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Room Temperature Tensile Properties of Titanium and Seven Titanium Alloys Prepared by Skull Casting

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ROOM TEMPERATURE TENSILE PROPERTIES OF TITANIUM AND SEVEN TITANIUM ALLOYS PREPARED BY SKULL CASTING

by

E. D. Calvert[1] and Ronald R. Lowery[2]

ABSTRACT

The room temperature tensile properties of commercially pure titanium and seven titanium alloys prepared by skull casting were determined in the as-cast and heat-treated conditions. Data were compared with property data from tensile tests on wrought alloys of the same compositions in the as-worked and heat-treated conditions. The alloys evaluated were Ti-5Al-2.5Sn, Ti-6Al-4V, Ti-6Al-4V-1Si, Ti-6Al-2Sn-4Zr-2Mo, Ti-6Al-6V-4Zr-4Mo, Ti-6Al-6V-2Sn, and Ti-11.5Mo-6Zr-4.5Sn. Test specimens were prepared from both static and centrifugal castings and from plate fabricated by forging and rolling vacuum-melted ingots.

The data indicate that the alpha and alpha-beta alloys have strength properties in the as-cast condition that are reasonably close to the strength properties of their wrought counterparts in the as-worked condition. An exception to this was the Ti-6Al-6V-4Zr-4Mo alloy for which insufficient data were available to form any firm conclusions.

Fine-grained cast structures of Beta III(Ti-11.5Mo-6Zr-4.5Sn) were shown to be generally stronger in the as-cast condition than the wrought alloy in the as-worked condition except for the yield strength of one structure that was unusually low. Heat treatment of this alloy produced properties that were unpredictable. Indications are, however, that optimization of heat treatment parameters for each cast structure could produce strength properties equal to that of wrought materials.

INTRODUCTION

About 20 years ago, researchers at the Albany, Oreg., laboratory of the Bureau of Mines recognized the potential need for titanium castings in the chemical, marine, and aircraft industries. A process was developed by which titanium could be melted in a water-cooled copper crucible and poured into suitable molds (2).[3] Because a "skull" or thin shell of metal froze and was

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[1] Metallurgist.

[2] Research physicist.

[3] Underlined numbers in parentheses refer to items in the list of references preceding the appendixes.

left behind in the crucible after the pour, the process was labeled "skull melting" or more appropriately "skull casting." In the ensuing years, this casting technique was refined by the Bureau and by commercial titanium melters, and today an industrial capability exists for producing both precision investment castings and massive castings of titanium weighing several hundred pounds. Titanium "skull casting" has become an important manufacturing method.

The obvious value of casting rests in the ability to directly prepare intricate and complex hardware by pouring liquid metal into shaped molds. This makes it possible to minimize, or avoid completely, metal-working and jointing operations and in so doing save in labor, materials, and capital outlay for costly fabricating equipment. However, it is not sufficient that the parts may be readily formed; they must also meet critical requirements of soundness and mechanical properties. Numerous titanium alloys have been developed to meet specific property requirements. The castability of commercially pure titanium and seven promising titanium alloys was recently investigated by the Bureau of Mines after screening a large number of alloys developed in the United States by different producers (3). It was intended that representative alpha, alpha-beta, and beta alloys be included. The compositions selected were as follows:

1. Alpha composition.
    - a. Commercially pure titanium.
    - b. Ti-5Al-2.5Sn.
2. Alpha-beta composition.
    - a. Ti-6Al-4V.
    - b. Ti-6Al-2Sn-4Zr-2Mo.
    - c. Ti-6Al-6V-4Zr-4Mo.
    - d. Ti-6Al-6V-2Sn.
3. Beta composition.
    - a. Ti-11.5Mo-6Zr-4.5Sn (Beta III).
    - b. Ti-8Mn.

This paper reports a continuation of the aforementioned work to comparatively evaluate the room temperature tensile properties of static and centrifugal skull-casting with wrought materials of these alloys. As-cast, as-worked and heat-treated properties were examined. The Ti-8Mn was not evaluated for tensile properties; instead, a silicon modification of the Ti-6Al-4V alloy was substituted.

It is common practice for commercial producers of titanium ingot to add controlled amounts of oxygen as TiO_2 to sponge metal electrodes to meet hardness specifications for wrought products. This cannot be done without affecting the carbon contents and properties of material relative to carbon. Because of this commercial practice, evaluation of the effects of carbon and oxygen on the properties of cast and wrought unalloyed titanium is a necessary part of this study.

Properties of cast structures of many of these alloys have been previously reported by other investigators (1, 4, 6) as have the properties of various mill products. No data, however, have been published that show properties of skull-cast and of wrought materials prepared by a single facility in which care was taken to assure that all starting raw material was of the same purity, that identical treatment throughout all processing steps was given to all the alloys of like composition, and that test specimens and conditions did not constitute a major variable.

EXPERIMENTAL WORK

Equipment

The furnace used to prepare evaluation castings is shown schematically in figure 1. Basically, it is a consumable electrode arc furnace equipped with an integral trunnion-mounted crucible and water jacket assembly that can be tilted to pour its molten contents. Molds are mounted in the separate chamber beneath the crucible. The mold table can be rotated at any speed from 0 to 700 rpm to make centrifugal castings.

Because titanium in the molten condition rapidly reacts with the atmospheric gases, melting must be done in vacuum or under an atmosphere of inert gas. For this reason, all furnace sections are joined with 0-ring seals, and pumps are provided whereby the furnace atmosphere can be reduced to low pressures.

Melting power is furnished from a bank of 23 dc selenium rectifiers connected in parallel. A maximum current of approximately 13,000 amperes at 40 volts potential is available to the melting unit. The maximum power required for this work, however, did not exceed 6,500 amperes arc current at about 30 volts arc potential.

A vacuum arc melting furnace of conventional design was used to prepare primary ingots for casting electrodes and double-melted ingots for fabrication.

Electrode Fabrication

Consumable electrodes for both forging ingots and castings were prepared by blending commercially pure, vacuum-distilled titanium sponge metal with appropriate amounts of titanium dioxide and graphite to adjust the contents of oxygen and carbon to desired levels, and of elemental metals or master alloys to produce the desired alloy composition. The alloying metals were in the form of powders, crushed reguli, or fine machine chips. The blended metals

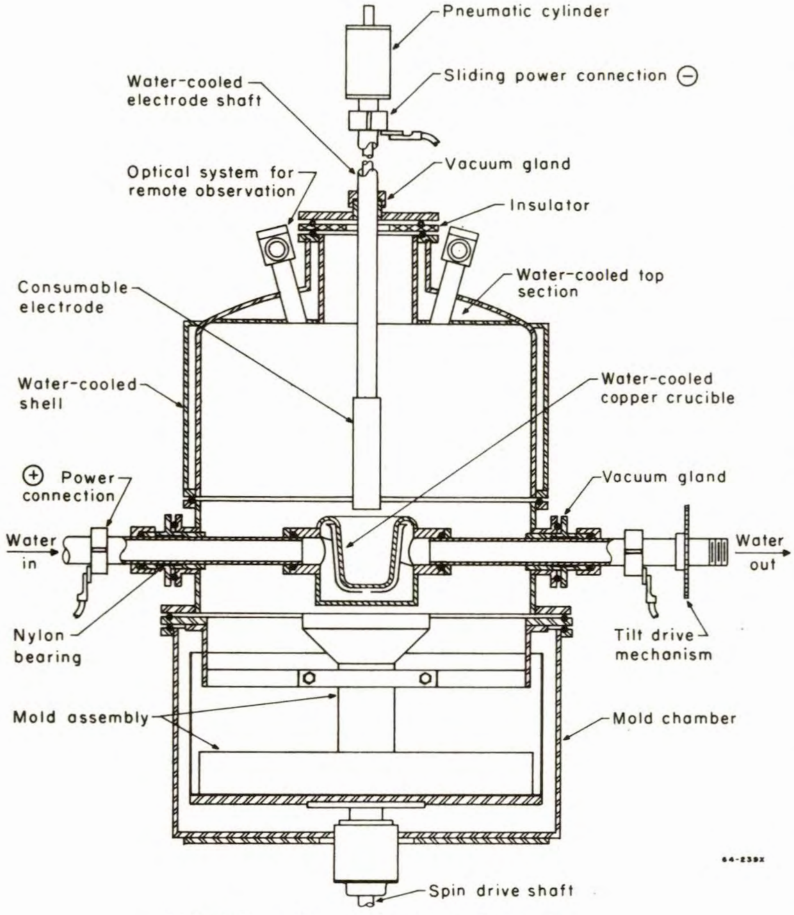

FIGURE 1. - Skull-casting furnace.

were then compacted at 40 tsi pressure in a hydraulic press to form rectangular bars. Several bars of the same composition were jointed end-to-end by tungsten inert gas welding and subsequently vacuum arc melted into tubular water-cooled molds to form cylindrical alloy ingots. Two or more of the ingots thus formed were jointed by welding and used for consumable electrodes for skull-casting heats and for preparation of double-melted ingots for forging.

Melting and Casting

Ingot melting and casting heats were basically the same. In both processes melting was accomplished by the consumable electrode arc melting technique. For ingot production the mold was a stationary water-cooled copper sleeve into which the electrode was melted and allowed to solidify. Castings were prepared by pouring molten metal into uncooled graphite molds from a tiltable water-cooled copper crucible.

Typically, casting heats were conducted using electrodes fabricated from previously melted alloy ingots. The electrodes were attached to a water-cooled copper shaft, which is the cathode of the melting system. A small amount of alloy scrap or machine turnings was placed in the casting crucible or ingot mold to serve as a starting pad; the furnace was then closed and evacuated. After the ultimate vacuum of the system was attained ($\sim 1 \times 10^{-3}$ torr), an arc was struck and melting began. During ingot melting, the power was adjusted to a level that was consistent with sound homogeneous ingots; it was maintained at that level until near the end of the melt at which time it was progressively reduced or interrupted and lowered in increments to hot top the ingot.

Casting heats utilized much greater power levels to achieve high melt rates and deep molten pools. Contrary to the aforementioned procedures for ingot melting, power was abruptly terminated at the end of the melt, and in an automatic sequence of events, the electrode was withdrawn from the crucible, and the crucible was tilted to empty its contents into the molds. Centrifugal castings were prepared in the same manner. However, instead of pouring into a stationary mold, metal was poured into a mold mounted on a turntable that revolved at 700 rpm to produce a force on the specimens of about 100 times that of gravity.

All of the melt stock for the casting heats and for preparation of forging ingots of each alloy were fabricated at the same time from identical lots of raw materials to insure compositional uniformity of the wrought and cast structures. Typical analyses of the alloys are presented in appendix B.

Specimen Preparation

Experiments were designed to obtain both large- and small-grained castings to approximate structures found in commercial cast hardware. Structures of castings with high cross-sectional areas were obtained by pouring 6-inch-diameter solid cylindrical castings approximately 10 inches long into graphite molds using equipment illustrated in figure 1. The grains in these castings were essentially equiaxed and ranged up to several millimeters in size depending upon alloy composition. Button head tensile specimens conforming to the specifications shown in figure 2 were machined longitudinally from a center slab of each cast ingot. This location was chosen because it contains the greatest structural uniformity. The structures of commercial castings of low-dimensional cross section were simulated by directly casting the tensile specimen shown in figure 2 in graphite molds. The cast dimensions were approximately 1/16 inch oversize to allow for shrinkage and machining. The grains in these castings were equiaxed and ranged in size from ASTM 1 to -3. Attempts to produce further changes in the cast structure were made by centrifugally casting the aforementioned shapes. The grain size of the centrifugally cast specimens was only slightly reduced from that of the statically cast specimens. However, casting soundness and uniformity of grain size were significantly improved.

To avoid contamination of test materials and to obtain consistency in mold properties such as density and thermal conductivity, all molds for this work were machined from high-density, low-ash, high-purity industrial graphite. The mold used to prepare both the centrifugal and static cast tensile specimens is shown in figure 3. It served two purposes, that of preparing the cast-to-shape tensile specimens and of casting fluidity spirals to aid in the evaluation of alloy castability, which has been discussed in another report (3). Figure 4 shows a typical rough casting as removed from the mold.

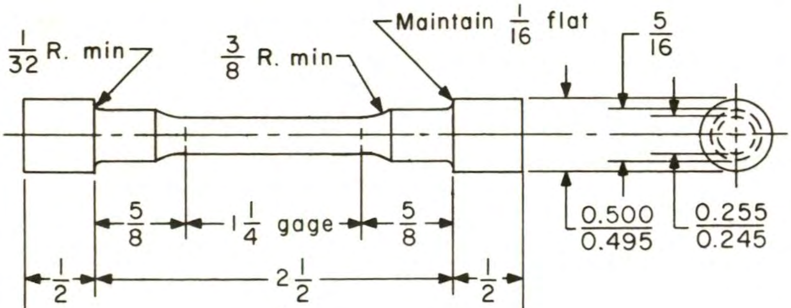

FIGURE 2. - Button head tensile specimen.

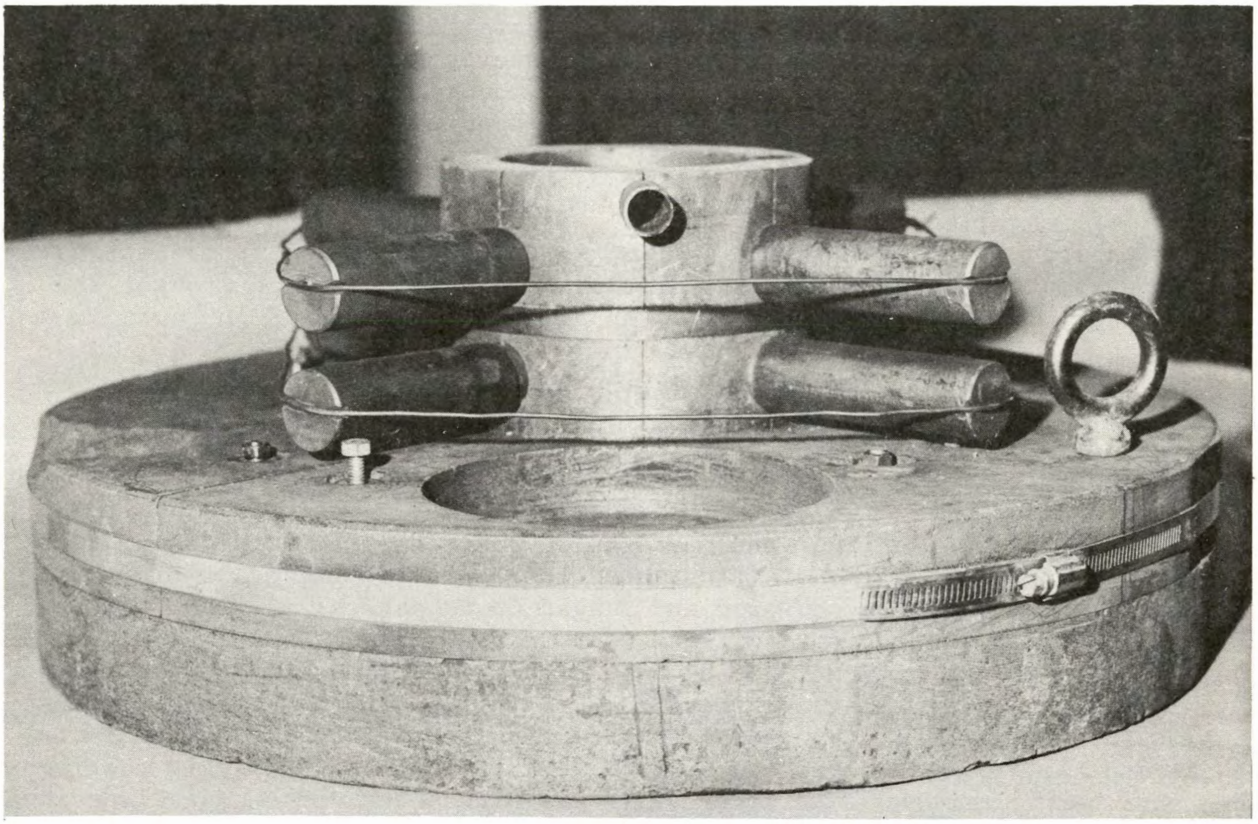

FIGURE 3. - Fluidity spiral—test specimen mold.

To directly compare the properties of cast alloys with the properties of forgings, ingots 6 inches in diameter by about 10 inches long were prepared by double arc melting in vacuum. After machine conditioning, ingots of each alloy were forged and hot rolled to 5/8-inch plate. Button head specimens conforming to specifications shown in figure 2 were then machined from the plate parallel to the rolling direction.

All test specimens, whether machined from castings or forgings, or prepared directly by casting to shape, were inspected radiographically and by dye penetrant tests to detect possible voids or flaws beneath the surface and to detect cracks or defects originating at the surface. Defective specimens were discarded.

Heat Treatments

Normally, structural materials and components for stress applications are not used in the as-cast or as-worked conditions. Rather, they are given some sort of heat treatment to optimize properties for specific applications. The alloys involved in this study were heat treated in vacuum according to schedules contained in the "Alloy Digest" (1). Attempts to optimize heat treatments for each alloy were beyond the scope of this study. Therefore, the time temperature relationships used may not have optimized the properties. They

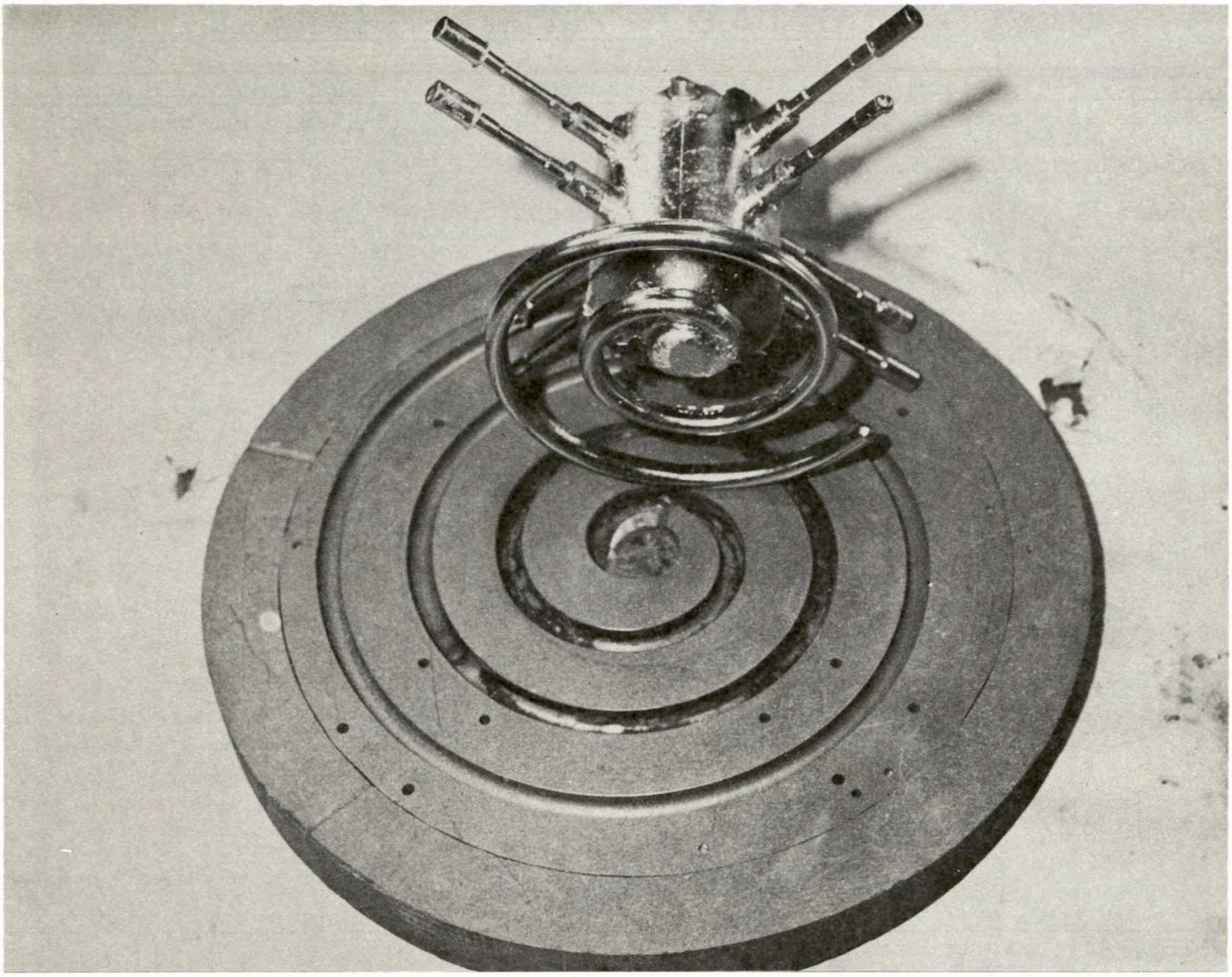

FIGURE 4. - Fluidity spiral—test specimen casting.

are, however, directly comparable for each of the structures whether cast or wrought. Test specimens were machined from the as-cast and as-worked ingots and castings prior to heat treating to minimize differences in properties that might result from heat treating specimens of different size and mass under the same conditions. The thermal treatments used for each alloy are shown in table 1.

TABLE 1. - Heat treatments for cast and wrought titanium alloys

Alloy designation	Thermal treatment	Heat treatment schedule
Commercially pure Ti....	Stress relieved..........	1,200° F (1 hr) G.C.
Ti-5Al-2.5Sn............	.....do..................	1,200° F (1 hr) G.C.
Ti-6Al-4V...............	Annealed.................	1,300° F (1 hr) G.C.
	Solution treated.........	1,700° F (30 min) W.Q.
	Solution treated and aged.	1,700° F (30 min) W.Q. + 1,000° F (4 hr) G.C.
Ti-6Al-4V-1Si...........	Same as for Ti-6Al-4V....	
Ti-6Al-2Sn-4Zr-2Mo......	Stress relieved..........	1,200° F (1 hr) G.C.
	Solution treated.........	1,750° F (1 hr) W.Q.
	Solution treated and aged.	1,750° F (1 hr) W.Q. + 1,000° F (4 hr) G.C.
Ti-6Al-6V-4Zr-4Mo.......	Annealed.................	1,575° F (4 hr) G.C.
	Solution treated.........	1,575° F (4 hr) W.Q.
	Solution treated and aged.	1,575° F (4 hr) W.Q. + 950° F (8 hr) G.C.
Ti-6Al-6V-2Sn...........	Annealed.................	1,300° F (1 hr) G.C.
	Solution treated.........	1,630° F (1-1/2 hr) W.Q.
	Solution treated and aged.	1,630° F (1-1/2 hr) W.Q. + 1,050° F (4 hr) G.C.
Ti-11.5Mo-6Zr-4.5Sn.....	Stress relieved..........	1,000° F (1 hr) G.C.
	Solution treated.........	1,450° F (15 min) W.Q.
	Solution treated and aged.	1,450° F (15 min) W.Q. + 950° F (8 hr) G.C.

NOTE.--All heat treatments conducted in vacuum.
G.C. = Gas cool.
W.Q. = Water quench.

Tensile Testing

All tensile tests were performed on standard 1/4-inch-diameter button head specimens as shown in figure 2. A 60,000-pound-capacity hydraulic universal test machine was used. Specimens were strained at a rate of 0.01 in/in/min. The rate was controlled by pacing the movement of the crosshead. Strain was measured and recorded with an ASTM class A averaging separable extensometer. After the 0.2 pct yield strength was exceeded, the extensometer was removed, and the specimen was strained at the same rate until failure. Elongation and reduction in area were taken in the normal manner after the test.

TENSILE PROPERTIES OF ALLOYS

Commercially Pure Titanium

The interstitials, oxygen and carbon, are known to offer substantial strengthening effects to titanium, but how these elements interrelate with the structure and tensile strength has not been clearly defined. Trends indicated by three levels of oxygen, 800, 1,200, and 1,800 ppm with carbon constant at 400 ppm, and three levels of carbon, 400, 1,000, and 1,500 ppm with oxygen constant at 800 ppm, were evaluated. The effects of these elements on the room temperature strength and ductility of unalloyed titanium is shown in table 2 and graphically in figures 5-6. Values presented for each oxygen-carbon combination are the average of three determinations.

TABLE 2. - Effect of oxygen and carbon on tensile properties of skull-cast and wrought, commercially pure titanium

Impurity, ppm		Ultimate tensile strength, psi × 10^3	Yield strength 0.2 pct offset, psi × 10^3	Elongation, pct	Reduction of area, pct
O	C				
SKULL-CAST 6-INCH-DIAMETER INGOTS--AS-CAST--COARSE STRUCTURE					
800	400	84.1	74.0	14.0	32.0
1,200	400	62.7	52.3	19.0	45.0
1,800	400	64.7	55.4	14.5	42.0
800	400	84.1	74.0	14.0	32.0
800	1,000	57.8	46.2	32.0	59.0
800	1,500	64.8	52.0	24.5	48.5
SKULL-CAST 1/4-INCH-DIAMETER TENSILE SPECIMEN--AS-CAST--FINE STRUCTURE					
800	400	93.4	80.9	15.0	32.0
1,200	400	67.9	56.9	25.5	53.0
1,800	400	73.7	62.3	20.5	40.5
800	400	93.4	80.9	15.0	32.0
800	1,000	67.0	53.8	28.7	66.3
800	1,500	71.3	62.2	24.5	55.0
COLD-MOLD INGOT, WROUGHT--VERY FINE STRUCTURE					
800	400	62.5	56.8	31.0	55.0
1,200	400	71.0	56.0	30.5	49.0
1,800	400	79.0	65.3	28.0	44.0
800	400	62.5	56.8	31.0	55.0
800	1,000	68.7	55.8	32.0	35.0
800	1,500	72.8	58.5	31.5	55.0

NOTE.--All test material stress relieved at 1,200° F for 1 hour.

These data show that for fine-grained wrought structures, increasing the concentration of either carbon or oxygen in titanium results in increased strength. A slight degradation of ductility is shown to result. The strength of the cast structures, however, did not follow trends that were indicated by wrought material tests. At the lowest levels of oxygen (800 ppm) and carbon (400 ppm), strengths for both the fine-grained 1/4-inch-diameter cast section and the coarse-grained 6-inch-diameter cast section were at their highest level. These structures were stronger than the strongest wrought unalloyed titanium evaluated but considerably less ductile. As the concentration of carbon or oxygen was increased, the tensile and yield strength rapidly decreased to values similar to the wrought material. When the concentration of these elements was further increased, a more normal trend of hardening was

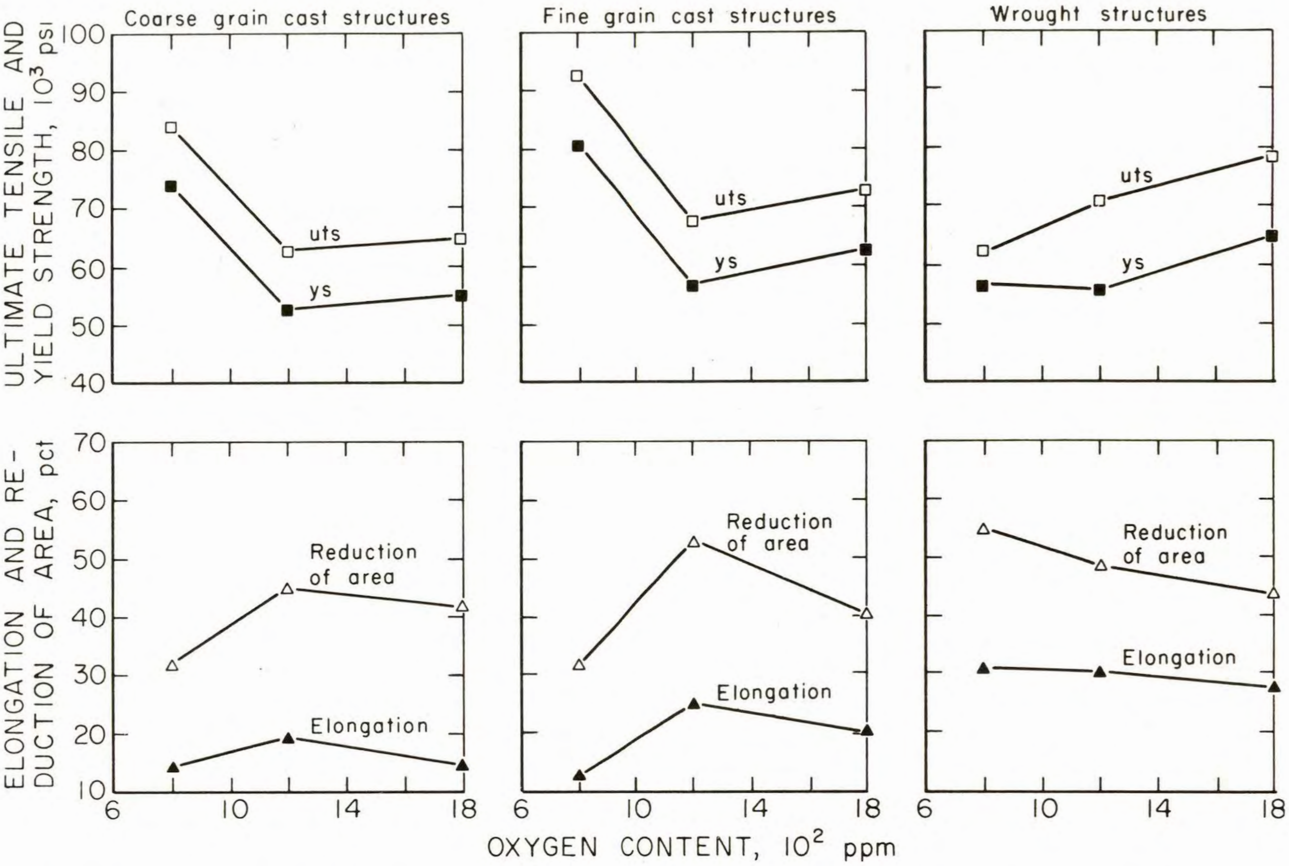

FIGURE 5. - Effect of oxygen on tensile properties of skull-cast and wrought commercially pure titanium.

observed, that is, a nearly linear variation of properties with oxygen or carbon. The reasons for the anomalous relationship between the strength of the cast structures and the interstitial contents is not presently understood.

Ti-5Al-2.5Sn

Titanium-5Al-2.5Sn is a single-phase alpha alloy developed for use in welded sections that require higher strength than is available in commercially pure titanium. Because it is single phase and therefore not heat treatable, any change in mechanical properties must be brought about by structural changes and redistribution of impurities. Attempts to accomplish this were made by forging, rolling, and skull casting as already discussed.

Average tensile properties of the four structures evaluated and shown in table 3 indicate that the strength and ductility of castings of this alloy are sufficiently close to those of wrought material to be useful in most applications.

TABLE 3. - Effect of structure on room temperature tensile properties of Ti-5Al-2.5Sn

Structure	Ultimate tensile strength, psi X 10^3	Yield strength 0.2 pct offset, psi X 10^3	Elongation, pct	Reduction of area, pct
Wrought[1]	122.0	106.4	13.5	37.5
6-inch-diam cast[2] ...	107.7	102.0	13.0	27.0
1/4-inch-diam static cast[3]	107.5	98.7	11.0	26.0
1/4-inch-diam centrifugal cast[4] ..	104.1	93.5	11.0	31.0

[1] Very fine structure.
[2] Coarse equiaxed structure.
[3] Fine equiaxed structure.
[4] Uniform fine equiaxed structure.

NOTE.--All test specimens stress relieved at 1,200° F for 1 hour.

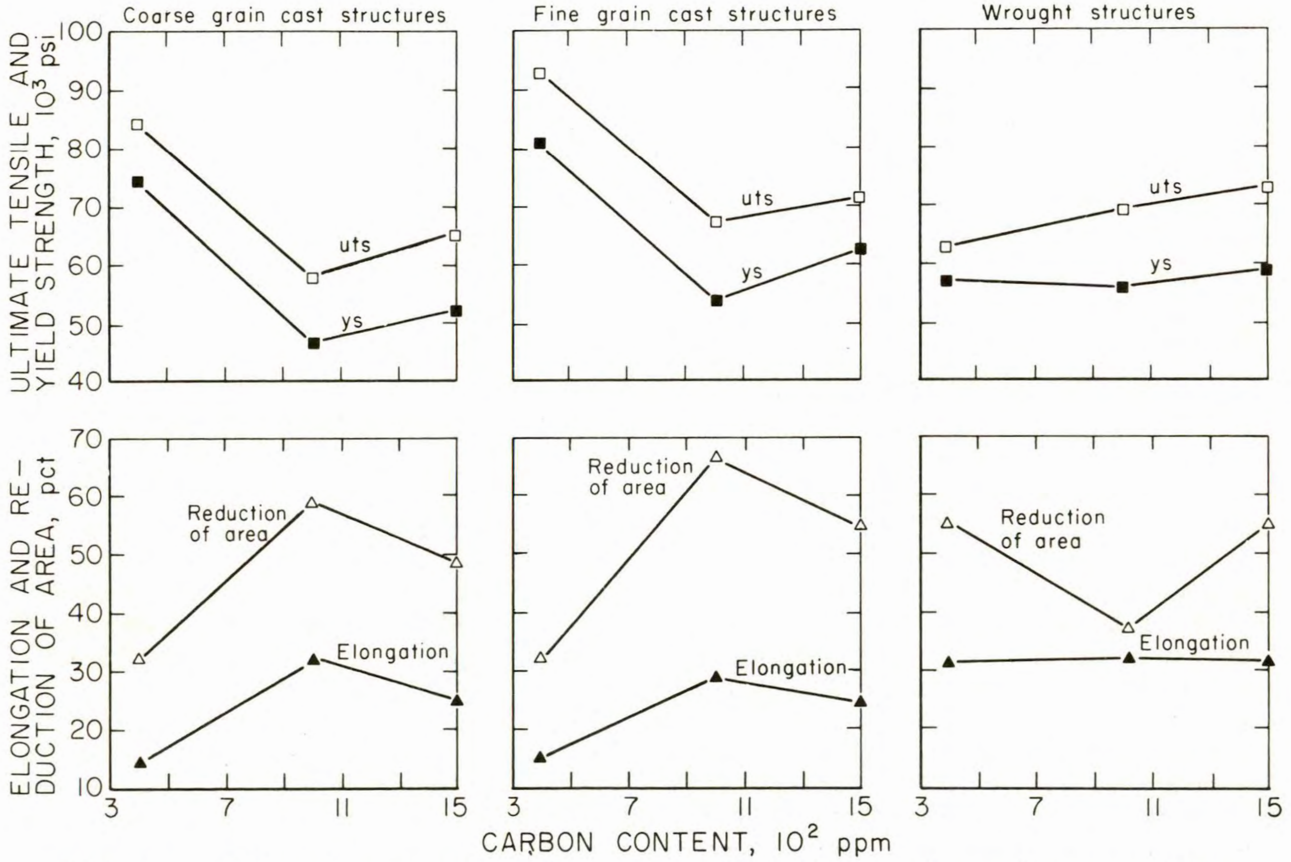

FIGURE 6. - Effect of carbon on tensile properties of skull-cast and wrought commercially pure titanium.

Ti-6Al-4V

This alloy is one of the most versatile of all the titanium alloys developed to date. It is used in a variety of forms, ranging from thin sheet, to heavy forgings, to castings. It is an alpha-beta alloy in which aluminum is used to stabilize alpha and vanadium to stabilize the beta phase. It can be annealed to high toughness and moderate strength in the alpha-beta range and heat treated to strengths comparable with that of high-strength steels. It has become the "workhorse" of titanium alloys and is the earliest and still most widely used titanium alloy for casting.

Data presented in table 4 shows that the room temperature tensile strength of both coarse- and fine-grained cast structures are essentially the same as the tensile strength of the wrought alloy in the as-worked condition. The yield strength and ductility of the cast materials, however, are considerably lower than that of the wrought. The wrought alloy is more responsive to heat treatment and achieves about 8 to 15 pct higher strengths after aging than do the cast alloys. Centrifugal cast specimens, which have a fine, uniform grain structure, appear to be generally stronger than either of the other two cast structures. In the as-cast condition, centrifugal cast specimens have ultimate tensile and yield strengths nearly equal to the heavily worked alloy in the as-worked condition. Their elongation and reduction of area, however, are only about half that of the wrought plate. Considering the appreciable decrease in strength of the cast structure after stress relieving, it is assumed that the castings prior to heat treatment are in a relatively high stress state. This could result from the practice of using fairly massive, highly conductive graphite molds that are at ambient temperature. The cast metal is rapidly cooled from the liquid state to below the stress relief temperature as contained heat is rapidly transferred from the charge to the mold and furnace components. The net result is that the casting is essentially quenched, and stresses are locked in.

Ti-6Al-4V-1Si

London, Antes, and Edelman (5) early in 1963 reported on work aimed at maximizing the mechanical properties of Ti-6Al-4V for a casting alloy. The basic composition was altered by substituting 2 pct Mo for one half of the vanadium and by adding silicon in small quantities. They found that in the range of 0.16 to 0.51 pct, both the yield and the ultimate tensile strength increased at the rate of 6,000 psi per 0.1 pct Si increase. Bureau of Mines data do not indicate strengthening at the rate reported by London and co-workers. The alloy systems, however, are not identical, and interactions between Mo, V, and Si differ. However, the amount obtained was appreciable as is shown in table 5. The deleterious effect of silicon on ductility is reflected by the low values of elongation and reduction in area for that alloy in all conditions. The Ti-6Al-4V-1Si cast products in the as-cast condition have strength levels somewhat higher than that of the wrought material before heat treatment.

TABLE 4. - Tensile properties of wrought and skull-cast Ti-6Al-4V in as-worked, as-cast, and heat-treated conditions

Specimen	Ultimate tensile strength, psi X 10^3	Yield strength 0.2 pct offset, psi X 10^3	Elongation, pct	Reduction in area, pct
5/8-inch plate:[1]				
Hot rolled...........	135.5	127.2	11	31
Annealed.............	135.8	127.2	10	24
Solution treated.....	154.2	131.6	11	31
Aged.................	173.0	157.0	5	14
Static cast 6-inch-diam:[2]				
As cast..............	132.7	119.5	6	20
Annealed.............	124.0	115.2	7	16
Solution treated.....	138.2	112.5	4	8
Aged.................	160.2	147.3	4	6
Static cast 1/4-inch-diam:[3]				
As cast..............	131.0	112.1	7	17
Annealed.............	126.2	118.4	8	13
Solution treated.....	135.8	111.3	4	6
Aged.................	146.4	130.2	3	3
Centrifugal cast 1/4-inch-diam:[4]				
As cast..............	139.0	130.0	6	15
Annealed.............	132.3	120.0	5	24
Solution treated.....	146.8	123.8	3	10
Aged.................	160.0	143.0	2	4

[1] Very fine structure.
[2] Coarse equiaxed structure.
[3] Fine equiaxed structure.
[4] Uniform fine equiaxed structure.

TABLE 5. - Room temperature tensile properties of Ti-6Al-4V-1Si in as-cast, as-worked, and heat-treated conditions

Specimen	Ultimate tensile strength, psi × 10^3	Yield strength 0.2 pct offset, psi × 10^3	Elongation, pct	Reduction in area, pct
5/8-inch plate:[1]				
As worked	151.2	133.2	11	23
Annealed	148.3	141.8	10	26
Solution treated	165.3	138.6	8	14
Aged	185.3	167.5	4	5
Static cast 6-inch-diam:[2]				
As cast	151.2	136.9	5	11
Annealed	151.1	142.0	2	5
Solution treated	158.0	137.8	2	2
Aged	168.9	157.8	0	0
Static cast 1/4-inch-diam:[3]				
As cast	158.6	143.4	3	5
Annealed	152.1	145.5	2	4
Solution treated	148.9	126.2	2	4
Aged	161.7	151.3	1	1
Centrifugal cast 1/4-inch-diam:[4]				
As cast	151.7	136.6	1	1
Annealed	ND	ND	ND	ND
Solution treated	ND	ND	ND	ND
Aged	175.0	164.5	1	<1

ND Not determined.
[1] Very fine grain.
[2] Coarse equiaxed grain.
[3] Fine equiaxed grain.
[4] Uniform fine equiaxed grain.

Ti-6Al-2Sn-4Zr-2Mo

This alloy can properly be classified as a super alpha alloy. It has a combination of high tensile strength, creep strength, and toughness. Its major applications are jet engine compressor parts and airframe skin components. Forging and rolling are the procedures normally used for preparing these parts. However, casting is the most direct method for producing components such as the compressor cases, blades, disks, wheels, and spacers. Therefore, evaluation of this alloy for casting is important.

Results of room temperature tensile tests are shown in table 6. The tensile strength of the fine-grained castings (1/4-inch-diam castings), whether statically or centrifugally cast, is nearly equal to the strength of the hot rolled plate in all conditions of thermal treatment. The plate and the centrifugally cast material is more ductile than either the 6-inch or the 1/4-inch static castings. This is probably due to grain refinement and homogenization induced by centrifuging or working.

TABLE 6. - Room temperature tensile properties of wrought and skull-cast Ti-6Al-2Sn-4Zr-2Mo in as-worked, as-cast, and heat-treated conditions

Specimen	Ultimate tensile strength, psi X 10^3	Yield strength 0.2 pct offset, psi X 10^3	Elongation, pct	Reduction in area, pct
5/8-inch plate:[1]				
Hot rolled...........	158.0	140.7	12	31
Stress relieved......	140.1	136.8	12	24
Solution treated.....	156.7	131.2	10	19
Aged.................	168.6	164.8	(5)	(5)
Static cast 6-inch-diam:[2]				
As cast..............	125.9	114.1	8	15
Stress relieved......	127.2	118.4	6	19
Solution treated.....	141.1	106.5	3	6
Aged.................	148.2	143.1	0	2
Static cast 1/4-inch-diam:[3]				
As cast..............	153.3	136.8	5	8
Stress relieved......	ND	ND	ND	ND
Solution treated.....	ND	ND	ND	ND
Aged.................	166.1	147.1	2	3
Centrifugal cast 1/4-inch-diam:[4]				
As cast..............	155.7	133.5	9	24
Stress relieved......	139.8	123.9	9	24
Solution treated.....	154.9	123.1	3	11
Aged.................	169.8	127.1	2	3

ND Not determined.

[1] Very fine structure.

[2] Coarse equiaxed structure.

[3] Fine equiaxed structure.

[4] Uniform fine equiaxed structure.

[5] Specimen broke outside of gage marking.

REM Metals Corp., in an interim engineering report to the Air Force Materials Laboratory (4), listed room temperature tensile properties from a larger number of investment castings of Ti-6Al-2Sn-4Zr-2Mo and Ti-11.5Mo-6Zr-4.5Sn after solution treating and aging. The data were generated as part of a program to optimize alloy chemistry, foundry practices, and heat treatment parameters to improve castability and mechanical properties. Even though neither compositions nor heat treatment parameters were optimized in the Bureau research, data indicate that the as-cast properties of the 1/4-inch cast specimen from Bureau studies are superior the the solution heat treated and aged (STA) properties reported by REM. The strength of the 6-inch casting is inferior to either of the smaller 1/4-inch castings in both as-cast and heat-treated conditions, but the STA properties are nearly equal to the STA properties reported by REM.

Although the ductility of cast structures of this alloy appears not as good as in the wrought product, both Bureau data and those of REM Metals indicate that this alloy is good for casting, and properties of castings are acceptable.

Ti-6Al-6V-4Zr-4Mo

This is a deep hardenable alpha-beta high-strength alloy. Deep hardenability is usually characteristic of beta-type alloys that generally have high density and low ductility. The alpha-beta alloys such as Ti-6Al-4V and Ti-6Al-6V-2Sn that show high-strength capability are not hardenable in section size much over 1 inch and 2-3/4 inches, respectively. This alloy offers relatively high strength in forged sections up to 6 inches, lower density than the beta alloys, and good hardenability.

The castability of this alloy was shown to be similar to that of unalloyed titanium (3). Fluidity spirals were nearly equal in lengths to that of unalloyed titanium, and the surfaces of the castings were smooth and essentially without flaw. This indicates that the 6-6-4-4 alloy would be suitable as a casting alloy if target properties are reached after thermal treatment.

Fine-grained tensile specimens, cast to shape by both static and centrifugal techniques, provided no useful data. All such specimens failed during load application in tensile testing procedure. The failures occurred outside the specified gage near the button head grip radii. Apparently, the cast structure of the test bars was notch sensitive or had microcracks originating from solidification stress.

Table 7 summarizes the tensile data collected from a 6-inch-diameter cold-mold ingot and a 6-inch diameter skull-cast ingot. In the aged condition, the properties of castings of this alloy did not equal those of components prepared by forging and rolling when comparable heat treatments were used.

TABLE 7. - Room temperature tensile properties of wrought and skull-cast Ti-6Al-6V-4Zr-4Mo in as-worked and heat-treated conditions

Specimen	Ultimate tensile strength, psi x 10^3	Yield strength 0.2 pct offset, psi x 10^3	Elongation, pct	Reduction in area, pct
5/8-inch plate:[1]				
Hot rolled.......	176	160	5	21
Aged.............	207	198	4	4
Static cast 6-inch-diam:[2]				
Aged.............	165	155	1	3

[1] Very fine grained.

[2] Coarse equiaxed grained.

Ti-6Al-6V-2Sn

This alpha-beta alloy is generally available as plate, bar, and forgings. The 6 pct aluminum stabilizes the alpha phase. Beta stabilization is accomplished by the 6 pct vanadium and low-level additions of copper and iron, each present at about a 0.5 pct concentration. The 2 pct tin is present to act as a neutral strengthener for both the alpha and beta phases. The alloy is heat treatable to high-strength levels by solution treatment and aging.

A comparison of the room temperature tensile properties of cast and wrought 6-6-2 alloy, shown in table 8, indicates that cast structures, both as-cast and stress-relieved, are superior in strength to wrought material in the as-worked and stress-relieved conditions. Ductility of the wrought material, however, is superior. Solution treatment and solution treatment plus aging appear to result in nearly equal strengths for all structures. The strength-ductility combinations of the uniformly fine-grained specimens prepared by centrifugal casting in all conditions except solution treated are very good. The ductility in the aged condition is superior to all other cast structures in the aged condition. These data suggest that castings of this alloy can be successfully used in application now being met by forgings. The extremely low yield strength of all specimens in the solution treated condition is difficult to reconcile with the relatively high tensile strength in that condition. The authors surmise it results from solution treatment near the beta transus of the βc composition, that is the limiting alloy composition for retention of 100 pct beta at room temperature after quenching from the beta field. Solution treatment at this temperature results in the retention of metastable beta that is mechanically unstable. This transforms to the alpha phase under stress, thus producing appreciable work hardening.

TABLE 8. - Room temperature tensile properties of wrought and skull-cast Ti-6Al-6V-2Sn alloy in as-worked, as-cast, and heat-treated conditions

Specimen	Ultimate tensile strength, psi X 10^3	Yield strength 0.2 pct offset, psi X 10^3	Elongation, pct	Reduction in area, pct
5/8-inch plate:[1]				
Hot rolled........	137.9	133.4	13	50
Annealed..........	135.0	130.3	10	40
Solution treated..	155.1	63.2	8	6
Aged..............	175.7	(2)	1	<1
Static cast 6-inch-diam:[3]				
Solution treated..	150.4	53.2	10	5
Aged..............	176.8	(2)	1	<1
Static cast 1/4-inch-diam:[4]				
As cast...........	173.2	157.2	3	7
Annealed..........	152.0	143.3	3	10
Solution treated..	148.1	52.5	8	14
Aged..............	175.2	(2)	1	<1
Centrifugal cast 1/4-inch-diam:[5]				
As cast...........	162.2	150.2	4	15
Annealed..........	147.0	138.2	6	17
Solution treated..	153.7	69.2	11	15
Aged..............	170.8	161.3	4	9

[1] Very fine grain structure.
[2] No extensometer used.
[3] Coarse equiaxed grain structure.
[4] Fine equiaxed grain structure.
[5] Uniform fine equiaxed grain structure.

Ti-11.5Mo-6Zr-4.5Sn (Beta III)

Beta III is an isomorphous metastable alloy that can be deep hardened to high strength by proper thermal treatment. It is more workable than the usual alpha and alpha-beta alloys. The main application of Beta III is for aircraft parts and fasteners where its combination of cold workability and high streng strength make it particularly attractive.

Even though the castability of Beta III appears not as good as the alpha and alpha-beta alloys (3), the potential advantage of forming complex parts directly with greater economy of material is inherent.

REM Metals Corp. also extensively evaluated this alloy (4). Although their data reflects only solution treated and aged properties, they show considerably higher ductility and yield strength values.

The room temperature tensile properties of wrought and cast material shown in table 9 indicates that relatively light castings in the cast condition will have properties that compare favorably with wrought products in the as-worked condition. The relatively low yield strength of the static cast 1/4-inch material, however, is out of line and unless it is erroneous, may reflect some structural weakness. Heavy cast sections represented by the 6-inch-diameter casting are weaker in the as-cast condition and in the aged condition than the wrought alloy in comparable conditions. The 1/4-inch-diameter centrifugal castings are as responsive to solution treatment and aging as the wrought alloy and superior in strength to both the heavy and light section static cast material in all heat-treated conditions except stress relieved. It should be pointed out that better strength-ductility combinations can be obtained on wrought material than is indicated by these data. This emphasizes the fact that heat treatment parameters were not optimum.

Both tensile and yield strengths of all castings and wrought material are quite low in the solution-treated condition. The ductility is quite high, as reflected in elongation and reduction in area measurements. These characteristics, resulting from the beta structure that predominates in this condition, make the alloy cold workable. During aging, alpha precipitates as a fine dispersion that produces the high strength reported for the aged condition. Despite the fact that this alloy is less castable than other alloys evaluated because of its relatively low fluidity, castings should not be overlooked as a means for preparing forging preforms. The good ductility and low strength in the solution treated condition make it amenable to cold working.

TABLE 9. - Room temperature tensile properties of wrought and skull-cast Ti-11.5Mo-6Zr-4.5Sn in as-worked, as-cast, and heat-treated conditions

Specimen	Ultimate tensile strength, psi X 10^3	Yield strength 0.2 pct offset, psi X 10^3	Elongation, pct	Reduction in area, pct
5/8-inch plate:[1]				
Hot rolled..........	144.7	144.7	5	21
Stress relieved......	169.5	168.3	5	7
Solution treated.....	113.8	90.6	27	61
Aged................	197.9	194.8	2	2
Static cast 6-inch-diam:[2]				
As cast.............	134.5	118.1	3	9
Aged................	172.6	165.9	4	12
Static cast 1/4-inch-diam:[3]				
As cast.............	153.8	122.1	4	16
Stress relieved......	149.0	125.3	4	11
Solution treated.....	94.3	60.8	38	46
Aged................	178.5	([4])	([5])	([5])
Centrifugal cast 1/4-inch-diam:[6]				
As cast.............	154.8	147.3	7	22
Stress relieved......	129.5	([4])	2	6
Solution treated.....	118.5	90.3	17	3
Aged................	202.5	([4])	0	0

[1] Very fine grained structure.
[2] Coarse equiaxed grain structure.
[3] Fine grain structure.
[4] No extensometer used.
[5] Failed outside of gage.
[6] Uniform fine grain structure.

CONCLUSIONS

Room temperature tensile data show that all of the cast alloys tested with the exception of Ti-6Al-6V-4Zr-4Mo have tensile and yield strength in the as-cast condition that are reasonably close to these properties of the wrought alloys in the as-worked condition. The tensile ductility of the cast alloys is less than that of wrought material of the same composition, perhaps because of the larger grains in the cast material and possible concentration of impurities at grain boundaries.

Heat treatment response as a function of structure was shown to be unpredictable. This probably is because optimization of heat treatment param- is dependent not only upon composition but upon stored energy in the crystal lattice due to deformation by work and upon grain size. Longer times and higher temperature must be used for the more slowly reacting cast materials to achieve the same results as wrought materials. This optimization of heat treatment, although an important factor in the development of maximum properties, was beyond the scope of this program.

Indications are that acceptable properties can be attained in the cast materials and that these properties are probably sensitive to castings size as well as technique.

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APPENDIX A.--ANALYSES OF RAW MATERIALS, PERCENT

Titanium sponge:[1]
Ti - 99.8 Mn - 0.02 N - 0.006 O - 0.04 H - 0.002
Fe - 0.02 Mg - 0.04 C - 0.01 Cl - 0.08 Si - 0.01

Aluminum-vanadium master alloy:[1]
Al - 57.75 P - 0.003 Mo - 0.04 Mn - 0.01 W - <0.005
V - 41.52 Si - 0.37 Cr - 0.019 Ni - 0.008 B - <0.001
C - 0.049 S - 0.001 Cu - 0.006 Ti - <0.01 Mg - <0.003
Fe - 0.19 Pb - <0.004

Vanadium:[2]
Fe - 0.003 to 0.03 Si - 0.01 to 0.1

Aluminum:[2]
Al - 10 to 100 Ga - 0.03 to 0.3 Ni - 0.003 to 0.03
Cu - 0.003 to 0.03 Mg - 0.03 to 0.3 Si - 0.03 to 0.3
Fe - 0.03 to 0.3 Mn - 0.003 to 0.03 Sn - 0.01 to 0.1
Ti - 0.001 to 0.01 V - 0.003 to 0.03

Silicon:[2]
Si - 10 to 100 Cr - 0.03 to 0.3 Mg - 0.001 to 0.01
Al - 0.03 to 0.3 Mn - 0.03 to 0.3 Cu - 0.0003 to 0.003
Fe - 0.1 to 1.0 Ca - 0.003 to 0.03 Mn - 0.03 to 0.3
Ti - 0.01 to 0.1 V - 0.03 to 0.3

Tin:[2]
Sn - 10 to 100 Fe - 0.01 to 0.1 Cu - 0.0003 to 0.003
Si - 0.001 to 0.01 Pb - 0.03 to 0.3

Zirconium:[2]
Zr - 10 to 100 Mg - 0.001 to 0.01 Cu - 0.00003 to 0.0003
Cr - 0.003 to 0.03 Fe - 0.001 to 0.01 Si - 0.001 to 0.01

Carbon:[2]
Al - 0.003 to 0.03 Fe - 0.01 to 0.1 Mn - 0.001 to 0.01
Si - 0.001 to 0.01 Mg - 0.0001 to 0.001 Cu - 0.00003 to 0.0003
Ni - 0.01 to 0.1 Ti - 0.0003 to 0.003

Titanium dioxide:[2]
Al - 0.03 to 0.3 Mg - 0.01 to 0.1 Cu - 0.00003 to 0.0003
Ti - 10 to 100 Si - 0.3 to 3.0

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[1] Vendor analysis.

[2] Qualitative spectrographic analysis by the Bureau of Mines. Elements not reported were not detected by this technique.

APPENDIX B.--TYPICAL ANALYSES OF CAST AND WROUGHT COMMERCIALLY PURE TITANIUM AND TITANIUM ALLOYS

TABLE B-1. - Typical analyses of cast and wrought commercially pure titanium

Sample		Concentration of interstitial elements in test castings, ppm			
		O	C	H	N
1......	Nominal..	800	400	-	-
	Actual...	823	414	23	124
2......	Nominal..	1,200	400	-	-
	Actual...	1,178	439	38	107
3......	Nominal..	1,800	400	-	-
	Actual...	1,800	447	38	85
4......	Nominal..	800	400	-	-
	Actual...	833	414	23	124
5......	Nominal..	800	1,000	-	-
	Actual...	778	987	43	87
6......	Nominal..	800	1,500	-	-
	Actual...	764	1,450	34	104

TABLE B-2. - Typical analyses of cast and wrought titanium alloys

Alloy		Concentration of alloy and interstitial elements in test castings[1]										Number of castings analyzed
		Al, pct	V, pct	Sn, pct	Zr, pct	Mo, pct	Si, pct	C, ppm	O, ppm	H, ppm	N, ppm	
Ti-5Al-2.5 Sn..	Nominal composition	5		2.5								
	Analytical range...	4.51 5.03		2.32 2.72				102 241	543 758	15 22	36 96	6
Ti-6Al-4V......	Nominal composition	6	4									
	Analytical range...	5.86 6.15	4.00 4.29					127 146	529 671	7 16	60 77	4
Ti-6Al-4V-1Si..	Nominal composition	6	4				1					
	Analytical range...	5.75 5.79	3.94 3.96				0.98 1.01	165 234	554 668	9 19	65 98	4
Ti-6Al-6V-2Sn..	Nominal composition	6	6	2								
	Analytical range[2]..	5.78 6.38	5.59 6.30	1.81 2.19				119 213	570 706	12 18	43 76	5
Ti-6Al-2Sn-4Zr-2Mo.	Nominal composition	6		2	4	2						
	Analytical range...	5.47 5.79		1.87 2.00	3.8 3.9	1.9 2.0		57 122	562 738	11 20	43 80	6
Ti-6Al-6V-4Zr-4Mo.	Nominal composition	6	6		4	4						
	Analytical range...	5.71 6.38	5.55 6.30		3.80 4.20	3.70 4.10		110 214	603 814	16 22	79 88	7
Ti-11.5Mo-6Zr-4.5Sn.	Nominal composition			4.5	6	11.5						
	Analytical range...			4.13 4.39	5.60 6.10	11.0 11.4		96 345	844 1,086	10 24	40 72	9

[1] Balance of alloy composition--titanium.

[2] Cu present--0.47 to 0.52 pct; Fe present - 0.44 to 0.52 pct.

APPENDIX C.--FORGING PARAMETERS FOR CONVERSION OF INGOTS TO PLATE

Commercially pure titanium--Forge ingot to sheet bar ∼50 pct reduction at 1,650° F, sand blast to clean surfaces, grind to remove edge cracks and defects, roll to 9/16-inch plate at 1,450° F.

Ti-5Al-2.5Sn--Forge to sheet bar ∼50 pct reduction at 1,900° F condition to clean surfaces and remove defects, roll to 9/16-inch plate at 1,650° F.

Ti-6Al-4V
Ti-6Al-4V-1Si--Forge to sheet bar ∼50 pct reduction at 1,850° F, condition to clean surfaces and remove defects, roll to 9/16-inch plate at 1,450° F.

Ti-6Al-2Sn-4Zr-2Mo--Forge to sheet bar ∼50 pct reduction at 1,850° F, condition to clean surfaces and remove defects, roll to 9/16-inch plate at 1,750° F.

Ti-6Al-6V-2Sn--Forge to sheet bar ∼50 pct reduction at 1,725° F, condition to clean surfaces and remove defects, roll to 9/16-inch plate at 1,550° F.

Ti-6Al-6V-4Zr-4Mo--Forge to sheet bar ∼50 pct reduction at 1,800° F, condition to clean surfaces and remove defects, roll to 9/16-inch plate at 1,575° F.

Ti-11.5Mo-6Zr-4.5Sn--Forge to sheet bar ∼50 pct reduction at 1,700° F, condition to clean surfaces and remove defects, roll to 9/16-inch plate at 1,400° F.

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