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MATERIALS DATA HANDBOOK

Aluminum Alloy 2014

(2nd Edition)

p.2 A

Revised by

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Prepared for

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

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PREFACE

The revised edition of the Materials Data Handbook on the aluminum alloy 2014 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, April 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 2014 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 2014 " 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.

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TABULAR ABSTRACT

Aluminum Alloy 2014

TYPE:

Wrought, heat treatable aluminum alloy

NOMINAL COMPOSITION:

Al-4.4Cu-0.8Mn-0.8Si-0.5Mg

AVAILABILITY:

Bare and clad sheet and plate, rod, bar, wire, tube, extruded shapes, forgings and forging stock.

TYPICAL PHYSICAL PROPERTIES:

Density	2.80 g/cm^3 at room temperature
Thermal Conductivity (O temper)	0.46 $cal/cm/cm^2/sec/^\circ C$
(T6 temper)	0.37 $cal/cm/cm^2/sec/^\circ C$
Av. Coeff. of Thermal Expansion	23.0 $\mu cm/cm/^\circ C$ (20–100°C)
Specific Heat	0.23 $cal/g\ ^\circ C$ at 100°C
Electrical Resistivity (O temper)	3.4 microhm-cm at 20°C
(T6 temper)	4.3 microhm-cm at 20°C

TYPICAL MECHANICAL PROPERTIES:

F_{tu} (O temper)	27.0 ksi (19.0 kg/mm^2)
(T6 temper)	70.0 ksi (49.2 kg/mm^2)
F_{ty} (O temper)	14.0 ksi (9.8 kg/mm^2)
(T6 temper)	60.0 ksi (42.2 kg/mm^2)
e(2 in, 50.8 mm) (O temper)	18 percent
(T6 temper)	13 percent
E (tension)	10.6 x 10^3 ksi (7.5 x 10^3 kg/mm^2)

FABRICATION CHARACTERISTICS:

Weldability	Good by fusion and resistance methods if proper procedures are used
Formability	Good in the annealed condition; difficult to form in T6 temper
Machinability	Good in the T6 temper

COMMENTS:

A high strength aluminum alloy, often used for heavy duty structures.

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 2014 is a heat-treatable wrought alloy, developed by the Aluminum Company of America in 1928 as a high strength alloy having good ductility and machinability for aircraft and other heavy-duty structural uses. The base alloy is similar to the commonly used 2024 (developed in 1931) in that copper is the primary alloying addition. Early in its history, 2014 was used mainly in the form of forging and extrusion products; at this time, the alloy is available in various products including sheet and plate (refs. 1.1, 1.3, 1.6, 1.7).

1.2 The alloy has good forming characteristics and can be welded satisfactorily using both fusion and resistance welding techniques. When used as sheet or plate, the alloy is frequently clad to provide improved resistance to corrosion in a variety of environments. An advantage of 2014 is that it may be formed in the as-quenched temper and subsequently artificially aged to the T6 temper (ref. 1.1). Thus, forming operations of greater severity can be performed than would be possible in the T6 condition.

1.3 Typical areas of application are use in heavy-duty structures, aircraft structures, bridges, and truck frames. The alloy is also used for rivets, structural fittings, and hardware. Alclad 2014 is used for high strength structural applications where high resistance to corrosion is required (refs. 1.3, 1.7).

1.4 <u>General Precautions</u>

1.41 Overheated material exhibiting eutectic melting or material oxidized at high temperature should not be used and cannot be salvaged by reheat treatment.

1.42 All quench operations should be performed as rapidly as possible because of possible precipitation and, consequently, reduced resistance to corrosion.

Chapter 1 - References

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

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

1.3 Alloy Digest, "Aluminum 2014," (Filing Code A-17), Engineering Alloys Digest, Inc., June 1954.

1.4 Metals Handbook, Vol. 1, "Properties and Selection of Metals," 8th Edition, American Society for Metals. Metals Park, Ohio, 1961.

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

1.6 Aluminum Association of America, "Aluminum Standards & Data: 1970-71," New York.

1.7 1971 SAE Handbook, Society of Automotive Engineers, New York.

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

Chapter 2

PROCUREMENT INFORMATION

2.1 General. Aluminum 2014 alloy is commercially available in a full range of sizes for sheet, plate, rod, bar, wire, tube, shapes, forgings, and forging stock. Products such as bar, rod, and shapes are produced as extrusions or by rolling and drawing. Alclad 2014 is available as sheet and plate. Detailed tables of standard tolerances for the various products available are given in reference 2.1.

2.2 Procurement Specifications. Specifications that apply to the 2014 alloy as of May 1971 are listed in table 2.2 for various products and tempers.

2.21 NASA Specifications, see table 2.21 (refs. 2.8, 2.9).

2.3 Major Producers of the Alloy (United States only)

Aluminum Company of America
1501 Alcoa Building
Pittsburgh, Pennsylvania

Harvey Aluminum
General Offices
Torrance, California

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

Olin-Mathieson Chemical Corporation
460 Park Avenue
New York, New York

Reynolds Metals Company
6601 West Broad Street
Richmond, Virginia

2.4 Available Forms, Sizes, and Conditions

2.41 Typical commercial sizes and tempers available for various products are listed in table 2.41.

TABLE 2.2. — Procurement Specifications (a)

Source	Refs. 2.1, 2.2, 2.6, 2.7				
Alloy	2014				
Product	Temper	Military	Federal	ASTM	AMS(b)
Bar, rod, shapes and tube (extruded)	F	-	-	B221-71	-
	O	-	QQ-A-200/2D	B221-71	-
	T4, T4510, T4511	-	QQ-A-200/2D	B221-71	-
	T42, T62	-	QQ-A-200/2D	B221-71	-
	T6510, T6511	-	QQ-A-200/2D	B221-71	-
	T6	-	QQ-A-200/2D	B221-71	4153F
Bar, rod, wire,	O	-	QQ-A-225/4C	B211-71	-
	T4	-	QQ-A-225/4C	B211-71	-
	T451	-	QQ-A-225/4C	-	-
	T6	-	QQ-A-225/4C	B211-71	4121D
	T651	-	QQ-A-225/4C	-	-
Sheet and plate	O	-	QQ-A-250d	B209-71	4028C
	T3	-	-	B209-71	-
	T6, T651	-	-	B209-71	4029E
	T62	-	-	B209-71	-
Alclad sheet and plate	F	-	QQ-A-250/3E	-	-
	O, T3, T4	-	QQ-A-250/3E	B209-71	-
	T42, T451	-	QQ-A-250/3E	B209-71	-
	T6, T651	-	QQ-A-250/3E	B209-71	-
	T62	-	-	B209-71	-
Forgings, stock	F	-	-	-	4134A, 4135J
, die	T4	-	QQ-A-367g	B247-70	4134A
, die	T6	MIL-A-22771B	QQ-A-367g	B247-70	4135J
, die	T652	MIL-A-22771B	-	-	-
, rolled rings	T6	-	-	-	4135J
, hand	T6	MIL-A-22771B	QQ-A-367g	-	4135J
, hand	T652	MIL-A-22771B	QQ-A-367g	-	-
Impact extrusions	F, O, T4, T6	MIL-A-12545B	-	-	-
Structural shapes (rolled or extruded)	T4, T6	MIL-A-25994	-	B308-70	-
Tube, seamless drawn	O, T4, T6	-	-	B210-70	-

(a) Current as of May 1971.   (b) See also reference 2.4, AA2014.

TABLE 2.21. — NASA-MSFC Specifications

Specification	Product	Tempers
MSFC-SPEC-104	Bare plate and sheet	O, T3, T4, T6, F, T651, T451
MSFC-SPEC-144B	Forgings, premium quality, heat treated	T4, T6, T652

TABLE 2.41. — Typical Availability and Size Ranges of Mill Products

Source	Ref. 2.1	
Alloy	2014	
Type	Temper	Dimensions (a)
Extrusion billets	-	Diam, in: 5-1/8, 6, 7, 9, 11, 14
Impact extrusions	O, T4, T6	Diam, in: ≤ 14. Lengths, ft: ≤ 12
Forgings	T6	(b)
Extruded shapes	O, T4	Circum. circle diam, in: ≤ 25; Thicknesses, in: 0.040 to >0.750 (b)
	T6	Circum. circle diam, in: ≤ 25 Thicknesses, in: 0.125 to >0.750 (b)
Coiled sheet, bare and alclad (c) mill finish	O, F	Thicknesses, in: 0.016 to 0.125 Widths, in: 0.5 to 60 Arbor sizes, in: 16 and 20
Flat sheet, bare and alclad (c) mill finish or skin quality finish	O, T3, T6	Thicknesses, in: 0.016 to 0.249 Widths, in: 3 to 60 Lengths, in: 24 to 180
Plate, mill finish	O, F, T4, T6, T451, T651	Thicknesses, in: 0.250 to 1.00 Widths, in: 6 to 72 Lengths, in: 48 to 180
Wire, rod, and bar (rolled or cold finished)	O, T4, T451, T6, T651	Thicknesses (or diam), in: ≤ 8.00
Tubing, drawn	O, T4, T6	Wall thicknesses, in: 0.018 to 0.500

(a) 1 inch = 25.4 mm; 1 foot = 0.3048 m.

(b) Consult manufacturer for range limits.

(c) Clad both sides with Al-6003.

Chapter 2 - References

2.1 The Aluminum Association, "Aluminum Standards & Data: 1970-71," New York.

2.2 ASTM Standards, Part 6, American Society for Testing and Materials, Philadelphia, 1971.

2.3 Olin Aluminum, "Olin Aluminum: Mill Products and Casting Alloys," 1971.

2.4 1971 SAE Handbook, Society of Automotive Engineers, New York.

2.5 Harvey Aluminum, "Mill Products - Alloys," June 1967.

2.6 Aerospace Material Specifications, Society Automotive Engineers, Inc., New York; latest Index, May 1971.

2.7 Department of Defense, Index of Specifications and Standards. Part I, Alphabetical Listing, and Part II, Numerical Listing; latest Index, May 1971.

2.8 George C. Marshall Space Flight Center, MSFC-SPEC-104, "Aluminum Alloy Bare, Plate and Sheet," April 2, 1961; amended April 30, 1964. Custodian: NASA-MSFC.

2.9 George C. Marshall Space Flight Center, MSFC-SPEC-144B, "Aluminum Forgings, Premium Quality, Heat Treated," August 13, 1966; amended September 8, 1964. Custodian: NASA-MSFC.

Chapter 3

METALLURGY

3.1 Chemical Composition

3.11 Nominal chemical composition of 2014 alloy, in percent (ref. 3.2):

Cu	4.4	Mn	0.8
Si	0.8	Mg	0.5
	Al	Balance	

3.111 Sheet and plate are available in Alclad condition. Cladding material is 6003 alloy; nominal composition, in percent:

Cr	0.25	Si	0.7
Mg	1.3	Al	Balance

Cladding is applied to both sides. The nominal cladding thickness per side is 10 percent of the total thickness of the composition if the latter is below 0.040 inch and 5 percent for total thickness of composite products 0.040 inch to 0.099 inch. For composite thicknesses of 0.100 inch and above, the nominal cladding thickness on each side is 2.5 percent (refs. 3.2, 3.5, 3.7). (Note: 1 inch = 25.4 mm.)

3.12 Chemical composition limits, in percent (ref. 3.2):

Cu	3.9 - 5.0	Cr	0.10 max
Si	0.50 - 1.2	Zn	0.25 max
Mn	0.40 - 1.2	Ti	0.15 max
Fe	0.7 max	Other	0.05 max each, total not to exceed 0.15
Mg	0.20 - 0.8		
	Al	Balance	

Conformity with these composition limits are normally checked by spectrochemical analysis or in accordance with the procedure outlined in ASTM E34, "Standard Methods for Chemical Analysis of Aluminum and Aluminum Base Alloys" (ref. 3.2).

3.13 Alloying Elements. The principal alloying elements are Cu, Mg, Mn, and Si. The aluminum-rich portions of the binary diagrams with each of these principal alloying elements are given in figures 3.131 and 3.132. The additions of Cu, Mn, and Mg render the alloy heat-treatable by a precipitation-hardening mechanism. The primary hardening agent is $CuAl_2$, modified by the presence of Mg. There also is a precipitation of metallic Si; both precipitates increase the attainable strength through artificial aging. The G.P. zones are responsible for the natural aging and artificial aging characteristics of the alloy. Mn is added to prevent the formation of the undesirable constituent Al-Cu-Fe-Si and acts together with Ti to cause grain refinement (ref. 3.8). Fe, Cr, and Zn are present as undesirable impurities. 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 percent Cu (ref. 3.4).

Since initial precipitation usually occurs along grain boundaries, zones lean in solutes will develop near the grain boundaries. These anodic zones will corrode selectively by an electrochemical process producing notches that cause stress concentrations. 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 influenced.

The amount of protection provided by cladding depends on the thickness and the purity of the cladding material, and also on the annealing and heat treatments (see Section 3.111).

3.2 Strengthening Mechanisms

3.21 General. The alloy can be strengthened by precipitation-hardening and cold work, although cold work is not generally used. The precipitation-hardening mechanisms are evident from the phase diagram relationships given in figures 3.131 and 3.132. Upon quenching from solution temperature to room temperature, precipitation occurs in the form of submicroscopic particles which represent obstacles to plastic flow and thus cause hardening. Cold working also can produce a considerable amount of 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 producing the T3, T451, T452, and T651 tempers. However, cold work is not normally used to develop commercial tempers for this alloy.

3.22 Heat Treatment

3.221 Anneal (O Condition): All products; heat to 400° to 426°C, 2 to 3 hours, follow by furnace cooling at a rate of 10°C/hour to at least 260°C (ref. 3.1). Intermediate anneals during repeated cold-working operations should be performed at 344°C for no more than 30 minutes at a time.

3.222 Solution Treatment: All products; heat to 496° to 507°C, hold 10 minutes to 1 hour in salt bath (or longer in air) depending on thickness, quench in cold water. If held at room temperature, a naturally aged T4 condition develops after 4 days. If the treatment is performed by the user, the proper designation is T42.

3.2221 It should be noted that the solution-treat temperature should be closely controlled. If temperature is too high, it may cause solid solution grain boundary melting, high temperature oxidation and eutectic melting which cannot be corrected by subsequent heat treat operations. Low temperature may result in incomplete solution of the hardening constituents with a loss in hardening potential. Rapid quenching is also important because of possible precipitation and consequently reduced corrosion resistance on slow cooling from the solution treating temperature. The maximum allowable quench delay times are given below:

Nominal Thickness		Maximum Time, sec
≤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

3.223 Precipitation Treatment: All products; heat T4 material to 168° to 174°C, hold 8 to 12 hours. Cooling rate is not critical. This treatment is usually performed by the supplier, and the condition is designated as T6 if performed by the user; otherwise, the designation is T62.

3.224 Other Treatments: The alloy can also be hardened by cold work, but this procedure is not generally used to develop strength in commercial tempers. Cold work, however, is employed for flattening (sheet or strip) or for stress relief.

3.2241 T3 Condition: 1-percent cold rolling of solution-treated material.

3.2242 T451 Condition: Stress relieve T4 material by stretching 1.5 to 3 percent for plate or 1 to 3 percent for rod, bar, and shapes.

3.2243 T452 Condition: Stress relieve T4 material by compression.

3.2244 T651 Condition: Artificially age T451 material at 172° to 182°C for 7.5 to 8.5 hours.

3.3 Critical Temperatures. Melting range 510° to 638°C. The oxidation resistance in normal atmospheres 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, $a_0 = 4.0413 \times 10^{-7}$ mm; for 5.0 percent Cu, $a_0 = 4.0290 \times 10^{-7}$ mm (ref. 3.6).

3.5 Microstructure. Figure 3.51 depicts the typical microstructure of the 2014 alloy in the (a) annealed, (b) naturally-aged T4 condition, and (c) artificially aged T6 condition, respectively. Structures in an overheated condition show rosettes; grain-boundary melting and grain boundary oxidation is displayed in extruded shapes.

3.6 Metallographic Procedures. In general, mechanical polishing is preferred to electropolishing, especially where larger microconstituents are present and the material is relatively soft, because objectionable relief effects produced by the electrolytic polishing may cause a misinterpretation of the microstructure (ref. 3.8). 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 suspended 600-grade aluminum oxide and final polishing on a similar wheel at 150 to 200 rpm with heavy magnesium oxide powder is recommended (ref. 3.6).

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.

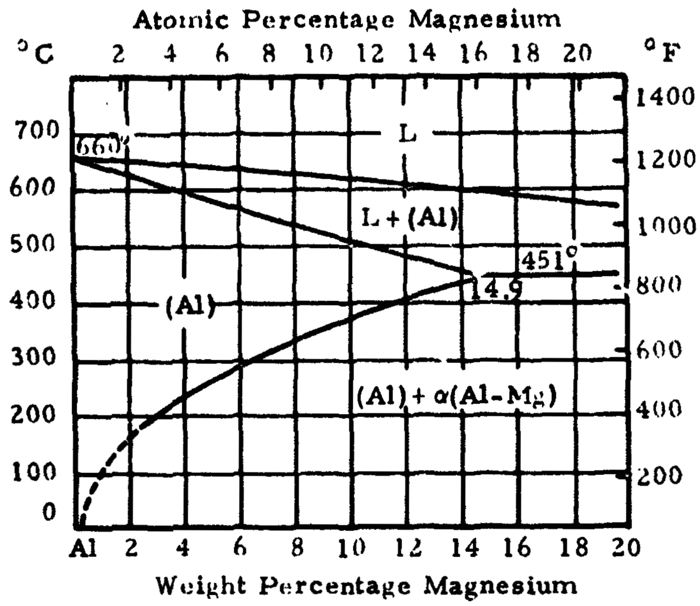
d) Final polish on a vibratory polisher using a microcloth containing a slurry of methyl alcohol and 0.1-μm aluminum oxide powder. A slurry of 0.1-μm aluminum oxide powder in a 10 percent solution of glycerine in distilled water may also be used for this step.

Etching reagents should be suited to the objective of the study. Keller's etch reveals microstructural details and grain boundaries satisfactorily. A 10-percent solution of sodium hydroxide gives better details of the microstructural 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 constituents present, especially when attention is paid to the colors of the various particles. Macroscopic studies of cracks, gross defects, forging lines, and grain structure should be made with the etching solutions indicated in table 3.6.

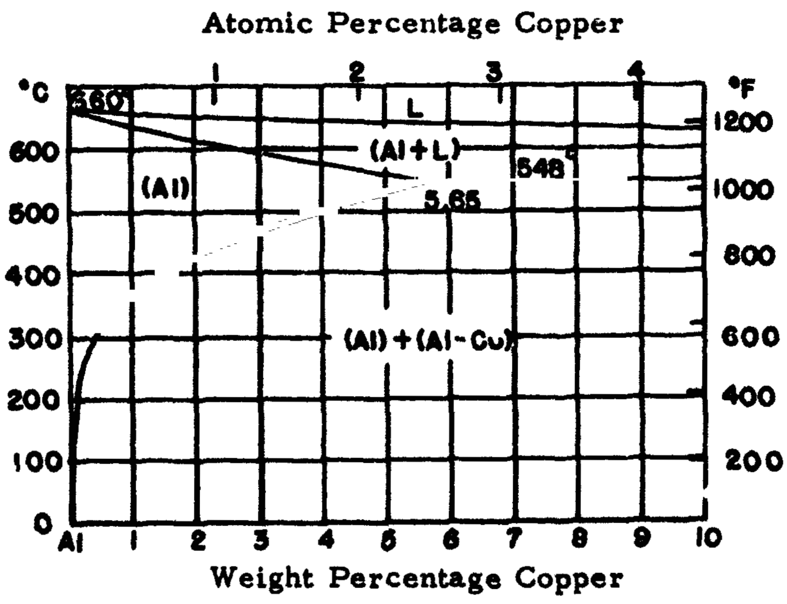
TABLE 3.6. – Etching Solutions for Revealing Macrostructure

Source	Ref. 3.6		
Alloy	2014		
Solution (a)	Composition		Specific Use
Sodium Hydroxide	NaOH Water	10 g 90 ml	For cleaning surfaces; revealing unsoundness, cracks and gross defects
Tucker's	HCl (conc.) HNO_3 (conc.) HF (48%) Water	45 ml 15 ml 15 ml 25 ml	For revealing structure of castings, forgings, etc.
Modified Tucker's	HCl (conc.) HNO_3 (conc.) HF (48%) Water	10 ml 10 ml 5 ml 75 ml	For revealing structure of all castings and forgings except high-silicon alloys
Flick's	HCl (conc.) HF (48%) Water	15 ml 10 ml 90 ml	For revealing grain structure of duraluminum type of alloys. Surface should be machined or rough polished

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



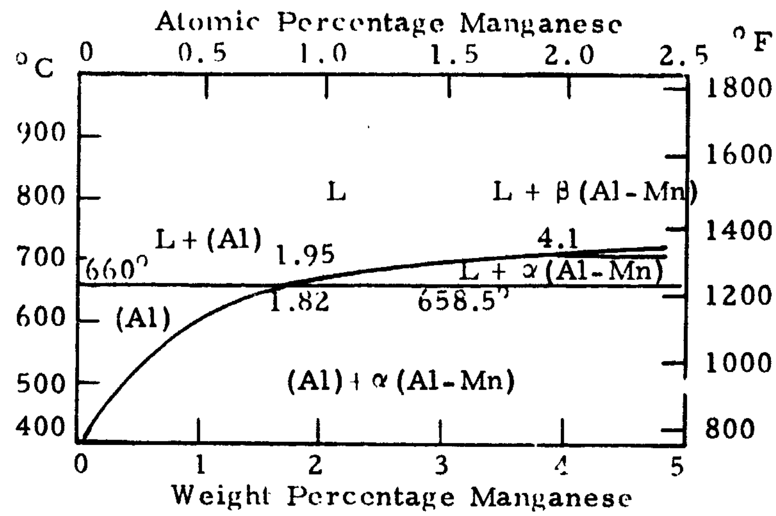
Aluminum - Magnesium



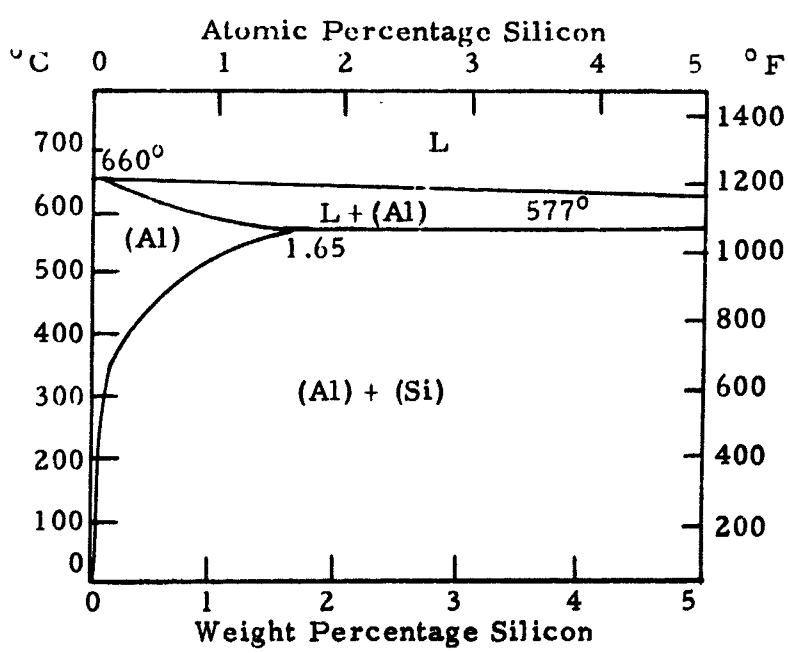
Aluminum—Copper

FIGURE 3.131. – Binary phase diagrams of the aluminum-rich portions of the Al-Mg and Al-Cu equilibrium diagrams.

(Ref. 3.3, 3.6)



Aluminum - Manganese



Aluminum - Silicon

FIGURE 3.132. – Binary phase diagrams of the aluminum-rich portions of the Al-Mn and Al-Si equilibrium diagrams.

(Ref. 3.3)

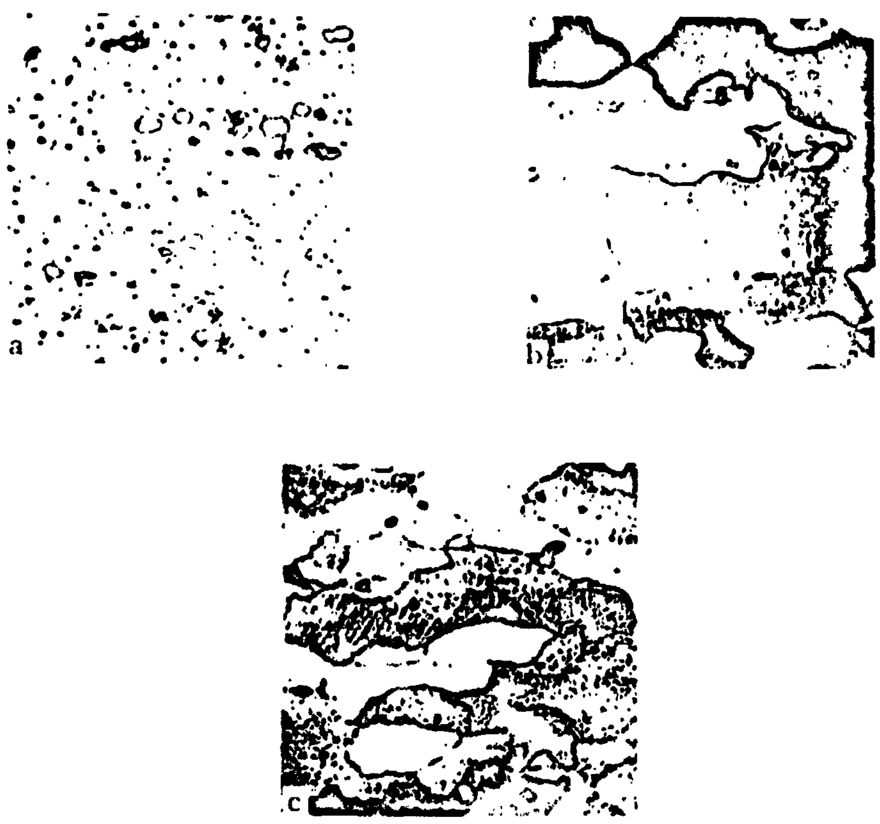


FIGURE 3.51. – Typical microstructure of 2014 aluminum alloy.

a) Annealed
b) T4 condition (naturally aged)
c) T6 condition (artificially aged)
Keller's etch, 500X

(Ref. 3.6)

Chapter 3 - References

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

3.2 The Aluminum Association, Aluminum Standards & Data: 1970-71, New York.

3.3 E.H. Wright and L.A. Willey, "Aluminum Binary Equilibrium Diagrams," Technical Paper No. 15, Aluminum Co. of America, 1960.

3.4 Metals Handbook, 8th Edition, Vol 1, "Properties and Selection of Metals," American Society for Metals, Metals, Park, Ohio, 1961.

3.5 Olin Aluminum, "Olin Aluminum Mill Products and Casting Alloys," 1971.

3.6 W.L. Fink, et al., Physical Metallurgy of Aluminum Alloys, American Society for Metals, Cleveland, Ohio, 1958.

3.7 Federal Specification, QQ-A-250/3E, January 18, 1971.

3.8 J.P. Vidosic, "Study of Phase Identification in Steel and Aluminum Alloys," Georgia Institute of Technology, Final Report, NASA Cortract NAS8-5117, September 1963.

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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; this metal is cast into ingots for further processing (ref. 4.1).

The additional alloying elements in aluminum 2014 are copper, magnesium, silicon, and manganese. Generally, the alloying phase of production practice involves the carefully controlled melting, alloying, and casting of 20,000- to 50,000-pound (9,000- to 23,000-kg) ingots. 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 are 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 causes 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, tempering, 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 with a cross-section shape and size that 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, drawing, or welding. Extruded tube is forced through an orifice as described in Section 4.27; a die and mandrel are used. Drawn tube is manufactured by a cold process which is similar to drawing bar and rod. A mandrel is used with one end fixed and a bulb attached to the other end. The tube is drawn over the mandrel bulb and through a die at the same time. 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 Company, "The Aluminum Data Book, Aluminum Alloys and Mill Products," 1958.

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

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Chapter 5

MANUFACTURING PRACTICES

5.1 General. This heat-treatable alloy 2014 is available as the bare alloy and in the Alclad condition (see table 2.2). The bare alloy is used typically as heavy-duty forgings, airplane fittings, and structural members. The Alclad 2014 is used for bridges and heavy-duty structures.

5.2 Forming

5.21 Sheet and Plate. The general formability of sheet material compared to other heat-treatable aluminum alloys is listed in table 5.21.

5.211 Cold Forming. The formability of this alloy as well as that of other aluminum alloys can be indexed on the basis of mechanical properties. High elongation and a considerable spread between yield and ultimate strength are indicative of good formability. The simplest and most widely used forming method is probably that of bending. The ease of bending is indicative of formability by most other forming operations. Table 5.2111 indicates the ease of forming in terms of recommended bend radii, as a function of temper and sheet and plate thickness, using typical mechanical properties for 0.100-inch (2.54-mm) sheet. It can be appreciated that forming should, wherever possible, be performed in the softest condition, i.e., the annealed "O" temper. Material formed in this condition may be heat treated later. If the severity of the forming operation is modest, the sheet or plate may be formed in the heat treated state, such as the T3 or T4 condition. It can also be appreciated that the T6 condition is extremely restricting as to the deformation which can be tolerated. Forming in the "O" temper followed by heat treatment involving the quenching of the alloy from 940° F (505° C) into cold water may distort the part, requiring excessive straightening and processing difficulties. In this case, the forming may be performed in the "W" or freshly quenched temper, since in this state it has a ductility nearly equal to that of the annealed condition. Forming or straightening should follow quenching as rapidly as possible because precipitation hardening occurs at room temperature. The as-quenched condition may be maintained by refrigeration, but conditions must be carefully controlled. Parts may be immersed in a solvent at –40° F (–40° C) prior to storage under refrigeration to help preserve the condition (ref. 5.10).

If operations are difficult with the fully aged (T6) condition, but annealing is not necessary to achieve the required degree of formability, the T4 temper is often satisfactory. The product can then be given maximum strength by aging to the T6 temper. Aluminum sheet is normally formed using operations such as:

Bending	Stamping
Flanging	Spinning
Rolling	Contour forming
Drawing	Bulging and expanding
Pressing	Beading and roll flanging
Stretching	Necking
Embossing	Curling
Coining	

Factors influencing the bending of 2014 sheet as described above also influence 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 to be expected and is encountered. Overforming is the common way of correcting the tendency. In addition, reducing the bend radius, increasing sheet thickness, forming at elevated temperatures, and increasing the total amount of plastic deformation decrease the extent of springback.

Cracking problems encountered in the brake-forming and assembly of LH_2 skin panels for the S-II stage from 2014-T651 led to a series of investigations by NASA-MSFC and its contractors. It was believed that the mode of cracking is associated with the high tensile stresses resulting from forming. The propensity toward cracking was relieved by modifications to the production method which include scarfing of the horizontal rib-ends to remove the sharp notch, reworking the boss area to minimize forming problems, the replacement of high-shear rivets with high-lock bolts in the splice plate, and the use of premium quality 2014-T651 plate (ref. 5.1).

Alloy 2014 sheets can be formed to many shapes by drawing, the most extensively employed method for mass production. Depending upon the desired shape, the part may be produced in one draw or, in some cases, the reduction is accomplished in successive draws using frequent annealing between successive draws to avoid exhausting the ductility and introducing cracks. Deep draws normally employ male and female metal dies. Forming in rubber (Guerin process) for relatively shallow parts, is a method where several thin layers of rubber are confined in a pad holder or retainer made of steel or cast iron. A descending ram on which this holder is mounted causes the aluminum sheet to be compressed against a form block to make the required part. If the aluminum is made to flow against a female die using fluid pressures behind a rubber diaphragm, the method is known as "hydroforming."

Other techniques, such as spinning and high-energy-rate methods, have also been successful. Explosive forming has achieved success and popularity during the last decade. However, before the full potential of this fabrication technique can be realized, it must be assured that this mode of forming is not detrimental to material behavior. In an investigation of the effects of explosive forming (dome shapes) on 2014 in the O and T6 conditions, comparison was made with isostatically formed counterparts produced by rubber pressing of terminal microstructure, hardness, tensile properties, fatigue life, and response to heat treatment. It was found that these properties do not depend significantly on the rate of forming. The explosive forming was performed in a 12-inch (30.5-cm) diameter open die using water as a transfer medium. The C-4 explosive charge was displaced 2.8 inches (7.1 cm) from the blank surface (ref. 5.11).

5.212 Hot Forming. When it is difficult to form heat-treated 2014-T6 by conventional methods, hot forming may be used. Maximum reheating periods which are recommended are as shown in table 5.2121. This treatment, in general, reduces the corrosion resistance of 2014 aged at room temperature. However, artificial aging after hot forming prevents this susceptibility to corrosion. Although formability at higher temperatures is easier, excessive heating should not be used because of strength loss. Under controlled conditions, however, loss of strength will seldom exceed 5 percent as the result of reheating in accordance with table 5.2121.

5.22 Shapes, Tube, and Pipe. Aluminum shapes are generally produced as extrusions. However, many standard structural shapes may also be produced by rolling. Shapes may be formed by continuous roll forming. The relative formability of alloy 2014 as tubes or extrusions is rated about midway between the 6000 and 7000 series of aluminum alloys. As pointed out in Section 5.21, better formability can be obtained in the softer tempers with the precautions noted. Alloy sections in the O temper are bent and formed more easily than those in the T3, T4, T6, and T6 heat-treated tempers, the last generally being the most difficult.

Stretching, wiping, or rolling are general methods used to form shapes and tubing. Draw bending is also used to form the contour for shapes and tubes. Sheets, shapes, and tubes are stretch formed by clamping at one end and pulling or stretching over a single male die so as to exceed the elastic limit. The metal section takes the shape of the die by stretching or elongating more in the heavier curvature areas than in the shallower ones. When working exceptionally thin-wall round, square, or rectangular tube on small radii, it is necessary to add a wiper and a flexible mandrel to provide extra support for the tube at the point of bending. Rolls can also be used for the forming, using dies to form the contours.

5.23 Forging. The heat-treatable 2014 is widely used for high strength forgings that exhibit good ductility and machinability. Forgings are produced by either the open die or closed die methods, using pressure or impact or a combination of these two techniques. In die forging, steady hydraulic pressure forces the alloy metal to fill a closed-die cavity. Rough hand-forged shapes are produced by forging between open flat dies using impact. Very large pieces weighing over two tons can be produced by the hand forging technique. Hand forgings are produced in the tempers defined in table 5.231.

As in all forgings, there is grain flow which results in anisotropy of properties. This must be considered for the evaluation of mechanical properties.

The forging process begins with the forging stock, which is usually produced by the rolling or extruding process and may be cold finished to obtain close tolerances. Forging stock is carefully conditioned and inspected to insure soundness and suitable surfaces for forging. Stock may vary in size from 3/8- to 8-inch diameter round stock, 3/8- to 4-inch square stock, and rectangles from 3/8 inch to as much as 10 inches on the maximum dimension (1 inch = 25.4 mm).

The recommended maximum forging temperature is 875° F (468° C) with a minimum finishing temperature of 650° F (343° C). The exact temperature is dependent upon the type of forging process employed. The stock may be shaped in one step or, in the case of complicated parts, in several operations involving several reheatings. In die forging, the flash resulting from excess metal overfilling the mold is removed by hot or cold trimming, sawing or grinding. 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. Straightening after heat treatment is often required. Templates with indicators and gages are used to determine "out-of-tolerance." Straightening is accomplished by hand methods or by "cold restrike" operations. Forgings are inspected for grain flow, dimensions, mechanical properties, and ultrasonic soundness.

Aluminum alloy 2014 is more easily forged than 7075, 7079, and 2218; it is less easily forged than aluminum 4032, 2011, 2025, 6061, and 6051 (ref. 5.2).

5.3 Machining

5.31 Conventional Machining. The aluminum alloy 2014 is readily machined in all conventional machining operations. The highest machinability is obtained in the hardest temper. In the softer tempers, the alloy tends to be somewhat gummy and is not as machinable. Hand forgings of 2014 which require a large amount of metal removal by roughing out before heat treatment should be machined in the F temper. In those cases where hand forgings are to be machined to very close dimensions with the additional requirement for a good surface condition, the T4 temper yields optimum results. Small hand forgings can be machined successfully in the T6 temper. 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. Grinding is performed typically with a wheel speed of 6000 ft/minute and a table speed of 60 ft/minute. The down feed will produce a rough finish if it is kept about 0.001 inch per pass. A fine finish will be produced if the down feed is kept to a mzximum of 0.0005 inch per pass. The cross feed is approximately one-third of the wheel width. The wheel type is A-46-KV with a water-base emulsion or chemical solution for the grinding fluid. (Note: 1 inch = 25.4 mm.)

5.32 Electrochemical and Chemical Machining

5.321 General. In many cases, the designer may wish to take advantage of the high strength-to-weight ratio inherent in the aluminum alloy by employing an integrally stiffened skin or bulkhead. The removal of adjacent pockets in thick aluminum plates can be programmed to leave a ribbed pattern in a thin, high-strength aluminum panel. For example, the waffle pattern left in 1-1/4 inch (3.2-cm) plate by milling pockets 1 inch (2.5 cm) deep allows high strength designs. Machining pockets of these dimensions in large plates by conventional metal cutting techniques requires extremely heavy and fixed tooling which has many disadvantages because of equipment versatility limitations. Alternative methods employing chemical and electrochemical methods have been proposed and are being investigated.

5.322 Electrochemical Milling. Electrochemical machining (ECM) for metal shaping subjects a chemically erodible workpiece to the action of anodic current flow in a suitable electrolyte. A second electrode, the tool, is provided for the cathodic action.

There are a number of tool workpiece configurations that may be employed in the ECM process depending upon the particular type of metal removal geometry desired. It is normally required that fresh electrolyte be supplied to the workpiece. The trepan-type tool is shown in figure 5.3221. In a device such as this, the electrolyte under pressure is supplied and escapes through the clearance between the tool and the workpiece. The cutting action is between the end of the tool and the workpiece. Under the cutting action, a hole corresponding to the tool outline is produced and a plug matching the under-sized shape of the tool hole is formed. In the plunge-type tool shown in figure 5.3222, because the working end of the tool is nearly solid, a cavity rather than a plug is produced. The shape of the tool cross-sections can vary from the simple squares, ovals, rounds, and D-shapes to rather complicated design shapes.

Alloy 2014 is essentially a pure aluminum as far as the rate of the electrochemical process is concerned. Hence, according to the Faraday laws, 1.26 in^3 (20.65 cm^3) of the metal can be removed per minute at 10,000 amperes (assuming 100 percent efficiency). In practice, efficiencies of 80 to 90 percent are usual. An electrolyte of 5- to 10-percent NaCl solution has been found to yield excellent results and the process can be carried out using 10–15 volts. The milling rate of the ECM process depends upon the current capacity of the power supply and the ability of the electrolyte system to provide fresh electrolyte. High electrolyte pressure requirements of 100–250 psi (0.07–0.18 kg/mm^2) provide even electrolyte flow and satisfactory cutting conditions. Tool forces in the ECM process are appreciable due to these high pressures required in the electrolyte gap. Temperatures of about 120° F (49° C) produce good quality finishes. Cooling coils to keep the temperature below 212° F (100° C) for these aqueous solutions may be required.

5.323 Chemical Milling. The removal of metal stock by chemical dissolution or "chem-milling" in general has also many potential advantages over conventional milling methods. Uniform attack with an acid or alkaline solution however, does not always take place.

It is difficult in chemical milling to maintain vertical sidewalls in cavities and holes. Preliminary experiments on 2014-T651 using 20-percent NaOH at 212°F (100°C) were not encouraging. Rough etched surface conditions and very slow metal removal rates were experienced.

Sample panels of 2014-T651 have been chemically milled to depths of 0.500 inch (12.7 mm) by using an acid spray technique that permits large parts to be chemically milled without immersion (ref. 5.14). Average milling rate is 0.0040 inch ±0.0018 inch (0.102 ± 0.05 mm) per minute. Surface roughness is controlled well within the allowable 125 rms. The etchant contains hydrochloric acid, acetic acid, and sodium dichromate.

TABLE 5.21. – Relative Formability of Heat-Treatable Alloys in Order of Decreasing Formability

Source	Ref. 5.3
Rating	Alloy
1	No. 21 and No. 22 (Brazing Sheet)
2	6061
3	6066
4	2024
5	2014
6	7075
7	7178

TABLE 5.2111. – Approximate Bend Radii for 90 Degree Cold Bend (a, c)

Source	Ref. 5.6												
Temper	F_{tu}, ksi		F_{ty}, ksi		e(b)	Sheet (inch)							
	min	max	min	max	min	1/64	1/32	1/16	1/8	3/16	1/4	3/8	1/2
O	-	30	-	14	16	0	0	0	0	0-1t	0-1t	1.5-3t	3-5t
T3	57	-	36	-	15	1-2t	1.5-3t	2-4t	3-5t	4-6t	4-6t	5-7t	5.5-8t
T4	57	-	34	-	15	1-2t	1.5-3t	2-4t	3-5t	4-6t	4-6t	5-7t	5.5-8t
T6	64	-	57	-	8	2-4t	3-5t	3-5t	4-6t	5-7t	6-10t	7-10t	8-11t

(a) Radii for various thicknesses expressed in terms of thickness, t

(b) Elongation, percent in 2-in gage section

(c) Mechanical properties (F_{tu}, F_{ty}, and e) are typical for 0.100-in sheet

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

TABLE 5.2121. -- Maximum Reheat Period for Alloy

Source		Ref. 5.5
Alloy		2014-T6
Temperature °F	°C	Time
300	149	20 to 50 hr
325	163	8 to 10 hr
350	177	2 to 4 hr
375	191	30 to 60 min
400	204	5 to 15 min
425	219	Time to temperature
450	232	Time to temperature

TABLE 5.231. — Heat Treatment of Hand Forgings

Source	Ref. 5.2
Alloy	2014
Temper	Treatment
F	As forged, no thermal treatment following fabrication operation
W	Solution heat treated and quenched in water at 140° F (60° C)
T4	Solution heat treated, quenched in water at 140° F (60° C) and natural aged to a substantially stable condition
T41	Solution heat treated, quenched in water at 212° F (100° C) and naturally aged to a substantially stable condition
T6	Solution heat treated, quenched in water at 140° F (60° C) and artificially aged
T652	Solution heat treated, quenched in water at 140° F (60° C), stress relieved by cold compression, artificially aged

TABLE 5.31. — Typical Factors for Common Machining Operations

Source	Ref. 5.7						
Alloy	2014, STA						
		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.[illegible]	T1, M1	1[illegible]00	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-1, C-3
	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			
	1 1/2 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
Note: 1 inch = 25.4 mm.

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

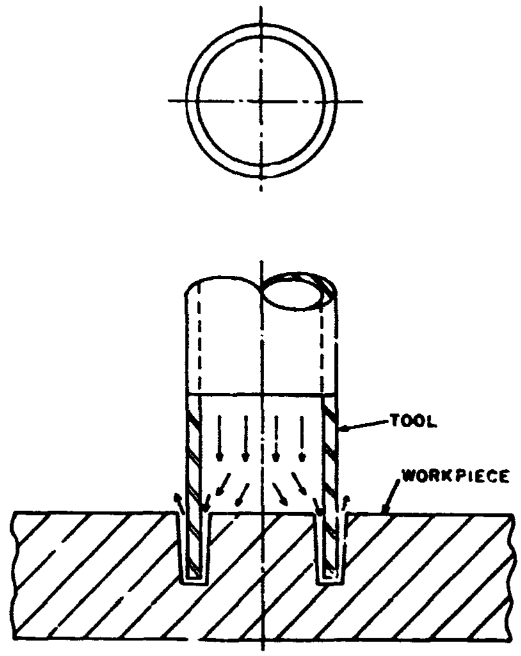

FIGURE 5.3221. – Trepan-type of ECM tool.
(Ref. 5.8)

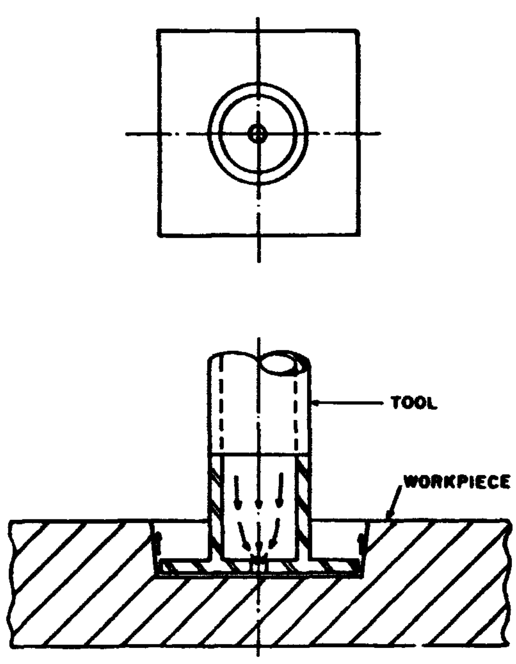

FIGURE 5.3222. – Plunge-type of ECM tool.
(Ref. 5.8)

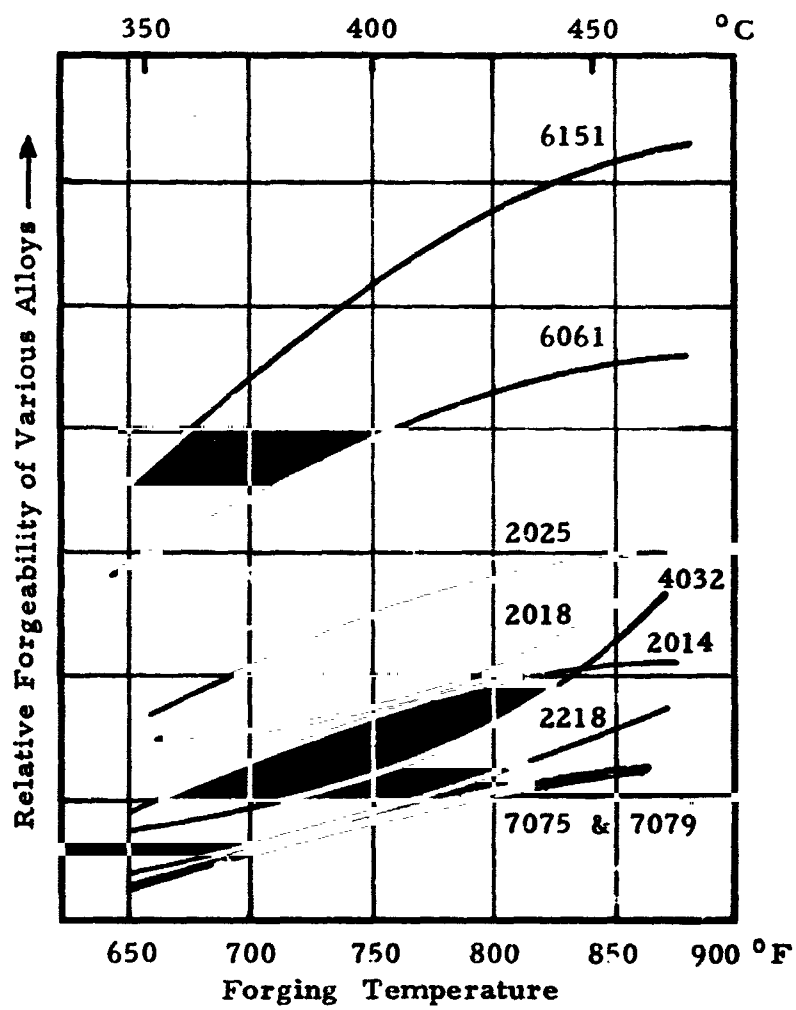

FIGURE 5.232. – Relative forgeability of various aluminum alloys.

(Ref. 5.2)

Chapter 5 - References

5.1 C.N. Irvine, "Forming Techniques Applicable to the Production of S-II Stage Skin Panels from 2014 Aluminum Alloy," NASA TM X-53637, July 25, 1967.

5.2 Kaiser Aluminum and Chemical Sales, Inc., "Kaiser Aluminum Forging Product Information." 1959.

5.3 ynolds Metals, Company, "Forming Aluminum," 1961.

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

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

5.6 The Aluminum Association, Aluminum Standards & Data: 1970-71, New York.

5.7 Machining Data, ORDP40, July 1961.

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

5.9 Reynolds Metals Company, "Machining Aluminum," 1964.

5.10 Metals Handbook, 8th Edition, Vol. 2, "Heat Treating, Cleaning, and Finishing," American Society for Metals, Metals Park, Ohio, 1961.

5.11 R.N. Orava, H.E Otto, and R. Mikesell, "Tensile and Fatigue Properties of Explosively and Conventionally Formed 2014 Aluminum Alloy," Metall. Trans., 2, 1675 (1971).

5.12 The Aluminum Association, "Aluminum Forging Design Manual," July 1970.

5.13 The Aluminum Association, "Aluminum Impacts: A Design Manual," January 1970.

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

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 2014 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 2014 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^{-54}	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 ft^2	Vulnerable Area cm^2	Prob'y No Destructive Impact, %	Av. No. of Destructive Impacts per Mission	Critical Thickness in	Critical Thickness 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

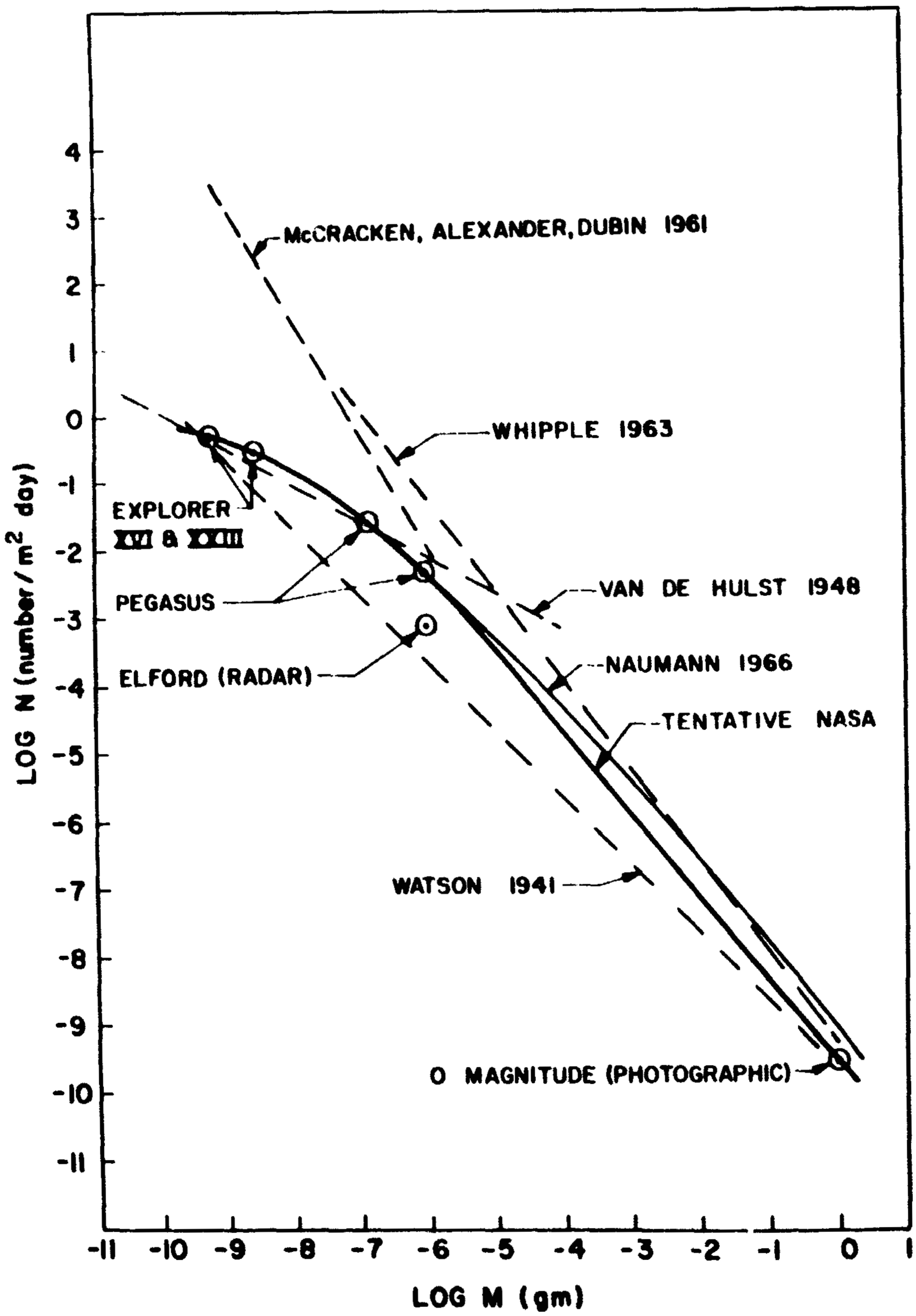

FIGURE 6.1. – Various estimates of meteoroid mass influx. (Ref. 6.3)

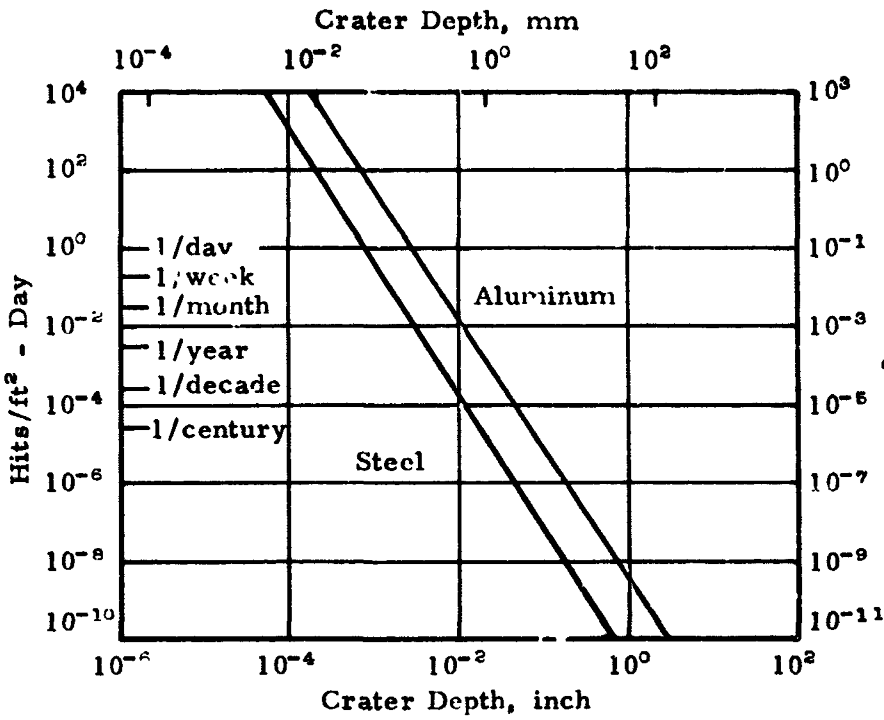

FIGURE 6.2. — Hit rate vs crater depth in the earth neighborhood but without earth shielding.

(Ref. 6.4)

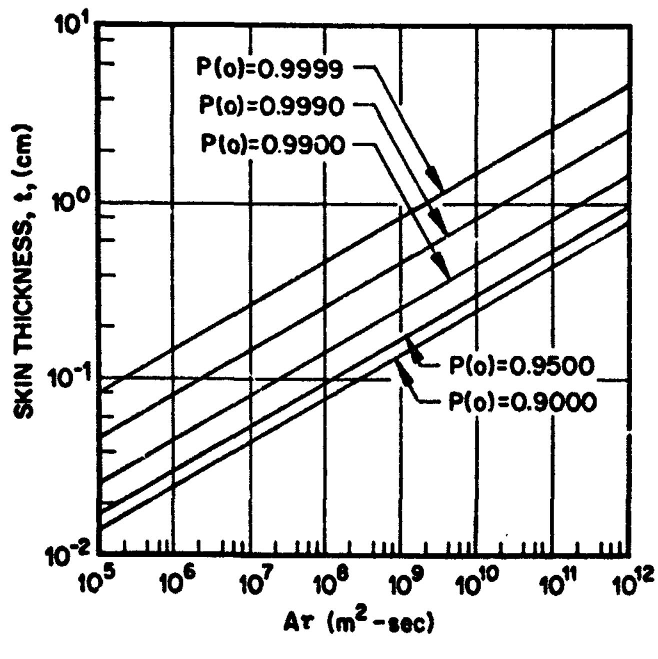

FIGURE 6.3. — Sheet thickness of Al as a function of the surface area–lifetime product required for various probabilities of no meteoroid puncture.

(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. J. 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-6C56, 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.

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Chapter 7

STATIC MECHANICAL PROPERTIES

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$E = 10.6 \times 10^3$ ksi (7.45×10^3 kg/mm^2)
Clad products, Cond. O, T3, T4, and T6;
$E = 10.5 \times 10^3$ ksi (7.38×10^3 kg/mm^2) (ref. 7.13)

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7.223 Design value of E at room temperature, $E = 10.5 \times 10^3$ ksi (7.38×10^3 kg/mm^2) (ref. 7.1).

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7.233 Design value of E_c at room temperature, $E_c = 10.7 \times 10^3$ ksi (7.52×10^3 kg/mm^2) (ref. 7.1).

7.24 Modulus of rigidity (shear modulus), G

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			T4	105
			T6	135 (Refs. 7.13, 7.14)
7.32	Rockwell scale	Cond	O	H87-98
			T4	B65-73
			T6	B80-86 (Ref. 7.14)

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TABLE 7.III. – NASA Specified Mechanical Properties for Die Forgings and Separately Forged Test Bars

Alloy		2014 (b)		
Specification		NASA-MSFC-SPEC-144B		
Max. section thickness		4 inches (10.16 cm)		
Temper	Orientation (A or B)	F_{tu}, min, ksi (a, c)	F_{ty}, min, ksi (a, c)	e(2 in or 4D) min, %
T4	A	55.0	30.0	11
T6	A	65.0	55.0	7
T6	B	64.0	56.0	3

(a) Tensile and yield strength test requirements may be waived for material in any direction in which the dimension is less than 2 inches (5.08 cm) 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 requirement specified for the T6 temper.

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

A Test specimen parallel to forging flow lines

B Test specimen not parallel to forging flow lines

TABLE 7.112. — NASA Specified Mechanical Properties for Hand Forgings

Alloy	2014-T6			
Specification	NASA-MSFC-SPEC-144B			
Thickness, inch (b)	Axis of Test Specimen	F_{tu}, min, ksi (c, d)	F_{ty}, min, ksi (c, d)	e(2 in or 4D) min, %
≤ 2.00	L	65.0	56.0	8
	LT	65.0	56.0	3
2.001 to 3.000	L	64.0	56.0	8
	LT	64.0	55.0	3
	ST	62.0	55.0	2
3.001 to 4.000	L	63.0	55.0	8
	LT	63.0	55.0	3
	ST	61.0	54.0	2
4.001 to 5.000	L	62.0	54.0	7
	LT	62.0	54.0	2
	ST	60.0	53.0	1
5.001 to 6.000	L	61.0	53.0	7
	LT	61.0	53.0	2
	ST	59.0	53.0	1
6.001-7.000	L	60.0	52.0	6
	LT	60.0	52.0	2
	ST	58.0	52.0	1
7.001 to 8.000	L	59.0	51.0	6
	LT	59.0	51.0	2
	ST	57.0	51.0	1

(a) Maximum cross-sectional area is 256 in^2 (1651 cm^2)

(b) Thickness is measured in the short transverse direction and applies to the "as forged" dimension before machining; 1 inch = 25.4 mm.

(c) Tensile property requirements may be waived for directions in which the dimension is less than 2 inches (5.08 cm).

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

TABLE 7.113. – NASA Specified Mechanical Properties for T652 Hand Forgings

Alloy	2014-T652			
Specification	NASA-MSFC-SPEC-144B			
Thickness, inch (a)	Axis of Test Specimen	F_{tu}, min, ksi (c, d)	F_{ty}, min, ksi (c, d)	e(2 in or 4D) min, %
≤ 2.000	L	65.0	56.0	8
	LT	65.0	56.0	3
2.001 to 3.000	L	64.0	56.0	8
	LT	64.0	55.0	3
	ST	62.0	55.0	2
3.001 to 4.000	L	63.0	55.0	8
	LT	63.0	55.0	3
	ST	61.0	51.0	2
4.001 to 5.000	L	62.0	54.0	7
	LT	62.0	54.0	2
	ST	60.0	50.0	1

(a) Maximum cross-sectional area is 256 in^2 (1651 cm^2)
(b) Thickness is measured in the short transverse direction and applies to the "as forged" dimension before machining; 1 inch = 25.4 mm
(c) Tensile property requirements may be waived for directions in which the dimension is less than 2 inches (5.08 cm).

TABLE 7.21. – Poisson's Ratio (Elastic and Plastic Values)

Source	Ref. 7.23	
Alloy	2014-T6	
Form	0.125-inch (3.175-mm) sheet	
Grain Direction	μ, elastic	μ, plastic
Longitudinal	0.33	0.44
Transverse	0.27	0.52

(a) Purchased in the form of clad, heat treated sheet; cladding removed prior to testing

TABLE 7.4111. – Design Mechanical Properties of Sheet and Plate

Alloy	AMS-4029				AMS-4014 (2014)											
Form	Sheet				Plate											
Condition	-T6				-T651											
Thickness, in.	0.020–0.039		0.040–0.249		0.250–0.499		0.500–1.000		1.001–2.000		2.001–2.500		2.501–3.000		3.001–4.000	
Basis	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
Mechanical properties:																
F_{tu}, ksi																
L	65	67	67	69	66	68	66	67	66	67	65	66	63	64	60	61
LT	64	66	66	67	67	69	67	68	67	68	65	66	63	64	59	60
ST	...	...	...	...	...	...	...	...	...	...	60	61	58	59	54	55
F_{ty}, ksi																
L	58	60	59	60	60	62	60	61	60	62	59	61	58	60	56	58
LT	57	59	58	59	59	61	59	60	59	61	58	60	57	59	55	57
ST	...	...	...	...	...	...	...	...	...	...	54	56	53	55	51	53
F_{cy}, ksi																
L	58	60	59	60	58	60	58	59	58	60	57	59	56	58	54	56
LT	58	60	60	61	61	63	61	62	61	63	60	62	59	61	57	59
ST	...	...	...	...	...	...	...	...	...	...	60	62	59	61	57	59
F_{su}, ksi	39	40	40	41	40	41	40	41	40	41	39	40	38	39	36	36
F_{bru}, ksi																
(e/D=1.5)	97	100	100	103	106	109	106	107	106	107	103	104	99	101	93	95
(e/D=2.0)	123	127	127	131	135	139	135	137	135	137	[illegible]	133	127	129	119	121
F_{bry}, ksi																
(e/D=1.5)	81	84	83	84	90	93	90	92	90	93	89	92	87	90	84	87
(e/D=2.0)	93	96	94	96	107	110	107	109	107	110	105	109	103	107	100	103
e, percent																
L	6	...	7	...	7	...	6	...	6	...	4	...	4	...	3	...
LT	6	...	7	...	7	...	6	...	4	...	2	...	2	...	1	...
ST	...	...	...	...	...	...	...	...	...	...	1	...	1	...	...	...

Alloy	AMS-4028								
Form	Plate								
Condition	-T62								
Thickness, in.	0.250–0.499		0.500–1.000		1.001–2.000		2.001–2.500	2.501–3.000	3.001–4.000
Basis	A	B	A	B	A	B	S	S	S
Mechanical properties:									
F_{tu}, ksi									
L	68	70	68	70	67	68	65	63	59
LT	67	69	67	69	67	68	65	63	59
ST	...	...	...	...	...	...	60	58	54
F_{ty}, ksi									
L	60	62	60	62	59	62	58	57	55
LT	59	61	59	61	59	62	58	57	55
ST	...	...	...	...	...	...	54	53	51
F_{cy}, ksi									
L	60	62	60	62	61	64	60	59	57
LT	61	63	61	63	61	64	60	59	57
ST	...	...	...	...	...	...	60	59	57
F_{su}, ksi	41	42	41	42	41	41	40	39	37
F_{bru}, ksi									
(e/D=1.5)	102	105	102	105	101	102	98	94	86
(e/D=2.0)	129	133	129	133	127	129	124	120	112
F_{bry}, ksi									
(e/D=1.5)	84	87	84	87	83	87	81	80	77
(e/D=2.0)	96	99	96	99	94	99	93	91	88
e, percent									
L	7	...	6	...	6	...	4	4	3
LT	7	...	6	...	4	...	2	2	1
ST	...	...	...	...	...	...	1	1	...

Note: 1 inch = 25.4 mm; 1 ksi = 0.70307 kg/mm^2 (Ref. 7.4)

TABLE 7.4112. – Design Mechanical Properties of Clad Sheet and Plate

Alloy	QQ-A-250/3 (Clad 2014)																							
Form	Sheet				Plate																			
Condition	-T6				-T651												-T62							
Thickness, in.	0.020–0.039		0.040–0.249		0.250–0.499		0.500–1.000 [b]		1.001–2.000 [b]		2.001–2.500 [b]		2.501–3.000 [b]		3.001–4.000 [b]		0.250–0.499		0.500–1.000 [b]		1.001–2.000 [b]	2.001–2.500 [b]	2.501–3.000 [b]	3.001–4.000 [b]
Basis	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	S	S	S	S
Mechanical Properties:																								
F_{tu}, ksi																								
L	62	64	65	67	63	65	63	64	63	64	62	63	60	61	57	58	65	67	65	67	64	62	60	56
T	61	63	64	66	64	65	64	65	64	65	62	63	60	61	56	57	64	66	64	66	64	62	60	56
ST	...	...	...	...	...	...	...	...	...	...	60	61	58	59	54	55	...	...	...	...	...	60	58	54
F_{ty}, ksi																								
L	54	56	57	59	58	60	57	58	57	59	56	58	55	57	53	55	58	60	57	59	56	55	54	52
LT	53	55	56	58	57	59	56	57	56	58	55	57	54	56	52	54	57	59	56	5[illegible]	[illegible]	55	54	52
ST	...	...	...	...	...	...	...	...	...	...	54	56	53	55	51	53	...	...	...	...	...	54	53	51
F_{cy}, ksi																								
L	54	56	57	59	56	58	55	56	55	57	54	56	53	55	51	53	58	60	57	59	58	57	56	54
LT	55	57	58	60	59	61	58	59	58	60	57	59	56	58	54	56	59	61	58	60	58	57	56	54
ST	...	...	...	...	...	...	...	...	...	...	60	62	59	61	57	59	...	...	...	...	...	60	59	57
F_{su}, ksi	38	39	39	40	39	40	39	39	39	39	37	38	36	37	34	34	39	40	39	40	39	38	37	35
F_{bru}, ksi																								
(e/D=1.5)	93	96	98	101	101	104	101	103	101	103	98	99	95	96	88	90	98	101	98	101	96	93	90	84
(e/D=2.0)	118	121	124	127	129	133	129	131	129	131	125	127	121	123	113	115	124	127	124	127	122	118	114	106
F_{bry}, ksi																								
(e/D=1.5)	75	78	80	83	87	90	86	87	86	89	84	87	83	86	80	83	81	84	80	82	79	77	76	73
(e/D=2.0)	87	90	91	94	103	107	101	103	101	105	100	103	98	101	94	98	93	96	91	95	90	88	86	83
e, percent																								
L	7	...	8	...	8	...	6	...	6	...	4	...	4	...	3	...	8	...	6	...	6	4	4	3
LT	7	...	8	...	8	...	6	...	4	...	2	...	2	...	1	...	8		6	...	4	2	2	1
ST	...	...	...	...	...	...	...	...	...	...	1	...	1	...	...	...	...	...	...	...	...	1	1	...

a) 1 inch = 25.4 mm; 1 ksi = 0.70307 kg/mm[2]

b) These values, except in the ST direction, have been adjusted to represent the average properties across the whole section, including the 2-1/2 percent per side nominal cladding thickness.

(Ref. 7.4)

TABLE 7.4113. – Design Mechanical Properties of Forgings

Alloy	MIL-A-22771, Type 2014							
Form	Die forgings	Hand forgings[a]						
Condition	-T6 and -T652	-T6 and -T652[b]						
Thickness, in.	≤ 4.000	≤ 2.000	2.001–3.000	3.001–4.000	4.001–5.000	5.001–6.000	6.001–7.000	7.001–8.000
Basis	S	S	S	S	S	S	S	S
Mechanical properties:								
F_{tu}, ksi								
L	65	65	64	63	62	61	60	59
LT	....	65	64	63	62	61	60	59
ST	64	....	62	61	60	59	58	57
F_{ty}, ksi								
L	55	56	56	55	54	53	52	51
LT	......	56	55	55	54	53	52	51
ST	54	......	55[b]	54[b]	53[b]	53[b]	52[b]	51[b]
F_{cy}, ksi								
L	55	56	56	55	54	53	....	....
LT	....	56	55	55	54	53	....	....
ST	54	....	....	....	....	....	....	....
F_{su}, ksi	39	40	39	39	38	38	....	....
F_{bru}, ksi								
(e/D=1.5)	....	91	90	88	87	85	....	....
(e/D=2.0)	....	117	115	113	112	110	....	....
F_{bry}, ksi								
(e/D=1.5)	....	78	78	77	76	74	....	....
(e/D=2.0)	....	90	90	88	86	85	....	....
e, per cent								
L	7	8	8	8	7	7	6	6
LT	....	3	3	3	2	2	2	2
ST	3	....	2	2	1	1	1	1

[a] Maximum cross-sectional area 256 sq. in.

[b] All properties are applicable to the T652 temper except $F_{ty}(ST)$, for which the values are as follows:

Thickness, in.	2.001-3.000	3.001-4.000	4.001-5.000	5.001-6.000	6.001-7.000	7.001-8.000
Fty (ST), ksi	52	51	50	50	49	48

"For die forgings, the *L* and *ST* values for the directions parallel (within ± 15 degrees) and not parallel (as close as possible to the short transverse direction) respectively, to the forging flow lines."

Note: 1 inch = 25.4 mm; 1 ksi = 0.70307 kg/mm²

(Ref. 7.4)

TABLE 7.4114. – Design Mechanical Properties of Bar, Rod, Wire, and Shapes; Rolled, Drawn, or Cold-Finished

Alloy	QQ-A-225/4 (2014)						
Form	Bar, rod, wire and shapes; rolled, drawn or cold-finished						
Condition	-T6 or -T651						
Thickness, in	Up to 1.000	1.001–2.000	2.001–3.000	3.001–4.000	4.001–5.000 [a]	5.001–6.000 [a]	6.001–8.000 [a]
Basis	A	A	A	A	A	A	S
Mechanical properties:							
F_{tu}, ksi:							
L	65	65	65	65	65	65	65
LT	64	63	62	61	60	59	....
F_{ty}, ksi:							
L	[b] 55	55	55	55	55	55	55
LT	[b] 53	52	51	50	49	48	....
F_{cy}, ksi:							
L	[b] 53	53	53	53	53	53	53
LT	....	....	....	....	....	....	....
F_{su}, ksi	38	38	33	38	38	38	38
F_{bru}, ksi:							
(e/D=1.5)	98	....	....	....	....	....	....
(e/D=2.0)	124	....	....	....	....	....	....
F_{bry}, ksi:							
(e/D=1.5)	[b] 77	....	....	....	....	....	....
(e/D=2.0)	[b] 88	....	....	....	....	....	....
e, percent:							
L	[b] 8	8	8	8	8	8	8
LT	[b] 4	3	2	1	1	1	....

[a] For rounds (rod) maximum diameter is 8.000 in.; for square, rectangular, hexagonal, or octagonal bar, maximum thickness is 4 in., and maximum cross-sectional area is 36 sq. in.

[b] Except for wire less than 0.125 in. in diameter, or for special shapes less than 0.062 in. thick.

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

(Ref. 7.4)

TABLE 7.4115. – Design Mechanical Properties of Extruded Bar, Rod, and Shapes

Alloy	QQ-A-200/2 (2014)										
Form	Extruded rod, bar, and shapes										
Condition	T6, T6510, and T6511[b]										T62[c]
Cross-sectional area, in.^{2}	≤ 25									>25, ≤32	≤ 32
Thickness, in.[a]	0.125-0.499		0.500-0.749		0.750-1.499		1.500-2.750		1.751 4.499	≤ 0.750	0.125-4.499
Basis	A	B	A	B	A	B	A	B	S	S	S
Mechanical properties:											
F_{tu}, ksi:											
L	60	62	64	68	68	70	68	71	68	68	60
T	60	62	58	61	61	63	61	64			
F_{ty}, ksi:											
L	53	57	58	62	60	63	60	63	60	58	53
T	49	53	50	54	52	55	52	55			
F_{cy}, ksi:											
L	52	56	57	61	59	62	59	62		....	
T	53	57	53	56	55	57	55	57		....	
F_{su}, ksi	41	43	35	37	37	38	37	39		39	
F_{bru}, ksi:											
(e/D = 1.5)	93	96	90	96	96	99	96	100		....	....
(e/D = 2.0)	123	127	115	122	122	126	122	128		....	....
F_{bry}, ksi											
(e/D = 1.5)	74	80	73	78	76	80	76	80		....	....
(e/D = 2.0)	87	94	85	91	88	93	88	93		....	....
e, percent:											
L	7	....	7	....	7	....	7	....	7	6	d
T[e]	5	....	5	....	2	....	2	....	....	....	....

[a]For extrusions with outstanding legs, the load carrying ability of such legs shall be determined on the basis of the properties in the appropriate column corresponding to the leg thickness.

[b]Except for F_{tu}, L, and F_{ty}, L, values are based on fewer data than recommended in MIL-HDBK-5.

[c]Not applicable to sections <3/8 in thickness.

[d]For cross-sectional area >25, e is 6.

[e]These properties apply when samples of material supplied in the O or F temper are heat treated by the producer to determine that the material will respond to proper thermal treatment. Properties obtained by the user, however, may be lower than those listed if the material has been formed or otherwise cold or hot worked, particularly in the annealed temper, prior to solution heat treatment.

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

(Ref. 7.4)

TABLE 7.4516. – Bearing Property Reductions for Thick Plate

Source	Ref. 7.1	
Alloy	2014	
Thickness, in (a)	Bearing Property Reduction, Percent	
	1.001-3.000	3.001-4.000
F_{bru} (e/D = 1.5)	20	15
F_{bru} (e/D = 2.0)	20	15
F_{bry} (e/D = 1.5)	5	0
F_{bry} (e/D = 2.0)	5	0

(a) 1 inch = 25.4 mm

TABLE 7.4613. – Fracture Test Data for Cylinders at -320°F (-196°C)

Source	Ref. 7.2									
Alloy	2014-T6									
Specimen	Specimen thickness, t		Crack depth, a		Crack length, 2c		Fracture stress, σ_H		Apparent fracture toughness, K_Q	
	in	cm	in	cm	in	cm	ksi	kg/mm²	ksi √in	kg/mm^3/2
Outside-surface crack	0.061	0.155	0.025	0.064	0.096	0.244	85.3	60.0	23.5	83.3
	↓	↓	0.040	0.102	0.100	0.254	80.7	56.7	23.1	81.9
	↓	↓	0.050	0.127	0.114	0.290	74.1	52.1	22.8	80.8
	↓	↓	0.025	0.064	0.140	0.356	80.7	56.7	24.0	85.0
	↓	↓	0.039	0.099	0.240	0.610	72.9	51.3	27.[illegible]	96.7
	↓	↓	0.042	0.107	0.240	0.610	66.9	47.0	25.0	88.6
	↓	↓	0.041	0.104	0.300	0.762	61.3	43.1	23.6	83.6
	↓	↓	0.047	0.119	0.340	0.864	56.0	39.4	22.8	80.8
	↓	↓	0.044	0.112	0.370	0.940	58.4	41.1	23.1	81.9
	↓	↓	0.060	0.152	0.380	0.965	49.9 (a)	35.1	18.0 (b)	63.8
	↓	↓	0.041	0.104	0.450	1.143	55.5	39.0	22.0	80.0
	↓	↓	0.024	0.061	0.500	1.270	73.7	51.8	23.5	83.3
	↓	↓	0.039	0.099	0.955	2.426	46.9	33.0	18.4	65.2
	↓	↓	0.034	0.086	1.000	2.540	47.9	33.7	17.4	61.7
Inside-surface crack	0.061	0.155	0.022	0.056	0.442	1.123	73.9	52.0	22.8	80.8
	0.061	0.155	0.042	0.107	0.985	2.502	46.8	32.9	17.3	61.3

(a) Leakage occurred at 41.0 ksi (28.8 kg/mm²)
(b) Computed using stress at leakage

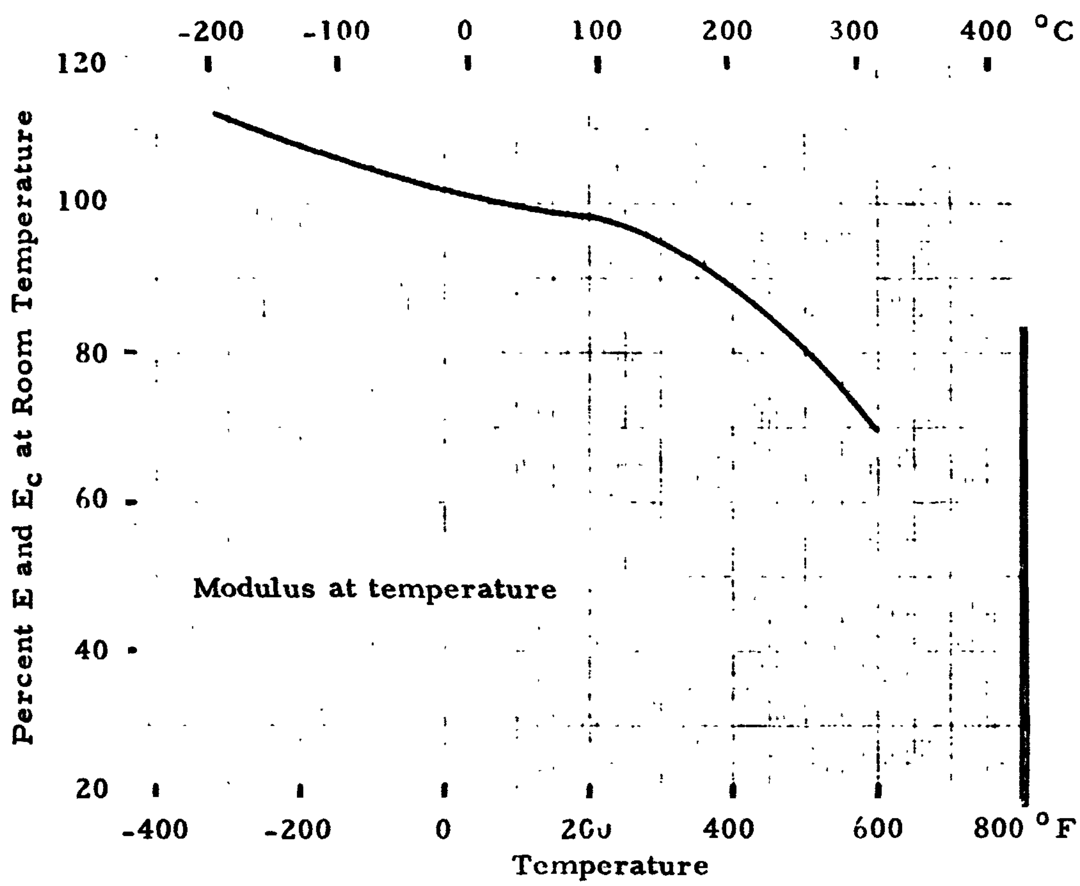

FIGURE 7.222. — Effect of temperature on the tensile and compressive modulus of 2014 and 2017 aluminum alloys.

(Ref. 7.4)

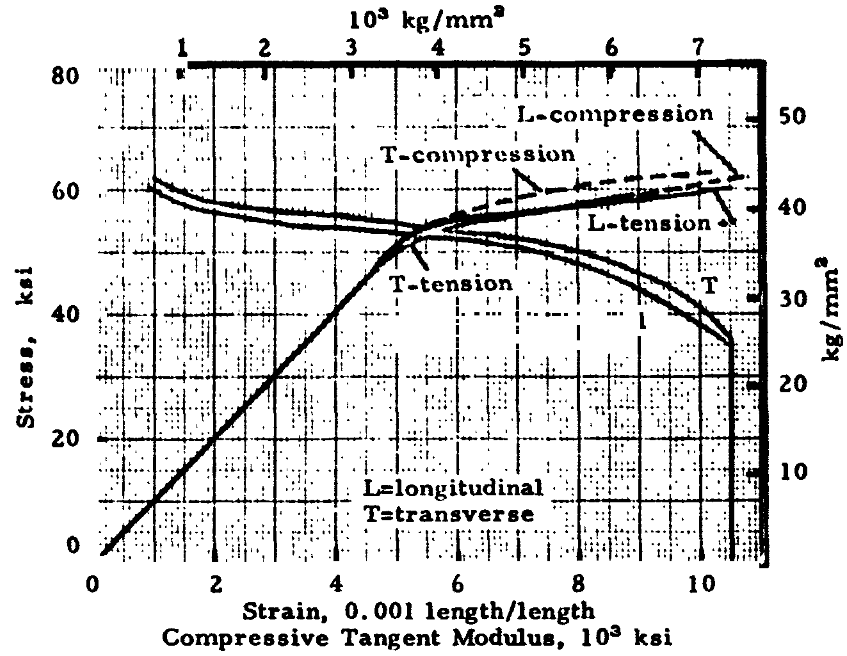

FIGURE 7.251. — Typical stress-strain and tangent-modulus curves for Clad 2014-T6 sheet at room temperature; thickness, 0.020-0.039 in (0.508-0.991 mm). (Ref. 7.4)

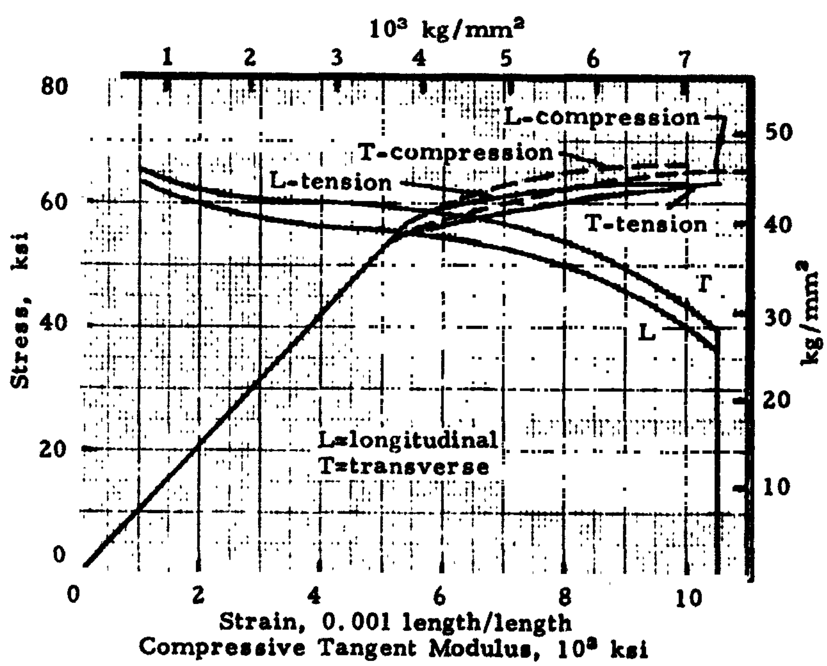

FIGURE 7.252. — Typical stress-strain and tangent-modulus curves for Clad 2014-T6 sheet at room temperature; thickness, 0.040-0.249 in(1.02-6.32 mm). (Ref. 7.4)

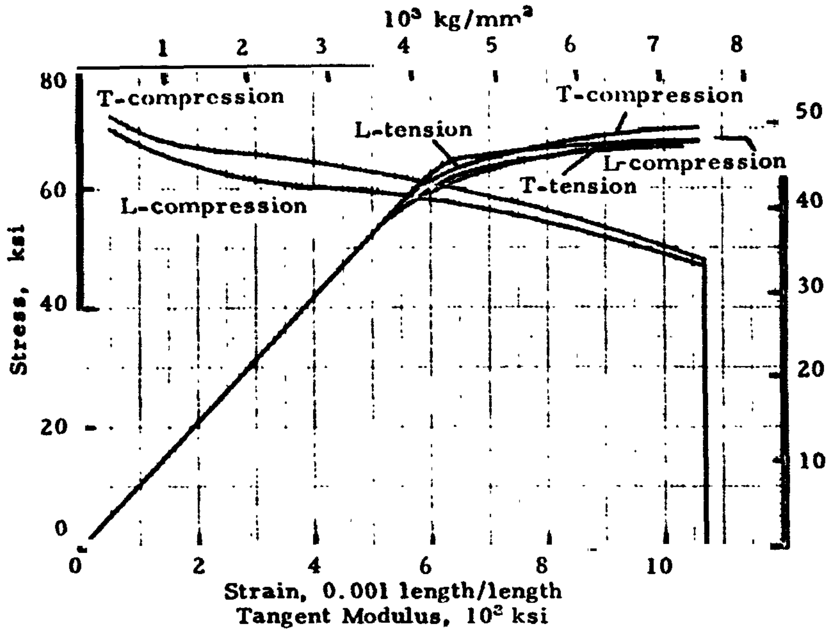

FIGURE 7.253. – Typical tensile and compressive stress-strain and tangent-modulus curves for 2014-T651 plate at room temperature; thickness, 0.250-2.000 inch (6.35-50.8 mm). (Ref. 7.4)

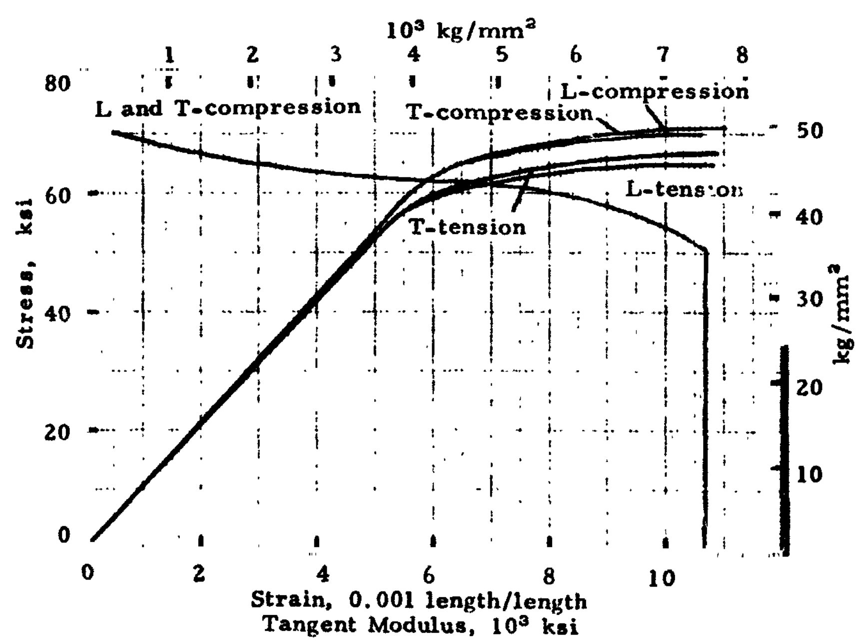

FIGURE 7.254. – Typical tensile and compressive stress-strain and tangent-modulus curves fo 2014-T62 plate at room temperature; thickness, 0.250-2.000 i ·h (6.35-50.8 mm). (Ref. 7.4)

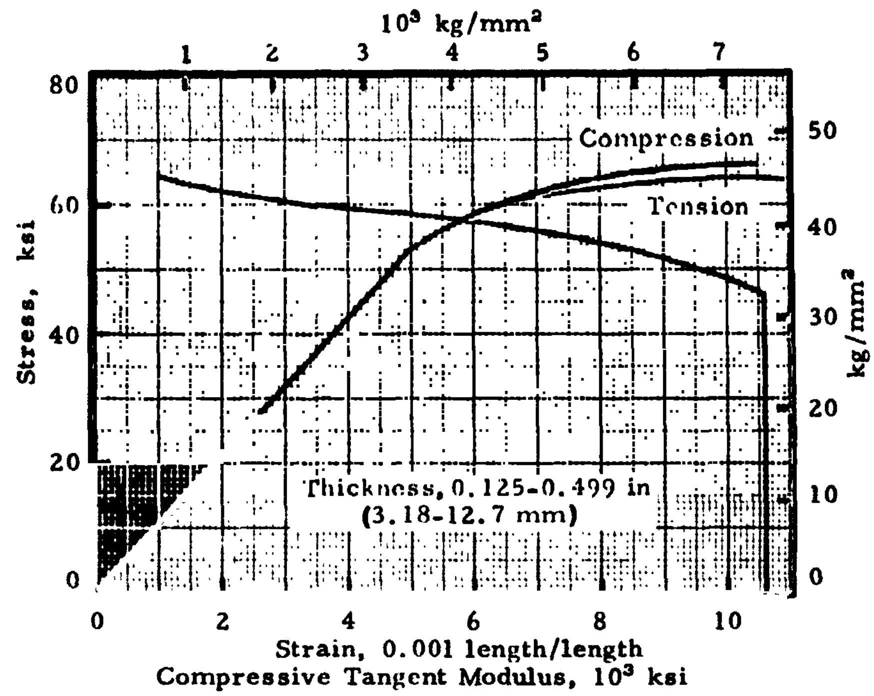

FIGURE 7.255. — Typical stress-strain and tangent-modulus curves for 2014-T6 extrusions at room temperature. (Ref. 7.4)

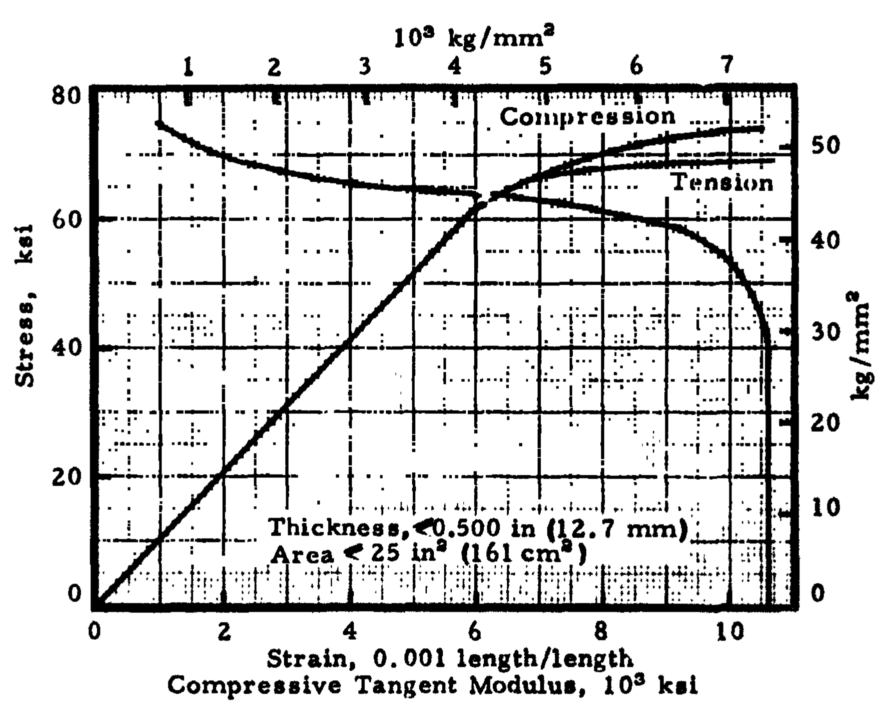

FIGURE 7.256. — Typical stress-strain and tangent-modulus curves for 2014-T6 extrusions at room temperature. (Ref. 7.4)

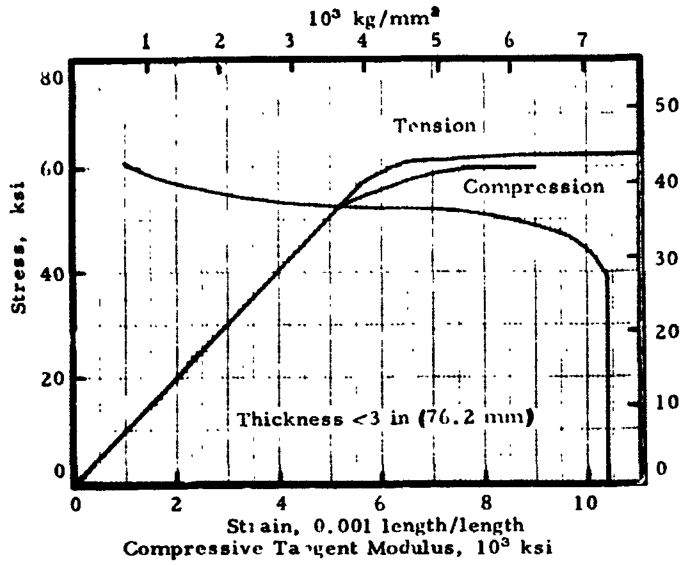

FIGURE 7.257. – Typical stress-strain and tangent-modulus curves for 2014-T6 rolled bar, rod, and shapes at room temperature (longitudinal). (Ref. 7.4)

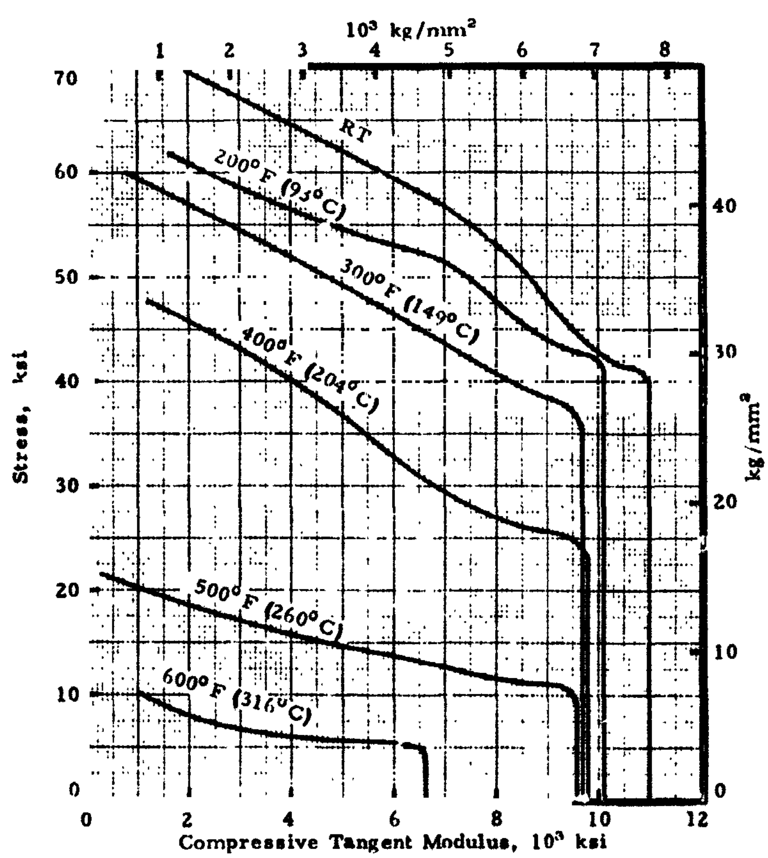

FIGURE 7.258. – Typical tangent modulus curves in compression for Clad 2014-T6 at room and elevated temperatures; thickness, 0.064 inch (1.63 mm). (Ref. 7.10)

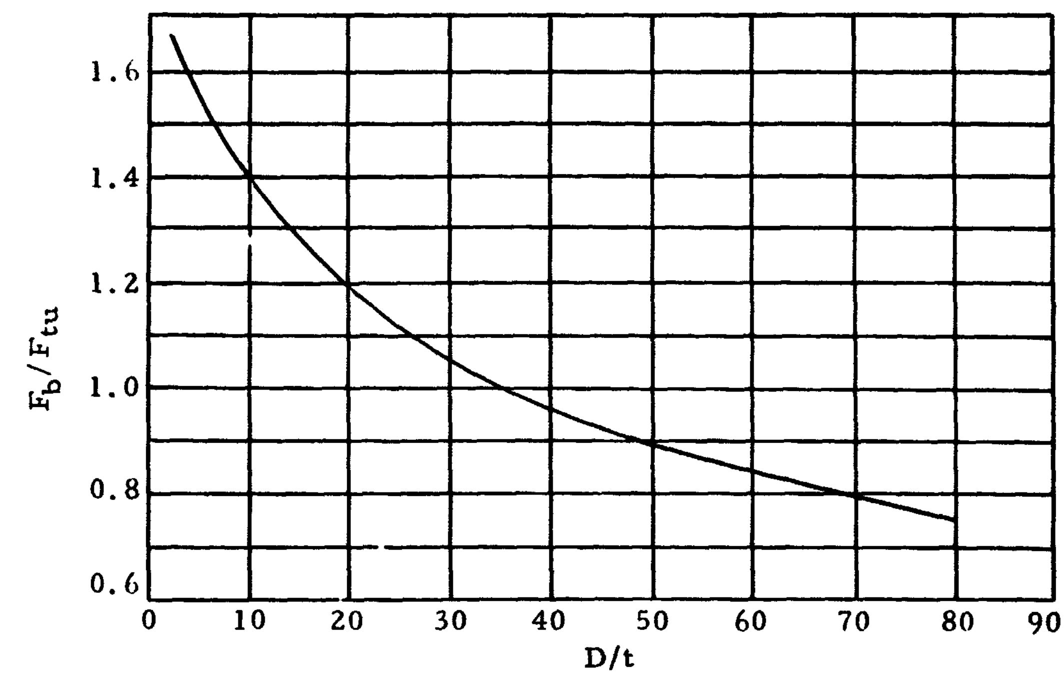

FIGURE. 7.271. – Bending modulus of rupture for 2014-T6 round tubing. (Ref. 7.4)

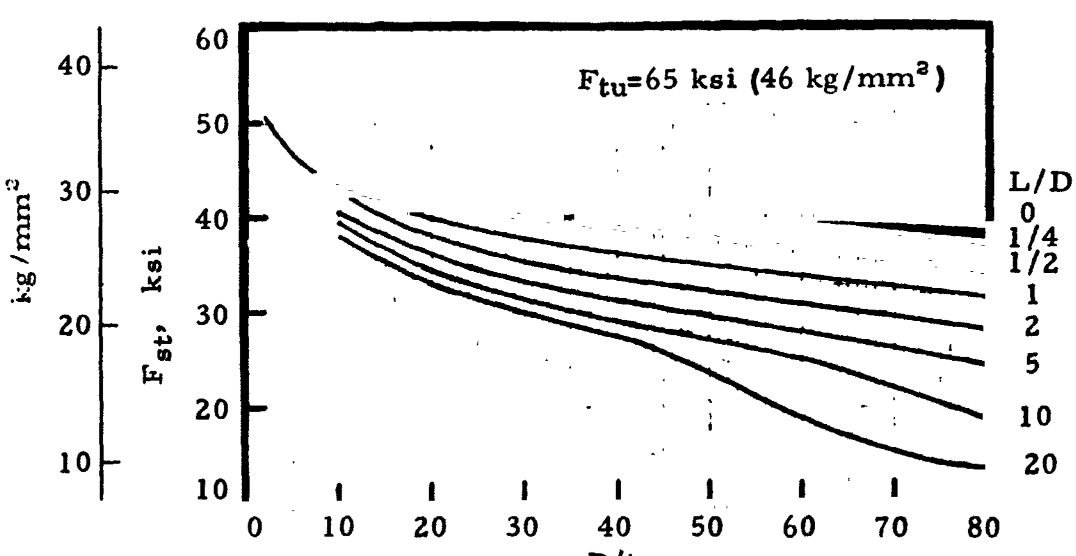

FIGURE 7.281. – Torsional modulus of rupture for 2014-T6 forging. [The curve representing material failure (L/D=0) is computed for F_{su} = 39 ksi (27 kg/mm^2), and does not allow for the possibility of reduced strength along the parting plane.] (Ref. 7.4)

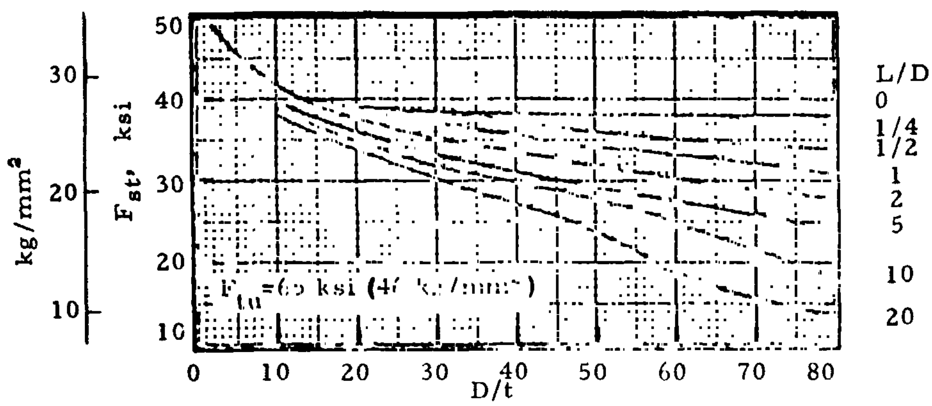

FIGURE 7.282. — Torsional modulus of rupture for 2014-T6 rolled rod. (Ref. 7.4)

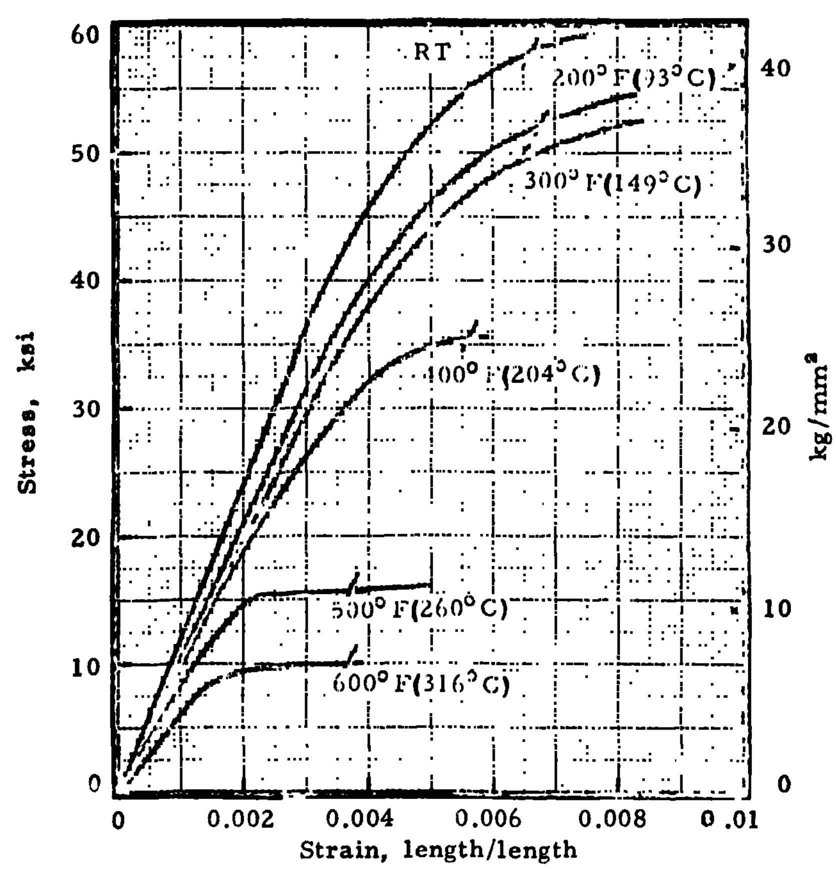

FIGURE 7.4121. — Stress-strain curves in tension for Clad 2014-T6 sheet at room and elevated temperatures; thickness, 0.064 inch (1.63 mm). (Ref. 7.10)

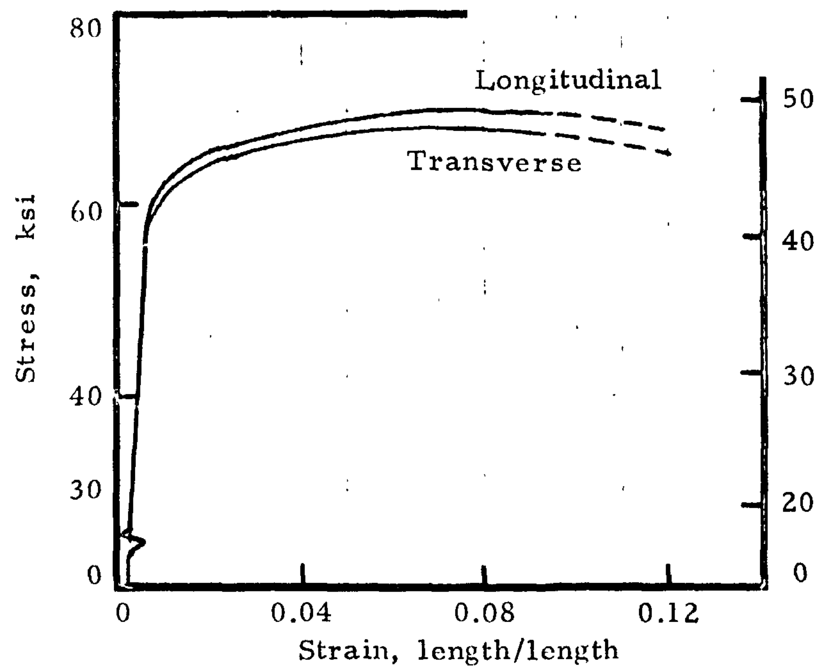

FIGURE 7.4122. – Typical tensile stress-strain curves (full-range) for 2014-T6 forgings at room temperature.
(Ref. 7.4)

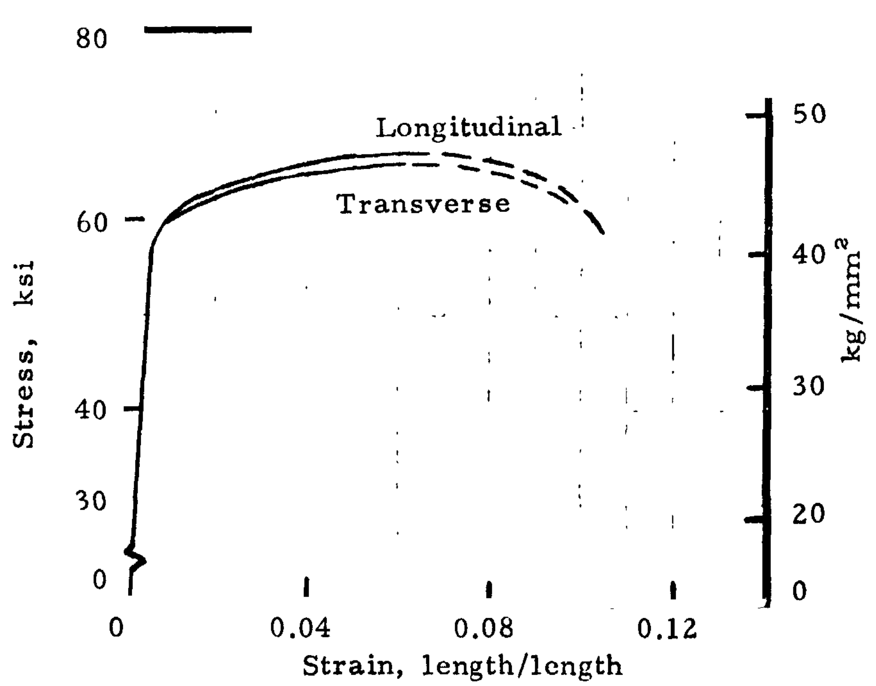

FIGURE 7.4123. – Typical tensile stress-strain curves (full-range) for 2014-T652 forgings at room temperature.
(Ref. 7.4)

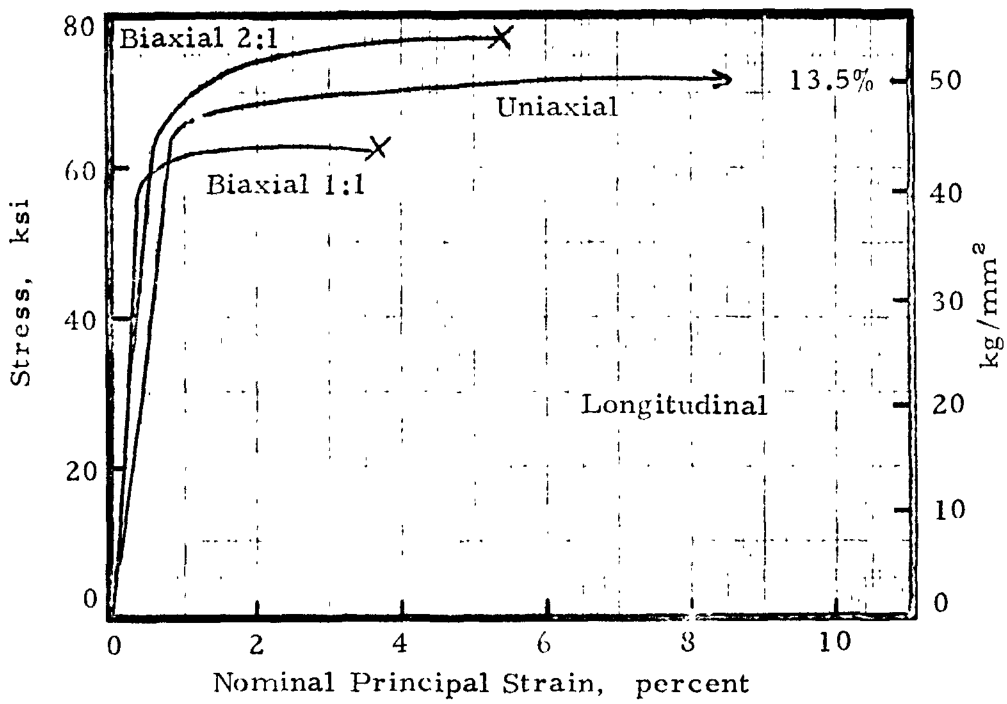

FIGURE 7.4124. — Typical uniaxial and biaxial stress-strain curves for 2014-T6 sheet; thickness, 0.125 in(3.18 mm). (Ref. 7.23)

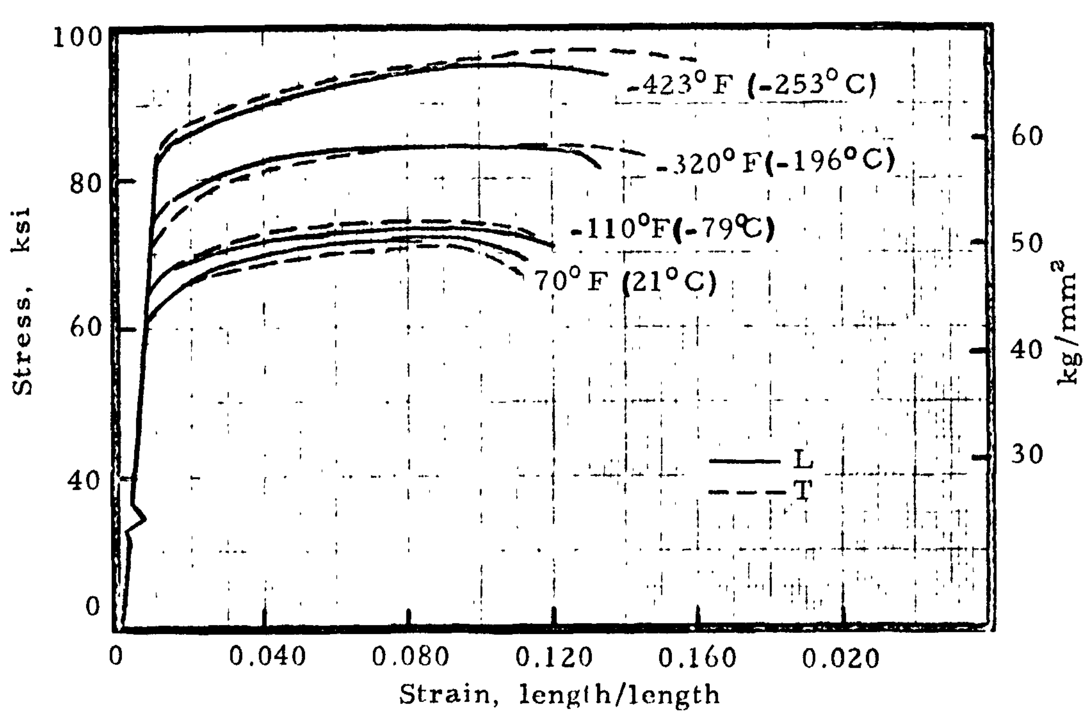

FIGURE 7.4125. — Stress-strain curves for 2014-T6 sheet at low temperatures. (Ref. 7.25)

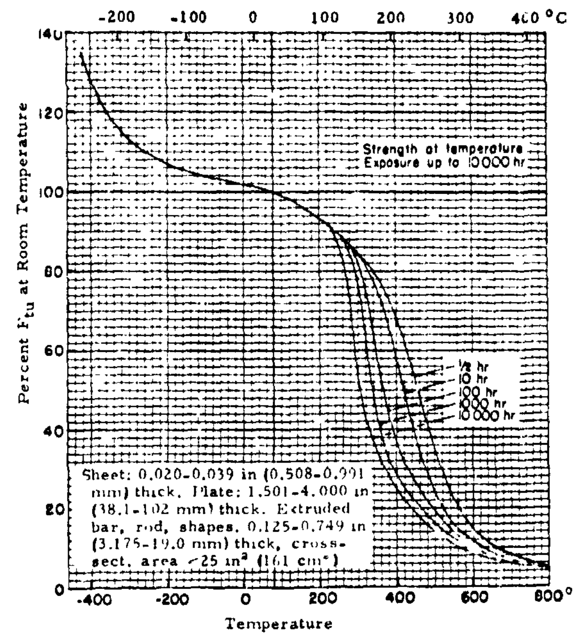

FIGURE 7.4131. – Effect of temperature on the ultimate strength of 2014-T6 bare and clad sheet and plate; rolled bar, rod, and shapes; hand and die forgings; extruded bar, rod, and shapes. (Ref. 7.4)

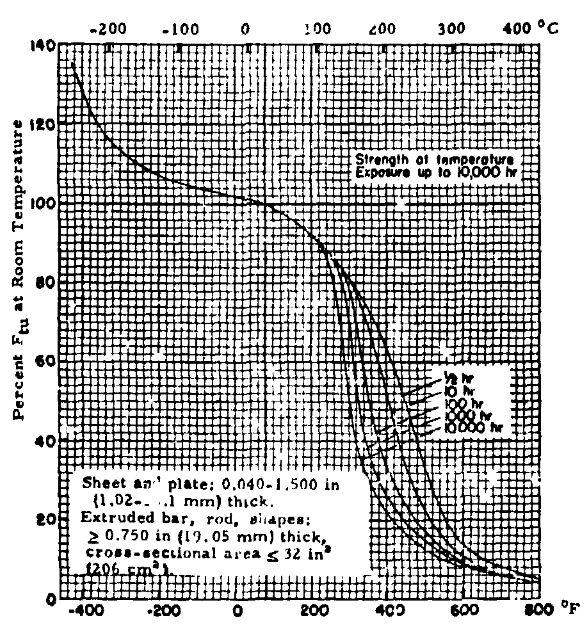

FIGURE 7.4132. – Effect of temperature on the ultimate strength of 2014-T6 bare and clad sheet and plate; extruded bar, rod, and shapes. (Ref. 7.4)

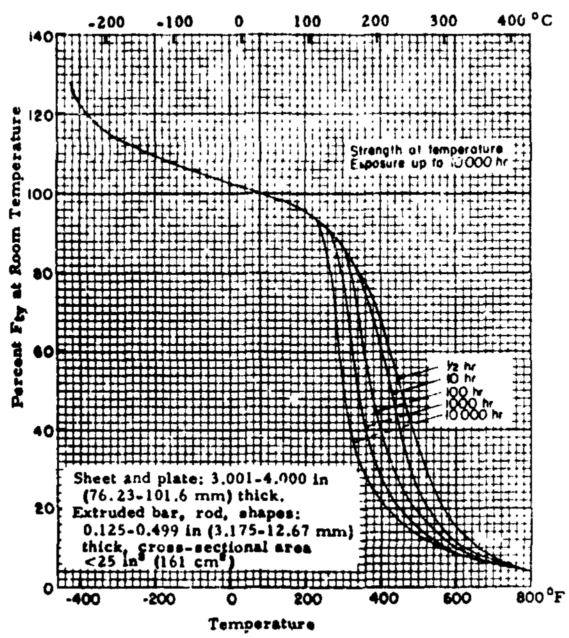

FIGURE 7.4133. — Effect of temperature on the tensile yield strength of 2014-T6 bare and clad plate; rolled bar, rod, and shapes; hand and die forgings; extruded bar, rod, and shapes. (Ref. 7.4)

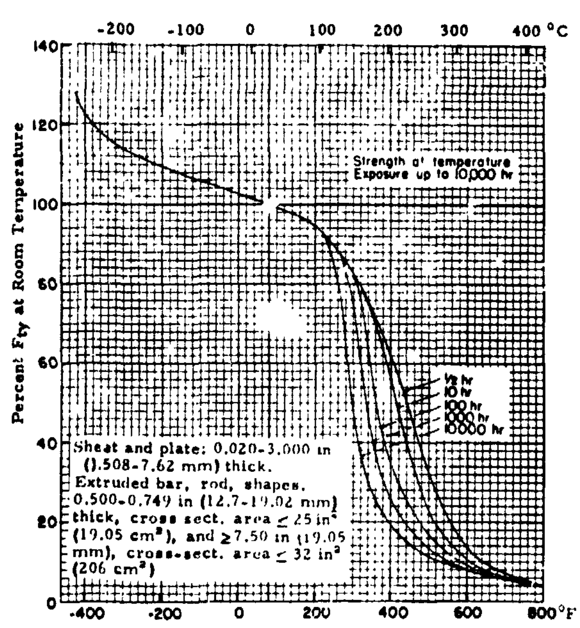

FIGURE 7.4134. — Effect of temperature on the tensile yield strength of 2014-T6 bare and clad sheet and plate; extruded bar, rod, and shapes. (Ref. 7.4)

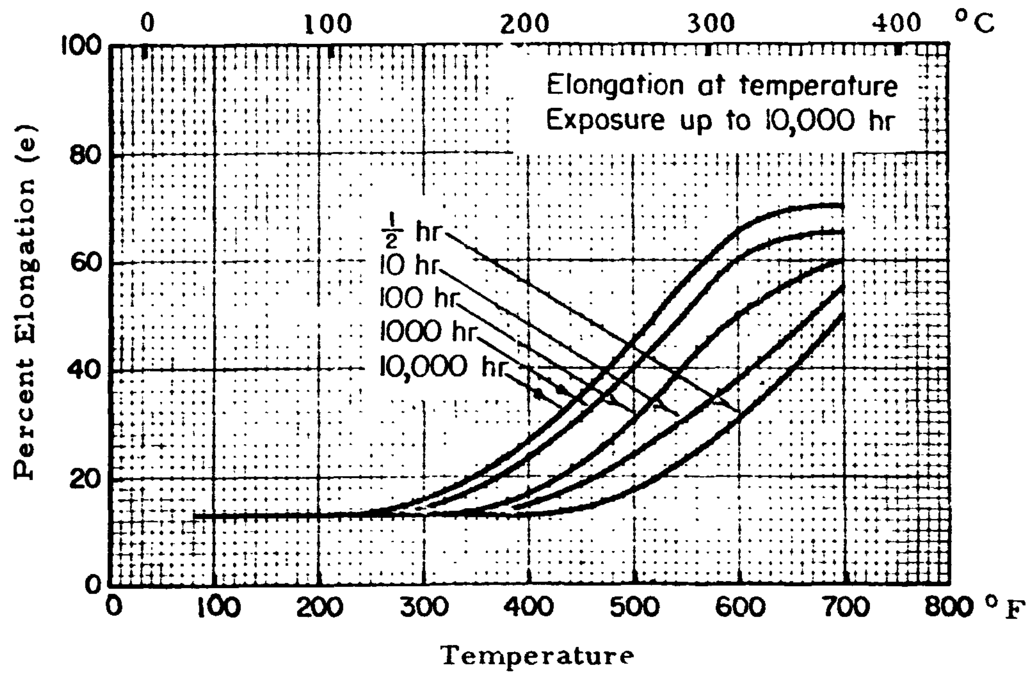

FIGURE 7.4135. — Effect of temperature on the elongation of 2014-T6 (all products except thick extrusions).
(Ref. 7.4)

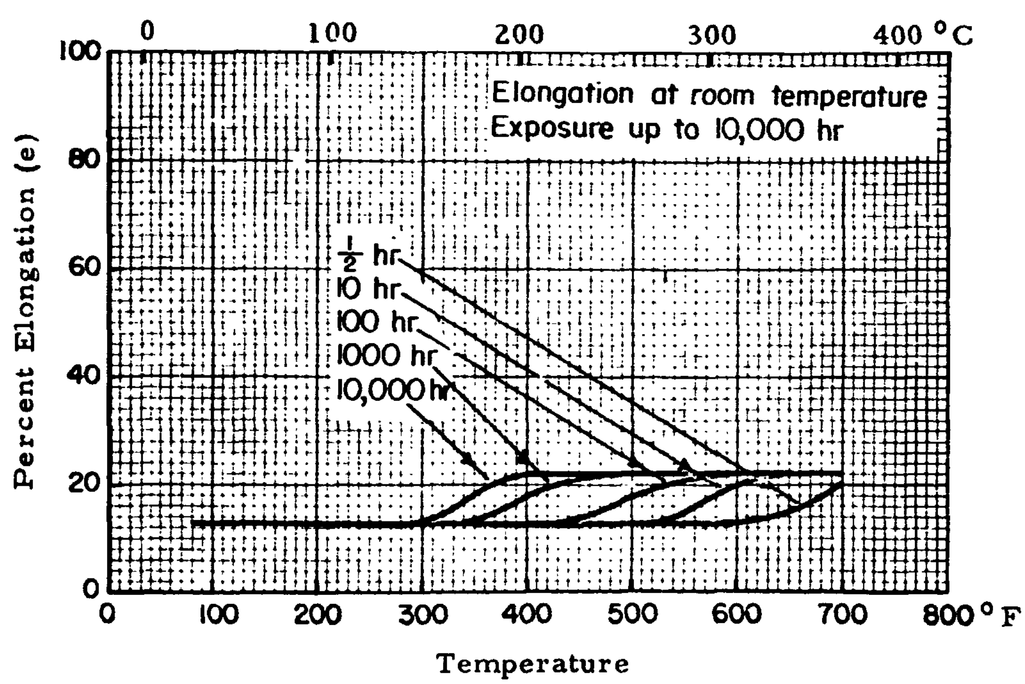

FIGURE 7.4136. — Effect of exp ıre at elevated temperatures on the room temperature elongation of 2014-T6 (all products except thick extrusions).
(Ref. 7.4)

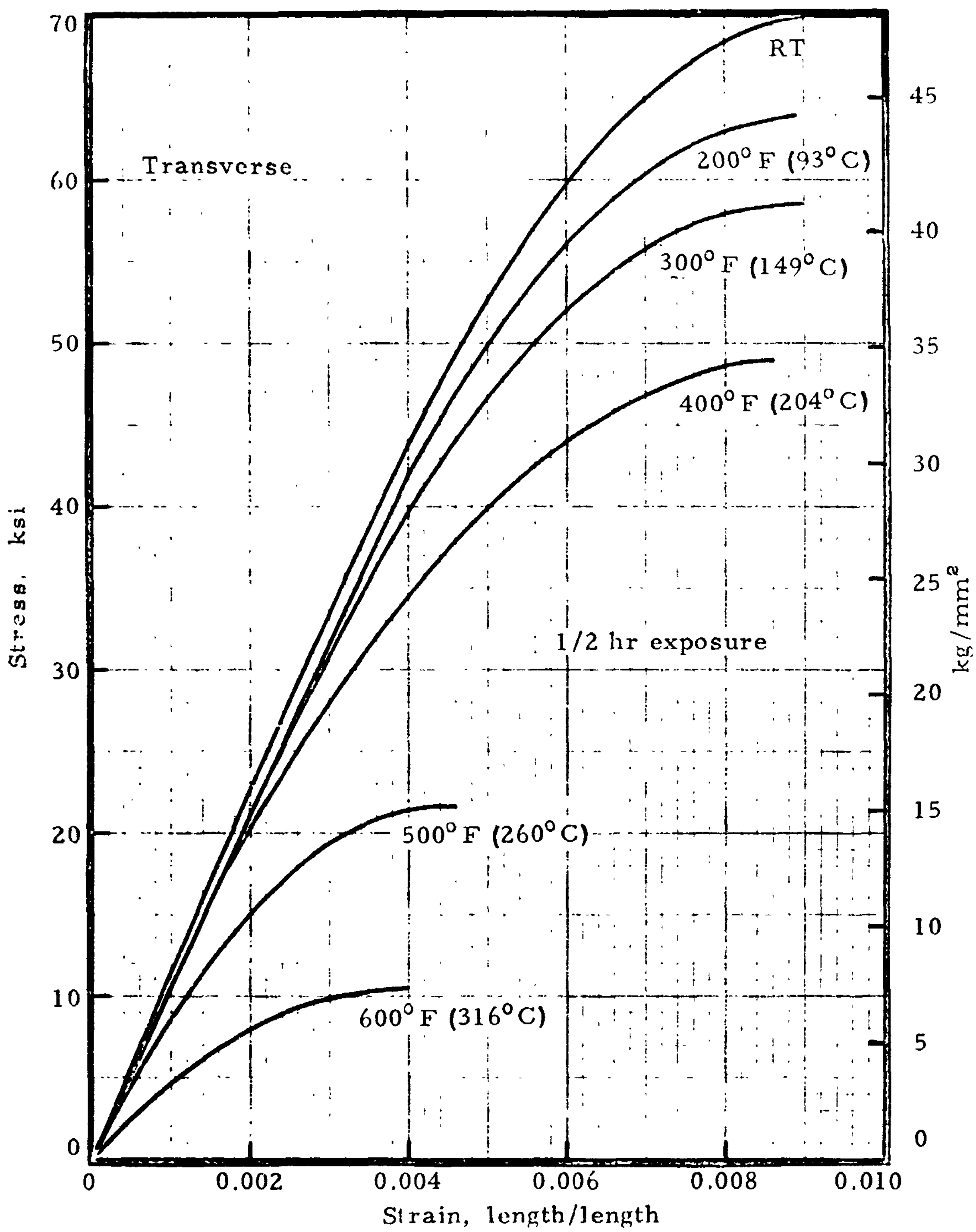

FIGURE 7.4221. – Typical stress-strain curves in compression for Clad 2014-T6 at room and elevated temperatures. (Refs. 7.1, 7.10)

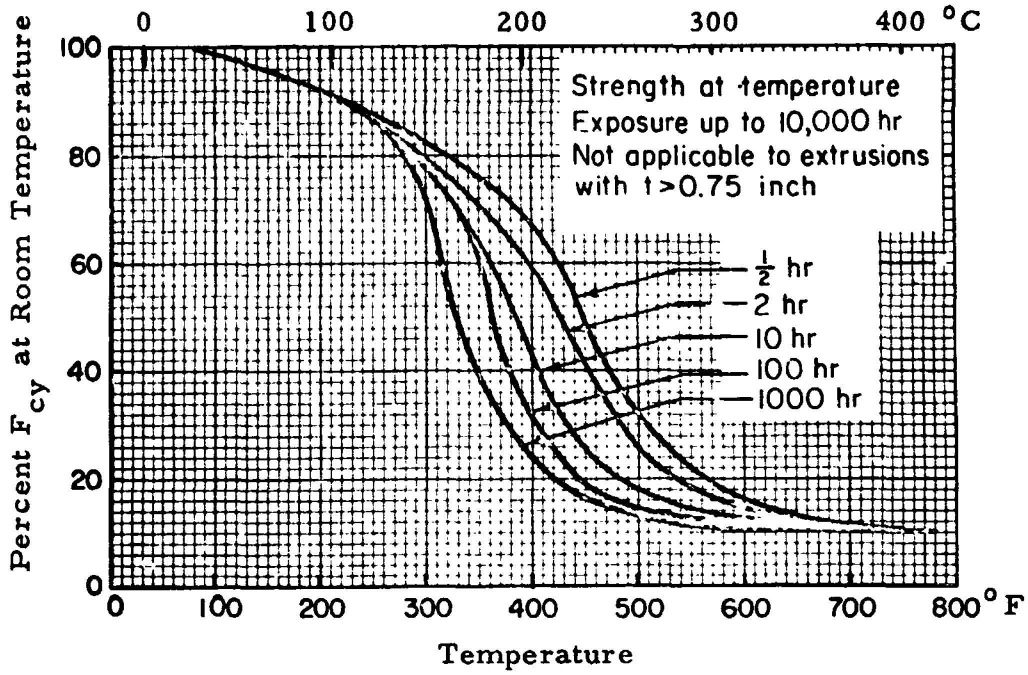

FIGURE 7.423. — Effect of temperature on the compressive yield strength Of 2014-T6 products (except thick extrusions). (Ref. 7.4)

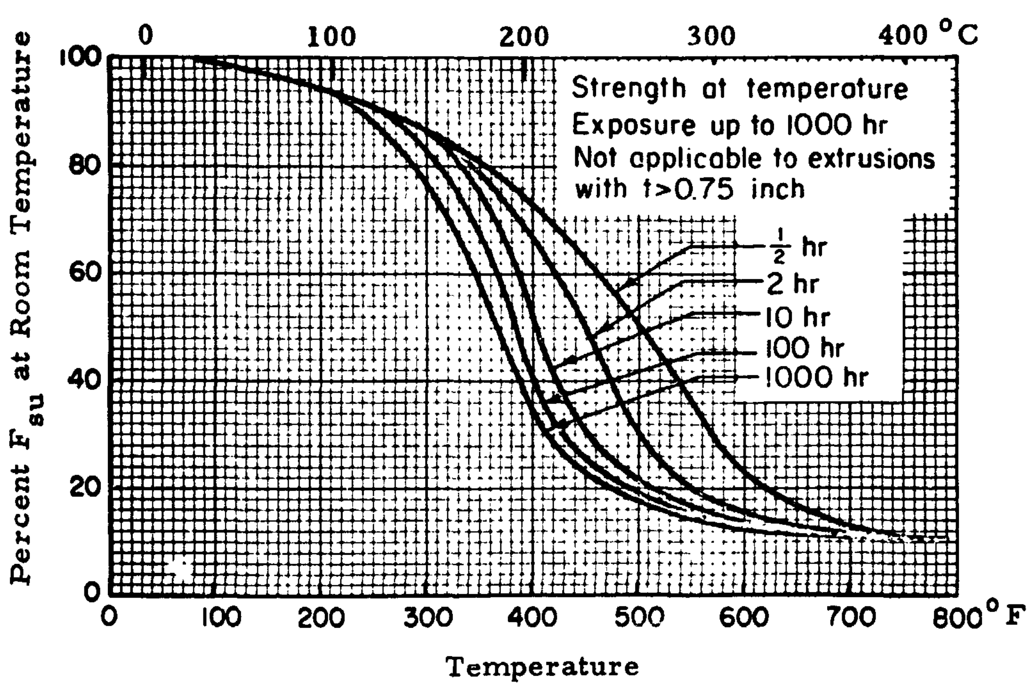

FIGURE 7.4416. — Effect of temperature on the ultimate shear strength of 2014-T6 products (except thick extrusions). (Ref. 7.4)

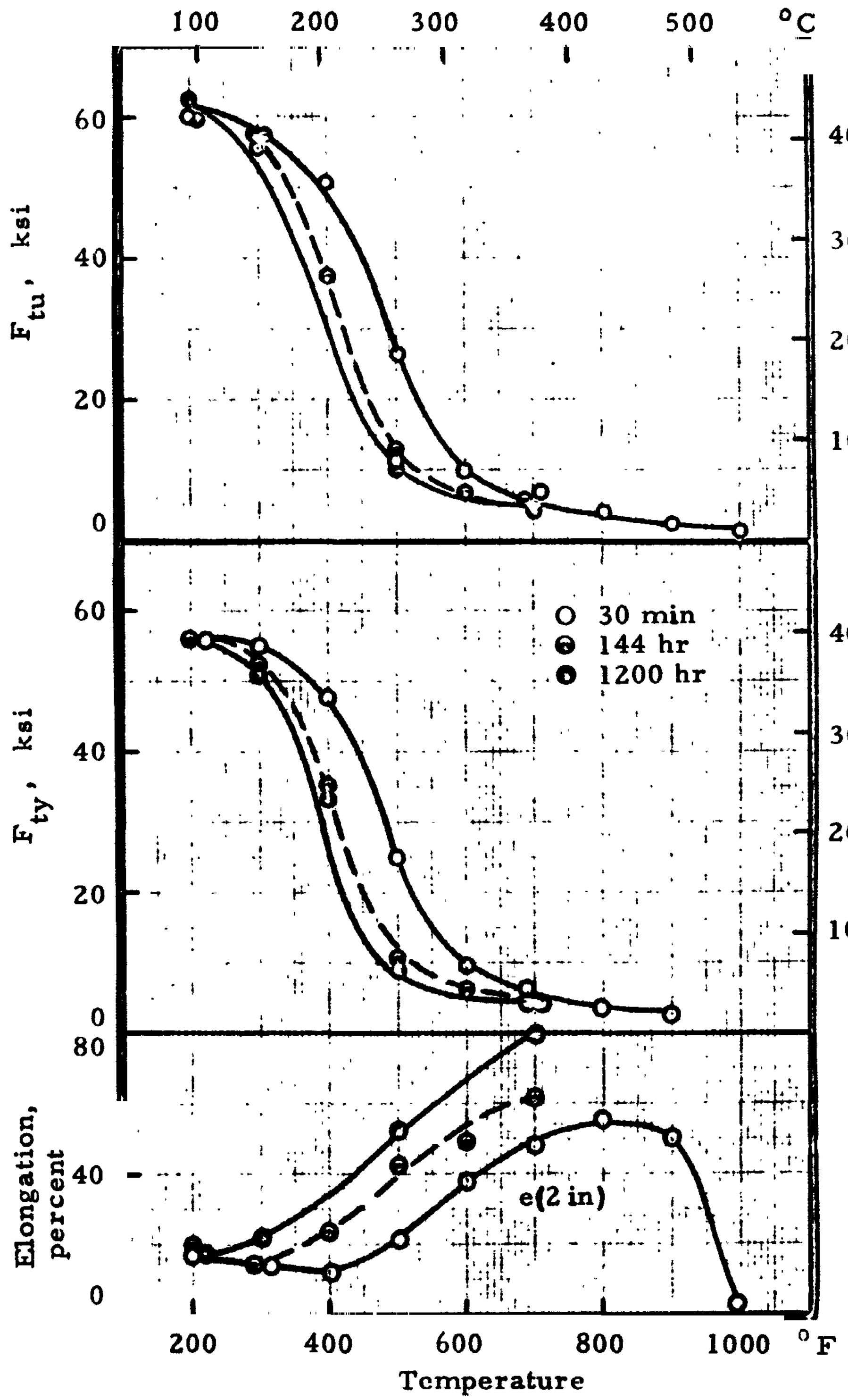

FIGURE 8.513. — Effect of exposure and elevated temperature on tensile properties of 2014-T6 forged rod.

(Ref. 8.5)

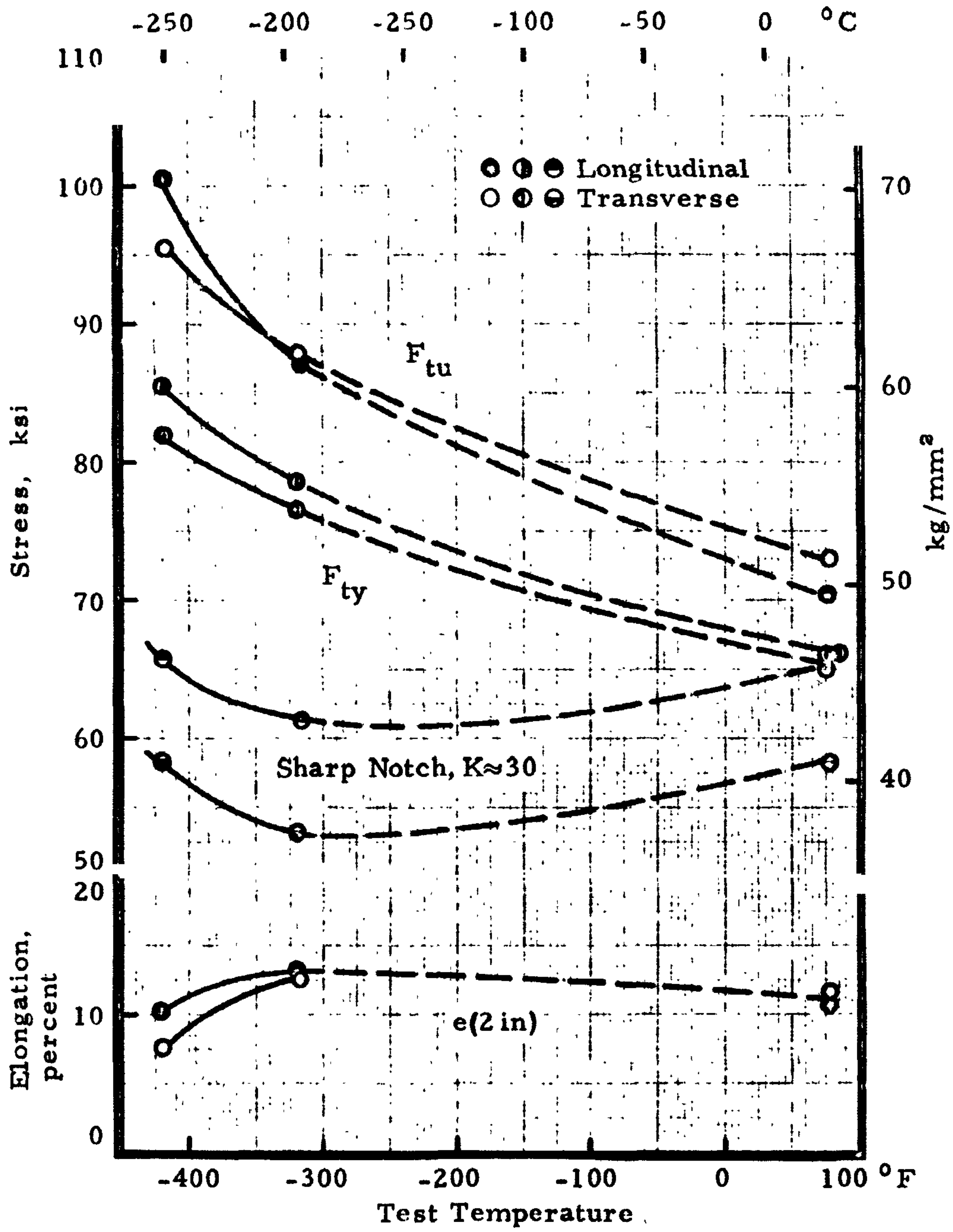

FIGURE 7.4611. — Effect of cryogenic temperatures on tensile and sharp notch properties of 2014-T6 sheet; thickness, 0.125 inch (3.175 mm).

(Ref. 7.18)

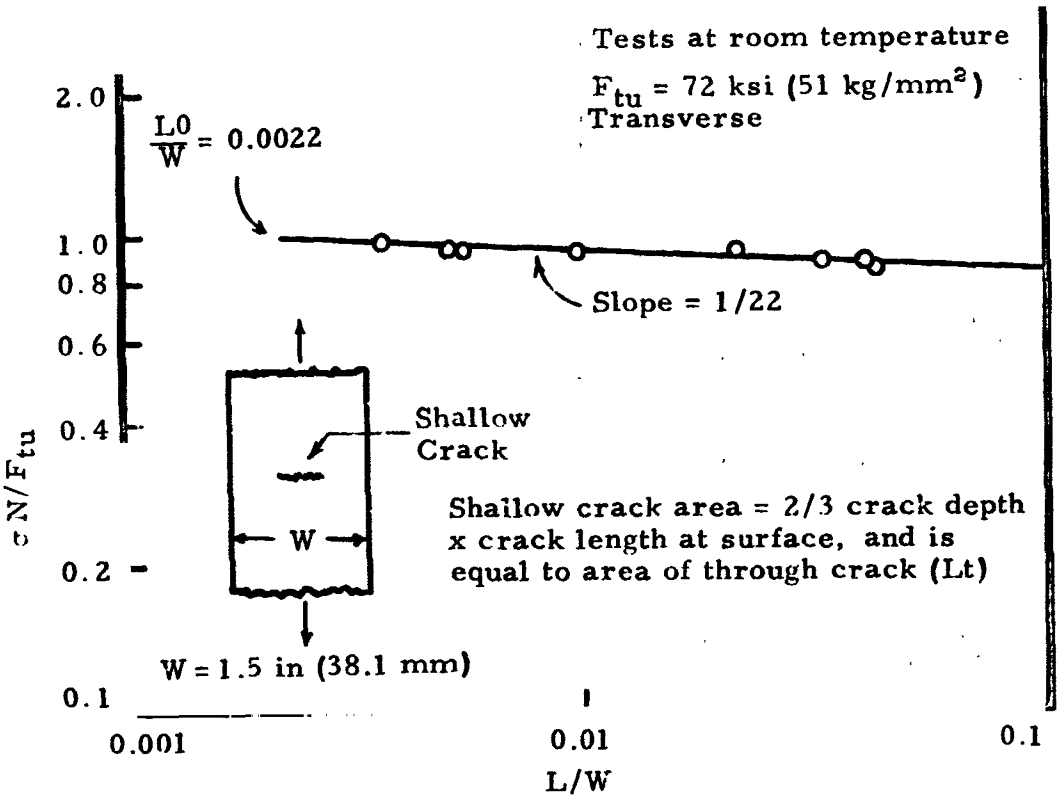

FIGURE 7.4612. – Strength of 2014-T6 sheet containing shallow cracks; thickness, 0.10 inch (2.54 mm).

(Ref. 7.22)

Chapter 7 - References

7.1 Military Handbook-5A, Dept. of Defense, FSC 1500, "Metallic Materials and Elements for Aerospace Vehicle Structures," February 1966; latest change order, January 1970.

7.2 W.S. Pierce, "Effects of Surface and Through Cracks on Failure of Pressurized Thin-Walled Cylinders of 2014-T6 Aluminum," NASA TN D-6099, November 1970.

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

7.4 Aluminum Standards & Data: 1970-71, The Aluminum Association, New York.

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

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

7.7 Aerospace Material Specifications, latest Index, May 1971, Society of Automotive Engineers, New York.

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

7.9 Aluminum Co. of America, "Alcoa Product Data - Specifications," Section A12A, July 1, 1963.

7.10 D.E. Miller, "Determination of Physical Properties of Ferrous and Nonferrous Structural Sheet Materials at Elevated Temperatures," AF TR-6517, Part 3, 1953.

7.11 Alloy Digest, "Aluminum 2014" (Filing Code: Al-17), Engineering Alloys Digest, Inc., June 1954.

7.12 Aluminum Co. of America, "Alcoa Aluminum Handbook," 1959.

7.13 Metals Handbook, Vol. 1, "Properties and Selection of Metals," 8th Edition, American Society for Metlas, 1961.

7.14 Materials in Design Engineering, "Materials Selector Issue, 60 (5), Mid-October 1964.

7.15 Aluminum Co. of America, Research Laboratories Data Sheet, August 1957.

7.16 General Dynamics/Astronautics, "Compilation of Materials Research Data, 4th Quarterly Report, Phase I," Report AD-62-0138-3, March 1962.

7.17 Bell Aerosystems Co., "Phase II, Cryogenic Properties of 2014-T6 and A-286," BLR-35 (M) Rev. A, June 1962.

7.18 M.P. Hanson, G.W. Stickley, and H.T. Richards, "Sharp Notch Behavior of Some High Strength Sheet Aluminum Alloys and Welded Joints at 75, -320, and -423°F," ASTM STP-287, 1960, p. 3.

7.19 W.R. Lucas and C.E. Cataldo, "Some Low Temperature Properties of Aluminum Alloy Weldments," ASTM STP-287, 1960, p. 108.

7.21 J.L. Christian, et al., "Structural Alloys for Cryogenic Service," Metal Progress, 83 (3), March 1963.

7.22 G.E. Bockrath, and J.B. Glassco, "Fracture Toughness of High Strength Sheet Metal," Douglass Missile and Space Systems Div., presented at ASM Western Metal Congress, March 1963.

7.23 E.L. Terry and S.W. McClaren, "Biaxial Stress and Strain Data on High Strength Alloys for Design of Pressurized Components," Chance-Vought Corp., ASD TDR 62-401, July 1962.

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

7.25 Prog. Report No. 1, Suppl. to Ref. 7.24, February 1965.

7.26 Reynolds Metals Co., "The Aluminum Data Book," 1965.

Chapter 8

DYNAMIC AND TIME DEPENDENT PROPERTIES

8.1 General

8.2 Specified Properties

8.3 Impact

8.31 Effect of cryogenic temperatures on Charpy V impact strength, figure 8.31.

8.4 Creep

8.41 Creep and creep rupture

8.411 Creep and creep rupture curves for 2014-T6 at elevated temperatures, figure 8.411.

8.42 Creep deformation, see also 8.411.

8.421 Short time total strain curves for clad 2014-T6 at elevated temperatures, figure 8.421.

8.43 Time-temperature-parameters

8.44 Isochronous stress-strain diagrams

8.441 Isochronous stress-strain curves in tension at 400°F, figure 8.441.

8.5 Stability (see also chapter 7)

8.51 Exposure effects

8.511 Effect of exposure and test temperature on tensile properties of clad sheet, figure 8.511.

8.512 Effect of exposure on room temperature tensile properties of 2014-T6 aluminum rod, figure 8.512.

8.513 Effect of exposure and elevated temperature on tensile properties of 2014-T6 aluminum rod, figure 8.513.

8.514 Effect of exposure on room temperature tensile properties of 2014-T6 aluminum rod, figure 8.514.

8.515 Effect of exposure and elevated temperature on tensile properties of 2014-T6 aluminum rod, figure 8.515.

8.6 Fatigue

8.61 Controlled stress cycling

8.611 Fatigue strength of alloy in various forms, table 8.611.

8.612 Stress range diagram for smooth and notched bar in T6 condition, figure 8.612.

8.613 Average stress range diagram for bar and extrusions, figure 8.613.

8.614 Scatter band of fatigue data for smooth and notched hand forged bar in T6 condition, figure 8.614.

8.615 Typical constant-life diagram for fatigue behavior of various wrought T3 products, figure 8.615.
8.62 Controlled strain cycling
8.621 Effect of strain cycling on fatigue life of bar stock, figure 8.621.
8.623 Damping
8.64 Thermal cycling
8.65 Stress concentration effects
8.651 See table 8.611 and figures 8.612, 8.614.
8.66 Environmental effects
8.661 S-N curves for alloy tested in air and in simulated sea water, figure 8.661.

TABLE 8.611. – Fatigue Strengths under Completely Reversed Flexure of Alloy in Various Forms

Source	Ref. 8.6						
Alloy	2014						
Specimen Type	Temper	Fatigue strength at indicated no. of cycles ksi (kg/mm^2)					
		10^3	10^4	10^5	10^6	10^7	5×10^8
Smooth machined round	T6	52 (37)	39 (27)	30 (21)	24 (17)	19 (13)	18 (13)
Sharply notched round	T6	31 (22)	21 (15)	14 (10)	10 (7.0)	9 (6.3)	9 (6.3)
Flat sheet	Clad T3	- -	31 (22)	20 (14)	17 (12)	15 (11)	15 (11)
Flat sheet	Clad T6	-	31 (22)	20 (14)	17 (12)	15 (11)	15 (11)

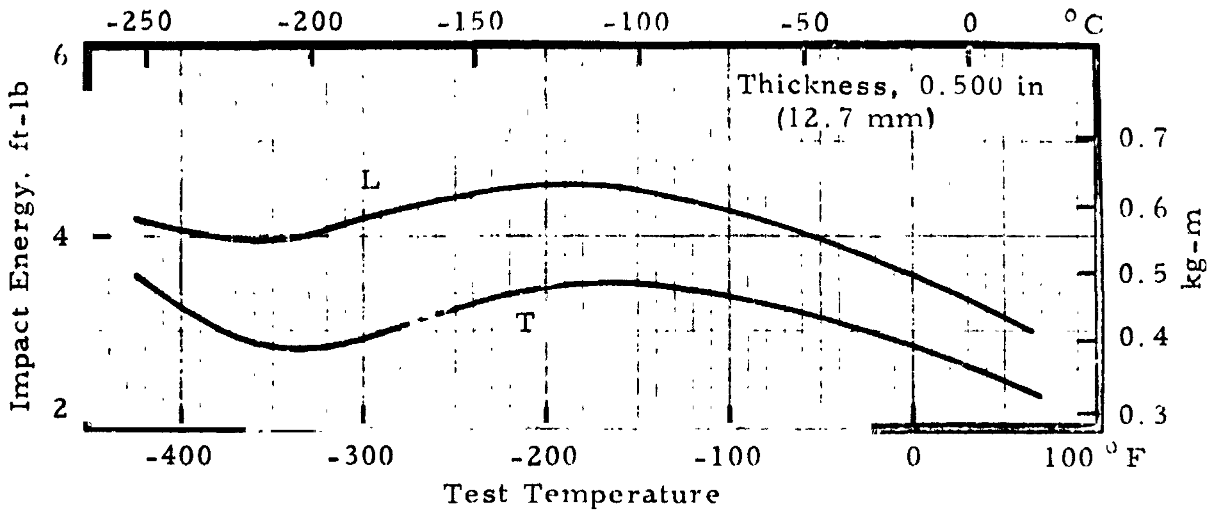

FIGURE 8.31. – Effect of cryogenic temperatures on Charpy V impact strength of 2014-T6 plate. (Ref. 8.12)

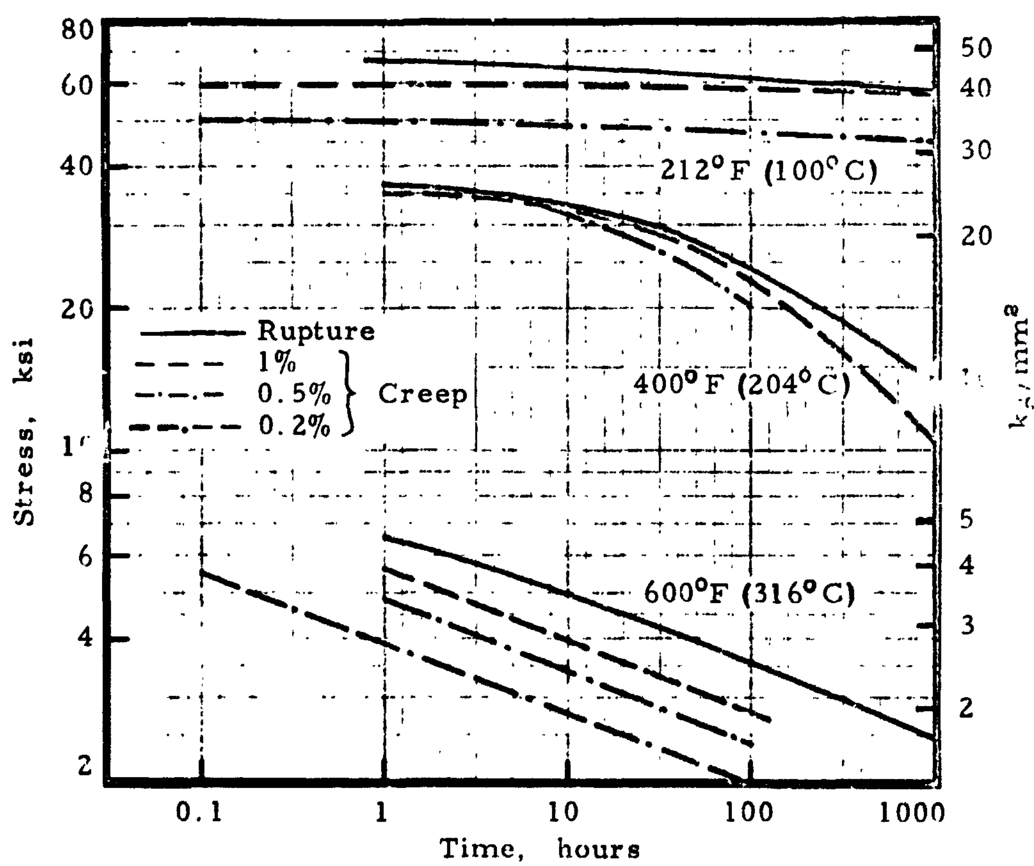

FIGURE 8.411. – Creep and creep rupture curves for 2014-T6 at elevated temperatures. (Ref. 8.1)

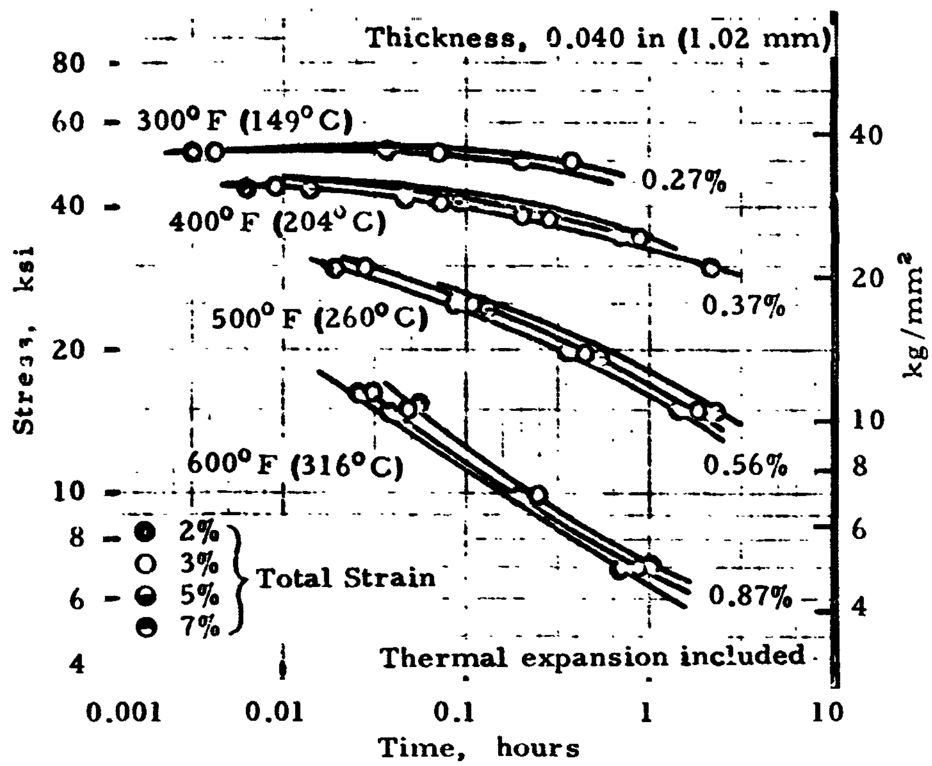

FIGURE 8.421. — Short time total strain curves for Clad 2014-T6 at elevated temperatures. (Ref. 8.2)

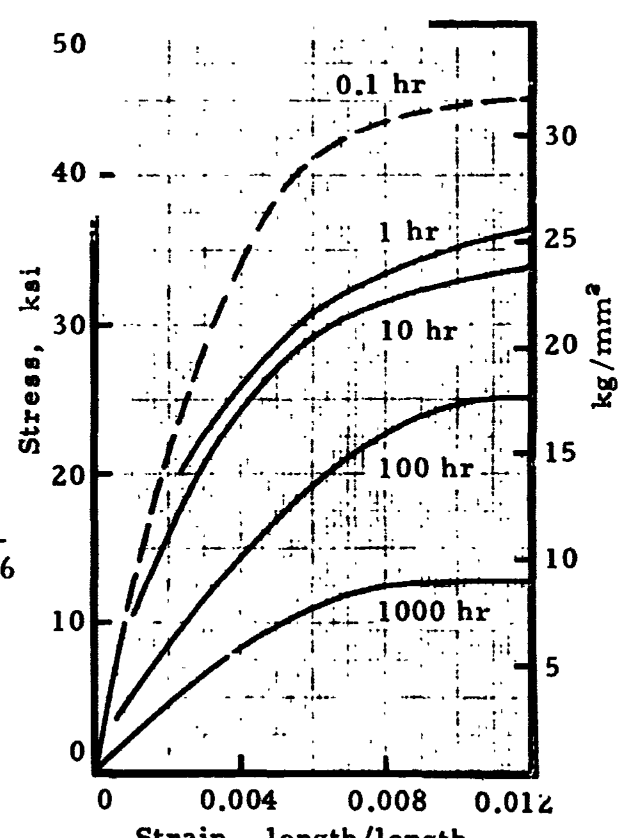

FIGURE 8.441. — Isochronous stress-strain curves in tension for 2014-T6 at 400° F (204° C). (Ref. 8.3)

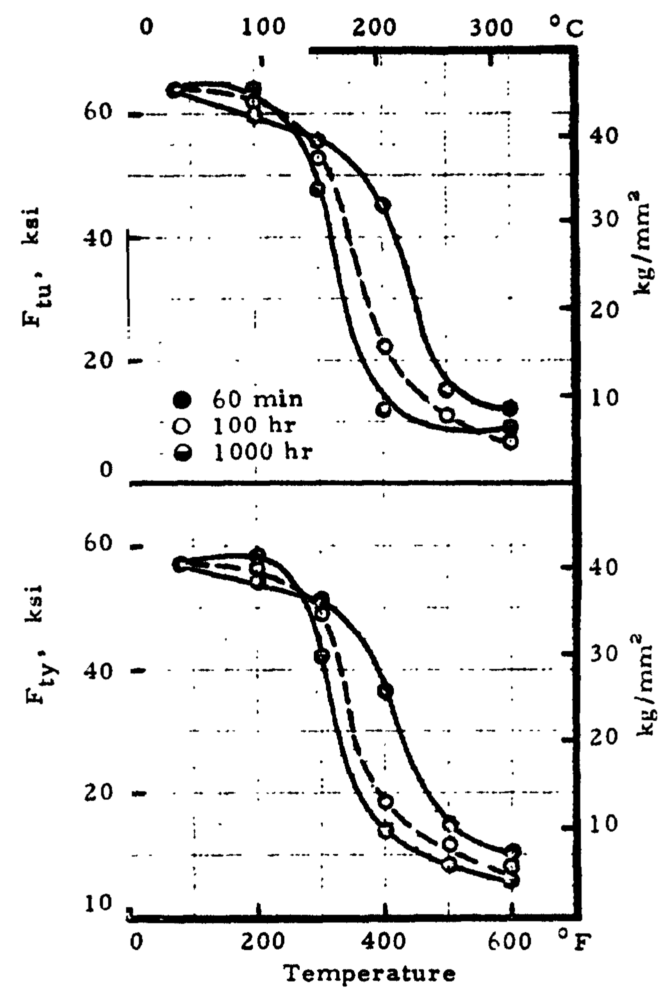

FIGURE 8.511. — Effect of exposure and test temperature on tensile properties of Clad 2014-T6 sheet; thickness, 0.064 in(1.63 mm). (Ref. 8.4)

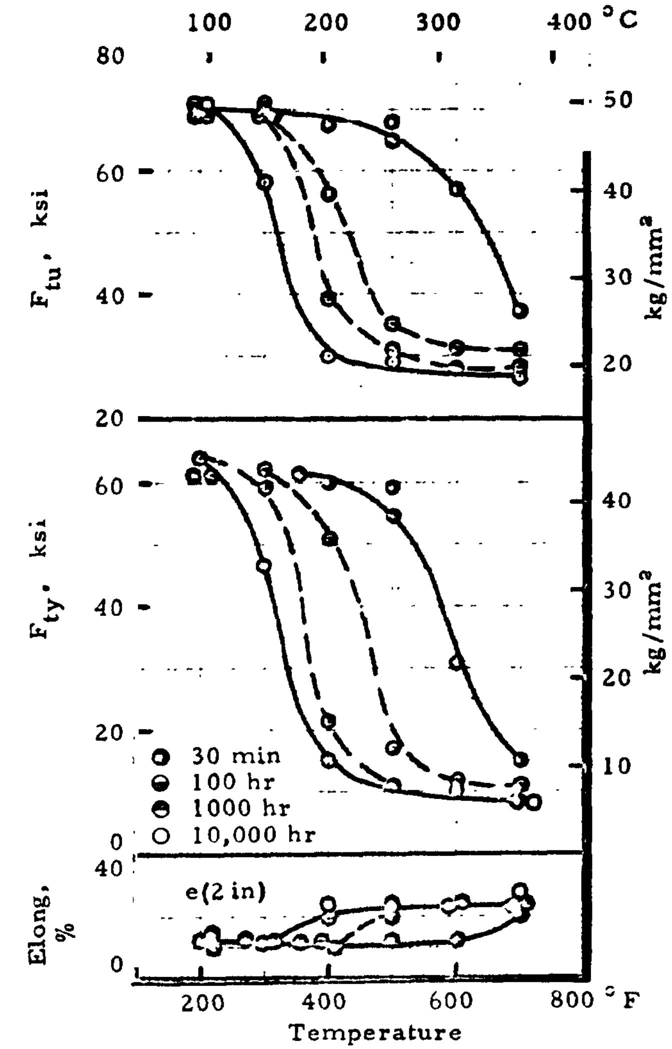

FIGURE 8.512. — Effect of exposure on room temperature tensile properties of 2014-T6 forged rod. (Ref. 8.5)

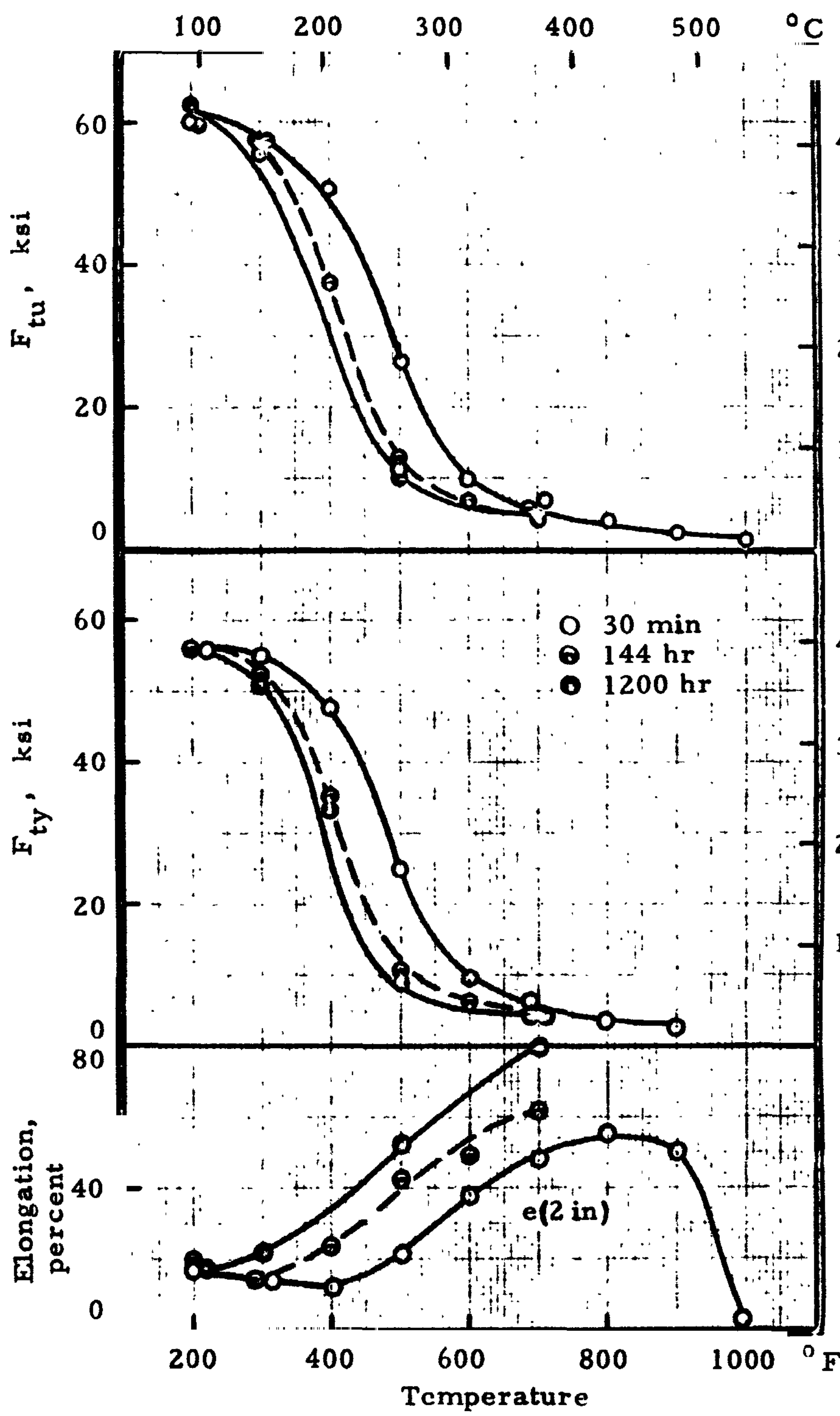

FIGURE 8.513. — Effect of exposure and elevated temperature on tensile properties of 2014-T6 forged rod.

(Ref. 8.5)

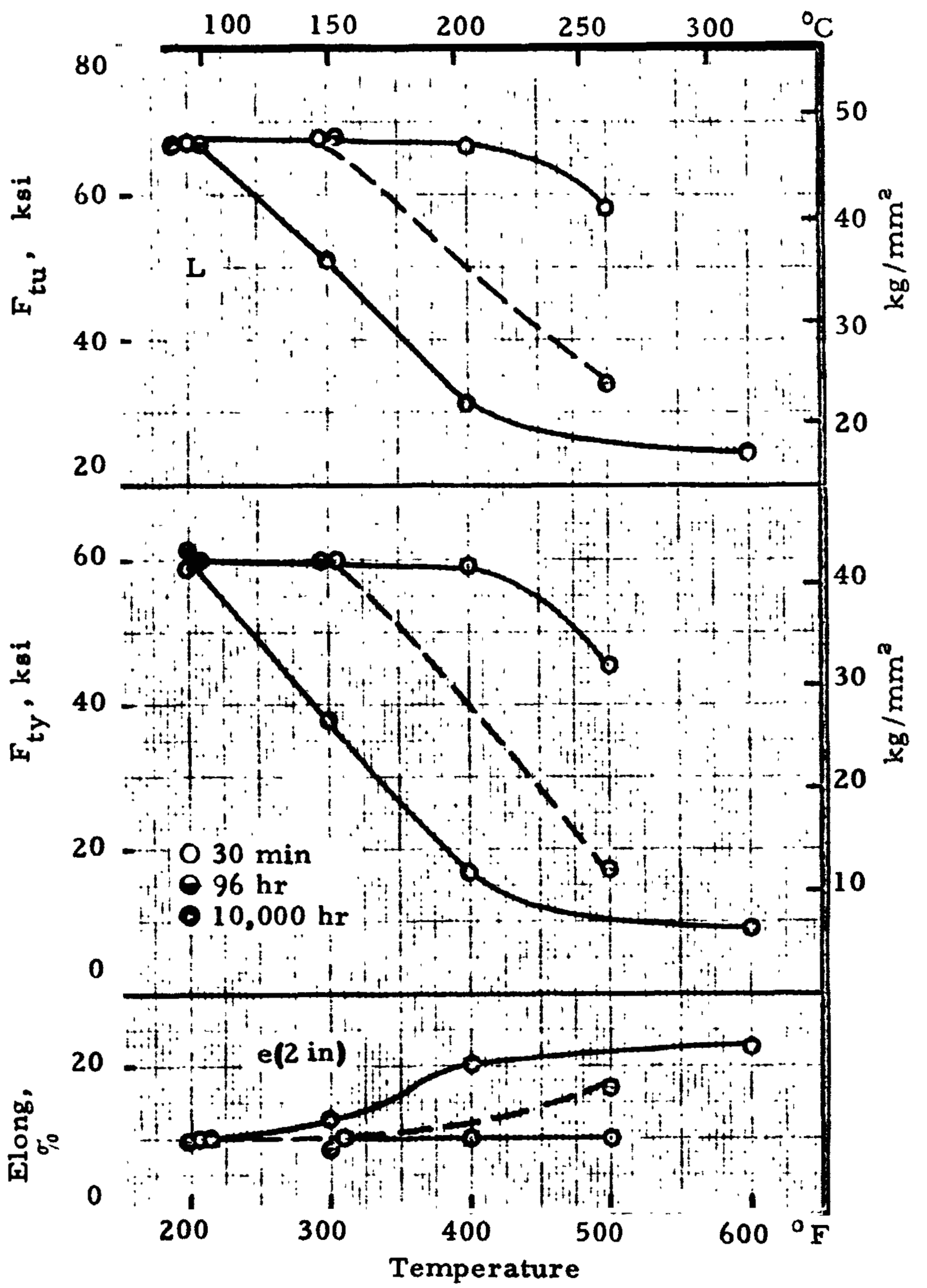

FIGURE 8.514. – Effect of exposure on room temperature tensile properties of 2014-T6 rolled and drawn rod.

(Ref. 8.5)

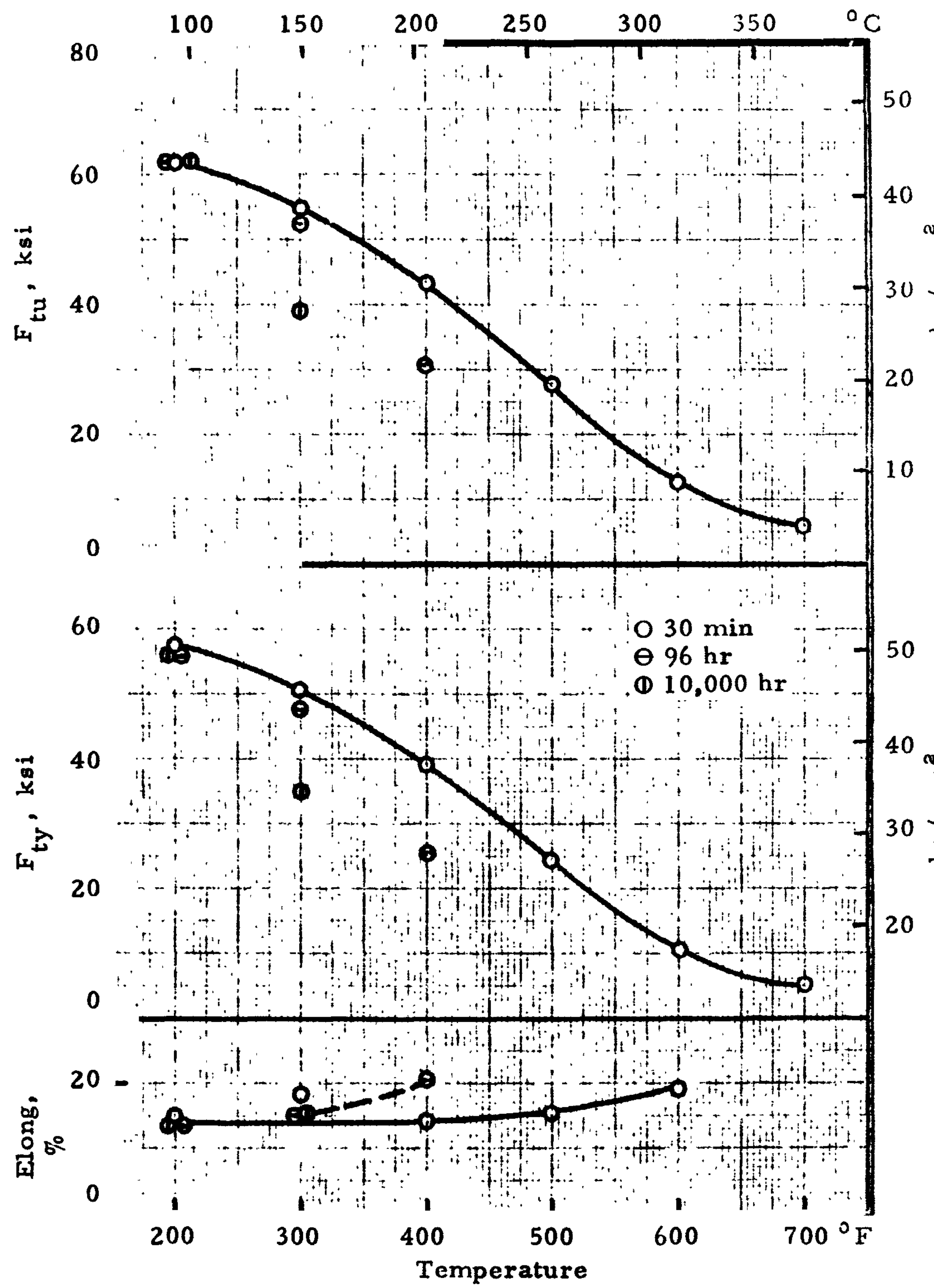

FIGURE 8.515. — Effect of exposure and elevated temperature on tensile properties of 2014-T6 rolled and drawn rod.

(Ref. 8.5)

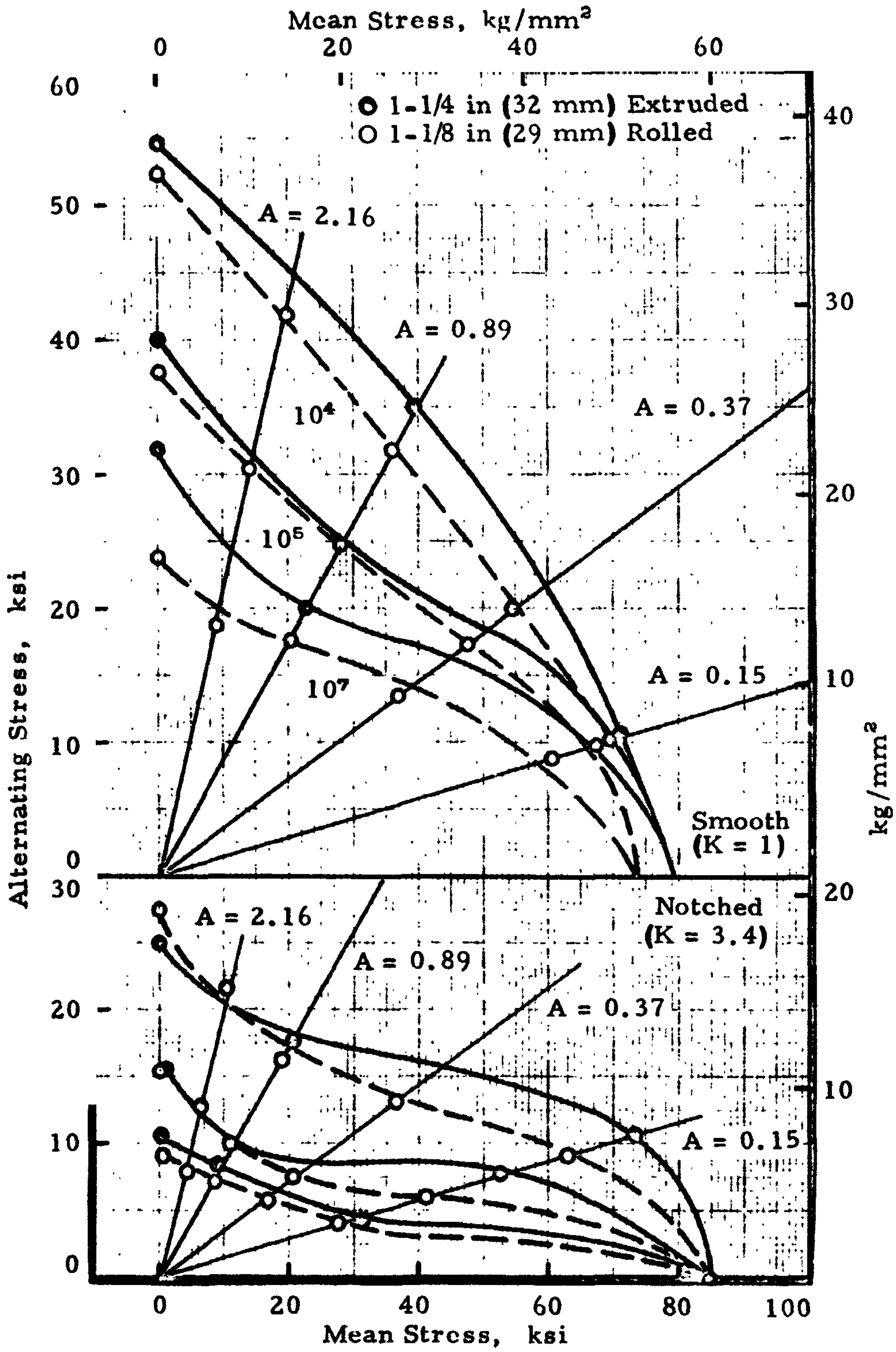

FIGURE 8.612. — Stress range diagrams for smooth and notched 2014-T6 bar.

(Ref. 8.7)

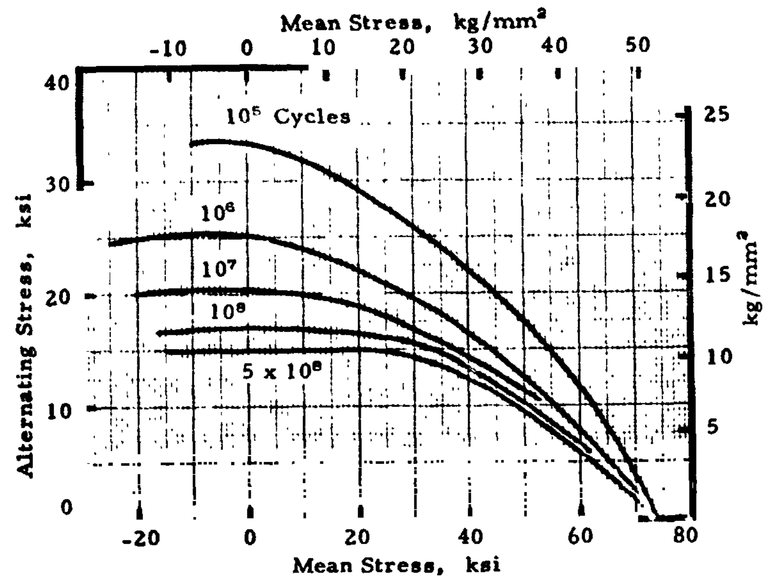

FIGURE 8.613. – Average stress-range diagram for 2014-T6 bar and extrusions.
(Ref. 8.8)

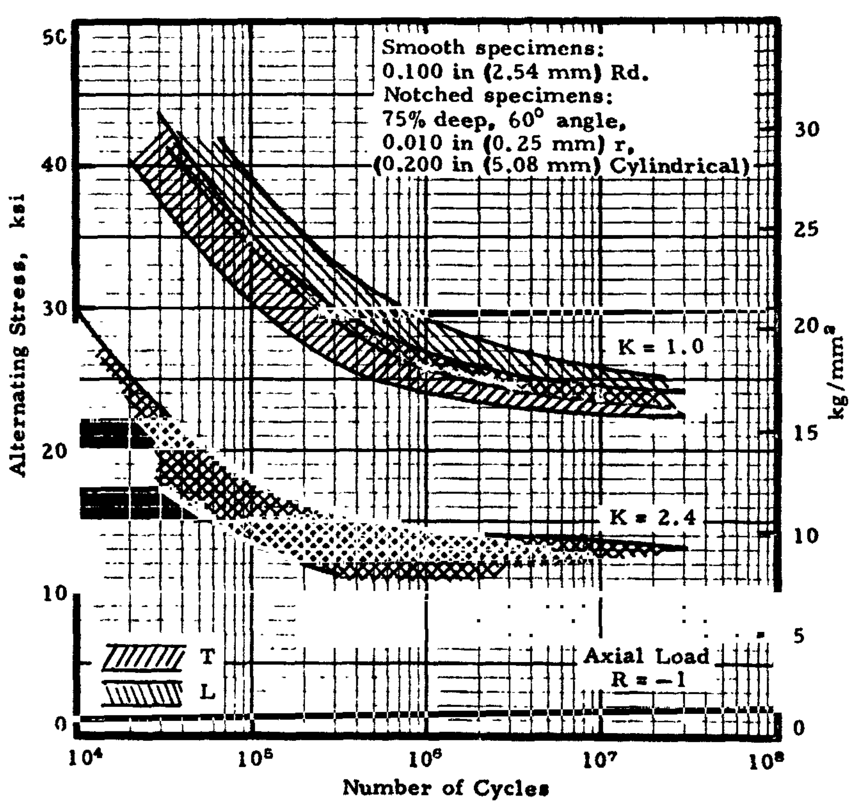

FIGURE 8.614. – Scatter band of fatigue data for smooth and notched 2014-T6 hand forged bar.
(Ref. 8.9)

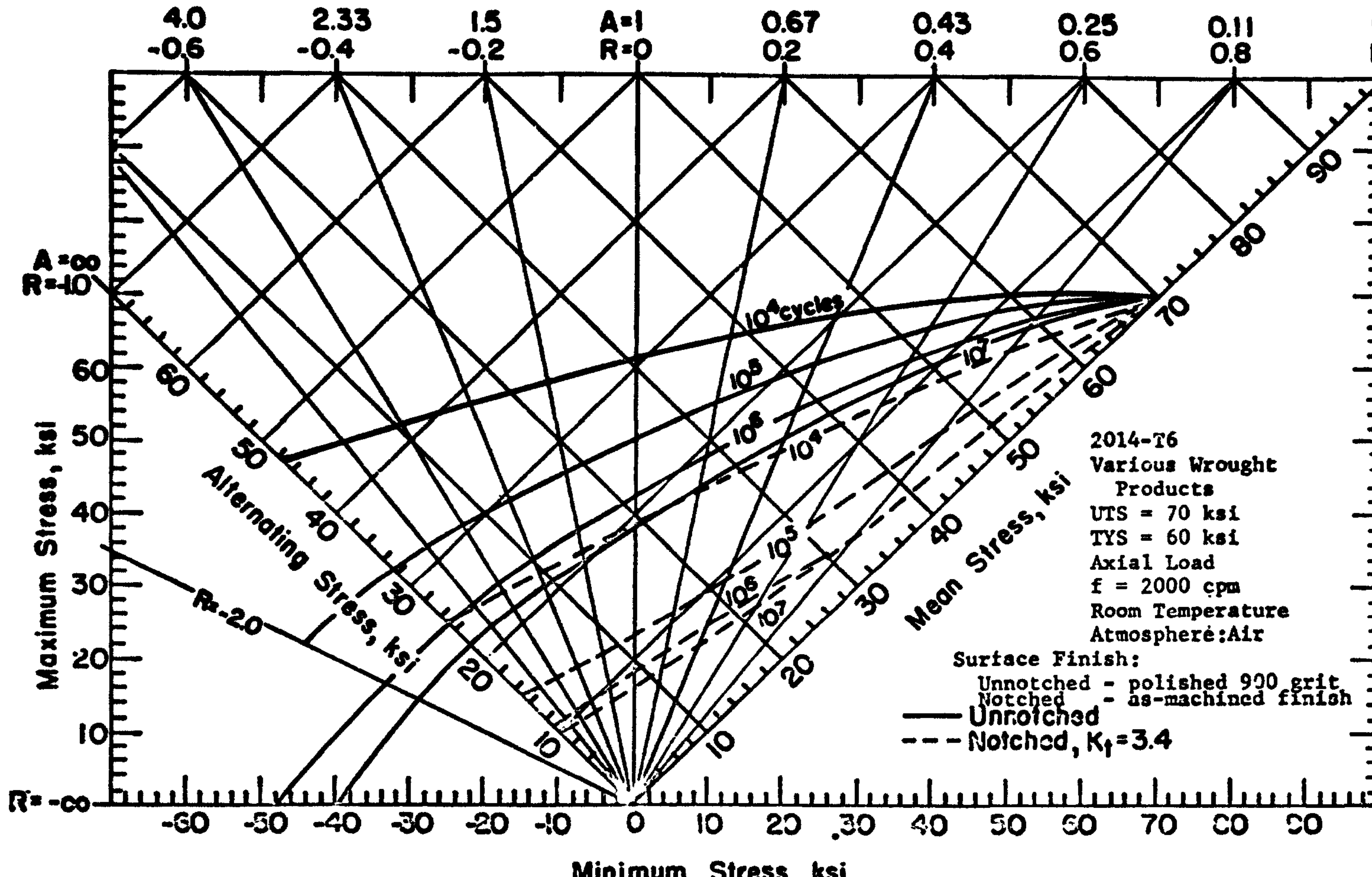

FIGURE 8.615. — Typical constant-life diagram for fatigue behavior of various wrought 2014-T6 products.
(1 ksi = 0.70307 kg/mm^2)
(Ref. 8.6)

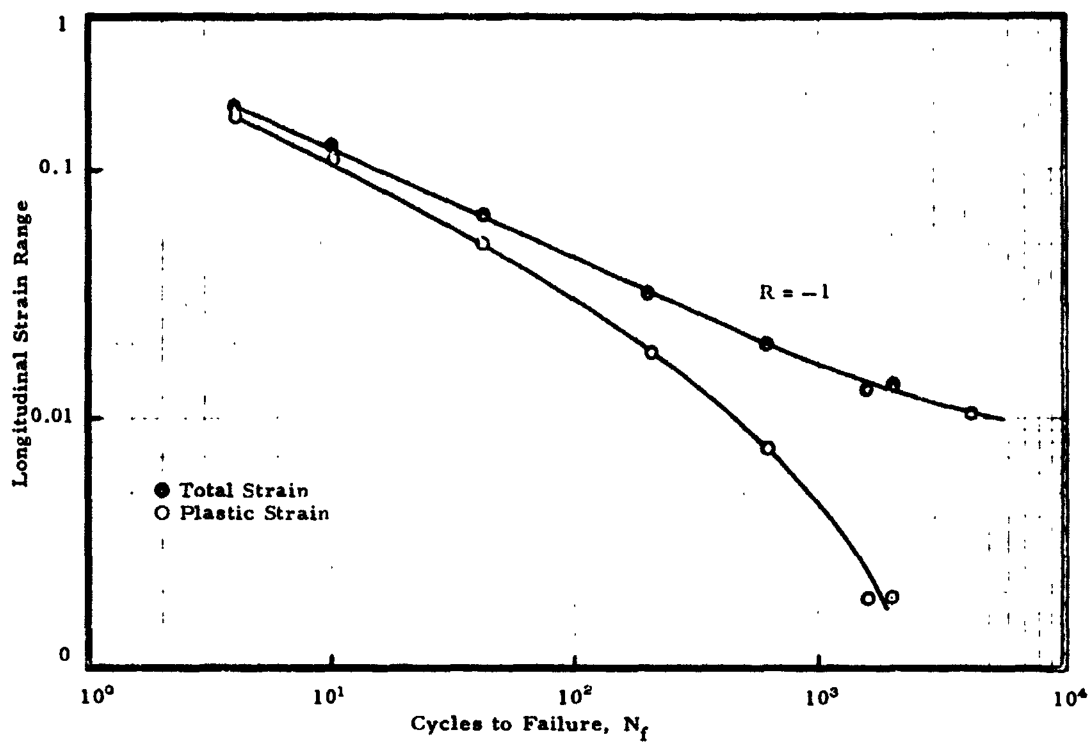

FIGURE 8.621. – Effect of strain cycling on fatigue life of 2014-T6 bar stock; diameter, 0.75 in (19.0 mm). (Ref. 8.10)

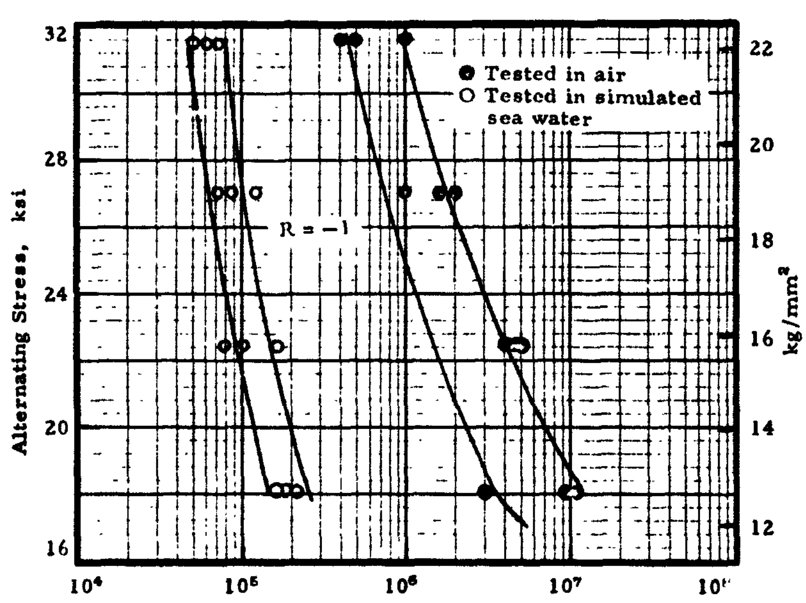

FIGURE 8.661. – S-N curves for 2014-T6 tested in air and in simulated sea water; rotating beam fatigue tests, 2000 cycles/minute. (Ref. 8.11)

Chapter 8 - References

8.1 Aluminum Co. of America, Research Laboratories Data Sheet, August 1957.

8.2 J.A. Van Echo, W.F. Wirth, and W.F. Simmons, "Short-Time Creep Properties of Structural Sheet Materials for Aircraft and Missiles," AF TR-6731, Pt. III, May 1955.

8.3 F.M. Howell and G.W. Stickley, "Isochronous Stress-Strain Curves for Several Heat-Treated Wrought Aluminum Alloys at 300° and 400° F," Alcoa Research Laboratories, Mechanical Testing Div., April 1958.

8.4 D.E. Miller, "Determining Physical Properties of Ferrous and Non-ferrous Structural Sheet Materials at Elevated Temperatures," AF TR-6517, Pt. 3, December 1953.

8.5 "Report on the Elevated Temperature Properties of Aluminum and Magnesium Alloys," ASTM STP-291, October 1960.

8.6 Military Handbook-5A, Dept. of Defense, FSC-1500, "Metallic Materials and Elements for Aerospace Vehicle Structures," February 1966; latest change order, January 1970.

8.7 B.J. Lazan, and A.A. Blatherwick, "Fatigue Properties of Aluminum Alloys at Various Direct Stress Ratios," WADC TR 52-307, Pt. II, December 1952.

8.8 F.M. Howell, and D.E. Miller, "Axial-Stress Fatigue Strengths of Several Aluminum Alloys," ASTM Proc., 55, 1955.

8.9 D.A. Paul and O.Y. Wang, "Fatigue Behavior of 2014-T6, 7075-T6, and 7079-T6 Aluminum Alloy Regular Hand Forgings," WADC TR 59-591, January 1960.

8.10 R.W. Smith, M.H. Hirschberg, and S.S. Manson, "Fatigue Behavior of Materials Under Strain-Cycling in Low and Intermediate Life Range," NASA TN D-1574, April 1963.

8.11 C.W. Austin, "Rotating Beam Fatigue and Corrosion Fatigue Properties of Aluminum and Magnesium Alloys," Report No. DS-TN-169, Army Ballistic Missile Agency, February 1958.

8.12 F.R. Schwartzberg, et al., "Cryogenic Materials Data Handbook," Martin Co., Denver, ML-TDR-64-280, August 1964.

Chapter 9

PHYSICAL PROPERTIES

9.1 Density (ρ)

0.101 lb/in^3 at 68°F
2.80 g/cm^3 at 20°C (refs. 9.2, 9.3)

9.2 Thermal Properties

9.21 Thermal conductivity, K, of various alloy tempers, table 9.21.

9.212 The thermal conductivity of 2014 aluminum at room temperature is up to 30 percent lower than that of electrical conductor grade aluminum. This indicates that the heat transfer depends markedly on temper and composition, or concentration and distribution of secondary elements. The allowed composition range for these secondary elements is rather large (ref. 9.3): copper, 3.9 to 5 percent; manganese, 0.40 to 1.20 percent, and magnesium, 0.20 to 0.80 percent. The resistance to heat flow due to impurities will therefore change noticeably from heat to heat of material, even with identical heat treatments.

9.22 Thermal expansion

9.221 Effect of temperature on the average coefficient of thermal expansion, figure 9.221.

9.222 Thermal expansion of plate at low temperatures, figure 9.222.

9.23 Specific heat (c_p)
0.23 cal/g $^\circ$C at 100°C
0.23 Btu/lb $^\circ$F at 212°F (ref. 9.2)

9.24 Thermal diffusivity
0.57 cm^2/sec at 25°C
2.28 ft^2/hr at 77°F

9.241 Data were calculated according to the equation: Diffusivity = $K/\rho c_p$. Therefore, one should expect similar deviations from the normal value as for the thermal conductivity (see 9.212).

9.3 Electrical Properties

9.31 Electrical resistivity and conductivity, table 9.31.

9.311 The electrical resistivity depends even more strongly than does the thermal conductivity (see 9.21) on impurity concentration and distribution. Therefore, the resistivity differs even more drastically in 2014 alloy from electrical conductor grade aluminum than the thermal conductivity. This means that changes in composition and variations in heat treatment will influence the resistivity values markedly (variations of the order of 10 percent may be expected).

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 structure changes can be determined from susceptibility measurements. This makes it possible to use these measurements for studies on the kinetics of precipitation processes in aluminum-copper alloy systems.

9.5 Nuclear Properties

9.51 General. Aluminum and its alloys have been used extensively in the construction of research and test nuclear reactors. However, its low melting point and high chemical reactivity, leading to relatively poor resistance to corrosion in nuclear environments, make it of doubtful value for power reactors operating at temperatures above 400° to 450°F (203° to 232°C) (ref. 9.8).

9.52 Radiation damage in aluminum alloys has not been studied extensively. However, data available indicate that exposure of aluminum alloys to high-flux neutron irradation (10^{9} nvt or greater) results in increases in hardness, tensile strength, and sometimes in corrosion rate. Increases in electrical resistivity have also been observed. Ductility usually is decreased. Changes in density, thermal expansion, or in dimensions appears to be negligible. No changes in microstructure have been observed unless the temperature exceeds the recrystallization temperature (ref. 9.9).

6 Other Physical Properties

9.61 Emissivity
In air: 0.035 to 0.07 at 77°F (25°C) (ref. 9.5).

9.62 Damping capacity.

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9.1 Military Handbook-5A, Dept. of Defense, FSC 1500, "Metallic Materials and Elements for Aerospace Vehicle Structures," February 1966; latest change order January 1970.

9.2 Metals Handbook, Vol. 1, "Properties and Selection of Metals," American Society for Metals, Metals Park, Ohio, 1961.

9.3 Aluminum Standards & Data: 1970-71, The Aluminum Association, New York.

9.4 Aluminum Co. of America, "Alcoa Aluminum Handbook," 1962.

9.5 North American Aviation, Inc., "Materials Property Manual and Summary Report."

9.6 Reynolds Metals Co., "The Aluminum Data Book," 1965.

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

9.8 W.K. Anderson et al., "Reactor Structural Materials: Engineering Properties as Affected by Nuclear Service," ASTM STP-314, American Society for Testing and Materials, May 1962, p. 52.

9.9 Reactor Handbook, Vol. I, "Materials," C.R. Tipton, Jr., Ed., 2nd Edition, Interscience Publishers, Inc., New York, 1960.

Chapter 10

CORROSION RESISTANCE AND PROTECTION

10.1 General. Despite its high chemical reactivity and affinity for oxygen, aluminum exhibits excellent resistance to corrosion in most common environments because it passivates spontaneously under normal oxidizing conditions. The passive film is a hard, strongly adhering layer of aluminum oxide, estimated as 20-100 x 10^{-7} mm 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 distrupt 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 condition, 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, 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 resistance to corrosion. 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. To maximize resistance to corrosion, the composition of an alloy should be maintained as homogeneous as possible since nonhomogeneities frequently initiate localized attack. This principle applies clearly to the aluminum—copper alloys, of which alloy 2014 is a typical example. Copper generally depresses the electrode potential of aluminum in the cathodic (noble) direction, but its concentration and distribution are significant, as shown in table 10.21.

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 results in copper depletion adjacent to the intermetallic compound, making the grain boundaries anodic to the grains and susceptible to intergranular corrosion (refs. 10.1, 10.7). Figure 10.22 shows the effect of aging duration on electrode potentials of grains and grain boundaries of an aluminum alloy containing 4.1 percent copper. This suggests that prolonged aging can restore uniformity and reduce intergranular corrosion susceptibility. From data such as these, it may be concluded that corrosion resistance of the 2014 alloy in the T4 condition improves with increased rate of cooling, whereas in the T6 condition it improves with decreased rate of cooling. Thus, in the T4 condition, thin sections exhibit better corrosion resistance than thick sections; the reverse applies to the T6 condition.

Tensile stress in the presence of moisture further reduces resistance to corrosion of aluminum—copper alloys, leading 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 protective oxide films. Extensive research on stressed 2024 alloy in aqueous solutions containing 5 percent NaCl and 0.3 percent H_2O_2 showed that on aging at 160°—200° C, maximum susceptibility to stress-corrosion cracking occurred before maximum tensile strength was attained (ref. 10.10).

10.3 Behavior of Aluminum Alloy 2014. Extensive information on the corrosion behavior of 2014 under a variety of exposure conditions is not available. However, some data have been published on stress corrosion in the atmosphere and in chloride environments. These are summarized in the following figures and tables, which also include comparable information on other common aluminum alloys. The data indicate that stress corrosion resistance of 2014 is comparable to 7075 and 7079, but inferior to 2219 (refs. 10.11, 10.12, 10.13).

10.31 Stress corrosion performance of 2014 and other aluminum alloys in inland industrial atmosphere (short transverse specimens from plate, extrusions, and forgings), figure 10.31.

10.32 Comparative stress corrosion performance of aluminum alloy forgings; alternate immersion in 3.5-percent NaCl solution, figure 10.32.

10.33 Loss in tensile strength of stressed specimens exposed to various environments, table 10.33.

10.34 Comparative stress corrosion resistance of heat treated aluminum—copper alloys, table 10.34.

10.35 A recent study was conducted on the stress-corrosion performance of 2014-T651 to determine the distribution of failures in specimens grouped broadly by manufacturer, specifications to which the sheets were prepared, and the method of preparation. Specimens were subjected to a stress of 10 ksi (7 kg/mm^2) for a period of one month in 3.5-percent NaCl alternate-immersion tests. Periodic examination was made for evidences if first cracking. As shown in table 10.35, a wide variation of results was obtained between the various groupings. Characteristic lifetimes were as low as 70 hours and as high as 1085 hours, indicating the differences which can occur because of differences in sources, specifications, etc. However, there is general agreement that Al—Cu alloys are not very resistant to corrosion in this medium.

10.4 Protective Measures. Anodizing, which thickens the surface oxide film, is widely used for corrosion protection of aluminum and its alloys. 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). Painting and inorganic inhibitors have also been applied with some success in specific cases (ref. 10.2).

Cladding with commercially pure aluminum or a more resistant alloy is the traditional method used for many applications. Alloys 6003 and 6053 are common cladding materials for 2014 (ref. 10.8). Careful heat treatment and proper fabrication to avoid localized tensile stresses and structural crevices are desirable to minimize attack and stress corrosion cracking.

Surface treatments are discussed in greater detail in Chapter 11.

TABLE 10.21. – Electrode Potentials vs 0.1N Calomel at 25°C

Source	Ref. 10.7	
Solution	Aqueous solution of 53 g NaCl and 3 g H_2O_2 per liter	
Al (99.95 + %)	-	0.85 volt
Alclad 2014	-	0.83 volt
2014-T6	-	0.78 volt
Al + 2% Cu (solid solution)	-	0.75 volt
$CuAl_2$	-	0.73 volt
Al + 4% Cu (solid solution)	-	0.69 volt
2014-T4	-	0.69 volt

TABLE 10.33. – Loss in Tensile Strength of Stressed Specimens Exposed to Various Environments

Source	Ref. 10.12			
Specimens	0.063-in (1.60-mm) production sheet			
Alloy	Environment	Exposure, days	Average loss in tensile strength, %	
			Unstressed	Stressed 75% of yield strength
2014-T6	A	365	7	7
	B	365	18	28
	C	84	42	55
2024-T3	A	365	6	9
	B	365	16	20
	C	84	33	40
2219-T81	A	300	-	-
	B	365	6	8
	C	84	21	26
7075-T6	A	365	2	5
	B	365	7	10
	C	84	13	22

Environments: A - Inland industrial
B - Sea coast
C - 3.5-percent NaCl, alternate immersion.

TABLE 10.34. — Comparative Stress Corrosion Resistance of Heat-Treated Aluminum—Copper Alloys

Source	Ref. 10.12					
Values	Highest sustained tensile stress without failure, ksi (a)					
Alloy	Test Direction	Plate	Bar	Extruded Shapes 0.25-1 in(b)	Extruded Shapes 1.25-2 in(c)	Hand Forgings
2014-T6	L	45	45	50	45	30
	LT	30	-	27	22	25
	ST	7	15	-	7	7
2024-T3, T4	L	35	30	>50	>50	-
	LT	20	-	37	18	-
	ST	7	10	-	7	-
2024-T6, T8	L	>50	>47	>60	>60	-
	LT	>50	-	50	50	-
	ST	43	>43	-	16	-

Test environment: 3.5-percent NaCl. alternate immersion, 12 weeks.
> indicates no failure at highest stress employed.
(a) 1 ksi = 0.70307 kg/mm^2. (b) 0.64-2.54 cm. (c) 3.81-5.08 cm.

TABLE 10.35. — Results of Stress-Corrosion Tests of Alloy in 3.5-Percent NaCl (Alternate Immersion)

Source		Ref. 10.8			
Alloy		2014-T651			
Test Conditions		Temperature. 21.7^0–25.6^{0}C; stress, 10 ksi (7 kg/mm^2)			
Group	Mfr.	Plate No.	No. of Specimens	Failures	Failure Times, hours
I	A	1	5	5	34, 84, 130, 439, 785
		2	5	4	34, 227, 327, 561
		3	5	3	42, 84, 696
		4	5	2	70, 210
		5	5	4	277, 445, 454, 590
	Group Totals		25	18	
II	B	6	5	3	145, 169, 329
		7	5	2	227, 552
	Group Totals		10	5	
III	C	8	5	5	38, 38, 88, 96, 199
		9	5	3	115, 178, 178
	Group Totals		10	8	
IV	A	10	5	5	15, 39, 39, 63, 110
		11	5	5	40, 70, 70, 70, 82
	Group Totals		10	10	

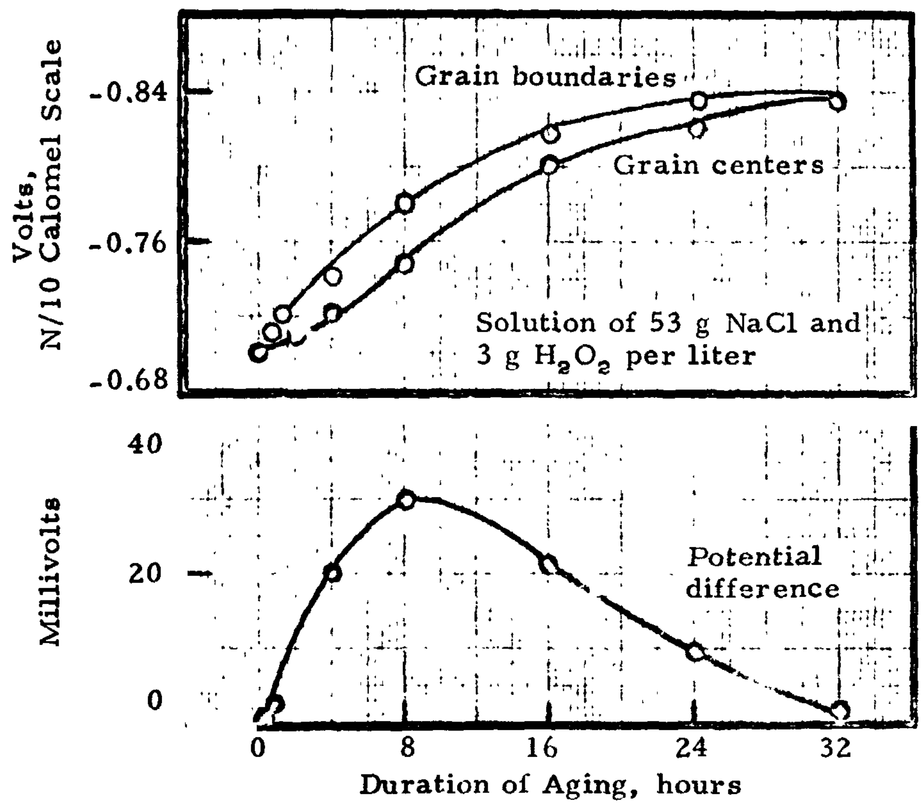

FIGURE 10.22 — Effect of duration of aging at 375° F (191°C) on the electrode potentials of grains and boundaries of a high purity Al-4.1Cu alloy.
(Ref. 10.7)

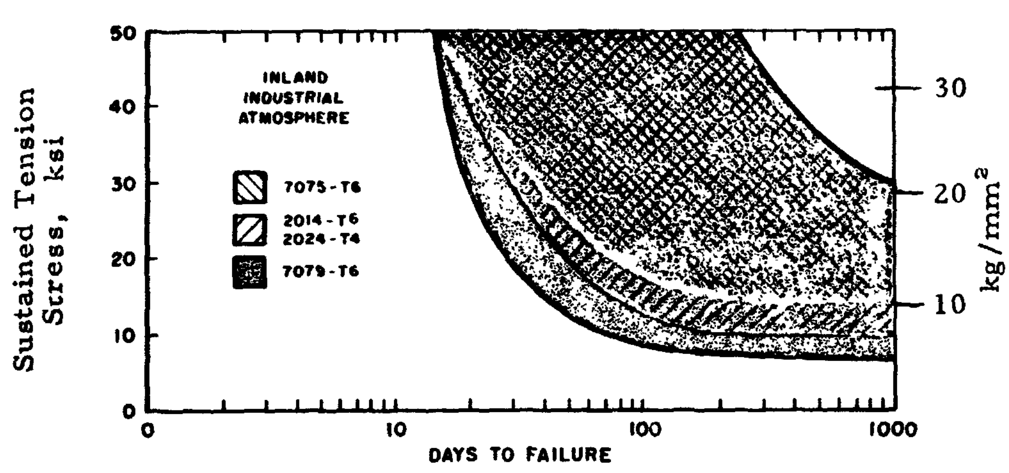

FIGURE 10.31. — Stress corrosion performance of 2014 and other aluminum alloys (short transverse specimens from plate, extrusions, and forgings).
(Ref. 10.12)

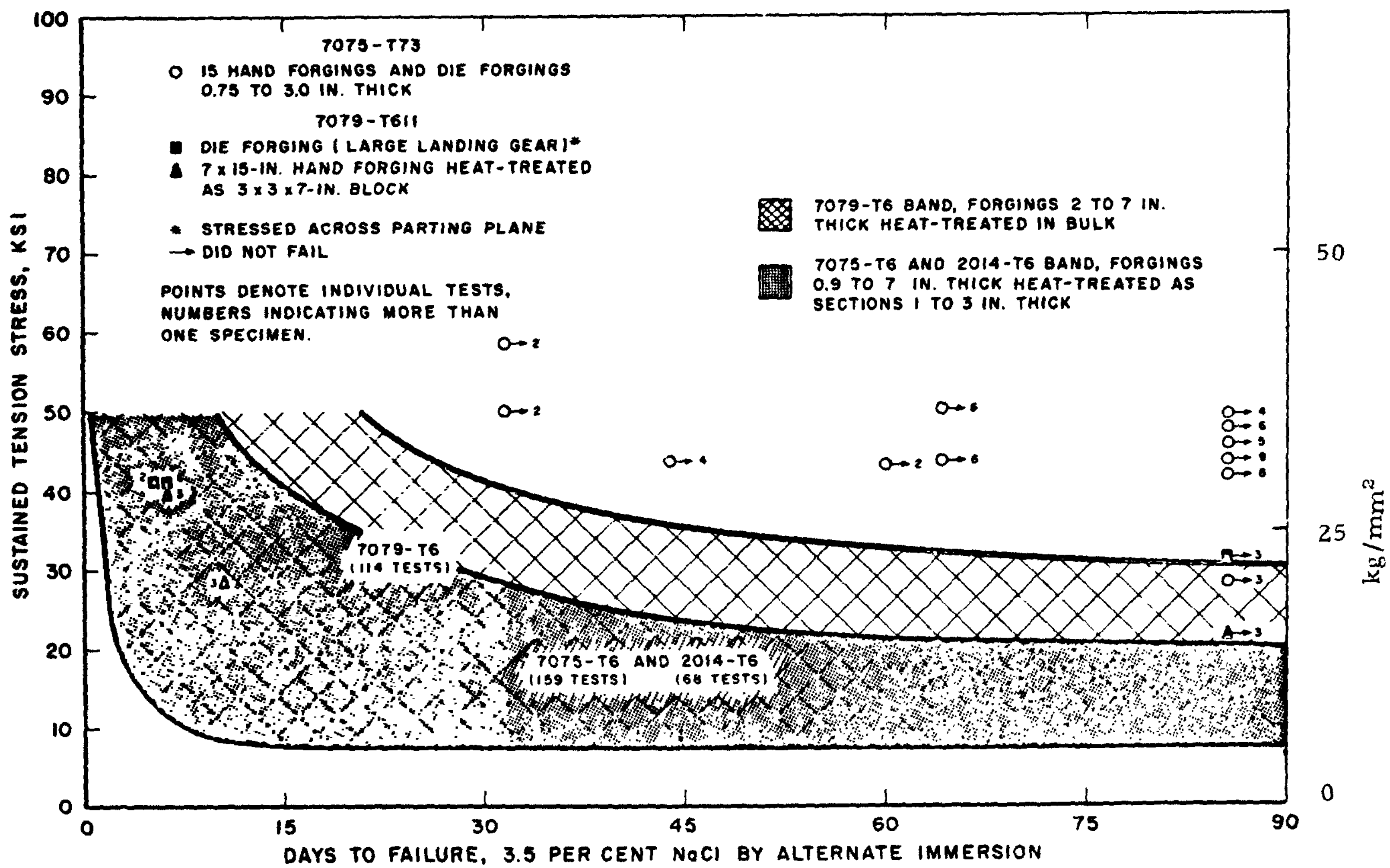

FIGURE 10.32. — Comparative stress corrosion performance of aluminum alloy forgings. (Ref. 10.12)

(1 inch = 25.4 mm)

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10.1 H.H. Uhlig, Corrosion and Corrosion Control, John Wiley & Sons, New York, N.Y., 1963, Ch. 20.

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

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

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

10.5 J. Draley and W. Ruther, Corrosion, 12, 441t (1956); J. Electrochem. Soc., 104, 329 (1957).

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

10.7 Metals Handbook, 8th Ed., Vol 1, "Properties and Selection of Metals," American Society for Metals, 1961.

10.8 M.O. Locks, "Analysis of Stress-Corrosion Testing of 2014-T651 Aluminum, Using Weibull Techniques," Corrosion, 27 (9), 386 (1971).

10.9 V.R. Evnas, Corrosion and Oxidation of Metals, Edward Arnold, Ltd., London, 1960, Ch. XVI.

10.10 W.D. Robertson, Trans. A.I.M.M.E., 166, 216 (1946).

10.11 J.A. Neck, M. Holt, and D.O. Sprowls, Metal Progress, 80, 87, 1961.

10.12 D.O. Sprowls and R.H. Brown, Metal Progress, 81(4), 79 (1962); 81 (5), 77 (1962).

10.13 F.H. Haynie and W.K. Boyd, "Stress-Corrosion Cracking of Aluminum Alloys," DMIC Report 228, July 1, 1966.

Chapter 11

SURFACE TREATMENTS

11.1 General. A wide variety of surface treatments can be applied to the 2014 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 (ref. 11.1).

11.2 Alclad Products. The 2014 alloy is available as Alclad sheet and plate which consists of bare 2014 core material clad with a thin coating of 6003 or 6053 alloy on both sides. the cladding 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 2014 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 cladding material only. The life of cladding is a function of its thickness and the severity of the environment. Alclad products, therefore, limit corrosion to the relatively thin, clad surface layer (ref. 11.2).

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 finishing are scratched-line finishes which remove minor surface defects and provide a decorative effect. 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 (0.0023 to 0.025 mm). Coatings produced in chromic acid vary from 0.00001 to 0.00009 inch (0.00025 to 0.00229 mm). 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. 11.9).

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 (0.025 to 0.254 mm). 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" (ref. 11.9). Processes most suitable for a wide range of applications are Alumilite 226 (oxide coatings, 0.002-inch (0.051-mm) thick) and Martin Hardcoat (coating thicknesses up to 0.004 inch (0.101 mm).

Martin Process: 15% H_2SO_4; 25°–32° F (-4 to 0° C); 25 asf (0.027 A/cm^2).
Alcoa Alumilite-226: 12% H_2SO_4 + 1% H_2CrO_4; 48°–52° F (9° to 11° C); 36 asf (0.038 A/cm^2).

A flash hardcoat of a very thin film can also be applied by these methods by shortening the normal cycle time. The Martin process should be specified where maximum hardness and corrosion resistance are required along with thickness buildups to 0.004 inch (0.101 mm). Alumilite-226 is selected where hardness and corrosion resistance are required and 0.002 inch (0.051 mm) is the acceptable maximum buildup. Further details of these processes are presented in reference 11.9.

11.42 A white anodize has been developed for alloy 2014 to provide a good reflectance value and excellent resistance to corrosion (ref. 11.10). 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 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 (see Chapter 3).

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 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 of varnish (0.24 kg/liter) 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 of 3 to 4 mils (0.076 to 0.102 mm) thickness, 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 565° C) for a period of 4 to 8 minutes (ref. 11.7).

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

11.2 Metals Handbook, 8th Ed., Vol. 1, "Properties and Selection of Metals", American Society for Metals, Metals Park, Ohio, 1961.

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

11.4 Metals Handbook, 1948 Ed., American Society for Metals, Metals Park, Ohio, 1948.

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

11.6 NASA Tech Brief, "Aluminum Alloys Protected Against Stress-Corrosion Cracking," 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 NASA Marshall Space Flight Center, unpublished data, 1965.

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

11.10 K.H. Dale, "Advances in Aluminum Anodizing," NASA Tech Brief, 69-10144, May 1969.

Chapter 12

JOINING TECHNIQUES

12.1 General. Aluminum alloy 2014 can be joined satisfactorily by fusion and resistance welding techniques and by riveting (or bolting). Brazing and soldering are not recommended because satisfactory materials and methods have not been developed for this alloy. Specifications for the 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 understood for successful welding of the metal or its alloys. Four important factors to consider 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. Parts should be well-supported during welding to prevent distortion (ref. 12.1).

The weldability and strength of the 2014 alloy are superior to 2024; however, the weldability is not as good as that of 2219 (ref. 12.27).

12.21 Fusion Welding. Although the 2014 alloy was developed in 1928, it was not considered to be weldable by fusion techniques until about 15 years later. Customarily the alloy, when fusion welded, is used as the "as-welded" condition and designers usually arrange to have the welded joint about twice the thickness of the parent metal to compensate for the lower strength in this condition (ref. 12.3).

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 which are discussed in greater detail in reference 12.2. A study was made in conjunction with the Saturn space vehicle program (ref. 12.6) to determine whether MIG or TIG welding processes are the most advantageous for joining 0.100-inch (2.54-mm) thick 2014-T6 sheet. Specimens welded in the laboratory and on production welding fixtures were subjected to various service conditions and test temperatures. The results of the study indicated the following:

1) TIG welds exhibited equal or slightly higher mechanical properties than MIG welds for most welding conditions and test temperatures studied.

2) TIG welds made on a copper backup bar generally had higher tensile properties than TIG welds made on a titanium backup bar.

3) TIG welds made on a copper backup bar with a small groove, 0.187 x 0.025 inch (7.75 x 0.635 mm), had the highest tensile strength, but the loss in strength with larger grooves was less than 10 percent.

4) An adhesive cure cycle performed after welding lowered the bend ductility of both MIG and TIG welds by 50 to 75 percent. TIG welds, made on a copper backup bar had higher bend ductility (both before and after the cure cycles) than MIG welds made on a titanium backup bar.

5) Ultimate and yield strengths of all welds were increased by the cure cycle and decreased by repair welding. Elongation was reduced by the cure cycle and unaffected by repair welding.

6) In the "as-welded" condition, the single pass welds made with 2319 wire generally exhibited slightly better tensile properties than welds made with 4043 filler wire. The 2319 wire welds, however, were adversely affected to a greater degree than 4043 wire welds by the "double cure" cycle.

7) MIG and TIG welded specimens both exhibited similar notch sensitivity in the presence of shallow surface cracks, figure 12.1.

8) Stress corrosion tests (alternate immersion in simulated ocean water) with bend specimens indicated that TIG welds made on a copper backup bar had greater corrosion resistance than MIG welds made on a titanium backup bar.

An investigation has been made of TIG welded 0.125-inch (3.175 mm) Alclad 2014 sheet material to examine the effects of preweld and post-weld treatments, welding speed, and stress corrosion (ref. 12.3). Single-pass square butt-welds, with 0- to 0.010-inch gap (0- to 0.254-mm), were made mechanically using Linde HQ shaved filler wire. The weld fixture had water-cooled copper hold-downs and a mild steel backup bar. Welds were made parallel to the rolling direction of the sheet and specimens were taken from the sheet transverse to the weld bead. Cleaning before welding consisted of a caustic dip followed by nitric acid and a water rinse. Abutting edges were filed with a clean vixen file. Tensile specimens had a 0.5 x 2.5 inch (12.7 x 50.8 mm) gage section with weld beam transverse at the center. Bend specimens were 6 inches (152 mm) long, bent around a 5T radius mandrel. Welds were ground flush on both tensile and bend specimens. No problems were encountered in making sound welds in the Alclad 2014 alloy sheet under laboratory conditions.

The inferior weldability of the Alclad 2014 alloy (as compared to the 6061 alloy) was attributed largely to its wide melting range of 230° F (950° to 1180° F, 510° to 638° C), which results in delay solidification of the base metal at the edge of the weld zone. While in this partially-melted condition, the joint has low strength and ductility and is subject to cracking from shrinkage stresses. All joints failed in the weld metal in both tensile and bend tests. On fully heat treated joints, the weld metal hardened to 80 percent of the base metal strength of 70 ksi (49.2 kg/mm^2). Hardness surveys across the welded joints were useful in determining the relative strengths of welds and heat affected zones as shown in figure 12.2.

Increase in welding speed improved the strength of 2014-T4 alloy, welded then aged, by improvement in the response to aging in the heat affected zone (HAZ). However, it appeared that speeds above 15 ipm (38 cm /min) did not result in significantly greater improvement, figure 12.3. Stress corrosion tests, in sodium chloride solution at 100° F (38° C), indicated that the as-welded joints had superior stress corrosion resistance to the joints which were aged after welding.

The effect of test temperature on butt-welded 0.063-inch (1.60-mm) sheet, welded by the TIG method, is shown in figure 12.4. Values obtained for the base metal are also included in this graph. The strength of welds made with 2319 filler wire is compared to that of welds made with 4043 wire; it can be seen that the 2319 wire gave slightly higher tensile values and weld joint efficiencies in this particular study. However, weld ductility was low for both filler wires (0.9 to 2.6 percent average elongation of 2319 wire welds and 0.6 to 1.8 percent average elongation for 4043 wire). Based on these results, 2319 filler wire would be preferred (refs. 12.10, 12.11).

The effect of test temperature on TIG welded sheet specimens is shown in figures 12.5 and 12.6 for 2014-T3 and 2014-T6, respectively. Yield and ultimate strengths for the parent metal are also given in these graphs for comparison. Fatigue curves for TIG butt-welded sheet specimens are given in figure 12.7 for room and cryogenic temperatures. An increase in strength is observed at low temperatures, but this increase is not as large as the static strength increase. This may signify some degree of embrittlement of the weld at -423° F (-253° C).

The problem of cracking in 2014 alloy fusion weld zones has been attributed to the composition of the base metal and the filler metal used. Cracking that occurs above the solidus temperature (hot cracking) was observed to be intergranular in nature. Cracking below the solidus temperature may be either transgranular or intergranular. Large heat affected zones and repeated rewelding (such as sometimes is done in repair welding) has frequently produced HAZ cracks. A precaution to prevent this type of cracking is to weld as rapidly as possible. using a minimum of heat. Rewelding should be avoided whenever possible (ref. 12.8).

The occurrence of porosity in 2014 alloy fusion welds is a problem that apparently is still not completely solved. Studies have indicated that gases (notably hydrogen) trapped in the weld zones are the principal, if not the sole cause of porosity in 2014 alloy weldments (refs. 12.5, 12.28). Hydrogen is soluble in liquid aluminum, but is nearly insoluble in the solid state. Thus any hydrogen present at solidification is rejected in the form of porosity as the alloy solidifes. Hydrogen normally comes from water vapor. At temperatures above 920° F (494° C), aluminum reacts with water to produce nascent hydrogen plus oxygen. The nascent hydrogen dissolves in molten aluminum and the oxygen combines to form aluminum oxide (ref. 12.7). The solubility of hydrogen in aluminum is shown in figure 12.8. Control of humidity and cleaning of filler wire to remove the oxide surface layer have helped to reduce porosity in 2014 welds. However, hydrogen in the interior of the base metal or filler wire is more difficult to eliminate (ref. 12.9).

The combined effect of porosity and mismatch has also been investigated for TIG welded 2014-T6 sheet (ref. 12.15). These studies have led to the conclusion that both porosity and mismatch are factors that contribute to the lowering of strength as each increases in magnitude. as shown in figure 12.9. Mismatch is somewhat the greater of the two factors. A project was conducted to produce high quality weldments in 2014 plate, in thicknesses from 1/4 to 1-1/2 inches (6.35-38.1 mm). Using the most advanced type of welding equipment (ref. 12.16), both TIG and MIG welds were made in the flat-, vertical and horizontal positions. It was concluded that to assure quality welds in thick plate, the following are essential:

1) Welding equipment must have self-contained contamination control (e.g., cathodic cleaning of filler wire just ahead of torch).

2) Weld schedule parameters must be precisely controlled.

3) Gases, filler wires, and base material must be controlled by adequate quality control procedures.

Manual welding of chemically milled sheet requires a land area of approximately twice the sheet thickness to dissipate weld heat and prevent loss in base metal properties. Studies were conducted on T6 sheet to determine the land width necessary to retain the HAZ and also to determine the tensile strength of repair welds for various land widths (ref. 12.24). It was found that, based on hardness data, a 2-inch (50.8-mm) wide land, 0.100 inch (2.54-mm) thick, will fully retain the weld HAZ of repaired welds. It was also determined that base metal tensile properties are only slightly affected by weld heat when widths of 1.5- to 2.0-inch (38.1-50.8 mm) lands are used, as shown in figure 12.10. Values of 59.1 ksi (41.6 kg/mm^2) can be expected with 90 percent confidence for 1.5-inch (38.1-mm), based on 58 tests. If 95 and 99 percent confidence is required, expected values for repairs are 57.8 and 55.4 ksi (40.6 and 39.0 kg/mm^2), respectively.

Other studies have led to notable gains in the strength and ductility of MIG welds in 2014-T6 sheet by producing weld beads with pronounced papillary depressions (ref. 12.25). Direct current-reversed polarity (DCRP) was used, and weld contour was controlled by proper balance of energy inputs, heat extraction, and shielding-gas flow during welding. Narrow heat affected zones that followed bead contour were obtained by positioning hold-down plates close to the sheet edges being welded. A 5- to 20-percent argon (balance helium) shielding gas mixture flowing at 75 cfh (35.4 l/sec) produced shallower root bead angles that increased tensile strengths 2 to 4 ksi (1.4 to 2.8 kg/mm^2). Welds up to 10 ksi (7.0 kg/mm^2) stronger than those normally obtained priorly were achieved. Figure 12.11 shows the tensile and bulge test properties of the MIG welded sheet for various argon-helium gas mixtures. The effect of weld travel speed on these properties is presented in figure 12.12.

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 for joining sheet, extrusions, and tubing. The localized spot welding is accomplished by using very high automatically controlled welding current for a short period of time with the addition of small quantities of filler metal (ref. 12.26). Filler metal alloys commonly used in the gas metal-arc spot welding of the 2014 alloy are 2319 and 4043 alloys. Gas tungsten-arc spot welding is similar to gas metal-arc spotwelding in that satisfactory spot welds can be made from one side of the joint. The use of the gas tungsten-arc spot weld process has become widespread in recent years for the assembly of products made from sheet metals (ref. 12.27).

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 variety of operations. Resistance welding heats only a small area of metal so that 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 because no fluxes are used during spot welding. In aircraft construction, it is recommended that the contact resistance of the elements to be joined be continually checked as a measure of surface cleanliness. Surface contact resistance should not exceed 50 microhms for best results. Details on surface cleaning are given in references 12.2 and 12.27.

The 2014 alloy in heat-treated tempers is successfully spotwelded but special practices are required, and the range of machine settings is rather narrow for this alloy. In the annealed temper, the alloy is difficult to weld and spotwelding in this condition is not recommended.

Spotwelded Clad 2014 has good resistance to corrosion in all tempers, but the resistance of bare 2014-T4 is poor and 2014-T6 is only fair (ref. 12.2). Clad 2014 may be joined by spotwelding to 1100, 3003, 5052, 6061, Clad 2014, Clad 2024, and Clad 7075. Bare 2014 may be joined to all of the above alloys except Clad 2014. According to Federal specifications QQ-A-261 and QQ-A-266, bare material may be spotwelded to clad material only with the specific approval of the procuring or certificating agency (ref. 12.12).

12.221 Mechanical Properties of Spot Welds. The use of spot welds on military structural parts is governed by the requirements of the procuring or certificating agency (ref. 12.12). The requirements for equipment, materials and production control of spot and seam welds in aluminum alloys is covered by military specification MIL-W-6858-B-1. The minimum distance suggested for joint overlap and spotweld spacing is given in table 12.7 for a number of sheet thicknesses. Minimum allowable edge distance for spot weld joints is presented in table 12.8. Table 12.9 gives design shear strength allowables for spot welds in bare and clad aluminum alloys; the thickness ratio of the thickest sheet to the thinnest outer sheet in the combination should not exceed 4:1.

In applications of spotwelding where ribs, intercostals, or doublers are attached to sheet, either at splices or at other points on the sheet panels, the allowable ultimate strength of the spot welded sheet should be determined by multiplying the ultimate tensile shear strength (MIL-HDBK-5A "A" values where available) by the appropriate efficiency factor as given in figure 12.13. The minimum values of the basic sheet efficiency in tension should not be applied to seam welds. Allowable ultimate tensile strengths for spot welded sheet less than 0.020 inch (0.508 mm) should be established on the basis of tests acceptable to the procuring or certificating agency (ref. 12.12).

The effect of cryogenic temperatures on the cross-tension and tensile-shear strength of singe spot welds in 2014-T6 sheet is shown in figure 12.14.

12.3 Brazing. Brazing of the 2014 alloy is not recommended. The melting point of 2014 is lower than that of the commercially available brazing alloys (ref. 12.19).

12.4 Riveting. Riveting is a commonly used method for joining aluminum, particularly 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. 12.1). Specifications for aluminum riveting are presented in table 12.10.

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. In most cases, failure of such joints occurs by shearing, by bearing or tearing of the sheet or plate. Table 12.11 gives the average shear strengths of driven rivets of various aluminum alloys. These values may be considered representative of properly driven rivets although, occasionally, driven rivets may fall below the average by about 5 to 10 percent. 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 greater detail on the riveting of aluminum alloys is given in references 12.20 and 12.21. Design data on mechanical joints using rivets or bolts may be found in MIL-HDBK-5A (ref. 12.12).

TABLE 12.1. – Welding Specifications

Source	Refs. 12.14, 12.22, 12.23			
Product or process	Federal	Military	ASTM	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)	QQ-R-566-a	..	B285-61T	4190B 4191A
Welding electrodes (flux coated)	-	MIL-E-15597C	B184-43T	-
Welding electrode wire	-	MIL-E-16053K	B285-61T	-
Flash welds (rings, flanges)	-	-	-	7488A

TABLE 12.7. – Suggested Minimum Joint Overlap and Spacing of Spot Welds for Aluminum Alloys

Source	Ref. 12.2	
Thinnest sheet in joint, inch (a)	Minimum joint overlap, inch (a)	Minimum weld spacing, inch (a)
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 = 25.4 mm.

TABLE 12.8. — Minimum Allowable Edge Distances for Spot-Welded Joints in Aluminum Alloys (a, b, c)

Source	Ref. 12.12
Nominal thickness of the thinner sheet, inch (d)	Edge distance, E, inch (d)
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 requirements 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 dependended on to develop full weld strength.

(d) 1 inch = 25.4 mm.

TABLE 12.9. – Spot Weld Maximum Shear Strength Standards

Source	Ref. 12.12			
Alloy	Aluminum alloys, bare and clad			
Nominal thickness of thinner sheet, inch (b)	Material ultimate tensile strength, lb (a, b)			
	Above 56 ksi (b)	28 to 56 ksi (b)	20 to 27 ksi (b)	19.5 ksi and below (b)
0.012	60	52	24	16
0.016	86	78	56	40
0.020	112	106	80	62
0.025	148	140	116	88
0.032	208	188	168	132
0.040	276	248	240	180
0.050	374	344	321	234
0.063	539	489	442	314
0.071	662	578	515	358
0.080	824	680	609	417
0.090	1002	798	695	478
0.100	1192	933	750	536
0.112	1426	1064	796	584
0.125	1698	1300	840	629
0.160	2490	-	-	-
0.190	3230	-	-	-

(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) 1 lb = 0.4536 kg; 1 inch = 25.4 mm; 1 ksi = 0.70307 kg/mm^2.

TABLE 12.10. – Specification for Aluminum Rivets

Source	Ref. 12.14		
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 12.11. — Ultimate Shear Strength (Average) for Driven Rivets (c, d)

Source	Ref. 12.20		
Alloy and Temper before Driving (a)	Driving Procedure	Temper after Driving	F_{su} (av) ksi (d)
1100-H14	Cold as received	1100-F	11
2017-T4	Cold, as received	2017-T3	39
2017-T4	Cold, immediately after quenching	2017-T31	[illegible]4 (b)
2024-T4	Cold, immediately after quenching	2024-T31	42 (b)
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 (b)
6061-T4	Hot, 990° to 1050° F(532°—566° C)	6061-T4[illegible]	24 (b)
6061-T6	Cold, as received	6061-T6	30
7277-T4	Hot, 850° to 975° F(454°—524° C)	7277-T41	36

(a) These designations should be used when ordering rivets.

(b) 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 kg/mm²) are attained by 6061-T31 about 4 months after driving. Values shown for 7277-T41 rivets are attained in about one week.

(c) 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.

(d) 1 ksi = 0.70307 kg/mm²

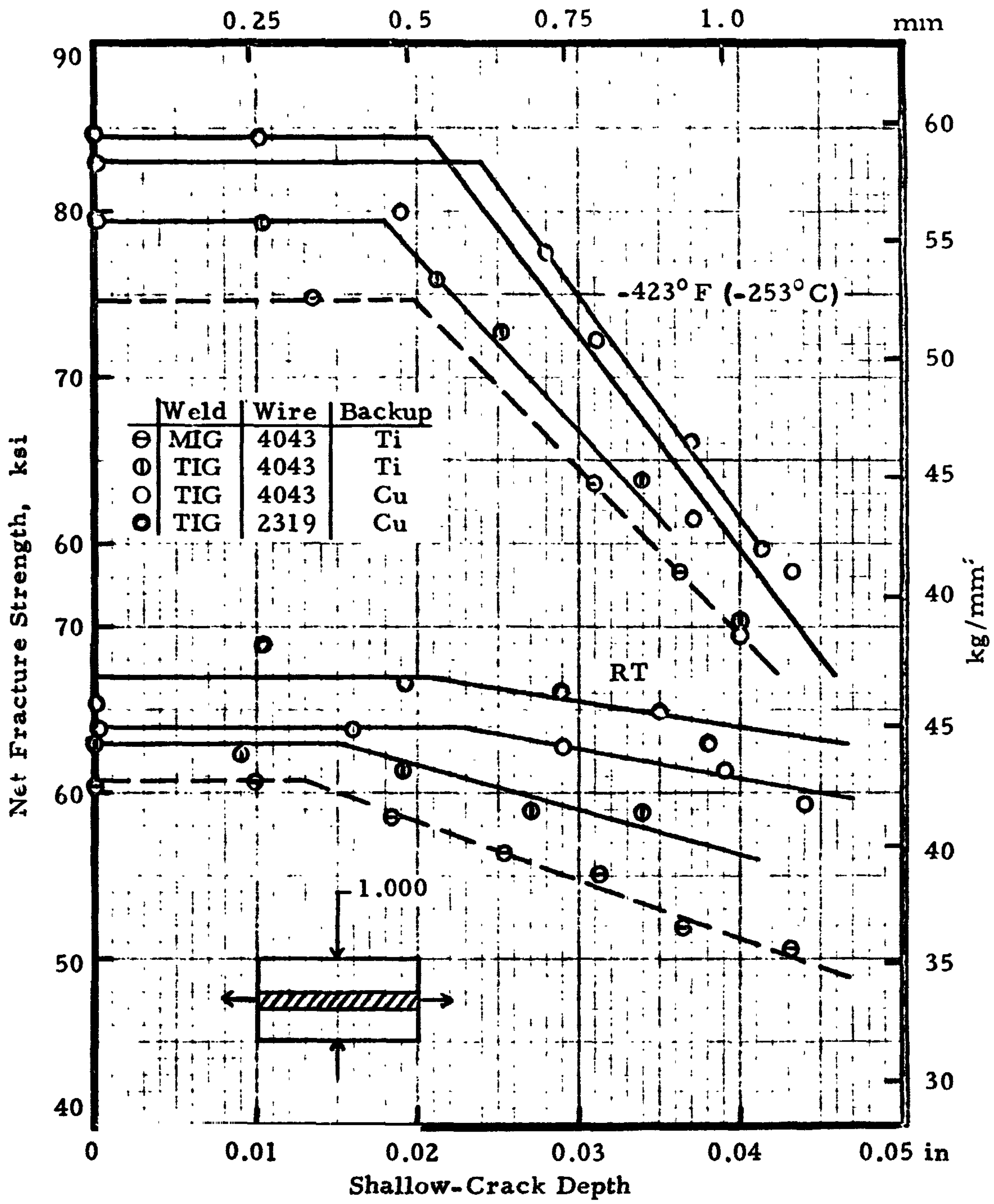

FIGURE 12.1. — Effect of shallow-crack depth on the fracture strength of MIG and TIG welded specimens of 0.100 in (2.54 mm) 2014-T6 sheet; welded plus double cure (heat rapidly to 230° F (110° C), heat 5° F/hr (2.6° C) from 230° F to 330° F (166° C), hold at 330° F for 2.5 hr, cool at 4.5° F/hr (2.5° C) from 330° F to 180° F (82° C)).

(Ref. 12.6)

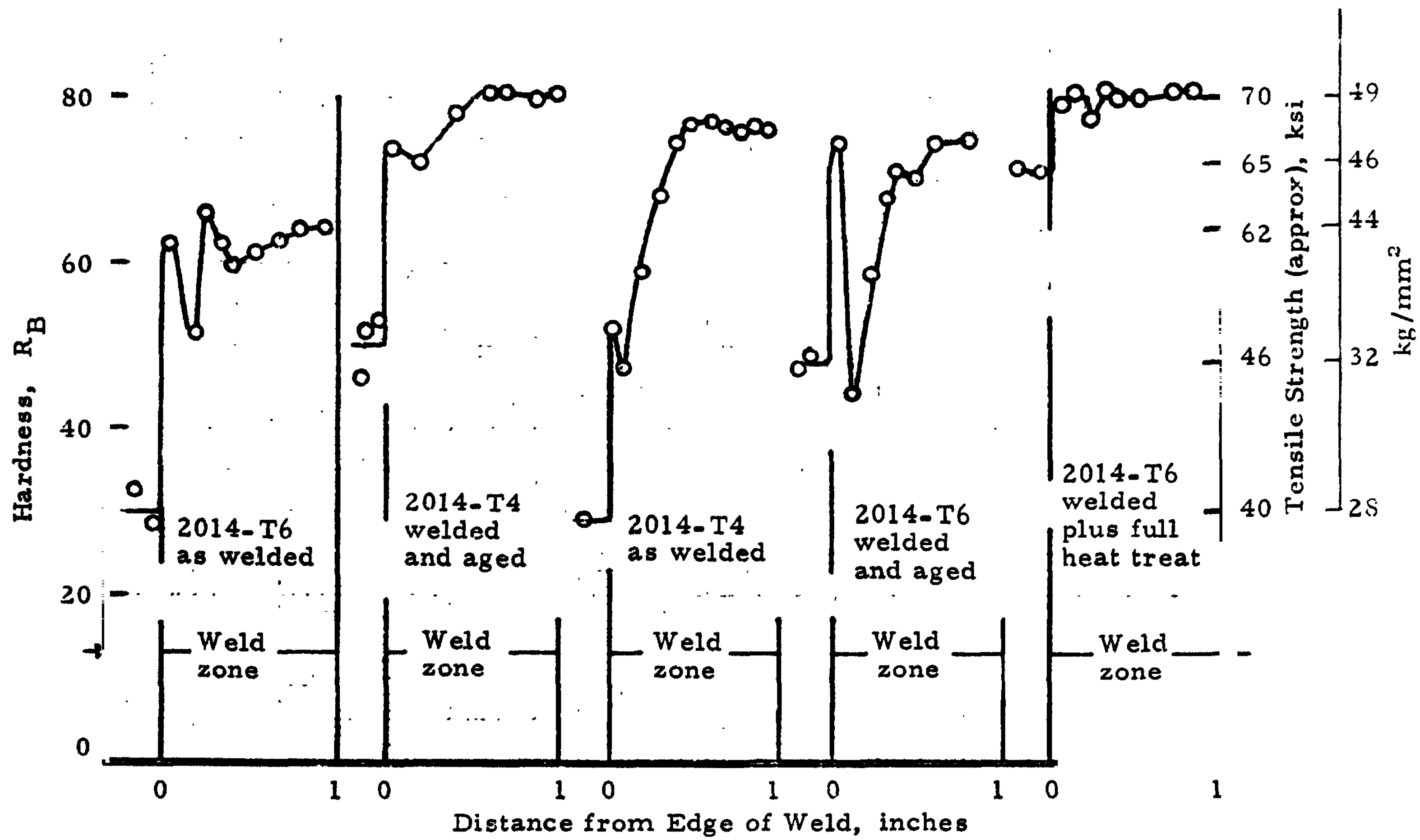

FIGURE 12.2. — Hardness survey on 2014-T4 and 2014-T6 weldments, welded at 20 ipm (50.8 cm/min); sheet, 0.125 in (3.175 mm); 1 inch = 25.4 mm.
(Ref. 12.3)

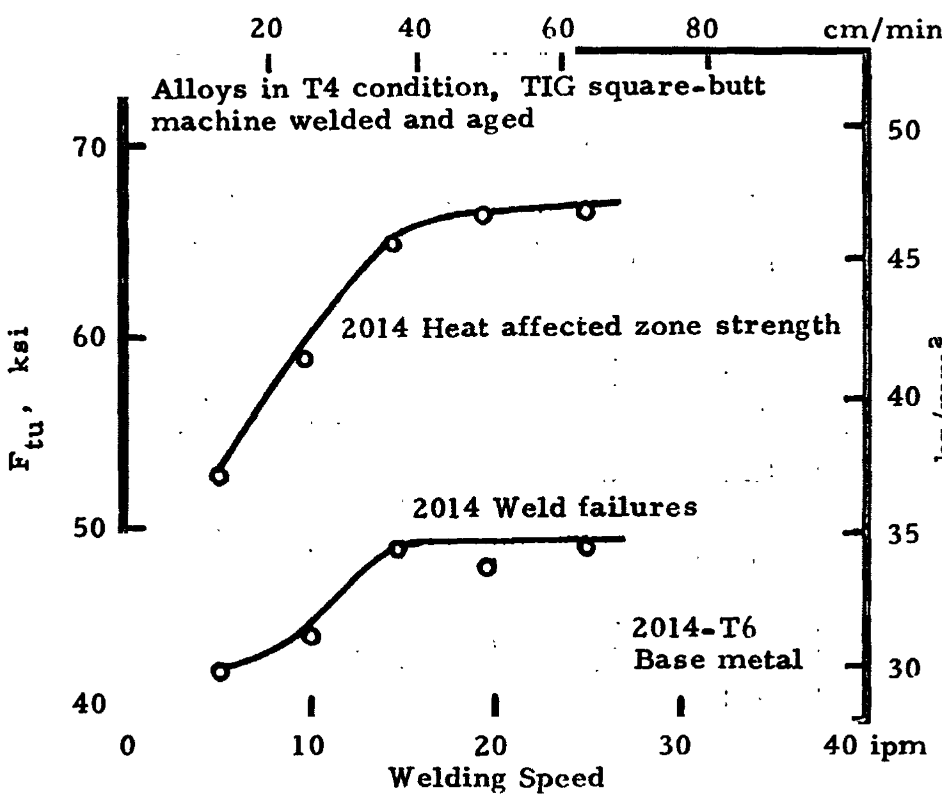

FIGURE 12.3. – Effect of welding speed on ultimate tensile strength of TIG welds in Alclad 2014 sheet; 0.125 in (3.175 mm).

(Ref. 12.3)

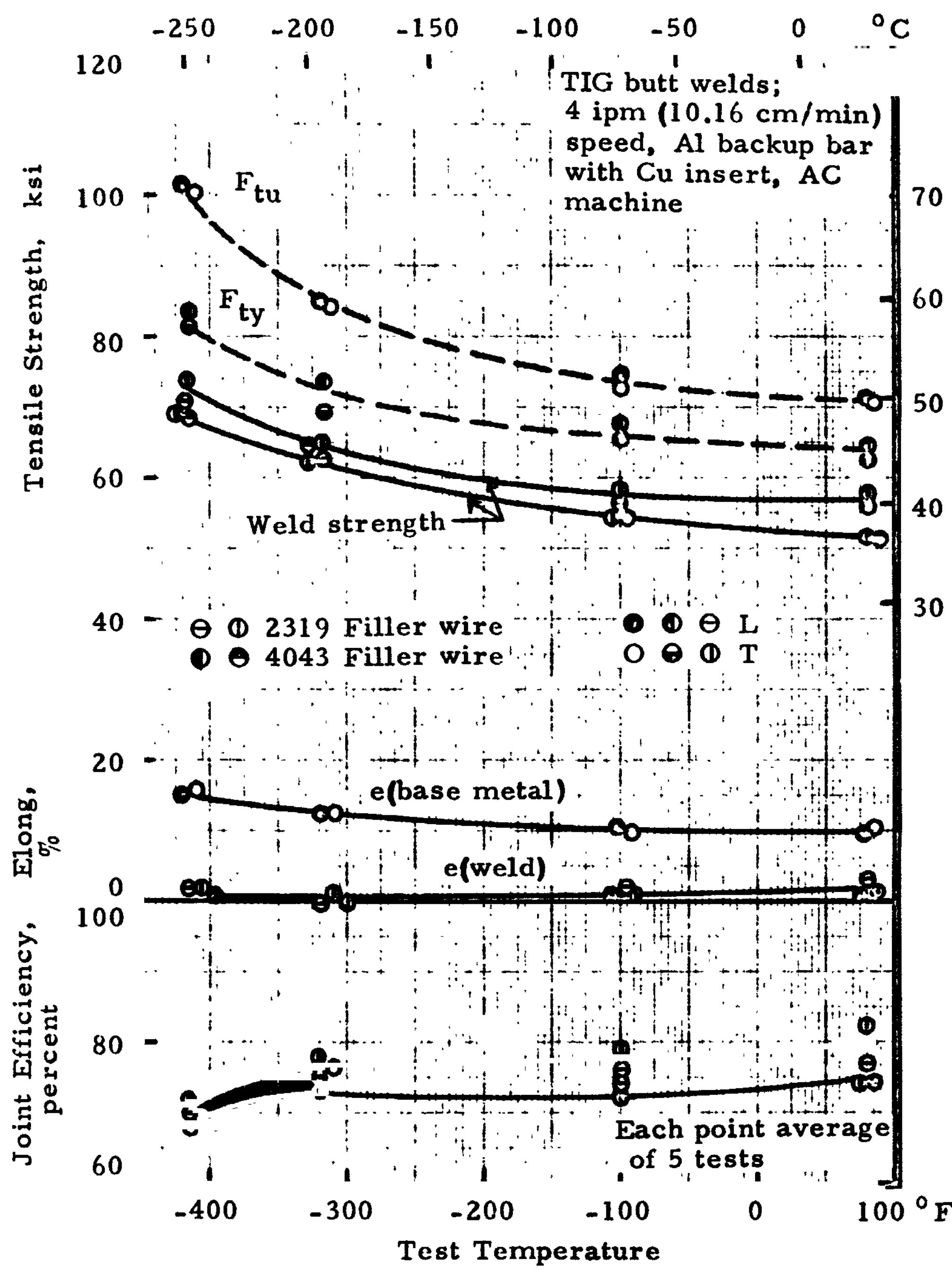

FIGURE 12.4. – Effect of test temperature on tensile properties of base metal and butt-welded 2014-T6 sheet; thickness, 0.063 inch (1.60 mm).

(Refs. 12.10, 12.11)

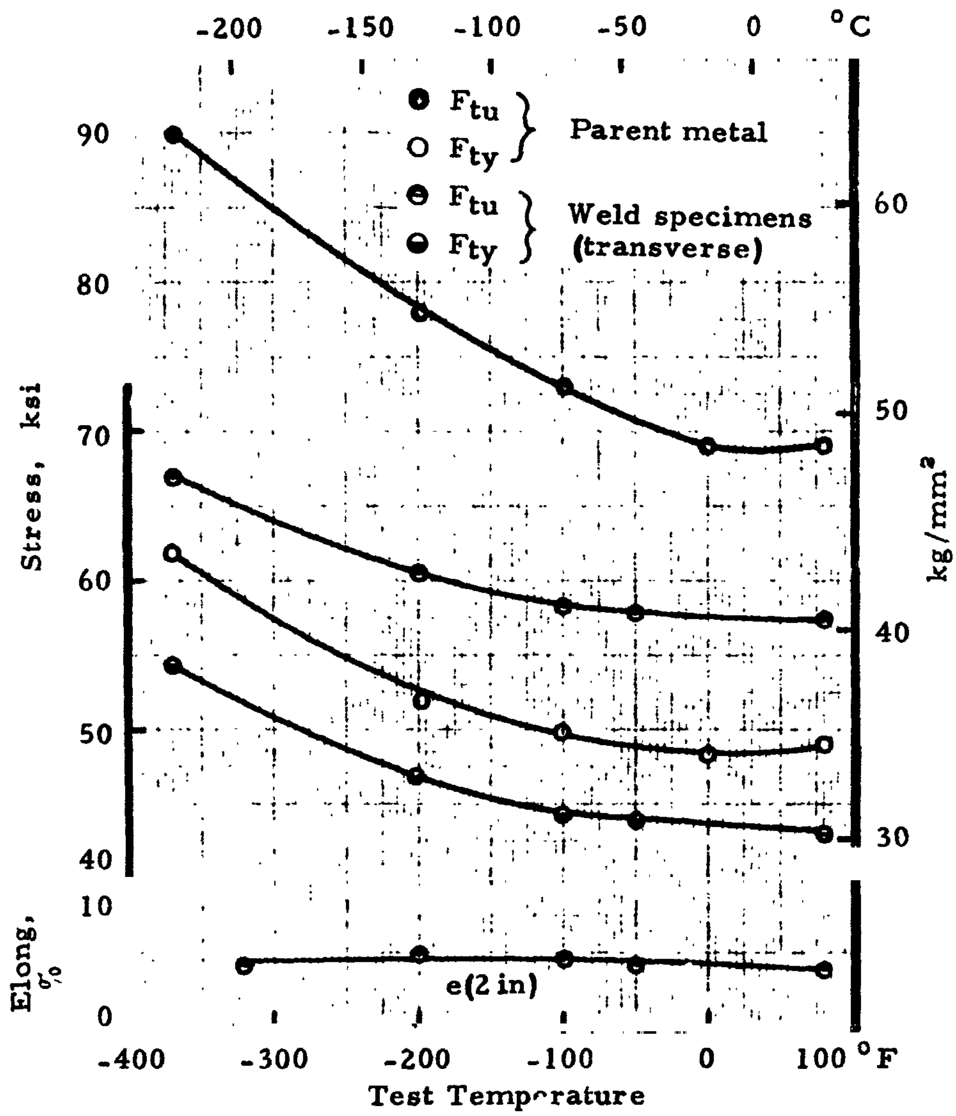

FIGURE 12.5. — Effect of cryogenic temperatures on tensile properties of 2014-T3 weldments and parent metal sheet, 0.062 to 0.125 in (1.57-3.18 mm). Weldments made by either the automatic TIG or MIG process.

(Ref. 12.13)

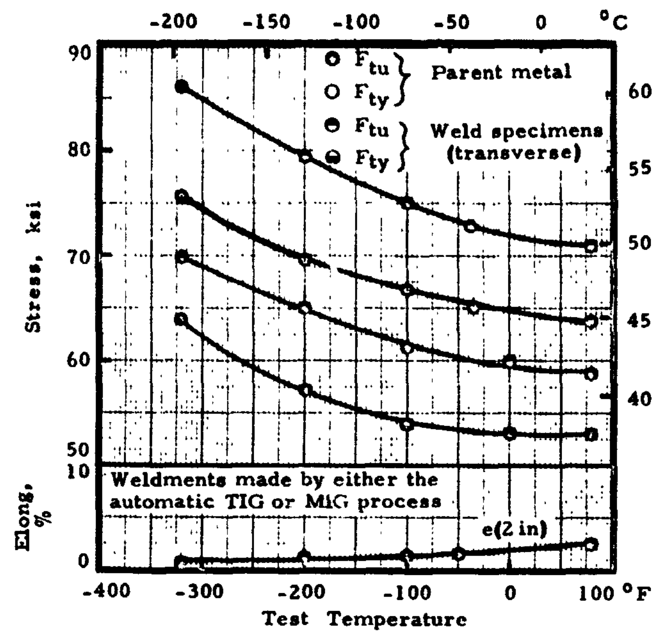

FIGURE 12.6. – Effect of cryogenic temperatures on tensile properties of 2014-T6 weldments and parent metal sheet, 0.062 to 0.125 inch (1.57-3.18 mm). (Ref. 12.13)

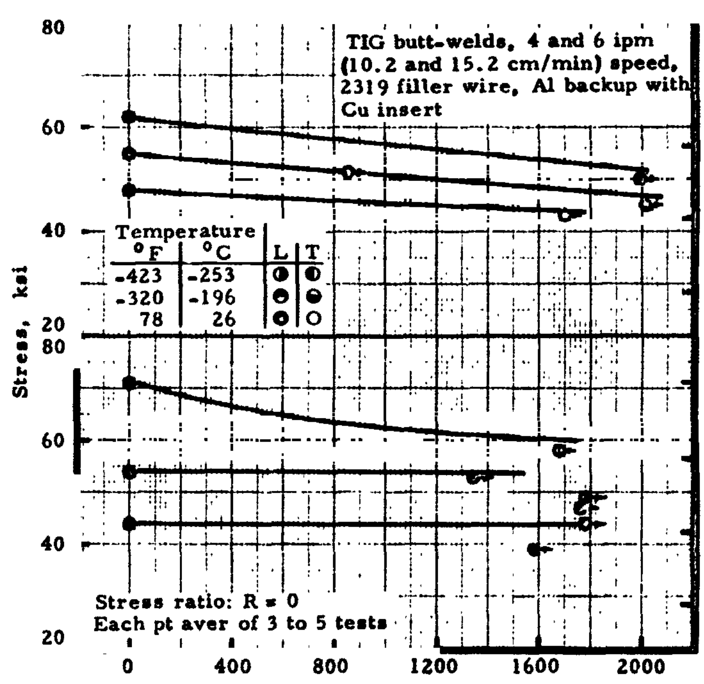

FIGURE 12.7. – S-N fatigue curves for TIG butt-welded 2014-T6 sheet, 0.063 and 0.125 inch (1.60 and 3.18 mm), at room and cryogenic temperatures. (Ref. 12.10)

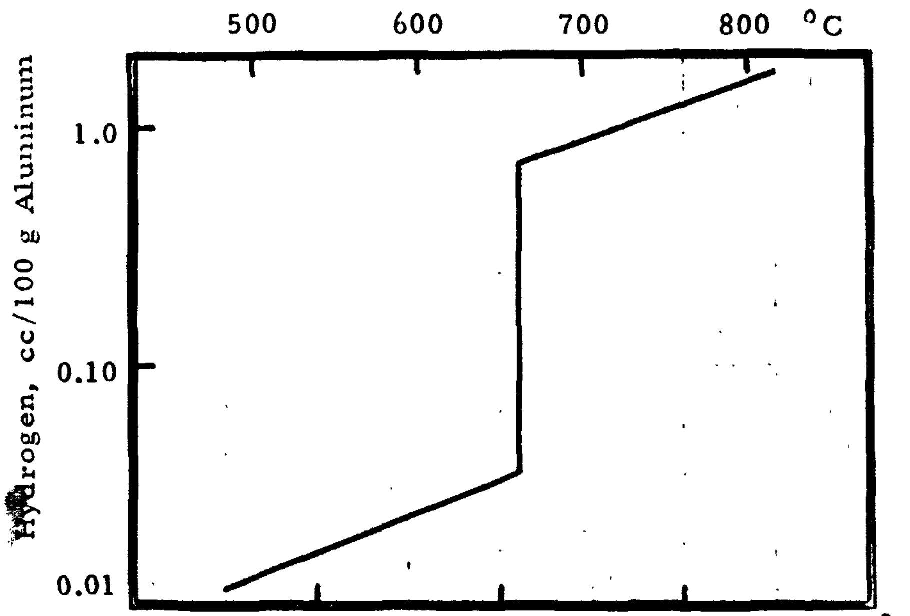

FIGURE 12.8. – Solubility of hydrogen in aluminum.
(Ref. 12.9)

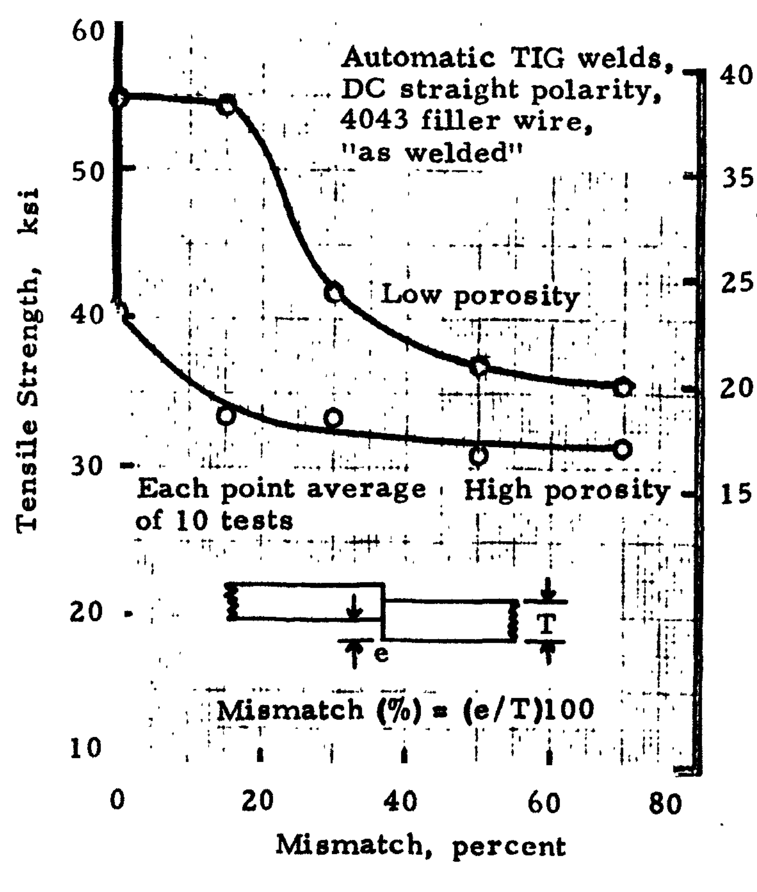

FIGURE 12.9. – Combined effect of porosity and mismatch for TIG welded 2014-T6 sheet. 0.090 inch (2.29 mm).
(Ref. 12.8)

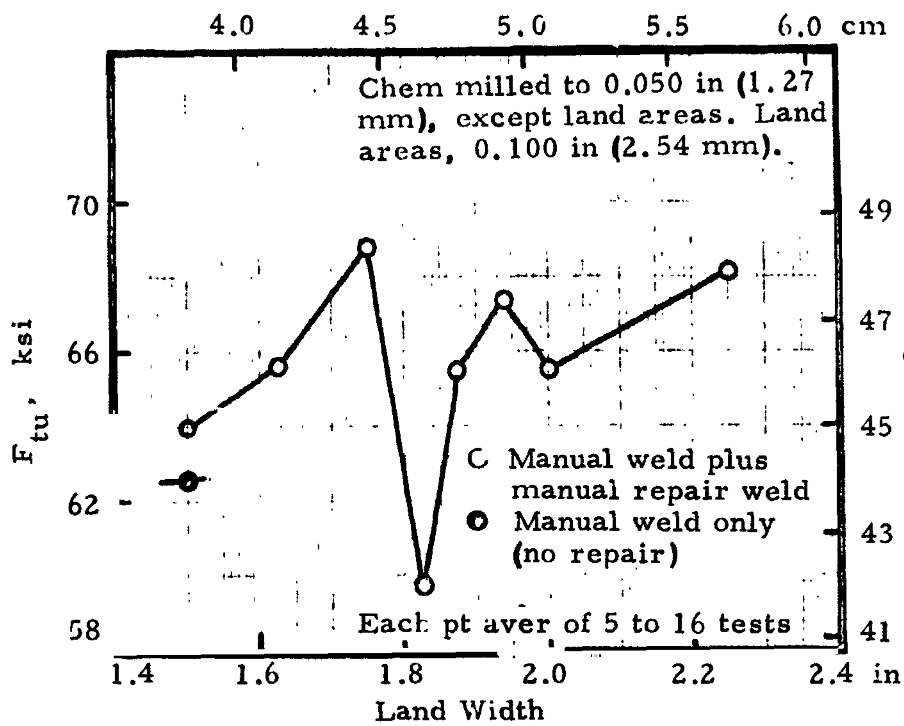

FIGURE 12.10. — Effect of land width on tensile strength of manual welded, chem-milled 2014-T6 sheet, 0.100 in (1.27 mm). (Ref. 12.24)

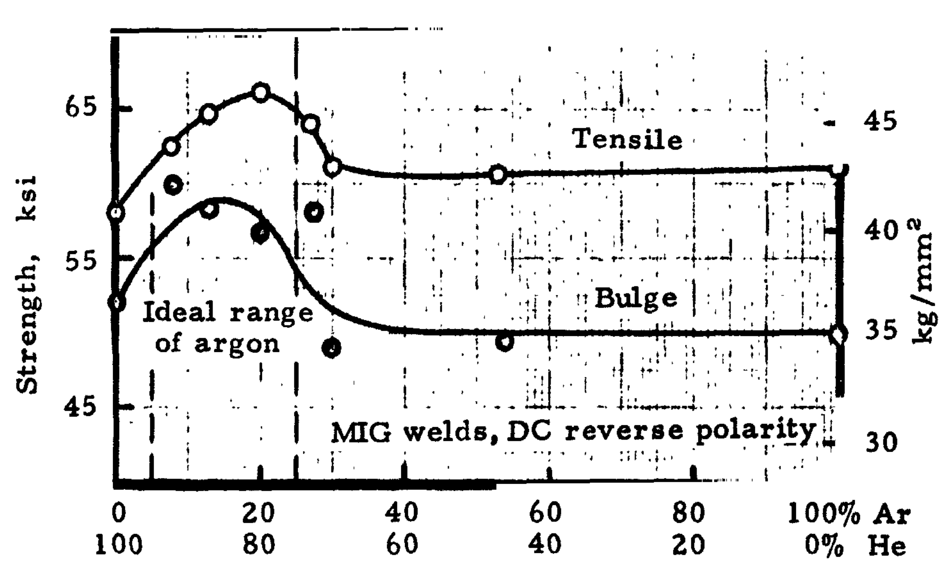

FIGURE 12.11. — Tensile and bulge properties of MIG welded 2014-T6 sheet, 0.090 in (2.29 mm) for various argon-helium gas mixtures. (Ref. 12.25)

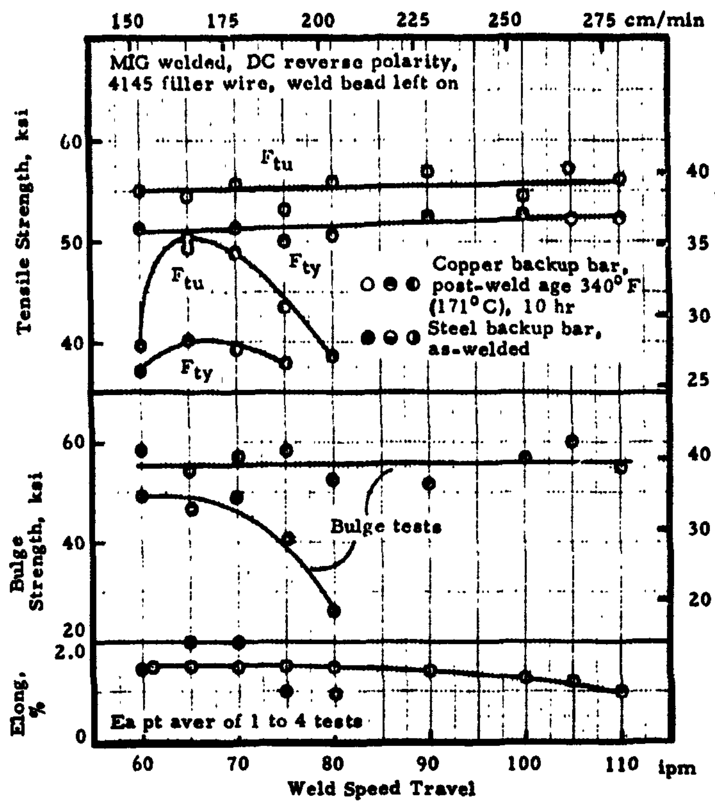

FIGURE 12.12. – Effect of weld travel speed on tensile properties and bulge strength of MIG welded 2014-T6 sheet, 0.090 in (2.90 mm). (Ref. 12.25)

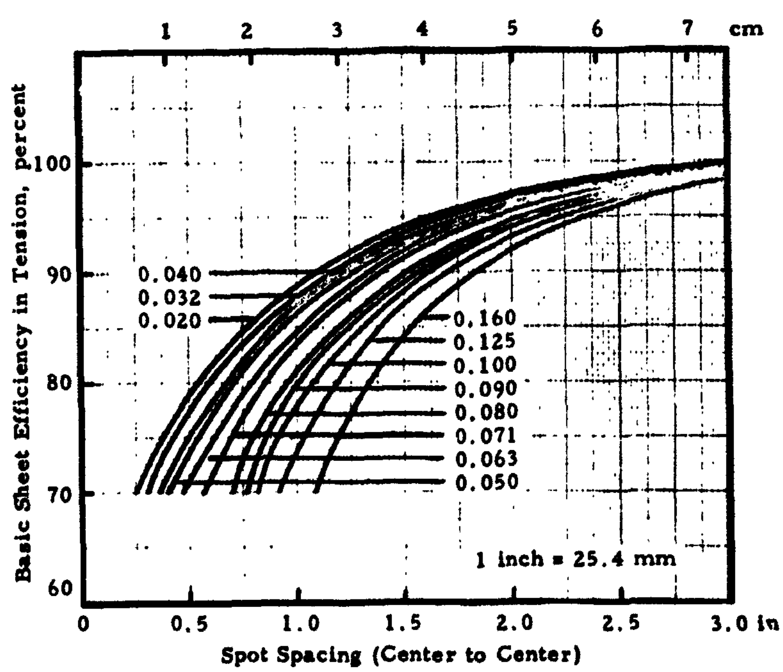

FIGURE 12.13. – Efficiency of the parent metal in tension for spotwelded aluminum alloys. (Ref. 12.6)

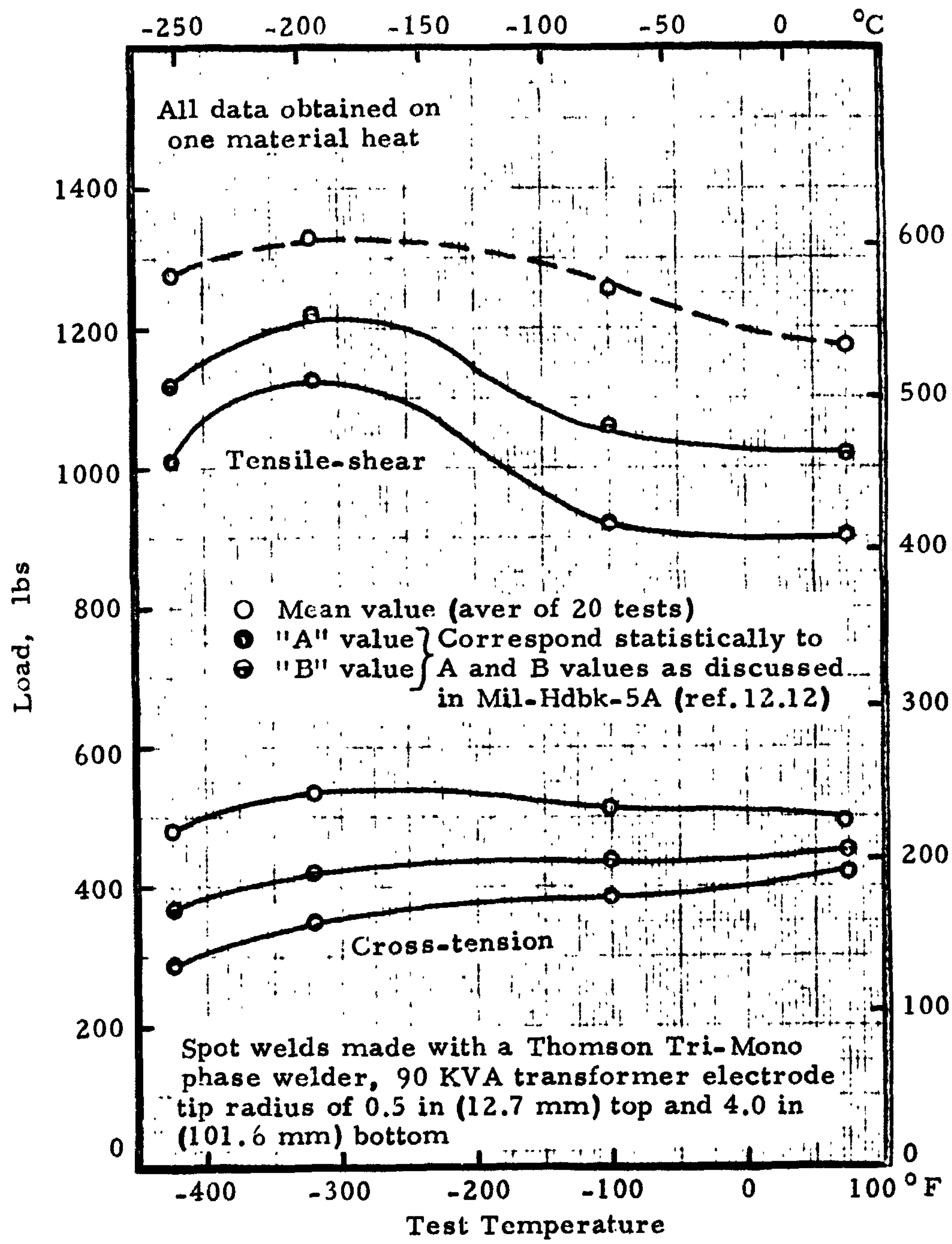

FIGURE 12.14. – Effect of low test temperatures on cross-tension and tensile-shear strength of single spot welds on 2014-T6 sheet, 0.063 in (1.60 mm).

(Ref. 12.11)

Chapter 12 - References

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

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

12.3 W.L. Burch, "Fusion Welding of 2014 Aluminum Alloys," Bell Lab. Report BLR 61-41(M)-Rev.A, Bell Aerosystems Co., December, 1961.

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

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

12.6 R.J. Davis, R.N. Hooker, and E.F. Kaluza, "Evaluation of MIG and TIG Welding Processes for Joining 2014-T6 Aluminum Alloy --Phase I," Douglas Aircraft Missiles and Space Systems Div., R&D Report SM-48383, 1964.

12.7 H. Brown, "Aluminum Fabrication versus Environmental Humidity," Minutes-Aluminum Welding Symposium, July 1964, NASA-George C. Marshall Space Flight Center, October 1964, p. 55.

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

12.9 F.R. Baysinger, "Observations on Porosity in Aluminum Weldments," Minutes-Aluminum Welding Symposium, July 1964, NASA-George C. Marshall Space Flight Center, October 1964, p. 121.

12.10 J.L. Christian, "Physical and Mechanical Properties of Pressure Vessel Materials for Application in a Cryogenic Environment," ASD TDR-62-258, Part I, March 1962.

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

12.12 Military Handbook 5-A, Dept. of Defense, FSC 1500, "Metallic Materials and Elements for Aerospace Vehicle Structures," February 1966; latest change order January 1970.

12.13 W.R. Lucas and C.E. C .'aldo, "Some Low-Temperature Properties of Aluminum Alloy Weldments," ASTM STP-287, 1960, p. 23.

12.14 Aluminum Co. of America, Alcoa Product Data, "Specifications," Section A12A, July 1, 1963.

12.15 B.G. Bandelin, "Evaluation of the Combined Effects of Porosity and Mismatch on the Weld Strengths of 6061-T6 (As Welded) Aluminum Alloys," Minutes-Aluminum Welding Symposium, July 1964, NASA-George C. Marshall Space Flight Center, October 1964, p. 290.

12.16 R.C. Manary, "Equipment Precautions Essential for High Quality Welds in Thick Aluminum," Minutes-Aluminum Welding Symposium, July 1964, NASA-George C. Marshall Space Flight Center, October 1964, p. 349.

12.17 W. Schivenk, "Influence of Welding Parameters in Electron Beam Welding Aluminum Alloys," Minutes-Aluminum Welding Symposium, July 1964, NASA-George C. Marshall Space Flight Center, October 1964, p. 9.

12.18 W. Groth, "Trends in Welding Aluminum," Metal Progress, 83(6), 76 (1963).

12.19 Aluminum Co. of America, "Brazing Alcoa Aluminum," 1958.

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

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

12.22 Index of Specifications and Standards, Dept. of Defense, Part I, Alphabetical Listing, Supplement, May 1971.

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

12.24 K.R. Agricola, "Manual and Repair Welding of Chemically Milled 2014-T6 Aluminum Sheet," Martin/Denver Rep. WDD-M-MI-57-60, August 1957.

12.25 J.R. Terrill, "Investigation toward Obtaining Significantly Higher Mechanical Properties of As-Welded Joints in High Strengh, Heat Treatable Aluminum Alloys," Alcoa Research Labs., DA Project No. 1-H-0-24401-A-11-01, Final Report No. 2-64-16, July 1964.

12.26 Welding Handbook, Secti... ., American Welding Society, New York, 1967.

12.27 Welding Handbook, Sec.2, American Welding Society, New York, 1964.

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