

1. General

Titanium castings have been produced commercially since the early 1960's. Design shapes that have been produced for aerospace applications for many years include impellers, brackets, window frames, hubs and bearing housings (10). Recent advances in foundry technology have resulted in use of larger complex structural aerospace castings (11). Numerous Ti-6Al-4V cast parts are in use on the airframes of many commercial aircraft as well as military systems (12, 13). The most ambitious structural application is the side of body joint on the F-22 (14).

For comparable heat treat conditions, Ti-6Al-4V castings exhibit the same or nearly the same strength, ductility, creep rupture and fatigue strengths, and elevated temperature stability as their wrought counterparts. The structural advantage of cast structure over built up structure is the elimination of mechanically fastened joints, which may result in a lighter weight structure.

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

1.1 Commercial Designations

Ti-6Al-4V

1.2 Alternate Designations

Ti-6-4

1.3 Specifications

- AMS 4985
- AMS 4991
- AMS 4962
- ASTM B367 Grade C-5
- MIL-T-81915 Type III

Note: Government specifications are being discontinued, and will be reissued as industry specifications, such as AMS specifications.

1.4 Composition

1.4.1 [Table] Chemical Composition.

1.5 Thermal/Mechanical Processing

Most Ti-6Al-4V castings produced commercially are supplied in the mill annealed (MA) condition per MIL-H-81200.

Annealing is usually accomplished at 1300-1550F 2-4 hours in vacuum or inert atmosphere.

Beta annealing is accomplished by heating in vacuum to a temperature above the beta transus, 1870-1910F.

Solution treating at a temperature below the beta transus, about 1800F followed by a 1000F age may result in higher tensile properties, but lower ductility.

The hot isostatic pressing process is used to ensure elimination of internal gas shrinkage cavities. This procedure is carried out in an inert atmosphere autoclave at 1650-1750F 2-4 hours at 15ksi pressure.

Some applications have used a beta solution treatment at 1900F followed by a 1000 - 1500F age. This technique is expected to normalize the effects of various casting methods and weld repairs to produce consistent material properties (14, 19). Additional fixturing may be required to maintain dimensional control during the beta heat treating process. Mechanical properties have not been shown to be significantly different from those obtained from standard mill annealed castings of the same configuration from the same producer (29).

A stress relief, consisting of heating to 1350-1550F in a vacuum or inert atmosphere is usually applied after weld repair.

1.6 Hardness

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

1.7 Forms and Conditions Available

Castings are available in as-cast and heat treated conditions. Consult casting producer.

1.8 Melting and Casting Practice

1.8.1 General

The usual method of melting titanium for the casting process is to use a consumable electrode vacuum arc system. Other melting methods include resistance heating, induction heating, tungsten arc melting, electron beam melting and plasma arc melting. (20)

Castings are poured either from remelted master heat base metal or directly from the master heat (1, 2). A master heat is metal of a single furnace charge. Gates, sprues, risers and rejected castings may be used in the preparation of a master heat,

Ti	
Al	6.0
V	4.0

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but may not be added directly without first melting and adjusting chemistry, for the pouring of castings (1, 2).

In common with unalloyed titanium and other titanium alloys, Ti-6Al-4V may react with the 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 commonly called "alpha case" and is extremely brittle.

1.8.2 Molding methods

Titanium castings are produced as sand castings from rammed graphite molds or as investment castings from ceramic shells made by the lost wax process. The choice depends on complexity of the part, required dimensional tolerances, surface finish and economic considerations.

The rammed graphite method is the traditional production practice. Tooling is relatively inexpensive. The mold material is pneumatically rammed around a wood pattern and cured at a high temperature. The molding process and tooling are essentially the same as those used in ferrous and nonferrous sand foundries. (19)

The investment casting technique is used to make complex shapes with better surface finish than obtained from rammed graphite molds. However tooling costs are higher. Investment castings rely on the lost wax technique. A ceramic shell is formed around a wax pattern. Several foundries have developed proprietary lost-wax ceramic shell systems.

Foundry practices focus on methods to control the extent of the reaction between the molten metal and the mold material. (19)

Surface contamination of the casting surface, alpha case, is picked up from the mold during pouring. This layer is removed by chemical milling. (16)

Permanent mold casting shows potential to provide lower costs and improved quality, including no alpha case for relatively small parts. The process involves casting into reusable metal molds that are resistant to erosion and reaction with the molten metal. (17, 18)

The tendency for gas formation from an incompletely fired expendable mold or decomposition of absorbed water on the mold and poor feeding characteristics require much heavier gating and risering for Ti-6Al-4V than for a comparable steel casting alloy (7, 8).

1.9 Special Considerations (see also 1.8)

1.9.1 Weld Repair

Weld repair of surface defects is an integral part of the manufacturing process. Tungsten inert gas welding in argon is commonly used. Generally all weld-repaired castings are stress relieved. Weld repair is not detrimental to the mechanical properties of cast Ti-6Al-4V. The HIP treatment can be made either before or after weld repair without any adverse effects (19, 28, 29).

2. Physical Properties and Environmental Effects**2.1 Thermal Properties**

2.1.1 Melting Range.
2800-3000F

2.1.2 Phase Changes.
Alloy transforms on cooling from beta to alpha + beta at approximately 1825F. This is referred to as the beta transus temperature.

2.1.2.1 Time-temperature-transformation diagrams

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

2.1.4 Thermal Expansion
 5.2×10^{-6} in/in/F. See also Ti-6Al-4V, Alloy Code 3707

2.1.5 Specific Heat
0.137 Btu per (lb F) at 400F. See also Ti-6Al-4V, Alloy Code 3707

2.1.6 Thermal Diffusivity

2.2 Other Physical Properties

2.2.1 Density 0.161 lb/cu. in

2.2.2 Electrical Properties
See Ti-6Al-4V, Alloy Code 3707

2.2.3 Magnetic Properties
See Ti-6Al-4V, Alloy Code 3707

2.2.4 Emittance
See Ti-6Al-4V, Alloy Code 3707

2.2.5 Damping Capacity

2.3 Chemical Environments

2.3.1 General Corrosion
See Ti-6Al-4V, Alloy Code 3707

2.3.2 Stress Corrosion
 $K_{iscc} = 58.3$ ksi in^{1/2}
Single edge notch cantilever specimen fatigue precracked per ASTM E399 and exposed to sea-water under load. (20)

2.4 Nuclear Environments

3. Mechanical Properties

3.1 Specified Mechanical Properties

3.1.1 [Table] AMS Specified mechanical properties

3.2 Mechanical Properties at Room Temperature

3.2.1 Tensile Stress-strain Diagrams and Tensile Properties

3.2.1.1 [Figure] Typical stress-strain curves for annealed cast ring segments from two heats.

3.2.1.2 [Table] Tensile properties including modulus of elasticity of annealed cast ring segments from two heats.

3.2.1.3 [Table] Mechanical property comparison for excised vs integrally cast specimens.

3.2.1.4 [Table] Comparison of room temperature properties from three sources of cast Ti-6Al-4V test material.

3.2.1.5 [Table] Tensile test results for Ti-6Al-4V alloy castings at room temperature.

3.2.1.6 [Figure] Frequency distribution of tensile properties of hot isostatically pressed and annealed Ti-6Al-4V casting test bars from 500 heats.

3.2.1.7 [Figure] Variation in tensile properties of five master heats for the as-cast and annealed conditions.

3.2.1.8 [Table] Comparison of room temperature tensile properties for two heat treatments of cast Ti-6Al-4V alloy.

3.2.1.9 [Figure] Effect of solution treat temperature on tensile properties of solution treated and aged cast-to-size specimens.

3.2.1.10 [Figure] Effect of solution treat and aging temperatures on tensile properties of cast compressor casing.

3.2.1.11 [Figure] Effect of aging temperature on tensile properties of three compressor casings cast from one heat.

3.2.1.12 [Figure] Effect of oxygen content on tensile properties of annealed cast-to-size specimens.

3.2.1.13 [Table] tensile properties of as-cast, annealed, and solution treated and aged castings from three casting manufacturers.

3.2.1.14 [Table] Tensile properties for a solution treated and annealed condition and two solution treated and aged conditions.

3.2.1.15 [Table] Effect of aging temperature on tensile properties of cast-to-size specimens.

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

3.2.1.17 [Table] Effect of exposure to elevated temperature with load on tensile properties of annealed cast compressor casing.

3.2.1.18 [Table] Tensile test results for several solution treat and aging conditions.

3.2.1.19 [Figure] Effect of thermal treatment on the 70F tensile properties of cast and HIP'ed Ti-6Al-4V and the wrought alloy.

3.2.1.20 [Table] Tensile test results for two heat treat conditions.

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

3.2.1.22 [Table] Effect of beta annealed vs. standard mill anneal on room temperature tensile properties of complex castings.

3.2.2 Compression Stress-strain Diagrams and Compression Properties.

3.2.2.1 [Table] Compressive yield strength and modulus of elasticity of cast ring segments from two heats.

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

3.2.3 Impact

3.2.3.1 [Table] Standard Charpy-V impact energy of annealed cast-to-size specimens from two heats.

3.2.3.2 [Table] Standard Charpy-V impact energy of annealed cast ring segments from two heats.

3.2.3.3 [Table] Standard Charpy-V impact energy of solution treated and aged casting.

3.2.3.4 [Table] Charpy V-notch results for Ti-6Al-4V alloy castings at room temperature.

3.2.3.5 [Table] Charpy V-notch and fracture toughness test results for several heat treatments.

3.2.4 Bending

3.2.5 Torsion and Shear

3.2.5.1 [Table] Shear strength of annealed cast ring segments from two heats.

3.2.5.2 [Table] Double shear strength of solution treated and aged casting.

3.2.6 Bearing

3.2.6.1 [Table] Bearing strength of annealed cast ring segments from two heats.

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- 3.2.6.2 [Table] Bearing strength of solution treated and aged casting.
- 3.2.7 Stress Concentration
- 3.2.7.1 Notch Properties
- 3.2.7.1.1 [Table] Mild-notch strength of annealed cast ring segments from two heats.
- 3.2.7.2 Fracture Toughness
- 3.2.7.2.1 [Table] Fracture toughness results.
- 3.2.8 Combined Loading
- 3.3 Mechanical Properties at Various Temperatures**
- 3.3.1 Tension Stress-strain Diagrams and Tensile Properties
- 3.3.1.1 [Figure] Effect of test temperature on tensile properties of five annealed cast compressor casing from three heats.
- 3.3.1.2 [Figure] 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.
- 3.3.1.3 [Figure] Effect of test temperature on tensile properties of annealed cast ring segments from two heats.
- 3.3.1.4 [Table] Summary of tensile test results at room and low temperatures from Ti-6Al-4V investment castings of standard composition and extra low interstitials from two foundries.
- 3.3.1.5 [Figure] Effect of test temperature on ultimate tensile strength of standard composition and extra low interstitials castings.
- 3.3.1.6 [Figure] Effect of test temperature on percent elongation of standard composition and extra low interstitials castings.
- 3.3.2 Compression Stress-strain Diagrams and Compression Properties.
- 3.3.3 Impact
- 3.3.4 Bending
- 3.3.5 Torsion and Shear
- 3.3.6 Bearing
- 3.3.7 Stress Concentration
- 3.3.7.1 Notch Properties
- 3.3.7.1 Fracture Toughness
- 3.3.7.1.1 [Table] Fracture toughness results summary (average KQ) of Ti-6Al-4V investment castings.
- 3.3.7.1.2 [Figure] Effect of test temperature on the fracture toughness of standard composition and extra low interstitials castings.
- 3.3.8 Combined Loading
- 3.4 Creep and Creep Rupture Properties**
- 3.4.1 [Table] Effect of solution and aging temperatures on 800F, 80 ksi stress rupture life of cast compressor casing.
- 3.4.2 [Table] Room temperature stress rupture results for mild-notch specimens machined from annealed cast compressor casing and annealed cast-to-size specimens.
- 3.4.3 [Table] 500F stress rupture properties of cast-to-size smooth and mild-notch specimens from two heats.
- 3.4.4 [Figure] Stress rupture curves at 700, 800, and 900 F for specimens machined from five annealed cast compressor casings from three heats.
- 3.4.5 [Figure] Creep rupture curves at 700, 800, 900, and 1000 F for specimens machined from annealed cast compressor casing and annealed cast-to-size specimens from one heat.
- 3.4.6 [Figure] Stress rupture curves at 700, 800, and 900 F for specimens machined from cast compressor casing aged at 1000 F.
- 3.5 Fatigue**
- 3.5.1 Conventional High Cycle Fatigue
- 3.5.1.1 [Figure] High-cycle axial fatigue results at 500 F for annealed smooth and mild-notch cast-to-size specimens from two heats.
- 3.5.1.2 [Figure] 150 hours, 500 F stress range diagram for smooth and mild-notch cast-to-size specimens from two heats.
- 3.5.1.3 [Figure] Room temperature axial load fatigue properties of smooth specimens from five annealed cast ring segments from two heats.
- 3.5.1.4 [Figure] Room temperature axial load fatigue properties of mild-notch specimens from five annealed cast ring segments from two heats.
- 3.5.1.5 [Figure] Room temperature smooth fatigue properties of annealed and solution treated and aged castings.
- 3.5.1.6 [Figure] Room temperature mild-notch fatigue properties of annealed and solution treated and aged castings from two casting manufacturers.
- 3.5.1.7 [Table] Room temperature HCF test results for Ti-6Al-4V cast test bars in various heat treat conditions (10 Hz, R= 0.1, Triangular Wave Form, $K_T = 1.0$).
- 3.5.1.8 [Figure] HCF data for annealed investment cast Ti-6Al-4V test bars.
- 3.5.1.9 [Figure] HCF data for investment cast Ti-6Al-4V test bars in the beta solution treated and aged condition.
- 3.5.1.10 [Figure] Comparison of average fatigue life curves for eight heat treat conditions.

- 3.5.1.11 [Figure] Effect of thermal treatment on the 70F HCF life of cast and HIP'ed Ti-6Al-4V alloy.
- 3.5.1.12 [Figure] Open Hole fatigue data comparing Beta Annealed (BA) to Mill Annealed (MA).
- 3.5.1.13 [Figure] Strain -Life fatigue data comparing Beta Annealed material to standard mill annealed condition.
- 3.5.2 Low-cycle Fatigue
- 3.5.2.1 [Figure] Low-cycle axial fatigue results at 500F for annealed mild-notched specimens cast -to-size from two heats.
- 3.5.3 Fatigue Crack Propagation
- 3.5.3.1 [Figure] Fatigue crack-growth rate comparison.
- 3.5.3.2 [Figure] Crack growth rate of Ti-6Al-4V mill annealed casting with no weld repair.
- 3.5.3.3 [Figure] Crack growth rate of weld repaired Ti-6Al-4V casting.
- 3.6 Elastic Properties**
- 3.6.1 Poisson's Ratio
See Ti-6Al-4V, Alloy Code 3707.
- 3.6.2 Modulus of Elasticity
See also Tables 3.2.1.2, 3.2.1.21, 3.2.2.1, 3.2.2.2, and 3.3.1.1.
- 3.6.2.1 [Figure] Effect of test temperature on tensile elastic modulus of annealed cast ring segments from two heats.
- 3.6.3 Modulus of Rigidity
See Ti-6Al-4V, Alloy Code 3707
- 3.6.4 Tangent Modulus
- 3.6.5 Secant Modulus
- 4 Fabrication**
- 4.1 Forming
- 4.2 Machining and Grinding
Consult Machinability Data Center, Metcut Research Associates, Cincinnati, Ohio.
- 4.3 Joining
See also Ti-6Al-4V, Alloy Code 3707.
- 4.4 Surface Treating
Residual surface contamination, known as alpha case, is removed from as-cast parts by chemical milling. (19)

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Table 1.4.1 Chemical Composition

SPECIFICATION	AMS 4985 (Ref. 35) AMS 4991 (Ref. 36)		AMS 4962 (Ref. 37)	
	Minimum	Maximum	Minimum	Maximum
Element				
Aluminum, percent	5.50	6.75	5.75	6.50
Vanadium, percent	3.50	4.50	3.60	4.50
Iron, percent		0.30		0.25
Oxygen, percent		0.20	0.13	0.17
Carbon, percent		0.10		0.07
Nitrogen, percent		0.05	0.01	0.03
Hydrogen, percent		0.015		0.01
Yttrium, percent		0.005		0.005
Residual Elements, each, percent		0.10		0.10
Residual Elements, total, percent		0.40		0.40
Titanium	Remainder		Remainder	

Table 3.1.1 AMS Specified Mechanical Properties

Specification	AMS 4985			AMS 4991			AMS 4962
	Separately Cast Bars	Castings		Separately Cast Bars	Castings		Castings
		Designated Areas	Non Designated Areas		Designated Areas	Non Designated Areas	
F_{tu} (ksi)	130	130	125	130	130	127	125
F_{ty} (ksi)	120	120	108	120	120	108	110
e (percent)	6	6	4.5	6	6	4.5	5.5

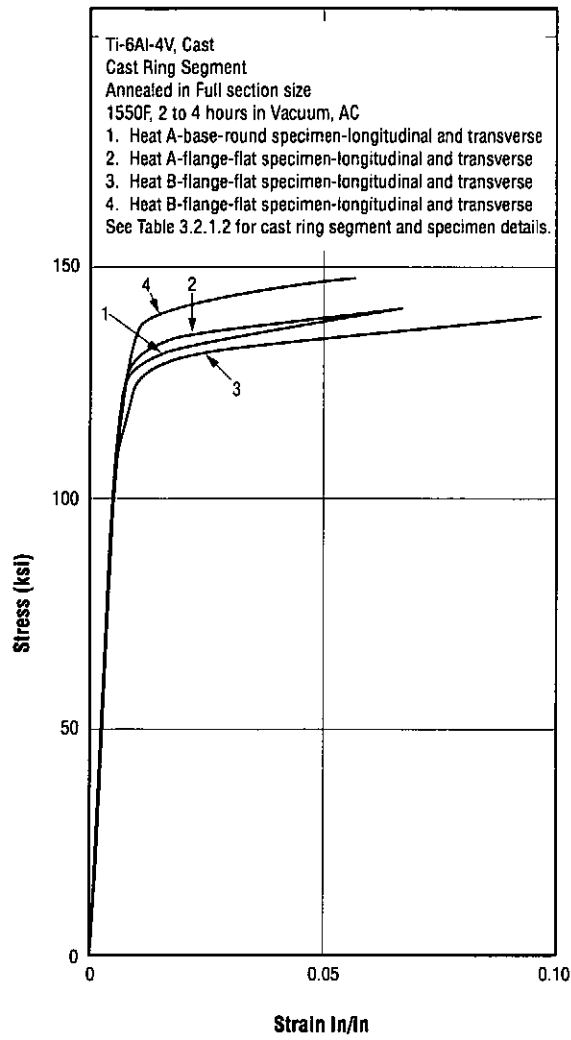


Figure 3.2.1.1 Typical stress-strain curves for annealed cast ring segments from two heats (Ref. 5)

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Accompanying Figure for Table 3.2.1.2 on next page

Table 3.2.1.2 Tensile properties including modulus of elasticity of annealed cast ring segments from two heats (Ref. 5)

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_u – ksi	126.7 - 139.0	134.0	3	23	124.0-137.5	132.7	2	15
F_y – 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	14.9-10.0	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_u – ksi	136.7 - 146.2	142.1	3	10(e)	135.8-147.9	141.2	3	18
F_y – 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_u – ksi	136.7 - 149.6	142.2	3	9	140.1 - 150.5	142.7	3	11
F_y – 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.

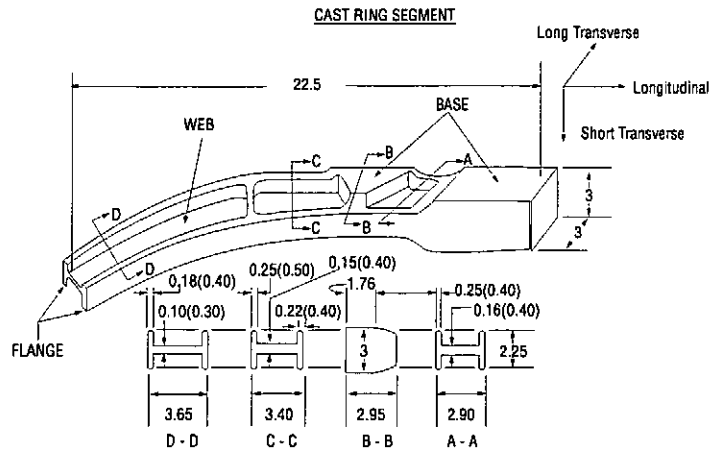
(e) One specimen failed outside test section.

(f) Not determined for one specimen.

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Figure accompanying Table 3.2.1.2



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

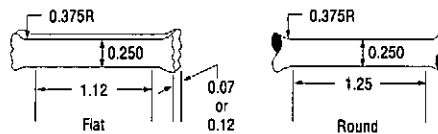


Table 3.2.1.3 Mechanical property comparison for excised vs. integrally cast specimens (Ref. 26)

Heat No.	Ultimate Tensile Strength (ksi)	Tensile Yield Strength (ksi)	Elongation (percent in 4D)	Reduction of Area (percent)
8840 ¹	136.6	127.2	10.0	24.4
Castings from 8840 ²	133.6	124.2	12.2	21.1
8842 ¹	139.2	127.4	9.0	20.2
Castings from 8842 ²	133.5	124.1	9.9	18.2
8876 ¹	142.5	133.1	9.0	21.7
Castings from 8876 ²	136.2	126.9	12.5	16.6
9003 ¹	139.6	129.8	9.0	20.5
Castings from 9003 ²	136.0	125.7	11.8	17.3

¹ Integrally cast specimen

² Excised from casting
 Castings consisted of hinge assembly, 38 in x 7 1/2 in, 0.25 – 1.375 in thick, and inlet lip support, 11 in x 5 1/2 in, .14 in – .26 in thick.

Castings were investment cast, AMS 4991 chemistry.
 Castings were HIP'ed.

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Table 3.2.1.4 Comparison of room temperature properties from three sources of cast Ti-6Al-4V test material (Ref. 29)

Heat treat: HIP 1650F/15 ksi 2 hrs + Anneal 1350F 2 hrs			
	Separately Cast Test Bars Avg. of 312 tests	Cast on Test Part Avg. of 1113 tests	Test Bars Machined from Casting Avg. of 292 tests
F_{tu} (ksi)	131.6	128.5	123.4
F_{ty} (ksi)	119.1	117.5	113.2
e (percent)	10.8	10.1	8.8
RA (percent)	20.8	22.2	16.6

Table 3.2.1.5 Tensile test results for Ti-6Al-4V alloy castings at room temperature (Ref. 27)

Specimen condition ¹ and number ²	F _{TU} (ksi)	F _{TY} (ksi)	ε (4D) (percent)	RA (percent)
Cast:				
10E	145.6	131.2	10.0	15.0
10F	146.5	130.5	10.5	19.0
13B	145.8	130.4	10.5	15.5
15B	146.4	131.2	11.0	15.5
15D	144.8	130.3	11.5	13.0
16D ⁴	142.0	129.3	9.5	15.5
Mean	145.2	130.5	10.5	15.6
Standard Deviation	1.7	.7	.7	1.9
Cast and hot pressed ⁵				
3D	138.1	125.2	12.5	17.5
5D	138.3	126.3	11.0	18.5
9C	138.7	125.5	14.0	18.5
Mean	138.4	125.7	12.5	18.2
Standard Deviation	.3	.6	1.5	.6
Cast, milled and hot pressed ⁵				
4C	138.6	126.1	13.0	19.0
4D	138.2	125.9	10.0	15.0
19E	140.2	128.4	14.0	19.0
Mean	139.0	126.8	12.3	17.7
Standard Deviation	1.1	1.4	2.1	2.3

¹ All specimens were annealed at 1300F for 2 hrs.

² Explanation of specimen numbers: 20 castings were poured from 5 heats and numbered as follows: Castings 1-4 were from the first heat; Castings 5-8 were from the second heat; Castings 9-12 were from the third heat; Castings 13-16 were from the fourth heat; Castings 17-20 were from the fifth heat. The letter indicates specimen location in each casting: A is adjacent to B; B is adjacent to C, etc. See also Table 3.2.3.4.

³ 4D indicates a length equal to 4 Dia of the gauge section.

⁴ Specimen broke in outer quarter of gauge section.

⁵ "Hot pressed" refers to hot isostatic pressing, 2 hrs at 1650F and 15ksi.

Note: Although the above table does not show an advantage to HIP on the tensile properties, the advantage of HIP as noted in Section 1.5 is to eliminate internal shrinkage cavities, improving durability and damage tolerance properties. Casting weight 3.3 lbs.

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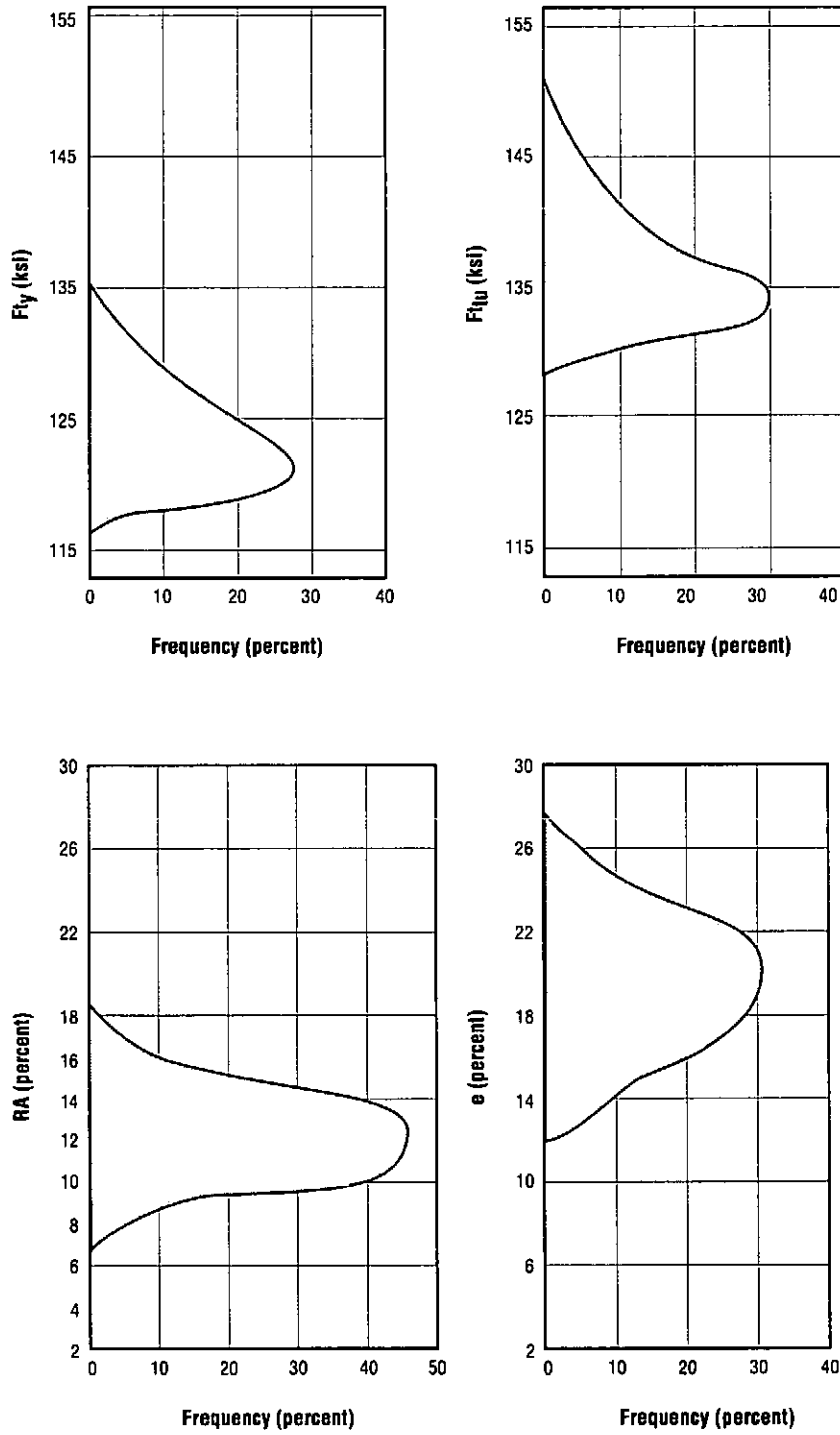


Figure 3.2.1.6 Frequency distribution of tensile properties of hot isostatically pressed and annealed Ti-6Al-4V casting test bars from 500 heats (Ref. 24)

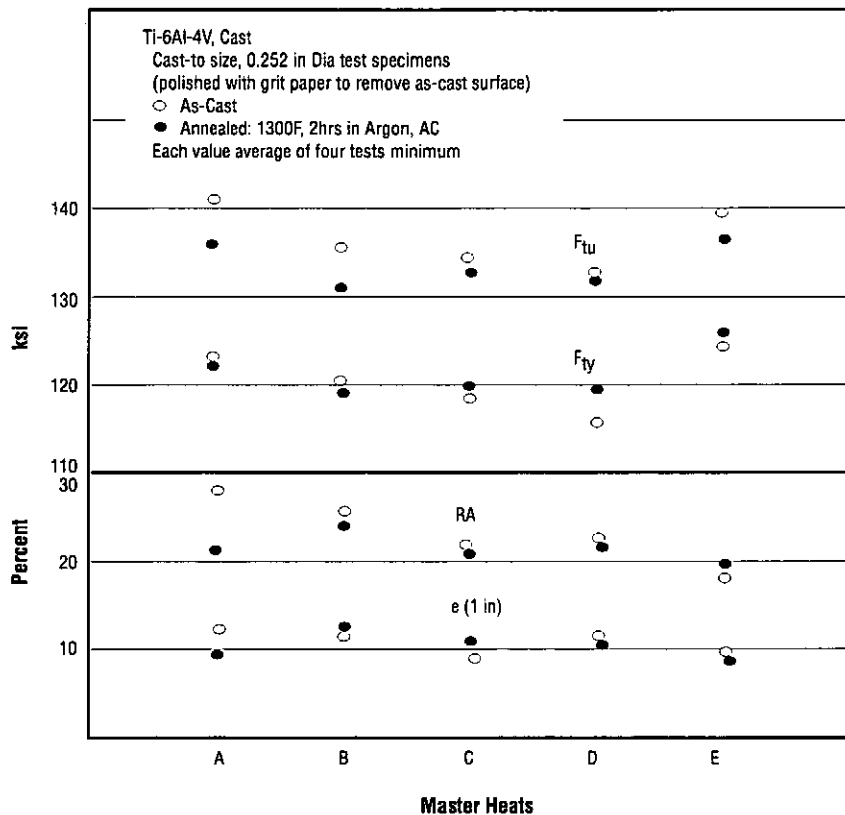


Figure 3.2.1.7 Variation in tensile properties of five master heats for the as-cast and annealed conditions (Ref. 9)

Table 3.2.1.8 Comparison of room temperature tensile properties for two heat treatments of cast Ti-6Al-4V alloy (Ref. 30)

Heat Treatment	HIP 1650F/15 ksi + Anneal 1550F	HIP 1750F/15 ksi + Solution treat 1750F Gas Fan Cool + Age 1150F
	Average of 136 tests	Average of 79 tests
F_{tu} (ksi)	132.0	138.7
F_{ty} (ksi)	118.1	124.8
e (percent)	11.8	9.6
RA (percent)	20.1	19.2

Ti-6Al-4V

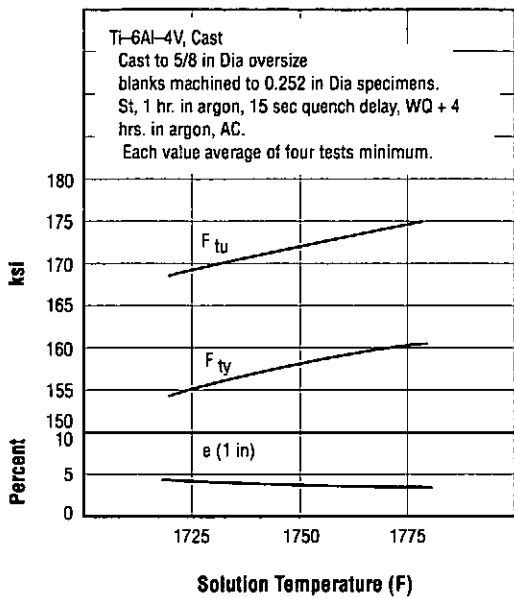


Figure 3.2.1.9 Effect of solution treat temperatures on tensile properties of solution treated and aged cast-to-size specimens (Ref. 9)

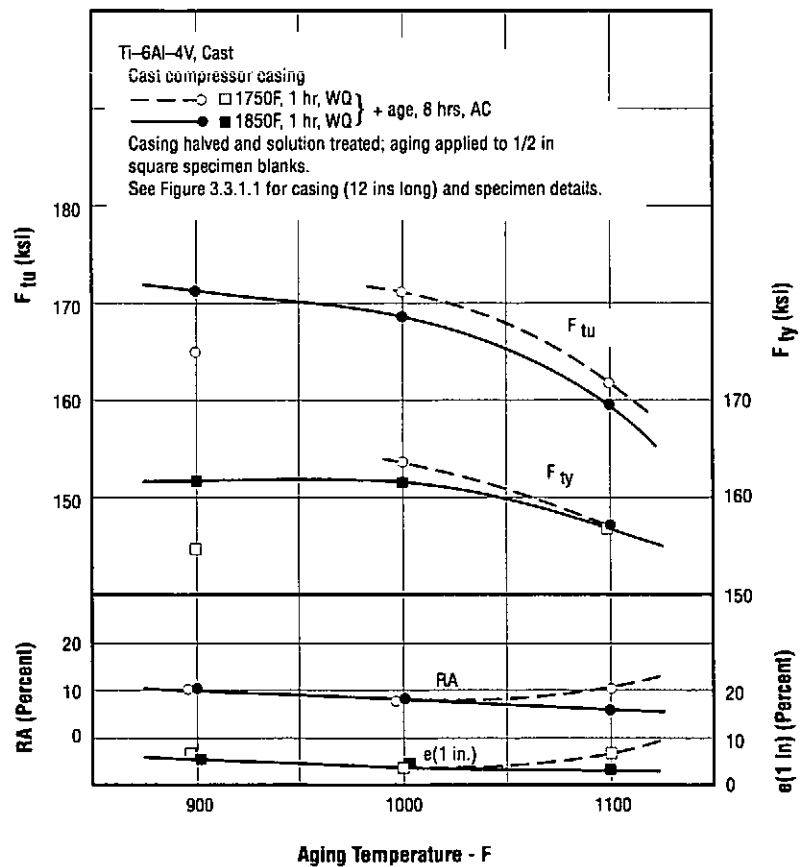


Figure 3.2.1.10 Effect of solution treat and aging temperatures on tensile properties of cast compressor casings (Ref. 4)

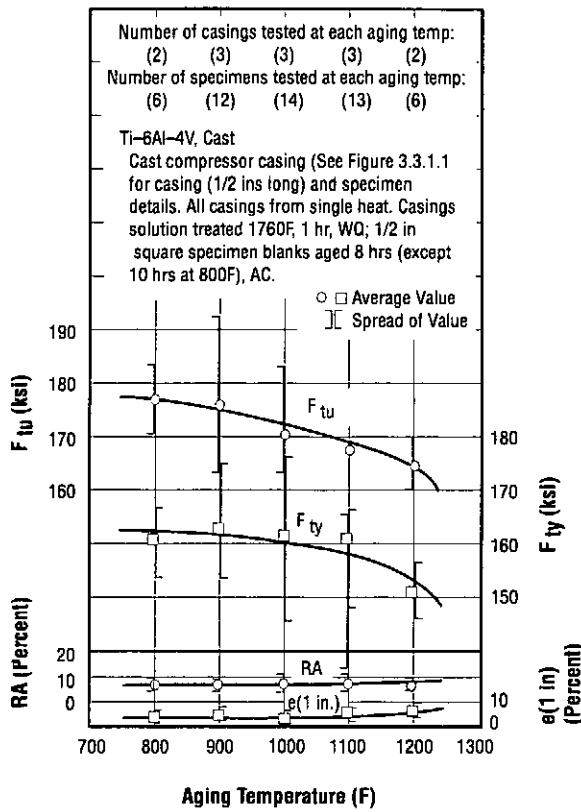


Figure 3.2.1.11 Effect of aging temperatures on tensile properties of three compressor casings cast from one heat (Ref. 4)

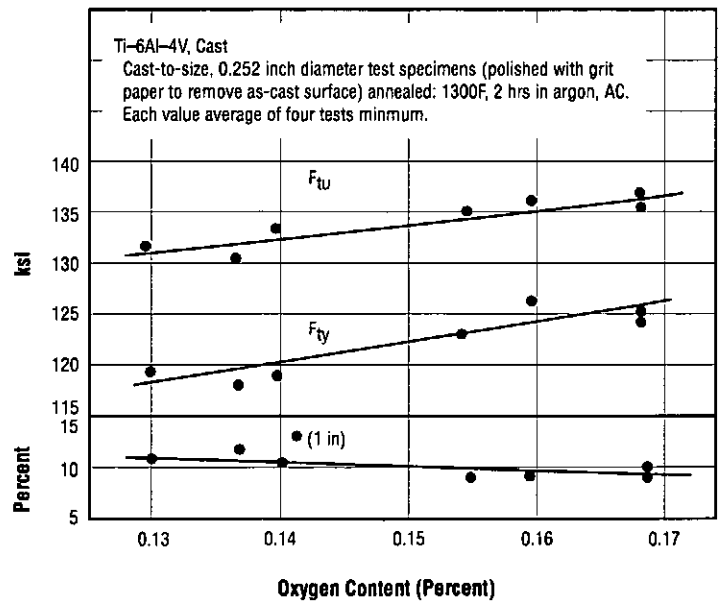


Figure 3.2.1.12 Effect of oxygen content on tensile properties of annealed cast-to-size specimens (Ref. 9)

Ti-6Al-4V

Table 3.2.1.13 Tensile properties of as-cast, annealed, and solution treated and aged castings from three manufacturers (Ref. 8)

Source	Lockheed-Georgia Company (8)			
Alloy	Ti-6Al-4V, Cast			
Form	Precision Castings			
Condition	Room Temperature Tensile Properties			
	F_{tu} (ksi)	F_{ty} (ksi)	e (1 in) (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 + Aged (d)	162	152	3.7	12.2
Casting Manufacturer Number 2 (g) (h)				
Solution Treated + Aged (d)	156	136	3.0	3.1
Casting Manufacturer Number 3 (e) (f)				
Solution Treated + Aged (d)	152	140	8.0	—

- (a) 10 lb casting; section thicknesses from 0.2 in to 2.0 in; 0.125 in. Dia 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: 1750F, 25 mins, WQ + 1000F, 4 hrs, AC.
- (d) 1 lb casting; section thickness 0.43 in; 0.25 in. Dia specimens, all located parallel to longitudinal axis of casting.
- (e) 1 lb casting; section thickness 0.43 in.; 0.25 in Dia specimens, all located parallel to longitudinal axis of casting.
- (f) Each value average of three tests.
- (g) 1 lb casting; section thickness 0.4 in in vicinity of specimen extraction; 0.25 in Dia specimens, all located in common direction with respect to casting geometry.
- (h) Each value average of four tests

Each casting manufacturer uses his own heat.

Table 3.2.1.14 Tensile properties for a solution treated and annealed condition and two solution treated and aged conditions (Ref. 6)

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 hr in Argon, 15 sec quench delay, WQ + 1300F, 2 hrs in Argon, AC
 (b) 1750F, 1 hr in Argon, 15 sec quench delay, WQ + 1000F, 4 hrs in Argon, AC
 (c) 1650F, 1 hr in Argon, 15 sec quench delay, WQ + 1000F, 4 hrs in Argon, AC

Table 3.2.1.15 Effects of aging temperature on tensile properties of cast-to-size specimens (Ref. 9)

Source		Precision Castparts Corporation (9)			
Alloy		Ti-6Al-4V, Cast			
Form		Cast- to-Size Specimens ^(a)			
Condition		1725F, 1 hr in Argon, 15 sec Quench Delay, WQ + Age			
Aging		Room temperature Tensile Properties ^(b)			
Temperature (F)	Time (Hours)	F _{tu} (ksi)	F _{ty} (ksi)	e (4D) (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

(a) Cast to 5/8 in. Dia blanks and machined to 0.252 in. Dia specimens.
 (b) Each value average of two tests.

Ti-6Al-4V

Table 3.2.1.16 Effects of salvage heat treatment on tensile properties of annealed, low-oxygen cast-to-size specimens (Ref. 9)

Source	Precision Castparts Corporation (9)			
Alloy	Ti-6Al-4V, Cast			
Form	Cast-to-Size Specimens			
Oxygen Content Weight Percent	Heat Treatment	Room temperature Tensile Properties ^(a)		
		F _{tu} (ksi)	F _{ty} (ksi)	e (4D) (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 hrs., AC

(c) 1750F, 1 hr., WQ + 1300F, 2 hrs AC.

Table 3.2.1.17 Effects of exposure to elevated temperatures with load on tensile properties of annealed cast compressor casing (Ref. 4)

Source			AVCO Corporation, Lycoming Division (4)			
Alloy			Ti-6Al-4V, Cast			
Form			Cast Compressor or casing (a)			
Condition			Annealed 1300F, 2 hrs, 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 in) (percent)	RA(percent)
Unexposed	Average Spread		143.9	131.0	9.4	15.5
			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	528.0	152.8	148.2	4.0	7.2
700	85	1510.0	155.1	154.7	2.0	8.2
700	80	1603.0	152.8	147.4	7.0	12.6
900	45	500.0	153.1	150.2	6.0	8.9

(a) See Figure 3.3.1.1 for compressor casing (20 in long) and specimen details.

(b) Casing annealed in full section size.

(c) Specimens tested as exposed: surface not dressed.

(d) Unexposed values from fifteen test; exposed values from individual tests.

Table 3.2.1.18 Tensile test results for several solution heat treat and aging conditions (Ref. 31)

Condition	Avg F_{tu} (ksi)	Avg F_{ty} (ksi)	Avg e (percent)	Avg RA (percent)	No. of Specimens
1 (Baseline)	139	122	11	19	6
2	153	134	7	13	6
3	152	136	7	12	6
4	146	130	8	12	5
5	150	134	8	15	5
6	153	135	9	15	6
7	148	135	8	12	6
8	150	136	6	13	6

Heat treat conditions:

1. Baseline (no solution treatment or aging).
2. Soln. treat 1880F/0.5 hr./water quench/1500F age/24hrs/air cool.
3. Soln. treat 1880F/0.5 hr./oil quench/1500F age/24hrs/air cool.
4. Soln. treat 1880F/0.5 hr./gas fan cool/1500F age/24hrs/air cool.
5. Soln. treat 1880F/0.5 hr./gas fan cool/1150F age/2 hrs/air cool.
6. Soln. treat 1880F/0.5 hr./gas fan cool/1000F age/8 hrs/air cool.
7. Soln. treat 1750F/1 hr./gas fan cool/1150F age/ 2 hrs/air cool.
8. Soln. treat 1750F/1 hr./gas fan cool/1000F age/ 8 hrs/air cool.

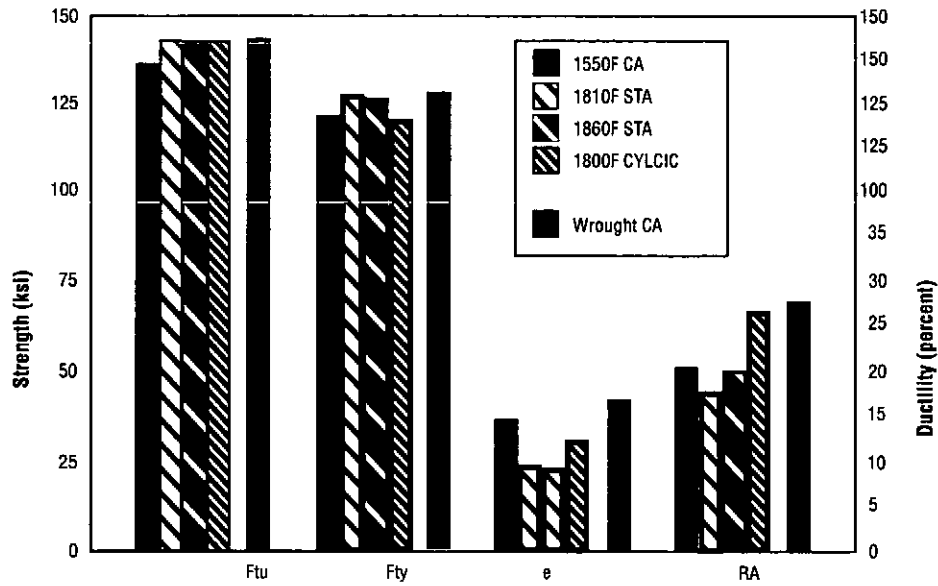
Beta transus. calculated to be 1825F.

All material was HIP'ed at 1650F/15ksi /2hrs.

Castings were oversized test bars, cast in clusters of 28.

Chemical composition in accordance with AMS4985.

Ti-6Al-4V



- 1550F CA Conventional anneal at 1550F/2 hrs. in vacuum/argon fan cool
- 1810F STA A "below beta" solution treatment and age, consisting of solution treatment at 1810F/1hr. in vacuum, an inert gas fan cool at a rate equivalent to air cooling (GFC)
- 1860F STA An "above beta" solution treatment and age, consisting of 1860F/1 hr. in vacuum /GFC + 1000F/8hrs in vacuum/GFC
- 1800 Cyclic A "below beta" cyclic exposure involving six cycles of 1800F/10 min in vacuum/GCF to 1000F/10 min. in vacuum/heat to 1800F, followed by a gas fan cool to 70F
- Wrought CA Conventional anneal applied to wrought products, 1550F/2 hrs.

Figure 3.2.1.19 Effect of thermal treatment on the 70F tensile properties of cast and HIP'ed Ti-6Al-4V alloy and the wrought alloy (Ref. 32)

Table 3.2.1.20 Tensile test results for two heat treat conditions (Ref. 28)

Ti-6Al-4V investment cast oversize test bars, .063 in. Dia x 5 in long						
Chemistry per AMS 4992						
Condition	Specimen No.	F _{TU} (ksi)	F _{TY} (ksi)	e (percent)	RA (percent)	E x 10 ⁶
Annealed 1550 F, 2 hrs., Gas furnace cool	1	129			22	
	2	133	122	10	19	18
	3	137	125	7	22	18
	Average	135	124	9	21	18
Beta Solution Treated 1880 F, 30 min., Gas furnace cool, + 1150 F 2 hrs., air cool	1	142	128	10	20	18
	2	145	132	9	16	17
	3	146	133	9	15	17
	Average	144	131	9	17	17

Ti-6Al-4V

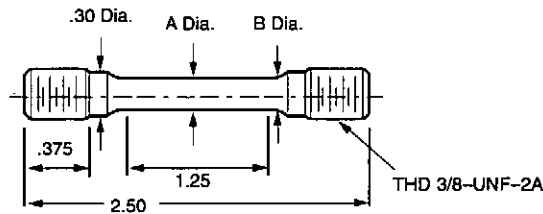
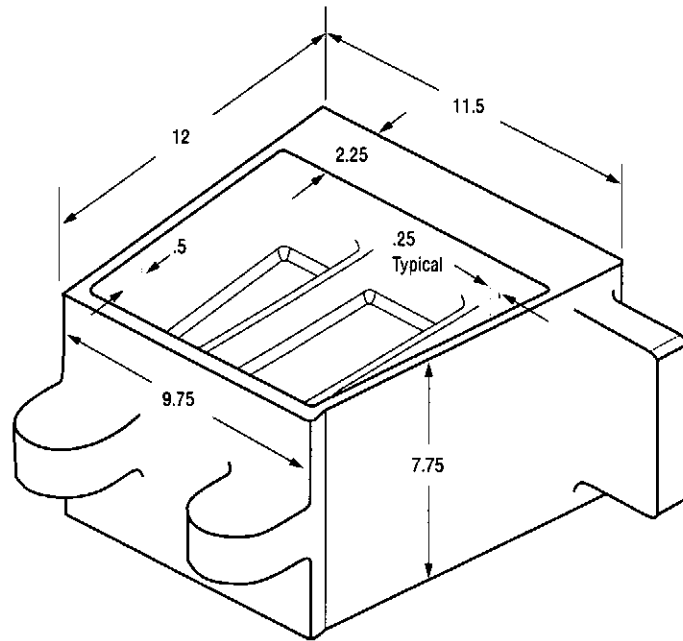
Table 3.2.1.21 Effect of 1000 hours exposure at 550F without load on tensile properties including elastic modulus of annealed ring segments from two heats (Ref. 5)

Source		LTV Aerospace Corporation, Vought Aeronautics				
Alloy		Ti-6Al-4V, Cast				
Form		Cast Ring Segments (a)				
Condition		Annealed 1550F, 2 to 4 hrs in Vacuum, AC (b)				
			Room Temperature Tensile Property			
Casting	Specimen (c) Orientation	Exposure Condition	F _u ksi	F _y ksi	E 10 ³ ksi	e (1 in) (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	16.8	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 3.2.1.2 for ring segment details.
(b) Annealed in full section size.
(c) See Table 3.2.1.2 for specimen configuration (flat type) and orientation.
(d) Exposed 350F, 1000 hrs.
(e) Incomplete load – displacement curve.
(f) Bad reading.

Table 3.2.1.22 Effect of beta anneal vs standard mill anneal on room temperature tensile properties of complex castings (Ref. 34)

Heat Treatment	Anneal at 1900F + 1550F age	Mill anneal at 1550F
F _{TU} (ksi)	130 - 144	130 - 135
F _{Ty} (ksi)	120 - 128	113 - 124



A	.250 Max - .245 Min
B	A +.002 TO A +.003

Dimensions are in Inches
Tensile Specimen Configuration

Two castings were supplied by Howmet. Each contained extensive planned weld repairs. One casting was HIP'ed at 1650F followed by 1550F anneal. The other was HIP'ed at 1650F followed by beta anneal at 1900F and aged at 1550F.

Ti-6Al-4V

Table 3.2.2.1 Compressive strength and modulus of elasticity of cast ring segments from two heats (Ref. 5)

Source		LTV Aerospace Corporation, Vought Aeronautics			
Alloy		Ti-6Al-4V, Cast			
Form		Cast Ring Segments (a)			
Condition		Annealed 1550F, 2 to 4 hrs in Vacuum, AC (b)			
		Specimen (c)		Room Temperature Tensile Property	
Heat	Casting	Location(a)	Exposure Condition	F _{cy} (ksi)	E _t (10 ³ ksi)(b)
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	Range	Longitudinal	146.4	15.4
B	2	Range	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	18.5
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 3.2.1.2 for ring segment and specimen orientation details.

(b) Annealed in full section size.

(c) Specimen 2.70 ins long, 0.65 in wide and 0.10 in thick.

For comparative tensile properties, see Table 3.2.1.2

Table 3.2.2.2 Compressive yield strength and modulus of elasticity of as-cast, annealed and solution treated and aged castings from two separate casting manufactures (Ref. 8)

Source	Lockheed – Georgia Company (8)		
Alloy	Ti-6Al-4V, Cast		
Form	Precision Castings		
	Room Temperature Properties		
Condition	F _{ty} (ksi) (a)	F _{cy} (ksi) (b)	E _c (0 ³ ksi) (b)
Casting Manufacturer Number 1 (c)			
As-Cast	127	137	16.7
Annealed (d)	126	148	17.0
Solution Treat + Age (e)	152	179	17.2
Casting Manufacturer Number 2 (f)			
Solution Treat + Age (e)	136	145	–
<p style="text-align: center;">Compression Specimen</p>			

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

Ti-6Al-4V

Table 3.2.3.1 Standard Charpy-V impact energy of annealed cast-to-size specimen from two heats (Ref. 4)

Source		AVCO Corporation Lycoming Division (4)
Alloy		Ti-6Al-4V, Cast
Form		Cast-to-Size specimens
Condition		Annealed 1300F, 2 hrs., AC ⁽¹⁾
Heat	Specimen Number	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

(1) Conventional tensile properties:

Heat A: $F_{tu} = 144.8$ ksi, $F_{ty} = 127.3$ ksi, $e(1 \text{ in}) = 11.7$ percent, $RA = 25.8$ percent

Heat B: $F_{tu} = 145.1$ ksi, $F_{ty} = 132.7$ ksi, $e(1 \text{ in}) = 10.5$ percent, $RA = 21.6$ percent

Table 3.2.3.2 Standard Charpy-V impact energy of annealed cast ring segments from two heats (Ref. 5)

Source		LTV Aerospace Corporation, Vought Aeronautics Division (5)			
Alloy		Ti-6Al-4V, Cast			
Form		Cast Ring Segments (a)			
Condition		Annealed 1550F, 2 to 4 hrs 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 3.2.1.2 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.

Table 3.2.3.3 Standard Charpy-V impact energy of solution treated and aged casting (Ref. 8)

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

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

Ti-6Al-4V

Table 3.2.3.4 Charpy V-notch results for Ti-6Al-4V alloy castings at room temperature (Ref. 27)

Specimen condition ¹ and number ²	Impact strength ³ (ft lb)
Cast:	
1A	23.0
7A	22.5
10A	23.3
11A	20.2
16A	19.9
20A	20.0
Mean	21.5 ⁵
Std. Dev.	1.6
Cast and hot pressed: ⁴	
5A	17.5
17A	19.0
18A	20.7
Mean	19.1 ⁵
Std. Dev.	1.6
Cast, milled, and hot pressed: ⁴	
2A	18.0
6A	18.5
19A	16.9
Mean	17.8 ⁵
St. Dev.	0.8

¹ All specimens were annealed at 1300F for 2 hrs.

² See Table 3.2.1.5 for explanation of specimen numbers and tensile properties.

³ Fracture type ductile.

⁴ "Hot pressed" refers to hot isostatic pressing.

⁵ Compare with average of 19.2 for specimens machined from investment cast aircraft parts.

Table 3.2.3.5 Charpy V-notch and fracture toughness test results for several heat treatments (Ref. 32).

Heat Treatment (See Fig. 3.2.1.19 for explanation of heat treatment)	Charpy V-Notch Impact Energy (ft lbs)	Fracture Toughness, K _Q (ksi in ^{-1/2})
1550F CA	25.6 24.9 <u>24.8</u> 25.1	96.7 88.5 <u>96.0</u> 93.7
Mean		
1810 F STA	22.6 21.2 <u>20.8</u> 21.5	
Mean		
1860F STA	20.0 19.2 <u>21.2</u> 20.1	
Mean		
1800F Cyclic	29.9 22.1 <u>26.2</u> 26.1	
Mean		

Table 3.2.5.1 Shear strength of annealed cast ring segments from two heats (Ref 5)

Source		LTV Aerospace Corporation, Vought Aeronautics Division (5)
Alloy		Ti-6Al-4V, Cast
Form		Cast Ring Segments (a)
Condition		Annealed 1550F, 2 to 4 hrs 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 3.2.1.2 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 3.2.1.2 for corresponding conventional tensile properties.

Ti-6Al-4V

Table 3.2.5.2 Double shear strength of solution treated and aged casting (Ref. 8)

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

- (a) 1-lb casting; section thickness 0.43 in; 0.375 in. Dia double-shear specimens oriented parallel to longitudinal axis of casting.
 (b) Solution treated and aged in full section size: 1750F, 25 mins., WQ + 100F, 4 hrs., AQ.
 (c) Average of two test.

Table 3.2.6.1 Bearing strength of annealed cast ring segments from two heats (Ref. 5).

Source		LTV Aerospace Corporation, Vought Aeronautics Division (5)	
Alloy		Ti-6Al-4V, Cast	
Form		Cast Ring Segments (a)	
Condition		Annealed 1550F, 2 to 4 hrs 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 3.2.1.2 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 3.2.1.2 for corresponding conventional tensile properties.

Table 3.2.6.2 Bearing strength of solution treated and aged castings (Ref. 8)

Source	LTV Aerospace Corporation, Vought Aeronautics Division (8)	
Alloy	Ti-6Al-4V, Cast	
Form	Precision Casting (a)	
Condition	Solution Treat + Age (b)	
Room temperature Bearing Properties (c)		
F_{bru} (c) (d) (ksi)	F_{bry} (c) (d) (ksi)	e/D
216	(d)	1.50
240	234	1.52
214	224	1.50

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

Ti-6Al-4V

Table 3.2.7.1.1 Mild-notch strength of annealed casting segments from two heats (Ref. 5).

Source	LTV Aerospace Corporation, Vought Aeronautics Division (5)		
Alloy	Ti-6Al-4V, Cast		
Form	Cast Ring Segments (a)		
Condition	Annealed 1550F, 2 to 4 hrs in Vacuum, AC (b)		
		Room Temperature Property	
Casting	Specimen Orientation (c)	F _y (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	148.0
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	–
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 3.2.1.2 for ring segment details.
 (b) Annealed in full section size.

Table 3.2.7.2.1 Fracture toughness test results (Ref. 26)

Fracture Toughness (K_{Ic}) (ksi in. ^{1/2})	
Ti-6Al-4V investment castings	
HIP'ed at 1650F/15 ksi/2 hrs	
Compact Tension (Per ASTM E-399)	Short-rod (Per SAE ARP 1704)
97.3	102.0
99.5	113.3
89.7	113.1
97.1	106.9
102.3	110.3

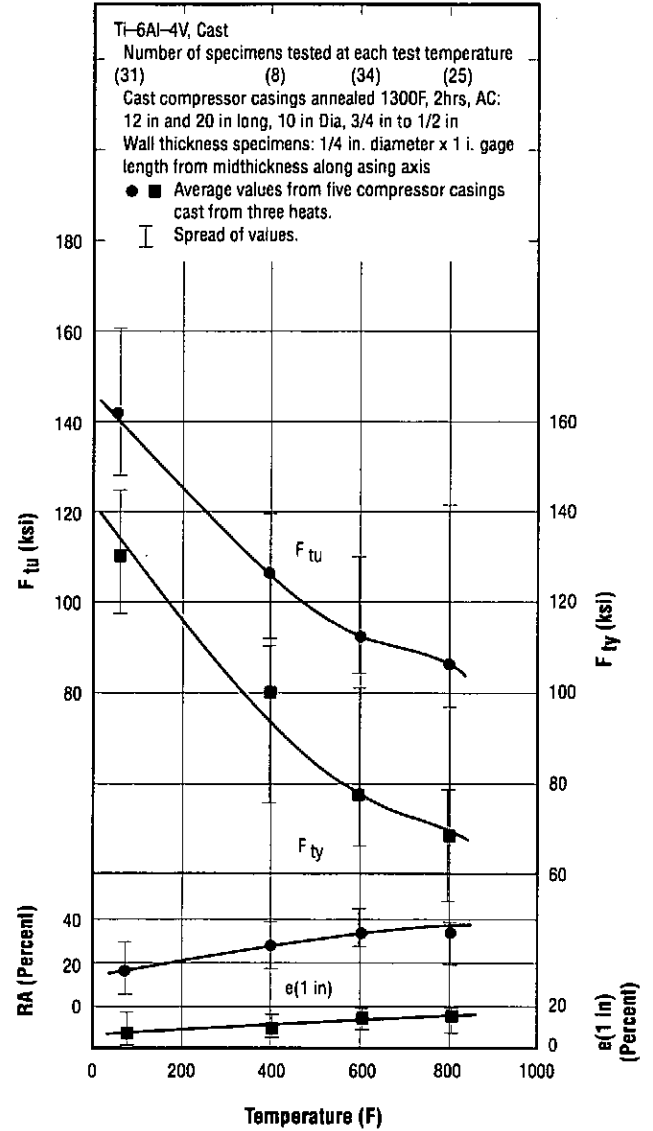


Figure 3.3.1.1 Effect of test temperatures on tensile properties of five annealed cast compressor casings from three heats (Ref. 4)

Ti-6Al-4V

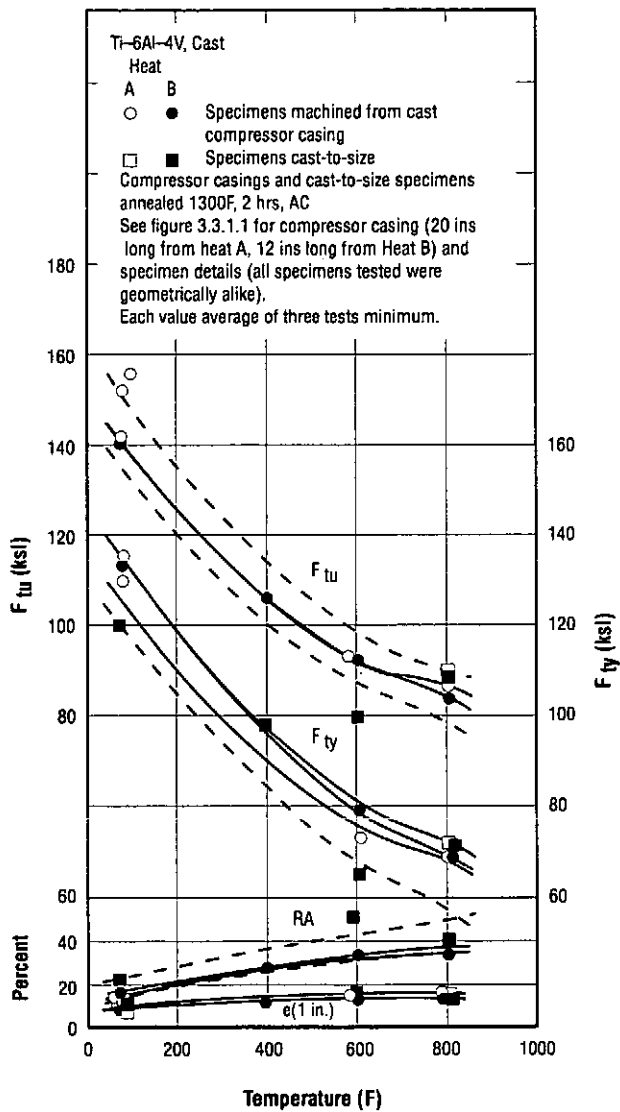


Figure 3.3.1.2 Effect of test temperatures on tensile properties of specimens machined from annealed cast compressor casings and annealed cast-to-size specimens each from two heats (Ref. 4)

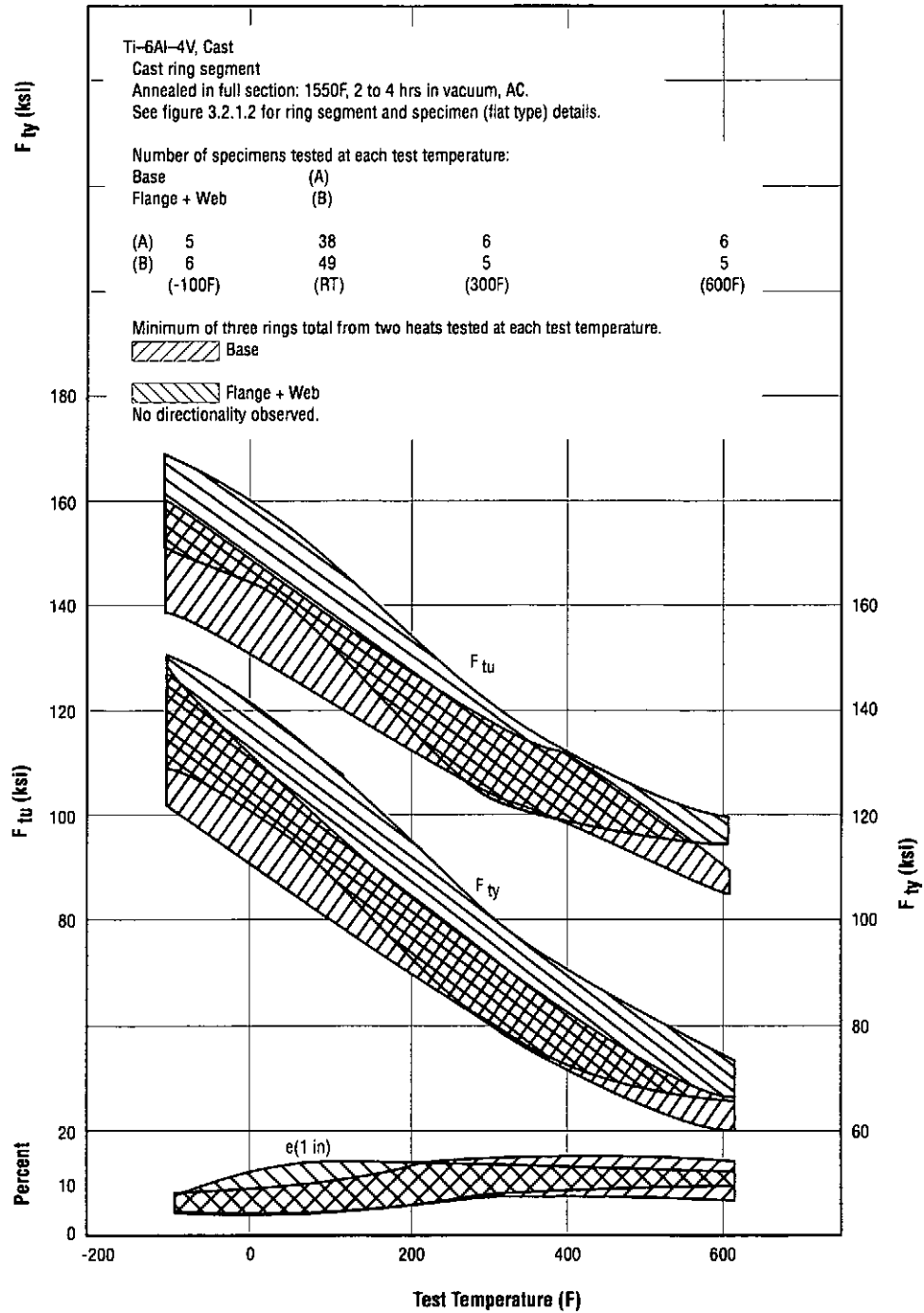


Figure 3.3.1.3 Effect of test temperatures on tensile properties of annealed cast ring segments from two heats (Ref. 5)

Ti-6Al-4V

Table 3.3.1.4 Summary of tensile test results at room and low temperatures from Ti-6Al-4V investment castings of standard composition and extra low interstitials from two foundries (Ref. 28)

Test group	Test Temperature (F)	F _{tu} (ksi)	F _{ty} (ksi)	e (percent)
Foundry A ELI ¹	RT	128.52	123.58	7.5
	-320	201.28	186.76	2.7
	-423	225.30	210.67	2.0
Foundry B STD ²	RT	129.23	118.33	6.16
	-320	206.77	197.20	4.0
	-423	221.30	213.40	2.75
Foundry A STD ² 1350 F Anneal	RT	135.83	129.38	9.3
	-320	211.09	201.33	6.0
	-423	241.99	223.61	4.5
Foundry B STD ² 1550 F Anneal	RT	133.61	123.93	7.67
	-32	210.76	197.39	6.0
	-4230	236.27	217.18	5.3

¹Extra low interstitials²Standard chemistry per AMS 4985

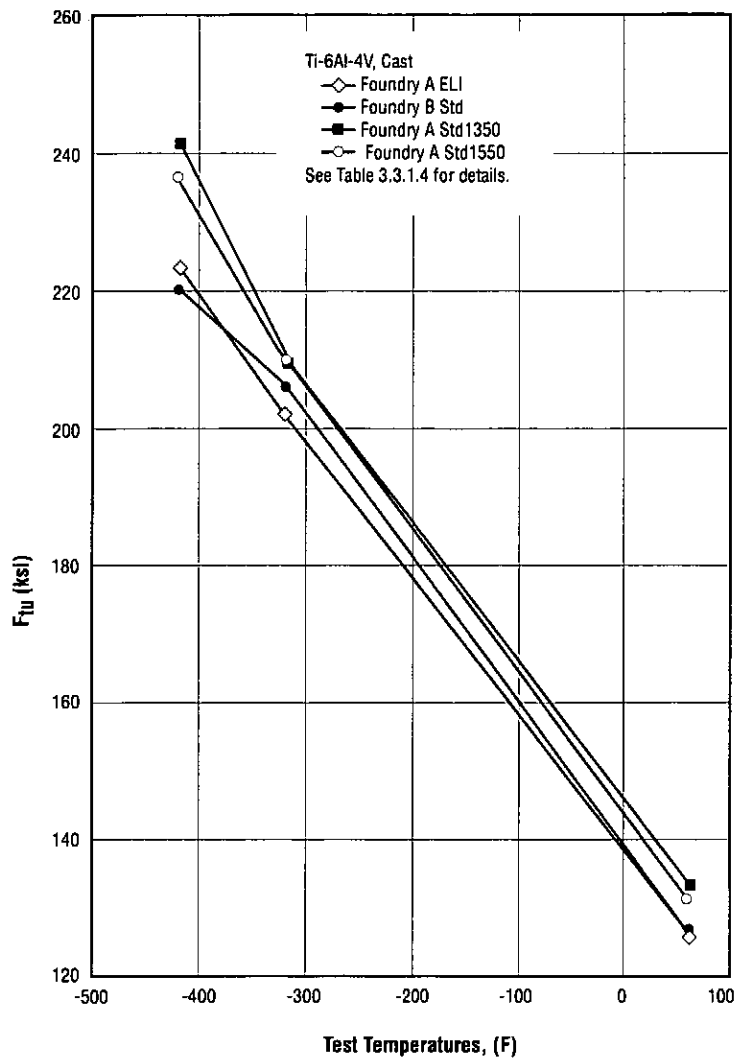


Figure 3.3.1.5 Effects of test temperature on ultimate tensile strength of standard composition and extra low interstitials casings (Ref. 28)

Ti-6Al-4V

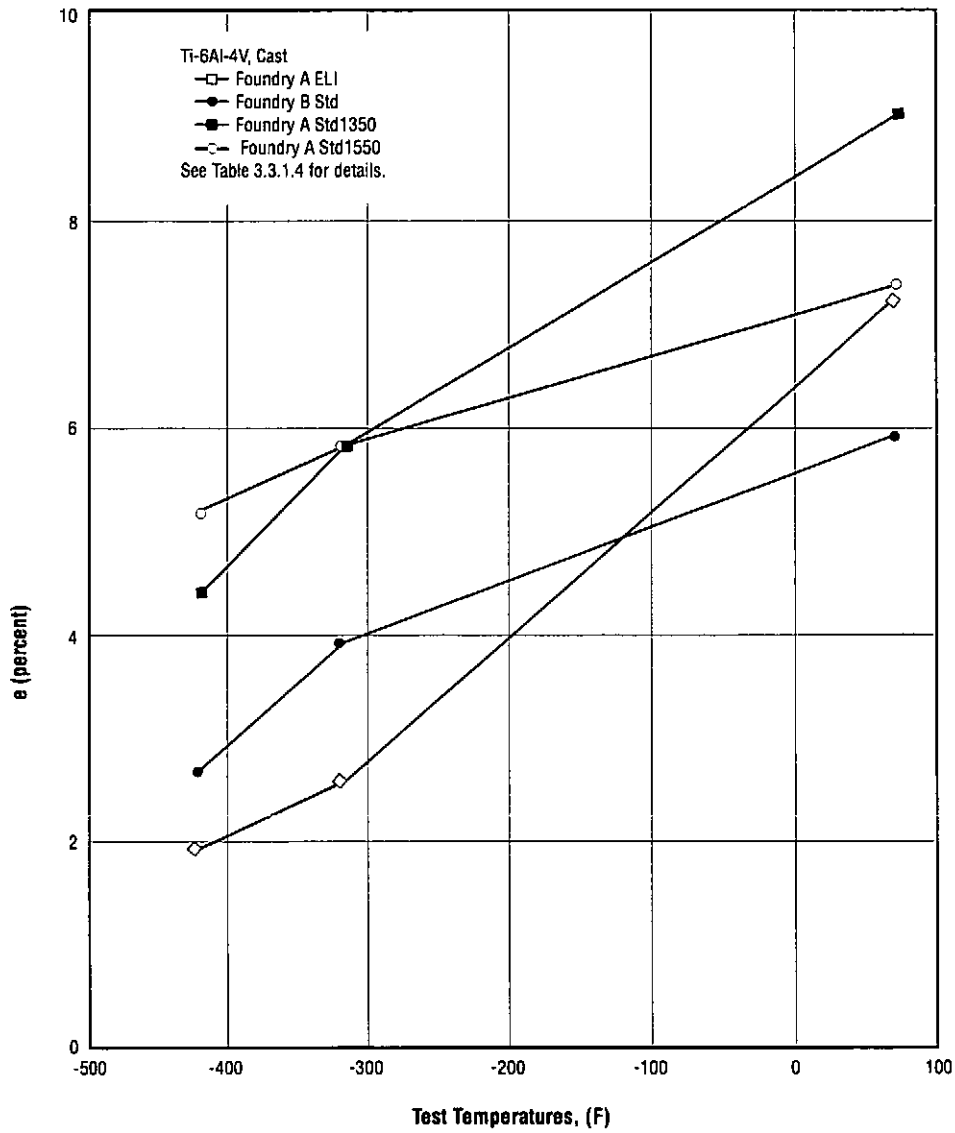


Figure 3.3.1.6 Effects of test temperature on percent elongation of standard composition and extra low interstitials casings (Ref. 28)

Table 3.3.7.1.1 Fracture toughness results summary of Ti-6Al-4V investment castings (Ref. 28)

Test Group ¹	Test Temp (F)	K _Q , (ksi in. ^{1/2})
Foundry A ELI	RT	102.44
	-320	76.76
	-423	67.49
Foundry B STD	RT	102.86
	-320	70.91
	-423	67.99
Foundry A STD 1350F Anneal	RT	94.39
	-320	60.21
	-423	54.84
Foundry A STD 1550F Anneal	RT	86.73
	-320	63.95
	-423	56.95

¹ See Table 3.3.1.4 for tensile properties and explanation of test group

² K_Q per ASTM E399

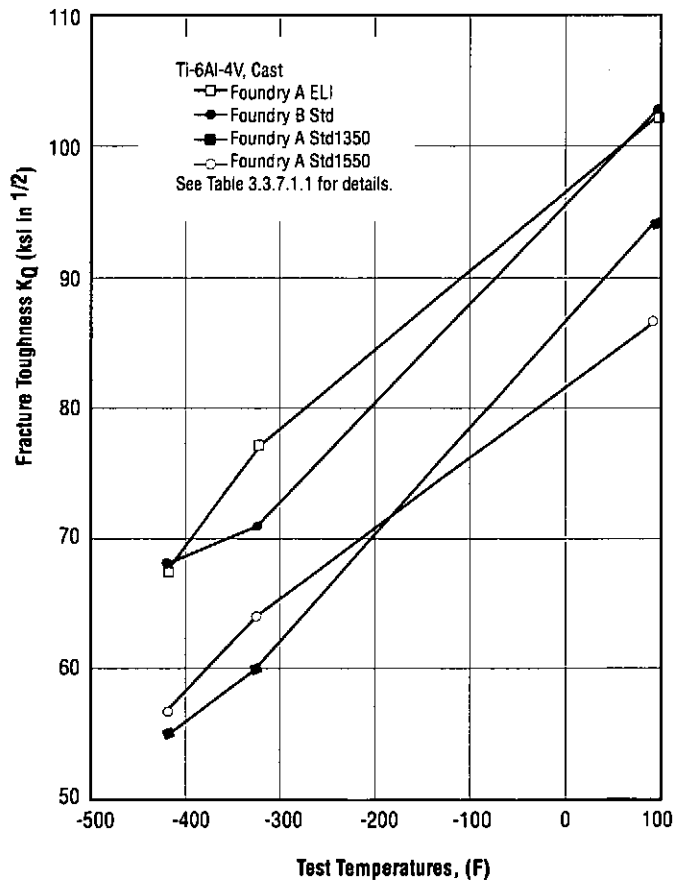


Figure 3.3.7.1.2 Effects of test temperature on the fracture toughness of standard composition and extra low interstitials castings (Ref. 28)

Ti-6Al-4V

Table 3.4.1 Effects of solution treat and aging temperatures on 800F, 80ksi stress rupture life of cast compressor casing (Ref.4)

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 hrs, AC (F)	Time to Rupture (hrs)	e (1 inch) (percent)
Solution Treat 1750F, 1 hr., 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 hr., 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 3.3.1.1 for compressor casing (12 ins long) and specimen details.

(b) Casing halved and solution treated; aging applied to 1/2 in square specimen blanks. See Figure 3.2.1.10 for room temperature tensile properties of material tested.

(d) Test retired.

Table 3.4.2 Room temperature stress rupture results for mild-notch specimens machined from annealed cast compressor casing and cast-to-size specimens (Ref.4)

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 hrs, AC (c)				
Heat	Specimen Number	Room Temperature Mild-Notch Stress Rupture Properties				Total Life hrs
		Hrs at Indicated Stress				
		160 ksi	170 ksi	180 ksi	190 ksi	
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 3.3.1.1 for compressor casing (20 ins long) and specimen details.
- (b) Specimens cast to 1/2 in. Dia oversize specimen blanks subsequently machined to finished specimens.
- (c) Cast compressor casing annealed in full section size: $F_u = 143.9$ ksi, $F_y = 131.0$ ksi, e (1 in) = 9.4 percent, RA = 15.5 percent.
 Cast-to-size specimens annealed as oversize specimen blanks: Heat B, $F_u = 144.8$ ksi, $F_y = 127.3$ ksi, e (1 in) = 11.7 percent, RA = 25.8 percent.
 Heat C, $F_u = 145.1$ ksi, $F_y = 132.7$ ksi, e (1 in) = 10.5 percent, RA = 21.6 percent.
- (d) Test retired.

Ti-6Al-4V

Table 3.4.3 500F stress rupture properties of cast-to-size smooth and mild-notch specimens from two heats (Ref.4)

Source		AVCO Corporation, Lycoming Division (4)		
Alloy		Ti-6Al-4V, Cast		
Form		Cast-to-Size Specimens (a)		
Condition		Annealed 1300F, 2 hrs., AC (c)		
		500F Stress Rupture Properties		
Heat	Specimen Number	Stress (ksi)	Life (hrs)	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 in. Dia cast oversize specimen blanks subsequently machined to finished specimens.
- (b) Annealed as oversize specimen blanks: Room Temperature
Tensile Properties – Heat A; $F_w = 144.8$ ksi $F_y = 127.3$ ksi, e (1 in) = 11.7 percent, RA – 25.8 percent.
Heat B; $F_w = 145.1$ ksi $F_y = 132.7$ ksi, e (1 in) = 10.5 percent, RA – 21.6 percent.
- (c) Smooth specimens 1/4 in. Dia x 1 in gage length.
- (d) Broke immediately after loading to indicated stress.
- (e) Test discontinued.
- (f) See Table 3.4.2 for mild-notch specimen configuration.

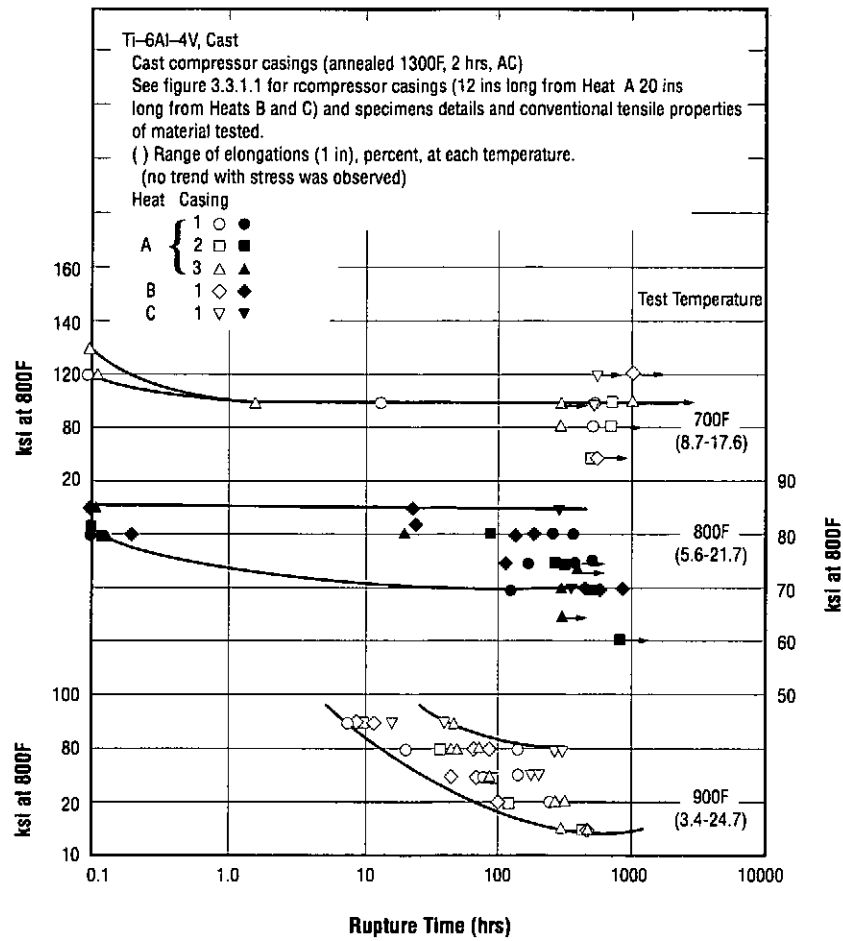


Figure 3.4.4 Stress rupture curves at 700, 800 and 900F for specimens machined from five annealed cast compressor casings from three heats (Ref. 5)

Ti-6Al-4V

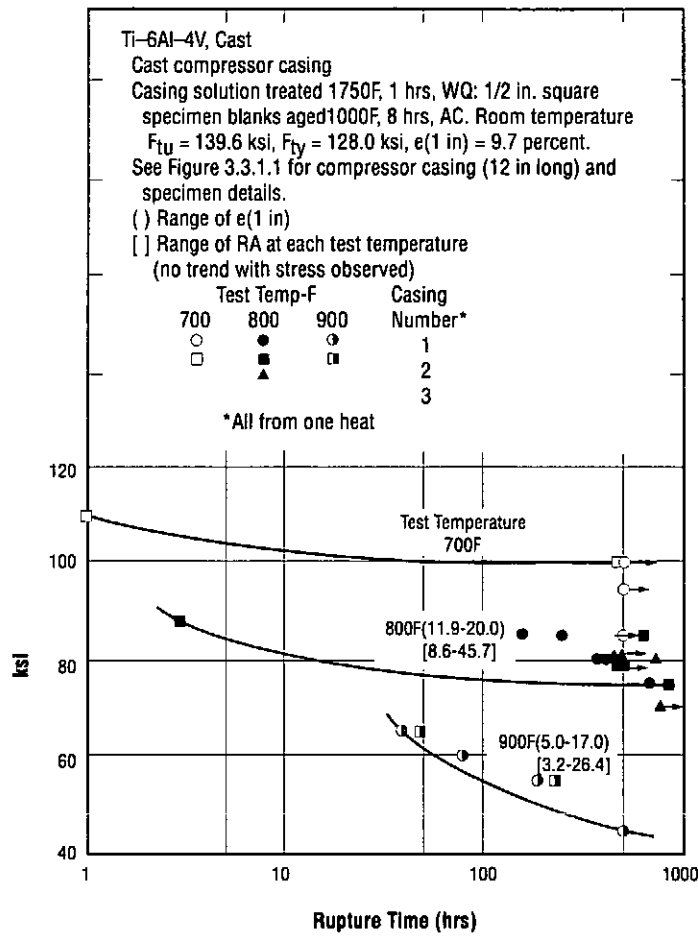


Figure 3.4.6 Stress rupture curves at 700, 800, and 900F for specimens machined from cast compressor casing aged at 1000F (Ref. 4)

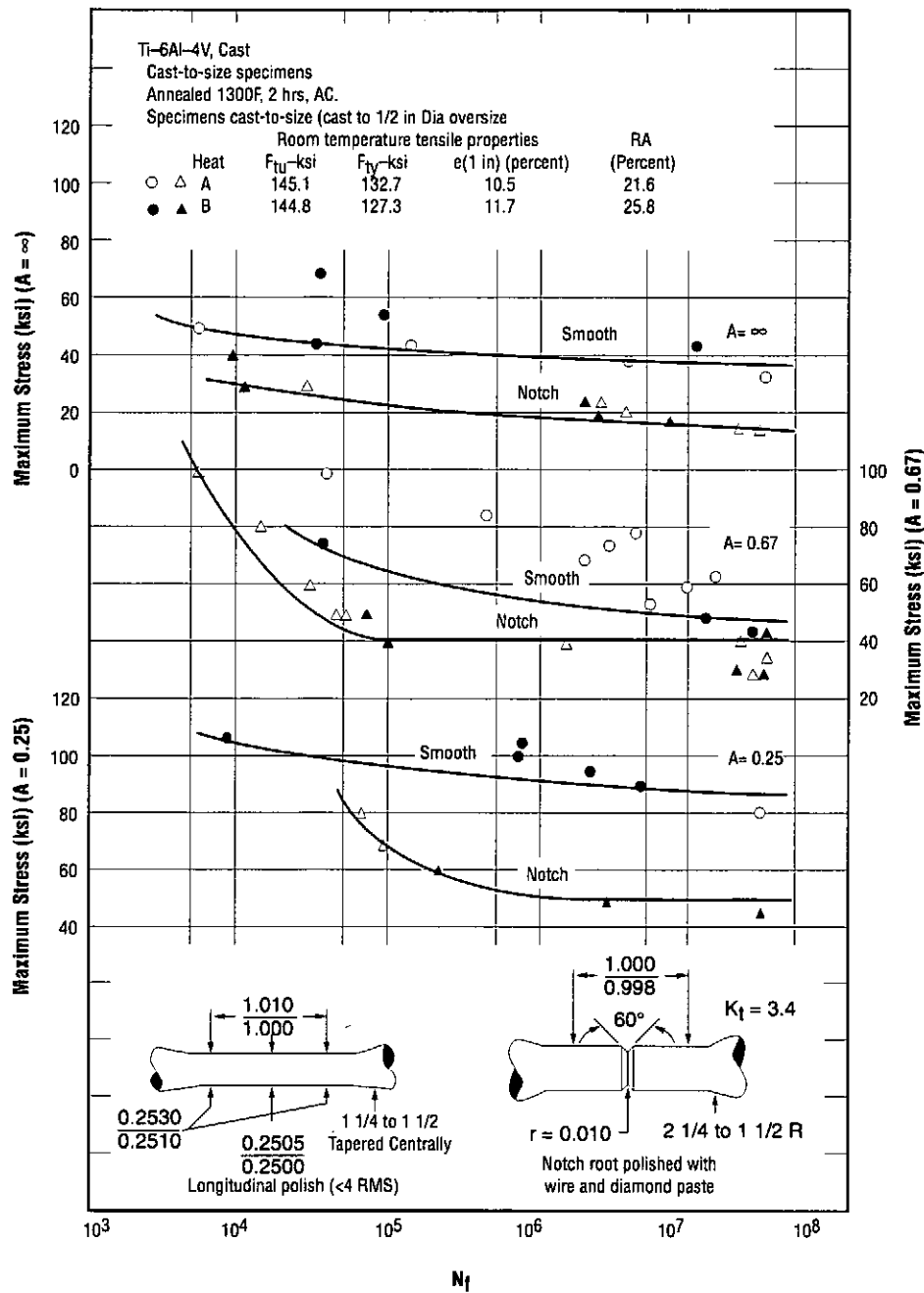


Figure 3.5.1.1 High-cycle axial fatigue results at 500F for annealed smooth and mild-notch cast-to-size specimens from two heats (Ref. 4)

Ti-6Al-4V

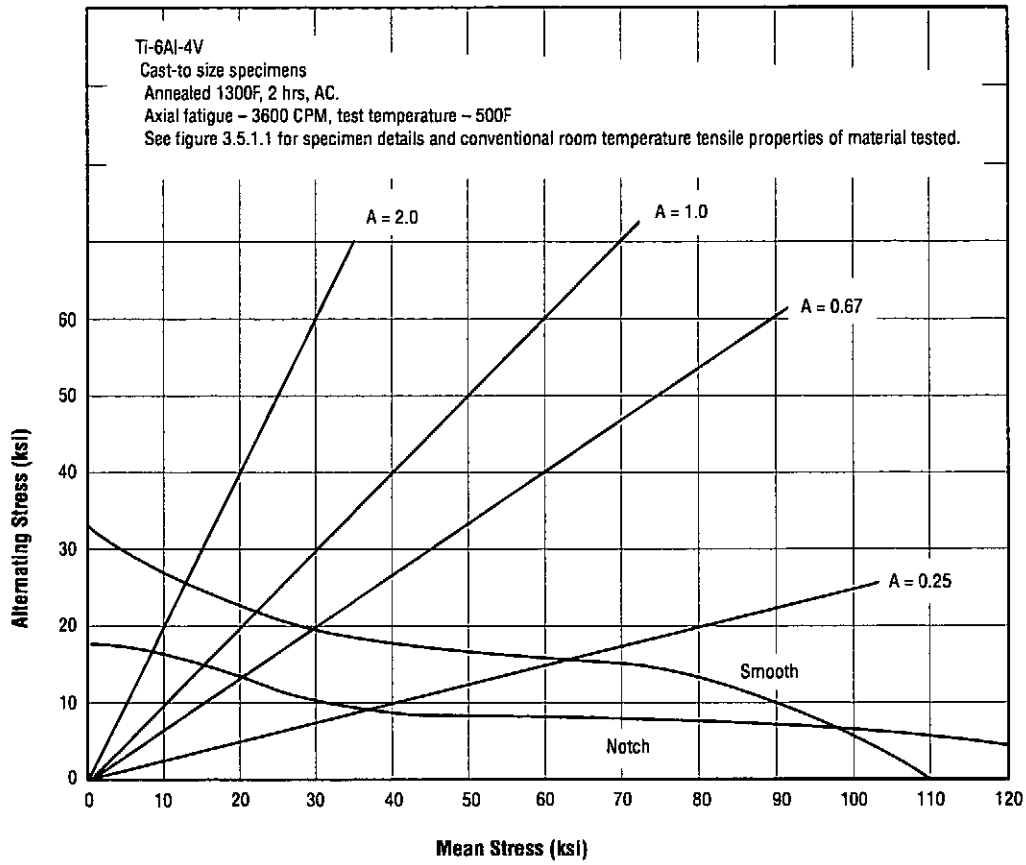


Figure 3.5.1.2 150 hours, 500F stress range diagram for smooth and mild-notch cast-to-size specimens from two heats (Ref. 4)

Ti-6Al-4V

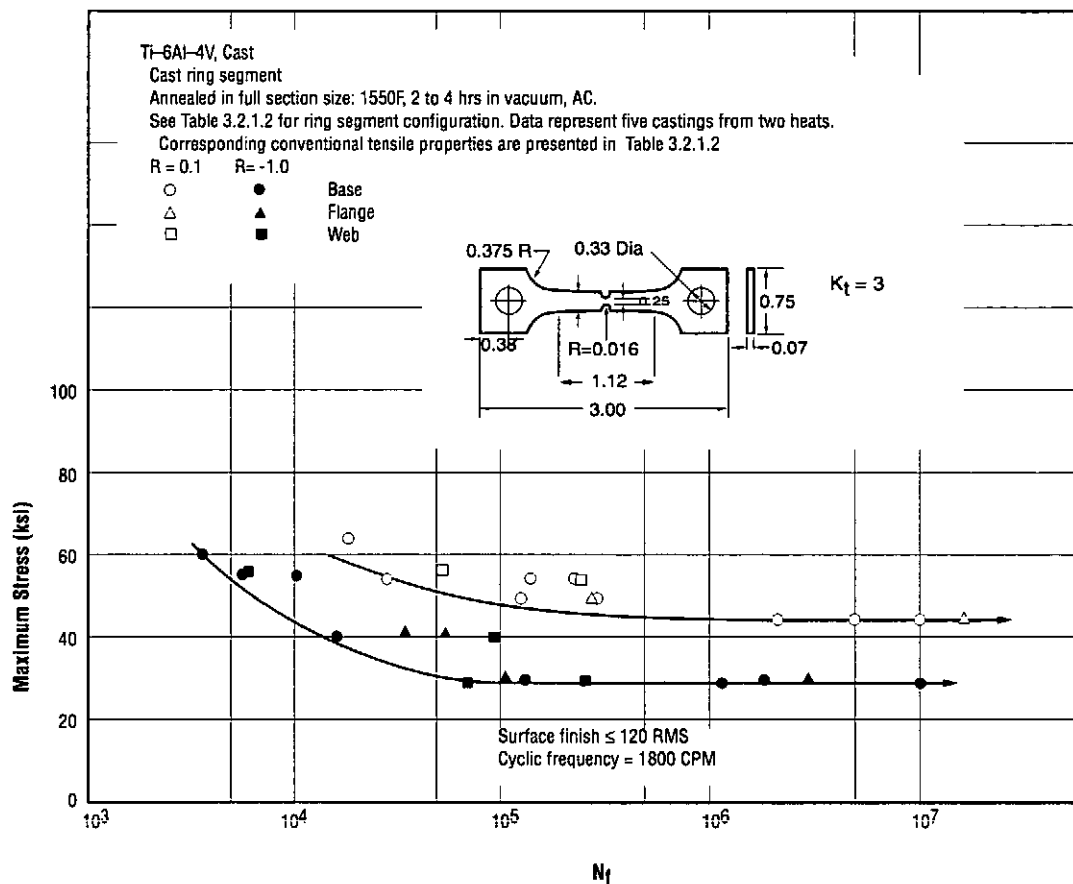


Figure 3.5.1.4 Room temperature axial load fatigue properties of mild-notch specimens from five annealed cast ring segments from two heats (Ref. 5)

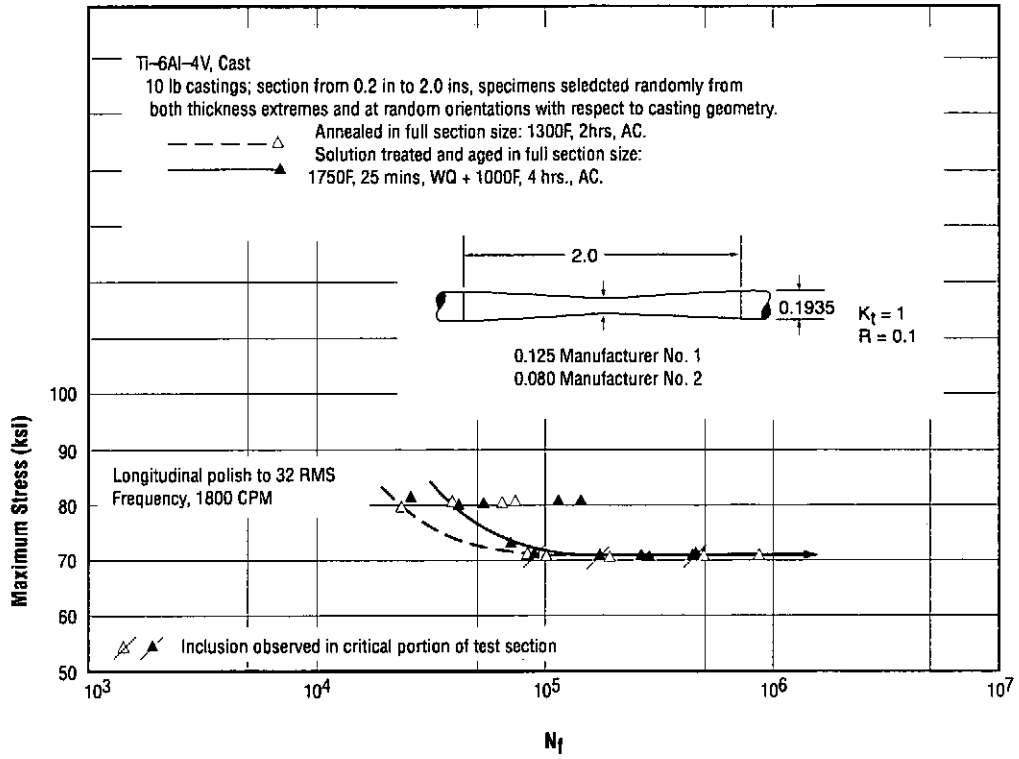


Figure 3.5.1.5 Room temperature smooth fatigue properties of annealed and solution treated and aged castings (Ref. 8)

Ti-6Al-4V

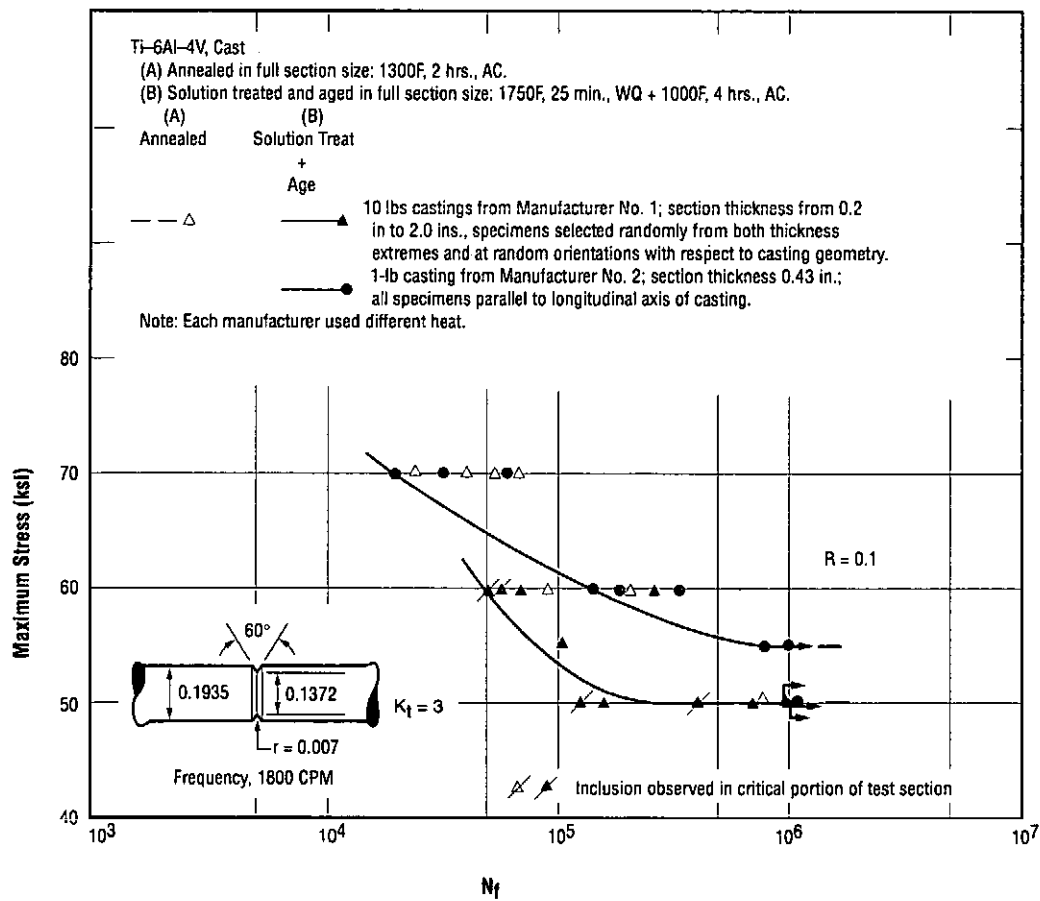


Figure 3.5.1.6 Room temperature mild-notch fatigue properties of annealed and solution treated and aged castings from two casting manufacturers (Ref. 8)

Table 3.5.1.7 Room temperature HCF test results for Ti-6Al-4V cast test bars in various heat treat conditions (Ref. 28)

Condition ¹	Max. Stress (ksi)	N _f
Annealed	105.0	72,100
	90.0	1,038,900
	87.5	1,034,300
	85.0	928,200
	84.0	1,426,200
	82.3	1,098,200
	82.0	1,413,400
	81.0	963,900
	81.0	433,300
BST	80.0	2,924,100
	115.0	31,400
	110.0	87,500
	105.0	229,500
	102.0	700,000
	100.0	870,200
	98.0	508,500
	97.5	639,600
	95.0	1,819,500
	92.5	5,500,000
	90.0	3,650,000 ²
	90.0	2,162,200
88.0	2,557,400	

10 Hz, R=0.1, Triangular wave form K_T = 1.0

¹ See Table 3.2.1.20 for room temperature tensile test results and definition of condition.

² Run-out.

Ti-6Al-4V

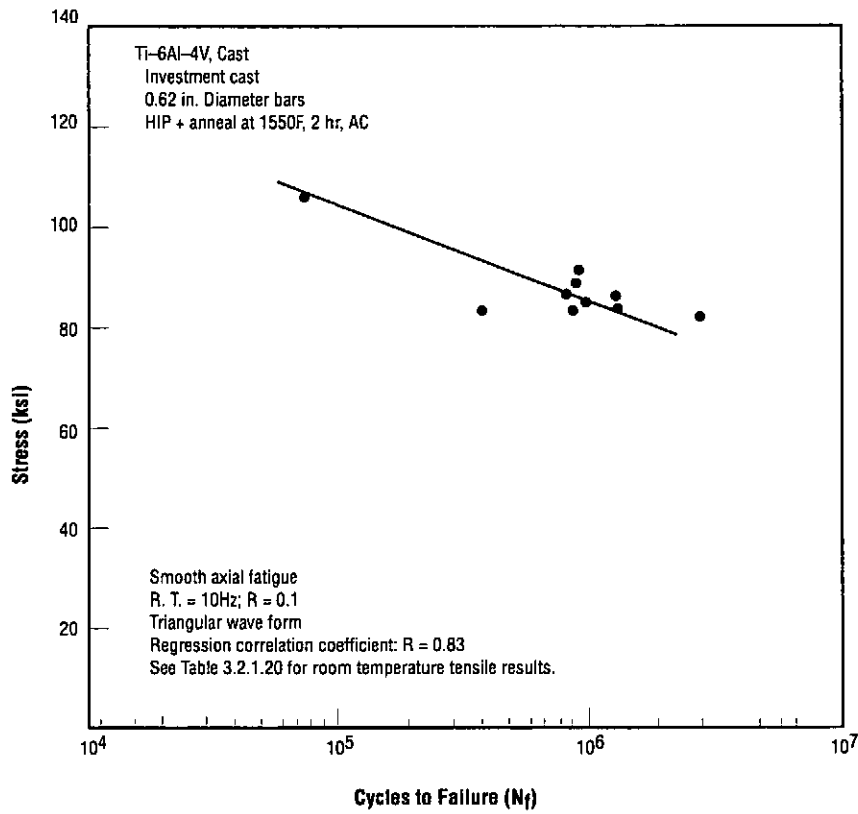


Figure 3.5.1.8 HCF data for annealed investment cast Ti-6Al-4V test bars (Ref. 28)

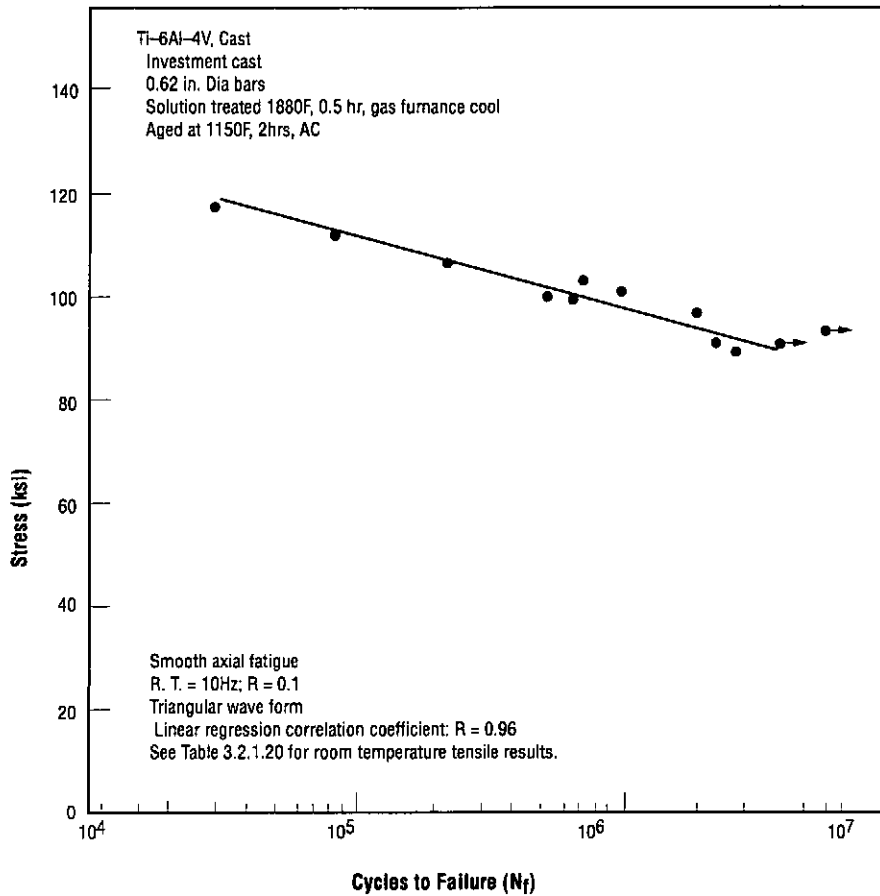


Figure 3.5.1.9 HCF data for investment cast Ti-6Al-4V test bars in the beta solution treated and aged condition (Ref. 28)

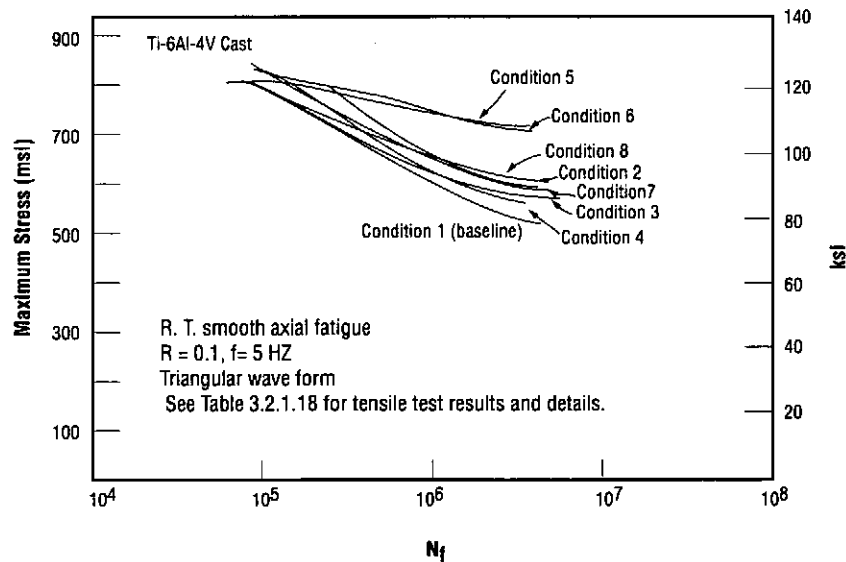


Figure 3.5.1.10 Comparison of average fatigue life curves for eight conditions (Ref. 31)

Ti-6Al-4V

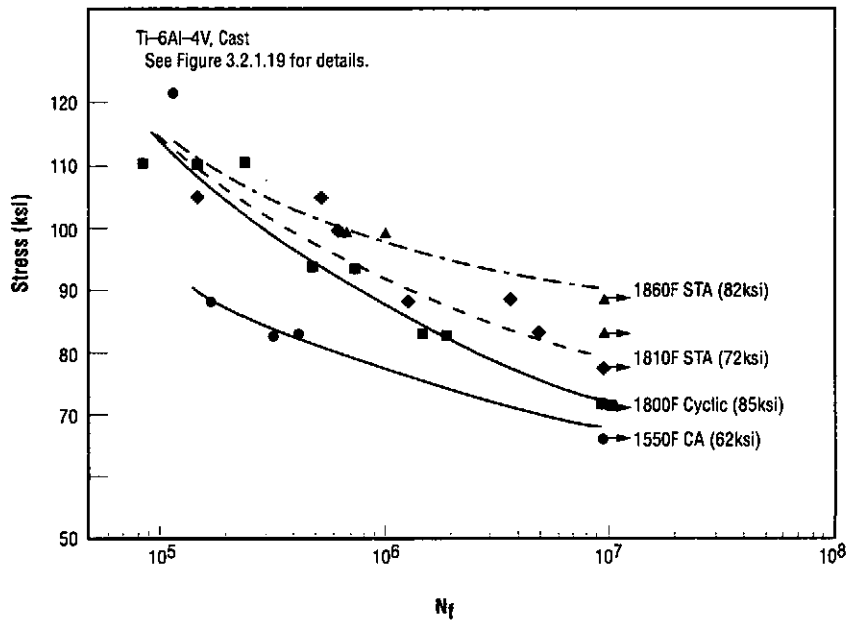


Figure 3.5.1.11 Effects of thermal treatment on the 70F HCF life of cast and HIP'ed Ti-6Al-4V alloy (Ref. 32)

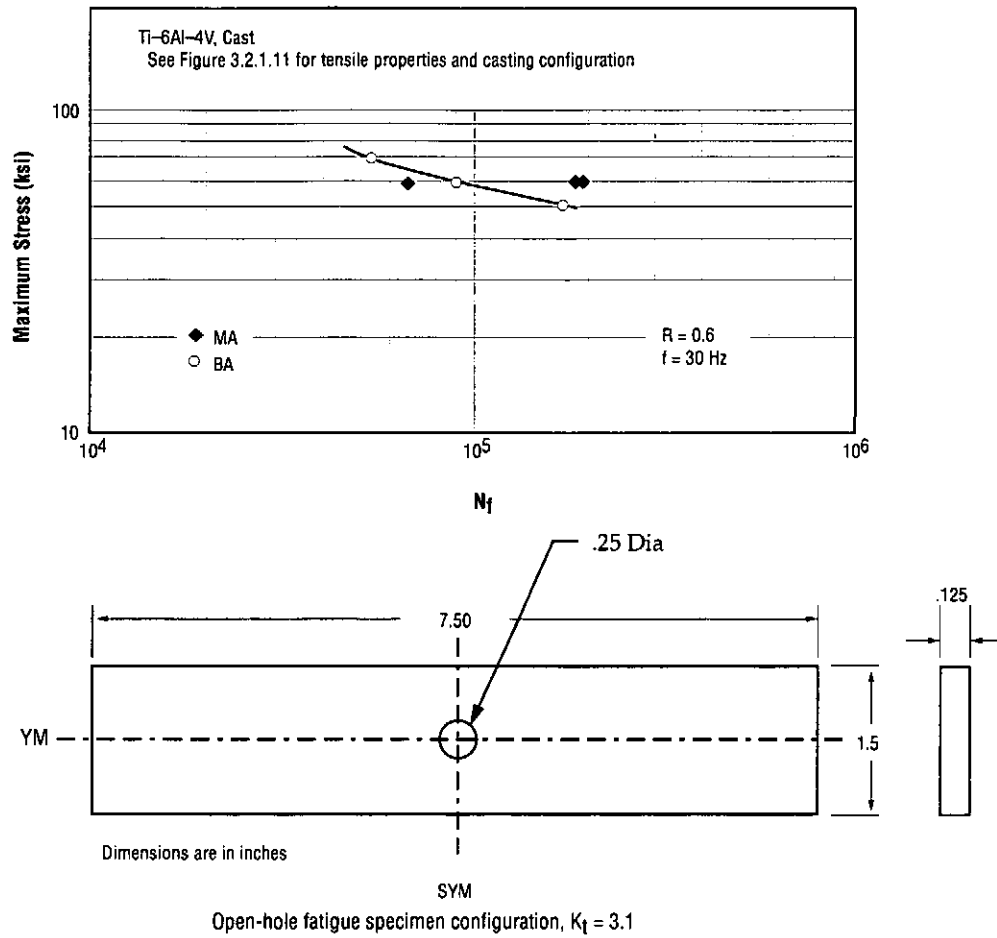
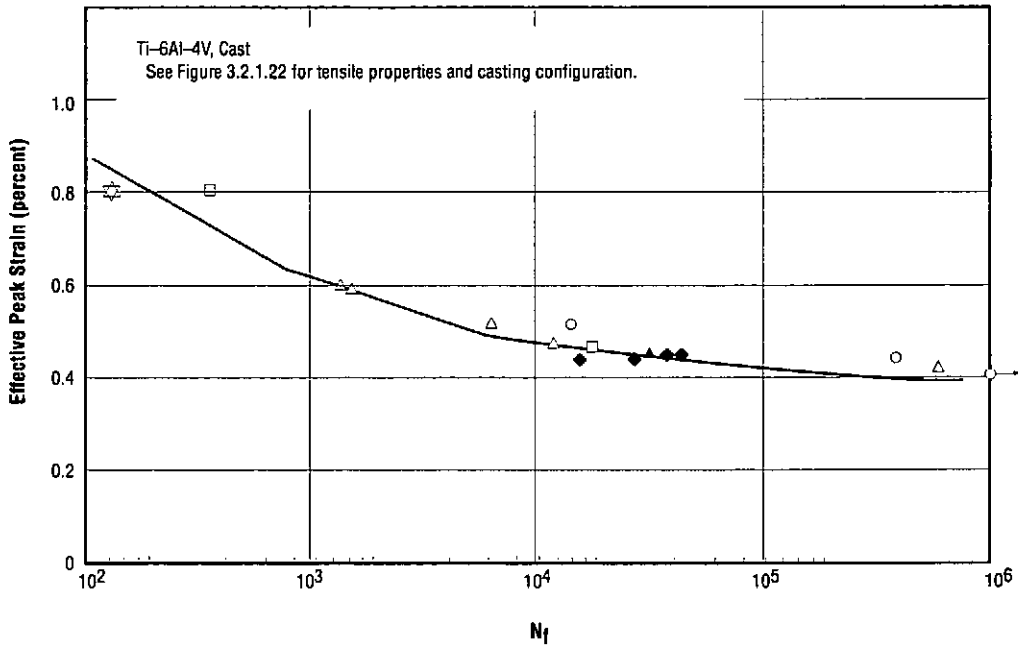


Figure 3.5.1.12 Open-hole fatigue data comparing beta annealed (BA) to mill annealed (MA) (Ref. 34)

Ti-6Al-4V



Open symbols represent beta annealed data with cooling rates of 67-157F/min. The solid symbols represent mill annealed data using a forced argon cool.

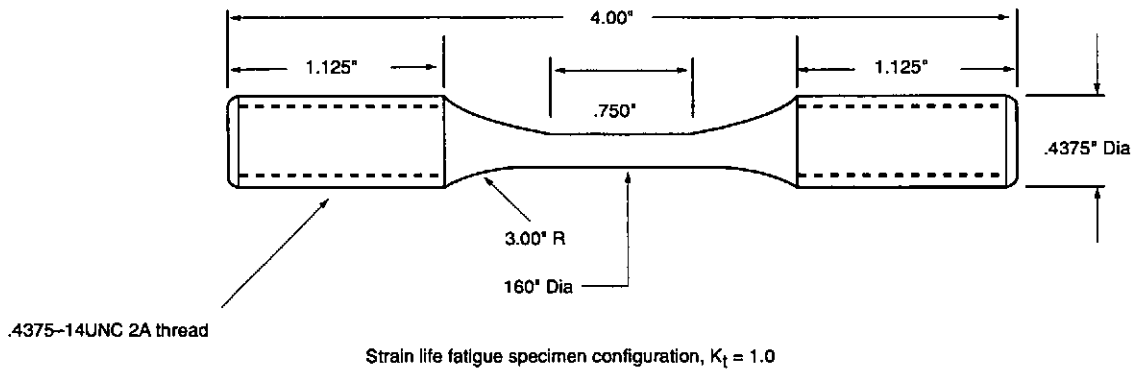


Figure 3.5.1.13 Strain-life fatigue data comparing beta annealed material to standard mill annealed condition (Ref. 34)

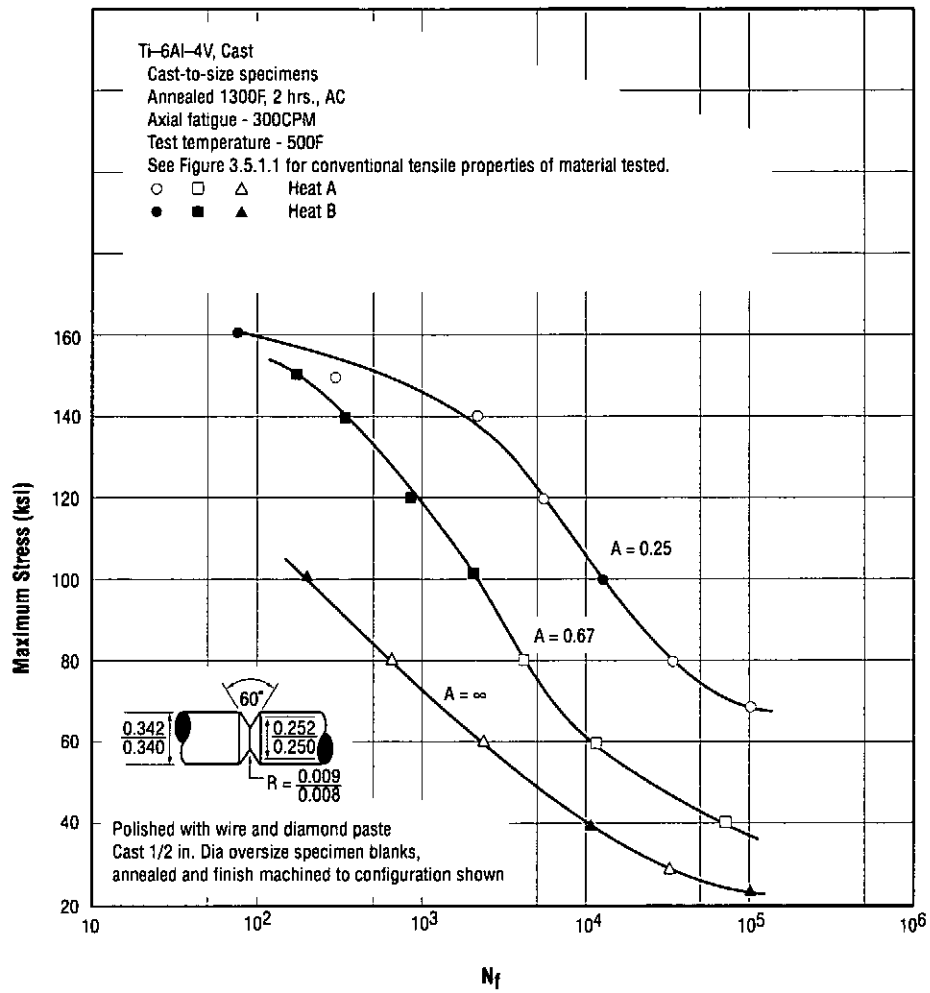


Figure 3.5.2.1 Low-cycle axial fatigue results at 500F for annealed mild-notch specimens cast-to-size from two heats (Ref. 4)

Ti-6Al-4V

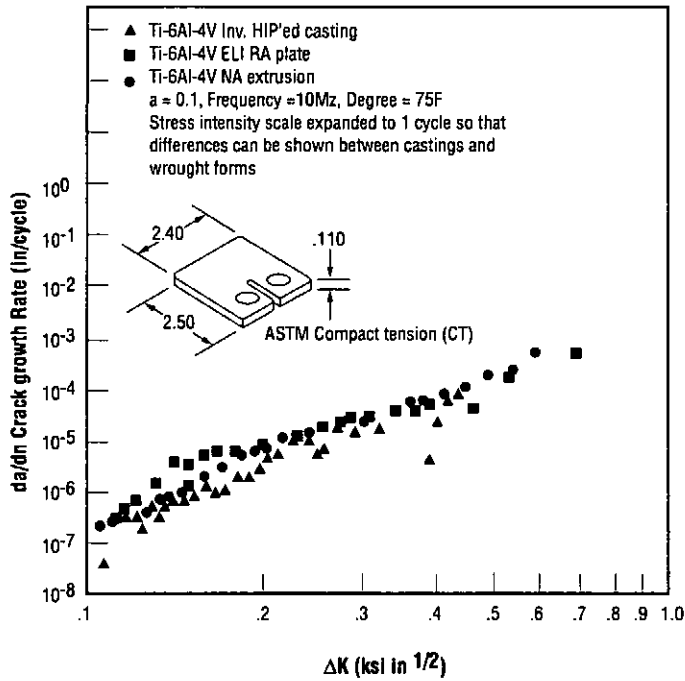


Figure 3.5.3.1 Fatigue crack-growth comparison (Ref. 26)

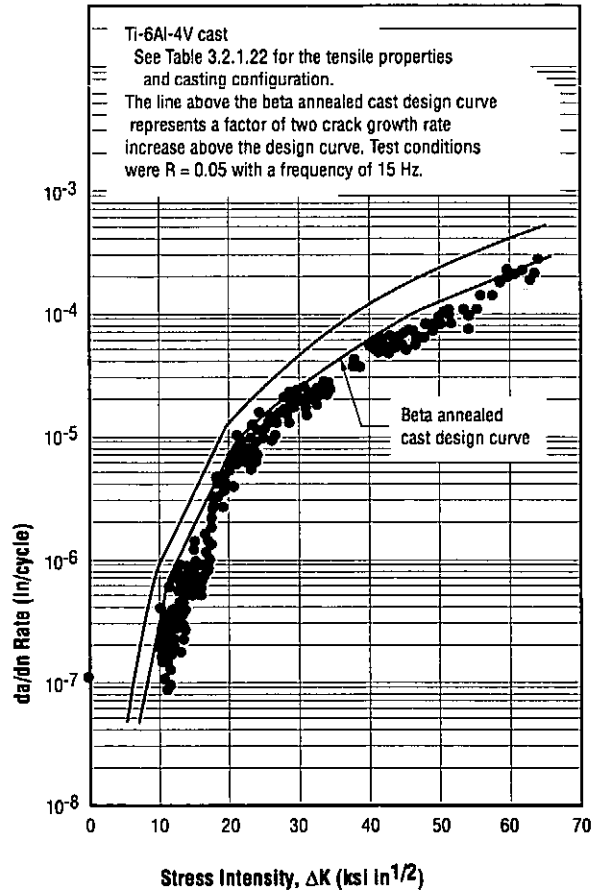


Figure 3.5.3.2 Crack-growth rate of Ti-6Al-4V mill annealed casting with no weld repair (Ref. 34)

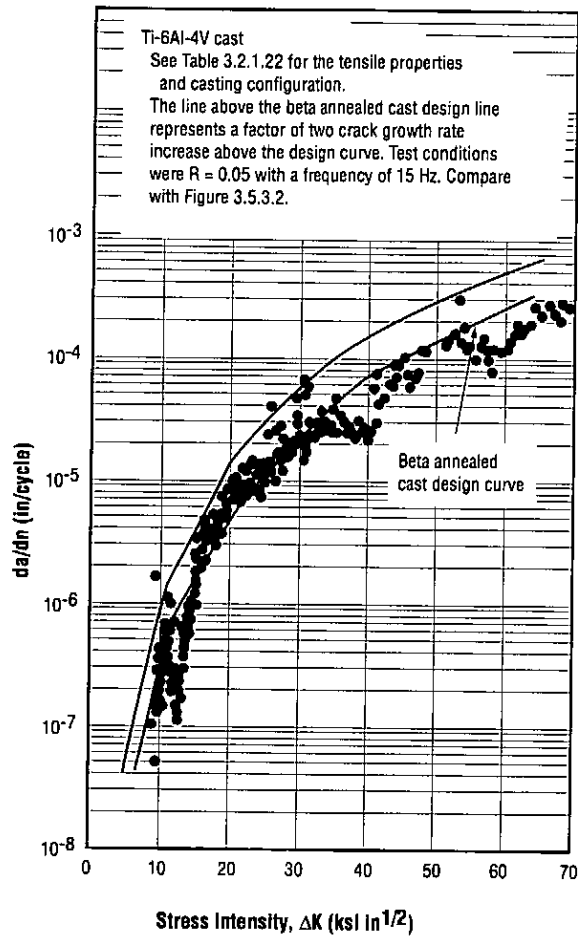


Figure 3.5.3.3 Crack-growth rate of weld repaired Ti-6Al-4V mill annealed casting (Ref. 34)

Ti-6Al-4V

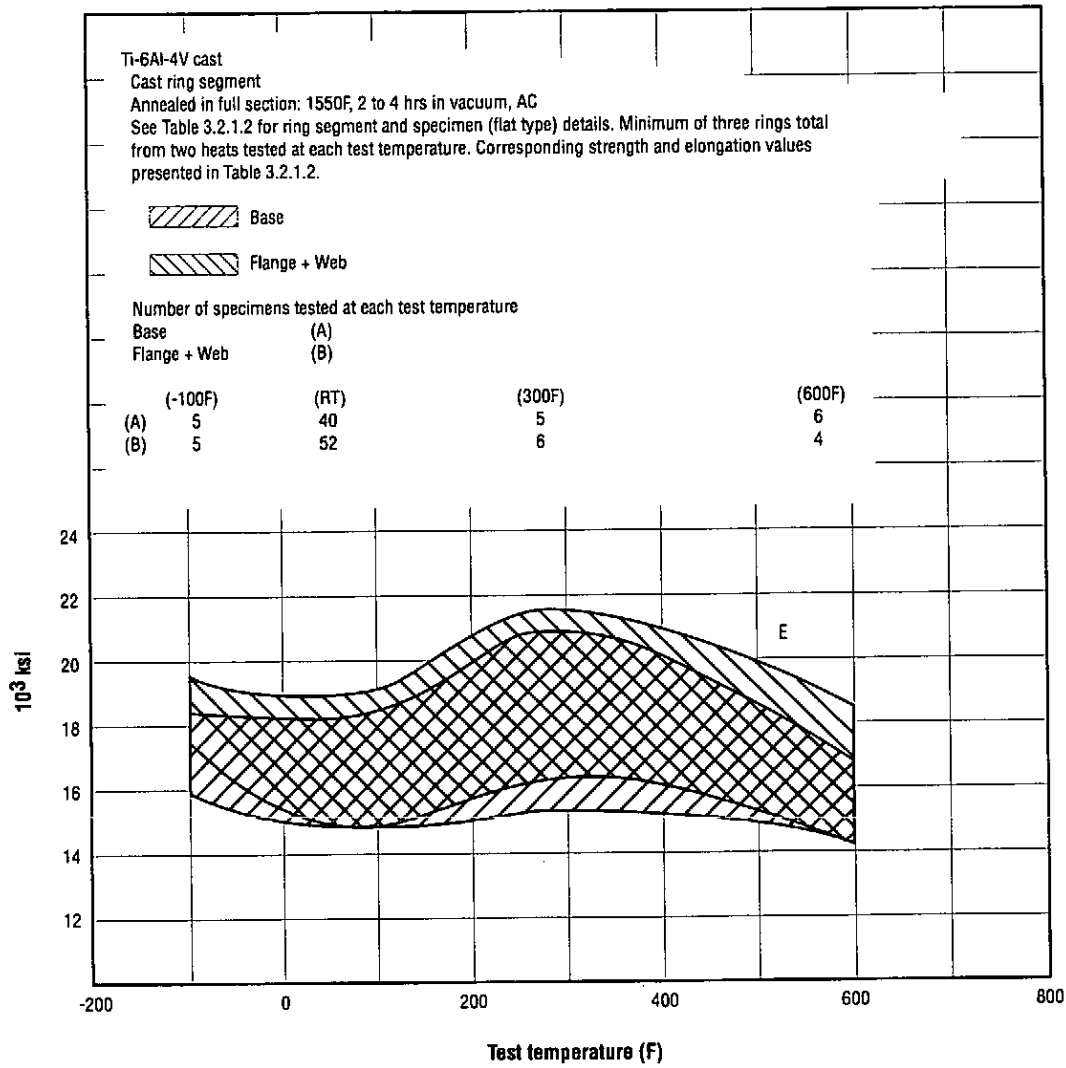


Figure 3.6.2.1 Effects of test temperature on tensile elastic modulus of elasticity of annealed cast ring segments from two heats (Ref. 5)

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