N72-30457

MATERIALS DATA HANDBOOK

Aluminum Alloy 5456
(2nd Edition)

DRA

Revised by

R. F. Muraca
J. S. Whittick

June 1972

Prepared for

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

Contract NAS8-26644

WESTERN APPLIED RESEARCH & DEVELOPMENT, INC.

1403-07 Industrial Road San Carlos, California 94070

PREFACE

The revised edition of the Materials Data Handbook on the aluminum alloy 5456 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, May 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 5456 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) Unites, 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 5456" was prepared by Western Applied Research & Development, Inc. under Contract No. NAS8-26644 for the George C. Marshall Space Flight Center of the National Aeronautics and Space Administration. The work was administered under the technical direction of the Astronautics Laboratory, Materials Division of the George C. Marshall Space Flight Center with Mr. Wayne R. Morgan acting as Project Manager.

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

TABLE OF CONTENTS

Page

Preface -- i
Acknowledgments -- ii
Table of Contents -- iii
Tabular Abstract -- iv
Symbols --- v
Conversion Factors -- viii

Chapter 1 General Information ---------------------------- 1

Chapter 2 Procurement Information ---------------------- 3

Chapter 3 Metallurgy ------------------------------------- 7

Chapter 4 Production Practices -------------------------- 13

Chapter 5 Manufacturing Practices ---------------------- 17

Chapter 6 Space Environment Effects -------------------- 27

Chapter 7 Static Mechanical Properties ------------------ 33

Chapter 8 Dynamic and Time Dependent Properties -------- 51

Chapter 9 Physical Properties ---------------------------- 61

Chapter 10 Corrosion Resistance and Protection ----------- 65

Chapter 11 Surface Treatments --------------------------- 71

Chapter 12 Joining Techniques --------------------------- 75

TABULAR ABSTRACT

Aluminum Alloy 5456

TYPE:

Wrought aluminum alloy, not heat treatable.

NOMINAL COMPOSITION:

Al-5.1Mg-0.8Mn-0.12Cr

AVAILABILITY:

Bare sheet and plate, extrusions, structural shapes, rod, bar, and pipe.

TYPICAL PHYSICAL PROPERTIES:

Density	2.65 g/cm^3 at room temperature
Thermal Conductivity	0.28 cal/cm^2/sec/cm/°C
Specific Heat	0.23 cal/g °C at 100°C
Av. Coeff. of Thermal Expansion	23.9 μcm/cm/°C at 20–100°C
Electrical Resistivity	5.9 microhm-cm at 20°C

TYPICAL MECHANICAL PROPERTIES:

F_{tu} (O temper)	45.0 ksi (31.6 kg/mm^2)
(H111 temper)	47.0 ksi (33.0 kg/mm^2)
(H112 temper)	45.0 ksi (31.6 kg/mm^2)
(H321 temper)	51.0 ksi (35.9 kg/mm^2)
F_{ty} (O temper)	23.0 ksi (16.2 kg/mm^2)
(H111 temper)	33.0 ksi (23.2 kg/mm^2)
(H112 temper)	24.0 ksi (16.9 kg/mm^2)
(H321 temper)	37.0 ksi (26.0 kg/mm^2)
e(2 in, 50.8 mm) (O temper)	24 percent
(H321 temper)	16 percent
E (tension)	10.3 x 10^3 ksi (7.2 x 10^3 kg/mm^2)

FABRICATION CHARACTERISTICS:

Weldability	Excellent (fusion and resistance methods)
Formability	Relatively poor
Machinability	Fair to good

COMMENTS:

Alloy has good corrosion resistance, moderately high strength, and excellent welding characteristics.

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/ft^2/sec/°F-inch	cal/g/cm^2/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 5456 is a nonheat-treatable wrought alloy, first made available in 1956. This alloy is one of the aluminum-magnesium group of alloys containing small additions of other elements.

1.2 The alloy has good corrosion resistance, moderately high strength, and excellent welding qualities without the necessity for post-weld treatment. It does not exhibit a ductile-to-brittle transition behavior when temperatures are lowered below room temperature. Machinability is only fair and the alloy has a tendency to yield gummy chips in the soft tempers and tends to build up burrs on cutting tools. Alloy 5456 may be fabricated at ambient temperatures successfully, but the amount of strain hardening during working should be restricted to avoid possible stress corrosion. The alloy is not susceptible to stress corrosion, however, in the tempers now produced when used at normal atmospheric temperatures. The 5456 alloy is available as sheet, plate, extrusions, rod, bar, and structural shapes and tubing (refs. 1.1 through 1.5).

1.3 Typical areas of application for 5456 alloy are high strength welded structures, storage tanks, deck housings, overhead cranes, vehicles, and heavy duty structures (ref.s 1.1 through 1.5).

1.4 General Precautions

1.41 The alloy is not recommended for continuous service at temperatures above 150°F (66°C) because of accelerated aging at elevated temperatures which may increase the susceptibility of the alloy to stress-corrosion cracking (ref. 1.6).

Chapter 1 - References

1.1 Alloy Digest, "Aluminum 5456" (Filing Code Al-70), Engineering Alloys Digest, Inc., September 1958.

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

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

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

1.5 Olin Aluminum, "Olin Aluminum Mill Products and Casting Alloys," 1970.

1.6 K. F. Thornton, "Alcoa Aluminum-Magnesium Alloys, Suitable for Structural Welding Applications," Alcoa Green Letter, November 1959; revised by R. L. Flucker, August 1962.

1.7 V. Weiss and J. Sessler, Eds., "Aerospace Structural Metals Handbook, Vol. II, Non-Ferrous Alloys," ASD TDR 63-741, 1971 Edition.

Chapter 2

PROCUREMENT INFORMATION

2.1 General. Aluminum alloy 5456 is available as sheet, plate, extrusions (shapes and tube), structural shapes, rod, bar, and pipe. Detailed tables of standard sizes and tolerances for the various products available are given in references 2.1 and 2.2.

2.2 Procurement Specifications. Specifications that apply to the 5456 alloy as of May 1971 are listed in table 2.2 for various products and tempers.

2.3 Major Producers of the Alloy (United States only)

Aluminum Company of America
1501 Alcoa Building
Pittsburgh, Pennsylvania

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

Olin Aluminum/Metals Division
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 The available forms, sizes, conditions, and tolerances for various 5456 alloy products are given in detail in references 2.1 and 2.2. Availability and dimensions of typical products are given in table 2.41.

TABLE 2.2. – Procurement Specifications (a, b)

Source	Refs. 2.3, 2.4, 2.5, 2.6, 2.7			
Alloy	5456			
Product	Temper	Military	Federal	ASTM
Bar, rod, shapes, tube (extruded)	O, H111, H112	MIL-A-21170A	QQ-A-200/7D	B221-71
	H311	MIL-A-21170A	QQ-A-200/7D	-
Bar, rod, shapes (rolled)	O, H111, H112	MIL-A-21170A	-	B308-70
	H311	MIL-A-21170A	-	B308-70
Forgings	O	-	-	B247-70
Seamless pipe (extruded or drawn)	O, H112	MIL-P-25995	-	B241-70
		-	-	B345-68
Sheet and plate	O, H24	MIL-A-19842C	QQ-A-250/9F	B209-71
	H112	-	QQ-A-250/9F	B209-71
	H311	-	-	-
	H321	MIL-A-19842C	QQ-A-250/9F	B209-71
	H323, H343	MIL-A-19842C	QQ-A-250/9F	B209-71
Tube (extruded)	O, H111, H112	-	-	B221-71
Seamless tube (drawn)	O	-	-	B210-70
Structural shapes (extruded or rolled)	O, H112, H311	MIL-A-25994, MIL-A-21170A	QQ-A-225C	B308-68
	H111	MIL-A-21170A	QQ-A-225C	B308-68
Armor plate(weldable)	-	MIL-A-46027D	-	-
Extruded armor	-	MIL-A-46083-1	-	-
Forged armor	-	MIL-A-45225B	-	-

(a) Specified as of May 1971

(b) See also SAE Handbook No. AA5456 (ref. 2.4)

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

Source	Ref. 2.8	
Alloy	5456	
Form	Temper	Dimensions
Coiled sheet (mill finish)	O, F, H19, H32, H34, H36, H38	0.020-0.125 in (0.508-3.18 mm) thick; 1/2-60 in (1.3-152 cm) wide; 8, 10, 12, 16, 20 in (20, 25, 30, 40, 50 cm) arbor size
Flat sheet (mill finish)	O, H19, H32, H34, H36, H38	0.009-0.249 in (0.23-6.32 mm) thick; 3-60 in (7.7-152 cm) wide; 12-80 in (30-203 cm) long
Plate (mill finish)	O, F	0.250-1.00 in (6.35-25.4 mm) thick; 6-72 in (15-183 cm) wide; 48-180 in (122-457 cm) long
Extruded shapes	O, H112	10-in (25.4-cm) circum circle, max

Chapter 2 - References

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

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

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

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

2.5 ASTM Standards, Part 6, Supplement, Nonferrous Metals Specifications, Electron Tube Materials, 1963; also Part 6, 1971.

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

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

2.8 Olin Aluminum, "Olin Aluminum Mill Products and Casting Alloys," 1970.

Chapter 3

METALLURGY

3.1 Chemical Composition

3.11 Nominal chemical composition of 5456 alloy, in percent (ref. 3.3):

Mg	5.1	Cr	0.12
Mn	0.8	Al	Balance

3.12 Chemical composition limits, in percent (ref. 3.11):

Mg	4.7-5.5	Ti	0.20 max
Mn	0.50-1.0	Cu	0.10 max
Cr	0.05-0.20	Others	
Si+Fe	0.40 max	Each	0.05 max
Zn	0.25 max	Total	0.15 max
	Al	Balance	

3.13 Alloying elements. Magnesium is the major alloying constituent in the 5456 alloy, with lesser quantities of manganese and chromium also present. Magnesium is soluble, while manganese (in the presence of iron) and chromium are relatively insoluble. The aluminum-rich portions of the binary diagrams for the aluminum-magnesium, aluminum-manganese, and aluminum-chromium systems are shown in figure 3.1. An aluminum-magnesium intermetallic compound can be formed, but its precipitation during an aging treatment does not increase the strength of the alloy. Thus, the alloy is not strengthened by thermal treatments (refs. 3.4, 3.5, 3.6).

3.2 Strengthening Mechanisms

3.21 General. The alloy is strengthened by a combination of solid solution strengthening and cold work. Cold working of this alloy is generally followed by a stabilization treatment, which is a high temperature aging treatment that permits most of the magnesium to remain in solid solution. This treatment improves the resistance to corrosion of the alloy. Increase in magnesium and manganese content results in strength increase with a corresponding decrease in ductility. The 5456 alloy has the highest magnesium content of any of the 5000 series of aluminum alloys (refs. 3.4, 3.5).

3.22 Heat Treatment. The alloy is not strengthened by thermal treatments and is therefore considered to be nonheat-treatable.

3.221 Annealing (O Condition). Heat to 343°C, hold at temperature only for sufficient time to bring all parts of the load to the annealing temperature. Cooling rate is not critical (ref. 3.1). An annealing temperature of 413°C is also recommended (refs. 3.2, 3.4).

3.3 Critical Temperatures

Liquidus temperature	638°C
Solidus temperature	571°C (ref. 3.4).

3.31 The solid solubility of magnesium in aluminum is shown below (ref. 3.7):

Temperature, °C	200	250	300	350	400	450
Weight-percent Mg	2.9	4.5	6.3	8.7	11.5	14.9

3.4 Crystal Structure. Face centered cubic. The lattice parameter depends primarily on the amount of Mg in solution. For aluminum with no Mg, $a_0 = 4.041 \times 10^{-7}$ mm and it increases to $a_0 = 4.089 \times 10^{-7}$ mm for aluminum with 10.75 atomic-percent Mg (ref. 3.6).

3.5 Microstructure. Data on the stable and metastable phase identification in Al-Mg alloys may be found in reference 3.10. The 5456 alloy also contains manganese and chromium. Phase identification of the relatively insoluble phases formed between aluminum, iron, manganese and silicon can be based largely on the studies for aluminum alloy 3003, with some modification due to the presence of chromium (ref. 3.9). References 3.8 and 3.9 are recommended as excellent sources of information on the identification of constituents in aluminum alloys.

3.6 Metallographic Procedures. In general, mechanical polishing is preferred to electropolishing, especially where larger microconstituents are present and the material is relatively soft, because objectionable relief effects produced by the electrolytic technique may cause misinterpretation of the microstructure. For homogeneous alloys, and for those containing finely dispersed particles (such as aged alloys), the electrolytic method is excellent. Most metallographers prefer to replace the grinding step by mill filing. The specimen is then polished on metallographic emery papers 0 to 000, wet with a solution of 50 g paraffin in 1 liter kerosene to keep the specimen bright and avoid imbedding of emery particles into the soft specimen surface.

Following the final kerosene wash, the kerosene itself must be removed with water and alcohol. Polishing is accomplished by a water suspension of No. 600 alundum flour on broadcloth or gamal-cloth on a disk rotating at about 300 rpm. Final polishing is carefully performed on a disk revolving at about 150 rpm. Miracloth, selvyt or "kitten's ear" broadcloth are used on the disk with levigated alumina or magnesium oxide in distilled water as the abrasive mixture.

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.

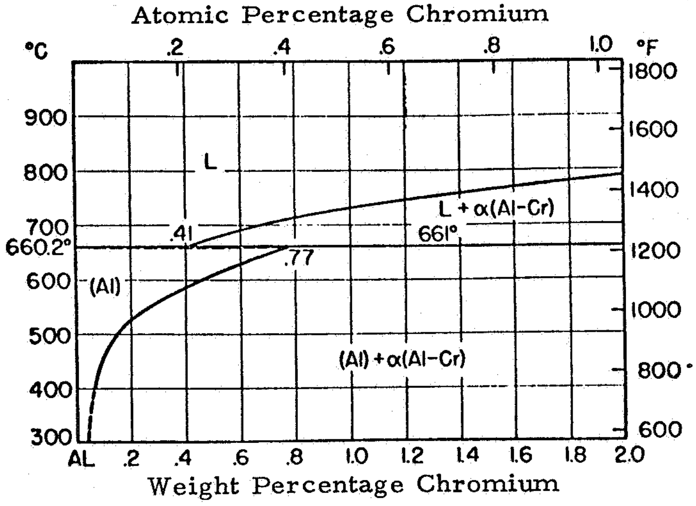
(d) Final polish on a vibratory polisher using a microcloth containing a slurry of methyl alcohol and 0.1-μm aluminum oxide powder. A slurry of 0.1-μm aluminum oxide powder in a 10-percent solution of glycerine in distilled water may also be used for this step.

Etching reagents have to be suited to the objective of the study. Kellers etch reveals microstructural details and grain boundaries satisfactorily. A 10-percent solution of NaOH gives better detail of the 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 for cracks, gross defects, forging lines and grain structure should be made with the following etching solutions: 10-percent NaOH (cracks, gross defects), Tucker's etc, modified Tucker's etch, and Flick's etch (ref. 3.6). These etching solutions for revealing the macrostructure are given in table 3.1.

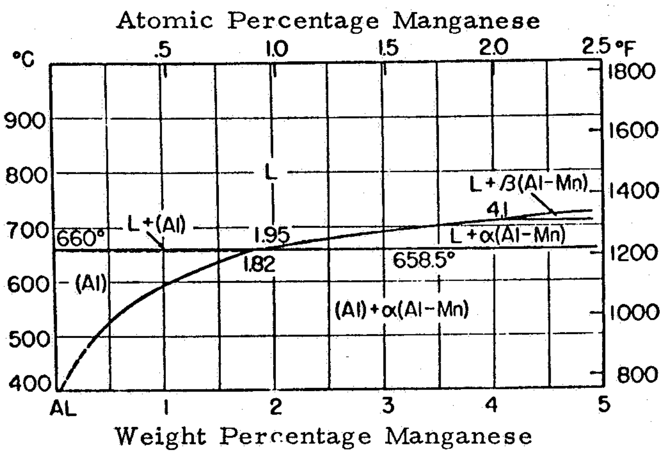
TABLE 3.1. — Etching Solutions for Revealing Macrostructure

Source	Ref. 3.9		
Alloy	5456		
Solution (a)	Composition		Specifications
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

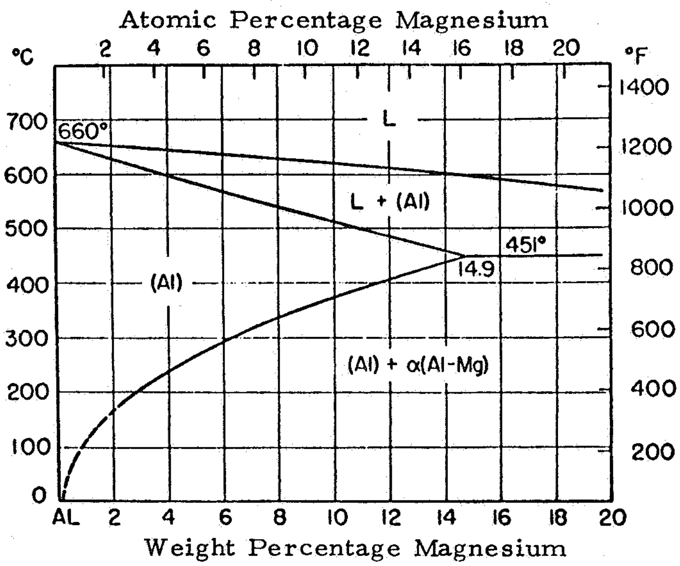
(a) All of these solutions are used at room temperature



Aluminum—Chromium



Aluminum—Manganese



Aluminum—Magnesium

FIGURE 3.1. — Aluminum-rich portions of binary equilibrium diagrams. (Ref. 3.7)

Chapter 3 - References

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

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

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

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

3.5 Marshall Space Flight Center, "Effect of Low Temperatures on Structural Metals," NASA SP-5012, December 1964.

3.6 W.L. Fink et al., Physical Metallurgy of Aluminum Alloys, American Society for Metals, 1949; reprinted 1958.

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

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

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

3.10 E.C.W. Perryman and G.B. Brook, "Mechanism of Precipitation in Aluminum-Magnesium Alloys," J. Inst. Metals, 79, 19 (1951).

3.11 1971 SAE Handbook, Society Automotive Engineers, Inc., New York.

Chapter 4

PRODUCTION PRACTICES

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

For the 5456 alloy, the major alloying elements added to the aluminum are magnesium, manganese, and chromium. Generally, this phase of production practice involves the melting, alloying, and casting of large 20,000- to 50,000-pound ($\approx$9,000 to 21,000 kg) ingots, carefully controlled. 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, but 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 cause the work to assume a cross-section shape more nearly approaching that desired. The final desired shape is produced at the last pair of rolls.

4.24 Plate is produced by hot rolling of ingots to slabs (approximately 60-percent reduction), usually in a 4-high reversible mill. The slabs are then further reduced 50 percent in a reversible 2-high mill. The last stage of hot rolling is done in a hot reversing mill, where the plate is progressively rolled to the final hot mill dimensions. Strong alloy 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 whose cross-section shape and size conforms to that of the orifice. Speeds, pressures, and temperatures must be closely controlled to insure uniform quality of extruded products.

4.28 Tube is produced by extruding, by drawing, or by welding. Extruded tube is forced through an orifice as described in 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 Available Tempers (refs. 4.2, 4.4, 4.5)

4.31 Aluminum alloy 5456 products are available from producers of the alloy in the following tempers:

H19	Strain hardened to ultimate tensile strength greater than can be achieved by cold reduction.
H24	Strain hardened and then partially annealed to half-hard condition.
H32, H38	Strain hardened and stabilized by low temperature treatment which results in slightly less tensile strength and improved ductility.
H111	Strain hardened only to obtain the desired mechanical properties with no thermal treatment. Applies to products which are strain hardened less than the amount required for a controlled H11 temper.

H112	Temper is acquired from shaping processes not having special control over the amount of strain ahrdening or thermal treatment but for which mechanical property limits or testing is required.
H321	Strain hardened and stabilized to one-quarter hard condition by a low temperature heating operation which prevents age softening at room temperature. H321, H322, and H323 are variations of the controlled H32 temper.
H343	Strain hardened and stabilized to one-half hard condition. This temperature is a variation of the controlled H34 temper.

4.4 Casting of Alloy Ingots

4.41 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 solidifes. Water is spryaed on the outside of the mold to promote rapid solidification. Additional processing may include scalping (machining of outside surfaces) or homogenizing (refs. 4.2, 4.3).

Chapter 4 - References

4.1 Kaiser Aluminum and Chemical Sales, Inc., "Kaiser Aluminum Sheet and Plate Product Information," 2nd Edition, January 1958.

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

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

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

4.5 Olin Aluminum, "Olin Aluminum Mill Products and Casting Alloys," 1970.

Chapter 5

MANUFACTURING PRACTICES

5.1 General. The nonheat-treatable 5456 alloy is one of the aluminum-magnesium series which finds principal application in structures that are fabricated predominately from sheet and plate and where welding is the method of joining (ref. 5.5). Most of these structures are designed on the basis of strength and ductility of welds and include dump trucks, rock bodies, bulk haulers, truck tanks, boats, cryogenic tanks and equipment, chemical processing equipment, and elevators for aircraft carriers. Several other applications are the first stage of the Saturn I and Saturn IB launch vehicles, a 140-ft diameter radio-telescope in the form of a fabricated parabolic dish, and the elevator for the nuclear-powered carrier Enterprise (ref. 5.6).

5.2 Forming

5.21 Sheet and Plate. The general formability of 5456 as a sheet material is considered to be limited compared to other nonheat-treatable alloys; it is rated as the most difficult to form, as indicated in table 5.21.

5.211 Cold Forming. The high strength of this alloy in not only the strain-hardened tempers but also the annealed temper restricts the capability for withstanding severe forming operations. Table 5.211 lists typical properties for 5456 sheet below 0.200-in (5.08 mm) thickness for several tempers and the corresponding recommended minimum bend radii. The H3 temper results from a stabilizing treatment. Cold-worked 5456 would tend to age-soften at room temperature. A thermal treatment at about 350° F (177° C) prevents this from happening (ref. 5.8). The specially developed H343 temper produces a metallurgical condition which shows excellent resistance to stress corrosion. Cold-worked 5456 may be susceptible to stress corrosion at temperatures above 150° F (65° C). If cold forming in excess of the established minimum limits is employed, a stress relief anneal of 4 hours at 450° ±25° F (232° ±13° C) will restore the good resistance to corrosion.

Aluminum sheets are normally formed using operations such as:

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

The factors influencing bending of 5456 sheet, as described previously, also influence the fourteen other forming operations in the same general manner. Because of the lower modulus of elasticity of aluminum compared with steel, a much greater "springback" is expected and 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. Alloy 5456 sheets can be formed to many shapes by drawing; this is the most extensively employed mass production method. 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.

Tapered plate was developed by one of the aluminum producers about 1950 for use in jet aircraft. Alloy 5456, rolled in a heavily powered screw-down plate-rolling mill to a taper section, is being used for large (125 feet in diameter, 48 feet high), flat-bottom ammonium nitrate storage tanks. The larger dimension of each plate thickness is utilized in the lower portions of the tank tapering to the less heavily stressed upper portions. The tapered plate tank saves from 5 to 10 percent in material compared to the conventional tiered or shell-plate construction. (Tank dimensions equivalent to 38 m x 15 m.)

It is the combination of properties and fabrication characteristics which are the significant factors leading to the selection of 5456 for aircraft applications. The 5456 alloy is commonly used in aircraft applications for spun or drawn pressure receptacles. Spinning is a specialized forming operation in which the work is forced against a chuck or form block while rotating. The chucks are usually made of hardwood (maple) or segmented and laminated construction (ref. 5.7). The segments are firmly glued together, joints are staggered, and each tier is solidly glued to the adjoining one or fastened with heavy wood screws. For large quantity production, chucks can be of carbon steel for shallow spinnings and of cast iron or alloy cast iron for deeper ones. Generally, spinning is devoted to concentric parts. There is no maximum size for spinning except as limited by existing equipment or material. Spinning requires considerable axial pressure which can be accommodated on horizontal lathes or vertical boring mills. Hot spinning to assist metal flow and reduce the spinning pressure is sometimes used.

5.212 Hot Forming. Warm forming for less severe configurations can be performed at 425° ±25° F (218° ±3° C). This will avoid the adverse effect of cold work and high residual stresses.

5.22 Shapes, Tubes, and Pipes. Either extrusion or rolling can be used to produce aluminum shapes. The standard shapes are I-beams, H-beams, channels, angles, teez, and zees. The relative formability of alloy 5456 as tubes or extrusions can be noted in table 5.21. In this form, the tubes or extrusions can be heated at 650° F (343° C) to produce the O temper.

5.23 Forgings. The 5456 alloy can be used for forgings in the H112 temper with sections up to about 4-inch (10-cm) maximum thickness. Forgings are made using either the open die or closed die methods and by impact or pressure. Small runs are made using hand-forging or open-die techniques. The process for most production forgings starts with the stock which can vary from 3/8-inch to 8-inch diameter round stock; from 3/8-inch to 4-inch square stock, and rectangles from 3/8 inch for the minimum dimension to as much as 10 inches on the maximum dimension. (Note: 1 inch = 25.4 mm.) Conditioning to remove localized surface defects is permitted at this point. The stock is carefully heated in the range of 650° to 875° F (393° to 468° C). After preheating, the stock can be forged to shape in one step or in the case of complicated parts in several operations, involving several reheatings. 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 a required operation. Templates combined with indicators and other gages are used to determine the out-of-tolerances. Straightening ranges from hand straightening to "cold restrike" operations.

The forgings are inspected for grain flow, mechanical properties, dimensions and ultrasonic soundness. A design manual for forgings is available from the Aluminum Association (ref. 5.13).

5.3 Machining

5.31 Conventional Machining. This alloy has machining qualities which are close to those of other nonheat-treatable aluminum alloys (such as 5154) though somewhat better than the lower strength alloys (ref. 5.12). High-speed steel cutting tools are satisfactory, but hard-carbide grades are preferred. Single point tools should have 20°–50° top rake, 10°–20° side rake, 8°–10° front and side clearance angles. The cutting is to be done at high speeds and fine to medium feeds. Cutting edges must be keen, smooth, and free from grinding scratches. Turnings are continuous, tough, and somwhat difficult to curl. In soft tempers, the turnings are somewhat gummy and tend to build up burrs on the tool. For many purposes, a soluble cutting oil is good. However, a kerosene-lard oil mixture is preferred.

In the particular case of the Saturn first stage, long 70-inch (178 cm) diameter fuel and oxidizer tanks are machined and fabricated from the 5456 alloy (ref. 5.10). Fourteen cylindrical skin sections are welded together to form the tank body. These fourteen sections start out as 1/8- to 1/4-inch (3.18 to 6.35 mm) thick sheets 330 inches (838 cm) long by 58 inches (147 cm) wide. These are vacuum clamped in a 12 x 30 ft (3.7 x 9.1 m) numerically-controlled skin mill which contours the interior of the skin surface to reduce thickness in noncritical areas. The feed rate is 90 ipm (229 cm/min) with the cutting spindle turning at 3600 rpm. A cutting tolerance of ±0.003 inch (0.076 mm) is maintained as two skin sections are cut simultaneously. After cutting, these skins are roll-formed and longitudinally welded.

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 and can be used as a guide. A wheel speed of 6000 ft/min is typically used for grinding. A down feed will produce a rough finish if it is kept about 0.001 inch per pass; a fine finish if the down feed is kept below 0.0005 inch per pass. The crossfeed is approximately one-third of the wheel width. (Note: 1 inch = 25.4 mm.)

5.32 Electrochemical and Chemical Machining

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

5.322 Electrochemical Milling. Electrochemical machining for metal shaping subjects the chemically erodible workpiece to the action of anodic current flow in a suitable electrolyte. A second electrode (which is the tool) is provided for the cathodic action. The basic principles are the same as those generalized in Faraday's Law of Electrolysis. However, the electrochemical machining, or ECM, process is the reverse of electrodeposition. An exception is that the cathodic process involves the evolution of hydrogen, in most cases, rather than the electrodeposition of a metal. 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 is supplied to the workpiece. Alloy 5456 is essentially a pure aluminum as far as the rate of electrochemical process is concerned. Hence, from the Faraday laws, it is rather easily shown that 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 encountered. An electrolyte of 5 to 10 percent NaCl solution has been found to yield excellent results and the process can be carried out using voltages of 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. Temperatures of about 120°F (50°C) produce good quality finishes.

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. The removal of metal by dissolving in an alkaline or acid solution is now routine for specialized operations on aluminum (ref. 5.1). For flat parts on which large areas having complex or wavy peripheral outlines are to be reduced only slightly in thickness, chemical milling is usually the most economical method. The curve shown in figure 5.323 is typical for selecting chemical or mechanical milling.

TABLE 5.21. — Relative Formability of Nonheat-Treatable Aluminum Alloys in Order of Decreasing Formability

Source	Ref. 5.7		
Rating	Sheet Materials	Extrusions	Tubes
↓	1060	1060	1060
	EC	EC	EC
	1100	1100	1100
	3003, No.11, No.12	3003	3003
	5005	5052	5050
	5357, 5457, 5657	5154	5052
	5050	5454	3004, 5154
	5052, 5652	5086	5454
	3004, 5154, 5254	5083	5086
	5454	5456	5083
	5086		5456
	5083		
	5456		

TABLE 5. 211. — Approximate Bend Radii for 90-Degree Cold Bend (a, b)

Source	Ref. 5.4											
Alloy	5456											
Temper	F_{tu}, ksi (c)		F_{ty}, ksi (c)		e (d)	Thicknesses, t, inch (c)						
	min	max	min	max	min	1/16	1/8	3/16	1/4	3/8	1/2
O	42	53	19	-	16	-	0-1t	1/2-1t	1/2-1t	1/2-11/2	1/2-2t
H321	46	59	33	46	12	-	2-3t	3-4t	3-4t	3-4t	3-4t
H323	48	58	36	46	6	1-2t	11/2-3t	11/2-31/2t	2-4t	-	-
H343	53	63	41	51	6	1-2t	11/2-3t	2-4t	21/2-41/2t	-	-

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

(b) Mechanical properties (F_{tu}, F_{ty}, and e) are minimum or maximum for thicknesses below 0.200.

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

(d) Elongation, percent in 2-in gage section.

TABLE 5.31. — Typical Factors for Common Machining Operations

Source	Ref. 5.11						
Alloy	5456						
Operation	Cutting Conditions	High Speed Tool			Carbide Tool		
		Speed ipm	Feed ipr	Tool Mat'l	Speed ipm	Feed ipr	Tool Mat'l
Single point turning	0.250 inch depth of cut	600	0.015	(a, b)	1100	0.015	C-2
	0.050 inch depth of cut	800	0.008	(a, b)	1400	0.008	C-3
Form tool	0.500 inch form tool width	450	0.0035	(a, b, c)	1000	0.0035	C-2
	0.750 inch form tool width	450	0.0035	(a, b, c)	1000	0.0035	C-2
	1.000 inch form tool width	450	0.003	(a, b, c)	1000	0.003	C-2
	1.500 inch form tool width	450	0.0025	(a, b, c)	1000	0.0025	C-2
	2.000 inch form tool width	450	0.002	(a, b, c)	1000	0.002	C-2
Boring	0.010 inch depth of cut	600	0.008	(a, b, c)	1100	0.010	C-2, C-3
	0.050 inch depth of cut	570	0.010	(a, b, c)	1050	0.015	C-2, C-3
	0.100 inch depth of cut	540	0.015	(a, b, c)	1000	0.020	C-2, C-3
Planing	0.500 inch depth of cut	300	0.060	(a, b)	300	0.060	C-2
	0.050 inch depth of cut	300	0.050	(a, b)	300	0.050	C-2
	0.010 inch depth of cut	300	3/4**	(a, b)	300	3/4**	C-2
Face milling	0.250 inch depth of cut	800	0.020*	(a, b)	max	0.018*	C-2
	0.050 inch depth of cut	1000	0.022*	(a, b)	max	0.020*	C-2
Drilling	1/8 inch nominal hole diameter	250	0.003	(a, b)			
	1/4 inch nominal hole diameter	250	0.007	(c)			
	1/2 inch nominal hole diameter	250	0.012	(c)			
	3/4 inch nominal hole diameter	250	0.016	(c)			
	1 inch nominal hole diameter	250	0.020	(c)			
	1 1/2 inch nominal hole diameter	250	0.025	(c)			
	2 inch nominal hole diameter	250	0.030	(c)			
	3 inch nominal hole diameter	250	0.030	(c)			
End milling	3/4 inch cutter diameter	700	0.010*	(b, d)	1200	0.007*	C-2
	1 to 2 inch cutter diameter	700	0.010	(b, d)	1200	0.009*	C-2
Profiling	1/8 inch cutter diameter	1000	0.001	(b, d)	1800	0.005*	C-2
	3/4 inch cutter diameter	1000	0.009*	(b, d)	1800	0.008*	C-2
	1 to 2 inch cutter diameter	1000	0.011	(b, d)	1800	0.010*	C-2

* Feed - inches per tooth

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

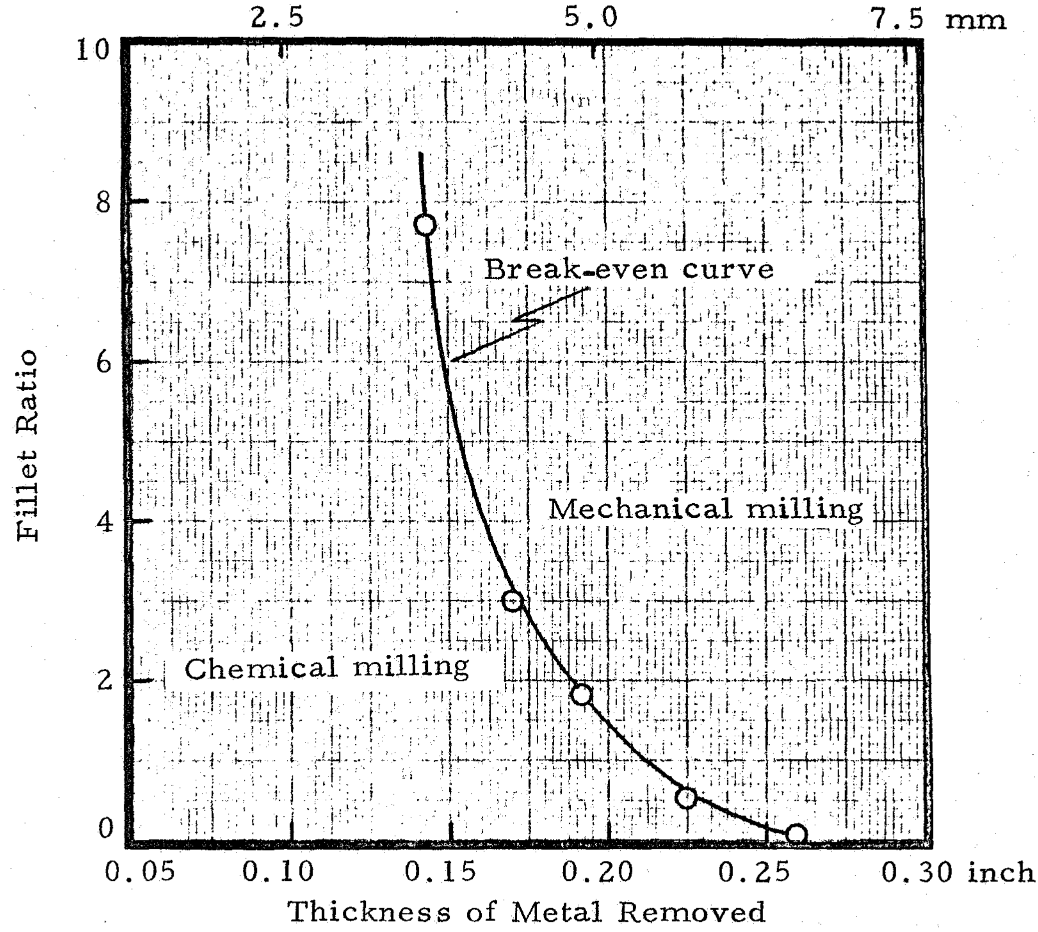
(a) T1 material

(b) M1 material

(c) HSS (high speed steel)

(d) M10 material

Note: 1 inch = 25.4 mm.



$$\text{Fillet ratio} = \frac{\text{Total length of fillet (ft)}}{\text{Total area of part (ft}^2\text{)}}$$

FIGURE 5.323. — A parameter for choice of method of metal removal from large areas having complex or wavy peripheral outlines.
(Ref. 5.1)

Note: The figure indicates a parameter for choice of metal removal from large areas having complex or wavy peripheral outlines. Chemical processes should always be used for metal removal of 0.125 inch (3.175 mm) or less. The choice for thicknesses of 0.125 to 0.250 inch (3.175—6.35 mm) depends on fillet ratio. Metal thicknesses above 0.250 inch should be mechanically milled.

Chapter 5 - References

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

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

5.3 Materials in Design Engineering, "Wrought Aluminum and Its Alloys," June 1965, p. 117.

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

5.5 Metal Progress, "What Metal Shall I Use..for High Strength Weld Structure," October 1961, p. 121.

5.6 Metal Progress, "Progress in Aluminum Alloys," October 1960, p. 137.

5.7 Reynolds Metals Company, "Forming Aluminum," 1961.

5.8 Materials in Design Engineering, June 1965, p. 120.

5.9 F. L. Siegrist, "How to Do More with Wrought Aluminum Alloys," Metal Progress, October 1962, p. 124.

5.10 E.J. Bulban, "Vought Producing C-1 First Stage Tanks," Aviation Week and Space Technology, May 21, 1962, p. 54.

5.11 Machining Data, ORDP 40-1, July 1961.

5.12 Kaiser Aluminum, "Temporary District Engineering Data Sheet, Aluminum 5456."

5.13 The Aluminum Association, "Aluminum Forging Design Manual," 1970.

5.14 Metals Handbook, Vol. 3, "Machining, American Society for Metals, Metals Park, Ohio, 1967.

5.15 Metals Handbook, Vol. 5, "Forging," American Society for Metals, Metals Park, Ohio, 1970.

5.16 Metals Handbook, Vol. 4, "Forming," American Society for Metals, Metals Park, Ohio, 1969.

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 5456 are sufficiently hardened so that nuclear and space indigenous radiation indusced 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 5456 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. 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 flus; 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 nm 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

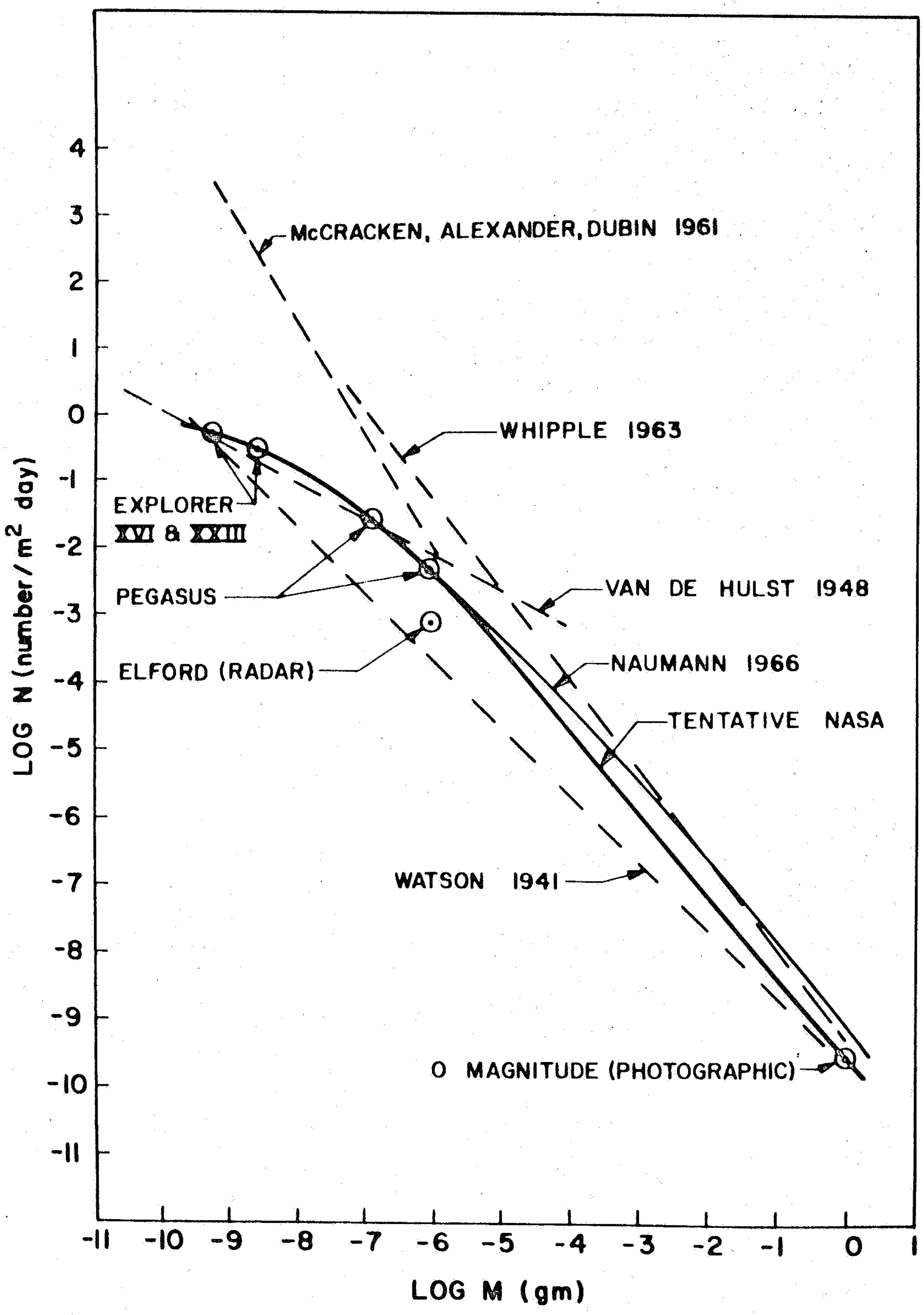


FIGURE 6.1. — Various estimates of meteoroid mass influx. (Ref. 6.3)

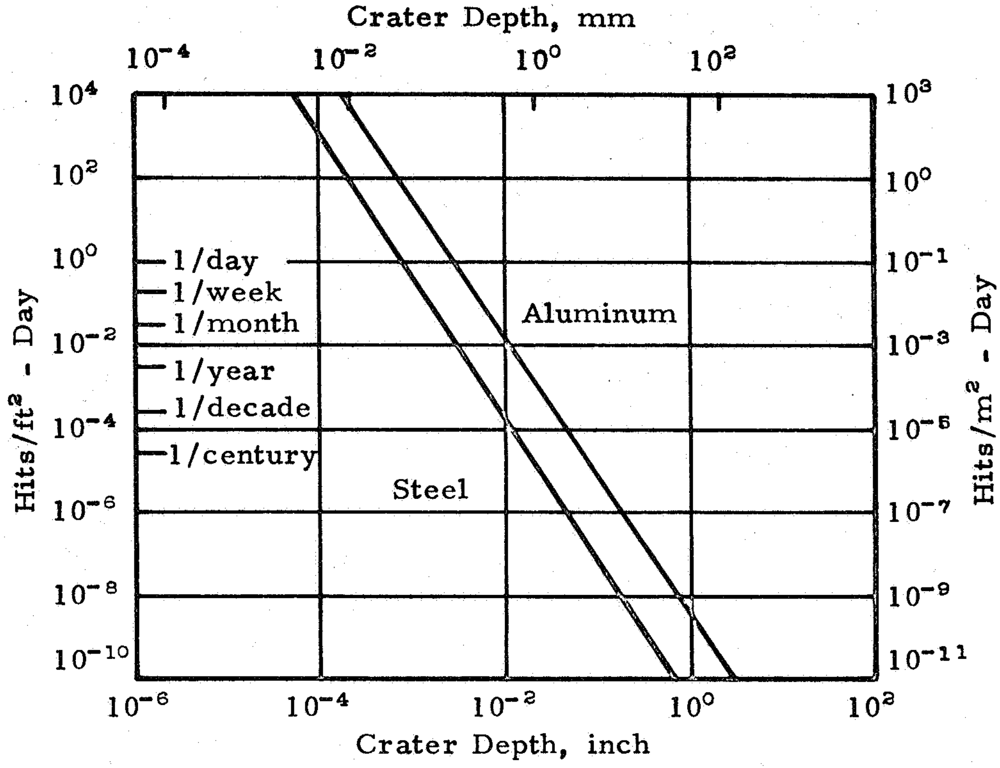


FIGURE 6.2. — Hit rate vs crater depth in the earth neighborhood but without earth shielding.

(Ref. 6.4)

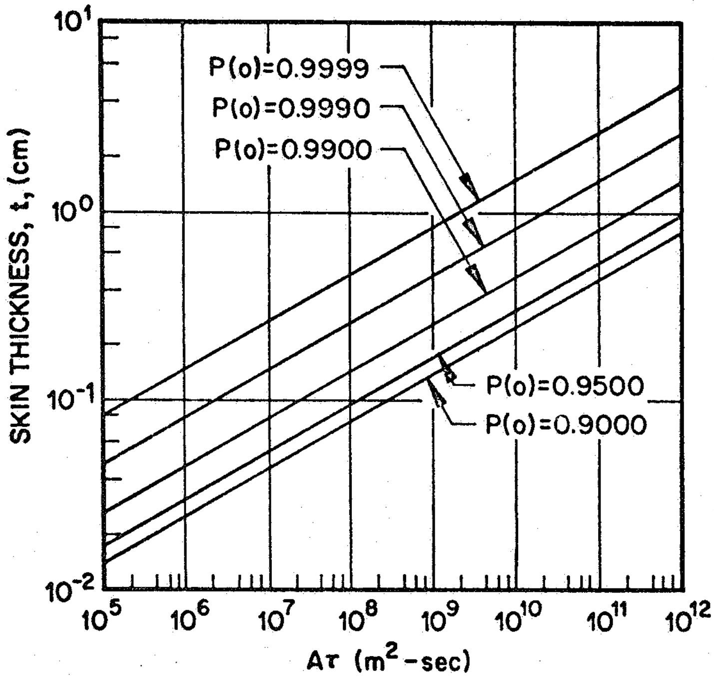


FIGURE 6.3. — Sheet thickness of Al as a function of the surface area—lifetime product required for various probabilities of no meteoroid puncture.

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

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

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

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

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

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

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

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

Chapter 7

STATIC MECHANICAL PROPERTIES

7.1 Specified Properties

7.11 NASA specified properties. None.

7.12 AMS specified properties

7.13 Military specified properties

7.14 Federal specified properties

7.15 ASTM specified properties

7.151 ASTM specified properties are given in reference 7.3.

7.16 Aluminum Association mechanical property limits

7.161 Aluminum Association mechanical property limits are given in reference 7.4.

7.2 Elastic Properties and Moduli

7.21 Poisson's ratio, 0.33 (ref. 7.5).

7.22 Young's modulus of elasticity, E

7.221 Design value of E for sheet and plate and extrusions at room temperature, 10.2×10^3 ksi (7.17×10^3 kg/mm^2) (ref. 7.1).

7.222 Typical value of E, 10.3×10^3 ksi (7.24×10^3 kg/mm^2) (refs. 7.6, 7.8).

7.223 Modulus of elasticity at low and room temperature, figure 7.223.

7.224 Modulus of elasticity at elevated temperatures, figure 7.224.

7.23 Compression modulus, E_c.

7.231 Design value of E_c at room temperature, 10.4×10^3 ksi (7.31×10^3 kg/mm^2) (ref. 7.1)

7.24 Modulus of rigidity (shear modulus), G.

7.241 Design value of G at room temperature, 3.85×10^3 ksi (2.71×10^3 kg/mm^2) (ref. 7.1).

7.25 Tangent modulus

7.251 Compressive tangent modulus curves for alloy in various forms and tempers, figure 7.251.

7.26 Secant modulus

7.3 Hardness

7.31 Brinell scale (500-kg load)

Condition		
O	70	
H112	70	
H311	75	
H321	90	
H323	90	
H343	94	(ref. 7.8)

7.4 Strength Properties

7.41 Tension (see also section 7.46)

7.411 Design tensile properties

7.4111 Design properties for sheet, plate, and extruded bar, rod and shapes, table 7.4111.
7.4112 Aluminum Association tensile property limits for sheet and plate in various tempers, table 7.4112.
7.412 Stress-strain diagrams (tension)
7.4121 Typical stress-strain curves at room temperature for extrusions, figure 7.4121.
7.4142 Typical stress-strain curves for 5456-H321 plate at room temperature, figure 7.4122.
7.413 Effect of test temperature on tensile properties
7.4131 Effect of low and elevated temperature on the tensile properties of alloy in condition O, figure 7.4131.
7.4132 Effect of low and room temperature on tensile properties of sheet in condition H321, figure 7.4132.
7.4133 Effect of low and room temperature on transverse and longitudinal tensile properties of sheet in condition H343, figure 7.4133.
7.4134 Effect of low and room temperature on tensile properties of sheet in condition H343, figure 7.4134.
7.4135 Effect of low and room temperature on tensile properties of sheet and plate in condition H343, figure 7.4135.
7.42 Compression
7.421 Design compression properties
7.4211 Design compression properties for sheet and plate and extruded bar, rod, and shapes, see table 7.4111.
7.422 Stress-strain diagram (compression)
7.4221 Stress-strain curves at room temperature for various forms and tempers, see figures 7.4121 and 7.4122.
7.43 Bending
7.44 Shear and torsion
7.441 Design shear properties
7.4411 Design shear properties for sheet and plate and extruded bar, rod, and shapes, see table 7.4111.
7.45 Bearing
7.451 Design bearing properties
7.4511 Design bearing properties for sheet and plate and extruded bar, rod, and shapes, see table 7.4111.
7.46 Fracture
7.461 Notch strength
7.4611 Effect of low and room temperature on tensile properties and notch strength of plate in O condition, figure 7.4611.
7.4612 Effect of low and room temperature on notch strength of sheet in H343 condition, figure 7.4612.
7.4613 Effect of low and room temperature on notch strength ratio of sheet in H343 condition, figure 7.4613.
7.4614 Tensile and sharp notch properties of sheet at room and low temperatures, figure 7.4614.
7.4615 Effect of low and room temperature on tensile properties and notch strength of plate in H321 condition, figure 7.4615.
7.462 Fracture toughness (plane stress)
7.4621 Effect of low temperature on fracture toughness of sheet in H343 condition, figure 7.4621.

TABLE 7.4111. – Design Mechanical Properties of Sheet, Plate, and Extrusions

Alloy	QQ-A-250/9 (5456)										QQ-A-200/7		
Form	Sheet and Plate										Extruded bar, rod, and shapes		
Condition	-O		-H112		-H321				-H323	-H343	-O	-H111	-H112
Thickness or diameter, in.	0.051–1.500	1.501–3.000	0.250–1.500	1.501–3.000	0.188–0.624	0.625–1.250	1.251–1.500	1.501–3.000	0.051–0.249	0.051–0.249	≤5.000 [b]	≤5.000 [b]	≤5.000 [b]
Basis	S	S	S	S	S	S	S	S	S	S	S	S	S
Mechanical properties:													
F_{tu}, ksi													
L	42	41	42	41	46	46	44	41	48	53	41	42	41
T	42	....	....	....	46	45	43	....	48	53	....	....	41
F_{ty}, ksi													
L	19	18	19	18	33	33	31	29	36	41	19	26	19
T	19	....	....	....	30	29	28	....	34	39	....	....	19
F_{cy}, ksi													
L	19	....	....	....	27	26	24	....	34	39	19	....	19
T	19	....	....	....	33	31	29	....	36	41	....	....	19
F_{su}, ksi	26	....	....	....	27	27	25	....	28	31	....	....	23
F_{bru}, ksi:													
(e/D=1.5)	63	....	....	....	67	67	64	....	70	77	....	....	57
(e/D=2.0)	84	....	....	....	84	84	80	....	91	101	....	....	74
F_{bry}, ksi:													
(e/D=1.5)	32	....	....	....	46	46	43	....	51	58	....	....	34
(e/D=2.0)	38	....	....	....	53	53	50	....	58	66	....	....	38
e, per cent:													
L	16	16	12	12	12	12	12	12	(a)	(a)	14	12	12

(a) e, 0.051-0.125 in, 6%; 0.126-0.249 in, 8%.

(b) Cross-sectional area ≥ 32 in^2 (206 cm^2).

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

(Ref. 7.1)

TABLE 7.4112. — Aluminum Association Tensile Property Limits for Sheet and Plate in Various Tempers

Source	Ref. 7.4					
Alloy	5456					
Temper	Thickness, in (a, b)	F_{tu}, ksi (c)		F_{ty}, ksi (c)		e(2 in or 4D), min, percent
		min	max	min	max	
O	0.051-1.500	42.0	53.0	19.0	30.0	16
	1.501-3.000	41.0	52.0	18.0	30.0	16
	3.001-5.000	40.0	-	17.0	-	14
	5.001-7.000	39.0	-	16.0	-	14
	7.001-8.000	38.0	-	15.0	-	12
H112	0.250-1.500	42.0	-	19.0	-	12
	1.501-3.000	41.0	-	18.0	-	12
H321	0.188-0.624	46.0	-	33.0	46.0	12
	0.625-1.250	46.0	-	33.0	45.0	12
	1.251-1.500	44.0	56.0	31.0	43.0	12
	1.501-3.000	41.0	56.0	29.0	43.0	12
H323	0.051-0.125	48.0	58.0	36.0	46.0	6
	0.126-0.249	48.0	58.0	36.0	46.0	8
H343	0.051-0.125	53.0	63.0	41.0	51.0	6
	0.126-0.249	53.0	63.0	41.0	51.0	8

(a) Type of specimen depends on thickness of material

(b) 1 inch = 25.4 mm.

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

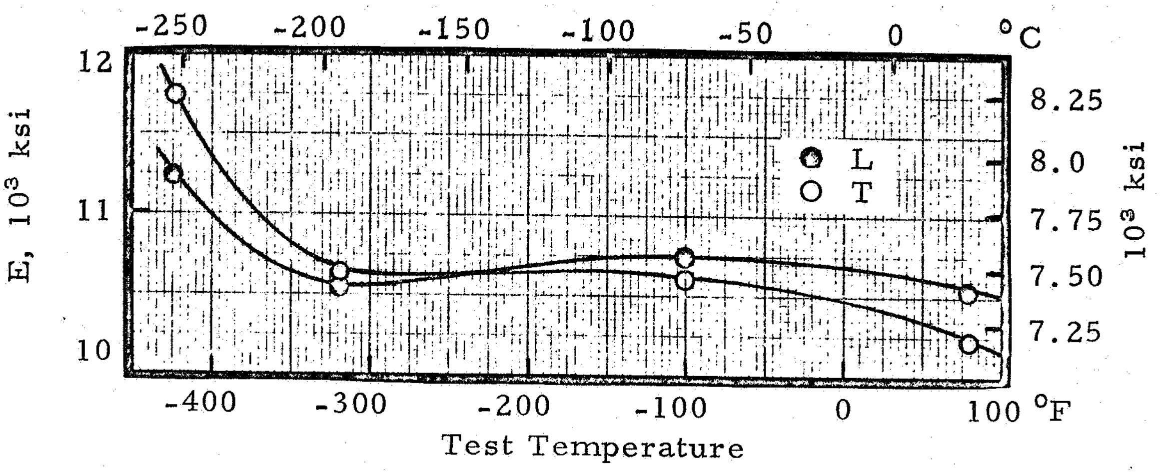


FIGURE 7.223. — Modulus of elasticity at low and room temperature for 5456-H343, 0.063-in (16.0-mm) sheet.

(Ref. 7.7)

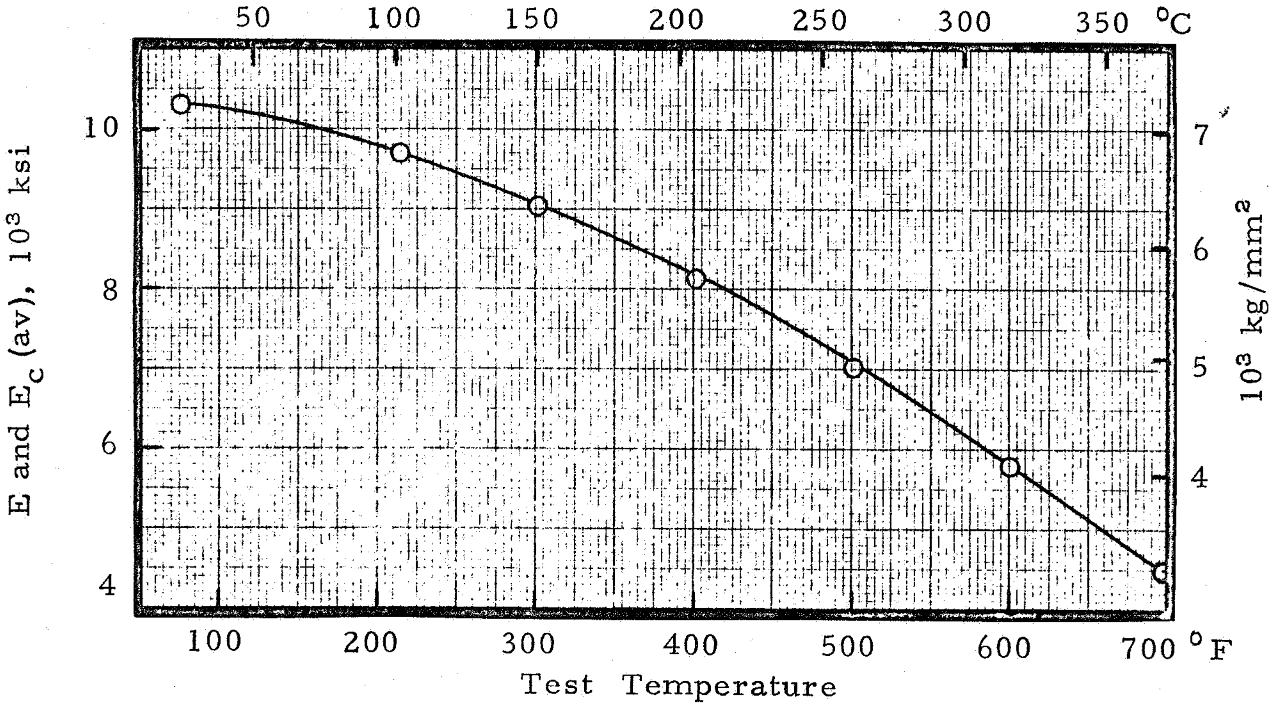


FIGURE 7.224. — Modulus of elasticity of 5456-H321 at elevated temperatures.

(Ref. 7.16)

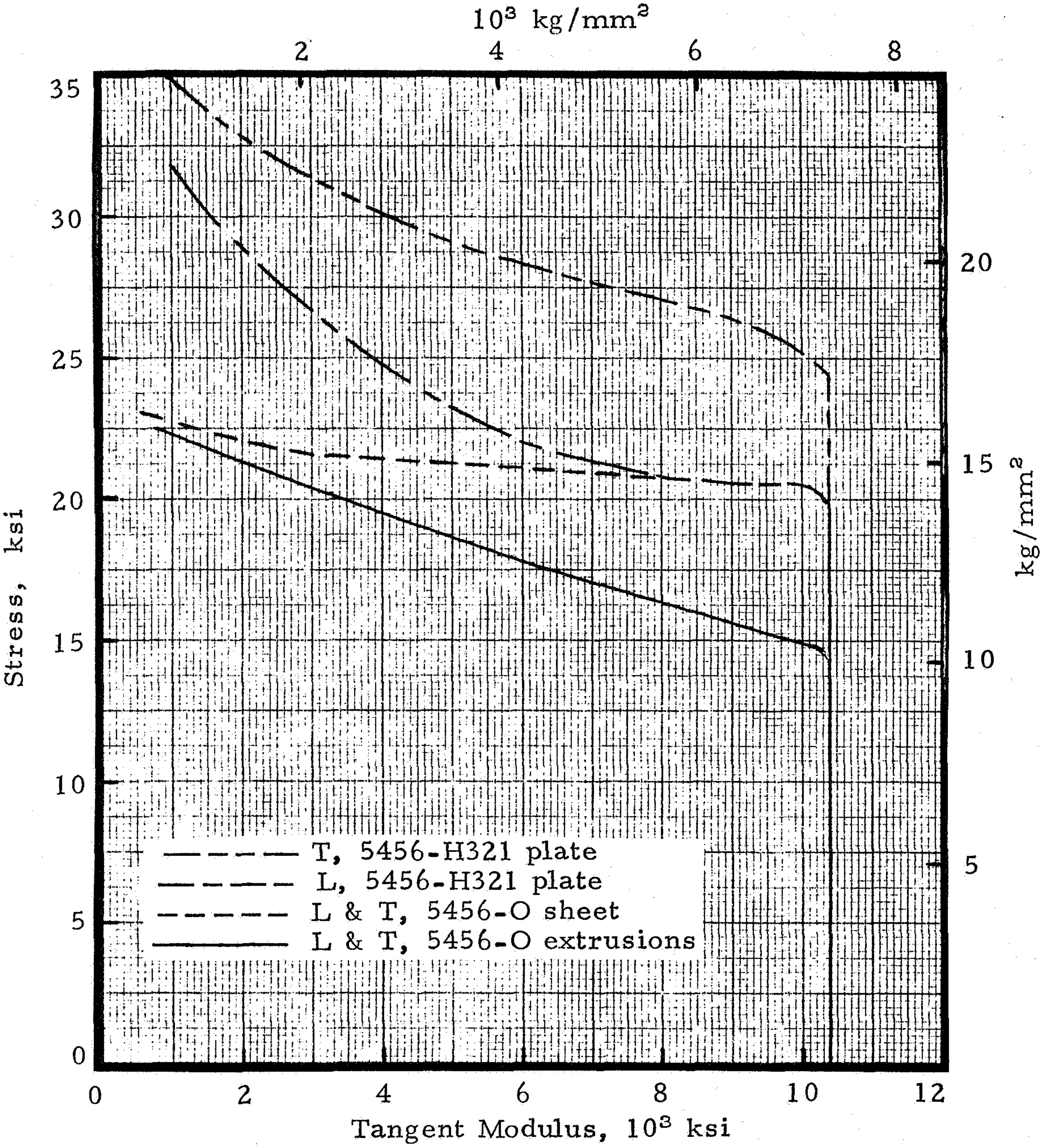


FIGURE 7.251. — Compressive tangent modulus curves at room temperature for 5456 in various forms and tempers.

(Ref. 7.1)

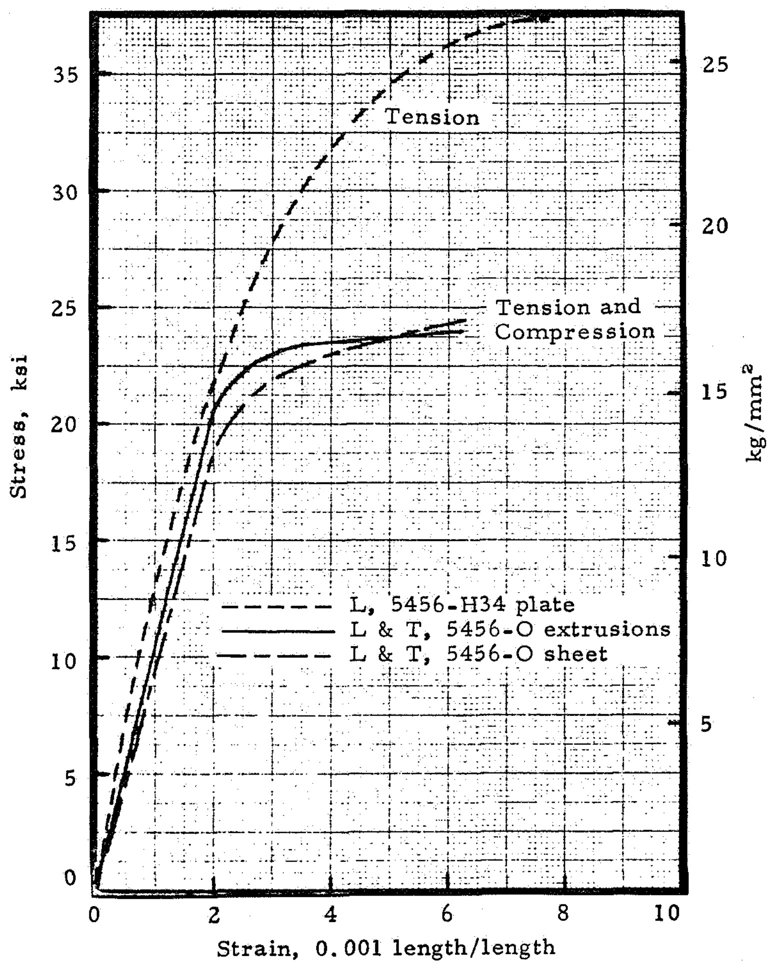


FIGURE 7.4121. — Typical stress-strain curves at room temperature for various forms and tempers of 5456.

(Ref. 7.1)

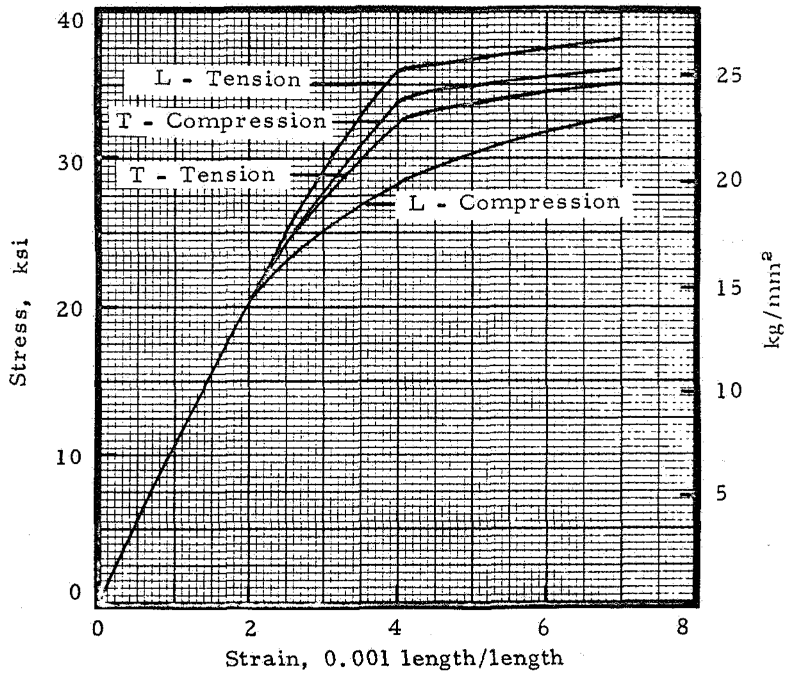


FIGURE 7.4122. — Typical stress-strain curves at room temperature for 5456-H321 plate, 0.625-1.250 inches (15.8-31.8 mm).

(Ref. 7.1)

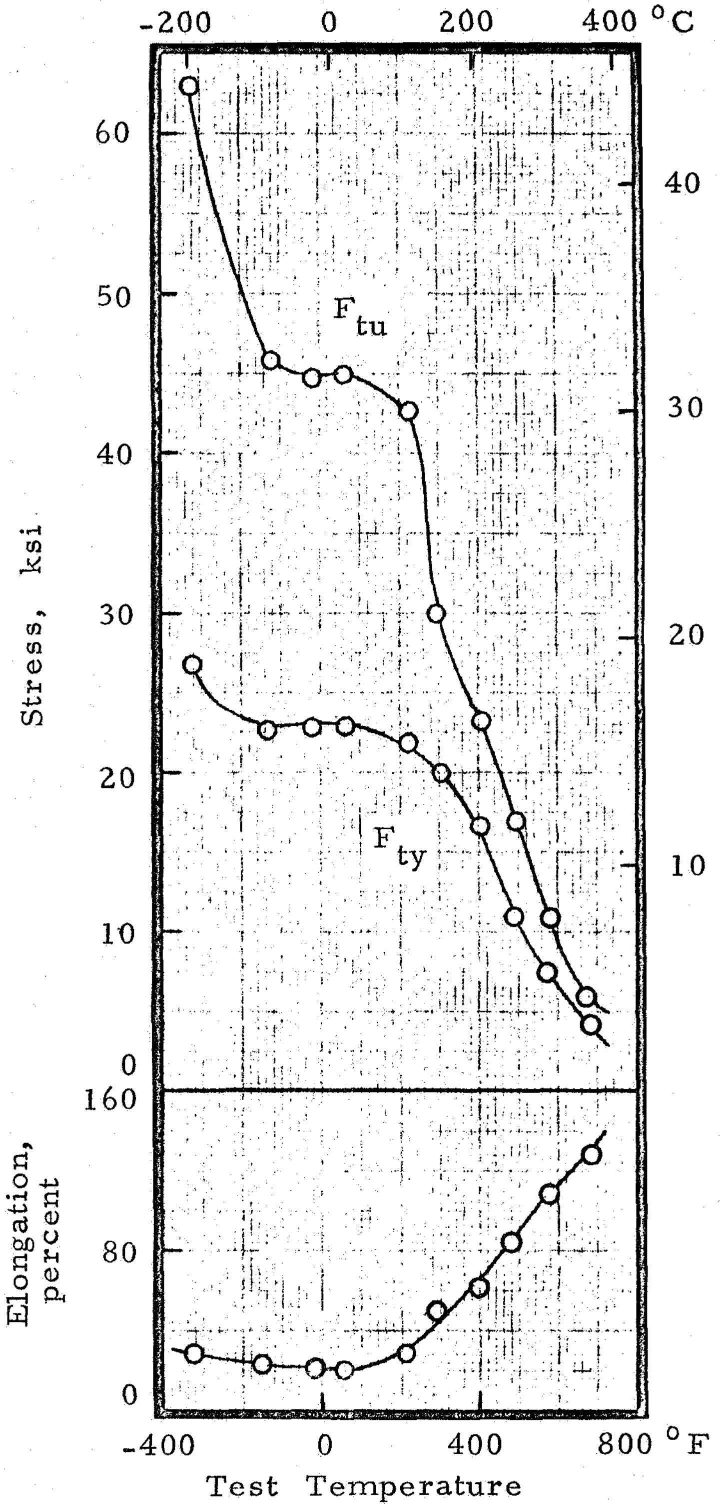


FIGURE 7.4131. — Effect of low and elevated temperatures on tensile properties of 5456-O (avg for various forms and sizes). (Ref. 7.9)

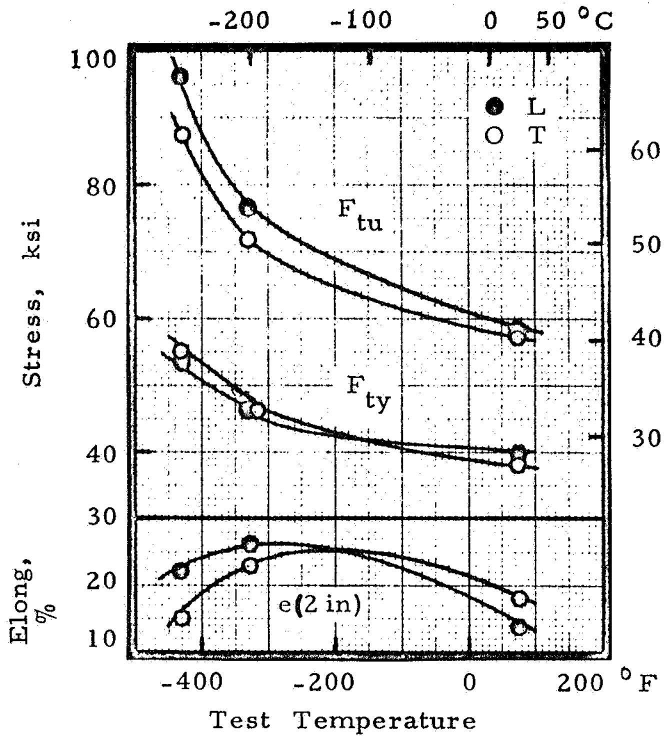


FIGURE 7.4132. — Effect of low and room temperature on tensile properties of 5456-H321 sheet, 0.125 in (3.175 mm). (Ref. 7.10)

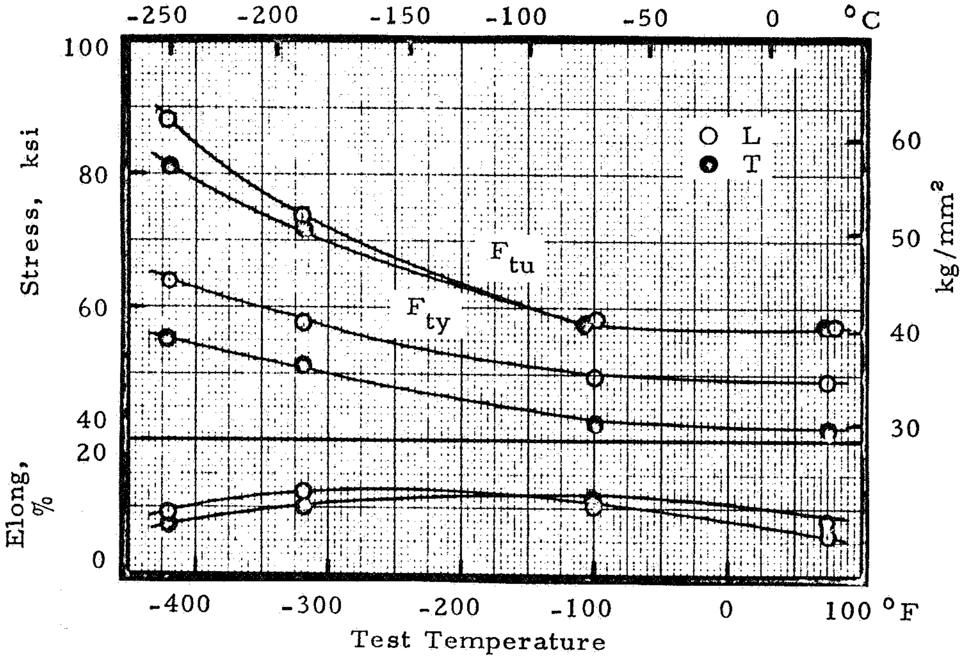


FIGURE 7.4133. — Effect of low and room temperature on transverse and longitudinal tensile properties of 5456-H343 sheet, 0.063 in (1.60 mm). (Ref. 7.7)

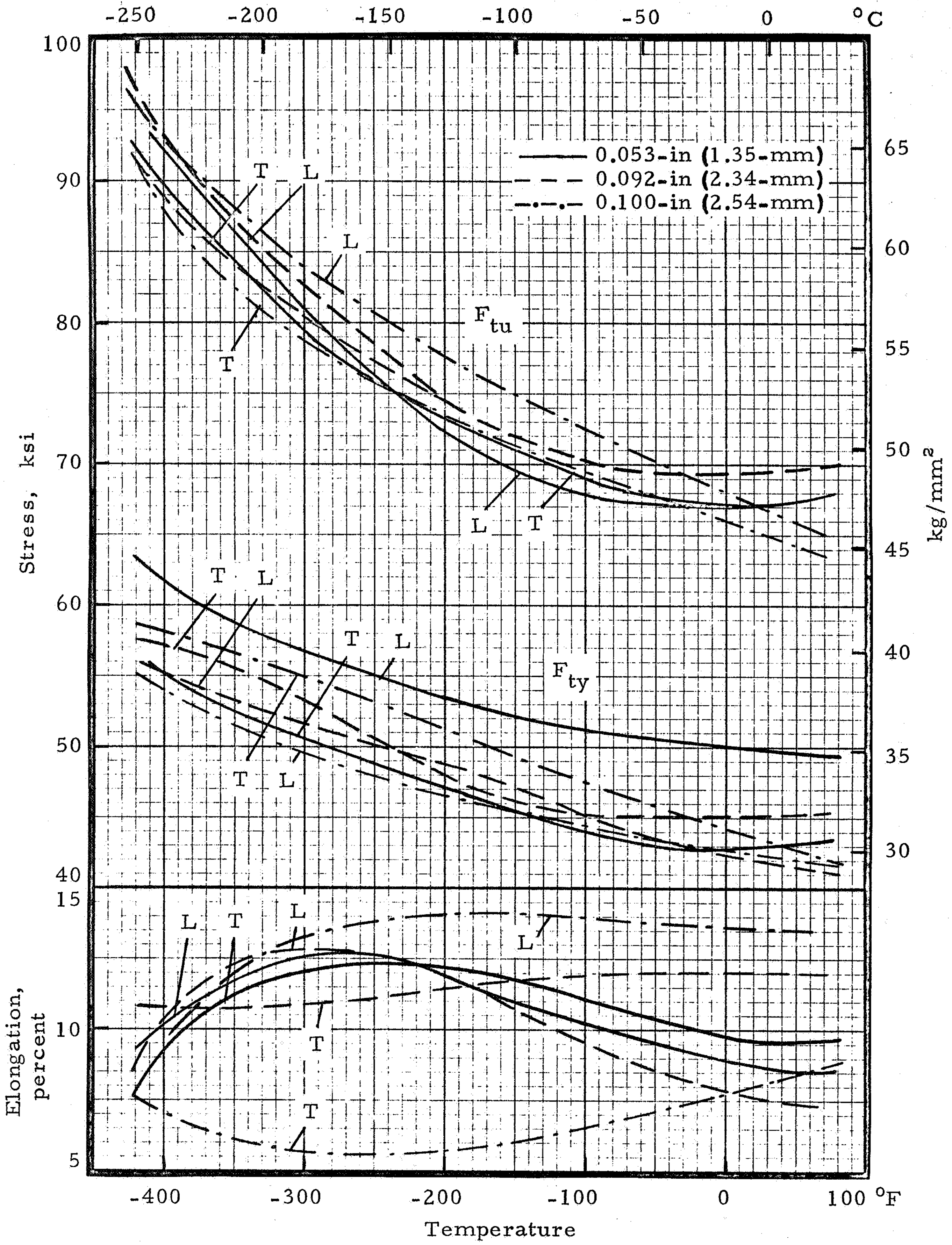


FIGURE 7.4134. — Effect of low and room temperature on tensile properties of 5456-H343 sheet.
(Refs. 7.7, 7.11, 7.12)

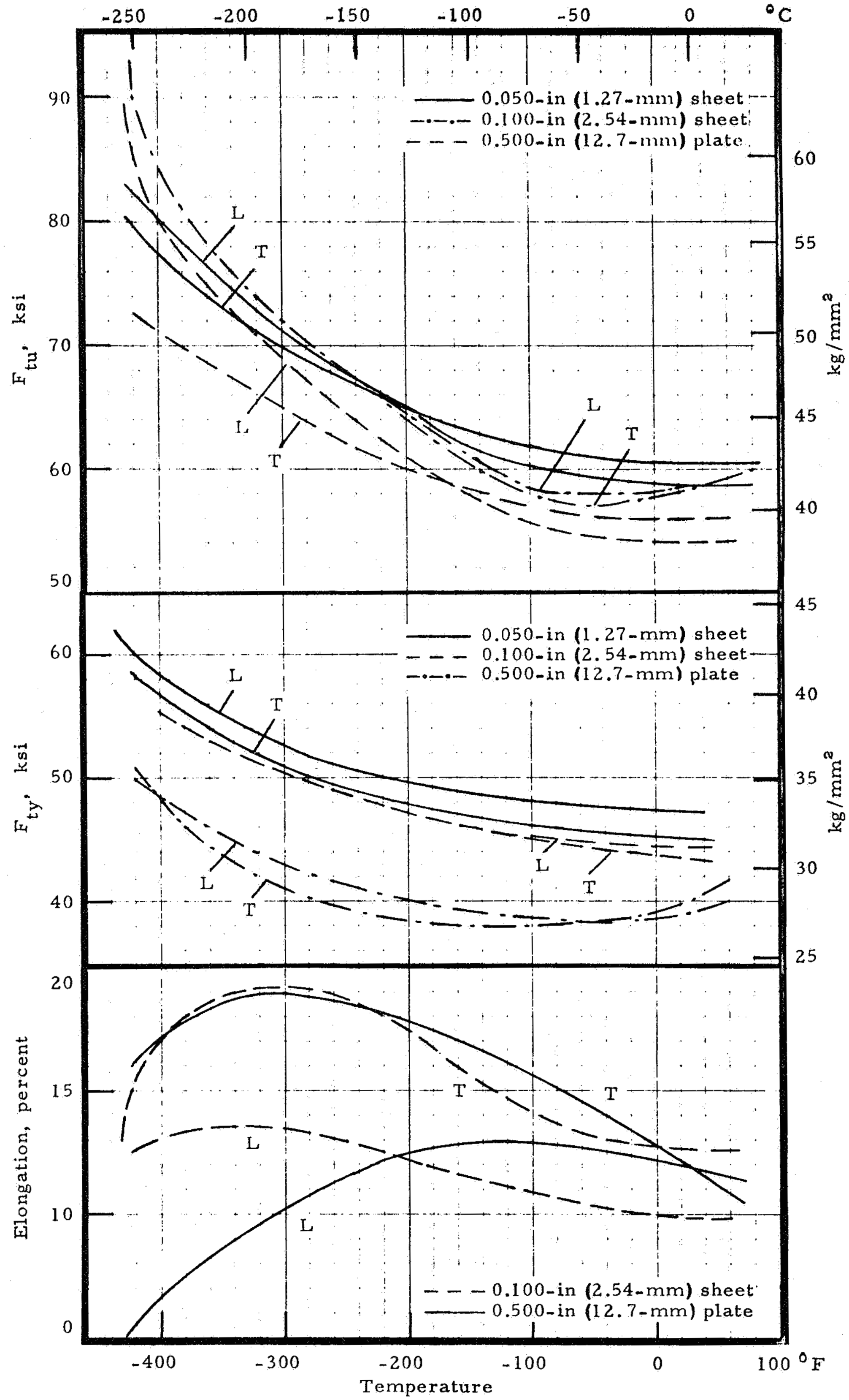


FIGURE 7.4135. — Effect of room and low temperature on tensile properties of 5456-H343 sheet and plate.
(Refs. 7.13, 7.14)

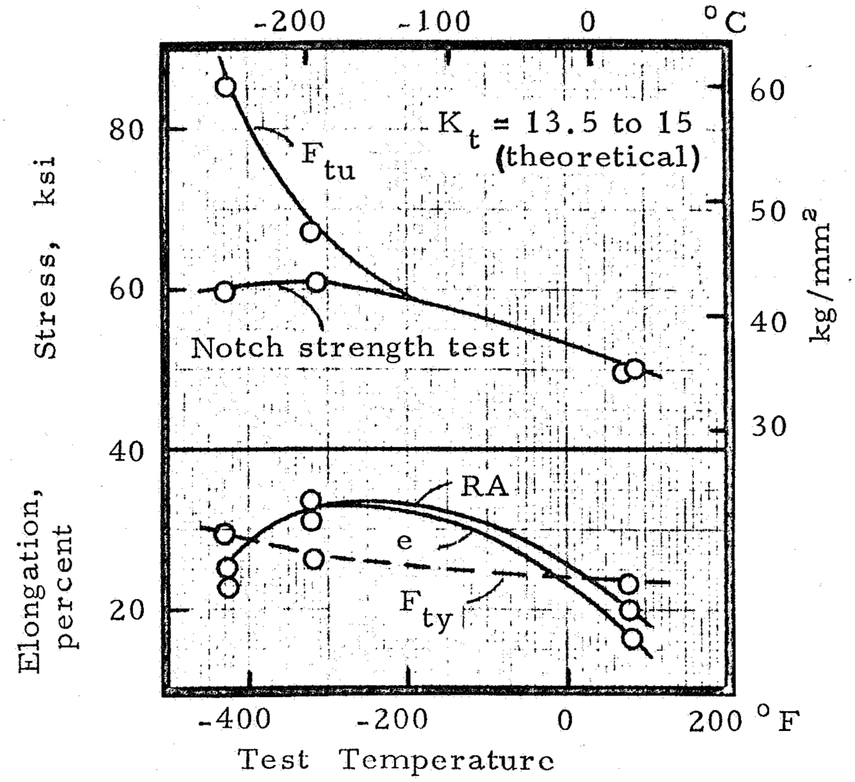
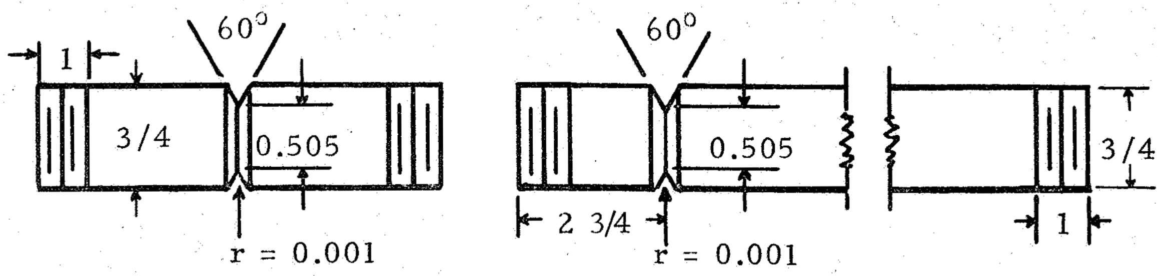


FIGURE 7.4611. — Effect of low and room temperature on tensile properties of 5456-H343 sheet.

(Ref. 7.15)



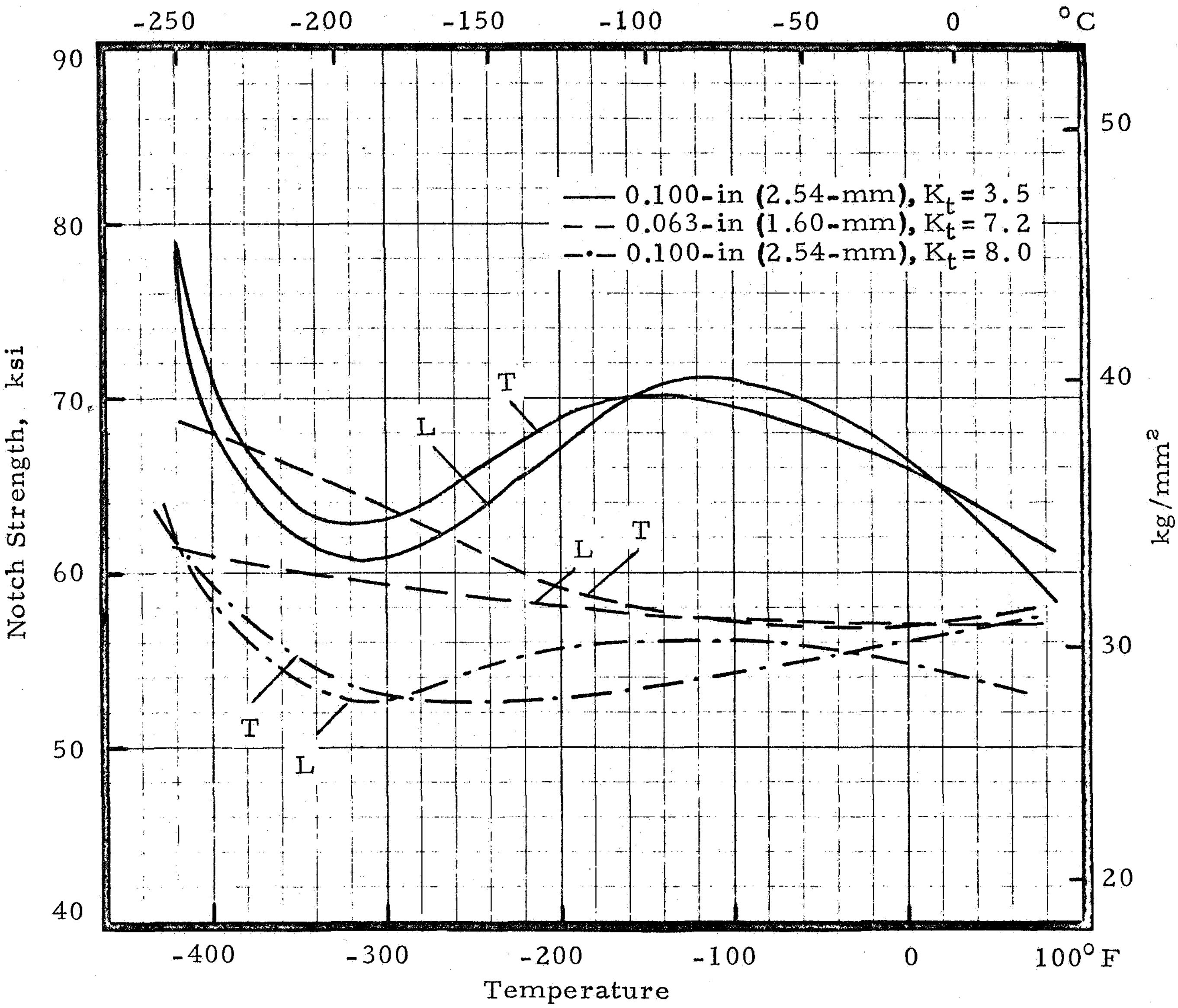


FIGURE 7.4612. – Effect of low and room temperature on notch strength of 5456-H343 sheet.

(Refs. 7.10, 7.13)

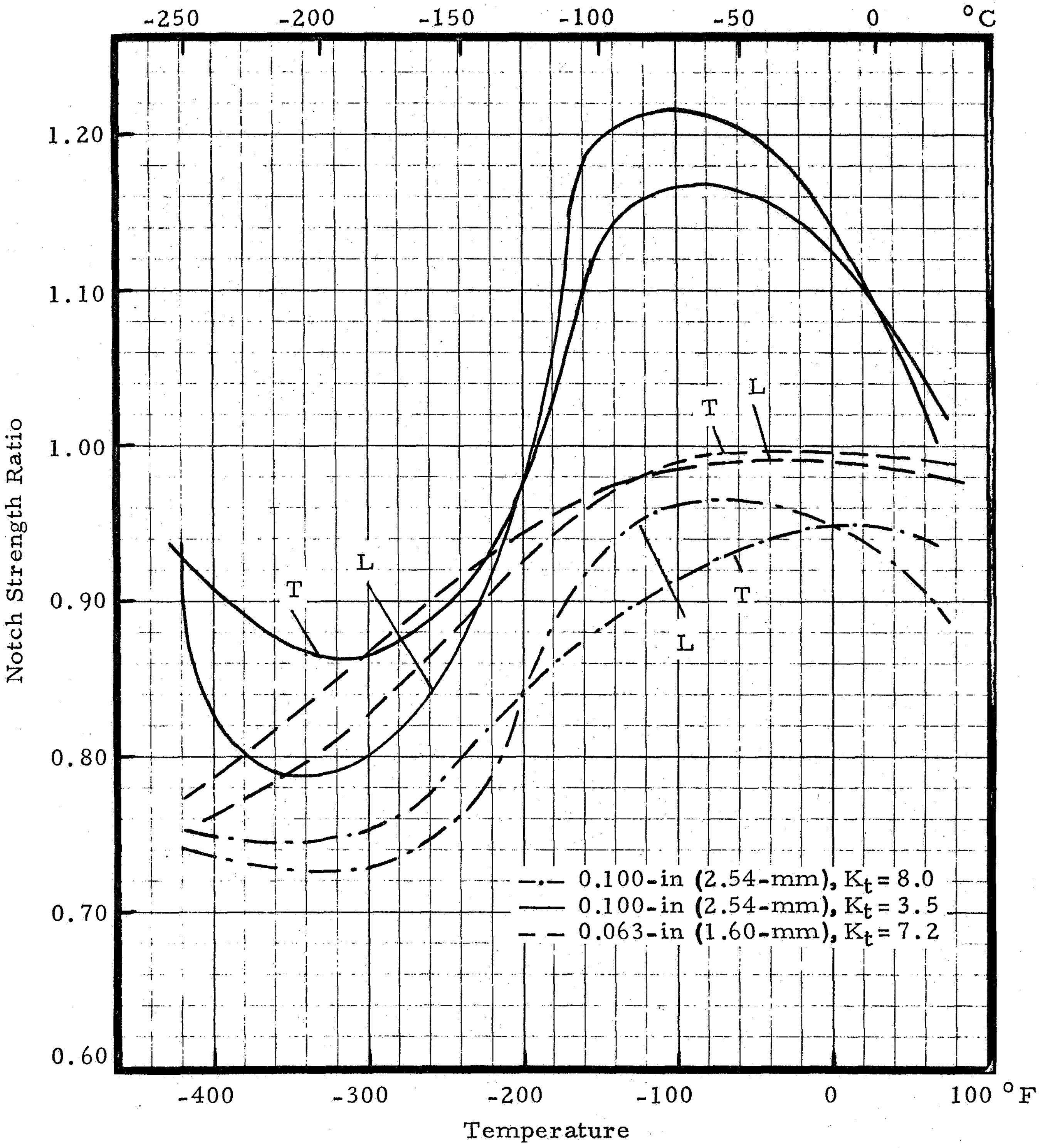


FIGURE 7.4613. – Effect of low and room temperature on notch strength ratio of 5456-H343 sheet.

(Refs. 7.10, 7.13)

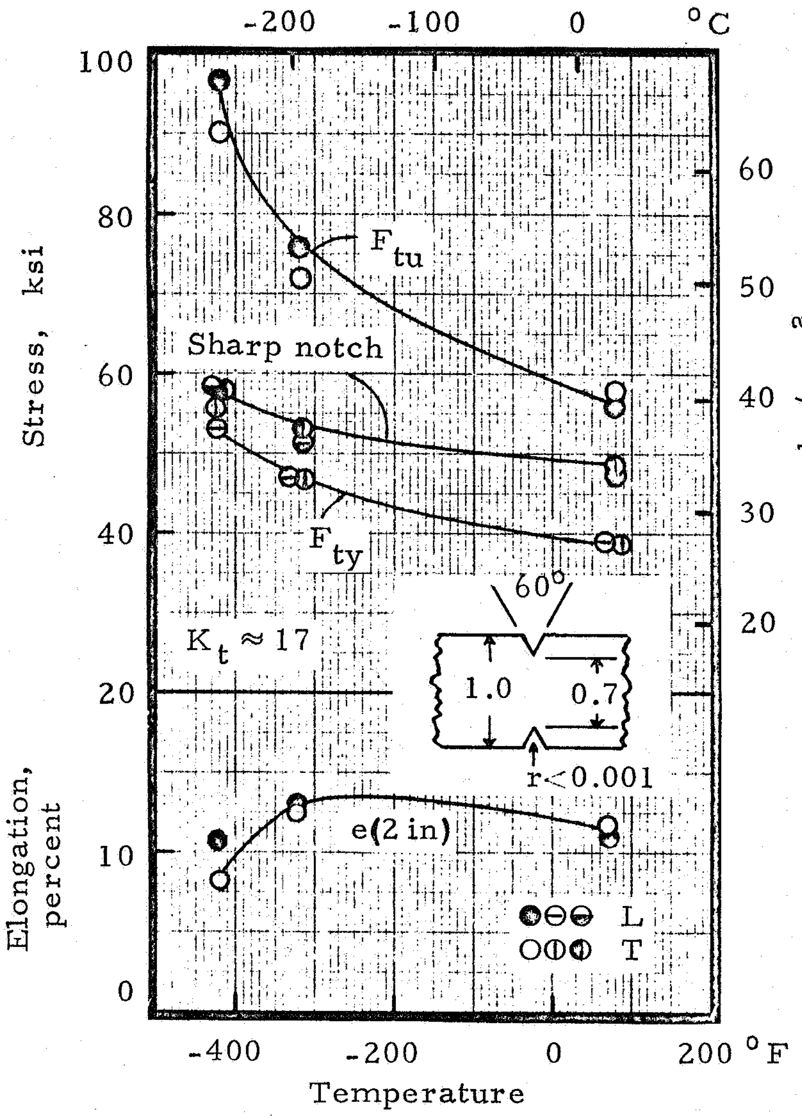


FIGURE 7.4614. – Tensile and sharp notch properties of 5456-H321 sheet at room and cryogenic temperatures; thickness, 0.125 inch (3.175 mm).

(Ref. 7.10)

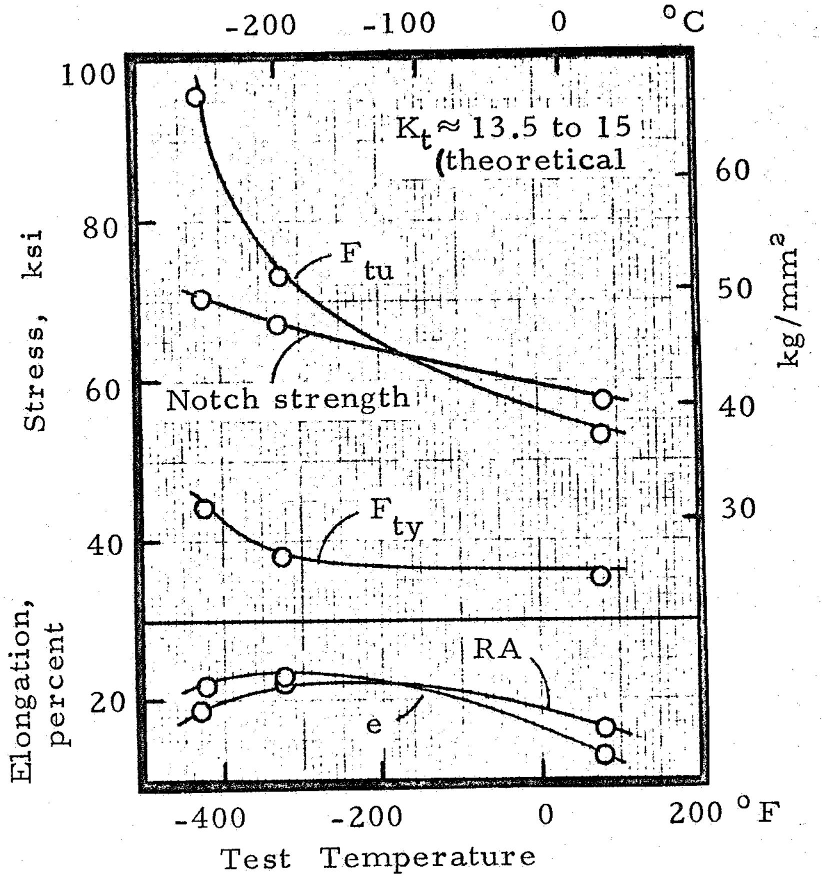


FIGURE 7.4615. — Effect of low and room temperature on tensile properties and notch strength of 5456-H321 plate. (Ref. 7.15)

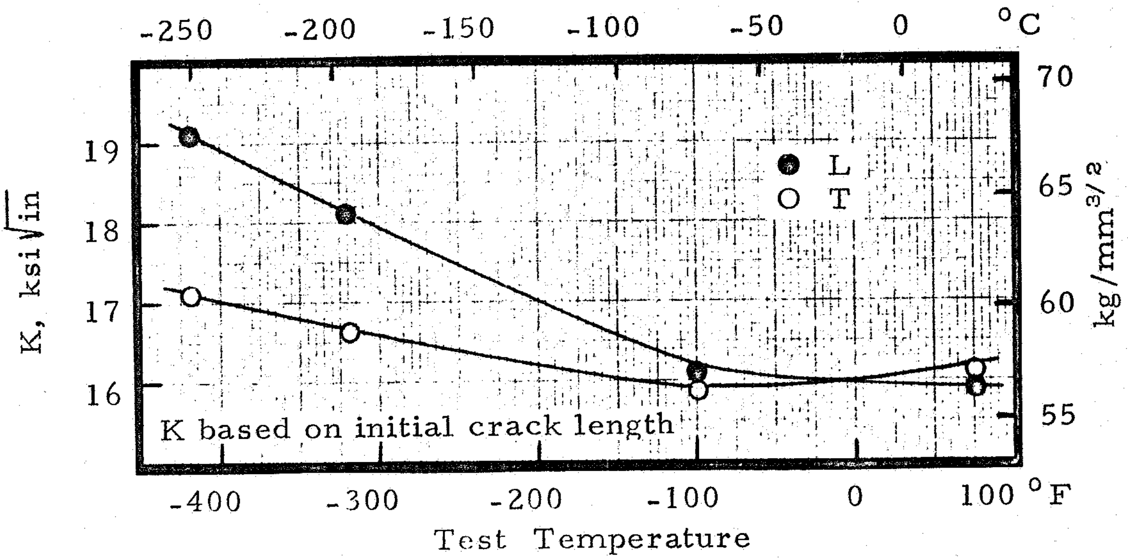


FIGURE 7.4621. — Effect of low temperature on fracture toughness of 5456-H343 sheet, 0.063-in (1.60-mm). (Ref. 7.7)

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

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

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

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

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

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

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

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

7.10 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 -423F," ASTM STP-287, 1961, p.3.

7.11 R. Markovich and F.R. Schwartzberg, "Testing Techniques and Evaluation of Materials for Use at Liquid Hydrogen Temperature," ASTM STP-302, 1961, p. 113.

7.12 P.C. Miller, "Low-Temperature Mechanical Properties of Several Aluminum Alloys and their Weldments," MTP-Sand M-M-61-16, Marshall Space Flight Center, October 1961.

7.13 Martin Co./Denver, "Cryogenic Materials Data Handbook," ML TDR 64-280, August 1964.

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

7.15 L.P. Rice, J.E. Campbell, and W.F. Simmons, "Tensile Behavior of Parent Metals and Welded 5000 Series Aluminum Alloy Plate at Room and Cryogenic Temperatures," Battelle Memorial Institute, August 1961.

7.16 Alcoa Research Laboratories, Aluminum Co. of America, unpublished data, 1962.

Chapter 8

DYNAMIC AND TIME DEPENDENT PROPERTIES

8.1 General. Very little information is currently available on the creep properties of the 5456 alloy. MIL-HDBK-5A reports that this alloy should not be used under high constant applied stress for continuous service at temperatures exceeding 150° F (66° C) because of the possibility of developing a susceptibility to stress corrosion cracking (ref. 8.1). Fatigue data on welded material are given in chapter 12.

8.2 Specified Properties

8.3 Impact

8.31 Impact strength of H343 plate, figure 8.31
8.32 Charpy impact energy for alloy in H321 temper:

RT	12 ft-lbs (1.7 kg-m)
-320° F(-196° C)	22 ft-lbs (3.0 kg-m)

8.33 Drop weight impact test data, table 8.33.

8.4 Creep

8.41 Typical creep rupture curves at elevated temperatures, figure 8.41.
8.42 Typical creep data for alloy at room temperature and 300° F(149° C), figure 8.42.
8.43 Typical creep data for alloy at 400° F (204° C), figure 8.43.
8.44 Typical creep data for alloy at 600° F (316° C), figure 8.44.

8.5 Stability

8.51 Effect of exposure at elevated temperatures on the room temperature tensile properties, figure 8.51.

8.6 Fatigue

8.61 Effect of low temperature on fatigue strength of H343 sheet, figure 8.61.
8.62 Fatigue limit for various tempers, table 8.62.
8.63 Typical fatigue data for alloy at elevated temperatures, figure 8.63.

TABLE 8.33. — Drop Weight Impact Test Data

Source			Ref. 8.4							
Alloy			5456							
Temperature			Room Temperature				-280° F (-173° C)			
Temper	Thickness		Critical height of drop		Permanent deformation		Critical height of drop		Permanent deformation	
	in	cm	in	cm	in	cm	in	cm	in	cm
O	1/4	0.6	45	114	1.1	2.8	42	107	0.9	2.3
	3/8	0.9	61	155	1.0	2.5	52	132	0.8	2.0
	1/2	1.3	92	234	1.0	2.5	88	224	0.9	2.3
H321	1/4	0.6	14	36	0.4	1.0	18	457	0.5	1.3
	3/8	0.9	37	94	0.8	2.0	41	104	0.6	1.5
	1/2	1.3	72	183	0.7	1.8	68	173	0.6	1.5

TABLE 8.62. — Fatigue Limit for Various Tempers

Source	Ref. 8.3				
Alloy	5456				
Condition	Fatigue Limit-Stress for 5 x 10^8 Cycles				
	O	H112	H321	H34	H38
Rotating beam, ksi	-	22	23	-	-
(kg/mm^2)	-	(15.5)	(16.2)	-	-
Reversed flexure, ksi	18	-	-	23	23
(kg/mm^2)	(12.7)	-	-	(16.2)	(16.2)

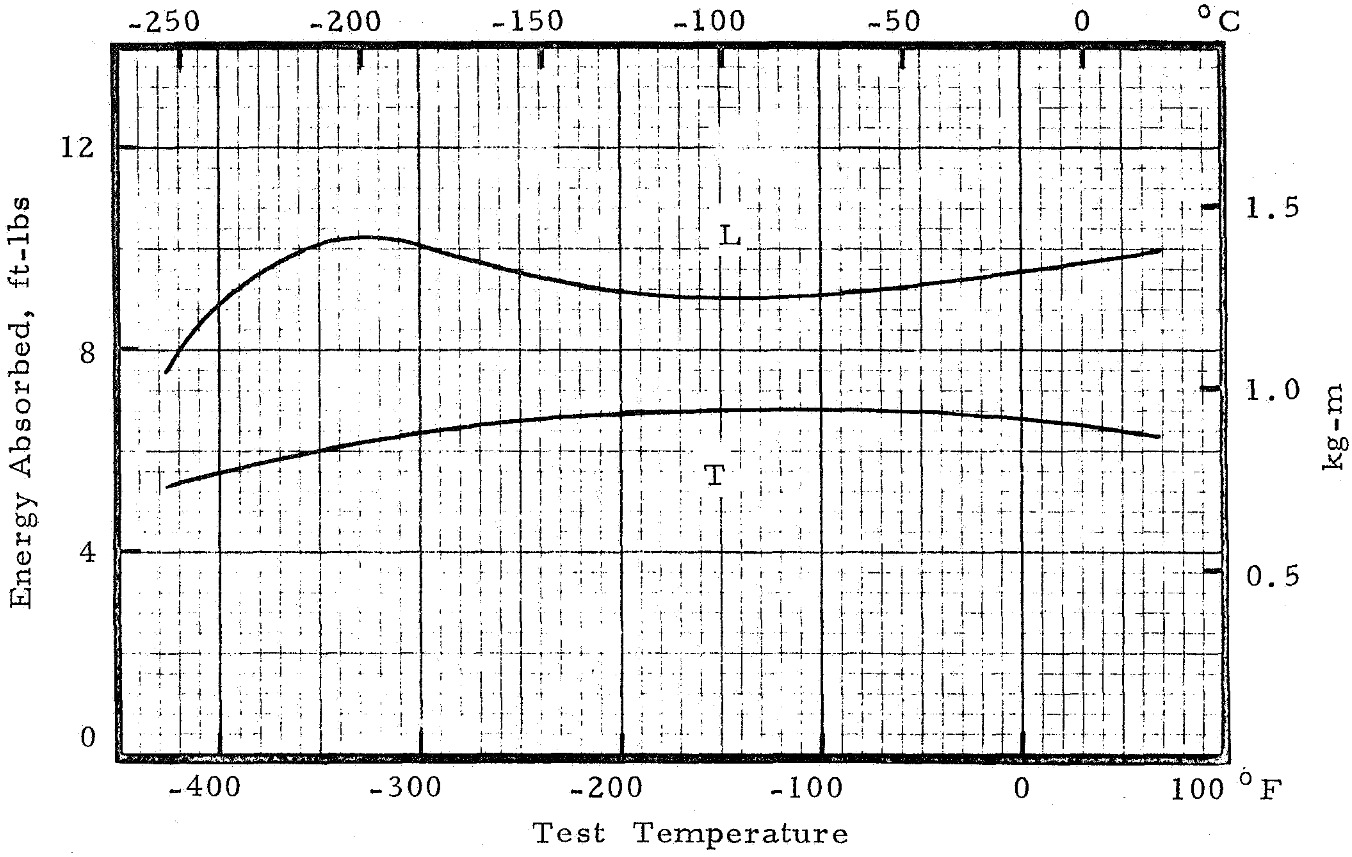


FIGURE 8.31. — Impact strength of 5456-H343 plate, 0.500 in (12.7 mm).

(Ref. 8.2)

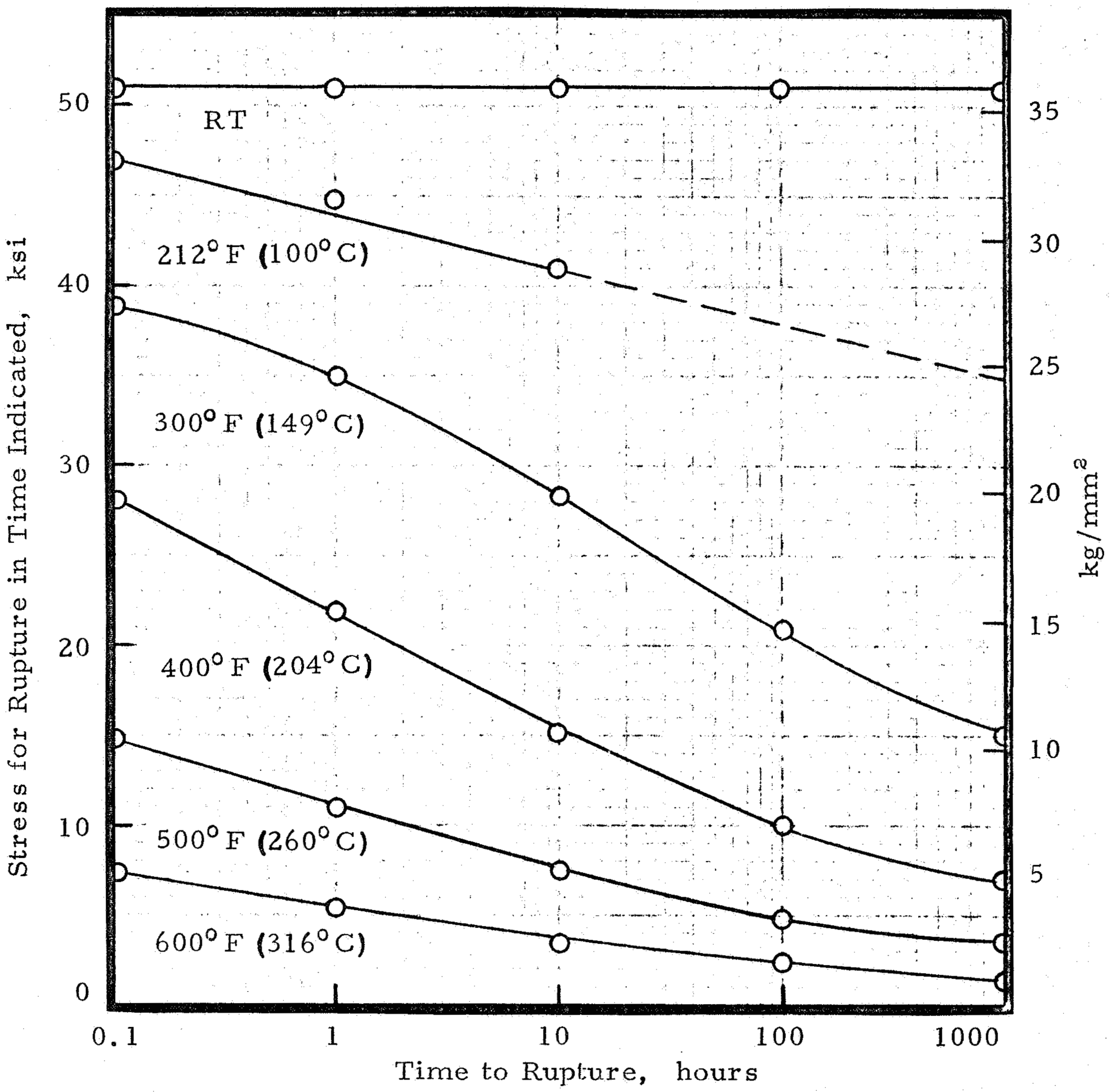


FIGURE 8.41. – Typical creep-rupture curves for 5456-H321 at elevated temperatures.

(Ref. 8.6)

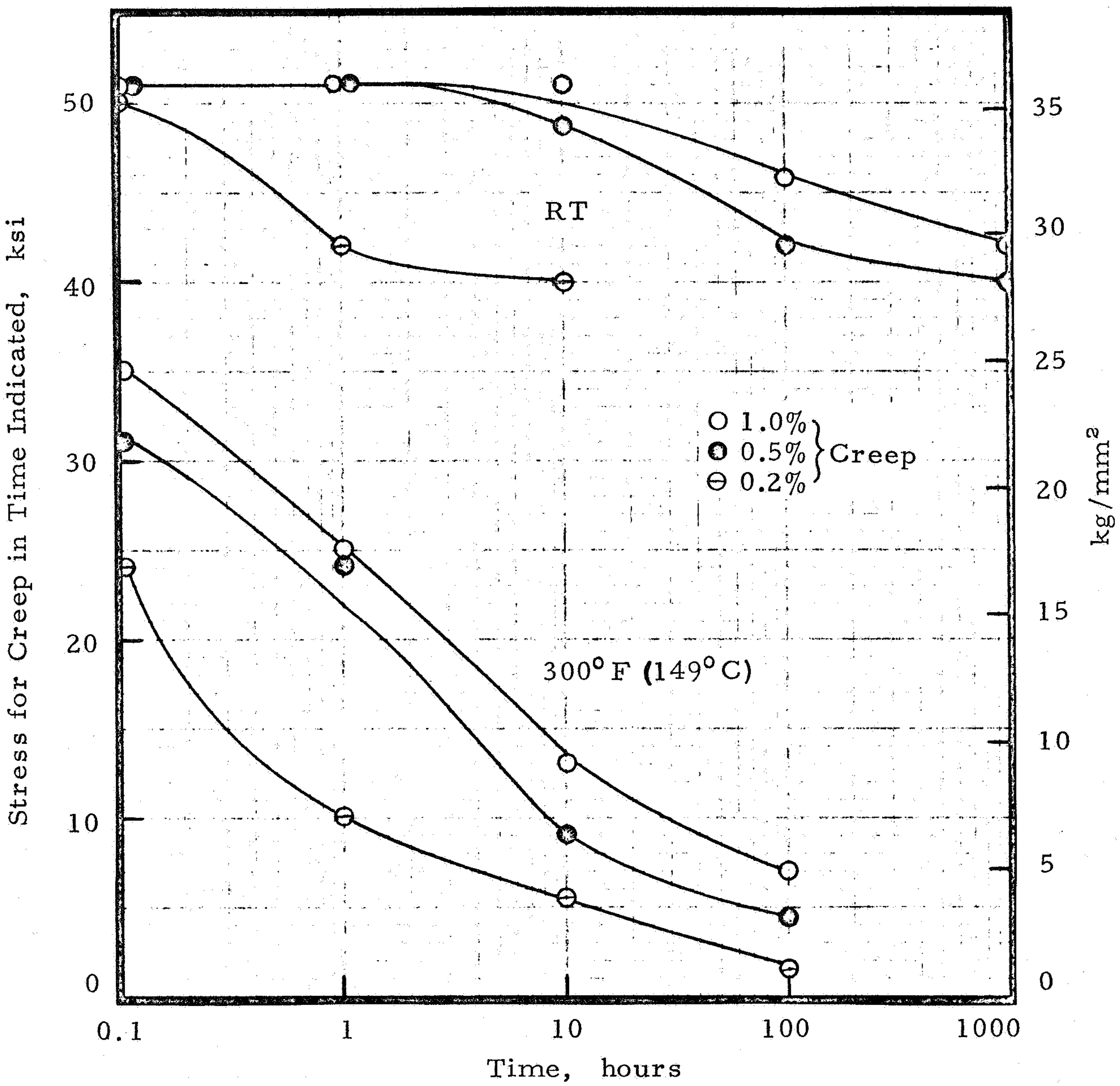


FIGURE 8.42. – Typical creep data for 5456-H321 at room temperature and at 300° F (149°C).

(Ref. 8.6)

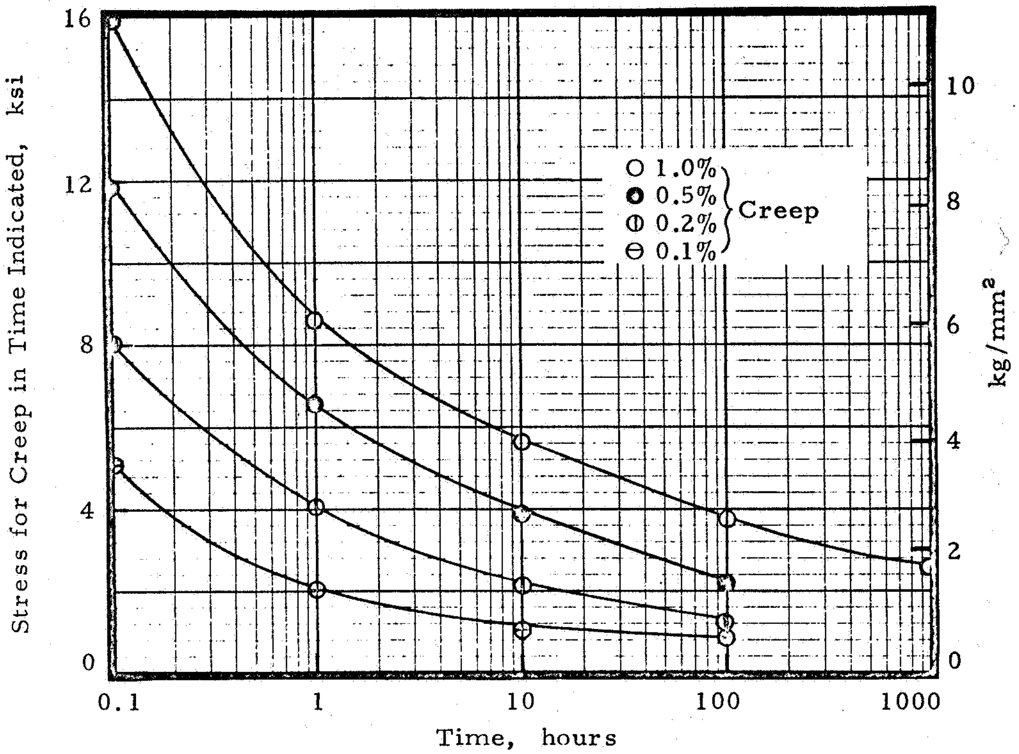


FIGURE 8.43. – Typical creep data for 5456-H321 at 400° F (204° C). (Ref. 8.6)

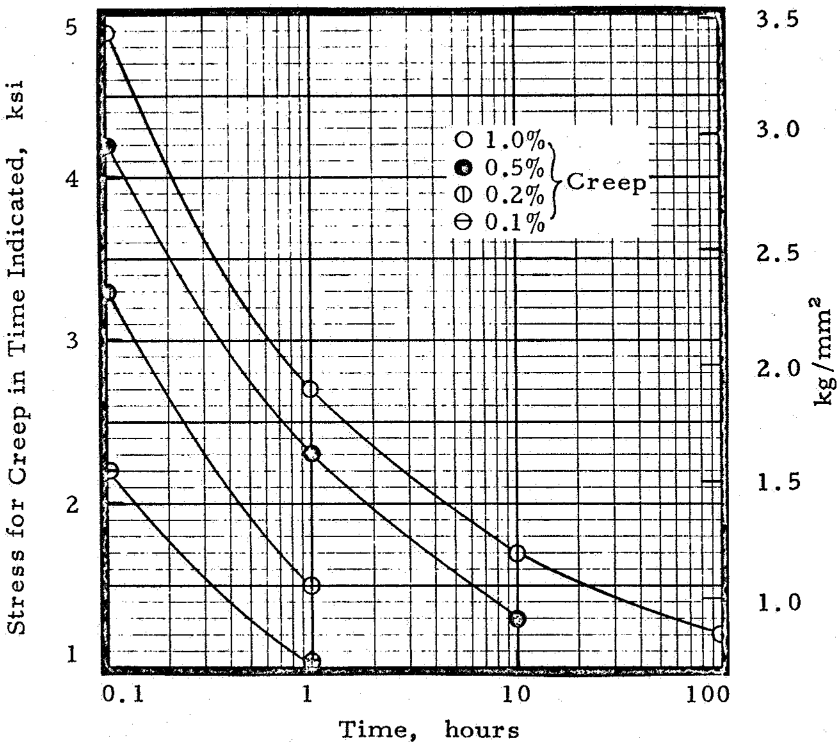


FIGURE 8.44. – Typical creep data for 5456-H321 at 600° F (316°C). (Ref. 8.6)

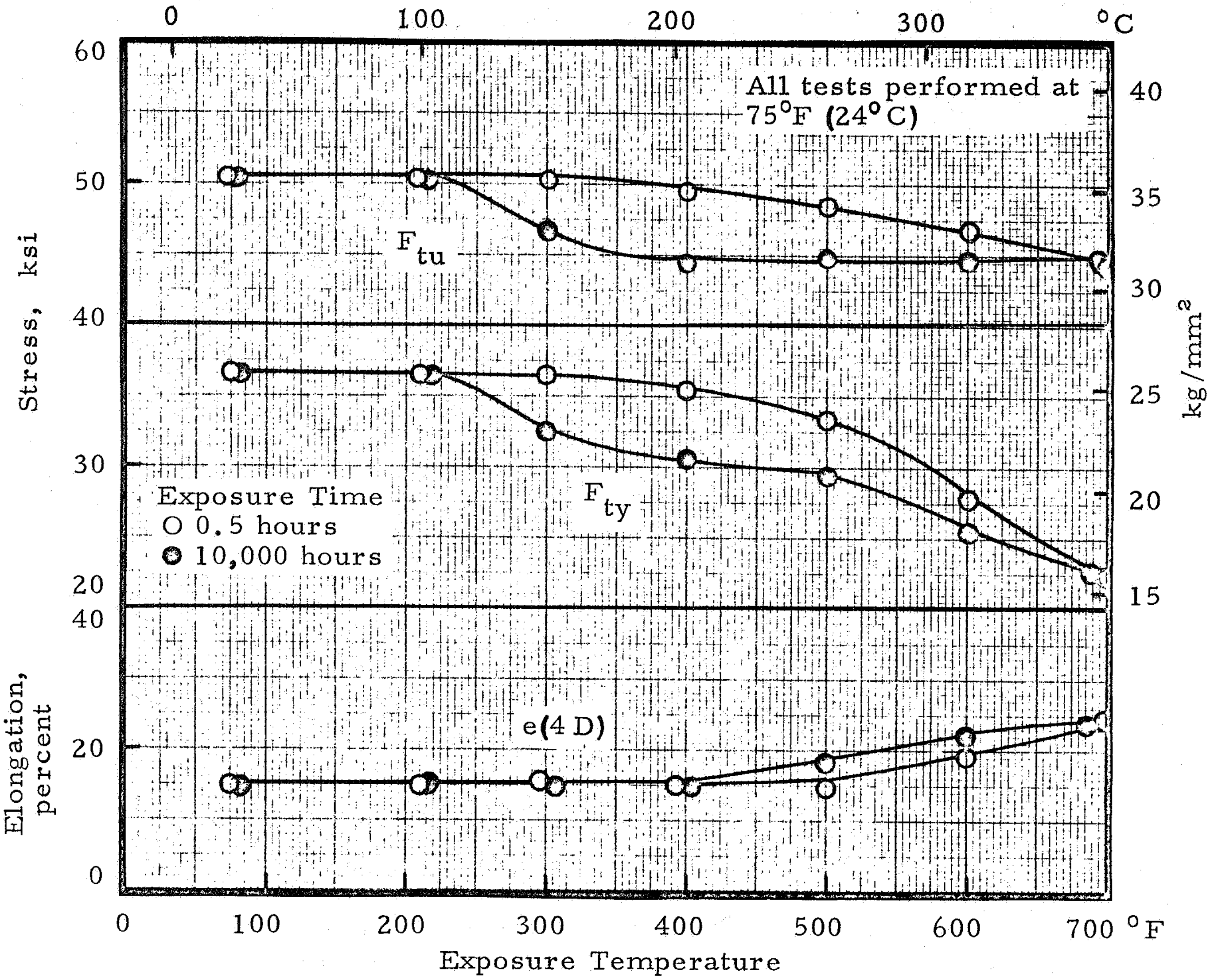


FIGURE 8.51. — Effect of exposure at elevated temperatures on the room temperature tensile properties of 5456-H321.

(Ref. 8.6)

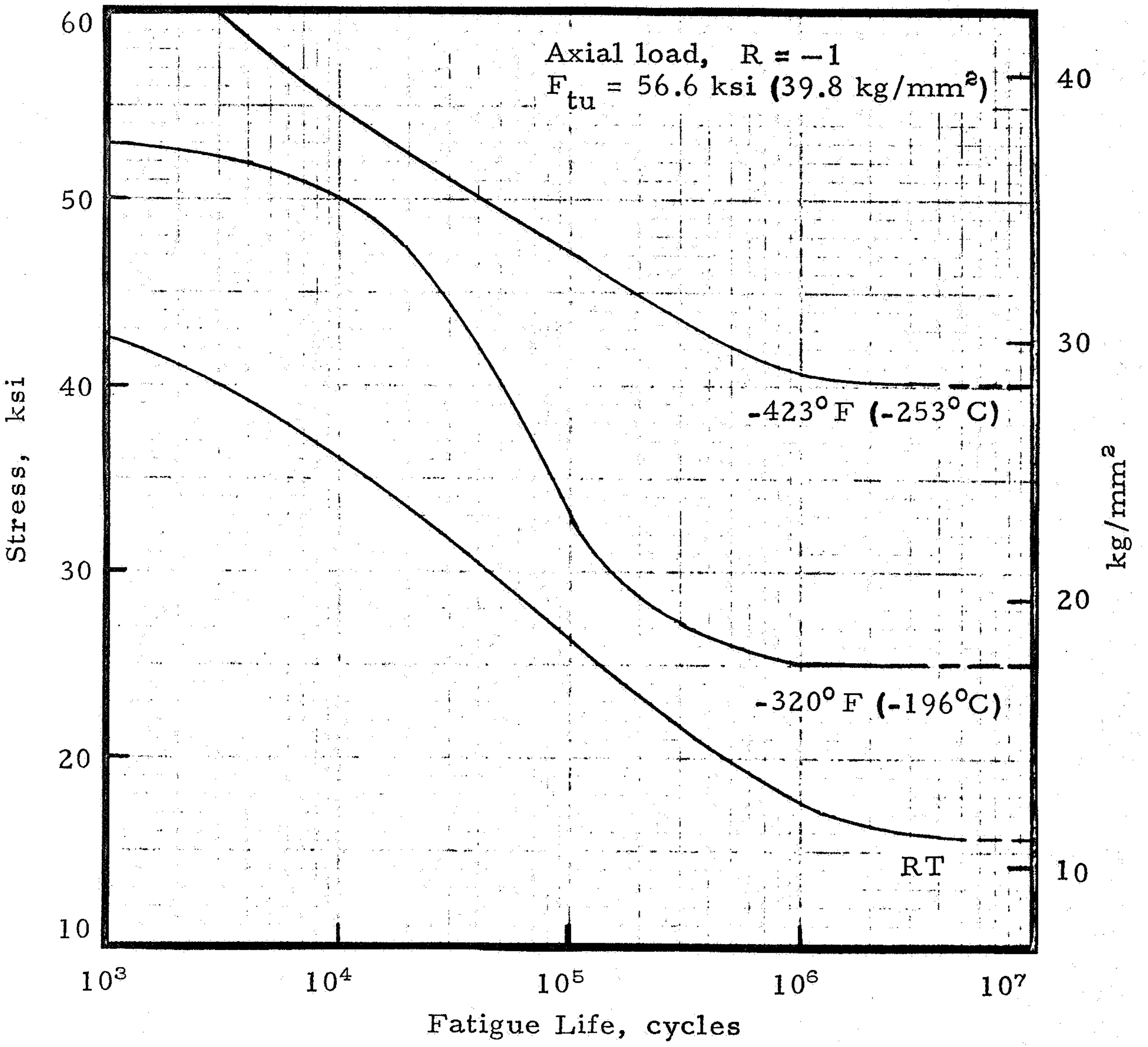


FIGURE 8.61. — Effect of low temperature on fatigue strength of 5456-H343 sheet, 0.100 inch (2.54 mm).

(Ref. 8.3)

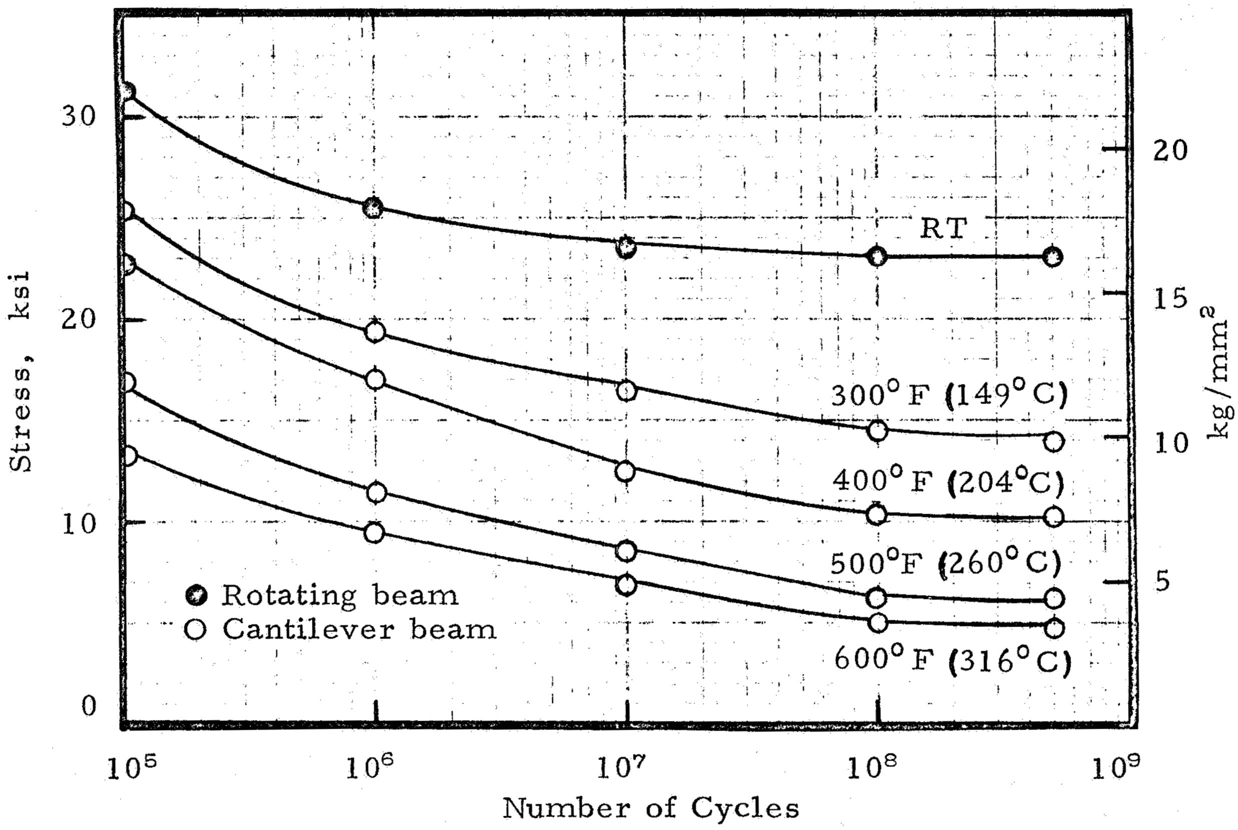


FIGURE 8.63. – Typical fatigue data for 5456-H321 at room and elevated temperatures.

(Ref. 8.6)

Chapter 8 - References

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

8.2 Martin Co./Denver, "Cryogenic Materials Data Handbook," ML-TDR-64-280, August 1964.

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

8.4 M. Holt, J.G. Kaufman, and E.T. Wandever, "Aluminum and Aluminum Alloys for Pressure Vessels," Welding Research Council, Bulletin 75, February 1962.

8.5 G.W. Stickley and J.D. Lyst, "Aluminum in Fatigue," Product Engineering, November 1964.

8.6 Aluminum Co. of America, Alcoa Research Laboratories, unpublished data, 1962.

Chapter 9

PHYSICAL PROPERTIES

9.1 Density (ρ)

0.096 lb/in^3 at $68^\circ F$, 2.65 g/cm^3 at $20^\circ C$ (refs. 9.1, 9.2)

9.2 Thermal Properties

9.21 Thermal conductivity, K, at $25^\circ C$, 0.28 $cal/cm^2/cm/^\circ C/sec$,
at $77^\circ F$, 68 $Btu/ft^2/ft/^\circ F/hr$
(Refs. 9.1, 9.2, 9.4, 9.8)

9.22 Average coefficient of thermal expansion (α)
68° to $212^\circ F$, 13.3×10^{-6} $in/in/^\circ F$
20° to $100^\circ C$, 23.9×10^{-6} $cm/cm/^\circ C$ (ref. 9.1)

9.221 Effect of temperature on average codfficient of thermal expansion, figure 9.221.

9.23 Specific heat (c_p)
0.23 $Btu/lb\ ^\circ F$ at $212^\circ F$
0.23 $cal/g\ ^\circ C$ at $100^\circ C$ (refs. 9.1, 9.4)

9.24 Thermal diffusivity
1.78 ft^2/hr at $77^\circ F$
0.457 cm^2/sec at $25^\circ C$
(Data calculated according to: Diffusivity = $K/\rho c_p$)

9.3 Electrical Properties

9.31 Electrical resistivity, O temper
36 ohms-cir mil/ft at $68^\circ F$
5.9 microhm-cm at $20^\circ C$ (refs. 9.2, 9.8)

9.32 Electrical conductivity at $20^\circ C$
29% of IACS (equal volume)
98% of IACS (equal weight) (refs. 9.2, 9.8)

9.4 Magnetic Properties

9.41 Permeability. The alloy is not ferromagnetic.

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 $450^\circ F$ (204° to $238^\circ C$) (ref. 9.6).

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 irradiation (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. 9.7).

9.6 Other Physical Properties

9.61 Emissivity

9.62 Damping capacity

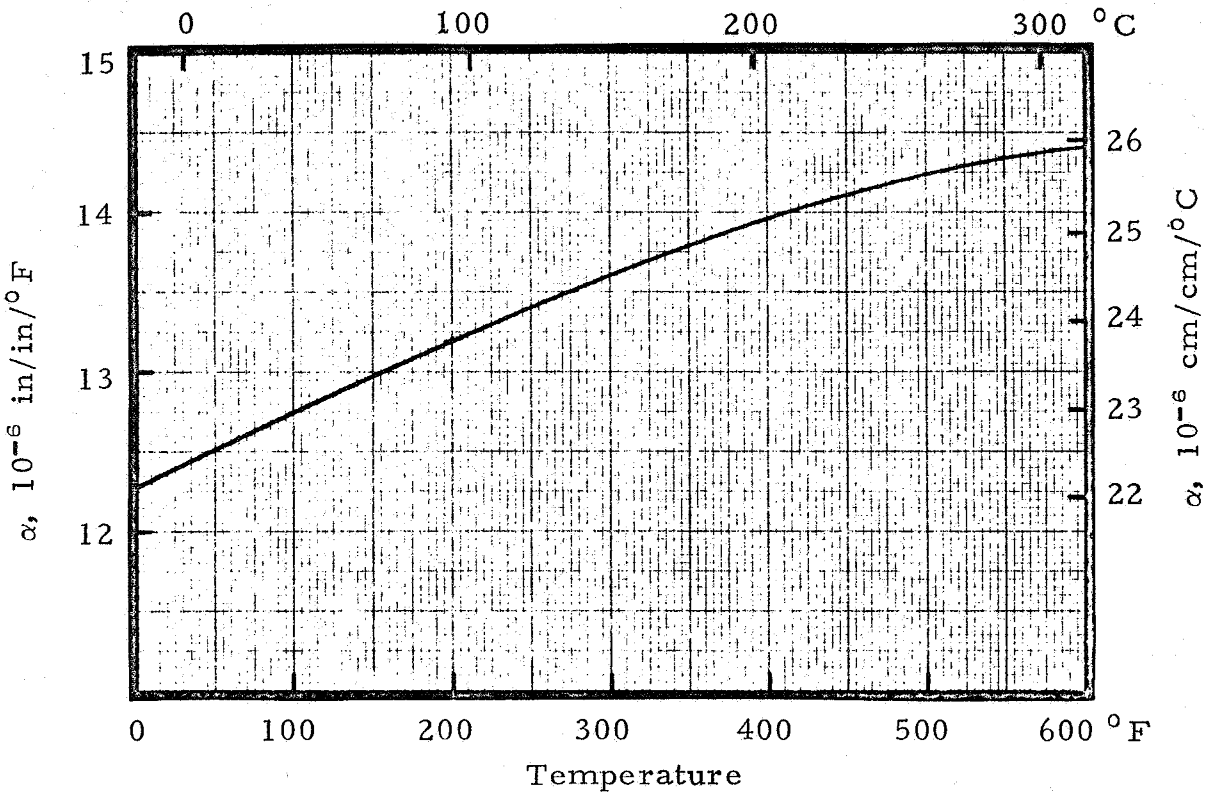


FIGURE 9.221. — Average coefficient of thermal expansion of 5456 from room temperature to indicated temperature.

(Ref. 9.1)

Chapter 9 - References

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

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

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

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

9.6 W.K. Anderson et al., "Reactor Structural Materials: Engineering Properties as Affected by Nuclear Service," ASTM STP-314, May 1962, p. 52.

9.7 Reactor Handbook, Vol. I, "Materials," C.R. Tipton, Jr., Ed., Interscience Publishers, Inc., New York, N.Y., 1960, p. 482.

9.8 1971 SAE Handbook, Society Automotive Engineers, Inc., New York.

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 at 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 disrupt the passive film. Outdoors, aluminum and its alloys weather to a pleasant gray color, with some initial superficial pitting which gradually ceases (ref. 10.2). Industrial soot, sulfur dioxide, sulfur trioxide, and marine spray tend to increase atmospheric corrosion, but hydrogen sulfide and carbon dioxide do not (ref. 10.3). Twenty-year tests at several marine, industrial and rural sites have shown that atmospheric attack on aluminum takes place principally in the first year and progresses very slowly beyond the second year (ref. 10.4). Even at high temperatures in dry atmospheres, aluminum is highly resistant to most common gases, except the halogens (ref. 10.2).

In aqueous environments, the resistance of aluminum to corrosion is greatest under neutral or slightly acid conditions, where the protective oxide film is most stable (pH 5.5–8.5 at room temperature, 4.5–7 at 95°C) (refs. 10.1, 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). Under some conditions, aluminum exhibits very poor resistance to chlorinated solvents and may even react explosively with them. However, such solvents, when properly inhibited, may be used for cleaning and degreasing without harm (ref. 10.6).

The purity of aluminum significantly affects the 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-Magnesium Alloys. The aluminum-magnesium alloys are resistant to corrosion in most marine and industrial applications and are similar to 6061-T6 alloy in this respect. These alloys may under certain conditions become susceptible to stress corrosion cracking. However, in comparison with the high strength aluminum alloys of the 2000 and 7000 series, their resistance is considered excellent.

Stress corrosion may be described as cracking that occurs over a period of time as the result of a susceptible metallurgical structure, sustained surface tensile stresses, and a corrosive environment. The environment need not be severe and in many cases cracking occurs without evidence of appreciable corrosion. The stresses which cause the cracking are usually residual stresses resulting from fabrication or faulty design and assembly. In the strain hardened aluminum-magnesium alloys, precipitation occurs over a period of years and in strain hardened alloys containing 4 percent or more magnesium, some susceptibility may develop in 5 to 10 years or perhaps shorter periods at normal atmospheric temperature. When temperature is increased, precipitation is more rapid and susceptibility to stress corrosion cracking may develop in a few days at 212°F (100°C) (ref. 10.7).

10.3 Behavior of 5456 Alloy. The 5456 alloy exhibits good resistance to corrosion in rural, marine, and industrial atmospheres, and is resistant to most neutral fresh waters. Under normal conditions and ordinary environments the alloy does not require painting or other surface protection. Alloy 5456 is resistant to the chemicals listed in table 10.1. Electrochemical corrosion plus excess strain, however, may lead to stress-corrosion cracking.

In aluminum-magnesium alloys, the magnesium is in excess of that in solid solution. The electrode potentials of Al-Mg solid solutions and constituents are given in table 10.2. Under some conditions, precipitation may occur in more or less continuous zones at grain boundaries or along planes of slip caused by plastic deformation. In a corrosive environment, the anodic constituent corrodes electrochemically and this action may lead to fissures in the metal. These fissures will act as stress raisers in the presence of high tensile stresses. When the fissures increase due to the mutually accelerating processes of electrolytic corrosion and increasing stress, the material is subject to stress corrosion (ref. 10.9). But, the relative susceptibility of 5456 to stress-corrosion cracking has been rated as "good," meaning the alloy can be used without stress-corrosion-cracking design limitations (ref. 10.10).

Susceptibility to stress-corrosion cracking may be kept to a minimum by restricting the use of the alloy to recommended tempers and to temperatures not exceeding 150° F (65° C) for continuous usage (ref. 10.11). Certain limitations have been placed on the cold work applied to the alloy. Material in the annealed (O) condition should not be formed at room temperature unless the material receives a stress relief thermal treatment of 4 hours at 450° ± 25° F (232° ± 14° C). Hot forming at 425° F (218° C) will avoid the adverse effects of cold work and high residual stresses.

The H323 and H343 tempers are recommended for sheet and plate up to 1.0 inch (25.4 mm) thick as these tempers appear to be free from susceptibility to stress corrosion. Forming of material in these tempers may be accomplished at room temperature with no requirement for subsequent thermal treatment.

Evidence available on material in the H321 temper indicates that cold forming such as bending over a 5t radius, produces no tendency for stress corrosion cracking. Hot forming at 425° F (218° C) avoids the adverse effects of cold work and residual stresses. If severe cold forming is applied, a stress relief treatment of 4 hours at 450°F (232° C) is recommended for assemblies other than weldments. Application of this thermal treatment to weldments may lead to increased stress corrosion tendencies. When welds require stress relief, heating at 550° F (288° C) for 15 minutes to 1 hour is recommended.

The H311 is recommended for extrusions; for purposes of stress-corrosion characteristics, this temper is equivalent to H321 temper. The conventional tempers, H32 and H34, are not recommended because both have exhibited susceptibility to stress corrosion cracking.

10.4 Protective Measures. Under normal conditions and ordinary environments, the 5456 alloy needs no surface protection. Stress corrosion may be minimized or eliminated by restricting the use of the alloy to recommended tempers, cold work limits, and to temperatures not exceeding 150° F (65° C) for continuous usage.

Surface protection is also discussed in Chapter 11.

TABLE 10.1. — Chemicals to Which Alloy is Resistant

Source	Ref. 10.8
Alloy	5456
	Alcohols Aldehydes Amides Ammonia and ammonia compounds Coal tar derivatives Essential oils Esters Gasoline and greases Hydrogen peroxide Ketones Many food products Many neutral aqueous inorganic salt solutions Nitric acid above 82 percent Nitroparaffins Organic acids and anhydrides Petroleum derivatives and waxes

TABLE 10.2. — Electrode Potential vs 0.1N Calomel (a)

Source	Ref. 10.9
(Aqueous solution of 53 g NaCl and 3 g H_2O_2 per liter)	
Al + Mg (7% Mg solid solution)	-0.89 volt
Al + Mg (5% Mg solid solution)	-0.88 volt
5456 aluminum alloy	-0.87 volt
Al + Mg (3% Mg solid solution)	-0.87 volt
Aluminum (99.95% pure)	-0.85 volt

(a) at 25° C

Chapter 10 - References

10.1 H.H. Uhlig, Corrosion and Corrosion Control, John Wiley & Sons, New York, 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 "Symposium on Atmopsheric Corrosion of Non-Ferrous Metals," ASTM STP-175, 1956.

10.5 J. Draley and W. Ruther, Corrosion, 12, 441t, 480t (1956); J. Electrochem. Soc., 1957, pp. 104, 329.

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

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

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

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

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

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

Chapter 11

SURFACE TREATMENTS

11.1 General. A wide variety of surface treatments can be applied to the 5456 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 (refs. 11.1, 11.2, 11.11).

11.2 Alclad Products. The 5456 alloy is not commercially available in Alclad products.

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 and are resistant to abrasion and corrosion. 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 (0.0025 to 0.025 mm). Coatings produced in chromic acid vary from 0.00001 to 0.00009 inch (0.00025 to 0.0022 mm). Anodic coatings provide good protection against corrosion and are excellent bases for paint coatings (ref. 11.1).

11.41 In recent years, a number of new methods have been developed for producing heavier anodic coatings of rom 0.001 to 0.010 inch (0.025 to 0.25 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% $H_2SO_4 + 1\%$ $H_2Cr_2O_4$; 48°–52° F (9° to 11°C); 36 asf (0.038 A/cm^2).

The Martin process should be specified where maximum hardness and corrosion resistance are required along with thickness buildups to 0.004 inch (0.102 mm). Alcoa 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 given in reference 11.9.

11.5 Chemical Finishes. Chemical finishes are of three main types. Finishes used for decorative effects include caustic etching, acid etching, and chemical polishing. Etched surfaces have a matte appearance while chemically polished surfaces are highly reflective and require protection by anodizing or lacquering.

Conversion coatings can be oxide, phosphate, or chromate types and are used primarily as base coatings prior to application of organic coatings. Miscellaneous special-purpose finishes include those produced by the Alrok process, modified Bauer-Vogel process, and processes for staining aluminum alloys.

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

11.7 Electroplating of aluminum alloys has gained increased commercial use in recent years. A commonly used finish consists of successive deposits of copper, nickel, and chromium. Other metals may be applied over the copper. Several etching methods produce a satisfactory base surface for electroplating. Also used is a method involving the immersion of 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 50^0 and 90^0F (10^0 and 33^0C) and contact with the metal part should not be for less than 5 minutes. The part is then rinsed with water and dried thoroughly. Where chemical treatment is impractical, mild sandblasting methods may be employed.

Anodic or chemical conversion coatings always form excellent bases for organic paint coatings.

A zinc chromate primer, MIL-P-8585 or equivalent, is recommended. Primer is applied to all surfaces and allowed to dry. 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 (0.23 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 in delaying failure. The most effective protection is obtained by applying a topcoat of epoxy-polyamide paint to shot-peened or metallized surfaces of the alloy. Satisfactory temporary protection is obtained by an electroplated galvanic coating, 3 to 4 mils thick (0.076-0.101 mm), 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 of 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 566° C) for a period of 4 to 8 minutes (ref. 11.7).

Chapter 11 - References

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 Edition, American Society for Metals.

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

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

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

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

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

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

11.11 Metals Handbook, 8th Ed., Vol. 2, "Cleaning and Finishing," American Society for Metals, Metals Park, Ohio, 1964.

Chapter 12

JOINING TECHNIQUES

12.1 General. The 5456 aluminum alloy can be joined by fusion and resistance welding techniques and by riveting or bolting. Specifications for the welding of 5456 and other 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. Aluminum is one of the most readily weldable of all metals when proper cleaning and welding procedures are established. It has individual characteristics, however, which must be well understood for successful welding of the metal or its alloys. Four important factors that must be considered are the low melting point, the presence of an oxide film, low strength at welding temperatures, and the fact that aluminum exhibits no characteristic color change even at temperatures up to the melting point. Care is required to minimize heat input. The oxide film must be removed and prevented from reforming by some inhibiting technique before a good bond can be obtained. Temperatures should be carefully measured by instrumentation rather than judged by appearance at elevated temperatures (ref. 12.1).

The 5456 alloy exhibits excellent fusion welding characteristics using inert-gas shielded processes. The alloy is also suitably welded by resistance techniques. The relatively high strength of welds in this alloy make it a good choice for high strength welded structures (refs. 12.2, 12.22, 12.24).

12.21 Fusion Welding. Aluminum alloy 5456 may be readily fusion welded by either the inert-gas consumable electrode (MIG) or inert-gas tungsten-arc (TIG) methods. Since the alloy is not heat-treatable by thermal processes, post-weld treatments are normally not required. Filler metals often used are 5183, 5556, and 5356. Although porosity in weld zones is always a problem to be considered in the fusion welding of aluminum alloys, some evidence indicates that 5456-H343 is less likely to have a serious porosity in welds than the heat treatable alloys such as 2014-T6 or 2219-T87 (refs. 12.3, 12.24).

Repair welding of 5456-H321 plate does not appear to increase the extent of the heat affected zone, nor affect the weld tensile properties significantly if proper precautions are observed (ref. 12.4). Repairs were repeated up to 6 times with little effect. Semiautomatic MIG welding was employed for these studies.

Properties of single and double pass fusion welds of H321 plate are shown in table 12.2. The results of guided face bend tents on single pass fusion welded H321 plate (0.25 inch (6.35 mm) thick) indicated that the minimum bend radius of longitudinal bends was 1.5t and transverse bends 2.0t. All welds were ground flush prior to testing. The minimum bend radius of unwelded plate was 1.7t (ref. 12.6). Details of the welding process employed were not given.

The Linde "short arc" semiautomatic MIG process was investigated to determine whether this process was efficient for welding high strength aluminum thin sheet. The process operates with a low voltage arc and a fast freezing puddle which results in low heat input. Distortion and burn-through are thus reportedly minimized. Tests were conducted on H343 sheet. Shielding gas used was welding grade argon. Post-weld cleaning consisted of light wire brushing to remove black residue. Machine settings and root openings are given in table 12.3. The tensile data obtained in these studies are presented in figure 12.1.

The effect of low temperature on base and welded H343 sheet is given in figure 12.2.

The effect of low temperature on weld strength of H24 sheet is given in figure 12.3. TIG (automatic) with 4043 filler rod was used for this investigation.

The effect of low temperature on weld-strength-ratio of annealed (O) and H321 material is shown in figure 12.4 for automatic MIG welds.

Tensile and notch tensile data for H321 welded sheet and plate are presented in figures 12.5 and 12.6, and for annealed plate in figure 12.7.

Figure 12.8 shows S-N low cycle fatigue curves for H343 MIG fusion welded sheet at room and cryogenic temperatures.

The effect of shot penning, hammer peening, and thermal stress relief on fatigue life of butt-welds is shown in figure 12.9.

The effect of low temperature on fatigue life of TIG welded sheet is illustrated in figure 12.10. Fatigue strengths in 10^6 cycles of base and welded plate and sheet are represented in figure 12.11.

12.22 Electrical Resistance Welding. Resistance welding (spot welding and seam welding) is a most useful and economic method of joining aluminum alloys. The processes are almost entirely automatic and standard welding machines are capable of handling a wide variety of operations. Resistance welding heats only a small area of metal. Thus, there is only a minimum of metallurgical disturbance, for a minimum length of time, which is important in the welding of aluminum alloys. Mechanical or chemical cleaning of the contact surfaces is necessary to obtain good spot welds in aluminum because no fluxes are normally used during resistance 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. Details on surface cleaning are given in references 12.13 and 12.24.

The 5456 alloy can be readily spotwelded or seam welded in all cold worked tempers. Resistance welding in the annealed (O) temper, however, is not recommended (ref. 12.13). Chemical or mechanical precleaning is necessary to make consistent, sound welds. Resistance to corrosion of spotwelded joints is excellent.

12.221 Properties of Spot Welds. Suggested minimum joint overlap and spacing and minimum allowable edge distances for spotwelded joints are presented in table 12.4.

Table 12.5 gives spotweld maximum shear strength standards for aluminum alloys.

The requirements for equipment, materials, and production control of spot and seam welds in aluminum alloys is covered by military specification MIL-W-6858B-1 (see table 12.1). In applications of spot welding 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 spotwelded sheet would be determined by multiplying the ultimate tensile sheet strength (MIL-HDBK-5A "A" values were available) by the appropriate efficiency factor as given in figure 12.12. The minimum values of the basic sheet efficiency in tension should not be applied to seam welds. Allowable ultimate tensile strength for spotwelded 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. 12.14).

12.23 Electron Beam Welding. There are substantial advantages to be gained by using electron beam welding for thick plate. Plates of 5456 in thicknesses of 0.50 to 6 inches (1.27 to 15.24 cm) have been welded with impressive speeds (ref. 12.23).

12.3 Brazing. Brazing of the 5456 aluminum alloy usually is not recommended because the high magnesium content in this alloy makes it difficult to braze successfully (ref. 12.18).

12.4 Riveting. Riveting is a commonly used method for joining aluminum and its alloys. It is reliable because riveting is a process that is well understood and highly developed. Also, modern riveting techniques are largely independent of the operator's skill and thus uniformity of riveted joints can be readily attained (ref. 12.1). Specifications that apply to riveting of aluminum alloys are given in table 12.6.

12.41 Aluminum alloy rivets are preferred for the fabrication of aluminum alloy structures, although cold-driven annealed steel rivets have also 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, bearing or tearing of the sheet or plate. Table 12.8 gives the average shear strengths of driven rivets of various aluminum alloys. These values may be considered representative of properly driven rivets although occasional driven rivets may fall below the average by 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. 12.14).

TABLE 12.1. – Welding Specifications for Aluminum Alloys

Source	Refs. 12.15, 12.16, 12.17			
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-566a	-	B285-61T	4190B, 4191A
Welding electrodes (flux coated)	-	MIL-E-15597C	B184-43T	-
Welding electrode wire	-	MIL-E-16053J	B285-61T	-
Flash welds (rings, flanges)	-	-	-	7488A

TABLE 12.2. — Tensile Properties of Fusion Welded Plate

Source	Ref. 12.6					
Alloy	5456-H321, 0.250-in (6.35-mm)					
Property	Base Metal	Single Pass Welds			Double Pass Welds	
		(b)	(c)	(d)	(b)	(c)
F_{tu}, ksi (e)	53.7	43.8	47.7	44.1	44.4	47.4
F_{ty}, ksi (e)	33.7	23.6	22.4	19.1	24.3	26.4
e(2 in), percent	13.0	9.5	8.9	24.9	9.8	10.5
Failure location	-	W	WT	-	W	WT, HAZ

(a) Each point average of at least 5 tests
(b) Transverse welds, ground flush
(c) Transverse welds, as-welded
(d) Longitudinal welds, ground flush
(e) 1 ksi = 0.70307 kg/mm^2
W - Weld
WT - Weld toe, fusion line
HAZ - Heat affected zone

TABLE 12.3. — Machine Settings and Root Openings for MIG Welds

Source	Ref. 12.7							
Alloy	5456-H343 (5456 filler wire)							
Sheet thickness, in (a)	Joint Type	Root Opening	Voltage, V	Current, A	Voltage Control	Ind. Control	Wire Feed	Argon Flow (b)
0.051	Butt	0-.01	15	85	4	1.5	45	35
	Tee	0-.01	15	85	4	1.5	45	35
0.062	Butt	0-.01	15	100	8	4	65	35
	Tee	0-.01	15	100	8	4	65	35
0.080	Butt	.03-.04	16	120	7	5.5	70	35
	Tee	0-.01	16	120	7	5.5	70	35
0.093	Butt	.03-.04	22	130	4	5.5	85	35
	Tee	0-.01	22	130	4	5.5	85	35
0.200	Butt	.1-.12	24	140	4	5.5	90	35
	Tee	0-.01	24	140	4	5.5	90	35

(a) 1 inch = 25.4 mm

(b) In ft^3/min. 1 ft^3 = 0.472 l/sec

TABLE 12.4. — Suggested Minimum Joint Overlap and Weld Spacing, and Minimum Allowable Edge Distances for Spotwelded Joints

Source	Refs. 12.13, 12.14		
Alloy	Aluminum Alloys		
Nominal thickness of thinner sheet, inch	Minimum joint overlap, inch	Minimum weld spacing, inch	Edge distance, E (min), inch
0.016 (d)	5/16	3/8	(a, 3/16
0.020	3/8	3/8	b, 3/16
0.025	3/8	3/8	c) 7/32
0.032	1/2	1/2	1/4
0.036	-	-	1/4
0.040	9/16	1/2	9/32
0.045	-	-	5/16
0.050	-	-	5/16
0.051	5/8	5/8	-
0.063	-	-	3/8
0.064	3/4	5/8	-
0.071	3/4	5/8	-
0.072	13/16	3/4	-
0.080	-	-	13/32
0.081	7/8	3/4	-
0.090	-	-	7/16
0.091	15/16	7/8	-
0.100	-	-	7/16
0.102	1	1	-
0.125	1-1/8	1-1/4	9/16
0.160	-	-	5/8

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

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

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

(d) 1 inch = 25.4 mm

[Ref. 12.13, overlap and spacing; ref. 12.14, edge distance]

TABLE 12.5. — Spot Weld Maximum Shear Strength Standards (a)

Source	Ref. 12.14			
Alloy	Aluminum Alloys (bare and clad)			
Nominal thickness of thinner sheet, inch	Above 56 ksi (d)	28 to 56 ksi	20 to 27.5 ksi	≤19.5 ksi
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 inch = 25.4 mm

(c) 1 lb = 0.4536 kg

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

TABLE 12.7. — Specifications for Aluminum Rivets

Source	Ref. 12.19		
Products	Federal	Military	AMS
Rivets	FF-R-556	MIL-R-1150	7220
	-	MIL-R-5674	7222
	-	MIL-R-12221	7223
Rivets, blind	-	MIL-R-7885	-
	-	MIL-R-8814	-
	-	MIL-R-27384	-
Rivet, wire	QQ-A-430	-	-

TABLE 12.8. — F_{su} (Average) for Driven Rivets (c)

Source	Ref. 12.10		
Alloy and Temper before Driving (a)	Driving Procedure	Alloy and 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	34(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-T43	24(b)
6061-T6	Cold, as received	6061-T6	30
7277-T4	Hot, 850° to 975° F (454°–524° C)	7277-T41	38

(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 are attained by 6061-T31 rivets 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/mm^2

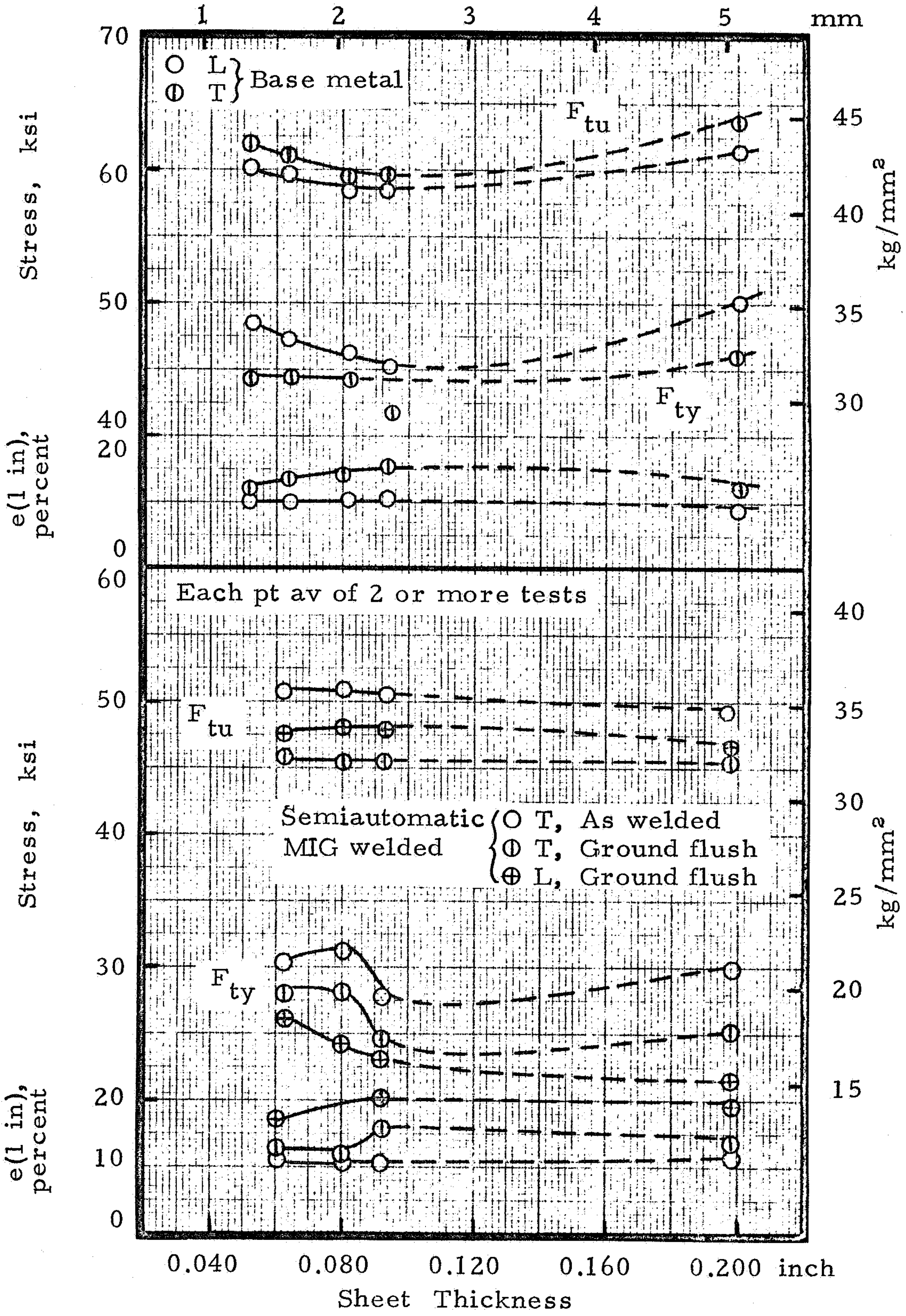


FIGURE 12.1. – Tensile properties of MIG-welded 5456-H343 sheet.
(Ref. 12.7)

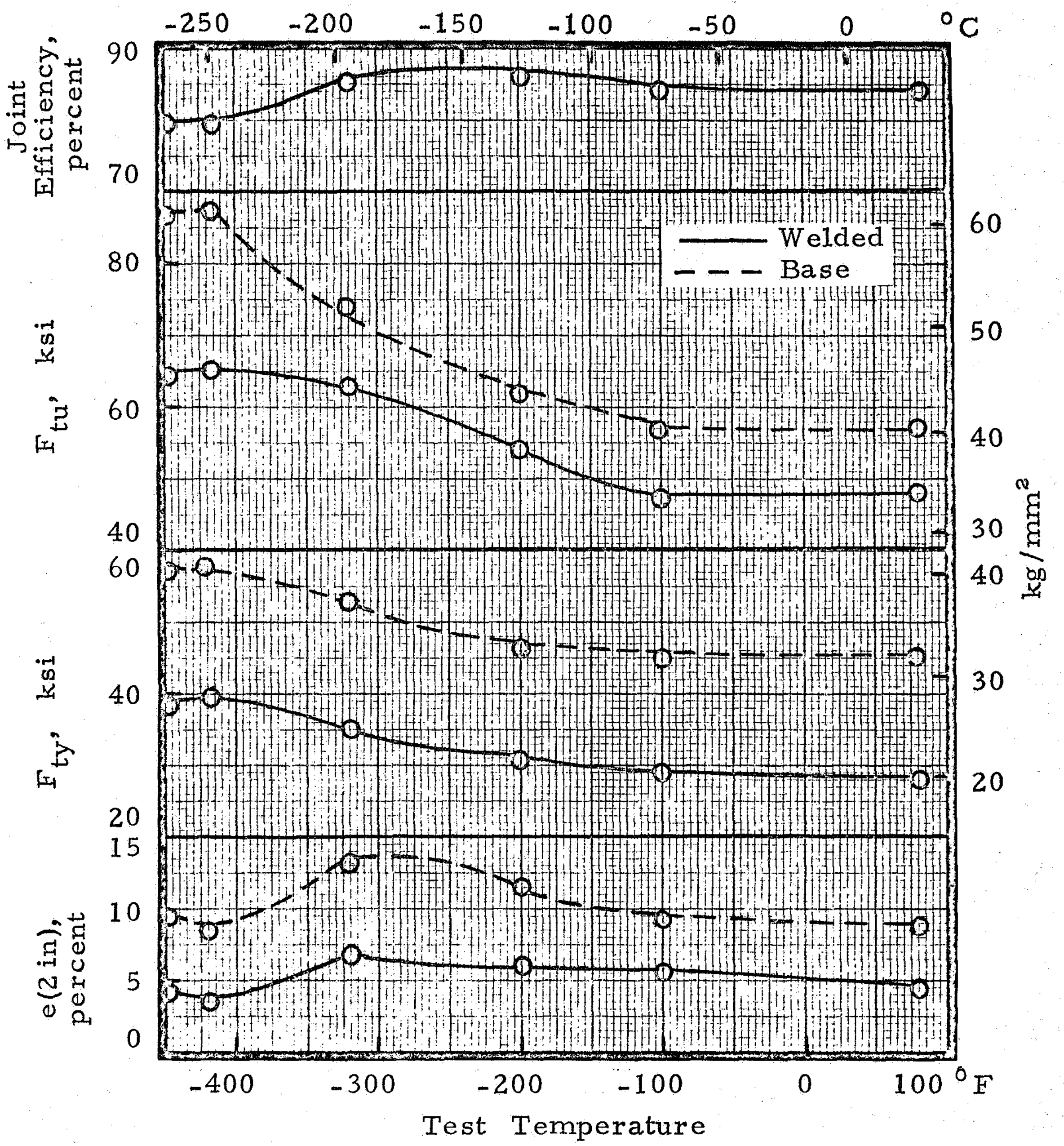


FIGURE 12.2. — Effect of low temperatures on base and TIG-welded 5456-H343 sheet, 0.062 inch (1.57 mm).

(Ref. 12.25)

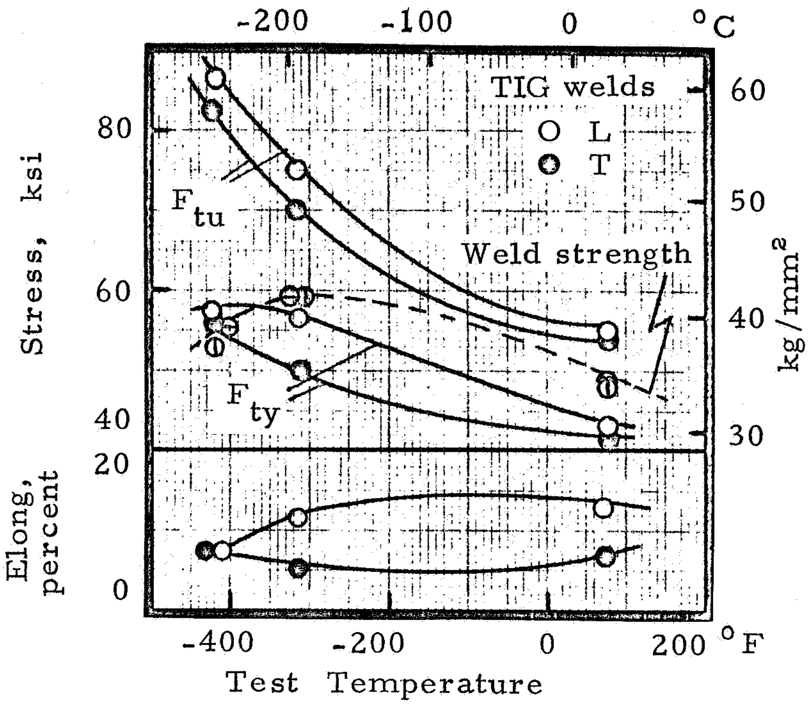


FIGURE 12.3. — Effect of low and room temperature on tensile properties and weld strength of 5456-H24 sheet, 0.103 inch (2.62 mm).

(Ref. 12.8)

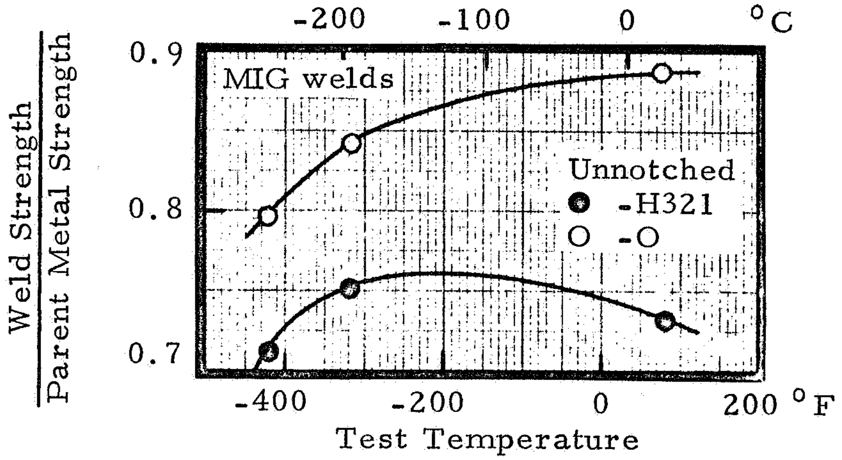
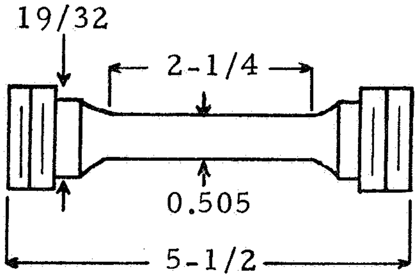
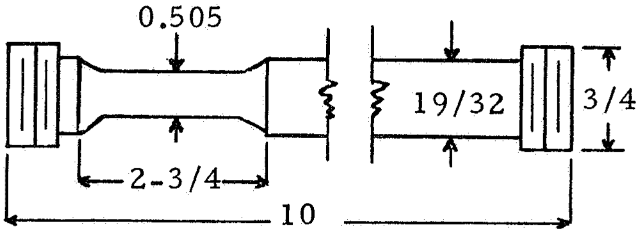


FIGURE 12.4. — Effect of low and room temperature on weld strength ratio of 5456 (MIG welds). (Ref. 12.9)





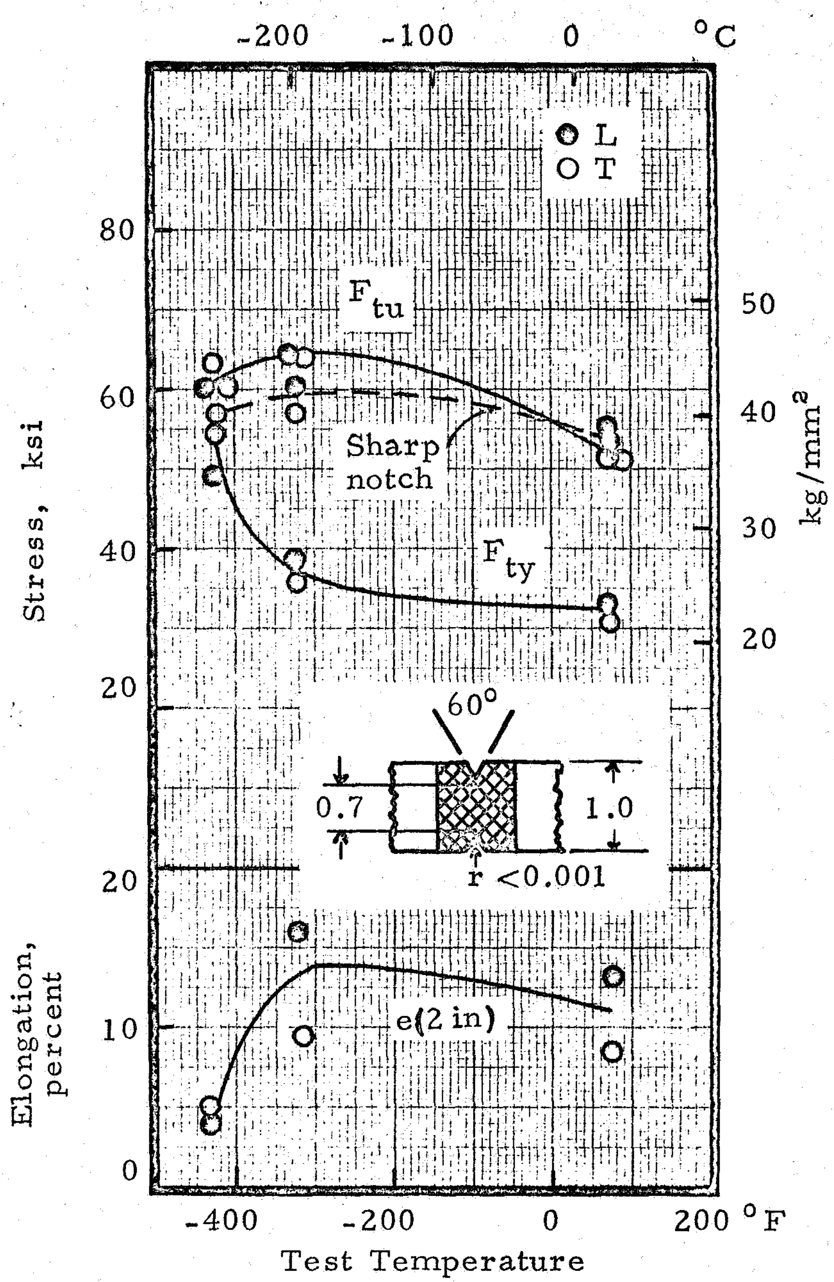


FIGURE 12.5. – Effect of low temperature on tensile and notch properties of welded 5456-H321 sheet (inert-gas shielded arc, 5556 filler metal); 0.125-inch (3.175-mm) sheet.

(Ref. 12.10)

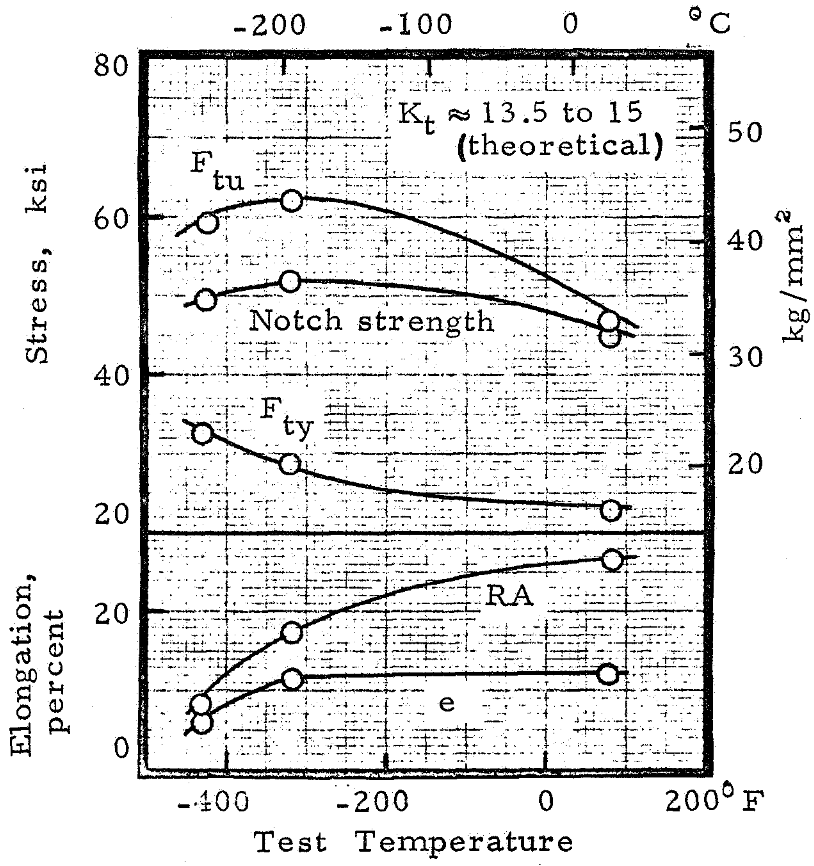


FIGURE 12.7. — Effect of low and room temperature on tensile properties and notch strength of MIG-welded 5456-H321 plate. (Ref. 12.9)

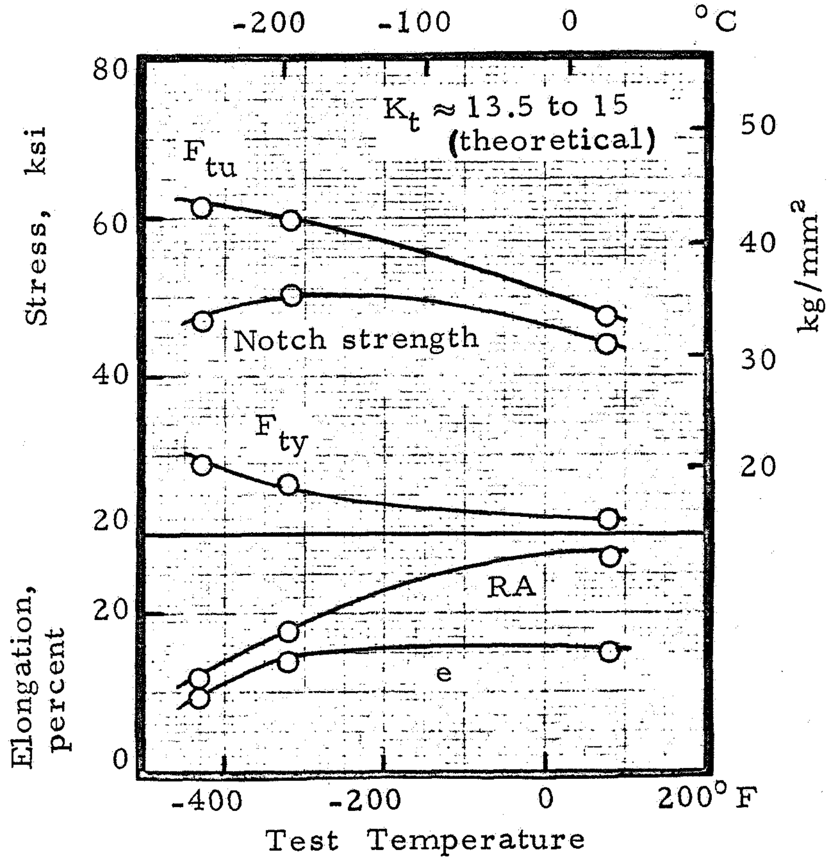


FIGURE 12.8. — Effect of low and room temperature on tensile properties and notch strength of MIG-welded 5456-O plate. (Ref. 12.9)

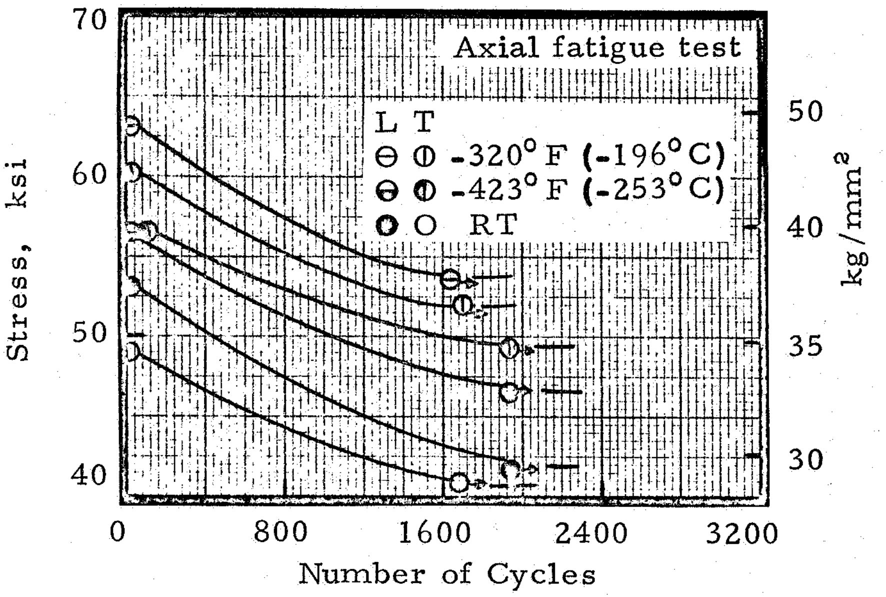


FIGURE 12.8. — S-N curve for MIG-welded 5456-H343 sheet specimen at room and low temperature. (Ref. 12.11)

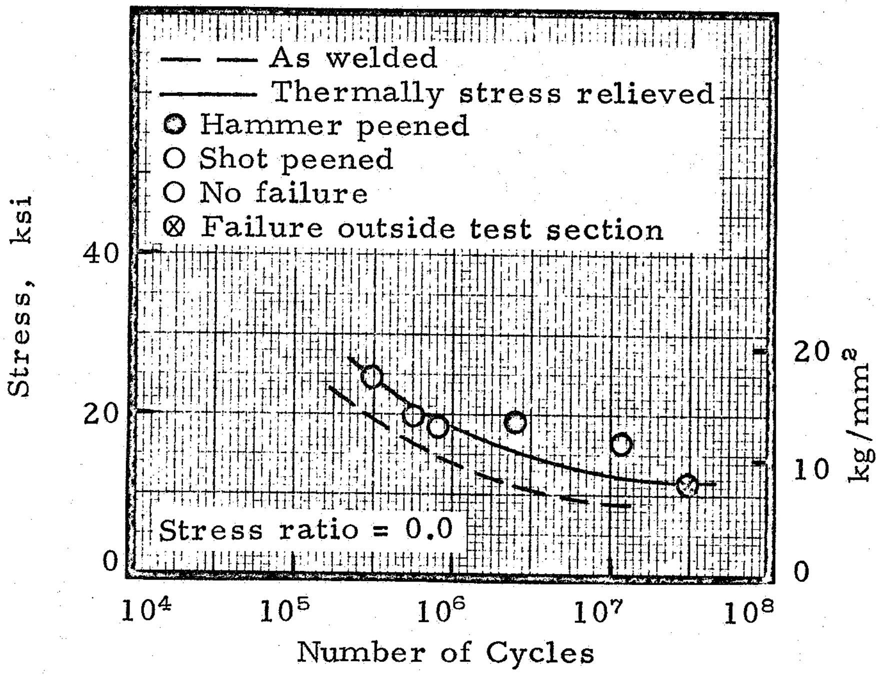


FIGURE 12.9. — Effect of shot peening, hammer peening, or thermal stress relief on fatigue life of longitudinal butt welds in 5456-H321. (Ref. 12.12)

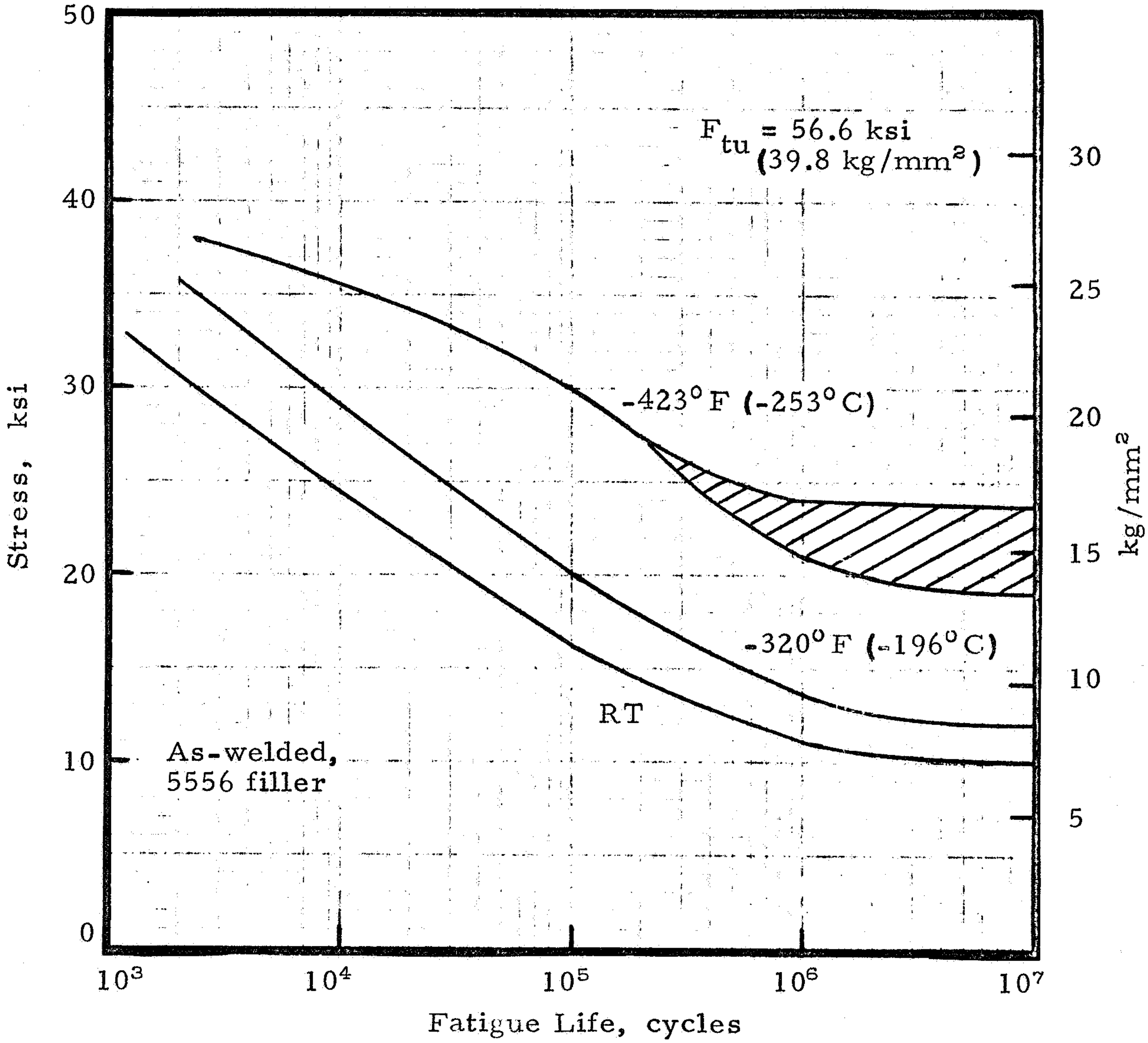


FIGURE 12.10. — Effect of low temperature on fatigue life of TIG-welded 5456-H343 sheet, 0.100 inch (2.54 mm).

(Ref. 12.5)

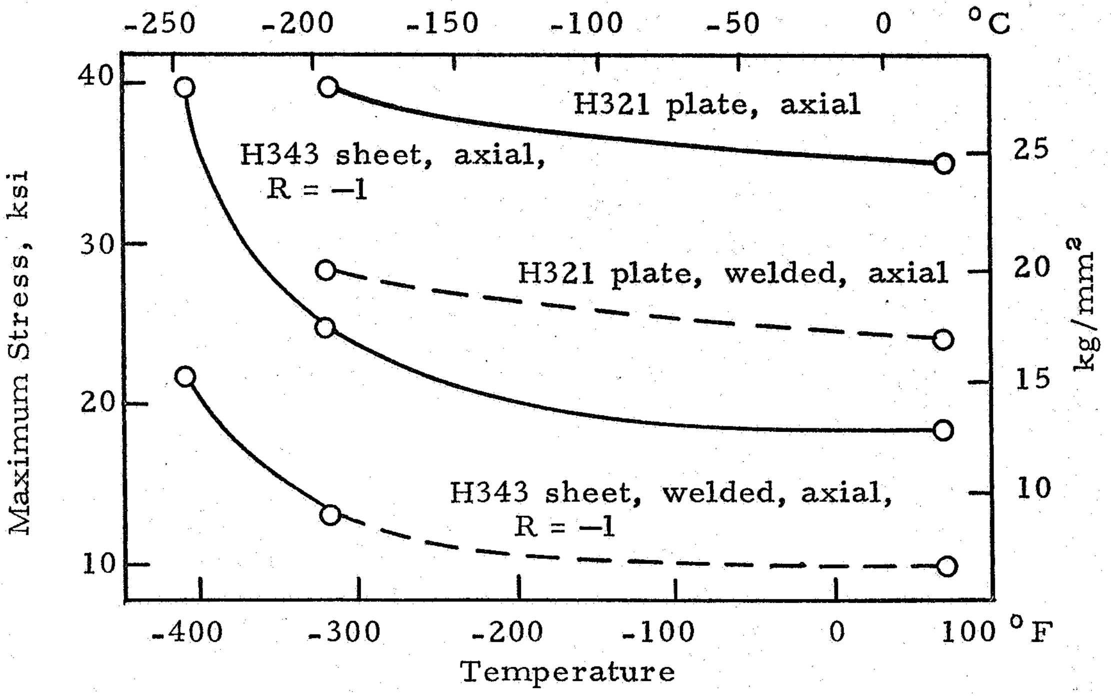


FIGURE 12.11. – Fatigue strengths in 10^6 cycles for 5456 base and welded material at low temperatures.

(Ref. 12.26)

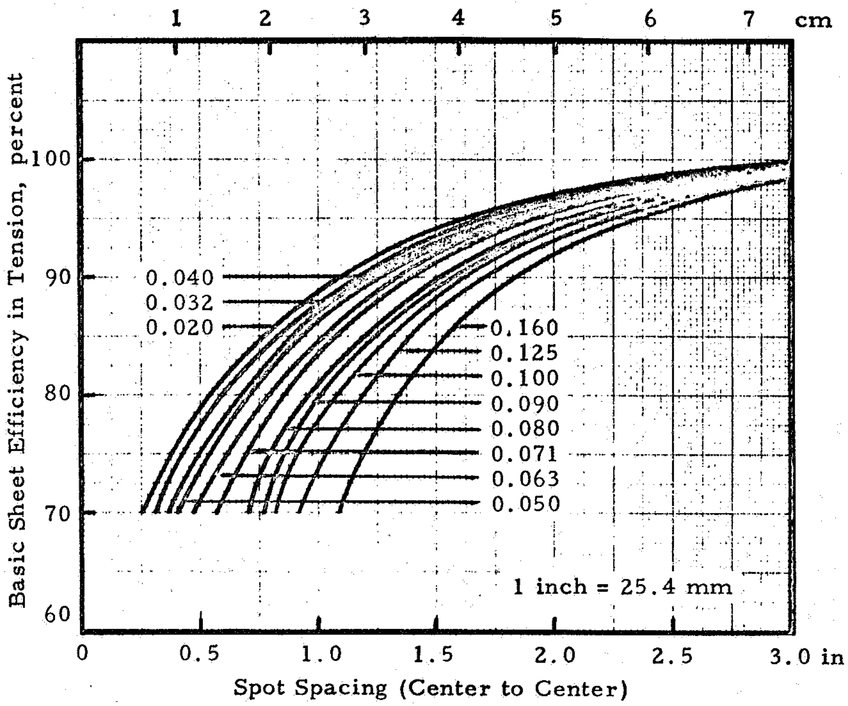


FIGURE 12.12. – Efficiency of the parent metal in tension for spot welded aluminum alloys.

(Ref. 12.14)

Chapter 12 - References

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

12.2 Alloy Digest, "Aluminum 5456," (Filing Code Al-70), Engineering Alloys Digest, Inc., September 1958.

12.3 D.M. Daley, Jr. and D.C. Jeffreys, "Development of Weld Fabricaction Techniques for the S-IC Saturn V Vehicle," Welding J., January 1964, p. 34.

12.4 F.G. Nelson, "Effects of Repeated Repair Welding of Two Aluminum Alloys," Welding J., Res. Suppl., April 1961, p. 166S.

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

12.6 Republic Aviation Corp., "Compilation of Unpublished Materials Information," Report No. RAC 357-4, March 1962.

12.7 R.H. Brookes, "MIG Welding of Aluminum-Magnesium Alloy 5456," Final Report 9067, McDonnell Aircraft Corporation, October 1962.

12.8 J.E. Campbell, "Review of Recent Developments in the Evaluation of Special Metal Properties," DMIC Memo 112, June 1961.

12.9 L.P. Rice, J.E. Campbell, and W.F. Simmons, "Tensile Behavior of Parent Metals and Welded 5000 Series Aluminum Alloy Plate at Room and Cryogenic Temperatures," The Aluminum Association, Battelle Memorial Institute, August 1961.

12.10 M.P. Hanson et al., "Sharp Notch Behavior of Some High Strength Sheet Aluminum Alloys and Welded Joints at 75, -320, and -423F," Proc. ASTM, 60, 1960.

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

12.12 G.E. Nordmark, "Peening Increases Fatigue Strength of Welded Aluminum," Metal Progress, 84 (5), 1963.

12.13 Aluminum Co. of America, "Welding Alcoa Aluminum," 1958.

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

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

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

12.17 *Aerospace Material Specifications*, Society of Automotive Engineers, Inc., New York, latest Index, May 1971.

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

12.19 Aluminum Co. of America, Alcoa Products Data, "Specifications," Section A12A, July 1963.

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

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

12.22 *Welding Handbook*, Sec. 5, American Welding Society, New York, 1967.

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

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

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

12.26 J.F. Campbell, "Aluminum Alloys for Cryogenic Service," *Mat. Res. Std.*, *4*(10), 540 (1964).