MATERIALS DATA HANDBOOK

Aluminum Alloy 2219

(2nd Edition)

Revised by

R. F. Muraca
J. S. Whittick

March 1972

CR-123777

Prepared for

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

Contract No. NAS8-26644

WESTERN APPLIED RESEARCH & DEVELOPMENT, INC.

1403-07 Industrial Road San Carlos, California 94070

PREFACE

The revised edition of the Materials Data Handbook on the aluminum alloy 2219 was prepared by Western Applied Research & Development, Inc. under contract with the National Aeronautics and Space Administration, George C. Marshall Space Flight Center, Marshall Space Flight Center, Alabama. It is a revised and updated version of the Handbook originally prepared by the Department of Chemical Engineering and Metallurgy at Syracuse University, March 1966.

It is intended that this Handbook present, in the form of a single document, a summary of the materials property information presently available on the 2219 alloy.

The Handbook is divided into twelve (12) chapters. The scope of the information presented includes physical and mechanical property data at cryogenic, ambient and elevated temperatures, supplemented with useful information in such areas as material procurement, metallurgy of the alloy, corrosion, environmental effects, fabrication and joining techniques. Design data are presented, as available, and these data are complemented with information on the typical behavior of the alloy. The major source used for the design data is the Department of Defense document, Military Handbook-5A.

Information on the alloy is given in the form of tables and figures, supplemented with descriptive text as appropriate. Source references for the information presented are listed at the end of each chapter.

Throughout the text, tables, and figures, common engineering units (with which measurements were made) are accompanied by conversions to International (SI) Units, except in the instances where double units would over-complicate data presentation, or where SI units are impractical (e.g., machine tools and machining). In these instances, conversion factors are noted. A primary exception to the use of SI units is the conversion of 1000 pounds per square inch to kilograms per square millimeter rather than newtons, in agreement with the ASTM that this unit is of a more practical nature for worldwide use.

ACKNOWLEDGMENTS

The second edition of "Materials Data Handbook: Aluminum Alloy 2219" was prepared by Western Applied Research & Development, Inc. under Contract No. NAS8-26644 for the George C. Marshall Space Flight Center of the National Aeronautics and Space Administration. The work was administered under the technical direction of the Astronautics Laboratory, Materials Division of the George C. Marshall Space Flight Center with Mr. Wayne R. Morgan acting as Project Manager.

Sincere appreciation is tendered to the many commercial organizations and Government agencies who have assisted in the preparation of this document.

TABLE OF CONTENTS

TABULAR ABSTRACT

Aluminum Alloy 2219

TYPE:

Wrought, heat treatable aluminum alloy

NOMINAL COMPOSITION:

Al-6.3Cu-0.3Mn-0.18Zr-0.1V-0.06Ti

AVAILABILITY:

Bare and clad sheet, plate, forgings, extrusions, armor plate, wire, rod, and bar

TYPICAL PHYSICAL PROPERTIES:

Density	2.84 g/cm^3 at room temperature
Thermal Conductivity (O temper)	0.41 cal/cm/cm^2/°C/sec
(T62 temper)	0.30 cal/cm/cm^2/°C/sec
Av. Coeff. of Thermal Expansion	22.3 microin/in/°C (20—100°C) 22.3 μcm/cm/°C
Electrical Resistivity (O temper)	3.9 microhm-cm at 20°C
(T62 temper)	5.7 microhm-cm at 20°C

TYPICAL MECHANICAL PROPERTIES:

F_{tu} (O temper)	25,000 psi (17.6 kg/mm^2)
(T62 temper)	60,000 psi (42.2 kg/mm^2)
F_{ty} (O temper)	11,000 psi (7.7 kg/mm^2)
(T62 temper)	42,000 psi (29.5 kg/mm^2)
e (2 inch, 50.8 mm) (O temper)	18 percent
(T62 temper)	10 percent
E (tension)	10.6 x 10^6 psi (7.5 x 10^3 kg/mm^2)

FABRICATION CHARACTERISTICS:

Weldability	Excellent (fusion and resistance methods)
Formability	Slightly superior to 2014 alloy
Machinability	Good in annealed condition

COMMENTS:

Alloy has good mechanical properties at cryogenic temperatures and at elevated temperatures up to 600°F (316°C). Recommended for applications requiring high strength weldments.

SYMBOLS

a	One-half notch section dimension
A	Area of cross section; "A" basis for mechanical property values (MIL-HDBK-5A)
Å	Angstrom unit
AC	Air cool
AMS	Aerospace Material Specifications
Ann	Annealed
ASTM	American Society for Testing Methods
Av or Avg	Average
B	"B" basis for mechanical property values (MIL-HDBK-5A)
b	Subscript "bending"
bcc	Body centered cubic
BHN	Brinell hardness number
br	Subscript "bearing"
Btu	British thermal unit(s)
°C	Degree(s) Celsius
c	Subscript "compression"
CD	Cold drawn
CF	Cold finished
cm	Centimeter
c_p	Specific heat
CR	Cold rolled
CW	Cold worked
CVM	Consumable vacuum melted
D or Dia	Diameter
DPH	Diamond pyramid hardness
e	Elongation in percent
E	Modulus of elasticity, tension
E_c	Modulus of elasticity, compression
e/D	Ratio of edge distance to hole diameter
E_s	Secant modulus
E_t	Tangent modulus
eV	Electron volt(s)
°F	Degree(s) Fahrenheit
f	Subscript "fatigue"
F_{bru}	Bearing ultimate strength
F_{bry}	Bearing yield strength

fcc	Face centered cubic
FC	Furnace cool
F_{cy}	Compressive yield strength
F_{su}	Shear stress; shear strength
F_{tu}	Ultimate tensile strength
F_{ty}	0.2% tensile yield strength (unless otherwise indicated)
g	Gram
G	Modulus of rigidity
HAZ	Heat affected zone in weldments
hcp	Hexagonal close pack
hr	Hour(s)
HT	Heat treat
IACS	International annealed copper standard
in	Inch
ipm	Inches per minute
°K	Degree(s) Kelvin
K	Stress intensity factor; thermal conductivity
K_c	Measure of fracture toughness (plane stress) at point of crack growth instability
kg	Kilogram
K_{Ic}	Plane strain fracture toughness value
ksi	Thousand pounds per square inch
K_t	Theoretical elastic stress concentration factor
L	Longitudinal
lb	Pound
LT	Long transverse (same as transverse)
M	Bending moment
m	Meter
M	Subscript "mean"
Max	Maximum
ml	Milliliter
MIL	Military
Min	Minimum
mm	Millimeter
N	Cycles to failure
NSR	Notch strength ratio
NTS	Notch tensile strength
OQ	Oil quench
ppm	Parts per million
pt	Point; part

r	Radius
RA	Reduction in area; Rockwell hardness A scale
RB	Rockwell hardness B scale
RC	Rockwell hardness C scale
rpm	Revolutions per minute
RT	Room temperature
SA	Solution anneal
sec	Second
S-N	S = stress; N = number of cycles
Spec	Specifications; specimen
ST	Solution treat; short transverse
STA	Solution treated and aged
T	Transverse
t	Thickness; time
Temp	Temperature
typ	Typical
Var	Variable
VHN	Vickers hardness number
W	Width
WQ	Water quench

CONVERSION FACTORS

To Convert	To	Multiply By
angstrom units	millimeters	1×10^{-7}
Btu/lb/°F	cal/g/°C	1
Btu/ft²/sec/°F-inch	cal/g/cm²/sec/°C-cm	1.2404
circular mil	square centimeters	$5.067\ 075 \times 10^{-6}$
cubic feet	cubic meters	0.028 317
cubic feet/minute	liters/second	0.4720
cubic inches	cubic centimeters	16.387 162
feet	meters	0.304 800 609
foot-pounds	kilogram-meters	0.138 255
gallons (U.S.)	liters	3.785 411 784
inches	millimeters	25.4
ksi (thousand pounds per square inch	kilograms/square millimeter	0.70307
microns	millimeters	0.001
mils	millimeters	0.0254
ounces (avoir.)	grams	28.349 527
ounces (U.S. fluid)	milliliters	29.5729
pounds (avoir.)	kilograms	0.453 592 37
pounds/foot	kilograms/meter	1.488 16
pounds/cubic foot	grams/cubic centimeter	0.016 018 463
square feet (U.S.)	square meters	0.092 903 41
square inches (U.S.)	square centimeters	6.451 625 8

Temperature in °C = (°F − 32) (5/9)

Temperature in °K = °C + 273.15

Chapter 1

GENERAL INFORMATION

1.1 Aluminum alloy 2219 is a heat-treatable wrought alloy developed by the Aluminum Company of America (Alcoa) in 1954 for applications at temperatures up to 600° F (315° C). Typical mechanical properties of 2219 in the 500°-600° F (260°-315° C) temperature range are superior to those of any other commercially available aluminum alloy (ref. 1.1). The weldability of the alloy is excellent. Mechanical properties of welded and unwelded 2219 at temperatures down to -423° F (-253° C) are also excellent.

1.2 The alloy has good tensile and yield strength and good fatigue and creep-rupture properties up to temperatures of 600° F (315° C). Its forming characteristics are similar and slightly superior to 2014 alloy. The alloy has good machining qualities in the annealed condition. It appears not to be susceptible to stress-corrosion cracking provided that proper heat treating procedures are employed. The 2219 alloy is available as sheet and plate, forgings, extrusions, armor plate, wire, rod, and bar; alclad 2219 is available as sheet and plate (refs. 1.2, 1.3).

1.3 Typical applications for 2219 alloy are in aircraft and automotive engine parts; it has special applications in missiles, space vehicles, and ground support equipment (ref. 1.2).

1.4 General Precautions

1.41 Care should be taken when reheat treatment of clad alloy is required because copper tends to diffuse through the cladding to the surface, thereby decreasing resistance to corrosion.

1.42 Any solution heat treatment of clad 2219 should be performed as quickly as is consistent with MIL-H-6088E. As a general rule, no more than one complete reheat treatment should be performed. The number of annealing treatments should be kept to a minimum and performed as rapidly as possible (ref. 1.1).

Chapter 1 - References

1.1 L.W. Mayer, "Aluminum Alloy 2219," Alcoa Green Letter, November 1963.

1.2 Alloy Digest, "Aluminum 2219," (Filing Code Al-96, Aluminum Alloy), Engineering Alloys Digest, Inc., New Jersey, October 1960.

1.3 Aluminum Standards and Data, 2nd Edition, The Aluminum Association, New York, New York, 1969 (second printing 1970).

1.4 Aerospace Structural Metals Handbook, J.G. Sessler and V. Weiss, Eds., AFML-TR-68-115, 1971 Edition.

Chapter 2

PROCUREMENT INFORMATION

2.1 General. Aluminum 2219 alloy is available as sheet, plate, forgings, extrusions, wire, rod, and bar. Alclad 2219 is available as sheet and plate. Detailed tables of standard sizes available and standard tolerances for the various products are given in references 2.1 and 2.2.

2.2 Procurement Specifications, table 2.2

2.21 NASA Specifications

2.211 MSFC-SPEC-144B, "Aluminum Alloy Forgings, Premium Quality, Heat Treated," August 13, 1963, and Amendment 1, September 8, 1964. Tempers: T4, T6, T31, T352, T81, T852. Prepared by George C. Marshall Space Flight Center. Custodian: NASA-MSFC.

2.3 Major Producers of the Alloy (United States only)

Aluminum Company of America
1501 Alcoa Building
Pittsburgh, Pennsylvania

Kaiser Aluminum and Chemical Sales, Inc.
919 North Michigan Avenue
Chicago, Illinois

Reynolds Metals Company
6601 West Broad Street
Richmond, Virginia

2.4 Available Forms, Sizes, and Conditions

2.41 Commercial sizes available for sheet, sheet circles, plate and plate circles, table 2.41.

TABLE 2.2. — Procurement Specifications (a)

Source	Ref. 2.3, 2.4, 2.5, 2.6					
Alloy	2219					
Product	Temper	Military	Federal	ASTM	SAE AMS	SAE HDBK
Sheet and plate	O	MIL-A-8920A	-	B209-71	4031B	AA2219
	F, T31, T351	MIL-A-8920A	-	B209-71	-	-
	T37, T62, T81	MIL-A-8920A	-	B209-71	-	-
	T851, T87	MIL-A-8920A	-	B209-71	-	-
Forgings	T6, T852	-	QQ-A-367f	-	-	-
	T6	-	-	B247-70	4143	-
Bar, rod, shapes, tubes (extruded)	O, T62	-	-	B221-71	-	-
	T8510, T8511	-	-	B221-71	4162	-

(a) Specifications as of June 1971

TABLE 2.41. –Commercial Sizes and Tempers Available for Sheet, Sheet Circles, Plate, and Plate Circles

Source	Ref. 2.1 (a)			
Alloy	2219			
Product	Temper	Thickness, inch (d)	Size, max (b, c, d) Width, in	Length, in
Alclad and bare sheet and sheet circles (flat, mill finish)	O, T31, T87	0.014-0.022	48	180
		0.023-0.029	60	180
		0.030-0.036	60	180
		0.037-0.059	84	200
		0.060-0.075	90	300
		0.076-0.095	90	300
		0.096-0.119	96	360
		0.120-0.249	102	360
Alclad and bare sheet and sheet circles (flat, mill finish)	T37, T87	0.020-0.031	24	-
		0.032-0.039	36	-
		0.040-0.059	48	-
		0.060-0.124	72	72
		0.125-0.249	84	84
Alclad and bare plate and plate circles (flat, mill finish)	T37, T87	0.250-0.374	90	90

(a) Consult producers of alloy for further information.
(b) Maximum diameter of circle same as maximum width of sheet.
(c) Sizes greater than indicated can be supplied subject to inquiry.
(d) 1 inch = 2.54 cm.

Chapter 2 - References

2.1 Aluminum Company of America, "Alcoa Aluminum Handbook," 1962.

2.2 Aluminum Standards and Data, 1970-71, Second Edition, Aluminum Association of America, New York, New York.

2.3 SAE Aerospace Material Specifications, Society of Automotive Engineers, Inc., latest Index, May 15, 1971.

2.4 Index of Specifications and Standards, Department of Defense, Part I, Alphabetical Listing, 1 July 1970; supplement, 1 May 1971.

2.5 ASTM Standards, Part 6, "Light Metals and Alloys," American Society for Testing Materials, 1971.

2.6 1971 SAE Handbook, Society of Automotive Engineers, Inc., New York, New York.

Chapter 3

METALLURGY

3.1 Chemical Composition

3.11 Nominal chemical composition of 2219 in percent (ref. 3.1):

Cu	6.3
Mn	0.3
Ti	0.06
V	0.10
Zr	0.18
Al	Balance

3.111 Sheet and plate are available in the Alclad condition. Cladding material is 7072 alloy. Nominal composition of 7072 alloy in percent (ref. 3.2):

Zn	0.9-1.3
Si + Fe	0.7
Mn	0.1 max
Cu	0.1 max
Mg	0.1 max
Others	
Each	0.05 max
Total	0.15
Al	Balance

The nominal cladding thickness per side is 10 percent of the total thickness of the composite if the latter is below 0.040 inch and 5 percent for a total thickness of composite products of 0.040 inch to 0.099 inch. For a total thickness of 0.100 inch or more the nominal cladding thickness on each side is 2.5 percent (ref. 3.3). (Note: 0.1 inch = 2.54 mm.)

3.12 Chemical composition limits, in percent (ref. 3.3):

Si	0.20 max
Fe	0.30 max
Cu	5.8 to 6.8
Mn	0.2 to 0.4
Mg	0.02 max
Zn	0.10 max
Ti	0.02 to 0.10
V	0.05 to 0.15
Zr	0.10 to 0.25
Others	
Each	0.05 max
Total	0.15
Al	Balance

These composition limits are normally checked by spectrochemical analysis or in accordance with the procedures outlined in ASTM E34, "Standard Methods for Chemical Analysis of Aluminum and Aluminum Base Alloys," (ref. 3.1).

3.13 Alloying elements. Copper is the primary hardening agent, with vanadium and zirconium acting as grain refiners by increasing the recrystallization temperature. Zirconium and manganese improve the strength properties, particularly at elevated temperatures. The primary precipitation hardening agent is $CuAl_2$ (see figure 3.13). Since Mg and Si are held to extremely low composition limits, the occurrence of their low melting eutectics (Al-Cu-Mn-Si) is essentially eliminated and the alloy can be solution treated just below the Al-Cu eutectic which occurs at 548° C. At this temperature, most of the $CuAl_2$ will go into solution (ref. 3.4). Copper and the other alloying elements decrease the resistance to corrosion of aluminum. The Al-Cu constituent is more cathodic than Al and more anodic than the solid solution containing more than 2.5% Cu (ref. 3.5, p.918). Since initial precipitation usually occurs along grain boundaries, zones lean in solutes will develop near the grain boundaries. These anodic zones may corrode selectively by an electrochemical process, producing notches that cause stress concentrations. However, this does not occur in properly heat treated and aged commercial tempers (ref. 3.6). As the alloy structure (i.e., precipitate and solid solution relationship) is modified by heat treatment, its resistance to corrosion, stress corrosion, and weathering will be altered. The amount of protection provided by the cladding depends on the thickness and the purity of the cladding material, and also on the annealing and heat treatment practice (see section 3.111).

3.2 Strengthening Mechanisms

3.21 General. The alloy can be strengthened by precipitation hardening and cold work. The precipitation hardening mechanisms are clearly evident from the phase diagram in figure 3.13. After quenching from the solution temperature to room temperature, slow precipitation occurs in the form of submicroscopic particles which represent obstacles to plastic flow and thus cause hardening. Cold working greatly accentuates precipitation hardening in this alloy. This is a general property of most aluminum alloys and is related to the crystal structure (fcc) and the stacking fault energy. Various processing operations utilize the effects of both mechanisms (i.e., cold working of the solution treated alloy at room temperature and subsequent aging at room or elevated temperatures).

Caution should be used when reheat treatment of alloy is contemplated. Studies at the Naval Air Material Center (ref. 3.7) have indicated that only one reheat treatment of 2219-T6 Alclad sheet was possible before copper began to diffuse through the clad material to the surface.

3.22 Heat Treatment.

Annealing (O Condition): The annealing treatment for precipitation hardening alloys is essentially an overaging treatment. Two to three hours at 400° to 413° C followed by slow cooling at 28° C/hr maximum to at least 260° C is recommended (ref. 3.8). Intermediate anneals during repeated cold working operations should be carried out at 344° C for no more than 30 minutes at a time.

Solution Treatment (T4 Condition): Heat to 532° to 543° C and hold from 20 minutes to 4.5 hours depending on thickness and equipment, following by a rapid cold water quench. The proper designation is T42 if the operation is performed by the user. It should be noted that the solution treating temperatures should be closely controlled. Higher temperatures may cause solid solution grain boundary melting, high temperature oxidation,and eutectic melting which cannot be repaired by subsequent heat treating operations. Lower temperatures may result in incomplete solution of the hardening constituents and thus a loss in hardening potential of the alloy. Rapid quenching is also important because of possible precipitation and consequently reduced corrosion resistance on slow cooling from the solution treating temperature. Maximum allowable quench delay times are listed below:

Nominal Thickness		Maximum Time, Seconds
≤0.016 inch	≤0.406 mm	5
0.017–0.031	0.432–0.787	7
0.032–0.090	0.812–2.29	10
≥0.091	≥2.31	15

Aging Treatment (T6 Condition): Heat T4 or T42 condition to 180° to 194° C and hold for 36 hours. If performed by user, for plate and extrusions, the correct temper designation is T62.

Cold Work and Combined Treatments: All Cold work and combined treatments together with the solution and aging treatments for various products are summarized in table 3.22 (ref. 3.9).

3.3 Critical Temperatures. Melting range 543° to 644° C. The oxidation resistance in normal atmosphere is generally good until the melting temperature is approached.

3.4 Crystal Structure. Face-centered cubic. The lattice parameter depends primarily on the amount of Cu in solution. For pure aluminum, a_0 = 4.0413 Å; for 5.5% Cu, a_0 = 4.0290 Å (ref. 3.9, p.49).

3.5 Microstructure. References 3.10 and 3.11 are recommended as excellent sources of information on the identification of constituents in aluminum alloys.

3.6 Metallographic Procedures. In general, mechanical polishing is preferred to electropolishing, especially where larger microconstituents are present and the material is relatively soft, as objectionable relief effects produced by the electrolytic polishing technique may cause a misinterpretation of the microstructure (ref. 3.11, p. 106). For homogeneous alloys, and for those conditions containing only finely dispersed particles, the electrolytic method is excellent. Preparatory polishing on metallographic polishing papers 0 to 000 should be performed wet with a solution of 50 g paraffin in 1 liter kerosene to keep the specimen bright and avoid imbedding of grinding compound particles into the soft specimen surface. Rough polishing on a "Kitten's Ear" broadcloth at 250 to 300 RPM with heavy magnesium oxide powder is recommended (refs. 3.10 and 3.12).

An alternate and popular method consists of the following steps:

a) Wet polishing (flowing water with 240-grit silicon carbide paper at approximately 250 RPM.
b) Wet polishing with 600-grit silicon carbide paper at approximately 250 RPM.
c) Polishing with 9-μm diamond paste on nylon cloth at 150 to 200 RPM using a mild soap solution for lubrication.
d) Final polish on a vibratory polisher using a microcloth containing a slurry of methyl alcohol and 0.1-μm aluminum oxide powder. A slurry of 0.1-μm aluminum oxide powder in a 10% solution of glycerine in distilled water may also be used for this step.

Etching reagents have to be suited to the objective of the study. Kellers etch reveals microstructural details and grain boundaries satisfactorily. A 10-percent solution of NaOH gives better detail of the microscturctural constituents but does not delineate the grain boundaries. Study of the "as polished" surface prior to etching may also give valuable information on the types of the constituents present, especially when attention is paid to the colors of the various particles. Macroscopic studies for cracks, gross defects, forging lines and grain structure should be made with the following etching solutions: 10% NaOH (cracks, gross defects), Tucker's etch, modified Tucker's etch, and Flick's etch (ref. 3.10, p. 95). These etching solutions for revealing the macrostructure are given in table 3.6.

TABLE 3.22. – Tempers and Aging Treatments for Aluminum Alloy 2219

Source	Ref. 3.8				
Temper	Sheet	Plate	Rod, Bar	Extrusions	Forgings
T31	Sol HT (d) + stretch (e)	-	-	-	-
T351 T352 (a)	-	Sol HT (d) + 1.5–3% stretch (e)	Sol HT (d) + 1–3% stretch (e)	-	Sol HT (d) + 2.5% CW (b, e)
T3511 T3510	-	-	-	Sol HT (d) + 1% stretch (e)	-
T37	Sol HT (d) + approx 8% CW (e)		-	-	Sol HT (d) + approx 8% CW (e)
T4	-	-	-	-	Sol HT (d, e, or f)
T42	Sol HT (d, f)				-
T6	-	-	-	-	T4 aged 26 hrs at 190° C
T62	T42 aged 36 hrs at 190° C (Alclad 18 hrs at 190° C)				-
T81	T31 aged 18 hrs at 177° C	-	-	-	-
T851 T852 (a)	-	T351 aged 18 hrs at 177° C	T351 aged 18 hrs at 190° C	-	T352 aged 18 hrs at 177°C
T8511 T8510	-	-	-	T351 aged 18 hrs at 190° C	-
T87	T37 aged 24 hrs at 163° C		-	-	T37 aged 24 hrs at 163°C (c)

(a) Forgings only
(b) By compression
(c) Hand forgings only
(d) Solution HT at 532° to 543° C, cold water quench
(e) By producer
(f) By customer

TABLE 3.6. – Etching Solutions for Revealing Macrostructure

Source	Ref. 3.12	
Alloy	2219	
Solution	Concentration (a)	Specific Use
Sodium Hydroxide	NaOH 10 g Water 90 ml	For cleaning surfaces, revealing unsoundness, cracks, and gross defects
Tucker's	HCl (conc.) 45 ml HNO_3 (conc.) 15 ml HF (48%) 15 ml Water 25 ml	For revealing structure of castings, forgings, etc.
Modified Tucker's	HCl (conc.) 10 ml HNO_3 (conc.) 10 ml HF (48%) 5 ml Water 75 ml	For revealing structure of all castings and forgings except high silicon alloys
Flick's	HCl (conc.) 15 ml HF (48%) 10 ml Water 90 ml	For revealing grain structure of duralumin type alloys. Surface should be machined or rough polished

(a) All of these solutions are used at room temperature.

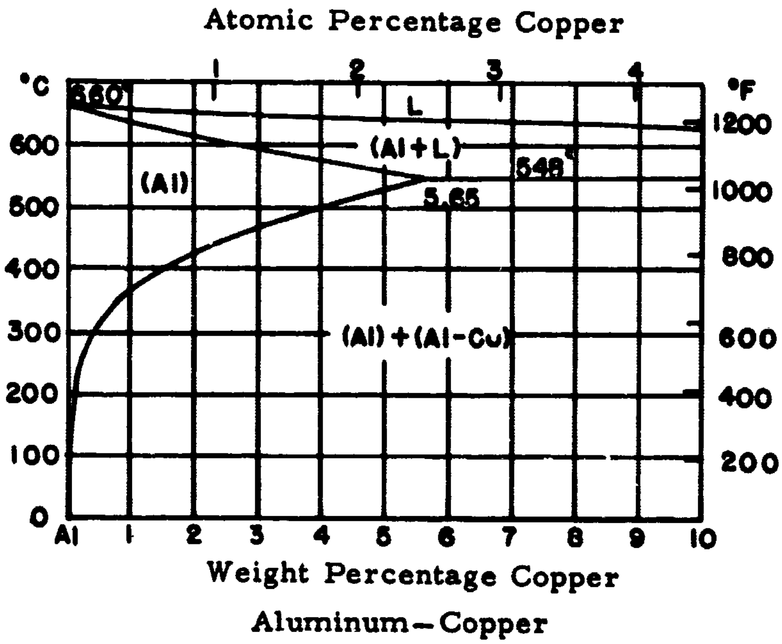


FIGURE 3.13. – Binary phase diagram of the aluminum rich portion of the Al-Cu equilibrium diagram.

(Courtesy Aluminum Co. of America)

Chapter 3 - References

3.1 Aluminum Standards and Data, Second Edition, The Aluminum Association, New York, N.Y., 1969 (second printing 1970).

3.2 1971 SAE Handbook, Society of Automotive Engineers, Inc., New York.

3.3 ASTM Standards, Part 6, B209-71, American Society for Testing Materials, 1971.

3.4 Martin-Denver Co., "Summary Information Regarding Aluminum Alloy 2219," Evaluation Report No. 1, MI-61-44, November 1961.

3.5 Metals Handbook, Eighth Edition, Vol. I, American Society for Metals, Metals Park, Novelty, Ohio, 1961.

3.6 J.A. Nock, Jr., et al., "A New High Strength Aluminum Alloy," Metal Progress, September 1961, p. 87.

3.7 R.G. Mahorter, Jr. and W.F. Emmons, "A Study of Creep Resistance, Formability and Heat Treatment of Clad X 2219-T6 Aluminum Alloy," Report No. NAMC-AML-AE 1100, Naval Air Material Center, August 1959.

3.8 Aluminum Company of America, "Alcoa Alloy 2219," March 1959.

3.9 L.W. Mayer, "Alcoa Aluminum Alloy 2219," Alcoa Green Letter, October 1960, revised November 1963.

3.10 F. Keller and G.W. Wilcox, "Identification of Constituents of Aluminum Alloys," Technical Paper No. 7, Aluminum Company of America, 1942, revised 1958.

3.11 J.P. Vidosic, "Study of Phase Identification in Steel and Aluminum Alloys," Georgia Institute of Technology, Final Report, Project No. A-641, NASA Contract NAS8-5117, September 1963.

Chapter 4

PRODUCTION PRACTICES

4.1 General. In the United States, aluminum and its alloys are produced from an ore of impure hydrated aluminum oxide known as "bauxite." Important sources of bauxite are located in Arkansas, Dutch Guiana, and Jamaica. The impure ore is converted into pure aluminum oxide (alumina) through a series of chemical processes. Oxygen is removed from the alumina by smelting in carbon-lined electric furnaces known as reduction pots. Pure molten aluminum is deposited at the bottom of the pot, and is periodically siphoned off and poured into molds to form "pigs" and "sows." A separate furnace operation is used to form "alloy pig" from the pure aluminum by the addition of alloying elements and this metal is cast into ingots for further processing (ref. 4.1).

For the 2219 alloy, the main additional alloying elements are copper and manganese. Small amounts of titanium, zirconium, and vanadium are also added. Generally, this phase of production practice involves carefully-controlled melting, alloying, and casting of large ingots (20,000 to 50,000 pounds (≈9000 to 23,000 kg)). After the ingots are scalped and preheated in vertical electric soaking pits, they are ready for further processing to a particular form of product.

4.2 Manufacture of Wrought Products

4.21 Bar and rod are normally produced by hot rolling or extruding. Cold finished bar and rod are produced by hot working to a size slightly larger than specified and reducing to final dimensions by cold working. A better surface finish and closer dimensional tolerances are obtained in this manner (ref. 4.2).

4.22 A similar process is used to produce rolled structural shapes, special rolls being required. Finishing operations include roller or stretch straightening, and heat treatment.

4.23 Roll-form shapes are produced by passing strip through a series of roller dies. Each successive pair of rolls cause the work to assume a cross-section shape more nearly approaching that desired. The final desired shape is produced at the last pair of rolls.

4.24 Plate is produced by hot rolling of ingots to slabs (approximately 60-percent reduction), usually in a 4-high reversible mill. The slabs are then further reduced 50 percent in a reversible 2-high mill. The last stage of hot rolling is done in a hot reversing mill, where the plate is progressively rolled to the final hot mill dimensions. Plate may be subjected to "stress relief" stretching (about 2-percent permanent set) to improve flatness and reduce warpage upon machining. Plate is then sheared or sawed to the required dimensions (ref. 4.2).

4.25 Sheet is usually produced from plate by cold rolling to final sheet thickness, followed by trimming, annealing, heat treating, stretching, and other finishing operations.

4.26 Wire is produced by drawing rod through a series of progressively smaller dies to obtain the desired dimensions.

4.27 Extrusions are produced by subjecting reheated cast billets to enough pressure to force the metal to flow through a die orifice, forming a product whose cross-section shape and size conforms to that of the orifice. Speeds, pressures, and temperatures must be closely controlled to insure uniform quality of extruded products.

4.28 Tube is produced by extruding or by welding. Extruded tube is made by forcing cast billets through an orifice as described in 4.27; a die and mandrel are used. Welded tube is produced by slitting coil stock into strips and passing the strips through a series of rolls to form tube; the longitudinal seam is welded as the tube leaves the last roll-forming station.

4.29 Forgings are made by pressing (press forging) or hammering (drop forging). Relatively heavy equipment is required since aluminum is not as plastic at its forging temperature as steel. Aluminum forgings compare favorably with structural steel in unit strength at about one-third the weight. With comparable strength and with a lower elastic modulus, aluminum alloys have a much higher impact-energy-absorbing capacity than mild steel.

4.3 Casting of Alloy Ingots

4.31 Metal for wrought products is alloyed in large 10- to 25-ton double hearth furnaces, carefully controlled and instrumented. The direct chill (DC) method is generally used for casting these ingots. Molten metal is poured into a mold and a hydraulic piston descends slowly as the metal solidifies. Water is sprayed on the outside of the mold to promote rapid solidification. Additional processing may include scalping (machining of outside surfaces) or homogenizing (refs. 4.2 and 4.3).

Chapter 4 - References

4.1 Kaiser Aluminum and Chemical Sales, Inc., "Kaiser Aluminum Sheet and Plate Product Information," Second Edition, January 1958.

4.2 Reynolds Metals Co., "The Aluminum Data Book, Aluminum Alloys and Mill Products," 1958.

4.3 Aluminum Company of America, "Alcoa Aluminum Handbook," 1962.

Chapter 5

MANUFACTURING METHODS

5.1 General. This heat-treatable alloy is available bare and in the Alclad condition. Although the alloy was originally developed for forged parts to be used up to 600° F (315° C), it is now available in many forms as shown in table 5.1.

5.2 Forming

5.21 Sheet and Plate. The alloy 2219 exhibits equal or superior formability characteristics to 2024 and 7075 for comparable tempers (ref. 5.3). Results of Olsen cupping tests indicate that the 2219 alloy is slightly more formable than 2024. Both alloys were tested clad and bare, in both "O" and "T6" conditions. Dimpling for riveting, on the basis of 3/16-inch dimples in 0.064-inch sheet, was satisfactory when performed at room temperature. However, 2219-T6 exhibited slight edge cracking when dimpled at room temperature. This was eliminated by hot-dimpling at 350° F (177° C) (ref. 5.12).

5.211 Cold forming. The formability of alloy 2219 sheet and plate is directly related to the temper strength and ductility. As with other aluminum alloys, high elongation as well as considerable spread between yield and ultimate strength will be indicative of good formability. The simplest and most widely used forming method is probably that of bending. Table 5.2111 indicates the ease of forming in terms of recommended minimum bend radii as a function of temper and sheet and plate thickness, using typical mechanical properties for 0.100-inch (0.254-cm) sheet.

Formability is at a maximum in the annealed temper and is equal to or slightly superior to that of other high strength aluminum alloys such as 2024 and 7075 (ref. 5.1). In general, severe forming and drawing operations should be done with annealed stock, and the tools must be clean and free of scratches. Less severe operations may be performed on material in the T42, T31, and T37 tempers. Although some mild forming operations can be performed on artificially aged material, the more critical operations should be done while the material is in the solution-treated or naturally-aged condition. Forming may be performed during the heat treatment cycle. Table 5.2112 indicates the heat treatments which are used and the resulting tempers for the alloy. The solution treatment for all products consists of heating to 995° F ±10° F (535° C ±5° C) and quenching into cold water. The alloy is then artifically aged. Since the alloy ages very slowly at room temperature, solution-treated and naturally-aged material retains good formability for a considerable period of time. In comparison, alloys 2014 and 2024 age rapidly enough at room temperature to develop high strength properties within four days. Artificial aging, upon completion of a forming operation, leads to much higher strength in the final structure. Aluminum sheets are normally formed using operations such as:

1. Bending
2. Flanging
3. Rolling
4. Drawing
5. Pressing
6. Stretching
7. Embossing
8. Coining
9. Stamping
10. Spinning
11. Contour Forming
12. Bulging and Expanding
13. Beading and Roll Flanging
14. Necking
15. Curling

The factors influencing bending of 2219 sheet as spelled out previously also influence the 14 other forming operations in the same general manner.

Because of the lower modulus of elasticity of aluminum compared with steel, a much greater "springback" is expected and indeed is encountered. Over-forming is the common way of correcting the tendency. All of the bending precautions described in the handbook on alloy 2014 should be considered.

5.22 Shapes, Tubes, and Pipes. The use of aluminum shapes of the 2219 alloy have been limited but this is a reflection of the fact that the manufacture of the alloy has only been from about 1960. However, the alloy is amenable to the standard production techniques.

5.23 Forging. Forgings are made using either the open die or closed die methods and by impact or pressure. Small runs are made using the hand-forging, open-die techniques. Hand forgings over a ton in weight can be made. As in all forgings, there is a grain flow in 2219 which is characteristic of the forging process. The resulting grain pattern results in anisotropy of properties and this must be considered for the property evaluations. The process for most production forgings starts with the stock which can vary from 3/8 inch to 8 inches diameter round stock; from 3/8 inch to 4 inches square stock; and rectangles from 3/8 inch for the minimum dimension to as much as 10 inches on the maximum dimension. Conditioning to remove localized surface defects is permitted at this point. The stock is carefully heated in the range of 650° to 875° F (362° to 457° C). After preheating, the stock can be forged to shape in one step or, in the case of complicated parts, in several operations involving several reheatings. Dies in the forging operation are heated with auxiliary gas or electric heaters. The flash resulting from excess metal overfilling in the mold is removed by hot or cold trimming, sawing, or grinding. Holes in the forging are pressed to produce "punchouts" in the forging. Sometimes the punchout is combined with the trim operation. Very close tolerances can be met in the standard forging by die coining (cold) to precise dimensions, usually within a few thousandths of an inch (70 μm). Straightening after heat treatment is often a required operation. Templates combined with indicators and other gages are used to determine the out-of-tolerances. Straightening ranges from hand straightening to "cold restrike" operations. (Note: 1 inch = 25.4 mm.)

The forgings are inpsected for grain flow, mechanical properties, dimensions, and ultrasonic soundness. A design manual for die forgings is available from the Aluminum Association (ref. 5.14).

5.3 Machining

5.31 Conventional machining. This alloy has good machining qualities in the annealed state (ref. 5.2). Since most of the machining is done in the heat treated condition, lathe tools should be ground to 10–20° side rake, and 8–10° clearance. Parting tools should have a 15–20° top rake with a 4–5° side rake. Planer and shaper tools for roughing cuts should have a 12–15° top rake, 32–38° side rake, and a 8–10° front and side clearance. Finishing tools should have a 45–50° top rake, 50–60° side rake, 8–10° front clearance, and little or no side clearance. Twist drills should have larger spiral angles than standard highly polished deep flutes, narrow bands, and up to 18° lip clearance. Threading taps should have highly polished flutes and should be undercut; spiral fluted taps are usually better than straight fluted. The rake angles should be increased to 12–18°. Soluble oil emulsions, kerosene, and kerosene-lard oil mixtures are recommended for most machining operations, but high viscosity lubricants are recommended for tapping operations.

It is difficult to produce a precise tabulation of machining parameters for each of the different types of operations. However, table 5.31 is a compilation of typical factors for many common machining operations (ref. 5.8) and can be used as a guide. Grinding typically uses a wheel speed of 6000 ft/min and a table speed of 60 ft/min. A down feed will produce a rough finish if it is kept about 0.001 inch per pass (25 μm), and a fine finish if the down feed is kept below 0.0005 inch per pass (12.5 μm). The cross feed is approximately one-third of the wheel width.

5.32 Electrochemical and Chemical Machining

5.321 General Remarks. Weight reductions are important for space vehicle components, particularly large boosters, where the fuel and oxidizer tanks are fabricated from precurved cylindrical and spherical sections of high-strength aluminum alloys. The use of sections which are "integrally stiffened" by ribs, which are left intact while the bulk of the metal stock is removed, has been examined for both electrochemical and chemical methods.

5.322 Electrochemical Milling. In the section on electrochemical milling for the 2014 alloy, the basic principles of the method are discussed. In electrochemical metal removal, Faraday's 'Law of Electrolysis' controls the rate of metal removal. Because this ECM is the reverse of electrodeposition or electroplating, the anode is the work piece. The tool configuration depends upon the particular type of metal removal geometry desired. The shape of the tool cross-section can vary from simple squares, ovals, rounds and D-shapes to rather complicated design shapes. A 5–10% NaCl solution is supplied under pressure (≈100–250 psi) and escapes through the clearance between the end of the tool and the work piece (ref. 5.9). At 10,000 amperes, 1.26 in^3 ($2 \times 10^{-5} m^3$) will be removed in one minute. Voltages of 10 to 15 volts yield excellent results. The temperature of the electrolyte is about 120° F (49° C) for good quality finishes.($P \approx .07-.18\ kg/mm^2$)

5.323 Chemical Milling. The removal of metal stock by chemical dissolution or "chemical milling," in general has many potential advantages over conventional milling methods. However, variations in etch rate, undercutting, and surface finish are a result of certain metallurgical factors which interfere with the "normal" electrochemical phenomena (ref. 5.10). Buffered caustic etchants with wetting and sequestering agents plus complex fluorides to improve surface finish are employed. When subjected to the chemical attack, the presence of high copper intermetallic precipitate at random sites over the surface results in small local cells (the copper areas become strongly cathodic). The formation of smut (complex hydroxide, silicates, etc.) adheres to the surface providing an undesirable masking effect. In addition, differential quenching conditions in the heat treatment or differential effects of mechanical working provide various amounts and dispersions of $CuAl_2$ particles. This leads to a difference in the physical form of the smut produced during chem-milling. In the "slow-attack" zones, a well-cemented coherent, adherent "paste" is produced which does not easily fall off the metal surface. In the "rapid-attack" zones, the placement of $CuAl_2$ particles is evidently such that no cohesion is established as the matrix is dissolved away. Work at IITRI continued to improve the method (ref. 5.10). For Bomarc fuel tanks, between 20 and 45% of the original thickness (0.16 and 0.25 inches, 0.42 and 0.64 cm) is chem-milled from selected shell areas for weight reduction (ref. 5.6).

Studies at Martin-Denver (ref. 5.11) have indicated that the 2219 alloy can be successfully chem-milled by Martin Process DP 65043 in the O temper and in fully heat-treated tempers. Solution-treated materials incur a rough surface (up to 350 RMS) when chem-milled. The results of chem-milling tests on 2219 alloy sheet are given in table 5.323.

The feasibility of chem-milling 9"x9" panels without immersion has been demonstrated at Lockheed Missiles & Space Co. (ref. 5.7). By utilizing an acid spray technique, depths of 0.500 inch (1.27 cm) with a variation of ±0.012 inch (0.3 mm) have been etched at an average rate of 0.0047 inch (0.12 mm) per minute.

TABLE 5.1. —Availability of Forms

Source	Ref. 5.1
Alloy	Forms
2219	Sheet, plate, rod, bar, extruded shapes, tubes, and forgings
Alclad 2219	Sheet and plate

TABLE 5.2111. — Suggested Minimum Bend Radii for 90 Degree Cold Bends (a)

Source	Ref. 5.13									
Alloy	2219 (b)									
Temper	1/64 in	1/32 in	1/16 in	1/8 in	3/16 in	1/4 in	3/8 in	1/2 in	3/4 in	1 in (c)
0	0	0	1/2-11/2t	1/2-11/2t	1/2-11/2t	1-2t	1-2t	2-3t	2-3t	3-4t
T42	0-1t	0-1t	1-2t	1-2t	11/2-21/2t	11/2-21/2t	2-3t	21/2-31/2t	3-4t	31/2-41/2t
T31	1/2-11/2t	1-2t	11/2-21/2t	11/2-3t	2-4t	2-4t	21/2-4t	3-5t		
T37	1/2-11/2t	1-2t	11/2-3t	21/2-4t	3-41/2t	31/2-5t	4-6t	5-7t		
T62, T81	2-31/2t	21/2-4t	3-5t	4-6t	4-6t	5-7t	5-7t	6-9t		
T87	21/2-4t	3-5t	4-6t	5-7t	51/2-8t	6-9t	7-10t	8-11t		

(a) These values are given as a function of the actual material thickness (t), and should be used as a guide only.
(b) Alclad 2219 can be bent over radii slightly smaller than those for the corresponding bare material.
(c) 1 inch = 2.54 cm.

TABLE 5.2112. – Heat Treatments for Various Products and Tempers

Source	Ref. 5.13
Alloy	2219
Temper	Product and Treatment
T4(a)	Solution treated and quenched in cold water
T31	Solution treat and stretch (Sheet)
T37	Solution treat and cold reduce by rolling (Sheet, plate, and forgings)
T42	Material in any form or temper, resolution treated by the user
T6	Solution treated and artificially aged (Forgings)
T62	Material in any form or temper, resolution treated and aged by the user
T81	Solution treated, stretched, and artificially aged (Sheet)
T87	Solution treated, cold reduced by rolling, and artificially aged (Sheet, plate, and forgings)

(a) Forgings only

TABLE 5.31. — Typical Factors for Common Machining Operations

Source	Ref. 5.8						
Alloy	2219						
		High Speed Tool			Carbide Tool		
Operation	Cutting Conditions*	Speed fpm	Feed ipr	Tool mat'l	Speed fpm	Feed ipr	Tool mat'l
Single point turning	0.250 inch depth of cut	600	0.015	T1, M1	1100	0.015	C-1
	0.050 inch depth of cut	800	0.008	T1, M1	1400	0.008	C-2
Form tool, turning	0.500 inch form tool width	450	0.0035	T1, M1	1000	0.0035	C-2
	0.750 inch form tool width	450	0.0035	HSS	1000	0.0035	C-2
	1.000 inch form tool width	450	0.003	HSS	1000	0.003	C-2
	1.500 inch form tool width	450	0.0025	HSS	1000	0.002	C-2
	2.000 inch form tool width	450	0.002	HSS	1000	0.002	C-2
Boring	0.010 inch depth of cut	600	0.008	T1, M1	1100	0.010	C-1, C-3
	0.050 inch depth of cut	570	0.010	HSS	1050	0.015	C-1, C-3
	0.100 inch depth of cut	540	0.015	HSS	1000	0.020	C-1, C-3
Planing	0.500 inch depth of cut	300	0.060	T1, M1	300	0.060*	C-2
	0.050 inch depth of cut	300	0.050	T1, M1	300	0.050	C-2
	0.010 inch depth of cut	300	3/4**	T1, M1	300	3/4**	C-2
Face milling	0.250 inch depth of cut	800	0.020*	T1, M1	max	0.018*	C-2
	0.050 inch depth of cut	1000	0.022*	T1, M1	max	0.020*	C-2
End milling (profiling)	3/4 inch cutter diameter	700	0.006*	M1, M10	1200	0.005*	C-2
	1/2 inch cutter diameter	700	0.009*	M1, M10	1200	0.008*	C-2
	1/8 inch cutter diameter	1000	0.0007*	M1, M10	1800	0.0005*	C-2
	3/8 inch cutter diameter	1000	0.005*	M1, M10	1800	0.004*	C-2
	3/4 inch cutter diameter	1000	0.007*	M1, M10	1800	0.006*	C-2
	1 to 2 inch cutter diameter	1000	0.010*	M1, M10	1800	0.009*	C-2
Drilling	1/8 inch nominal hole diameter	250	0.003	M1, M10			
	1/4 inch nominal hole diameter	250	0.007	HSS			
	1/2 inch nominal hole diameter	250	0.012	HSS			
	3/4 inch nominal hole diameter	250	0.016	HSS			
	1 inch nominal hole diameter	250	0.020	HSS			
	11/2 inch nominal hole diameter	250	0.025	HSS			
	2 inch nominal hole diameter	250	0.030	HSS			
	3 inch nominal hole diameter	250	0.030	HSS			

*Feed - inches per tooth

**Feed - 3/4 the width of square nose finishing tool

Note: 1 inch = 25.4 mm.

TABLE 5.323. —Results of Chemical Milling Test on 2219 Alloy Sheet

Source	Ref. 5.11			
Alloy	2219 (0.088 and 0.100 inch sheet)			
Test	Chemical Milling (11 in x 12 in Test Panels) (a, d)			
Temper	Weight Loss, g	Metal Thickness Removed, mils	Weight Loss, g	Metal Thickness Removed, mils
0	118.1	19 to 21	215.3	47 to 69
T42	93.3	20 to 21	185.7	33 to 35
T31	96.8	13 to 15	163.4	33 to 41
T62	110.9	22 to 25	204.7	40 to 42
T81	113.7	23 to 24	215.1	41 to 43
T62+(b)	124.2	23 to 27	222.5	45 to 49
T81+(c)	124.8	24 to 26	196.6	44 to 46
T62	109.4	21 to 23	194.4	41 to 43

(a) Chem-milled area was approximately 100 in^2 (Martin Company, Process DP65043).
(b) Aged to T62 from "SW" condition (solution treated and refrigerated).
(c) Aged from T31 to T81
(d) 1 inch = 2.54 cm; 1 mil = 0.025 mm.

Chapter 5 - References

5.1 J.A. Nock, Jr., M. Holt, and D.O. Sprowls, "A New High-Strength Aluminum Alloy," Metal Progress, September 1961, p. 87.

5.2 Alloy Digest, "Aluminum 2219," Engineering Alloys Digest, Inc., October 1960.

5.3 Kaiser Aluminum and Chemical Sales, Inc., "Alloy Technical Data," March 15, 1962.

5.4 Aluminum Company of America, "Alcoa Aluminum Handbook," 1962.

5.5 Metalworking News, August 20, 1962.

5.6 S.L. Sears and R.S. Crial, "Welding 2219 Aluminum for Bomarc Fuel Tanks," Metal Progress, November 1961, p. 88.

5.7 G. Dufour, "Acid Spray Technique Mills Aluminum Alloy Materials without Immersion," NASA Tech Brief 67-10463, November 1967.

5.8 ORD P 40-1, "Machining Data," July 1961.

5.9 Armour Research Foundation, "Deep Pocket Milling of Aluminum Alloy Using Electrochemical or Other Processes," Report No. ARF-B235-14, June 21, 1963.

5.10 Armour Research Foundation, "Investigation of Random Thickness Variations in Chem-Milled 2219-T37 Aluminum Alloy," Project No. B6031 with NASA/MSFC.

5.11 Martin-Denver, "Summary Information Regarding Aluminum Alloy 2219," Evaluation Report No. 1, MI-61-44, November 1961.

5.12 R.G. Mahorter, Jr. and W.F. Emmons, "A Study of Creep Resistance, Formability and Heat Treatment of Clad X2219-T6 Aluminum Alloy," Report No. NAMC-AML-AE-1100, Naval Air Materials Center, August 1959.

5.13 L.W. Mayer, "Alcoa Aluminum Alloy 2219," Alcoa Green Letter, Aluminum Company of America, October 1960; revised November 1963.

5.14 Aluminum Associaiton, Aluminum Forging Design Manual, First Edition 1967; second printing, 1970.

Chapter 6

SPACE ENVIRONMENT EFFECTS

6.1 General. Aluminum alloys have been used in both structural and nonstructural applications in launch vehicles and spacecraft with excellent success since, in general, the aluminum alloys are relatively insensitive to degradation in typical space environment conditions. The vapor pressures of the structural aluminum alloys are sufficiently high (table 6.1) so that the combined temperature—vacuum effects generally are negligible. Structural alloys such as 2219 are sufficiently hardened so that nuclear and space indigenous radiation induced defects do not significantly affect mechanical and physical properties, at room ambient and elevated temperatures, below accumulated doses of about 10^{22} particles/cm^2. When irradiated at cryogenic temperatures, the threshold may be lowered one or two decades, but the probabilities of experiencing doses on this order of magnitude are extremely remote except in the vicinity of nuclear reactors.

Elevated temperatures, hard vacuums, high energy radiations, and micrometeoroids can singularly and collectively influence surface characteristics of 2219 by desorption processes and erosion. These phenomena might be of great importance if optical properties, lubrication, certain electrical properties, etc., were critical design parameters.

Sputtering of the surface by atomic or molecular particles can deteriorate surface finishes in a relatively short period. A 300-Å coating of aluminum (10^{-5} g/cm^2) can be destroyed in one month during a period of low intensity solar wind or in several hours during a solar storm, for example. The threshold energies of particles required to remove one or more atoms of the surface material they impinge are quite low, of the order of 6, 11, and 12 eV for O, N_2 and O_2 particles, respectively. Estimates of surface erosion by sputtering are given in table 6.2 for aluminum alloys.

Micrometeoroids can produce surface erosion similar to sputtering, although perhaps on a more macroscopic scale, as well as punctures. Micrometeoroids vary widely in mass, composition, velocity, and flux; generalizations about the rates of erosion and penetration, therefore, must be used with care. The predicted and measured frequency of impact as a function of meteoroid mass is given in figure 6.1. Data are given in figures 6.2 and 6.3 on the penetration and cratering of aluminum alloy skins of various thicknesses. Calculations of armor thickness required for protection of different structures and orientations are given in table 6.3. The design of bumper-hull meteoroid protection systems is discussed in reference 6.12.

The surface erosion of aluminum alloys due to corpuscular radiation is probably insignificant, amounting to something of the order of 254 nanometers per year. Indigenous space radiation, however, will tend to accelerate the removal of surface films, which might result in loss of lubricity and an increased propensity to "cold weld." The interaction of indigenous radiation with desorption gases might cause some spurious, transient electrical conditions when aluminum alloys are used for electrical applications. The interaction of indigenous radiation with the alloys may produce some internal heating that might be significant for small items and may induce some radioactivity.

TABLE 6.1. — Evaporation Rates in Vacuum of Typical Elements Used in Aerospace Alloys (a, b)

Source	Ref. 6.14				
Element	Evaporation Rate, $g/cm^2/sec$				
	−100° C	0° C	100° C	250° C	500°C
Aluminum	1.2×10^{-81}	1.1×10^{-48}	2.0×10^{-33}	1.7×10^{-21}	6.5×10^{-12}
Titanium	$<10^{-99}$	2.5×10^{-60}	4.1×10^{-42}	7.4×10^{-28}	2.0×10^{-16}
Iron	$<10^{-99}$	6.8×10^{-64}	2.4×10^{-44}	4.8×10^{-29}	9.1×10^{-17}
Nickel	$<10^{-99}$	5.7×10^{-70}	1.3×10^{-48}	6.7×10^{-32}	1.7×10^{-18}
Copper	1.2×10^{-94}	1.4×10^{-56}	6.2×10^{-39}	4.0×10^{-25}	4.7×10^{-14}
Chromium	9.5×10^{-92}	1.0×10^{-64}	1.4×10^{-37}	3.8×10^{-24}	2.2×10^{-13}
Vanadium	$<10^{-99}$	1.9×10^{-87}	2.1×10^{-61}	5.0×10^{-41}	1.2×10^{-24}
Manganese	2.2×10^{-72}	1.1×10^{-42}	6.5×10^{-28}	3.8×10^{-18}	1.6×10^{-9}
Silicon	$<10^{-99}$	1.9×10^{-62}	3.6×10^{-43}	4.3×10^{-28}	5.5×10^{-16}
Magnesium	2.9×10^{-36}	5.3×10^{-20}	1.8×10^{-12}	1.3×10^{-6}	6.6×10^{-2}
Zinc	3.5×10^{-30}	5.1×10^{-16}	1.8×10^{-9}	2.3×10^{-4}	2.80

(a) The actual evaporation rate of each element in combination with others will be lower.

(b) The values may be in error by several orders of magnitude as they have been extrapolated from high-temperature data. The rates at low tempeatures will be considerably less than the values given in the table.

TABLE 6.2. —Estimated Rate of Removal and Time to Remove 1×10^{-7} mm of Aluminum by Sputtering

Source	Ref. 6.2			
	Orbiting Vehicle		Escaping Vehicle	
Height, km	Rate, atom cm^{-2} sec^{-1}	Time, sec/1×10^{-7} mm	Rate, atom cm^{-2} sec^{-1}	Time, sec/1×10^{-7} mm
100	3.1×10^{16}	1.9×10^{-2}	3.4×10^{17}	1.8×10^{-3}
220	2.0×10^{13}	30	2.0×10^{17}	3.0×10^{-3}
700	2.2×10^{9}	2.7×10^{5}	3.4×10^{11}	1.8×10^{3}
2500	4.3×10^{5}	1.4×10^{9}	1.6×10^{8}	3.8×10^{6}

TABLE 6.3. —Computed Thicknesses of Armor Required for Protection from Meteoroid Impact over a Period of 1000 Days

Source	Ref. 6.11							
Structure	Orientation (a)	Vulnerable Area		Prob'y No Destructive Impact, %	Av. No. of Destructive Impacts per Mission	Critical Thickness	
		ft^2	cm^2			in	cm
Plane	i, leading	1000	92.9	99.5	0.005	0.209	0.530
		500	46.5	99.75	0.0025	0.209	0.530
	i, trailing	1000	92.9	99.5	0.005	0.109	0.278
		500	46.5	99.75	0.0025	0.109	0.278
	j, either side alone	2000	185.8	99.0	0.01	0.232	0.590
		1000	92.9	99.5	0.005	0.232	0.590
	k, either side alone	2000	185.8	99.0	0.01	0.197	0.500
		1000	92.9	99.5	0.005	0.197	0.500
Cylinder	i	2000	185.8	99.0	0.01	0.215	0.547
	j	2000	185.8	99.0	0.01	0.190	0.481
	k	2000	185.8	99.0	0.01	0.205	0.521
Sphere	(random)	2000	185.8	99.0	0.01	0.198	0.502

(a) i = direction of the apex of earth's movement
j = direction within ecliptic plane, approximately away from sun, exactly perpendicular to apex of earth motion
k = direction perpendicular to ecliptic plane, southward

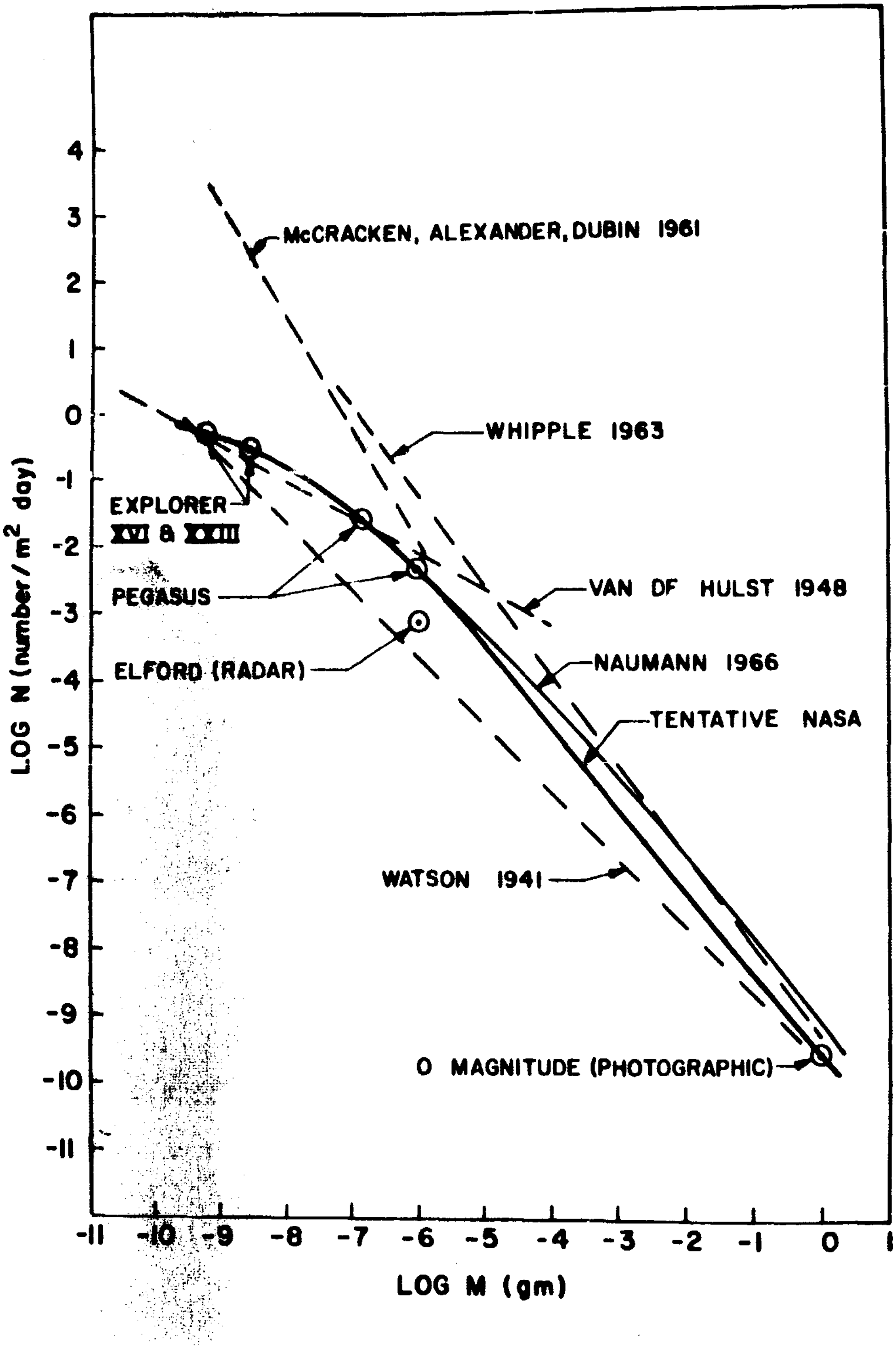


FIGURE 6.1. – Various estimates of meteoroid mass influx.
(Ref. 6.3)

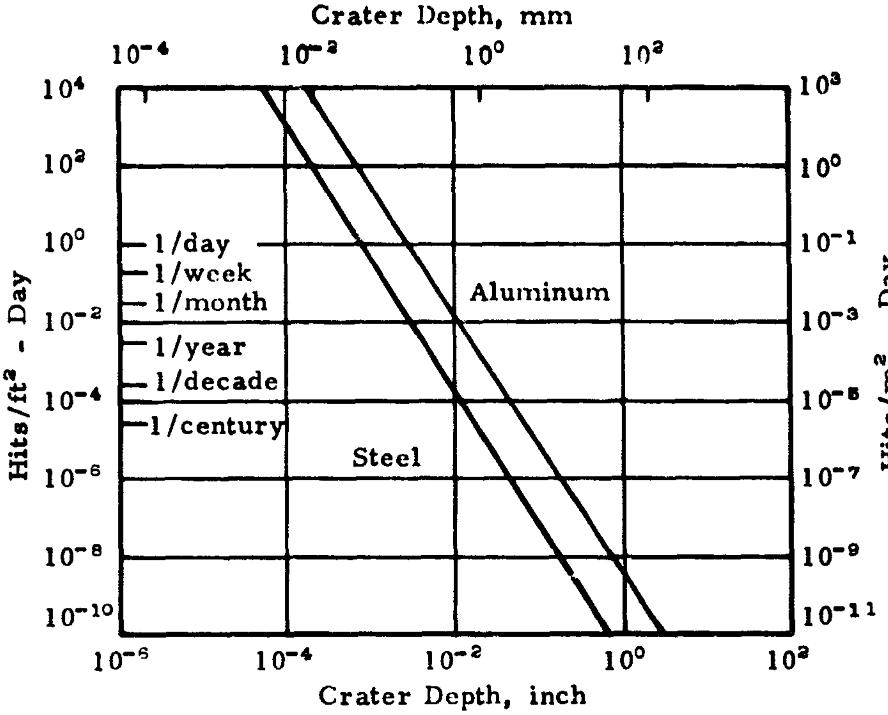


FIGURE 6.2. – Hit rate vs crater depth in the earth neighborhood but without earth shielding.

(Ref. 6.4)

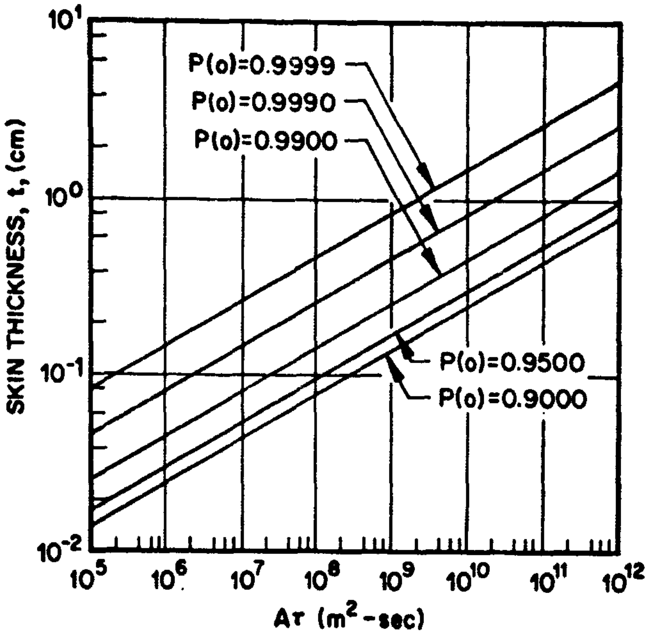


FIGURE 6.3. – Sheet thickness of Al as a function of the surface area–lifetime product required for various probabilities of no meteoroid puncture.

(Ref. 6.1)

Chapter 6 - References

6.1 C.G. Goetzel, J.B. Rittenhouse, and J.B. Singletary, Eds., Space Materials Handbook, Addison-Wesley Press, Palo Alto, California, 1965.

6.2 J.R. Redus, "Sputtering of a Vehicle Surface in a Space Environment," NASA TN D-1113, June 1962.

6.3 SAMPE, The Effects of the Space Environment on Materials, Western Periodicals Co., North Hollywood, California, 1967.

6.4 L.E. Kaechele and A.E. Olshaker, "Meteoroids — implications for the design of space structures," Aerospace Engineering, 19, May 1960.

6.5 K.S. Clifton and P.J. Naumann, "Pegasus Satellite Measurements of Meteoroid Penetration," NASA TM X-1316, 1966.

6.6 F.L. Whipple, "On Meteoroids and Penetration," J. Geophys. Res., 68, 4929 (1963).

6.7 H.C. van de Hulst, "Zodiacal Light in the Solar Corona," Astrophys. J., 105, 471 (1947).

6.8 F.G. Watson, Between the Planets, The Blakiston Co., Philadelphia, 1941; revised, Harvard University Press, Cambridge, Mass., 1956.

6.9 C.W. McCracken et al., "Direct Measurements of Interplanetary Dust Particles in the Vicinity of the Earth," Nature, 192, 441 (1961).

6.10 R.J. Naumann, "The Near-Earth Meteoroid Environment," NASA TN D-3717, November 1966.

6.11 C.D. Miller, "Meteoroid Hazard Evaluation for Simple Structures with Various Orientations," NASA TN D-6056, October 1970.

6.12 C.R. Nysmith, "A Discussion of the Modes of Failure of Bumper-Hull Structures with Applications to the Meteoroid Hazard," NASA TN D-6039, October 1970.

6.13 W.M. Alexander et al., "Zodiacal Dust: Measurement by Mariner IV," Science, 106, 1240 (1965).

6.14 S. Dushman, Vacuum Techniques, John Wiley & Sons, New York, 1949.

Chapter 7

STATIC MECHANICAL PROPERTIES

7.1 Specified Properties

7.11 NASA Specified Properties
7.111 NASA specified mechanical properties for die forgings and separetly forged test bars, table 7.111.
7.112 NASA specified mechanical properties for hand forgings, table 7.112.
7.12 AMS Specified Properties
7.121 AMS specified tensile properties for sheet and plate, table 7.121.
7.122 AMS specified bend factors for sheet and plate, table 7.122.
7.13 Military Specified Properties
7.14 Federal Specified Properties
7.15 ASTM Specified Properties
7.16 Aluminum Association Mechanical Property Limits
7.161 Aluminum Association tensile property limits for sheet and plate, table 7.161.
7.162 Aluminum Association tensile property limits for Alclad sheet and plate, table 7.162.
7.163 Aluminum Association tensile property limits for rolled or cold-finished bar, rod and wire, table 7.163
7.164 Aluminum Association tensile property limits for extruded bar, rod, shapes, and tubing, table 7.164
7.165 Aluminum Association tensile property and hardness limits for die forgings, table 7.165.
7.166 Aluminum Association tensile property limits for hand forgings, table 7.166.

7.2 Elastic Properties and Moduli

7.21 Poisson's ratio
7.22 Young's modulus of elasticity, E
7.221 Design value of E at room temperature for sheet and plate, $E = 10.5 \times 10^3$ ksi (ref. 7.1) = 7.5×10^3 kg/mm^2
7.222 Effect of elevated temperatures on modulus of elasticity, figure 7.222.
7.223 Effect of low temperatures on modulus of elasticity of T81 sheet, figure 7.223.
7.231 Compression modulus, E_c
7.231 Design value of E_c at room temperature for sheet and plate, $E = 10.8 \times 10^3$ ksi (ref. 7.1) = 7.6×10^3 kg/mm^2.
7.24 Modulus of rigidity (shear modulus), G
7.241 Design value of G at room temperature for sheet and plate, $G = 4.0 \times 10^3$ ksi (ref. 7.1) = 2.8×10^3 kg/mm^2.
7.25 Tangent modulus
7.251 Typical compressive tangent-modulus curves for T62 sheet and plate at room temperature, figure 7.251.
7.252 Typical compressive tangent-modulus curves for T81 sheet and plate at room temperature, figure 7.252.

7.253 Typical compressive tangent-modulus curves for T87 sheet and plate at room temperature, figure 7.253.

7.26 Secant modulus

7.3 Hardness

7.31 Brinell scale (500 kg, 10-mm ball)

Condition	T31, T351	96	
	T37	110	
	T62	113	
	T81, T851	123	
	T87	128	(ref. 7.23)

7.4 Strength Properties (see also 7.1)

7.41 Tension, see also figure 7.4612.

7.411 Design and typical tensile properties.

7.4111 Design mechanical properties for sheet and plate, table 7.4111

7.4112 Design mechanical properties in metric units, table 7.4112.

7.4113 Design properties for Alclad sheet and plate, table 7.4113.

7.4114 Typical mechanical properties for various tempers of sheet and plate, table 7.4114.

7.412 Stress-strain diagrams (tension).

7.4121 Stress-strain curves for alloy in T6 condition at room and elevated temperatures, figure 7.4121.

7.4122 Stress-strain curves for T62 sheet at low temperatures, figure 7.4122.

7.4123 Stress-strain curves for T81 sheet at low temperatures, figure 7.4123.

7.4124 Stress-strain curves for T87 sheet at low temperatures, figure 7.4124.

7.4125 Typical tensile stress-strain curves for T62 sheet at room temperature, figure 7.4125 (see also figure 7.251).

7.126 Typical tensile stress-strain curves for T81 sheet at room temperature, figure 7.4126 (see also figure 7.252).

7.127 Typical tensile stress-strain curves for T87 sheet at room temperature, figure 7.4127 (see also figure 7.253).

7.413 Effect of test temperature and exposure on tensile properties.

7.4131 Effect of temperature on the ultimate tensile strength (F_{tu}) of T62 bare and clad sheet and plate 0.040-1.000 inch thick, figure 7.4131.

7.4132 Effect of temperature on the tensile yield strength (F_{ty}) of T62 bare and clad sheet and plate 0.040-1.000 inch thick, figure 7.4132.

7.4133 Effect of temperature on the ultimate tensile strength (F_{tu}) of T81 bare and clad sheet and plate, figure 7.4133.

7.4134 Effect of temperature on the tensile yield strength (F_{ty}) of T81 bare and clad sheet and plate, figure 7.4134.

7.4135 Effect of temperature on the ultimate tensile strength (F_{tu}) of T87 bare and clad sheet and plate, figure 7.4135.

7.4136 Effect of temperature on the tensile yield strength (F_{ty}) of T87 bare and clad sheet and plate, figure 7.4136.

7.4137 Minimum tensile properties for 2219-T6 after 10,000 hours exposure, figure 7.4137.

7.4138 Minimum tensile properties for 2219-T81 after 10,000 hours exposure, figure 7.4138.

7.4139 Minimum tensile elongation for 2219 alloy in T62 and T81 conditions after 10,000 hours exposure, figure 7.4139.

7.414 Effect of test temperature on tensile properties.

7.4141 Typical tensile properties at low and elevated temperatures for alloy in T6 and T62 conditions, figure 7.4141.

7.4142 Tensile property bands for T62 sheet at low temperatures, figure 7.4142.

7.4143 Tensile properties of T6 extrusions at elevated temperatures, figure 7.4143.

7.4144 Tensile property bands for T81 sheet at low temperatures, figure 7.4144.

7.4145 Typical tensile properties of T81 sheet at elevated temperatures, figure 7.4145.

7.4146 Natural aging response of solution treated alloy, figure 7.4146.

7.4147 Effect of irradiation at cryogenic temperatures on tensile properties, table 7.4147.

7.42 Compression

7.421 Design compression properties

7.4211 Design compressive yield strength (F_{cy}) for sheet and plate, see tables 7.4111 and 7.4113.

7.4212 Typical compressive yield strength for various tempers, see table 7.414.

7.4213 Typical F_{cy} for T62 sheet and plate, figure 7.4213.

7.43 Bending

7.44 Shear and torsion

7.441 Design shear properties

7.4411 Design shear strength (F_{su}) for sheet and plate, see tables 7.4111 and 7.4113.

7.4412 Typical F_{su} for alloy in various tempers, see table 7.4114.

7.4113 Effect of low temperature on shear strength of sheet, figure 7.4413.

7.4414 Typical F_{su} curve for T62 sheet and plate, figure 7.4414.

7.45 Bearing

7.451 Design bearing properties

7.4511 Design bearing propertites for sheet and plate, see tables 7.4111 and 7.4113.

7.4512 Typical bearing properties for alloy in various tempers, see table 7.4114.

7.4513 Typical bearing strength of alloy in T31 and T81 conditions, figure 7.4513.

7.46 Fracture

7.461 Notch strength

7.4611 Effect of stress concentration factor on notch strength of T62 and T81 sheet, figure 7.4611.

7.4612 Effect of low test temperature on tensile and notch properties, figure 7.4612.

7.4613 Effect of test temperature on net fracture strength of T81 sheet, figure 7.4613.

7.462 Plane-strain fracture toughness

7.4621 Average plane-strain fracture toughness data, table 7.4621.

TABLE 7.111. – NASA Specified Mechanical Properties for Die Forgings and Separately Forged Test Bars

Alloy	2219-T6 (b)	
Specification	NASA-MSFC-SPEC-144B	
Maximum section, thickness	4 inches (10.16 cm)	
Orientation	A	B
F_{tu} (min), ksi (a, c)	58.0	56.0
F_{ty}, 0.2% offset (min), ksi (a, c)	38.0	36.0
e(2 in (5.08 cm) or 4D), min, %	8	4

A Test specimen parallel to forging flow lines
B Test specimen not parallel to forging flow lines
(a) Tensile and yield strength test requirements may be waived for material in any direction in which the dimension is less than 2 in because of the difficulty in obtaining a tension test specimen suitable for routine control testing.
(b) Die forgings in some configurations of this alloy can be purchased in the heat treated and mechanically stress relieved T652 temper conforming to the mechanical properties requirements specified for the T6 temper.
(c) 1 ksi = 0.70307 kg/mm²

TABLE 7.112. – NASA Specified Mechanical Properties for Hand Forgings

Alloy	2219				
Specification	NASA-MSFC-SPEC-144B				
Temper	Thickness (b)	Axis of Test Specimen	F_{tu}(min), ksi (c, d)	F_{ty}(min), ksi (c, d)	e(2 in (5.08 cm) or 4D), min, %
T6	≤4.000 in (10.16 cm)	L	58.0	40.0	6
		LT	55.0	37.0	4
		ST	53.0	35.0	2
T852	≤4.000 in (10.16 cm)	L	62.0	50.0	6
		LT	62.0	49.0	4
		ST	60.0	46.0	3
T352	<4.000 in (10.16 cm)	L	42.0	25.0	12
		LT	40.0	23.0	8
		ST	39.0	20.0	7

(a) Maximum cross-sectional area is 256 in² (1.652 m²).
(b) Thickness is measured in the short transverse direction and applies to the dimension "as forged," before machining.
(c) Tensile property requirements may be waived for directions in which the dimension is less than 2 inches.
(d) 1 ksi = 0.7037 kg/mm².

TABLE 7.121. – AMS Specified Tensile Properties for Sheet and Plate

Alloy	2219			
Specification	AMS 4031B			
Condition	0		T4 or T42	
Thickness, in (c)	0.040 to 0.499	0.500 to 2.000	0.040 to 1.000	1.000 to 2.000
F_{tu} (max), ksi (a, d)	32.0	32.0	54.0	56.0
F_{ty} (max), ksi	16.0	-	36.0	36.0
e(2 in) min, % (b)	12	-	6	6

(a) Test specimens shall conform to ASTM E8-57T except from material less than 3/4 inch wide, and shall be cut across the direction of rolling except from material less than 9 inches wide.
(b) e applies only to material 3/4 inch and over in width.
(c) 1 inch = 2.54 cm.
(d) 1 ksi = 0.70307 kg/mm^2

TABLE 7.122.– AMS Specified Bend Factors for Sheet and Plate

Alloy	2219					
Specification	AMS 4031B					
Condition	0			T4 and T42		
Thickness, in (a)	$\leq$0.250	0.250 to 0.750	0.750 to 1.000	$\leq$0.0625	0.0625 to 0.250	0.250 to 0.500
Bend factor (b)	4t	6t	8t	8t	12t	16t

(a) 1 inch = 2.54 cm.
(b) Axis of bend parallel to direction of rolling.

TABLE 7.161. – Aluminum Association Tensile Property Limits for Sheet and Plate (a)

Source	Ref. 7.4					
Alloy	2219					
Standards	Aluminum Association Mill Products					
Temper	Thickness, inch	F_{tu}, ksi Min	F_{tu}, ksi Max	F_{ty}, ksi Min	F_{ty}, ksi Max	e(2 in or 4D), min, %
0	0.020-2.000	-	32.0	-	16.0	12
T31 (d, v)	0.020-0.039	46.0	-	29.0	-	8
	0.040-0.249	46.0	-	28.0	-	10
T351 (d)	0.250-2.000	46.0	-	28.0	-	10
	2.001-3.000	44.0	-	28.0	-	10
	3.001-4.000	42.0	-	27.0	-	9
	4.001-5.000	40.0	-	26.0	-	9
	5.001-6.000	39.0	-	25.0	-	8
T37	0.020-0.039	49.0	-	38.0	-	6
	0.040-2.000	49.0	-	37.0	-	6
	2.001-2.500	49.0	-	37.0	-	6
	2.501-3.000	47.0	-	36.0	-	6
	3.001-4.000	45.0	-	35.0	-	5
	4.001-5.000	43.0	-	34.0	-	4
T62 (b, w)	0.020-0.039	54.0	-	36.0	-	6
	0.040-0.249	54.0	-	36.0	-	7
	0.250-1.000	54.0	-	36.0	-	8
	1.001-2.000	54.0	-	36.0	-	7
T81	0.020-0.039	59.0	-	44.0	-	6
	0.040-0.249	62.0	-	46.0	-	7
T851 (d)	0.250-1.000	62.0	-	46.0		8
	1.001-2.000	62.0	-	46.0	-	7
	2.001-3.000	62.0	-	45.0	-	6
	3.001-4.000	60.0	-	44.0	-	5
	4.001-5.000	59.0	-	43.0	-	5
	5.001-6.000	57.0	-	42.0	-	4
T87	0.020-0.039	64.0	-	52.0	-	5
	0.040-0.249	64.0	-	52.0	-	6
	0.250-1.000	64.0	-	51.0	-	7
	1.001-3.000	64.0	-	51.0	-	6
	3.001-4.000	62.0	-	50.0	-	4
	4.001-5.000	61.0	-	49.0	-	3

Footnotes: see page 46.
Note: 1 inch = 25.4 mm; 1 ksi = 0.70307 kg/mm^2.

TABLE 7.162. – Aluminum Association Tensile Property Limits for Alclad Sheet and Plate (a)

Source	Ref. 7.4					
Alloy	2219					
Standards	Aluminum Association Mill Products					
Temper	Thickness, inch	F_{tu}, Min	ksi Max	F_{ty}, Min	ksi Max	e(2 in or 4D), min, %
0	0.020-2.000	-	32.0	-	16.0	12
T31 (v)	0.040-0.099	42.0	-	25.0	-	10
	0.100-0.249	44.0	-	26.0	-	10
T351 (d, v)	0.250-0.499	44.0	-	26.0	-	10
T37 (v)	0.040-0.099	45.0	-	34.0	-	6
	0.100-0.249	47.0	-	35.0	-	6
	0.250-0.499	47.0	-	35.0	-	6
T62 (b, w)	0.020-0.039	44.0	-	29.0	-	6
	0.040-0.099	49.0	-	32.0	-	7
	0.100-0.249	51.0	-	34.0	-	7
	0.250-0.499	51.0	-	34.0	-	8
	0.500-1.000	54.0	-	36.0	-	8
	1.001-2.000	54.0	-	36.0	-	7
T81	0.020-0.039	49.0	-	37.0	-	6
	0.040-0.099	55.0	-	41.0	-	7
	0.100-0.249	58.0	-	43.0	-	7
T851 (d)	0.250-0.499	58.0	-	42.0	-	8
T87	0.040-0.099	57.0	-	46.0	-	6
	0.100-0.249	60.0	-	48.0	-	6
	0.250-0.499	60.0	-	48.0	-	7

Footnotes; see page 46.

Note: 1 inch = 25.4 mm; 1 ksi = 0.70307 kg/mm^2.

TABLE 7.163. — Aluminum Association Tensile Property Limits for Rolled or Cold-Finished Bar, Rod, and Wire (f)

Source	Ref. 7.4					
Alloy	2219					
Standards	Aluminum Association Mill Products					
Temper	Diameter, inch	F_{tu}, ksi Min	F_{tu}, ksi Max	F_{ty}, ksi Min	F_{ty}, ksi Max	e(2 in or 4D) min, %
T851	0.500-2.000	58.0	-	40.0	-	4
	2.001-4.000	57.0	-	39.0	-	4

Footnotes: see page 46.
Note: 1 inch = 25.4 mm; 1 ksi = 0.70307 kg/mm².

TABLE 7.164. — Aluminum Association Tensile Property Limits for Extruded Rod, Bar, Shapes, and Tubing (f)

Source	Ref. 7.4						
Alloy	2219						
Standards	Aluminum Association Mill Products						
Temper	Thickness, inch	Area, in²	F_{tu}, ksi Min	F_{tu}, ksi Max	F_{ty}, ksi Min	F_{ty}, ksi Max	e(2 in or 4D), min, %
0 (c)	All	All	-	32.0	-	18.0	12
T31, T3510,	≤0.499	≤25	42.0	-	26.0	-	14
T3511 (d, x)	0.500-2.999	≤25	45.0	-	27.0	-	14
T62 (b)	≤0.999	≤25	54.0	-	36.0	-	6
	≤1.000	≤32	54.0	-	36.0	-	6
T81, T8510, T8511 (d, w, y)	≤2.999	≤32	58.0	-	42.0	-	6

Footnotes: see page 46.
Note: 1 inch = 25.4 mm; 1 ksi = 0.70307 kg/mm².

TABLE 7.165. — Aluminum Association Tensile Property and Hardness Limits for Die Forgings

Source	Ref. 7.4						
Alloy	2219						
Standards	Aluminum Association Mill Products						
Temper	Grain	Brinell Hardness*	F_{tu}, ksi Min	F_{tu}, ksi Max	F_{ty}, ksi Min	F_{ty}, ksi Max	e(2 in or 4D) min, %
T6	A (n)	100	58.0	-	38.0	-	10
T6	B (u)	100	56.0	-	36.0	-	4

* 500-kg load, 10-mm ball
A Parallel to grain flow
B Not parallel to grain flow

Footnotes: see page 46.

Note: 1 inch = 25.4 mm; 1 ksi = 0.70307 kg/mm^2.

TABLE 7.166. — Aluminum Association Tensile Property Limits for Hand Forgings (p, q)

Source	Ref. 7.4									
Alloy	2219									
Standards	Aluminum Association Mill Products									
Temper	Thickness, inch (r)	F_{tu}, ksi L	F_{tu}, ksi LT	F_{tu}, ksi ST	F_{ty}, ksi L	F_{ty}, ksi LT	F_{ty}, ksi ST	e(2 in or 4D) L	e(2 in or 4D) LT	e(2 in or 4D) ST
T6	≤4.000	58.0	55.0	53.0	40.0	37.0	35.0	6	4	2
T852	≤4.000	62.0	62.0	60.0	50.0	49.0	46.0	6	4	3

L - Longitudinal (m)
LT - Long transverse
ST - Short transverse

Footnotes: see page 46.

Note: 1 inch = 25.4 mm; 1 ksi = 0.70307 kg/mm^2

Footnotes for Aluminum Association Standards

(a) Test specimens taken transverse to rolling direction for widths ≥ 9 inches and parallel to rolling direction for widths < 9 inches.

(b) Material heat treated from any temper by the user should attain the properties applicable to this temper.

(c) O temper material shall be capable of developing properties for T6 temper after heat treatment.

(d) For stress relieved tempers, properties other than those specified may differ from the corresponding properties of the basic temper.

(e) For plate 0.500 inches or over in thickness, the listed properties apply to core material only. Strengths of composite (core plus clad) are slightly lower depending on thickness of cladding.

(f) Specimens taken parallel to direction of extrusion, rolling, or drawing.

(g) O temper material within the size limitations specified for T4 temper, shall upon heat treatment be capable of developing properties applicable to T4 temper.

(h) For rounds (rod) maximum diameter is 8000 inches; for square, rectangular, hexagonal, or octagonal bar maximum thickness is 4 inches and 36 square inches cross-section area.

(j) Round tube 2 inches or less in diameter, and square tube 1.5 inches or less on a side are tested in full-section.

(k) For round tube over 2 inches diameter, for square tube over 1.5 inches on a side, for all sizes other than round or square or when full section cannot be used, a cutout specimen is employed.

(m) Tensile tests are performed and properties guaranteed only when specifically required by purchase order or contract.

(n) These values apply to standard 0.5-inch diameter test specimens machined from separately forged coupons representative of the forgings. For specimens machined from forgings up to 4 inches in thickness or diameter with specimen axis substantially parallel to direction of grain flow, requirements apply except minimum e shall be 70 percent of values in the table.

(p) Maximum cross-sectional area is 256 square inches.

(q) These properties are not applicable to upset biscuit forgings or to rolled or forged ring forgings.

(r) Thickness measured in short transverse direction.

(s) Applies to all available widths of sheet and plate.

(t) The measurement of e and F_{ty} is not required for wire less than 0.125 inch in thickness.

(u) These values apply to standard specimens machined from forgings up to 4 inches with the specimen axis not parallel to the direction of grain flow.

(v) Upon artificial aging, T3 and T31, T37, T351, T361, and T451 temper material shall be capable of developing the mechanical properties applicable to the T81, T87, T851, T861, and T651 tempers, respectively.

(w) This temper is not available from the material producer.

(x) Upon artificial aging, T31, T3510, T3511, T4, T4510, and T4511 temper material shall be capable of developing the mechanical properties applicable to the T81, T8510, T6, T6510, and T6511 tempers, respectively.

(y) These properties can usually be obtained by the user when the material is properly solution heat treated or solution and precipitation heat treated from the O (annealed) or F (as fabricated) temper.

Note: 1 inch = 25.4 mm; 1 ksi = 0.70307 kg/mm^2.

TABLE 7.4111. – Design Mechanical Properties for Sheet and Plate

Alloy	2219															
Form	Sheet and plate															
Condition	T62		T81		T851											
Thickness, in.	0.020–2.000		0.020–0.249		0.250–1.000		1.001–2.000		2.001–3.000		3.001–4.000		4.001–5.000		5.001–6.000	
Basis	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
Mechanical properties:																
F_{tu}, ksi:																
L	54	55	62	63	62	63	62	63	....	....	....	....	....	....	....	....
LT	54	55	62	63	62	63	62	63	62	63	60	61	59	60	57	58
F_{ty}, ksi:																
L	36	37	47	48	47	48	47	48	....	....	....	....	....	....	....	....
LT	36	37	46	47	46	47	46	47	45	46	44	45	43	44	42	43
F_{cy}, ksi:																
L	38	39	48	49	48	49	47	48	....	....	....	....	....	....	....	....
LT	38	39	49	50	49	50	49	50	....	....	....	....	....	....	....	....
F_{su}, ksi	32	32	36	36	36	36	36	37	....	....	....	....	....	....	....	....
F_{bru}, ksi:																
(e/D=1.5)	84	86	95	97	95	97	95	97	....	....	....	....	....	....	....	....
(e/D=2.0)	109	111	121	123	121	123	120	122	....	....	....	....	....	....	....	....
F_{bry}, ksi:																
(e/D=1.5)	63	65	77	78	77	78	77	78	....	....	....	....	....	....	....	....
(e/D=2.0)	79	82	93	95	93	95	93	95	....	....	....	....	....	....	....	....
e, percent:																
LT	(a)	....	(a)	....	8	....	7	....	6	....	5	....	5	....	4	....

Alloy	2219													
Form	Sheet and plate													
Condition	T87													
Thickness, in.	0.020–0.039		0.040–0.249		0.250–1.000		1.001–2.000		2.001–3.000		3.001–4.000		4.001–5.000	
Basis	A	B	A	B	A	B	A	B	A	B	A	B	A	B
Mechanical properties:														
F_{tu}, ksi:														
L	63	64	63	64	63	64	63	64	....	....	....	....	....	....
LT	64	65	64	65	64	65	64	65	64	65	62	63	61	62
F_{ty}, ksi:														
L	51	52	52	53	51	52	51	52	....	....	....	....	....	....
LT	52	53	52	53	51	52	51	52	51	52	50	51	49	50
F_{cy}, ksi:														
L	52	53	52	53	51	52	51	52	....	....	....	....	....	....
LT	55	56	55	56	54	55	54	55	....	....	....	....	....	....
F_{su}, ksi	37	38	37	38	37	38	38	38	....	....	....	....	....	....
F_{bru}, ksi:														
(e/D=1.5)	99	101	99	101	99	101	99	101	....	....	....	....	....	....
(e/D=2.0)	126	128	126	128	126	128	126	128	....	....	....	....	....	....
F_{bry}, ksi:														
(e/D=1.5)	84	86	84	86	83	84	83	84	....	....	....	....	....	....
(e/D=2.0)	97	99	97	99	95	97	95	97	....	....	....	....	....	....
e, percent:														
LT	5	....	6	....	7	....	6	....	6	....	4	....	3	....

[a] T62 and T81: 0.020-0.039 in, 6 percent; 0.040-0.249 in, 7 percent.
T62: 0.250-1.000 in, 8 percent; 1.001-2.000 in, 7 percent.

Note: 1 inch = 25.4 mm; 1 ksi = 0.70307 kg/mm^2

TABLE 7.4112.— Design Mechanical Properties in Metric Units

Source	Calculated from data of reference 7.1																													
Alloy	2219																													
Condition	T62		T81		T851												T87													
Thickness, cm	0.051-5.080		0.051-0.632		0.635-2.540		2.543-5.080		5.083-7.620		7.623-10.160		10.163-12.700		12.703-15.240		0.051-0.099		0.102-0.632		0.635-2.540		2.543-5.080		5.083-7.620		7.623-10.160		10.163-12.700	
Basis	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
F_{tu}, kg/mm^2																														
–L	38.0	38.7	43.6	44.3	43.6	44.3	43.6	44.3									44.3	45.0	44.3	45.0	44.3	45.0	44.3	45.0						
–T	38.0	38.7	43.6	44.3	43.6	44.3	43.6	44.3	43.6	44.3	42.2	42.9	41.5	42.2	40.1	40.8	45.0	45.7	45.0	45.7	45.0	45.7	45.0	45.7	45.0	45.7	43.6	44.3	42.9	43.6
F_{ty}, kg/mm^2																														
–L	25.3	26.0	33.0	33.7	33.0	33.7	33.0	33.7									35.9	36.6	36.6	37.3	35.9	36.6	35.9	36.6						
–T	25.3	26.0	32.3	33.0	32.3	33.0	32.3	33.0	31.6	32.3	30.9	31.6	30.2	30.9	29.5	30.2	36.6	37.3	36.6	37.3	35.9	36.6	35.9	36.6	35.9	36.6	35.7	35.9	34.5	35.2
F_{cy}, kg/mm^2																														
–L	26.7	27.4	33.7	34.5	33.7	34.5	33.7	34.5									36.6	37.3	36.6	37.3	35.9	36.6	35.9	36.6						
–T	26.7	27.4	34.5	35.2	34.5	35.2	34.5	35.2									38.7	39.4	38.7	39.4	38.0	38.7	38.0	38.7						
F_{su}, kg/mm^2	22.5	22.5	25.3	25.3	25.3	25.3	25.3	26.0									26.0	26.7	26.0	26.7	26.0	26.7	26.0	26.7						
F_{bru}, kg/mm^2																														
(e/D=1.5)	59.1	60.5	66.8	68.2	66.8	68.2	66.8	68.2									69.6	71.0	69.6	71.0	69.6	71.0	69.6	71.0						
(e/D=2.0)	76.6	78.0	85.1	86.5	85.1	86.5	84.4	85.8									88.6	90.0	88.6	90.0	88.6	90.0	88.6	90.0						
F_{bry}, kg/mm^2																														
(e/D=1.5)	44.3	45.7	54.1	54.8	54.1	54.8	54.1	54.8									59.1	60.5	59.1	60.5	58.4	59.1	58.4	59.1						
(e/D=2.0)	55.5	57.7	65.4	66.8	65.4	66.8	65.4	66.8									68.2	69.6	68.2	69.6	66.8	68.2	66.8	68.2						
e, percent, –LT	(a)	-	(a)	-	8	-	7	-	6	-	5	-	5	-	4	-	5	-	6	-	7	-	6	-	6	-	4	-	3	-

(a) T62 and T81: 0.051-0.099 cm, 6%; 0.102-0.632 cm, 7%.
T62: 0.635-2.54 cm, 8%; 2.543-5.080 cm, 7%

TABLE 7.4113. – Design Properties for Alclad Sheet and Plate

Source	Ref. 7.23						
Alloy	2219						
Temper	T62		T81		T851	T87	
Thickness, inch (a)	0.040-0.099	0.100-2.000	0.040-0.099	0.100-0.249	0.250-2.000	0.040-0.099	0.100-2.000
F_{tu}, ksi (b) -L	49	52	55	57	57	57	59
-T	49	52	56	58	58	58	60
F_{ty}, ksi -L	32	34	40	42	42	45	47
-T	32	34	39	41	41	45	47
F_{cy}, ksi -L	34	36	40	42	42	45	47
-T	34	36	41	43	43	48	50
F_{su}, ksi	29	31	32	33	33	33	34
F_{bru} (e/D=1.5), ksi	[illegible]	78	81	84	84	84	87
(e/D=2.0), ksi	98	104	106	110	110	110	114
F_{bry} (e/D=1.5), ksi	51	54	58	61	61	63	66
(e/D=2.0), ksi	61	65	66	70	70	72	75
e(2 in or 4D), % -T	6	6	6	6	6	5	5

(a) 1 inch = 2.54 cm (b) 1 ksi = 0.70307 kg/mm²

TABLE 7.4114. – Typical Mechanical Properties for Various Tempers of Bare Sheet and Plate

Source	Ref. 7.23						
Alloy	2219						
Temper	O	T42	T31 T351	T37	T62	T81 T851	T87
F_{tu}, ksi (a) -L	-	-	52	56	56	66	68
-T	25	50	52	56	58	66	68
F_{ty}, ksi -L	-	-	36	45	40	50	56
-T	11	25	34	44	40	50	56
e(2 in) -L	-	-	20	12	10	10	10
-T	18	20	16	10	10	10	10
F_{cy}, ksi -L	-	-	-	-	44	53	57
-T	-	-	-	-	44	54	60
F_{su}, ksi	-	-	-	-	36	38	40
F_{bru} (e/D=1.5), ksi	-	-	-	-	90	96	100
(e/D=2.0), ksi	-	-	-	-	120	125	131
F_{bry} (e/D=1.5), ksi	-	-	-	-	67	76	80
(e/D=2.0), ksi	-	-	-	-	80	87	91
Hardness, Brinell (500 kg, 10-mm ball)	-	-	96	110	113	123	128

(a) 1 ksi = 0.70307 kg/mm²

TABLE 7.4147. – Effect of Irradiation at –196° C with Fast Fluence ($7.5 \times 10^{17} n/cm^2$) on the Tensile Properties of Aluminum Alloy

Source	Refs. 7.24 and 7.25								
Alloy	2219								
Form	Test Temp., °C	Yield Strength, ksi (b)		Ultimate Tensile Strength, ksi		Notched Tensile Strength, ksi		Total Elongation, percent	
		Unirr.	Irr.	Unirr.	Irr.	Unirr.	Irr.	Unirr.	Irr.
Sheet	–196	49.2	63.1	73.1	75.0	67.5	75.4	9.1	8.0
	–196 (a)	49.2	51.8	73.1	74.2	67.5	67.9	9.1	10.1
	27	42.0	41.5	59.7	58.4	56.5	53.5	7.0	6.8
Forging, axial direction	–196	53.6	79.0	72.3	80.7	88.2	91.4	7.6	2.3
	–196 (a)	53.6	54.6	72.3	72.1	88.2	88.1	7.6	6.7
	27	47.3	47.2	62.1	61.4	75.5	72.2	7.4	6.6
Forging, radial direction	–196	51.7	78.3	74.8	80.5	93.0	105.4	14.3	5.6
	–196 (a)	51.7	53.5	74.8	80.5	93.0	92.3	14.3	13.8
	27	46.3	46.8	61.8	61.7	77.3	77.7	10.9	11.4

(a) >0.5 meV

(b) 1 ksi = 0.70307 kg/mm^2

TABLE 7.4621. -- Average Plane-Strain Fracture-Toughness Data

Source	Refs. 7.9 and 7.12										
Alloy	2219										
Temper	Spec-imen Type (a)	Specimen Orienta-tion (b)	Yield Strength, ksi	Tensile Strength, ksi	Bend Test Span, in	Av. K_{IC} (c) ksi $\sqrt{in.}$	$\left(\frac{K_{IC}}{Y.S.}\right)^2$	Specimen Dimensions, in. Thick-ness	Width	Crack Length	No. of Tests
T851	Plate	L	51.0	-	12.0	35.5	0.48	1.4	3.0	1.5	2
T851	Plate	T	50.8	-	12.0	33.3	0.43	1.4	3.0	1.6	4
T851	SEN	L	59.3	73.4	-	36.0	0.37	1.0	5.0	1.6	4
T851	NB-3	L	59.3	73.4	-	(38.3)	0.42	1.0	2.0	1.0	3
T851	SEN	T	58.4	74.3	-	(37.3)	0.41	1.0	5.0	6.0	8
T851	NB-4	T	58.4	74.3	-	35.5	0.37	1.0	2.0	1.0	4
T87	SEN	L	57.9	72.0	-	33.0	0.33	1.0	5.0	1.6	2
T87	SEN	T	55.2	72.0	-	39.9	0.29	1.0	5.0	1.6	2

(a) SEN = single-edge-notch; NB-3 = notch-bend with 3-point loading; NB-4 = notch-gend with 4-point loading.
(b) L = longitudinal; T = transverse.
(c) K_{IC} values in parentheses do not comply with requirement that specimen be $\geq 2.5(K_{IC}/Y.S.)^2$
Note: 1 ksi = 0.70307 kg/mm^2; 1 inch = 2.54 cm; 1 ksi$\sqrt{in}$ = 3.543 kg/mm$^{3/2}$.

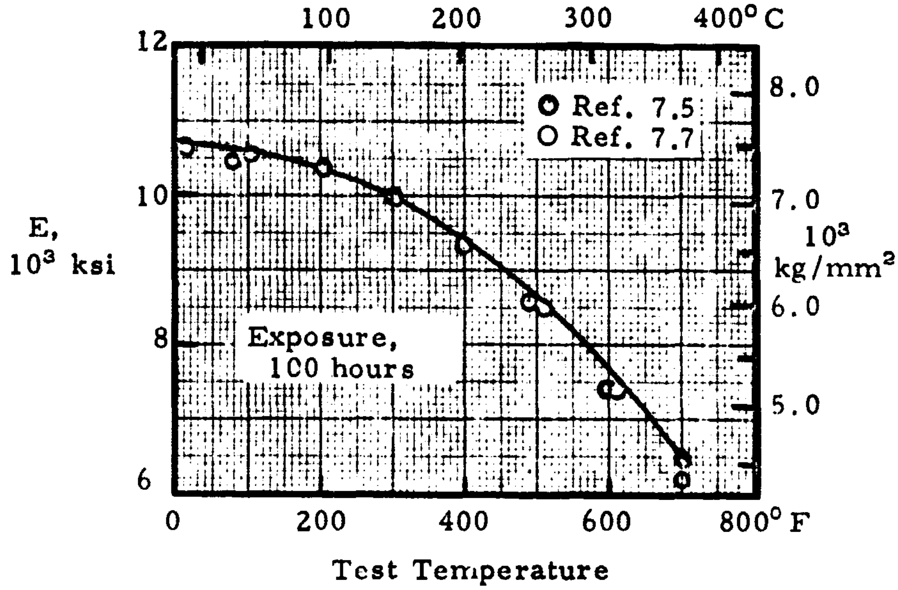


FIGURE 7.222.—Effect of elevated temperatures on modulus of elasticity of 2219-T6 forgings. (Refs. 7.5, 7.7)

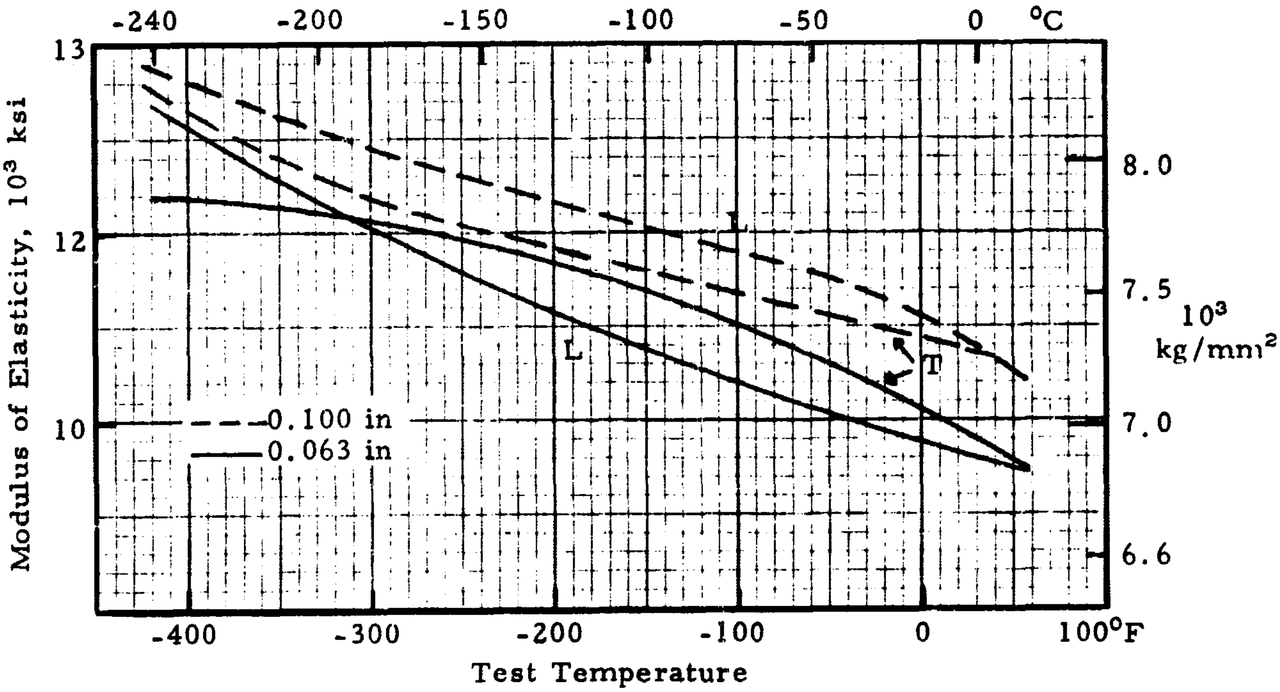


FIGURE 7.223.— Effect of low temperature on modulus of elasticity of 2219-T81 sheet. (1 inch = 25.4 mm) (Refs. 7.15, 7.16)

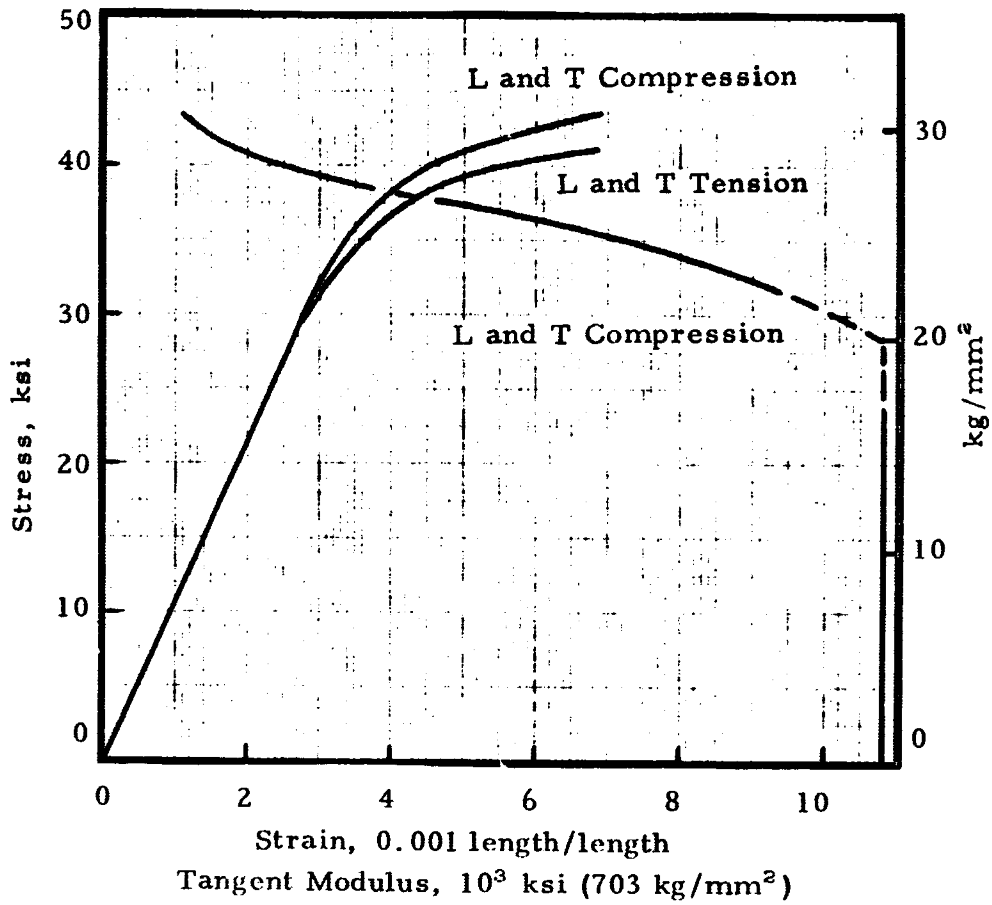


FIGURE 7.251. – Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 2219-T62 sheet and plate at room temperature; thickness, 0.125-2.00 inches (3.175-50.8 mm).

(Ref. 7.1)

C-2

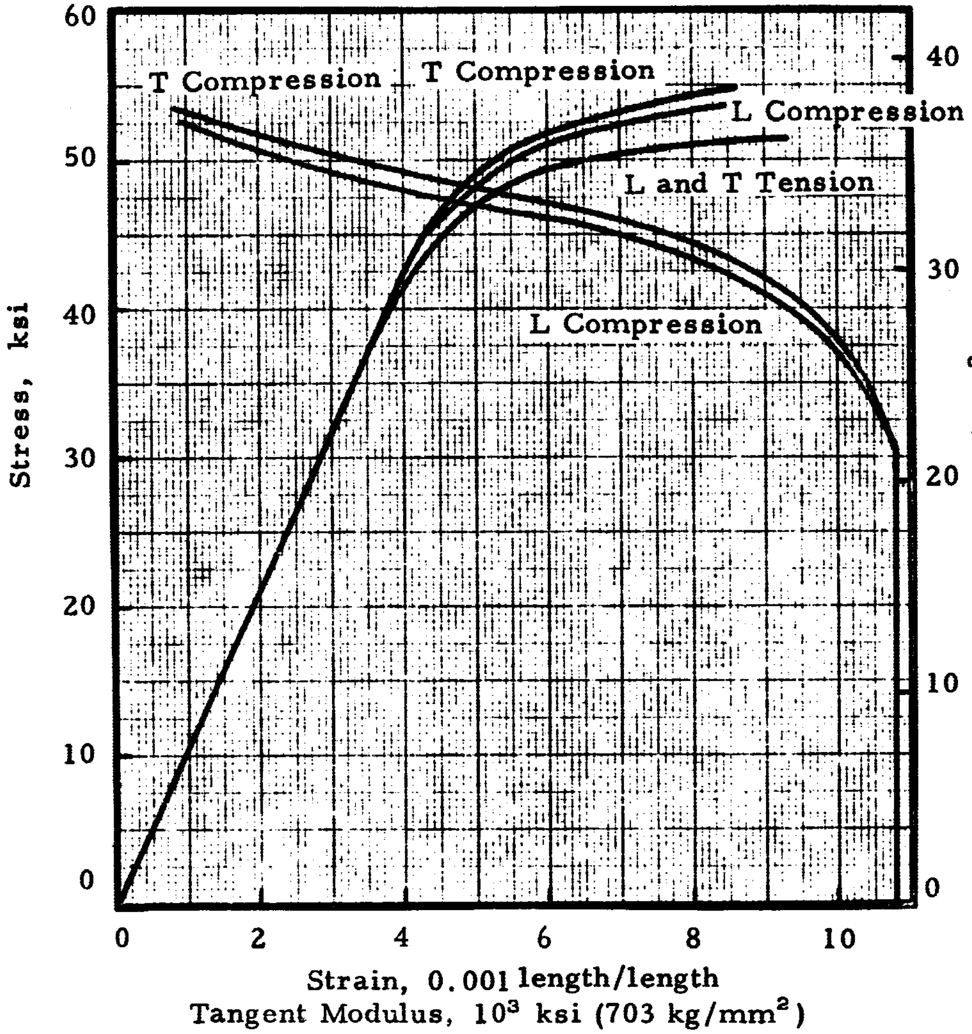


FIGURE 7.252. — Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 2219-T81 sheet and plate at room temperature; thickness, 0.125-2.00 inches, (3.175-50.8 mm).

(Ref. 7.1)

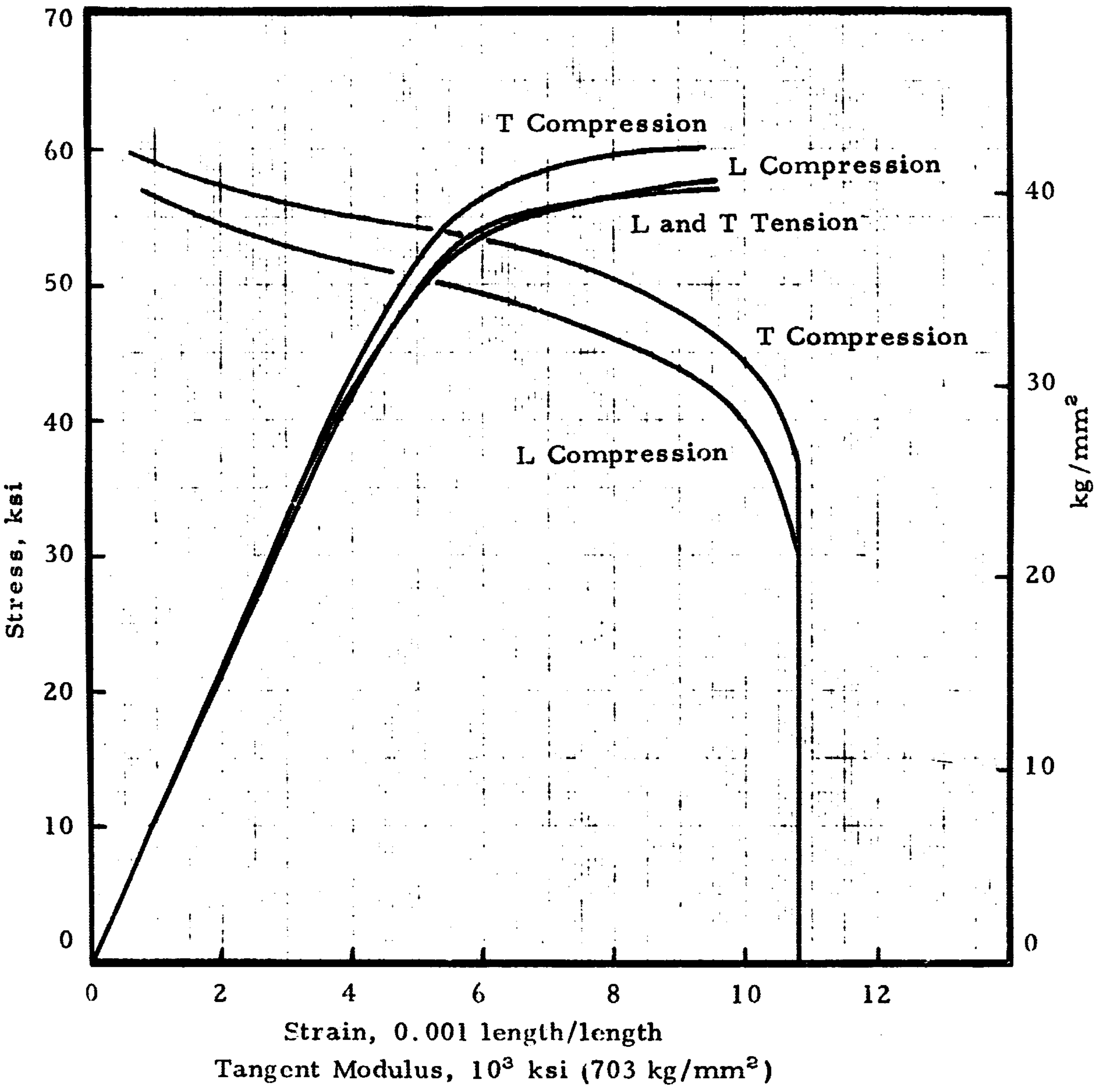
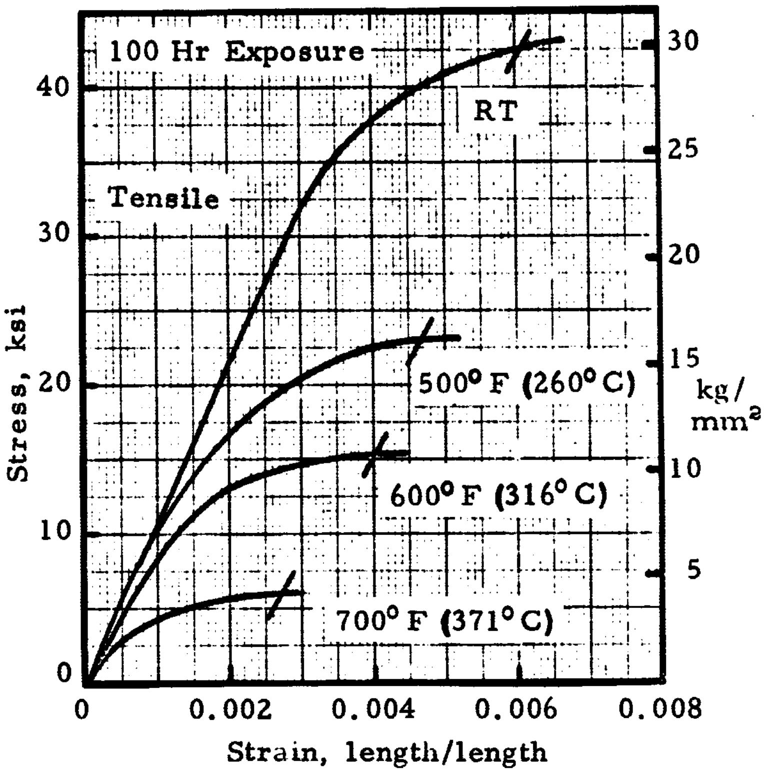


FIGURE 7.253. — Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 2219-T87 sheet and plate at room temperature; thickness, 0.125-2.00 inches (3.175-50.8 mm).

(Ref. 7.1)

FIGURE 7.4121.— Stress-strain curves for 2219-T6 at room and elevated temperatures.

(Ref. 7.7)



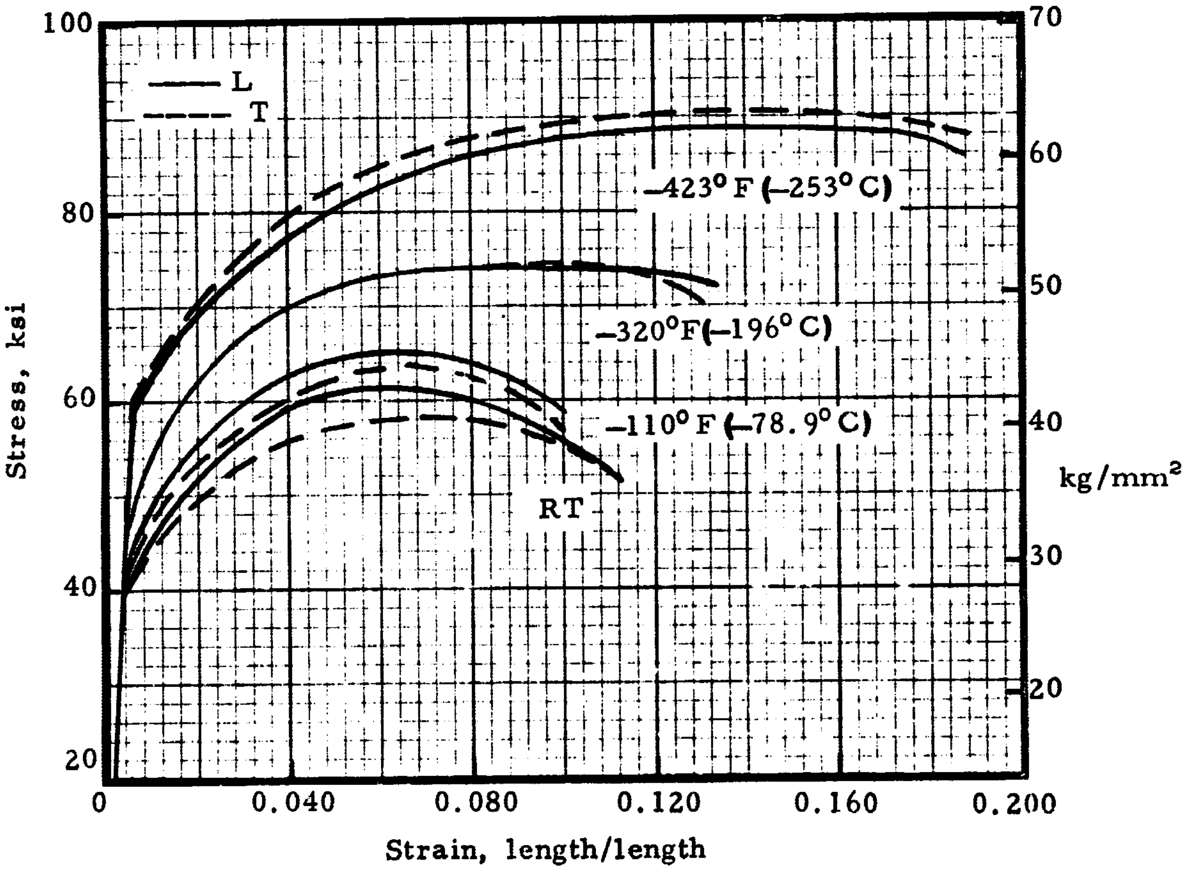


FIGURE 7.4122.— Stress-strain curves for 2219-T6 sheet (0.100 inch, 2.54 mm) at low temperatures.

(Ref. 7.15)

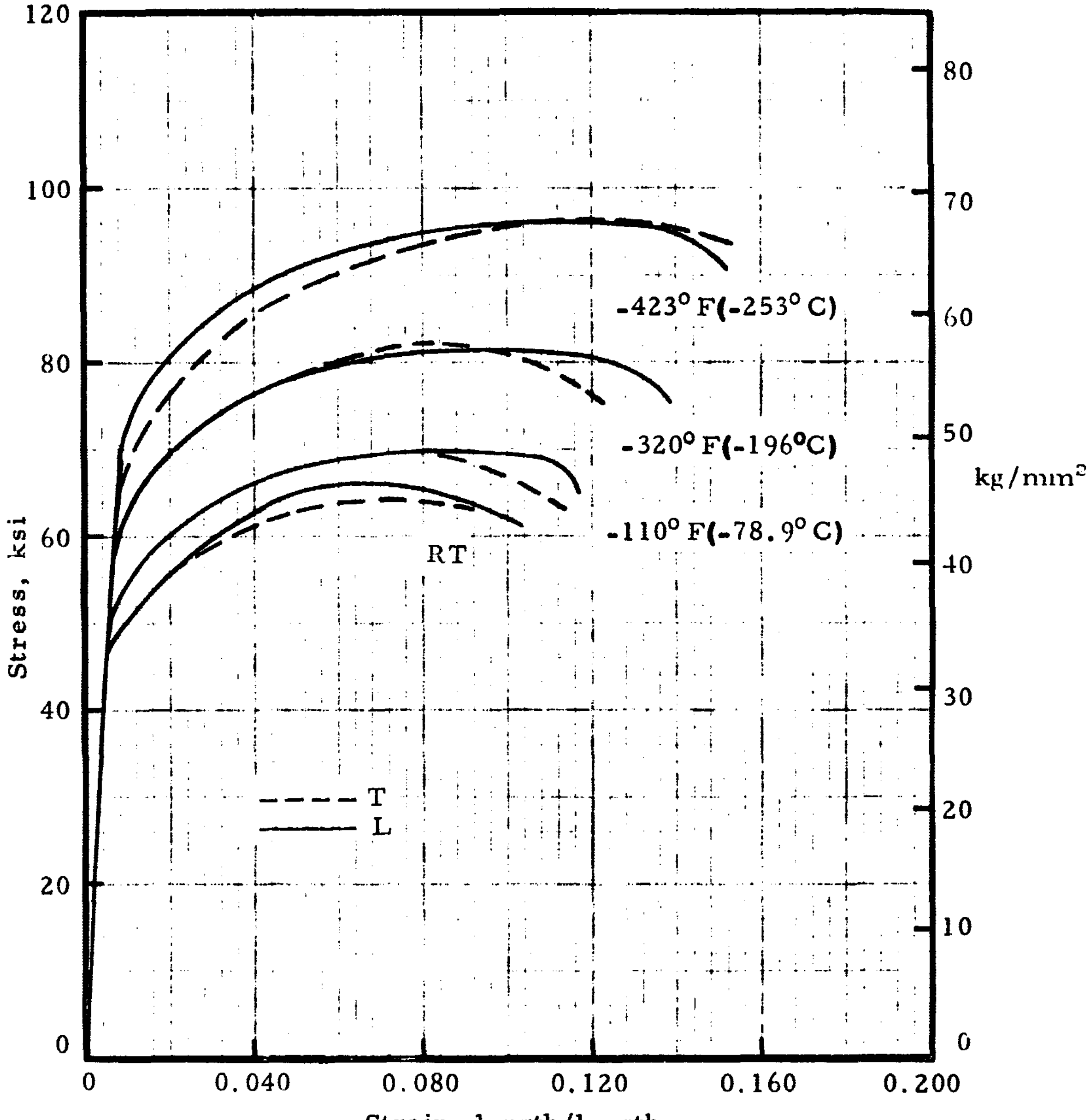


FIGURE 7.4123. – Tensile stress-strain curves for 2219-T81 sheet (0.100 in, 2.54 mm) at low temperatures.

(Ref. 7.15)

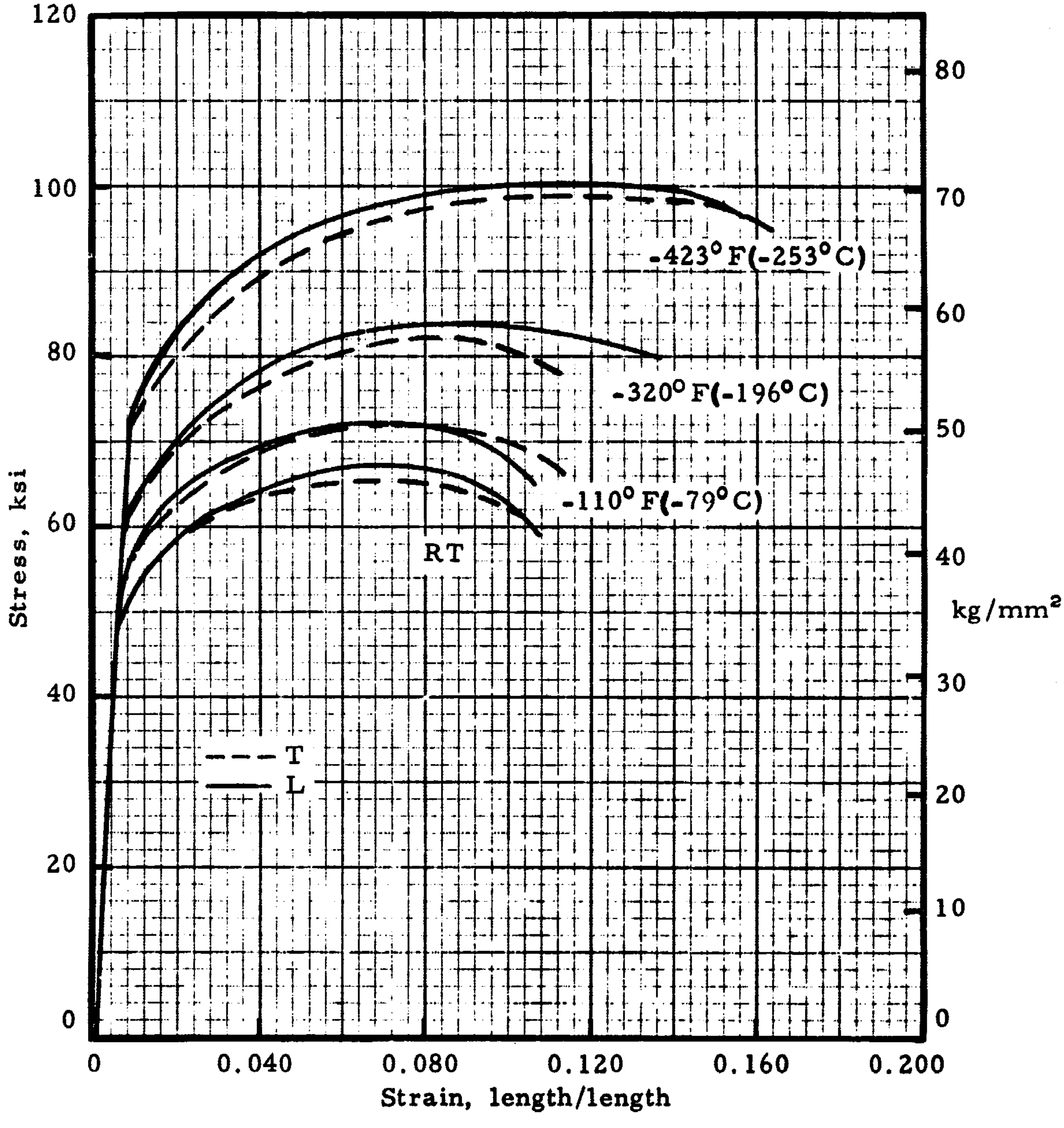


FIGURE 7.4124. — Tensile stress-strain curves for 2219-T87 sheet (0.100 in, 2.54 mm) at low temperatures.

(Ref. 7.15)

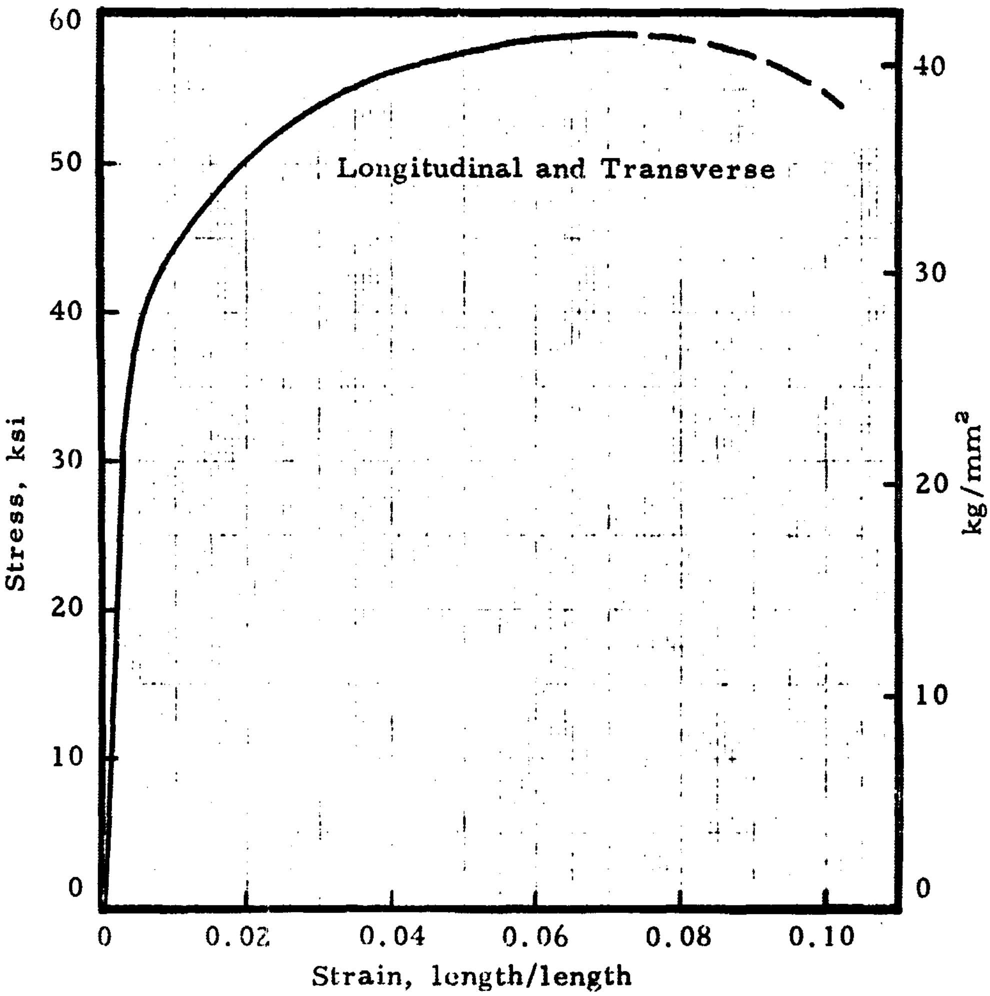


FIGURE 7.4125. — Typical tensile stress-strain curve (full-range) for 2219-T62 sheet and plate at room temperature; thickness, 0.125-2.00 inches (3.175-50.8 mm).

(Ref. 7.1)

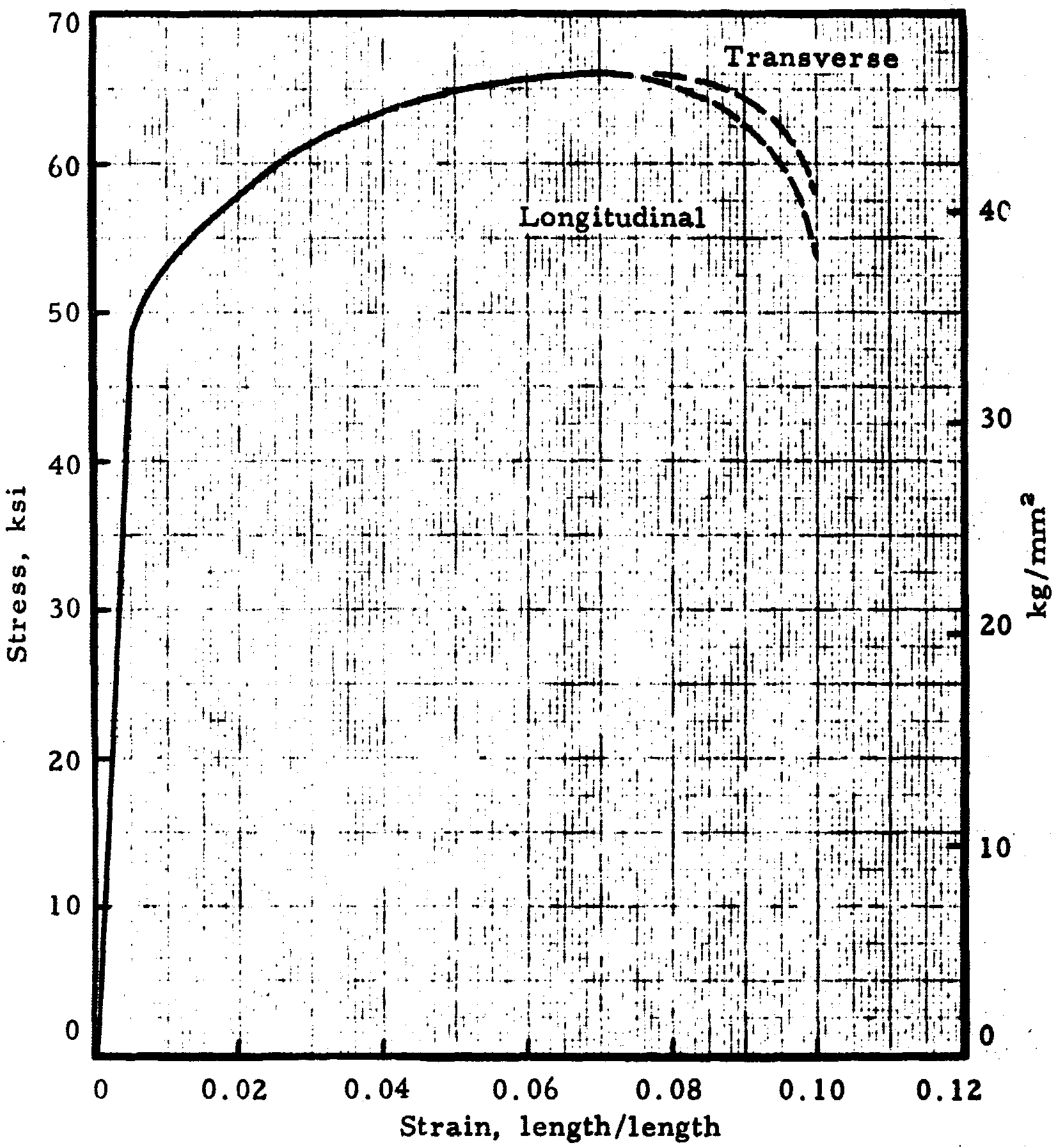


FIGURE 7.4126. — Typical tensile stress-strain curve (full-range) for 2219-T81 sheet and plate at room temperature; thickness, 0.125-2.00 inches (3.175-50.8 mm).

(Ref. 7.1)

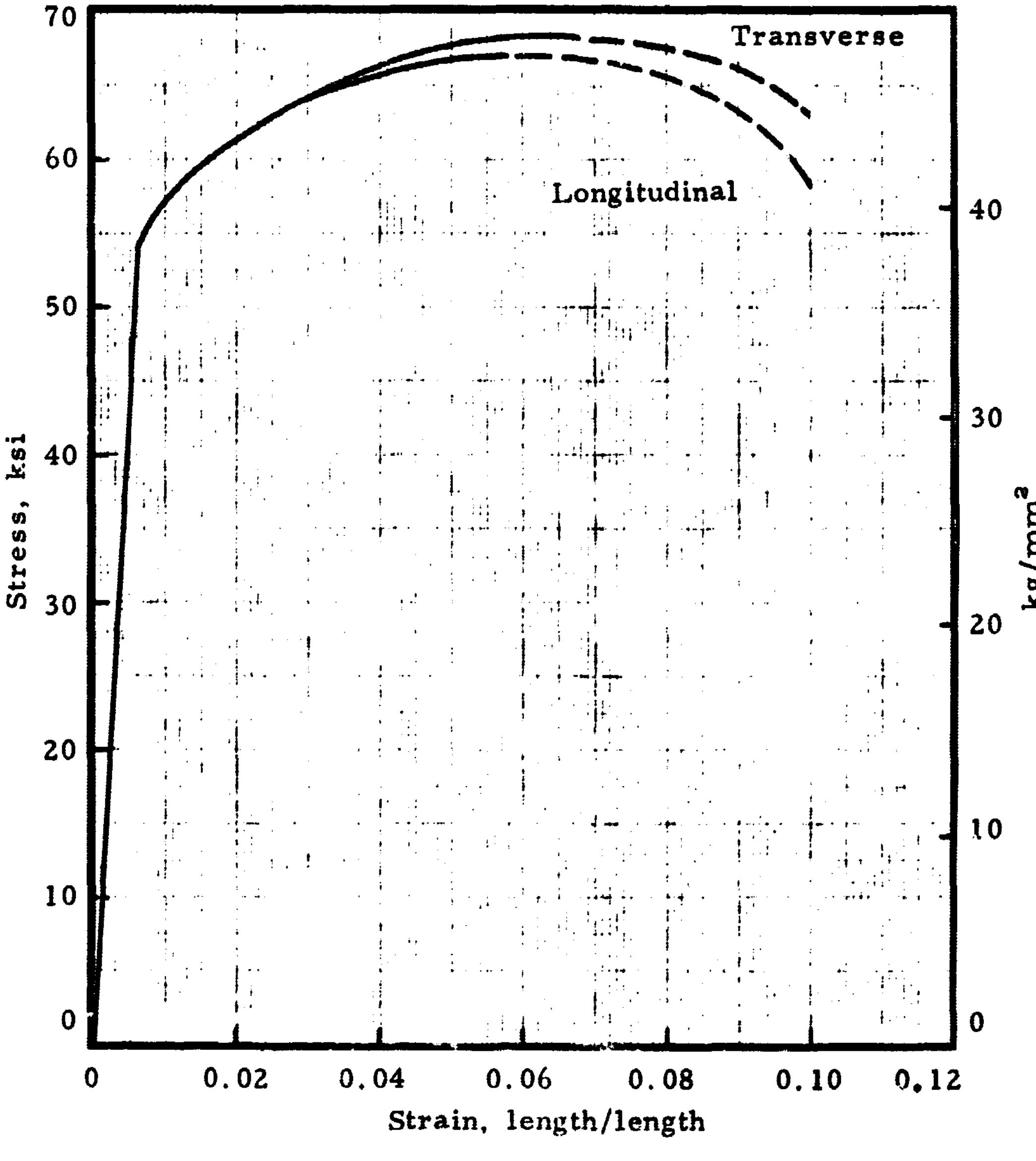


FIGURE 7.4127. – Typical tensile stress-strain curve (full-range) for 2219-T87 sheet and plate at room temperature; thickness, 0.125-2.00 inches (3.175-50.8 mm).

(Ref. 7.1)

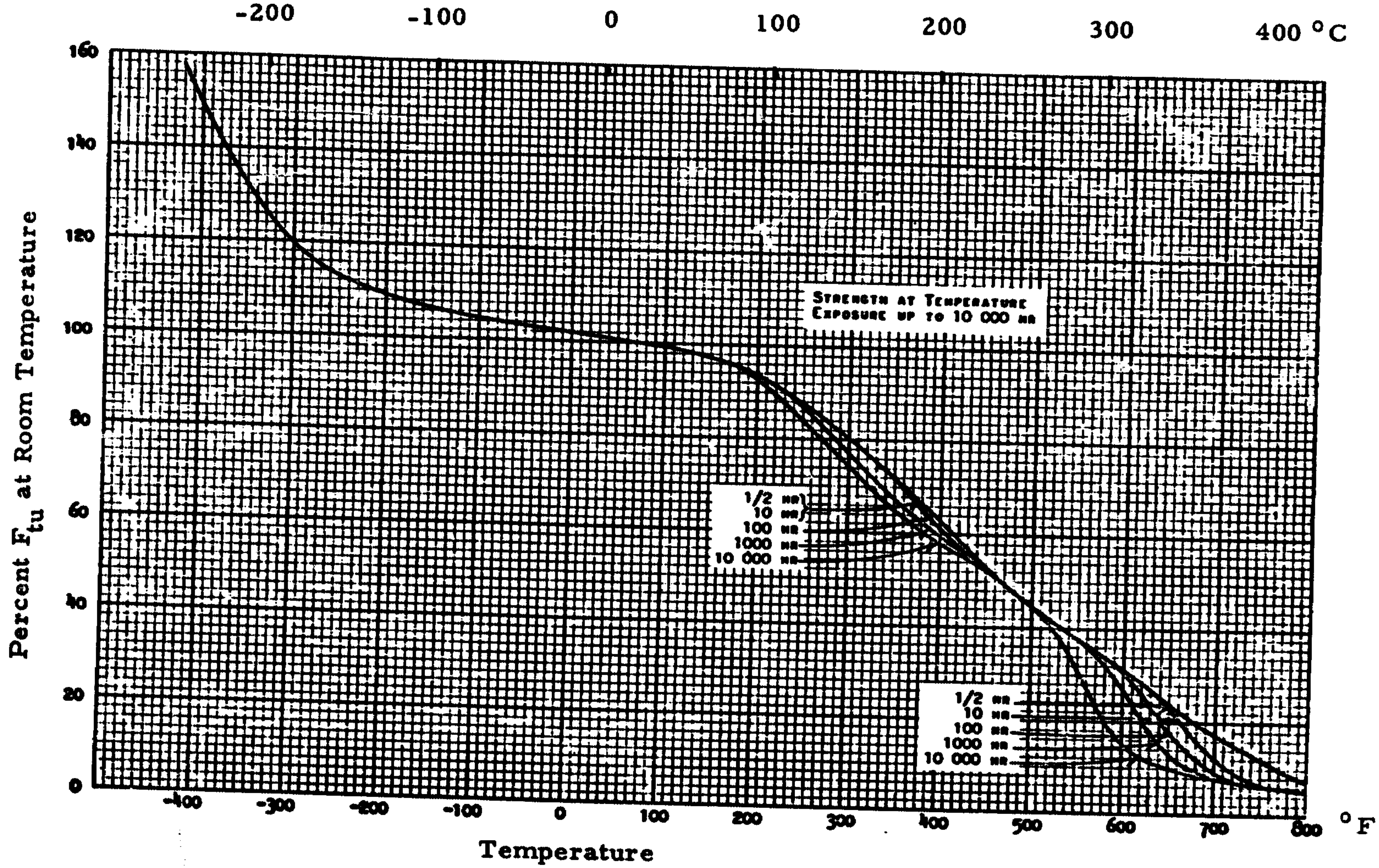


FIGURE 7.4131. — Effect of temperature on the ultimate tensile strength of 2219-T62 bare and clad sheet and plate, 0.040-1.000 in (1.016-25.4 mm) thick. (Ref. 7.1)

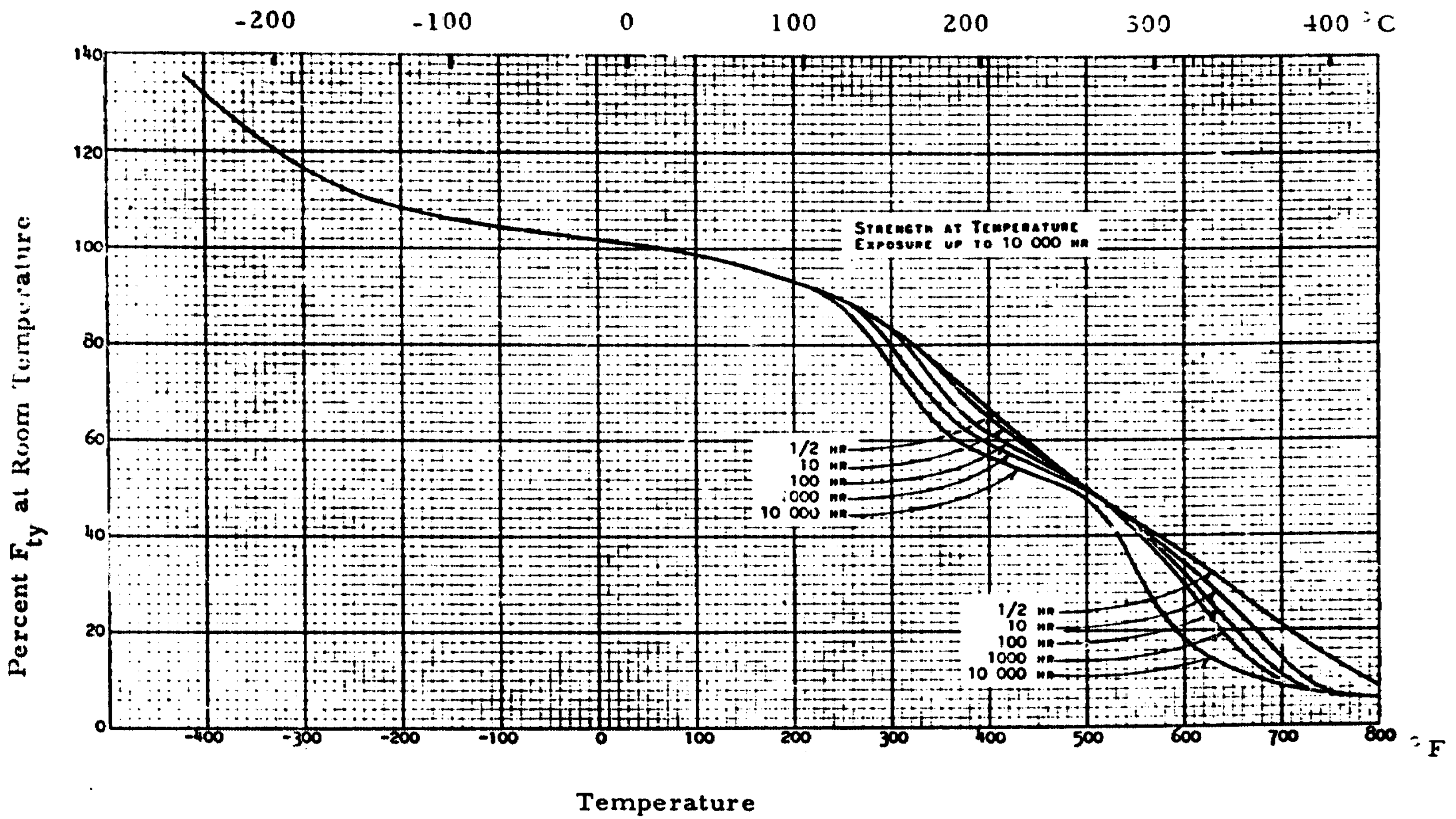


FIGURE 7.4132. — Effect of temperature on the tensile yield strength of 2219-T62 bare and clad sheet and plate, 0.040-1.000 inch (1.016-25.4 mm) thick. (Ref. 7.1)

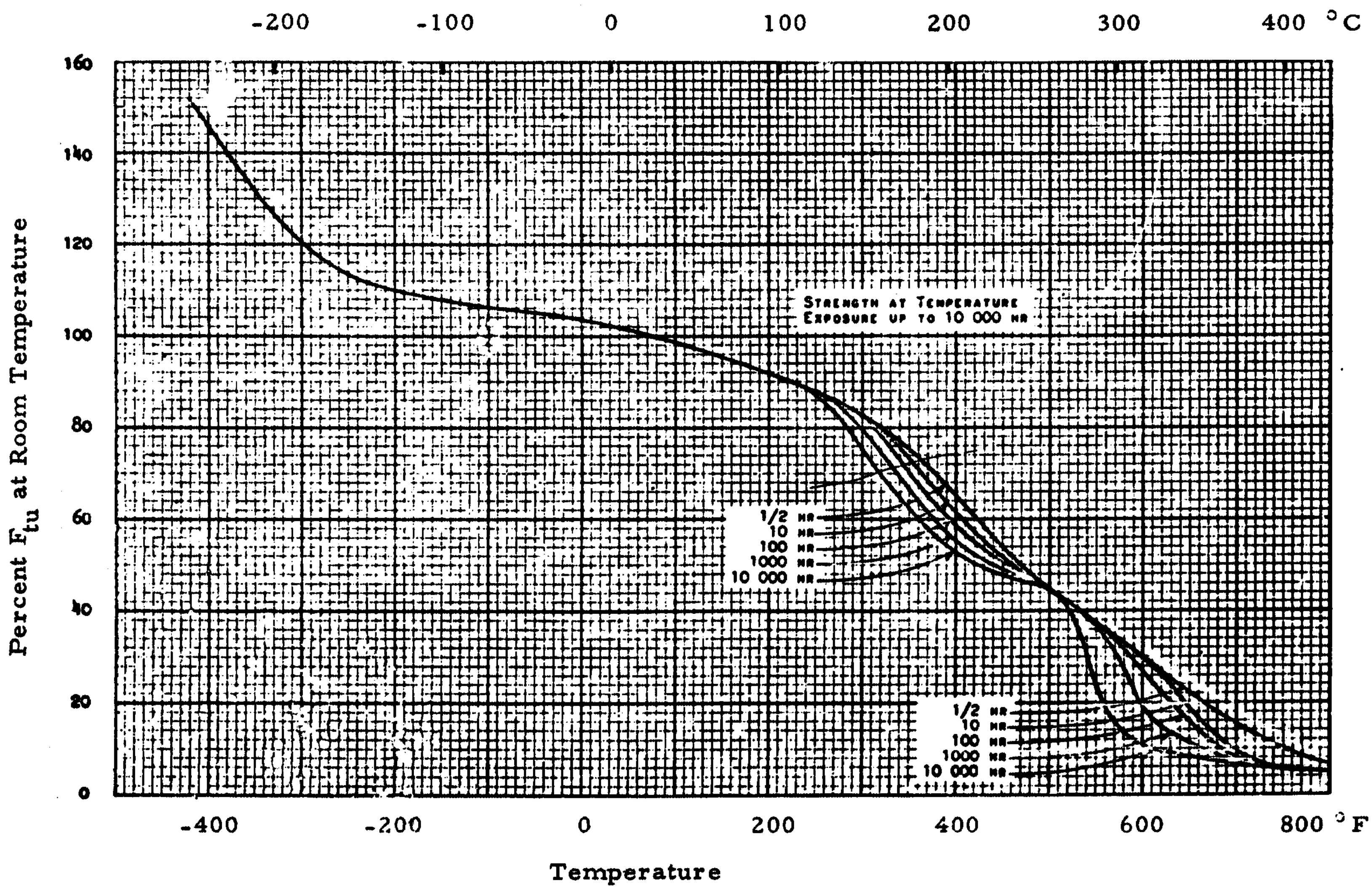


FIGURE 7.4133. — Effect of temperature on the ultimate tensile strength of 2219-T81 bare and clad sheet and plate. (Ref. 7.1)

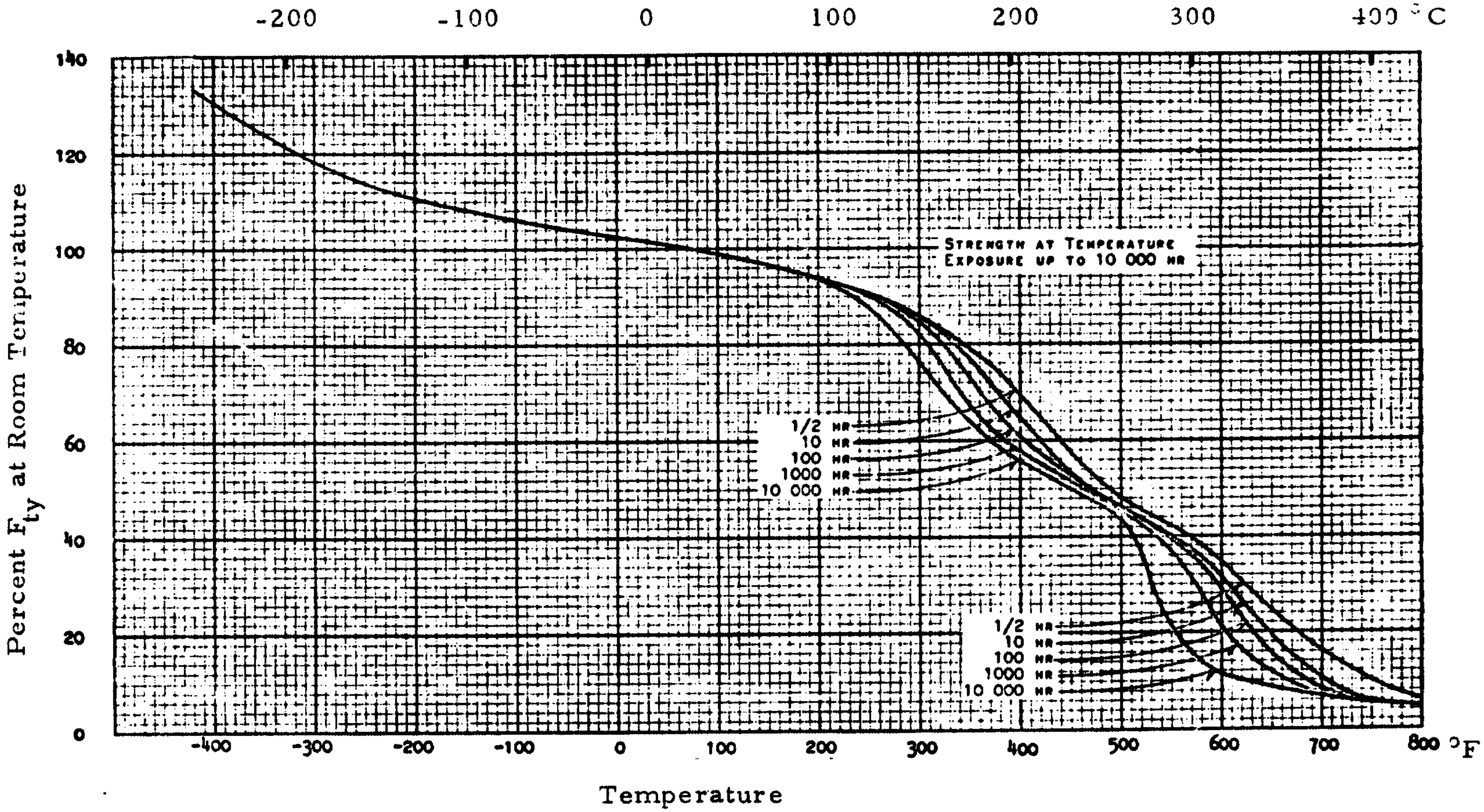


FIGURE 7.4134. — Effect of temperature on the tensile yield strength of 2219-T81 bare and clad sheet and plate. (Ref. 7.1)

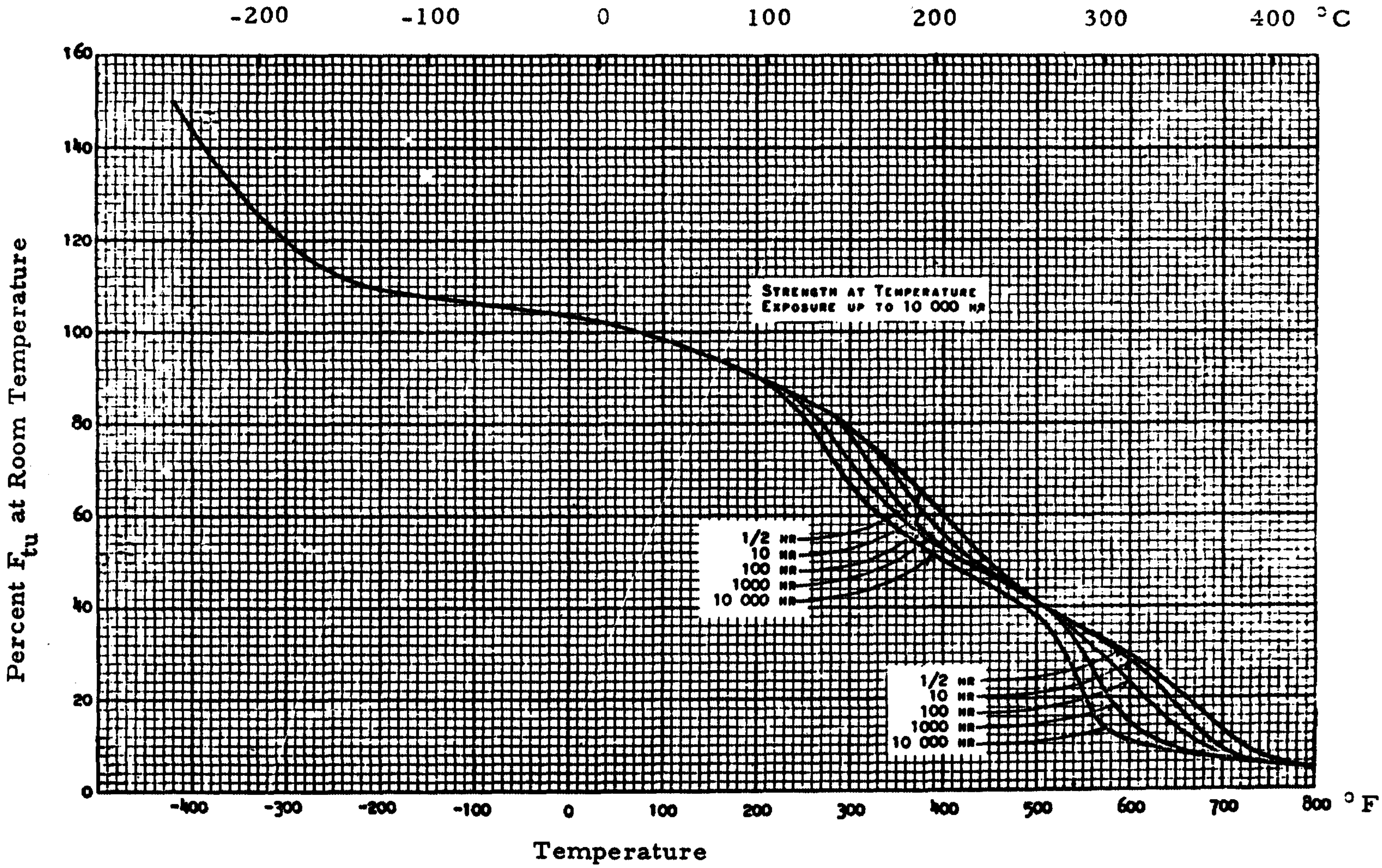


FIGURE 7.4135. — Effect of temperature on the ultimate tensile strength of 2219-T87 bare and clad sheet and plate. (Ref. 7.1)

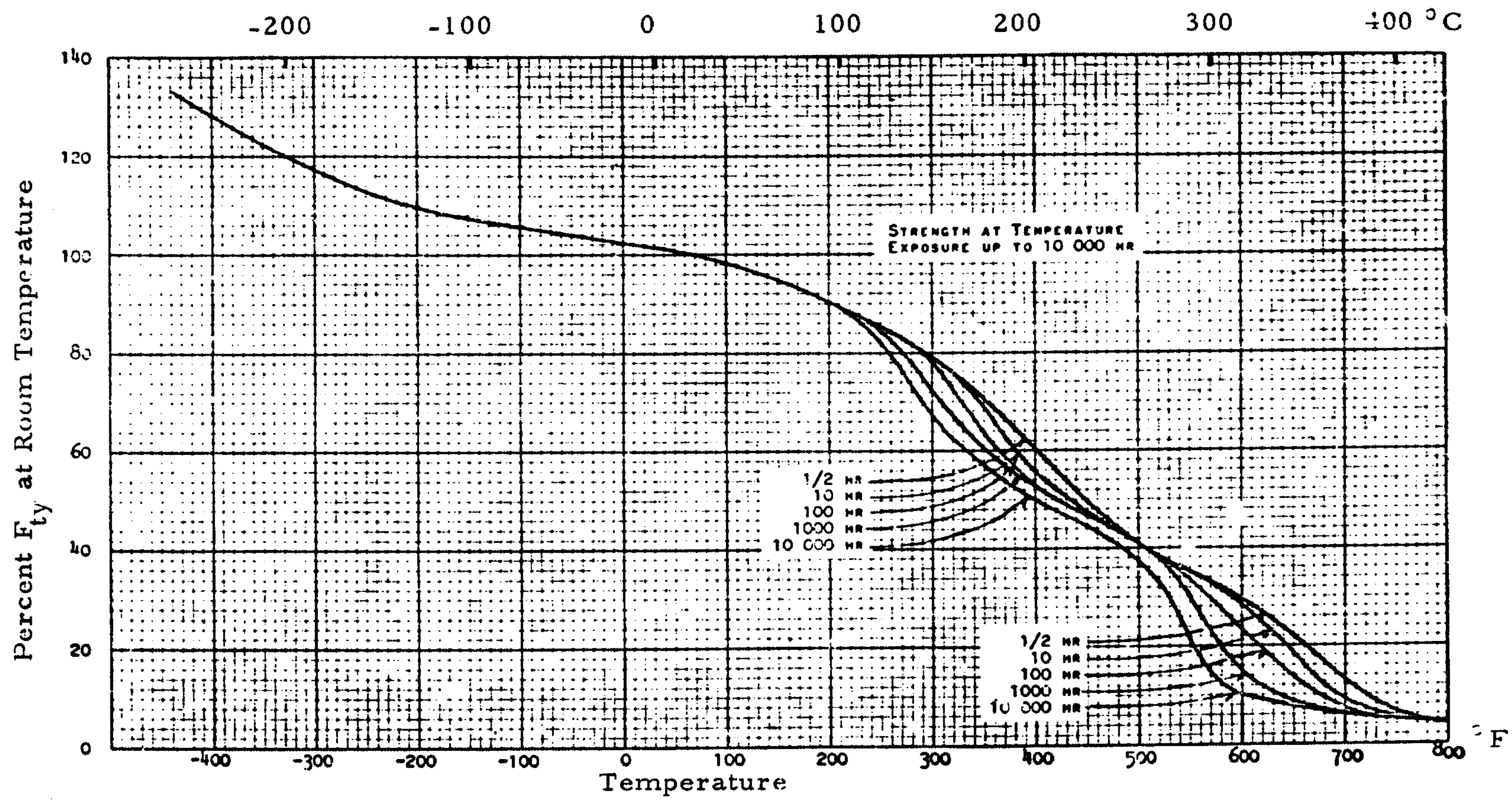


FIGURE 7.4136. — Effect of temperature on the tensile yield strength of 2219-T87 bare and clad sheet and plate. (Ref. 7.1)

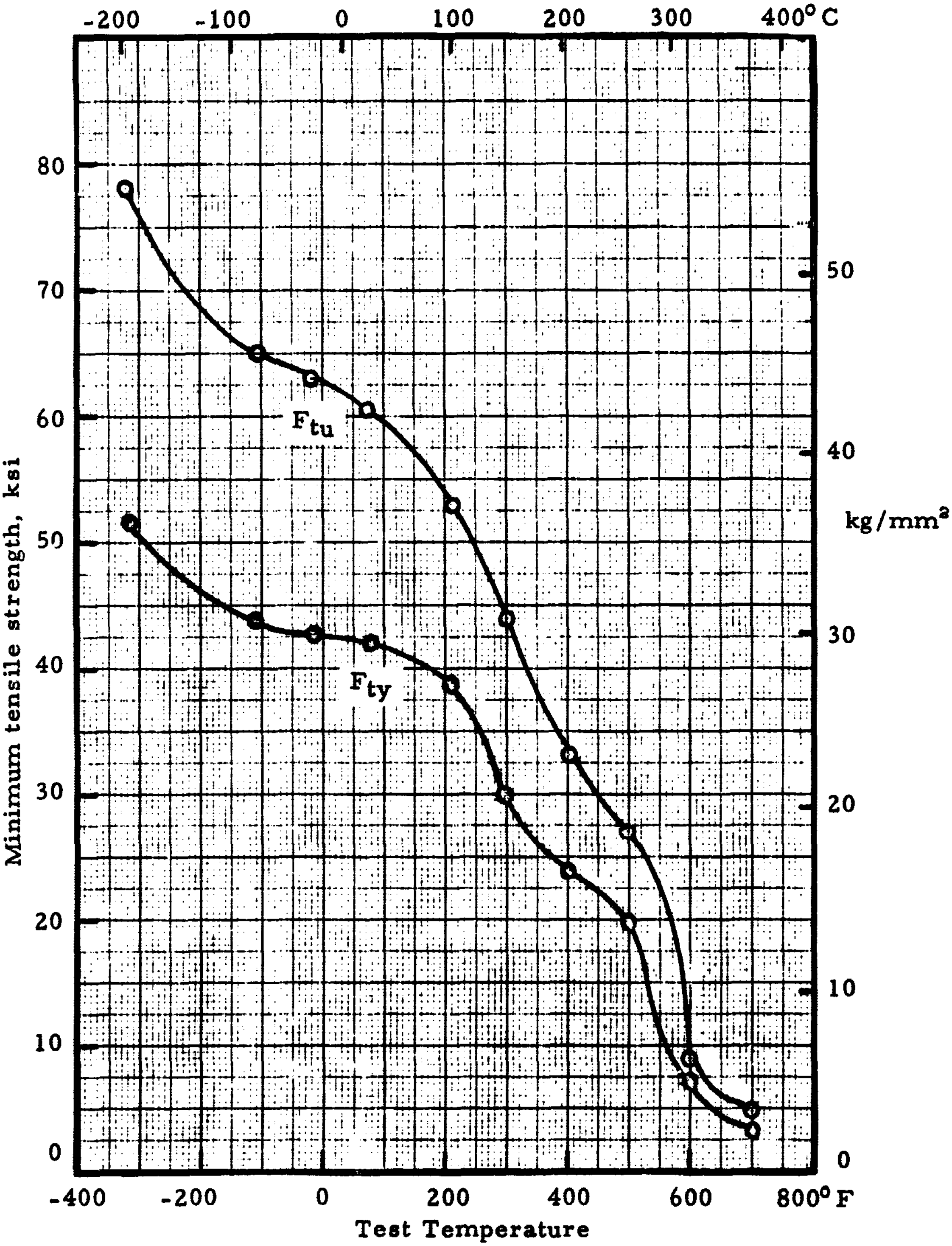


FIGURE 7.4137. — Minimum tensile properties for 2219-T62 after 10,000 hours exposure at temperature indicated under no load. Strain rate: 5 ksi (3.5 kg/mm²)/min to F_{ty}, 0.050 length/length/min to failure. (Ref. 7.6)

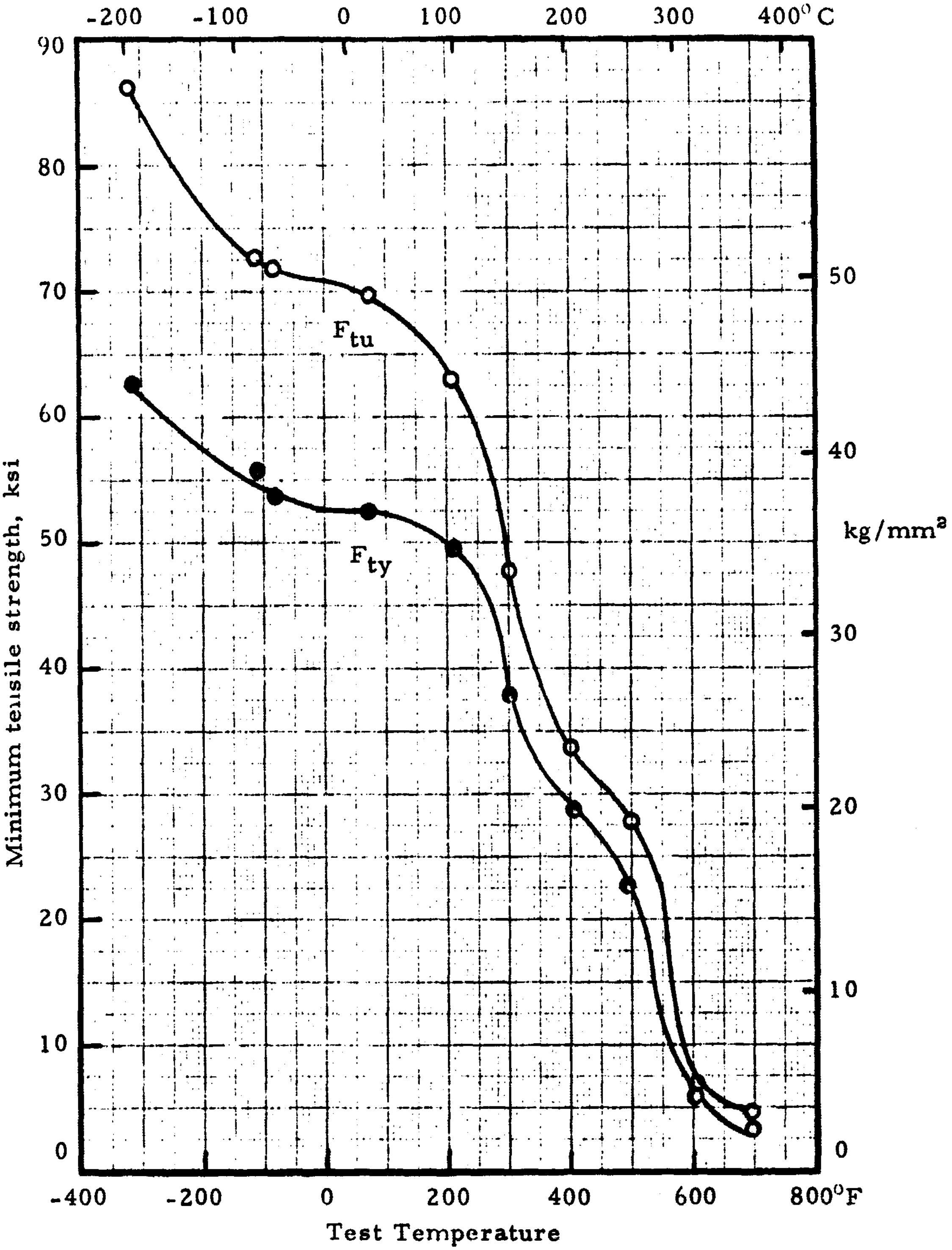


FIGURE 7.4138. – Minimum tensile properties for 2219-T81 after 10,000 hours exposure at temperature indicated under no load.

Strain rate: 5 ksi (3.5 kg/mm²)/min to F_{ty},
0.050 length/length/min to failure.

(Ref. 7.6)

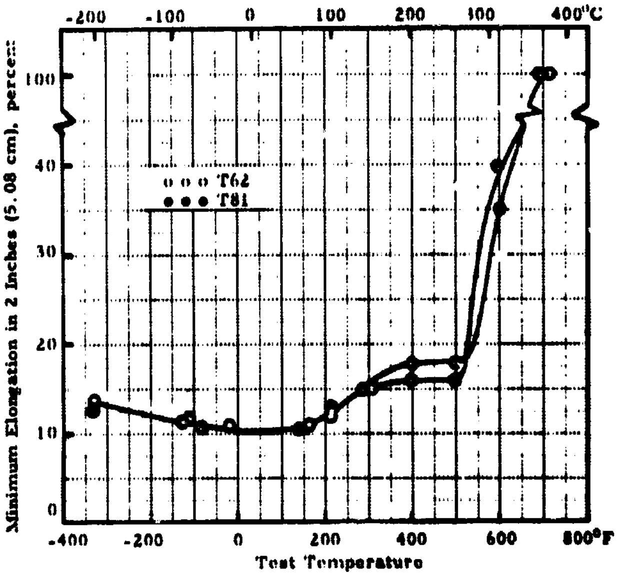


FIGURE 7.4139. — Minimum tensile elongation for 2219 alloy in T62 and T81 conditions after 10,000 hours exposure at temperature indicated under no load. (Ref. 7.6)

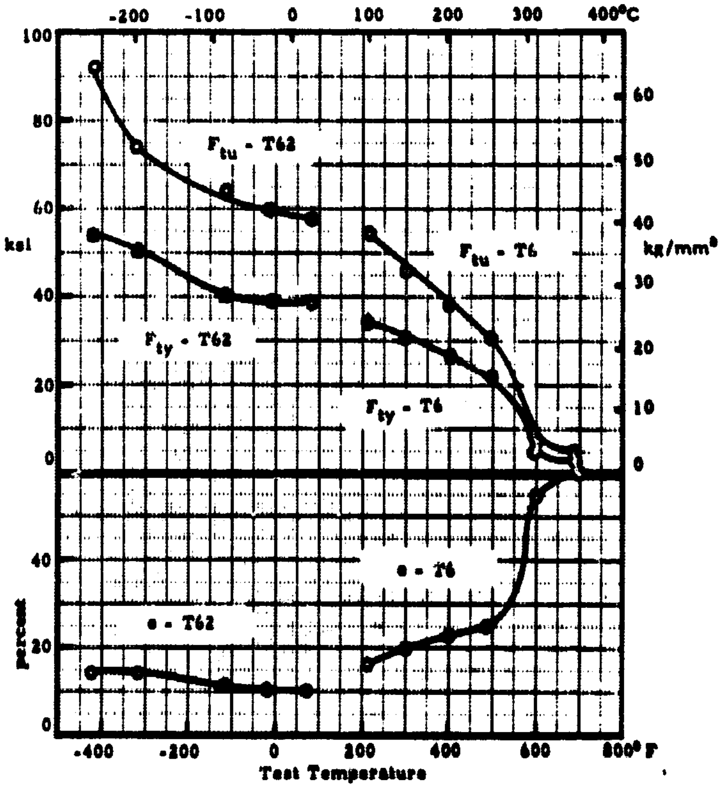


FIGURE 7.4141. — Typical tensile properties at low and elevated temperatures for 2219 alloy in T62 and T6 conditions. (Ref. 7.13)

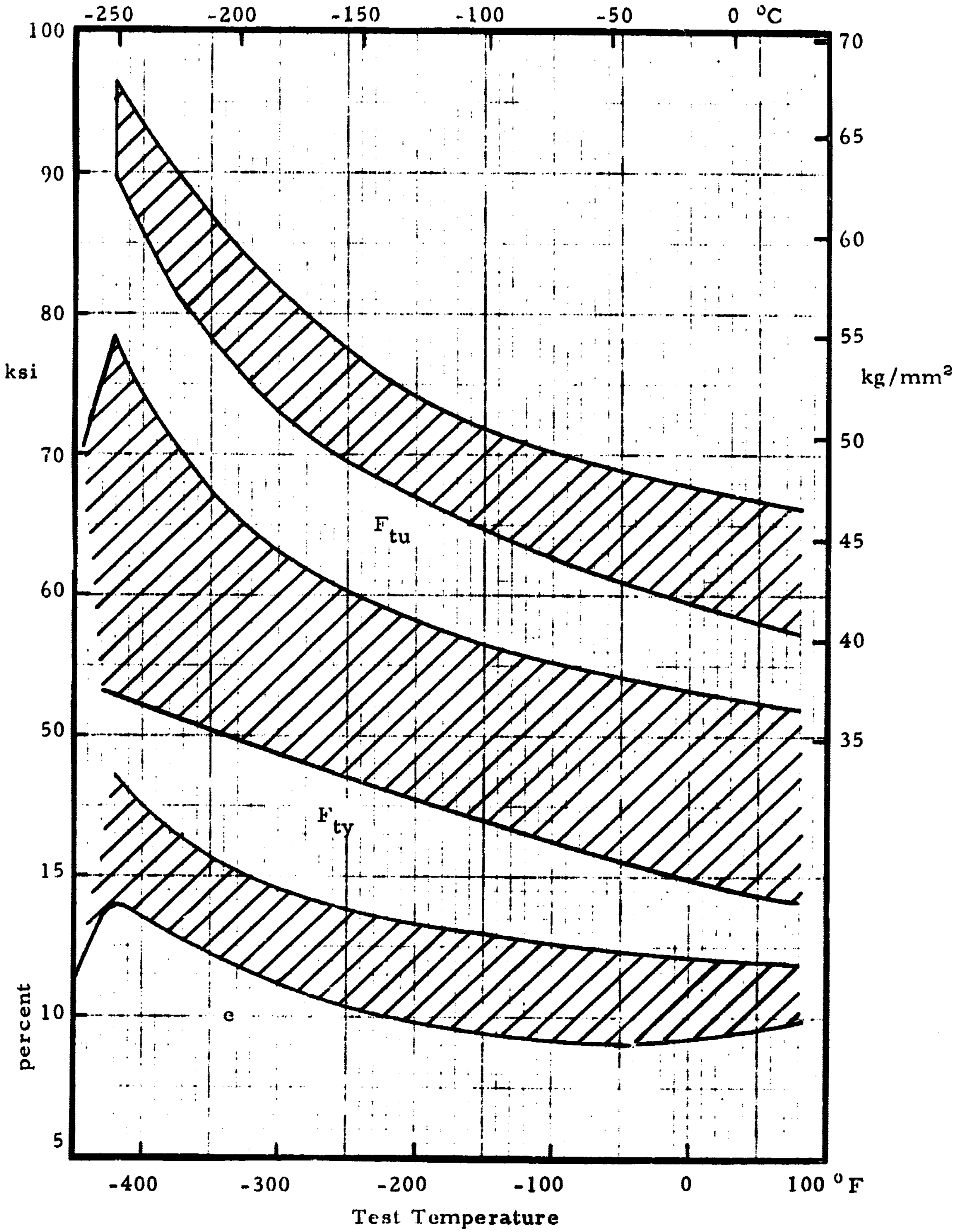


FIGURE 7 4142. — Tensile property bands for 2219-T62 sheet at low temperatures; thicknesses, 0.090 to 0.125 inch (2.29 to 3.18 mm). (Refs. 7.15, 7.17, 7.18, 7.19)

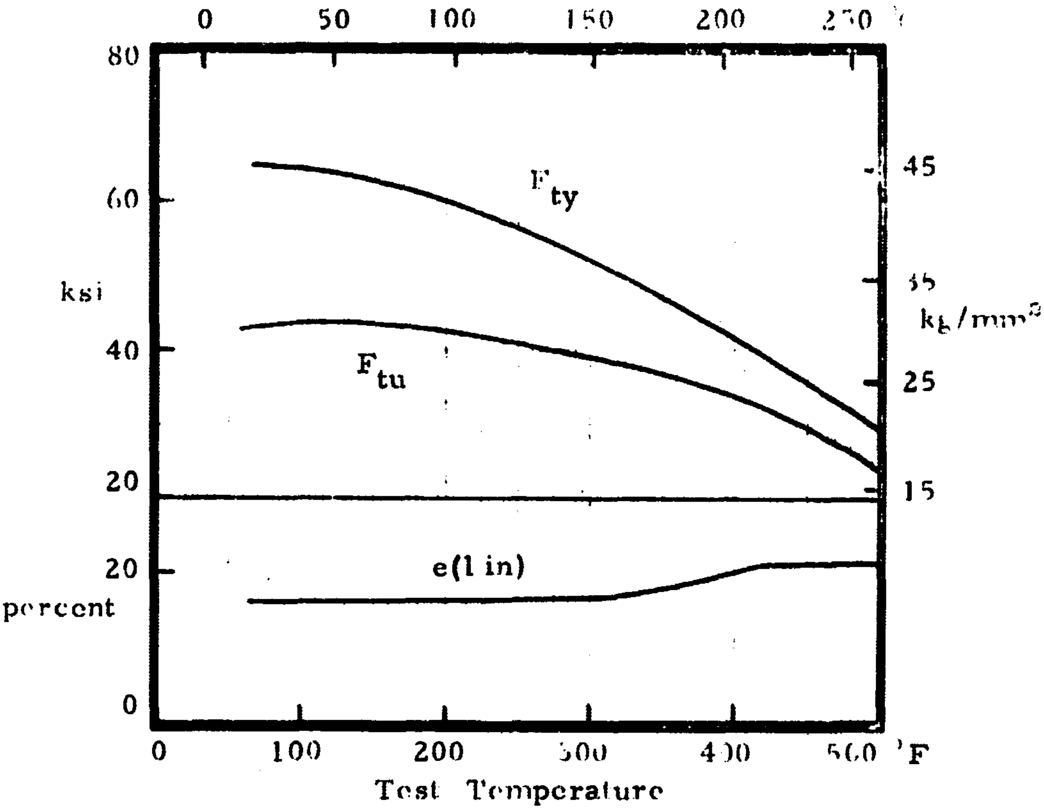


FIGURE 7 4143. — Tensile properties of 2219-T6 extrusions after 100-hour exposures at elevated temperatures.

(Ref. 7.8)

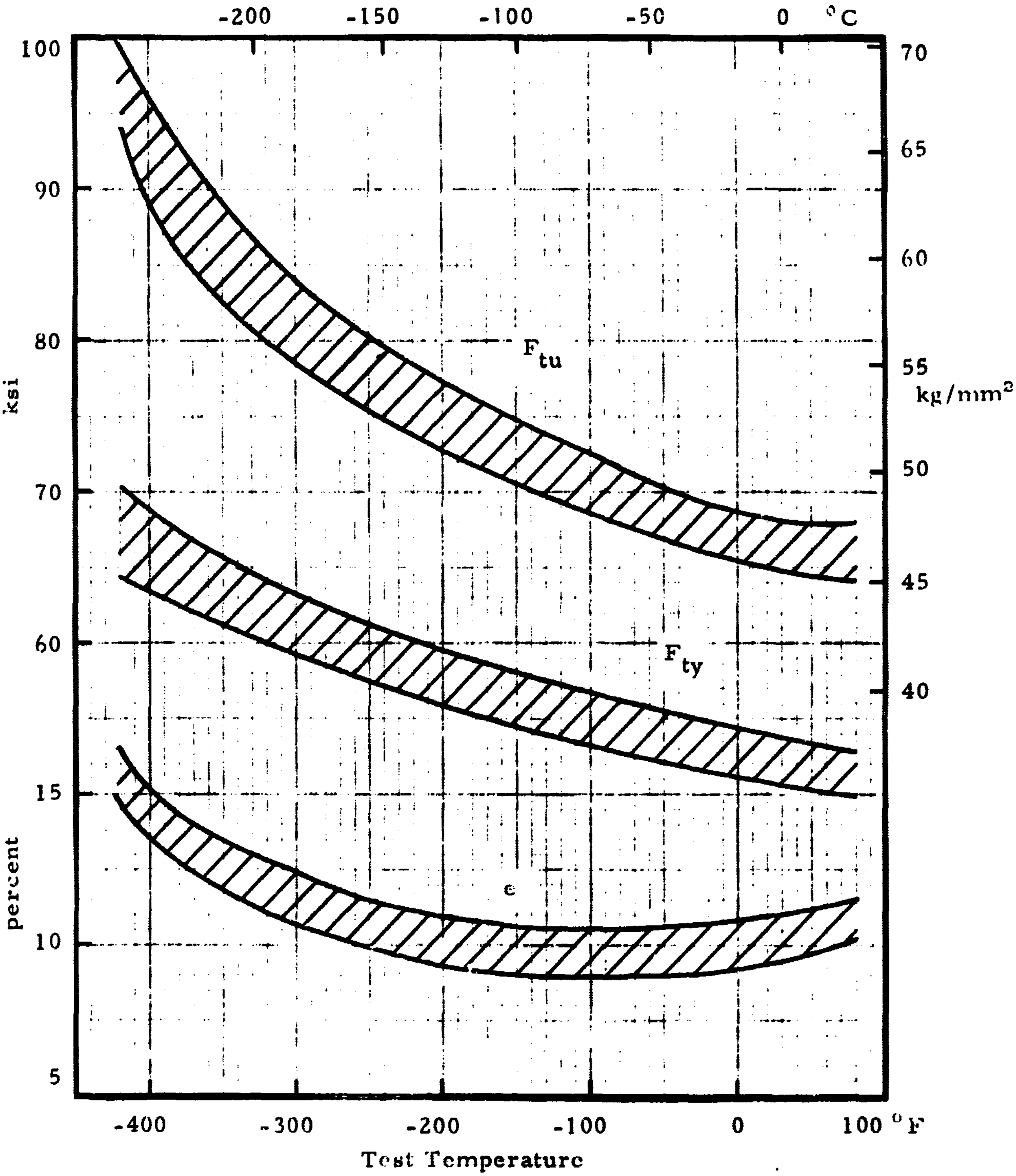


FIGURE 7.4144. —Tensile property bands for 2219-T81 sheet at low temperatures; sheet thicknesses, 0.063 to 0.100 inch (0.596 to 0.540 mm).

(Refs. 7.15, 7.16, 7.18, and 7.20)

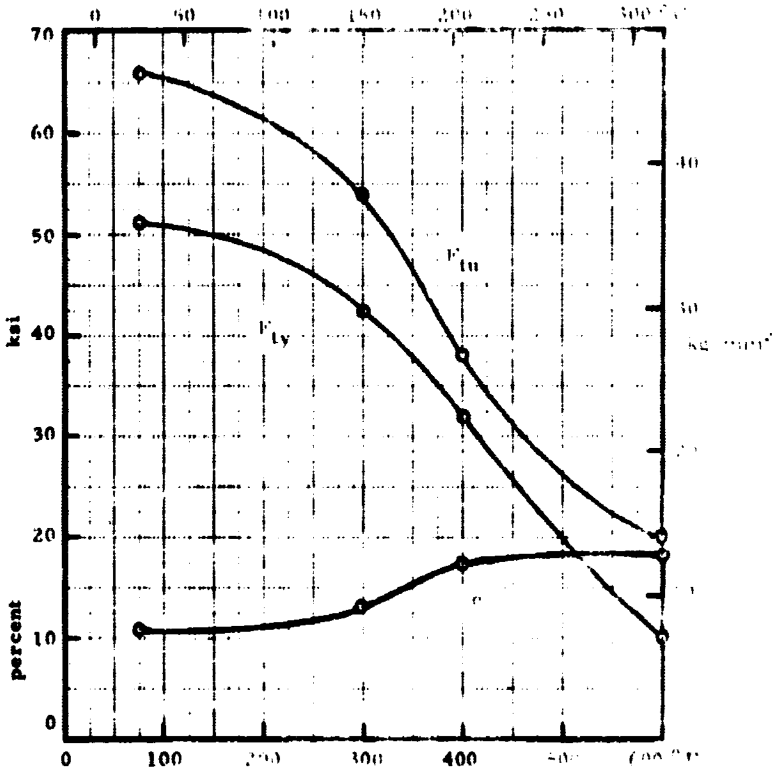


FIGURE 7.4145. – Typical tensile properties of 2219-T81 sheet at elevated temperatures; thickness, 0.100 inch (2.54 mm).
(Ref. 7.14)

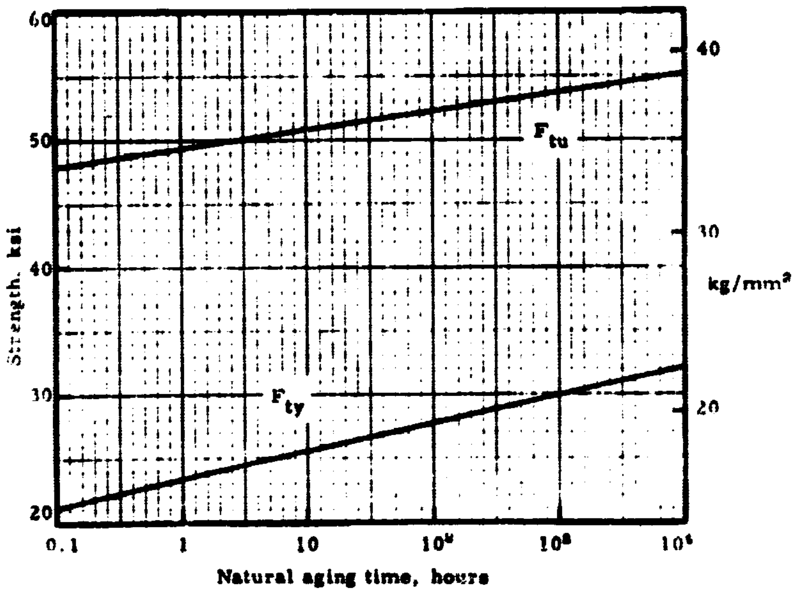


FIGURE 7.4146. – Natural aging response of solution treated 2219 alloy (solution treated at 1000°F (538°C) plus cold water quench).
(Ref. 7.23)

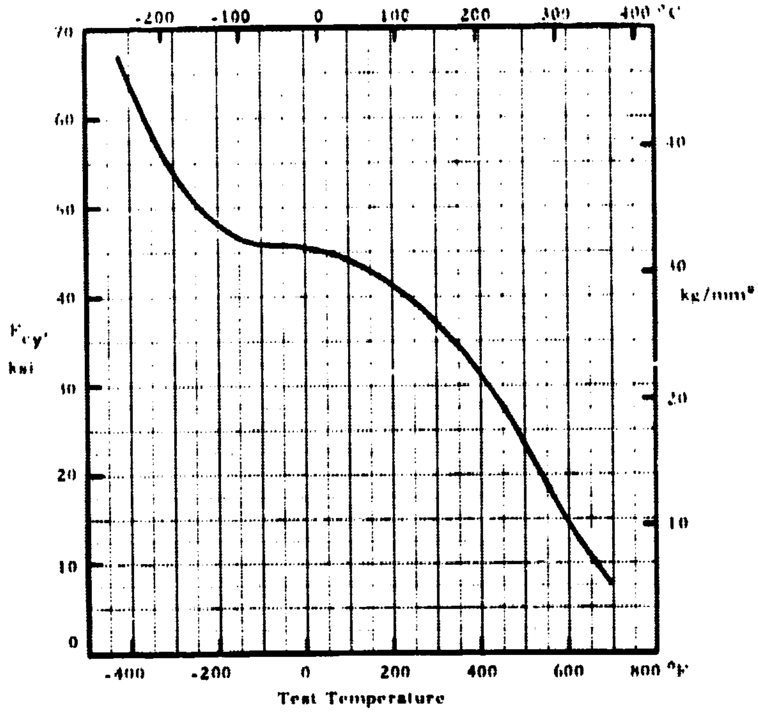


FIGURE 7.4213. – Typical compressive yield strength (F_{cy}) for 2219-T62 sheet and plate.

(Ref. 7.5)

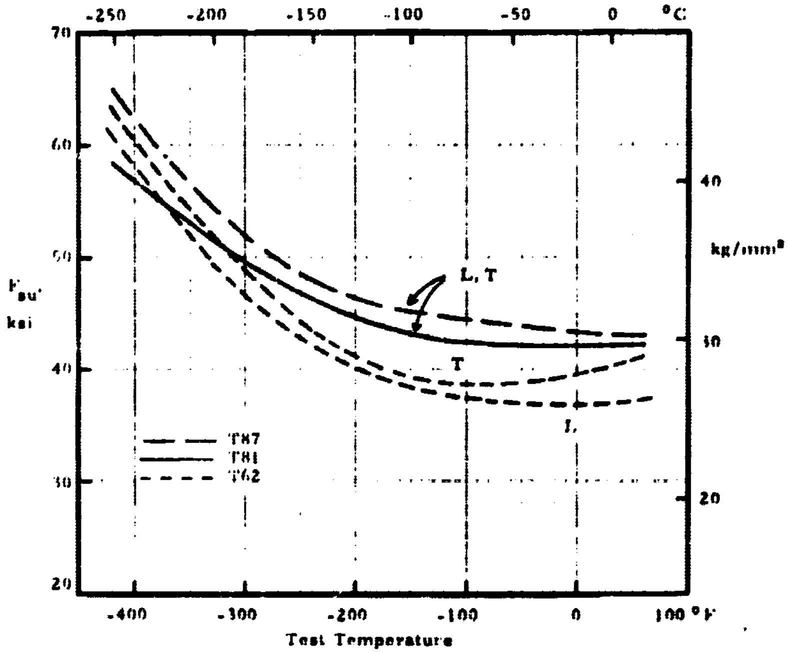


FIGURE 7.4413. – Effect of low temperature on shear strength (F_{su}) of 2219 sheet; thickness, 0.100 inch (2.54 mm).

(Ref. 7.15)

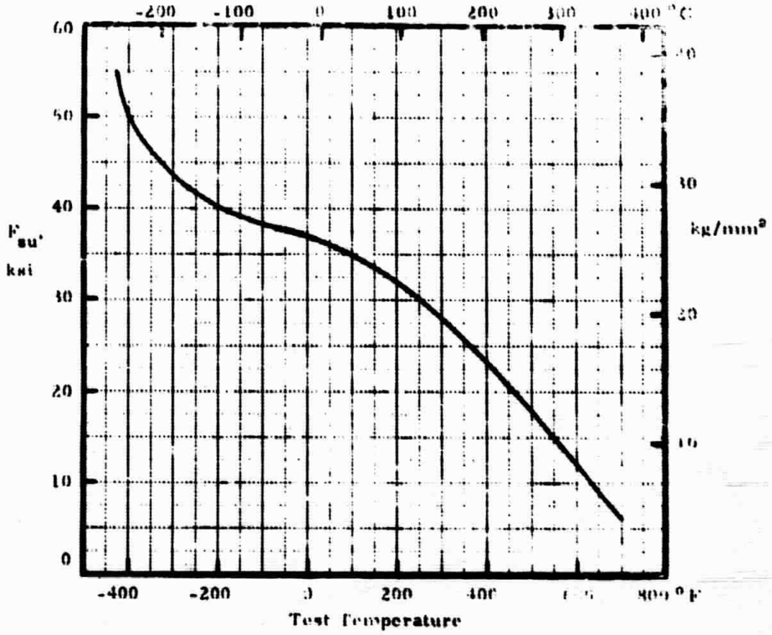


FIGURE 7.4414. – Typical curve for shear strength (F_{su}) of 2219 sheet and plate.

(Ref. 7.5)

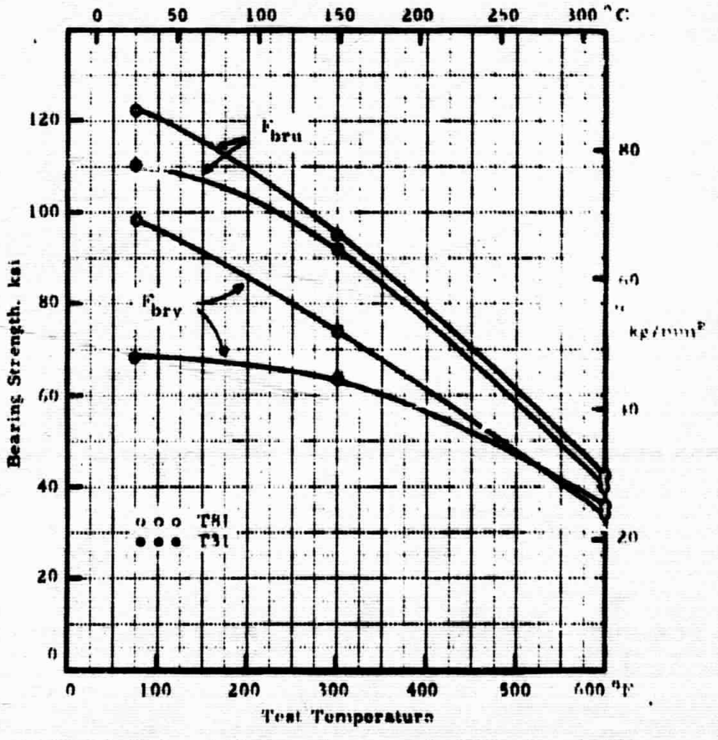


FIGURE 7.4513. – Typical bearing strength of 2219 sheet in T31 and T81 condition (e/D 2.0); thickness, 0.100 inch (2.54 mm).

(Ref. 7.14)

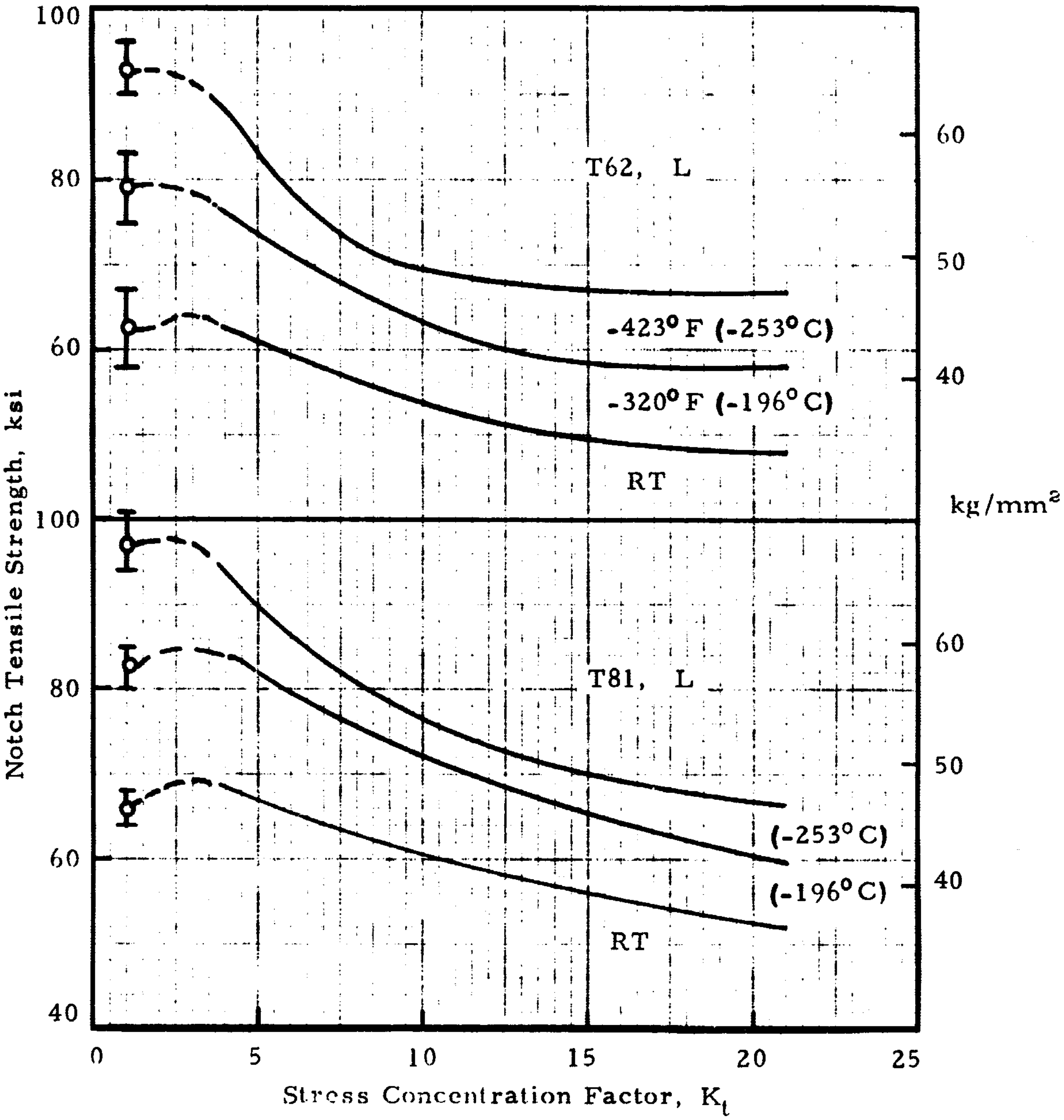


FIGURE 7.4611. – Effect of stress concentration factor on notch strength of 2219-T62 and -T81 sheet; sheet thicknesses, 0.063 to 0.125 inch (1.600 to 3.175 mm).

(Refs. 7.15, 7.16, 7.17, 7.18, and 7.20)

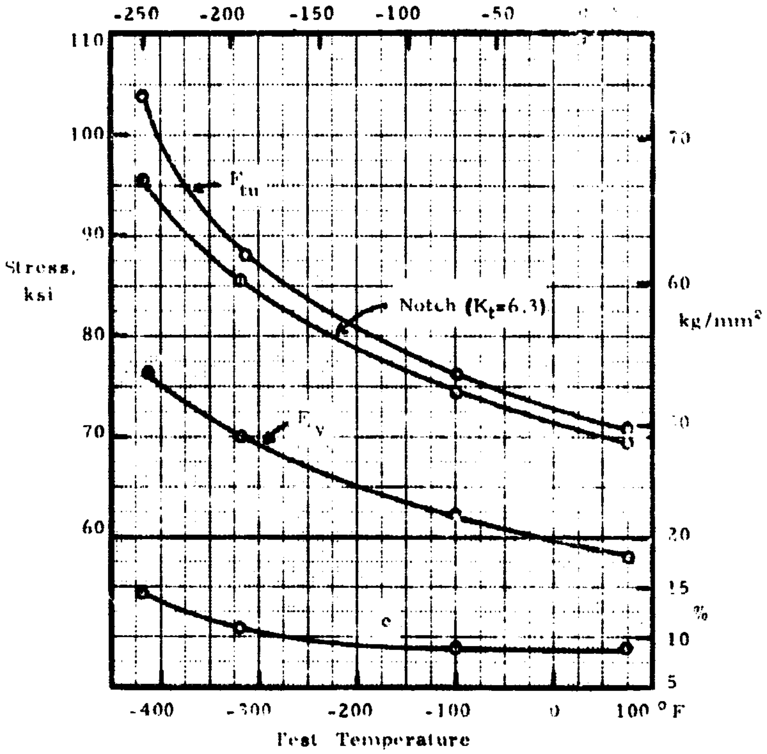


FIGURE 7.4612. — Effect of low test temperatures on tensile and notch properties of 2219-T87

(Ref. 7.21)

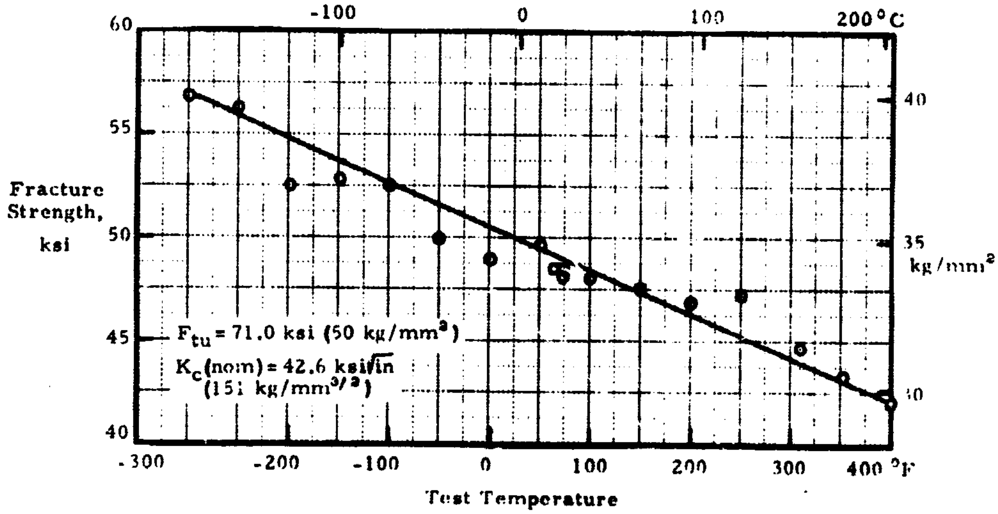


FIGURE 7.4613. — Effect of test temperature on net fracture strength of 2219-T87 sheet; thickness 0.060 inch (1.524 mm). ASTM specimen, 3-inch (7.62-cm) wide. K_c based on initial crack length.

(Ref. 7.11)

Chapter 7 - References

7.1 Military Handbook-5A, "Metallic Materials and Elements for Flight Vehicle Structures," Department of Defense, FSC 1500, February 8, 1966; through Change Notice 4, January 5, 1970.

7.2 NASA/Marshall Space Flight Center, "Effects of Low Temperatures on Structural Metals," NASA SP-5012, December 1964.

7.3 Aluminum Company of America, "Aluminum Sheet and Plate - General Information, Mechanical Properties, Physical Properties," Section AC2A Product Data, December 1961.

7.4 Aluminum Standards and Data, Second Edition, Aluminum Association, New York, December 1969, second printing, August 1970.

7.5 Aerojet-General Corp., "Materials Properties Data Book," Report No. 2275 to AEC-NASA, NERVA Program, revised July 1964.

7.6 Aluminum Company of America, "Alcoa Aluminum Handbook," 1962.

7.7 W.P. Achback, R.J. Favor and W.S. Hyler, "Materials-Property-Design Criteria for Metals," WADC TR-55-150, Part VI, October 1955.

7.8 P.L. Hendricks, "Metallurgical Investigation of Aluminum Alloy X2219-T6," WADC TR-58-57, June 1958.

7.9 J.E. Campbell, "Plain-Strain Fracture-Toughness Data for Selected Metals and Alloys," DMIC Report S-28, June 1969.

7.10 Alloy Digest, "Aluminum 2219," (Filing Code: Al-96), Aluminum Alloy, Engineering Alloys Digest, Inc., October 1960.

7.11 J. Viglione and W.F. Worden, "Fracture Toughness Properties of Some Alloy Steels and Aluminum and Titanium Alloys," Report No. NAEC-AML-2111, Naval Air Engineering Center, March 1965.

7.12 C.N. Freede, et al., "Comparison of Fracture Toughness Test Procedures for Aluminum Alloys," NRL Report 6853, Naval Research Laboratory, Washington, D.C., February 17, 1969.

7.13 Reynolds Metals Company, "The Aluminum Data Book," 1965.

7.14 Martin-Denver, "Summary Information Regarding Aluminum Alloy 2219," Evaluation Report No. 1, MI-61-44, November 1961.

7.15 F.R. Schwartzberg and S.H. Osgood, Cryogenic Materials Data Handbook, Air Force Report No. ML-TDR-64-280 and supplement.

7.16 J.L. Christian and A. Hurlich, "Physical and Mechanical Properties of Pressure Vessel Materials for Application in Cryogenic Environment," ASD-TDR-62-258, Part II, April 1963.

7.17 M.P. Hanson, et al., "Sharp-Notch Behavior of Some High Strength Aluminum Alloys and Welded Joints at 75, −320, and −423 F," ASTM-STP 287, 1960.

7.18 F.R. Schwartzberg and R.D. Keys, "Mechanical Properties of 2000 Series Aluminum Alloys at Cryogenic Temperatures," Martin-Denver Co. Report R-61-32, October 1961.

7.19 C.V. Lovoy, "Low Temperature Mechanical Properties X 2020-T6 and 2219-T6 Aluminum Sheet Alloys," IN-P&VE-M-62-3, Marshall Space Flight Center, May 1962.

7.20 J.L. Christian, "Mechanical Properties of Aluminum Alloys at Cryogenic Temperatures," MRG-190, Convair/Astronautics, December 1962.

7.21 J.L. Christian, J.E. Chafey, A. Hurlich, J.F. Watson, and W.E. Witzell, "Structural Alloys for Cryogenic Service," Metals Progress, 83, (3), March 1963.

7.22 F.R. Schwartzberg et al., "Determination of Low Temperature Fatigue Properties of Aluminum and Titanium Alloys," Annual Summary Report under NASA Contract NAS8-2631, Martin-Denver, July 1963.

7.23 L.W. Mayer, "Alcoa Aluminum Alloy 2219," Alcoa Green Letter, October 1960, latest revision November 1963.

7.24 M. Kangilaski, "Radiation Effects Design Handbook: Sec. 7, Structural Alloys," NASA CR-1873, October 1971.

7.25 J.J. Lombardo, et al., "Cryogenic Radiation Effects on NERVA Structural Materials," Paper presented at 69th Ann. Mtg., ASTM, Atlantic City, New Jersey, June 27-July 1, 1966.

PRECEDING PAGE BLANK NOT FILMED

Chapter 8

DYNAMIC AND TIME DEPENDENT PROPERTIES

8.1 General. Aluminum alloy 2219 exhibits good fatigue and creep-rupture properties up to temperatures of about 600° F (315° C).

8.2 Specified Properties

8.3 Impact

8.31 Impact strength of T87 plate at low temperatures, figure 8.31.

8.4 Creep

8.41 Creep-rupture curves for extrusions in T6 condition at 400° and 600° F (204° and 315° C), figure 8.41.

8.42 Creep and cree-rupture curves for alloy in T6 condition from 300° to 700° F (149° to 371° C), figure 8.42.

8.43 Creep data for clad sheet in T6 condition at 400° F (204° C), figure 8.43.

8.44 Creep data for clad sheet in T6 condition at 500° F (260° C), figure 8.44.

8.45 Creep data for clad sheet in T6 condition at 600° F (315° C), figure 8.45.

8.5 Stability

8.51 Effect of exposure temperature on room temperature transverse tensile properties of plate, figure 8.51.

8.52 Effect of exposure temperature on room temperature tensile properties of 2219-T6 forged rod, figure 8.52.

8.53 Effect of exposure and test temperature on tensile properties of forged rod, figure 8.53.

8.54 Effect of exposure and test temperature on transverse tensile properties of plate, figure 8.54.

8.6 Fatigue

8.61 Fatigue limit in rotating beam tests at 5×10^8 cycles, table 8.61.

8.62 Fatigue strength of forged rod at elevated temperatures, table 8.62.

8.63 Fatigue strength of extrusions at elevated temperatures, table 8.63.

8.64 S-N curves for forgings at 400° and 600° F (204° and 315° C), figure 8.64.

8.65 Fatigue strength of sheet in T87 condition at room temperature and low temperature, figure 8.65.

TABLE 8.61. – Fatigue Limit in Rotating Beam Tests

Source	Ref. 8.4	
Alloy	2219	
Test	Rotating Beam Fatigue (5×10^8 cycles)	
Condition	T6	T86
Fatigue limit, ksi (kg/mm²)	15 (10.5)	15 (10.5)

TABLE 8.62. – Fatigue Strength of Forged Rod at Elevated Temperatures

Source		Ref. 8.2				
Alloy		2219-T6				
Test		Rotating Beam Fatigue (R = –1)				
Temperature		Fatigue Strength (at cycles shown), ksi (kg/mm²)				
°F	°C	10^5	10^6	10^7	10^8	5×10^8
RT		30 (21.1)	25 (17.6)	21 (14.8)	18.5 (13.0)	17.5 (12.3)
300	149	27 (19.0)	22 (15.5)	17.5 (12.3)	14.5 (9.4)	13.5 (8.7)
400	204	25 (17.6)	22 (15.5)	15 (10.5)	12 (8.4)	11 (7.7)
500	260	22 (15.5)	17 (12.0)	12 (8.4)	9 (6.3)	8 (5.6)
600	315	18 (12.7)	13 (9.1)	9 (6.3)	7 (4.9)	6.5 (4.5)

TABLE 8.63. – Fatigue Strength of Extrusions at Elevated Temperatures

Source		Ref. 8.1				
Alloy		2219-T6				
Test		Direct Stress Fatigue Tests (R = 0)				
Temperature		Thickness		Fatigue Strength (at cycles), ksi (kg/mm²)		
°F	°C	inch	cm	10^5	10^6	10^7
400	204	1.5	3.81	36 (25.3)	28 (19.7)	22 (15.5)
600	315	1.5	3.81	25 (17.6)	20 (14.1)	14 (9.8)
600	315	0.125	0.32	25 (17.6)	20 (14.0)	16 (11.2)

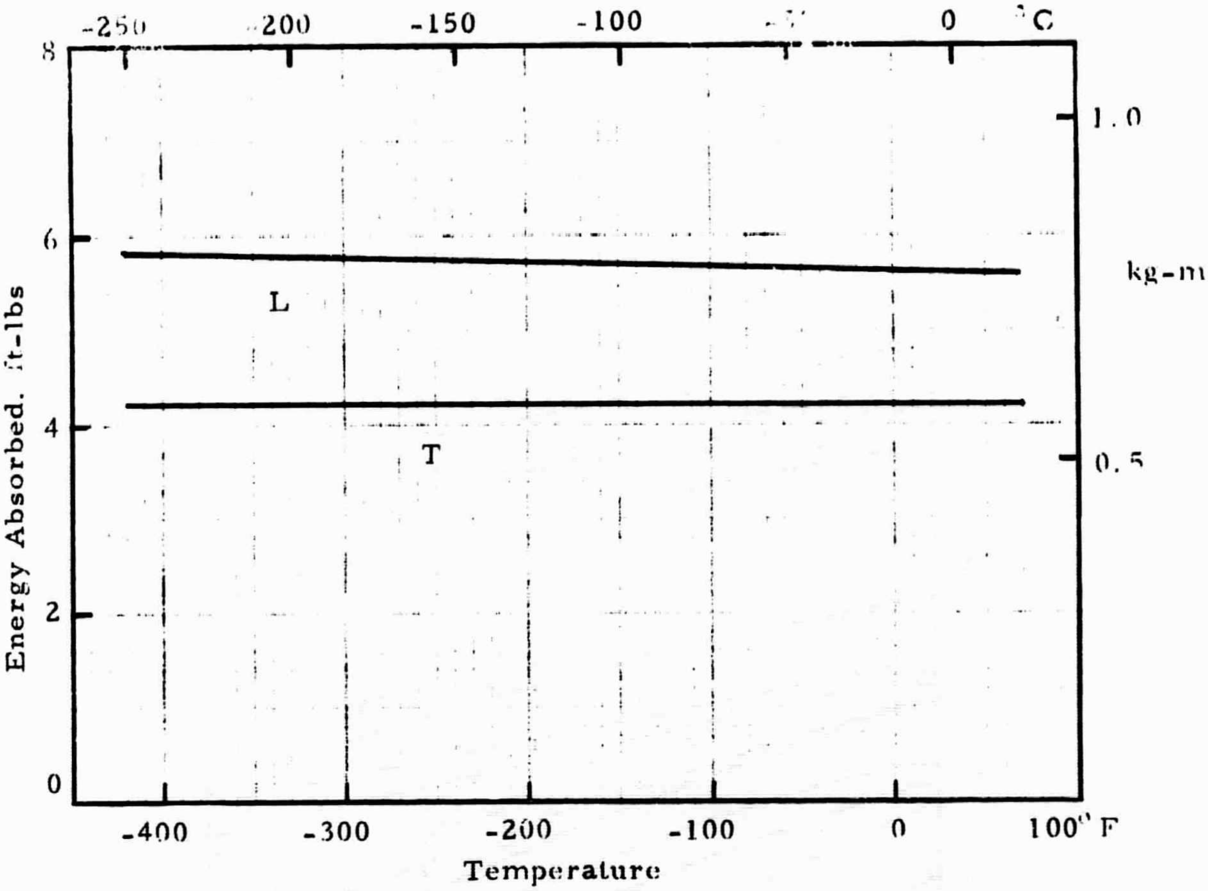


FIGURE 8.31. — Impact strength of T87-2219 plate at low temperatures; thickness, 0.500 inch (1.27 cm). (Ref. 8.6)

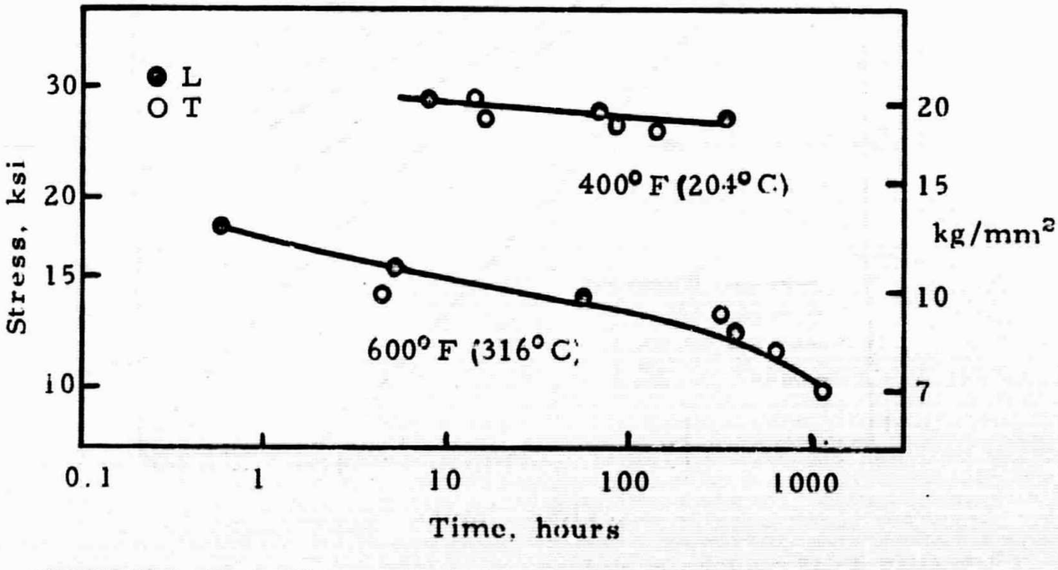


FIGURE 8.41. — Creep rupture curves (L. T) for 2219-T6 extrusion at elevated temperatures.

(Ref. 8.1)

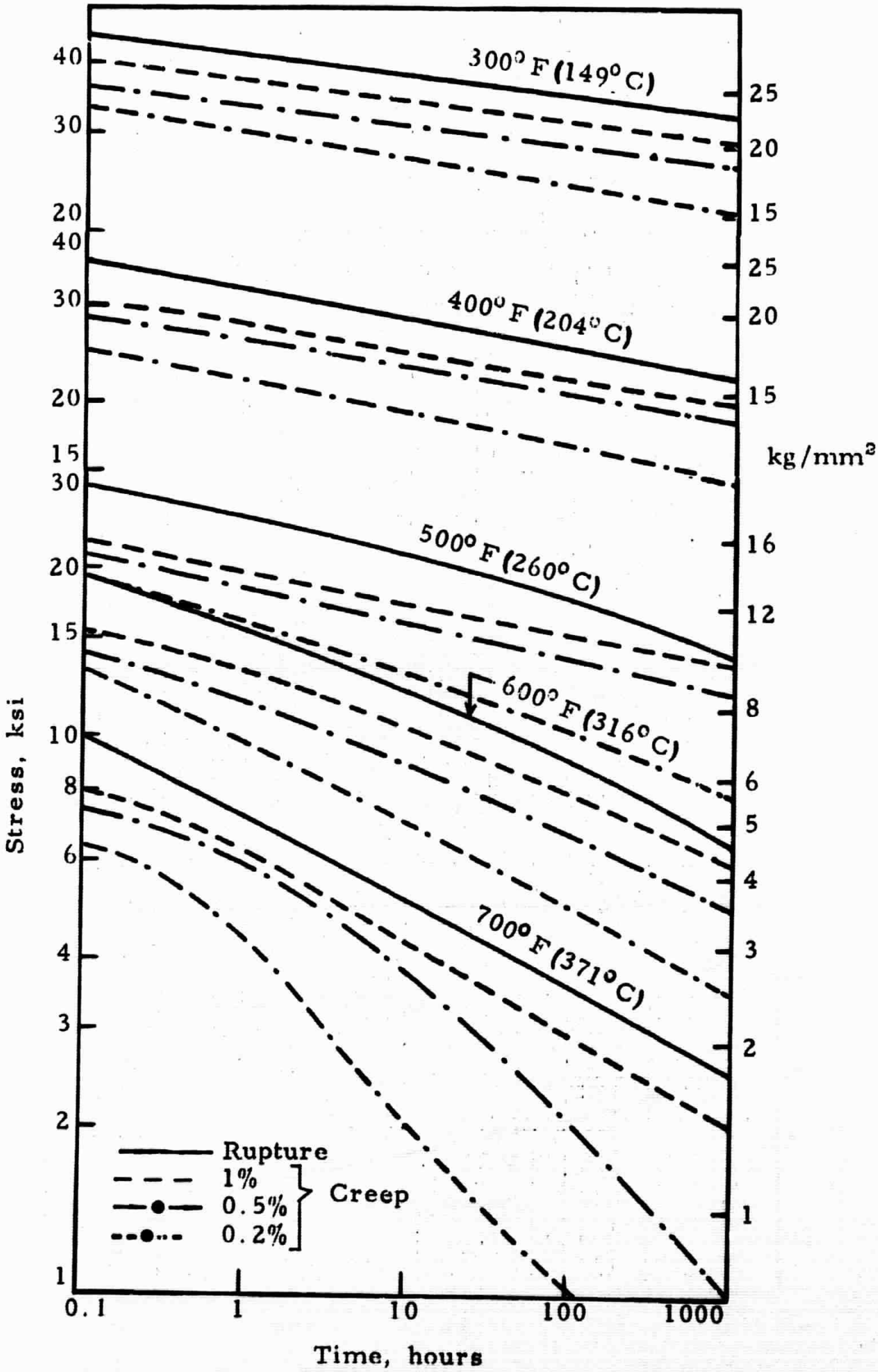


FIGURE 8.42. – Creep and creep rupture curves for 2219-T6 forged bar at elevated temperatures.

(Ref. 8.2)

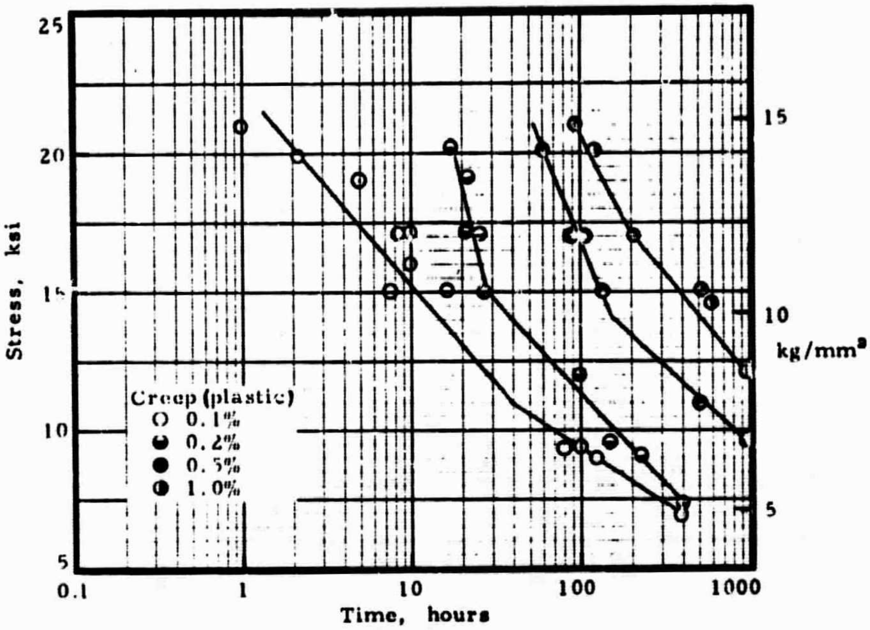


FIGURE 8.43. – Creep data for clad 2219-T6 sheet at 400° F (204° C); thickness, 0.064 in (1.626 mm).
(Ref. 8.7)

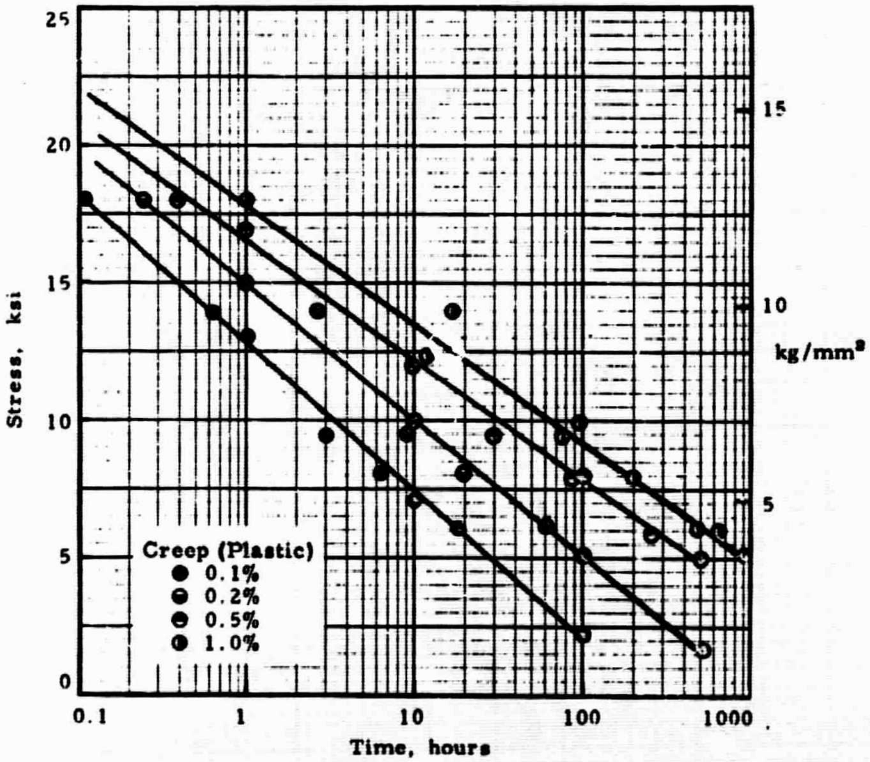


FIGURE 8.44. – Creep data for clad 2219-T6 sheet at 500° F (260° C); thickness, 0.064 inch (1.626 mm).
(Ref. 8.7)

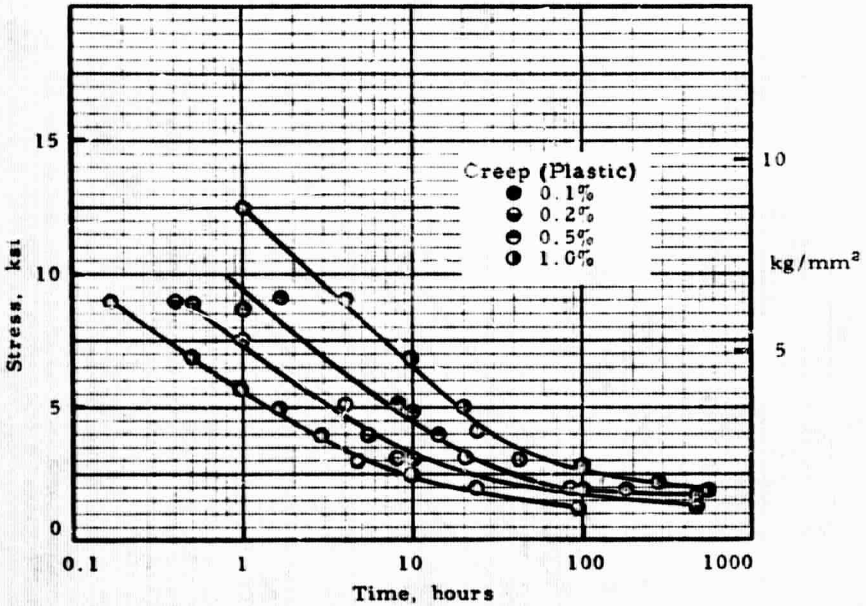


FIGURE 8.45. – Creep data for clad 2219-T6 sheet at 600° F (316° C); thickness, 0.064 inch (1.626 mm).

(Ref. 8.7)

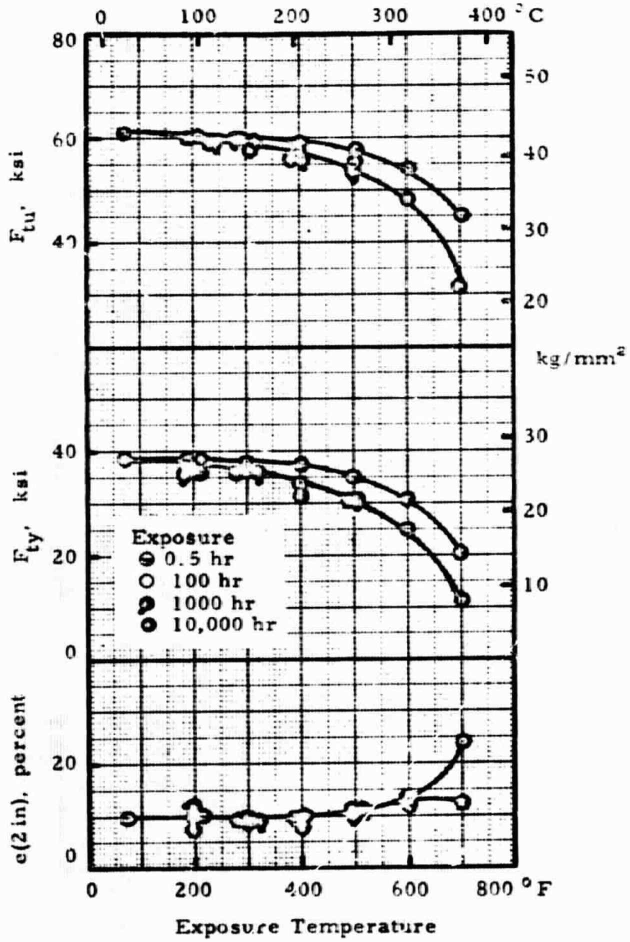


FIGURE 8.51. – Effect of exposure temperature on room temperature transverse tensile properties of 2219-T6 plate; thickness, 2 inches (5.08 cm).

(Ref. 8.3)

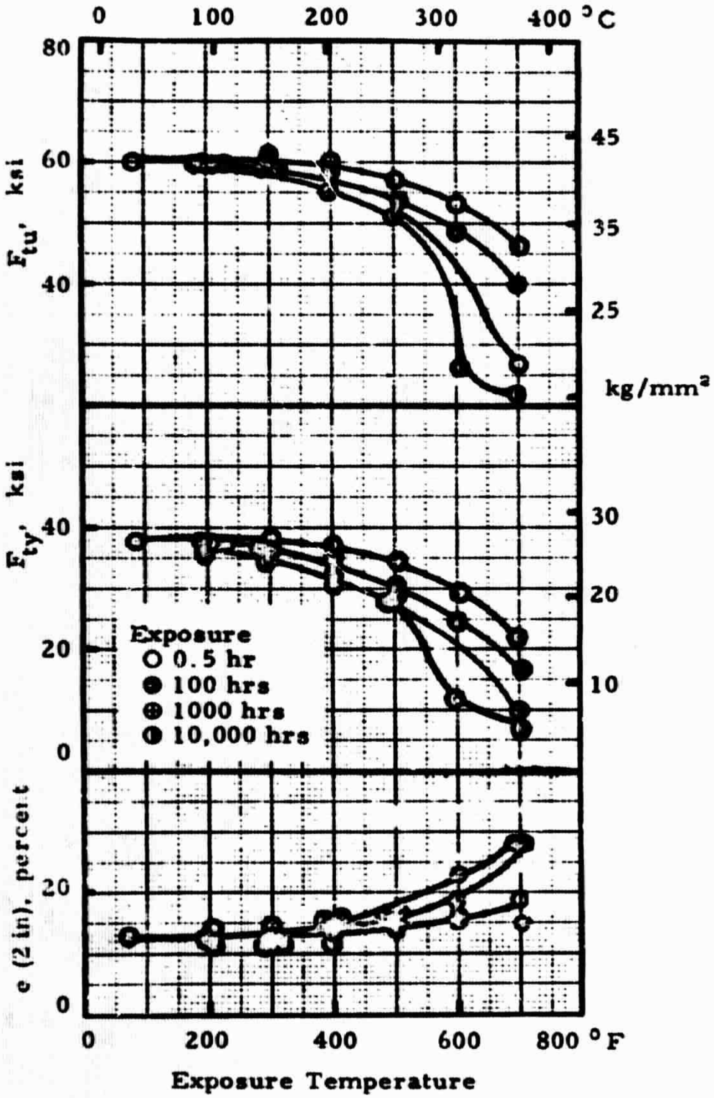


FIGURE 8.52. — Effect of exposure temperature on room temperature tensile properties of 2219-T6 forged rod.

(Ref. 8.3)

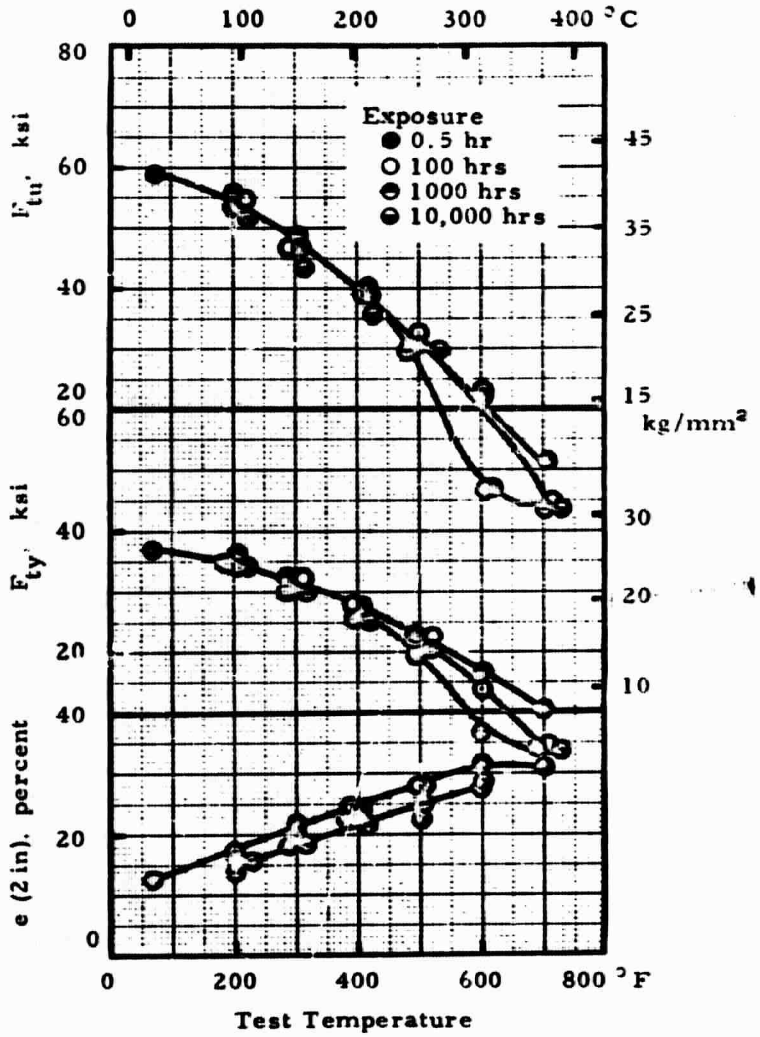


FIGURE 8.53. — Effect of exposure and test temperature on tensile properties of 2219-T6 forged rod.

(Ref. 8.3)

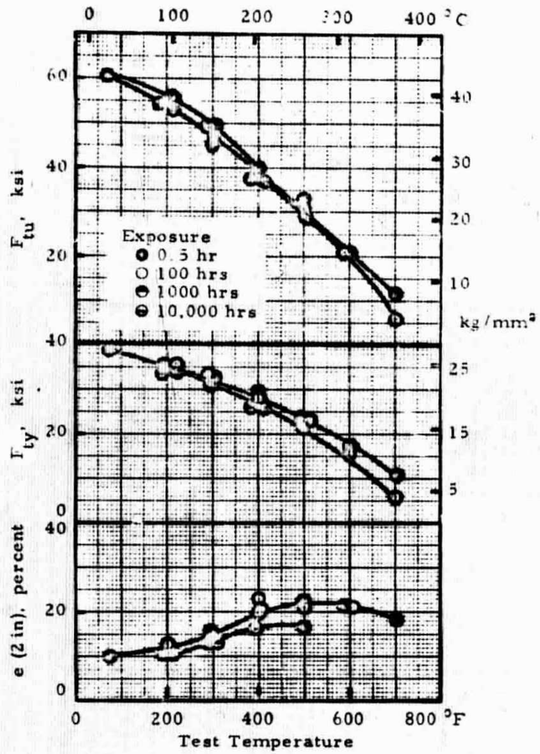


FIGURE 8.54. – Effect of exposure and test temperature on transverse tensile properties of 2219-T6 plate; thickness 2 inches (5.08 cm).
(Ref. 8.3)

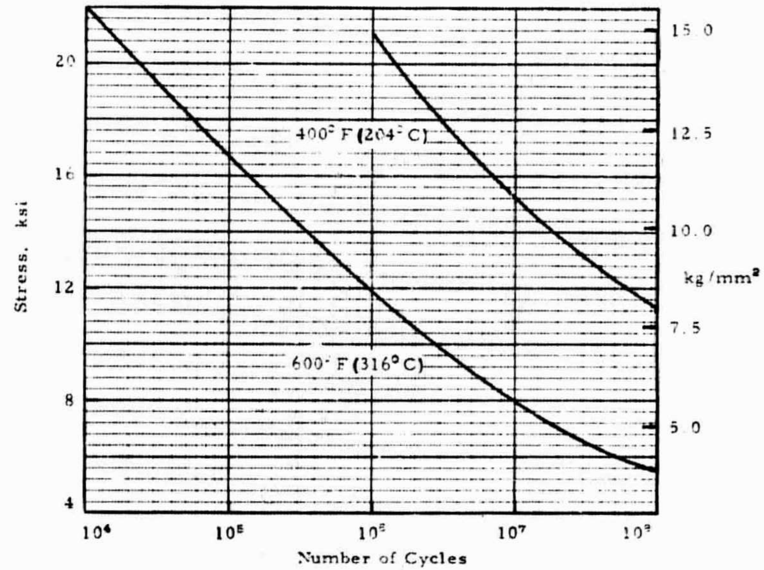


FIGURE 8.64. – S-N curves for 2219-T6 forgings at elevated temperatures.
(Ref. 8.5)

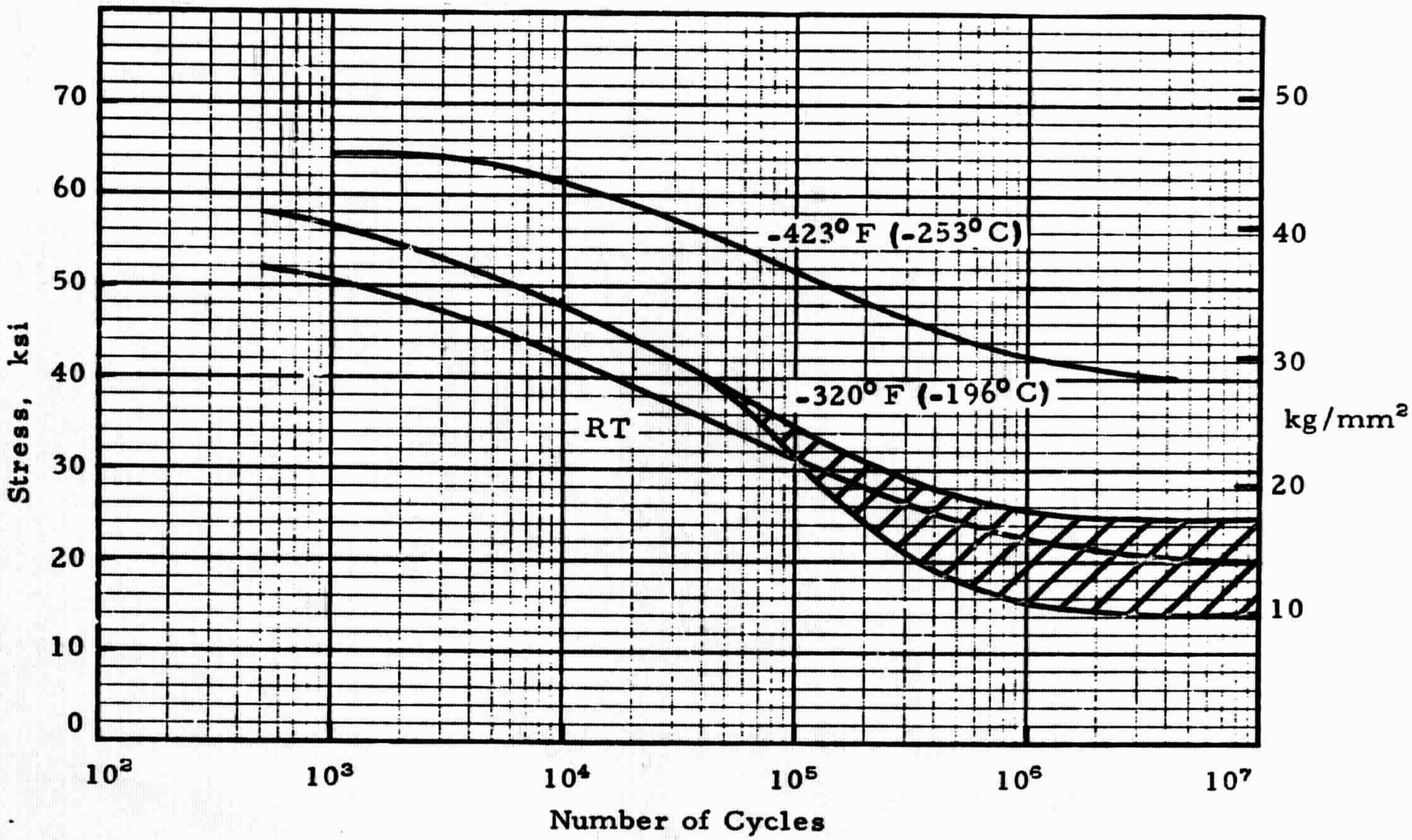


FIGURE 8.65. — Fatigue strength of 2219-T87 sheet at room temperature and low temperatures; thickness, 0.100 inch (2.54 mm).
F_{tu} = 66.7 ksi (46.9 kg/mm^2).
Axial load fatigue, R = −1. (Ref. 8.8)

Chapter 8 - References

8.1 P. L. Hendricks, "Metallurgical Investigation of Aluminum Alloy X2219-T6," WADC-TN-58-57, June 1958.

8.2 Aluminum Company of America, Data Sheets, May 24 and July 25, 1957.

8.3 "The Elevated Temperature Properties of Aluminum and Magnesium Alloys," ASTM STP-291, 1960.

8.4 G. W. Stickley and J. O. Lyst, "Aluminum in Fatigue," Product Engineering, November 1954.

8.5 E. H. Dix, Jr., "Aluminum Alloys for Elevated Temperature Applications," ASME Paper No. 56-AV-8, 1956.

8.6 F. Schwartzenberg, et al., Cryogenic Materials Data Handbook, ML-TDR-64-230, August 1964, and supplements.

8.7 R. G. Mahorter, Jr. and W. F. Emmons, "A Study of Creep Resistance, Formability and Heat Treatment of Clad X2219-T6 Aluminum Alloy," Report No. NAMC-AML-AE 1100, Naval Air Material Center, August 1959.

Chapter 9

PHYSICAL PROPERTIES

9.1 Density (ρ)

In figure 9.1 the density (ρ) of Al-2219 is given as a function of temperature. Values were calculated from room temperature data (ρ = 0.102 lb/in^3), and the average thermal expansion coefficient, α_{av}, using the relation:

$$\rho(t) = \rho(68^\circ F)\,[1 - 3\alpha_{av}(t - 68^\circ F)] \quad \text{(ref. 9.1, p. 36, 39).}$$

9.11 Specific gravity, 2.84 g/cm^3 (ref. 9.3).

9.2 Thermal Properties

9.21 Thermal conductivity (K), table 9.21.

9.211 Critical appraisal of data
The thermal conductivity of 2219 aluminum is, at room temperature, much lower than that of electrical conductor grade. Therefore, the heat transfer depends markedly on temper and composition. The allowed composition range for secondary elements is rather large (ref. 9.1). This should produce a corresponding variation in the thermal conductivity. Data of K can be regarded only as nominal.

9.22 Thermal expansion (α), figure 9.22.

9.221 Thermal expansion of plate at low temperatures, figure 9.221.

9.23 Specific heat (c_p) at 212° F, 0.23 Btu/lb/° F (ref. 9.5), or 0.23 gram calories/gram/° C.

9.24 Thermal diffusivity
No data found.

9.25 Melting range, 1010° to 1190° F (543° to 643° C), reference 9.3.

9.3 Electrical Properties

9.31 Electrical resistivity, table 9.31.

9.311 Critical appraisal of data
The electrical resistivity depends markedly on impurity concentration and distribution. The allowed composition change for secondary elements is rather large. Therefore, the electrical resistance will change noticeably from heat to heat of material, even with identical heat treatments.

9.32 Electrical conductivity, table 9.32.

9.4 Magnetic Properties

9.41 Permeability. The alloy is not ferromagnetic.

9.42 Susceptibility. The susceptibility changes strongly with heat treatment. Reversible and irreversible microstructural changes can be determined from susceptibility measurements. This makes it possible to use these measurements for studies in the kinetics of precipitation processes in Al-Cu alloy systems.

9.5 Nuclear Properties

No data found.

9.6 Other Physical Properties

9.61 Emissivity. No data found.

9.62 Damping capacity. No data found.

9.63 Crystal structure, fcc.

TABLE 9.21. – Thermal Conductivity

Source	Ref. 9.3			
Alloy	2219			
Condition	K, cal/cm/cm^2/$^\circ$C/sec	T, $^\circ$C	K, btu/in/ft^2/$^\circ$F/hr	T, $^\circ$F
O	0.41	25	190	77
T31, T37	0.27	25	780	77
T62, T81, T87	0.30	25	870	77

TABLE 9.31. – Electrical Resistivity

Source	Ref. 9.3	
Alloy	2219	
Condition	Microhm-in at 68° F	Microhm-cm at 20° C
O	1.54	3.9
T31, T37	2.44	6.2
T62, T81, T87	2.24	5.7

TABLE 9.32. – Electrical Conductivity at 20° C (68° F), (Percent IACS)

Source	Ref. 9.3	
Alloy	2219	
Condition	Equal Volume	Equal Weight
O	44	138
T31, T37	28	88
	30	94

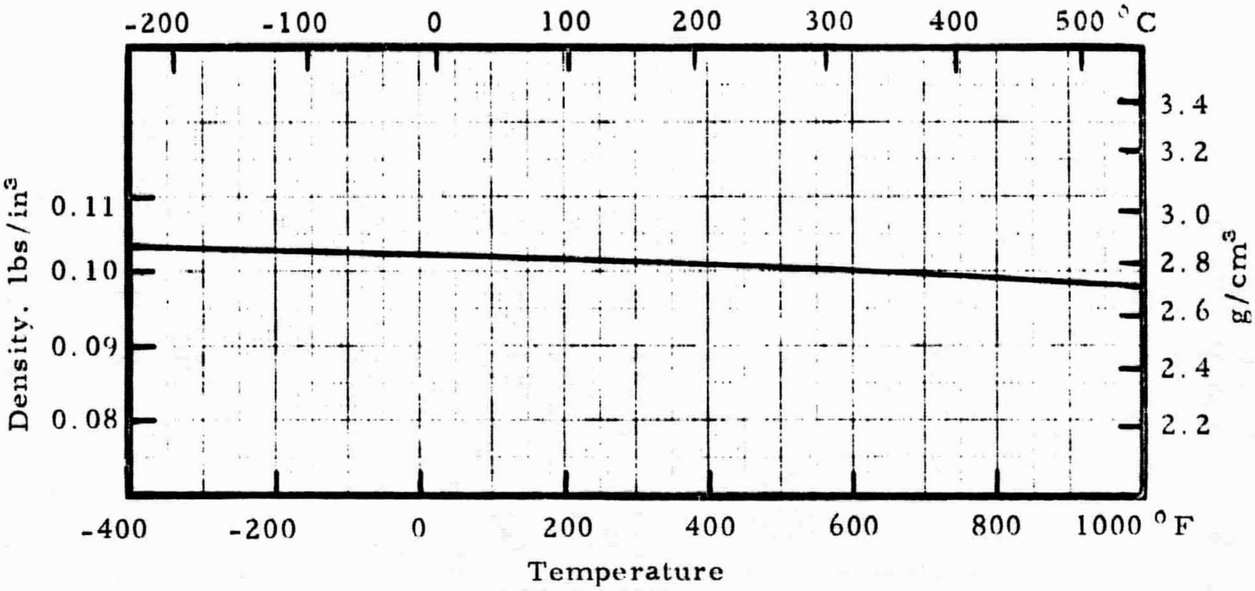


FIGURE 9.1. – Density of 2219 alloy versus temperature. (Ref. 9.1)

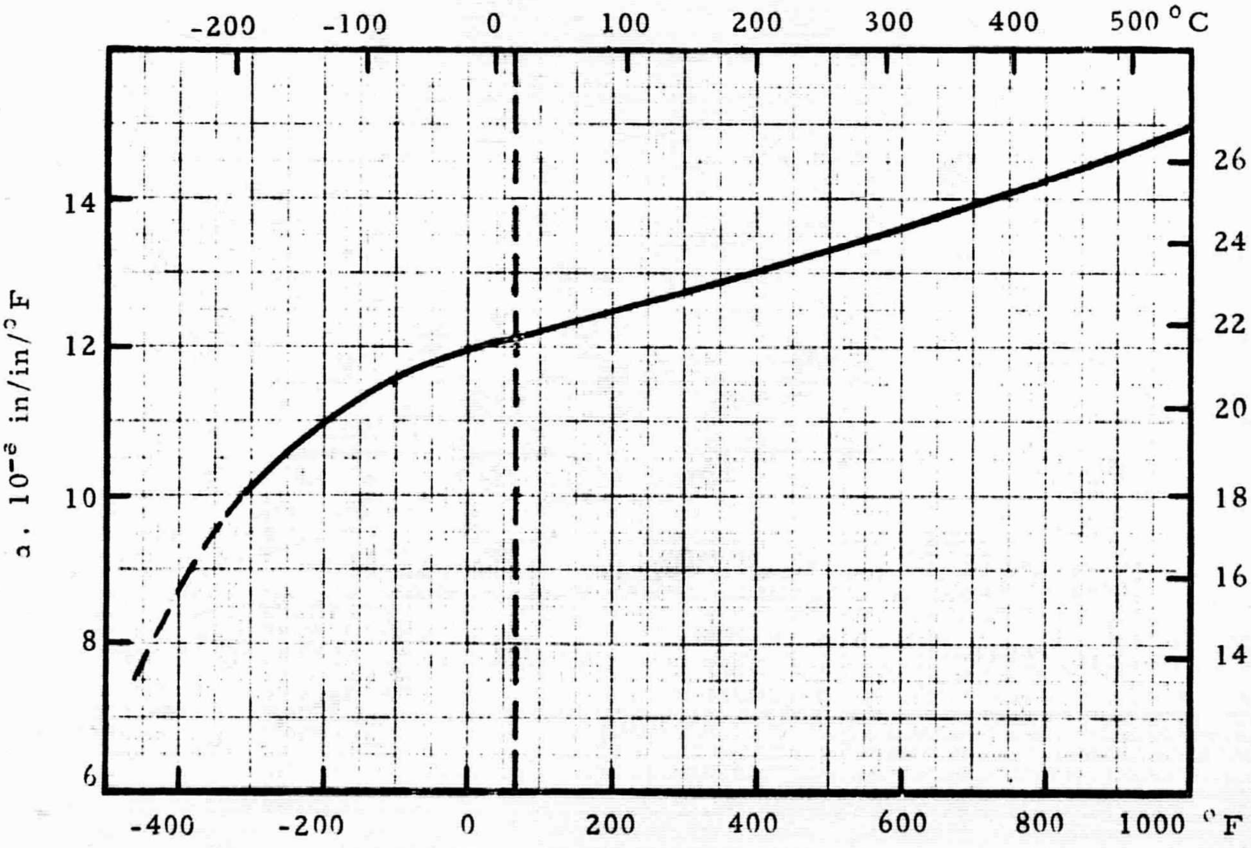


FIGURE 9.22. – Linear coefficient of thermal expansion from room temperature to temperature indicated. (Refs. 9.1, 9.5)

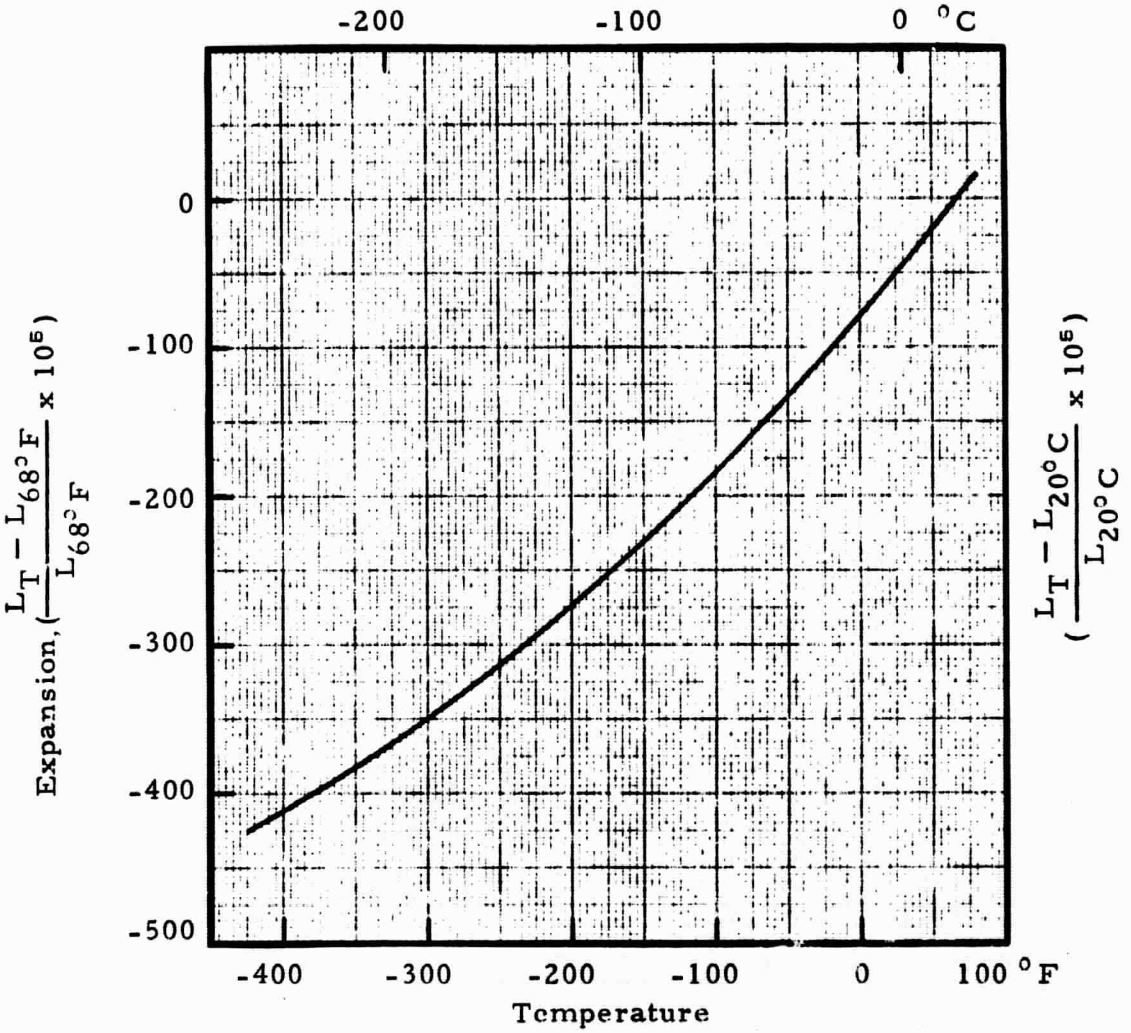


FIGURE 9.221. – Thermal expansion of .219-T87 plate (L); thickness, 0.500 inch (1.27 cm)

(Ref. 9.2)

Chapter 9 - References

9.1 Aluminum Company of America, "Alcoa Aluminum Handbook," 1962.

9.2 F.R. Schwartzberg et al., "Cryogenic Materials Data Handbook," ML-TDR-64-280, August 1964.

9.3 Aluminum Association, Aluminum Standards & Data, 1970-71, 2nd Edition, December 1969, second printing August 1970.

9.4 Martin-Denver, "Summary Information Regarding Aluminum Alloy 2219," Evaluation Report No. 1, MI-61-44, November 1961.

9.5 L.W. Mayer, Alcoa Green Letter, "Aluminum Alloy 2219," November 1963.

Chapter 10

CORROSION RESISTANCE AND PROTECTION

10.1 General. Despite its high chemical reactivity and affinity for oxygen, aluminum exhibits excellent corrosion resistance in most common environments because it passivates spontaneously and very rapidly under normal oxidizing conditions. The passive film is a hard strongly adhering layer of aluminum oxide, estimated as 200–300 Å thick on aluminum exposed to air (ref. 10.1), which protects the metal from direct attack. Thus, the corrosion rate of aluminum generally decreases with time, except under severe or specific exposure conditions which tend to disrupt the passive film. Outdoors, aluminum and its alloys weather to a pleasant gray color, with some initial superficial pitting which gradually ceases (ref. 10.2). Industrial soot, sulfur dioxide, sulfur trioxide, and marine spray tend to increase atmospheric corrosion, but hydrogen sulfide and carbon dioxide do not (ref. 10.3). Twenty-year tests at several marine, industrial, and rural sites have shown that atmospheric attack on aluminum takes place principally in the first year and progresses very slowly beyond the second year (ref. 10.4). Even at high temperatures in dry atmospheres, aluminum is highly resistant to most common gases, except the halogens (ref. 10.2).

In aqueous environments, corrosion resistance of aluminum is greatest under neutral or slightly acid conditions, where the protective oxide film is most stable (pH 5.5–8.5 at room temperature, 4.5–7 at 95° C) (refs. 10.1 and 10.5). Strong alkalies and strong nonoxidizing acids destroy the oxide and greatly accelerate corrosion. Pitting attack occurs in waters containing chloride or other halogen ions, particularly at crevices or stagnant areas where passivity breakdown is accelerated by differential aerative effects. Traces of copper, iron, and mercury ions are also effective in promoting localized attack via galvanic cells formed between aluminum and metal deposited by replacement reactions (ref. 10.1). Since aluminum is strongly anodic to most other common metals, galvanic coupling with them generally produces severe attack on the aluminum, especially in sea water (ref. 10.2).

Aluminum and its alloys are rather resistant to most molten salts. However, molten metals generally attack aluminum, particularly zinc and tin, which form alloys (ref. 10.2) Even a small amount of mercury is especially harmful since it breaks down passivity and amalgamates, causing rapid perforation of aluminum piping or sheet (ref. 10.1). Aluminum exhibits very poor resistance to uninhibited chlorinated solvents and may even react explosively with them (ref. 10.6).

Aluminum purity significantly affects its corrosion resistance. High purity metal is more resistant than commercially pure aluminum which, in turn, is generally more resistant than most alloys (ref. 10.1). Corrosion resistance of specific alloys is affected by composition, heat treatment, and stress conditions, as discussed further below.

10.2 Aluminum–Copper Alloys. For maximum resistance to corrosion, the composition of an alloy should be kept as homogeneous as possible since nonhomogeneities frequently initiate localized attack. This principle applies to the Al–Cu alloys, of which 2219 is a typical example. Copper generally depresses the electrode potential of aluminum in the cathodic (noble) direction, but the copper concentration and distribution are significant. For optimum corrosion resistance of Al–Cu alloys, copper should be maintained in solution by rapid quenching from above the homogenizing temperature (about 900° F, 482° C). If the cooling rate is not rapid enough, the compound $CuAl_2$ forms preferentially along the grain boundaries. This can result in copper depletion adjacent to the intermetallic compound, making the grain boundaries anodic to the grains and susceptible to intergranular corrosion (refs. 10.1 and 10.7).

Tensile stress in the presence of moisture may lead to intergranular stress corrosion cracking. Susceptibility toward this type of attack is heightened by the presence of grain boundary precipitates, although authorities disagree on the details of the mechanism involved (refs. 10.1, 10.7, 10.9). Attack is particularly severe in the presence of chloride ions which weaken the protective oxide films.

10.3 Resistance of Aluminum Alloy 2219. The 2219 alloy has somewhat less resistance to atmospheric corrosion than other Al–Cu alloys such as 2014 and 2024. This is less than the lower strength alloys such as 6061 (ref. 10.10). General surface corrosion characteristics of naturally aged tempers, T31 and T37, are similar to those of 2024-T3. The corrosion resistance of the artificially aged tempers, particularly T81 and T87, appears to vary considerably from lot to lot and has led to some disagreement in the literature when the resistance of the naturally aged tempers is compared with the artificially aged tempers. One source reports that the corrosion resistance of the artificially aged tempers is superior to that of the naturally aged tempers. Data supporting this contention are presented in table 10.1 (ref. 10.11). Another investigation compared the difference in corrosion behavior between 2219-T37 and 2219-T87. Weight loss and type and depth of attack were obtained, with and without an Iridite coating after 1, 3, 5, and 7 days in 5-percent continuous salt spray. These data are shown in table 10.2. A greater weight loss with the T87 temper and the beneficial effect of the Iridite coating in reducing attack of both tempers was noted. Depth of attack values were greater with the T37 temper since corrosion was intergranular as opposed to a pitting attack with the T87 temper; although the depth of attack was less for the T87 temper, the total amount of corrosion was greater (ref. 10.14).

Studies have indicated that the stress-corrosion resistance of 2219-T87 is equal to 7075-T73 alloy in the short transverse grain direction (ref. 10.15). The stress corrosion resistance of the T62, T81, and T87 tempers is reported as excellent provided that no deviation is made from the recommended heat treatment methods (ref. 10.10); also see table 10.3 (ref. 10.11). The artificially aged tempers (T81 and T87) have shown a high resistance to exfoliation in 3.5% NaCl (intermittent spray) and Miami tidewater exposure tests. Tests on forgings, in the T6 and T852 tempers, and T62 and T81 extrusions have also indicated high resistance to exfoliation and stress corrosion cracking (ref. 10.11).

The salt spray corrosion resistance of anodized bare 2219-F sheet was evaluated after 24 hours of exposure at 600° F (316° C). It was found that bare 2219-F with Type I or Type II anodized coatings (applied per MIL-A-8625A) exhibited no corrosion after a 24-hour heat soak at 600° F followed by 250 hours of salt spray exposure. The same alloy with 0.001-inch (0.025 mm) Hardas coating showed an average of 2.6 pits/in^2 (0.2/cm^2) of exposed surface (ref. 10.12). Metallographic examinations were made of parent metal test panels of 2219 sheet in various tempers after 20-percent salt spray exposure for different exposure times (ref. 10.13). The results on this particular lot of material showed that the solution heat treat condition was the most resistant and the annealed condition the least resistant to salt spray attack. The effect of salt-spray corrosion on the tensile properties of sheet in various tempers is shown in figure 10.1. Studies have also indicated that 2219-T81 alloy is resistant to corrosion by dry nitrogen tetroxide and Aerozine-50 in long term applications. The alloy is compatible with liquid oxygen and liquid hydrogen. An investigation at the Boeing Company (refs. 10.17, 10.18) demonstrated that no significant evidence is present in precracked specimens of alloy 2219-T6E46 exposed to hydrogen gas at pressures up to 10,000 psi (7.0307 kg/mm^2), and that this material is superior to Alloy 718 and titanium 6Al-4V for high-pressure hydrogen-gas tankage.

It is reported that no adverse effect on corrosion resistance is encountered on reheating of any properly artificially aged temper of 2219. The recommended maximum reheating times are given in table 10.4.

10.4 Protective Measures. Anodic coatings are widely used for the corrosion protection of aluminum alloys. These oxide coatings are hard and are resistant to abrasion and corrosion. Cathodic protection has also proved effective in retarding both general dissolution and localized attack, although overprotection by this method should be avoided to insure against harmful accumulation of alkali at the cathode surface (ref. 10.1).

Paints and inorganic inhibitors have also been applied successfully in specific cases (ref. 10.2).

The 2219 alloy is available as Alclad sheet and plate, which is bare 2219 with a thin coating of 7072 on both sides. The clad material is chosen to provide a surface having a high resistance to corrosion and sufficiently anodic to the 2219 core to afford electrochemical protection.

It is also important that careful heat treatment and proper fabrication techniques be used with this alloy to avoid localized tensile stresses and structural crevices so as to minimize localized attack and stress corrosion cracking. Surface treatments are discussed in more detail in Chapter 11.

10.5 Solution Potential and Electrical Conductivity Measurements.
Solution potential and electrical conductivity measurements were obtained on 2219 alloy samples, with and without an Iridite coating, to determine the effect of temper on the response of the alloy. These data are shown in table 10.5. The similarity of the potential values of the bare and Iridite coated samples indicates that the Iridite coating does not provide a complete barrier against the corrosive media. It was postulated that the primary protective properties are a result of the hexavalent chromium content serving as an anodic inhibitor. The difficulty in forming an impervious chemical conversion coating of any type on high copper alloys was noted (ref. 10.14).

The protection afforded by conversion coatings is often seriously reduced when the alloy is welded or otherwise heated. It has been found at Marshall Space Flight Center (ref. 10.16) that damaged Iridite 14-2 or Alodine 1200 on alloy 2219-T87 can be replaced with initial protective value if an area within 6 inches of the weld is stripped manually and then recoated by sponge or spray application with a solution two or three times stronger than that used originally. Additionally, spray applications of the conventional solution improve worn or abraded coatings.

TABLE 10.1 – Corrosion Resistance of Heat Treated Sheet

Source	Ref. 10.11				
Alloy	2219				
Temper	Type of Attack (a)	Loss in Tensile Strength, percent (b, c)			
		48-hr AI, NaCl–H_2O_2		12-wk AI, 3.5% NaCl	
		Not Stressed	Stressed 75% of F_{ty} (d)	Not Stressed	Stressed 75% of F_{ty} (e)
O	P + I	8	-	14	-
T31	I	16	23	25	34
T37	I	18	30	32	43
T62	I	14	17	25	38
T81	P	11	14	17	24
T87	P	11	14	14	26

(a) P = pitting; I = intergranular (MIL-H-6088E)
(b) Exposed as cross-grain machined tension specimens, 0.064-inch (1.625-mm) thick.
(c) AI = alternate immersion
(d) Stressed as simple beam with dead weight load
(e) Stressed by bending in constant-deflection fixtures.

TABLE 10.2 – Corrosion of Alloy in 5% Continuous Salt Spray

Source	Ref. 10.14			
Alloy	2219			
Condition and Temper	Exposure, days	Weight Loss, mg/in^2 (a, b)	Type	Av. Depth, mils
Uncoated, T37	1	5.1	Intergranular	4.6
	3	8.7		4.4
	5	12.0		5.2
	7	16.1		4.4
Uncoated, T87	1	6.9	Pitting	1.6
	3	10.3		1.8
	5	13.6		1.4
	7	18.2		1.5
Iridite Coated, T37	1	0.19	Not Determined	-
	3	0.25		-
	5	0.48		-
	7	0.68		-
Iridite Coated, T87	1	0.26		-
	3	0.42		-
	5	0.58		-
	7	0.98		-

(a) Corrosion product was removed by immersion in concentrated HNO_3
(b) 1 in^2 = 6.4516 x 10^{-4} m^2; 1 mil = 0.025 mm.

TABLE 10.3 — Stress Corrosion Cracking

Source	Ref. 10.11			
Alloy	2219			
Form	0.064-in (1.625-mm) Sheet			
Temper	12 weeks AI (c) 2.5% NaCl		1 year sea coast atmosphere	
	F/N (b)	Days to Fail	F/N	Days to Fail
O	2/2	7, 12	2/2	82, 82
T31	2/2	5, 7	2/2	82, 82
T37	0/2	OK 84	0/2	OK 365
T62	0/2	OK 84	0/2	OK 365
T81	0/2	OK 84	0/2	OK 365
T87	0/2	OK 84	0/2	OK 365

(a) Plastically deformed tension specimen blanks, stressed in constant bend deflection fixtures
(b) F/N denotes ratio of number of failures to number exposed
(c) AI = alternate immersion

TABLE 10.4 — Recommended Maximum Reheating Times

Source		Ref. 10.10
Alloy		2219
Temper		All
Temp., °F	°C	Time, hr (a)
500	260	to temperature
450	232	1/2
425	213	1
400	204	5
375	189	50
350	176	100
325	156	1000
300	149	10,000 plus

(a) These times and temperatures are based on a 5% maximum decrease in mechanical properties.

TABLE 10.5 — Potential and Conductivity Measurements

Source	Ref. 10.14		
Alloy	2219		
Condition	Temper	Potential (a)	Conductivity, % IACS
Uncoated	F	802 mv	42.6
	T37	643 mv	28.7
	T87	797 mv	32.2
Iridite Coated	F	801 mv	-
	T37	632 mv	-
	T87	796 mv	-

(a) Against a 0.1 N calomel electrode in 53 g/l NaCl, 9 ml/l 30% H_2O_2

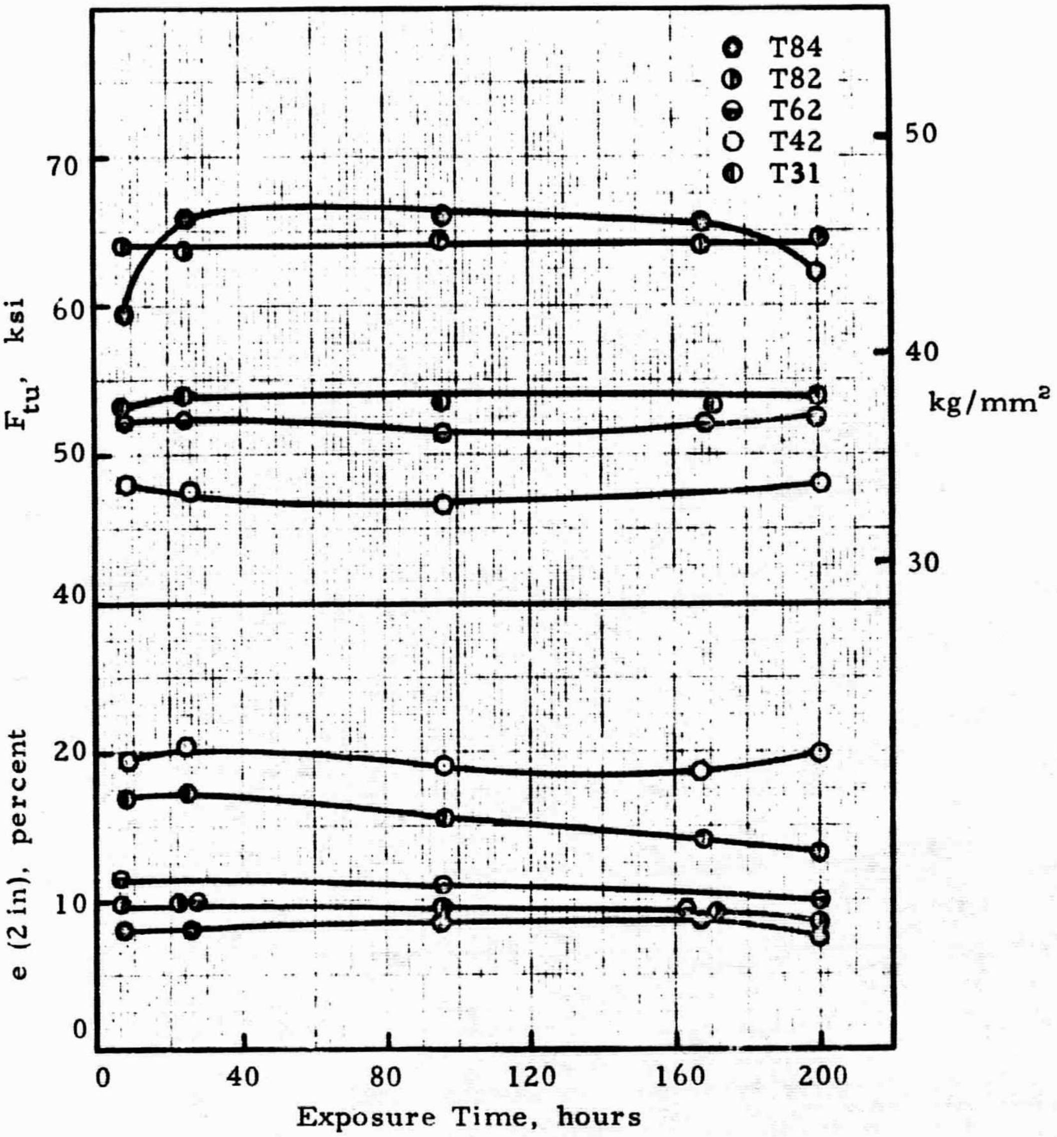


FIGURE 10.1. – Effect of salt-spray (20% NaCl) corrosion on tensile properties of 2219 sheet in various tempers; thicknesses, 0.088-0.100 inch (2.235-2.54 cm).

(Ref. 10.13)

10.1 H.H. Uhlig, Corrosion and Corrosion Control, John Wiley & Sons, New York, 1963, Ch. 28.

10.2 L.L. Shreir, Corrosion, John Wiley & Sons, New York, 1963, Vol. I., Sec. 4.1.

10.3 P.M. Aziz and H.P. Goddard, Corrosion, 15, 529t (1959).

10.4 Symposium on Atmospheric Corrosion of Non-Ferrous Metals, ASTM STP-175, 1956.

10.5 J. Draley and W. Ruther, Corrosion, 12, 441t, 480t (1958).

10.6 A. Hamstead, G. Elder, and J. Canterbury, Corrosion, 14, 189t (1958

10.7 K.F. Thornton, "Alcoa Aluminum-Magnesium Alloys Suitable for Structural Welding Applications," Alcoa Green Letter, November 1957; revised by R.L. Flucker, August 1962.

10.8 Materials in Design Engineering, Materials Selector Issue, Mid-October 1964.

10.9 Metals Handbook, "Properties and Selection of Metals," 8th Edition, American Society for Metals, 1961, Vol. I.

10.10 L.W. Mayer, "Alcoa Aluminum Alloy 2219," Alcoa Green Letter, October 1960; latest revision November 1963.

10.11 J.A. Nock, Jr., et al., "A New High Strength Aluminum Alloy," Metal Progress, 80, September 1961.

10.12 J.L. Cozart, "Determination of Corrosion Protective Surface Treatment for Bare 2219-F Alloy at Elevated Temperature," Convair/Fort Worth Report No. FTDM-2222, August 1962.

10.13 Martin/Denver, "Summary Information Regarding Aluminum Alloy 2219," Evaluation Report No. 1, MI-61-44, November 1961.

10.14 W.G. Zelley, "Development of Improved Conversion Coating for Aluminum Alloys," Contract NAS8-11226, Alcoa Research Labs, May 1965.

10.15 B.W. Lifka, et al., "Investigation of the Stress-Corrosion Cracking of High Strength Alumnium Alloys," Contract NAS8-5430, Tenth Quarterly Report, October 1965.

10.16 R.H. Higgins, "Renewal of Corrosion Protection of Coated Aluminum after Welding," NASA Tech Brief 69-10150, May 1969.

10.17 P.M. Lorenz, "Effects of Pressurized Hydrogen upon Inconel 718 and 2219 Aluminum," Paper W9-13.2, WESTEC Conference (ASM), Los Angeles, California, March 10-13, 1969.

10.18 J.E. Campbell, "Effects of Hydrogen Gas on Metals at Ambient Temperature," DMIC Report 5-31, April 1970.

Chapter 11

SURFACE TREATMENTS

11.1 General. A wide variety of surface treatments can be applied to the 2219 alloy (and other aluminum alloys) to protect and improve the appearance of the surface. These include mechanical, chemical, and electrochemical finishes and organic, porcelain, and paint coatings. Alclad forms of aluminum alloys have a very high inherent resistance to corrosion and may be used without benefit of protective coatings for some applications (ref. 11.1).

11.2 Alclad Products. The 2219 alloy is available as Alclad sheet and plate which consists of bare 2219 core material clad with a thin coating of 7072 alloy on both sides. The clad material is metallurgically bonded to the core material. It is chosen to provide a surface having a high resistance to corrosion and sufficiently anodic to the 2219 core to afford electrochemical protection to it in corrosive environments. Consequently, any spot of attack can penetrate only as deep as the core alloy where further progress is stopped by cathodic protection. Corrosion is thus confined to the clad material only. The life of the cladding is a function of its thickness and severity of the environment. Alclad products, therefore, limit corrosion to a relatively thin clad surface layer (refs. 11.2, 11.8).

11.3 Mechanical Finishes. Mechanical finishes are used to alter the texture of the alloy surface to provide a more decorative appearance or as a treatment prior to other finishing such as painting. Grinding, polishing, and buffing result in smoother reflective surfaces. Abrasive blasting (sand or grit) gives a rough matte finish which is often used as a base for organic coatings. Scratch finishing, satin finishing, Butler finishing, and skin finishes are scratched-line finishes which remove minor surface defects and provide a decorative effect. Mechanical methods remove the original heavy oxide film. For this reason, mechanically finished parts are often given a protective coating by anodizing or lacquering. The possibility of generating an explosive mixture of fine powder and air during mechanical finish operations should be recognized (ref. 11.3).

11.4 Anodizing. Anodic coatings are hard, abrasion- and corrosion-resistant oxide coatings. The alloys can be anodically coated in a number of electrolytes, but most commercial anodizing is done by either the sulfuric acid or chromic acid process. The thickness of the coating is dependent upon the anodizing time. Coatings produced by the sulfuric acid process vary in thickness from 0.0001 to 0.001 inch (2.54 to 25.4 μm). Coatings produced in chromic acid vary from 0.00001 to 0.00009 inch (0.254 to 2.29 μm). Anodic coatings provide good protection against corrosion and are excellent bases for paint coatings (ref. 11.1). However, the chromic acid process does not provide as corrosion-resistant a coating as does the sulfuric acid process (ref. 11.11).

11.41 In recent years, a number of new methods have been developed for producing heavier anodic coatings of from 0.001 to 0.010 inch (25.4 to 254 μm). These methods require electrolytes which enable the oxide growth process to continue until the desired coating thickness is obtained.

Another recent development in coatings is that of hard anodizing, designated as "hardcoating." Processes most suitable for a wide range of applications are Alumilite 226 (oxide coatings, 0.002 inch or 50.8 μm thick) and Martin Hardcoat (coating thicknesses up to 0.004 inch or 101 μm). A flash hardcoat of a very thin film can also be applied by these methods by shortening the normal time cycle. The operating conditions for the baths employed in these processes are given in table 11.1. The Martin process should be specified where maximum hardness and corrosion resistance are required along with thickness buildups to 0.004 inch. Alumilite 226 is selected where hardness and corrosion resistance are required and 0.002 inch is the acceptable maximum buildup. Further details of these processes are presented in reference 11.9.

11.42 A white anodize has been developed by the Reynolds Co. for alloy 2219 to provide a good reflectance value and excellent resistance to corrosion (ref. 11.4). The technique consists of 4 steps: (1) surface preparation by mechanical and chemical pretreatment; (2) anodizing in a 26-percent sulfuric acid electrolyte containing glycerol, lactic acid, and titanium ammonium lactate; (3) pigmentation with lead sulfate in a complex acetate solution; (4) sealing with a polyorganosiloxane after boiling-water sealing.

11.5 Chemical Finishes. Chemical finishes are of three main types. Finishes used for decorative effects include caustic etching, acid etching, and chemical polishing. Etched surfaces have a matte appearance while chemically polished surfaces are highly reflective and require protection by anodizing or lacquering. Conversion coatings can be oxide, phosphate, or chromate types and are used primarily as base coatings prior to application of organic coatings. Miscellaneous special-purpose finishes include those produced by the Alrok process, modified Bauer-Vogel process, and processes for staining aluminum alloys.

11.6 Electropolishing. This process produces a highly reflective surface and is often used for surface preparation prior to microscopic examination of metallurgical structure.

11.7 Electroplating of aluminum alloys has gained increased commercial use in recent years. A commonly used finish consists of successive deposits of copper, nickel, and chromium. Other metals may be applied over the copper. A satisfactory base surface for electroplating is provided by immersing the aluminum part in a solution of sodium zincate of controlled composition. Brass, iron, silver, or chromium can be applied directly over this zinc immersion coating (ref. 11.4).

11.8 Painting. When severe conditions of exposure are to be encountered, it is frequently desirable to protect aluminum alloy surfaces with paint. Prior to painting, the surface should be properly prepared before priming. Dirt may be removed by brushing and grease or oil may be removed by means of solvent or degreasing techniques. The parts are then immersed in (or swabbed with) a solution of phosphoric acid and organic grease solvents diluted with water. A number of proprietary solutions of this type are available commercially. Solution temperature should be between 50° and 90° F (10° and 32° C) and contact with the metal part should not be for less than 5 minutes.

The part is then rinsed with water and dried thoroughly. Where chemical treatment is impractical, mild sandblasting methods may be employed. A chemical conversion coating per MIL-C-5541 or an anodize coating is necessary prior to priming with zinc chromate primer per MIL-P-8585. For severe conditions of exposure, both primer and joint compound should be used at joints.

All surfaces except contacting surfaces may be given a second coat of paint consisting of two pounds of aluminum paste pigment (ASTM Spec. D962, Type II, Class B) per gallon (239.6 g/l) of varnish which meets Federal Spec. TT-V-86b, Type II or equivalent. The final assembled structure may be finished with one coat of aluminum paint. One or more coats of alkyd base enamel (pigmented to desired color) may be substituted for aluminum paint (ref. 11.5).

11.81 To minimize stress-corrosion cracking when the alloy is subjected to sustained surface stresses and corrosive environments, certain surface treatments and protective coatings are effective. The most effective protection is obtained by applying a topcoat of epoxy-polyamide paint to shot-peened or metallized surfaces of the alloy. Satisfactory temporary protection is obtained by an electroplated galvanic coating (3 to 4 mils thick), or a topcoat of paint containing epoxy-polyamide or polyurethane resins. The former is preferred and can be used on unprimed surfaces. Care is necessary to prevent breaking or scratching the paint film. Shot peening alone will provide good surface protection (if all surfaces are treated) when corrosive environment is not severe. Anodic films and zinc-rich paints are the least effective coatings for preventing stress-corrosion cracking (ref. 11.6).

11.9 Porcelain Enameling. The principal difference between porcelain enameling of aluminum alloys and other metals is the use of porcelain frits which melt at lower temperatures. High lead frits are commonly used and they can be formulated in a wide variety of colors and surface finishes. The enamel slip is sprayed onto chemically cleaned and treated surfaces and then fired at temperatures of 950° to 1050° F (510° to 717° C) for a period of 4 to 8 minutes (ref. 11.7).

TABLE 11.1 – Baths for Hard Anodized Coatings

Source	Ref. 11.9	
Alloy	Aluminum Wrought Alloys	
Parameters	Process	
	Martin (a)	Alumilite (b)
Composition	15% H_2SO_4	12% H_2SO_4, 1% $H_2Cr_2O_4$
Electrolyte Temp., °F , °C	25 to 32 –4 to 0	48 to 52 9 to 11
Current Density	25 asf	36 asf

(a) Developed by the Martin Company

(b) Developed by the Aluminum Company of America

Chapter 11 - References

11.1 1971 SAE Handbook, Society of Automotive Engineers, New York.

11.2 Metals Handbook, Vol. I, "Properties and Selection of Metals," 8th Edition, American Society for Metals, 1961.

11.3 Reynolds Metals Co., "The Aluminum Data Book, Aluminum Alloys and Mill Products," 1958.

11.4 K.H. Dale, "Advances in Aluminum Anodizing," NASA Tech Brief B69-10144, May 1969.

11.5 Aluminum Company of America, "Alcoa Structural Handbook," 1960.

11.6 Alcoa Research Labs, "Aluminum Alloys Protected Against Stress-Corrosion Cracking," NASA Tech Brief 65-10172, June 1965.

11.7 J. Vaccari, "Wrought Aluminum and Its Alloys," Materials and Processes Manual No. 231, Materials in Design Engineering, June 1965.

11.8 Aluminum Company of America, "Alcoa Aluminum Handbook," 1962.

11.9 C.R. Kliemann, "Hard Anodizing of Aluminum Components," Metal Progress, July 1965, p. 63.

11.10 J.L. Cozart, "Material: Bare 2219-F Aluminum Alloy: Elevated Temperature Corrosion Protective Treatment," Report No. FTDM-2222, General Dynamics/Fort Worth, August 1962.

11.11 George C. Marshall Space Flight Center, Marshall Space Flight Center, Alabama, Unpublished Data, 1965.

Chapter 12

JOINING TECHNIQUES

12.1 General. The 2219 aluminum alloy can be joined satisfactorily by fusion and resistance welding techniques and by riveting. Brazing, gas welding, and soldering are not recommended, since satisfactory materials and methods have not been developed for this alloy. Specifications for welding of aluminum alloys are presented in table 12.1

12.2 Welding. Reliable, sound, high quality welds have been made in aluminum alloys for many years. Although aluminum is one of the most readily weldable of all metals, it has individual characteristics which must be well understood for successful welding of the metal or its alloys. Four important factors that must be considered are the low melting point, the presence of an oxide film, low strength at elevated temperatures, and the fact that aluminum exhibits no characteristic color changes even at temperatures up to the melting point. The welding of aluminum alloys requires care to prevent excessive melting of the material. The oxide film must be removed and prevented from reforming by some inhibiting technique before a good bond can be obtained. Part s should be well supported during welding to prevent distortion (ref. 12.2).

12.21 Fusion Welding. The 2219 alloy exhibits the best weldability of the 2xxx series of aluminum alloys. In particular, its susceptibility to weld cracking is less than that of 2014. This is due to the absence of magnesium and silicon as alloying elements. These elements form ternary and quaternary eutectics of low melting points and thus increase the melting range of the alloy. Both the wide range of melting temperature and the presence of phases with a low melting temperature are known to cause weld cracking as discussed in references 12.3 and 12.4

The filler rod used to fusion weld 2219 has the same composition as 2219 plus titanium and is designated as 2319.

Frequently the alloy, when fusion welded, is used in the "as welded" condition. To compensate for the low strength in this condition, designers usually arrange to have the welded joint thicker than the parent metal. For highest strength, ductility, toughness, and corrosion resistance, a full heat treatment after welding is recommended (ref. 12.5).

12.211 Fusion Welding Methods. One of the most important advances in aluminum welding has been the development of inert-gas-shielded methods that do not require a flux. The "tungsten-inert-gas" (TIG) method and the "metal-arc-consumable electrode"

(MIG) method have both contributed significantly to the advancement of the "state of the art" of aluminum welding. TIG and MIG techniques each have inherent advantages and disadvantages and are discussed in detail in reference 12.6. The main problem with these fusion welding processes is the occurrence of porosity in the weld which adversely affects the mechanical properties. Investigations of the factors that can cause porosity are reviewed in detail in reference 12.37. It has been indicated that gases (notably hydrogen) trapped in weld zones are the principal cause of porosity in 2219 alloy weldments (ref. 12.7). Hydrogen is soluble in liquid aluminum but is nearly insoluble in solid aluminum. Thus, any hydrogen present at solidification is rejected in the form of porosity as the alloy solidifies. At temperatures above 920° F (493° C), aluminum reacts with water to produce "nascent" hydrogen plus oxygen. The hydrogen dissolves in molten aluminum and the oxygen combines to form aluminum oxide (ref. 12.8). The solubility of hydrogen in aluminum is shown in figure 12.1. Control of humidity and cleaning of filler wire to remove the oxide surface layer have helped to reduce porosity in 2219 alloy welds. However, hydrogen in the interior of the base metal or filler wire is more difficult to eliminate (ref. 12.4). It has also been found that porosity is more prevalent in multipass welds than in single pass welds. Apparently, successive beads pick up gas contamination from preceding beads to cause a cumulative effect (ref. 12.9). TIG welding results in slightly lower porosity levels in the weld than MIG welding. The speed of welding has a sizeable influence on the porosity level for both methods as indicated in figure 12.2. The effect of increasing levels of porosity on mechanical properties is shown in figure 12.3.

Another strength reducing factor is mismatch of the pieces to be joined, as is shown in figure 12.4.

The mechanical properties of welded 2219 also depend upon the following factors: Sheet or plate thickness, heat-treatment condition before and after welding, welding method (i.e., manual or automatic), type of back-up bar used, and the testing temperature.

The effect of original temper and post-weld treatment on the strength and elongation of TIG and MIG welded sheets and plates of various thicknesses is shown in table 12.2. The results indicate that the best properties are obtained by welding parts in the solution treated or "as fabricated" condition, which are subsequently solution treated and reaged to the T6 condition. Material in the T81, T87, T31, or T37 condition, which is aged after welding or left in the as-welded condition, shows that some increase in strength can be obtained by post-weld aging.

Typical tensile properties of 0.75-inch (1.90-mm) 2219-T87 welded and unwelded plate are tiven in table 12.3.

The effect of cryogenic temperatures on the tensile strength and elongation of 2219 welded sheet in the T81 or T87 condition is shown in figures 12.5 and 12.6. Similar data for the T62 condition is given in figure 12.7.

C-3

Both the base metal and the weld strength increase with decreasing elongation. The joint efficiency is about 70 percent and the elongation only about 2 percent. Both values are nearly constant at all testing temperatures. Failure occurs in the weld heat-affected zone before any significant amount of elongation occurs in the parent metal (ref. 12.13). The "A" and "B" values shown in figure 12.5 are lower bounds on the weld strengths, as defined in MIL-Handbook 5A. It should be noted that they are relatively low at –423° F (-253° C) which indicates a greater scatter of the tensile data than at higher temperatures.

The effect of high temperatures, welding procedure, elimination of the weld bead, and post-weld heat treatment on the tensile strength and the "A" and "B" values (MIL-Handbook 5a) is shown in figure 12.8.

The tensile strength of 2219 in all conditions is lowered by increasing the testing temperatures. The "as-welded" tensile strength at room temperature is decreased more with respect to the parent material than at 400° F (204° C) and higher temperatures. Furthermore, the scatter of the experimental results is higher at room temperature than at elevated temperatures, particularly for the manually welded panels.

The strength and ductility of panels with reheat treatment after welding closely approximates that of the parent material. Machine welded panels have slightly higher strength and ductility than manually welded panels. The tension and elongation values of the panels which are reaged after welding are quite similar to the values of the panels in the "as welded" condition. There is no significant difference between machine and manually welded properties.

The room temperature strength of the "as welded" and reaged panels is markedly reduced when the weld beads are ground flush. At elevated temperatures, however, the effect of weld bead reinforcements is generally negligible. Except where weld defects are present, the grinding of weld bead reinforcements does not materially affect the strength of the reheat treated panels.

The strength of a weld in general will be higher when less heat is needed to fusion weld. Thus, the weld metal zone and heat affected zone should be as small as possible. This can be achieved by using suitable welding speeds and back-up bars. The effect of these two variables on the limit of the temperature zones above 500° F (260° C) is shown in figures 12.9 and 12.10. The temperature gradient caused by the welding process will result in a gradual decrease in strength from the base metal to the weld. This is shown in figure 12.11 where the Rockwell "B" hardness across the weld is plotted as a function of welding speed and back-up material. The change in mechanical properties across the weld can also be shown in terms of stress-strain data as indicated in figure 12.12. This figure, in which only the initial part of the stress-strain curves is plotted, shows that the strength of the material increases with the distance from the weld. The effect of weld procedures and post-weld heat treatment on bulge properties of 2219 sheet is illustrated in table 12.4 and figure 12.13. These results indicate that 2219 is the most easily welded and the least sensitive to variations in weld procedures of all the high strength, heat-treatable aluminum alloys. When reheat treated after welding, the alloy consistently develops bulge strengths equal to the tensile strength of the base metal. The T81 and T87 tempers are recommended for assemblies to be left in the "as welded" condition. For assemblies to be post-weld heat treated, the F temper (as-fabricated) is recommended because of its lower cost. Other tempers, however, are also satisfactory. The recommended post-weld treatment practice is T62 for maximum bulge strength.

The fatigue properties of butt welded 2219-T87 aluminum are excellent, particularly at -423° F (-253°C) where the endurance limit is substantially higher than at room temperature as shown in figure 12.14. The low-cycle fatigue data of figure 12.15 indicate that specimens can be cycled up to 2000 cycles at 75, 85, or 95 percent of the static joint strength without failure. The low temperature strengths are higher than those at room temperature. S-N curves for the T87 sheet are given in figure 12.16.

The range of angles to which 2219 in the T6E46 condition can be bent over a ram of radius 5T is given in table 12.5.

12.212 Gas Metal Arc Spot Welding (or inert-gas spot welding) is used to make high strength localized welds with light equipment and from one side only. It is a quick and reliable method to join sheet, extrusions, and tubing. The localized welding is accomplished by using very high automatically controlled welding currents for a short period of time with the addition of a small quantity of filler metal (ref. 12.26). Filler metals recommended are 2319 and 4043. The tensile shear breaking loads of 0.064-inch (1.6-mm) thick 2219-T6 aluminum overlap joints, welded with 2319 filler of an experimental investigation, are 695 pounds (313 kg) for a nonpenetrating and 1300 pounds (585 kg) for a penetrating weld spot (ref. 12.34).

12.22 Electrical Resistance Welding. Resistance welding (spot welding and seam welding) is a most useful, practical, and economic method of joining aluminum alloys. The welding process is almost entirely automatic and standard welding machines are capable of handling a wide variety of operations. Resistance welding heats only a small area of metal. Thus, there is only a minimum of metallurgical disturbance for a minimum length of time, which is important in the welding of aluminum alloys.

Mechanical or chemical cleaning of the contact surfaces is necessary to obtain good spot welds in aluminum as no fluxes are used during spotwelding. In aircraft construction, it is recommended that the contact resistance of the elements to be joined be continually checked to ensure surface cleanliness. Surface contact resistance should not exceed 50 microhms for best results. Details on surface cleaning are given in reference 12.25, page 48.

12.221 Mechanical Properties of Spot Welds. Very little information on spot welding of 2219 is available. The effect of cryogenic temperatures on the cross-tension and tensile shear strength of single spot welds of 2219-T81 sheet is shown in figure 12.17. The data indicate that spotwelded 2219-T81 sheet has sufficient strength at cryogenic and room temperatures. The tensile shear curves, however, show a tremendous scatter, as can be seen from the low "A" and "B" strength values. Furthermore, between -320° and -423° F (-196° and -253°C), the cross tension strength drops rather sharply, indicating some loss in toughness in this temperature range. The suggested minimum joint overlap and spacing of spot welds is presented in table 12.6 and the minimum allowable edge distance for spotwelded joints is shown in table 12.7. Spot weld maximum shear strength standards are given in table 12.8.

12.3 Brazing. Brazing of the 2219 alloy is not recommended. The melting point of 2219 is lower than that of the commercially available brazing alloys (ref. 12.30).

12.4 Riveting. Riveting is a commonly used method for joining aluminum, particularly the heat-treatable alloys. It is reliable because riveting is a method that is well understood and highly developed. Also, modern riveting methods are largely independent of the operator's skill and thus uniformity of riveted joints can be readily attained (ref. 12.2). Specifications for aluminum riveting are presented in table 12.9.

12.41 Aluminum alloy rivets are preferred for the fabrication of aluminum alloy structures, although cold-driven annealed steel rivets have been used successfully for some applications. To determine the strength of riveted joints, it is necessary to know the strength of the individual rivet. The average shear strength for driven rivets of various aluminum alloys is given in table 12.10. In most cases, such joints fracture by shearing, by bearing or tearing failure of the sheet or plate. It is customary to use a slightly larger factor of safety for the shear strength of rivets than is employed for other parts of an assembly. The design of joints where rivets are subjected to tensile loads should be avoided. Bolted connections may be used where high tensile stresses preclude the use of riveting. Information in detail on the riveting of aluminum alloys is given in references 12.31 and 12.32. Design data on mechanical joints using rivets or bolts may be found in MIL-Handbook 5A (ref. 12.33).

12.5 Electron Beam Welding. Electron beam welding is not yet a major process for joining aluminum in production, but has sufficient promise to be mentioned (ref. 12.37). In this process, fusion is accomplished by bombarding the workpiece with a dense stream of high-velocity electrons in an evacuated chamber. The joint design is a square-butt joint with no gap; a filler metal is not required.

12.51 Impressive welding speeds have been cited for 2219 in thicknesses of 0.5 to 6 inches (1.27 to 15.24 cm) (refs. 12.38, 12.39): strength and joint efficiency developed in plate gages have been superior to those formed by gas tungsten-arc or gas metal-arc (ref. 12.39). In an improved technique developed at Westinghouse Electric Corp. (ref. 12.40), the power density of the beam relative to the speed of the workpiece is such that the material is melted but not vaporized as it is in the usual technique; an inclined weld front is produced. Several hundred welds of the bead-through-plate variety were made with 2219-T87.

TABLE 12.1. – Welding Specifications

Source	Refs. 12.1, 12.21, 12.22, 12.23			
Alloy	2219			
Product or Process	Federal	ASTM	Military	AMS
Weldments (aluminum and aluminum alloys)			MIL-W-22248	
Welding of aluminum alloys			MIL-W-8604	
Welding (aluminum alloy armor)			MIL-W-45206	
TIG welding, aluminum alloy for structures			MIL-W-45205	
Welding; resistance, aluminum alloys			MIL-W-45210A	
Welding; spot, seam, or stitch(Al, steel, Mg, Ti)			MIL-W-6858B	
Welding rods (aluminum-2319)	QQ-R-566-2	B285		4190A 4191A
Welding electrodes (flux coated)		B184	MIL-E-15597C	
Welding electrode wire		B285	MIL-E-16053J	
Flash welds (rings, flanges)				7488C

TABLE 12.2. — Effect of Original Temper and Post-Weld Heat Treatment on Elongation of Welded 2219 (Al-2319 Filler)

Source	Ref. 12.5				
Form	Sheet and Plate				
Original temper and heat treatment	Thickness, inch (a)	No. of samples	F_{tu} ksi (a)	F_{ty} ksi (a)	e - % (b)
T81 or T87 AW	0.064	22	47	32	3
T81 or T87 AW	0.125	23	43	30	3
T81 or T87 AW	0.250	10	40	-	1
T81 or T87 AW	0.500	4	40	-	1
T31 age - T87	0.064	22	49	43	2
or T37 age - T87	0.125	23	44	38	2
T37 age T87	0.250	10	46	-	0.6
T37 age T87	0.500	4	41	-	1
O or F age HTAT62	0.064	9	59	40	8
O or F age HTAT62	0.125	12	57	39	8
O or F age HTAT62	0.250	5	60	43	4
O or F age HTAT62	0.500	2	52	-	3

(a) 1 inch = 2.54 cm; 1 ksi = 0.70307 kg/mm^2
(b) Gage length, 2 in for 0.064 and 0.125 sheet
Gage length, 8 in for thickness >0.125 sheet

TABLE 12.3. — Typical Tensile Properties of Welded and Unwelded Plate

Source	Ref. 12.12				
Alloy	2219-T87, 0.75-inch (1.9-cm) plate				
Weld Method	Condition of weld	Test temp, °F (b)	F_{tu}, ksi (a)	F_{ty}, ksi (a)	e - % (2 in)
-	Base metal	72	68.2	56.3	13
TIG	As welded	72	43.1	26.7	4.3
MIG	As welded	72	41.5	26.1	3.6
-	Base metal	–320	84.6	68.2	16.3
TIG	As welded	–320	50.8	30.8	4.9
MIG	As welded	–320	55.7	31.9	4.0

(a) 1 ksi = 0.70307 kg/mm^2
(b) 72°F = 22.2°C; –320°F = -196°C.

TABLE 12.4. – Tensile and Bulge Tests of Fusion Welds in Sheet (a)

Source	Ref. 12.20							
Alloy	2219							
Thickness	0.064 in (1.625 mm)						0.125 in (6.35 mm)	
Weld Method	SA (b)			DCSP (c)				
Temper	T87	T37 (d)	T31 (e)	T87	T37 (d)	T31 (e)	T87	T37 (d)
F_{tu}, ksi (f)	46	53	52	47	53	53	45	50
F_{ty}, ksi (f)	37	49	48	34	47	45	29	41
e (2 in), %	1.9	1.3	1.5	1.5	1.6	1.2	2.2	1.8
S (g)	0.5	1.6	2.4	1.2	1.4	0.4	1.0	1.0
Bulge Tests								
Tensile, ksi	47	54	55	50	44	42	48	47
Height, in	0.37	0.47	0.54	0.42	0.48	0.44	0.45	0.43
S (g)	2.1	1.8	1.4	1.5	0.4	1.4	1.6	1.1

(a) All welds made in flat position by completely automatic procedures
(b) SA - MIG welds, "short arc" with 0.030 electrode, 1 He/1 Ar gas mixture
(c) DCSP - TIG welds, straight polarity, He gas mixture, 1/16 inch cold wire feed
(d) Aged to T87
(e) Aged to T81
(f) 1 ksi = 0.70307 kg/mm²

(g) S = standard deviation = $\sqrt{\frac{(x-\bar{x})^2}{n-1}}$

TABLE 12.5. – Bend Angle of TIG Welded (2319 Filler) 2219-O Plate with T6E46 Post Weld Heat Treatment Bend over a Ram with a Bend Radius of 5T

Source	Ref. 12.3				
Alloy	2219-T6E46 = 0.25 inch (6.35 mm) thick (T) plate				
Total No. of Specimens	Type of weld	Repair filler wire	Bend angle, degrees		
			max	min	avg
18	Plate to plate	None	60	40	58
18		2319	60	16	26
32	Plate to forging	None	60	19	34
16		2319	47	15	23

TABLE 12.6. – Suggested Minimum Joint Overlap and Spacing of Spot Welds

Source	Ref. 12.25	
Alloy	Aluminum Alloys	
Thinnest sheet in joint, inch (a)	Minimum joint overlap, inch	Minimum weld spacing, inch
0.016	5/16	3/8
0.020	3/8	3/8
0.025	3/8	3/8
0.032	1/2	1/2
0.040	9/16	1/2
0.051	5/8	5/8
0.064	3/4	5/8
0.072	13/16	3/4
0.081	7/8	3/4
0.091	15/16	7/8
0.102	1	1
0.125	1-1/8	1-1/4

(a) 1 inch = 2.54 cm

TABLE 12.7. – Minimum Allowable Edge Distances for Spotwelded Joints (a, b, c)

Source	Ref. 12.33
Alloy	Aluminum Alloys
Nominal thickness of the thinner sheet, inch (d)	Edge distance, E, in
0.016	3/16
0.020	3/16
0.025	7/32
0.032	1/4
0.036	1/4
0.040	9/32
0.045	5/16
0.050	5/16
0.063	3/8
0.071	3/8
0.080	13/32
0.090	7/16
0.100	7/16
0.125	9/16
0.160	5/8

(a) Intermediate gages will conform to the requirement for the next thinner gage shown

(b) Edge distances less than those specified above may be used provided there is no expulsion of weld metal or bulging of the edge of the sheet or damage to bend radii by electrode

(c) Values may be reduced for nonstructural applications or applications not depended on to develop full weld strength

(d) 1 inch = 2.54 cm

TABLE 12.8. — Spot Weld Maximum Design Shear Strength in Panels for Bare and Clad Aluminum Alloys: Weld SPEC MIL-W-6858 (a, b, c)

Source	Ref. 12.33			
Alloy	Aluminum alloys, bare and clad			
Nominal thickness of thinner sheet, inch (d)	Material ultimate tensile strength			
	≥ 56 ksi (e)	20 to 56 ksi (e)	19.5 to 28 ksi (e)	< 19.5 ksi (e)
0.010	48	40	-	-
0.012	60	52	24	16
0.016	88	80	56	40
0.020	112	108	80	64
0.025	148	140	116	88
0.032	208	188	168	132
0.040	276	248	240	180
0.050	372	344	320	236
0.063	536	488	456	316
0.071	660	576	516	360
0.080	820	684	612	420
0.090	1004	800	696	476
0.100	1192	936	752	540
0.112	1424	1072	800	588
0.125	1696	1300	840	628
0.160	2496	1952	-	-
0.190	3228	2592	-	-
0.250	5880	5120	-	-

(a) The reduction in strength of spotwelds due to cumulative effects of time-temperature-stress factors is not greater than the reduction in strength of the parent metal

(b) Strength based on 80 percent of minimum values specified in MIL-W-6858

(c) The allowable tensile strength of spotwelds is 25 percent of the shear strength

(d) 1 inch = 2.54 cm

(e) 1 ksi = 0.70307 kg/mm^2

TABLE 12.9. – Specifications for Aluminum Rivets

Source	Ref. 12.1		
Products	Federal	Military	AMS
Rivets	FF-R-556a	MIL-R-1150A-1	7220C
	-	MIL-R-5674B-1	7222C
	-	MIL-R-12221B	7223
Rivets, blind	-	MIL-R-7885A-1	-
	-	MIL-R-8814-1	-
	-	MIL-R-27384	-
Rivet, wire	QQ-A-430-1	-	-

TABLE 12.10. – F_{su} (Average) for Driven Rivets (a)

Source	Ref. 12.31		
Alloy and Temper before Driving (b)	Driving Procedure	Alloy and Temper after Driving	F_{su} (Av), ksi
1100-H14	Cold, as received	1100-F	11(c)
2017-T4	Cold, as received	2017-T3	39
2017-T4	Cold, immediately after quenching	2017-T31	34(d)
2024-T4	Cold, immediately after quenching	2024-T31	42(d)
2117-T4	Cold, as received	2117-T3	33
5056-H32	Cold, as received	5056-H321	30
6053-T61	Cold, as received	6053-T61	23
6061-T4	Cold, immediately after quenching	6061-T31	24(d)
6061-T4	Hot, 990° to 1050° F (532°–566° C)	6061-T43	24(d)
6061-T6	Cold, as received	6061-T6	30
7277-T4	Hot, 850° to 975° F (454°–524°C)	7277-T41	38

(a) These values are for rivets driven with core point heads. Rivets driven with heads requiring more pressure may be expected to develop slightly higher strengths

(b) These designations should be used when ordering rivets

(c) 1 ksi - 0.70307 kg/mm²

(d) Immediately after driving, the shear strengths of these rivets are about 75% of the values shown. On standing at ambient temperatures, they age harden to develop full shear strength. This action takes about 4 days for 2017-T31 and 2024-T31 rivets. Values shown for 6061-T31 and 6061-T43 rivets are attained in about 2 weeks. Values of 26 ksi (18.3 kg/mm²) are attained by 6061-T3 rivets about 4 months after driving. Values shown for 7277-T41 rivets are attained in about one week.

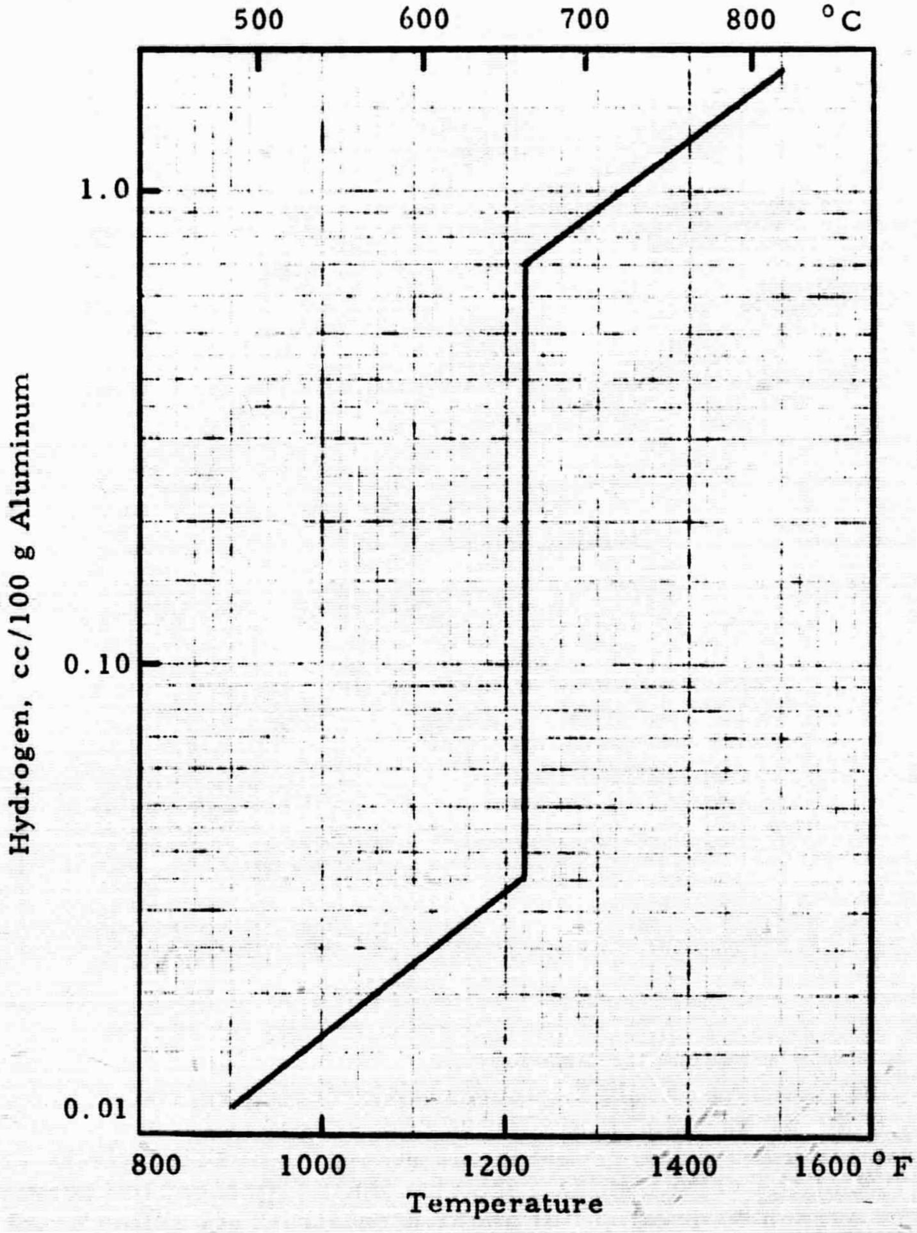


FIGURE 12.1.— Solubility of hydrogen in aluminum.
(Ref. 12.9)

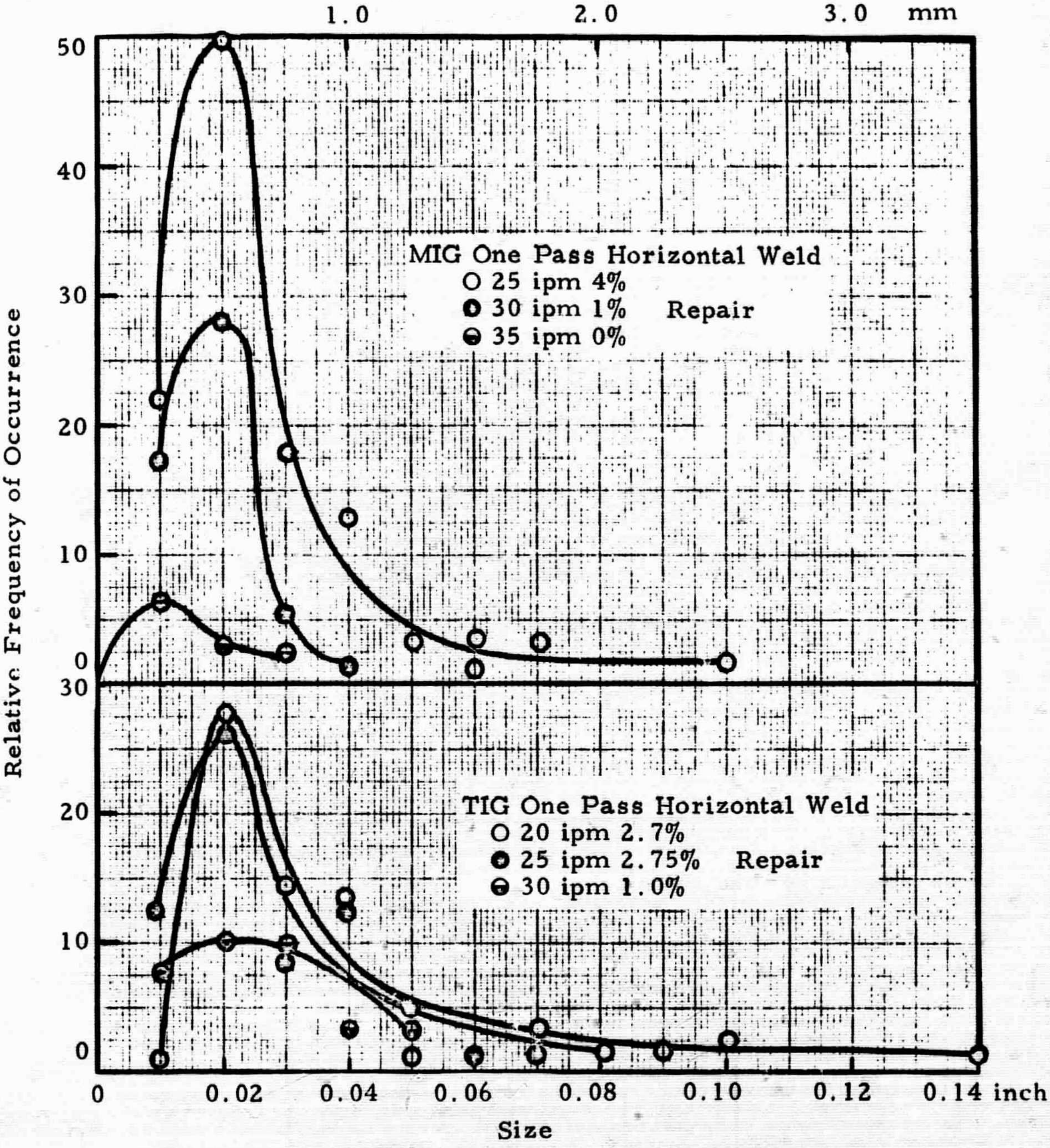


FIGURE 12.2. – Effect of welding speed on the occurrence and size of porosity in a 2219-T87 cylinder joined by TIG and MIG butt welding; cylinder, 132-inch diameter (3.35 mm), 0.224-inch thick (5.69-mm).

(Ref. 12.10)

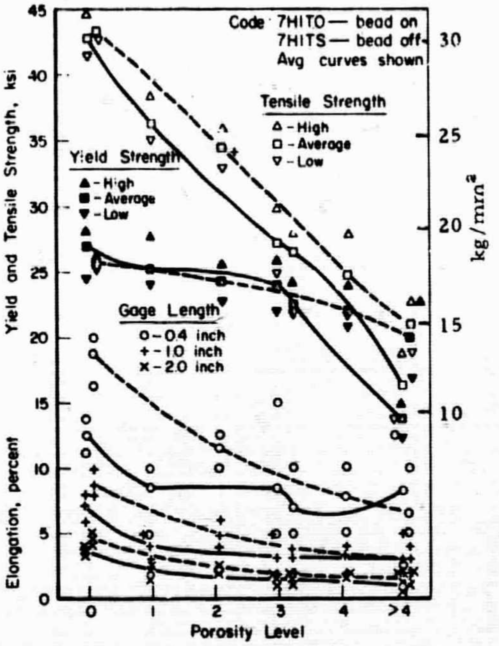


FIGURE 12.3. – Tensile properties of 2219-T87 sheet containing increasing levels of porosity (as graded by radiography); thickness, 1/4-inch (6.35 mm).

(Ref. 12.38)

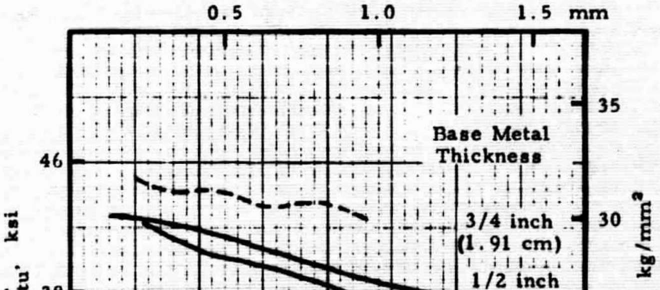


FIGURE 12.4. – Effect of weld joint misalignment on the tensile strength of TIG welded 2219-T87 joints.

(Ref. 12.11)

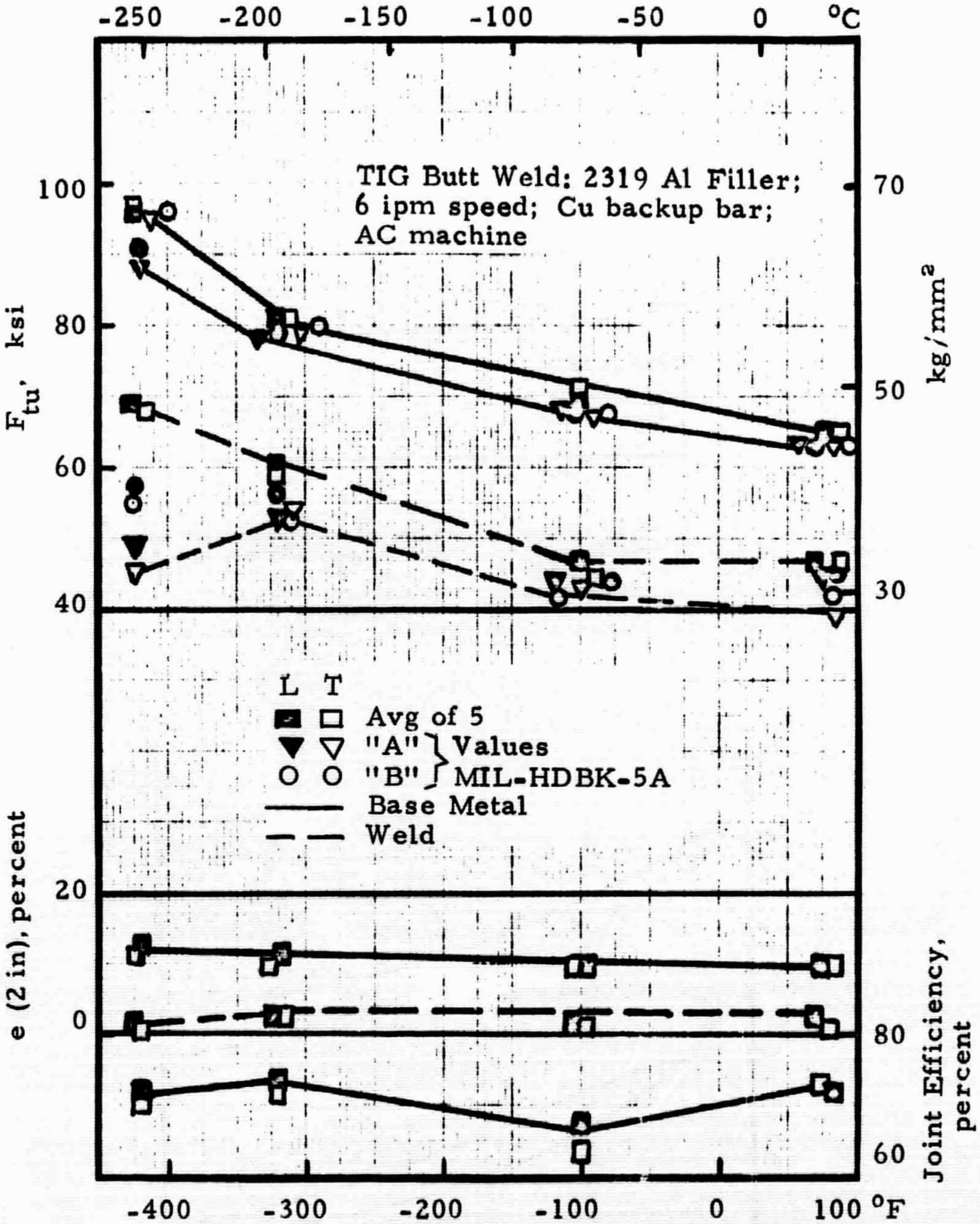


FIGURE 12.5. – Effect of test temperature on tensile properties of base metal and butt-welded 2219-T81 sheet; thickness 0.063 inch (1.600 cm).

(Ref. 12.13)

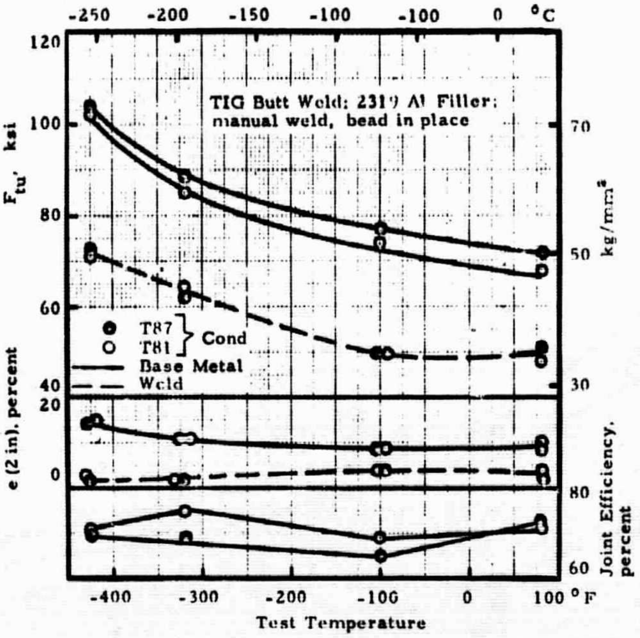


FIGURE 12.6. — Effect of test temperature on tensile properties of base metal and butt-welded 2219 sheet; thickness, 0.063 inch (1.600 cm).

(Ref. 12.14)

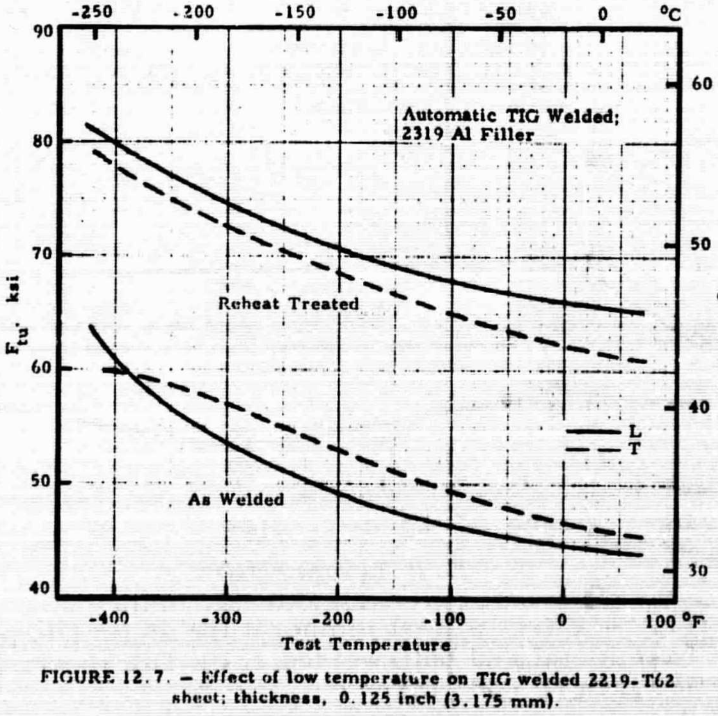


FIGURE 12.7. — Effect of low temperature on TIG welded 2219-T62 sheet; thickness, 0.125 inch (3.175 mm).

(Ref. 12.19)

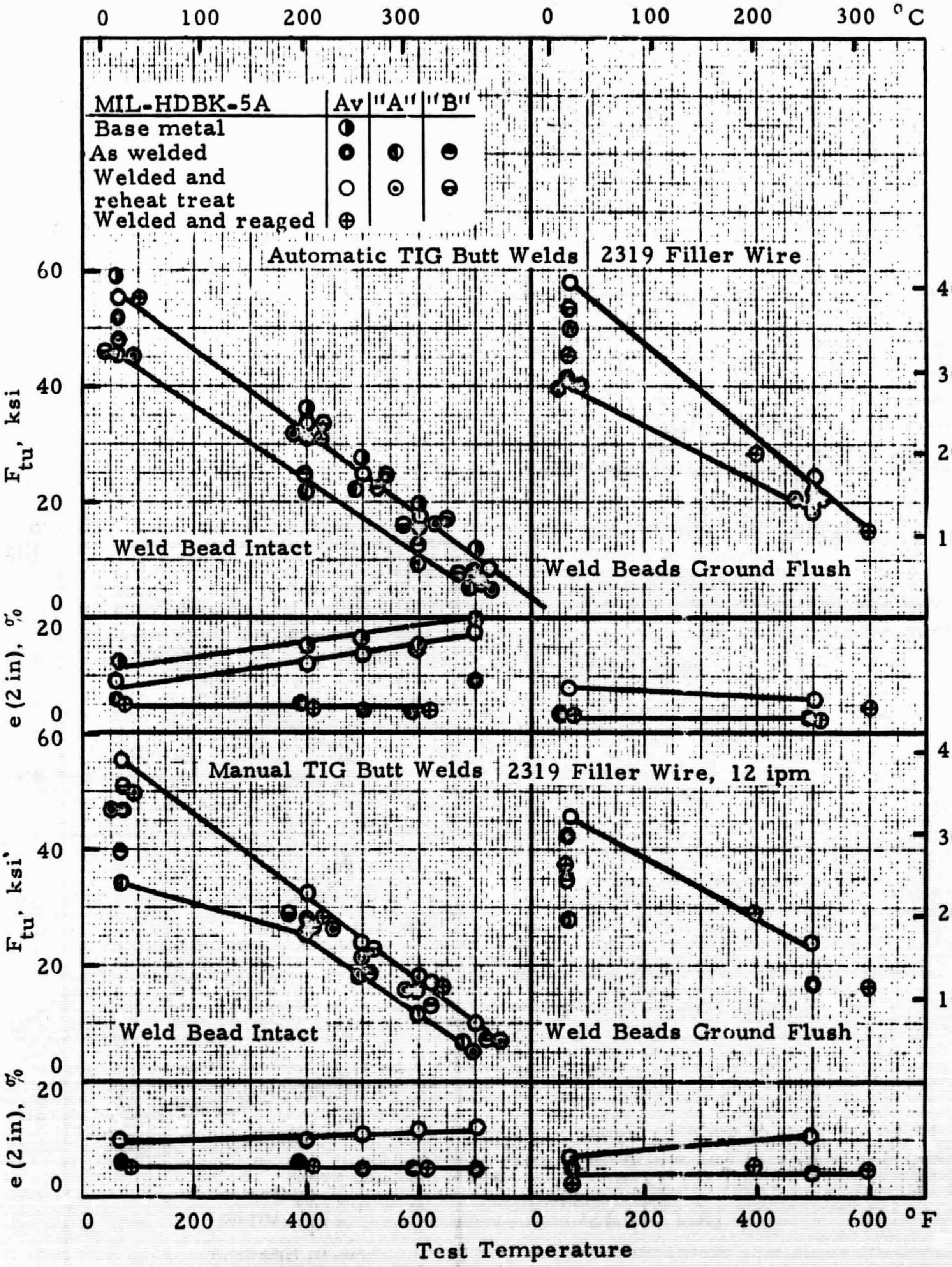


FIGURE 12.8. – Effect of temperature and welding procedure on tensile strength and elongation of butt-welded 2219-T6 sheet; thickness, 0.071 inch (1.803 mm). (Ref. 12.15)

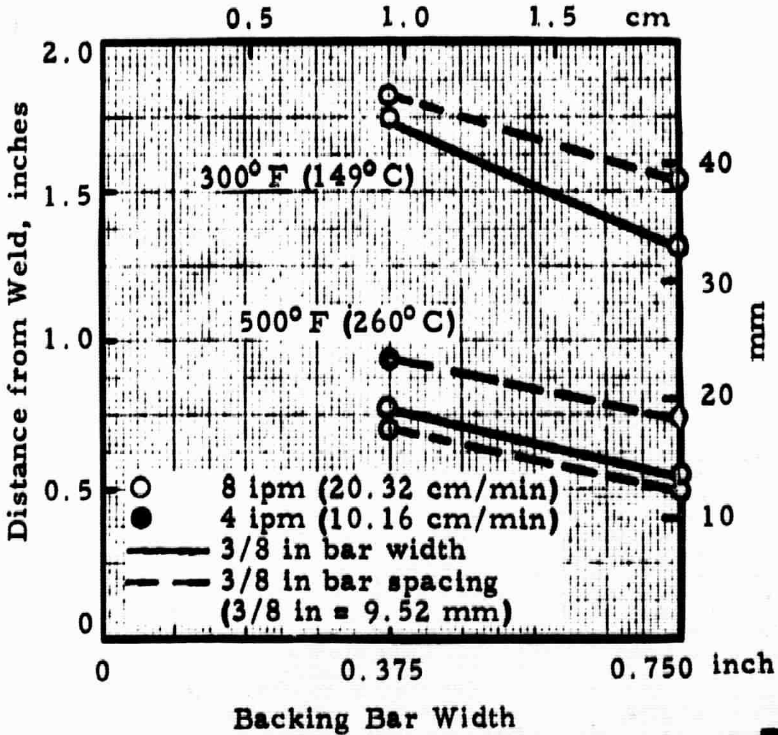


FIGURE 12.9.—Effect of welding speed and backup bar gap and width on welding temperature limit for 2219.

(Ref. 12.16)

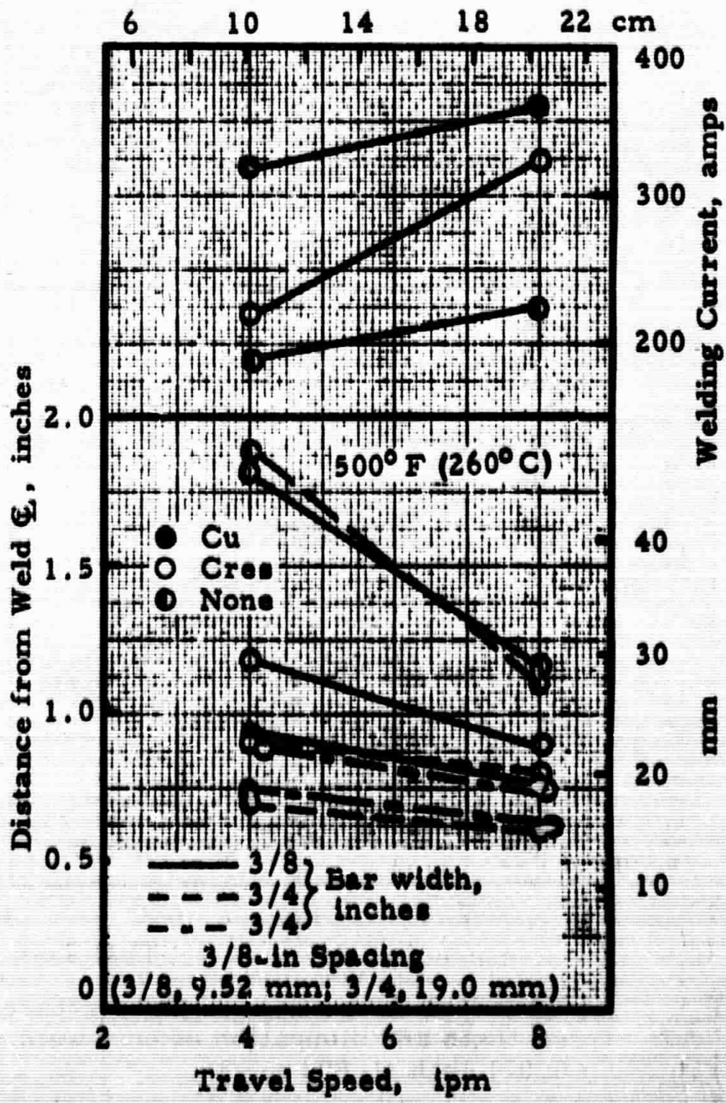


FIGURE 12.10.—Effect of welding speed and backup bar material and width on welding temperature limit for 2219.

(Ref. 12.16)

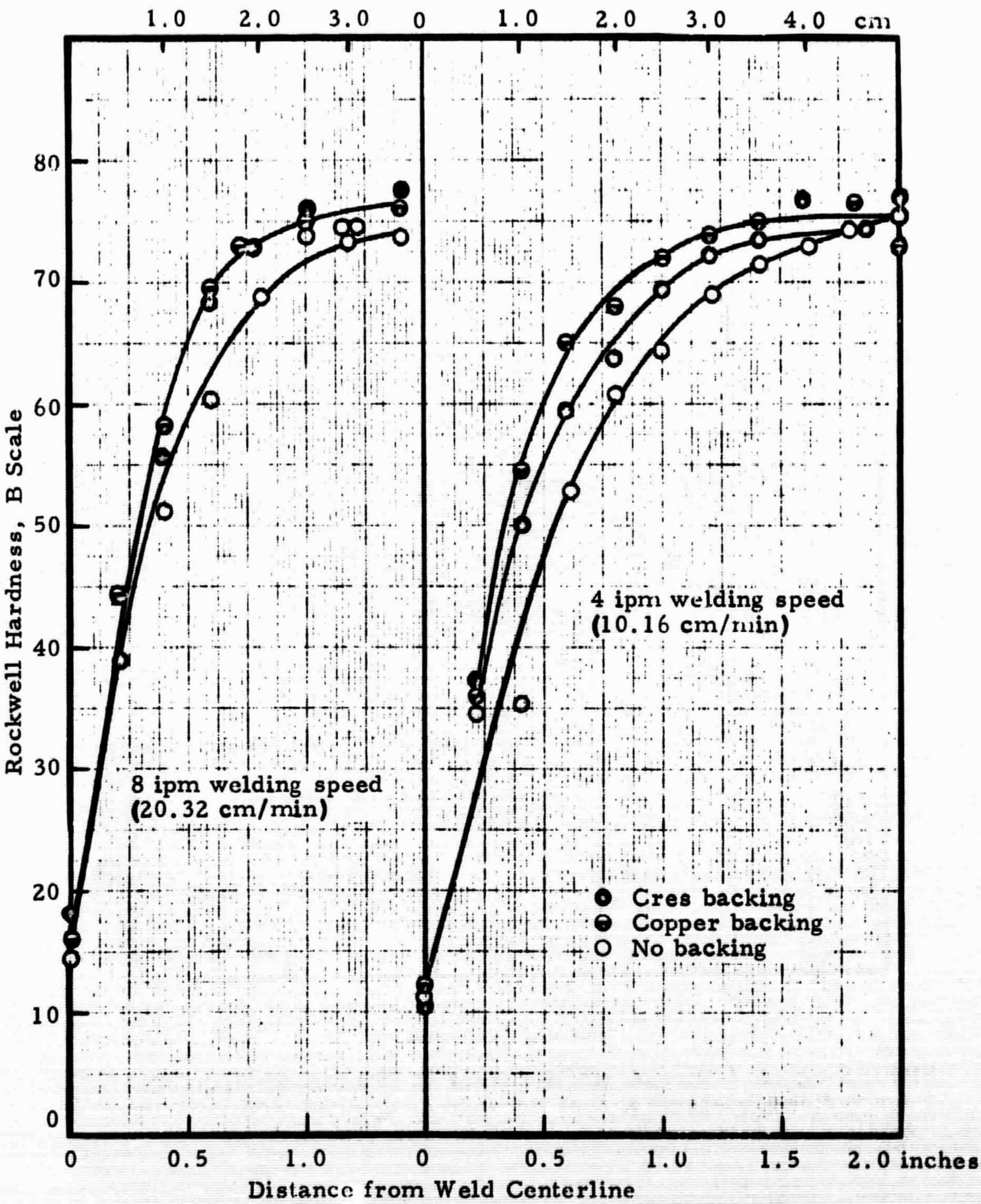


FIGURE 12.11. – Effect of weld backing and welding speed on hardness values of TIG butt-welded 2219-T87 plate; thickness, 3/8 inch (9.52 cm).

(Ref. 12.16)

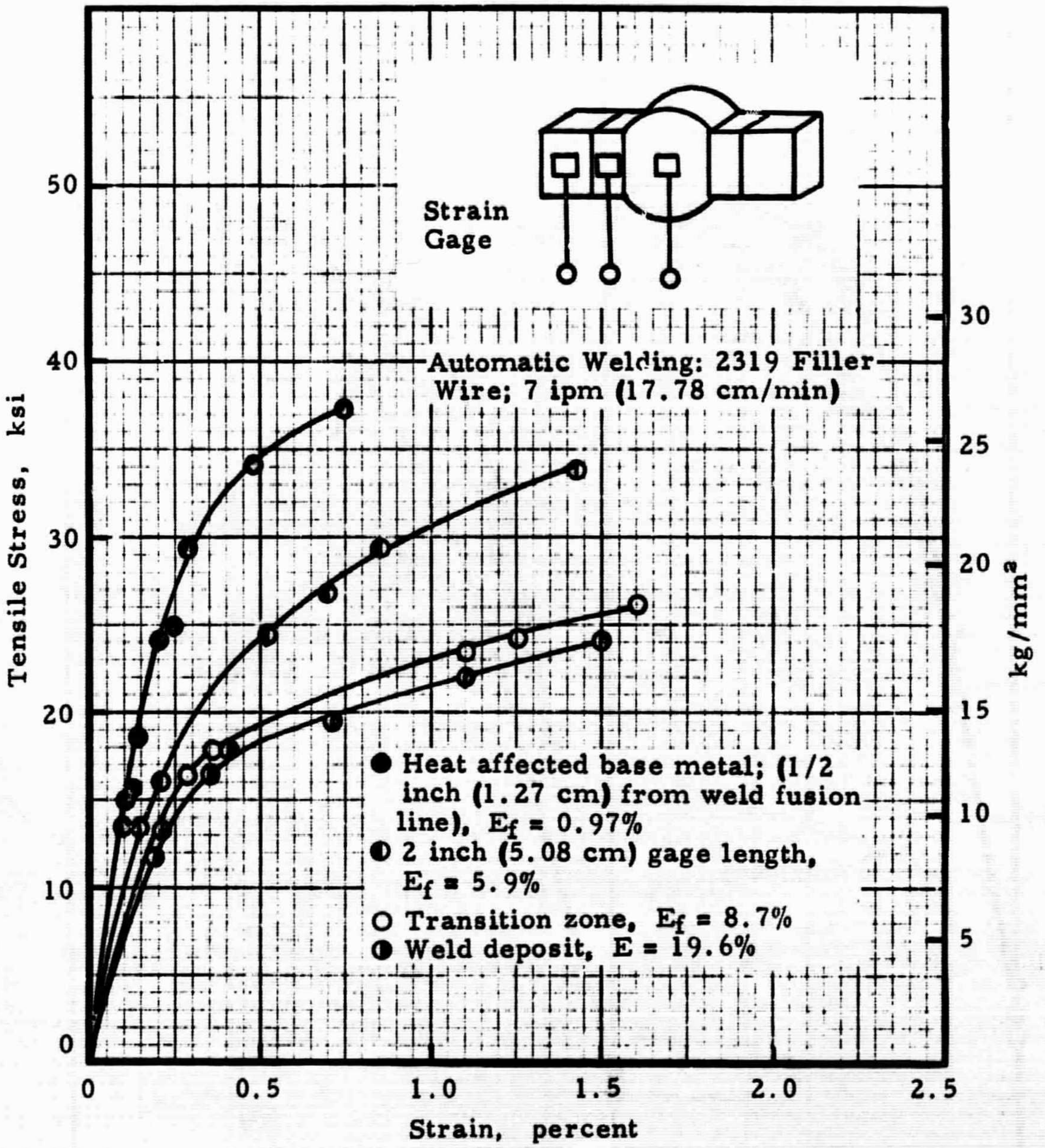


FIGURE 12.12. – Stress-strain curves of TIG butt-welded 2219-T87 for various locations across the weld as derived from miniature strain gage data; thickness, 0.250 inch (6.35 mm).

(Ref. 12.36)

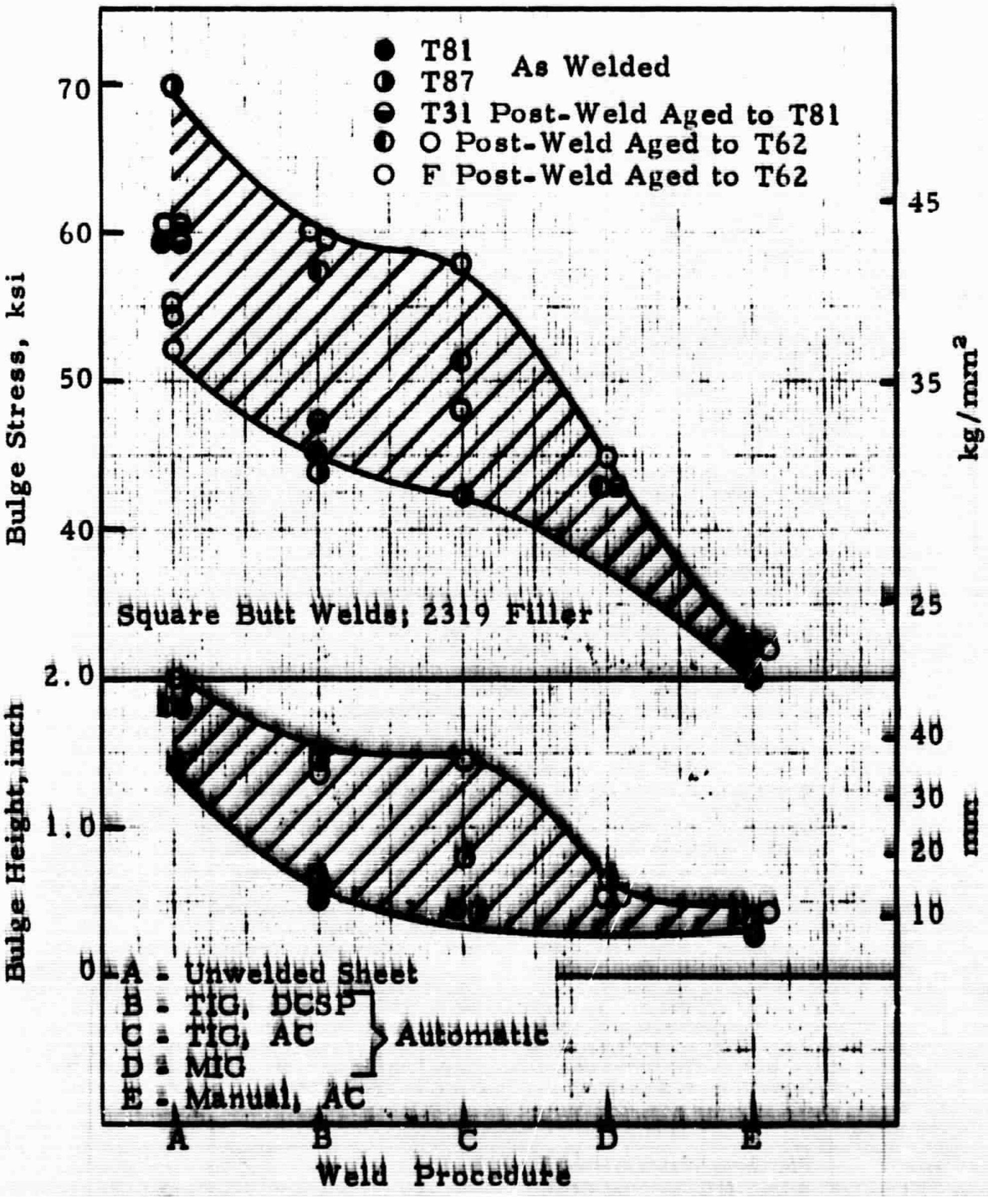


FIGURE 12.13. – Effect of weld procedure and heat treatment on bulge properties of 2219 sheet; thickness, 0.064 inch (1.626 mm).

(Ref. 12.5)

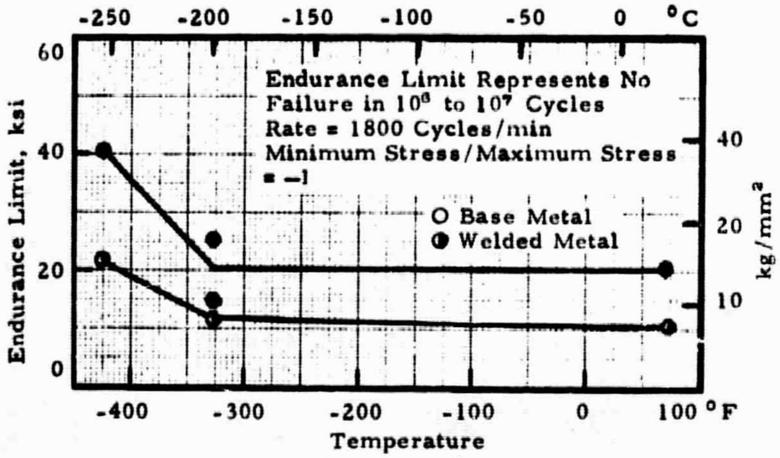


FIGURE 12.14. – Effect of temperature on endurance limit of base metal and butt-welded 2219-T87 sheet; thickness, 0.063 inch (1.600 mm).

(Ref. 12.17)

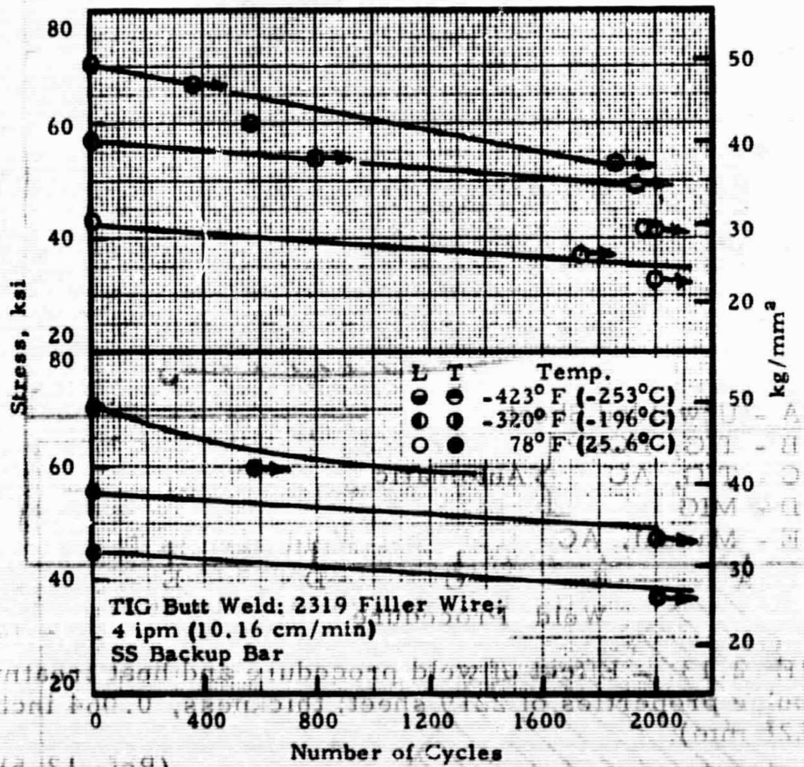


FIGURE 12.15. – S-N curves for TIG butt-welded 2219-T87 sheet at room and cryogenic temperatures; thickness, 0.125 inch (3.175 mm).

(Ref. 12.13)

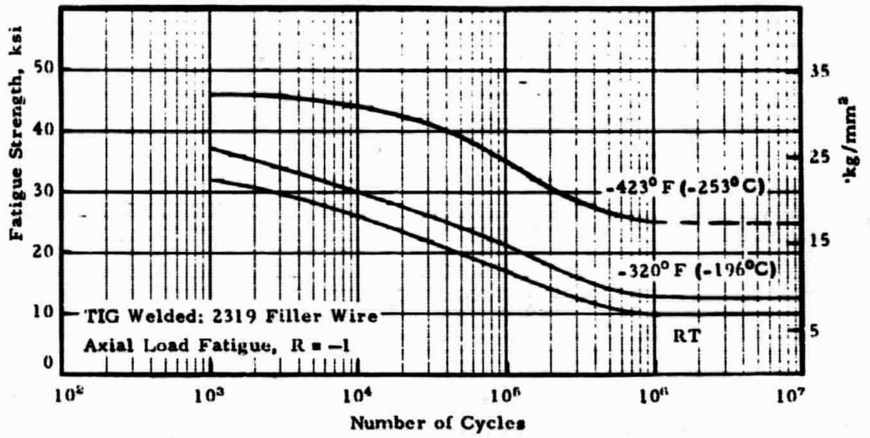


FIGURE 12.16. – Fatigue strength of as-welded 2219-T87 sheet at at room and cryogenic temperatures; thickness, 0.125 inch (3.175 mm).

(Ref. 12.18)

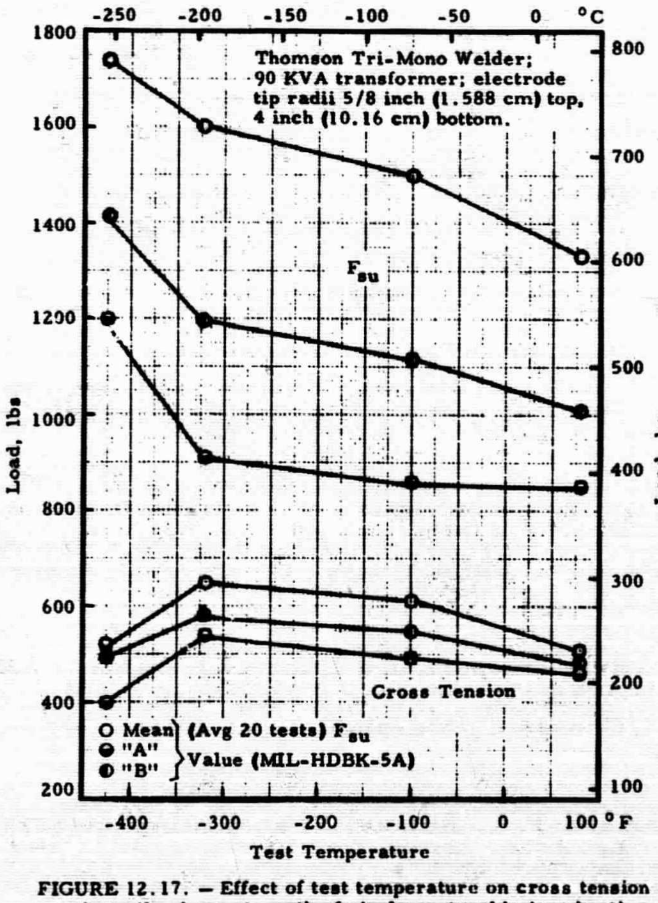


FIGURE 12.17. – Effect of test temperature on cross tension and tensile shear strength of single spot welds (one heat) on 2219-T81 sheet; thickness, 0.063 inch (1.600 mm).

(Ref. 12.25)

Chapter 12 - References

12.1 Aluminum Company of America, Alcoa Product Data "Specifications," Section A12A, July 1, 1963.

12.2 Reynolds Metals Company, "The Aluminum Data Book - Aluminum Alloys and Mill Products," 1958.

12.3 C.H. Crane and W.G. Smith, "Application of 2219 Aluminum Alloy to Missile Pressure-Vessel Fabrication," Welding Journal, 40 (1), 33-s (1961).

12.4 P.J. Rieppel, "Weld Defects in Aluminum versus Base-Plate and Filler Wire Composition," Battelle Memorial Institute, Minutes - Aluminum Welding Symposium, July 1964, NASA/George C. Marshall Space Flight Center, October 1964, p. 63.

12.5 I.B. Robinson, F.R. Collins, and J.D. Dowd, "Welding High Strength Aluminum Alloys," Welding J., 41, 221-s (1962).

12.6 Aluminum Company of America, "Alcoa Structural Handbook," Eighth Printing, 1960.

12.7 Z.P. Saperstein and D.D. Pollack, "Porosity Formation and Solidification Phenomena in Aluminum Welds," Douglas Aircraft Co., Minutes-Aluminum Welding Symposium, July 1964, NASA/George C. Marshall Space Flight Center, October 1964, p. 96.

12.8 H. Brown, "Aluminum Fabrication versus Environmental Humidity," TRW, Inc./Electromechanical Division, Minutes - Aluminum Welding Symposium, July 1964, NASA/George C. Marshall Space Flight Center, October 1964, p. 55.

12.9 F.R. Baysinger, "Observations on Porosity in Aluminum Weldments," Kaiser Aluminum and Chemical Co., Minutes - Aluminum Welding Symposium, July 1964, NASA/George C. Marshall Space Flight Center, October 1964, p. 55.

12.10 G. Case, "Time-Temperature Effects on Welds in 2219-T87 Aluminum Alloy," NASA/MSFC, Minutes - Aluminum Welding Symposium, July 1964, NASA/George C. Marshall Space Flight Center, October 1964, p. 151.

12.11 H.B. Farner and T.R. Rutkay, "Fabricating the S-1C Space Booster," Welding J., 44, 29 (1965).

12.12 D.M. Daley and D.C. Jefferys, "Development of Weld Fabrication Techniques for the S-1C Saturn V Vehicle," Welding J., 43 (1), 34 (1964).

12.13 J.L. Christian, "Physical and Mechanical Properties of Pressure Vessel Materials for Application in a Cryogenic Environment," ASD-TDR-62-258, General Dynamics/Astronautics, Part II, March 1962.

12.14 J.L. Christian and J.F. Watson, "Mechanical Properties of Several 2000 and 6000 Series Aluminum Alloys at Cryogenic Temperatures," General Dynamics, Contract AF 33(616)-7984, 2nd Quarterly Progress Report, December 1962.

12.15 L. Yates, R. Peck, and J. Gilmore, "Evaluation of the Mechanical Properties and the Weldability of 0.071-in X-2219-T6 Aluminum Alloy Sheet," North American Aviation, Inc./Missile Division, Report MDL-229, January 1960.

12.16 C.L. Cline, "An Analysis of Heat Transfer During the Welding of 2219-T87 Aluminum Alloy Plate," Lockheed Missiles & Space Company, Minutes = Aluminum Welding Symposium, July 1964, NASA/. George C. Marshall Space Flight Center, October 1964, p. 165.

12.17 J.E. Campbell, "Evaluation of Special Metal Properties," DMIC Review of Recent Developments, December 20, 1963.

12.18 F.R. Schwartzberg et al., "Determination of Low Temperature Fatigue Properties of Aluminum and Titanium Alloys," Annual Summary Report, Martin Co., Denver, July 1963.

12.19 M.P. Hanson et al., "Sharp Notch Behavior of Some High Strength Aluminum Alloys and Welded Joints at 75, –320, and –423 F, ASTM STP-287, 1960.

12.20 F.R. Collins, "Investigation Toward Obtaining Significantly Higher Mechanical Properties of As-Welded Joints in High Strength Heat-Treatable Aluminum Alloys," Report No. 2-6-44, Aluminum Co. of America, September 1961.

12.21 Index of Specifications and Standards, Department of Defense, Part I, Alphabetical Listing, Supplement, May 1971.

12.22 ASTM Standards, Part 6, "Light Metals and Alloys," 1971.

12.23 SAE Aerospace Material Specifications, Society of Automotive Engineers, May 1971.

12.24 G. Cooper, F. Palermo, and J.A. Browning, "Recent Deveopments in Plasma Welding," Welding J., 44(4), 268 (1965).

12.25 Aluminum Co. of America, "Welding Alcoa Aluminum," Third Printing, 1958.

12.26 Welding Handbook, Sec. 2, American Welding Society, N.Y., 1967.

12.27 "Flash Welded Combat Vehicles," Govt. Research Report, AD-602 874, U.S. Dept. of Commerce, Washington, D.C.

12.28 W. Groth, "Trends in Welding Aluminum," Lockheed Missiles & Space Co., Metal Progress, 83(6), 76 (1963).

12.29 Welding Handbook, Sec. 3, Ch.3, American Welding Society, New York, 1967.

12.30 Aluminum Co. of America, "Brazing Alcoa Aluminum," 1959.

12.31 Aluminum Co. of America, "Alcoa Structural Handbook," 1960.

12.32 Aluminum Co. of America, "Riveting Alcoa Aluminum," 1960.

12.33 Military Handbook 5A, "Metallic Materials and Elements for Flight Vehicle Structures," Department of Defense, Washington, D.C., February 1966, latest change order, January 1970.

12.34 R.A. Stocker, "Gas Metal-Arc Spot Welding of Aluminum," Welding J., 41 (9), 815 (1962).

12.35 E.F. Deesing, "A Study of the Resistance and Fusion Welding Characteristics of X-2219 Aluminum Alloy," Report No. NAMC-AML-AE-1109, Naval Air Material Center, February 1960.

12.36 N.G. Lenamond, J. McDonald, Jr., and K.K. Speirs, "Strain Distribution and Failure Mechanisms in 2219-T87 Aluminum Weldments," Southwest Research Institute, Mintes - Aluminum Welding Symposium, July 1964, NASA/George C. Marshall Space Flight Center, October 1964, p. 185.

12.37 R.P. Meister and D.C. Martin, "Welding of Aluminum and Aluminum Alloys," DMIC Report 236, April 1, 1967.

12.38 Martin Co., "Analytical and Statistical Study of the Effects of Porosity on Weld Joint Performance, Contract NAS8-11335, March 1966, NASA document No. N66-24588.

12.39 H. James, "Electron Beam Welding," Paper No. 6, Session No.2, Aluminum Welding Seminar, Chicago, Illinois, February 23-25, 1966.

12.40 M.W. Brennecke, "Electron-Beam-Welded Heavy-Gage Aluminum Alloy 2219," Welding J., 44 (1), 27s (1965).

12.41 B. Schumacher, "Improved Electron-Beam Welding Technique," NASA Tech Brief 70-10127, June 1970.