MATERIALS DATA HANDBOOK

Titanium 6Al-4V

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PREFACE

This Materials Data Handbook on titanium 6Al-4V alloy 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 intended that this Handbook present, in the form of a single document, a summary of the materials property information presently available on titanium 6Al-4V.

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

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

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

ACKNOWLEDGMENTS

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

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TABULAR ABSTRACT

Titanium 6Al-4V

TYPE:

Titanium alloy, alpha-beta grade, heat-treatable, weldable, and readily formed

NOMINAL COMPOSITION:

Ti-6.2Al-4.0V

AVAILABILITY:

Sheet, strip, plate, bar, billet, wire, extrusions, tubing, castings, forgings

TYPICAL PHYSICAL PROPERTIES:

Density	4.424 g/cc at 20°C
Thermal Conductivity	0.012 cal/g/cm^2/°C/sec at 20°C
Av. Coeff. of Thermal Expansion	8.8 μcm/cm/°C (0°–100°C)
Specific Heat	0.135 cal/g °C at 20°C
Electrical Resistivity	171 microhms-cm at 20°C

TYPICAL MECHANICAL PROPERTIES:

F_{tu} (annealed)	138 ksi (97 kg/mm^2)
F_{ty} (annealed)	128 ksi (90 kg/mm^2)
e(2-inch, 50.8-mm)	12 percent
E (tension)	16.5 x 10^3 ksi (11.6 x 10^3 kg/mm^2)

FABRICATION CHARACTERISTICS:

Weldability	Reliable by fusion, resistance, and pressure techniques with proper precautions
Formability	Similar to stainless steels; must be protected against contamination
Machinability	Readily machined with proper precautions

COMMENTS:

Alloy has good hot strength at temperatures up to 750°F (399°C). It has excellent resistance to corrosion in most common media, but is sensitive to impact in liquid oxygen and other strong oxidizers. Alloy is susceptible to stress-corrosion cracking in the presence of strong oxidizers, methanol, and "hot-salt" environments.

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
$^\circ$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 Introduced in 1954, titanium 6Al-4V is as close as possible to a general-purpose titanium alloy. The alloy is a highly stabilized alpha-beta alloy, with aluminum as the alpha stabilizer and vanadium as the beta stabilizer, which impart high toughness with good hot strength at temperatures up to 750° F (399° C) (ref. 1.1).

1.2 The alloy is highly resistant to salt water, many acids, alkalis, and other chemicals; it is near the noble end of the electrochemical series and galvanic couples behave like austenitic steels (ref. 1.2). It is protected by an inherent oxide film at low or moderate temperatures, but is subject to oxidation at elevated temperatures.

1.3 Titanium 6Al-4V is machined readily if attention is paid to the rapid heat buildup at the cutting interfaces, the reaction with the cutting tool (e.g., galling), and the low modulus. Welding is reliable after considerations such as joint preparation, fit-up, and shielding of the weld and heated zones. All stardard sheet metal techniques can be used for forming titanium 6Al-4V alloy. The normal forging temperature is 1750° F (954° C), about 75° F (24° C) below the beta-phase transus (ref. 1.1).

1.4 Titanium 6Al-4V is available as sheet, strip, bar, billet, wire, extruded shapes, forgings, and castings (refs. 1.1 – 1.4).

1.5 Typical applications of the alloy are in aircraft and missile structures, pressure vessels, in chemical processing industries, and in food processing industries (refs. 1.1 through 1.5).

1.6 General Precautions

1.61 **The alloy is not to be used for containment of liquid oxygen because it is impact sensitive in this medium, and burning propagates once it has been initiated. It is also impact sensitive in red fuming nitric acid and nitrogen tetroxide.**

Titanium 6Al-4V is susceptible to stress-corrosion cracking in media such as red fuming nitric acid, nitrogen tetroxide, methyl alcohol, and "hot-salt" environments (refs. 1.6, 1.7).

Chapter 1 - References

1.1 Titanium Metals Corp. of America, "Properties of 6Al-4V," Titanium Engineering Bulletin No. 1, November 1968.

1.2 Harvey Titanium, "Titanium," January 1970.

1.3 Alloy Digest, "MST 6Al-4V" (Filing Code Ti-9), Engineering Alloys Digest, Inc., New Jersey, December 1955.

1.4 Teledyne/Rodney Metals, "Rodney Metals," December 1970.

1.5 W.F. Simmons and H.J. Wagner, "Current and Future Usage of Materials in Aircraft Gas Turbine Engines," DMIC Memorandum 245, February 1, 1970.

1.6 E.L. White and J.J. Ward, "Ignition of Metals in Oxygen," DMIC Report 224, February 1, 1960.

1.7 J.B. Rittenhouse, J.S. Whittick, et al., "Corrosion and Ignition of Titanium Alloys in Fuming Nitric Acid," WADC TR-56-414, February 1957.

1.8 Aerospace Structural Metals Handbook, J.G. Sessler and V. Weiss, Eds., AFML TR-68-15, 1971 Edition.

Chapter 2

PROCUREMENT INFORMATION

2.1 General. Titanium alloy 6Al-4V is available as sheet, strip, plate, bar, billet, wire, extruded shapes, and tubing.

2.2 Procurement Specifications. Specifications that apply to the alloy are listed in table 2.2 for various products.

2.3 Major Producers of the Alloy (United States)

C-120AV	Crucible Steel Co. of America Pittsburgh, Pennsylvania
HA-6510	Harvey Titanium Torrance, California
MST-6Al-4V	Reactive Metals Los Angeles, California
RS-120A	Republic Steel Corp. Cleveland, Ohio
Ti 6Al-4V	Teledyne/Rodney Metals New Bedford, Massachusetts
Ti 6Al-4V	Titanium Metals Corp. of America West Caldwell, New Jersey

2.4 Available Forms, Sizes, and Conditions. Forms, sizes, and conditions of commercially available titanium 6Al-4V are listed in table 2.4. The alloy is also produced in an extra-low-interstitial (ELI) grade for cryogenic applications.

TABLE 2.2. – Specifications for Titanium Alloy 6Al-4V

Source	Refs. 2.1, 2.2, 2.3		
Alloy	Titanium 6Al-4V		
Product	Specification No. (a) Military	ASTM	AMS
Plate, sheet, and strip, cont. rolled, annealed	-	-	4906
Plate, sheet, and strip, ELI, annealed	MIL-T-9046F	-	4907B
Plate, sheet, and strip, annealed	MIL-T-9046F	B265-70	4911B
Bars and forgings	MIL-T-9047E	-	4928F
Bars and forgings, sol. and prec. HT	-	-	4965A
Bars and forgings, annealed, HT	-	-	4967C
Extrusions	-	-	4935B
Welding wire	-	-	4954A
Welding wire, ELI	-	-	4956
Wrought alloy, for critical components	MIL-T-46035A	-	-
Wrought alloy, for critical applications	MIL-T-46038A	-	-
Castings	-	B367-69	-
Bolts and screws, HT, roll-threaded	-	-	7460B
Bolts and screws, upset headed, HT, roll-thread	-	-	7461A

(a) As of May 1971.

TABLE 2.4. — Available Forms, Sizes and Conditions (a)

Source	Refs. 2.4 through 2.7	
Alloy	Titanium 6Al-4V and 6Al-4V ELI	
Form	Condition	Sizes
Forging billet	Ann	up to 400 in^2 (2581 cm^2)
Bar stock	Ann, ST, STA	0.5 to 16 in^2 (3.23 to 103 cm^2) lengths to 90 ft (27.4 m) max
Extrusions, up to 11-in (28-cm) circum diam	Ann	lengths of 20 to 75 ft (6.1 to 23 m)
	ST, STA	lengths to 40 ft (12 m) max
Wire	Ann	0.010-0.312 in (0.025-0.792 cm) diam; lengths, to 30 ft (9 m) coils, to 500 ft (152 m)
Sheet, strip, and plate: 0.010-0.187 in (0.025-0.475 cm)	Ann	up to 48 in wide (122 cm), lengths to 144 in (366 cm)
	ST, STA	up to 48 in (122 cm) wide, lengths to 120 in (305 cm)
Plate: 0.187 to 1.000 in (0.475- 2.54 cm)	Ann, ST, STA	max, 48 in x 144 in (122 cm x 366 cm)
Tubing, seamless	Ann	0.25 to 6.0 in (0.64-15.2 cm) diam
Tubing, welded	Ann	1 to 10 in (2.54 to 25.4 cm) diam
Pipe, seamless	Ann	0.25 to 1 in (0.64-2.54 cm) diam
Castings	Ann	Rammed mold: size to be contained within 100-in (254 cm) diam Precision: up to 24 in (61 cm) diam and 24 in in height

(a) Contact producers for special sizes and requirements.

Chapter 2 - References

2.1 *AMS Specifications*, Society of Automotive Engineers, New York, latest Index, May 1971.

2.2 *Index of Specifications*, Dept. of Defense, Alphabetical Listing. latest Index, May 1971.

2.3 *ASTM Standards*, Part 7, American Society for Testing Methods, 1971.

2.4 Titanium Metals Corp. of America, "Properties of Ti-6Al-4V," Titanium Engineering Bulletin No. 1, November 1968.

2.5 Harvey Titanium, "Titanium," September 1968.

2.6 Teledyne/Rodney Metals, "Rodney Metals," December 1970.

2.7 D.J. Maykuth, et al., "Titanium Base Alloys: 6Al-4V," DMIC Handbook, February 1971.

Chapter 3

METALLURGY

3.1 Chemical Composition

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

C, max	0.08	O, max	0.20
Al	6.15	H, max	0.015
V	4.0	Fe, max	0.25
N, max	0.05	Others, max	0.40

Ti, Balance

3.12 Chemical composition limits, table 3.12.

3.13 Alloying elements. Aluminum and vanadium are the major alloying constituents with lesser amounts of iron and oxygen and traces of other elements.

The low-temperature form of pure titanium has a close-packed hexagonal crystal structure, alpha (α), that transforms to a body-centered-cubic structure, beta (β), at 1625° F (885° C). The aluminum in titanium 6Al-4V stabilizes the alpha structure and raises the temperature of the $\alpha + \beta \rightarrow \beta$ transformation temperature (or beta transsus) to 1820° ±25° F (994° C); by this mechanism, strength at elevated temperatures is increased. The vanadium lowers the transformation temperature and makes the beta phase stable at lower temperatures; it also increases the strength level (1) by substitutional solid-solution hardening and (2) by stabilizing the elevated temperature phase (beta), thus making the $\beta \rightarrow \alpha$ hardening reaction possible through heat treatment. By the addition of vanadium, hot workability is improved since more of the ductile beta phase is present at hot working temperatures. (Refs. 3.4, 3.5, 3.8)

The ternary diagram of figure 3.13 illustrates the $\alpha \rightarrow \beta$ phase relationships of titanium 6Al-4V.

Alpha-beta alloys may form varying amounts of an omega (ω) phase under certain conditions of heat treatment. This is a transition phase formed during the beta-decomposition process at temperatures below about 900° F (483° C). The formation of the omega phase should be avoided since it causes hardening and embrittlement. Hence, when titanium 6Al-4V is worked or heated at or above 1200° F (649° C) it should either be furnace-cooled through the 1200°–1000° F range (649°–594° C) to effect the $\beta \rightarrow \omega \rightarrow \alpha$ transformation (ref. 3.8). The combination of hot work at temperatures in the beta field and finishing by furnace cooling or annealing at 1000°–1300° F (538°–704° C), generally used for titanium alloys, produces a fine dispersion of the alpha and beta-enriched phases that provides an optimum combination of thermal stability and tensile ductility.

3.14 Interstitial elements. The transformation kinetics of the $\alpha \rightarrow \beta$ reaction are accelerated by the presence of interstitials (e.g., C, O, N) dissolved in the beta phase (refs. 3.6, 3.8). An increase in strength occurs with increased interstitial content at normal to elevated temperatures. However, at cryogenic temperatures, brittleness may occur, particularly under severe stress conditions. In view of these considerations, extra-low-interstitial (ELI) grades of titanium 6Al-4V, with a maximum oxygen content of 0.13 percent have been developed for service at temperatures down to –423° F (–253° C). For cryogenic applications, titanium 6Al-4V-ELI is used in the annealed condition (ref. 3.5).

The effects of oxygen content and temperature on tensile and notch-tensile properties are illustrated in table 3.14.

3.2 Strengthening Mechanisms

3.21 General. Strengthening heat treatments for titanium 6Al-4V are predicated on the retention of the high-temperature beta phase to room temperature for subsequent controlled decomposition during aging (ref. 3.5). Accordingly, a high-temperature solution treatment is followed by a lower temperature aging treatment.

Recommended and specified heat treatments for the alloy are given in table 3.21.

3.22 Annealing. (See table 3.21.) For sheet and small bars, a fast air-cool will result in a slight loss of strength (ref. 3.5).

3.23 Stress Relief. (See table 3.21.)

3.24 Age Hardening. (See table 3.21.) Heat treating times must be kept to a minimum because of contamination and oxidation problems that are time-dependent and occur at high temperatures. To insure uniformity of heat treatment throughout heavier sections, longer times are recommended. Where machining follows heat treatment (e.g., bars, forgings, and extrusions), contamination is less of a problem in heavier sections (ref. 3.5).

Overaging is accomplished at temperatures over 1000° F (538° C) and up to 1150° F (622° C) for periods of 1 to 8 hours. The overaging treatment may be used to lower the strength of a material that has been heated to a high-strength level, and may also be used to increase tensile ductility (ref. 3.5).

3.241 The effects of age-hardening on the tensile properties of titanium 6Al-4V bar stock are shown in table 3.241.

3.242 The variation in heat treatment response of titanium 6Al-4V forgings is given in table 3.242.

3.3 Critical Temperatures

3.31 Melting range, 2950°–3050° F (1621°–1677° C) (ref. 3.9).
Beta transus, 1750°F (954° C) (ref. 3.5).

3.4 Crystal Structure (See Section 3.13)

3.5 Microstructure

3.51 The microstructure of titanium 6Al-4V is influenced by chemical composition and heat treatment. The structure resulting from annealing temperatures of 1300° to 1600° F (704° to 871° C) is primarily alpha phase, with beta retained in the grain boundaries (see figure 3.51). The high proportion of alpha is due to the relatively high solubility of vanadium in the alpha phase and the presence of an alpha stabilizer (aluminum). The alloy can be strengthened by subsequent aging, that is, by solution annealing and quenching from temperatures higher in the alpha-beta field (see figure 3.13). The increase in heat-treatment response is caused by the increased amount of beta phase in the structure and by the change in alloy content of the beta phase with increasing temperature. As solution annealing temperature is increased, the vanadium content of the equilibrium beta phase eventually is lowered below the limit at which beta is retained on quenching. The beta transforms partially to alpha (martensite) after solution annealing to about 1750° F (954° C); at 1550° F (843° C), beta is retained.

At the solution annealing temperature of 1750° F (954° C), however, the beta phase is mechanically unstable after quenching and martensite can be formed during plastic straining. Maximum heat-treatment response (see table 3.242) is attainable after solution annealing in the beta field. However, a loss in ductility accompanies the increase in strength; hence, solution anneals usually are not carried out in the all-beta range but rather in the alpha-beta range from intermediate to high (ref. 3.6).

A typical fusion-weld microstructure is completely different from that normally observed in the base metal in that it consists generally of very large equiaxial grains; this microstructure is to be considered as normal for any titanium alloys that have been fusion welded (ref. 3.11).

3.6 Metallographic Procedures

3.61 There is a marked tendency of titanium to drag and smear during grinding and polishing for metallographic examination. Sharp abrasives and a large quantity of lubricants, such as water or kerosene, are used in rough grinding. Standard polishing techniques are employed, with aluminum oxide as the abrasive on airplane-wing cloth and water as a lubricant (ref. 3.10).

Electropolishing (with perchloric acid and acetic anhydride) has been used successfully. An alcohol bath containing aluminum chloride and zinc chloride also can be used. The alcohol bath (nonexplosive) contains 90 ml ethanol, 10 ml n-butyl alcohol, and 6 g aluminum chloride (added slowly). Operating parameters are: 30–60 volts, 1–5 amp/in^2 (0.15–0.77 amp/cm^2), 75°–85° F (24°–29° C), 1 to 6 minutes; a stainless steel cathode is used (ref. 3.10).

3.62 Etching reagents for titanium and its alloys are given in table 3.62.

TABLE 3.12. — Chemical Composition Limits in Weight Percent

Source	Refs. 3.2, 3.3			
Alloy	Titanium 6Al-4V			
Form	Plate, Sheet, and Strip		Extrusions	Castings
Specification	AMS-4911B	ASTM-B265-70	AMS-4935B	ASTM-B367-69
Al	5.50-6.75	5.5-6.75	5.50-6.75	5.5-6.75
V	3.50-4.50	3.5-4.5	3.50-4.50	3.5-4.5
Fe, max	0.30	0.40	0.30	0.40
O, max (a)	0.20	0.20	0.20	0.25
C, max	0.08	0.10	0.10	0.10
N, max	0.05	0.05	0.05	-
H, max	0.015	0.015(b)	0.0125	0.0100
Others (each)	-	0.05	0.10	0.10
Others (total)	0.40	0.30	0.40	0.40
Ti	balance	balance	balance	balance

(a) Max content of ELI grade is 0.13 percent O.

(b) Lower hydrogen may be obtained by negotiation with manufacturers.

TABLE 3.14. — Tensile and Notch Tensile Properties of 1/4-Inch (6.35 mm) Plate at Various Temperatures and Two Oxygen Levels

Source	Ref. 3.5										
Alloy	Titanium 6Al-4V (a)										
Condition	Annealed										
Oxygen, Wt-%	**Test Temp,** °F	°C	F_{tu}, ksi	kg/mm^2	F_{ty}, ksi	kg/mm^2	Elongation, %	Redn. of Area, %	NTS (K_t=6.7) ksi	kg/mm^2	NTS/UTS
0.08	**-320**	**-196**	210.7	148.1	201.4	141.2	19.0	43.5	273.4	192.2	1.30
0.08	**-110**	**- 79**	159.0	111.9	151.8	106.7	20.0	37.7	221.8	155.9	1.39
0.08	**RT**		134.1	94.3	126.5	88.9	21.0	43.8	201.2	141.4	1.50
0.16	**-320**	**-196**	229.6	161.4	216.3	152.1	21.0	36.0	245.2	172.4	1.07
0.16	**-110**	**- 79**	177.4	124.7	167.9	118.0	24.0	35.0	219.7	154.4	1.24
0.16	**RT**		151.0	106.1	143.3	100.7	21.0	42.5	208.8	146.8	1.38
Solution Treated and Aged											
0.08	**-320**	**-196**	251.0	176.8	236.3	166.1	2.0	7.9	270.1	189.9	1.08
0.08	**-110**	**- 79**	194.3	136.6	183.0	128.7	16.0	46.2	239.9	168.7	1.23
0.08	**RT**		166.0	116.7	152.6	107.3	18.0	57.4	226.1	159.0	1.36
0.08	**340**	**171**	141.5	99.5	123.0	86.5	18.0	66.1	214.3	150.7	1.51
0.08	**800**	**427**	122.8	86.3	100.2	70.4	17.0	69.4	-	-	-
0.16	**-320**	**-196**	268.7	188.9	250.9	176.4	4.0	5.6	246.0	173.0	0.92
0.16	**-110**	**- 79**	212.2	149.2	197.3	138.7	12.0	28.9	230.0	161.7	1.08
0.16	**RT**		181.7	127.7	168.6	118.5	14.5	44.7	222.1	156.2	1.22
0.16	**340**	**171**	156.5	110.0	134.3	94.4	17.0	55.6	224.6	157.9	1.44
0.16	**800**	**427**	132.3	93.0	102.2	71.8	16.0	67.3	-	-	-

(a) **Smooth tensile specimens, 1/8-in diam x 1/2-in gage length** (3.175 x 12.7 mm)
Notched tensiles, 0.133-in notch diam (3.378 mm)
STA cycle: 1725° F (941° C), 1/2 hr; WQ; plus 1000° F (538° C), 4 hr, AC

TABLE 3.21. — Recommended and Specified Heat Treatments for Alloy in Various Forms

Alloy	Titanium 6Al-4V				
Form	**Stress Relieving**	Annealing	Soln. Treating	Aging	Ref./Spec.
Sheet and light plate	**1000° to 1200° F (538° to 649° C) 1 to 4 hrs, AC**	1350° ±25° F (732° ±14° C) 4 hrs, FC to 1050° F (560° C), AC	1660° to 1700° F (905° to 927° C) 5–10 min, WQ	1000° F (538° C) 4 hrs, AC	Ref. 3.5
	-	1300° to 1600° F (a) (704° to 905° C)	-	-	AMS-4911B
Plate over 1/4 in (6.35 mm) *	**1000° to 1200° F (538° to 649° C)**	1350° ±25° F (732° ±14° C)	1700° to 1750° F (927° to 955° C)	1000° F (538° C) 4 hrs, AC	Ref. 3.5
Bars, forgings, and extrusions	**1000° to 1200° F (538° to 649° C) 1 to 4 hrs, AC**	Same as sheet, but AC permissible because of heavier sections	1750° ±25° F (955° ±14° C) 2 hrs, WQ	1000° F (538° C) 4 hrs, AC	Ref. 3.5
Extrusions	**1050° ±25° F (566° ±14° C) 1 hr, AC**	1300° to 1400° F (a) (704° to 760° C)	-	-	AMS-4935A
Castings (post-weld)	-	1200° F (649° C) 1/2-hr per inch (25.4 mm.) thickness, AC			ASTM-B367-69
Bars and forgings	-	-	1750° ±25° F (955° ±14° C) 1–2 hrs, WQ	1000° ±15° F (538° ±8° C) 4–8 hrs, AC	AMS-4967C

(a) Must be capable of meeting material specifications after heating to 1325° ±25° F (718° ±14° C), holding at heat for 20 minutes, cooling in air, and descaling.

*** Treating times same as for sheet, except soln treating for 1/2 hour.**

TABLE 3.241. — Effect of Age Hardening Treatment on Tensile Properties of Bar Stock

Source		Ref. 3.7				
Alloy		Titanium 6Al-4V, 0.5-in (12.7-mm) bar (a)				
Solution Temp.		Tensile Strength		Yield Strength		Elongation in 4D, %
°F	°C	ksi	kg/mm^2	ksi	kg/mm^2	
1550	843	149	105	142	99.8	18
1600	871	154	108	143	100.5	17
1650	899	159	112	144	101	16
1700	927	161	113	145	102	16
1725	941	165	116	153	108	16

(a) Aged 8 hrs at 900° F (482° C), AC

TABLE 3.242. — Variation in Heat Response of Forgings

Source	Ref. 3.7		
Alloy	Titanium 6Al-4V		
Specimen	Properties at Room Temperature		
	0.2% Yield Strength		Elongation, percent
	ksi	kg/mm^2	
0.5-in (12.7-mm) min sect. thickness			
As forged and annealed (a)	**129.0**	**90.7**	**22**
As forged and heat treated (b)	**161.0**	**113.2**	**17**
1.0-in (25.4-mm) min sect. thickness			
As forged and annealed (a)	**128.5**	**90.3**	**21**
As forged and heat treated (b)	**158.5**	**111.4**	**17**
2.0-in (50.8-mm) min sect. thickness			
As forged and annealed (a)	**129.3**	**90.9**	**21**
As forged and heat treated (b)	**143.3**	**100.7**	**17**
3.0-in (76.2-mm) min sect. thickness			
As forged and annealed (a)	**126.3**	**88.8**	**19**
As forged and heat treated (b)	**134.5**	**94.6**	**14**

(a) 2 hrs at 1300° F (704° C)
(b) 1 hr at 1725° F (941° C), WQ, 20 hrs at 900° F (482° C)

TABLE 3.62. – Etching Reagents for Titanium and Titanium Alloys

Source		Ref. 3.10	
Composition		**Procedure**	**Use**
HF (48%) Glycerol	50 ml 50 ml	Swab or immerse, 1–10 sec	Darkens alpha but not beta
HF (48%) Water	2 ml 98 ml	Swab or immerse, 5–25 sec	Darkens alpha but not beta
HF (48%) HNO_3 (conc) Glycerol	25 ml 25 ml 50 ml	Swab or immerse, 1–10 sec	Alpha and beta both light, nitric acid brightens surface and removes residue
HF (48%) HNO_3 (conc) Water	1 ml 12 ml 87 ml	Swab or immerse, 10–30 sec	Etches alpha and beta light, nitric acid brightens surface
Kroll's reagent: HF (48%) HNO_3 (conc) Water	 1–3 ml 2–6 ml to 100 ml	Swab 3–10 sec, or immerse 10–20 sec	General purpose; does not stain, brings out grain boundaries

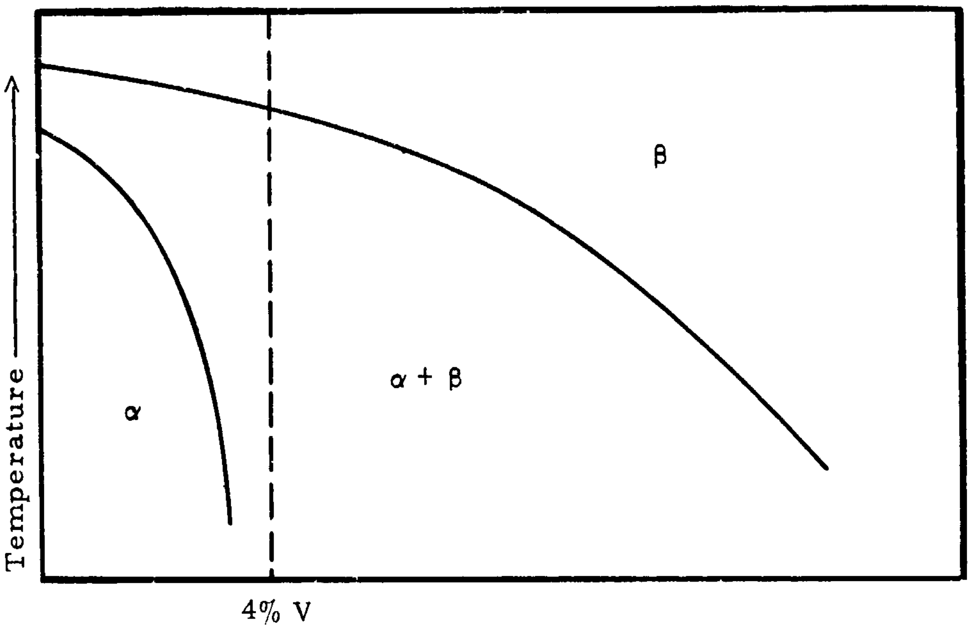

FIGURE 3.13. — Schematic diagram showing phase relationships for titanium 6Al-4V.

(Ref. 3.6)

FIGURE 3.51. — Microstructure of titanium 6Al-4V after annealing at 1300° F (704° C) for 2 hours, shows stable beta in an alpha matrix.

(Ref. 3.6)

Chapter 3 - References

3.1 Teledyne/Rodney Metals, Technical Data Sheet No. 28, in Rodney Metals," December 1970.

3.2 ASTM Standards, Part 7, American Society for Testing Methods, 1971.

3.3 AMS Specifications, Society Automotive Engineers, Inc., New York, latest Index, May 1971.

3.4 Titanium Metals Corp. of America, "How to Use Titanium," January 1970.

3.5 Titanium Metals Corp. of America, "Properties of Ti-6Al-4V," November 1968.

3.6 D.J. Maykuth, et al., "Titanium-Base Alloys: 6Al-4V," DMIC Handbook, February 1971.

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

3.8 D.J. Maykuth, "Residual Stresses, Stress Relief, and Annealing of Titanium and Titanium Alloys," DMIC Report S-23, July 1, 1968.

3.9 1971 SAE Handbook, Society Automotive Engineers, Inc., New York.

3.10 H.R. Ogden, "Titanium and Its Alloys," in C.R. Tipton, Ed., Reactor Handbook, Vol. I, Interscience Publishers, New York, 1960.

3.11 Welding Handbook, Sect. 5, Ch. 91, American Welding Society New York, 1967.

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Chapter 4

PRODUCTION PRACTICES

4.1 General. Titanium was identified as an element by William Gregor in 1790, but it wasn't until 1947 that practical methods were developed (by the U.S. Bureau of Mines) for separating it from its ores. Deposits of the most important ores, rutile (TiO_2) and ilmenite ($FeTiO_3$), are widely scattered with major economic deposits found in Australia, Canada, Finland, India, Norway, Malaya, Sierra Leone, Republic of South Africa, and the United States. Ilmenite is more abundant, but rutile contains more titanium and commands a better price.

Titanium absorbs oxygen and nitrogen from the air at a measurable rate at 1200° F (649° C) and at a rapid rate above 2100° F (1149° C). These elements, along with carbon and hydrogen, form brittle interstitial alloys. Hence, reduction, melting, and certain process operations must be carried out in vacuum or in an atmosphere of inert gas.

The ore, usually rutile, is reduced by chlorination to yield a gravel-like substance known as sponge. In this process (Kroll process), the ore is mixed with coke or tar and charged in a chlorinator. Heat is applied and chlorine gas is passed through the charge to react with the ore to form titanium tetrachloride ($TiCl_4$); oxygen is removed as CO and CO_2. The $TiCl_4$ is purified by continuous fractional distillation and then reacted with sodium or magnesium under an inert atmosphere to yield metallic titanium sponge and $MgCl_2$ or NaCl. The chloride salt is then electrolyzed and recycled in the process. (Refs. 4.1, 4.2, 4.3, 4.4.)

4.2 Manufacture of Wrought Products

4.21 Melting. For pure titanium, the sponge is treated by a high temperature process to remove the last traces of chloride or is leached with aqua regia in a 20-ton titanium vessel and melted twice under vacuum to produce titanium ingots in sizes up to 10,000 pounds (3,732 kg) each.

For titanium alloys, the sponge is blended with the desired elements to insure uniformity of composition. The blend is pressed into briquets which are welded together to form an electrode that is melted in a vacuum arc furnace. The arc is struck between the consumable electrode and a layer of titanium in a water-cooled copper crucible. The molten titanium on the outer surface solidifies on contact with the cold wall and forms a shell or "skull" to contain the molten pool. The ingot is not poured; it freezes under vacuum in the melting furnace. To assure complete solution and uniform distribution of elements, the ingot is remelted in a second consumable furnace to produce the final ingot, typically 24 inches (61 cm) in diameter, about 5 feet (1.5 m) high, and weighing 4000 pounds (1493 kg). Larger ingots can be produced for special applications. (Refs. 4.1, 4.2.)

4.22 Most major alloy producers do not engage in the forging business itself, but utilize forging capabilities for ingot forging in order to provide billet material for sale to forging companies (ref. 4.5).

4.23 Billets are produced by hot rolling or forging and are available as-forged, as-rolled, or annealed in rounds, squares, rectangles, hexagons, or octagons. Bar stock, available as rounds, squares, and rectangles, is produced by hot rolling or forging, depending on the size of bar, tolerances required, etc. In general, rounds are lathe-turned for optimum surface condition. Shapes other than rounds may be ground-finished, blast-cleaned and pickled, or blast-cleaned and pickled plus ground-finished. (Refs. 4.2, 4.3)

Billet or bar stock for heat-treated applications is produced with a slightly higher oxygen content to assist in obtaining higher strength levels. Thus, titanium 6Al-4V produced for a heat-treated application can be used in an annealed application with no deleterious effects, provided extremely low cryogenic temperatures are not encountered. The reverse is not true in that titanium 6Al-4V with a lower oxygen content intended for annealed applications will have lower STA strength levels; as a result, high STA levels are not available in the ELI grade (ref. 4.6).

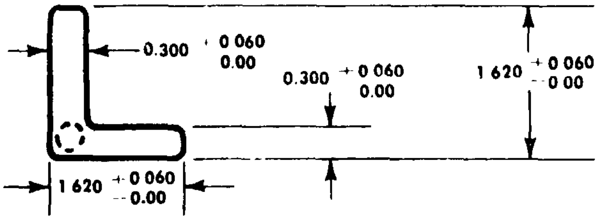
4.24 Welding wire in coils or on spools is produced by cold drawing. Straight lengths are produced by centerless grinding.

4.25 Fastener stock is produced by hot heading, machining, and cold-roll threading, starting from centerless-ground, close-tolerance bar stock.

4.26 Sheets and plates are produced by hot rolling between steel sheets on hand mills, or by the use of continuous hot-strip mills, Sendzimir cold rolling equipment, and vacuum annealing furnaces.

4.3 Prior to about 1960, extrusions and castings were not readily available because they were difficult to form by conventional techniques. However, they are now commercially available in many shapes and forms, limited only by the size of vacuum process equipment available.

4.31 Dimensions and mechanical properties of typical extrusions are illustrated in figure 4.31.

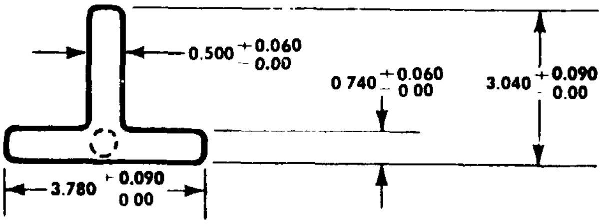


	No. Tests	Range	Avg.	Std. Deviation
Yield Strength (KSI)	105	151/170	158.9	3.76
Tensile Strength (KSI)	105	168/190	176.2	3.95
Elongation (%)	105	6/16	10.5	2.70
Red of Area (%)	105	21/31	24.3	2.76

Dimensions in inches

1 inch = 25.4 mm

1 ksi = 0.70307 kg/mm^2



	No Tests	Range	Avg.	Std. Deviation
Yield Strength (KSI)	140	146/164	155.8	2.96
Tensile Strength (KSI)	140	160/176	168.6	2.29
Elongation (%)	140	6/15	10.7	1.98
Red. of Area (%)	140	20/31	21.8	1.98

FIGURE 4.31. — Dimensions and mechanical properties of typical extruded angle section and Tee-section, STA titanium 6Al-4V.

(Ref. 4.6)

Chapter 4 - References

4.1 J.W. Stamper, "Titanium," in Mineral Facts and Problems, Bureau of Mines Bulletin No. 630, 1965.

4.2 Harvey Titanium, "Titanium," September 1968.

4.3 Titanium Metals Corp. of America, "How to Use Titanium," January 1970.

4.4 H.R. Ogden, "Titanium and Its Alloys," in C.R. Tipton, Ed., Reactor Handbook, Vol. I, Interscience Publishers, New York, 1960.

4.5 D.J. Maykuth, et al., "Titanium Base Alloys: 6Al-4V," DMIC Handbook, February 1971.

4.6 Titanium Metals Corp. of America, "Properties of Titanium 6Al-4V," Technical Bulletin No. 1, November 1968.

Chapter 5

MANUFACTURING PRACTICES

5.1 General. Titanium and its alloys are often compared with austenitic stainless steels in methods, degree of difficulty, and cost of fabrication. In contrast with aluminum, costs of fabrication may run 10 percent higher for detail assembly to 90 percent higher for certain forming operations. Salient differences compared with the fabrication of aluminum or stainless steels are the requirements for higher forming forces, a higher galling rate, a resistance to sudden deformation, a general requirement for heat in production of complex sheet metal details, and a low shrinkability (ref. 5.1).

5.11 Certain fundamental precautions are necessary for heating titanium 6Al-4V (or other titanium alloys) for forming, forging, or heat treating (ref. 5.2):

(a) Furnace temperature must be controlled carefully since only small increments of temperature changes will affect the resulting properties of ST and STA material.

(b) Furnace atmosphere must be carefully controlled, particularly against hydrogen contamination which leads to a brittle titanium hydride phase that causes planes of weakness and oxygen contamination that can cause surface embrittlement. Protective coatings are sometimes useful against interstitial contamination.

(c) Only chlorine-free solvents should be used for cleaning because of the susceptibility of titanium alloys to stress-corrosion cracking under the conditions of residual stress and surface contamination by chlorine.

5.2 Forming

5.21 Sheet and plate. Titanium alloys can be formed in standard machines to tolerances similar to those obtained in the forming of stainless steels, but higher forces are required. However, springback of 15° to 25° in the included bend angle must be expected, and springback of 50° to 60° is not uncommon in some operations. In order to avoid or reduce springback and to gain an increase in ductility, forming of titanium-alloy sheet is done by hot forming or by cold preforming and then hot sizing (refs. 5.1 through 5.6).

Hot sizing is a method of creep-forming rough-shaped parts between matched metal dies at elevated temperatures. The operation is performed at a temperature where residual elastic stresses are relieved and the part is slowly strained to the exact shape of the die (ref. 5.2). The reaction is time-dependent and is accomplished at temperatures in excess of 1000° F (538° C), but is best at about 1300° F (704° C). Suggested operating parameters for hot sizing are given in table 5.21.

5.211 Forming annealed sheet. Many parts of modest contours are made cold, using operations such as:

- Press forming
- Drawing
- Drop hammer forming
- Press-brake forming
- Contour roll forming
- Three-roll forming
- Stretch forming

However, cold forming is limited by the minimum bend factor, the uniform elongation of titanium 6Al-4V, and the degree of springback. The effect of temperature on the bendability of the alloy is shown in table 5.211 (refs. 5.2, 5.4).

Annealed material may be formed at temperatures up to and including 1350° F (732° C) without affecting mechanical properties, but it must be recognized that oxidation becomes sufficiently significant at temperatures over 1100° F (599° C) that descaling and conditioning operations are required. Use of temperatures in excess of 1350° F (732° C) requires ideal conditions (refs. 5.2, 5.4). Operations used in hot forming include:

- Press forming
- Drop hammer forming
- Sizing
- Press brake forming
- Contour roll forming
- Three roll forming
- Stretch forming
- Drawing.

5.212 Forming solution-treated sheet. Solution-treated sheet may be formed in the same manner as annealed sheet, but if hot-forming is required, it is pointed out that an aging reaction will occur at temperatures in excess of 500° F (260° C). Because aging changes the forming characteristics, the work should be performed at temperatures below 500° F or at the maximum permissible temperature of 1000° to 1100° F (538° to 599° C) where overaging occurs. Hot sizing and aging can be done in a common operation (ref. 5.2).

5.213 Forming aged sheet. Only parts that require gentle forming should be made from aged sheet because of the limited formability of fully-aged material. Creep-forming is used on more complex materials, such as those reqiuring a double contour. Caution must be exercised to prevent overaging in excess of 1000° F (538° C) (ref. 5.2).

5.22 Descaling and pickling. Descaling is accomplished mechanically by methods such as grinding and grit blasting; it may also be performed chemically by acid pickling or by immersion in molten caustic or hydride baths.

Scale removal in a nitric acid–hydrofluoric acid bath is limited to very slight scale formed at temperatures below 1100° F (589° C). For higher temperature scales, acid pickling is ineffective and a bath of caustic soda or sodium hydride is used. Oxidizing additives in the baths, such as nitrates, are recommended to reduce the tendency of hydrogen pickup by the titanium alloy.

Pickling is performed generally for dimensional reasons or to remove surface-oxygen contamination. The pickling bath consists of nitric acid and hydrofluoric acid, with a ratio of HNO_3 to HF of about 10:1. Run at bath temperatures between 100° to 150° F (38° to 66° C), rate of attack will be from 1 mil/min to 5/mil/min (0.025—0.125 mm), depending on bath conditions. There is the possibility that hydrogen pickup can occur during pickling (ref.5.2).

5.23 Forging. Essentially the same shapes as are forgeable from steel and other metals can be forged from titanium alloys; however, for the same amount of metal flow, more power is required. Methods used for forging include open-die, closed-die, upset and roll forging, and ring rolling. Often, two methods are used in sequence to obtain a desired shape (ref. 5.4).

The normal forging temperature for titanium 6Al-4V is 1750° F (954° C), which is about 75° F (24° C) below the beta transus (ref. 5.2). Hot working at or over the beta transus temperature will lead to detrimental results in mechanical properties that may be associated with the transformation to an acicular structure that occurs on cooling from the beta phase. Final forging temperatures are kept below the beta transus to eliminate evidence of acicular-transformed beta product resulting from former hot-working steps and to cause discrete alpha globules to form and grow while high in the $\alpha + \beta$ region; such microstructures are associated with optimum ductility. There is, however, strong evidence that transformed acicular microstructures are (by certain measurements of toughness) superior to equiaxed microstructures containing primary alpha islands (ref. 5.2).

Heating above the beta transus temperature may be accompanied by considerable concurrent plastic working, such as in the extrusion process or in rapid forging operations. Excellent toughness characteristics will be yielded by such a process if transformation conditions are controlled following the heating above the beta transus temperature (ref. 5.2).

Lower temperature limits of forging are predicated on the alloy's ability to deform without rupturing. They are also dependent on considerations such as power supply, die configuration, and available equipment (ref. 5.2).

Forgings of titanium 6Al-4V will produce microstructures that provide excellent mechanical properties if a 30-percent final reduction from below the beta transus temperature is utilized for material in the annealed and in the STA conditions (ref. 5.2).

5.3 Machining

5.31 Negative factors to consider in the machining of titanium alloys include: (1) A rapid heat buildup at the cutting interface because titanium is a poor conductor of heat; (2) Reaction with the cutting tool by smearing, galling, and welding; (3) A low modulus that permits the workpiece to move away from the cutting tool with more ease than comparable metals (refs. 5.2, 5.3, 5.7, 5.8).

Primary factors to consider in machining titanium 6Al-4V include:

(a) Low cutting speeds.
(b) Heavy cutting feed rates.
(c) Large volume of nonchlorinated cutting fluid.
(d) Sharp tools.
(e) Never stop feeding while tool and work are in moving contact.
(f) Rigid set-ups. (Refs. 5.2, 5.3, 5.8)

High-speed steels are used most generally for machining titanium because of their low initial cost and the flexibility of available tool configurations. The optimum cutting tools for machining titanium are the cemented carbides (which are generally used only where production rates are high); also, carbides are limited generally to single-point tool operation (ref. 5.2).

Cutting fluids are used primarily as coolants to remove excessive heat buildup; water-based fluids do a better job than oils (ref. 5.2). A weak solution of rust inhibitor and/or water-soluble oil is most practical for high-speed cutting operations. For slow-speed and complex operations, oils do a better job. Nonchlorinated cutting fluids should be used to alleviate stress-corrosion cracking in post-machining operations (ref. 5.2).

Vitrified-bonded wheels are the most effective for hard wheel grinding. Aluminum oxide gives the best results, but is limited to the lower grinding speeds. If higher speeds are necessary, silicon-carbide wheels can be used. For belt grinding, a silicon-carbide abrasive is preferable to aluminum oxide (ref. 5.2). Moderate cutting speeds are recommended, and periodic dressings are necessary to keep the wheel in proper condition. Whenever a choice is available, milling is recommended over grinding (ref. 5.3).

5.32 Milling. The predominant mode of failure in milling is chipping. In the cutting phase during each revolution, some welding of titanium may take place on the cutting edge. Subsequently, the welded-on chips are knocked off, along with a small part of the cutting edge. Wear of this type can be lessened by producing a thin chip as the cutting teeth leave the work; this means a climb out with the feed going in the same direction as the cutting teeth in slab or peripheral cutting. In face milling, it means placing the cutter so that the teeth emerge on a line parallel to the direction of the tool; light feeds at low speeds should be used. A rigid set-up of the tool is required, and sharp tools must be maintained (refs. 5.3, 5.8, 5.9).

5.33 Recommended practices for machining titanium 6Al-4V are given in table 5.33.

5.4 Chemical Milling

5.41 Etchants used generally for chemical milling of titanium alloys are aqueous solutions of hydrofluoric acid. For example, 10 percent hydrofluoric acid solution maintained at 104° F (40° C) gives good results with titanium 6Al-4V (ref. 5.11). More complex mixtures of proprietary etchants include $HF-HNO_3$ mixtures or $HF-CrO_3$ mixtures; special reagents may be added for enhancing etching characteristics and inhibiting hydrogen pick-up (refs. 5.7, 5.12). Production etching rates for titanium alloys range from 0.0010 to 0.0015 inch (25.4–38.0 µm) per minute. Typical tolerances are about ±0.002 inch (50.8 µm) in depth and 15 to 50 microinches (0.38–1.3 µm) surface roughness (see table 5.41).

Titanium 6Al-4V tank segments have been successfully chemically milled to close tolerances with an etchant developed to provide a lower rate of etching than can be obtained with standard etchants used in production, that is, 13 µm (0.5 mil) per minute or less compared with 25–38 µm/min (see above). The slow rate is required to achieve the precise thickness control necessary for the selective chemical milling procedure, which involves final milling in 25-µm (1-mil) steps (ref. 10.14).

A. Etchant composition and conditions:

Nitric acid (67° HNO_3): 2.1–2.3 kg (75–85 oz)
Hydrofluoric acid (70%): 0.5–0.6 kg (18–22 oz)
Titanium ion: 1.3–105 g (0.045–3.7 oz)
Water: to make 3.8 liters (1 gal)

Operating temperature: 21°–35° C (70°–95° F)

Note: Add 225 g (8 oz) dodecylbenzene sulfonic acid per 3785 liters (1000 gals) of solution, for each day of usage.

B. Selective chemical milling steps:

Preliminary. Use standard procedures of cleaning, pickling, and masking for close tolerance chemical milling, and mill major metal areas until minimum thickness in one area approaches the lower thickness limit, and rinse.

1. **Make Vidigage readings and mark on chemically milled surface.**
2. **Clean part, but do not remove Vidigage readings.**
3. **Mask chemically milled surfaces (remainder of part is masked).**
4. **Copy Vidigage readings and mark contour pattern on maskant.**
5. **Starting with thickest areas, remove maskant in steps until a uniform thickness has been obtained over the area being chemically milled.**
6. **Spray rinse parts as they are being removed from the etchant.**

The results of some tensile, compressive, and other tests showed that chemical milling had no significant effect on the mechanical properties of titanium 6Al-4V (ref. 5.12). However, chemical milling may cause pitting or intergranular attack. Also, hydrogen may be absorbed to an extent depending on the amount of beta phase present, the composition of the etchant, and the time and temperature of exposure. In one study, an alpha alloy was not embrittled, titanium 6Al-4V was slightly embrittled, and an all-beta alloy was severely embrittled. By vacuum annealing, ductility could be restored to the all-beta alloy. Hence, conditions for chemical milling must be carefully controlled so that hydrogen absorption is minimized (ref. 5.7).

5.42 Electrochemical Milling. Data and information on electrolytes and operations for electrochemical milling (ECM) are largely proprietary. However, it has been reported that waffle-grid panels have been successfully produced by ECM (refs. 5.12, 5.13). Some loss in fatigue strength of the riser portions of the grid was attributed to the relatively rough surface finish of the risers. In an instance of machining as-forged compressor blades, the ECM surfaces were very smooth with surface roughness values of 8 to 10 microinches (0.203 to 0.254 μm).

TABLE 5.21. – Suggested Parameters for Hot Sizing

Source	Ref. 5.12	
Alloy	Titanium 6Al-4V	
Temperature	Tool Material	Lubricant
1000° to 1300°F (538° to 704°C)	Mild steel High-silicon cast iron High-silicon modular cast iron H-13 tool steel Type 310 and RA330 stainless st. Inconel X Hastelloy X Incoloy 802 Nicrosil Cast H-H Type II	Colloidal graphite (e.g., Everlube T-50 Formkote)

TABLE 5.211. – Effect of Temperature on Minimum Bend Radius

Source		Ref. 5.2	
Alloy		Titanium 6Al-4V Sheet, Annealed	
Temperature		Bend radius, 105° x thickness (in)	
°F	°C	min	typical
70	21	4.5	3.3
400	205	4.0	3.0
600	316	4.0	2.7
800	427	4.0	2.4
1000	538	3.0	1.8
1200	649	2.5	0.8
1400	760	1.5	-
1500	816	1.0	-

TABLE 5.33. — Recommended Practices for Machining Titanium 6Al-4V Alloy

Source	Ref. 5.10									
Operation	Tool Material	Tool Geometry (a)	Test Tool (b)	Depth of Cut	Feed	Wear-land	Annealed (c)		STA (d)	
							Cutting Speed	Tool Life	Cutting Speed	Tool Life
Turning	C2	BR:0°; SR:6°; SCEA:6°; ECEA:6°; Relief:6°; NR:0.040 in	5/8 in^2 brazed tool	0.050 in	0.009 in/rev	0.016 in	165 ft/min	68 min	150 ft/min	70 min
Turning	M3	BR:0°; SR:5°; SCEA:0°; ECEA:5°; Relief:5°; NR:0.020 in	5/8 in^2 tool bit	0.050	0.005 in/rev	0.060	65	64 min	55	70 min
Face milling	C2	AR:0°; RR:-10°; CA: 30°; TR:-9°; incl:5°; ECEA:6°; Cl:12°	4-in diam single tooth face mill	0.050 (2-in width)	climb cut 0.006 in/tooth	0.016	95	42 in/tooth	95	62 in/tooth
Face milling	T15	AR:0°; RR:0°; CA:30°; TR:0°; incl:0°; ECEA: 6°; Cl:12°	4-in diam single tooth face mill	0.050 (2-in width)	climb cut 0.005 in/tooth	0.060	75	50 in/tooth	75	44 in/tooth
Drilling	M10	118° point angle; Cl:7°; helix angle:29°; plain point	0.203-in diam drill; 2-3/4 in flute length	1/2 in (through hole)	0.005 in/rev	0.015	35	85 holes	25	30 holes
Tapping	M10	3-flute taper tap, spiral point, 70% thread	1/4-20 NC taper tap	1/2 in (through hole)	-	tap breakage	15	75 holes	15	15 holes

(a) BR = back rake; SR = side rake; SCEA = side cutting edge angle; ECEA = end cutting edge angle; NR = nose radius; AR = axial rake; RR = radial rake, CA = corner angle; TR = resultant rake; incl = inclination; Cl = clearance; NC = national coarse; C2 = carbide; M1, M2, M3, M10, T15 = high speed steels.

(b) Cutting fluids: soluble oil, 1:20, for turning and milling; highly sulfurized oil for drilling and tapping.

(c) Hardness, BHN 312.

(d) Hardness, BHN 365.

Note: 1 inch = 25.4 mm; 1 foot = 30.48 cm.

TABLE 5.41. – Comparison of Data and Characteristics of Systems for Chemically Milling Different Alloy Types

Source	Ref. 12.15		
Item	Titanium Alloys	Steels	Aluminum Alloys
Principal reactants	Hydrofluoric acid	Hydrochloric acid–nitric acid	Sodium hydroxide
Etch rate			
mils/min	0.6 to 1.2	0.6 to 1.2	0.8 to 1.2
μm/min	15 to 30	15 to 30	20 to 30
Optimum etch depth			
inch	0.125	0.125	0.125
mm	3.175	3.175	3.175
Etchant temperature			
°F	115 ±5	145 ±5	195 ±5
°C	46 ±3	63 ±3	91 ±3
Exothermic heat			
Btu/ft^2/mil	160	130	95
cal/cm^2/mm	1699	1380	1008
Average surface finish			
rms microinch	40 to 100	60 to 120	80 to 120
rms μm	1.02 to 2.54	1.52 to 3.05	2.03 to 3.04

Chapter 5 - References

5.1 Titanium Metals Corp. of America, "How to Use Titanium," January 1970.

5.2 Titanium Metals Corp. of America, "Properties of Titanium 6Al-4V," November 1968.

5.3 Harvey Titanium, "Titanium," September 1968.

5.4 Metals Handbook, Vol. 4, "Forming," 8th Edition, American Society for Metals, Metals Park, Ohio, 1969.

5.5 R.E. Avery and S.C. Orr, "Improved Fabrication Techniques and Lower Costs Favor Titanium's Use," Corrosion, 14 (1), 119 (1958).

5.6 G.T. Bedford, W.J. Weeks, and A.G. Caterson, Chem. Eng., 63 (12), 238 (1956).

5.7 Metals Handbook, Vol. 3, "Machining," 8th Edition, American Society for Metals, Metals Park, Ohio, 1967.

5.8 Titanium Metals Corp. of America, "Titanium Machining Techniques," Engineering Bulletin No. 7, August 1969.

5.9 A.L. Winkler, "Milling Titanium Alloys," Iron Age, October 10, 1957, page 126.

5.10 Metcut Research Associates and Air Force Materials Laboratory, Metal Progress Databook: 1968, page 114.

5.11 American Machinist, April 22, 1968, page 150.

5.12 D.J. Maykuth, et al., "Titanium Base Alloys: 6Al-4V," DMIC Handbook, February 1971.

5.13 J.A. Gurklis, "Metal Removal by Electrochemical Methods and Its Effects on Mechanical Properties of Metals," DMIC Report 213, January 7, 1965.

5.14 D.M. Shuford, "Chemical Milling Close Tolerance Titanium Tank Segments," Plating, 57, 605 (1970).

5.15 Harvey Titanium, "Machining of Titanium," August 1970.

Chapter 6

SPACE ENVIRONMENT EFFECTS

6.1 General. Titanium and its alloys are used successfully in both structural and nonstructural applications for launch vehicles and spacecraft. In general, these alloys are relatively insensitive to degradation under typical space environment conditions.

6.2 The low pressure encountered in space is conducive to the loss of materials of construction by sublimation (or evaporation) because molecules which leave the surface of materials are not returned by collisions with ambient gas molecules. Thus, above altitudes of about 160 km, the mean free path of a molecule at ambient temperatures is so long in comparison with the size of the spacecraft that any molecule which leaves the surface will not return. Loss of material by sublimation in the vacuum of space is intuitively obvious, but the effect of very high vacuum on the rupture and fatigue properties of materials is unexpected; however, experiments have indicated that the density of the gas surrounding a material is an important parameter defining its behavior under stress. Apparently, the character of the gas layer adsorbed on materials influences certain mechanical properties. Thus, prolonged exposure of materials to a space environment will alter or remove adsorbed gas layers and some of the physical properties of the materials in space will be different than on earth.

The removal of material from a spacecraft structure will obviously lead to an overall weakening of members. The weakening of a member can be simply computed by knowledge of the mass-strength relationship. Where gross sublimation of a material is involved, tests made before and after exposure of specimens to a vacuum will furnish experimental values. Ideally, the tests should be performed in an atmosphere closely resembling the space environment; however, for practical evaluation of the effects of sublimation, the most important condition to be met is that a molecule leaving the surface of the test piece has a negligible chance of returning.

The rate of evaporation of an ideal, pure substance is given by Langmuir's equation:

$$E = \frac{P}{17.14}\sqrt{\frac{M}{T}}$$

where E is the rate in $g\text{-}sec^{-1}\text{-}cm^{-2}$ of exposed surface, M is the molecular weight of the material, P is the equilibrium vapor pressure in torr, and T is the absolute temperature, °K.

Comparison of predictions from the above equation with experimental data indicate that the Langmuir equation is conservative; thus, the equation must be employed cautiously. Further, it is necessary to recognize that its use to predict vacuum volatility is limited by:

a. The vapor pressure, P, in the equation is the equilibrium pressure. In the space environment, molecules which leave the surface of the liquid or solid phase do not return, and thus equilbrium is not established.

b. The molecular weight of the evaporating molecules must be known; for most materials, this molecular weight is frequently different than assumed (association).

c. Oxide films or thin coatings may act as barriers to the escape of molecules.

d. In practice, most materials are complex mixtures (alloys or polymers) which defy simple treatment. The average assumed molecular weight of a system can not be used in the equation.

e. The process of evaporation for systems of practical interest is very different from the purely random process assumed to ideal systems. For example, evaporation from localized planes of high surface energy is much greater than from planes of low energy; this leads to uneven evaporation, and etching of the surface becomes evident.

As is evident from the above discussion, the Langmuir equation is limited to approximations of evaporation rates in a space environment; it is useful in that it assists in the selection of appropriate materials of construction for spacecraft. For example, the equation indicates that every substance has a rate of evaporation in free space as long as the absolute temperature is not zero. Thus, at a given temperature, say 25° C, one should select materials which exhibit very low vapor pressures; obviously, the usual metals of construction (iron, copper, etc.) can qualify, but there is some question about the lighter metals such as cadmium, magnesium, aluminum, etc. Table 6.1 illustrates the estimated sublimation losses suffered by metals in a space environment over a moderate range of temperatures; it is anticipated that at lower temperatures, the rate of evaporation will be infinitesimal. It is evident that zinc does not appear to be a useful metal for the construction of spacecrafts or components which are exposed to the high vacuum of space. Pure magnesium metal barely qualifies for the construction of spacecrafts; however, the alloys of magnesium which are currently used show considerably lower losses because the surface presented to the space environment acts as a barrier for sublimation (oxide-chromate conversion coatings, etc.). Thin films of lead (as in soldered joints) may be weakened by prolonged exposure to the space environment. On the other hand, a thin coating of pure tin will act as an efficient barrier for sublimation of other materials. (Ref. 6.5).

6.3 **The effects of nuclear and indigenous space radiation on the mechanical properties of titanium alloys are not clearly defined since no tensile tests of significance have been performed on irradiated specimens (ref. 6.15). Tests performed with difficulty on titanium 6Al-4V at cryogenic temperatures indicate that, at a relatively-low fast fluence (10^{18} n/cm^2), radiation causes increases in yield and ultimate strengths and reductions of ductility.**

Sputtering of the surface by atomic or molecular particles can deteriorate surface finishes in a relatively short period. The sputtering process is associated with a minimum threshold energy value for atomic or molecular particles striking a material surface. Typical values which have been obtained for this threshold energy are 6, 11, and 12 eV for O, N_2, and O_2 particles, respectively, to remove one or more atoms from the materials' surface upon which they impinge (ref. 6.11). Loss of metal by this mechanism can vary over a wide range and the greatest loss may be expected during solar storms (ref. 6.4). However, loss of metal by sputtering has little structural significance, although it may seriously affect optical and emissive properties of the material surface.

The surface erosion of metals and alloys due to corpuscular radiation is probably insignificant, amounting to something of the order of .25 μm per year. Indigenous space radiation, however, will tend to accelerate the removal of surface films on titanium alloys, which might result in the 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 if the alloy is used for electrical applications.

6.4 Micrometeoroids can produce surface erosion similar to sputtering but on a more macroscopic scale, and may also produce punctures. They vary widely in mass, composition, velocity, and flux; generalizations about rates of erosion and penetration, therefore, must be used with care. The predicted frequency of impact as a function of meteoroid mass is given in figure 6.1. Calculations of armor thickness required for meteoroid protection are given in reference 6.11.

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^{-18}
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.**

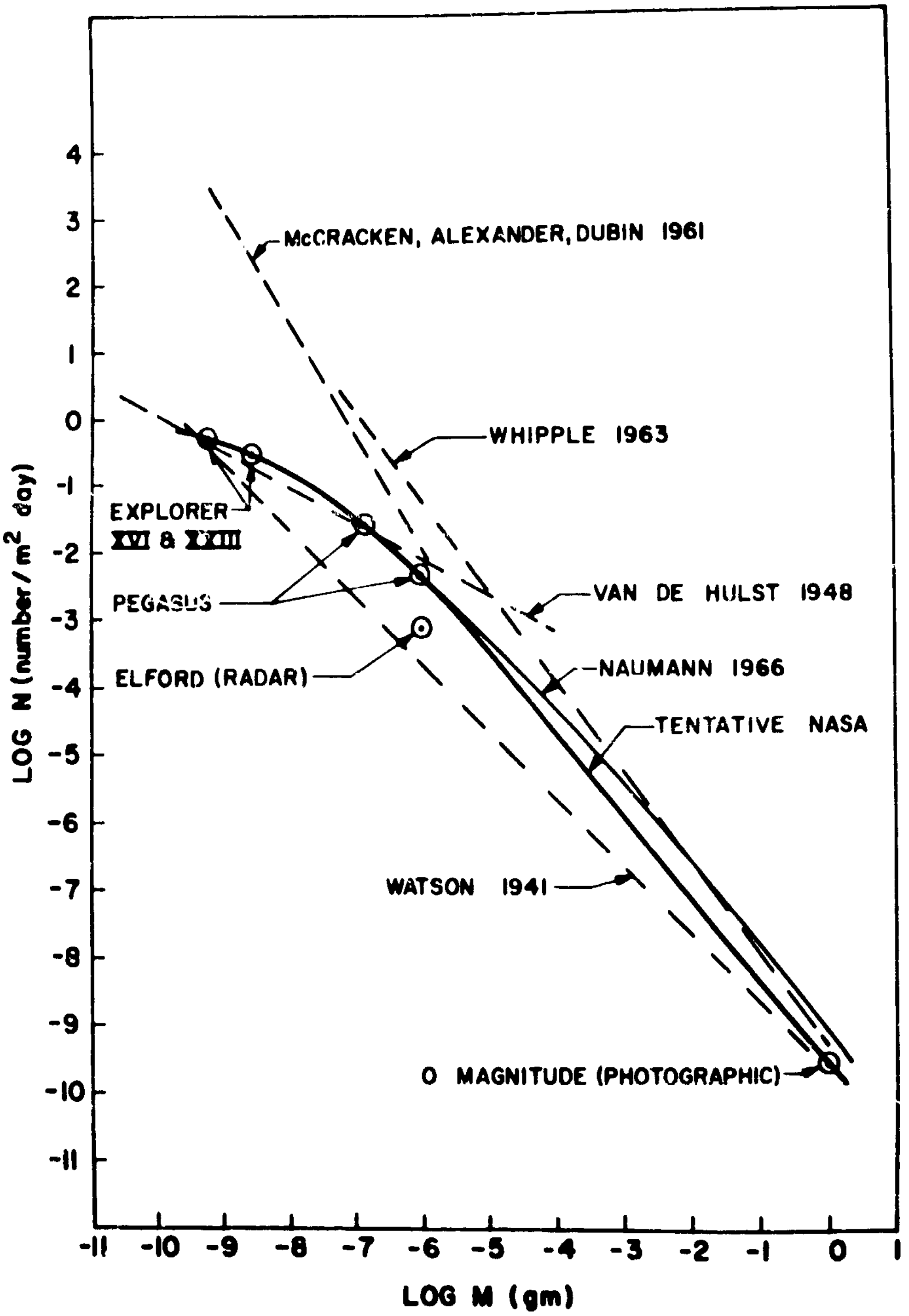


FIGURE 6.1. — Various estimates of meteoroid mass influx. (Ref. 6.3)

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 R.F. Muraca, et al., "Design D[illegible] for Pressurized Gas Systems," NASA Contract NAS7-105, November 1963.

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

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

6.8 F.G. Watson, Between the Planets, The Blakiston Co, Philadelphia; 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 K.S. Clifton and P.J. Naumann, "Pegasus Satellite Measurements of Meteoroid Penetration," NASA TM X-1316, 1966.

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.

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

Chapter 7

STATIC MECHANICAL PROPERTIES

7.1 Specified Properties

7.11 NASA Specified Properties

7.12 AMS Specified Properties (see table 2.2 for specification numbers and descriptions).

7.13 Military Specified Properties (see table 2.2).

7.14 Federal Specified Properties

7.15 ASTM Specified Properties (see table 2.2).

7.2 Elastic Properties and Moduli

7.21 Poisson's ratio, 0.342 (ref. 7.1).

7.22 Young's modulus of elasticity, E.

7.221 Design value of E for all forms, 16.0×10^3 ksi (11.2×10^3 kg/mm^2). (ref. 7.2).

7.222 Dynamic modulus of elasticity for annealed and STA titanium 6Al-4V versus temperature, figure 7.222.

7.23 Compression modulus, E_c

7.231 Design value of E_c for all forms, 16.4×10^3 ksi (11.5×10^3 kg/mm^2). (ref. 7.2).

7.232 Effect of temperature on the tensile and compressive modulus of annealed sheet and bar, figure 7.232.

7.233 Effect of temperature on the tensile and compressive modulus of solution-treated and aged alloy, figure 7.233.

7.24 Modulus of rigidity (shear modulus), G

7.241 Design value of G for all forms, 6.2×10^3 ksi (4.4×10^3 kg/mm^2)(ref. 7.2).

7.25 Tangent modulus

7.251 Typical compressive tangent modulus curves (longitudinal) for solution treated and aged alloy at room and elevated temperatures, figure 7.251.

7.252 Typical compressive tangent modulus curves (transverse) for solution treated and aged alloy at room and elevated temperatures, figure 7.252.

7.26 Secant modulus

7.3 Hardness

7.31 Typical hardness values for all wrought forms, annealed, RC = 30 (refs. 7.4, 7.5).

7.32 Specified hardness for castings, BHN = 365, max (ref. 7.8).

7.4 Strength Properties (see also Chapter 3)

7.41 Tension

7.411 Design tensile properties

7.4111 Design tensile properties for sheet, strip, and plate, table 7.4111.

7.4112 Design tensile properties for bars and forgings, table 7.4112.

7.4113 Design tensile properties for extruded bars, rods, and special shaped sections, table 7.4113.

7.412 Stress-strain diagrams (tension)

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7.4124 Typical tensile stress-strain curves at cryogenic, room, and elevated temperatures for annealed alloy, figure 7.4124.

7.413 Effect of temperature on tensile properties

7.4131 Effect of temperature on the ultimate tensile strength of STA alloy, figure 7.4131.

7.4132 Effect of temperature on the tensile yield strength of STA alloy, figure 7.4132.

7.4133 Effect of cryogenic and elevated temperatures on ultimate tensile strength of annealed sheet and bar, figure 7.4133.

7.4134 Effect of cryogenic and elevated temperatures on tensile yield strength of annealed sheet and bar, figure 7.4134.

7.4135 Effect of temperature on tensile properties of annealed sheet, figure 7.4135.

7.4136 Effect of cryogenic and elevated temperatures on elongation of annealed sheet and bar, figure 7.4136.

7.4137 Effect of cryogenic temperatures on tensile properties of annealed bar stock and sheet, table 7.4137.

7.4138 Effect of temperatures to 1600° F (871° C) on mechanical properties of annealed and STA specimens, table 7.4138.

7.42 Compression

7.421 Design compression properties

7.4211 Design compression properties for sheet and strip, see table 7.4111.

7.4212 Design compression properties for annealed bars and forgings, see table 7.4112.

7.422 Stress strain diagrams (compression)

7.4221 Typical compressive stress-strain curves at room and elevated temperatures for annealed bar, figure 7.4221.

7.4222 Typical compressive stress-strain curves at room and elevated temperatures for annealed sheet, figure 7.4222.

7.4223 Typical compressive stress-strain curves (longitudinal) at room and elevated temperatures for STA sheet, figure 7.4223.

7.4224 Typical compressive stress-strain curves (transverse) at room and elevated temperatures for STA sheet, figure 7.4224.

7.423 Effect of temperature on compressive strength

7.4231 Effect of room and elevated temperatures on compressive yield strength of annealed alloy sheet and bar, figure 7.4231.

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7.442 Design shear properties for annealed bars and forgings, see table 7.4112.

7.443 Effect of temperature on ultimate shear strength of annealed sheet and bar, figure 7.443.
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7.454 Effect of temperature on the bearing yield strength of annealed sheet and bar, figure 7.454.
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7.461 Notch strength
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7.462 Fracture toughness
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7.4622 Fracture toughness of alloy at various strength levels, figure 7.4622.

TABLE 7.4111. – Design Mechanical Properties of Titanium 6Al-4V Sheet, Strip, and Plate

Alloy	MIL–T-9046, Type III, Comp. C							
Form	Sheet, strip, and plate							
Condition	Annealed			Solution-treated and aged				
Thickness or diameter, in.	≤ 0.1875		0.1876–4.000	≤ 0.1875	0.1875 to 0.750	0.751 to 1.000	1.001 to 2.000	2.001 to 4.000
Basis	A	B	S	S	S	S	S	S
Mechanical properties:								
F_{tu}, ksi	134	139	130	160	160	150	145	130
F_{ty}, ksi	126	131	120	145	145	140	135	120
F_{cy}, ksi:								
L	132	138	126	154				
T	132	138	126	162				
F_{su}, ksi	79	81	76	100				
F_{bru}, ksi:								
(e/D = 1.5)	197	204	191	238				
(e/D = 2.0)	252	261	245	286				
F_{bry}, ksi:								
(e/D = 1.5)	171	178	163	210				
(e/D = 2.0)	208	216	198	232				
e, percent:								
In 2 in.	[a]8		10	[b]5	8	6	6	6

[a] 8–0.025 to 0.062 in.
10–0.063 in. and above.

[b] 5–0.050 in. and above.
4–0.033 to 0.049 in.
3–0.032 in. and below.

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

(Ref. 7.2)

TABLE 7.4112. — Design Mechanical Properties of Titanium 6Al-4V Bars and Forgings

Alloy	MIL-T-9047, Type III, Comp. A										
Form	Bars and forgings										
Condition	Annealed	Solution-treated and aged									
Width, in.			0.5001–8.000	1.001–4.000	4.001–8.000	1.501–4.000	4.001–8.000	2.001–4.000	4.001–8.000	3.001–8.000	4.001–8.000
Thickness, in.	≤3.000	≤0.5000	≤0.5000	0.5001–1.000		1.001–1.500		1.501–2.000		2.001–3.000	3.001–4.000
Basis	S	S	S	S	S	S	S	S	S	S	S
Mechanical properties:											
F_{tu}, ksi	130	165	160	155	150	150	145	145	140	135	130
F_{ty}, ksi	120	155	150	145	140	140	135	135	130	125	120
F_{cy}, ksi	126										
F_{su}, ksi	80										
F_{bru}, ksi:											
(e/D = 1.5)	196										
(e/D = 2.0)	248										
F_{bry}, ksi:											
(e/D = 1.5)	174										
(e/D = 2.0)	205										
e, percent:											
In 4D	10										
L		10	10	10	10	10	10	10	10	10	8
T			10	10	10	10	10	10	10	8	6

Note: 1 inch = 25.4 mm; 1 ksi = 0.70307 kg/mm^2 (Ref. 7.2)

TABLE 7.4113. – Design Mechanical Properties of Titanium 6Al-4V Extrusions

Alloy	MIL-T-81556, Type III, Comp. A					
Form	Extruded Bars, Rods, and Special Shaped Sections					
Condition	Annealed	Solution Treated and Aged				
Thickness or diameter, in.	≤4.00	≤0.50	0.51–0.75	0.76–1.00	1.01–2.00	2.01–4.00
Basis	S	S	S	S	S	S
Mechanical properties:						
F_{tu}, ksi	130	160	155	150	140	130
L						
T						
F_{ty}, ksi	120	150	145	140	130	120
L						
T						
F_{cy}, ksi						
L						
T						
F_{su}, ksi						
F_{bru}, ksi:						
(e/D = 1.5)						
(e/D = 2.0)						
F_{bry}, ksi:						
(e/D = 1.5)						
(e/D = 2.0)						
e, per cent:						
In 2 in.	......	6	......	......	......	......
In 4 D	10	......	6	6	6	6

Note: 1 inch = 25.4 mm; 1 ksi = 0.70307 kg/mm^2 (Ref. 7.2)

TABLE 7.4137. — Tensile Properties of Annealed Sheet and Bar Stock at Cryogenic Temperatures

Source		Refs. 7.9, 7.10							
Alloy		Titanium 6Al-4V							
Material		Temperature		F_{tu},		F_{ty},		Elongation, %	
		°F	°C	ksi	kg/mm²	ksi	kg/mm²	in/1"	in/2"
Bar stock, 5/8-in diam (15.9 mm)		70	21	143	101	133	94	14	-
		-105	- 76	186	131	181	127	12	-
		-240	-151	214	150	203	143	10	-
		-320	-196	240	169	219	154	9	-
		-452	-253	262	184	252	177	9	-
Sheet, 0.060 in (1.52 mm)		70	21	151	106	141	99	13.0	-
		-105	- 76	169	119	157	110	2.5	-
		-240	-151	192	135	173	122	8.0	-
		-320	-196	221	155	214	150	7.0	-
Sheet, 0.062 in (1.57 mm)	-L	75	24	138.9	97	133.0	94	-	11.0
	-T			150.9	106	145.6	102	-	11.3
	-L	-100	- 73	161.3	113	157.9	111	-	9.3
	-T			170.4	120	169.2	119	-	10.0
	-L	-200	-129	178.3	125	176.7	124	-	6.5
	-T			189.6	133	188.8	132	-	5.2
	-L	-320	-196	218.1	153	214.0	150	-	13.0
	-T			220.5	155	218.8	154	-	14.8
	-L	-423	-253	239.6	168	240.4	169	-	1.7
	-T			241.9	170	240.2	169	-	2.0
	-L	-450	-268	242.3	170	-	-	-	0.2

TABLE 7.4138. — Mechanical Properties of Alloy at Temperatures to 1600° F (871° C)

Source	Ref. 7.13							
Alloy	Titanium 6Al-4V (a, b, c)							
Condition	Temperature °F	°C	F_{tu} ksi	kg/mm²	F_{ty} (0.2% offset) ksi	kg/mm²	e(2in), % (e)	RC (e)
Annealed	RT		142.5	100.1	138.7	97.5	12	35
	1000	538	79.2	55.7			11	
	1200	649	52.3	36.8			16	
	1400	760	28.1	19.8			24	
	1600	871	12.5	8.8			32	
STA (d)	RT		160.0	112.5	152.5	107.3	3	37
	1000	538	99.0	69.6			8	
	1200	649	54.9	38.6			12	
	1400	760	27.0	19.0			20	
	1600	871	12.5	8.8			30	

(a) Each value represents the average of at least 3 tests

(b) Strength values listed are within ±0.5 ksi (0.35 kg/mm²); room temperature elongation values are within ±0.5%

(c) Elevated temperatures were held within 0–6° F (0–3° C) of listed values

(d) Solution heat treated at 1700° F (927° C), 30 min; WQ; aged 5 hrs at 950° F (510° C)

(e) 2 inch = 50.8 mm; RC = hardness Rockwell C scale

TABLE 7.4611. – Effect of Heat Treatment on Static Notch Strength of Alloy

Source	Ref. 7.4				
Alloy	Titanium 6Al-4V				
Heat Treatment	SNS/UTS Ratio (a)	UTS at RT		Static Notch Strength	
		ksi	kg/mm^2	ksi	kg/mm^2
1300° F (704° C) 1 hr, AC	1.40	150	105	210	148
1500° F (816° C) 1 hr, AC	1.36	165	116	225	158
1500° F (816° C) 1 hr, FC to 1200° F (649° C)	1.43	150	105	215	151
1750° F (954° C) 1 hr, WQ, 1100° F (599° C) 8 hrs, AC	1.26	[illegible]	123	220	155

(a) $K_t = 4.5$

TABLE 7.4612. – Effect of Cryogenic Temperature on Notched-Unnotched Strength Ratio of Annealed Alloy Sheet

Source	Refs. 7.9, 7.10					
Alloy	Titanium 6Al-4V					
Thickness	K_t	Temperature		F_{ty} (Unnotched)		Unnotched/Notched Strength Ratio
		°F	°C	ksi	kg/mm^2	
0.060 in (1.52 mm)	11.1	70	21	151	106	1.01
	11.1	-105	-76	169	119	0.98
	11.1	-240	-151	192	135	0.92
	10.0	-320	-196	221	155	0.78
0.062 in (1.57 mm)	10.0	75	24	138.9	97	1.02
	10.0	-100	-73	161.3	113	1.00
	10.0	-200	-129	178.3	125	0.99
	10.0	-320	-196	218.1	153	0.82
	10.0	-423	-253	239.6	168	0.61
	10.0	-450	-268	242.3	170	0.62

TABLE 7.4621. — Average Plane-Strain Fracture Toughness Data for Alloy

Source	Ref. 7.11										
Alloy	Titanium 6Al-4V										
Form	Test Temp. °F	°C	F_{ty}, ksi (a)	F_{tu}, ksi (a)	Test Specimen Orient. (b)	Av K_{IC}, ksi$\sqrt{in}$	$\left[\frac{K_{IC}}{Y.S.}\right]^2$	Specimen Dimensions, in(a) Thickness	Width	Crack Length	No. of Tests
Plate (c)	75	23.9	133	143	RW	(75.8)*	0.32	0.78	1.5	0.3	2
1-inch Plate (d)	75	23.9	148	157	RW	46.3	0.098	1.00	1.00	0.19-0.30	3
	75	23.9	-	-	WR	42.2	0.081	1.00	1.00	0.19-0.30	3
	-50	-45.6	-	144	RW	45.6	0.061	1.00	1.00	0.27-0.35	2
	-100	-73.3	185	190	RW	46.2	0.062	1.00	1.00	0.18-0.26	3
1-inch Plate (d)	75	23.9	167	175	RW	47.1	0.094	0.9	1.00	0.20-0.44	3
	75	23.9	-	-	WR	37.2	0.056	0.9	1.00	0.20-0.28	3
	-50	-45.6	175	176	RW	40.5	0.054	1.00	1.00	0.20-0.38	3
	-100	-73.3	-	180	RW	42.3	0.059	1.00	1.00	0.20-0.30	3
1-inch Plate (d)	75	23.9	158	169	RW	51.3	0.132	1.00	1.00	0.20-0.39	3
	-50	-45.6	177	189	RW	53.0	0.090	1.00	1.00	0.23-0.34	3
	-100	-73.3	173	184	RW	53.5	0.095	1.00	1.00	0.20-0.31	3
3-inch Forged Plate (e)	75	23.9	140	-	RW	80.9	0.33	2.00	4.00	2.0	3
	75	23.9	140	148	WR	79.3	0.32	2.00	4.00	2.0	3
	100	37.8	133	141	WR	71.1	0.29	2.00	4.00	2.0	2
	150	65.6	127	138	WR	78.0	0.38	2.00	4.00	2.0	2
	32	0	148	155	WR	65.0	0.19	2.00	4.00	2.0	2
	0	-17.8	147	155	WR	69.6	0.22	2.00	4.00	2.0	2
	-40	-40.0	153	160	WR	71.5	0.22	2.00	4.00	2.0	2
	-75	-59.5	159	165	WR	68.1	0.19	2.00	4.00	2.0	2

*K_{IC} value in parenthesis does not comply with requirement that specimen thickness be equal to or greater than 2.5 $(K_{IC}/Y.S.)^2$. [1 ksi$\sqrt{in}$ = 3.543 kg/mm$^{3/2}$]

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

(b) R = rolling direction; W = width direction

(c) 1750° F (954° C), WQ, 1000° F (538° C), 4 hrs.

(d) 1700° F (927° C), AC, 1000° F (538° C), 4 hrs.

(e) 1750° F (954° C), AC, 1000° F (538° C), 4 hrs

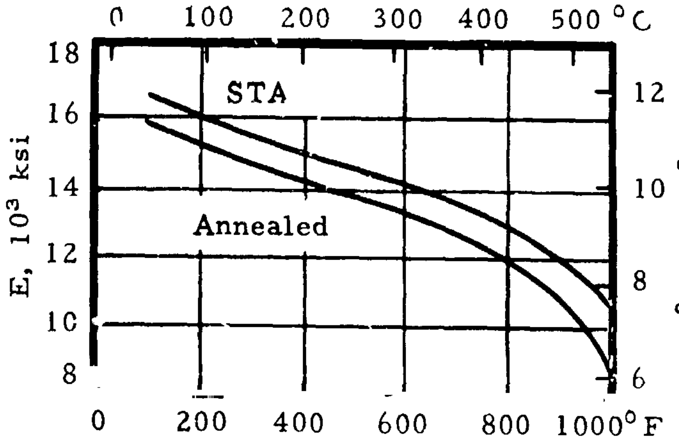

FIGURE 7.222. – Dynamic modulus of elasticity of titanium 6Al-4V versus temperature. (Ref. 7.3)

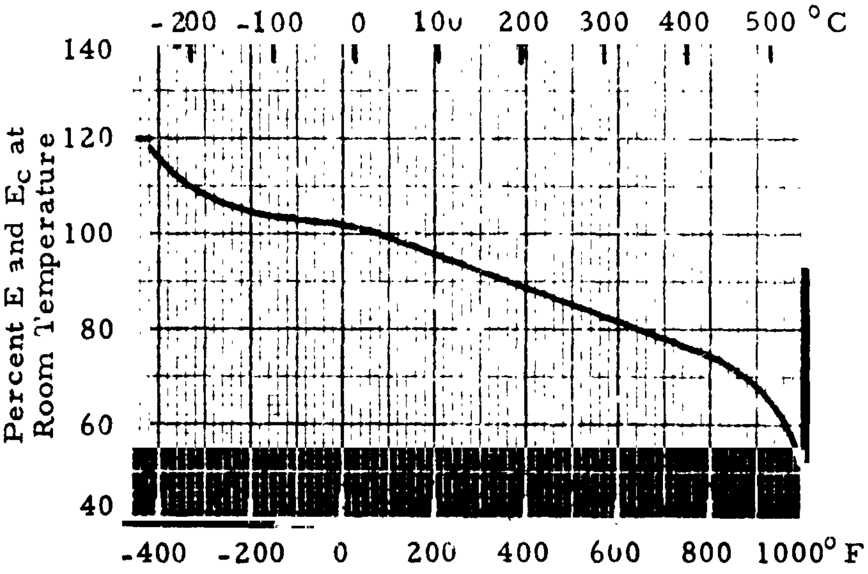

FIGURE 7.232. – Effect of temperature on E and E_c of annealed titanium 6Al-4V sheet and bar. (Ref. 7.2)

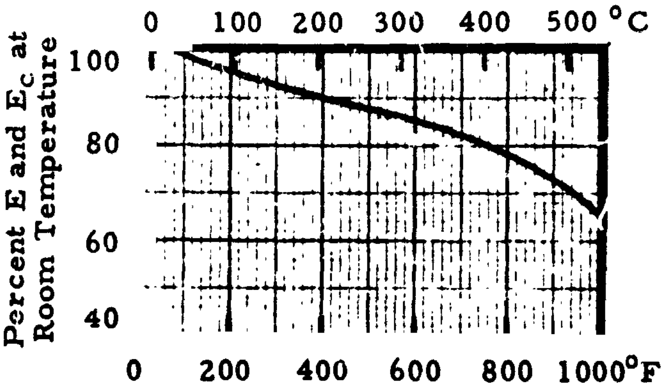

FIGURE 7.233. – Effect of temperature on E and E_c of STA titanium 6Al-4V. (Ref. 7.2)

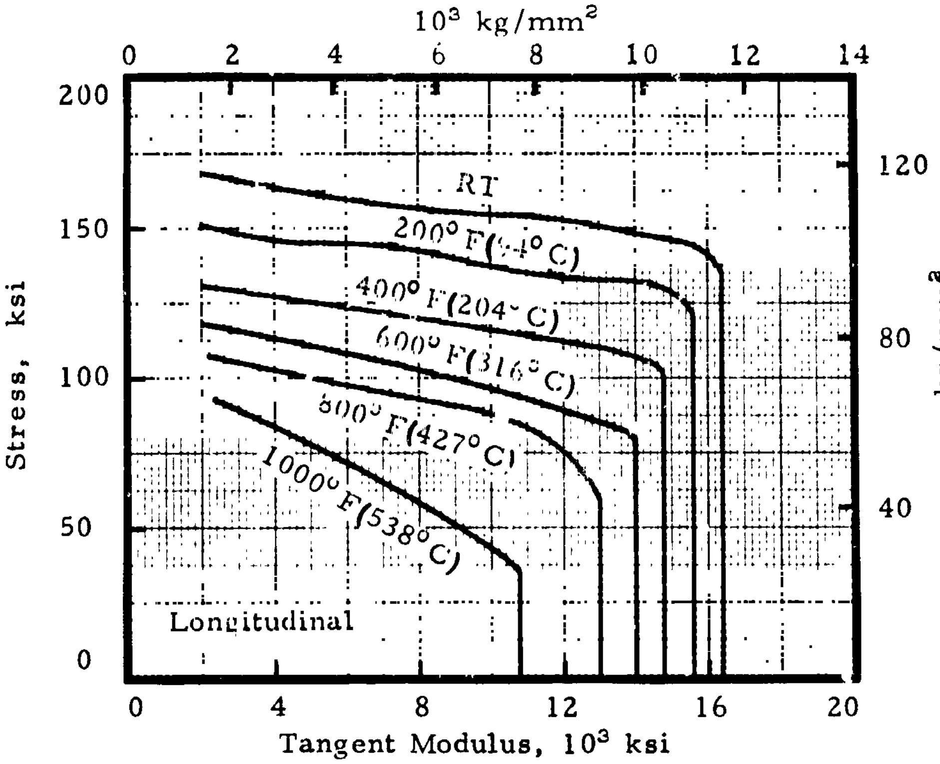

FIGURE 7.251. – Typical compressive tangent modulus curves for STA titanium 6Al-4V sheet at room and elevated temperatures. (Ref. 7.2)

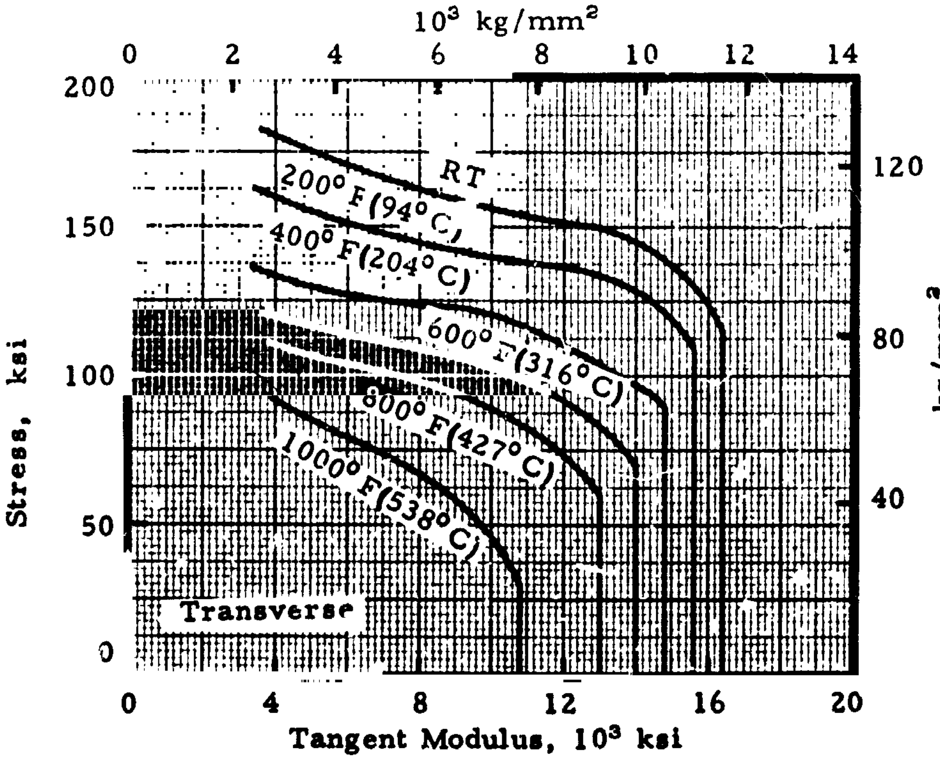

FIGURE 7.252. – Typical compressive tangent modulus curves for STA titanium 6Al-4V sheet at room and elevated temperatures. (Ref. 7.2)

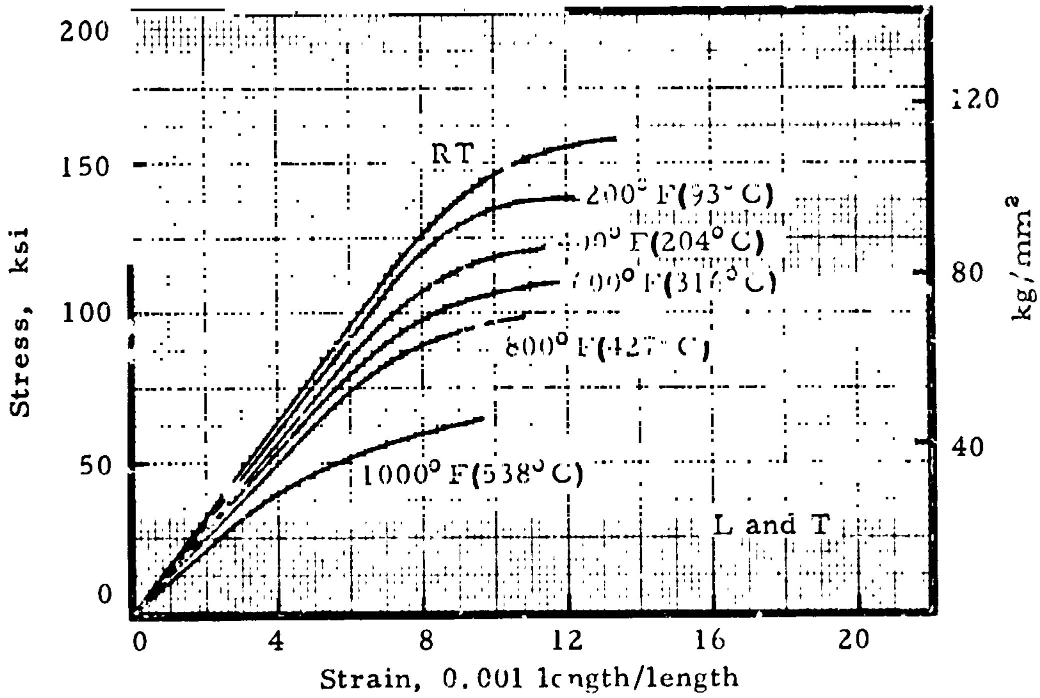

FIGURE 7.4121. – Typical tensile stress-strain curves for STA annealed titanium 6Al-4V sheet at room temperature. (Ref. 7.2)

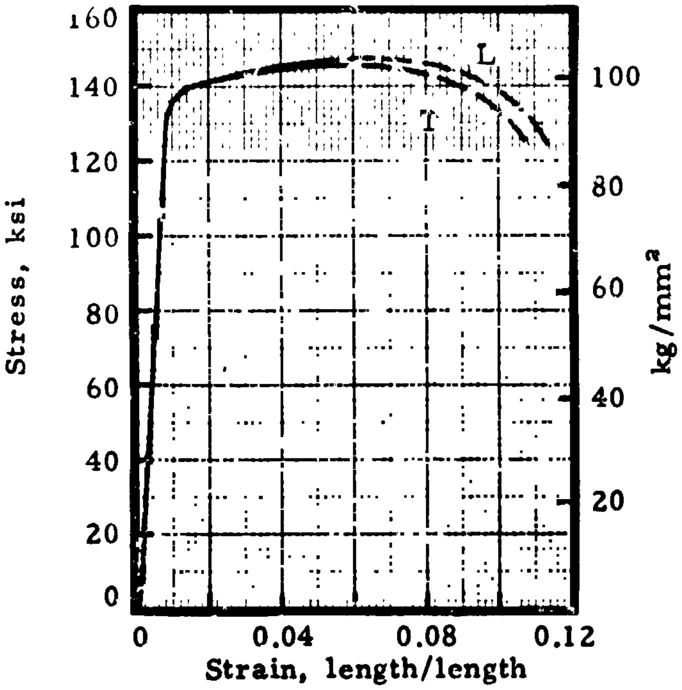

FIGURE 7.4122. – Typical full-range stress-strain curves for annealed titanium 6Al-4V sheet at room temperature. (Ref. 7.2)

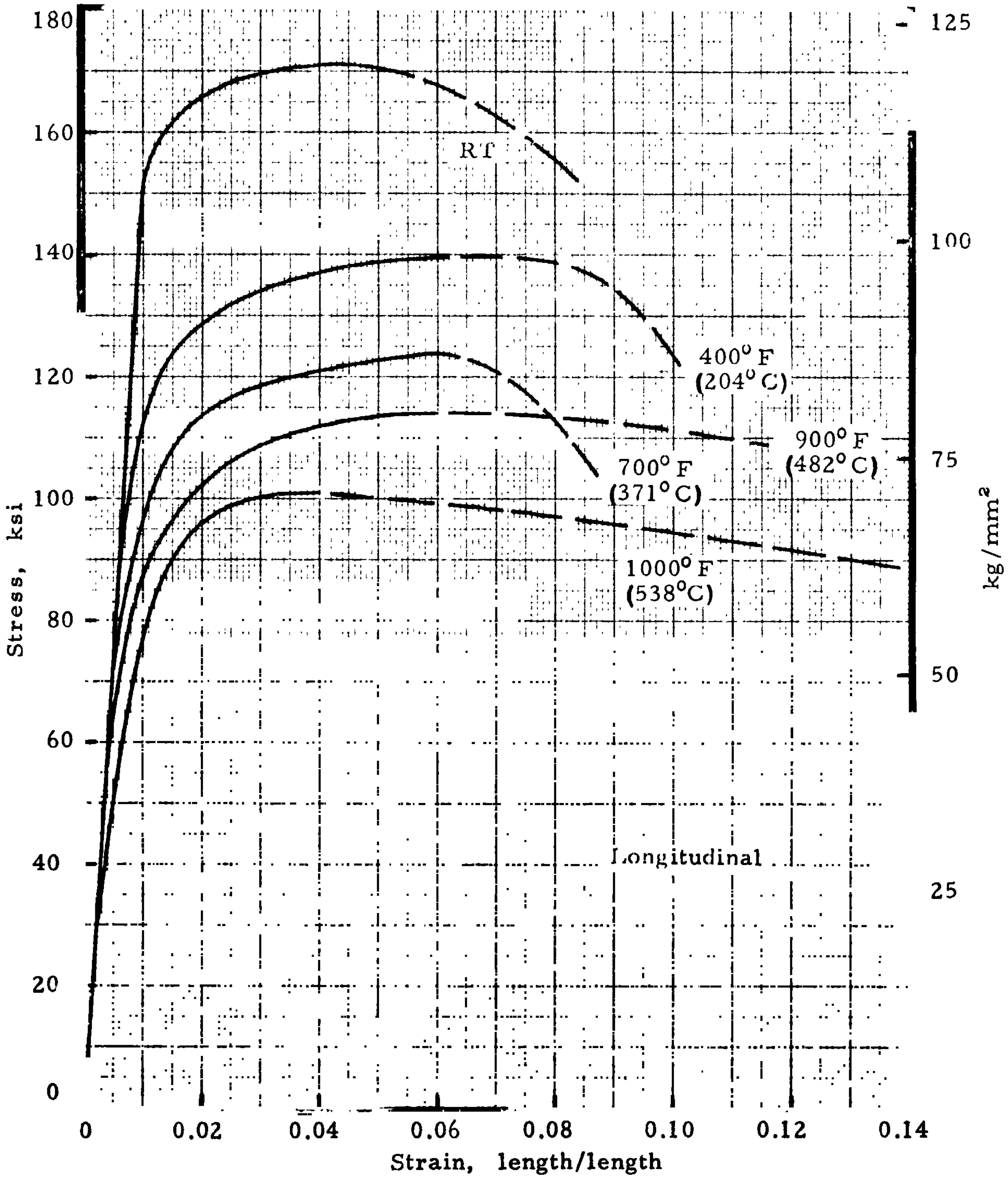

FIGURE 7.4123. – Typical full-range stress-strain curves for STA titanium 6Al-4V at room and elevated temperatures.

(Ref. 7.2)

B

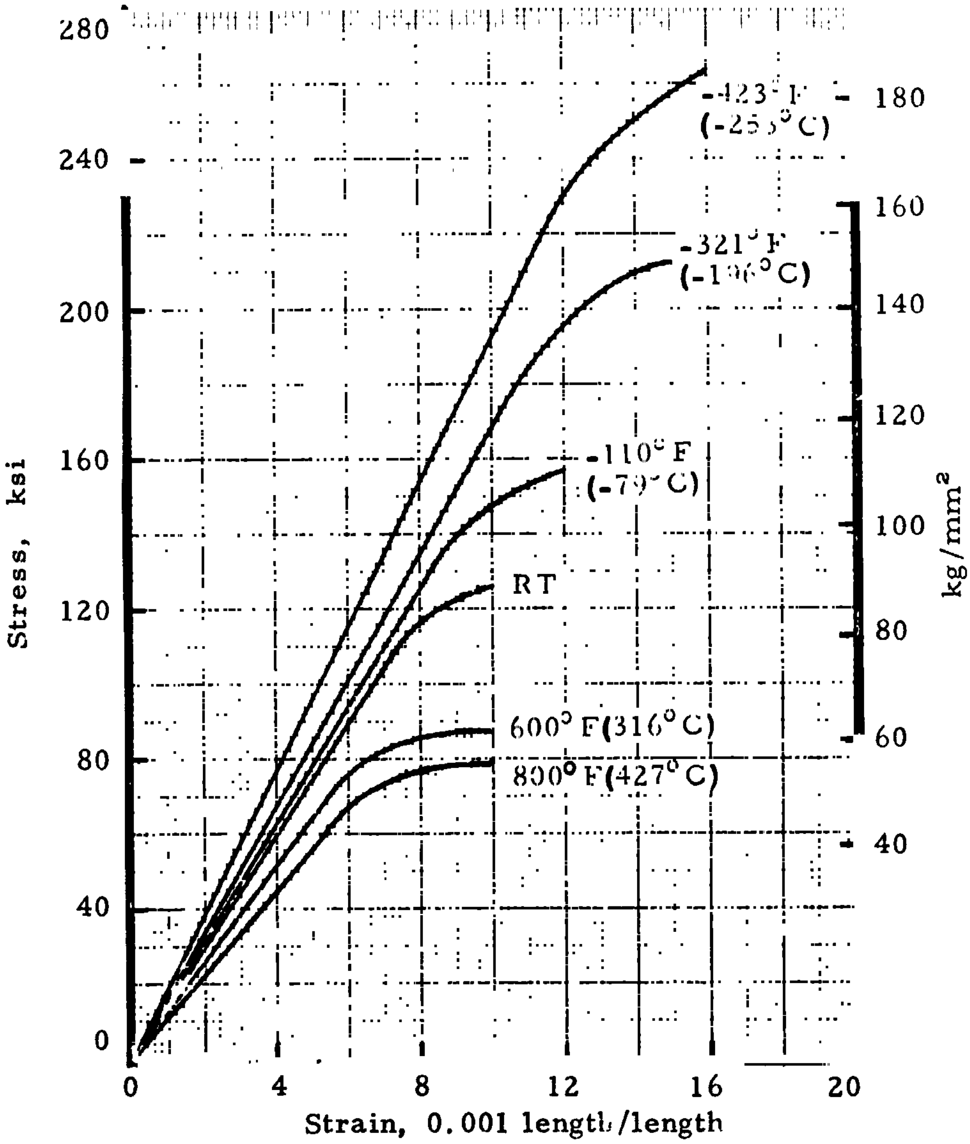

FIGURE 7.4124. — Typical tensile stress-strain curves at cryogenic, room, and elevated temperatures for annealed titanium 6Al-4V.

(Ref. 7.2)

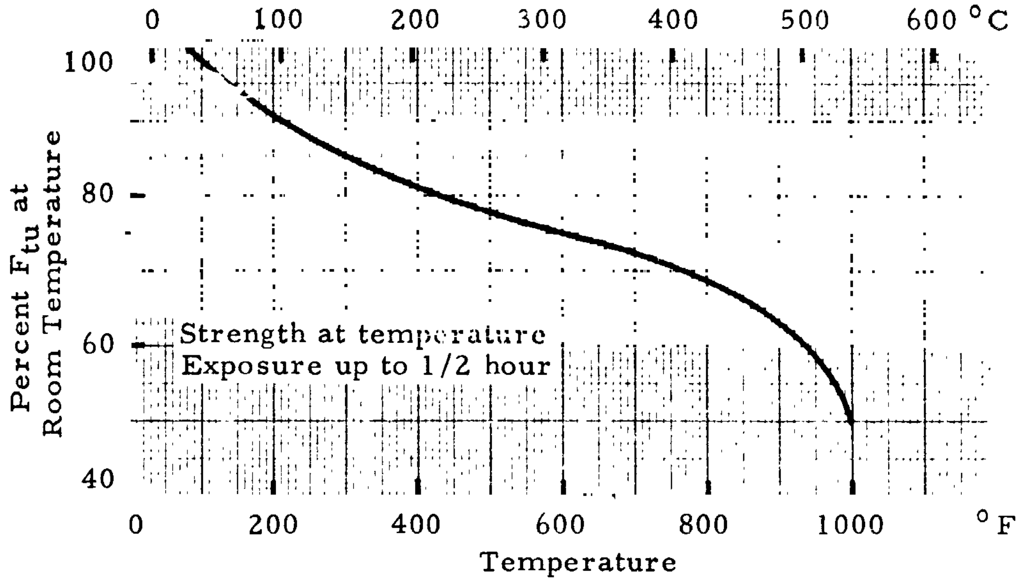

FIGURE 7.4131. – Effect of temperature on the ultimate tensile strength of STA titanium 6Al-4V. (Ref. 7.2)

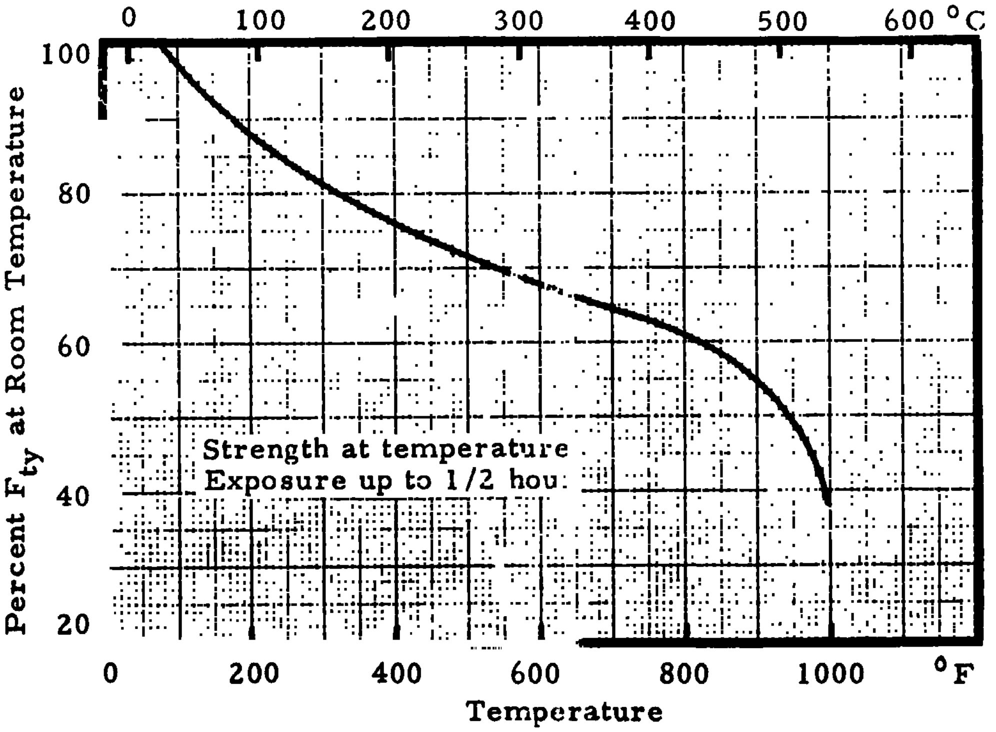

FIGURE 7.4132. – Effect of temperature on the tensile yield strength of STA titanium 6Al-4V. (Ref. 7.2)

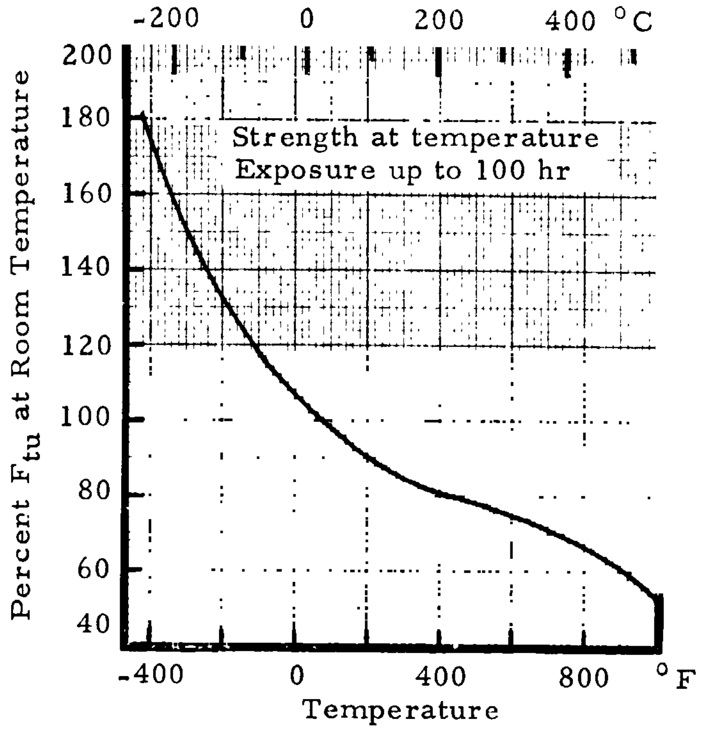

FIGURE 7.4133. — Effect of temperature on the ultimate tensile strength of annealed titanium 6Al-4V sheet and bar. (Ref. 7.2)

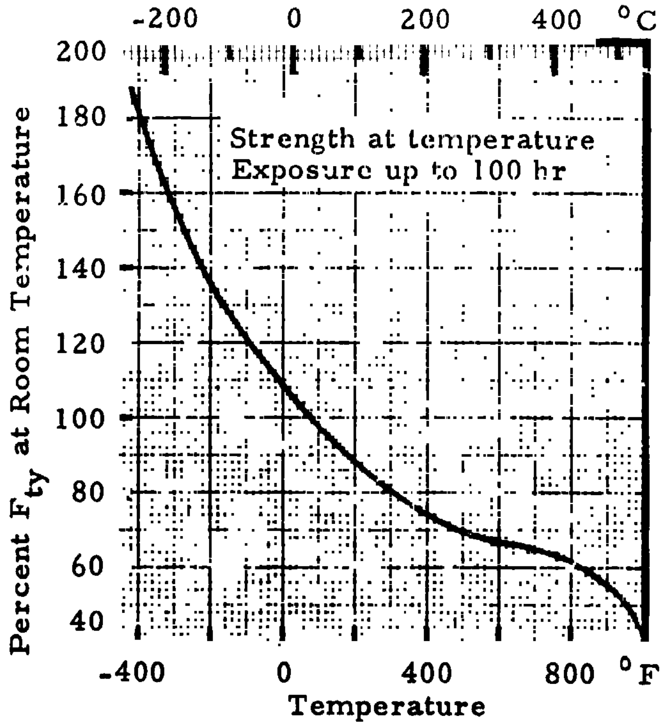

FIGURE 7.4134. — Effect of temperature on the tensile yield strength of annealed titanium 6Al-4V sheet and bar. (Ref. 7.2)

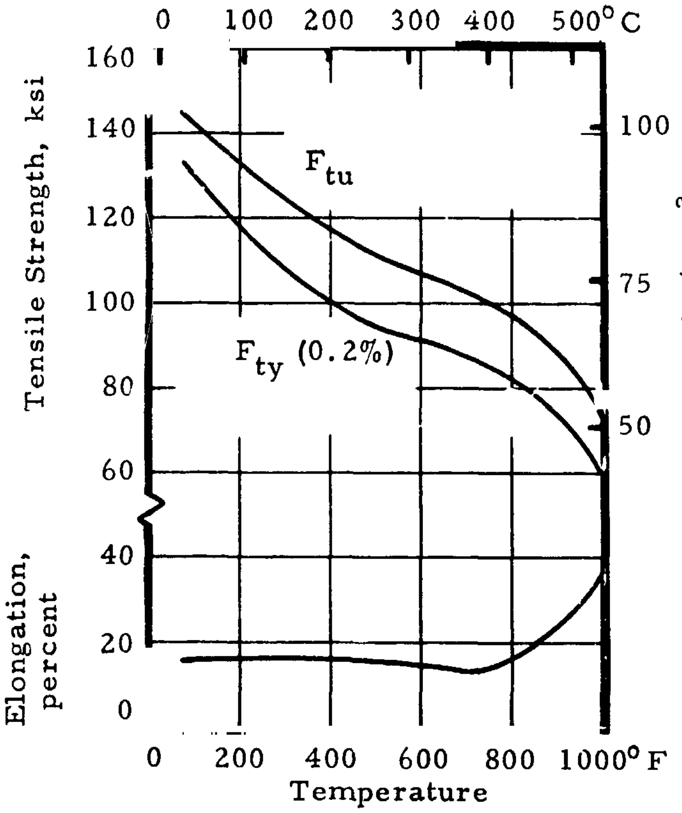

FIGURE 7.4135. – Effect of temperature on tensile properties of annealed titanium 6Al-4V sheet. (Ref. 7.3)

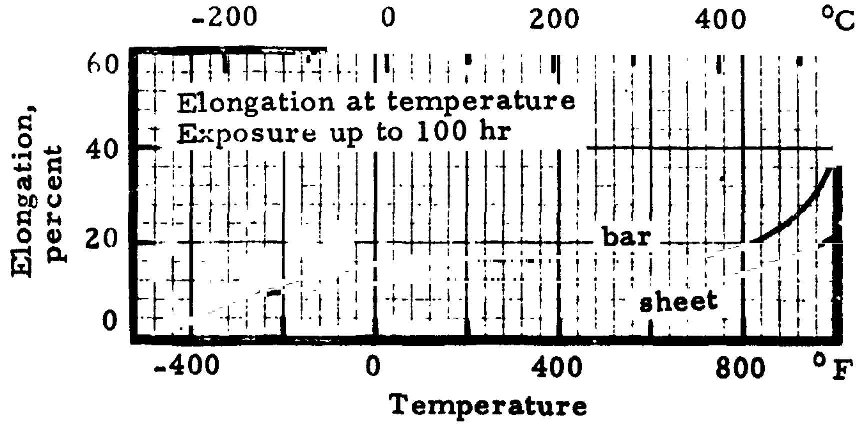

FIGURE 7.4136. – Effect of temperature on the elongation of annealed titanium 6Al-4V sheet and bar. (Ref. 7.2)

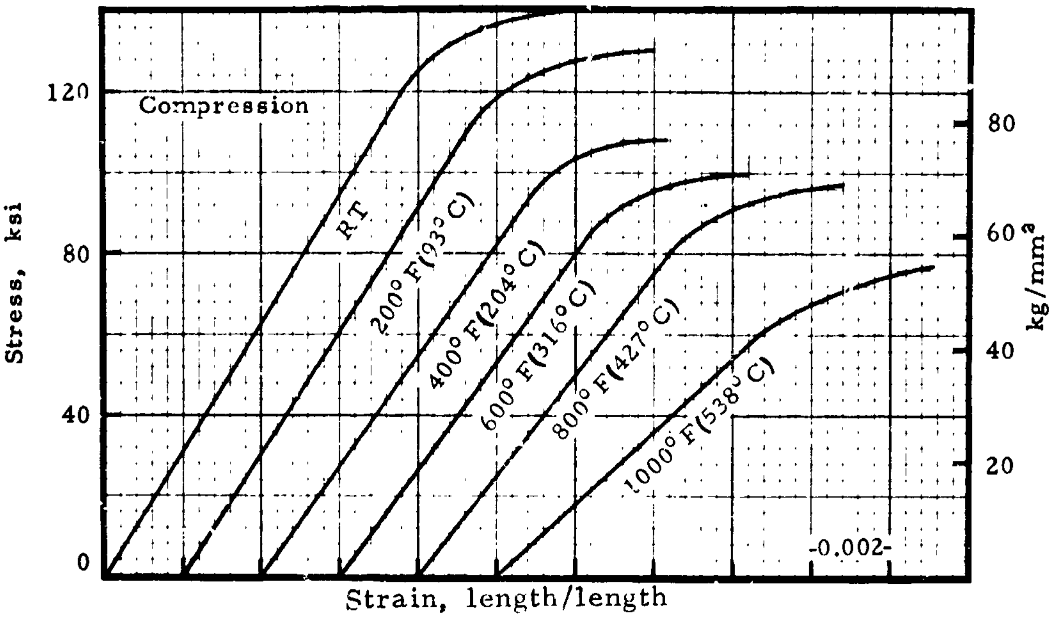

FIGURE 7.4221. – Typical stress-strain curves at room and elevated temperatures for annealed titanium 6Al-4V bar.
(Ref. 7.3)

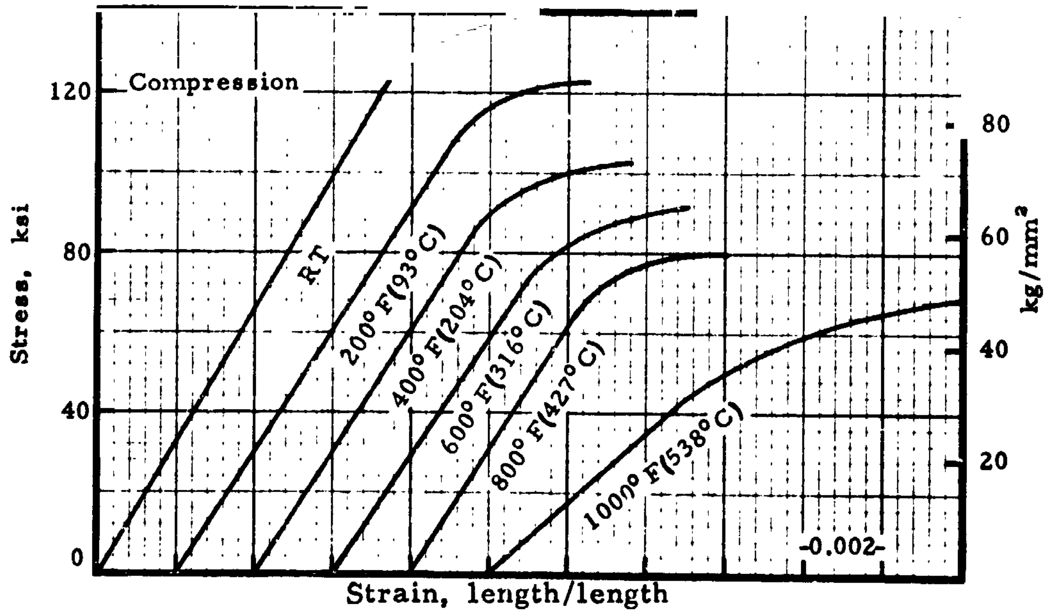

FIGURE 7.4222. – Typical stress-strain curves at room and elevated temperatures for annealed titanium 6Al-4V sheet.
(Ref. 7.3)

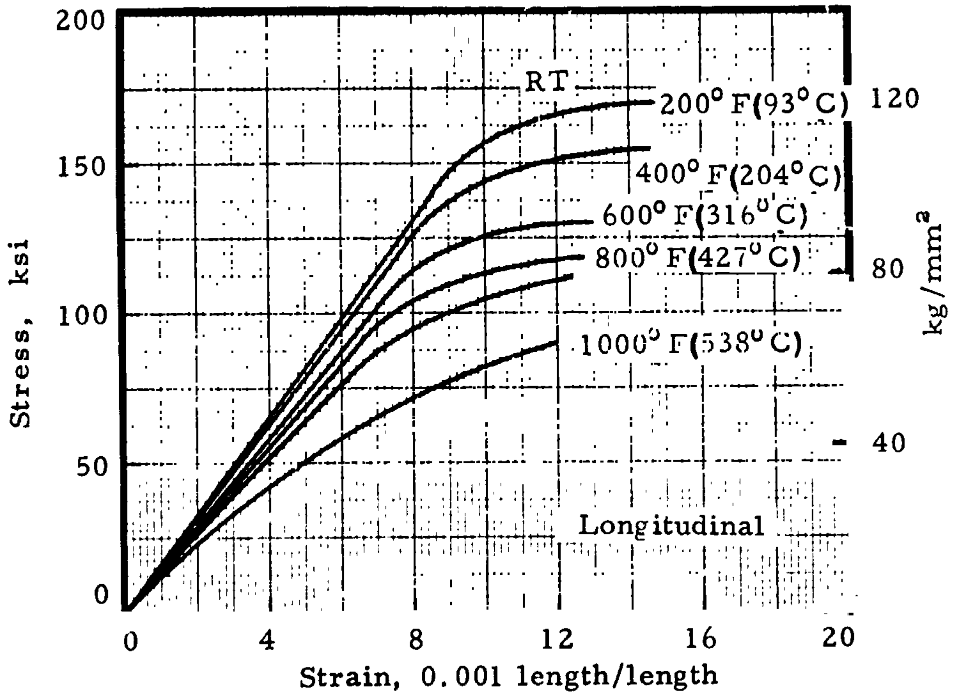

FIGURE 7.4223. – Typical compressive stress-strain curves for STA titanium 6Al-4V sheet at room and elevated temperatures. (Ref. 7.2)

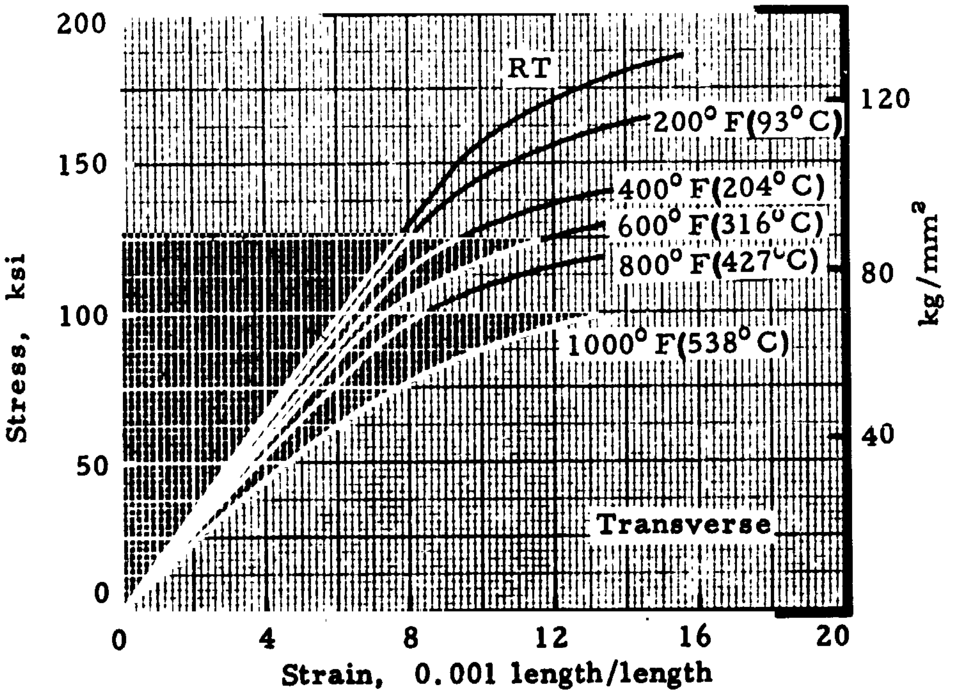

FIGURE 7.4224. – Typical compressive stress-strain curves for STA titanium 6Al-4V sheet at room and elevated temperatures. (Ref. 7.2)

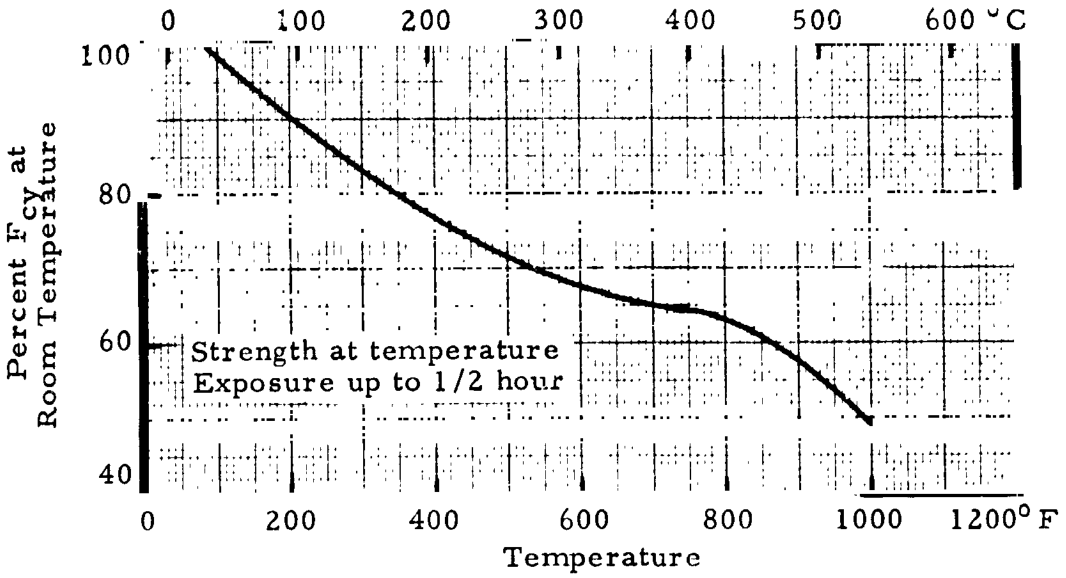

FIGURE 7.4231. — Effect of temperature on the compressive yield strength of annealed titanium 6Al-4V sheet and bar. (Ref. 7.2)

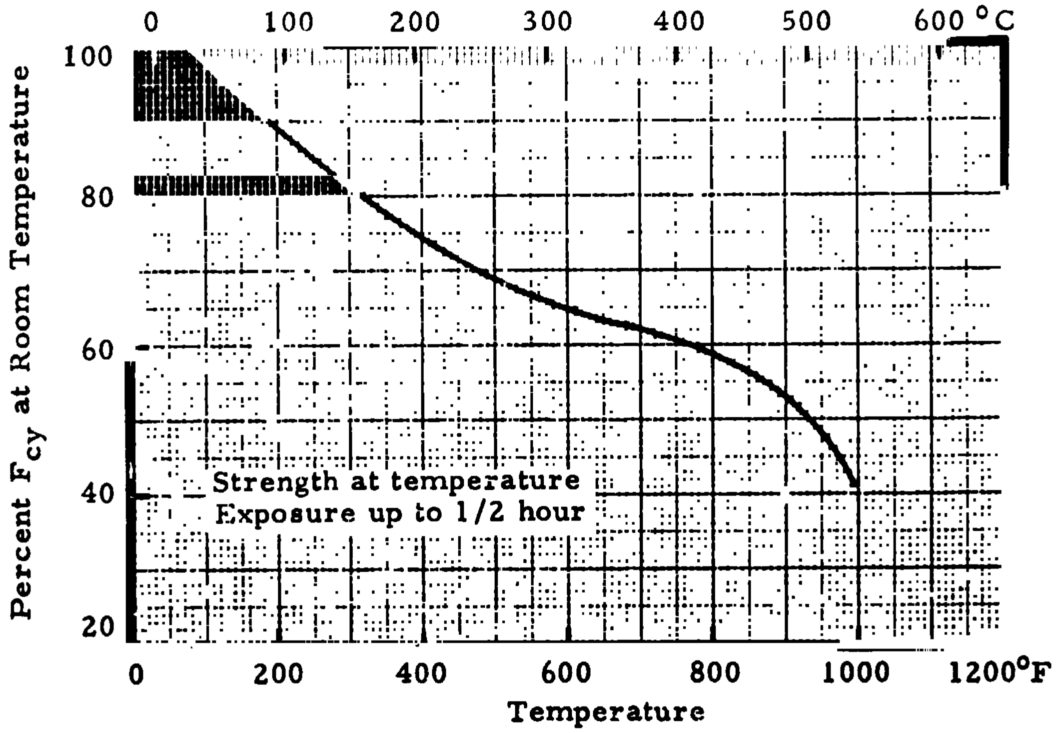

FIGURE 7.4232. — Effect of temperature on the compressive yield strength of STA titanium 6Al-4V sheet and bar. (Ref. 7.2)

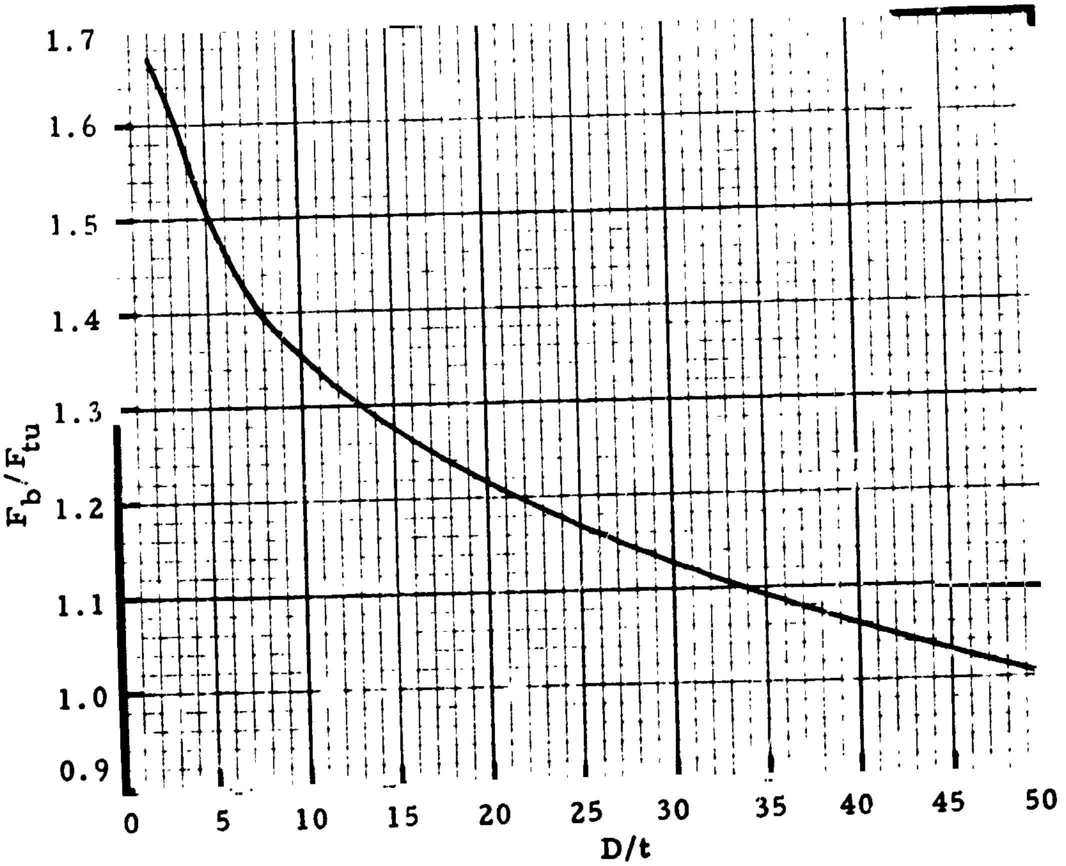

FIGURE 7.432. — Bending modulus of rupture for aged titanium 6Al-4V round tubing manufactured from bar material.
(Ref. 7.2)

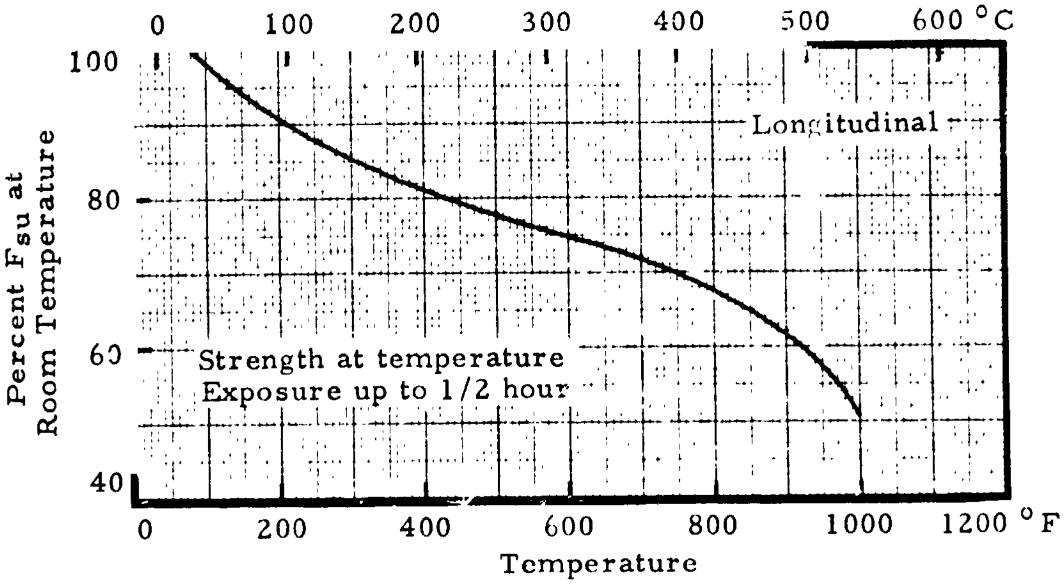

FIGURE 7.443. – Effect of temperature on the ultimate shear strength of STA titanium 6Al-4V sheet and bar. (Ref. 7.2)

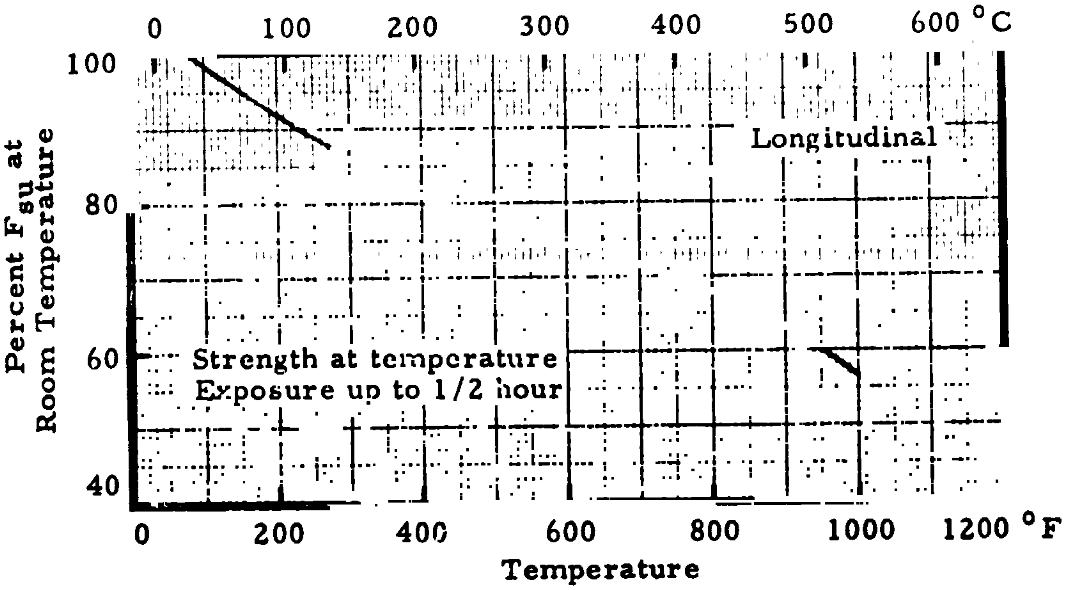

FIGURE 7.444. – Effect of temperature on the ultimate shear strength of annealed titanium 6Al-4V sheet and bar. (Ref. 7.2)

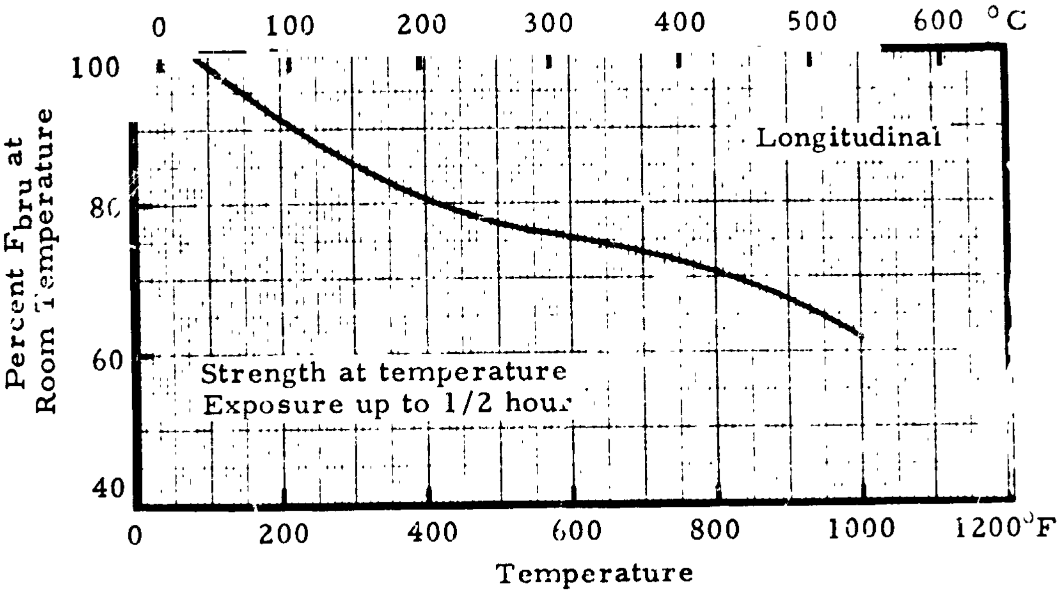

FIGURE 7.453. – Effect of temperature on the ultimate bearing strength of annealed titanium 6Al-4V sheet and bar.
(Ref. 7.2)

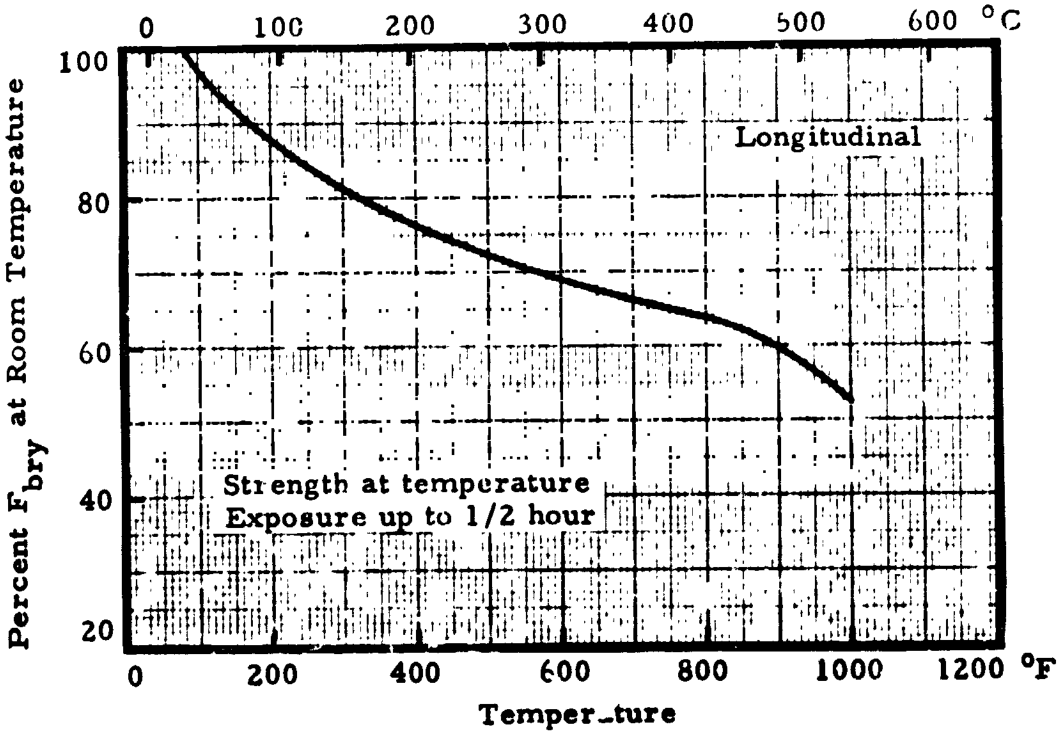

FIGURE 7.454. – Effect of temperature on the bearing yield strength of annealed titanium 6Al-4V sheet and bar.
(Ref. 7.2)

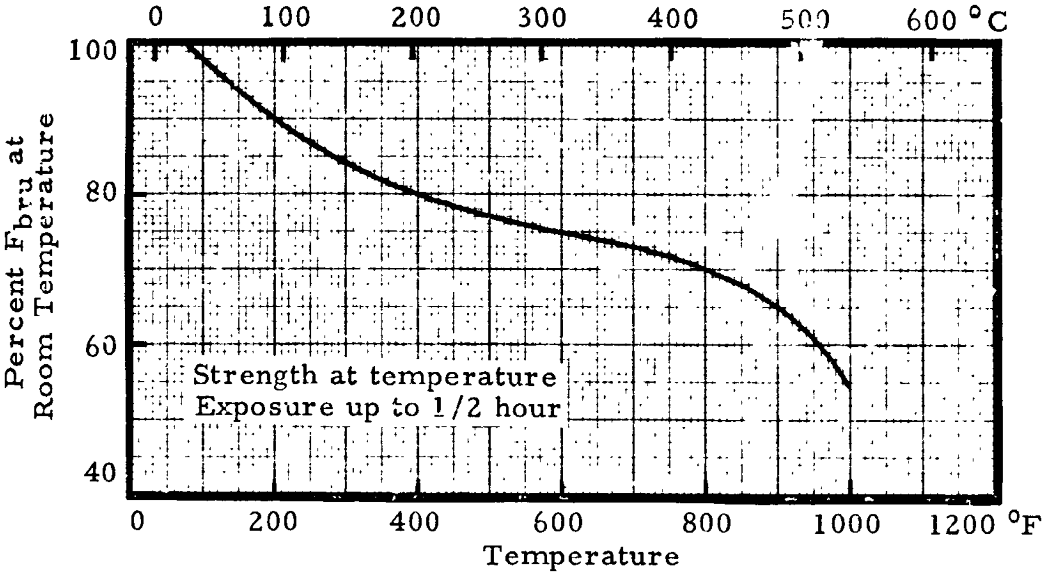

FIGURE 7.455. – Effect of temperature on the ultimate bearing strength of STA titanium 6Al-4V sheet and bar. (Ref. 7.2)

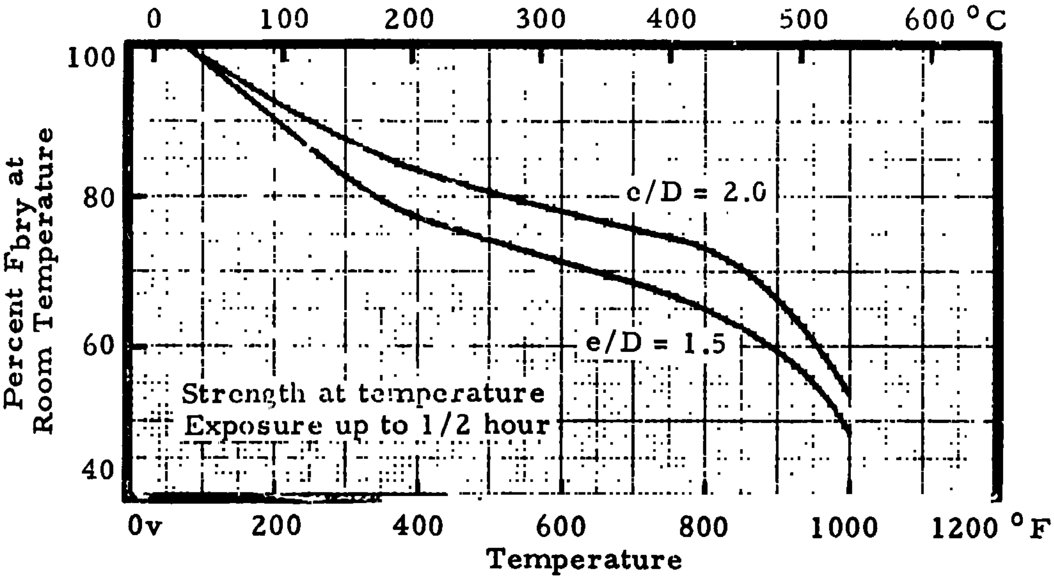

FIGURE 7.456. – Effect of temperature on the bearing yield strength of STA titanium 6Al-4V. (Ref. 7.2)

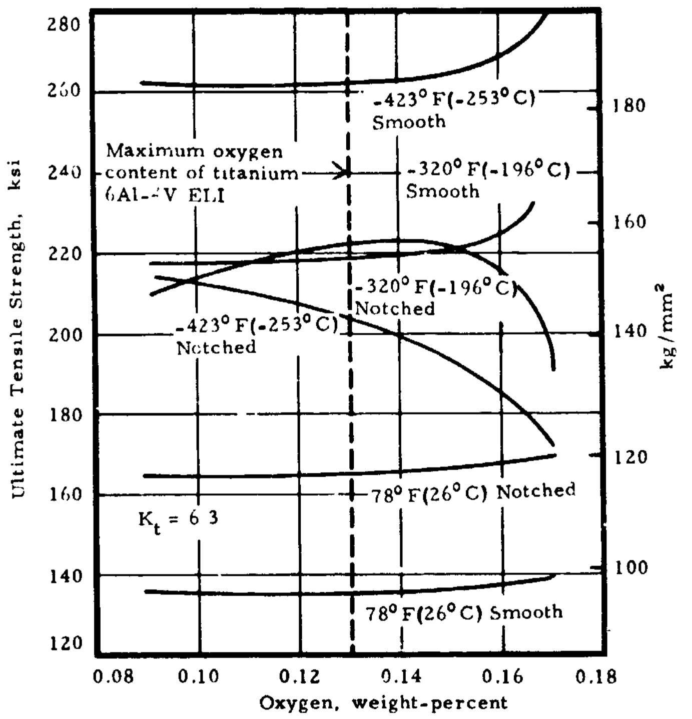

FIGURE 7 4613 -- Effect of temperature and oxygen content on room and cryogenic tensile properties of smooth and notched Ti-6A -4V sheet. (Ref. 7.3)

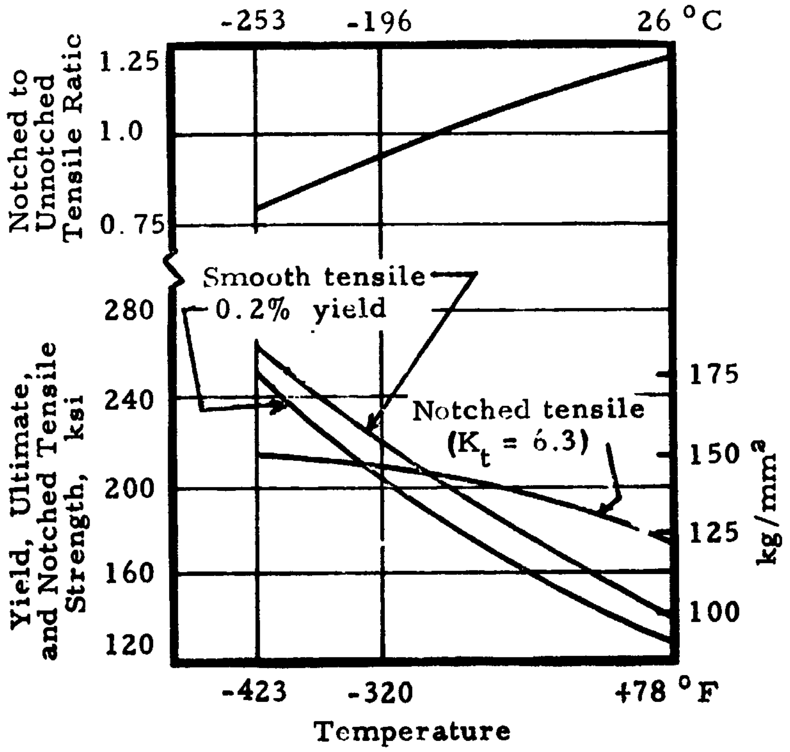

FIGURE 7.4614. — Effect of temperature on cryogenic behavior of smooth and notched titanium 6Al-4V ELI sheet. (Ref. 7.3)

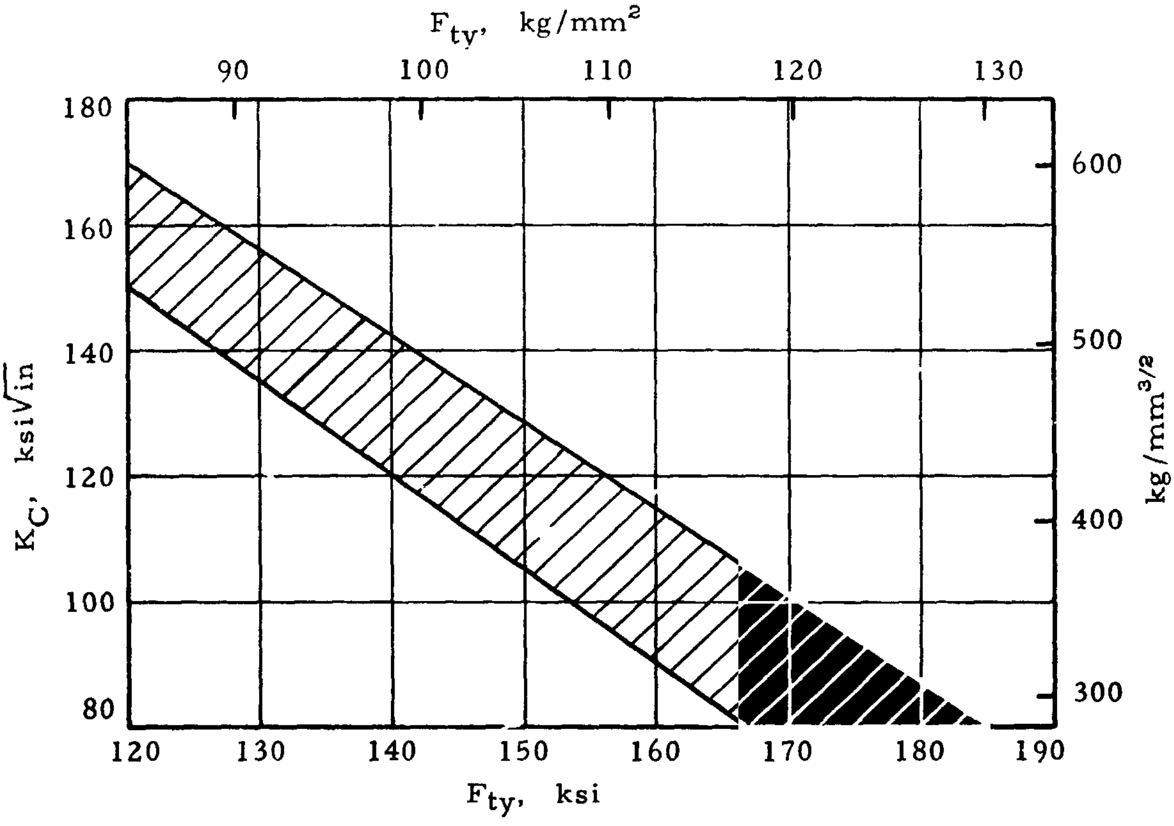

FIGURE 7.4622. — Fracture toughness of titanium 6Al-4V at various strength levels.

(Ref. 7.3)

Chapter 7 - References

7.1 D.J. Maykuth et al., "Titanium Base Alloys: 6Al-4V," DMIC Handbook, February 1971.

7.2 Military Handbook-5A, Department of Defense, "Metallic Materials and Elements for Aerospace Vehicles and Structures," FSC-1500, February 1966, latest change order January 1970.

7.3 Titanium Metals Corp. of America, "Properties of Ti-6Al-4V," November 1968.

7.4 Alloy Digest, "MST 6Al-4V" (Filing Code Ti-9), Engineering Alloys Digest, Inc., December 1955.

7.5 Titanium Metals Corp. of America, "How to Use Titanium," January 1970.

7.6 1971 SAE Handbook, Society of Automotive Engineers, Inc., New York.

7.7 Rodney Metals/Teledyne, "Rodney Metals," December 1970.

7.8 ASTM Standards, Part 7, B367-69, American Society for Testing Materials, 1971.

7.9 C.F. Hickey, Jr., "Mechanical Properties of Titanium and Aluminum Alloys at Cryogenic Temperatures," ASTM Proc., 62, 765 (1962).

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

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

7.12 Harvey Titanium, "Titanium," September 1968.

7.13 C.R. Johnson and J.D. Grimsley, "Short-Time Stress Rupture of Prestressed Titanium Alloys under Rapid Heating Conditions," NASA TN D-6052, November 1970.

Chapter 8

DYNAMIC AND TIME DEPENDENT PROPERTIES

8.1 General. Titanium 6Al-4V generally has good dynamic and time dependent properties. The fatigue properties of the alloy are reported as excellent (refs. 8.1—8.4); however, it has been pointed out that up to 1960 the fatigue properties were not on a statistically sound basis because too few comparable test results were available (ref. 8.5). More recently, it has been suggested that fatigue data be evaluated only in conjunction with information on surface preparation that indicates the state of stress on test specimens (ref. 8.6).

Up to about 800° F (427°C), titanium alloys generally maintain good creep and rupture properties at a level between ferritic and austenitic steels (ref. 8.2).

Titanium alloys are generally stable over the region at which they resist oxidation and retain their useful strength. The stability of alpha-beta alloys is dependent upon composition and heat treatment. Titanium 6Al-4V may be considered to be stable to 600° to 700° F (316° to 371° C), but exposure to stress and temperature for long times must be considered (ref. 8.5).

8.2 Specified Properties

8.21 AMS Specifications for annealed bars and forgings, and annealed extrusions require that axial load of 170 ksi (119 kg/mm^2) on appropriately designed specimens shall not produce rupture within 5 hours at room temperature (ref. 8.7).

8.3 Impact

8.31 Charpy-V impact strengths of alloy from cryogenic to elevated temperatures, figure 8.31.

8.4 Creep

8.41 Typical stress versus temperature curves for creep deformation and rupture of annealed bar, figure 8.41.

8.42 Typical 100-hour creep and rupture curves versus temperature for STA sheet, figure 8.42.

8.43 Typical 100-hour creep and rupture curves versus temperature for STA bar, figure 8.43.

8.44 Typical creep properties for STA sheet, figure 8.44.

8.45 Stress rupture curves for titanium 6Al-4V (longitudinal, resistance heat), figure 8.45.

8.5 Stability (see also Chapter 7, sect. 7.4)

8.51 Typical stress stability data for alloy, table 8.51.

8.6 Fatigue (see also Chapter 12)

8.61 Typical constant-life fatigue diagram for annealed bar at room temperature, figure 8.61.

8.62 Typical constant-life fatigue diagram for STA sheet at room temperature, figure 8.62.

8.63 Typical constant-life fatigue diagram for STA sheet at 600°F (316°C), figure 8.63.

8.64 Typical constant-life fatigue diagram for STA sheet at 800°F (431°C), figure 8.64.

8.65 Fatigue test data for annealed sheet before and after exposure at 287°C for 26,300 hours, table 8.65.

TABLE 8.51. — Typical Stress Stability Data for Alloy

Source	Ref. 8.1									
Alloy	Titanium 6Al-4V									
Condition	Test Condition	Test Time, hr	F_{tu}, ksi	F_{tu}, kg/mm^2	F_{ty}, ksi	F_{ty}, kg/mm^2	e(1 in), %	Redn. of Area, %	RC Hardness Before	RC Hardness After
Annealed	**Unstressed, 70° F (21° C)**	-	134.5	94.6	124.3	87.4	19.7	42.3	35.3	34.8
	Stress, 50 ksi (35 kg/mm^2), 650° F (343°C)	16	142.2	100.0	125.1	88.0	18.3	49.4	35.4	34.3
		100	154.6	108.7	133.2	93.6	15.4	44.0	36.2	34.2
		300	149.3	105.0	132.9	93.4	17.8	40.4	34.3	35.5
		1000	148.9	104.7	129.5	91.0	13.4	41.0	35.6	35.0
	Stress, 50 ksi (35 kg/mm^2), 750° F (399° C)	16	146.1	102.7	130.4	91.7	16.1	42.9	34.2	33.9
		100	139.0	97.7	128.1	90.1	15.6	42.9	35.0	34.4
		300	148.4	104.3	132.9	93.4	20.5	42.6	35.2	33.8
		1000	146.9	103.3	130.4	91.7	17.3	45.3	35.7	34.7
	Stress, 50 ksi (35 kg/mm^2) 850° F (454° C)	16	144.0	101.2	128.3	90.2	16.7	38.8	35.5	33.8
		100	136.1	95.7	123.0	86.5	15.6	47.7	36.1	34.6
		300	142.9	100.5	132.9	93.4	17.4	33.7	35.1	34.2
		1000	156.1	109.7	140.9	99.1	15.4	30.4	34.7	34.1
STA	**Unstressed, 70° F (21° C)**	-	166.0	116.7	152.6	107.3	18.0	57.4	-	-
	Stressed, 45 ksi (32 kg/mm^2), 800° F (427° C)	150	171.1	120.3	151.1	106.2	16.0	54.8*		

*** Tensile tested as exposed.**

TABLE 8.62. — Results of Fatigue Tests Before and After Exposure for 23,000 Hours at 288°C (550° F)

Source	Ref. 8.9										
Alloy	Titanium 6Al-4V, Annealed										
Before Exposure						After Exposure					
K_T = 1 (a)			K_T = 4 (a)			K_T = 1 (a)			K_T = 4 (a)		
S_{max}		Fatigue life, kilocycles	S_{max}		Fatigue life, kilocycles	S_{max}		Fatigue life, kilocycles,	S_{max}		Fatigue life, kilocycles
ksi	kg/mm²		ksi	kg/mm²		ksi	kg/mm²		ksi	kg/mm²	
120	84.4	16	60	42.2	7	130	91.4	8	60	42.2	4.4
		22	55	38.7	12			10			4.5
		28			12			11			4.5
110	77.3	14			16	120	84.4	19	52	36.6	8.5
		52	50	35.2	17			29			9.2
		54			21			34			9.4
100	70.3	46			26	110	77.3	27	45	31.6	15
		94	45	31.6	13			50			19
		145			24			96			21
95	66.8	78			31	100	70.3	64	40	28.1	28
		113	40	28.1	57			65			29
		321			57			81			30
		691			112			581	35	24.6	69
90	63.3	615			152			833			82
		902			315	90	63.3	432			89
85	59.8	62	36	25.3	60			1,080	34	23.9	112
		544			85			1,403			>10,000
		600			1,870	85	59.8	2,919	33	23.2	>10,000
		847	34	23.9	1,846			3,057			>10,000
		1,058			2,105			8,981	32	22.5	>10,000
76	53.4	2,091			2,704			>10,000			
		2,176			>10,000	75	52.7	>10,000			
		3,087	32	22.5	>10,000			>10,000			
72	50.6	2,910			>10,000	65	45.7	>10,000			
		6,526			>10,000						
		9,081									

K_T = 1, unnotched specimens; K_T = 4, notched specimens

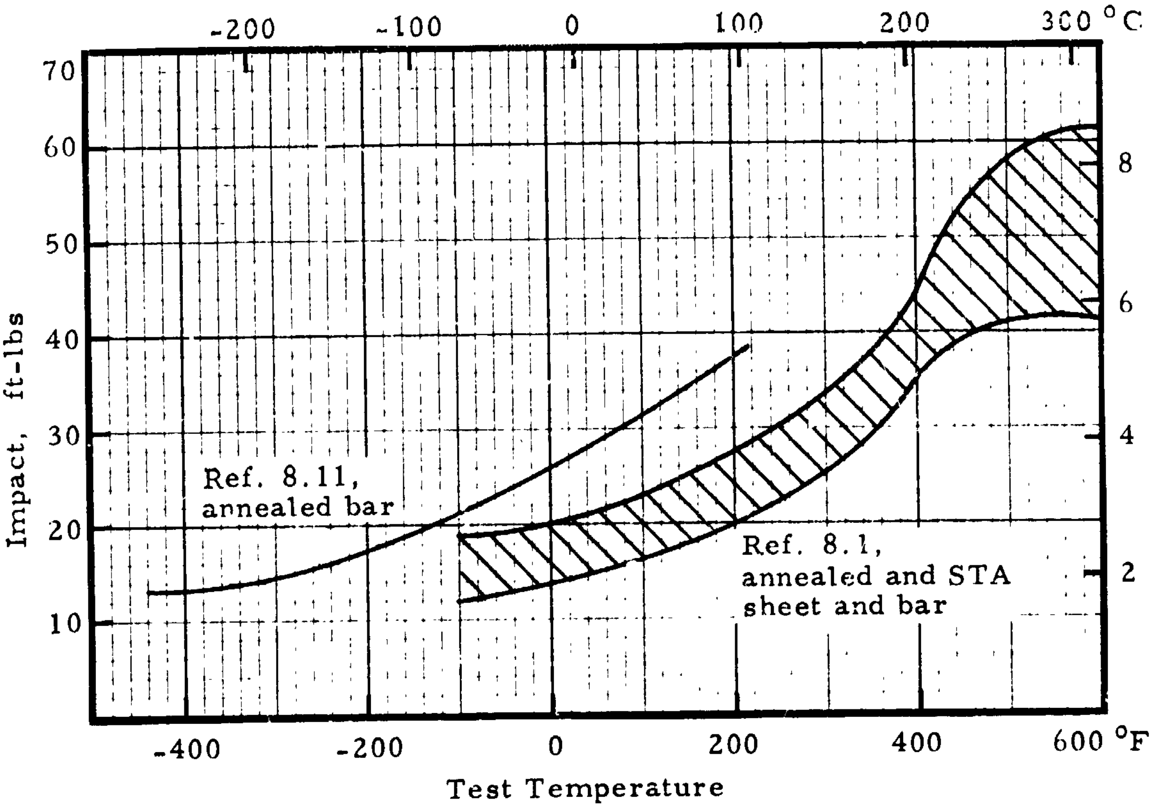

FIGURE 8.31. – Charpy-V impact strengths of titanium 6Al-4V from cryogenic to elevated temperatures. (Refs. 8.1, 8.11)

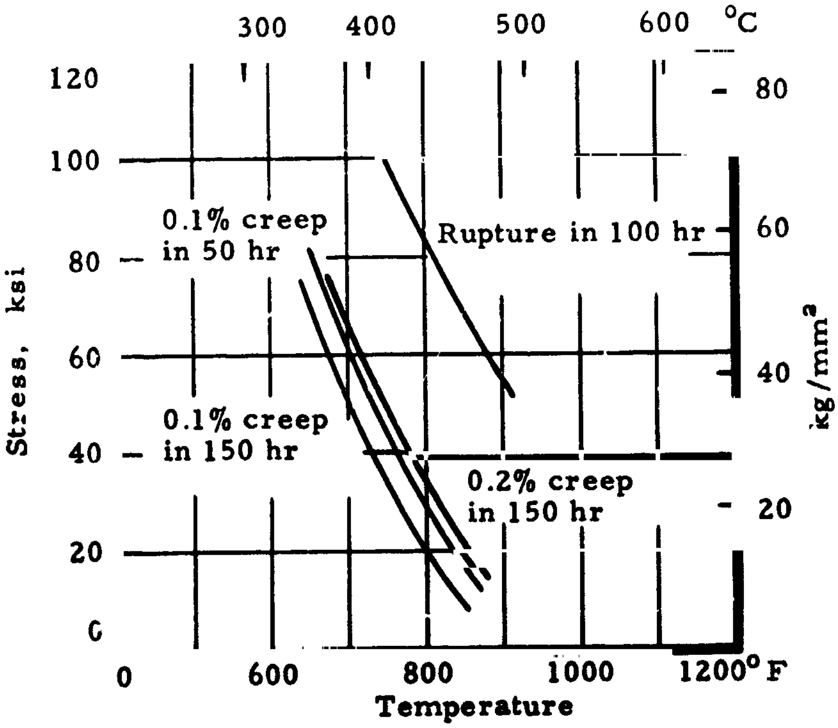

FIGURE 8.41. – Typical stress versus temperature curves for creep deformation and rupture of annealed titanium 6Al-4V bar. (Ref. 8.1)

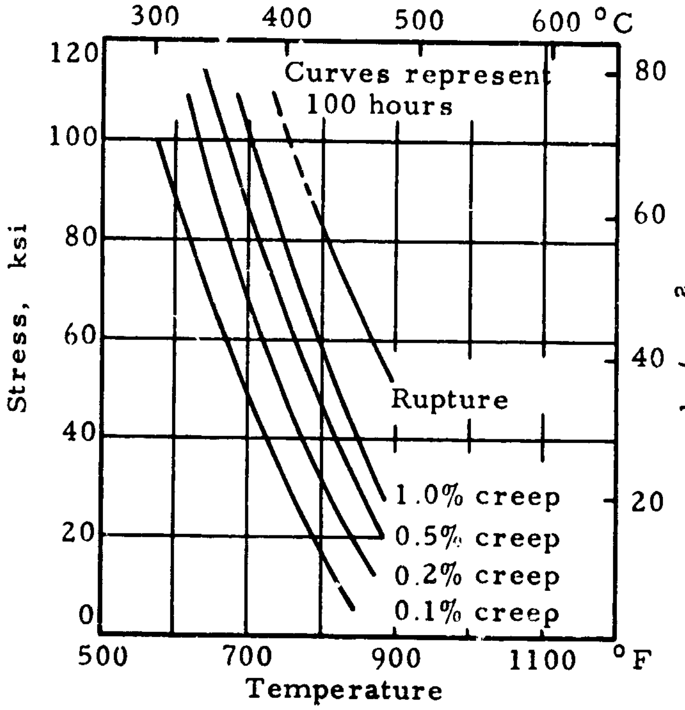

FIGURE 8.42. — Typical 100-hr creep and rupture curves versus temperature of STA titanium 6Al-4V sheet. (Ref. 8.1)

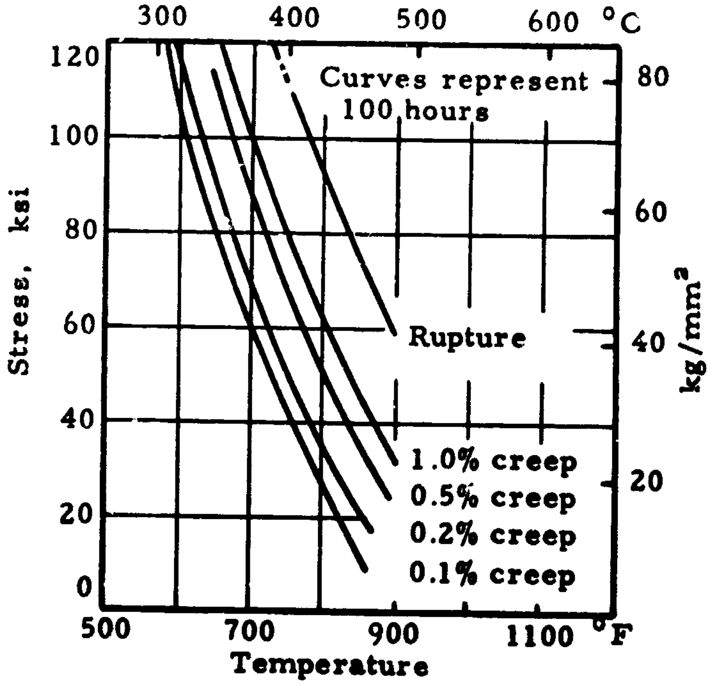

FIGURE 8.43. — Typical 100-hr creep and rupture curves versus temperature of STA titanium 6Al-4V bar. (Ref. 8.1)

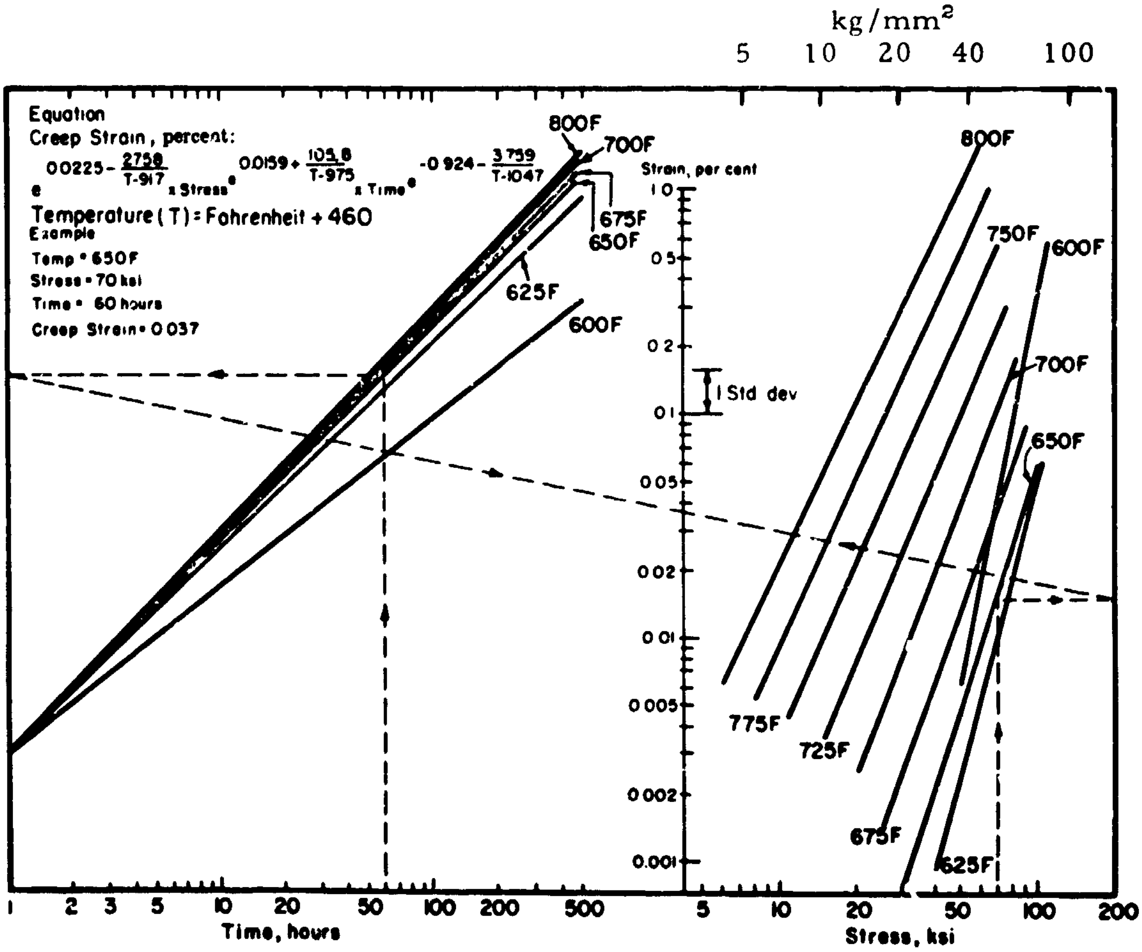

FIGURE 8.44. – Typical creep properties of STA titanium 6Al-4V sheet. [1 ksi = 0.70307 kg/mm². °F – 32 x 5/9 = °C.] (Ref. 8.8)

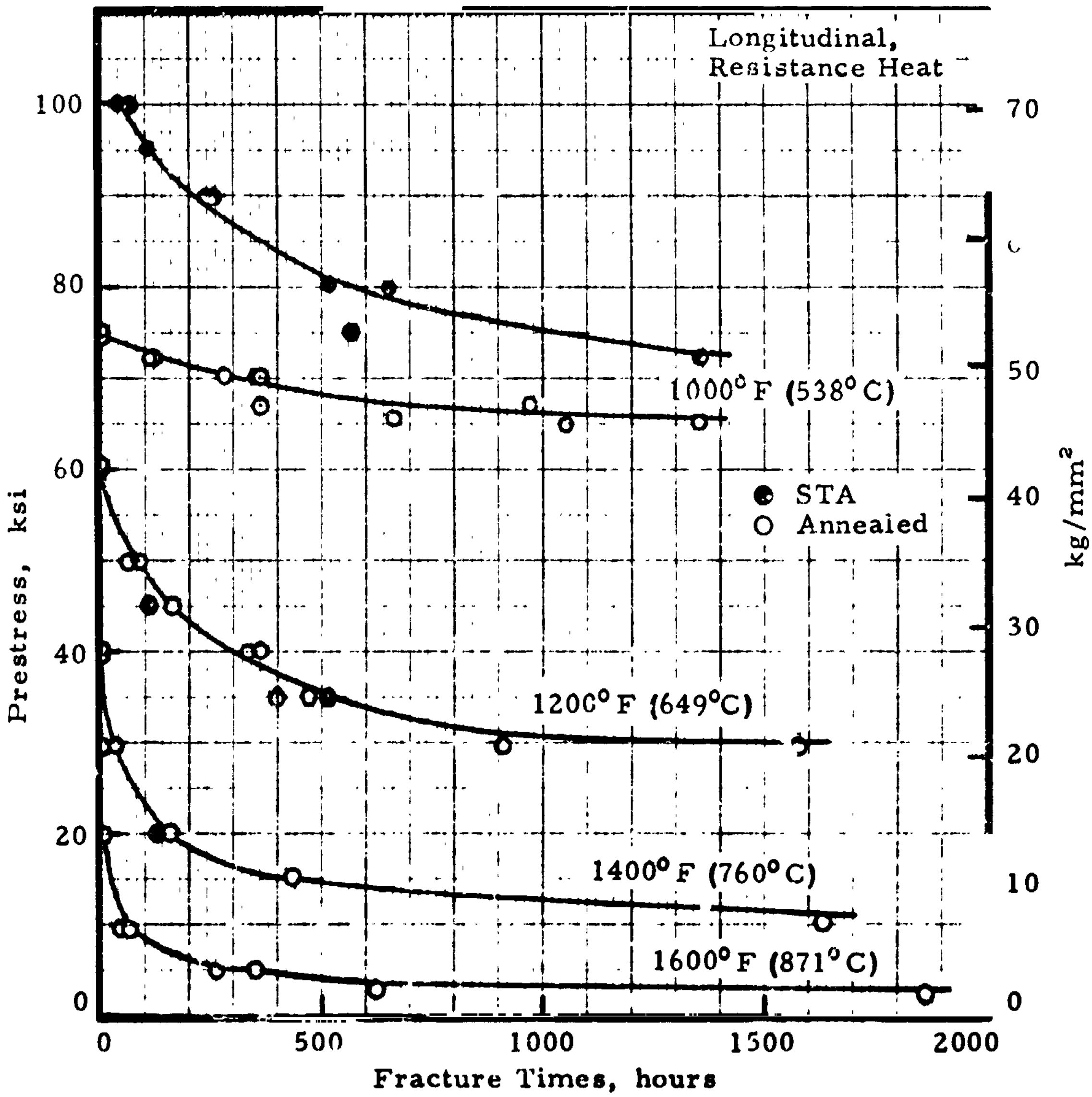

FIGURE 8.45. — Stress-rupture curves for titanium 6Al-4V sheet, 0.08 inch (2.03 mm). Solution heat treated 1700° F (927° C), 30 min, WQ, and aged at 950° F (510°C), 5 hr.

(Ref. 8.12)

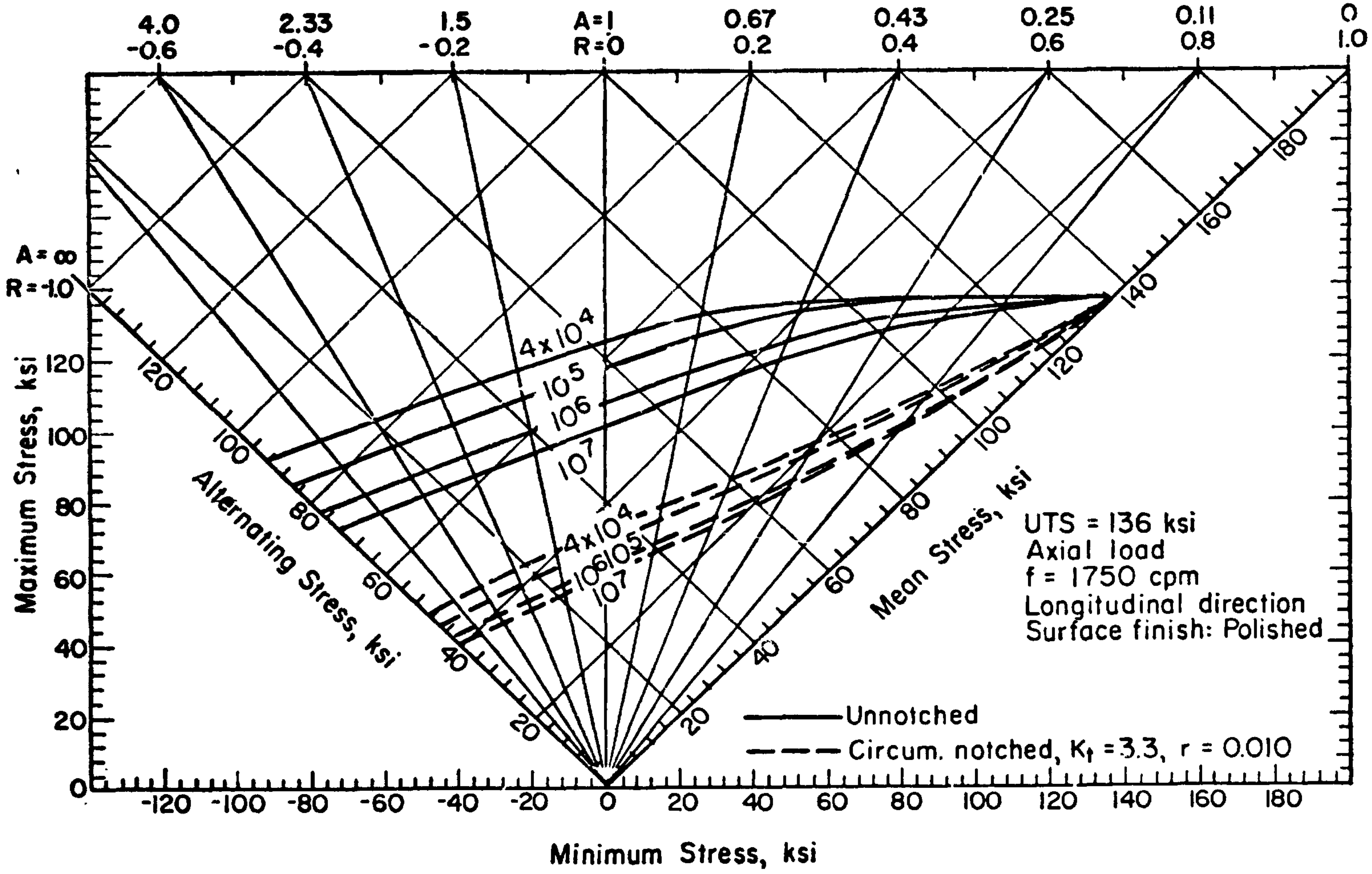

FIGURE 8.61. – Typical constant-life fatigue diagram for annealed titanium 6Al-4V bar at room temperature. (Note: 1 ksi = 0.70307 kg/mm^2)

(Ref. 8.8)

D

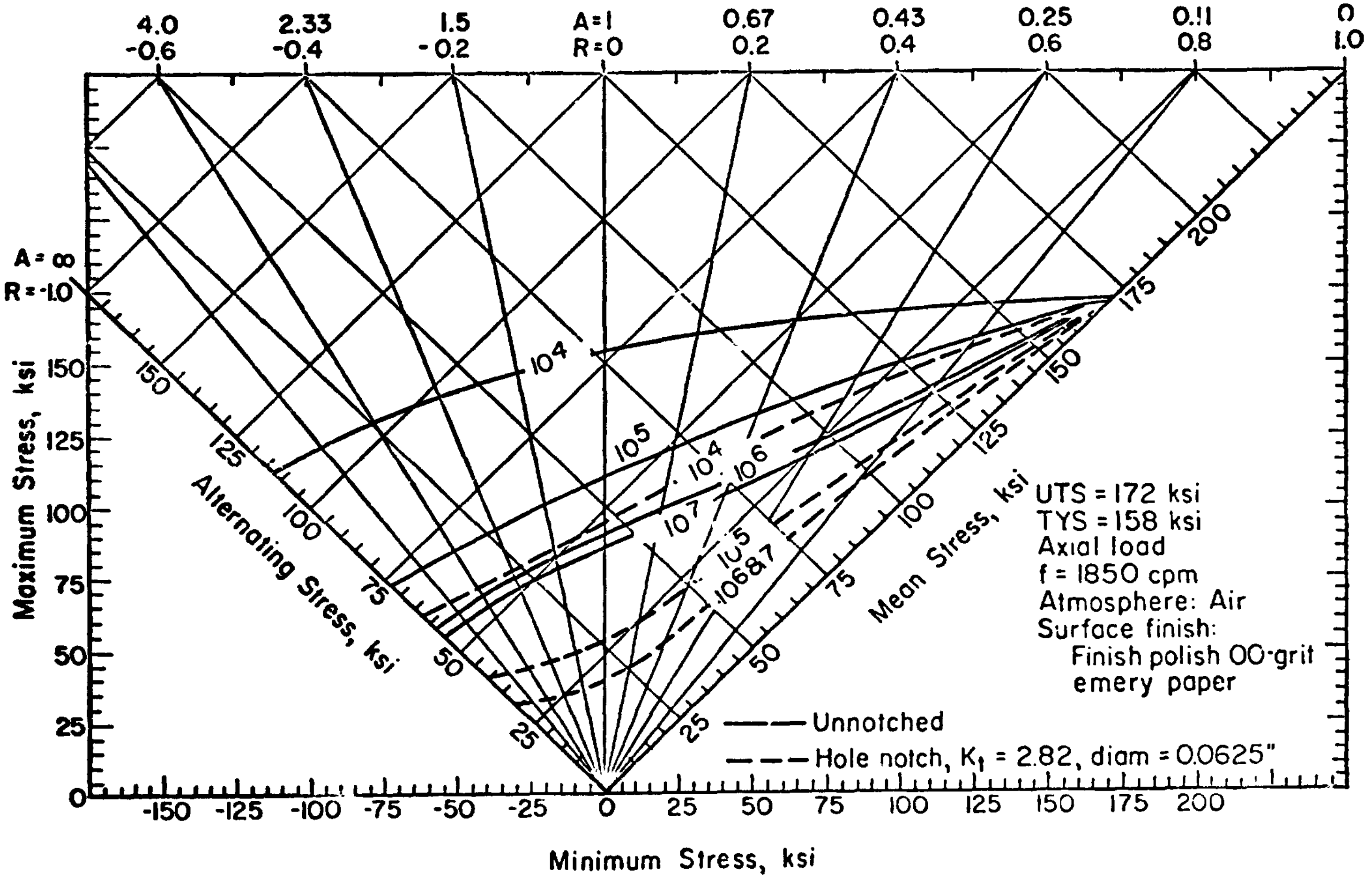

FIGURE 8.62. – Typical constant-life fatigue diagram for STA titanium 6Al-4V bar at room temperature. (Note: 1 ksi = -/70307 kg/mm^2)

(Ref. 8.8)

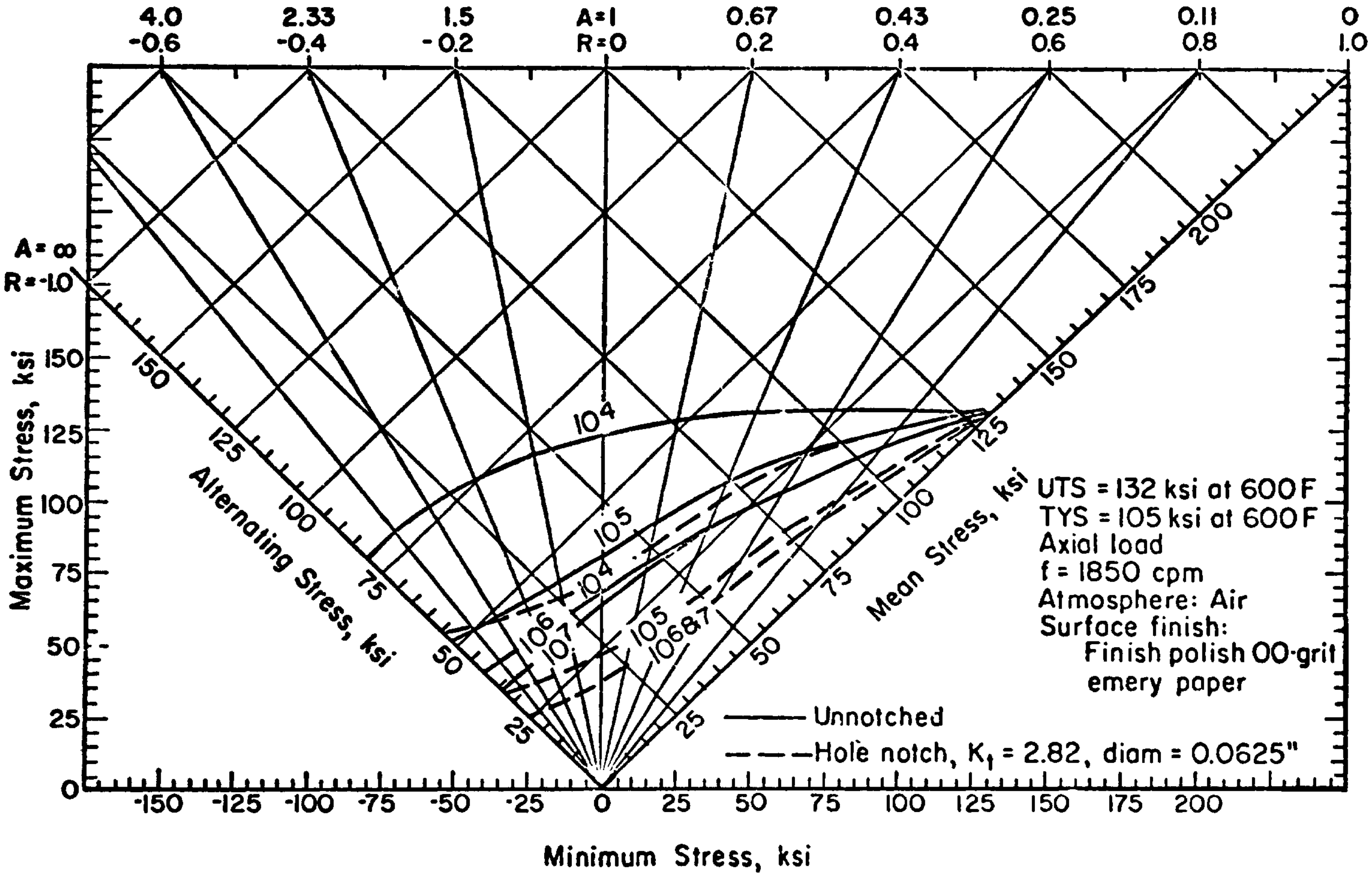

FIGURE 8.63. — Typical constant-life fatigue diagram for STA titanium 6Al-4V sheet at 600° F(316° C). (1 ksi = 0.70307 kg/mm^2)

(Ref. 8.8)

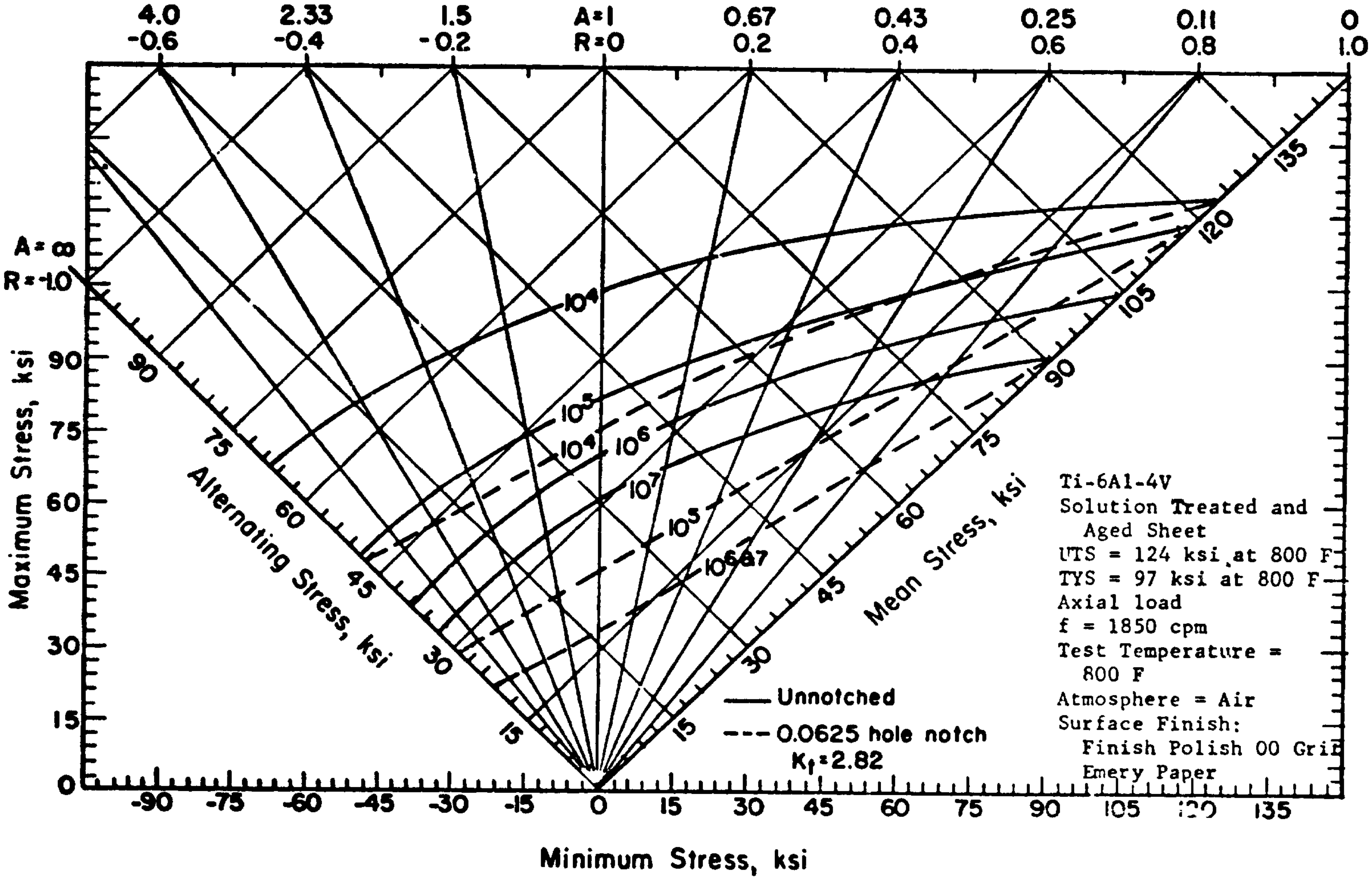

FIGURE 8.64. — Typical constant-life fatigue diagram for STA titanium 6Al-4V sheet at 800° F (427° C).
(1 ksi = 0.70307 kg/mm^2)

(Ref. 8.8)

Chapter 8 - References

8.1 Titanium Metals Corp. of America, "Properties of Titanium 6Al-4V," Titanium Engineering Bulletin No.1, November 1968.

8.2 Harvey Titanium, "Titanium," September 1968.

8.3 Titanium Metals Corp. of America, "How to Use Titanium," January 1970.

8.4 H. Smallen and J.K. Stanley, "A Guide to Advanced Metals," Machine Design, 42 (16), 130 (1970).

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

8.6 D.J. Maykuth et al., "Titanium-Base Alloys: 6Al-4V," DMIC Handbook, February 1971.

8.7 AMS Specification 4935B; AMS Specification 4928F.

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

8.9 W. Illg and L.A. Imig, "Fatigue of Four Stainless Steels, Two Titanium Alloys, and Two Aluminum Alloys Before and After Exposure to Elevated Temperatures for Up to Three Years," NASA TN D-6145, April 1971.

8.10 I.E. Figge, "Residual Strength of Several Titanium and Stainless Steel Alloys," NASA TN D-2045, December 1963.

8.11 C.F. Hickey, Jr., "Mechanical Properties of Titanium and Aluminum Alloys at Cryogenic Temperatures," ASTM Proc., 62, 765 (1962).

8.12 C.R. Johnson and J.D. Grimsley, "Short-Time Stress Rupture of Prestressed Ttianium Alloys under Rapid Heating Conditions," NASA TN D-6052, November 1970.

Chapter 9

PHYSICAL PROPERTIES

9.1 Density at room temperature

0.160 lbs/in^3 (4.424 g/cm^3) (refs. 9.1, 9.2).

9.2 Thermal Properties

9.21 Thermal conductivity, K, of annealed bar versus temperature, figure 9.21.
9.22 Specific heat of alloy versus temperature, figure 9.22.
9.23 Mean coefficient of thermal expansion expansion, figure 9.23
9.24 Thermal diffusivity

9.3 Electrical Properties

9.31 Electrical resistivity versus temperature of annealed alloy, figure 9.31.

9.4 Magnetic Properties

9.41 Alloy is nonmagnetic. [cf., permeability of pure titanium is 1.00005 at 20 oersteds (ref. 9.4)]

9.5 Nuclear Properties

9.51 As indicated in Chapter 6 (ref. 9.5), little data of statistical significance are available on the effects of nuclear radiation of titanium 6Al-4V. However, indications from tests performed with difficulty at cryogenic temperatures are that yield and ultimate strengths are increased by nuclear radiation and that ductility is reduced.

9.6 Other Physical Properties

9.61 Emissivity
9.62 Damping Capacity

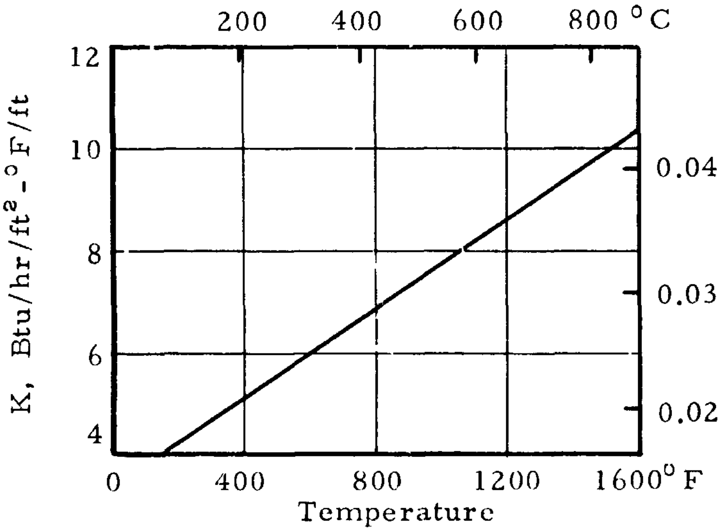

FIGURE 9.21. — Thermal conductivity versus temperature of titanium 6Al-4V annealed bar. (Ref. 9.2)

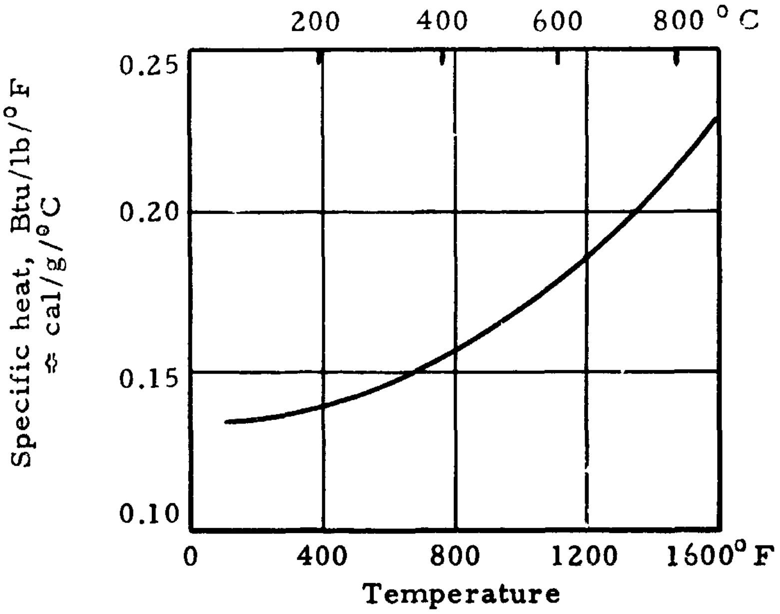

FIGURE 9.22. — Specific heat versus temperature of titanium 6Al-4V. (Ref. 9.2)

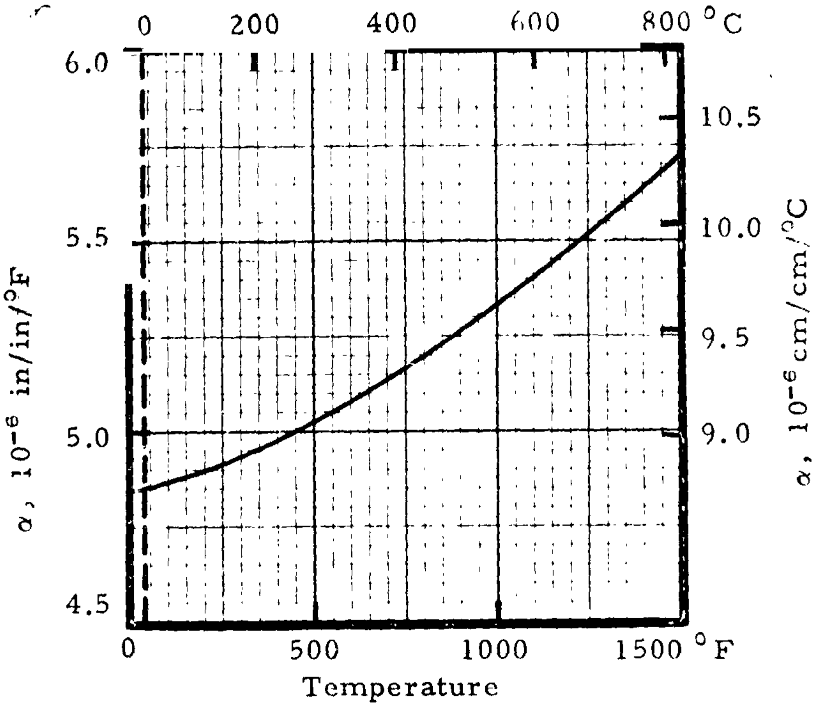

FIGURE 9.23. – Mean coefficient of thermal of titanium 6Al-4V from 32° F (0° C) to indicated temperature. (Ref. 9.2)

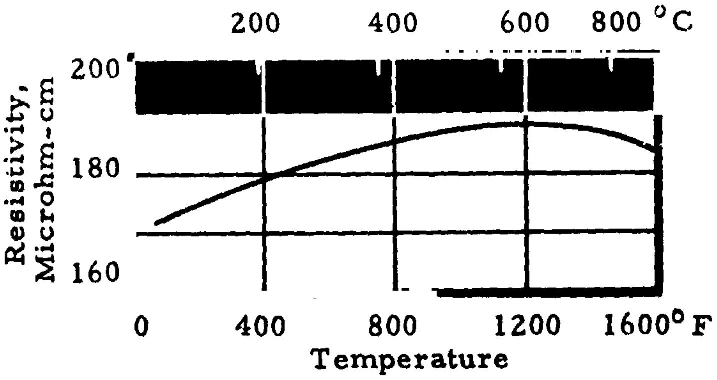

FIGURE 9.31. – Electrical resistivity versus temperature of annealed titanium 6Al-4V. (Ref. 9.2)

Chapter 9 - References

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

9.2 Titanium Metlas Corp. of America, "Properties of Titanium 6Al-4V," November 1968.

9.3 Metals Reference Book, C.J. Smithells, Ed., 4th Ed., Plenum Press, New York, 1967, Vol. III.

9.4 Harvey Titanium, "Titanium," September 1968.

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

Chapter 10

CORROSION RESISTANCE AND PROTECTION

10.1 General. The resistance to corrosion of commercially pure titanium is far superior to that of common engineering metals in normal atmospheres, sea water, moist chlorine, metallic chlorides, bleaching solutions, and (under certain conditions) nitric, sulfuric, and hydrochloric acids; it is not generally subject to stress corrosion (refs. 10.1 through 10.6).

The resistance to corrosion of titanium alloys is somewhat less than that of the base metal, but still superior to other structural materials (refs. 10.7, 10.8). The alloys are subject to stress-corrosion cracking in media such as fuming nitric acid, nitrogen tetroxide, methyl alcohol, and "hot salt" environments (refs. 10.8, 10.9, 10.10).

> It must be cautioned that titanium 6Al-4V is subject to impact sensitivity in the presence of liquid oxygen and red fuming nitric as well as other oxidizing substances under certain conditions (refs. 10.10 through 10.16).

The resistance to corrosion of titanium and its alloys is based on a natural, tenacious, self-healing oxide film that forms on any titanium surface that is exposed to an oxidizing environment (refs. 10.3, 10.8). The most protective films are usually developed when water, even in trace amounts, is present in the environment (ref. 10.16). When the alloy is exposed to highly oxidizing environments in the absence of moisture, a protective film is not formed and rapid oxidation, often pyrophoric, may take place (refs. 10.10 through 10.15).

The oxide film affords protection only at low or moderate temperatures. For example, pure titanium is not resistant to oxidation at high temperatures, and oxidizes at elevated temperatures as low as 480° F (250° C) at a rate that increases as the temperature increases (ref. 10.3).

10.2 Resistance of Ti-6Al-4V. The alloy is resistant to corrosion in media such as pure hydrocarbons, chlorinated and fluorinated hydrocarbons, and most acids. However, materials that hydrolyze in the presence of water, such as HF or HCl, may attack the alloy (ref. 10.16).

10.21 Salt Water Corrosion. Titanium 6Al-4V resists general attack, pitting, intergranular, and crevice corrosion in salt water (ref. 10.9).

The results of flexural fatigue tests of steel, aluminum, and titanium alloys conducted in a salt water environment (ref. 10.17) indicate that: (1) mechanical notches are more damaging in high-cycle than low-cycle fatigue tests; (2) on the basis of fatigue strength to density ratio, titanium 6Al-4V is approximately equal to steel and aluminum alloys; (3) the highest fatigue strengths and ratios of fatigue strength to density at intermediate and long lives are displayed by titanium alloys.

10.22 Liquid Oxygen. Burning can begin when a fresh surface of titanium 6Al-4V such as a crack or fracture is exposed to gaseous oxygen, even at −250° F (−157° C) and at a pressure of 50 to 100 psi (0.035 to 0.070 kg/mm²). Since the alloy is impact sensitive to oxygen at levels below that for many organic compounds, the oxide protective layer is not protective once the reaction starts. The reaction process propagates once it has been initiated (ref. 10.16).

10.23 Hydrogen. Titanium 6Al-4V is susceptible to embrittlement which may result from storage with high-pressure hydrogen, the formation of hydrides, or absorption of hydrogen during various metal processing techniques (ref. 10.18).

In an investigation of hydrogen embrittlement at McDonnell Douglas (ref. 10.19), precracked specimens of annealed titanium 6Al-4V were cycled under axial loading conditions in controlled atmospheres of hydrogen, nitrogen, and helium at a pressure of 2 psi (0.0014 kg/mm²) above atmospheric pressure. The results of the tests indicated that the hydrogen-gas environment had a marked effect in increasing crack growth rate at all testing temperatures above −110° F (−79° C) compared with rates in nitrogen or helium. Contamination of the hydrogen with oxygen led to retarded crack growth rates. At temperatures below −110° F to −423° F (−253° C), the specimens had longer fatigue lives in hydrogen than in nitrogen or helium as testing temperatures were decreased. It was concluded that storage with liquid hydrogen should have no adverse effects on titanium 6Al-4V, but storage with gaseous hydrogen at temperatures above −110° F (−79° C) is not recommended.

The tensile properties of notched and unnotched STA titanium 6Al-4V specimens were compared in helium and hydrogen atmospheres at temperatures from −320° F (−196° C) to 72° F (22° C) by workers at Rocketdyne (ref. 10.20). At −320° F, the notch strength of the alloy was the same in both helium and hydrogen and was essentially independent of pressure from 14.7 to 2000 psi (0.010 to 1.4 kg/mm²). As temperature and pressure were increased, the notch strength in hydrogen became less than that in helium. At 72° F and 2000 psi, a 45-percent loss of notch strength was incurred. The tensile strengths of unnotched specimens were approximately the same in hydrogen as in helium under all test conditions. The results of post examination of the specimens indicated no hydride-phase formation or intergranular fracture, which are characteristic of internal hydrogen embrittlement in the alpha-beta titanium alloys. This is attributed to the short duration of the tests and the slow diffusivity of hydrogen at cryogenic temperatures. It was concluded that hydrogen embrittlement occurs by the same mechanisms operative for iron- and nickel-base alloys, and appears to be related to the atomic structure of the alloy but not to its propensity to absorb quantities of hydrogen or to form a hydride phase.

10.24 Red Fuming Nitric Acid (RFNA). In a study of the corrosion behavior and pyrophoric susceptibility of titanium alloys stored with RFNA (ref. 10.14), it was shown that corrosion rates increase with increasing NO_2 content in the range of 0 to 20 percent NO_2 and decrease with increasing water content in the range of 0 to 2 percent H_2O: see table 10.24. Metallographic examination indicated a possible galvanic or electrochemical mechanism for the attack by liquid-phase fuming nitric acid.

Ignition or pyrophoric reactions can be initiated by impact or friction on titanium 6Al-4V after exposure to FNA containing 0 to 1.25 percent H_2O and from 2.5 to 28 percent NO_2 for periods of time longer than 4 hours. The ignition phenomenon is associated with a chemical change in the metal surface. It was observed that, upon removal from the FNA and washing, the metal can be ignited by probing with a glass rod or hardened-steel tool after moistening with fresh acid. (The corrosion product on pure titanium was found to be finely-divided titanium metal, and on the alloys to be finely-divided alloy metal.)

The tendency for stress-corrosion cracking of titanium 6Al-4V increases with NO_2 in the range of 0 to 20 percent and decreases with increasing water in the range of 0 to 1 percent over a temperature range of 25° to 71° C. Stress-relieving heat treatment will alleviate the tendency twoard stress-corrosion cracking, but will not remove the susceptibility to phyrophoric reactions (ref. 10.14).

10.25 Nitrogen Tetroxide (N_2O_4). Titanium 6Al-4V has been shown to be entirely compatible with N_2O_4 when stored for 1-1/2 years at a temperature of about 110°F (43°C). The corrosion rates for 14 specimens stored in individual capsules were less than 3 micro-inches (7×10^{-5} mm) per year; vapor pressures in the test capsules varied only with fluctuations in temperature, indicating no decomposition of the N_2O_4. Information on the composition of the original N_2O_4 was not available, but post-test analysis of the "cleanest" tests indicated average impurities of 0.057 percent H_2O, 0.015 percent NO, and 0.0067 percent chloride (ref. 10.21).

10.26 Fluorine-Type Oxidizers. In a critical survey of passivation techniques for metals to be used with fluorine-type oxidizers (ref. 10.22) it was found that data on the compatibility of titanium 6Al-4V with oxygen difluoride (OF_2) and FLOX (fluorine-oxygen) are widely scattered and are based on distressingly short-term corrosion tests. It was summarized that the alloy appears to have acceptable corrosion rates in storage tests of two weeks or less, but is sensitive to impact in the presence of fluorine oxidizers (e.g., ref. 10.15). The alloy dissolves in chlorine trifluoride (ClF_3).

In a subsequent investigation (ref. 10.23), titanium and titanium 6Al-4V were subjected to various tests in the presence of OF_2 to ascertain the degree of deflagration purported to ensue. The tests were conducted at a pressure of less than 1.5 atmospheres (safety limits of apparatus) and at room temperature on the premise that ignition of freshly-torn surfaces might progress more rapidly than at the low temperatures characteristic with the use of OF_2. The results of tests with thin foils, machined chips, and notched thick foils were all negative; there were no signs of flammability, ignition, or change in pressure. This raises the question that the impact sensitivity reported for OF_2 (ref. 10.15) may have been due to the presence of moisture (ice is detonated by impact in ABMA cup tests).

10.27 Hydrazines. A post-test analysis of titanium 6Al-4V specimens and various hydrazine fuels stored for 2 to 3 years at about 110° F (43° C) indicates that the alloy is virtually unaltered by corrosive attack (corrosive rates of less than 5 x 10^{-5} mm per year) as shown in table 10.27. However, decomposition of the fuels --a most important consideration-- varies from being of the order of control-fuel decomposition at the same temperature to a rate that is doubled or greater (ref. 10.24). Examination of the data for control fuels and fuels containing titanium 6Al-4V specimens (and recognition of the sensitivity of hydrazine fuels to catalytic decomposition) clearly indicates the necessity for rigid control of fuel composition and the cleanliness of surfaces that come into contact with the fuels.

10.3 Stress Corrosion. Stress-corrosion cracking can occur in titanium 6Al-4V exposed to RFNA, N_2O_4, anhydrous methanol, or "hot salt" media (refs. 10.8, 10.14, 10.16). It has been stated that stress-corrosion cracking problems disappear by adding NO to N_2O_4 and water to methanol (refs. 10.8, 10.16).

10.31 Stress-corrosion Cracking in N_2O_4. Subsequent to a series of failures (commencing in 1965) due to stress-corrosion cracking of titanium 6Al-4V tanks containing N_2O_4, a number of studies were made, with conclusions that: (1) When no significant or measurable amounts of NO were present (red N_2O_4) and the system was exposed to moderately high stresses at temperatures in the range of 85° to 165° F (29° to 74° C), stress corrosion cracking occurred. (2) When the N_2O_4 contained an excess of NO (green N_2O_4), stress-corrosion cracking did not occur. (3) Up to 0.08-percent addition of chloride as NOCl did not initiate stress-corrosion cracking. (4) Stress-corrosion cracking occured in green N_2O_4 which had been oxygenated. (5) Stress-corrosion cracking was eliminated by addition of sufficient H_2O to red N_2O_4 (ref. 10.25).

Additional work by one group (ref. 10.26) indicates that titanium alloy composition has a marked influence on the resistance to corrosion and the stress-corrosion fracture mode. Resistance to corrosion decreases with increasing content of vanadium, but aluminum content has no significance. Titanium 6Al-4V was susceptible to stress-corrosion cracking in oxygenated (red) N_2O_4 at 250 psig (0.18 kg/mm^2) oxygen and 106° F (41° C).

10.32 Stress-Corrosion Cracking in Hot-Salt Environments. In late 1955, surface cracking was observed on titanium 6Al-4V alloys undergoing

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creep testing at 700° F (371° C). It was established later that the cracks were often associated with human fingerprints. Since testing of specimens under stress in contact with pure NaCl resulted in the production of cracking at high temperatures, this phenomenon has become known as "hot-salt" corrosion cracking (ref. 10.16).

In tests performed with titanium 8Al-1Mo-1V (ref. 10.27), it was shown that when a titanium alloy coated with an apparently dry halide salt is heated to 250° to 260° C, a hydrogen halide is formed by pyrohydrolysis. This hydrogen halide penetrates the protective oxide film and attacks the metal. Hydrogen generated by the reaction of the pyrohydrolytic hydrogen halide and metal is partially absorbed by the metal surface. The surface is embrittled and then cracking can be initiated by residual (or applied) stress.

Titanium 6Al-4V appears midway in the results of a study to determine the relative susceptibility to hot-salt stress-corrosion cracking of several titanium alloys (ref. 10.28). On the basis of potential use strength (crack threshold stress divided by 0.2-percent creep stress), titanium 6Al-4V was the most resistant alloy. However, the ratings can be altered by heat treatment and processing variations. Residual compressive stresses and cyclic exposures also reduce susceptibility to stress corrosion.

Simulated turbine-engine compressor environmental variables, such as air velocity, pressure, dewpoints, salt concentration, and salt-decomposition temperatures, exerted only minor effects. Crack thresholds for all alloys are decreased by increasing exposures from 100 to 1000 hours. Substantial increases in hydrogen content of all stress-corroded specimens support a concept that hydrogen produced by corrosion is responsible for hot-salt stress-corrosion embrittlement and cracking of titanium alloys (ref. 10.28).

10.4 Corrosion Protection. Specific treatment for titanium 6Al-4V is not required for use in normal atmospheric environments, environments free of halide gases, aqueous salt environments, or in media containing any of a great number of industrial chemicals.

10.41 It has been shown in salt-spray tests that the best protection of aluminum alloy surfaces in contact with titanium 6Al-4V is afforded by sulfuric acid-anodized coatings (ref. 10.29); properly applied chromic acid-anodized coatings are also protective. The anodic coatings are poor electrical conductors and prevent the formation of galvanic couples between aluminum alloys and titanium 6Al-4V.

10.42 It is suggested that the use of titanium 6Al-4V filler wire for welding rather than commercially pure titanium filler wire will minimize the formation of hydride in titanium 6Al-4V and subsequent hydrogen embrittlement (ref. 10.18).

10.43 The effect of water content in RFNA or N_2O_4 on the stress-corrosion cracking of titanium 6Al-4V has been discussed earlier in this chapter.

10.44 Surface treatments for corrosion protection are discussed in chapter 11.

TABLE 10.24. — Average Corrosion Rates for Alloy Stored in Fuming Nitric Acid with Varying Nitrogen Tetroxide and Water Contents

Source	Ref. 10.14					
Alloy	Titanium 6Al-4V (annealed)					
FNA Composition, %			Storage Time	Storage Temp, °C	Corrosion Rate, mpy (a)	Remarks
NO_2	H_2O	HF				
0	0	-	1 week	54	8.16	not susceptible to ignition
	1				4.32	
	2				3.02	
10	0	-	1 week	54	20.76	ignition sensitive
	1				5.77	ignition sensitive
	2				4.58	--
20	0	-	1 week	54	96.83	ignition sensitive
	1				4.32	ignition sensitive
	2				3.35	--
13.5	2.5	-	30 days	30	0.20	--
				71	6.66	sparked when probed
MIL-N-7254A Specification:						
0.5 (max)	1.5-2	-	90	54	0.71	no ignition
12-14	2.5	-	90	54	3.68	no ignition
12-14	2.5	0.5	90	54	13.4	no ignition, pitted

(a) Liquid phase in test cell (vapor phase rates are much lower).

1 mpy = 0.0254 mm/year.

TABLE 10.27. — Test and Analysis Data for Alloy Stored at 110° F (43° C) in Hydrazine and Hydrazine Mixtures

Source	Ref. 10.22			
Alloy	Titanium 6Al-4V			
Fuel/Specimen	Storage Pressures at 110° F (a)			Corr. Rate, µin/yr (b)
	1 yr	2 yr	3 yr	
N_2H_4				
Controls (3)	2.6-5.5	6.7-10.5	9.6-14.6	-
Coated with Apiezon-L	1.8	15.7	23.6	1.0
EPR-bonded (c)	12.1	17.7	27.0	-
N_2H_4-$N_2H_5NO_3$				
Controls (4)	2.6-4.7	2.6-6.7	3.3-8.3	-
Controls (2), initiated 1 year later	7.8, 18.5	15.6, 36.4	20.0, 45.5	-
ELI grade	4.9	8.6	11.0	0.4
ELI with Al-6061-T6	4.7	8.9	11.8	0.7
Regular grade	5.6	13.7	19.3	<0.1
With Al-6061-T6	4.9	9.2	12.2	<0.1
N_2H_4-UDMH (50-50)				
Controls (2)	8.1, 12.3	11.9, 28.4	-	-
Regular grade	9.5	19.7	-	0.6
	6.5	8.7	-	0.6
	7.9	11.1	-	0.8
	10.2	8.7	-	0.8
	7.8	13.0	-	0.8
	8.6	14.0	-	0.6
	17.8	29.8	-	1.2
	7.8	9.6	-	0.6
	11.3	10.1	-	1.5

(a) Pressures normalized to uniform ullage; 1 psi = 7.0307×10^{-4} kg/mm^2

(b) 1 µin/yr = 2.5×10^{-6} cm/yr

(c) Apiezon-coated and EPR bonded specimens were regular grade.

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10.1 G.T. Bedford, et al., "Titanium Moves into Process Equipment," Chem. Eng., 63 (12), 238 (1956).

10.2 The Refining Engineer, September 1958, p. C-12.

10.3 H.R. Ogden, "Titanium and Its Alloys," in C.R. Tipton, Jr., Ed., Reactor Handbook, Vol. 1, Interscience Publishers, New York, 1960.

10.4 Steel, December 29, 1958, p. 143.

10.5 H.H. Uhlig, Corrosion and Corrosion Control, John Wiley & Sons, New York, 1963.

10.6 Harvey Titanium, "Titanium," September 1968.

10.7 Rodney Metals/Teledyne, "Machining Metals for Your Needs," December 1970.

10.8 H. Smallen and J.K. Stanley, "A Guide to Advanced Metals," Machine Design, 42 (16), 130 (1970).

10.9 Titanium Metals Corp. of America, "Properties of Titanium 6Al-4V," November 1968.

10.10 Titanium Metals Corp. of America, "How to Use Titanium," January 1970.

10.11 E.L. White and J.J. Ward, "Ignition of Metals in Oxygen," DMIC Report 229, February 1, 1960.

10.12 P.M. Ambrose, et al., "Investigation of Accident Involving Titanium and Red Fuming Nitric Acid, December 29, 1953," U.S. Dept. Interior, Circ. No. 7711, March 1955.

10.13 C.W. Funk, et al., "Studies of Less Critical Materials for Rocket Components," Aerojet-General/Azusa Report No. 913, February 1955.

10.14 J.B. Rittenhouse, J.S. Whittick, et al., "Corrosion and Ignition of Titanium Alloys in Fuming Nitric Acid," WADC TR 56-414, February 1957.

10.15 N.A. Tiner, W.D. English, and W.M. Toy, "Compatibility of Structural Materials with High-Performance O-F Oxidizers," AFML TR 65-414, November 1965.

10.16 D.J. Maykuth et al., "Titanium Base Alloys: 6Al-4V," DMIC Handbook, February 1971.

10.17 R.C. Schwab and E.J. Czyryca, "Effects of Notches and Saltwater Corrosion on the Flexural Fatigue Behavior of High-Strength Structural Alloys," ASTM STP-462, 203 (1970).

10.18 C.E. Cataldo, "Effects of Hydrogen on Metals," NASA Tech Brief 69-10372, September 1969.

10.19 G.F. Pittinato, "The Reactivity of Hydrogen with Ti-6Al-4V under Fatigue Cycling at Ambient and Cryogenic Temperatures," ASM Trans. Quart., 62 (2), 410 (1969).

10.20 R.J. Walter and W.T. Chandler, "Effect of Hydrogen Environment on Inconel 718 and Ti-6Al-4V under Simulated J-2 Engine Operating Conditions," Rocketdyne/North American Rockwell Report No. R-7920, Contract NAS8-19C, Feb. 1 - June 30, 1969.

10.21 R.F. Muraca and J.S. Whittick, "The Results of Long-Term Storage Tests for Compatibility of Nitrogen Tetroxide with Various Spacecraft Materials," Special Report No 2 under Contract JPL-951581 (NAS7-100), May 15, 1967.

10.22 R.F. Muraca, J.S. Whittick, and J.A. Neff, "Treatment of Metal Surfaces for Use with Space Storable Propellants: A Critical Survey," Special Report 951581-8 under Contract JPL-951581 (NAS7-100), August 15, 1968.

10.23 R.F. Muraca et al., "Chemistry Support Services," Monthly Report No. 25 under JPL Contract 951581 (NAS7-100), June 30, 1968.

10.24 R.F. Muraca, J.S. Whittick, and C.A. Crutchfield, "The Results of Long-Term Storage Tests for Compatibilities of Spacecraft Materials with Hydrazine and Hydrazine Mixtures," Special Report 951581-6 under Contract JPL-951581 (NAS7-100), October 1, 1967.

10.25 P.J. Moreland and W.K. Boyd, "Stress Corrosion Cracking of Ti and Ti-6Al-4V Alloy in Dinitrogen Tetroxide," Corrosion, 26 (4), 153 (1970).

10.26 J.D. Boyd, et al., "The Effect of Composition on the Mechanism of Stress-Corrosion Cracking of Titanium Alloys in N_2O_4, Aqueous, and Hot-Salt Environments. Part II," NASA CR-1846, October 1971.

10.27 R.S. Ondrijcin, "The Hot-Salt Stress-Corrosion Cracking of Titanium Alloys," NASA CR-1829, October 1971.

10.28 H.R. Gray, "Relative Susceptibility of Titanium Alloys to Hot-Salt Stress Corrosion," NASA TN D-6498, November 1971.

10.29 C.A. Kuster, "Corrosion Protection of Aluminum Alloys in Contact with Other Metals," NASA Tech Brief 69-10098, April 1969.

Chapter 11 - Surface Treatments

11.1 General. The surface of titanium 6Al-4V may be treated mechanically, chemically, or electrochemically. The purpose of various surface treatments is to remove scale, improve resistance to corrosion, or minimize tendency to galling and seizures. A review of the effects of surface condition on the mechanical properties of titanium has recently become available (ref. 11.5).

11.2 Lubricant and Wear Coatings. The resistance of titanium 6Al-4V to wear and galling is poor, and lubrication is difficult. These conditions can be attributed to the nature of the adsorbed gas film on the metal's surface (ref. 11.3). Liquid lubricants have little effect on untreated titanium alloys, but solid lubricants applied to properly roughened surfaces can give useful wear life. Mechanical or chemical roughening combined with chemical and electrochemical conversion coatings provide the optimum treatment for bonding solid lubricants to titanium.

Wear-resistant surfaces responsive to lubrication may be provided by surface-hardening processes, such as nitriding and oxidizing, even at high loads. For improvement of wear resistance, the most practical surface treatments include spraying of metallic or ceramic compounds (e.g., molybdenum, titanium oxide, chromium oxide, and tungsten carbide).

11.3 Treatments for Alleviating Stress-Corrosion Cracking. It has been demonstrated that the surface conditions exert a major influence on susceptibility to stress-corrosion cracking of titanium 6Al-4V in hot-salt media. As shown in figure 11.4, the threshold curves for cracking of machined specimens are substantially higher than those exhibited by chemically-milled specimens (ref. 11.4). Thus, residual compressive stresses resulting from machining or shot-peening can protect titanium 6Al-4V from hot-salt stress corrosion. Nonetheless, this protective influence can anneal out during long times at elevated temperatures.

11.31 Glass-bead peening has been used successfully to alleviate stress-corrosion cracking of titanium 6Al-4V tanks containing nitrogen tetroxide; peening parameters were established to provide compressive residual stresses of the order of 100 ksi (70 kg/mm^2) (ref. 11.7).

11.4 Treatment for Use with Storable Propellants. The procedure for passivation of titanium 6Al-4V recommended by the Jet Propulsion Laboratory for use with nitrogen tetroxide and hydrazine (ref. 11.6) includes: (1) Treatment for one minute in a mixture of nitric acid at a concentration of 1.5 pints/gallon and hydrofluoric acid at a concentration of 3 ounces per gallon; balance water. After a distilled water rinse (pH of run-off water equals pH of source water within pH 0.5), the surface is dried by a stream of moisture-free nitrogen or by baking in a vacuum oven at 59°C for 5 minutes. (1 oz/gal = 7.8 ml/l.)

11.5 Electroplating is one of the most widely used techniques for applying metallic coatings to metals and nonmetals for improvement of surface characteristics. However, it has been difficult to electroplate titanium and its alloys with adherent coatings because of the inherent oxide film on the surface of the metal and its immediate reformation subsequent to its removal by mechanical or chemical techniques (ref. 11.8).

In view of the fact that copper or nickel are not impact sensitive in the presence of oxygen, an investigation was made of techniques for electrodeposition of these metals on titanium 6Al-4V to provide a protective coating for use of the alloy in LOX auxiliary tanks (ref. 11.9). Particular attention was paid to treatment of the alloy surfaces and handling prior to electroplating. Success was obtained with the following procedure.

1. Etching

Bath: 875 ml glacial acetic acid and 125 ml 70 percent hydrofluoric acid per liter of solution; maintain at 35° C.

Procedure: Dry parts in an oven at 66° C. Connect the parts anodically outside the tank. Adjust voltage to 5 volts. Immerse parts in the bath, adjust voltage (within one minute) to 10 volts and maintain for a minimum of 30 minutes. Transfer to rinsing bath within 30 seconds, DO NOT DRAIN, and rinse thoroughly.

2. Nickel Plating

Strike: Wood's nickel bath or all-chloride bath. Connect parts and apply cathodic voltage of approximately 3 volts. Immerse parts in nickel solution and adjust current to 46 ma/cm^2 for 3 minutes. Do not interrupt current during plating or a laminated deposit will result. Rinse thoroughly.

Plate: Nickel sulfamate solution (commercially available). Connect parts and apply 3 cathodic volts. Immerse parts in plating solution and adjust current to 77 ma/cm^2 for 10 minutes. Do not interrupt current during plating. Rinse thoroughly and dry.

11.6 Electroless Plating. A review of literature on electroless plating indicates that the cladding of titanium alloys with electroless nickel has attractive advantages over electrodeposition techniques for aerospace use. For example:

a. There is less chance of hydrogen absorption, thus minimizing hydrogen embrittlement.

b. Coating of difficultly accessible internal areas, corners, and crevices (e.g., supply valves and lines) is assured without recourse to complicated rack and anode designs.

c. Electroless nickel coatings have less porosity and greater hardness than electrodeposited coatings.

Electroless deposition is defined as the autocatalytic reduction of metal from solution. Plating solutions consist essentially of nickel salts and reducing agent (generally sodium hypophosphite), along with other compounds to improve solution and deposit characteristics. Nickel deposition proceeds by catalytic dehydrogenation of hypophosphite with consequent liberation of electrons for the reduction of metal ions (refs. 11.10, 11.11).

Military Standard MIL-C-26074 covers electroless nickel, listing Class I, the "as-plated condition," and Class II, as heat treated to increase hardness.

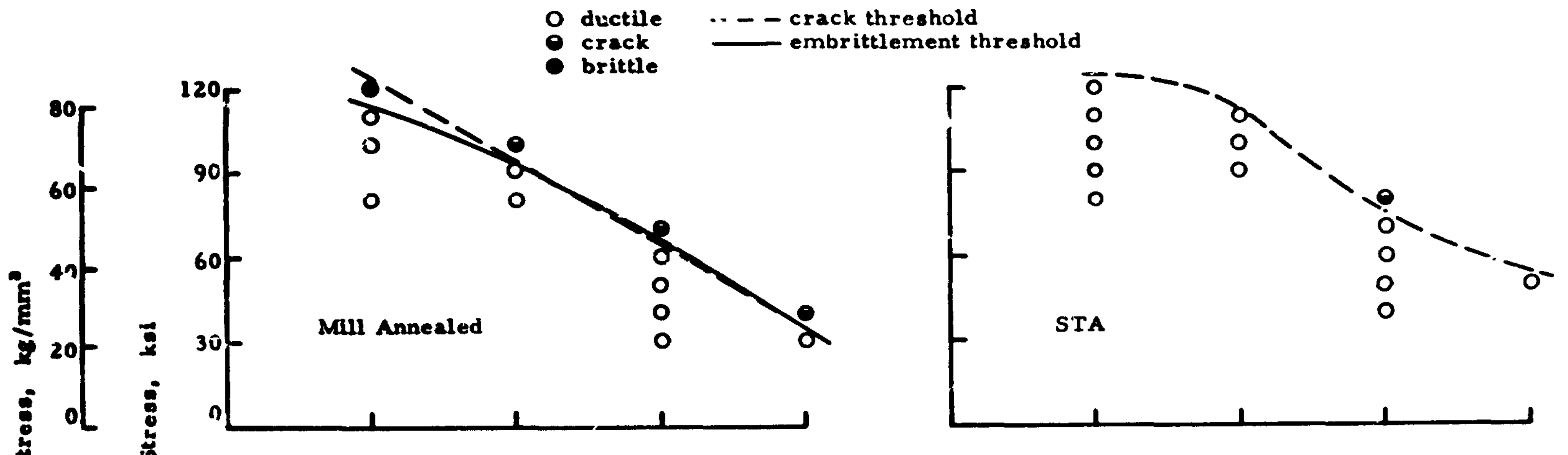
Descriptions of pretreatment, electroless plating parameters and procedures, and post treatment for titanium and its alloys are given in references 11.3 and 11.10 through 11.15. A successful procedure for electroless nickel plating of titanium 6Al-4V is described below (ref. 11.12).

> Pretreatment. Vapor degrease specimens in trichloroethylene. Then vapor blast in a blast cabinet with 100 grit aluminum oxide at 30 to 40 psi (0.021 to 0.028 kg/mm^2) until appearance is uniform and immediately immerse in a slurry of the grit for not more than 10 minutes; remove and brush away grit under a stream of running water. Immediately remove specimens to an activating solution of hot (66°C), slightly acidified, 10-percent nickel chloride solution for 2 minutes and transfer to the plating bath.
>
> Plating. Bath composition and conditions are summarized in table 11.6. If plating does not start immediately, initiate the reaction by touching the specimen with a more electropositive metal (aluminum) to create a galvanic cell. Make the titanium specimen the cathode for a few seconds by applying an external emf until gaseous hydrogen evolution is observed. Plating rate is about 0.02 mil (0.005 mm) per hour --typically two hours for a plating thickness of 0.4 mil (0.01 mm). Remove specimens from the bath, rinse in hot running water, and store in a dessicator at least 24 hours prior to heat treating.
>
> Heat Treatment (Diffusion Bonding). For successful bonding, oxidation during heat treatment must be prevented or minimized; hence, treatment in vacuum is recommended, which also permits higher temperatures. The best mechanical properties for titanium 6Al-4V are obtained by heating at 840°C for 4 hours at a pressure of at least 5 x 10^{-4} mm Hg. The specimens are then furnace cooled in an argon atmosphere.

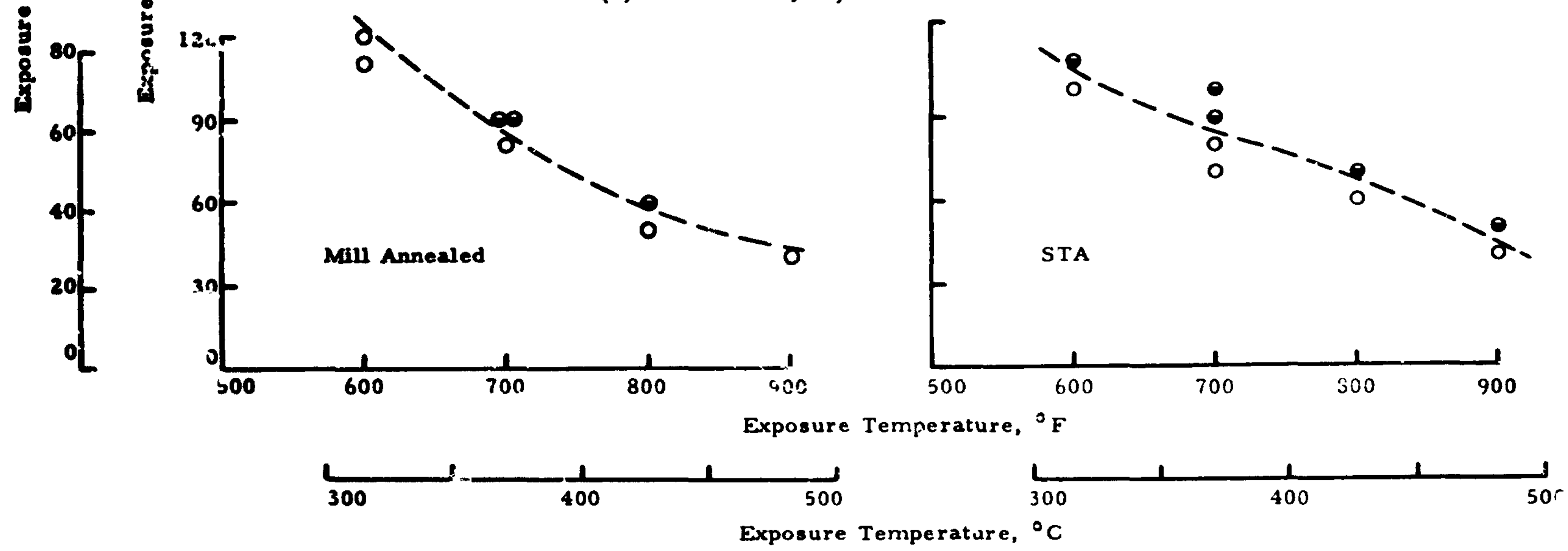
TABLE 11.6. — Electroless Bath Composition and Plating Conditions

Source	Ref. 11.12		
Alloy	Titanium 6Al-4V		
Chemical	Bath Composition		
	Formula	Grams/liter	Moles/liter
Nickel Chloride	$NiCl_2 \cdot 6H_2O$	30	0.126
Sodium Hypophosphite	$NaH_2PO_2 \cdot H_2O$	10	0.094
Sodium Citrate	$Na_3C_6H_5O_7 \cdot 2H_2O$	100	0.325
Ammonium Chloride	NH_4Cl	50	0.934
Sodium Chloride	$NaCl$	5	0.085
Molar Ratio	$\frac{\text{Ni}}{\text{Hypophosphite}} = \frac{0.126}{0.094} = 1.34$		

Conditions		
Temperature	pH Range	pH Control
88° C	8 – 9	$NH_4OH:H_2O$, 1:1



(a) As machined, dynamic air



(b) Chemically milled, dynamic air

FIGURE 11.4. — Effect of machining and chemical milling on stress-corrosion cracking of mill-annealed and STA titanium 6Al-4V exposed to a hot-salt environment for 90 to 100 hours

(Ref. 11.4)

Chapter 11 - References

11.1 Titanium Metals Corp. of America, "Properties of Titanium 6Al-4V," Titanium Engineering Bulletin No. 1, November 1968.

11.2 Titanium Metals Corp. of America, "How to Use Titanium," January 1970.

11.3 S.J. Kostman, "Lubricants and Wear Coatings for Titanium," ASTM STP-432, 208 (1968).

11.4 H.R. Gray, "Relative Susceptibility of Titanium Alloys to Hot-Salt Stress Corrosion," NASA TN D-6498, November 1971.

11.5 D.N. Williams and R.A. Wood, "Effects of Surface Condition on the Mechanical Properties of Titanium and Its Alloys," MCIC-71-01, National Technical Information Service, Springfield, Virginia 22151.

11.6 Jet Propulsion Laboratory, Spec. No. GMZ-50521-GEN-A, Log No. 0093.

11.7 T.T. Bales, C.R. Manning, Jr., and W.B. Lisagor, "Equipment and Procedures for Glass-Bead Peening Titanium-Alloy Tanks," NASA TN D-4288, January 1968.

11.8 S. Abkowitz, J.J. Burke, and R.H. Hiltz, Jr., Titanium in Industry, Van Nostrand and Co., New York, 1955, p. 145.

11.9 E. C. Brown, "Copper and Nickel Adherently Electroplated on Titanium Alloy," NASA Tech Brief 67-10532, December 1967.

11.10 ASTM STP-265, "Symposium on Electroless Nickel Plating," 1959.

11.11 F. Pearlstein, "Electroless Deposition of Metals: Principles and Applications," Proc. 8th Ann. Nat. Conf. on Environmental Effects on Aircraft and Propulsion Systems, Bordentown, New Jersey, Oct. 8-10, 1968, p. 161.

11.12 M. Levy and J.B. Romolo, "Improved Adhesion of Electroless Nickel Plate on Titanium Alloys," 48th Ann. Tech. Proc., Am. Electroplaters' Society, 1961, p. 135.

11.13 W.J. Babkes, "An Adherent Electrodeposit on Titanium," Products Finishing, August 1962, p. 72.

11.14 W.B. Harding, "Electroplating on Titanium and Titanium Alloys," Plating, 50, February 1963, p. 131.

11.15 L. Domnikov, "Plating on Titanium and Its Alloys," Metal Finishing, 65, April 1967, p. 58.

Chapter 12

JOINING TECHNIQUES

12.1 General. The most important technique for joining of titanium and its alloys is welding by fusion, resistance, or pressure, but procedures are considerably different from those employed for common structural metals because of problems of contamination (refs. 12.1 – 12.10). Methods for evaluating weldments are given in detail in reference 12.13.

12.2 Pretreatment. The part to be welded and the filler wire must be cleaned to eliminate contaminants. Acetone or alcohol is recommended for degreasing; trichlorethylene (or other chlorinated solvents) is to be avoided. Fingerprinting of parts once they have been cleaned must also be avoided. A sharp file may be used to deburr edges. A stainless steel wire brush may be used to clean rough dirt; steel wool or sandpaper must never be used to prepare surfaces. After the filler wire is cleaned, the end should be snipped off just prior to introduction to the weld puddle to ensure elimination of oxygen or nitrogen absorption during cooling in air from prior use (refs. 12.2–12.5, 12.9, 12.10).

12.3 Fusion Welding (refs. 12.1 – 12.10). Pieces to be welded should be clamped, not tacked (unless the tacks are shielded with the same care as the parts to be welded). Filler wire should be used when welding gages of 3/32 inch (2.38 mm) or greater and when a joint fitup is crude. The wire is fed continuously (not dabbed) into the weld zone at the junction of the weld joint and arc cone.

The most important consideration in welding titanium alloys is to replace the air at the top and bottom of the weld with helium or argon. In other words, success in welding titanium lies in the art of shielding. A minimum gas flow rate is used for shielding; excessive flow may cause turbulence and lead to contamination.

Coated electrodes are never used since titanium will react with all flux coatings. In general, best results are obtained with thoriated-tungsten electrodes; they retain their points longer and operate at cooler temperatures than other electrodes.

12.31 The tungsten-arc inert-gas-shielded (TIG) process is the most generally used method for fusion welding of titanium 6Al-4V. It is used almost exclusively for sheet-gage materials of thicknesses to near 0.125 inch (3.175 mm), and can be employed successfully for a wide range of heavier plate sizes. However, the advantages of consumable-electrode welding become evident for thicknesses greater than 0.250 inch (6.325 mm). Typical conditions for TIG welding of 0.062-inch (1.625-mm) titanium 6Al-4V sheet are given in table 12.31.

12.32 Inert-gas shielded metal-arc (MIG) welding which employs filler wire as the electrode is recommended for heavier-gage materials, but is also used successfully for butt-welded joints on gages as light as 0.125 inch (3.175 mm) and on some fillets as light as 0.060 inch (1.524 mm). The advantages of MIG welding include more deposit per unit time and less consumption of power, which are desirable for joints in plate thicknesses because fewer weld passes are required to complete a joint. However, MIG welding of titanium produces an excessive amount of spatter and requires optimum inert-gas shielding. Typical conditions for MIG (consumable electrode) welding of titanium 6Al-4V plate are summarized in table 12.32.

12.33 Joint Designs. Joint designs used for welding titanium alloys are essentially the same as those used for other metals. Since the molten weld metal has a high fluidity, it is advisable to weld as close the the flat position as possible. Square-butt joints are used only up to about 0.125 inch (3.175 mm). The "buried-arc" technique used for aluminum alloys is not effective with titanium; thus, welds in thicker sheets require joint preparation. Some filler metal is added, generally commercially pure titanium. For square butt welds, filler metal is added to provide a weld bead containing about 30 percent by volume of filler metal and 70 percent of resolidified parent metal. For some applications of titanium 6Al-4V, the root of the initial pass is ground out for refilling to get more filler alloy into the weld bead. Typical mechanical properties of titanium 6Al-4V butt welds are summarized in table 12.33.

12.34 Stress Relief of Weldments. Stress relief is recommended when complex or heavy weldments are involved. Recommended times and temperatures are given in table 12.34.

The welding of titanium 6Al-4V is generally associated with rocket motor cases and pressure vessels. For this purpose, individual forgings are fully heat-treated and machined prior to welding. Fusion welding with commercially pure Ti-50A filler wire produces a diluted weld with characteristics superior to a weld with titanium 6Al-4V filler. The lower strength in the diluted weld is compensated by thickening the wall in the weld area. Treatment at 1000° F (538° C) after welding relieves the weld with no effect on the parent metal.

Solution heat treatment and aging of titanium 6Al-4V welds is not recommended because of the resulting lower fracture toughness of these welds.

12.4 Resistance Welding (refs. 12.4 — 12.6). Methods for resistance welding of titanium 6Al-4V are similar to those for other metals. Because of the close proximity of mating surfaces and the short period of the welding cycle, inert gas protection is not required. In general, techniques for welding stainless steels are applicable.

12.41 Recommended settings and typical properties of spot-welded titanium 6Al-4V are given in table 12.41. Tension shear and and cross tension strength of spot welds are illustrated in figure 12.41. Spotweld strength, ratio and diameter vs welding current are represented in figures 12.411 and 12.412.

12.42 The effects of spotwelding strain-gage attachments on the fatigue behavior of titanium 6Al-4V have been examined (ref. 12.11). Test results for the alloy indicated much lower fatigue strengths for specimens with strain gages attached by spotwelding than for plain specimens (see figure 12.42). It is postulated that changes in microstructure are responsible for the losses in fatigue strength.

12.5 Other Welding Methods for titanium 6Al-4V include pressure welding, flash welding, and electron-beam welding (refs. 12.4, 12.6, 12.10).

12.51 Pressure welding is used primarily for prototype assemblies. Conventional gas-pressure welding equipment is satisfactory, and welds are made in the same manner as for steel. Parts to be joined are machined to ensure intimate contact in the machine.

12.52 Flash welding is used almost exclusively for rings for jet engines. It is better adaptable to titanium 6Al-4V than arc, spot, or seam welding becuase molten metal is not retained in the joint (so that cast structures are not present) and the hot metal in the joint is upset which may improve the ductility of the heat affected zone. Machine capacity to weld titanium alloys does not differ greatly from that required for steel. Mechanical properties of flash welds can closely approach those of the parent metal.

Inert gas shielding is not required (but may be used) for joints with solid cross sections. If used, Fiberglas enclosures are suitable for containing the gas. Inert gas is introduced into assemblies with hollow cross sections or into joints in tubing.

Joint designs are similar to those used for other metals. Flat edges are satisfactory for welding sheet and plate up to 0.250 inch (6.35 mm) thickness. For thicker sections, edges are sometimes beveled slightly. In general, short flashing times and fast flashing speeds are used to weld titanium alloys. These conditions are requisite for minimizing weld contamination and are possible because of the low thermal and electrical conductivities.

12.53 Electron-beam welding may be used for all thicknesses of titanium 6Al-4V to at least 2.25 inches (5.715 cm), and is used extensively in some advanced aircraft applications. Because welding is conducted in a vacuum chamber, contamination is virtually nonexistent. For very thick materials, an alternate procedure is to complete the weld made in two passes from the same side. The first pass is made at high power to achieve complete penetration; the second is made at reduced power to smooth the upper weld surface. Typical conditions for electron-beam welding are given in table 12.53.

12.6 Brazing (ref. 12.10). Primary problems connected with brazing of titanium 6Al-4V include the high reactivity of the element titanium with the constituents of brazing alloys and contaminants such as oxygen, nitrogen, etc., and the specific problem that normal brazing cycles are sometimes incompatible with the recommended heat treatment cycle. Conventional techniques should be employed for brazing the alloy. Special tools are available for brazing titanium-alloy tubing. Inert-gas or vacuum environments are necessary because of the reactivity problem.

Silver alloys are the most highly recommended filler metals for brazing titanium alloys, although brazing temperature may be in excess of the beta-transus temperature. In order to optimize the brazing system, elements such as lithium (up to 3 percent) have been added to the silver. However, silver-lithium alloys are susceptible to high-temperature oxidation (800° F, 427° C) when heated in air and have poor resistance to corrosion in salt-spray environments.

A promising system for brazing based on silver involves the use of aluminum. Investigation of Ag-Al alloys for brazing titanium alloys, however, has shown difficulties with excessive wetting, joint embrittlement, and low resistance to corrosion. Other reports indicate good strength, low base-metal erosion, and good resistance to salt corrosion.

12.61 In an investigation to determine the compressive behavior of titanium 6Al-4V skin stiffeners selectively reinforced with boron-aluminum composite, the composite strips were brazed to the stiffeners in vacuum at 1130° F (610° C) by using 0.003-inch (0.076-mm) thick aluminum-718 alloy foil as the filler. A pressure of 25 psi (0.018 kg/mm^2) was applied to the braze in order to maintain contact between the strips, stiffeners, and foils (ref. 12.12). As shown in figure 12.61, the analysis of test results indicated that improvements in structural performance of composite-reinforced specimens in comparison with unreinforced specimens exceeded 25 percent over the range from room temperature to 800° F (427° C) in terms of both initial buckling and maximum strengths. No evidence of failure was observed in the braze between the boron-aluminum composite and the titanium alloy.

12.7 Other Methods of Bonding. Adhesive bonding, deformation bonding, and diffusion bonding show promise for use with titanium 6Al-4V (ref. 12.10). The primary considerations are the same as for fusion welding, that is, precleaning of surfaces, appropriate process temperatures, and minimization of contamination.

12.8 Mechanical Fasteners. Properties to be considered in selecting mechanical fastener types or materials include required strength levels, fastener configuration, weight, resistanct to corrosion, compatibility with structural material, thermal effects, cost, and production factors such as availability and installation characteristics (ref. 12.10).

12.81 Properties of materials suitable for titanium structures are given in table 12.81.

12.82 Shear strengths of rivets for joining of 6Al-4V are given in table 12.82.

TABLE 12.31. – Recommended Weld Settings for Tungsten-Arc Open-Air Machine Welding of 0.064-Inch (1.625-mm) Sheet

Source	Ref. 12.4	
Alloy	Titanium 6Al-4V	
Parameter	Without Filler	With Filler
Electrode diam, inch (a)	1/16	1/16
Filler wire diam, inch	-	1/16
Wire feed rate, ipm	-	22
Voltage	10	10
Amperes	90-100	120-130
Nozzle ID, inch	9/16-5/8	9/16-5/8
Primary shield, ft^3/hr (b)	15 (argon)	15 (argon)
Trailing shield, ft^3/hr	20 (argon)	40 (argon)
Backup shield, ft^3/hr	4 (helium)	5 (helium)
Backup material	Cu or steel	Cu or steel
Backup groove, inch	1/4 x 1/16 deep	1/4 x 1/16 deep
Electrode travel, ipm	10	12
Power supply	DCSP (c)	DCSP

(a) 1 inch = 25.4 mm. (b) 1 ft^3/hr = 0.028 m^3/hr.
(c) DCSP, direct-current straight polarity.

TABLE 12.32. – Typical Conditions for MIG Welding of Plate

Source	Ref. 12.10			
Alloy	Titanium 6Al-4V			
Process	Manual	Manual(a)	Machine(a)	Machine(a)
Plate thickness, inch (b)	0.625	2.00	0.625	2.00
Electrode diam, inch	0.062	0.062	0.062	0.062
Arc voltage, volts	38	38	45	33
Current (DCRP), amperes	310	310	360	325
Welding speed, ipm	manual	manual	15	25
Argon flowrate, ft^3/hr (c)				
Torch	36	36	50	(e)
Trailing shield	(d)	(d)	60	(e)
Backup	(d)	(d)	6	(e)

(a) Multipass procedure. (b) 1 inch = 25.4 mm.
(c) 1 ft^3/hr = 0.028 m^3/hr. (d) Not reported (e) Argon chamber.

TABLE 12.33. – Typical Mechanical Properties of Butt Welds

Source	Ref. 12.8				
Alloy	Titanium 6Al-4V				
Specimen	F_{tu}, ksi	F_{tu}, kg/mm^2	F_{ty}, ksi	F_{ty}, kg/mm^2	Elongation, (2 in), %
STA parent metal	164	115	154	108	9.8
STA, as-welded	153	108	141	99	2.0
STA, welded, and stress relieved	153	108	141	99	2.2

(2 in = 50.8 mm)

TABLE 12.34. – Recommended Stress-Relieving Times and Temperatures for Weldments

Source	Ref. 12.4		
Alloy	Titanium 6Al-4V		
Condition	Temperature °F	Temperature °C	Time, hrs
Annealed	900 1000 1100	482 538 593	20 2 1
ST (a)	900 1000	538 593	15 4
STA	900 1000	538 593	15 5

(a) These cycles will also age the parent metal.

TABLE 12.41. – Recommended Settings for and Typical Properties of Spot Welded Sheet

Source	Ref. 12.4			
Alloy	Titanium 6Al-4V			
Parameter	Sheet Thickness, inches (a)			
	0.035	0.062	0.070	0.090
Joint overlap, inches (a)	1/2	5/8	5/8	3/4
Squeeze time, cycles	60	60	60	60
Weld time, cycles	7	10	12	16
Hold time, cycles	60	60	60	60
Electrode type	3-in spherical radius, 5/8-in diam, Class 2 copper			
Electrode force, lbs (b)	600	1,500	1,700	2,400
Weld current, amps	5,550	10,600	11,500	12,500
Cross tension strength, lbs	600	1,000	1,850	2,100
Tension shear strength, lbs	1,720	5,000	6,350	8,400
Ratio C-T/T-S	0.35	0.20	0.29	0.25
Weld diameter, inches	0.255	0.359	0.391	0.431
Nugget diameter, inches	-	0.331	-	-
Weld penetration, %	-	87.3	-	-
Electrode indentation, %	-	3.1	-	-
Sheet separation, inches	0.0047	0.0087	0.0079	0.0091

(a) 1 inch = 25.4 mm

(b) 1 lb = 0.454 kg

TABLE 12.53. -- Typical Conditions for Electron Beam Welding

Source	Ref. 12.10		
Alloy	Titanium 6Al-4V		
Thickness, inches (a)	Acceleration Voltage, kV	Beam Current, mA	Travel Speed, ipm
0.05	85	4	60
0.191	28.2	170	98
0.2	125	8	18
0.2 (b)	28	180	50
0.375/0.45	36	220/230	55/60
0.375/0.45 (c)	36	230/250	55/60
0.5	37 (d)	310 (a)	90
0.5	19 (e)	80 (e)	90
0.52	45	225	45
1.0	23	300	15
1.0	37-40	350/400	50/60
1.2	50	350	48
1.75	55	360	40
2.0	55	470	40
2.0	46 (d)	495 (d)	41
2.0	19 (e)	105 (e)	44
2.25	48 (d)	450 (d)	30
2.25	20 (e)	110 (e)	30

(a) 1 inch = 25.4 mm

(b) 100 ipm of 1/16 inch wire

(c) 60-80 ipm of 1/16 inch wire

(d) Settings for penetration pass

(e) Settings for seal pass.

TABLE 12.81. – Properties of Fastener Materials Suitable for Titanium Structures

Source	Ref. 12.14					
Alloy	Titanium 6Al-4V					
Fastener	F_{tu}, ksi			Coefficient of Expansion, 10^{-6} in/in/°F(c)		Density, lb/in³(d)
	70° F	600° F	1200° F(b)	70-600° F	70-1200° F	
Unalloyed Ti	65	20		5.1		0.163
Monel	85	75		8.6		0.319
Ti-6Al-4V	160	120		5.8		0.160
Ti-11Mo-6Zr-4Sn	130	96		4.7		0.183
	180	133				
Ti-6Al-6V-2Sn	155	128		5.2		0.164
MP35N	260	220		8.2		0.304
Custom 455	245	204		6.31		0.280
PH13-80	220	174		6.2		0.279
AFC77	300	270		5.87		0.282
A-286	160	136				
	200(e)	170	130	9.47	9.88	
Waspalloy	185		162	7.4	8.0	0.296
Inconel-718	208	170	150	7.7	8.4	0.297
Rene' 41	208	206	193	7.05	7.8	0.296

(a) 1 ksi = 0.70307 kg/mm² (b) °F–32 x 5/9 = °C

(c) x 1.8 = 10^{-6} cm/cm/°C (d) 1 lb/in³ = 27.68 g/cm³

(e) With cold work.

TABLE 12.82. – Shear Strength of Rivets for Joining Alloy

Source	**Ref. 12.15**		
Alloy	**Titanium 6Al-4V**		
Rivet Material	**F_{su} in 6Al-4V Sheet, lbs(a)**		
	1/8 inch(b)	**5/32 inch**	**3/16 inch**
"Closed-cycle," low-carbon Ni alloy, explosive protruding head	**347**	**565**	**789**
"Closed-cycle," low-carbon Ni alloy, explosive countersunk head	**347**	**565**	**789**

(a) 1 lb = 0.435 kg **(b) 1 inch = 25.4 mm**

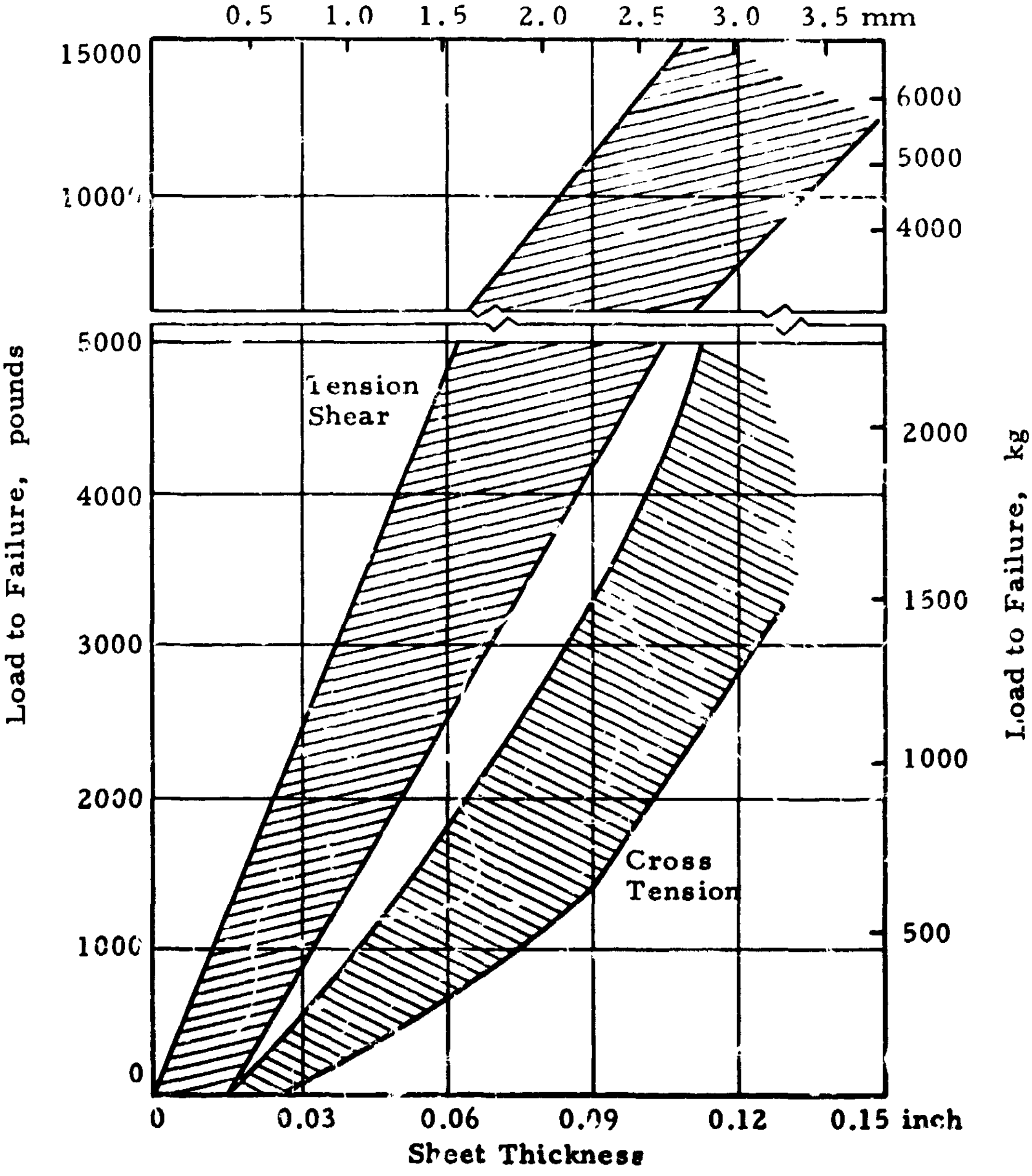
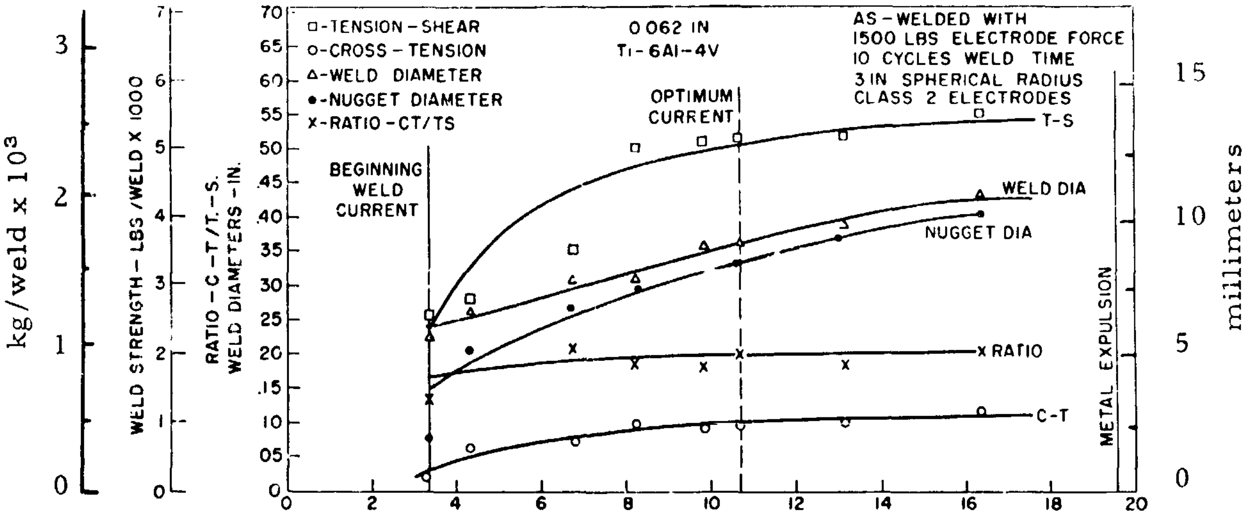


FIGURE 12 41. – Tension shear and cross tension strength of spot welds in titanium 6Al-4V alloy.

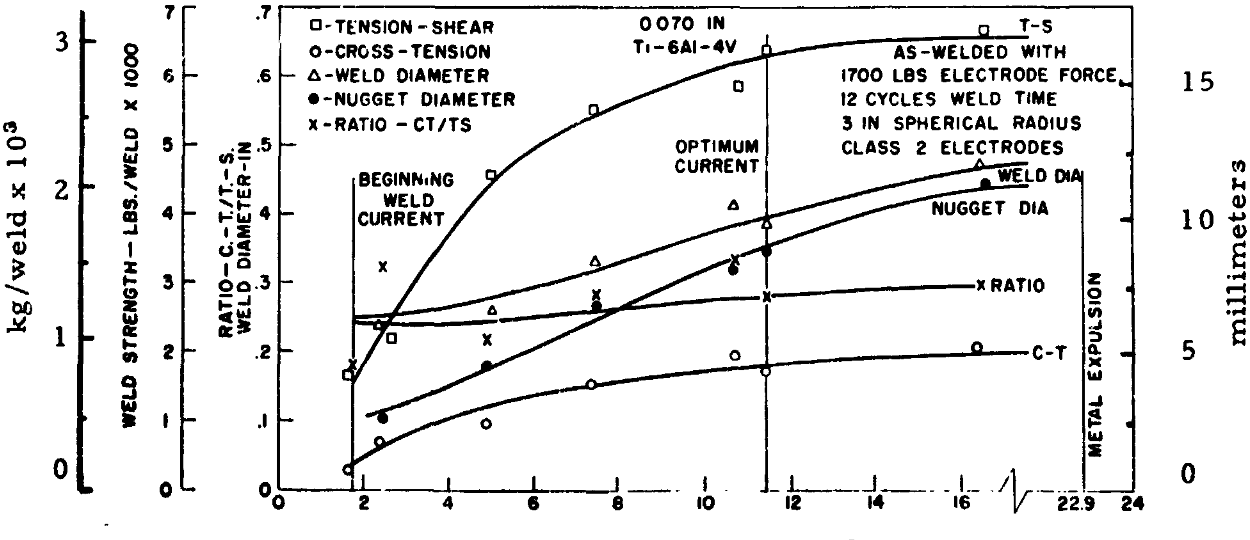
(Ref. 12.4)



Welding Current, amperes x 10^3

FIGURE 12.411. – Spotweld strength, ratio, diameter vs welding current for titanium 6Al-4V sheet; 0.062 in = 1.57 mm.

(Ref. 12.5)



Welding Current, amperes x 10^3

FIGURE 12.412. – Spotweld strength, ratio, diameter vs welding current for titanium 6Al-4V sheet; 0.070 in = 1.78 mm.

(Ref. 12.5)

B

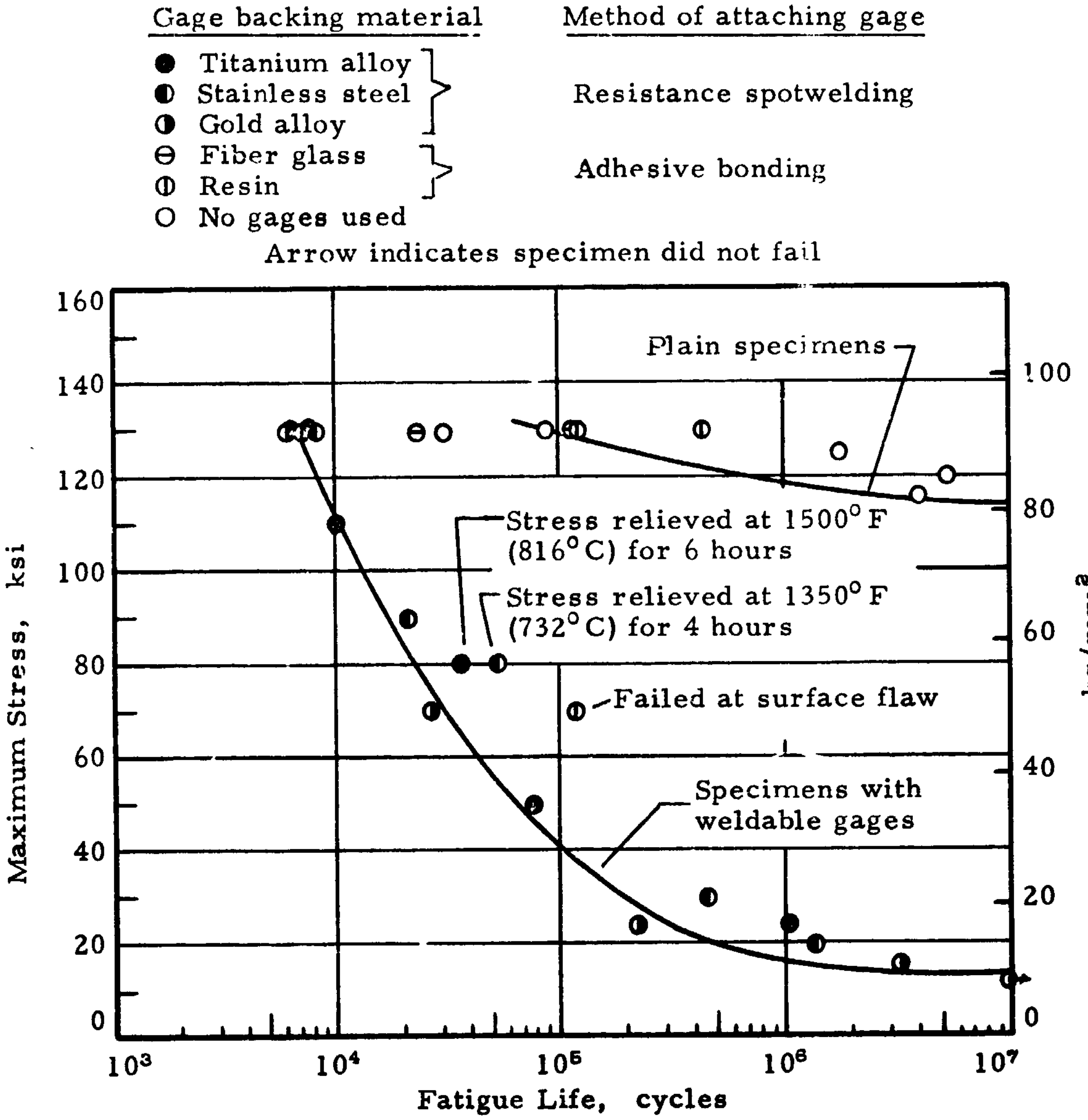


FIGURE 12.42. – Constant-amplitude fatigue data for titanium 6Al-4V specimens with spotwelded strain gages at room temperature; R = 0.05.

(Ref. 12.11)

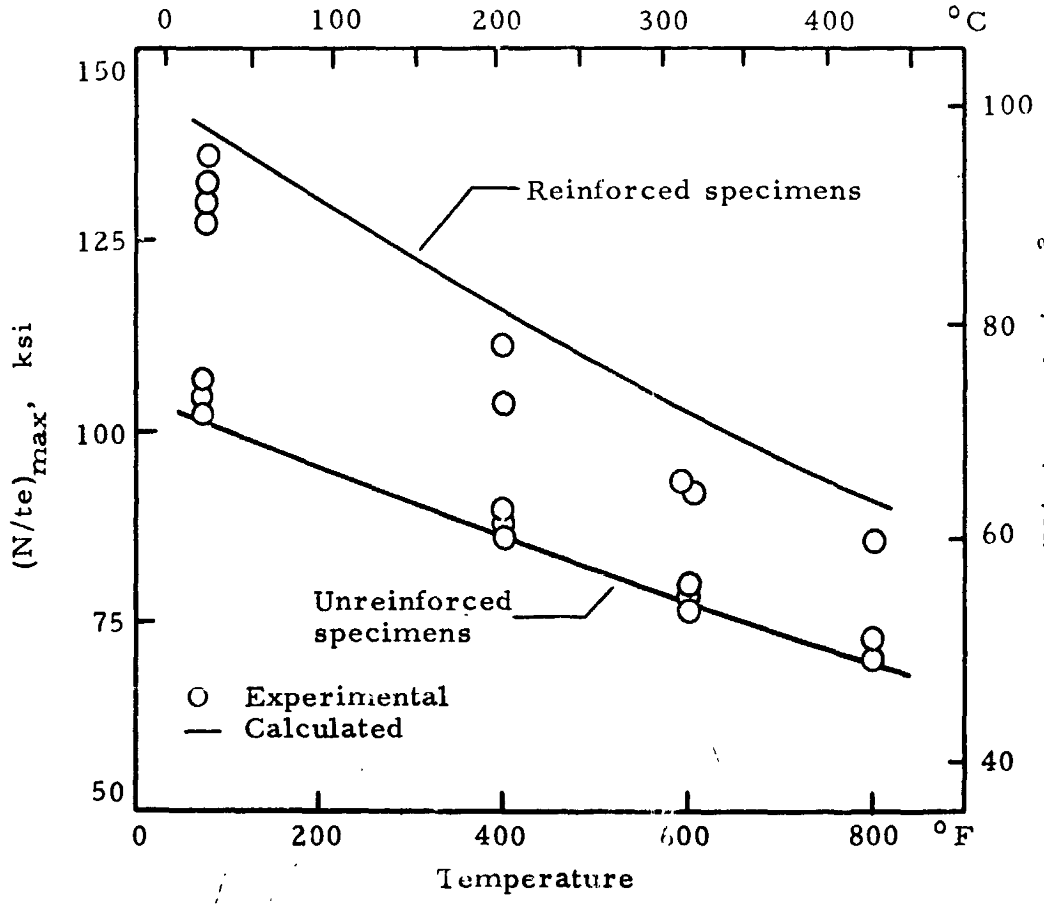


FIGURE 12.61. — Comparison of titanium-weight-equivalent maximum strength of (Al-B) reinforced and unreinforced titanium 6Al-4V skin-stiffener specimens on basis of temperature. (N=uniformly distributed load per unit width; te = titanium-weight-equivalent thickness.)

(Ref. 12.12)

Chapter 12 - References

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

12.2 R.E. Avery and S.C. Orr, "Improved Fabrication Techniques and Lower Cost Favor Titanium's Use," Corrosion, 14, January 1958, p. 119.

12.3 Titanium Metals Corp. of America, "How to Use Titanium," January 1970.

12.4 Titanium Metals Corp. of America, "Properties of Titanium 6Al-4V," Titanium Engineering Bulletin No. 1, November 1968.

12.5 Titanium Metals Corp. of America, "Titanium Welding," Titanium Engineering Bulletin No. 6, revised September 1964.

12.6 Harvey Titanium, "Titanium," September 1968.

12.7 Welding Handbook, Section 5, Chapter 91, American Welding Society, New York, 1967.

12.8 Welding Handbook, Section 5, Chapter 92, American Welding Society, New York, 1967.

12.9 Welding Handbook, Section 4, Chapter 73, American Welding Society, New York, 1967.

12.10 Titanium Base Alloys: 6Al-4V, DMIC Handbook, February 1971.

12.11 L.A. Imig, "Effect of Strain-Gage Attachment by Spotwelding and Bonding on Fatigue Behavior of Ti-6Al-4V, Rene' 41, and Inconel X," NASA TN D-5973, October 1970.

12.12 H.W. Herring, R.L. Carri, and R.C. Webster, "Compressive Behavior of Titanium Alloy Skin Stiffener Specimens Selectively Reinforced with Boron-Aluminum Composite," NASA TN D-6548, November 1971.

12.13 J.J. Vagi, R.P. Meister, and M.D. Randall, "Weldment Evaluation Methods," DMIC Report 244, August 1968.

12.14 J.N. Howell, "Mechanical Fasteners for High-Temperature Structures," Nat. SAMPE Tech. Conf., Sept. 9-11, 1969, on Aircraft Structures and Materials Applications, Vol. 1, Western Periodicals Co., No. Hollywood, California, 1969.

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