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Ti-6Al-4V Alloy Castings Prepared in Zircon Sand Molds and the Effect of Hot Isostatic Pressing

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

A	ampere	$in/in \cdot min^{-1}$	inch per inch per minute
°C	degree Celsius	ksi	thousand pounds (force) per square inch
°F	degree Fahrenheit	lb	pound (mass)
ft	foot	mL	milliliter
ft/s	foot per second	mm	millimeter
ft•lbf	foot pound (force)	mtorr	millitorr
g	gram	pct	percent
gal	gallon	V	volt
h	hour	psi	pound (force) per square inch
Hz	hertz	wt pct	weight percent
in	inch		

Ti-6Al-4V ALLOY CASTINGS PREPARED IN ZIRCON SAND MOLDS AND THE EFFECT OF HOT ISOSTATIC PRESSING

By Jack I. Paige,[1] Philip G. Clites,[2] and Jack L. Henry[3]

ABSTRACT

The Bureau of Mines conducted studies to provide data on the room temperature mechanical properties of Ti-6Al-4V alloy cast in waterglass-bonded zircon sand and to determine the effect of hot isostatic pressing (HIP) on these properties. Data on the cast and annealed Ti-6Al-4V alloy were compared with published data for forged and investment-cast Ti-6Al-4V alloy.

The average Charpy V-notch impact strength compared favorably with the typical values of 17 ft•lbf for wrought material and 19.2 ft•lbf for investment-cast material. The room temperature mechanical properties of cast and annealed material compared favorably with published values for investment-cast Ti-6Al-4V alloy and exceeded the specifications for (1) titanium and titanium alloy castings, grade C-5 according to ASTM B367-69, and (2) titanium alloy bars and forgings as specified in AMS4928H, except for the AMS4928H minimum requirement for reduction in area (25 pct). The minimum requirements are: tensile strength, 130 ksi; yield strength, 120 ksi (0.2 pct); and elongation, 6 pct. None of the specimens tested met the AMS4928H minimum requirement for reduction in area. The HIP process healed the internal casting porosity in the test specimens, but the fatigue strength was not significantly improved. The fatigue properties of both the cast and cast plus hot isostatically pressed castings were significantly lower than those of wrought products.

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INTRODUCTION

Titanium, by virtue of its low density, excellent corrosion resistance, and good mechanical properties, is a potential substitute for some alloys that contain such critical and strategic metals as cobalt, chromium, and nickel. While titanium currently is produced from imported raw materials, there is no shortage of titanium reserves in the world (14),[4] and technology exists for the utilization of domestic sources that are considered adequate to meet projected demands. Also, weight reductions achieved through the use of titanium often result in increased operating efficiency and improved performance.

Unfortunately, the high cost of titanium components has limited their use. Numerous research studies have been undertaken to reduce this high cost through the production of near-net shapes by casting (8, 16-17). Casting reduces costs through improved material utilization and reduced machining costs, but casting defects and a highly notch-sensitive colony structure cause crack initiation, which can lead to failure. In addition, the characteristic porosity of cast structures results in property variability, which has to be compensated for by overdesign of cast components.

HIP may be used as a method of improving the properties of titanium castings, and many titanium castings are routinely hot pressed.[5] HIP closes and heals porosity in titanium castings and reduces the scatterband for data on properties, permitting more effective use of titanium's high strength-to-weight ratio. Research conducted on investment-cast titanium, particularly Ti-6Al-4V alloy, has provided data on the tensile and fatigue properties of titanium castings (16).

Eylon, Froes, and Gardiner (8) provided an excellent summary of titanium casting technology and pointed out that increased use of cast parts will result in lower cost, enhanced mechanical properties (particularly fatigue), and improved shape making (dimensional control and reproducibility; increased size, thinner sections, smaller radii, and better surface finish). Commercial titanium founders currently use investment molds for critical aerospace hardware and less expensive rammed graphite molds for chemical processing equipment and marine hardware. A method for making ceramic molds has recently been developed for large components requiring accurate dimensions (8), such as pump impellers, but these molds are more expensive than rammed graphite molds.

Previous Bureau of Mines research (10-12) resulted in the development of several formulations for sand molds for titanium casting. Compared with investment molds and machined or rammed graphite molds, sand molds have the advantage of potentially lower cost, since automatic molding machines can be used in their preparation. Sand molds also require less energy-intensive bake-out cycles. Of the various sand formulations developed by the Bureau, waterglass-bonded zircon sand provided the least metal-mold reaction and a minimum of oxygen-rich layer (alpha case) on the cast surfaces. Research on this molding system (11) yielded data on the mechanical properties of unalloyed titanium, including limited fatigue data. The present study was undertaken to provide previously unavailable data on the room temperature mechanical properties of Ti-6Al-4V alloy cast in waterglass-bonded zircon sand molds. The effect of HIP was also studied. The Bureau conducted this study as part of its effort to improve the quality of and lower the cost of preparing near-net-shape titanium components.

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[4]Underlined numbers in parentheses refer to items in the list of references at the end of this report.

[5]In this report, "hot pressed," "hot pressing," "hot press," and "HIP" all indicate hot isostatic pressing.

ACKNOWLEDGMENTS

The authors thank William A. Aschoff, production manager, Industrial Materials Technology, Inc., Portland, OR, who hot pressed the castings used in this study. The authors also thank Ronald Trudo, titanium plant manager, and William J. Barice, metallurgical development manager, both employed by Precision Cast Parts Corp., Portland, OR, who chemically milled selected samples and gave advice on commercial practices of the titanium industry, respectively.

MATERIALS

The titanium alloy chosen for this study was the widely used Ti-6Al-4V, for which data on mechanical properties of forged product, castings, and hot-pressed castings are readily available. A 4-in-diam 10-ft-long machined bar, purchased from a commercial vendor, was cut into 2-ft lengths, which were used as electrodes for the Bureau's skull casting furnace (5). Analyses furnished by the vendor and those obtained from samples taken from the bar are given in table 1 along with the requirements for grade C-5 according to ASTM specification B367-69 (1).

Sand used for the molds was commercial zircon sand purchased in 100-lb bags from domestic sources. Chemical analyses for the sand are given in table 2, and the sand size distribution is given in table 3.

TABLE 1. - Analyses of Ti-6Al-4V alloy electrode stock, percent

Element	Vendor's analyses	Bureau analyses	Grade C-5 requirements
Al.....	6.70	6.20	5.5-6.75
C......	.02	.046	.10 max
Fe.....	.18	.20	.40 max
H......	.0048	.0037	.0100 max
N......	.010	.017	.05 max
O......	.187	.171	.25 max
V......	4.10	3.78	3.5-4.5
Y......	<.005	ND	([1])

ND Not detected.

[1]Other elements (including yttrium) 0.10 pct max each; total other elements 0.40 pct max.

TABLE 2. - Chemical analyses of as-received zircon sand

Oxide	Wt pct	Oxide	Wt pct
Al_2O_3......	0.09	SiO_2.......	32.5
CaO........	.013	TiO_2.......	.45
Fe_2O_3......	.63	ZrO_2.......	64.2
HfO_2.......	1.25		

The binder used for all molds was grade D waterglass purchased in 5-gal lots. Care was taken to insure that the waterglass was fresh, as this material reacts with CO_2 in the atmosphere to produce colloidal SiO_2 and Na_2CO_3. The Na_2CO_3 that forms will decompose when exposed to

TABLE 3. - Size distribution of as-received zircon sand

Particle size, µm	Weight, g	Wt pct	Cumulative wt pct
Plus 297...........	0.1	0.2	0.2
Minus 297 plus 210..	1.4	2.8	3.0
Minus 210 plus 149..	11.6	23.2	26.2
Minus 149 plus 105..	23.8	47.6	73.8
Minus 105 plus 74...	12.8	25.6	99.4
Minus 74 plus 53....	.2	.4	99.8
Minus 53...........	.1	.2	100
Total..........	50.0	100.0	NAp

NAp Not applicable.

molten titanium during casting, and the CO_2 produced will cause porosity in the castings (10).

Metal was poured from the ladle during skull casting into a machined graphite funnel and sprue arrangement that carried metal through machined graphite gates into the zircon sand molds. The sprue and gates were machined from grade CS graphite.

PROCEDURE

MOLD PREPARATION

Mold preparation followed the procedure described by Koch (12). The sand was riddled through a No. 18 U.S. standard sieve to remove foreign matter and then mixed with grade D waterglass and water. The mix used for all molds was 25 mL of waterglass and 25 mL of tap water per kilogram of dry sand. Mixing was done in a rotary cement mixer, and molds were hand rammed onto wood patterns shortly after mixing to prevent reaction of the waterglass with atmospheric CO_2. Figure 1 shows the wood pattern used for hand ramming and a cured cope section of a mold. The molds were not assembled until after firing because of limited green strength. Cope and drag sections of the mold were held in a drying oven at 194° F (90° C) until they could be fired at 1,650° F (900° C) for 2 h. The molds were assembled after firing and held at 194° F (90° C) until they were loaded into the skull furnace for casting.

MELTING AND CASTING

Figure 2 shows the interior of the casting chamber of the casting furnace with four molds grouped around a central sprue. The central sprue was a machined graphite cylinder, 2-1/2-in ID and 6 in long, from which four 3/4-in-ID machined graphite gates led to the sand molds. The molds were poured with the specimen blanks in the vertical position. In order to place the molds as close to the sprue as possible, two of the molds were connected to the sprue with 2-in-long

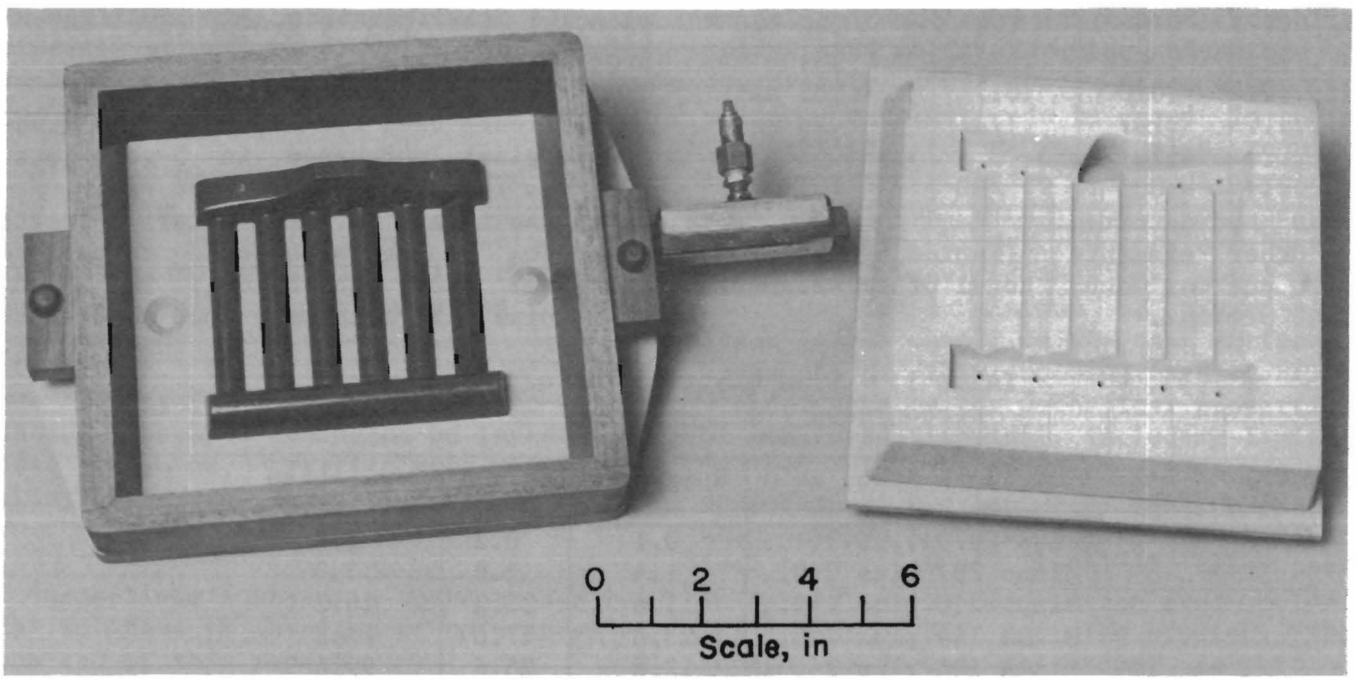

FIGURE 1. - Wood pattern used for hand ramming and a cured cope section of the mold.

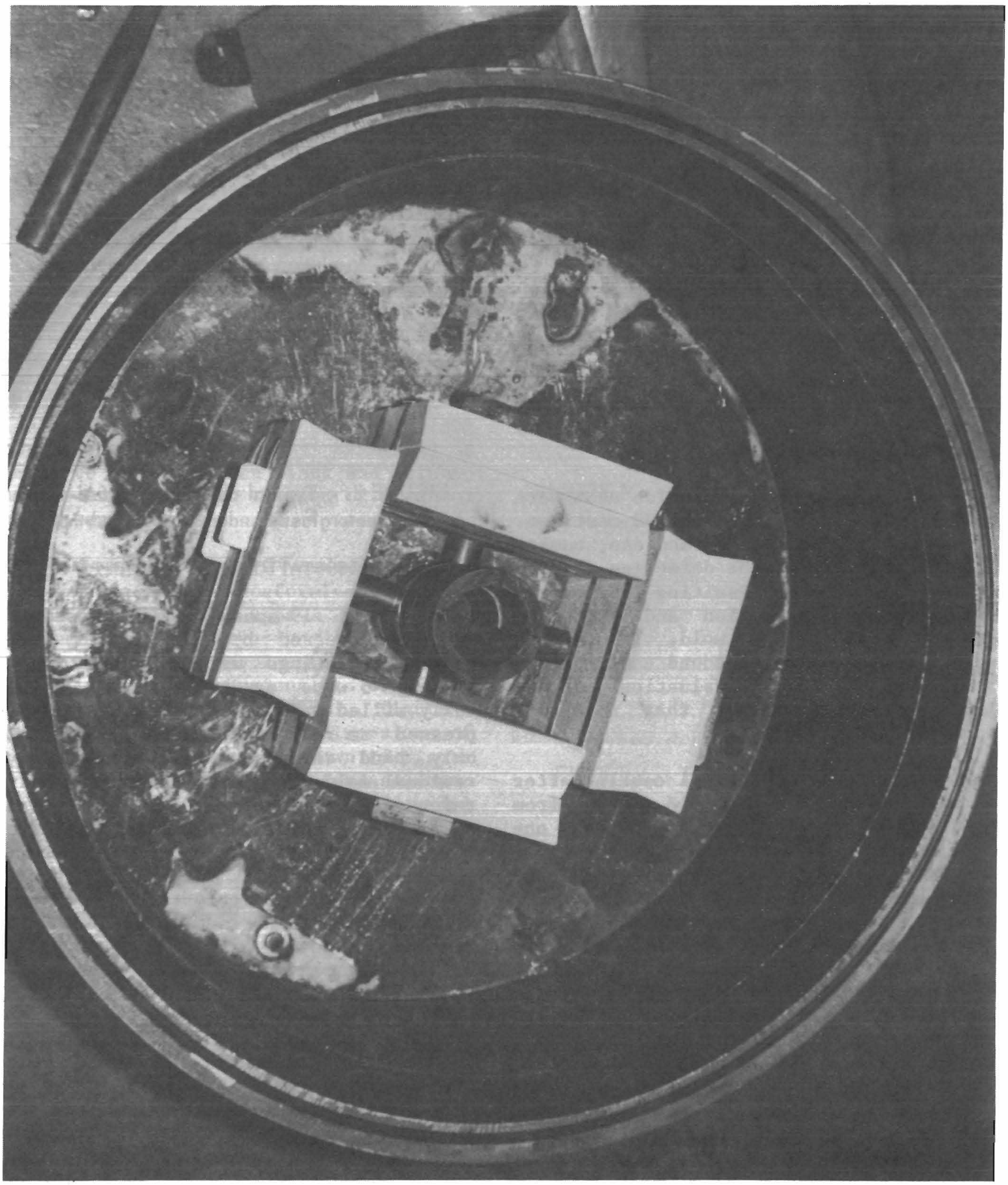

FIGURE 2. - Casting chamber with four zircon sand molds grouped around central machined graphite sprue.

gates, and two were connected with 4-in-long gates.

Melting stock for each casting heat was a 2-ft length of 4-in-diam Ti-6Al-4V alloy bar. As soon as the molds and the melting stock were loaded, the furnace was evacuated to a furnace pressure of approximately 1 mtorr. Melting was conducted in vacuum at a typical arc current of 6,500 A and an arc potential of 30 V. The ladle for this furnace was 8 in. in diameter and 8 in deep and provided sufficient volume to pour approximately 45 lb of molten titanium, which was sufficient to fill the sprue and molds. More detailed information on the skull melting operation practiced by the Bureau is given in references 5 and 6.

Five casting heats of 4 molds each were poured, yielding a total of 20 castings. Of these, 19 were sound, and one, number 12, was defective. The defective casting contained blowholes resulting from excessive mold-metal reaction and/or inadequate venting of the mold. The casting weight for each of the sound castings was 3.31±0.02 lb. X-ray evaluation of selected castings showed that each was sound internally.

Figure 3 shows a typical casting after it was removed from the mold and cut from the sprue. Each casting provided one 5/8-in square bar approximately 4 in long and five 5/8-in-diam rods 4-in long. Charpy V-notch specimens were machined from the square bars, and tensile and fatigue specimens were machined from the round rods. Each casting was numbered as follows: castings 1 through 4 represented the first heat, 5 through 8 the second heat, etc. The six specimen blanks were identified as A through F, starting with the square bar as A. Thus, specimen blank 5A was the square bar from casting 5, specimen blank 5B was the round rod next to the square bar, and 5F was the round rod furthest from the square bar.

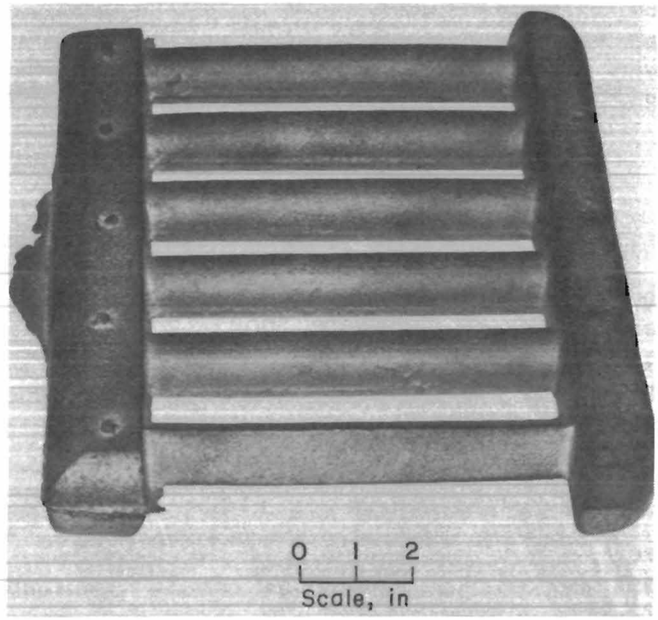

FIGURE 3. - Typical casting of Ti-6Al-4V alloy from waterglass-bonded zircon sand mold.

HOT ISOSTATIC PRESSING (HIP)

Ten of the 19 sound castings produced were hot pressed by a commercial firm. These 10 castings were divided into 2 groups: 5 were sandblasted and chemically milled prior to HIP, and 5 were hot pressed as removed from the mold with only hand chipping employed to remove residual mold material. Chemical milling removed an estimated 0.002 in from all surfaces of the casting and eliminated the alpha case from the cast surface. This is an accepted commercial practice and is done to prevent diffusion of oxygen from the alpha case into the body of the casting during HIP. The disadvantage of removing the alpha case is that chemical milling can also expose subsurface porosity, and this porosity and any interconnected porosity will not be healed by HIP. Since there is some controversy over the value of chemical milling and since sandblasting might also expose subsurface porosity, only half of the castings to be hot pressed was so treated, and the remaining half was neither sandblasted nor chemically milled.

The castings were hot pressed for 2 h at 1,650° F (899° C) and an argon pressure of 15,000 psi. Following the high pressure portion of the cycle, the castings were cooled to 72° F (21° C) in 9 h and then removed from the pressure vessel.

PREPARATION OF TEST SPECIMENS

Test blanks were cut from the castings and machined into Charpy impact, tensile, and fatigue specimens. Charpy impact specimens were randomly selected from the square bars from the castings, and tensile and fatigue specimens were chosen randomly from the five round specimen blanks from each casting. Random selection was accomplished by assigning a number to each specimen blank and selecting the samples with the aid of a random number generator.

Impact specimens were standard Charpy V-notch specimens conforming to ASTM specification E23-82, type A (3). Their configuration and dimensions are shown in figure 4. Tensile specimens were small-size specimens proportional to standard, conforming to ANSI/ASTM E8-81, figure 8 (2). The configuration and dimensions of the tensile specimens are shown in figure 5. Fatigue specimens were standard, conforming to ANSI/ASTM E466-76, figure 1 (4). Their configuration and dimensions are shown in figure 6. The buttonhead ends shown in figure 6 were chosen over a threaded grip because previous tests made with threaded grips resulted in a high incidence of failure in the thread root. Typical machined specimens for the Charpy impact, tensile, and fatigue tests are shown in figure 7.

After machining, all test specimens were annealed at 1,300° F (704° C) for 2 h to remove any residual strain. Specimens were packed in Ti-6Al-4V alloy machine chips in a carbon steel container lined with Ti-6Al-4V alloy sheet. The

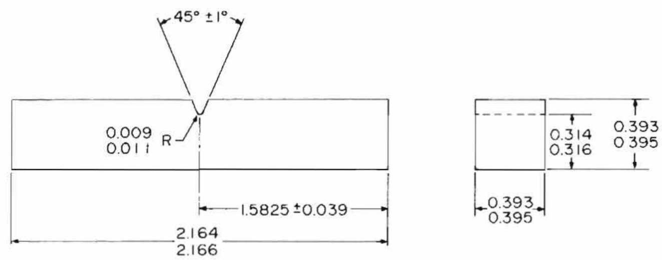

FIGURE 4. - Charpy V-notch test specimen. (Measurements in inches.)

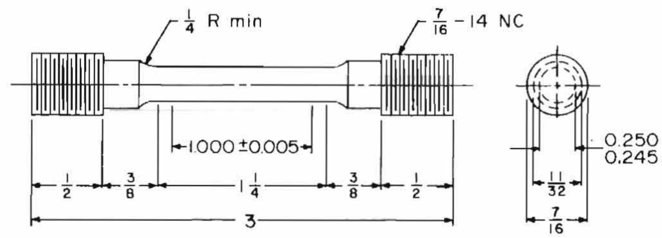

FIGURE 5. - Tensile test specimen. (Measurements in inches.)

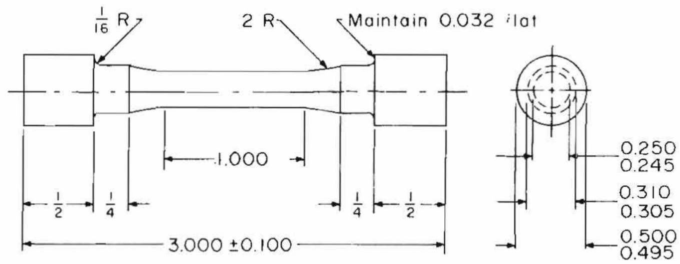

FIGURE 6. - Fatigue test specimen. (Measurements in inches.)

container was sealed by welding, evacuated, and backfilled with helium. A stainless steel thermocouple well was placed through a Swagelok[6] fitting to monitor the temperature while the container was heated in an open electric furnace. Following the 2-h annealing treatment, the container was removed from the furnace and air cooled to room temperature before the specimens were removed.

[6]Reference to specific products does not imply endorsement by the Bureau of Mines.

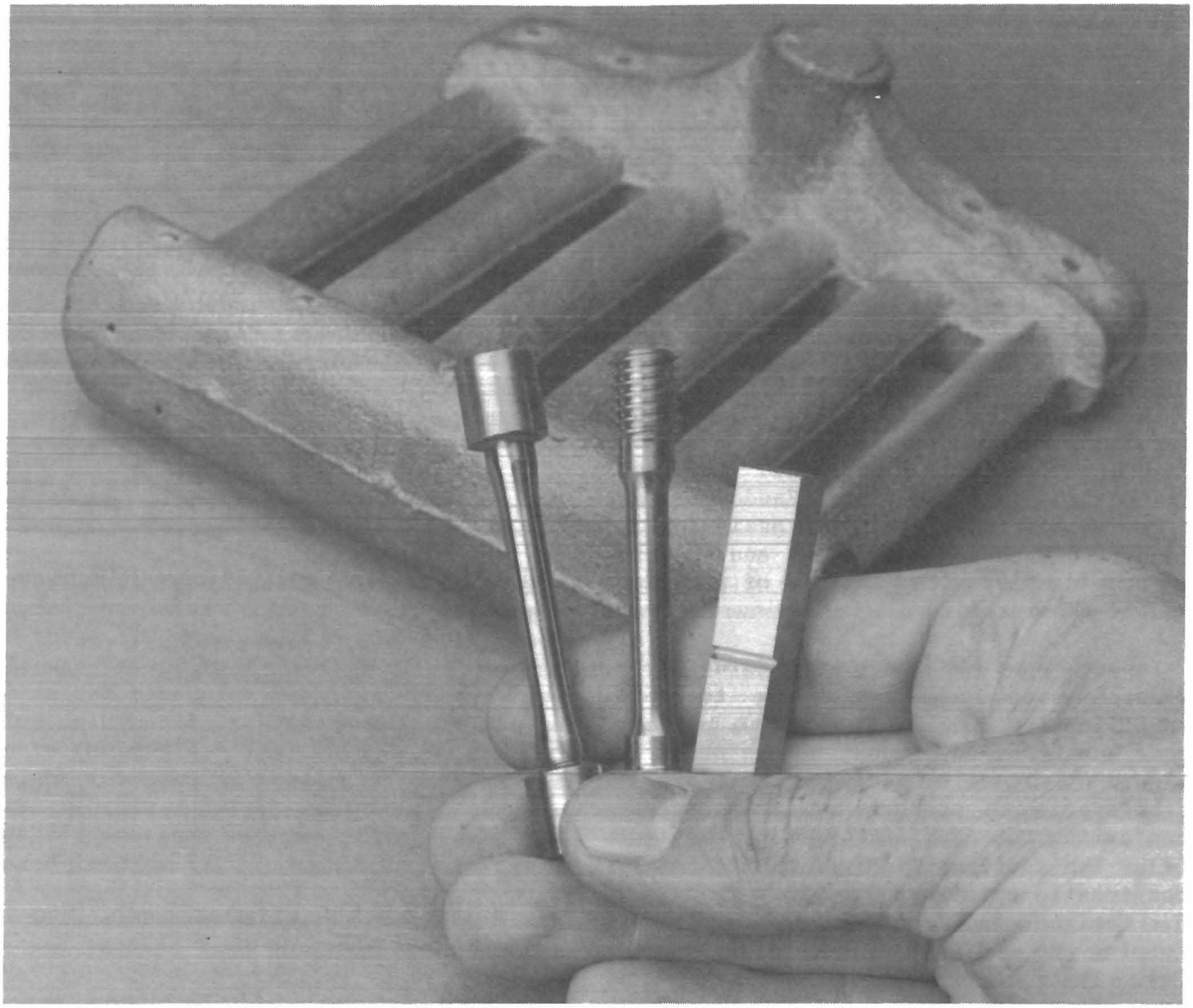

FIGURE 7. - Machined test specimens. (Left to right: for fatigue, tensile, and Charpy V-notch tests.)

MICROSTRUCTURE

A typical structure of the cast Ti-6Al-4V alloy test specimens is shown in figure 8. The castings had a transformed beta structure containing acicular alpha and/or Widmanstatten and alpha-plate colonies. Grain-boundary alpha also developed along the boundaries of the beta grains during cooling through the alpha-beta phase region. The mathematical-average transformed beta-grain size, as determined by counting grains along a specified length, was approximately 1 mm.

Two types of pores are generally found in cast parts. The first is the result of trapped gas and has a spherical shape, the second is the result of shrinkage porosity and typically has an interdendritic inner pore structure (9). A spherical gas pore is shown in figure 8. No evidence of dendritic pores was found in any of the examined test specimens.

HIP did not change the cast structure of the test specimens. Similar results

FIGURE 8. - Typical structure of cast Ti-6Al-4V alloy.

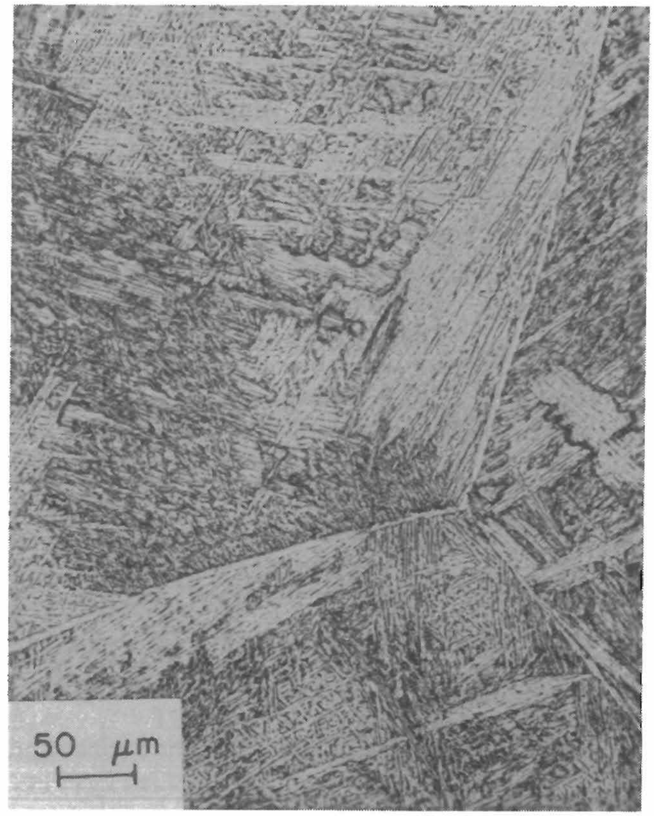

FIGURE 9. - Typical structure of cast and hot-pressed Ti-6Al-4V alloy.

have been reported by Eylon (7). A typical structure of the cast and hot-pressed Ti-6Al-4V alloy test specimens is shown in figure 9. The average grain size for the hot-pressed specimens was approximately 1.3 mm. The mixture of acicular alpha and/or Widmanstatten, alpha-plate colonies, and grain-boundary alpha remained about the same. However, the HIP cycle was effective in closing the pores; no residual porosity was detected in any of the examined hot-pressed specimens.

Since the cast structure is very stable in the alpha-plus-beta field (8), no alterations in the cast morphology were expected or detected in any of the examined specimens following the annealing step.

TEST PROCEDURES AND RESULTS

Table 4 lists the results of the Charpy V-notch testing for the cast; cast and hot-pressed; and cast, milled, and hot-pressed test specimens. Tests were performed on a RIEHLE model R-21314 pendulum C-type machine. The linear velocity of the hammer at the instant of striking was 18.1 ft/s. The temperature of the specimens was 72° F (22° C).

Table 5 lists the results of the tensile testing of the cast; cast and hot-pressed; and cast, milled, and hot-pressed test specimens. The specimens were prepared and tested in accordance with ANSI/ASTM specification B367-69 (1). After inspection, the specimens were gauge-marked and placed in the grips of the testing machine, and an extensometer was attached to the specimen and to a stress-strain recorder. The tensile test was performed by loading at a strain rate of 0.005 in/in·min^{-1} through a specified offset of 0.2 pct. The extensometer was then removed, and the specimen was loaded to failure at a strain rate of 0.05 in/in·min^{-1}.

TABLE 4. - Charpy V-notch results for Ti-6Al-4V alloy castings at room temperature

Specimen condition[1] and number[2]	Impact strength,[3] ft·lbf
Cast:	
1A	23.0
7A	22.5
10A	23.3
11A	20.2
16A	19.9
20A	20.0
Mean	21.5
Standard deviation	1.6
Cast and hot pressed:[4]	
5A	17.5
17A	19.0
18A	20.7
Mean	19.1
Standard deviation	1.6
Cast, milled, and hot pressed:[4]	
2A	18.0
6A	18.5
19A	16.9
Mean	17.8
Standard deviation	.8

[1]All specimens were annealed at 1,300° F for 2 h.
[2]See text for explanation of specimen numbers ("Melting and Casting" section).
[3]Fracture type ductile.
[4]"Hot pressed" refers to hot isostatic pressing.

The results of the fatigue testing of the cast; cast and hot-pressed; and cast, milled, and hot-pressed specimens are shown in tables 6, 7, and 8, respectively. (The results are ranked in the tables according to the maximum stress applied, in descending order. Within each group, the specimens are listed in an increasing numerical sequence, but the specimens were randomly selected for both maximum stress applied and order of testing.) The fatigue tests were performed on an electrohydraulic closed-loop test machine. A sinusoidal tension-tension load program was used in which the maximum tensile stress (S_{max}) was equal to approximately 38 to 78 pct of the room temperature yield strength. The minimum tensile stress (S_{min}) applied to the specimen was arbitrarily chosen to equal 10 pct of S_{max}. High frequencies were arbitrarily chosen so the testing could be completed in a minimum amount of time. The frequencies used were 10 Hz for tests with S_{max} of 100, 90, or 80 ksi and 15 Hz for tests with S_{max} of 70, 60, or 50 ksi. The specimens were inspected for surface defects prior to testing using dye penetrant, and the results are shown in the tables. After the dye-penetrant inspection, the specimens were measured to determine the minimum cross-sectional area necessary for calculating the loads required to achieve S_{max} and S_{min}. The specimen to be tested was then loaded into the test machine, and the program was initiated. The cycles to failure were automatically recorded.

TABLE 5. - Tensile test results for Ti-6Al-4V alloy castings at room temperature

Specimen condition[1] and number[2]	Tensile strength, ksi	Yield strength (0.2 pct), ksi	Elongation in 4D,[3] pct	Reduction in area, pct
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 1,300° F for 2 h.
[2]See text for explanation of specimen numbers ("Melting and Casting" section).
[3]4D indicates a length equal to 4 diameters of the gauge section.
[4]Specimen broke in outer quarter of gauge length.
[5]"Hot pressed" refers to hot isostatic pressing.

DISCUSSION OF RESULTS

CHARPY V-NOTCH TESTS

The average impact strengths determined by Charpy V-notch testing of annealed machined specimens at room temperature were 21.5 ft·lbf, for a cast specimen; 19.1 ft·lbf cast, and hot pressed; and 17.8 ft·lbf, cast, milled, and hot pressed; which all compare favorably with the impact strength of forged Ti-6Al-4V alloy (13), which is typically 17 ft·lbf. A comparable figure, 19.2 ft·lbf, was found in the literature for specimens machined from investment-cast aircraft engine parts (16).

TENSILE TESTS

The room temperature tensile test properties of Ti-6Al-4V alloy castings were determined from annealed round specimens. The average values for tensile strength, yield strength (0.2 pct), and elongation exceeded the minimum requirements for grade C-5 according to ASTM specification B367-69 (1). The minimum requirements

TABLE 6. - High-cycle fatigue test results for Ti-6Al-4V alloy in the cast and annealed condition at room temperature

(Specimens ranked according to maximum stress)

Specimen	Defect class	Maximum stress, ksi	Number of cycles	Remarks
1C.........	DF	100	24,500	TRF; 2 GP's at 1/4 diam.
7E.........	DF	100	31,300	GP just under outside surface.
15F........	DF	100	32,800	GP at center, GP just under outside surface.
16B........	DF	100	23,800	BIS; NDF.
20E........	D	100	18,400	GP in center, GP just under outside surface.
7C.........	D	90	63,600	GP in center.
7F.........	DF	90	48,400	GP just under outside surface.
10B........	D	90	41,500	GP at center, GP at 1/4 diam.
13C........	D	90	26,100	GP at 1/4 diam.
16F........	DF	90	56,600	2 GP's near center.
1F.........	DF	80	104,100	GP in center.
10D........	DF	80	100,000	NDF.
11E........	DF	80	90,000	TRF; NDF.
20D........	DF	80	148,000	TRF; NDF.
20F........	DF	80	58,000	GP in center, GP just under outside surface.
11D........	DF	70	288,300	BIS; NDF.
15C........	D	70	60,100	GP on perimeter.
15E........	DF	70	112,900	NDF.
16C........	DF	70	93,600	GP just under outside surface.
20B........	D	70	83,400	GP on perimeter.
1D.........	DF	60	148,900	1 large (>0.1-in) hole in center.
7D.........	DF	60	212,100	NDF.
10C........	DF	60	199,800	NDF.
13E........	D	60	136,600	GP just under perimeter.
1E.........	D	50	278,900	NDF.
7B.........	D	50	3,208,100	Near-radius breaker, GP in center.
11B........	D	50	725,300	NDF.
11F........	D	50	138,700	BIS; NDF.
16E........	DF	50	222,600	NDF.

BIS Broke in shoulder. GP Gas pocket.
D Surface defect noted. NDF No defects in fracture surface.
DF Surface defect free. TRF Thread-root failure.

for forged parts used in flight vehicle structures (15) are 130 ksi for tensile strength, 120 ksi for yield strength (0.2 pct), 10 pct elongation, and 25 pct reduction in area. The values shown in table 5 compare favorably with these requirements with the exception of the minimum requirement for reduction in area. None of the specimens tested met this minimum. The room temperature tensile properties of round specimens machined from investment castings as reported in the literature (16) are as follows:[7] tensile strength, 133.8 and 135.1 ksi; yield strength (0.2 pct), 127.8 and 124.1

[7]The two values given for each tensile strength property are average values obtained from test specimens machined from an outer ring casting (first value given) and an inner ring casting (second value given); the outer and inner rings were separately cast for use in an aircraft engine.

TABLE 7. - High-cycle fatigue test results for Ti-6Al-4V alloy in the cast, hot-pressed (HIP), and annealed condition at room temperature

(Specimens ranked according to maximum stress)

Specimen	Maximum stress, ksi	Number of cycles	Remarks[1]	Specimen	Maximum stress, ksi	Number of cycles	Remarks[1]
17B.....	100	25,200	BIS; NDF.	9B......	80	1,058,300	NDF.
17D.....	100	23,000	BIS; NDF.	9D......	80	81,900	BIS; NDF.
18C.....	100	41,000	BIS; NDF.	17C.....	80	77,400	BIS; NDF.
18D.....	100	23,000	BIS; NDF.	18B.....	80	593,300	BIS; NDF.
9F......	90	35,900	BIS; NDF.	3E......	70	6,722,300	NDF.
17E.....	90	NAp	Grip failure.	3F......	70	4,665,300	NDF.
18E.....	90	20,300	NDF.	5B......	70	856,800	BIS; NDF.
18F.....	90	31,900	BIS; NDF.	5F......	70	261,600	BIS; NDF.
3B......	80	1,559,500	BIS; NDF.	9E......	70	76,400	NDF.

BIS Broke in shoulder.
NAp Not applicable.
NDF No defects in fracture surface.
[1]Surfaces of all specimens were defect free.

TABLE 8. - High-cycle fatigue test results for Ti-6Al-4V alloy in the cast, milled, hot-pressed (HIP), and annealed condition at room temperature

(Specimens ranked according to maximum stress)

	Maximum stress, ksi	Number of cycles	Remarks[1]
6B.........	100	44,200	NDF.
8B.........	100	36,900	BIS; NDF.
8D.........	100	26,000	NDF.
6C.........	90	61,000	Radius break; NDF.
8E.........	90	54,100	BIS; NDF.
19D........	90	74,600	BIS; NDF.
2B.........	80	85,500	BIS; NDF.
2F.........	80	126,500	NDF.
19B........	80	74,600	BIS; NDF.
4E.........	70	162,700	BIS; NDF.
4F.........	70	>10,000,000	Runout, did not break.
6E.........	70	115,800	BIS; NDF.
8C.........	70	127,800	BIS; NDF.
8F.........	70	151,300	BIS; NDF.
19C........	70	156,600	NDF.
19F........	70	87,200	BIS; NDF.
2E.........	60	>10,000,000	Runout; did not break.
6D.........	50	>10,000,000	Do.

BIS Broke in shoulder.
NDF No defects in fracture surface.
[1]Surfaces of all specimens except 19F were defect free.

ksi; elongation, 6.0 and 9.6 pct; and reduction in area, 16.6 and 20.9 pct. From the same study, the following values were reported for specimens from hot-pressed investment castings: tensile strength, 129.2 and 139.5 ksi; yield strength (0.2 pct), 120.9 and 126.3 ksi; elongation, 6.7 and 8.4 pct; and reduction in area, 18.8 and 20.8 pct. The tensile properties of the sand castings (table 5) also compare favorably with the tensile properties of the investment castings from the study cited above.

The lower values for the tensile properties of the hot-pressed specimens, compared to those of the cast specimens, in table 5, are due to the HIP process. The HIP process, with its slow cooling cycle, promotes a coarsening of the microstructure which reportedly increases the notch sensitivity and reduces the values of the tensile properties (7, 16). While the hot pressing did eliminate porosity, the lower ultimate strength and yield strength values indicate that the cooling rate during HIP is important in determining the degree of benefit HIP will have on the cast Ti-6Al-4V alloy.

FATIGUE TESTS

Room temperature fatigue tests were conducted on round cast test specimens with a buttonhead grip configuration. Ten tests were initially made, five with a threaded grip and five with a buttonhead grip to evaluate the grip types. With the threaded grip, a high incidence of thread-root failures was encountered, and therefore the buttonhead grip was selected for the remainder of the specimens in the test program. The buttonhead grip worked quite well for the cast specimens, but a larger-than-expected number of shoulder breaks--61 pct--was encountered during testing of the hot-pressed specimens. When this problem was first encountered, it was believed to be due to improperly machined collets on the test machine. However, several different sets of collets were tried, but no improvement in results was achieved. Examination after testing indicated that the stress concentration in the radius of the buttonhead shoulder was sufficiently high to initiate fracture in the shoulder.

The data for the high-cycle fatigue tests, in which failure occurred in the gauge length and visible defects were less than 10 pct of the area of the fracture surface, are shown in figure 10. The solid line in the figure shows typical fatigue data for annealed Ti-6Al-4V alloy (bar) at room temperature (18). The scatter in the fatigue data for the castings was large enough that no statistical significance may be determined between the data for the cast and hot-pressed specimens. The general trend of the data indicates that HIP does improve the fatigue life at stresses of 70 ksi and below. The trend for the cast specimens indicates that no samples tested at 70, 60, or 50 ksi would exceed a fatigue life of 1 million cycles, with a 50-pct confidence level. The trend for the hot-pressed specimens indicates that a fatigue life of 1 million cycles would be exceeded at a stress of 70 ksi or below, with a 50-pct confidence level.

Other researchers have reported similar results. Eylon and Strope (9) also obtained good tensile properties with cast Ti-6Al-4V alloy, but they reported

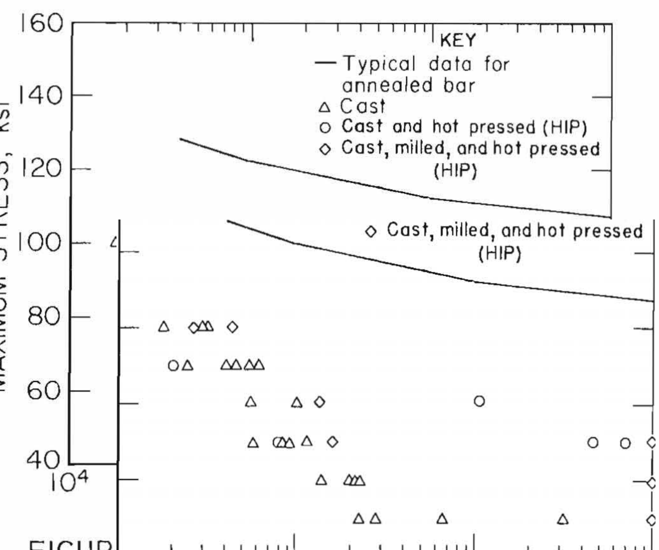

FIGURE 10. - High-cycle fatigue test results for Ti-6Al-4V alloy at room temperature.

significantly lower fatigue life compared to that of beta-rolled and annealed or beta-forged Ti-6Al-4V alloy with similar microstructure. They also encountered high fatigue data scatter and attributed it to a combination of casting defects and a highly notch-sensitive alpha colony structure. Eylon's later work with hot-pressed castings (7) showed that the HIP process healed the porosity, but that the fatigue life was only marginally improved when compared to the fatigue life of typical wrought material. The fatigue testing was done on flat specimens, and for this reason no comparisons should be made with the data from this investigation. Stewart and Hess (16) also reported no significant difference in fatigue properties for thin-section material in the investment-cast and investment-cast-and-hot-pressed condition. They concluded that variation in microstructure, test specimen uniformity, and surface condition obscured any demonstration of HIP benefit to room temperature fatigue properties. Unfortunately, their high-cycle fatigue testing of round specimens was done by the rotating beam method, and therefore no comparisons should be made between their data and the data in tables 6, 7, and 8.

The increased notch sensitivity brought about by the coarsening of the microstructure during HIP is probably the most detrimental factor in reducing the fatigue life of cast Ti-6Al-4V alloy. Commercial HIP units are currently available that provide sufficient cooling rates to obtain a finer colony structure and ensure that adequate mechanical properties are attained. An alternative suggested by Stewart (16) would be to beta-solution heat treat in place of the post-HIP anneal to refine the alpha-platelet morphology.

CONCLUSIONS

The room temperature mechanical and fatigue properties of Ti-6Al-4V alloy cast in waterglass-bonded zircon sand molds were investigated. Castings were hot pressed to close the internal casting porosity and improve the fatigue life of the material. The HIP process healed the casting pores, but no significant improvement in the fatigue life was observed. Comparison of the data to published data for forged Ti-6Al-4V alloy and for Ti-6Al-4V alloy cast in investment molds showed that--

1. The average impact strengths (Charpy V-notch) were 21.5 ft•lbf, for a cast specimen; 19.1 ft•lbf cast and hot pressed; and 17.8 ft•lbf, cast, milled, and hot pressed; which all compare favorably with forged and investment-cast Ti-6Al-4V alloy.

2. The room temperature tensile properties of cast; cast and hot pressed; and cast, milled, and hot-pressed specimens all exceeded the minimum requirements, with the exception of reduction in area, for (1) grade C-5 according to ASTM specification B367-69 and (2) titanium alloy bars and forgings as specified in AMS4928H.

3. Although the internal casting porosity was healed by the HIP process, the fatigue strength was not significantly improved, and the values obtained were significantly lower than those of wrought products.

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