1. GENERAL

Ti-679 is a complex super-alpha alloy developed by Imperial Metal Industries of Great Britain and covered by U. S. Patent Number 3,049,425. The alloy is produced and marketed in the United States by the Titanium Metals Corporation of America (TMCA) under license from the British firm. Appearing in 1958, the alloy is currently used for compressor components in British jet engines.

The combination of low-aluminum, medium-zirconium, and high-tin strengthens and stabilizes the alpha phase. Considerable strengthening at all temperatures is derived from the active eutectoid compound Ti_xSi_y. The alloy may be classified as both a weakly stabilized, martensitic alloy and an active eutectoid. It displays the isothermal transformation characteristics of two phase titanium alloys.

For comparable products in the annealed condition, the strength of this alloy from room temperature to 1000F exceeds that of Ti-6Al-4V and Ti-8Al-1Mo-1V and is about equal to Ti-6Al-2Sn-4Zr-2Mo. Its creep strength is superior to Ti-8Al-1Mo-1V and Ti-6Al-4V at all temperatures, but inferior to Ti-6Al-2Sn-4Zr-2Mo at temperatures above 900F. At elevated temperatures, this alloy is less fatigue resistant than Ti-8Al-1Mo-1V and Ti-6Al-2Sn-4Zr-2Mo. The alloy appears to be metallurgically stable up to 850F.

Forgeability and machinability of this alloy are comparable to Ti-8Al-1Mo-1V. Welding of this alloy is not recommended.

1.01 Commercial Designation

Ti-679, IMI-679

1.02 Alternate Designation

1.03 Specifications

Table 1.03

TABLE 1.03

Form	Condition	Specification
Bars, Forgings, Forging Stock	Fully Annealed (in accordance with MIL-H-81200)	MIL-T-9047D (09 June 67)
Bars, Forgings	1650F, 1hr, AC + 930F, 24hrs, AC	AMS-4974 (01 November 67)
Bars, Forgings, Forging Stock	1650F, 1hr, AC + 930F, 24hrs, AC	The Garrett Corporation Airesearch Manufacturing Co EMS-94902 (13 May 66)
Forged Parts	1650F, 1hr, AC or OQ + 930F, 24hrs, AC	General Electric Company 4012158-092 (10 October 63)
Compressor Blades, Vanes	1650F, 1hr, AC + 930F, 24hrs, AC	General Electric Company C50T83-S5 (08 December 66)
Bars, Forgings, Forging Stock	1650F, 1hr, OQ + 930F, 24hrs, AC	General Motors Corporation Allison Division EMS-59034-B (22February 67)
Bars, Forgings, Forging Stock	1650F, 1hr, AC +930F, 24hrs, AC	General Motors Corporation Allison Division EMS-59035-A (29 August 67)
Bars	1650F, 1hr, AC (or faster) + 930F, 24hrs, AC	United Aircraft Corporation Pratt & Whitney Division PWA-1206-A (05 October 65)
Forgings	1650F, 1hr, AC (or faster) + 930F, 24hrs, AC	United Aircraft Corporation Pratt & Whitney Division PWA-1205-A (05 October 65)

1.04 Composition

1.041 Producer's specified composition, Table 1.041.

TABLE 1.041

Source	T.M.C.A. (4)(5)		
	Weight Percent		
	Min.	Max.	Nom.
Tin	10.50	11.500	11.00
Zirconium	4.00	6.000	5.00
Aluminum	2.00	2.500	2.25
Molybdenum	0.80	1.200	1.00
Silicon	0.15	0.270	0.21
Oxygen		0.150	0.10
Iron		0.120	
Carbon		0.040	
Nitrogen		0.040	
Hydrogen		0.008	
Titanium	Balance		

1.042 Users' specified composition, Table 1.042.

TABLE 1.042

Source*	(19)		(20)		(21)		(22)		(23)		(24)		(25)	
	Weight Percent													
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Tin	10.50	11.50	10.50	11.50	10.50	11.50	10.50	11.50	10.50	11.50	10.50	11.50	10.50	11.50
Zirconium	4.00	6.00	4.00	6.00	4.00	6.00	4.00	6.00	4.00	6.00	4.00	6.00	4.50	5.50
Aluminum	2.00	2.50	2.00	2.50	2.00	2.50	2.00	2.50	2.00	2.50	2.00	2.50	2.10	2.90
Molybdenum	.80	1.20	.80	1.20	.80	1.20	.80	1.20	.80	1.20	.80	1.20	.50	1.50
Silicon	.15	.27	.15	.27	.15	.27	.15	.27	.15	.27	.15	.27	.15	.35
Oxygen		.20		.17		.15		.15		.15		.15		.20
Iron		.20		.12		.12		.12		.12		.12		.30
Carbon		.08		.04		.04		.04		.10		.10		.15
Nitrogen		.050		.04		.04		.04		.050		.050		.050
Hydrogen		.008		.010		.015		.0125		.0125		.0125		.0125
Titanium	Balance		Balance		Balance		Balance		Balance		Balance		Balance	

*See Table 1.03 for product forms and conditions.

1.05 Heat Treatment

1.051 Stress relief anneal. 900 to 950F, 5 to 10 hours AC, (26)(27)

1.052 Duplex anneal. 1650F, 1 to 2 hours, AC + 930F, 24 hours, AC. (5)(26)(28)

This alloy is used almost exclusively in the duplex annealed condition, claimed to produce optimum mechanical properties (5). The 1650F solution anneal is in the alpha + beta (+compound) field and the 930F stabilization anneal temperature is in the alpha + compound field. Imperial Metal Industries reports (28) that nearly all transformation from beta to alpha occurs during air cooling from the solution temperature (1650F) to approximately 1200F. The 930F treatment only stabilizes the alloy further. This is substantiated by the data of Table 3.0213 which shows only a 7 ksi increase in strength on aging (stabilization annealing). The solution treating temperature of 1650F is not critical (5). A range of 1630 to 1670F should produce identical tensile properties. The same is true of the aging (stabilization anneal) temperature. A range of 910 to 950F should produce identical results for an aging cycle of 24 hours.

1.053 Solution treat and age. 1650F, 1 to 2 hours, OQ or WQ + 930F, 24 hours, AC. (28)(29)

Maximum tensile and creep strength is developed in the solution treated and aged condition (5). As seen from Figure 2.0121, however, relatively rapid cooling from the solution temperature is required to prevent the beta-to-alpha transformation from going to completion. The aging response, therefore, is directly related to the rapidity of the quench.

Table 3.0213 gives the aging response as a function of quench rate. Air cooling produces only limited aging response, and furnace cooled samples do not respond to the aging treatment at all. Water quenching, on the other hand, produces a substantial increase in strength on subsequent aging. The reason for these different responses is apparent in Figure 2.0121 which shows the various cooling rates superimposed on the T-T-T diagram (The "alpha prime transus" shown on the diagram represents a temperature above which alpha-beta solution treated material will transform to alpha prime (Martensite) at the M_s temperature on water quenching. Below this temperature the beta is retained on quenching). Table 3.0214 indicates rolled bar oil-quenched from the solution temperature (compared to air cooling) prior to aging is stronger by 19 to 28 ksi depending on the heat treated section size. Additional data (Table 3.0213) show a 32 ksi strengthening due to water quenching from the solution temperature as compared with air cooling for specimens subsequently aged.

1.06 Hardness

1.061 Effect of exposure to elevated temperature on room temperature hardness of bar, Figure 1.061.

1.062 Since hardness is, in general, related to alloy strength characteristics, the variation in strength properties with as-quenched section size provides a useful measure of alloy hardenability. Figure 3.0215 shows the influence of as-quenched section size on the solution treated (water quenched) and aged smooth tensile properties of sections up to 4 inches square. Results from both as-forged sections and sections machined from the largest forged section are presented. As expected, the highest strengths were obtained for the outside location and were nearly constant over the range of sizes investigated. As-forged sections down to 1 inch square exhibit a strength and ductility difference from center to edge. In contrast, a 1 inch square section machined from the 4 inch forging exhibits uniform strength and ductility throughout. The difference between center and edge properties for sections greater than 1 inch square, whether as-forged or machined from the larger forging, increases to as much as 20 ksi as the section size increases to 4 inches square. Results for a small forging water quenched from the solution temperature and subsequently aged (Table 3.0212) agree well with the above bar results (Figure 3.0215) at comparable section sizes.

Table 3.0216 and Figure 3.0322 give the variation in smooth tensile and compressive strengths, respectively, for a heavy ring forging duplex annealed in full section size. As expected, the general strength level is lower than that quoted above for forgings water quenched from the solution temperature prior to aging. However, the tensile properties of the duples annealed forging vary less from center to edge (10 ksi maximum difference in the heaviest section). As shown in Figure 3.0312, this small difference in tensile properties is not exceeded at test temperatures ranging from -110 to +550F and, as shown by the room temperature results of Table 3.02712, is unaltered by 1000 hrs exposure at 550F without load. The heavy section mild-notch (Table 3.02711) and crack-notch (Table 3.03713) tensile properties of the duplex annealed ring forging are uniform throughout. So too are the room temperature ultimate shear strength (Table 3.0352) and room temperature and 550F smooth fatigue strengths (Figure 3.056)

Additional results for duplex annealed hammer-forged (Figure 3.0314) and press-forged (Figure 3.0315) compressor wheels show no greater difference than 10 ksi in tensile strength as a function of forging section size at temperatures ranging from room temperature to 1000F. Where comparisons can be made, exposure to elevated temperature with load does not alter these results, see Tables 3.0217 and 3.0218.

1.07 Forms and Conditions Available

Alloy is commercially available as bar and billet (26)

1.08 Melting and Casting Practice

1.081 Alloy is double consumable electrode vacuum melted.

1.09 Special Considerations

1.091 Silicide segregation. This alloy differs from other alpha-beta alloys in containing 0.21 percent silicon. Investigators in the United States and Great Britain have demonstrated that silicon additions up to 0.5 percent reduce the creep rate of titanium alloys in the range 600 to 1000F (28). However, silicon is benificial only if the melting and processing cycles are controlled to produce a fine uniform dispersion (particle size of one micron or less) of titanium silicide, Ti_5Si_3 (28). Large particles or agglomerations of small particles can result in lower mechanical properties, as shown by the following.

Tensile results (13) from four compressor discs showed low elongations and reductions of area in 7 of 8 tests from the hub area of the wheels. For the seven, elongations ranged from 2.5 to 7.0 percent and reductions of area from 3.9 to 13.0 percent. The eighth specimen showed higher values of ductility, 11.0 percent elongation and 27.8 percent reduction of area. Rim locations of the same discs consistently showed elongations of 13.0 to 15.0 percent and reductions of area of 32.7 to 38.8 percent. Macroscopic examination of the fracture surfaces of the low ductility specimens showed that fractures initiated along bands containing heavy concentrations of silicides. The fact that these segregated areas were apparent only in the center of the parts involved indicates that this condition is probably associated with melting practice.

A later study (14) showed concentrations of heavy, light-etching particles, identified in microprobe analysis as silicides, in the center and mid-radius areas of 6 inch diameter bars. Three tensile blanks were extracted from the mid-radius area of one of the bars, duplex annealed, machined and tested. In contrast to the above results for compressor discs, all three specimens from bar displayed ductilities within the normal range. All fractures, however, originated at segregated bands and in one case fracture took place outside the necked-down area of the specimen. Room temperature low-cycle and high-cycle, axial load fatigue tests have been made of the shaft and hub sections of a 24 inch diameter compressor disc which showed evidence of silicide segregation, but the results were inconclusive (15).

At this writing, no data are available on the possible damaging influence of segregation on the fracture toughness of this alloy. For critical applications where plane strain fracture toughness may be the limiting design consideration, the influence of segregation on this property should be evaluated.

It has been the experience of one forger that segregated areas are limited to the top half and center of affected heats, supporting the conclusion that the problem is probably related to melting practice (15). In this regard, the producer of the alloy points out that eutectoid formers (silicon, copper, iron, etc.) often present a segregation problem until appropriate melting and processing schedules are developed. This, of course, is part of the development of such alloys, and no problems with segregation for the present alloy have been reported by the producer in the past three years (31).

1.092 Stability - General. For certain applications (particularly in commercial aircraft) metallurgical stability is an important design consideration. While no systematic investigations have been made to firmly establish the threshold combinations of stress-time-temperature below which the alloy is metallurgically stable, available data suggest that caution be exercised in the use of this alloy in applications where stability is a requirement.

Alloy stability is usually evaluated by comparing the conventional room temperature tensile properties of specimens with and without prior exposure at stress-time-temperature combinations appropriate to the intended application. Results of this sort for bar and forgings are presented in Figures and Tables 3.0217 through 3.02112. Figure 3.0317 gives the conventional tensile properties of rolled bar exposed without load to elevated temperature and tested at the exposure temperature. The influence of elevated temperature exposure without load on the subsequent room temperature mild-notch and crack-notch tensile properties is reported in Tables 3.02712 and 3.03713, respectively. The effect of prior exposure on room temperature hardness is shown in Figure 1.061. For all stability results reported here, the tested articles were in the duplex annealed condition.

1.093 Stability - 150 hours. 150 hours exposure at temperature-stress combinations ranging from 850F, 65 ksi to 950F, 45 ksi has a small but inconsistent effect on the subsequent room temperature tensile strength and ductility of hammer forged compressor wheels (Table 3.0217). On the other hand, similar press forged wheels exposed 150 hours at 950F, 45 ksi and 1000F, 35 ksi were unchanged in strength but, with only one exception, seriously reduced in ductility (Table 3.0219). For rolled bar, exposure up to 1000F for 10 and 100 hours without load produces no change in room temperature strength and ductility (Figure 3.02112).

1.094 Stability - 300 hours. The room temperature tensile properties of a single compressor wheel forging (Table 3.02110) exposed to temperature-stress combinations of 800F, 75 ksi and 850F, 65 ksi for si for 300 hours were unaffected except for a slightly lower reduction of area value for a single specimen for which 50 - 75 percent of its deformation occured on loading. At 750F, 88 ksi, 300 hours exposure all specimens from this same compressor wheel forging deformed considerably on loading, and low reduction of area fractures were observed in about half of the specimens tested. These low values were associated with what appeared to be stress corrosion cracks. This, of course, is unrelated to metallurgical instability effects.

1.095 Stability - 1000 hours. 1000 hour exposure of hammer forged compressor wheel specimens at 950F, 45 ksi produces very serious losses in tensile ductility with an increase in strength (Table 3.0218). Rolled bar exposed 1000 hours begins to develop an increase in tensile strength with a corresponding loss in reduction of area at 800F (with no load). At 1000F, the gain of strength and loss of ductility for bar is substantial (Figure 3.02112).

The room temperature mild-notch (Table 3.02712) and crack-notch (Table 3.03713) tensile properties of ring forging specimens exposed 1000 hours without load at a moderate temperature (550F) were unaffected by the exposure. Unfortunately these data are scant and one should be aware that a different result might be obtained from cracked specimens exposed at higher temperatures and for longer times.

1.096 Fracture toughness. Alloy is claimed to have relatively poor fracture toughness in sheet form (7, p.3). No data are available on the fracture toughness of forms other than sheet. For applications where the alloy's fracture toughness may be the limiting design consideration, these data should be developed.

1.097 Stress corrosion. No data are available on the stress corrosion characteristics of this alloy. On the basis of results obtained on other titanium alloys, however, particular attention should be given to the influence of agressive environments in the presence of cracks. Such environments include aqueous chloride solutions and possibly certain organic solvents such as methanol. For some applications, as in jet engines, hot salt stress corrosion characteristics would be necessary design information. The results of Table 3.02110 suggest that stress corrosion cracking in air might warrant consideration.

1.098 Erosion. It has been reported (32) that titanium erodes approximately 40 percent faster than steel in engine-blading applications in jet engines. No data on this relatively unfamiliar characteristic are available at the time of this writing.

2. PHYSICAL AND CHEMICAL PROPERTIES

2.01 Thermal Properties

2.011 Melting range. Approximately 3100F.

2.012 Phase changes. Beta transus 1730 ± 15F. Alpha prime transus 1600 - 1630F (see 1.053 for definition of alpha prime transus).

2.0121 Time-temperature-transformation diagram, Figure 2.0121.

2.0122 Ti-Si binary phase diagram showing compound formation Ti_5Si_3, Figure 2.0122.

2.013 Thermal conductivity.

2.0131 Thermal conductivity of bar, Figure 2.0131.

2.014 Thermal expansion.

2.0141 Thermal expansion for bar, Figure 2.0141.

2.015 Specific heat.

2.0151 Specific heat for bar, Figure 2.0151.

2.016 Thermal diffusivity.

2.02 Other Physical Properties

2.021 Density. 0.174 lb per cu inch, 4.82 gr per cu cm (26)

2.022 Electrical properties.

2.0221 Electrical resistivity, Figure 2.0221.

2.023 Magnetic properties. Alloy is nonmagnetic.

2.024 Emittance.

2.025 Damping capacity.

2.03 Chemical properties

2.04 Nuclear Properties

Ti
11 Sn
5 Zr
2.5 Al
1 Mo
0.25 Si

Ti-679

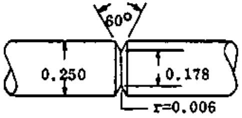
3. MECHANICAL PROPERTIES

3.01 Specified Mechanical Properties

3.011 Producer's guaranteed mechanical properties not yet established (29).

3.012 AMS specified mechanical properties, Table 3.012.

TABLE 3.012

Source	AMS (22)							
Alloy	Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si							
Form	Bars and Forgings							
Condition	1650F, 1hr, AC + 930F, 24hrs, AC							
Nominal Diameter or Thickness - Inch	Property Specification							
	Conventional Tensile Properties							
	Room Temperature				800F (1)			
	F_{tu} minimum ksi	F_{ty} minimum ksi	e(2in or 4D) - min percent	RA minimum percent	F_{tu} minimum ksi	F_{ty} minimum ksi	e(2in or 4D) - min percent	RA minimum percent
Bars and Forgings:								
Up to 1.000 Inclusive	145	135	10	20	105	80	15	30
Over 1.000 to 2.000 Inclusive	145	135	10	20	100	80	15	30
Over 2.000 to 3.000 Inclusive (2)	140	130	10	20	95	75	12	25
	Room Temperature Notched Stress Rupture							
Bars under 5 sq. in. cross-sectional area and all forgings Bars 5 sq. in. and over cross-sectional area	(3) @ 165ksi, 5hrs min. (3) @ 155ksi, 5hrs min.				Preferred Specimen (See reference for alternate specimens)			
	1000F Smooth Stress Rupture							
All bars and forgings	(4) @ 70ksi, 23hrs min. life. Test to rupture. RT elong (4D) after rupture shall be ≥ 10 percent							
	Creep Stability							
All forgings	Specimen exposed 100hrs at 800F, 70ksi shall not show more than 0.2 percent creep elongation							

(1) To be held at temperature for thirty minutes before testing.

(2) Over 3.000 inch diameter or distance between parallel sides, tensile properties shall be as agreed upon by purchaser and vendor.

(3) The initial stress may be less than specified and increased to the specified stress in 10 ksi increments at intervals of not less than five hours.

(4) Test stress may exceed 70 ksi, but shall not be changed during test. Time and elongation requirements shall be as specified for 70 ksi applied stress.

3.013 Users' specified mechanical properties, Table 3.013.

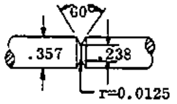
TABLE 3.013

Source	G.E. (25)		G.E. (24)		Pratt and Whitney (21)						Garrett (23)	
Alloy	Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si											
Form	Forged Parts		Compressor Blades and Vanes		Bars < 5 sq in Cross-Sectional Area		Bars ≥ 5 sq in Cross-Sectional Area		Forgings		Bars, Forgings, and Forging Stock	
Condition	1650F, 1hr, AC or OQ+930F,24hrs, AC		1650F, 1hr, AC +930F,24hrs, AC		1650F, 1hr, AC or Faster + 930F, 24hrs, AC						1650F, 1hr, AC + 930F, 24hrs, AC	
Property	Specified Value At :				Specified Value At:						Specified Value At (f):	
	RT	900F	RT	900F	RT	800F(d)	RT	800F(d)	RT	800F(d)	RT	900F
F_{tu} - ksi min.	140	95	140	95	145	105	130	95	145	105	140	95
F_{ty} - ksi min.	130	75	130	75	130	77	120	70	130	77	130	75
e(4D) - % min.	10	10	10	10	10	12	10	12	10	12	10	10
RA - % min.	20	20	20	20	25	30	25	30	25	30	20	20
RT Notch Stress Rupture (See Table 3.012 for Specimen Drawing)	@150ksi, 5hrs min life (a)		@160ksi, 5hrs min life (c)		@165ksi, 5hrs min life (c)		@155ksi, 5hrs min life (c)		@165ksi, 5hrs min life (c)		@160ksi, 5hrs min life (c)	
Smooth Stress Rupture	@60ksi, 950F,35hrs min life (b)		not specified		@ 1000F, 70ksi (e), 23hrs min. life. Test to rupture. RT elong (4D) after rupture shall be ≥ 10 percent						@60ksi, 950F, 35hrs min life (b)	
Creep Stability	Shall meet RT tensile properties above after 100hrs exposure at 900F, 48ksi				not specified						Shall meet RT tensile properties above after 100hrs exposure @ 900F, 48ksi (g)	
Hardness	not specified				Shall not exceed RC-40						not specified	

(a) Initial stress may be less than 150 ksi and increased to 150ksi in 10 ksi increments at intervals of not less than 5 hours. If no failure in 5 hours at 150ksi, stress shall be increased in 10ksi increments at 5 hour intervals until failure or 200ksi, 5 hours, is obtained.
(b) Test to rupture or 70 hours.
(c) Initial stress may be less than specified and increased to specified stress in 10ksi increments at intervals of not less than 5 hours.
(d) Specimens to be held at temperature for 30 minutes before testing.
(e) Test stress may exceed 70ksi, but shall not be changed during test. Time and elongation requirements shall be specified for 70ksi applied stress.
(f) Specimen taken from any location of bars, forgings, and forging stock up to 2 1/4 inch minimum section thickness, and from mid-radius location of sections over 2 1/4 inch minimum thickness.
(g) Not a requirement for acception or rejection of material.

3.014 Users' specified mechanical properties, Table 3.014.

TABLE 3.014

Source	Allison (20)	Allison (30)	
Alloy	Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si		
Form	Bars and Forgings		
Condition	1650F, 1hr, AC + 930F, 24hrs, AC	1650F, 1hr, OQ + 930F, 24hrs, AC	
Property	Specified Value at 850F(a)	Specified Value(b)at:	
		RT	840F(a)
F_{tu} - ksi min.	100	161	119
F_{ty} - ksi min.	80	139	80
e(4D) - % min.	12	10	12
RA - % min.	30	20	
Creep Stability	Specimen exposed 100hrs, 750F, 70ksi shall not exceed 0.1% creep strain	Specimen exposed 100hrs, 840F, 56ksi shall not exceed 0.1% creep strain	
Mild-notch tensile		≥ 1.3 times smooth tensile strength	
	(Preferred specimen, see reference for alternate specimens)		

(a) Specimen to be held at temperature 30 minutes before testing.
(b) For section sizes up to 1 inch in diameter or distance between parallel sides.

3.02 Mechanical Properties at Room Temperature
3.021 Tension (see also 3.031).
3.0211 Effect of solution temperature on solution treated tensile properties of forged bar, Table 3.0211.

TABLE 3.0211

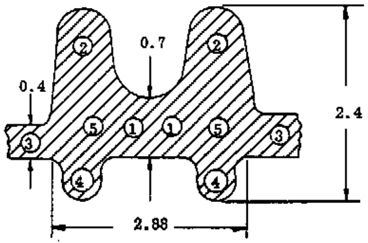
Source	(5, p.5)			
Alloy	Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si			
Form	1 1/8 inch square forging*			
Condition	Solution Treated, 1hr, WQ			
Solution Temp.-F	RT Tensile Properties			
	F_{tu} ksi	F_{ty} ksi	e percent	RA percent
1700	194.6	169.0	6.0	23.7
1675	186.9	168.3	----	----
1650	176.8	151.5	12.0	43.0
1600	176.2	152.0	12.0	41.0
1575	154.8	118.1	19.0	41.8
1550	155.8	104.7	18.0	39.1

*Machined to 1/2 inch round, then solution treated.

3.0212 Effect of aging cycle and specimen location on tensile properties of forging, Table 3.0212.

TABLE 3.0212

Source	(5)			
Alloy	Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si			
Form	Forging			
Condition	1650F, 1hr, WQ + age, AC (in full section)			
	Aging Cycles			
	930F, 1hr	930F, 12hrs	930F, 24hrs	1050, 24hrs
F_{tu}, ksi	176.8 (1) 188.5 (3) 162.9 (5)	179.6 (1) 191.9 (3) 167.8 (5)	178.8 (1) 192.9 (3) 173.9 (5)	178.0 (1) 179.2 (3) 175.1 (5)
F_{ty}, ksi	154.4 (1) 165.1 (3) 139.8 (5)	158.0 (1) 169.4 (3) 145.2 (5)	158.0 (1) 170.9 (3) 151.7 (5)	161.0 (1) 156.0 (3) 154.6 (5)
e, percent	12.0 (1) 12.0 (3) 14.0 (5)	12.0 (1) 11.0 (3) 18.0 (5)	11.0 (1) 10.0 (3) 10.0 (5)	10.0 (1) 16.0 (3) 12.0 (5)
RA, percent	41.0 (1) 45.3 (3) 48.0 (5)	40.0 (1) 41.4 (3) 47.0 (5)	40.0 (1) 35.3 (3) 42.0 (5)	33.5 (1) 42.1 (3) 32.2 (5)
See drawing below for specimen location				



Cross-section of 12 inch long Navajo forging used for quenching studies.

3.0213 Aging response of forged bar quenched at various rates from the solution temperature, Table 3.0213.

TABLE 3.0213

Source	(5, p.13)				
Alloy	Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si				
Form	1 1/8 in Square Forging*				
Quench Rate From 1650F Solution Treatment	Aging Treatment	F_{tu} ksi	F_{ty} ksi	e %	RA %
As Forged		151.2	136.5	14.0	49.9
Furnace Cooled	930F, 24hrs, AC	143.7	132.1	11.0	23.1
Furnace Cooled	None	143.8	133.0	11.0	25.8
Air Cooled	930F, 24hrs, AC	167.3	149.6	17.5	44.4
Air Cooled	None	159.8	142.8	16.0	47.4
Water Quenched	930F, 24hrs, AC	199.6	180.0	10.0	32.9
Water Quenched	None	176.8	151.5	12.0	43.0
*Heat treated in full section size.					

3.0214 Effect of quenching rate from the solution temperature on the tensile properties of solution treated and aged bar of various sizes, Table 3.0214.

TABLE 3.0214

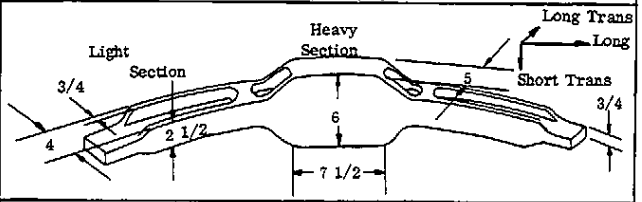
Source	(11)							
Alloy	Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si							
Form	Rolled Bar							
Condition	1650F, 1hr min., AC +930F, 24hrs, AC				1650F, 1hr min., OQ+930F, 24hrs, AC			
Heat Treated Section Size (1) Inch	F_{tu} ksi	F_{ty} ksi	e percent	RA percent	F_{tu} ksi	F_{ty} ksi	e percent	RA percent
3(edge)	151.0	------	21	42	170.0	142.0	18	40
3(center)	150.5	127.5	18	34	169.0	139.0	16	34
2	158.5	131.5	16	31	174.0	145.0	14	32
1 1/2	160.0	135.5	17	29	179.5	147.0	18	33
1	160.0	134.0	17	31	182.0	150.0	14	31
1/2	166.0	147.0	17	30	194.0	163.0	12	29
(1) Originally 3 1/2 inches diameter								

3.0215	Effect of heat treated section size on the tensile properties of forged bar, Figure 3.0215.
3.0216	Variation in room temperature tensile properties of large ring forgings as a function of specimen location and orientation, Table 3.0216.

TABLE 3.0216

Source	(9, pp.53-54 and 58-59)				
Alloy	Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si				
Form	Large Ring Forging				
Condition	1650F, 1hr, fan cool + 930F, 24hrs, AC(1)				
Specimen Location	Specimen Orientation	RT Tensile Properties (2)(3)			
		F_{tu} ksi	F_{ty} ksi	e(1 in) ksi	RA percent
Forging Heavy Section					
Edge	Long	149.7	134.5	13.3	33.7
		(146.5)	(133.2)	(14.7)	(39.7)
Mid-Radius	"	144.8	130.3	14.7	35.0
Center	"	143.3	128.8	14.0	35.0
		(142.0)	(128.0)	(15.7)	(40.3)
Edge	Long Trans	147.0	133.8	13.7	40.3
Mid-Radius	" "	142.5	127.7	13.3	40.3
Center	" "	139.6	124.7	14.0	42.3
		(139.2)	(124.8)	(17.0)	(44.0)
Edge	Short Trans	148.2	133.8	14.0	40.0
		(149.8)	(135.3)	(15.0)	(41.3)
Mid-Radius	" "	144.3	129.8	14.7	41.0
Center	" "	138.4	123.7	13.0	38.3
		(144.2)	(129.3)	(14.0)	(37.7)
Forging Light Section					
Flange	Short Trans	149.6	135.3	16.0	41.0

Ring Forging



(1) Heat treated in full section size
(2) Each value average of three tests.
(3) Unbracketed values - Forging No. 2
Braketed values - Forging No. 1 Both from same ingot

3.0217 Effect of 150 hours exposure to elevated temperature with load on the room temperature tensile properties of hammer forged compressor wheels, Table 3.0217.

TABLE 3.0217

Source	(17, pp. 12, 13, 15, and 16)							
Alloy	Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si							
Form	24in diameter hammer forged compressor wheels							
Condition	1650F, 1hr, AC + 930F, 24hrs, AC							
	Creep Exposure Conditions				Subsequent RT Tensile Properties			
Location - Direction	Temp F	Stress ksi	Time hr	Total Creep percent	F_{tu} ksi	F_{ty} ksi	e(1 in) percent	RA percent
Hammer Forged Compressor Wheel "A" (See Fig. 3.0314)								
Web - Tang	Unexposed				152.8	137.1	15.0	34.2
Web - Tang	850	65	165	0.160	145.7	133.0	15.0	36.0
Web - Tang	900	55	166	0.210	148.2	136.6	11.0	38.6
Rim - Tang	Unexposed				149.8	135.0	13.8	33.9
Rim - Tang	850	65	150	0.144	166.1	151.0	14.0	36.2
Rim - Tang	900	55	150	0.164	157.2	142.0	12.0	22.6
Rim - Tang	950	45	166	0.185	153.5	140.3	11.0	26.5
Web-Radial	Unexposed				144.6	125.6	14.0	37.0
Web-Radial	950	45	150	0.240	156.4	140.6	14.0	32.3
Hammer Forged Compressor Wheel "B" (See Fig. 3.0314)								
Web - Tang	Unexposed				155.1	138.2	12.5	32.3
Web - Tang	900	55	150	0.164	157.2	142.0	12.0	22.6
Rim - Tang	Unexposed				159.8	145.6	13.0	33.1
Rim - Tang	850	65	150	0.144	166.1	151.0	14.0	36.2
Web-Radial	Unexposed				154.0	139.1	13.8	41.7
Web-Radial	950	45	150	0.240	156.4	140.0	14.0	32.3
Both wheels from same heat. 0.250 inch diameter specimens.								

3.0218 Effect of 1000 hours exposure to elevated temperature with load on the room temperature tensile properties of hammer forged compressor wheels, Table 3.0218.

TABLE 3.0218

Source	(17, pp. 12, 13, 15, 16)							
Alloy	Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si							
Form	24in diameter hammer forged compressor wheels							
Condition	1650F, 1hr, AC+930F, 24hrs, AC							
	Creep Exposure Conditions				Subsequent RT Tensile Properties			
Location - Direction	Temp F	Stress ksi	Time hr	Total Creep percent	F_{tu} ksi	F_{ty} ksi	e(1 in) percent	RA percent
Hammer Forged Compressor Wheel "A" (See Fig. 3.0314)								
Rim - Tangential	Unexposed				149.8	135.0	13.8	33.9
Rim - Tangential	850	65	1000	0.408	156.0	145.3	14.0	28.9
Rim - Tangential	900	55	1000	0.364	156.8	142.1	15.0	28.9
Web - Radial	Unexposed				144.6	125.6	14.0	37.0
Web - Radial	950	45	1000	1.668	149.2	135.5	6.0	8.7
0.250 inch diameter specimens								

	Ti
11	Sn
5	Zr
2.5	Al
1	Mo
0.25	Si

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3.0219 Effect of 150 hours exposure to elevated temperature with load on the room temperature tensile properties of press-forged compressor wheels, Table 3.0219

TABLE 3.0219

<table>
<tr><td>Source</td><td colspan="8">(17, pp.18, 19, 21, and 22)</td></tr>
<tr><td>Alloy</td><td colspan="8">Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si</td></tr>
<tr><td>Form</td><td colspan="8">22in diameter press forged compressor wheels</td></tr>
<tr><td>Condition</td><td colspan="8">1650F, 1hr, AC + 930F, 24hrs, AC</td></tr>
<tr><td rowspan="2">Location - Direction</td><td colspan="4">Creep Exposure Conditions</td><td colspan="4">Subsequent RT Tensile Properties</td></tr>
<tr><td>Temp F</td><td>Stress ksi</td><td>Time hr</td><td>Total Creep - %</td><td>F_{tu} ksi</td><td>F_{ty} ksi</td><td>e(1 in) percent</td><td>RA percent</td></tr>
<tr><td colspan="9">Press Forged Compressor Wheel "A" (See Fig. 3.0315)</td></tr>
<tr><td>Coupling-Axial</td><td></td><td colspan="2">Unexposed</td><td></td><td>148.5</td><td>133.5</td><td>13.0</td><td>34.8</td></tr>
<tr><td>Coupling-Axial</td><td>900</td><td>55</td><td>150</td><td>0.256</td><td>150.3</td><td>137.2</td><td>14.0</td><td>31.0</td></tr>
<tr><td>Coupling-Axial</td><td>950</td><td>45</td><td>150</td><td>0.679</td><td>149.4</td><td>133.3</td><td>12.0</td><td>17.7</td></tr>
<tr><td>Coupling-Tang</td><td></td><td colspan="2">Unexposed</td><td></td><td>152.0</td><td>138.8</td><td>15.0</td><td>35.1</td></tr>
<tr><td>Coupling-Tang</td><td>1000</td><td>35</td><td>150</td><td>0.880</td><td>147.4</td><td>135.4</td><td>7.0</td><td>13.2</td></tr>
<tr><td>Rim-Tangential</td><td></td><td colspan="2">Unexposed</td><td></td><td>154.0</td><td>139.0</td><td>14.5</td><td>32.7</td></tr>
<tr><td>Rim-Tangential</td><td>850</td><td>65</td><td>150</td><td>0.152</td><td>152.9</td><td>141.0</td><td>13.0</td><td>29.5</td></tr>
<tr><td>Rim-Tangential</td><td>900</td><td>55</td><td>150</td><td>0.196</td><td>154.2</td><td>141.0</td><td>12.0</td><td>25.4</td></tr>
<tr><td>Rim-Tangential</td><td>950</td><td>45</td><td>150</td><td>0.264</td><td>154.4</td><td>141.0</td><td>10.0</td><td>19.8</td></tr>
<tr><td colspan="9">Press Forged Compressor Wheel "B" (See Fig. 3.0315)</td></tr>
<tr><td>Coupling-Axial</td><td></td><td colspan="2">Unexposed</td><td></td><td>150.5</td><td>133.1</td><td>14.0</td><td>38.8</td></tr>
<tr><td>Coupling-Axial</td><td>900</td><td>55</td><td>150</td><td>0.212</td><td>149.0</td><td>134.7</td><td>14.0</td><td>36.2</td></tr>
<tr><td>Coupling-Axial</td><td>950</td><td>45</td><td>150</td><td>0.372</td><td>151.5</td><td>137.6</td><td>9.0</td><td>13.9</td></tr>
<tr><td>Coupling-Tang</td><td></td><td colspan="2">Unexposed</td><td></td><td>153.8</td><td>138.0</td><td>15.0</td><td>40.8</td></tr>
<tr><td>Coupling-Tang</td><td>1000</td><td>35</td><td>150</td><td>0.340</td><td>151.5</td><td>139.6</td><td>5.0</td><td>9.4</td></tr>
<tr><td>Rim-Tangential</td><td></td><td colspan="2">Unexposed</td><td></td><td>155.8</td><td>139.9</td><td>14.5</td><td>37.3</td></tr>
<tr><td>Rim-Tangential</td><td>850</td><td>65</td><td>150</td><td>0.128</td><td>156.4</td><td>142.5</td><td>12.0</td><td>29.5</td></tr>
<tr><td>Rim-Tangential</td><td>900</td><td>55</td><td>150</td><td>0.156</td><td>154.2</td><td>140.0</td><td>13.0</td><td>27.5</td></tr>
<tr><td>Rim-Tangential</td><td>950</td><td>45</td><td>150</td><td>0.160</td><td>155.0</td><td>140.5</td><td>14.0</td><td>28.8</td></tr>
<tr><td colspan="9">Wheels from different heats.
0.250 inch diameter specimens.</td></tr>
</table>

Ti
11 Sn
5 Zr
2.5 Al
1 Mo
0.25 Si

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3.02110 Effect of 300 hours exposure to elevated temperature with load on room temperature tensile properties of compressor wheel forgings, Table 3.02110.

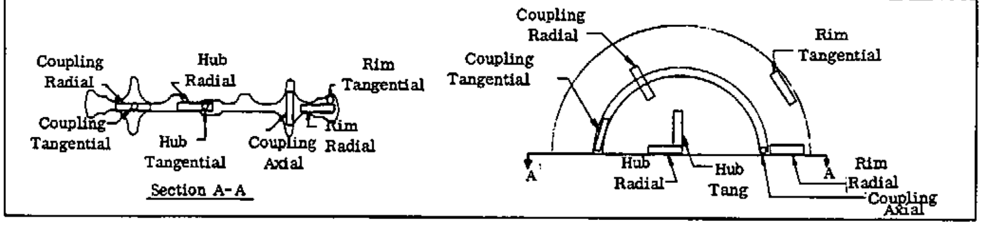
TABLE 3.02110

Source		(12)						
Alloy		Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si						
Form		24 1/2 inch diameter compressor wheel forging						
Condition		1650F, 1hr, AC + 930F, 24hrs, AC						
Location	Direction	300 hr Exposure At:			Subsequent RT Tensile Properties *			
		Temp F	Stress ksi	Deformation %	F_{ty} ksi	F_{tu} ksi	e(1 in) percent	RA percent
Rim	Tangential	750	88	.419**	145.0	149.0	11.1	24.6***
Rim	Radial	750	88	.476**	142.5	145.0	16.3	36.0
Coupling	Tangential	750	88	.330**	142.3	145.8	12.9	10.9***
Coupling	Radial	750	88	.385**	140.0	141.0	13.2	29.4
Coupling	Axial	750	88	.500**	139.5	140.6	12.3	29.4
Hub	Tangential	750	88	.333**	141.3	145.0	13.0	18.8***
Hub	Radial	750	88	.374**	140.0	143.8	17.0	36.0
Rim	Tangential	800	75	.195	140.5	148.0	15.9	39.2
Rim	Tangential	800	75	.178	142.0	150.5	17.0	36.0
Rim	Tangential	850	65	.154	139.0	149.0	17.1	39.2
Rim	Radial	850	65	.192	136.0	144.0	18.9	42.3
Coupling	Tangential	850	65	.161	136.0	145.2	18.5	36.0
Coupling	Radial	850	65	.283	132.0	141.0	15.6	36.0
Coupling	Axial	850	65	.191	129.0	137.3	11.4	22.7
Hub	Tangential	850	65	.227	137.0	148.5	12.2	18.8***
Hub	Radial	850	65	.235	134.0	145.0	17.6	36.0
Rim	Tangential		None		135.6	150.2	14.5	40.1
Rim	Radial		None		133.6	150.4	14.0	42.5
Coupling	Tangential		None		137.6	154.8	14.5	43.7
Coupling	Radial		None		130.0	147.8	11.5	30.5
Coupling	Axial		None		134.4	151.4	14.5	41.4
Hub	Tangential		None		136.0	152.2	15.0	40.1
Hub	Radial		None		132.4	148.6	13.5	38.8

*Tests made after creep exposure without surface conditioning.

**Approximately 50 to 75 percent of plastic deformation occurred on loading.

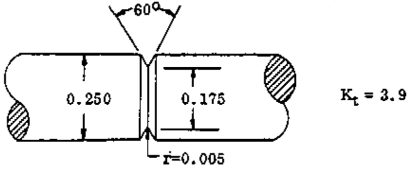
***Fracture originated at what is thought to be stress corrosion crack.



3.02111 Effect of 0.1 percent creep prestrain on the room temperature tensile properties of forgings, Figure 3.02111.
3.02112 Effect of exposure to elevated temperature on room temperature tensile properties of bar, Figure 3.02112.
3.02113 Typical room temperature tension stress-strain curve for large ring forging, Figure 3.02113.
3.022 Compression (see also 3.032).
3.0221 Stress-strain diagram (see also 3.0321).
3.023 Impact (see also 3.033).
3.024 Bending.
3.025 Torsion and shear (see also 3.035).
3.026 Bearing (see also 3.036).
3.027 Stress concentration (see also 3.037).
3.0271 Notch properties (see also 3.0371).

3.02711 Room temperature mild notch strength of large ring forging, Table 3.02711.

TABLE 3.02711

Source	(9, pp.58-59 and 63)		
Alloy	Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si		
Form	Large Ring Forging		
Condition	1650F, 1hr, Fan Cool + 930F, 24hrs, AC(1)		
Specimen Location	Specimen Orientation	F_{ty}(3) ksi	Mild Notch Strength(4) - ksi
Forging Heavy Section Properties (2)			
Edge	Long	134	208
Center	Long	129	205
Edge	Long Trans	134	207
Mid-Radius	Long Trans	128	203
Edge	Short Trans	134	204
Mid-Radius	Short Trans	130	201
			

(1) Heat treated in full section size.
(2) See Table 3.0216 for forging configuration and size.
(3) Each value average of three tests.
(4) Each value average of two tests.

3.0272 Fracture toughness.
3.028 Combined properties.

3.03 Mechanical Properties at Various Temperatures
3.031 Tension.
3.0311 Effect of test temperature on tensile properties of bar, Figure 3.0311.
3.0312 Variation in large ring forging heavy section tensile properties as a function of specimen location, orientation, and test temperature, Figure 3.0312.
3.0313 Variation in large ring forging light section tensile properties as a function of specimen location, orientation, and test temperature, Figure 3.0313.
3.0314 Effect of test temperature on tensile properties of hammer forged compressor wheels, Figure 3.0314.
3.0315 Effect of test temperature on tensile properties of press forged compressor wheels, Figure 3.0315.
3.0316 Effect of test temperature on tensile properties of forgings, Figure 3.0316.
3.0317 Effect of exposure to elevated temperature on tensile properties of bar at the exposure temperature, Figure 3.0317.
3.032 Compression (see also 3.022).
3.0321 Effect of test temperature on compressive yield strength of bar, Figure 3.0321.
3.0322 Effect of test temperature on compressive yield strength of large ring forgings, Figure 3.0322.
3.0323 Typical compressive stress-strain curves for large ring forging at room temperature and 550F, Figure 3.0323.
3.033 Impact.
3.0331 Effect of test temperature on standard Charpy-V impact energy for bar, Figure 3.0331.
3.034 Bending.
3.035 Torsion and shear.
3.0351 Effect of test temperature on ultimate shear strength of bar, Figure 3.0351.

3.02712 Effect of exposure to elevated temperature on room temperature smooth and mild-notch tensile properties of large forging, Table 3.02712.

TABLE 3.02712

Source			(9, pp. 53, 63, and 90-91)				
Alloy			Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si				
Form			Large Ring Forging				
Condition			1650F, 1hr, Fan Cool + 930F, 24hrs, AC (1)				
Exposure Time/ Temp	Specimen Location	Specimen Orientation	Subsequent RT Properties				
			F_{tu} ksi	F_{ty} ksi	e(1in) percent	RA percent	Mid-Notch(2) Strength- ksi
Forging Heavy Section Properties (3) (4)							
None	Center	Long	142	128	15.7	40.3	
1000hrs/550F	Center	Long	142	129	13.0	39.0	
None	Edge	Long	146	133	14.7	39.7	207
1000hrs/550F	Edge	Long	150	137	15.0	35.5	203

(1) Heat treated in full section size.
(2) See Table 3.02711 for specimen drawing.
(3) See Table 3.0216 for forging configuration and size.
(4) Each value average of two tests.

3.0352 Ultimate shear strength of large ring forging at room temperature and 550F, Table 3.0352.

TABLE 3.0352

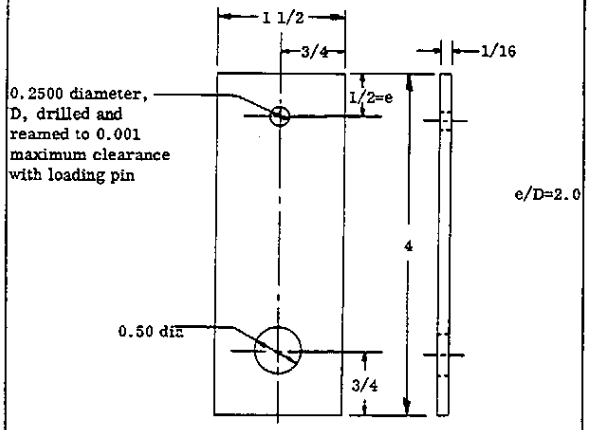
Source	(9, p.74)		
Alloy	Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si		
Form	Large Ring Forging		
Condition	1650F, 1hr, Fan Cool+930F, 24hrs, AC(1)		
Specimen Location (2)	Specimen Orientation (2)	Test Temp-F	F_{su} (3) ksi
Edge or Center	Long	RT	100.9
Edge or Center	Long	550	71.2

(1) Heat treated in full section size.
(2) Specimens 1.000 inch long by 0.250 inch in diameter taken from forging heavy section (see Table 3.0216 for forging configuration and size).
(3) Each value average of duplicate tests.

3.036 Bearing.
3.0361 Bearing strength of large ring forging at room temperature and 550F, Table 3.0361.

TABLE 3.0361

Source	(9, p.75)			
Alloy	Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si			
Form	Large Ring Forging			
Condition	1650F, 1hr, Fan Cool+930F, 24hrs, AC(1)			
Specimen Location	Specimen Orientation	Test Temp F	F_{bry}(3) ksi	F_{bru}(3) ksi
Web(2)	Long(2)	RT	231.4	305.8
Flange	Long	550	176.7	231.0



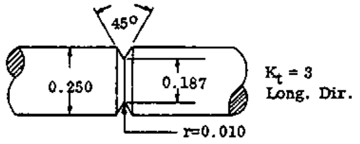
(1) Heat treated in full section size (see table 3.0216 for forging configuration and size).
(2) See Fig. 3.0313 for detail of forging light section.
(3) Each value average of duplicate tests.

3.037 Stress concentration (see also 3.027).
3.0371 Notch properties (see also 3.0271).

3.03711 Effect of test temperature on mild-notch strength of bar, Table 3.03711.

TABLE 3.03711

Source	(7, pp. 293 and 297)		
Alloy	Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si		
Form	1/2x1 1/8 inch rolled bar		
Condition	1650F, 2hrs, AC + 930F, 24hrs, AC		



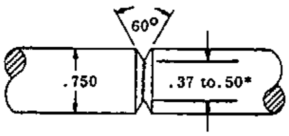
	Test Temperature - F		
	70	400	800
F_{ty}* - ksi	138.6	100.3	83.1
NTS** -ksi	218.7	175.6	164.8

*Each value average of ten tests.
**Each value average of duplicate tests.

3.03712 Effect of test temperature on mild-notch strength of forging, Figure 3.03712.
3.03713 Smooth and crack-notch tensile properties of large ring forging as a function of specimen location and test temperature in both unexposed and exposed (1000 hours, 550F) conditions, Table 3.03713.

TABLE 3.03713

Source	(9, pp.53-54 and 79)			
Alloy	Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si			
Form	Large Ring Forging			
Condition	1650F, 1hr, Fan Cool+930F, 24hrs, AC(1)			
Specimen Location	Specimen Orientation	Heavy Section Properties(2)		
		Test Temp F	F_{ty} ksi	Crack Notch Strength-ksi
Unexposed				
Edge	Short Trans	-110	158	88
Center	Short Trans	-110	---	93
Edge	Short Trans	RT	135	103
Center	Short Trans	RT	129	104
Exposed				
Edge	Short Trans	RT	135	107
Center	Short Trans	RT	129	109



Pre-cracked Round Bar
*Starter notch net dia 0.6in; net dia reduced from 0.6in to value shown by fatigue cracking

(1) Heat treated in full section size.
(2) See Table 3.0216 for forging configuration and size.
(3) Specimens exposed 1000 hrs at 550F (unstressed) and tested without surface treatment.

3.0372 Fracture toughness.
3.038 Combined properties.

3.04 Creep and Creep Rupture Properties

3.041 Creep deformation curves for bar at 800F, Figure 3.041.

3.042 Creep deformation curves for bar at 900F, Figure 3.042.

3.043 Creep deformation curves for bar at 1000F, Figure 3.043.

3.044 Minimum creep rate curves for bar at 800, 900 and 1000F, Figure 3.044.

3.045 0.1 percent creep curves for forgings, Figure 3.045.

3.046 Time to 0.1 percent and 0.2 percent creep deformation for compressor wheel forging, Table 3.046.

TABLE 3.046

Source		(12)		
Alloy		Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si		
Form		24 1/2in dia Compressor Wheel Forging		
Condition		1650F, 1hr, AC + 930F, 24hrs, AC		
			Time to	
Location*	Direction	Creep Exposure	0.1% Creep hrs	0.2% Creep hrs
Rim	Tangential	750F - 88 ksi	125	---
Rim	Radial	"	183	---
Coupling	Tangential	"	70	---
Coupling	Radial	"	380**	---
Coupling	Axial	"	65	380**
Hub	Tangential	"	195	---
Hub	Radial	"	140	---
Rim	Tangential	800F - 75 ksi	35	292
Rim	Tangential	"	50	385**
Rim	Tangential	850F - 65 ksi	50	---
Rim	Radial	"	15	345**
Coupling	Tangential	"	62	---
Coupling	Radial	"	6	62
Coupling	Axial	"	44	335**
Hub	Tangential	"	12	155
Hub	Radial	"	16	148

*See Table 3.02110 for specimen locations within wheel forging

**Extrapolated

3.047 300 hours creep deformation for compressor wheel forging, Table 3.047

TABLE 3.047

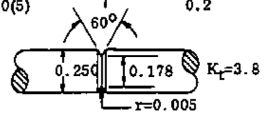
Source		(12)		
Alloy		Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si		
Form		24 1/2in dia Compressor Wheel Forging		
Condition		1650F, 1hr, AC + 930F, 24hrs, AC		
Location*	Direction	Plastic Deformation on Loading--Percent	300hrs Creep Deformation--Percent	Total 300hrs Plastic Deformation--Percent
		750F - 88 ksi		
Rim	Tangential	0.279	0.140	0.419
Rim	Radial	0.348	0.128	0.476
Coupling	Tangential	0.174	0.156	0.330
Coupling	Radial	0.304	0.081	0.385
Coupling	Axial	0.322	0.178	0.500
Hub	Tangential	0.210	0.123	0.333
Hub	Radial	0.241	0.133	0.374
		800F - 75 ksi		
Rim	Tangential	0.000	0.195	0.195
Rim	Tangential	0.000	0.178	0.178
		850F - 65 ksi		
Rim	Tangential	0.000	0.154	0.154
Rim	Radial	0.000	0.192	0.192
Coupling	Tangential	0.000	0.161	0.161
Coupling	Radial	0.000	0.283	0.283
Coupling	Axial	0.000	0.191	0.191
Hub	Tangential	0.000	0.227	0.227
Hub	Radial	0.000	0.235	0.235

* See Table 3.02110 for specimen location within wheel forging

3.048 Master creep curves for compressor wheel forgings, Figure 3.048.

3.049 Room temperature mild-notch creep rupture properties of compressor wheel forgings, Table 3.049

TABLE 3.049

Source	(17, pp.14,16,19, and 22)	
Alloy	Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si	
Form	Compressor Wheel Forgings	
Condition	1650F, 1hr, AC + 930F, 24hrs, AC	
	RT Mild-Notch Creep Rupture Properties	
Location - Direction	Stress at Failure ksi	Time to Failure hrs
Hammer Forged Compressor Wheel "A" (1)		
Web-Radial	190(2)	5.1
Web-Radial	190(2)	4.8
Web-Tangential	190(2)	0.4
Web-Tangential	190(2)	0.4
Hammer Forged Compressor Wheel "B" (1)		
Rim-Axial	180(3)	5.3
Rim-Axial	200(3)	0.2
Rim-Tangential	210(3)	0.2
Web-Radial	200(3)	1.6
Press Forged Compressor Wheel "A" (4)		
Rim-Radial	190(5)	3.8
Rim-Radial	190(5)	0.6
Coupling-Tangential	190(5)	4.9
Coupling-Tangential	190(5)	4.6
Press Forged Compressor Wheel "B" (4)		
Rim-Radial	190(5)	0.3
Rim-Radial	190(5)	0.1
Coupling-Tangential	180(5)	5.2
Coupling-Tangential	190(5)	0.2
		

(1) See Fig. 3.0314 for wheel configuration; wheels "A" and "B" from same heat.

(2) Stress increased from 150 ksi in 10 ksi increments approximately every 5 hrs.

(3) Stress increased from 170 ksi in 10 ksi increments approximately every 5 hrs.

(4) See Fig. 3.0315 for wheel configuration; wheels "A" and "B" from different heats.

(5) Stress increased from 180 ksi in 10 ksi increments approximately every 5 hrs.

	Ti
11	Sn
5	Zr
2.5	Al
1	Mo
0.25	Si

Ti-679

3.0410 Creep rupture properties of compressor wheel forging at 800 and 900F, Table 3.0410.

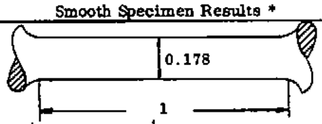
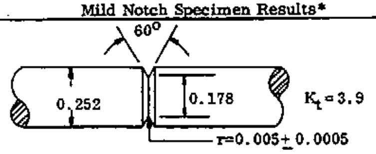
TABLE 3.0410

Source	(12)		
Alloy	Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si		
Form	24 1/2in dia Compressor Wheel Forging		
Condition	1650F, 1hr, AC + 930F, 24hrs, AC		
	Creep Exposure		Time to Rupture hrs
Location - Direction*	Stress ksi	Temp F	
Rim-Tangential	85	800	1171.8
Rim-Tangential	90	800	1001.0
Rim-Tangential	110	800	0.1
Rim-Tangential	95	900	73.8
Rim-Radial	80	900	1670.6
Rim-Radial	95	900	226.9
Rim-Radial	100	900	137.0
Rim-Radial	100	900	195.0
Coupling-Axial	100	800	1491.0**
Coupling-Axial	105	800	743.0**
Coupling-Axial	110	800	0.8
Coupling-Axial	90	900	191.7

* See Table 3.02110 for specimen locations within wheel forging.
** Test still in progress.

3.0411 Smooth and mild-notch creep rupture properties of forging at various temperatures, Table 3.0411.

TABLE 3.0411

Source	(16)			
Alloy	Ti-11Sn-5Ar-2.25Al-1Mo-0.21Si			
Form	15 in diameter x 1.3 in thick Hammer Forging***			
Condition	1650F, 1 hr, AC + 930F, 24 hrs, AC			
Temp F	Stress ksi	Test Duration hrs	e(1 in) percent	RA percent
Smooth Specimen Results *				
				
750	108	332.6	No Rupture - Test Discontinued	
750	85	550.1	No Rupture - Test Discontinued	
850	100	184.5	No Rupture - Test Discontinued	
850	80	407.5	No Rupture - Test Discontinued	
950	90	183.7	No Rupture - Test Discontinued	
950	75	321.6	17.7	38.0
Mild Notch Specimen Results*				
				
70	150	5.0	No Rupture - Stress Raised 10ksi**	
	160	17.1	No Rupture - Stress Raised 10ksi	
	170	5.0	No Rupture - Stress Raised 10ksi	
	180	19.2	No Rupture - Stress Raised 10ksi	
	190	5.5	No Rupture - Stress Raised 10ksi	
	200	17.5	No Rupture - Stress Raised 10ksi	
	210	0.2	Rupture	

*Specimens from edge location, tangential direction.
**Stress increased from 150ksi in 10ksi increments if no failure in times shown; notch rupture data all from a single specimen.
***Forging "A", Fig. 3.0316.

3.0412 Creep rupture properties of hammer forged and press forged compressor wheels at various temperatures using a combination specimen, Table 3.0412.

TABLE 3.0412

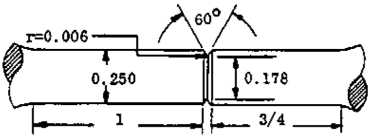
Source	(17, pp.13,15,18,and 21)
Alloy	Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si
Form	Compressor Wheel Forgings
Condition	1650F, 1hr, AC + 930F, 24hrs, AC

Stress Rupture Properties

Temp F	Stress ksi	Specimen Location - Direction	Time to Rupture hrs	e(1 in) percent	Location of Failure
Hammer Forged Compressor Wheel "A"*					
950	80.0	Web-Radial	236.9	21.6	Smooth Section
1000	65.0	Web-Radial	190.0	29.6	Smooth Section
Hammer Forged Compressor Wheel "B"*					
950	80.0	Web-Radial	198.8	22.6	Smooth Section
1000	65.0	Web-Radial	107.5	27.9	Smooth Section
Press Forged Compressor Wheel "A"**					
950	60.0	Rim-Tangential	726.8	23.9	Smooth Section
950	60.0	Rim-Radial	879.1	22.6	Smooth Section
950	80.0	Rim-Tangential	152.7	21.3	Smooth Section
950	80.0	Rim-Radial	33.8	14.6	Smooth Section
1000	65.0	Rim-Tangential	123.5	27.9	Smooth Section
		Rim-Radial	89.2	----	Notched Section
Press Forged Compressor Wheel "B"**					
950	60.0	Rim-Tangential	1468.0	17.3	Smooth Section
950	60.0	Rim-Radial	1631.5	29.9	Smooth Section
950	80.0	Rim-Tangential	215.2	19.9	Smooth Section
950	80.0	Rim-Radial	198.6	25.3	Smooth Section
1000	65.0	Rim-Tangential	154.4	17.3	Smooth Section
1000	65.0	Rim-Radial	151.1	27.9	Smooth Section

*See Fig. 3.0314 for wheel configuration. Wheels "A" and "B" from same heat.

**See Fig. 3.0315 for wheel configuration. Wheels "A" and "B" from different heats.



Combination - Bar Specimen

3.05 Fatigue Properties

3.051 Axial load smooth and mild-notch fatigue properties for bar at 70F, Figure 3.051.

3.052 Axial load smooth and mild-notch fatigue properties for bar at 400F, Figure 3.052.

3.053 Axial load smooth and mild-notch fatigue properties for bar at 800F, Figure 3.053.

3.054 Constant-life fatigue diagram for bar at several temperatures (smooth specimens), Figure 3.054.

3.055 Constant-life fatigue diagram for bar at several temperatures (mild-notch specimens), Figure 3.055.

3.056 Axial tension smooth and mild-notch fatigue properties of large ring forging at room temperature and 550F, Figure 3.056.

3.057 Mild-notch fatigue strength of forgings at 70 and 800F, Figure 3.057.

3.06 Elastic Properties

3.061 Static tensile modulus of elasticity at room and elevated temperatures for bar, Figure 3.061.

3.062 Dynamic modulus of elasticity at room and elevated temperatures for bar, Figure 3.062.

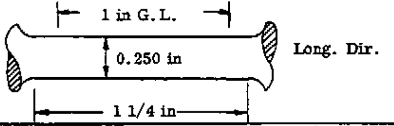
3.063 Static compressive modulus of elasticity at room and elevated temperatures for bar, Figure 3.063

3.064 Comparison of precision and conventional room temperature static tensile moduli of elasticity for bar, Table 3.064.

TABLE 3.064

Source	(18, p.15)
Alloy	Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si
Form	2 1/4 in dia Rolled Bar
Condition	1650F, 1hr, AC + 930F, 24hrs, AC

E(1) (Precision) 10^3 ksi	E(2) (Conventional) 10^3 ksi	F_{tu} ksi	F_{ty} ksi	e(1 in) percent	RA percent
15.6	15.4	145.5	130.0	23.0	48.1
15.8	15.4	149.5	134.0	21.0	45.1



(1) Tuckerman strain measuring system used, measurement sensitive to 2×10^{-6} inch per inch.

(2) Conventional Riehle extensometer used.

3.065 Precision static tensile and compressive room temperature moduli of elasticity for large ring forging, Table 3.065.

TABLE 3.065

Source	(9, pp. 93-94)		
Alloy	Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si		
Form	Large Ring Forging (1)		
Condition	1650F, 1hr, Fan Cool+930F, 24hrs, AC(2)		
Test Direction	Specimen Location	Specimen Orientation	Precision Static Elastic Modulus (3) 1000 ksi
Tension	Edge	Long	E=15.7
Tension	Edge	Long Trans	E=16.1
Compression	Edge	Long	E_c=16.1
Compression	Edge	Long Trans	E_c=16.5

(1) Specimens extracted from heavy section of forging. See Table 3.0216 for forging configuration and size.
(2) Heat treated in full section size.
(3) Tuckerman Optical Strain measuring system used. Each value average of three tests on same specimen.

4. FABRICATION

4.01 Formability

4.011 Forging

To develop the best combination of mechanical properties, this alloy is forged at 1650F. During final forging, the entire piece must be worked below 1730F, the beta transus temperature. Large amounts of forging work (by reductions of 8:1 or 9:1 in upsetting, for instance) produce 135-140 ksi yield strength for the duplex annealed condition (28).

The forgeability of this alloy is good, being, in terms of cracking resistance, about the same as Ti-8Al-1Mo-1V but not as good Ti-6Al-4V or Ti-6Al-6V-2Sn (10, p. 14).

The forgeability of an alloy is not only concerned with the amount of plastic deformation it can withstand without cracking but also the energy needed to deform the material and the allowable forging temperature range. This alloy is compared with other titanium alloys with respect to these variables in Table 4.0111.

4.0111 Forging characteristics of Ti-679 and other titanium alloys, Table 4.0111.

TABLE 4.0111

Source			(10, p. 14)			
Alloy	Type	Alpha Transus ± 25° F	Beta Transus ± 25° F	Die Forging Range, F	Required Pressure[a] 1000psi	Resistance to Cracking
Commercially Pure	Alpha	1660	1760	1550-1700	65-75	
Ti-5Al-2.5Sn	Alpha	1735	1900	1775-1850	75-85	Good
Ti-8Al-1Mo-1V	Alpha-Beta	1700	1900	1775-1850	75-85	Fair-Good
Ti-5Al-5Sn-5Zr	Alpha	1715	1815	1700-1800	75-85	Poor-Fair
Ti-7Al-12Zr	Alpha	1710	1825	1700-1800	75-85	Fair
IMI-679	Alpha-Beta	----	1750	1650-1725	75-85	Fair-Good
Ti-6Al-4V	Alpha-Beta	----	1820	1650-1800	75-85	Good-Excellent
Ti-6Al-4V-ELI	Alpha-Beta	----	1820	1650-1800	75-85	Good-Excellent
Ti-6Al-6V-2Sn	Alpha-Beta	----	1735	1575-1675	65-75	Excellent
Ti-7Al-4Mo	Alpha-Beta	----	1840	1680-1825	75-85	Good
Ti-4Al-4Mn	Alpha-Beta	----	1700	1500-1650	65-75	Good
Ti-13V-11Cr-3Al	Beta	----	1325	1600-1800	85-100	Excellent

[a] For forging in hydraulic press; approximately 50 percent more energy should be added to these figures for hammer forgings as titanium alloys are strain rate sensitive.

4.02 Machining and Grinding

Machining this alloy is somewhat difficult due to its high rate of work hardening (16). Machining is accomplished with the same general techniques and degree of difficulty as other titanium alloys (16).

4.03 Welding

4.05 Heat Treatment

4.05 Surface Treatment

	Ti
11	Sn
5	Zr
2.5	Al
1	Mo
0.25	Si

Ti-679

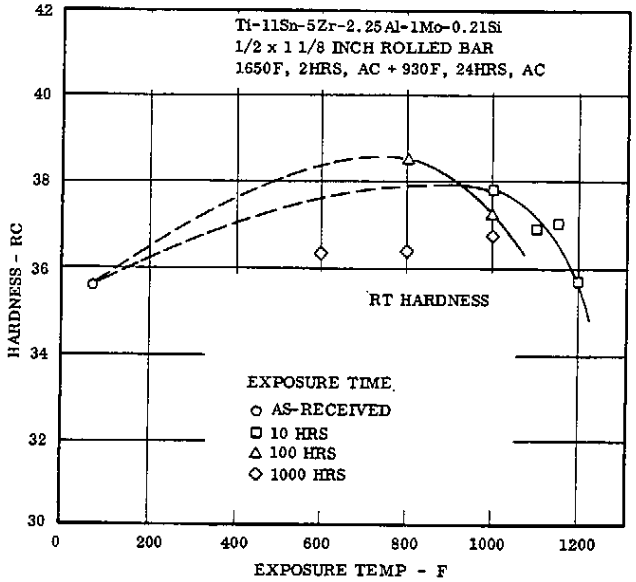


FIG. 1.061 EFFECT OF EXPOSURE TO ELEVATED TEMPERATURE ON ROOM TEMPERATURE HARDNESS OF BAR. (7, p. 302)

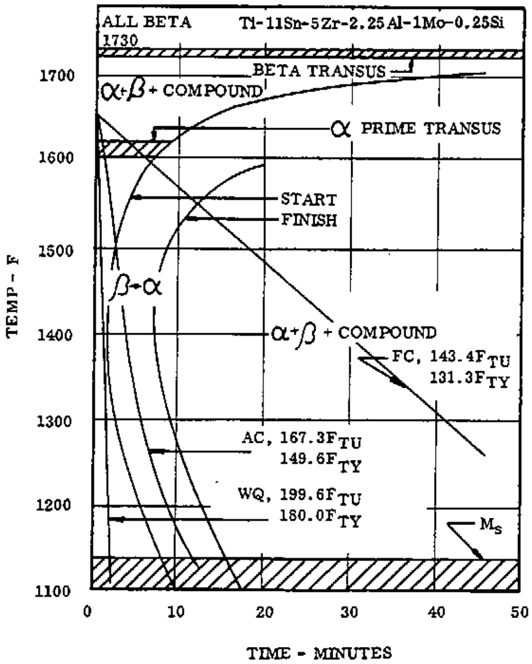


FIG. 2.0121 TIME-TEMPERATURE-TRANSFORMATION DIAGRAM (STRENGTH VALUES SHOWN ARE IN UNITS OF KSI AND ARE FOR SPECIMENS SOLUTION TREATED AS SHOWN AND AGED 930F, 24 HRS, AC) (5, p. 13)

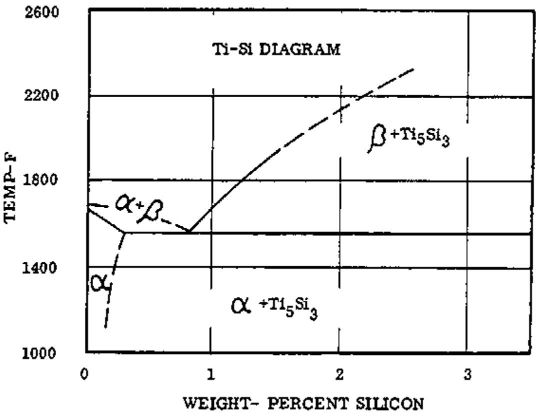


FIG. 2.0122 Ti-Si BINARY PHASE DIAGRAM SHOWING COMPOUND FORMATION Ti_5Si_3 (5, p.8)

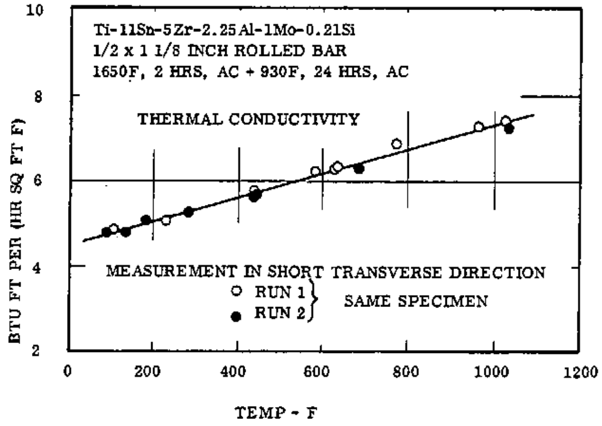


FIG. 2.0131 THERMAL CONDUCTIVITY OF BAR (7, p. 321)

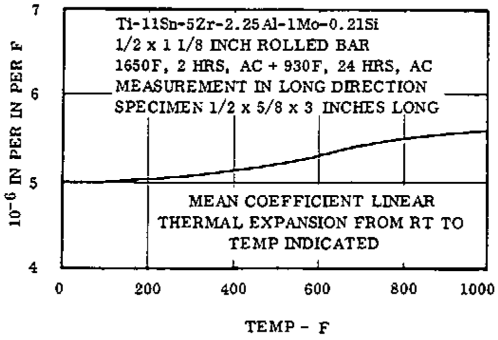


FIG. 2.0141 THERMAL EXPANSION FOR BAR (7, p.329)

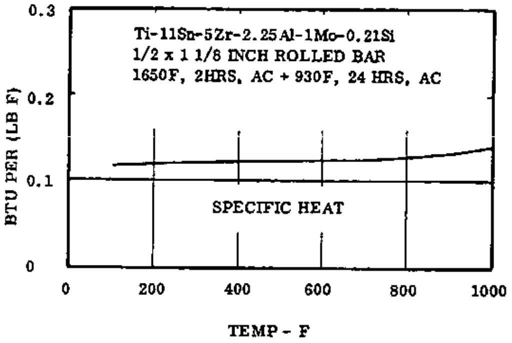


FIG. 2.0151 SPECIFIC HEAT FOR BAR (7, p.218)

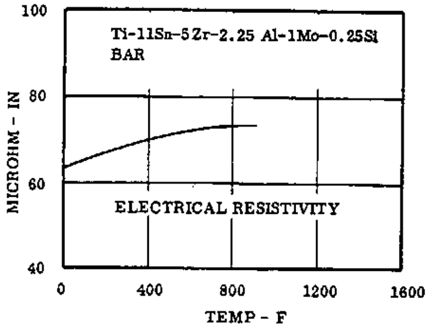


FIG. 2.0221 ELECTRICAL RESISTIVITY (4,p.2)(5,p.4)

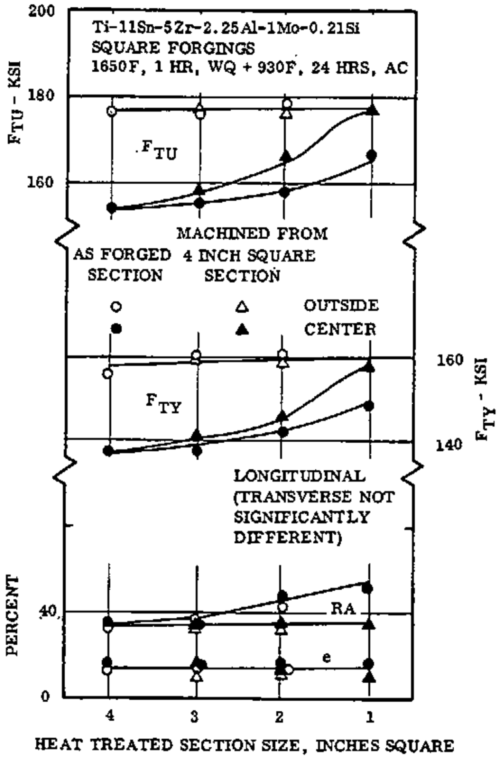


FIG. 3.0215 EFFECT OF HEAT TREATED SECTION SIZE ON THE TENSILE PROPERTIES OF FORGED BAR (8)

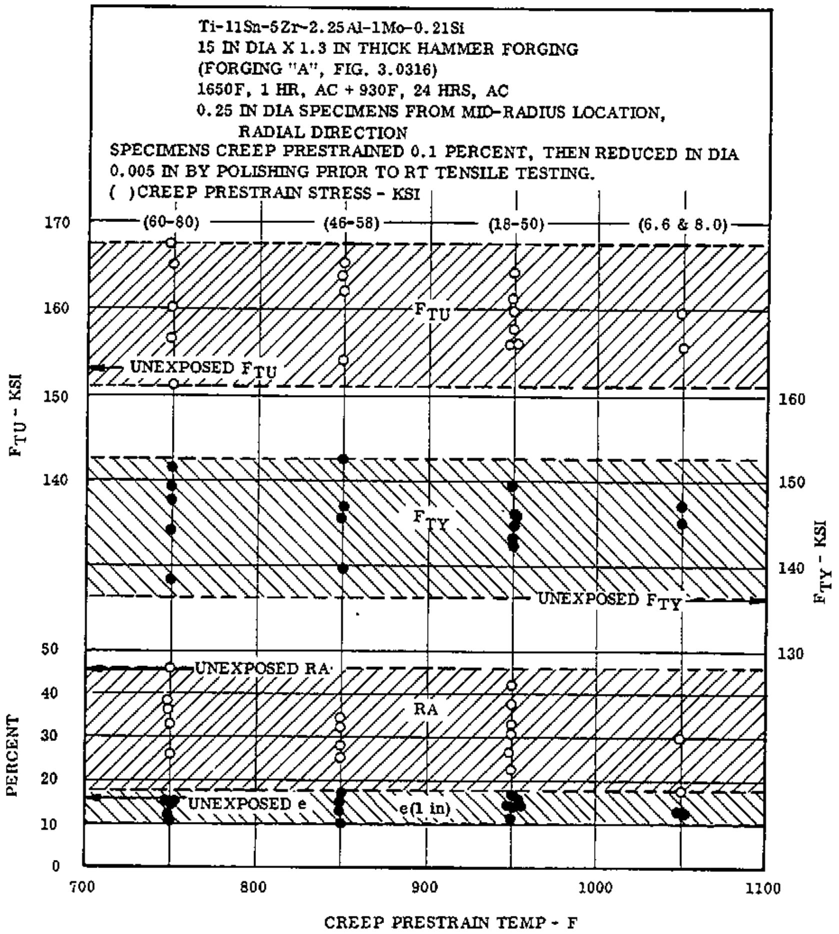


FIG. 3.02111 EFFECT OF 0.1 PERCENT CREEP PRESTRAIN ON ROOM TEMPERATURE TENSILE PROPERTIES OF FORGING (16)

	Ti
11	Sn
5	Zr
2.5	Al
1	Mo
0.25	Si

Ti-679

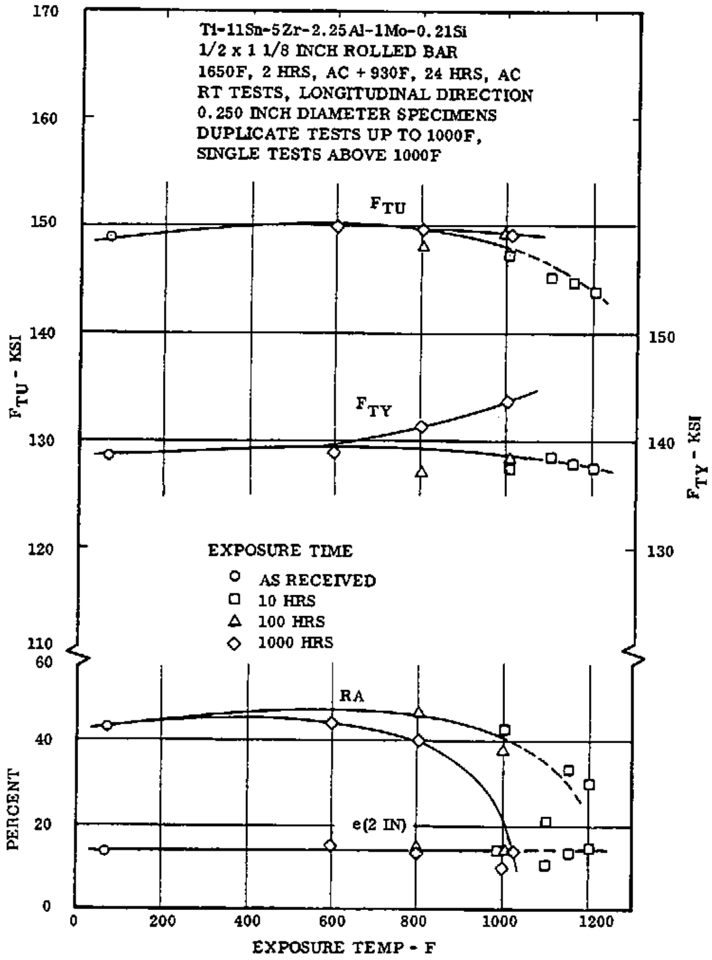


FIG. 3.02112 EFFECT OF EXPOSURE TO ELEVATED TEMPERATURE ON ROOM TEMPERATURE TENSILE PROPERTIES OF BAR (7, pp. 305-306)

	Ti
11	Sn
5	Zr
2.5	Al
1	Mo
0.25	Si

Ti-679

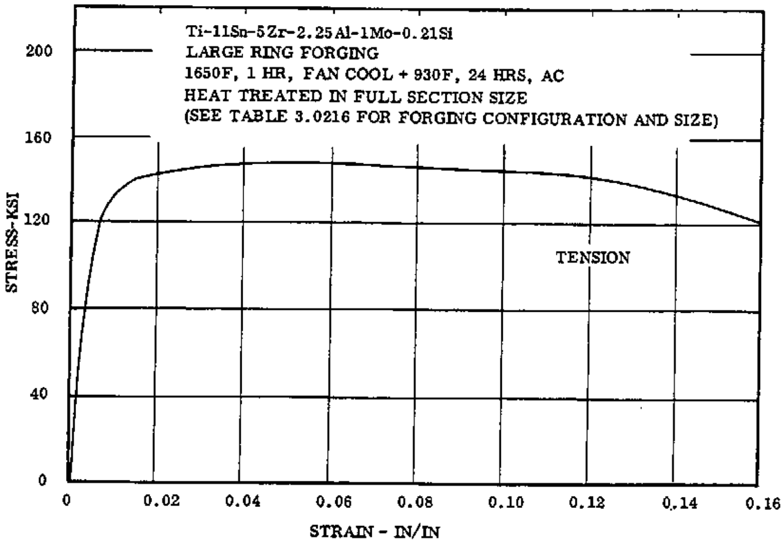


FIG. 3.02113 TYPICAL ROOM TEMPERATURE TENSION STRESS - STRAIN CURVE FOR LARGE RING FORGING (9, p. 45)

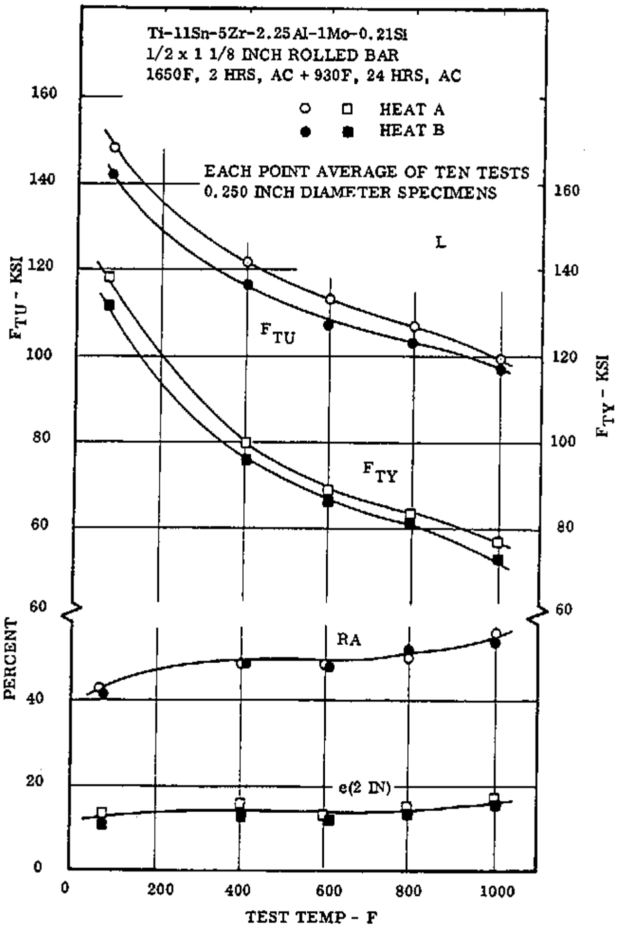


FIG. 3.0311 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF BAR (7, pp. 293-296)

	Ti
11	Sn
5	Zr
2.5	Al
1	Mo
0.25	Si

Ti-679

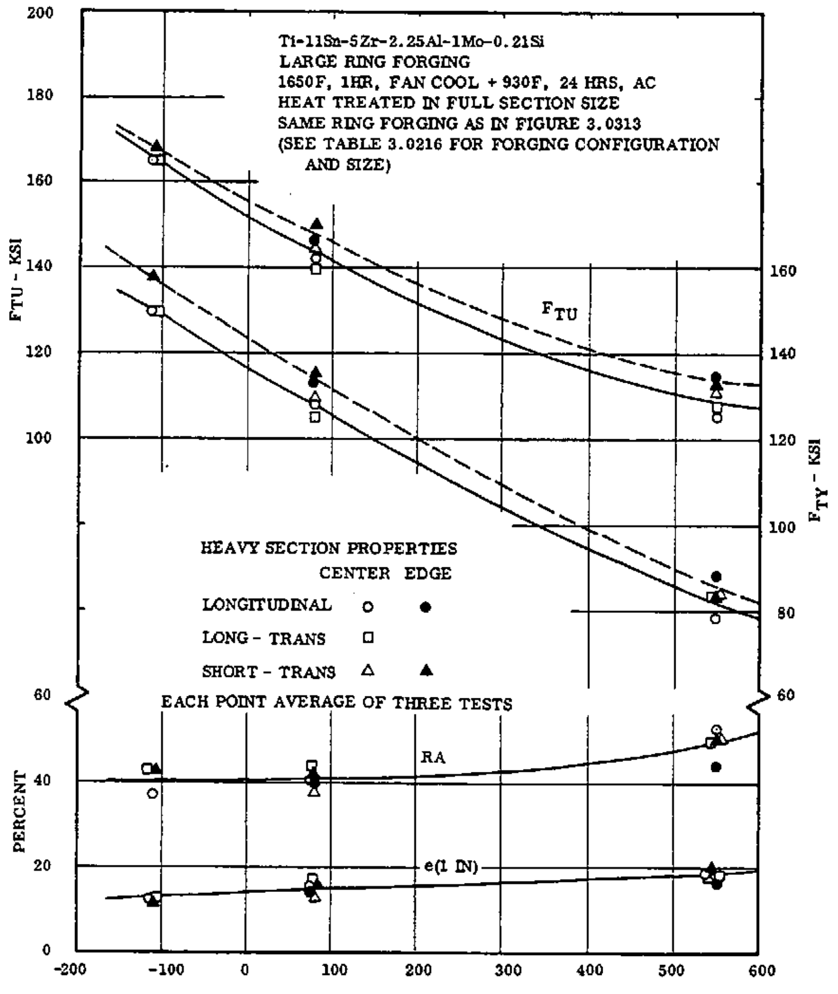


FIG. 3.0312 VARIATION IN LARGE RING FORGING HEAVY-SECTION TENSILE PROPERTIES AS A FUNCTION OF SPECIMEN LOCATION, ORIENTATION, AND TEST TEMPERATURE (9, pp.53-55)

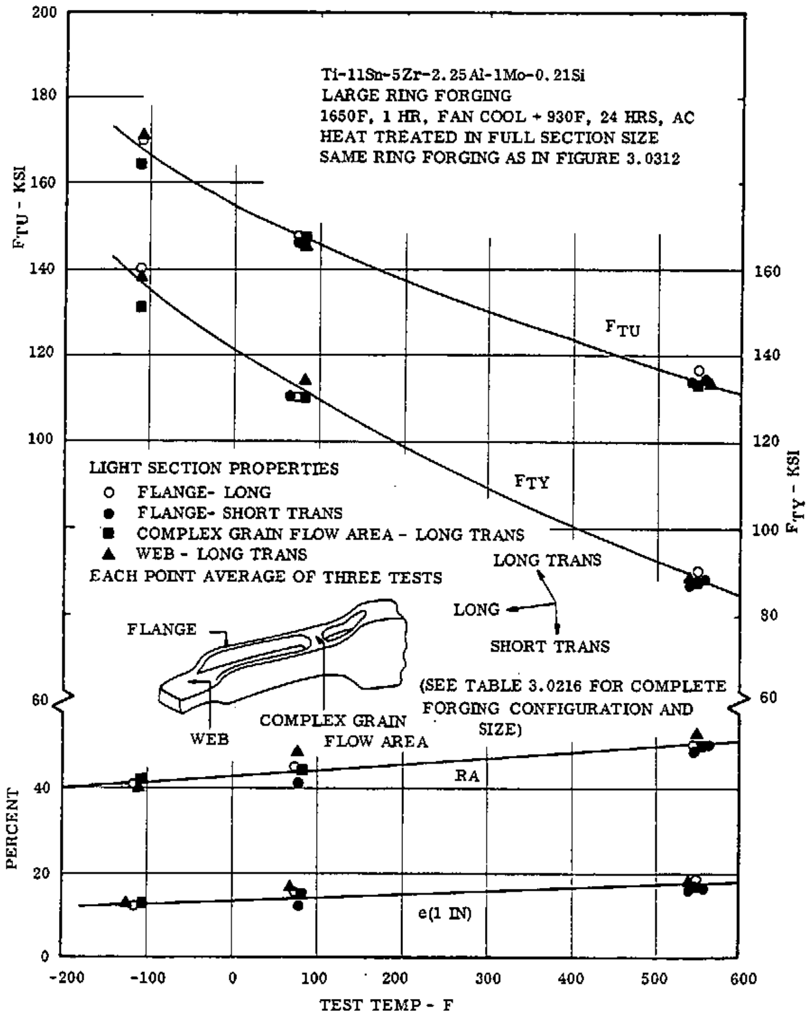


FIG. 3.0313 VARIATION IN LARGE RING FORGING LIGHT-SECTION TENSILE PROPERTIES AS A FUNCTION OF SPECIMEN LOCATION, ORIENTATION, AND TEST TEMPERATURE (9. pp. 56-57)

	Ti
11	Sn
5	Zr
2.5	Al
1	Mo
0.25	Si

Ti-679

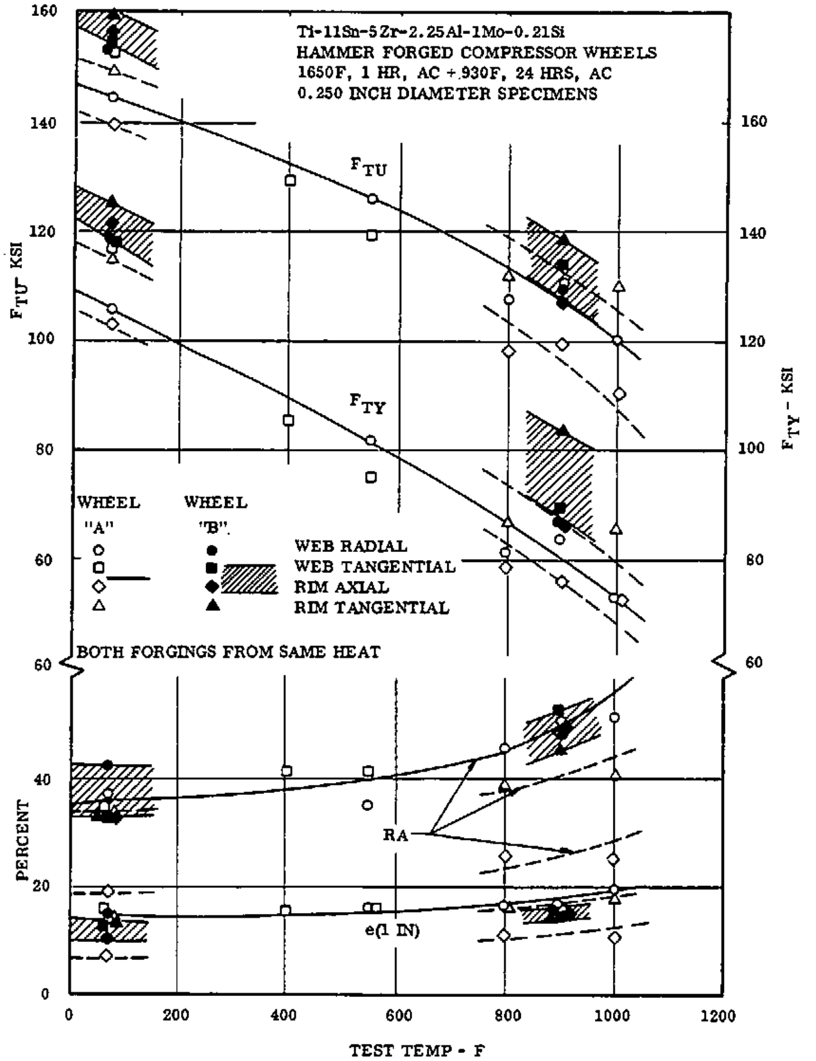
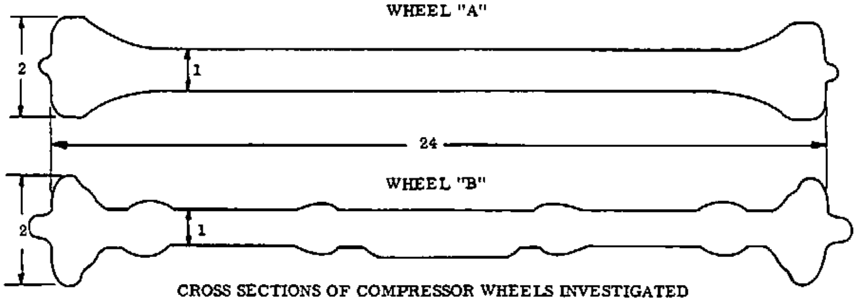


FIG. 3.0314 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF HAMMER FORGED COMPRESSOR WHEELS (17, pp.12 and 15)



CROSS SECTIONS OF COMPRESSOR WHEELS INVESTIGATED

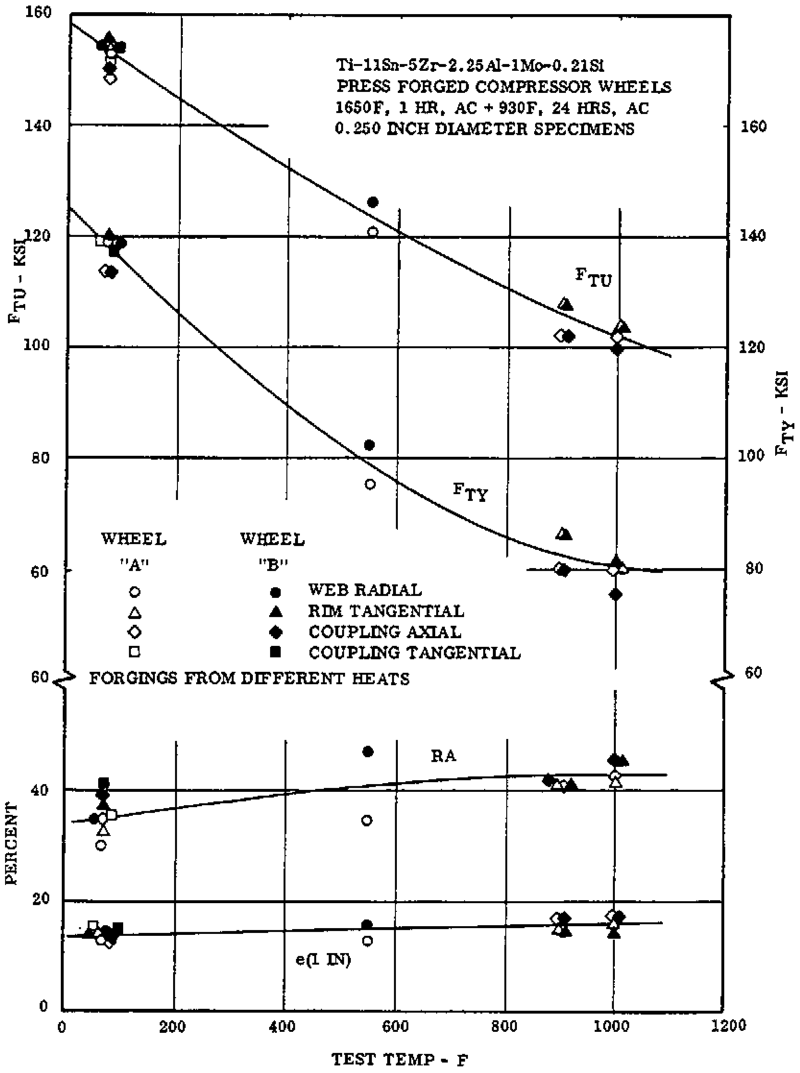
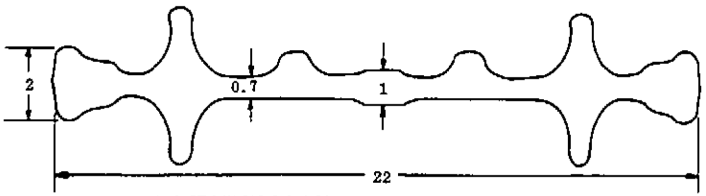


FIG. 3.0315 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF PRESS FORGED COMPRESSOR WHEELS. (17, pp. 18 and 21)



CROSS SECTION OF COMPRESSOR WHEELS INVESTIGATED

	Ti
11	Sn
5	Zr
2.5	Al
1	Mo
0.25	Si

Ti-679

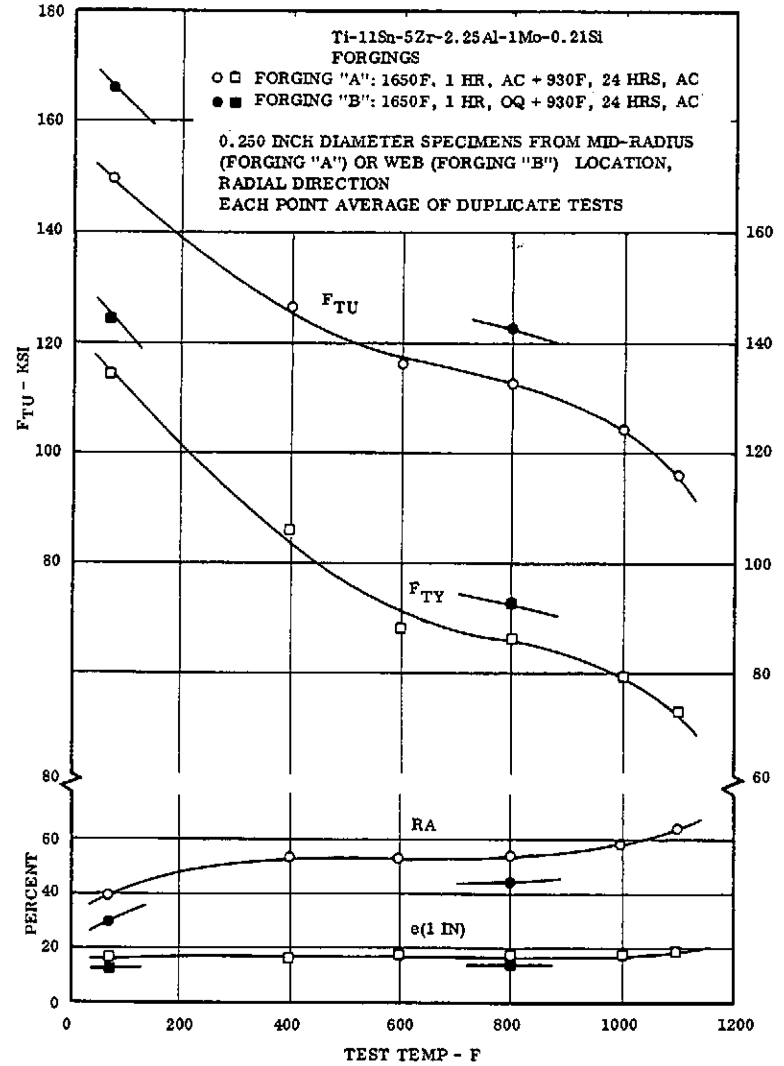
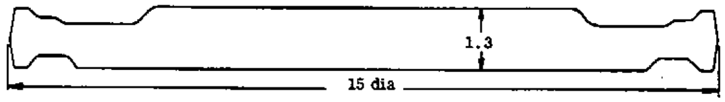
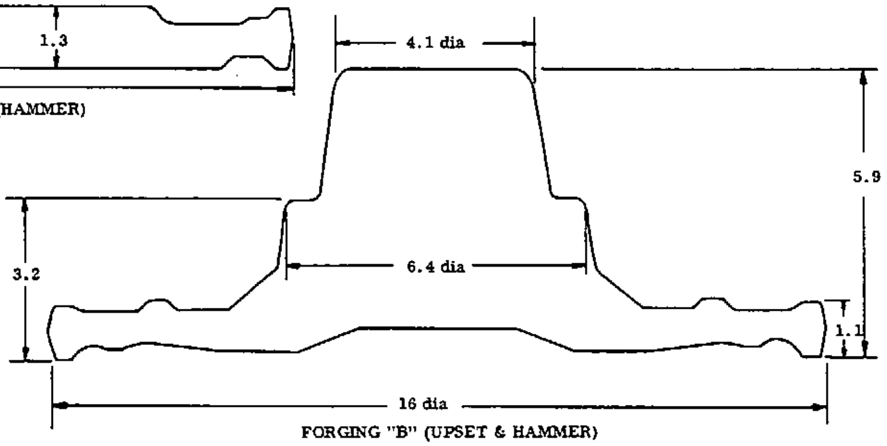


FIG. 3.0316 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF FORGINGS (16)



FORGING "A" (HAMMER)



FORGING "B" (UPSET & HAMMER)

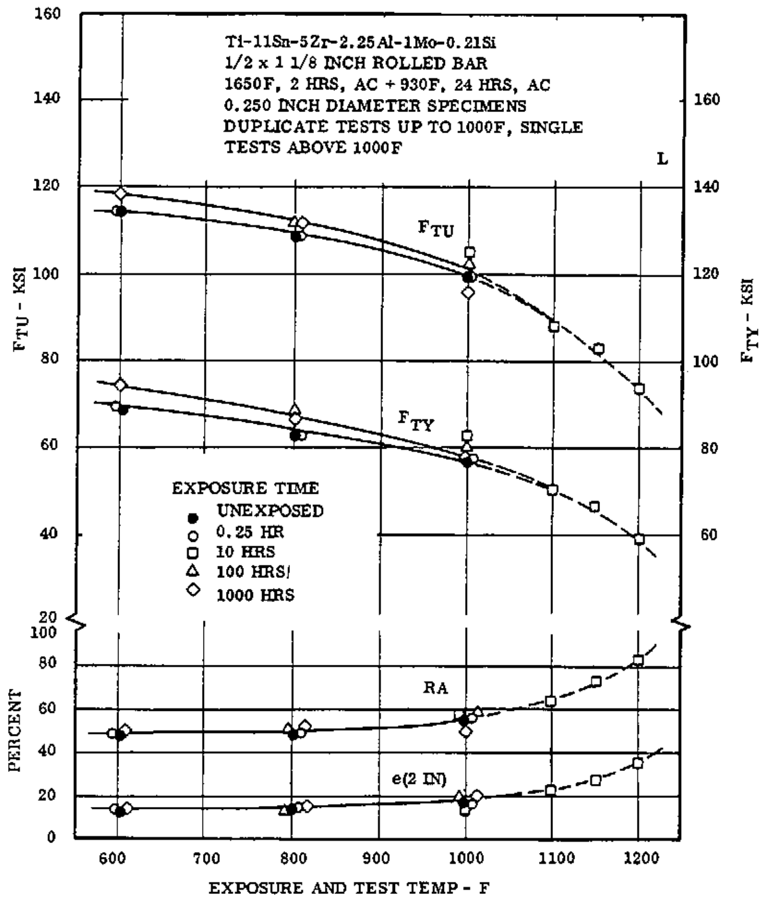


FIG. 3.0317 EFFECT OF EXPOSURE TO ELEVATED TEMPERATURE ON TENSILE PROPERTIES OF BAR AT THE EXPOSURE TEMPERATURE. (7, pp. 146 and 305-306)

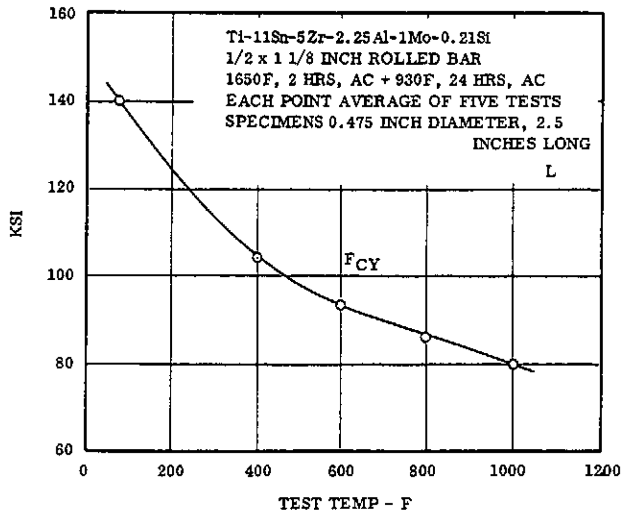


FIG. 3.0321 EFFECT OF TEST TEMPERATURE ON COMPRESSIVE YIELD STRENGTH OF BAR. (7, p. 299)

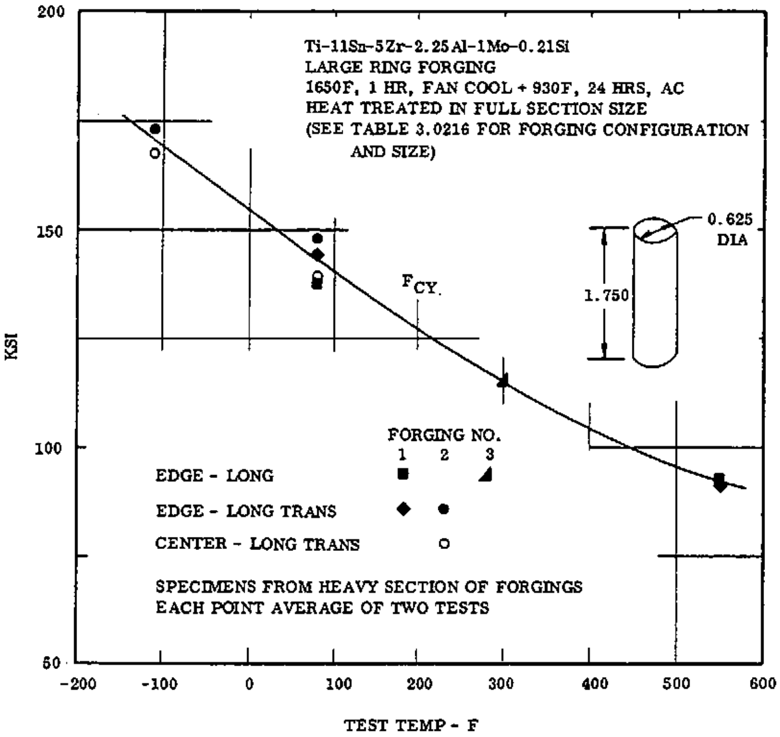


FIG. 3.0322 EFFECT OF TEST TEMPERATURE ON COMPRESSIVE YIELD STRENGTH OF LARGE RING FORGINGS (9, pp.71-72)

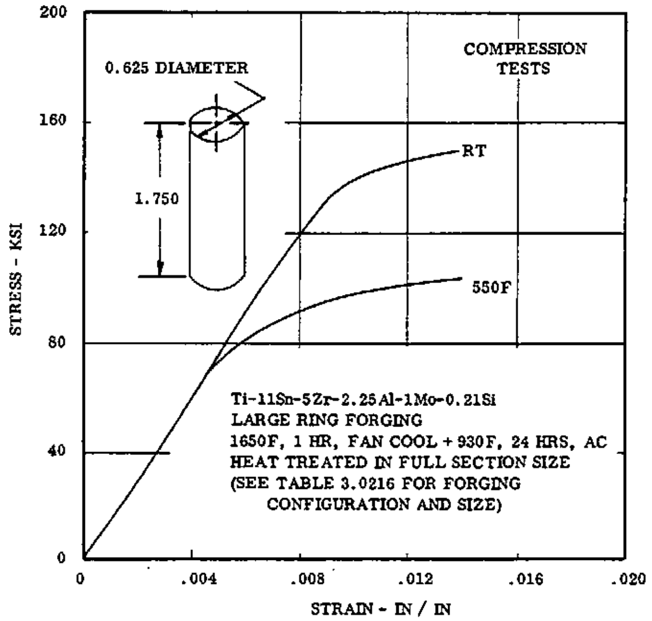


FIG. 3.0323 TYPICAL COMPRESSIVE STRESS-STRAIN CURVES FOR LARGE RING FORGING AT ROOM TEMPERATURE AND 550F (9, pp.67-68)

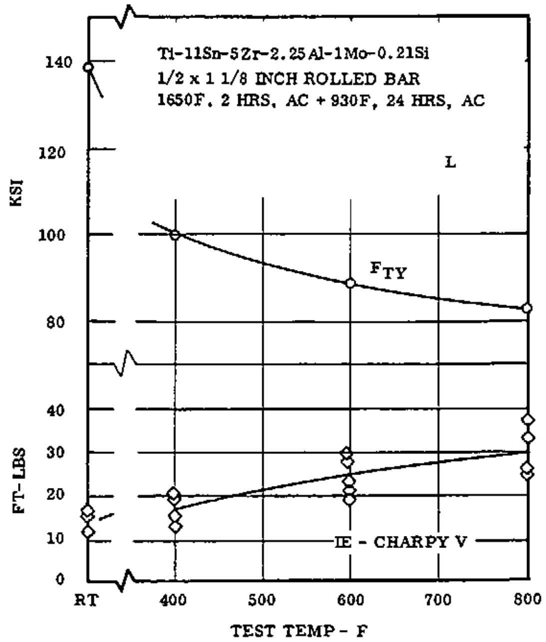


FIG. 3.0331 EFFECT OF TEST TEMPERATURE ON STANDARD CHARPY V IMPACT ENERGY FOR BAR (7, pp. 146 and 309)

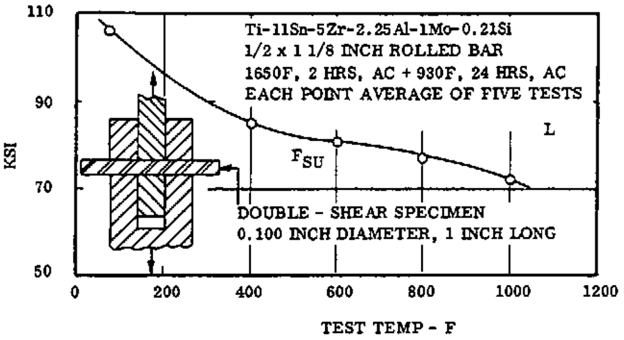


FIG. 3.0351 EFFECT OF TEST TEMPERATURE ON ULTIMATE SHEAR STRENGTH OF BAR (7, p.301)

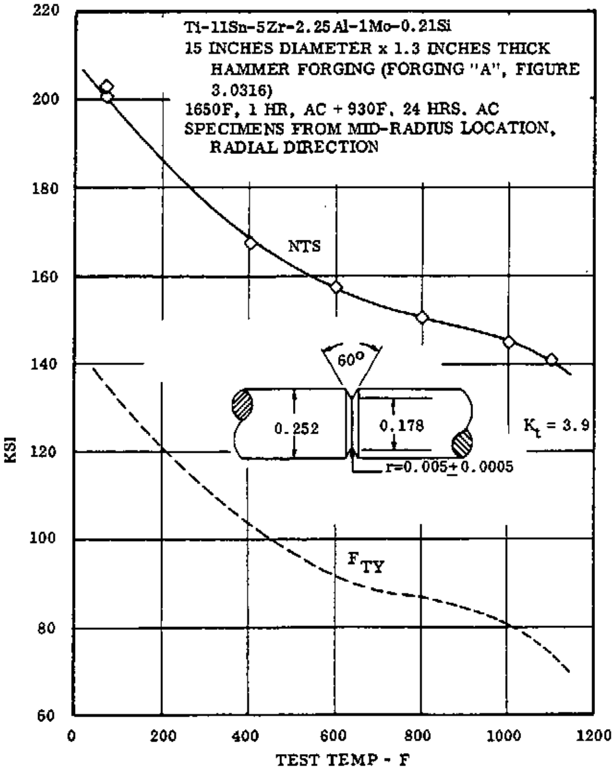


FIG. 3.03712 EFFECT OF TEST TEMPERATURE ON MILD-NOTCH STRENGTH OF FORGING (16)

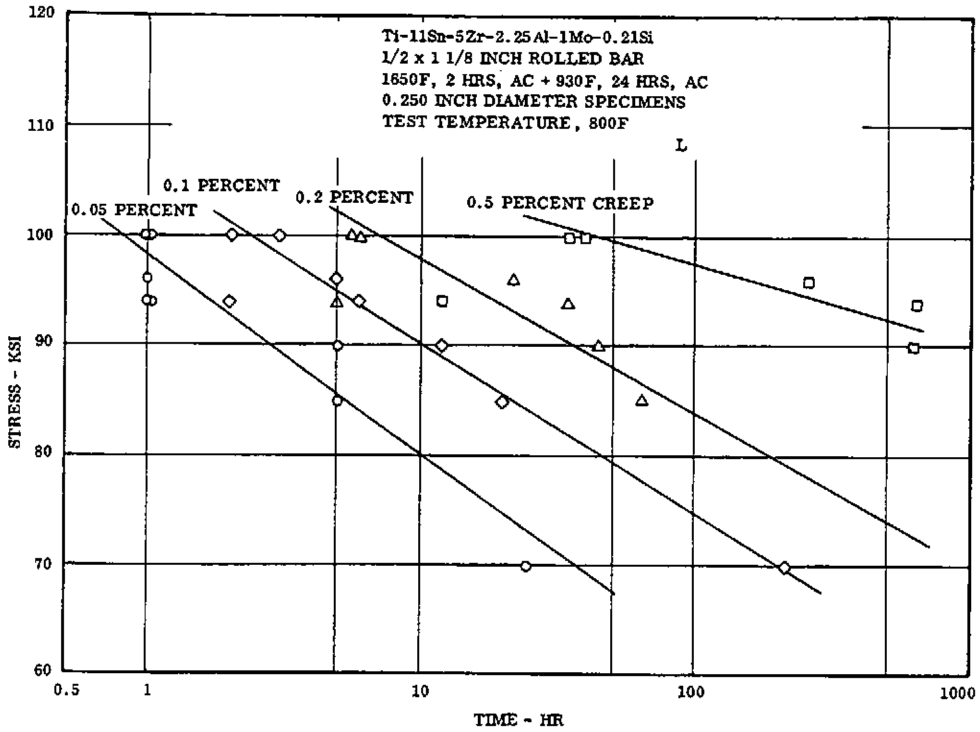


FIG. 3.041 CREEP DEFORMATION CURVES FOR BAR AT 800F (7, p.308)

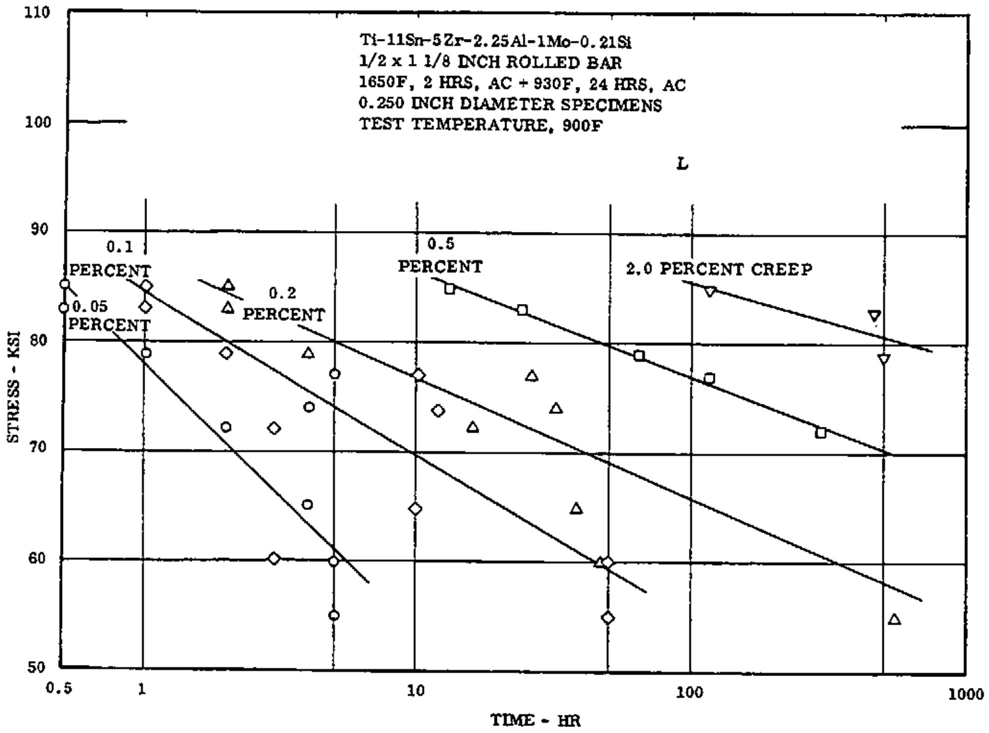


FIG. 3.042 CREEP DEFORMATION CURVES FOR BAR AT 900F (7, p.308)

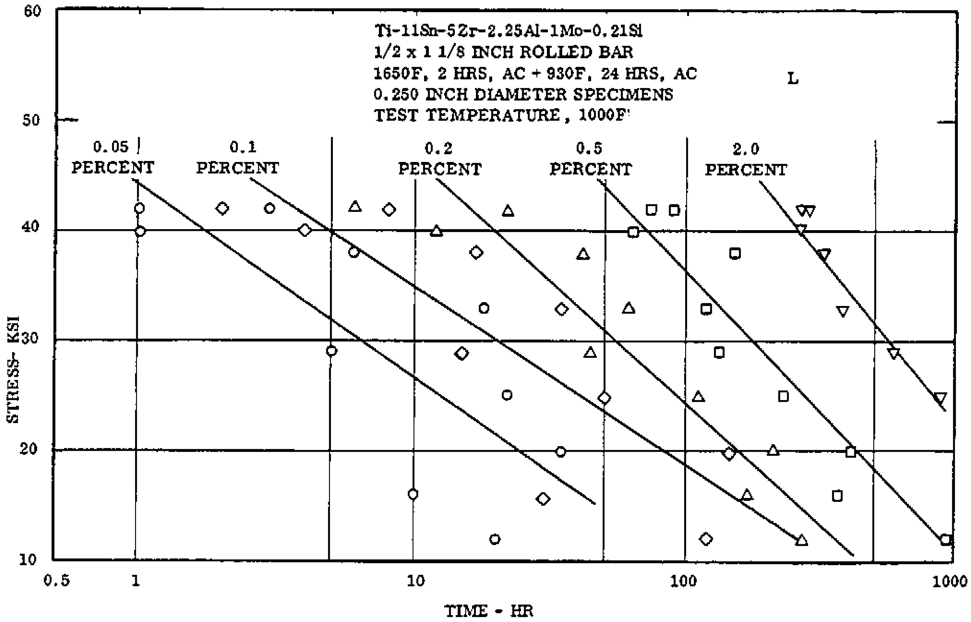


FIG. 3.043 CREEP DEFORMATION CURVES FOR BAR AT 1000F (7, p.308)

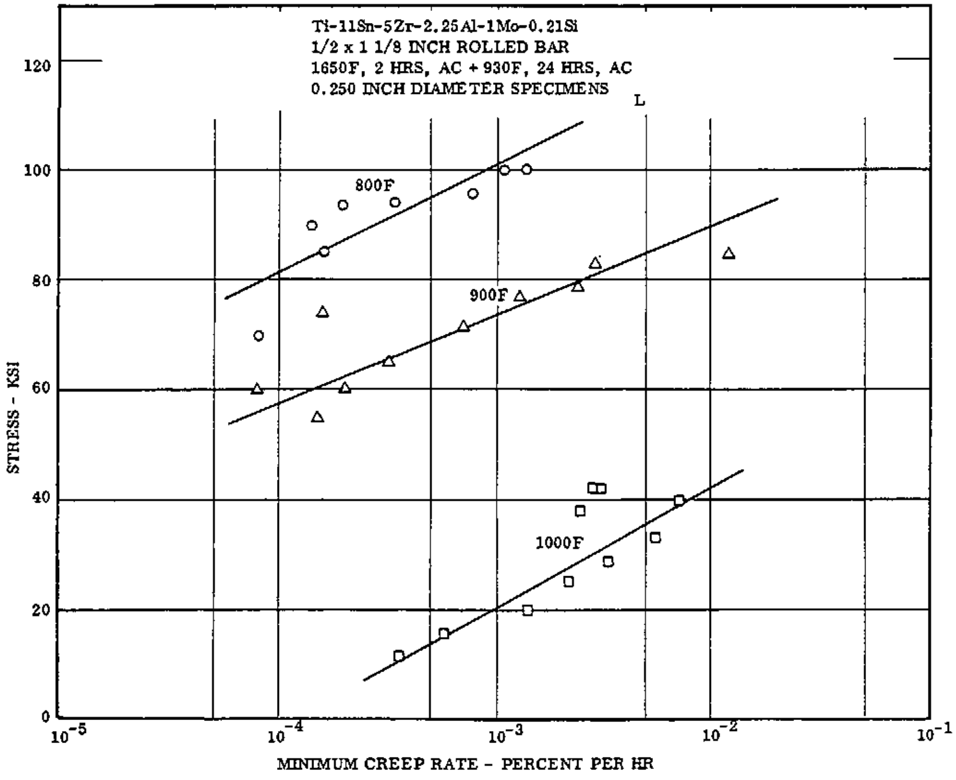


FIG. 3.044 MINIMUM CREEP RATE CURVES FOR BAR AT 800, 900, AND 1000F (7, p.308)

	Ti
11	Sn
5	Zr
2.5	Al
1	Mo
0.25	Si

Ti-679

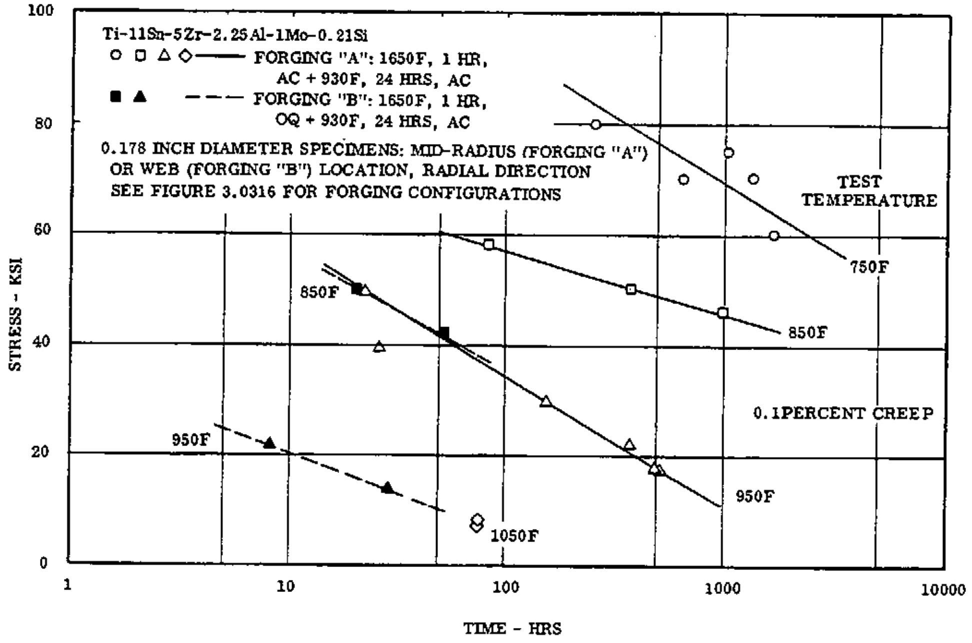


FIG. 3.045 0.1 PERCENT CREEP CURVES FOR FORGINGS (16)

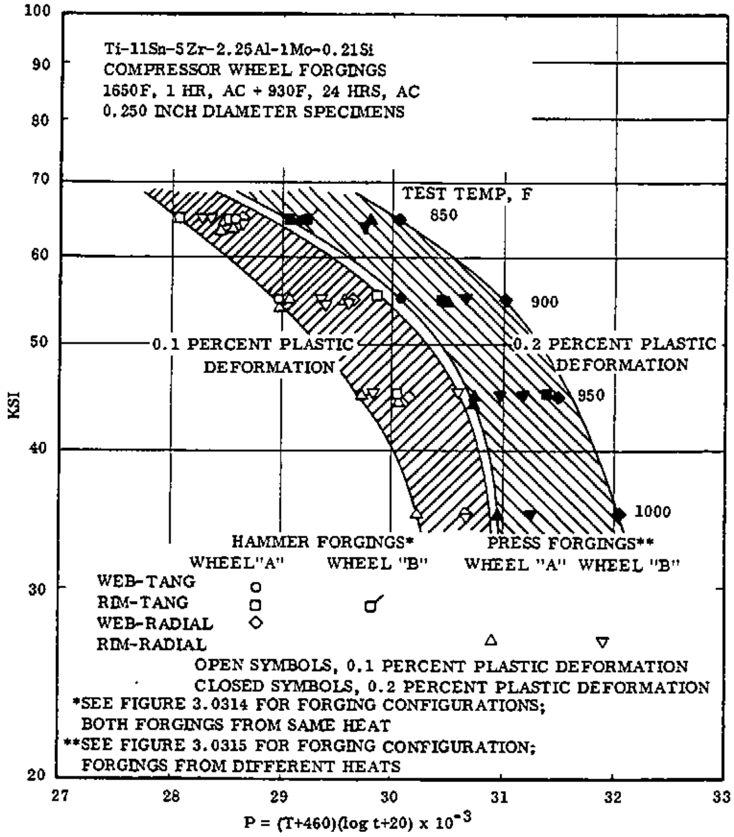


FIG. 3.048 MASTER CREEP CURVES FOR COMPRESSOR WHEEL FORGINGS (17, pp.13,16,19, and 22)

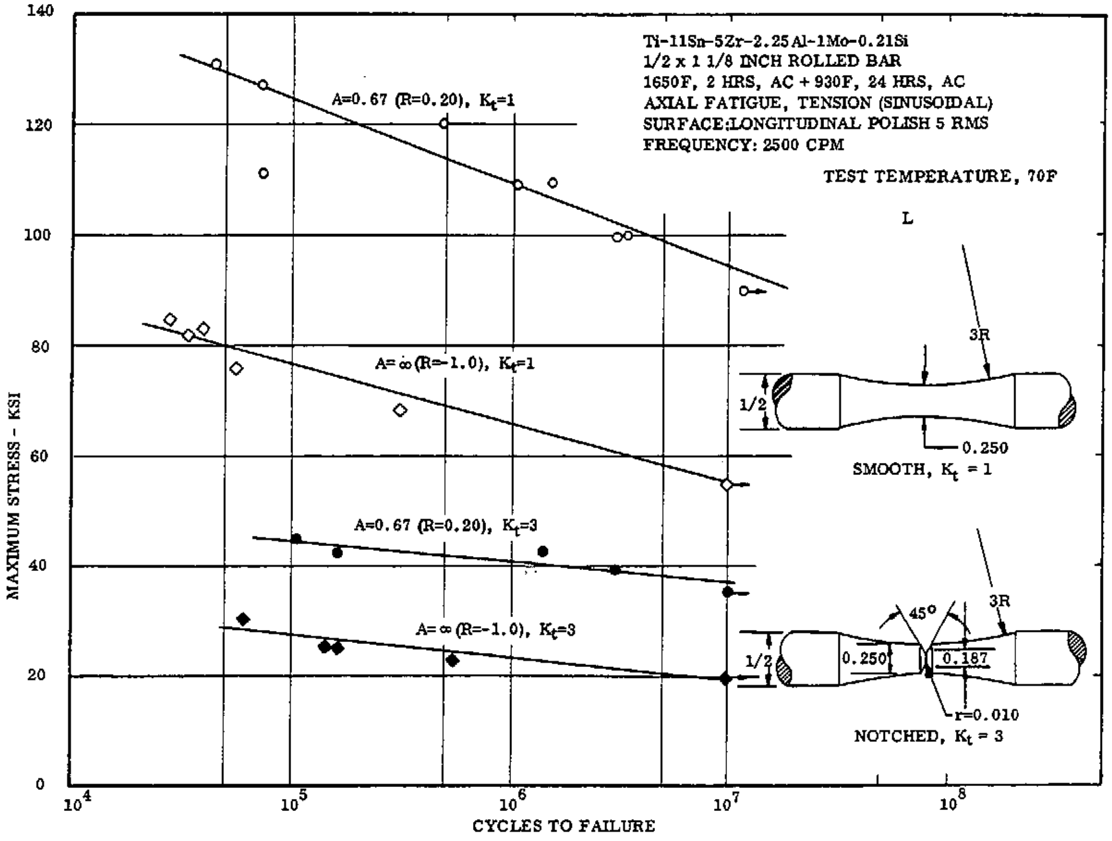


FIG. 3.051 AXIAL LOAD SMOOTH AND MILD-NOTCH FATIGUE PROPERTIES FOR BAR AT 70F (7, pp.312-313)

	Ti
11	Sn
5	Zr
2.5	Al
1	Mo
0.25	Si

Ti-679

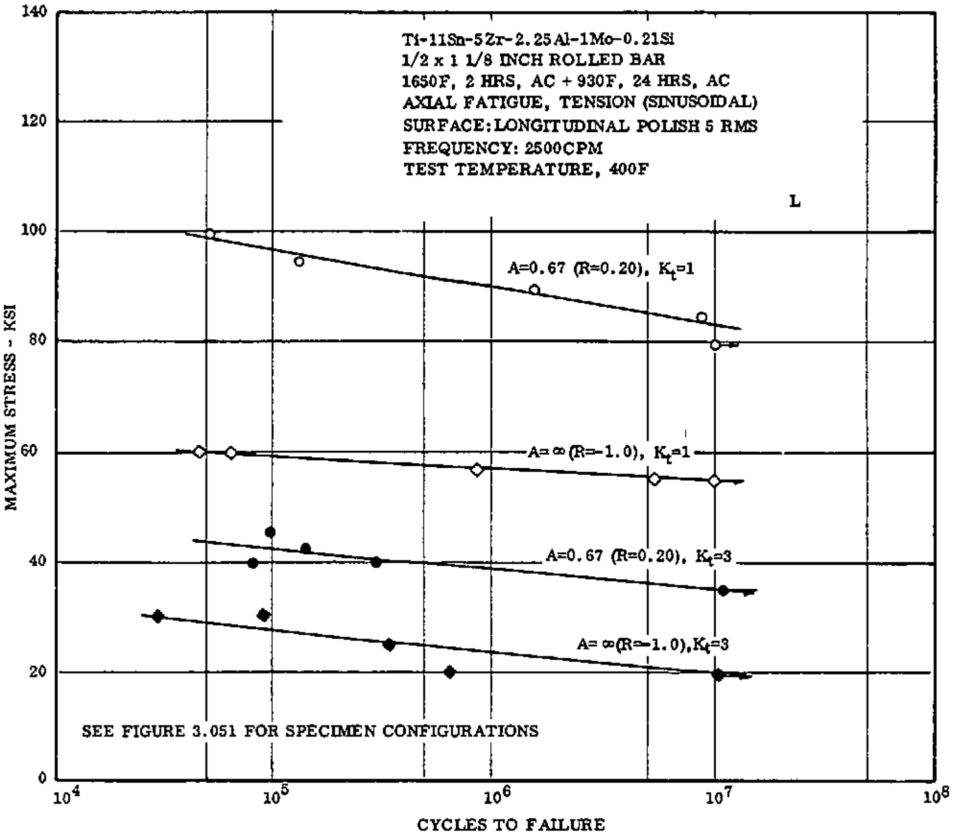


FIG. 3.052 AXIAL LOAD SMOOTH AND MILD-NOTCH FATIGUE PROPERTIES FOR BAR AT 400F(7, pp. 312-313)

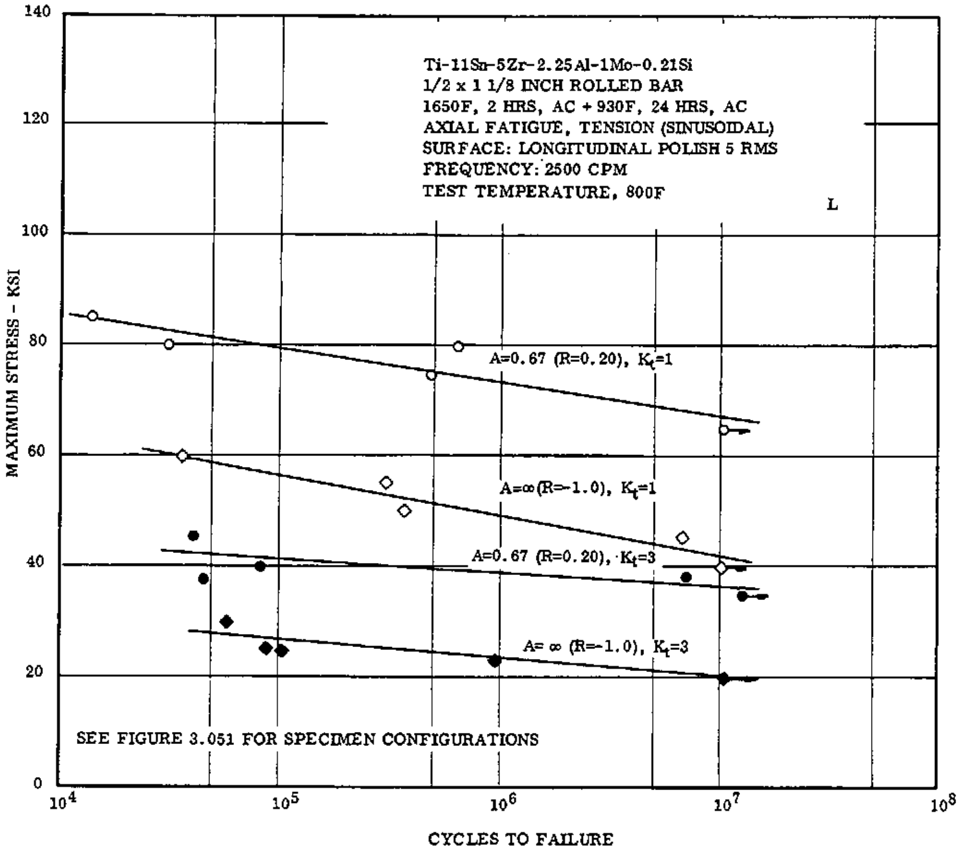


FIG. 3.053 AXIAL LOAD SMOOTH AND MILD-NOTCH FATIGUE PROPERTIES FOR BAR AT 800F (7, pp.312-313)

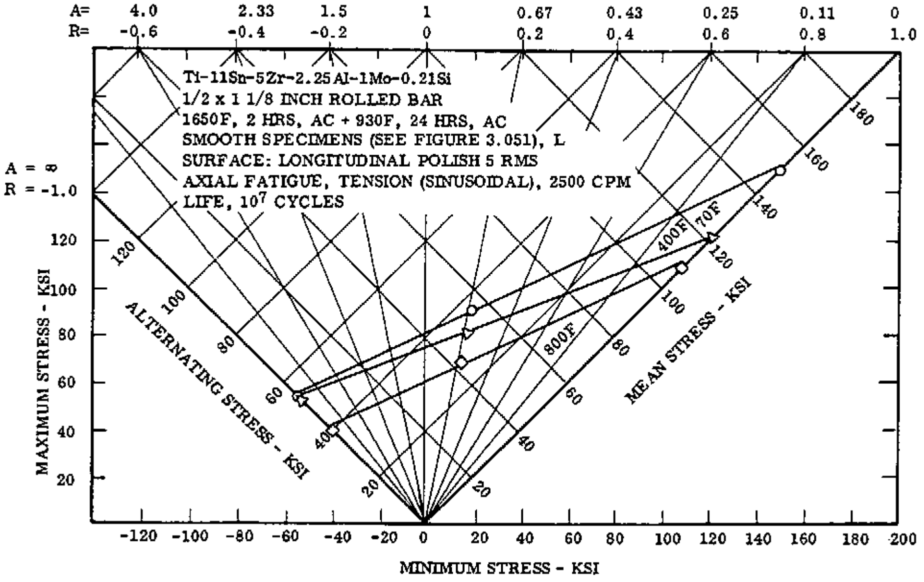
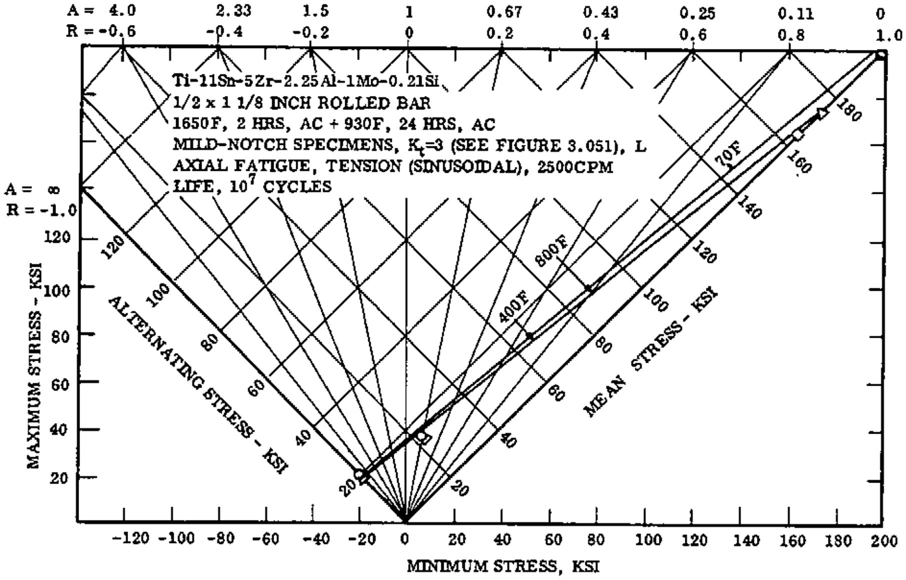
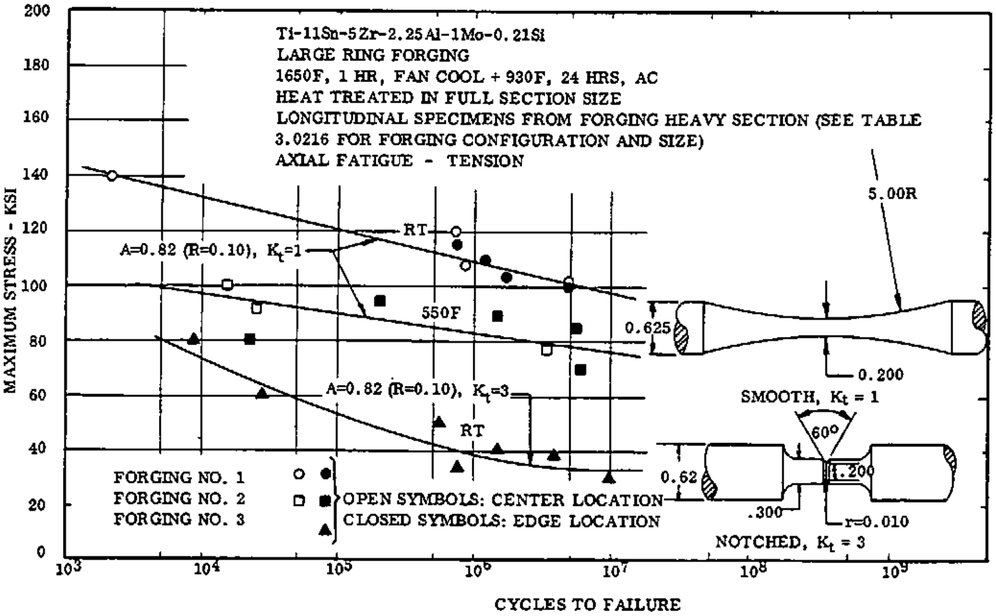


FIG. 3.054 CONSTANT-LIFE FATIGUE DIAGRAM FOR BAR AT SEVERAL TEMPERATURES (SMOOTH SPECIMENS) (7, pp. 192, 312)



Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si
1/2 x 1 1/8 INCH ROLLED BAR
1650F, 2 HRS, AC + 930F, 24 HRS, AC
MILD-NOTCH SPECIMENS, K_t=3 (SEE FIGURE 3.051), L
AXIAL FATIGUE, TENSION (SINUSOIDAL), 2500CPM
LIFE, 10^7 CYCLES

FIG. 3.055 CONSTANT-LIFE FATIGUE DIAGRAM FOR BAR AT SEVERAL TEMPERATURES (MILD-NOTCH SPECIMENS, K_t=3) (7, pp. 193, 313)



Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si
LARGE RING FORGING
1650F, 1 HR, FAN COOL + 930F, 24 HRS, AC
HEAT TREATED IN FULL SECTION SIZE
LONGITUDINAL SPECIMENS FROM FORGING HEAVY SECTION (SEE TABLE 3.0216 FOR FORGING CONFIGURATION AND SIZE)
AXIAL FATIGUE - TENSION

FIG. 3.056 AXIAL TENSION SMOOTH AND MILD-NOTCH FATIGUE PROPERTIES OF LARGE RING FORGING AT ROOM TEMPERATURE AND 550F. (9, pp.87-88)

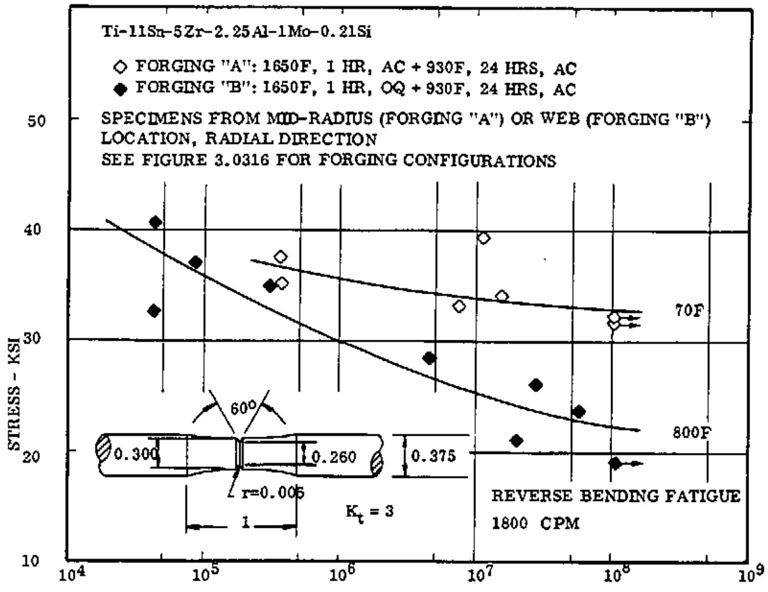


FIG. 3.057 MILD-NOTCH FATIGUE STRANGTH OF FORGINGS AT 70 AND 800F (16)

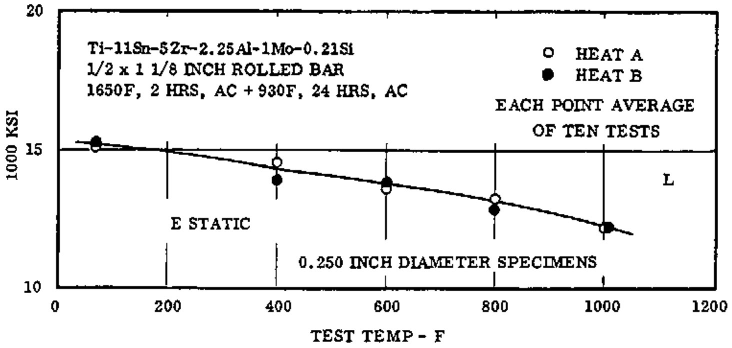


FIG. 3.061 STATIC TENSILE MODULUS OF ELASTICITY AT ROOM AND ELEVATED TEMPERATURES FOR BAR (7, pp. 293-296)

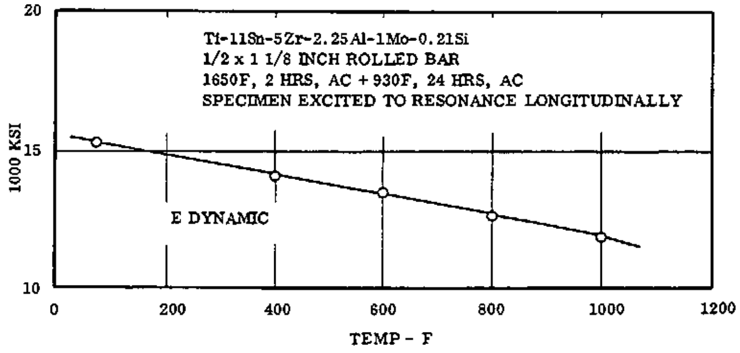


FIG. 3.062 DYNAMIC MODULUS OF ELASTICITY AT ROOM AND ELEVATED TEMPERATURES FOR BAR (7, p.196)

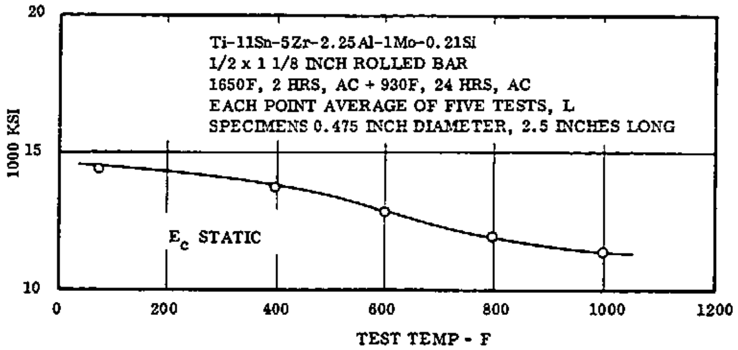


FIG. 3.063 STATIC COMPRESSIVE MODULUS OF ELASTICITY AT ROOM AND ELEVATED TEMPERATURES FOR BAR (7, p.299)

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