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AUTHOR: J. L. SHANNON

NONFERROUS ALLOYS

Ti	
6	Al
4	V

Ti-6Al-4V Cast

1. GENERAL
Titanium castings have been produced commercially since the early 1960's. Most have been of static structural components, but applications involving rotating parts such as impellers, radial flow compressor wheels, and stub shafts are presently being considered (9). Design shapes that have been produced for aerospace applications include some impellers, brackets, window frames, hubs and bearing housings (11).

For comparable heat-treated conditions, Ti-6Al-4V castings exhibit the same or somewhat lower strength, ductility, creep rupture and fatigue strengths, and elevated temperature stability than their wrought counterparts.

The feeding of this alloy is less than that of steel casting alloys and repair welding is frequently required. Most of the data presented were obtained from castings which contained sound repair welds. The data indicate that repair welding, if done properly, has no perceptible influence on mechanical properties. Results from castings with obviously defective repair welds have not been included since such castings would normally be withheld from service.

1.01 Commercial Designation
6Al-4V Titanium Alloy, Cast.

1.02 Alternate Designations
Ti-6Al-4V, Cast; OMC 165-A; OMC 164-B.

1.03 Specifications
Table 1.03.

TABLE 1.03

Alloy	Ti-6Al-4V, Cast
Form	Investment Castings
Condition	Specification
As-cast	AVCO Corporation, Lycoming Division, Specification M3407, November 30, 1966
As-cast or annealed 1300 to 1550F, 1 to 8 hours in inert atmosphere or vacuum, cool in inert atmosphere	Precision Castparts Corporation, Specification TD-TCD-1, April 29, 1968
Annealed 1525 to 1575F, 2 to 4 hours, air cool	LTV Aerospace Corporation, Vought Aeronautics Division, Specification 207-4-401
	Boeing Airplane Company Material Specification BMS 7-181*
	Lockheed Material, Specification C-03-1069*

* Copy of specification unavailable to author at time of writing.

1.04 Composition
1.041 Casting manufacturer's proposed specified composition, Table 1.041.

TABLE 1.041

Source	Precision Castparts Corporation (2)	
	Weight Percent	
	Minimum	Maximum
Aluminum	5.50	6.75
Vanadium	3.50	4.50
Iron	-	0.30
Carbon	-	0.10
Oxygen	-	0.20
Hydrogen	-	0.015
Nitrogen	-	0.07
Other Elements*	-	0.40
Titanium	Balance	

* Need not be reported.
(see 1.083 for preparation of metal for pouring)

1.042 User's specified composition, Table 1.042.

TABLE 1.042

Source	AVCO Corporation, Lycoming Division (1)	
	Weight Percent	
	Minimum	Maximum
Aluminum	5.50	6.75
Vanadium	3.50	4.50
Iron	-	0.30
Carbon	-	0.10
Oxygen	-	0.20
Hydrogen	-	0.0125
Nitrogen	-	0.05
Other Elements*	-	0.40
Titanium	Balance	

* Need not be reported.
(see 1.083 for preparation of metal for pouring)

1.05 Heat Treatment
(see also Ti-6Al-4V, Alloy Code 3707)

1.051 Anneal, 1300 to 1550F, 1 to 8 hours, AC.

1.052 Solution treat and age. Recommended solution treating and aging schedules have not yet been established. However, some developmental results are now available. Figure 3.0216 shows that solution temperatures high in the alpha-beta region result in increased strength but reduced ductility, and Figure 3.0217 shows that beta solution treating results in a reversion to low strength at aging temperatures of 1000 to 1100F with no improvement in ductility. Aging between 900 and 1100F provides only a modest range of achievable strength levels (Figures 3.0217 and 3.0218 and Table 3.0219). Quench delay time after solution treating in excess of 10 to 15 seconds produces lowered tensile properties with increased ductility (9)(6).

1.053 Salvage heat treatment. The strength of this alloy is markedly influenced by its oxygen content. As shown in Figure 3.03113, oxygen variations of as little as 0.01 weight percent can alter the strength by 1000 to 1500 psi. Master heats with oxygen levels below 0.13 weight percent often do not meet minimum strength requirements for the annealed condition. These heats require a salvage heat treatment of the type developed for forgings worked above the beta transus (9): 1750F, 1 hour, WQ + 1300F, 2 hours, AC.

1.0531 Effect of salvage heat treatment on the room temperature tensile properties of annealed, low oxygen cast-to-size specimens, Table 3.02110.

1.06 Hardness
Annealed condition, 311 BHN (3000 kg load) (3).

1.07 Forms and Conditions Available
Castings available in as-cast, annealed, and solution treated and aged conditions.

1.08 Melting and Casting Practice
1.081 Design parameters for precision castings for two casting manufacturers, Table 1.081

	Ti
6	Al
4	V

Ti-6Al-4V
Cast

TABLE 1.081

Alloy	Ti-6Al-4V, Cast	
Form	Precision Castings	
Source	Precision Castparts Corporation (6)	Howmet Corporation, Misco Division (10)
Linear Tolerances	Length ≤ 1 inch ± 0.010 inch per inch Length > 1 inch ± 0.015 inch per inch	± 0.005 inch per inch minimum
Section Thickness	0.060 inch minimum wall	0.115 inch ± 0.015 inch minimum wall
Fillet Radii	1 to 2 1/2 times the adjoining section thickness	0.030 inch ± 0.015 inch minimum
Corners and Edges	0.030 inch ± 0.030 inch	0.030 inch ± 0.015 inch minimum
Draft	Preferred, 2 degrees	Preferred, 3 degrees
Core Limits:		
Supported Both Ends		
Length	4 x diameter maximum	3 x diameter maximum
Diameter	0.100 inch minimum	0.250 inch minimum
Supported one End		
Length	3 x diameter maximum	2 x diameter maximum
Diameter	0.200 inch minimum	0.250 inch minimum
Surface Quality	125 RMS or better	90 to 125 RMS
Size of Casting	12 inch depth, 20 inch diameter present 42 inch x 50 inch x 7 inch length, future.	24 inch x 24 inch x 24 inch
Weight of Casting	150 pounds maximum	

1.082 Skull melting. Early attempts at melting and casting titanium using induction furnaces were unsuccessful because of molten titanium's reactivity with and contamination from the furnace crucible. Noncontaminated melts are now produced by consumable electrode "skull" melting in a water-cooled or NaK-cooled copper crucible. A skin of solid titanium, called a "skull", is formed which provides a nonreactive wall between the molten titanium and the copper crucible. Melting is done under an inert gas or vacuum to prevent contamination with the atmosphere. When done under vacuum, 100 microns maximum pressure is claimed to result in the best arc stability and, consequently, minimal losses in alloy content (9).

The basic operation of skull melting is identical to conventional consumable arc melting, except that arc power (current) requirements are about twice that of conventional arc melting (9). This is so that a large molten pool forms rapidly and that a minimum of alloy solidifies before the melt is poured (13). The size of the molten pool will depend on melt rate, crucible size, and electrode configuration. When a sufficient pool is formed, the power is cut, the electrode stub withdrawn, and the charge poured into the mold by tilting the copper crucible. The complete sequence takes only a matter of minutes, with the casting portion taking only seconds. The time from electrode withdrawal to completion of pour is very critical due to the narrow solidification range of most titanium alloys, particularly Ti-6Al-4V (9).

The temperature of the melt is a continuous gradient from the hottest region (near the arc) to the coldest (near the crucible wall). It is desirable to estimate the melt temperature before pouring so that the optimum pouring temperature be established whereby castings free of laps, cold shuts, seams and misruns will be consistently poured (13). Direct temperature measurement is not easily made. With arc furnaces, radiation from the arc makes precise temperature measurements using optical pyrometers impossible. At least one attempt to use a thermocouple measurement of melt temperature was unsuccessful, but for unknown reason (13). Presently the average melt temperature is computed from the total energy input, and the heat distribution derived from the volume and temperature of the crucible coolant (9). Heat input is closely controlled by current and voltage settings to provide consistency among melts.

1.083 Master heats. Castings are poured either from remelted master heat metal or directly from the master heat (1)(2). A master heat is metal of a single furnace charge multiple melted using consumable electrode practice, at least one of the melting cycles being performed under vacuum. Gates, sprues, risers and rejected castings may be used in the preparation of a master heat but may not be remelted directly, without refining, for pouring of castings (1)(2). Castings are poured without loss of protective vacuum or inert gas atmosphere between melting and pouring.

1.09 Special Considerations

1.091 Metal-mold reaction. In common with unalloyed titanium and other titanium alloys, Ti-6Al-4V may react with mold materials producing a contaminated surface layer which is dependent on time, temperature, and the presence of the contaminating interstitial elements carbon, oxygen, hydrogen, and nitrogen. The layer is sometimes called "alpha case" (usually oxygen stabilized) and is extremely brittle, being as much as 20 RC higher in hardness than the uncontaminated base metal (6). Two of the three largest casting manufacturers allow metal-mold reactions to take place and subsequently chemically mill to remove contamination. The third casting manufacturer has developed a proprietary process by which he claims surface contamination is avoided, eliminating the need for subsequent processing. In all instances, case-free, dimensionally-accurate castings are furnished.

1.092 Fluidity, feeding and superheating. There appears to be some misuse of terms in the titanium casting literature as regards the ability to produce a sound casting of intricate detail. If fluidity is defined as the distance molten metal will flow in a given mold cavity, then titanium may be said to possess good fluidity (6). Feeding, on the other hand, is a term used to define the distance that will be soundly filled; and in this category titanium falls a bit short. Superheating before pouring will improve feeding for most alloys. However, effective superheating in the consumable electrode melting process cannot be accomplished because as the input power is increased, the electrode consumption rate is increased, not the temperature of the molten pool. This, coupled with the narrow solidification range for Ti-6Al-4V is responsible for its poor feeding characteristics. Since the stream of metal flowing into the mold is very near its solidification point, progressive solidification starts immediately with little chance for proper thermal gradients to set up and produce directional solidification. This leads to centerline shrinkage and entrapped gas porosity.

The tendency for gas formation (from an incompletely fired expendable mold or decomposition of absorbed water on the mold) and the poor feeding characteristics require much heavier gating and risering for Ti-6Al-4V than for a comparable steel casting alloy (7)(9).

While many experimental details are unavailable at the time of this writing, a recent study has shown that porosity in smooth, axial-load fatigue specimens does not appreciably influence performance unless the porosity is near or at the surface of the specimens (11). The influence of porosity on other material properties or of other types of casting imperfections on any property has not been investigated. Indeed, more study is indicated, particularly on the effect of casting defects on toughness, before extensive use of titanium castings in structural applications can be made.

1.093 Stability. For certain applications (particularly in commercial aircraft), metallurgical stability is an important design consideration. While no systematic investigations have been made to establish the threshold combinations of stress-time-temperature below which the alloy is metallurgically stable, very limited data (Tables 3.02111 and 3.02112) suggest that caution be excercised in the use of this alloy if stability is a design requirement.

1.094 Stress corrosion. The results presented in section 2.031 are too limited to form general conclusions regarding the stress corrosion characteristics of this alloy. On the basis of the results obtained on other titanium alloys, however, particular attention should be given to the influence of aggressive 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.

1.095 Erosion. It has been reported that titanium erodes approximately 40 percent faster than steel in engine-blading applications in jet engines (15). No data on this relatively unfamiliar characteristic are available at the time of this writing.

1.096 Interstitials. (see Ti-6Al-4V, Alloy Code 3707).

2. PHYSICAL AND CHEMICAL PROPERTIES

2.01 <u>Thermal Properties</u>

2.011 Melting range, 2800 to 3000F.

2.012 Phase changes. Alloy transforms on cooling from beta to alpha + beta at approximately 1825F.

2.0121 Time-temperature-transformation diagrams.

2.013 Thermal conductivity. At 400F, 5.1 Btu ft per (hr sq ft F), (see also Ti-6Al-4V, Alloy Code 3707).

2.014 Thermal expansion. From 68 to 800F, 5.2×10^{-6} inch per inch per F (see also Ti-6Al-4V, Alloy Code 3707).

2.015 Specific heat. At 400F, 0.137 Btu per (lb F). (see also Ti-6Al-4V, Alloy Code 3707).

2.016 Thermal diffusivity.

2.02 <u>Other Physical Properties</u>

2.021 Density, 0.161 lb per cu in, 4.5 gr per cu cm.

2.022 Electrical properties (see Ti-6Al-4V, Alloy Code 3707).

2.023 Magnetic properties (see Ti-6Al-4V, Alloy Code 3707).

2.024 Emittance (see Ti-6Al-4V, Alloy Code 3707).

2.025 Damping capacity.

2.03 <u>Chemical Properties</u>
(see also Ti-6Al-4V, Alloy Code 3707)

2.031 Bend specimens 6.0 inch x 0.50 inch x 0.06 inch were extracted from the web location, longitudinal direction of two cast ring segments of the type shown in Table 3.0212 and were exposed 1000 hours each at 80 and 100 ksi nominal stress levels in both 5 percent NaCl salt spray at 95F and NaCl coat at 550F with no failures or apparent damage (5).

2.04 <u>Nuclear Properties</u>

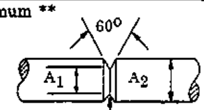
3. MECHANICAL PROPERTIES

3.01 <u>Specified Mechanical Properties</u>

3.011 Casting manufacturer's proposed specified mechanical properties, Table 3.011.

TABLE 3.011

Source	Precision Castparts Corporation (2)
Alloy	Ti-6Al-4V, Cast
Form	Investment Casting
Condition	As-Cast or Annealed 1300 to 1550F, 1 to 8 Hours in Inert Atmosphere or Vacuum, Cool in Inert Atmosphere
Conventional Room Temperature Tensile Properties*	
F_{tu} - ksi, minimum	130
F_{ty} - ksi, minimum	120
e(4D) - percent, minimum	5
RA - percent, minimum	10
Hardness, RC maximum	39
Room Temperature Notched Stress Rupture	
At 170 ksi, 5 hours minimum **	
Area A_1 = 1/2 Area A_2	r=0.005 ± 0.0005



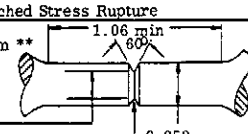
* Separately cast smooth specimens from each master heat, cast in manner representative of parts to be cast, or smooth specimens machined from randomly selected castings; specimens of standard proportions with 0.25 inch uniform diameter.

**Initial load may be less than 170 ksi and increased to 170 ksi in 10 ksi increments at intervals of not less than 5 hours.

3.012 User's specified mechanical properties, Table 3.012.

TABLE 3.012

Source	AVCO Corporation, Lycoming Division (1)
Alloy	Ti-6Al-4V, Cast
Form	Investment Casting
Condition	As-Cast
Conventional Room Temperature Tensile Properties*	
F_{tu} - ksi, minimum	130
F_{ty} - ksi, minimum	120
e(4D) - percent, minimum	6.0
RA - percent, minimum	12.0
Room Temperature Notched Stress Rupture	
At 170 ksi, 5 hours minimum **	



* Eight separately cast smooth specimens required from each master heat, cast in manner representative of parts to be cast: 0.252 inch to 0.253 inch diameter x 1.06 inch minimum gage length.
Smooth specimens machined from randomly selected castings: 0.155 inch to 0.157 inch diameter x 1.06 inch minimum gage length.

**Initial load may be less than 170 ksi and increased to 170 ksi in 10 ksi increments at intervals of not less than 5 hours.

3.02 <u>Mechanical Properties at Room Temperature</u>

3.021 Tension (see also 3.031).

3.0211 Typical mechanical properties for as-cast condition, Table 3.0211.

TABLE 3.0211

Source	DMIC (3)	
Alloy	Ti-6Al-4V, Cast	
Form	Castings	
Condition	As-Cast	
Quality	Nonaircraft	Aircraft*
F_{tu} - ksi	145	147
F_{ty} - ksi	130	130
e - percent	8	10
E - 10^3 ksi	17.0	17.0
Hardness, BHN (3000 Kg Load)	321	311
IE, Standard Charpy-V ft lbs	15	17

* Low oxygen

Ti
6 Al
4 V

Ti-6Al-4V
Cast

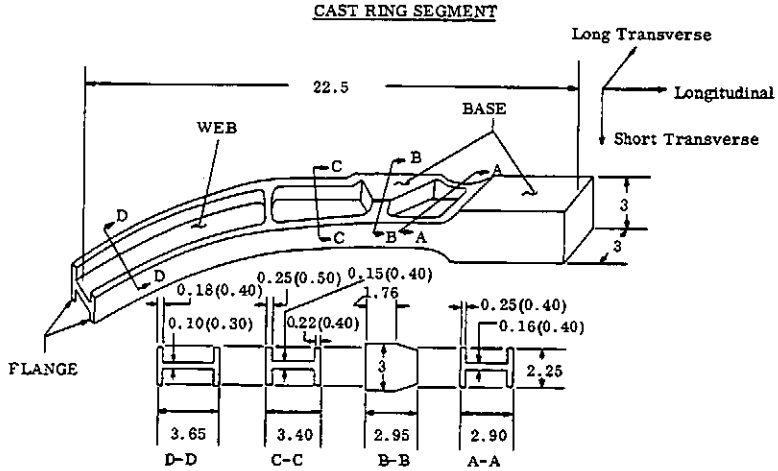
3.0212 Tensile properties including modulus of elasticity of annealed cast ring segments from two heats, Table 3.0212.

TABLE 3.0212

Source	LTV Aerospace Corporation, Vought Aeronautics Division (5)							
Alloy	Ti-6Al-4V, Cast							
Form	Cast Ring Segment							
Condition	Annealed 1550F, 2 to 4 Hours in Vacuum, AC (a)							
	Tensile Properties (b)							
	Heat A				Heat B			
	Spread of Values	Average	Number of Castings Tested	Total Number of Tests	Spread of Values	Average	Number of Castings Tested	Total Number of Tests
	BASE - Longitudinal, Long Transverse, and Short Transverse Directions (c)							
F_{tu} - ksi	126.7-139.0	134.0	3	23	124.0-137.5	132.7	2	15
F_{ty} - ksi	108.4-119.6	113.0	3	22(d)	102.1-114.9	110.2	2	15
E - 10^3 ksi	15.3- 18.2	16.7	3	24	14.9- 17.5	16.2	2	16
e(1 inch) percent	6.0- 9.0	7.3	3	23	4.0- 10.0	7.4	2	15
RA - percent	13.5- 29.6	20.6	2	7	15.8- 32.5	24.6	2	6
	FLANGE - Longitudinal Direction							
F_{tu} - ksi	136.7-146.2	142.1	3	10(e)	135.8-147.9	141.2	3	18
F_{ty} - ksi	111.9-129.3	121.1	3	11	111.6-128.7	119.3	3	18
E - 10^3 ksi	15.5- 17.6	16.6	3	13	14.9- 19.0	16.7	3	19
e(1 inch) percent	4.0- 11.0	6.9	3	10(e)	4.0- 14.0	7.8	3	17(f)
	WEB - Long Transverse Direction							
F_{tu} - ksi	136.7-149.6	142.2	3	9	140.1-150.5	142.7	3	11
F_{ty} - ksi	114.0-132.2	121.7	3	9	111.4-130.9	119.3	3	11
E - 10^3 ksi	15.6- 17.2	16.8	3	9	16.0- 17.7	16.7	3	11
e(1 inch) percent	4.0- 10.0	7.0	3	9	4.0- 11.0	7.5	3	11

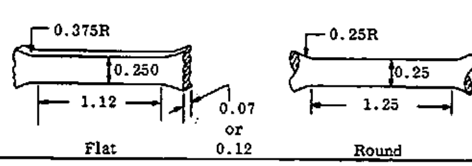
(a) Annealed in full section size.
(b) All values determined using flat specimens, except RA values, which were determined from separate round specimens.
(c) No directionality observed.
(d) Load-displacement curve incomplete for one test.
(e) One specimen failed outside test section.
(f) Not determined for one specimen.

CAST RING SEGMENT



Unbracketed flange and web dimensions are for cast-to-size ring segment; bracketed flange and web dimensions are for cast "oversize" ring segment. Results presented were obtained using specimens from ring segments of both sizes.

TEST SPECIMENS



Ti
6 Al
4 V

Ti-6Al-4V Cast

3.0213 Tensile properties of as-cast, annealed, and solution treated and aged castings from three casting manufacturers, Table 3.0213.

TABLE 3.0213

Source	Lockheed-Georgia Company (8)			
Alloy	Ti-6Al-4V, Cast			
Form	Precision Castings			
	Room Temperature Tensile Properties			
Condition	F_{tu} ksi	F_{ty} ksi	e(1 inch) percent	RA percent
Casting Manufacturer Number 1 (a)(b)				
As-Cast	139	127	6.1	15.2
Annealed (c)	134	126	6.6	21.6
Solution Treated + Age (d)	162	152	3.7	12.2
Casting Manufacturer Number 2 (e)(f)				
Solution Treat + Age (d)	156	136	3.0	3.1
Casting Manufacturer Number 3 (g)(h)				
Solution Treat + Age (d)	152	140	8.0	-

(a) 10 pound casting; section thicknesses from 0.2 inch to 2.0 inches; 0.125 inch diameter specimens selected randomly from both thickness extremes and at random orientations with respect to casting geometry.
(b) Each value average of four tests minimum.
(c) Annealed in full section size: 1300F, 2 hours, AC.
(d) Solution treated and aged in full section size: 1750F, 25 minutes, WQ + 1000F, 4 hours, AC.
(e) 1 pound casting; section thickness 0.43 inch; 0.25 inch diameter specimens, all located parallel to longitudinal axis of casting.
(f) Each value average of three tests.
(g) 1 pound casting; section thickness 0.4 inch in vicinity of specimen extraction; 0.25 inch diameter specimens, all located in common direction with respect to casting geometry.
(h) Each value average of four tests.

Each casting manufacturer used his own heat.

3.0214 Variation in tensile properties of five master heats for the as-cast and annealed conditions, Figure 3.0214.

3.0215 Typical tensile properties for a solution treated and annealed condition and two solution treated and aged conditions, Table 3.0215.

TABLE 3.0215

Source	Precision Castparts Corporation (6)		
Alloy	Ti-6Al-4V, Cast		
Form	Precision Castings		
Condition	Solution Treat+ Anneal	Solution Treat + Age	
	(a)	(b)	(c)
F_{tu} - ksi	146.5	168.6	155.0
F_{ty} - ksi	134.0	152.3	140.5
e(4D) - percent	7.5	4.0	6.3
RA - percent	11.9	8.0	12.7

(a) 1735F, 1 hour in Argon, 15 second quench delay, WQ + 1300F, 2 hours in Argon, AC.
(b) 1750F, 1 hour in Argon, 15 second quench delay, WQ + 1000F, 4 hours in Argon, AC.
(c) 1650F, 1 hour in Argon, 15 second quench delay, WQ + 1000F, 4 hours in Argon, AC.

3.0216 Effect of solution treat temperature on tensile properties of solution treated and aged cast-to-size specimens Figure 3.0217.

3.0217 Effect of solution treat and aging temperatures on tensile properties of cast compressor casing, Figure 3.0217.

3.0218 Effect of aging temperature on tensile properties of three compressor casings cast from one heat, Figure 3.0218.

3.0219 Effect of aging temperature on tensile properties of cast-to-size specimens, Table 3.0219.

TABLE 3.0219

Source		Precision Castparts Corporation (9)			
Alloy		Ti-6Al-4V, Cast			
Form		Cast-to-Size Specimens*			
Condition		1725F, 1 Hour in Argon, 15 Second Quench Delay, WQ + Age			
Aging		Room Temperature Tensile Properties**			
Temperature F	Time Hours	F_{tu} ksi	F_{ty} ksi	e(1 inch) percent	RA percent
950	2	178.9	163.3	3.0	5.1
1000	4	173.3	160.4	3.7	5.0
1100	4	170.0	158.2	4.4	6.1

* Cast to 5/8 inch diameter blanks and machined to 0.252 inch diameter specimens.
** Each value average of two tests.

3.02110 Effect of salvage heat treatment on tensile properties of annealed, low-oxygen cast-to-size specimens, Table 3.02110.

TABLE 3.02110

Source	Precision Castparts Corporation (9)			
Alloy	Ti-6Al-4V, Cast			
Form	Cast-to-Size Specimens			
		Room Temperature Tensile Properties (a)		
Oxygen Content Weight Percent	Heat Treatment	F_{tu} ksi	F_{ty} ksi	e(1 inch) percent
0.113 / 0.116	Anneal (b)	131.0	118.4	11.5
	Salvage (c)	143.9	131.6	8.3
0.118 / 0.124	Anneal (b)	132.3	119.4	10.7
	Salvage (c)	148.4	136.9	8.1

(a) Each value average of eight tests on six master heats.
(b) 1300F, 2 hours, AC.
(c) 1750F, 1 hour, WQ + 1300F, 2 hours, AC.

3.02111 Effect of exposure to elevated temperatures with load on tensile properties of annealed cast compressor casing, Table 3.02111.

TABLE 3.02111

Source			AVCO Corporation, Lycoming Division (4)			
Alloy			Ti-6Al-4V, Cast			
Form			Cast Compressor Casing (a)			
Condition			Annealed 1300F, 2 Hours, AC (b)			
Specimen Exposure Conditions			Subsequent Room Temperature Tensile Properties (c)(d)			
Temp F	Stress ksi	Time Hours	F_{tu} ksi	F_{ty} ksi	e(1 inch) percent	RA percent
Unexposed		Average	143.9	131.0	9.4	15.5
		Spread	161.5/139.5	143.1/126.5	12.0/4.0	20.3/7.9
700	90	529.3	148.6	146.5	3.0	5.4
700	85	528.9	152.8	148.2	4.0	7.2
700	85	1510.0	155.1	154.7	2.0	8.2
700	80	1603.3	152.8	147.4	7.0	12.6
900	45	500.0	153.1	150.2	6.0	8.9

(a) See Figure 3.0311 for compressor casing (20 inches long) and specimen details.
(b) Casing annealed in full section size.
(c) Specimens tested as exposed; surface not dressed.
(d) Unexposed values from fifteen tests; exposed values from individual tests.

Ti
6 Al
4 V

Ti-6Al-4V
Cast

3.02112 Effect of 1000 hours exposure at 550F without load on tensile properties including elastic modulus of annealed cast ring segment from two heats, Table 3.02112.

TABLE 3.02112

Source	LTV Aerospace Corporation, Vought Aeronautics Division (5)					
Alloy	Ti-6Al-4V, Cast					
Form	Cast Ring Segment (a)					
Condition	Annealed 1550F, 2 to 4 Hours in Vacuum, AC (b)					
			Room Temperature Tensile Properties			
Casting	Specimen (c) Orientation	Exposure Condition	F_{tu} ksi	F_{ty} ksi	E 10^3ksi	e(1 inch) percent
BASE (a) - Heat A						
1	Long Trans	Unexposed	134.6	111.9	15.4	8.0
1	Long Trans	Unexposed	135.4	110.0	16.5	9.0
1	Long Trans	Exposed (d)	134.5	123.0	17.1	3.0
2	Short Trans	Unexposed	126.7	110.7	16.6	8.0
2	Short Trans	Unexposed	138.4	(e)	(e)	9.0
2	Short Trans	Exposed (d)	140.7	125.1	16.8	7.0
BASE (a) - Heat B						
1	Long Trans	Unexposed	135.9	112.6	16.0	9.0
1	Long Trans	Unexposed	131.6	108.5	17.5	6.0
1	Long Trans	Exposed (d)	147.4	124.8	16.8	8.0
2	Short Trans	Unexposed	129.9	103.7	14.9	10.0
2	Short Trans	Unexposed	136.7	112.0	15.2	7.0
2	Short Trans	Unexposed	137.5	114.8	16.0	4.0
2	Short Trans	Exposed (d)	144.3	124.4	16.5	9.0
FLANGE (a) - Heat A						
1	Longitudinal	Unexposed	140.9	116.2	17.0	5.0
1	Longitudinal	Unexposed	140.8	115.8	16.3	7.0
1	Longitudinal	Unexposed	139.8	113.8	16.4	6.0
1	Longitudinal	Unexposed	136.7	111.9	16.2	6.0
1	Longitudinal	Unexposed	-	-	17.5	-
1	Longitudinal	Unexposed	142.6	121.0	16.6	6.0
1	Longitudinal	Exposed (d)	146.1	133.0	17.1	5.0
2	Longitudinal	Unexposed	143.3	120.7	17.3	9.0
2	Longitudinal	Unexposed	-	-	16.3	-
2	Longitudinal	Unexposed	146.2	129.3	16.5	11.0
2	Longitudinal	Exposed (d)	149.7	131.4	17.5	4.0
FLANGE (a) - Heat B						
1	Longitudinal	Unexposed	139.5	115.8	16.7	6.0
1	Longitudinal	Unexposed	138.9	113.7	16.8	7.0
1	Longitudinal	Unexposed	143.6	117.8	16.8	10.0
1	Longitudinal	Unexposed	137.1	111.6	15.2	7.0
1	Longitudinal	Unexposed	144.3	118.1	16.4	6.0
1	Longitudinal	Unexposed	140.5	117.8	16.3	10.0
1	Longitudinal	Unexposed	-	-	17.7	-
1	Longitudinal	Unexposed	143.3	123.5	19.0	8.0
1	Longitudinal	Unexposed	142.1	124.2	16.4	6.0
1	Longitudinal	Unexposed	138.5	112.8	17.7	8.0
1	Longitudinal	Unexposed	142.5	128.7	14.9	4.0
1	Longitudinal	Exposed (d)	148.3	130.1	17.0	9.0
2	Longitudinal	Unexposed	140.2	116.5	17.2	10.0
2	Longitudinal	Unexposed	143.7	122.3	16.0	12.0
2	Longitudinal	Unexposed	139.2	119.9	16.7	14.0
2	Longitudinal	Unexposed	135.8	117.7	16.4	7.0
2	Longitudinal	Unexposed	142.1	126.7	16.9	(f)
2	Longitudinal	Exposed (d)	148.3	130.1	17.6	6.0

(a) See Table 3.0212 for ring segment details.
(b) Annealed in full section size.
(c) See Table 3.0212 for specimen configuration (flat type) and orientation.
(d) Exposed 550F, 1000 hours.
(e) Incomplete load-displacement curve.
(f) Bad reading.

3.02113 Effect of oxygen content on tensile properties of annealed cast-to-size specimens, Figure 3.02113.

3.02114. Typical room temperature stress-strain curves for annealed cast ring segments from two heats, Figure 3.02114.

3.022 Compression.

3.0221 Compressive yield strength and modulus of elasticity of cast ring segments from two heats, Table 3.0221.

TABLE 3.0221

Source		LTV Aerospace Corporation, Vought Aeronautics Division (5)			
Alloy		Ti-6Al-4V, Cast			
Form		Cast Ring Segment (a)			
Condition		Annealed 1550F, 2 to 4 Hours in Vacuum, AC (b)			
		Specimen (c)		Room Temperature Compressive Properties	
Heat	Casting	Location(a)	Orientation (a)	F_{cy} ksi	E_c 10^3 ksi
A	1	Base	Longitudinal	124.9	21.6
A	1	Base	Long Trans	123.5	20.5
A	2	Base	Short Trans	121.9	15.8
A	2	Base	Short Trans	129.5	17.5
B	1	Base	Longitudinal	130.6	17.5
B	1	Base	Long Trans	125.6	16.9
B	2	Base	Short Trans	123.1	17.5
A	2	Flange	Longitudinal	145.4	15.4
B	2	Flange	Longitudinal	145.4	17.4
A	3	Web	Longitudinal	151.4	16.9
A	3	Web	Longitudinal	154.1	16.5
B	1	Web	Longitudinal	140.4	16.5
B	1	Web	Longitudinal	132.4	17.1
B	2	Web	Long Trans	140.1	18.3
B	3	Web	Long Trans	136.4	16.4

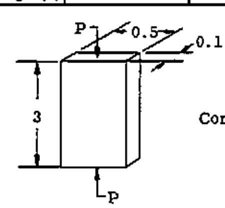
(a) See Table 3.0212 for ring segment and specimen orientation details.
(b) Annealed in full section size.
(c) Specimen 2.70 inches long, 0.65 inch wide and 0.10 inch thick.

For comparative tensile properties, see Table 3.0212

3.0222 Compressive yield strength and modulus of elasticity of as-cast, annealed and solution treated and aged castings from two separate casting manufacturers, Table 3.0222.

TABLE 3.0222

Source	Lockheed-Georgia Company (8)		
Alloy	Ti-6Al-4V, Cast		
Form	Precision Castings		
Condition	Room Temperature Properties		
	F_{ty} - ksi (a)	F_{cy} - ksi (b)	E_c - 10^3 ksi (b)
Casting Manufacturer Number 1 (c)			
As-Cast	127	137	16.7
Anneal (d)	126	143	17.0
Solution Treat+Age (e)	152	179	17.2
Casting Manufacturer Number 2 (f)			
Solution Treat+Age (e)	136	145	-



Compression Specimen

(a) Each value average of three tests minimum.
(b) Each value average of two tests minimum.
(c) 10 pound casting; section thicknesses from 0.2 inch to 2.0 inches; specimens selected randomly from both thickness extremes and at random orientations with respect to casting geometry.
(d) Annealed in full section size: 1300F, 2 hours, AC.
(e) Solution treated and aged in full section size: 1750F, 25 minutes, WQ + 1000F, 4 hours, AC.
(f) 1 pound casting; section thickness 0.43 inch; all specimens located parallel to longitudinal axis of casting.

Castings furnished by manufacturer Number 1 were from different heat than castings furnished by manufacturer Number 2.

3.023 Impact (see also Table 3.0211).

3.0231 Standard Charpy-V impact energy of annealed cast-to-size specimens from two heats, Table 3.0231.

TABLE 3.0231

Source		AVCO Corporation, Lycoming Division (4)
Alloy		Ti-6Al-4V, Cast
Form		Cast-to-Size Specimens
Condition		Annealed 1300F, 2 Hours, AC*
Heat	Specimen Number	IE, Standard Charpy-V ft lbs
A	1	19.5
A	2	20.0
A	3	20.0
A	4	21.0
A	5	20.0
B	1	21.0
B	2	19.0
B	3	20.0
B	4	21.0
B	5	20.0

*Conventional tensile properties:
Heat A: F_{tu} = 144.8 ksi, F_{ty} = 127.3 ksi, e(1 inch) = 11.7 percent, RA = 25.8 percent
Heat B: F_{tu} = 145.1 ksi, F_{ty} = 132.7 ksi, e(1 inch)= 10.5 percent, RA = 21.6 percent

3.0232 Standard Charpy-V impact energy of annealed cast ring segments from two heats, Table 3.0232.

TABLE 3.0232

Source				LTV Aerospace Corporation, Vought Aeronautics Division (5)	
Alloy				Ti-6Al-4V, Cast	
Form				Cast Ring Segment (a)	
Condition				Annealed 1550F, 2 to 4 Hours in Vacuum, AC (b)	
				Room Temperature Properties	
Heat	Casting	Specimen Location(a)	Specimen Orientation(a)	F_{ty} ksi	IE, Std Charpy-V ft lbs
A	1	Base	Long Trans	111.9	19.0
A	1	Base	Long Trans	110.0	16.0
A	1	Base	Short Trans	114.9	15.0
A	1	Base	Short Trans	110.9	15.0
A	2	Base	Longitudinal	110.2	18.0
A	2	Base	Longitudinal	111.8	-
A	2	Base	Long Trans	111.1	16.0
A	2	Base	Short Trans	110.7	18.0
B	1	Base	Short Trans	114.3	15.0
B	1	Base	Short Trans	102.1	15.0
B	2	Base	Longitudinal	104.8	21.0
B	2	Base	Longitudinal	108.5	-
B	2	Base	Long Trans	110.4	18.0
B	2	Base	Long Trans	110.9	19.0
B	2	Base	Long Trans	114.9	17.0
B	2	Base	Short Trans	103.7	14.0
B	2	Base	Short Trans	112.0	-
B	2	Base	Short Trans	114.8	-
A	1	Flange	Longitudinal	111.9-121.0(c)	14.0
B	1	Flange	Longitudinal	111.6-128.7(d)	14.0

(a) See Table 3.0212 for ring segment and specimen orientation details.
(b) Annealed in full section size.
(c) Range of values from five tests.
(d) Range of values from ten tests.

3.0233 Standard Charpy-V impact energy of solution treated and aged casting, Table 3.0233.

TABLE 3.0233

Source	Lockheed-Georgia Company (8)
Alloy	Ti-6Al-4V, Cast
Form	Precision Casting (a)
Condition	Solution Treat + Age (b)
IE, Standard Charpy-V (ft lbs)	8.46 (c)

(a) 1 pound casting; section thickness 0.43 inch.
(b) Solution treated and aged in full section size: 1750F, 25 minutes, WQ + 1000F, 4 hours, AC.
(c) Single value from specimen oriented parallel to longitudinal axis of casting.

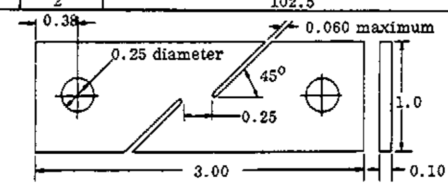
3.024 Bending.

3.025 Torsion and shear.

3.0251 Shear strength of annealed cast ring segments from two heats, Table 3.0251.

TABLE 3.0251

Source		LTV Aerospace Corporation, Vought Aeronautics Division (5)
Alloy		Ti-6Al-4V, Cast
Form		Cast Ring Segment (a)
Condition		Annealed 1550F, 2 to 4 Hours in Vacuum, AC (b)
Heat	Casting	F_{su} (c)(d) - ksi
A	1	93.9
A	2	95.3
A	3	95.3
B	1	94.4
B	2	102.5



(a) See Table 3.0212 for ring segment details.
(b) Annealed in full section size.
(c) Flange location, longitudinal direction (see Table 3.02141).
(d) Values average of from two to seven tests for each casting.
See Table 3.0212 for corresponding conventional tensile properties.

3.0252 Double shear strength of solution treated and aged casting, Table 3.0252.

TABLE 3.0252

Source	Lockheed-Georgia Company (8)
Alloy	Ti-6Al-4V, Cast
Form	Precision Casting (a)
Condition	Solution Treat + Age (b)
F_{su} - ksi	94.7(c)

(a) 1-pound casting; section thickness 0.43 inch; 0.375 inch diameter double-shear specimens oriented parallel to longitudinal axis of casting.
(b) Solution treated and aged in full section size: 1750F, 25 minutes, WQ + 1000F, 4 hours, AC.
(c) Average of two tests.

Ti
6 Al
4 V

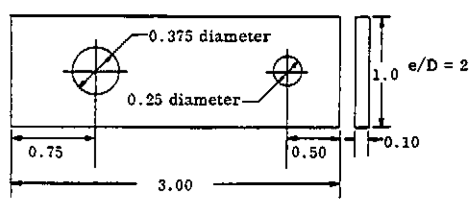
Ti-6Al-4V
Cast

3.026 Bearing.

3.0261 Bearing strength of annealed cast ring segments from two heats, Table 3.0261.

TABLE 3.0261

Source	LTV Aerospace Corporation, Vought Aeronautics Division (5)		
Alloy	Ti-6Al-4V, Cast		
Form	Cast Ring Segment (a)		
Condition	Annealed 1550F, 2 to 4 Hours in Vacuum, AC (b)		
Heat	Casting	F_{bru}(c)(d) - ksi	F_{bry}(c)(d) - ksi
A	1	283.0	224.6
A	2	279.4	227.7
A	3	253.3	209.1
B	1	279.6	214.9
B	2	300.1	245.4



(a) See Table 3.0212 for ring segment details.
(b) Annealed in full section size.
(c) Flange location, longitudinal direction (see Table 3.0212).
(d) All values are averages of from two to six tests for each casting except that for casting 2, Heat B, which is a single datum point.

See Table 3.0212 for corresponding conventional tensile properties.

3.0262 Bearing strength of solution treated and aged casting, Table 3.0262.

TABLE 3.0262

Source	Lockheed-Georgia Company (8)	
Alloy	Ti-6Al-4V, Cast	
Form	Precision Casting (a)	
Condition	Solution Treat + Age (b)	
Room Temperature Bearing Properties (c)		
F_{bru} - ksi	F_{bry} - ksi	e/D
216	(d)	1.50
240	234	1.52
244	224	1.50

(a) 1 pound casting; section thickness 0.43 inch; specimens oriented parallel to longitudinal axis of casting.
(b) Solution treated and aged in full section size: 1750F, 25 minutes, WQ + 1000F, 4 hours, AC.
(c) Specimen thickness = 0.090 inch; D = 0.187 inch.
(d) Bearing failure occurred before 0.2 percent strain was achieved.

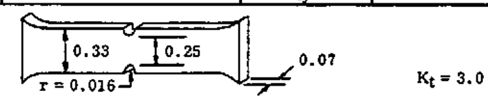
3.027 Stress concentration.

3.0271 Notch properties.

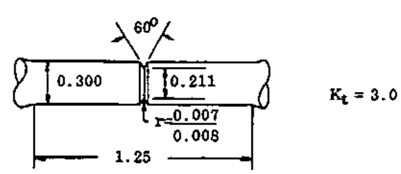
3.02711 Mild-notch strength of annealed cast ring segments from two heats, Table 3.02711.

TABLE 3.02711

Source	LTV Aerospace Corporation, Vought Aeronautics Division (5)		
Alloy	Ti-6Al-4V, Cast		
Form	Cast Ring Segment (a)		
Condition	Annealed 1550F, 2 to 4 Hours in Vacuum, AC (b)		
		Room Temperature Properties	
Casting	Specimen Orientation (c)	F_{ty} - ksi	NTS - ksi



Casting	Specimen Orientation (c)	F_{ty} - ksi	NTS - ksi
BASE (a) - Heat A			
1	Long Transverse	110.0	166.1
1	Long Transverse	111.9	-
2	Longitudinal	110.2	172.4
2	Longitudinal	111.8	-
2	Short Transverse	110.7	146.0
BASE (a) - Heat B			
1	Long Transverse	112.6	152.2
1	Long Transverse	108.5	-
2	Longitudinal	104.8	159.5
2	Longitudinal	108.5	-
2	Short Transverse	103.7	155.9
2	Short Transverse	112.0	-
2	Short Transverse	114.8	-
FLANGE (a) - Heat A			
2	Longitudinal	120.7	167.9
2	Longitudinal	129.3	-
FLANGE (a) - Heat B			
2	Longitudinal	116.5	165.2
2	Longitudinal	122.3	-
2	Longitudinal	119.9	-
2	Longitudinal	117.7	-
2	Longitudinal	126.7	
WEB (a) - Heat B			
1	Longitudinal	113.6	160.3
1	Longitudinal	118.4	-
1	Longitudinal	111.4	-
2	Long Transverse	120.2	168.4
2	Long Transverse	126.7	-
2	Long Transverse	123.1	-
2	Long Transverse	123.0	-



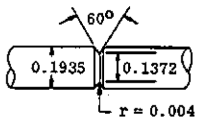
Casting	Specimen Orientation (c)	F_{ty} - ksi	NTS - ksi
BASE (a) - Heat A			
2	Longitudinal	122.5	157.3
2	Longitudinal	123.5	-
BASE (a) - Heat B			
2	Longitudinal	118.6	154.2
2	Longitudinal	125.2	-

(a) See Table 3.0212 for ring segment details.
(b) Annealed in full section size.
(c) See Table 3.0212 for specimen orientations relative to casting configuration.

3.02712 Mild-notch strength of as-cast, annealed, and solution treated and aged castings, Table 3.02712.

TABLE 3.02712

Source	Lockheed-Georgia Company (8)	
Alloy	Ti-6Al-4V, Cast	
Form	Precision Casting (a)	
	Room Temperature Properties	
Condition	F_{ty} - ksi (b)	NTS - ksi (c)
As-Cast	127	202
Anneal (d)	126	207
Solution Treat + Age (e)	152	216



$K_t = 3.9$

(a) 10 pound casting; section thicknesses from 0.2 inch to 2.0 inches, specimens selected randomly from both thickness extremes and at random orientations with respect to casting geometry.
(b) Each value average of four tests minimum.
(c) Each value average of three tests.
(d) Annealed in full section size: 1300F, 2 hours, AC.
(e) Solution treated and aged in full section size: 1750F, 25 minutes, WQ + 1000F, 4 hours, AC.

3.0272 Fracture toughness. No data are available on the plane strain fracture toughness of this alloy in the cast condition. For applications where the alloy's fracture toughness may be the limiting design consideration, these data should be developed. Inasmuch as the ductility of this alloy in the cast form is less than that for its wrought counterpart, to say nothing of the basic difference in structure for the two forms, existing toughness data for the wrought form should not be applied to cast material.

3.028 Combined properties.

3.03 <u>Mechanical Properties at Various Temperatures</u>

3.031 Tension.

3.0311 Effect of test temperature on tensile properties of five annealed cast compressor casings from three heats, Figure 3.0311.

3.0312 Effect of test temperature on tensile properties of specimens machined from annealed cast compressor casings and annealed cast-to-size specimens each from two heats, Figure 3.0312.

3.0313 Effect of test temperature on tensile properties of annealed cast ring segments from two heats, Figure 3.0313.

3.0314 Stress-strain diagrams (see 3.02111).

3.032 Compression (see 3.022).

3.0321 Stress-strain diagrams.

3.033 Impact (see 3.023).

3.034 Bending.

3.035 Torsion and shear (see 3.025).

3.036 Bearing (see 3.026).

3.037 Stress concentration.

3.0371 Notch properties (see 3.0271).

3.0372 Fracture toughness (see 3.0272).

3.038 Combined properties.

3.04 <u>Creep and Creep Rupture Properties</u>

3.041 Stress rupture curves at 700, 800, and 900F for specimens machined from five annealed cast compressor casings from three heats, Figure 3.041.

3.042 Creep rupture curves at 700, 800, 900, and 1000F for specimens machined from annealed cast compressor casing and annealed cast-to-size specimens from one heat, Figure 3.042.

3.043 Stress rupture curves at 700, 800, and 900F for specimens machined from cast compressor casing aged at 1000F, Figure 3.043.

3.044 Effect of solution treat and aging temperatures on 800F, 80 ksi stress rupture life of cast compressor casing, Table 3.044.

TABLE 3.044

Source	AVCO Corporation, Lycoming Division (4)	
Alloy	Ti-6Al-4V, Cast	
Form	Cast Compressor Casing (a)	
Condition	Solution Treated and Aged (b)	
	Stress Rupture Properties at 800F, 80 ksi	
Age Temperature, 8 hours, AC F	Time to Rupture hours	e(1 inch) percent
Solution Treat 1750F, 1 hour, WQ		
900	500.2	-
900	510.7	-
900	512.8	-
1000	502.1 (c)	-
1000	501.2 (c)	-
1000	504.3 (c)	-
1000	757.3	14.6
1100	502.1 (c)	-
1100	503.2 (c)	-
Solution Treat 1850F, 1 hour, WQ		
900	549.6 (c)	-
900	548.4 (c)	-
900	546.6 (c)	-
1000	540.5 (c)	-
1000	526.8 (c)	-
1000	521.7 (c)	-
1100	506.6 (c)	-
1100	504.5 (c)	-
1100	504.2 (c)	-

(a) See Figure 3.0311 for compressor casing (12 inches long) and specimen details.
(b) Casing halved and solution treated; aging applied to 1/2 inch square specimen blanks. See Figure 3.0217 for room temperature tensile properties of material tested.
(c) Test retired.

Ti
6 Al
4 V

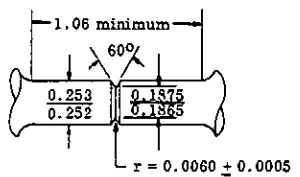
Ti-6Al-4V
Cast

3.045 Room temperature stress rupture results for mild-notch specimens machined from annealed cast compressor casing and annealed cast-to-size specimens, Table 3.045.

3.046 500F stress rupture properties of cast-to-size smooth and mild-notch specimens from two heats, Table 3.046.

TABLE 3.045

Source		AVCO Corporation, Lycoming Division (4)				
Alloy		Ti-6Al-4V, Cast				
Form		Cast Compressor Casing (a) or Cast- to-Size Specimens (b)				
Condition		Annealed 1300F, 2 hours, AC (c)				
		Room Temperature Mild-Notch Stress Rupture Properties				
	Specimen	Hours at Indicated Stress				Total Life
Heat	Number	160 ksi	170 ksi	180 ksi	190 ksi	hours
Cast Compressor Casing						
A	1	-	1.2	-	-	1.2
A	2	10.0	-	-	-	(d)
A	3	9.0	-	-	-	(d)
Cast-to-Size Specimens						
B	1	-	5.0	1.1	-	6.1
B	2	-	5.0	0.2	-	5.2
B	3	-	9.9	0.4	-	10.3
B	4	-	6.8	-	-	6.8
C	1	-	10.6	5.0	1.2	16.8
C	2	-	5.2	-	-	5.2
C	3	-	5.8	1.9	-	7.7
C	4	-	10.3	0.7	-	11.0
C	5	-	5.0	2.8	-	7.8



(a) See Figure 3.0311 for compressor casing (20 inches long) details.
(b) Specimens cast to 1/2 inch diameter oversize specimen blanks subsequently machined to finished specimens.
(c) Cast compressor casing annealed in full section size: F_{tu} = 143.9 ksi, F_{ty} = 131.0 ksi, e(1 inch) = 9.4 percent, RA = 15.5 percent.
Cast-to-size specimens annealed as oversize specimen blanks:
Heat B, F_{tu}=144.8 ksi, F_{ty}=127.3 ksi, e(1 inch)=11.7 percent, RA=25.8 percent
Heat C, F_{tu}=145.1 ksi, F_{ty}=132.7 ksi, e(1 inch)=10.5 percent, RA=21.6 percent
(d) Test retired.

TABLE 3.046

Source		AVCO Corporation, Lycoming Division (4)		
Alloy		Ti-6Al-4V, Cast		
Form		Cast-to-Size Specimens (a)		
Condition		Annealed 1300F, 2 hours, AC (b)		
		500F Stress Rupture Properties		
Heat	Specimen Number	Stress ksi	Life hours	e(1 inch) percent
Smooth (c)				
A	1	100.0	(d)	12.0
A	2	95.0	200.8 (e)	-
A	3	90.0	253.3 (e)	-
B	1	100.0	245.7 (e)	-
B	2	98.5	209.6 (e)	-
B	3	97.5	204.9 (e)	-
Mild-Notch (f)				
A	1	175.0	(d)	-
A	2	165.0	(d)	-
A	3	155.0	(d)	-
B	1	154.0	(d)	-
B	2	152.0	200.8 (e)	-
B	3	150.0	238.1 (e)	-

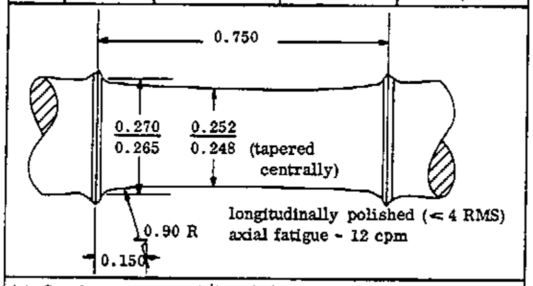
(a) 1/2 inch diameter cast oversize specimen blanks subsequently machined to finished specimens.
(b) Annealed as oversize specimen blanks: Room Temperature Tensile Properties - Heat A; F_{tu} = 144.8 ksi, F_{ty} = 127.3 ksi, e(1 inch) = 11.7 percent, RA - 25.8 percent
Heat B; F_{tu} = 145.1 ksi, F_{ty} = 132.7 ksi, e(1 inch) = 10.5 percent, RA = 21.6 percent
(c) Smooth specimens 1/4 inch diameter x 1 inch gage length.
(d) Broke immediately after loading to indicated stress.
(e) Test discontinued.
(f) See Table 3.045 for mild-notch specimen configuration.

3.05 Fatigue Properties

3.051 Low-cycle axial fatigue results at 500F for annealed smooth specimens cast-to-size from two heats, Table 3.051.

TABLE 3.051

Source	AVCO Corporation, Lycoming Division (4)			
Alloy	Ti-6Al-4V, Cast			
Form	Cast-to-Size Specimens (a)			
Condition	Annealed 1300F, 2 Hours, AC (b)			
	500F Low-Cycle Fatigue Properties			
Heat	Strain Ratio, A	Alternating Strain in / in	Maximum Strain in / in	Cycles to Failure
(c)	∞	0.0145	0.0145	144
A	∞	0.0115	0.0115	508
A	∞	0.0115	0.0115	290
A	∞	0.0115	0.0115	450
A	∞	0.010	0.010	1,060
B	∞	0.0076	0.0076	1,700
A	∞	0.0058	0.0058	3,803
B	∞	0.0049	0.0049	13,925
B	∞	0.004	0.004	50,067(d)
(c)	0.67	0.016	0.040	1,002
B	0.67	0.008	0.020	873
B	0.67	0.005	0.0125	2,509
B	0.25	0.010	0.050	325
A	0.25	0.008	0.040	9,722



(a) Specimens cast to 1/2 inch diameter oversize specimen blanks, subsequently machined to configuration shown.
(b) Annealed as oversize specimen blanks: see Figure 3.053 for conventional room temperature tensile properties of material tested.
(c) Not identified, except as from same producer as of other two heats.
(d) Test retired.

3.052 Low-cycle axial fatigue results at 500F for annealed mild-notch specimens cast-to-size from two heats, Figure 3.052.

3.053 High-cycle axial fatigue results at 500F for annealed smooth and mild-notch cast-to-size specimens from two heats, Figure 3.053.

3.054 150 hours, 500F stress range diagram for smooth and mild-notch cast-to-size specimens from two heats, Figure 3.054.

3.055 Room temperature axial load fatigue properties of smooth specimens from five annealed cast ring segments from two heats, Figure 3.055.

3.056 Room temperature axial load fatigue properties of mild-notch specimens from five annealed cast ring segments from two heats, Figure 3.056.

3.057 Room temperature smooth fatigue properties of annealed and solution treated and aged, castings, Figure 3.057.

3.058 Room temperature mild-notch fatigue properties of annealed and solution treated and aged castings from two casting manufacturers, Figure 3.058.

3.06 Elastic Properties
(For E, see also Tables 3.0211, 3.0212 and 3.02112. For E_c, see also Tables 3.0221 and 3.0222)

3.061 Effect of test temperature on tensile elastic modulus of annealed cast ring segments from two heats, Figure 3.061.

4. FABRICATION

4.01 Formability

4.02 Machining and Grinding
Consult Air Force Machinability Data Center, Metcut Research Associates, Cincinnati, Ohio 45209.

4.03 Welding
Repair welding of titanium castings is a common practice and, according to one source, will probably be necessary for the forseeable future because of the poor feeding characteristics of titanium (see 1.092)(14). Most of the data reported in this chapter (from references 5, 8, 11, and 14) were from castings for which weld repairs were allowed. Thus the influence of repair welding is reflected in the data scatter. It should be pointed out, however, that unsound welds or welds containing obvious defects were not included in the published results. This was considered acceptable since weld-repaired castings with obvious weld defects would normally be withheld from service. Weld repair procedures are outlined in references 7 and 12.

4.04 Surface Treatment

	Ti
6	Al
4	V

Ti-6Al-4V
Cast

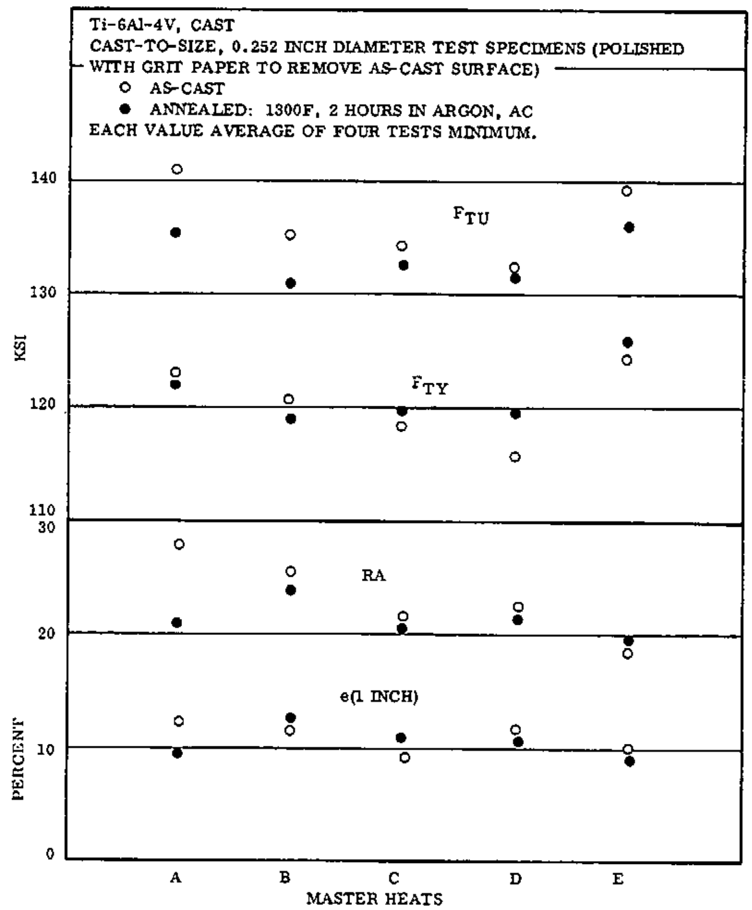


FIG. 3.0214 VARIATION IN TENSILE PROPERTIES OF FIVE MASTER HEATS FOR THE AS-CAST AND ANNEALED CONDITIONS. (9)

	Ti
6	Al
4	V

Ti-6Al-4V Cast

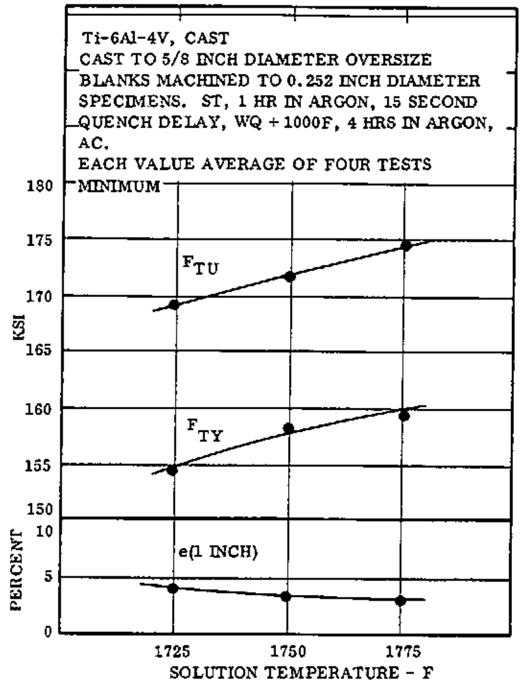


FIG. 3.0216 EFFECT OF SOLUTION TREAT TEMPERATURE ON TENSILE PROPERTIES OF SOLUTION TREATED AND AGED CAST-TO-SIZE SPECIMENS. (9)

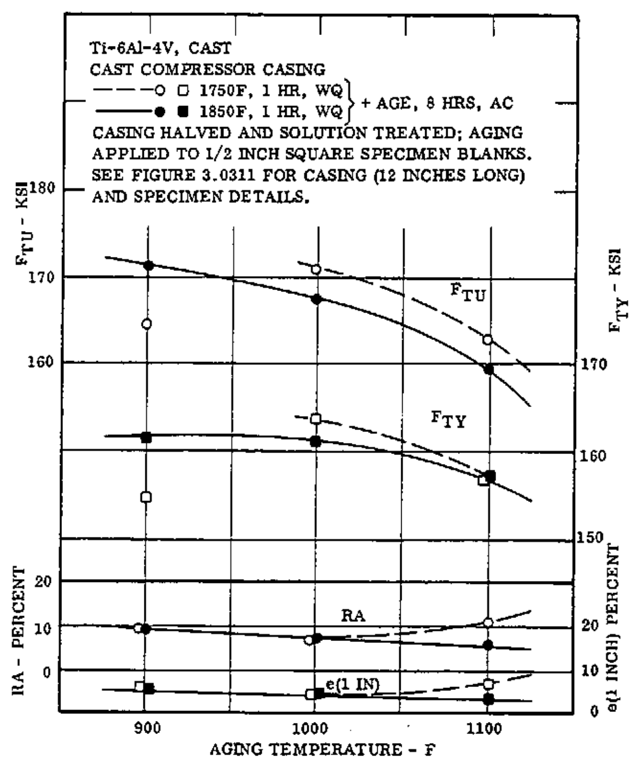


FIG. 3.0217 EFFECT OF SOLUTION TREAT AND AGING TEMPERATURES ON TENSILE PROPERTIES OF CAST COMPRESSOR CASING. (4)

Ti
6 Al
4 V

Ti-6Al-4V
Cast

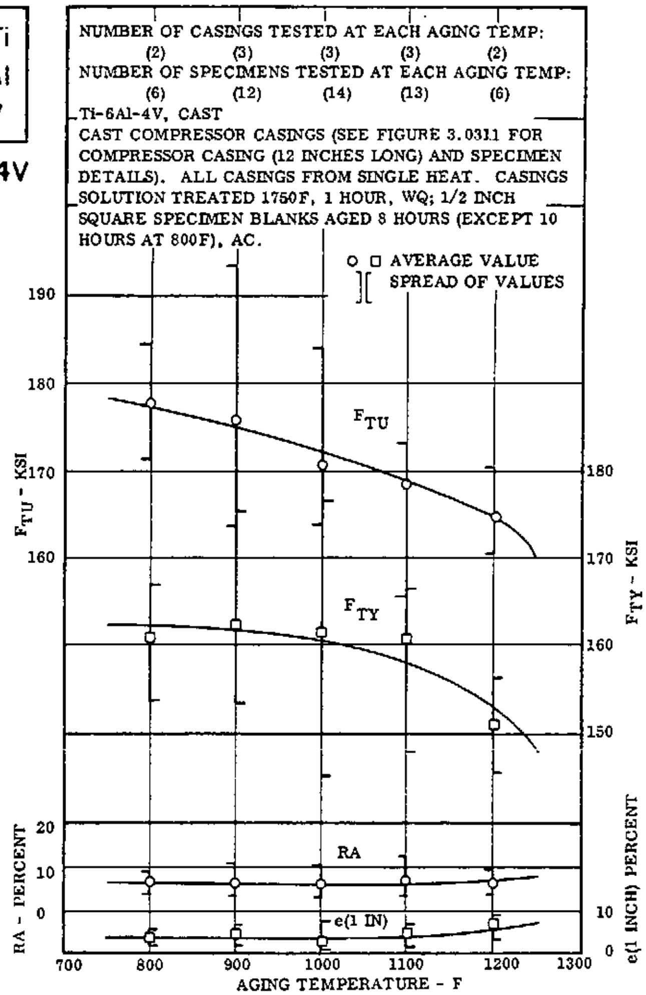


FIG. 3.0218 EFFECT OF AGING TEMPERATURE ON TENSILE PROPERTIES OF THREE COMPRESSOR CASINGS CAST FROM ONE HEAT. (4)

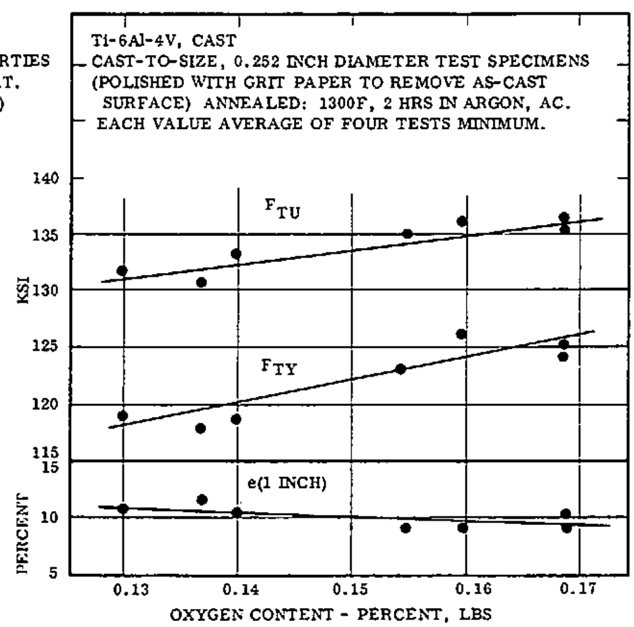


FIG. 3.02113 EFFECT OF OXYGEN CONTENT ON TENSILE PROPERTIES OF ANNEALED CAST-TO-SIZE SPECIMENS. (9)

Ti
6 Al
4 V

Ti-6Al-4V
Cast

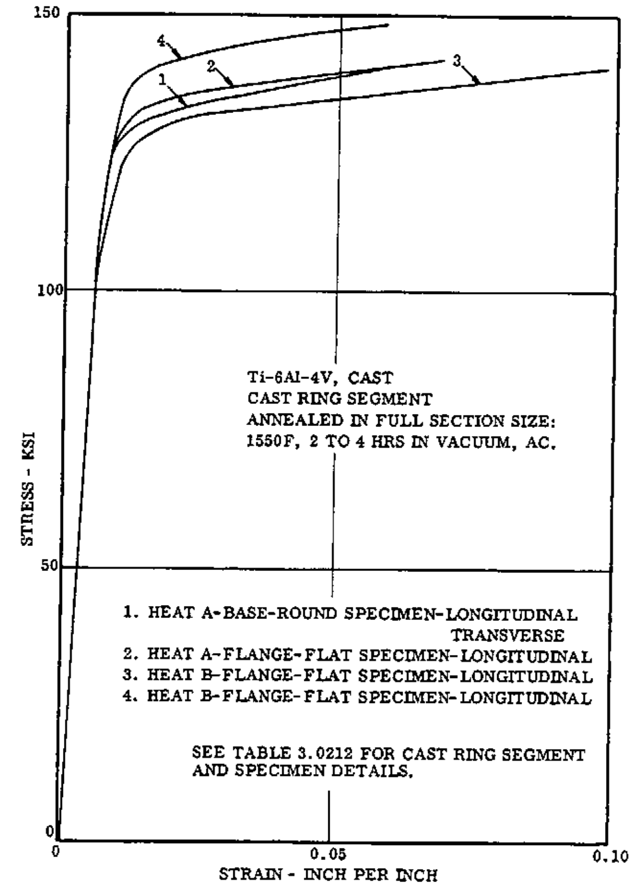


FIG. 3.02114 TYPICAL STRESS-STRAIN CURVES FOR ANNEALED CAST RING SEGMENTS FROM TWO HEATS. (5)

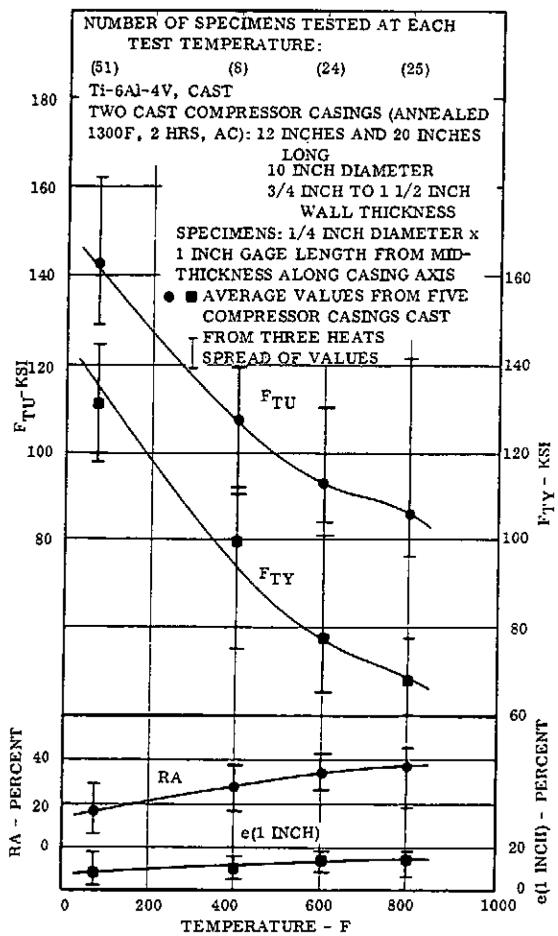


FIG. 3.0311 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF FIVE ANNEALED CAST COMPRESSOR CASING FROM THREE HEATS. (4)

Ti 6 Al 4 V

Ti-6Al-4V Cast

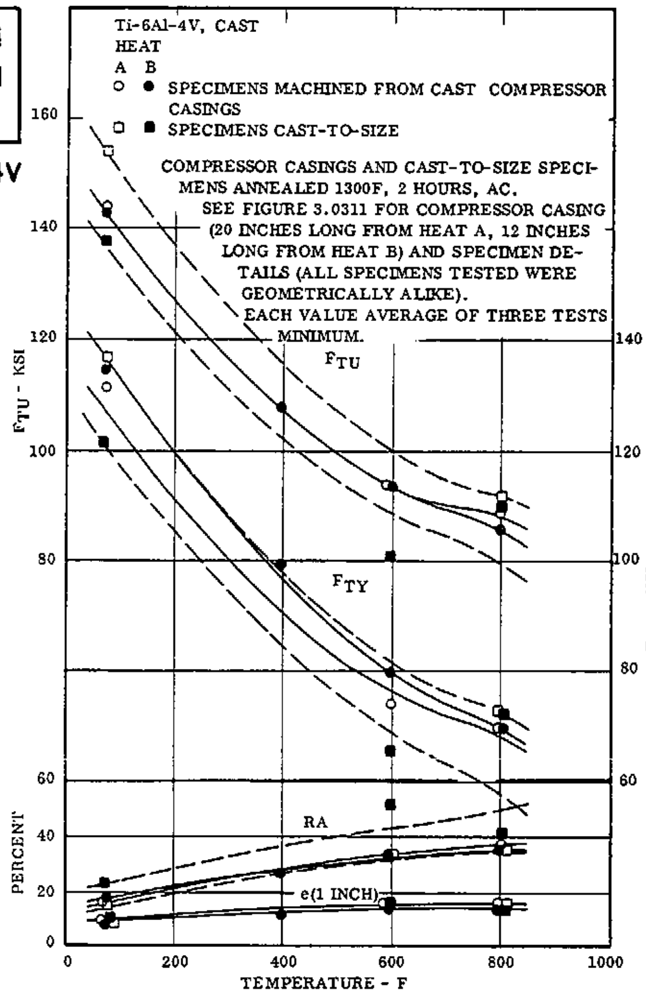


FIG. 3.0312 EFFECT OF TEST TEMPERATURES ON TENSILE PROPERTIES OF SPECIMENS MACHINED FROM ANNEALED CAST COMPRESSOR CASINGS AND ANNEALED CAST-TO-SIZE SPECIMENS EACH FROM TWO HEATS. (4)

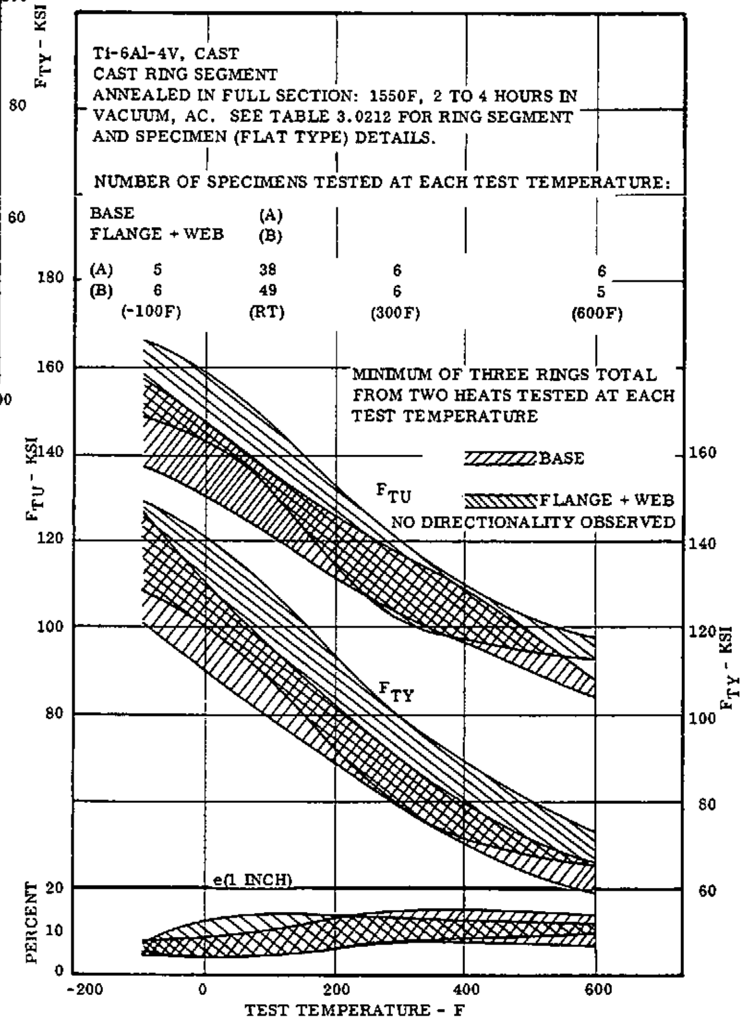


FIG. 3.0313 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF ANNEALED CAST RING SEGMENTS FROM TWO HEATS. (5)

	Ti
6	Al
4	V

Ti-6Al-4V Cast

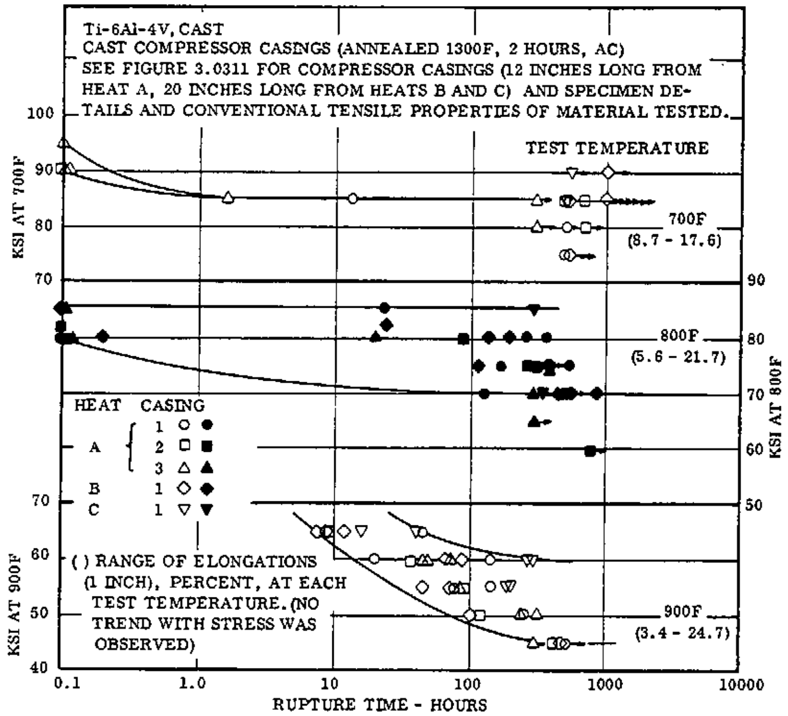


FIG. 3.041 STRESS RUPTURE CURVES AT 700, 800, AND 900F FOR SPECIMENS MACHINED FROM FIVE ANNEALED CAST COMPRESSOR CASINGS FROM THREE HEATS. (4)

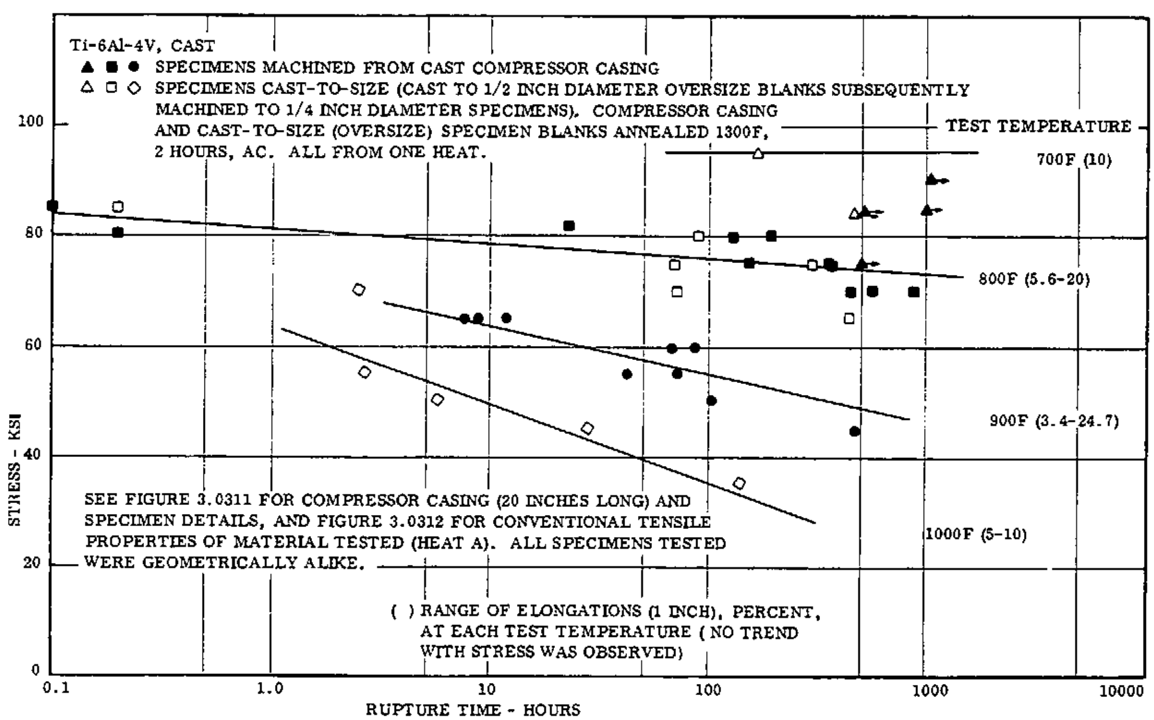


FIG. 3.042 CREEP RUPTURE CURVES AT 700, 800, 900, AND 1000F FOR SPECIMENS MACHINED FROM ANNEALED CAST COMPRESSOR CASING AND ANNEALED CAST-TO-SIZE SPECIMENS FROM ONE HEAT. (4)

Ti
6 Al
4 V

Ti-6Al-4V Cast

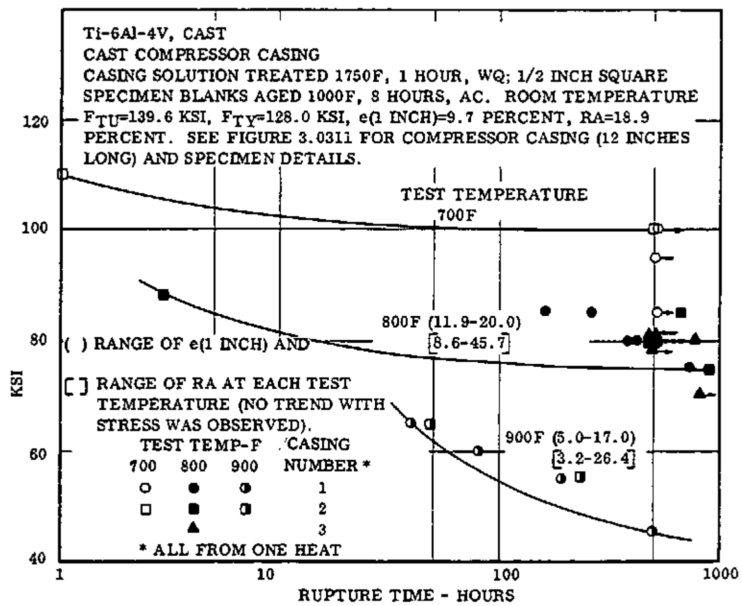


FIG. 3.043 STRESS RUPTURE CURVES AT 700, 800, AND 900F FOR SPECIMENS MACHINED FROM CAST COMPRESSOR CASING AGED AT 1000F. (4)

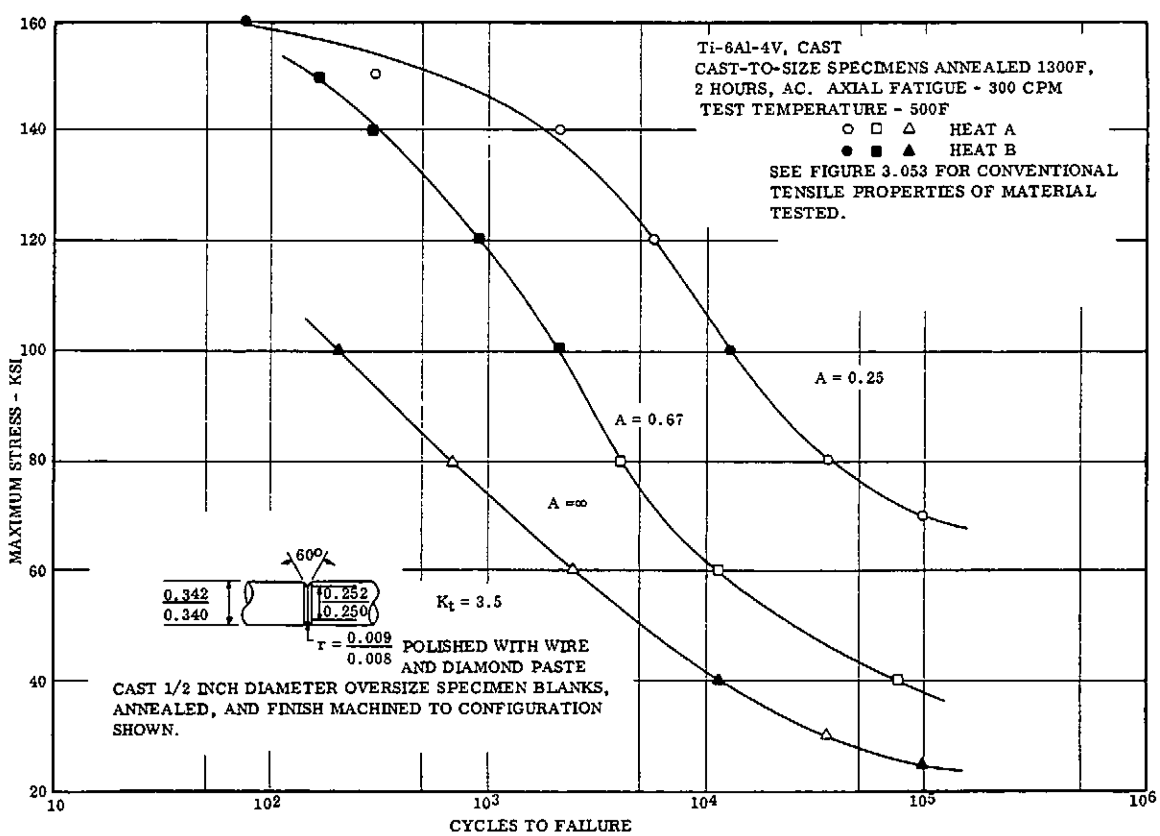


FIG. 3.052 LOW-CYCLE AXIAL FATIGUE RESULTS AT 500F FOR ANNEALED MILD-NOTCH SPECIMENS CAST-TO-SIZE FROM TWO HEATS. (4)

	Ti
6	Al
4	V

Ti-6Al-4V
Cast

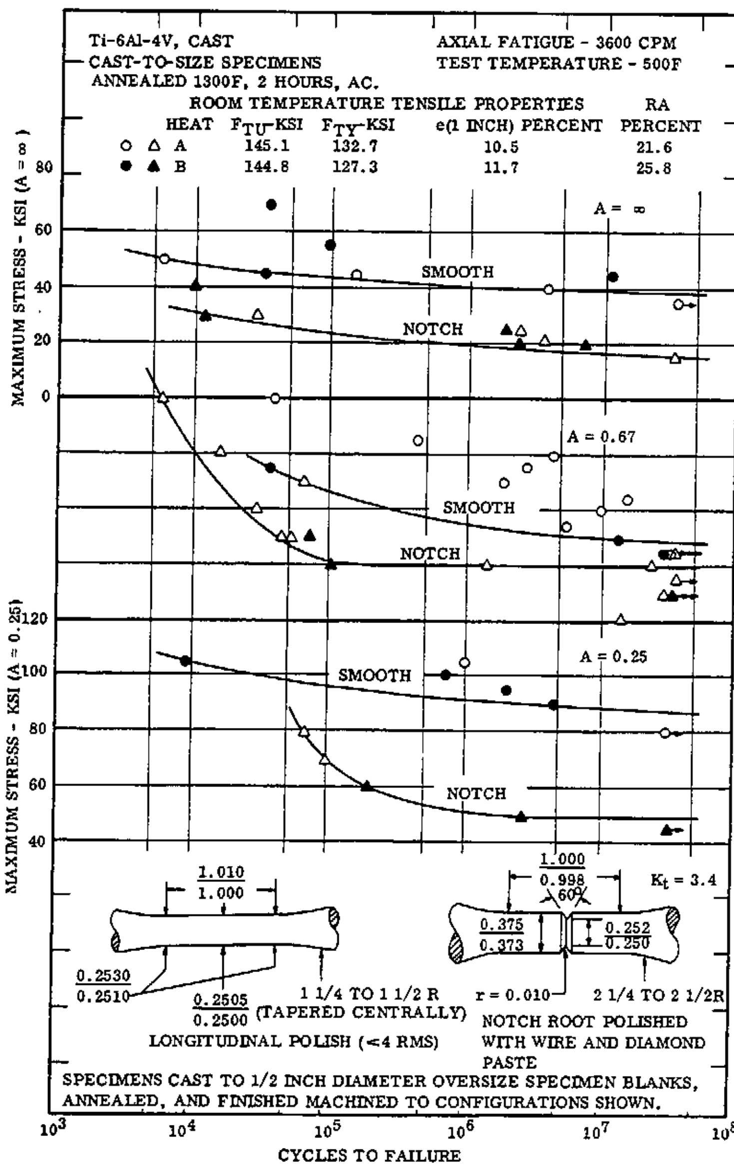


FIG. 3.053 HIGH-CYCLE AXIAL FATIGUE RESULTS AT 500F FOR ANNEALED SMOOTH AND MILD-NOTCH CAST-TO-SIZE SPECIMENS FROM TWO HEATS. (4)

Ti
6 Al
4 V

Ti-6Al-4V Cast

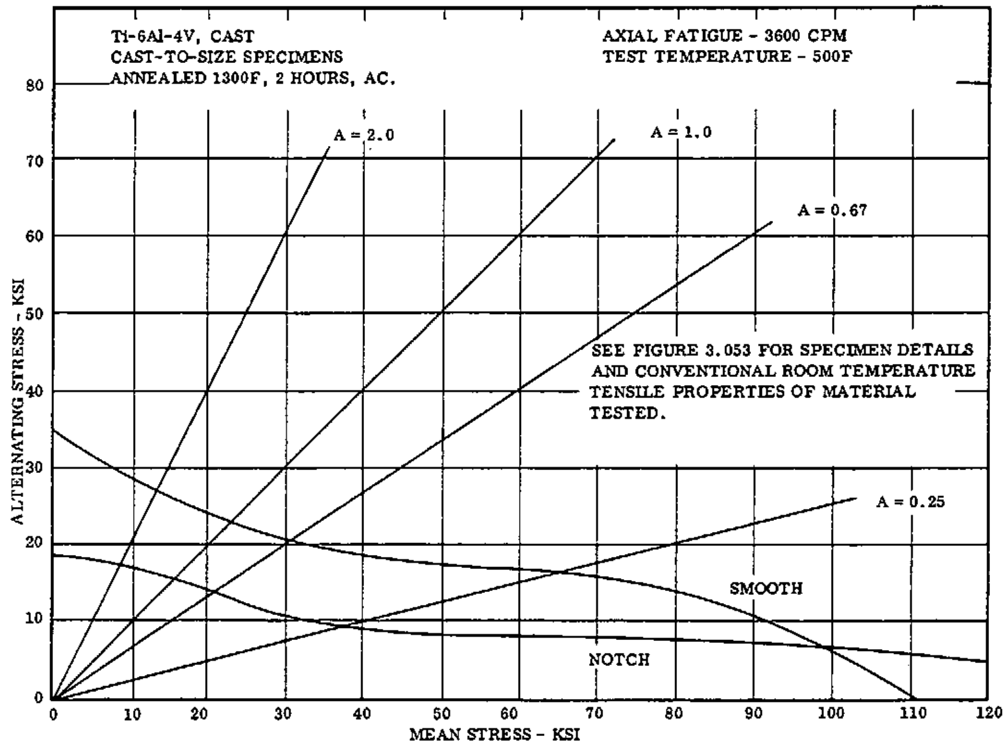


FIG. 3.054 150 HOURS, 500F STRESS RANGE DIAGRAM FOR SMOOTH AND MILD-NOTCH CAST-TO-SIZE SPECIMENS FROM TWO HEATS. (4)

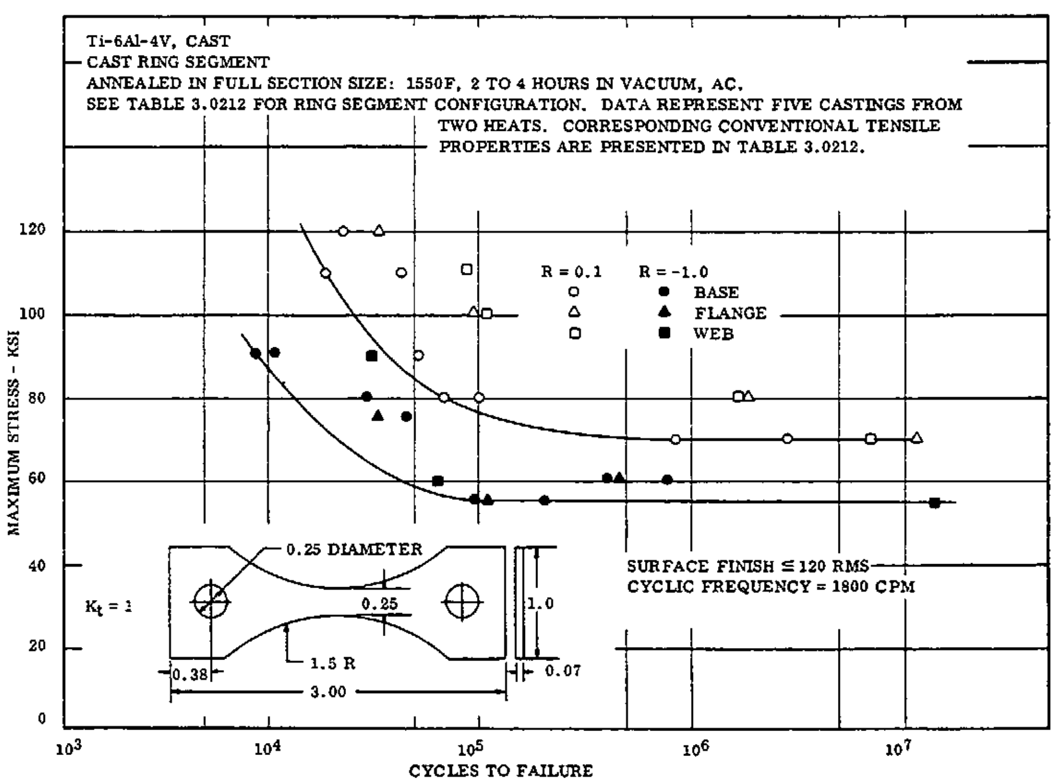


FIG. 3.055 ROOM TEMPERATURE AXIAL LOAD FATIGUE PROPERTIES OF SMOOTH SPECIMENS FROM FIVE ANNEALED CAST RING SEGMENTS FROM TWO HEATS. (5)

	Ti
6	Al
4	V

Ti-6Al-4V
Cast

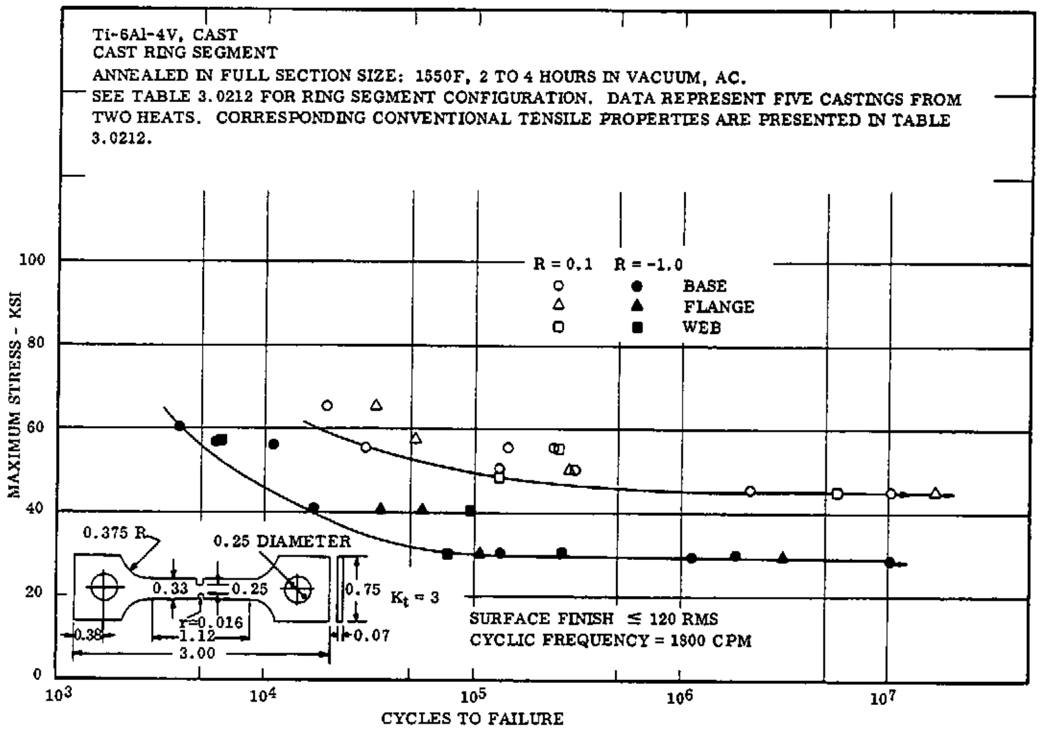


FIG. 3.056 ROOM TEMPERATURE AXIAL LOAD FATIGUE PROPERTIES OF MILD-NOTCH SPECIMENS FROM FIVE ANNEALED CAST RING SEGMENTS FROM TWO HEATS. (5)

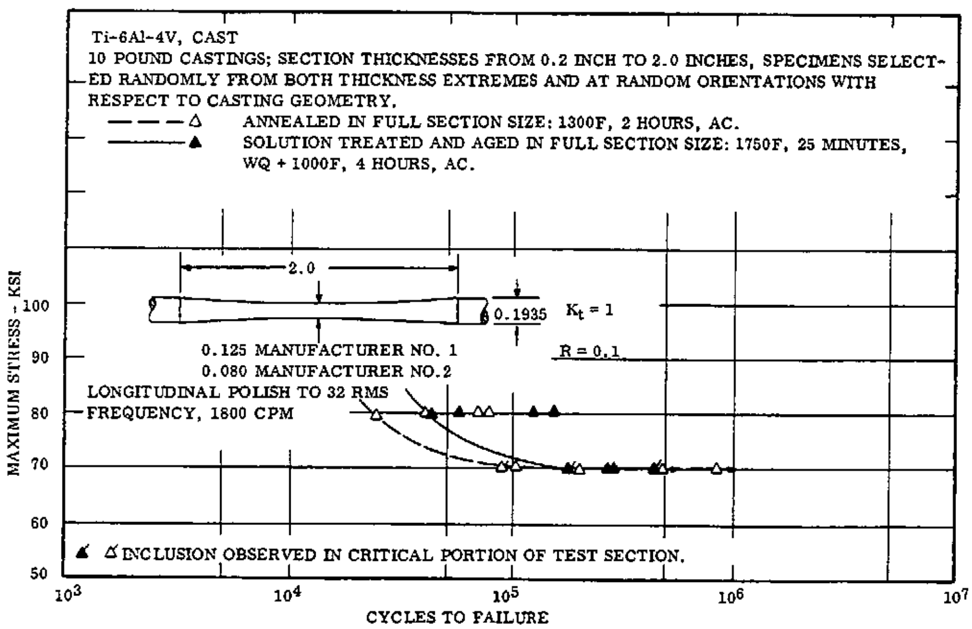


FIG. 3.057 ROOM TEMPERATURE SMOOTH FATIGUE PROPERTIES OF ANNEALED AND SOLUTION TREATED AND AGED CASTINGS. (8)

Ti
6 Al
4 V

Ti-6Al-4V
Cast

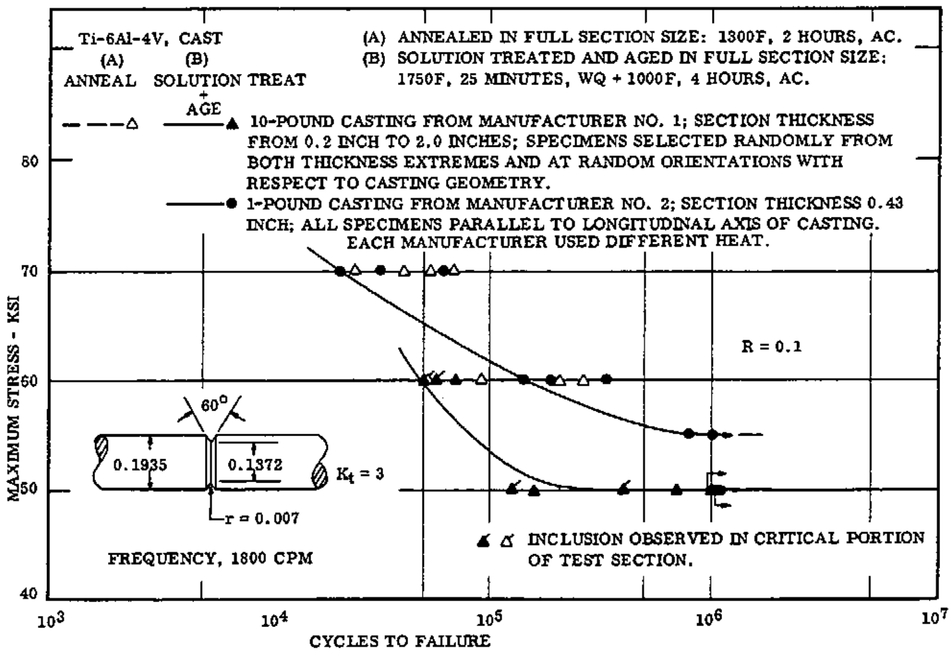


FIG. 3.058 ROOM TEMPERATURE MILD-NOTCH FATIGUE PROPERTIES OF ANNEALED AND SOLUTION TREATED AND AGED CASTINGS FROM TWO CASTING MANUFACTURERS. (8)

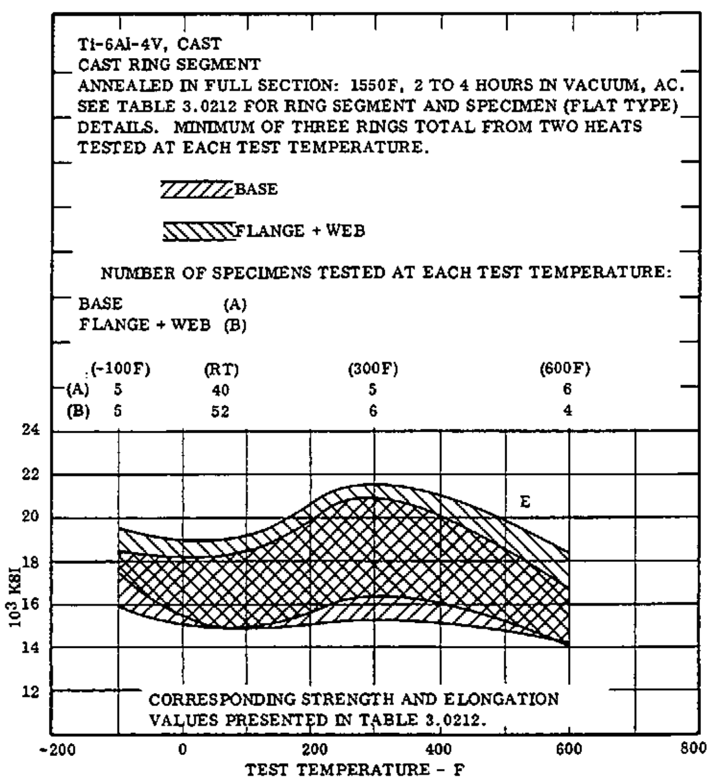


FIG. 3.061 EFFECT OF TEST TEMPERATURE ON TENSILE ELASTIC MODULUS OF ANNEALED CAST RING SEGMENTS FROM TWO HEATS. (5)

REFERENCES

1. AVCO Corporation, Lycoming Division, Stratford, Connecticut, Specification No. M3407 (November 30, 1966).
2. Precision Castparts Corporation, Portland, Oregon, Specification No. TD-TCD-1 (April 29, 1968).
3. Wood, R. A. "A Tabulation of Designations, Properties, and Treatments of Titanium and Titanium Alloys," DMIC Memorandum 171 (July 15, 1963).
4. Private communication with R. P. Dalal of AVCO Corporation, Lycoming Division, Stratford, Connecticut.
5. McClaren, S. W., Cook, O. H., and Pascador, G., "Processing, Evaluation, and Standardization of Titanium Alloy Castings," LTV Aerospace Corporation, Vought Aeronautics Division, work performed under Contract F33615-67-C-1173 (BPSN 66-139999-2001-9169-99) with Air Force Materials Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, 45433, and published as Technical Report AFML-TR-68-264 (April, 1969).
6. Private communication with M. Lasker of Precision Castparts Corporation, Portland, Oregon.
7. Poole, H. G., "Fundamentals of Casting Titanium," Oregon Metallurgical Corporation, Albany, Oregon, presented at Titanium Metallurgy Course, New York University School of Engineering and Science (September 13-15, 1965).
8. Private communication with H. W. Stemme of Lockheed-Georgia Company, Marietta, Georgia.
9. Coney, D. M., and Lasker, M. F., "Precision Casting of Ti-6Al-4V," Precision Castparts Corporation, Portland, Oregon (June 18, 1969).
10. Published in reference No. 5 above.
11. Soffa, L. L., "Titanium Castings for Airframe Structural Applications," Lockheed-California Company, Division of Lockheed Aircraft Corporation, Burbank, California (September 8, 1967).
12. "Now Available: Cast Titanium and Zirconium," Oregon Metallurgical Corporation, Albany, Oregon.
13. Lang, R. M., Schippereit, G. H., and Kura, J. G., "Production of Titanium Shaped Castings," TML Report No. 60, Titanium Metallurgical Laboratory, Battelle Memorial Institute, Columbus 1, Ohio (December 12, 1956).
14. Harmsworth, C. L., McClaren, S. W., and Cook, O. H., "Castings," Machine Design, pp. 167-171 (June 20, 1968).
15. Jahnke, L. P., "Titanium in Jet Engines," Aircraft Engine Technology Division, General Electric Company, Cincinnati, Ohio, paper presented at the International Conference on Titanium, London, England (May 21-24, 1968) referenced by R. A. Wood and D. J. Maykuth, "Titanium and Titanium Alloys," Review of Recent Developments, Battelle Memorial Institute (August 23, 1968).

The following report contains very recent data on Ti-6Al-4V, Cast in several heat treated conditions, but was unavailable to the author at the time of this writing: Parkinson, F. L., "Mechanical Property Data on Ti-6Al-4V Castings," Boeing Report T6-3606 (1969).