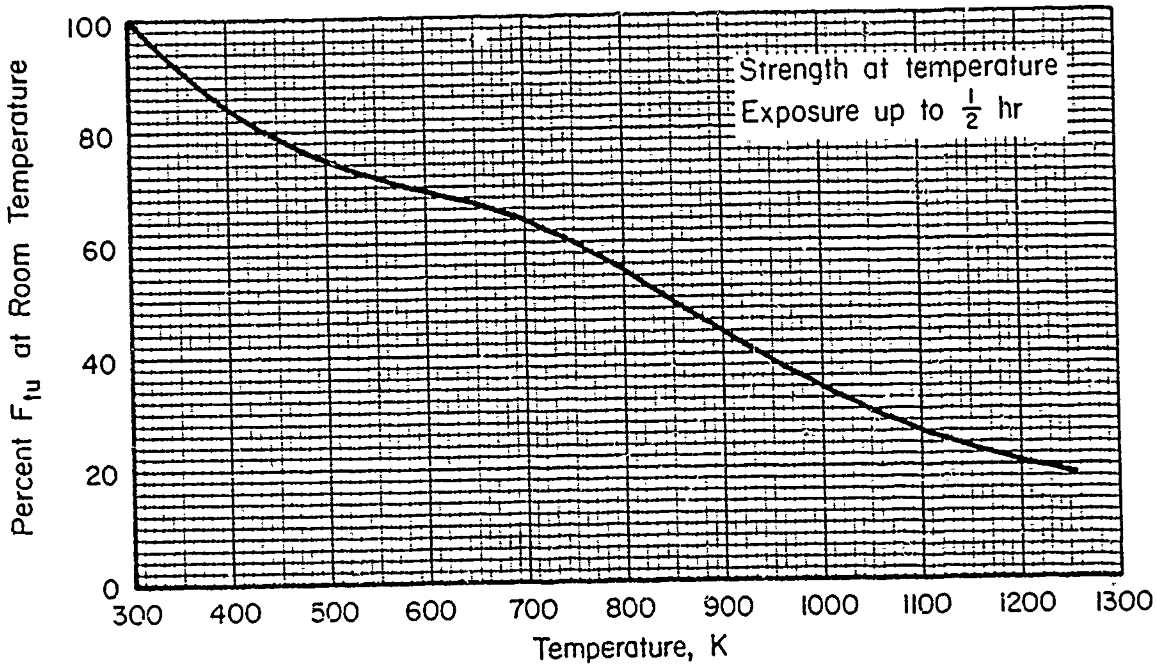


FIGURE 6.4.1.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of L-605 alloy (sheet).

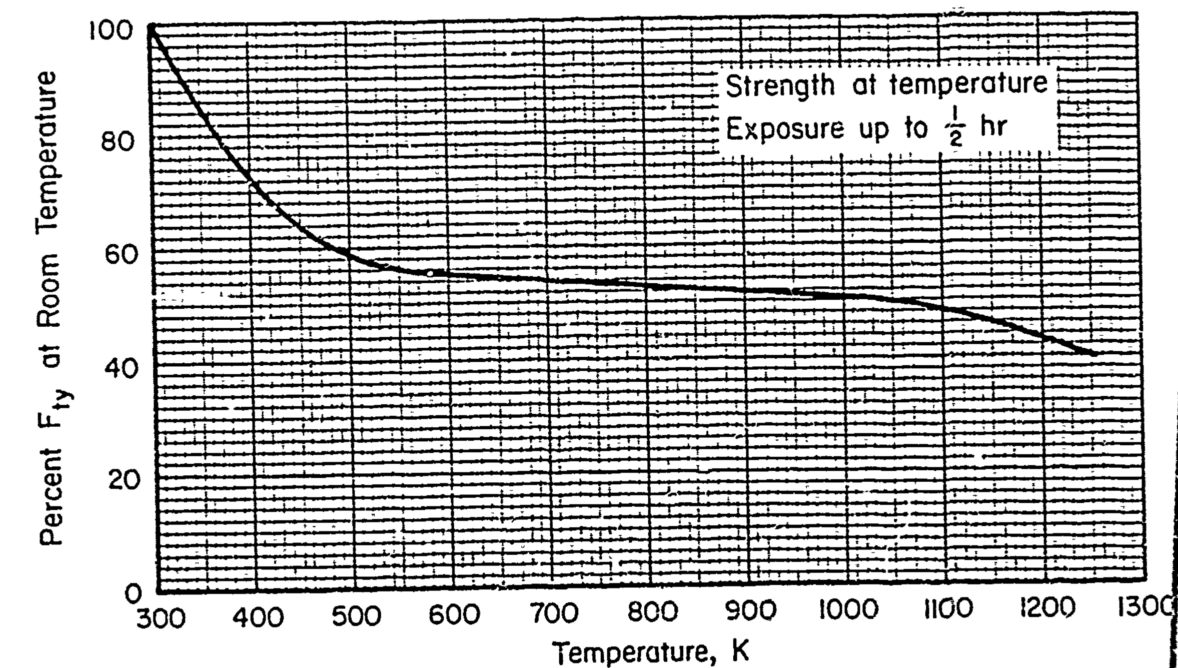


FIGURE 6.4.1.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of L-605 alloy (sheet).

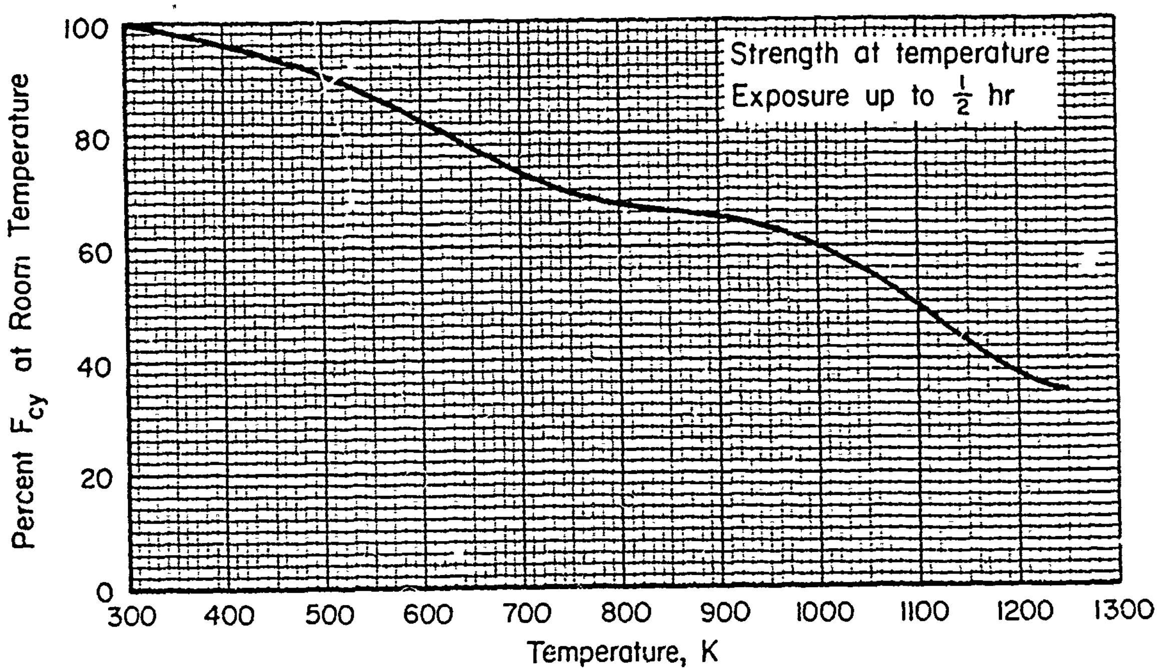


FIGURE 6.4.1.1.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of L-605 alloy (sheet).

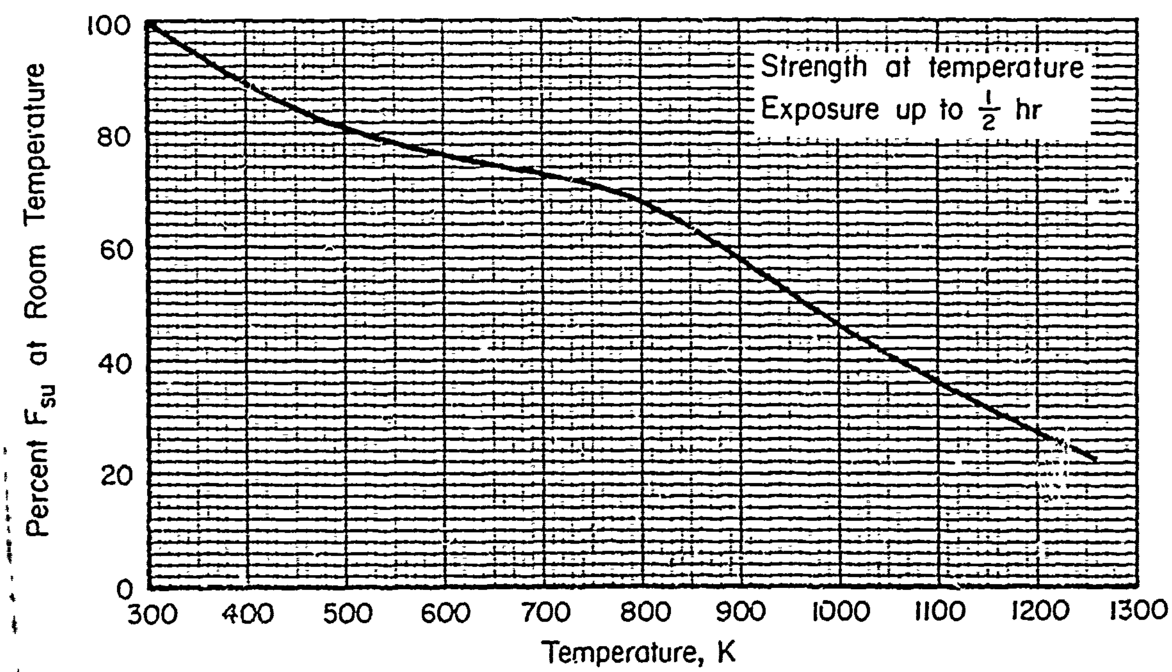


FIGURE 6.4.1.1.2(b). Effect of temperature on the ultimate shear strength (F_{su}) of L-605 alloy (sheet).

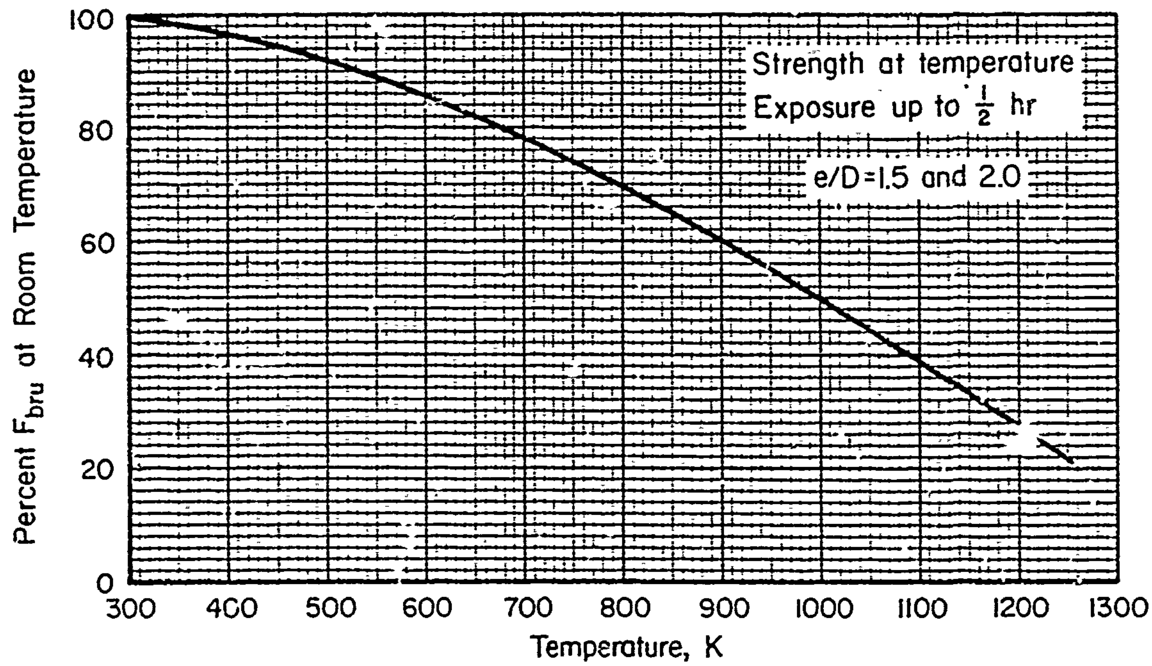


FIGURE 6.4.1.1.3(a). Effect of temperature on the ultimate bearing strengt (F_{bru}) of L-605 alloy (sheet).

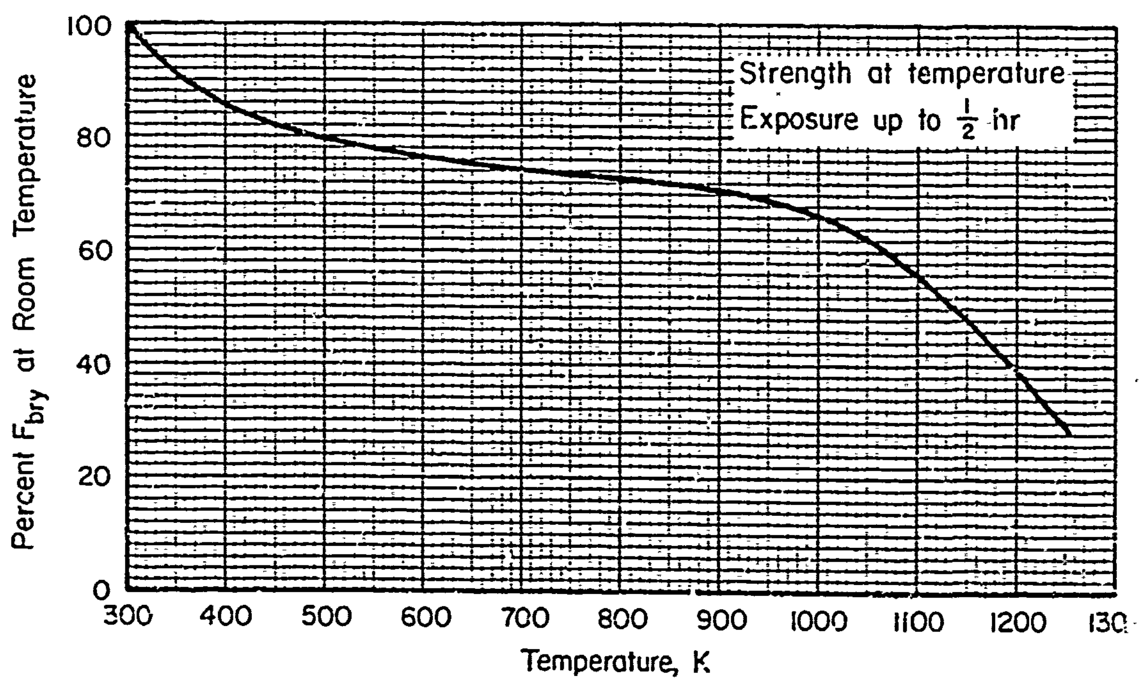
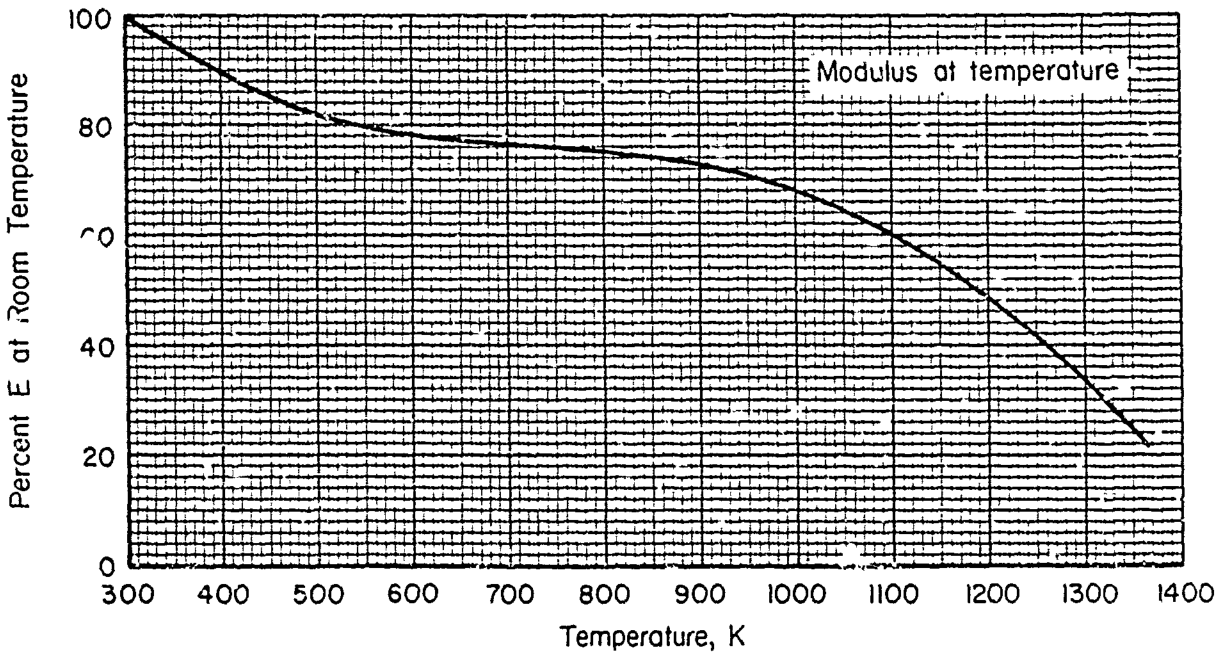


FIGURE 6.4.1.1.3(b). Effect of temperature on the bearing yield strengtl (F_{bry}) of L-605 alloy (sheet).



GURE 6.4.1.1.4(a). Effect of temperature on the tensile modulus (E) of L-605 alloy.

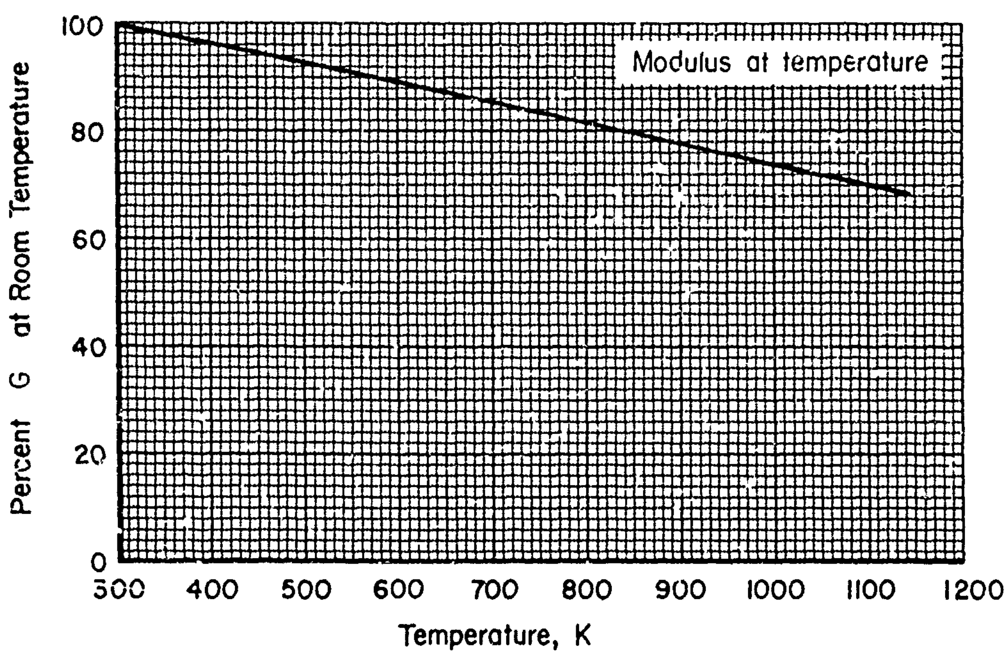


FIGURE 6.4.1.1.4(b). Effect of temperature on the shear modulus (G) of L-605 alloy.

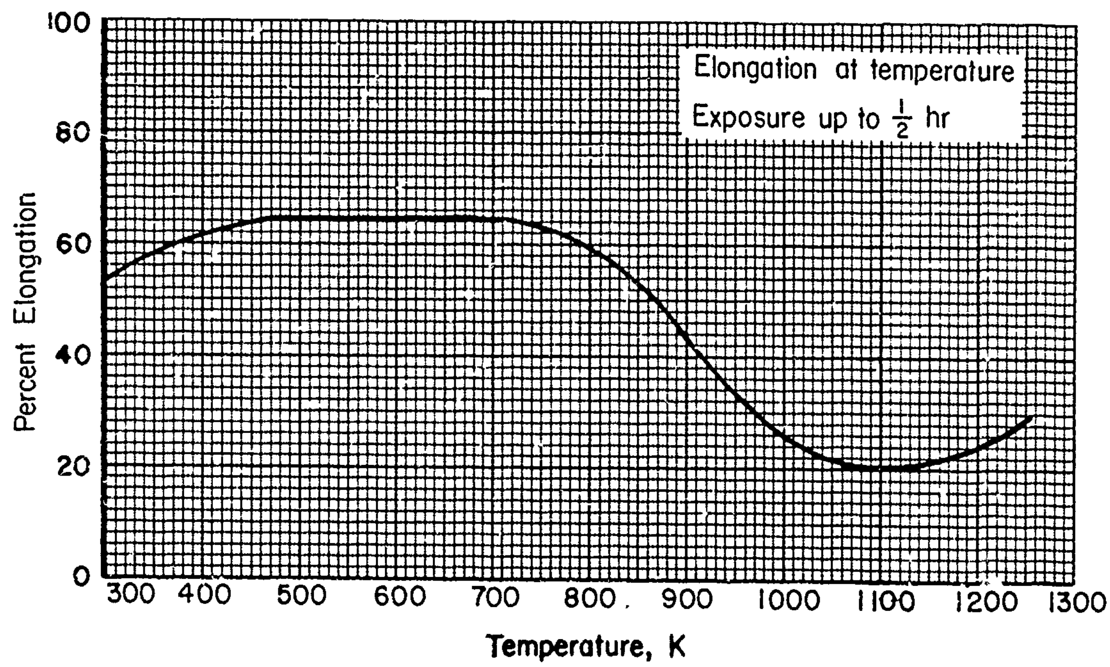


FIGURE 6.4.1.1.5. Effect of temperature on the elongation (e) of L-605 alloy (>.508 thickness).

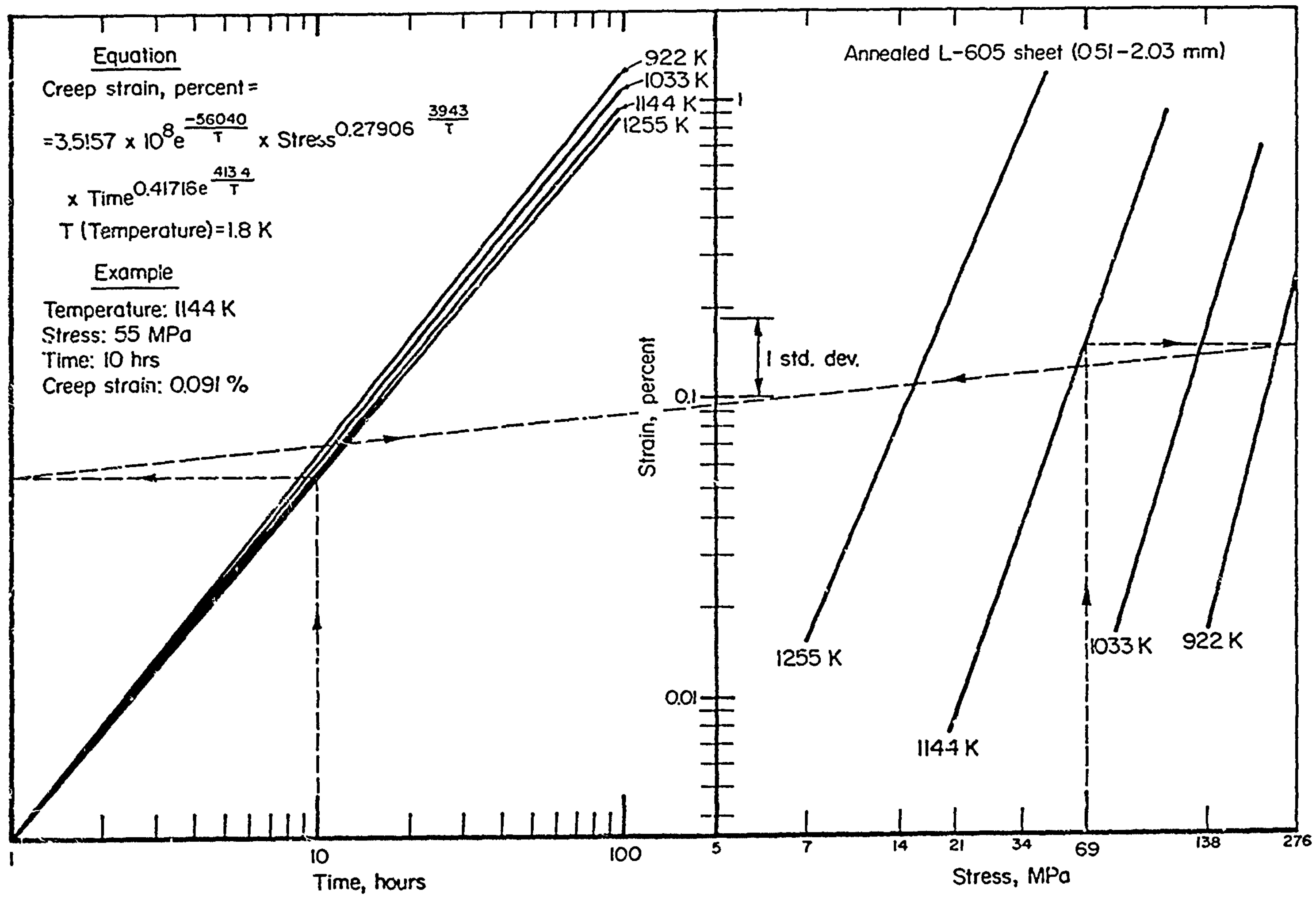


FIGURE 6.4.1.1.7. Typical creep properties of L-605 alloy (sheet).

Chapter 7

BERYLLIUM AND SPECIAL PURPOSE METALS AND ALLOYS

7.1 General

This chapter contains the engineering properties and related characteristics of beryllium and various special purpose metals and alloys.

In addition to the strength properties which are reported in other material chapters, some properties or characteristics may be found in this chapter relating to the special purposes or uses of these alloys. For example, the electrical conductivity is reported for the copper-base alloys and a section is included on toxicity of particles of beryllium and its compounds, such as beryllium oxide.

The organization of the chapter is in sections by base metal and subdivided as shown in Table 7.1.

TABLE 7.1. *Beryllium and Special Purpose Metals Index*

Section	Designation
7.2	Beryllium
7.2.1	Vacuum hot-pressed shapes (S200E and HP20)
7.2.2	Cross-rolled sheet (SR200D and PS20)
7.3	Copper and copper alloys
7.3.1	Tin bronzes
7.3.2	Manganese bronzes
7.3.3	Aluminum bronzes
7.3.4	Beryllium coppers
7.4	MP35N Alloy

7.2 Beryllium

7.2.0 GENERAL

This section contains the engineering properties and related characteristics of beryllium used in aerospace structural applications. Effects of elevated temperature on these properties are included. Where available, other properties and characteristics are included. Factors influencing design values and procedures are included in the comments relating to specific properties.

Beryllium is a lightweight, high modulus, moderate temperature metal which is advantageous for specific aerospace applications. It is available in the form of vacuum hot-pressed shapes and cross-rolled sheet. Properties are included in MIL-HDBK-5 for these two forms. Beryllium is also available as plate and foil, forgings, extrusions, and drawn wire, although not covered by government specification for these forms. Structural designs utilizing beryllium sheet should allow for anisotropy, particularly the very low short transverse properties. Because of the low ST properties, sheet cannot be bent or formed at low temperatures. To insure that design properties are retained in the finished part, the final machined surface should be etched to remove any damage left by machining operations. Additional information on the fabrication of beryllium may be found in References 7.20 (a) through (f).

7.2.0.1 *Manufacturing Considerations*— Machining.— Carbide tools are most often used in machining beryllium. Mechanical metal removal techniques generally cause microcracks and twins. Finishing cuts are usually 0.125 mm to 0.050 mm or less in depth to minimize surface damage. Although most machining operations are performed without coolant, to avoid as far as possible contamination of the chips, the use of coolant can reduce, in some cases, 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 to remove the machining damage, normally 0.050 mm minimum, from structurally loaded parts. A combination of 1005 K stress relief followed by an 0.0125 mm etch does not restore full structural properties, but may be acceptable for close tolerance parts. Damage-free metal removal techniques include chemical milling and electrochemical machining.

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 at this time. 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 to insure success. Reference 7.2.0(f).

Surface Treatment.—A surface treatment such as chemical etching to remove the machined surface of metal is recommended to insure the properties specified. All of the design allowables are for material so prepared. This surface treatment is especially important when beryllium is to be mechanically joined. Reference 7.2.0(d) has data 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. Reference 7.2.0(a) through (e) outlines the hazard and methods to control it.

7.2.1 VACUUM HOT-PRESSED SHAPES (S200E and HP20).

7.2.1.0 *Comments and Room-Temperature Properties.*—The vacuum hot-pressed shapes are produced from beryllium powder with a 2 percent maximum beryllium oxide content and no alloying elements, though residual impurities of Fe and Al on excess of about 150 ppm may affect properties. Numerous other compositions are available for special purposes but are not yet covered in this document. A material specification for hot-pressed shapes is presented in Table 7.2.1.0(a).

TABLE 7.2.1.0(a). *Material Specification for Vacuum Hot-Pressed Beryllium Shapes*

Specification	Form
MIL-B-21531	Bars, rods, and shapes

Beryllium hot-pressed block can be forged, rolled, extruded, drawn and shear formed but requires temperatures of 644 K and higher because of the brittleness. A temperature range of 811–1033 K is recommended. Forming procedures are given in more detail in Reference 7.2.0(b).

Room-Temperature Properties

Hot-pressed shapes are anisotropic in nature. The room-temperature transverse yield and ultimate strength have been found to be higher than the longitudinal properties and the certifying data may be run transverse and thus reflect the higher properties. Room-temperature mechanical and physical properties are shown in Table 7.2.1.0(b). Notch tensile test data are available in Reference 7.2.1.0(a). The effect of temperature on physical properties is shown in Figure 7.2.1.0.

At present S200E and HP20 products are available only in the vacuum hot-pressed condition.

7.2.1.1 *Vacuum Hot-Pressed Condition.*—The effect of temperature on the mechanical properties of vacuum hot-pressed beryllium is presented in Figures 7.2.1.1.1(a) through 7.2.1.1.5.

TABLE 7.2.1.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF VACUUM HOT-PRESSED BERYLLIUM (BARS, RODS, AND SHAPES)

SPECIFICATION	MIL-T-21531			
FORM	BARS, RODS, AND SHAPES			
CONDITION	AS HOT PRESSED			
PRESSING SIZE, KG	≤ 2268		> 2268	
BASIS	A	B	A	B
MECHANICAL PROPERTIES:				
FTU, MPA:				
L[a]	276	303	262	290
LT[a]	276	324	276	303
FTY, MPA:				
L	186	221	179	200
LT	186	221	179	200
FCY, MPA:				
L	186	221	179	200
LT	186	221	179	200
FSU, MPA	228	248	...	...
FBRU, MPA:				
(E/D=1.5)	607	689	...	...
(E/D=2.0)	758	862	...	...
FBRY, MPA:				
(E/D=1.5)	...	...	...	...
(E/D=2.0)	...	...	...	...
EL, PERCENT:				
L	...	...	1	...
T	1	...	1	...
E, GPA	293.0			
EC, GPA	293.0			
G, GPA	137.9			
MU	0.10 (L AND T)			
PHYSICAL PROPERTIES:				
OMEGA, MG/M3	1.83 (MIN.)			
C, J/(G*K)	SEE FIGURE 7.2.1.0			
K, W/(M*K)	SEE FIGURE 7.2.1.0			
ALPHA, 10-6 M/(M*K)	SEE FIGURE 7.2.1.0			

[a]GRAIN DIRECTION: L - PARALLEL TO PRESSING DIRECTION
T - NORMAL TO PRESSING DIRECTION.

[b]THE A VALUE IS HIGHER THAN SPECIFICATION AS FOLLOWS: FTU(T) = 296 MPA.

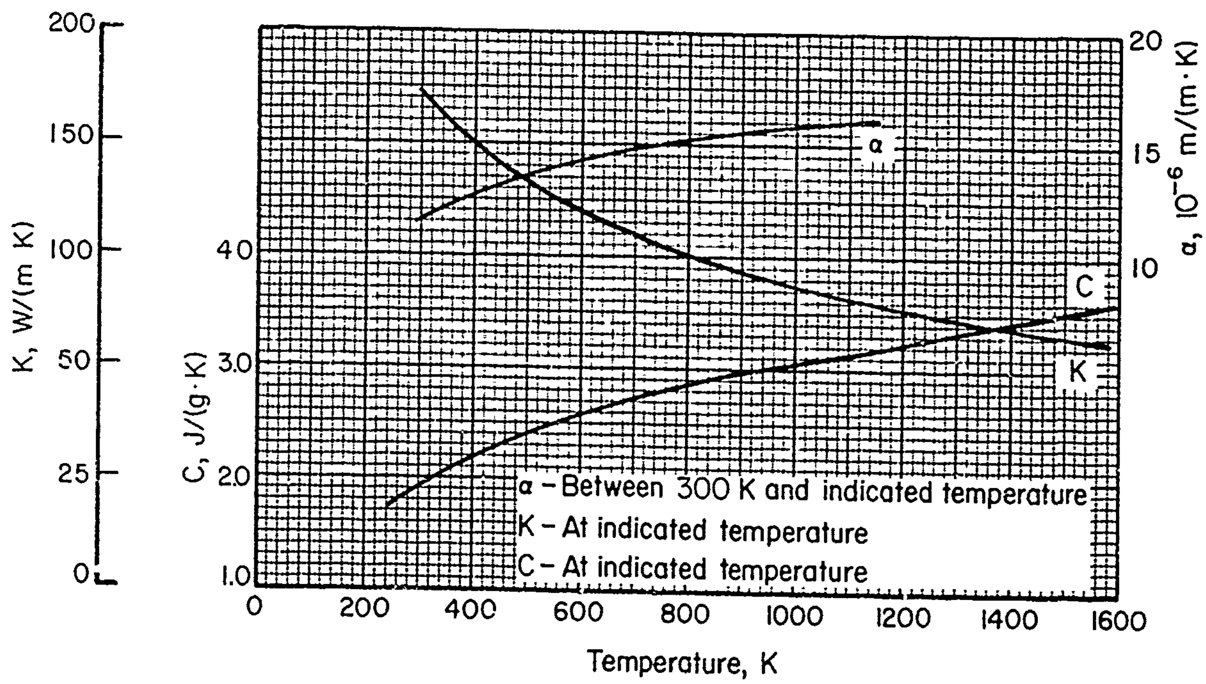


FIGURE 7.2.1.0. Effect of temperature on the physical properties of beryllium vacuum hot-pressed shapes.

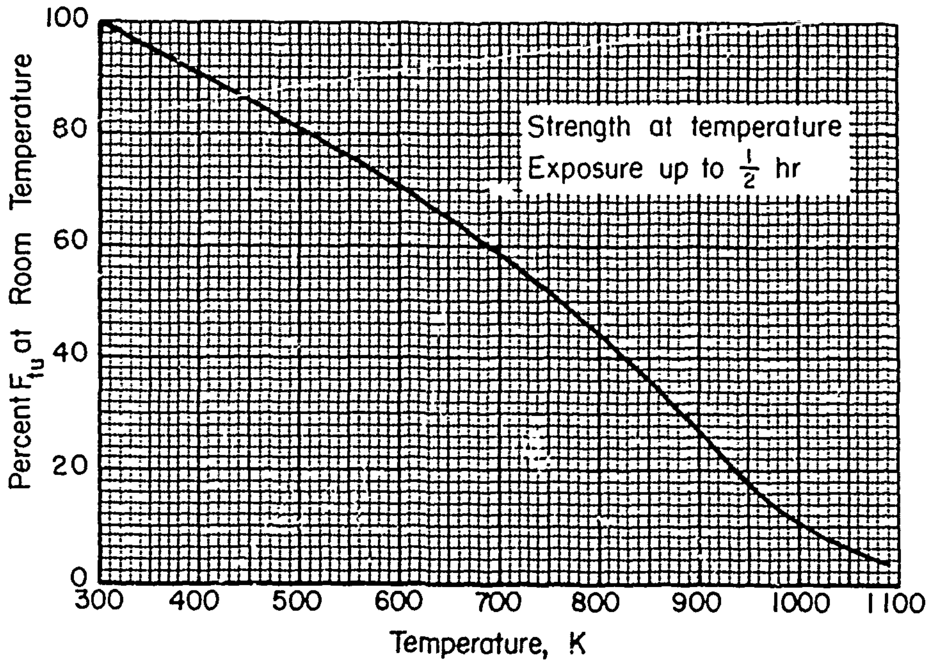


FIGURE 7.2.1.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of vacuum hot-pressed beryllium (bars, rods, and shapes).

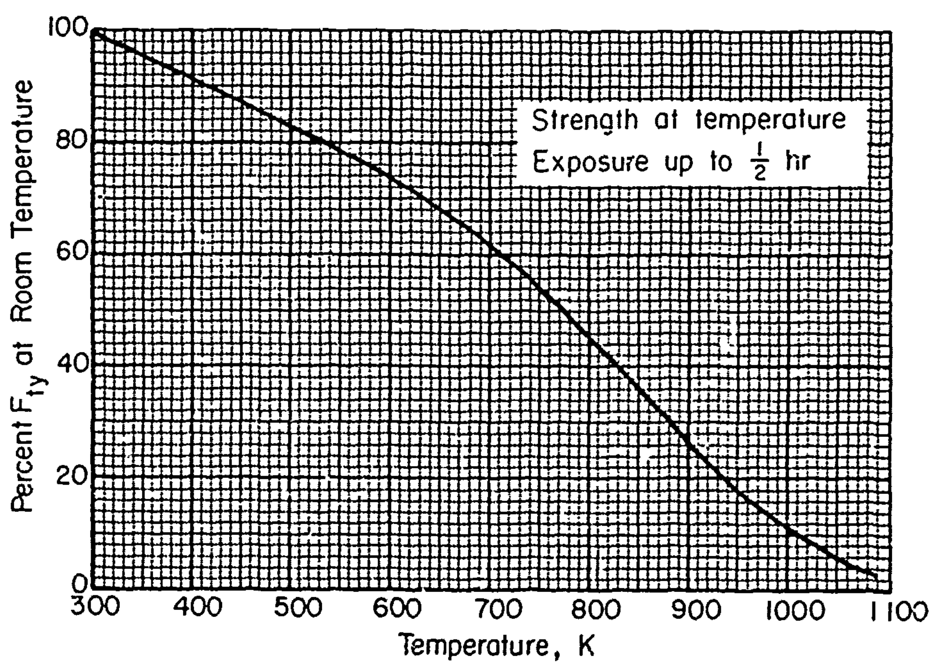


FIGURE 7.2.1.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of vacuum hot-pressed beryllium (bars, rods, and shapes).

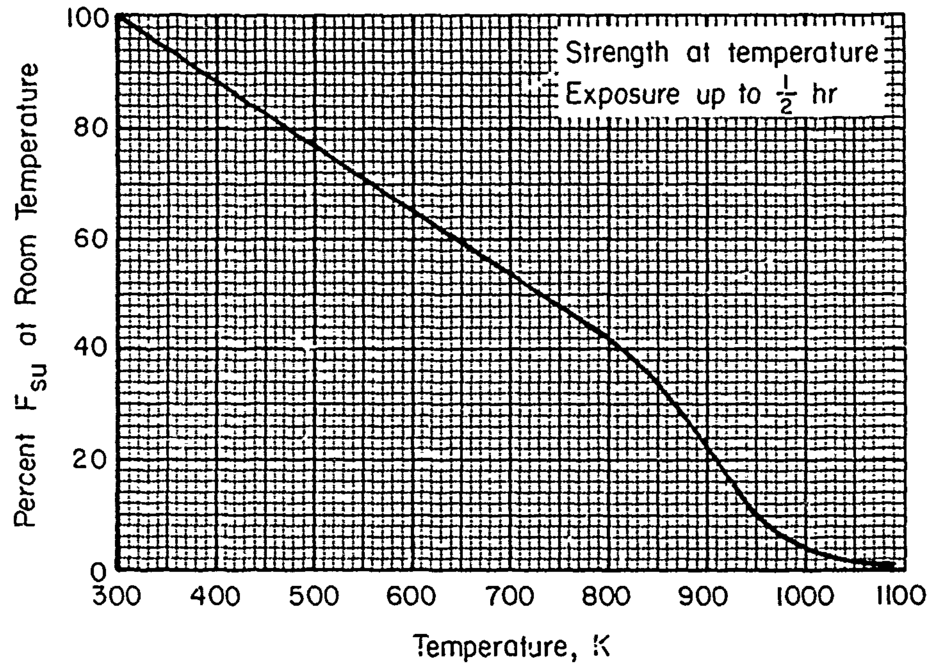


FIGURE 7.2.1.1.2(b). Effect of temperature on the ultimate shear strength (F_{su}) of vacuum hot-pressed beryllium (bars, rods, and shapes).

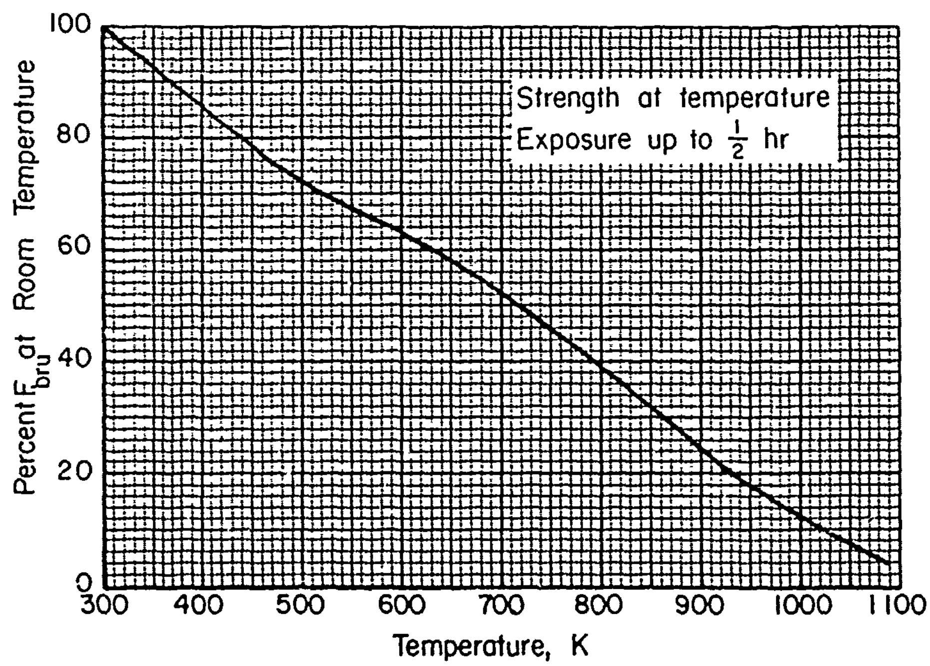


FIGURE 7.2.1.1.3(a). Effect of temperature on the ultimate bearing strength (F_{bru}) of vacuum hot-pressed beryllium (bars, rods, and shapes).

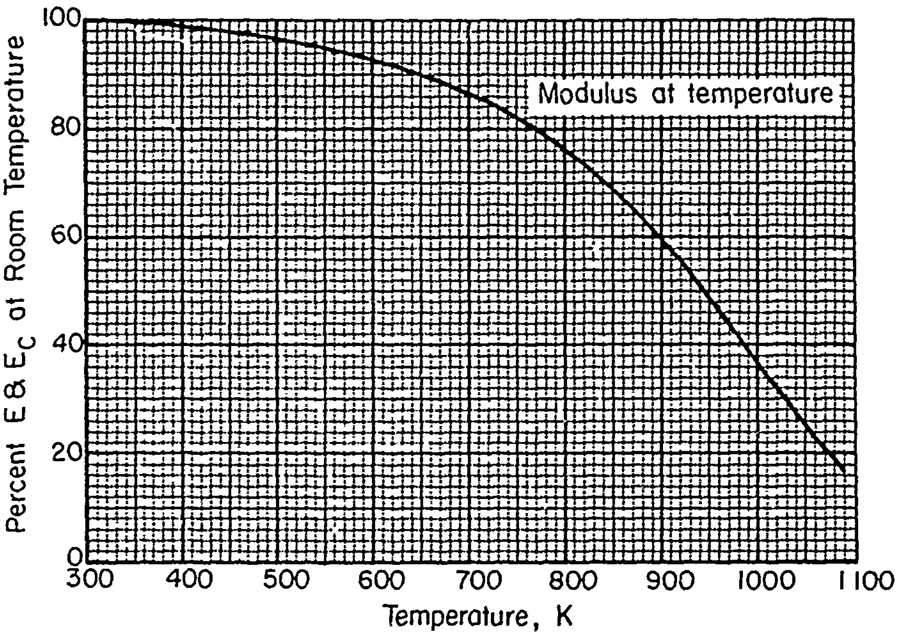


FIGURE 7.2.1.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of vacuum hot-pressed beryllium (bars, rods, and shapes).

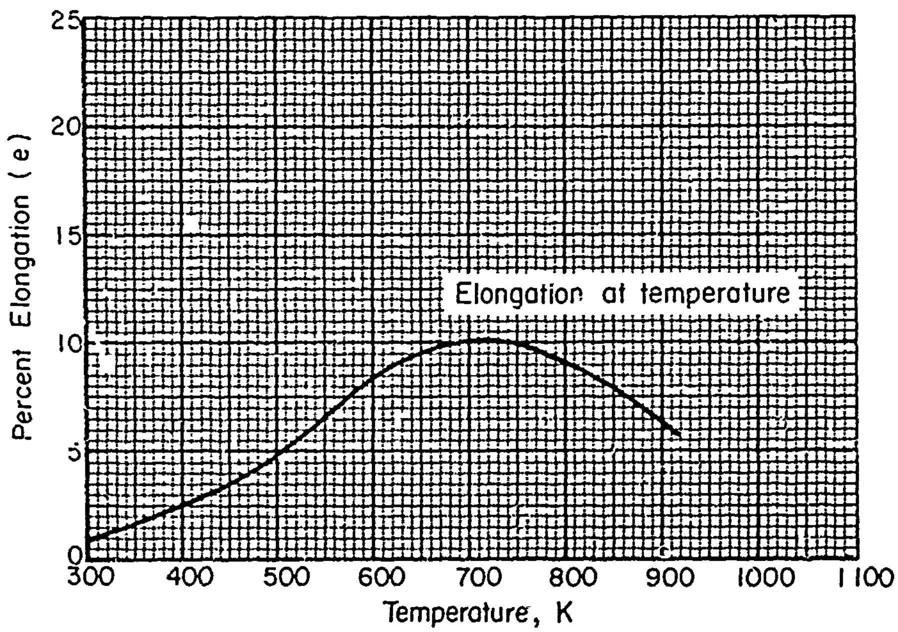


FIGURE 7.2.1.1.5. Effect of temperature on the elongation of vacuum hot-pressed beryllium (bars, rods, and shapes).

7.2.2 CROSS-ROLLED SHEET (SF200D and PS20)

7.2.2.0 *Comments and Room-Temperature Properties.*—Cross-rolled sheet is produced by cross rolling from a block of consolidated beryllium powder with a 2 percent maximum beryllium oxide content. A material specification is presented in Table 7.2.2.0(a).

TABLE 7.2.2.0(a). *Material Specification for Cross-Rolled Beryllium Sheet and Plate*

Specification	Form
MIL-B-8964	Sheet and plate

In addition to the comments on beryllium machining in Section 7.2.0 General, it is noted that the drilling of sheet may lead to delamination and breakout unless the drillhead is of the controlled torque type and the drills are of carbide burr type.

Beryllium sheet should be formed at 978–1005 K for best forming with minimum springback. Do not form above 1061 K if original properties are to be retained.

Room-Temperature Properties

Room-temperature mechanical and physical properties for beryllium sheet are shown in Table 7.2.2.0(b). The effect of temperature on physical properties is shown in Figure 7.2.2.0. The condition index for this material is as follows:

Section	Condition
7.2.2.1	Stress relieved

7.2.2.1 *Stress Relieved Condition.*—No effect of temperature curves are available for this condition.

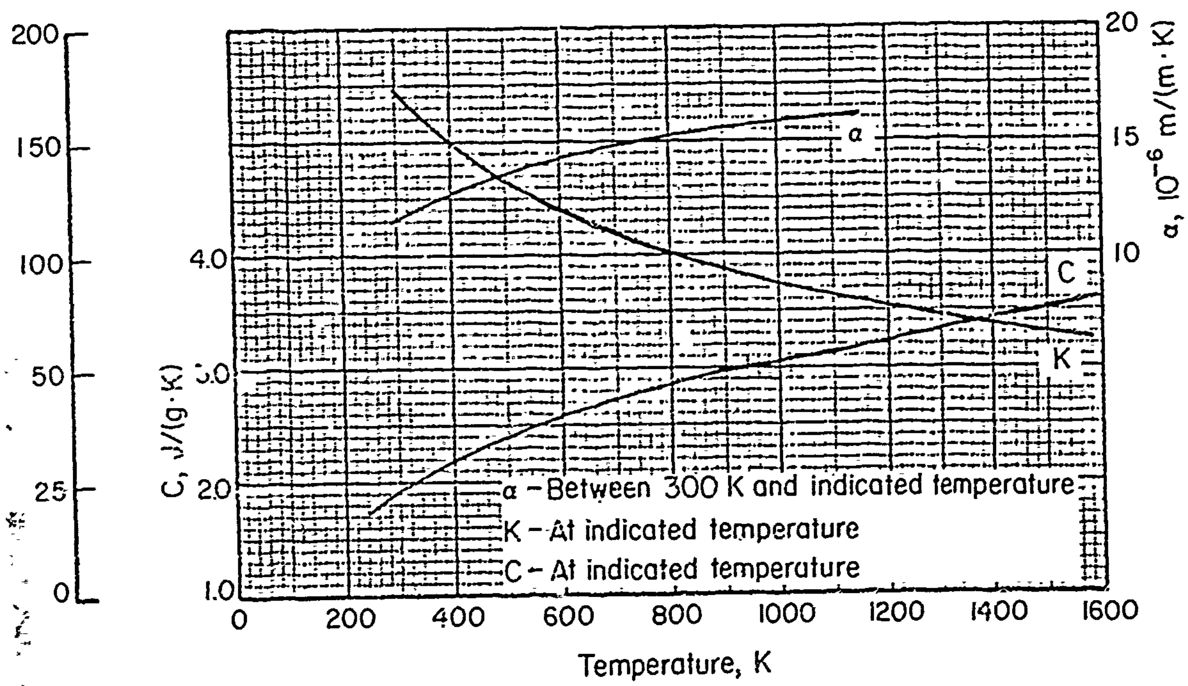


FIGURE 7.2.2.0. Effect of temperature on the physical properties of beryllium vacuum hot-pressed shapes.

TABLE 7.2.2.0(B). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF CROSS-ROLLED BERYLLIUM (SHEET AND PLATE)

SPECIFICATION..........	MIL-B-8964							
FORM..................	SHEET AND PLATE							
CONDITION.............	STRESS RELIEVED[a]							
THICKNESS, MM.........	0.51-1.25		1.26-1.76		1.77-6.33		6.34-11.44	11.45-15.24
BASIS.................	A	B	A	B	A	B	S	S
MECHANICAL PROPERTIES:								
FTU, MPA:								
L..................	448	469	448	483	448	483	448	414
LT.................	448	469	448	483	448	483	448	414
FTY, MPA:								
L..................	290	324	296[b]	345	296	338	310	276
LT.................	290	324	296[b]	345	296	338	310	276
FCY, MPA:								
L..................	...	...	...	...	...	...	...	...
LT.................	...	...	...	...	...	...	...	...
FSU, MPA..............	...	...	...	...	...	...	...	...
FBRU, MPA:								
(E/D=1.5).........	...	...	...	...	...	...	...	...
(E/D=2.0).........	...	...	...	...	...	...	...	...
FBRY, MPA:								
(E/D=1.5).........	...	...	...	...	...	...	...	...
(E/D=2.0).........	...	...	...	...	...	...	...	...
EL, PERCENT:								
L..................	7	...	9	...	4	...	4	3
LT.................	8	...	9	...	4	...	4	3
E, GPA................	293.0							
EC, GPA...............	293.0							
G, GPA................	137.9							
MU....................	0.10 (L AND LT)							
PHYSICAL PROPERTIES:								
OMEGA, MG/M3..........	1.85							
C, J/(G*K)............	SEE FIGURE 7.2.2.0							
K, W/(M*K)............	SEE FIGURE 7.2.2.0							
ALPHA, 10-6 M/(M*K)..	SEE FIGURE 7.2.2.0							

[a] PROPERTIES IN THESE COLUMNS ARE APPLICABLE TO SPECIMENS THAT HAVE BEEN MACHINED AND ETCHED PER MAB-205-M. REDUCED PROPERTIES SHOULD BE EXPECTED IN MATERIAL HAVING AN AS-ROLLED OR MACHINED SURFACE.

[b] ESTIMATED VALUE BASED ON LIMITED DATA.

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 are 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 (339 K). Creep, stress relaxation and diminishing stress rupture strength are factors of concern above 339 K. Copper alloys frequently are used at temperatures up to 522 K. The range between 522 K and 672 K is considered very high for copper alloys, since copper and many of its alloys begin to oxidize slightly above 450 K 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 beryllium copper retain strength up to their aging temperatures of 533 K to 672 K.

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 beryllium copper. Beryllium copper, aluminum, manganese and tin 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 even continuously cast into various shapes. The tin bronzes, sometimes called phosphor bronze because phosphorous is used to deoxidize the melt and improve castability, is the lowest strength alloy considered herein. 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 bronzes, 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 which respond to heat treatment, have even 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. Beryllium copper is the highest strength copper-base bearing material, due to its great response to precipitation hardening. Beryllium copper is also available in static and centrifugal cast form but is generally used as wrought shapes, such as extrusions, forgings and mill shapes.

Beryllium copper, 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. Beryllium copper resists softening up to 533 K, which is higher than other common copper alloys. Beryllium copper springs are usually fabricated from strip and wires.

Consult References 7.3.0(a) through (c) for more information.

7.3.1 TIN BRONZES

7.3.1.0 *Comments and Properties.*—The tin bronzes (and leaded tin bronzes) are the copper-tin or copper-tin-lead alloys which have been deoxidized with phosphorous. The alloys were formerly also known as phosphor bronzes. They are readily cast by a number of techniques.

A material specification for tin bronze is listed in Table 7.3.1.0(a). A cross index to the Copper Development Association (CDA) and ASTM designations is given in Table 7.3.1.0(b).

TABLE 7.3.1.0(a). *Material Specification for Tin Bronzes*

Specification	Form
QQ-C-390	Castings

Room-Temperature Properties

Room-temperature mechanical and physical properties are presented in Table 7.3.1.0(c). The effect of temperature on physical properties is shown in Figure 7.3.1.0.

TABLE 7.3.1.0(b). *Cross Index to CDA and ASTM Designation*

QQ-C-390 Alloy No.	CDA Alloy No.	ASTM
D2	910	—
D3	923	B143-2B (Sand), B271-2B (Centrifugal)
D4	922	B61, B143-2A (Sand), B271-2A (Centrifugal)
D5	903	B143-1B (Sand), B271-1B (Centrifugal)
D6	905	B22-D, B143-1A (Sand), B271-1A (Centrifugal)

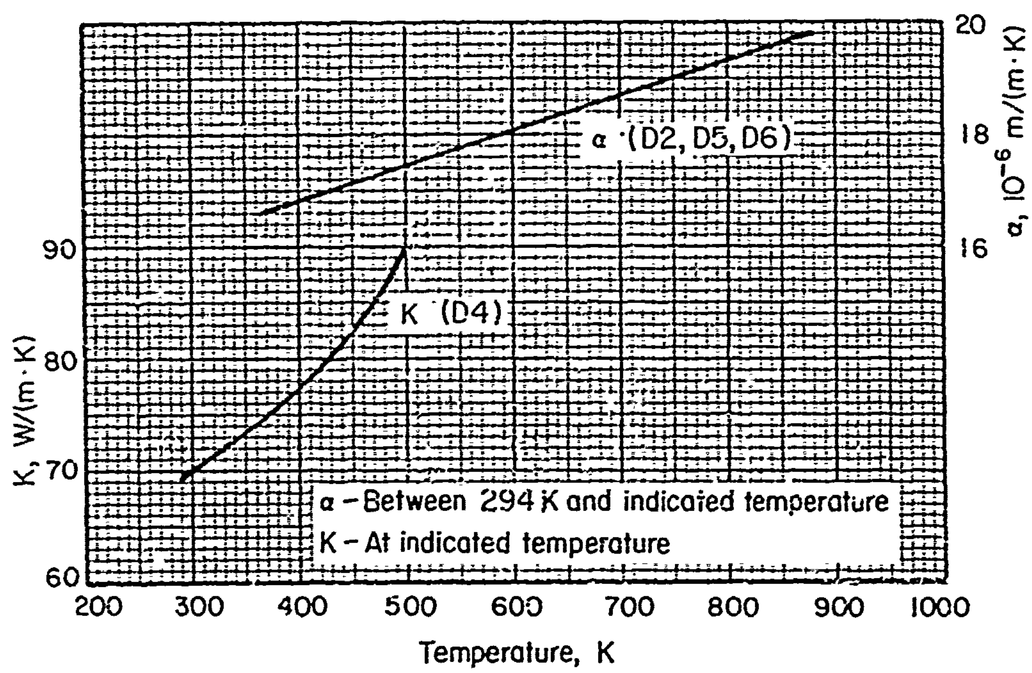


FIGURE 7.3.1.0. Effect of temperature on the physical properties of tin bronze (castings).

TABLE 7.3.1.0(C). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF TIN BRONZE COPPER ALLOYS (CASTINGS)[a,b]

ALLOY	D2	D3	D3[c]	D4	D5	D6
SPECIFICATION	QQ-C-390					
FORM	STATIC AND CENTRIFUGAL CASTINGS					
CONDITION	AS CAST					
BASIS	S	S	S	S	S	S
MECHANICAL PROPERTIES:						
FTU, MPA	207	241	207[d]	234	276	276
FTY, MPA	...	...	...	...	...	...
FCY, MPA	...	...	...	...	...	...
FSU, MPA	...	...	...	...	...	...
FBRU, MPA:						
(E/D=1.5)	...	...	...	...	...	...
(E/D=2.0)	...	...	...	...	...	...
FBRY, MPA:						
(E/D=1.5)	...	...	...	...	...	...
(E/D=2.0)	...	...	...	...	...	...
EL, PERCENT	1	18	12[d]	22	20	20
E, GPA	110.3	96.5		96.5	96.5	103.4
EC, GPA	...	...		...	...	...
G, GPA	...	...		...	...	...
MU	...	...		...	...	...
PHYSICAL PROPERTIES:						
OMEGA, MG/M3	...	8.77		8.64	8.80	8.72
C, J/(G*K)	0.38 (AT 293 K)	0.38 (AT 293 K)		0.38 (AT 293 K)	0.38 (AT 293 K)	0.38 (AT 293 K)
K, W/(M*K)	...	75 (AT 293 K)		SEE FIGURE 7.3.1.0	75 (AT 293 K)	75 (AT 293 K)
ALPHA, 10-6 M/(M*K)	SEE FIGURE 7.3.1.0	18.0 (293 TO 450 K)		18.0 (293 TO 373 K)	SEE FIGURE 7.3.1.0	SEE FIGURE 7.3.1.0
ELECTRICAL CONDUCTIVITY, % IACS	9.3	12.0		14.3	12.0	11.0

[a] REFERENCE SHOULD BE MADE TO THE SPECIFIC REQUIREMENTS OF THE PROCURING OR CERTIFYING AGENCY WITH REGARD TO THE USE OF THE VALUES IN THIS TABLE IN THE DESIGN OF CASTINGS.

[b] MECHANICAL PROPERTIES ARE BASED ON MINIMUM GUARANTEED TENSILE PROPERTIES FROM SEPARATELY CAST TEST BARS. THE PROPERTIES OF PRODUCTION CASTING MAY BE AS LOW AS 75 PERCENT OF THE TABULATED VALUES.

[c] OPTIONAL PROPERTIES WHEN REQUIRED.

[d] WHEN MADE FROM SCRAP, PROPERTIES APPLY ONLY WHEN REQUIRED.

7.3.2 MANGANESE BRONZES

7.3.2.0 *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 in the foundry.

A material specification for manganese bronze is listed in Table 7.3.2.0(a). A cross index to CDA and ASTM designations is given in Table 7.3.2.0(b).

Room-Temperature Properties

Room-temperature mechanical and physical properties are shown in Table 7.3.2.0(c).

TABLE 7.3.2.0(a). *Material Specification for Manganese Bronzes*

Specification	Form
QQ-C-390	Castings

TABLE 7.3.2.0(b). *Cross Index to CDA and ASTM Designations*

QQ-C-390 Alloy No.	CDA Alloy No.	ASTM
C1	868	—
C2	864	B132-A, B147-7A (Sand), B271-7A (Centrifugal)
C3	865	B147-8A (Sand), B271-8A (Centrifugal)
C4	862	B147-8B (Sand), B27-8B (Centrifugal)
C5	861	—
C6	—	—
C7	863	B22-E, B147-8C (Sand), B271-8C (Centrifugal)

TABLE 7.3.2.0(C1). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF MANGANESE BRONZE COPPER ALLOYS (CASTINGS)[a,b]

ALLOY	C1	C2	C3	C4	C5
SPECIFICATION	QQ-C-390				
FORM	STATIC CASTINGS				
CONDITION	AS CAST				
BASIS	S	S	S	S	S
MECHANICAL PROPERTIES:					
FTU, MPA	538	414	448	621	621
FTY, MPA	...	...	...	...	...
FCY, MPA	...	...	...	...	...
FSU, MPA	...	...	...	...	...
FBRU, MPA:					
(E/D=1.5)	...	...	...	...	...
(E/D=2.0)	...	...	...	...	...
FBRY, MPA:					
(E/D=1.5)	...	...	...	...	...
(E/D=2.0)	...	...	...	...	...
EL, PERCENT	18	15	20	18	18
E, GPA	103.4	96.5	103.4	103.4	103.4
EC, GPA	...	...	...	...	...
G, GPA	...	...	...	...	...
MU	...	...	...	...	...
PHYSICAL PROPERTIES:					
OMEGA, MG/M3	8.03	8.33	8.33	7.97	7.97
C, J/(G*K)	0.38 (AT 293 K)	0.38 (AT 293 K)	0.38 (AT 293 K)	0.38 (AT 293 K)	0.38 (AT 293 K)
K, W/(M*K)	...	88 (AT 293 K)	87 (AT 293 K)	35 (AT 293 K)	35 (AT 293 K)
ALPHA, 10-6 M/(M*K)	...	19.8 (293 TO 473 K)	20.3 (293 TO 373 K)	21.6 (293 TO 533 K)	21.6 (293 TO 533 K)
ELECTRICAL CONDUCTIVITY, % IACS	9.0	19.0	22.0	7.5	7.5

[a] REFERENCE SHOULD BE MADE TO THE SPECIFIC REQUIREMENTS OF THE PROCURING OR CERTIFYING AGENCY WITH REGARD TO THE USE OF THE VALUES IN THIS TABLE IN THE DESIGN OF CASTINGS.

[b] MECHANICAL PROPERTIES ARE BASED ON MINIMUM GUARANTEED TENSILE PROPERTIES FROM SEPARATELY CAST TEST BARS. THE PROPERTIES OF PRODUCTION CASTINGS MAY BE AS LOW AS 75 PERCENT OF THE TABULATED VALUE.

[illegible] MECHANICAL AND PHYSICAL PROPERTIES OF MANGANESE BRONZE COPPER ALLOYS (CASTINGS)[a,b] (CONTINUED)

ALLOY	C6	C7	C3	C5	C7
SPECIFICATION	QQ-C-390				
FORM	STATIC CASTINGS		CENTRIFUGAL CASTINGS		
CONDITION	AS CAST		AS CAST		
BASIS	S	S	S	S	S
MECHANICAL PROPERTIES:					
FTU, MPA	669	758	448	621	758
FTY, MPA	...	...	...	...	...
FCY, MPA	...	...	...	...	...
FSU, MPA	...	...	...	...	...
FBRU, MPA:					
(E/D=1.5)	...	...	...	...	...
(E/D=2.0)	...	...	...	...	...
FBRY, MPA:					
(E/D=1.5)	...	...	...	...	...
(E/D=2.0)	...	...	...	...	...
EL, PERCENT	12	12	20	18	12
E, GPA	...	97.9	...	...	...
EC, GPA	...	...	...	...	...
G, GPA	...	...	...	...	...
MU	...	...	...	...	...
PHYSICAL PROPERTIES:					
OMEGA, MG/M3	...	7.83	8.33	7.97	7.83
C, J/(G*K)	...	0.38 (AT 293 K)	0.38 (AT 293 K)	0.38 (AT 293 K)	0.38 (AT 293 K)
K, W/(M*K)	...	35 (AT 293 K)	87 (AT 293 K)	35 (AT 293 K)	35 (AT 293 K)
ALPHA, 10-6 M/(M*K)	...	21.6 (293 TO 533 K)	20.3 (293 TO 373 K)	21.6 (293 TO 533 K)	21.6 (293 TO 373 K)
ELECTRICAL CONDUCTIVITY, % IACS	...	8.0	22.0	7.5	8.0

[a] REFERENCE SHOULD BE MADE TO THE SPECIFIC REQUIREMENTS OF THE PROCURING OR CERTIFYING AGENCY WITH REGARD TO THE USE OF THE VALUES IN THIS TABLE IN THE DESIGN OF CASTINGS.

[b] MECHANICAL PROPERTIES ARE BASED ON MINIMUM GUARANTEED TENSILE PROPERTIES FROM SEPARATELY CAST TEST BARS. THE PROPERTIES TO PRODUCTION CASTINGS MAY BE AS LOW AS 75 PERCENT OF THE TABULATED VALUES.

7.3.3 ALUMINUM BRONZES

7.3.3.0 *Comments and Properties.*—The aluminum bronzes are copper-base alloys with an addition of aluminum up to 14 percent. The commercial aluminum bronze alloys normally contain aluminum within limits of 5 and 12 percent, with additions of iron, nickel, and manganese. The alloys covered by QQ-C-390 involve variations in percentages of these elements. The strength of aluminum bronzes can be varied by adjustment of composition and by heat treatment.

Some material specifications for aluminum bronzes are presented in Table 7.3.3.0(a). A cross index to CDA and ASTM designations is in Table 7.3.3.0(b).

Room-Temperature Properties

Room-temperature mechanical and physical properties are shown in Tables 7.3.3.0(c) through (e). The effect of temperature on physical properties is shown in Figure 7.3.3.0.

TABLE 7.3.3.0(a). *Material Specifications for Aluminum Bronzes*

Specification	Form
QQ-C-390	Castings
AMS 4631	Bars, rods, and forgings

TABLE 7.3.3.0(b). *Cross Index to CDA and ASTM Designations*

QQ-C 390 Alloy No.	CDA Copper Alloy No.	ASTM
G1	—	—
G3	955	B148-9D (Sand), B271-9D (Centrifugal)
G4	955	B148-9D (Sand)
G5	954	B148-9C (Sand), B271-9C (Centrifugal)
G6	952	B148-9A (Sand), B271-9A (Centrifugal)
G7	953	B148-9B (Sand), B271-9B (Centrifugal)
G8	—	—

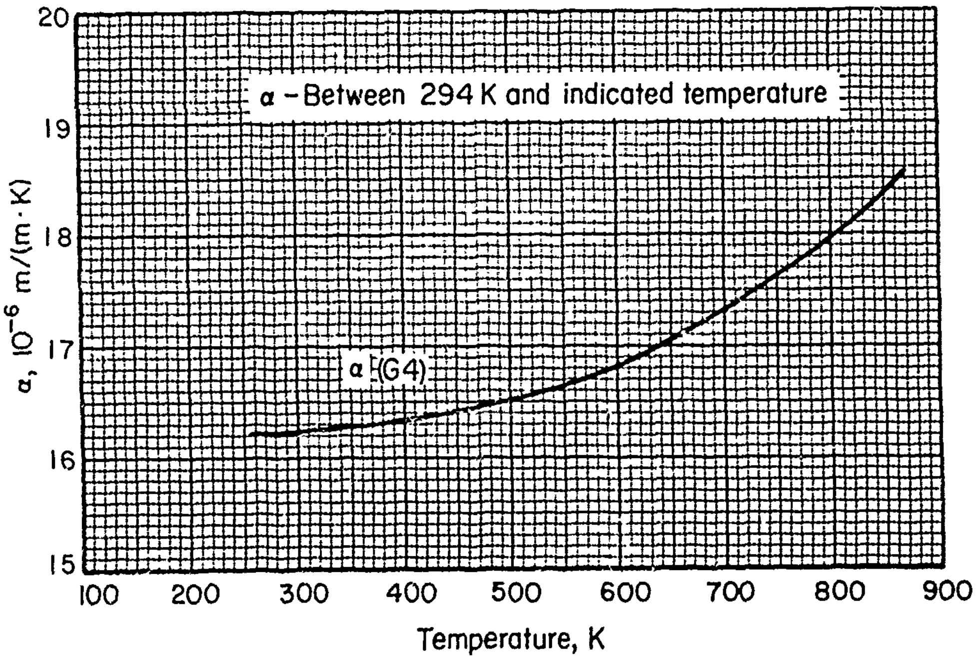


FIGURE 7.3.3.0. Effect of temperature on the physical properties of aluminum bronze (castings).

TABLE 7.3.3.0(C). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF ALUMINUM BRONZE COPPER ALLOYS (STATIC CASTINGS)[a,b]

ALLOY	G1		G3		G4	G5		G6	G7		G8
SPECIFICATION	QQ-C-390										
FORM	STATIC CASTINGS										
CONDITION	AS CAST	HEAT TREATED	AS CAST	HEAT TREATED	AS CAST	AS CAST	HEAT TREATED	AS CAST	AS CAST	HEAT TREATED	AS CAST
BASIS	S	S	S	S	S	S	S	S	S	S	S
MECHANICAL PROPERTIES:											
FTU, MPA	621	758	621	758	586	517	621	448	448	552	586
FTY, MPA	276[c]	414[c]	276[c]	414[c]	241[c]	207[c]	310[c]	172[c]	172[c]	276[c]	241[c]
FCY, MPA	...	...	...	...	...	...	...	...	...	...	...
FSU, MPA	...	...	...	...	...	...	...	...	...	...	...
FBRU, MPA:											
(E/D=1.5)	...	...	...	...	...	...	...	...	...	...	...
(E/D=2.0)	...	...	...	...	...	...	...	...	...	...	...
FBRY, MPA:											
(E/D=1.5)	...	...	...	...	...	...	...	...	...	...	...
(E/D=2.0)	...	...	...	...	...	...	...	...	...	...	...
EL, PERCENT	...	...	...	...	...	...	...	...	...	...	...
E, GPA	...		110.3		110.3	106.9		103.4	110.3		...
EC, GPA	...		...		...	...		...	...		...
G, GPA	...		...		...	...		...	...		...
MU	...		...		...	...		...	...		...
PHYSICAL PROPERTIES:											
OMEGA, MG/M3	...		7.53		7.53	7.45		7.64	7.53		
C, J/(G*K)	...		0.42 (AT 293 K)		0.42 (AT 293 K)	0.42 (AT 293 K)		0.38 (AT 293 K)	0.38 (AT 293 K)		
K, W/(M*K)	...		42 (AT 293 K)		42 (AT 293 K)	59 (AT 293 K)		50 (AT 293 K)	63 (AT 293 K)		
ALPHA, 10-6 M/(M*K)	...		d		e	d		d	d		
ELECTRICAL CONDUCTIVITY, % IACS	...		8.5		8.5	13.0		11.0	13.0		

[a] REFERENCE SHOULD BE MADE TO THE SPECIFIC REQUIREMENTS OF THE PROCURING OR CERTIFYING AGENCY WITH REGARD TO THE USE OF THE VALUES IN THIS TABLE IN THE DESIGN OF CASTINGS.

[b] MECHANICAL PROPERTIES ARE BASED ON MINIMUM GUARANTEED TENSILE PROPERTIES FROM SEPARATELY CAST TEST BARS. THE PROPERTIES OF PRODUCTION CASTINGS MAY BE AS LOW AS 75 PERCENT OF THE TABULATED VALUE.

[c] AS DETERMINED BY EXTENSION-UNDER-LOAD METHOD. LIMITING EXTENSION FOR YIELD STRENGTH DETERMINATION EQUALS 0.005 MM PER MM OF GAGE LENGTH.

[d] 16.2 (293 TO 573 K).

[e] SEE FIGURE 7.3.3.0.

[illegible] MECHANICAL AND PHYSICAL PROPERTIES OF
ALUMINUM BRONZE COPPER ALLOYS (CENTRIFUGAL CASTINGS)[a,b]

ALLOY	G1		G2	G3		G5			G6	G7		G8
SPECIFICATION	QQ-C-390											
FORM	CENTRIFUGAL CASTINGS											
CONDITION	AS CAST	HEAT TREATED	HEAT TREATED	AS CAST	HEAT TREATED	AS CAST	HEAT TREATED	HEAT TREATED	AS CAST	AS CAST	HEAT TREATED	AS CAST
BASIS	S	S	S	S	S	S	S	S	S	S	S	S
MECHANICAL PROPERTIES:												
FTU, MPA	621	758	758	621	758	517	621	758[c]	448	448	552	586
FTY, MPA	276[d]	414[d]	414[d]	276[d]	414[d]	207[d]	310[d]	414[c,d]	172[d]	172[d]	276[d]	241[d]
FCY, MPA	...	...	...	...	...	...	...	...	...	...	...	...
FSU, MPA	...	...	...	...	...	...	...	...	...	...	...	...
FBRU, MPA:												
(E/D=1.5)	...	...	...	...	...	...	...	...	...	...	...	...
(E/D=2.0)	...	...	...	...	...	...	...	...	...	...	...	...
FBRY, MPA:												
(E/D=1.5)	...	...	...	...	...	...	...	...	...	...	...	...
(E/D=2.0)	...	...	...	...	...	...	...	...	...	...	...	...
EL, PERCENT	6	5	5	6	5	12	6	5[c]	20	20	12	18
E, GPA	...	...	110.3	110.3		106.9			...	...	...	...
EC, GPA	...	...	...	...		...			...	...	...	...
G, GPA	...	...	...	...		...			...	...	...	...
MU	...	...	...	...		...			...	...	...	...
PHYSICAL PROPERTIES:												
OMEGA, MG/M3	...		7.53	7.53		7.45			7.64	7.53		
C, J/(G*K)	...		0.42 (AT 293 K)	0.42 (AT 293 K)		0.42 (AT 293 K)			0.38 (AT 293 K)	0.38 (AT 293 K)		
K, W/(M*K)	...		42 (AT 293 K)	42 (AT 293 K)		59 (AT 293 K)			50 (AT 293 K)	63 (AT 293 K)		
ALPHA, 10-6 M/(M*K)	...		e	e		e			e	e		
ELECTRICAL CONDUCTIVITY, % IACS	...		8.5	8.5		13.0			11.0	13.0		

[a]REFERENCE SHOULD BE MADE TO THE SPECIFIC REQUIREMENTS OF THE PROCURING OR CERTIFYING AGENCY WITH REGARD TO THE USE OF VALUES IN THIS TABLE IN THE DESIGN OF CASTINGS.

[b]MECHANICAL PROPERTIES ARE BASED ON MINIMUM GUARANTEED TENSILE PROPERTIES FROM SEPARATELY CAST TEST BARS. THE PROPERTIES OF PRODUCTION CASTINGS MAY BE AS LOW AS 75 PERCENT OF THE TABULATED VALUE.

[c]OPTIONAL PROPERTIES APPLICABLE WHEN MATERIAL IS INTENDED FOR SHAFT SLEEVES IN HIGHLY STRESSED SHAFTING.

[d]AS DETERMINED BY EXTENSION-UNDER-LOAD METHOD. LIMITING EXTENSION FOR YIELD STRENGTH DETERMINATION EQUALS 0.005 MM PER MM OF GAGE LENGTH.

[e]16.2 (293 TO 573 K).

TABLE 7.3.3.0(E). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF ALUMINUM BRONZE COPPER ALLOY (BARS, RODS, AND FORGINGS

SPECIFICATION	AMS 4631			
FORM	BARS, RODS, AND FORGINGS			
CONDITION	STRESS RELIEVED			
THICKNESS, MM	≤ 12.71	12.72-25.41	25.42-50.81	50.82-76.20
BASIS	S	S	S	S
MECHANICAL PROPERTIES:				
FTU, MPA:				
L	621	607	607	517
T	...	...	...	...
FTY, MPA:				
L	310	303	290	255
T	...	...	...	...
FCY, MPA:				
L	310	303	290	255
T	...	...	...	...
FSU, MPA	345	331	324	283
FBRU, MPA:				
(E/D=1.5)	689	669	648	572
(E/D=2.0)	758	724	696	621
FBRY, MPA:				
(E/D=1.5)	345	331	324	283
(E/D=2.0)	372	365	352	310
EL, PERCENT:				
L	15	15	20	30
T	...	...	...	...
E, GPA	110.3			
EC, GPA	110.3			
G, GPA	42.7			
MU	0.30			
PHYSICAL PROPERTIES:				
OMEGA, MG/M3	...			
C, J/(G*K)	...			
K, W/(M*K)	...			
ALPHA, 10-6 M/(M*K)	...			

7.3.4 BERYLLIUM COPPER

7.3.4.0 *Comments and Properties.*—The alloys termed beryllium copper are a family of copper-base alloys containing beryllium or beryllium plus cobalt as strengtheners. Two of these alloys are covered in this section and are identified by Copper Development Association alloy designations CDA 170 and CDA 172. CDA 170 and CDA 172 are high-strength alloys containing 1.70 and 1 92 (nominal) percent beryllium, respectively These alloys are available in all mill forms but are usually used in the form of strip, wire, and rod. Material specifications for beryllium copper alloys are presented in Table 7.3.4.0(a).

TABLE 7.3.4.0(a). *Material Specifications for Beryllium Copper*

Specification	Form
QQ-C-530 (CDA 172)	Bar, rod, and wire
QQ-C-533 (CDA 170 and 172)	Strip

Manufacturing Considerations.—The beryllium copper alloys are normally received in either the solution-treated (A) or solution-treated plus cold-worked (1/4 H, 1/2 H, or H) conditions. After forming and joining, they are strengthened by means of precipitation-hardening thermal treatments. When it is not feasible to heat treat these parts after forming, the material is often formed in an underaged temper, with resulting decrease in strength from the values listed in Table 7.2.4.0(c).

Environmental Considerations.—For alloys CDA 170 and 172 the maximum service temperature is 422 K for continuous exposure, although these alloys may be exposed for periods of up to 100 hours at 533 K without substantial decrease in residual strength.

Heat Treatment.—Typical aging treatments applied to material furnished in the unaged tempers are presented in Table 7.3.4.0(b). It should be noted that material furnished in the aged tempers has been aged to meet specified tensile properties or hardness and some deviation from the listed heat treatments can be expected.

Room-Temperature Properties

Room-temperature mechanical properties are shown in Table 7.3.4.0(c). The effect of temperature on physical properties is depicted in Figure 7.3.4.0.

TABLE 7.3.4.0(b). *Typical Aging Treatments for Beryllium Copper Alloys*

Alloy	Original Temper	Aging Treatment	Final Temper
CDA 170 and 172	A	3 hr at 589/603 K	AT
	1/4 H 1/2 H H	2 hr at 589/603 K	1/4 HT 1/2 HT H

TABLE 7.3.4.0(A). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF BERYLLIUM COPPER

ALLOY	CDA 172					CDA 172				CDA 170			
SPECIFICATION	QQ-C-530					QQ-C-533				QQ-C-533			
FORM	BAR AND ROD					STRIP				STRIP			
CONDITION	AT	HT				AT	¼ HT	½ HT	HT	AT	¼ HT	½ HT	HT
THICKNESS, MM	≥ 0.51	0.51-9.53	9.54-25.1	25.42-50.80	> 50.80	...	...	...	...	...	...	...	...
BASIS	S	S	S	S	S	S	S	S	S	S	S	S	S
MECHANICAL PROPERTIES:													
FTU, MPA:													
L	1140	1280	1240	1210	1210	1140	1210	1280	1310	1030	1100	1170	1240
LT	...	...	...	...	...	...	...	...	...	...	...	...	...
FTY, MPA:													
L	896	1100	1070	1030	896	965	1030	1100	1140	896	931	1000	1070
LT	...	...	...	...	...	...	...	...	...	...	...	...	...
FCY, MPA:													
L	896	1100	1070	1030	896	965	1030	1100	1140	896	931	1000	1070
LT	...	...	...	...	...	...	...	...	...	...	...	...	...
FSU, MPA	621	696	676	655	655	621	655	696	717	565	600	641	676
FBRU, MPA:													
(E/D=1.5)	1140	1280	1240	1210	1210	1140	1210	1280	1310	1030	1100	1170	1240
(E/D=2.0)	1230	1380	1340	1300	1300	1230	1300	1330	1410	1120	1190	1260	1340
FBRY, MPA:													
(E/D=1.5)	896	1100	1070	1030	896	965	1030	1100	1140	896	931	1000	1070
(E/D=2.0)	986	1400	1170	1140	986	1060	1140	1210	1250	986	1020	1100	1170
EL, PERCENT:													
L	3	1	1	2	2	3	2	1	1	3	2	1	1
LT	...	...	...	...	...	...	...	...	...	...	...	...	...
E, GPA	127.6												
EC, GPA	...												
G, GPA	50.3												
MU	0.27												
PHYSICAL PROPERTIES:													
OMEGA, MG/M3	8.25												
C, J/(G*K)	SEE FIGURE 7.3.4.0												
K, W/(M*K)	SEE FIGURE 7.3.4.0												
ALPHA, 10-6 M/(M*K)	SEE FIGURE 7.3.4.0												

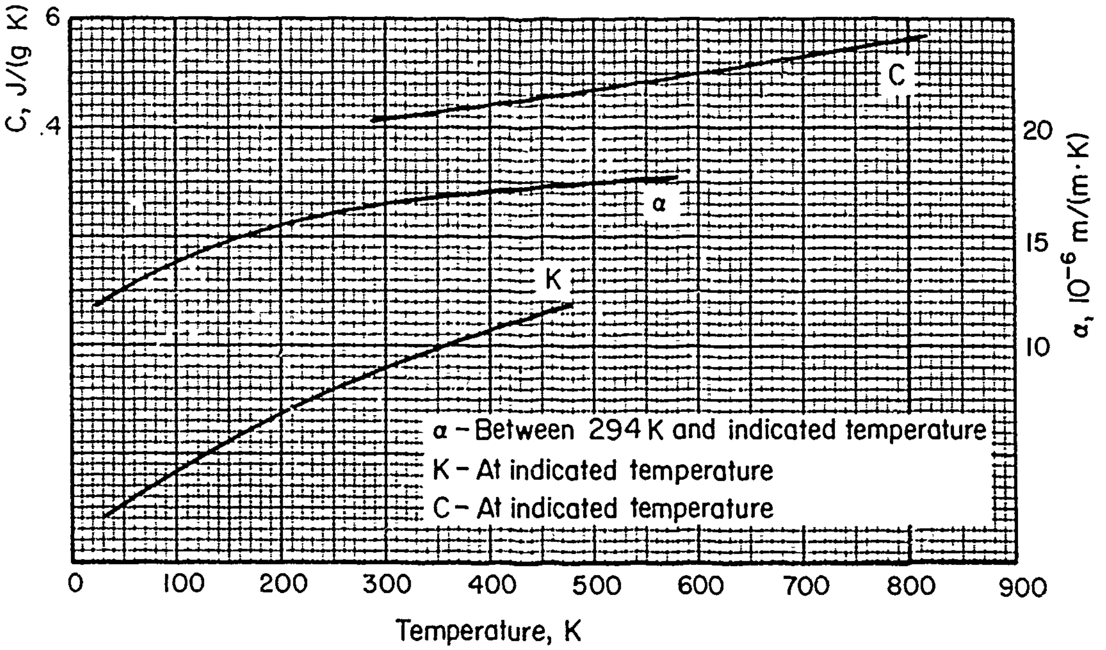


FIGURE 7.3.4.0. Effect of temperature on the physical properties of beryllium copper, precipitation heat treated.

7.4.1 MP35N ALLOY

7.4.1.0 *Comments and Properties.*—MP35N is a vacuum induction, vacuum arc remelted alloy based on the quarternary of cobalt, nickel, chromium, and molybdenum, 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 672 K. Exposure to temperatures above 672 K for extended periods of time may cause embrittlement. (Parts would be limited to the size, ⩽ 31.7 mm thickness for 1790 MPa minimum, of bar which can be work strengthened to meet specification strength requirements).

Material specifications for MP35N are presented in Table 7.4.1.0(a).

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)

Manufacturing Considerations.—The work hardening characteristics of MP35N are similar to 304 stainless steel. Drawing, swaging, rolling, and shear forming are excellent ways of deforming for work strengthening. The machineability of MP35N is similar to the nickel-base alloys.

Environmental Considerations.—MP35N has excellent corrosion, crevice corrosion and stress corrosion resistance in seawater Initial tests have indicated that MP35N does not appear to be susceptible to hydrogen embrittlement.

Heat Treatment.—After work strengthening, MP35N is aged at 811–866 K ± 15 K for 4 hours and air cooled.

Room-Temperature Properties

The room-temperature mechanical and physical properties for MP35N are presented in Table 7.4.1.0(b). The effect of temperature on physical properties is shown in Figure 7.4.1.0.

7.4.1.1 *Work Strengthened and Aged Condition.*—Effect-of-temperature curves for various mechanical properties are shown in Figures 7.4.1.1.1(a) through 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(9). DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF MP35N ALLOY (BAR)

SPECIFICATION	AMS 5844 AND AMS 5845	
FORM	BAR	
CONDITION	SOLUTION TREATED, COLD DRAWN, AND AGED	
THICKNESS, MM	≤ 25.40	
BASIS	A	B
MECHANICAL PROPERTIES:		
FTU, MPA:		
L	1790[a]	1900
LT	...	...
FTY, MPA:		
L	1590[b]	1830
LT	...	...
FCY, MPA:		
L	...	...
LT	...	...
FSU, MPA	1000	1010
FBRU, MPA:		
(E/D=1.5)	...	...
(E/D=2.0)	...	...
FBRY, MPA:		
(E/D=1.5)	...	...
(E/D=2.0)	...	...
EL, PERCENT:		
L	8	...
LT	...	...
E, GPA	231.7	
EC, GPA	...	
G, GPA	86.2	
MU	0.34	
PHYSICAL PROPERTIES:		
OMEGA, MG/M3	8.41	
C, J/(G*K)	0.75 (273 TO 294 K)	
K, W/(M*K)	SEE FIGURE 7.4.1.0	
ALPHA, 10-6 M/(M*K)	SEE FIGURE 7.4.1.0	

[a] THE A VALUE OF 1834MPA IS HIGHER THAN SPECIFICATION MINIMUM.
[b] THE A VALUE OF 1765MPA IS HIGHER THAN SPECIFICATION MINIMUM.

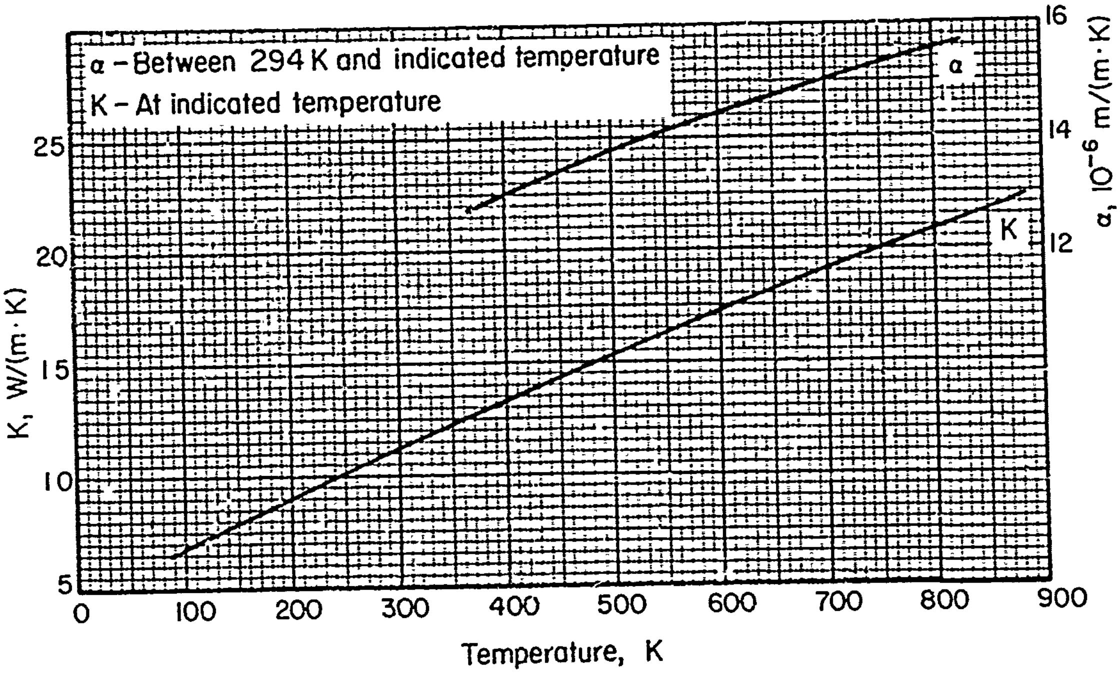


FIGURE 7.4.1.0. Effect of temperature on the physical properties of MP35N alloy.

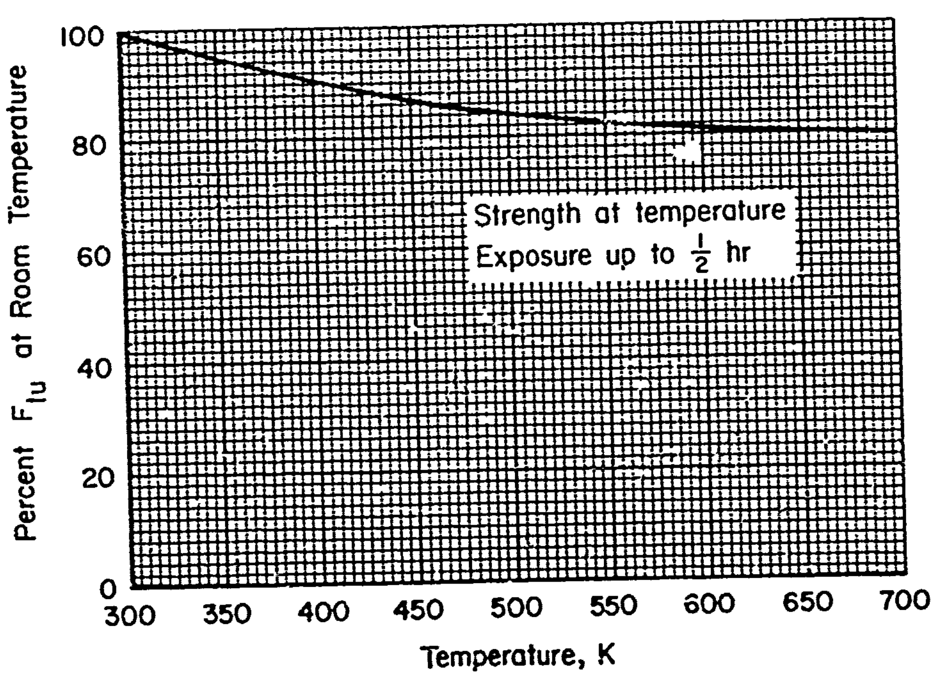


FIGURE 7.4.1.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of cold worked and aged MP35N bar, F_{tu} = 1793 MPa

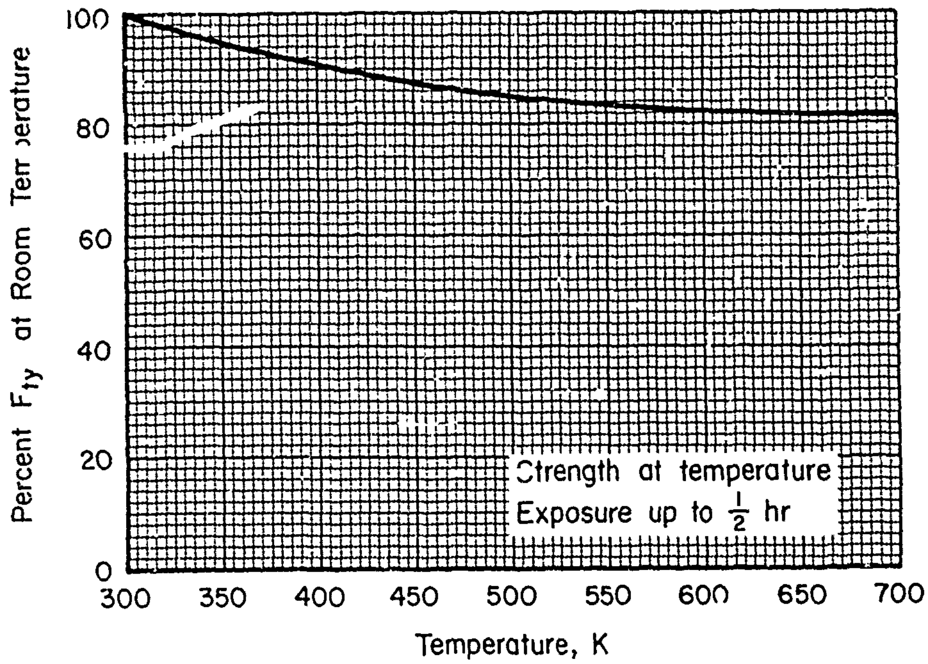


FIGURE 7.4.1.1.(b). Effect of temperature on the tensile yield strength (F_{ty}) of cold worked and aged MP35N(bar), F_{tu} = 1793 MPa.

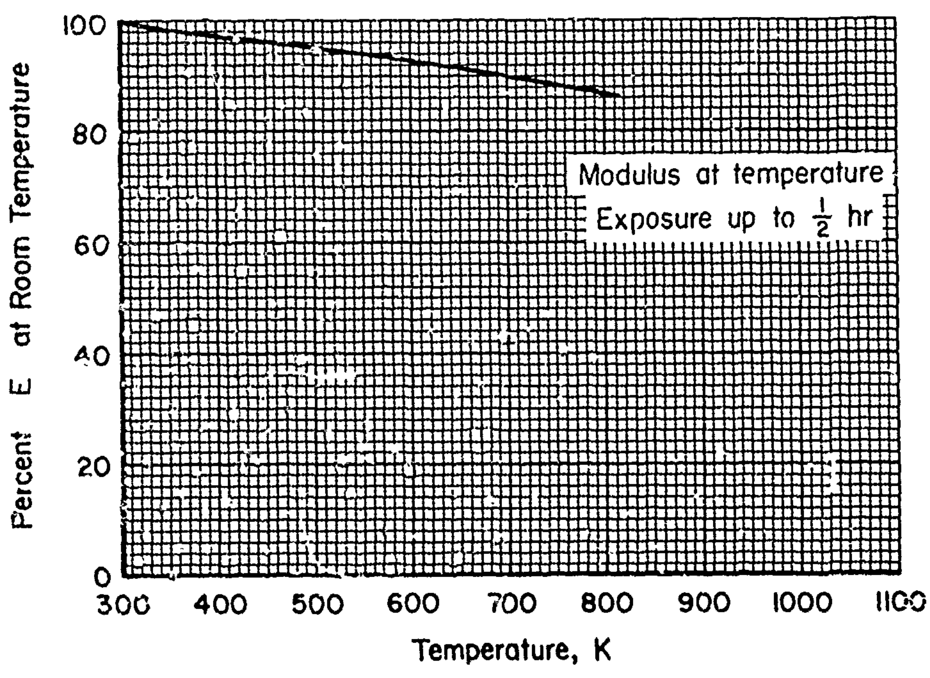


FIGURE 7.4.1.1.4(a). Effect of temperature on the tensile modulus (E) of MP35N alloy (bar).

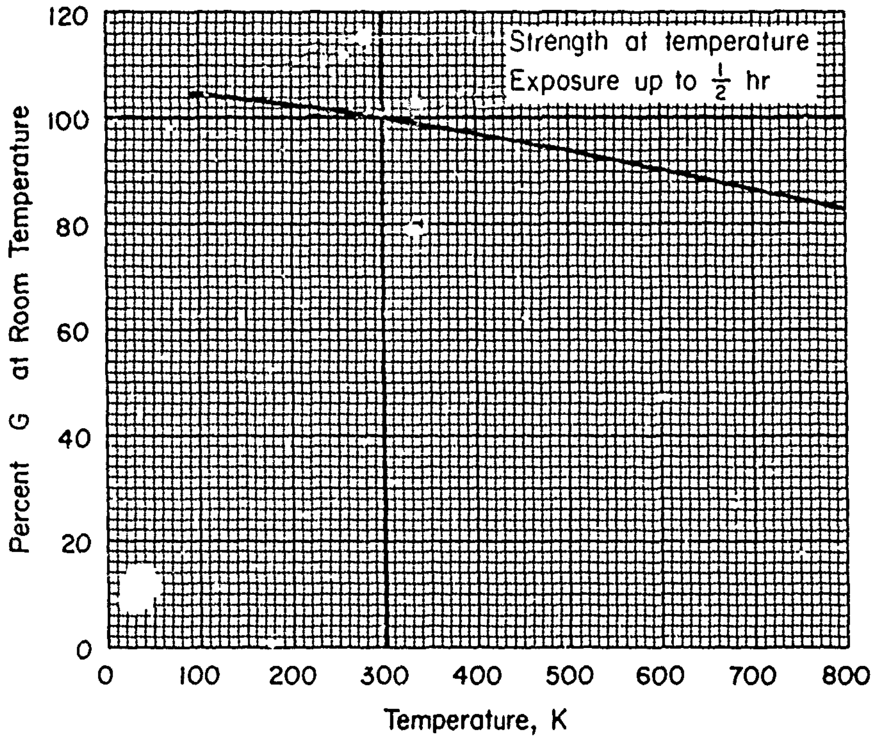


FIGURE 7.4.1.1.4(b). Effect of temperature on the shear modulus (G) of MP35N alloy (bar).

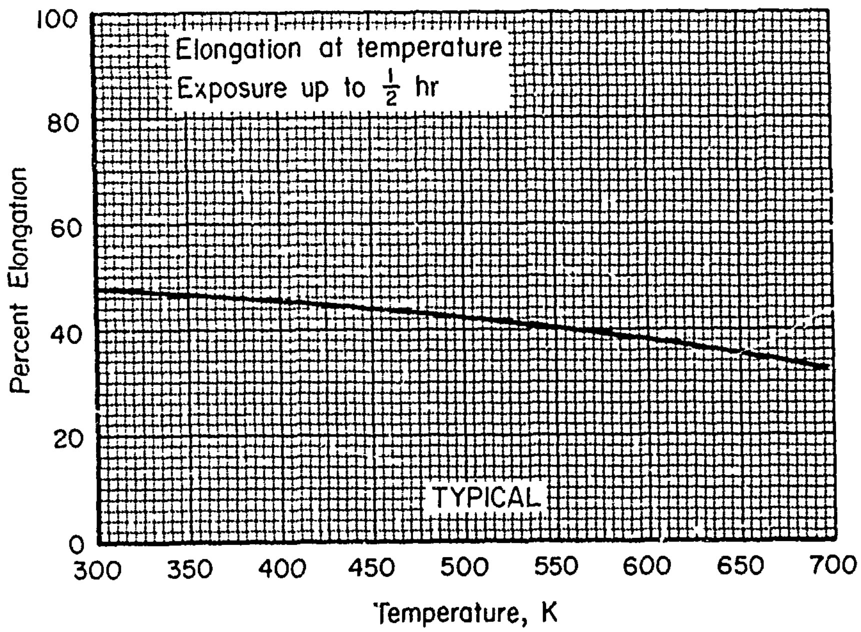


FIGURE 7.4.1.1.5. Effect of temperature on the elongation (e) of cold worked and aged MP35N (bar), F_{tu} = 1793 MPa.

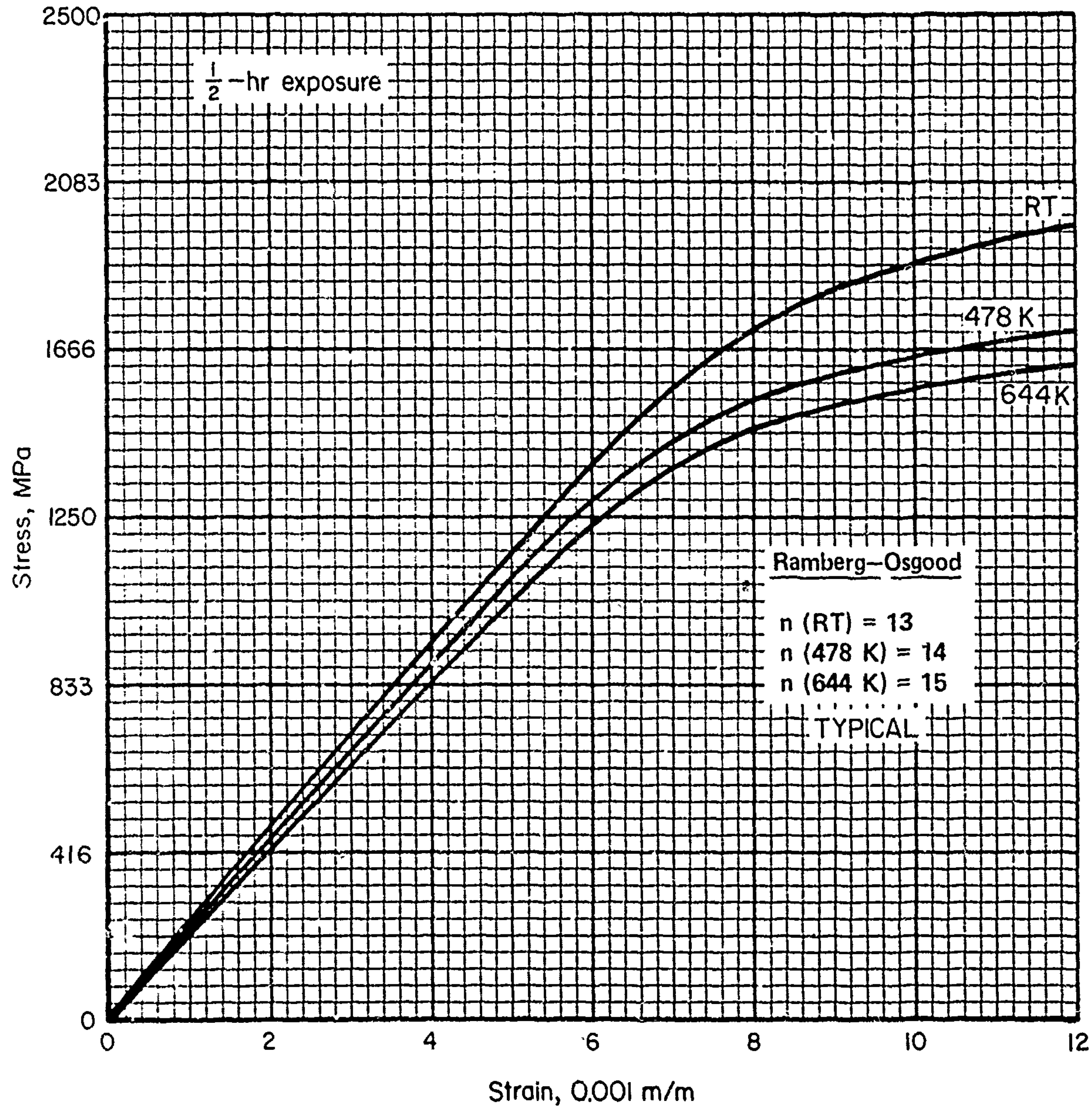


FIGURE 7.4.1.1.6. Typical tensile stress-strain curves at room and elevated temperatures for cold worked and aged MP35N (bar). F_{tu} = 1793 MPa.

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