New Titanium Alloys for Structural Forgings

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The mechanical properties of several of the newer titanium alloys are compared with present production alloys. Smooth tensile, notched tensile, notched-time-fracture, precracked charpy, and fatigue data are presented for those alloys developed primarily for applications below 600°F. Included in this group are: Ti-13V-11Cr-3Al, Ti-6Al-6V-2Sn, Ti-8Al-1V-1Mo, Ti-6Al-6V-2Sn-3.5Zr-1Cu-1Fe, Hylite 51, Ti-6Al-4V, and Ti-5Al-2.5Sn. Creep, creep stability, and stress rupture are reported for those compositions designed for elevated temperature service (over 600°F). This group includes: Ti-5Al-5Sn-5Zr, Ti-7Al-12Zr, IMI-679, Hylite 60, and Ti-6Al-2Sn-4Zr-2Mo. All data presented were obtained on specimens from closed die forgings produced in typical airframe and engine configurations. All of the alloys were found to be forgeable in current production equipment. For high-strength, moderate-temperature applications (up to 600°F), the Ti-6Al-6V-2Sn and Ti-6Al-6V-2Sn-3.5Zr-1Cu-1Fe compositions are quite promising. Among the alloys for elevated temperature application, the Hylite 60 and Ti-6Al-2Sn-4Zr-2Mo compositions appear to have achieved the aim of a creep-stable titanium for 1000°F service.

Introduction

TITANIUM has been used in the aerospace industry for approximately ten years. Most designers are familiar with the properties of the common alloys such as Ti-6Al-4V and Ti-5Al-2.5Sn. It is the purpose of this paper to present the properties of some of the newer alloys, which appear to have potential for future designs. The discussion will be divided into two categories: alloys for structural application where only moderate temperatures (up to approximately 600°F) are experienced, and alloys for applications where properties at elevated temperatures (up to 1000°F) are of prime importance. The data to be presented have been generated as part of a continuing program to evaluate the forgeability and mechanical properties of titanium alloys. All of these alloys have been successfully forged in conventional forging equipment (hammers and hydraulic presses). The properties have been obtained on closed die forgings in typical airframe and engine configurations. No attempt has been made to evaluate all the alloy compositions available, but only those which are now in production or have immediate production potential. The alloys to be discussed have all been made in production size heats.

The bulk of the titanium used in the industry to date has been in jet engine compressor components and pressure vessels for liquid- and solid-fueled rockets. In the past few years, the trend to higher operating temperatures and the development of higher strength alloys has caused designers to consider titanium as a primary structural material. One prediction indicates that 50–75% of the weight of the airframe of the supersonic transport (SST) and Mach 3 craft will be titanium and that an even higher percentage will be used for hypersonic vehicles.[1,2] (Fig. 1). The prediction also indicates that we will be using alloys at the 170- to 200-ksi yield strength level. The development of the higher strength capability has also made titanium attractive for helicopter, VTOL, and conventional subsonic aircraft where the constant battle for weight reduction goes on.

Alloys for Service to 600°F

To date, titanium airframe structural forgings have been made almost exclusively in two alloys: Ti-5Al-2.5Sn and Ti-6Al-4V. The Ti-5Al-2.5Sn alloy is an all-alpha alloy not heat treatable. It is used in the annealed condition at approximately 115-ksi yield strength. The Ti-6Al-4V composition is an alpha-beta alloy capable of heat treatment to 150- to 160-ksi yield strength, but is presently used in most applications in the annealed condition at the 130-ksi yield strength level. Among the alloys that should be considered for structural applications that would encounter service tem-

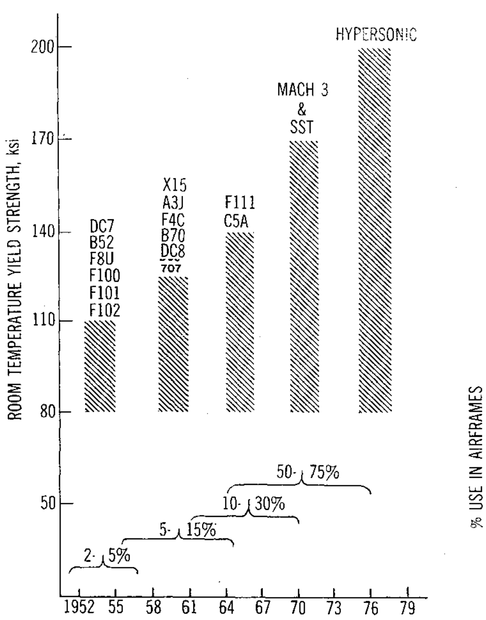

Fig. 1 Range of titanium and titanium-alloy yield strengths and percent used in airframes vs time.

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Table 1 Nominal composition and density of selected titanium alloys

Designation	Composition, wt %											Density, lb/in.^{3}
	Al	Mo	V	Sn	Zr	Si	Cr	Cu	Fe	C	Ti	
Ti–5Al–2.5Sn	5.0	...	...	2.5	...	...	...	...	...	0.05	Bal.	0.162
Ti–6Al–4V	6.0	...	4.0	...	...	...	...	...	...	0.08	Bal.	0.160
Ti–8Al–1V–1Mo	8.0	1.0	1.0	...	...	...	...	...	...	0.08	Bal.	0.158
IMI–679	2.5	1.0	...	10.00	5.0	0.2	...	...	...	0.04	Bal.	0.175
Hylite 51	4.0	4.0	...	4.0	...	0.5	...	...	...	0.15	Bal.	0.166
Ti–6Al–6V–2Sn	6.0	...	6.0	2.0	...	...	...	...	...	0.05	Bal.	0.164
Ti–13V–11Cr–3Al	3.0	...	13.0	...	...	...	11.0	...	...	0.08	Bal.	0.176
Ti–6Al–6V–2Sn (Mod)	6.0	...	6.0	2.0	3.5	...	...	1.0	1.0	0.10	Bal.	0.167

peratures up to 600°F are the following: Ti–8Al–1V–1Mo, IMI–679, Hylite 51, Ti–6Al–6V–2Sn, Ti–13V–11Cr–3Al, and modifications of the Ti–6Al–6V–2Sn composition. Some of these alloys are not new in the sense that they are recently developed compositions; however, generally they are new for the airframe application. The composition and density of these alloys are given in Table 1.

The Ti–6Al–4V, Ti–8Al–1V–1Mo, Ti–6Al–6V–2Sn, and modified Ti–6Al–6V–2Sn are all alpha beta type alloys, capable of heat treatment to high strengths but limited in the thickness of section through which full heat treated strength can be attained. This limit is approximately 1 in. At thickness greater than 1 in., strength will decrease significantly. The British developed IMI–679 and Hylite 51 alloys are alpha-beta types, but contain silicon as an alloying addition which the U.S. developed alloys do not. The Ti–13V–11Cr–3Al alloy is the only all-beta alloy currently in production. This alloy is capable of attaining full strength in section sizes up to 10 in. in thickness. A recent development of an extra low interstitial grade of this alloy appears to offer significant improvement in uniformity of properties, fatigue, and fracture toughness. However, evaluation of this new grade is not complete at this time. The modified Ti–6Al–6V–2Sn composition (Zr, Cu, and Fe have been added) shown is one of a series of alloys developed by Farrar and Margolin of New York University under U. S. Army Material Research Agency sponsorship.[3,4] This is the only one of the Farrar-Margolin alloys which we have actually forged into full-size hardware. Indications are that some of the others under development will be still stronger.

Table 2 shows a list of some typical structural forgings and the alloys in which they were forged. The approximate weights and maximum and minimum section sizes are given as an indication of the wide range of parts that have been produced.

Figure 2 shows the forging made for Lockheed Aircraft for an Air Force Materials Laboratory sponsored program on

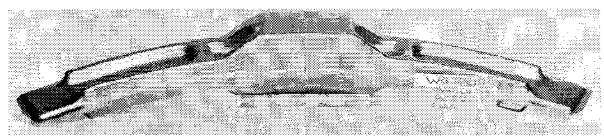


Fig. 2 Fuselage ring fitting.

evaluation of large titanium alloy forgings. Several parts were produced in this configuration in standard grade Ti–6Al–6V–2Sn, extra low interstitial grade Ti–6Al–6V–2Sn, Ti–13V–11Cr–3Al, two oxygen levels of Ti–6Al–4V and IMI–679.

Figure 3 shows a helicopter rotor cuff forging. It was produced in Ti–6Al–6V–2Sn and Ti–13V–11Cr–3Al for Sikorsky Aircraft for any Army Aviation Materials Laboratory sponsored program.

Table 2 Typical titanium aircraft (structural) forgings

Type of part	Alloy	Approx. wt., lb	Maximum section size, in.	Minimum section thickness, in.
Jet engine fan blades	Ti–6Al–6V–2Sn Ti–6Al–4V[a] Ti–6Al–6V–2Sn (Mod) Ti–8Al–1V–1Mo	7.5	$1\frac{1}{4} \times 2\frac{1}{4}$	0.250
Engine support	Ti–6Al–4V[a]	16	$1\frac{1}{2} \times 2$	0.250
Landing gear wheel	Ti–6Al–4V	50	$1\frac{1}{2} \times 1\frac{1}{2}$	0.190
Helicopter rotor cuff (S-61)	Ti–6Al–6V–2Sn Ti–13V–11Cr–3Al	90	7×6	2.0
Airframe spar (Navajo)	Ti–5Al–2.5Sn Ti–6Al–4V Ti–8Al–1V–1Mo IMI-679 (TMCA & British) Hylite 51 Ti–6Al–6V–2Sn Ti–13V–11Cr–3Al Ti–6Al–6V–2Sn (Mod)	110	6×6	0.625
Fuselage ring fitting (F-104)	Ti–6Al–6V–2Sn (std. & ELI) Ti–6Al–4V (2 O_2 Levels) IMI-679 Ti–13V–11Cr–3Al	110	6×6	0.75
Landing gear	Ti–13V–11Cr–3Al	400	9 (diam)	1.0
Helicopter rotor hub (CH-53A)	Ti–6Al–4V[a]	775	19 (diam)	0.75

[a] Currently in production.

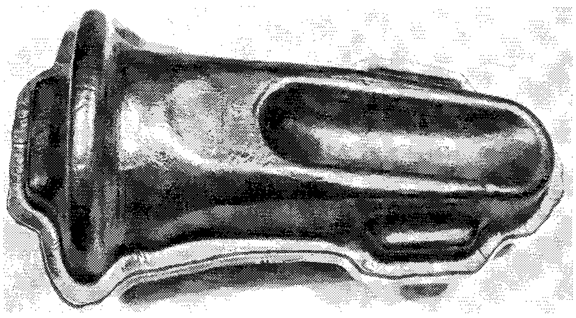


Fig. 3 Helicopter rotor cuff.

Figure 4 shows our standard airframe evaluation shape. It is an ideal configuration for evaluation of forgeability and mechanical properties because of the high ribs, thin webs, and massive center section. This shape has been used to evaluate all of the subject alloys.

Forging of all of the alloys with the exception of the all-beta alloy was done at temperatures in the alpha-beta field to produce a microstructure of equiaxed primary alpha in a transformed matrix. This is the structure required by most current specifications. Some typical microstructures of forgings from these alloys are shown in Figs. 5–7.

Figure 5 shows a typical alpha-beta alloy forged and solution treated in the alpha-beta field. This particular microstructure is of the Ti–6Al–4V alloy.

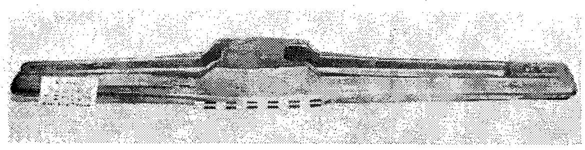


Fig. 4 Airframe spar.

Figure 6a shows IMI–679, one of the British alpha-beta alloys containing silicon. This part was also forged and solution heat treated in the alpha-beta field. An electron micrograph is shown to illustrate the shape and distribution of the silicide particles (Fig. 6b).

Figure 7 shows the typical solution treated and aged structure obtained with the all-beta alloy, Ti–13V–11Cr–3Al.

First, we will compare the potential low temperature (<600°F) candidate alloys for strength.

Figure 8 shows typical yield strengths for forgings of these alloys. These values are not maximum strengths attainable with these materials, but yield strength levels where reasonable ductility in terms of elongation and reduction of area is retained. Also shown is the yield strength/density ratio which will change the ranking of some of the alloys slightly.

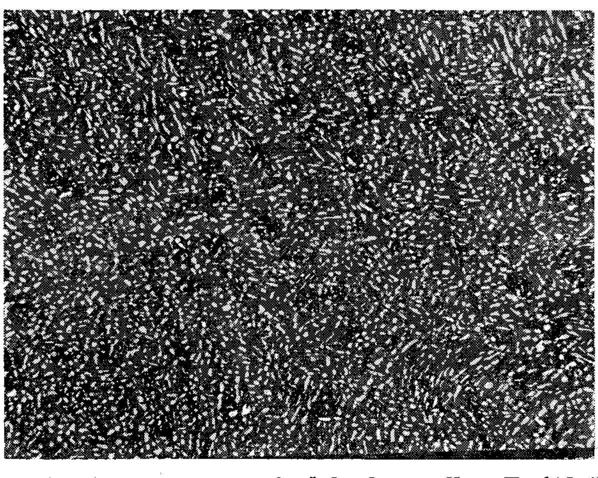


Fig. 5 Microstructure of alpha-beta alloy Ti-6Al-4V, 50×.

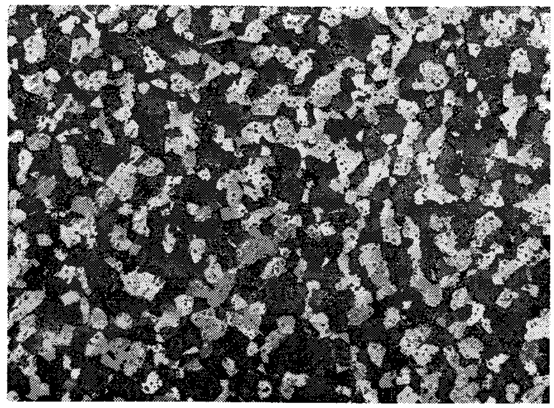


Fig. 6a Microstructure of alpha-beta alloy containing silicon, IMI-679, 300×.

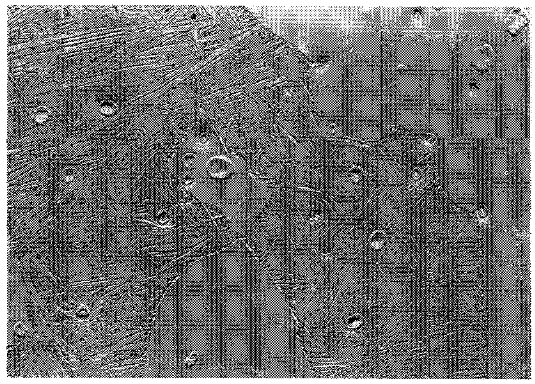


Fig. 6b Electron micrograph of alloy IMI-679 showing shape and distribution of silicide particles, 6000×.

Figure 9 shows a cut-up diagram of our airframe evaluation forging and Table 3 shows typical tensile properties that were obtained in this configuration in the subject alloys. All were heat treated as full-size parts to show the effect of section size on heat treat response. The heat treatments used are also shown in Table 3. It should be noted that in both heavy and thin sections of all alloys there is very little change in tensile properties with grain direction. This is an important ad-

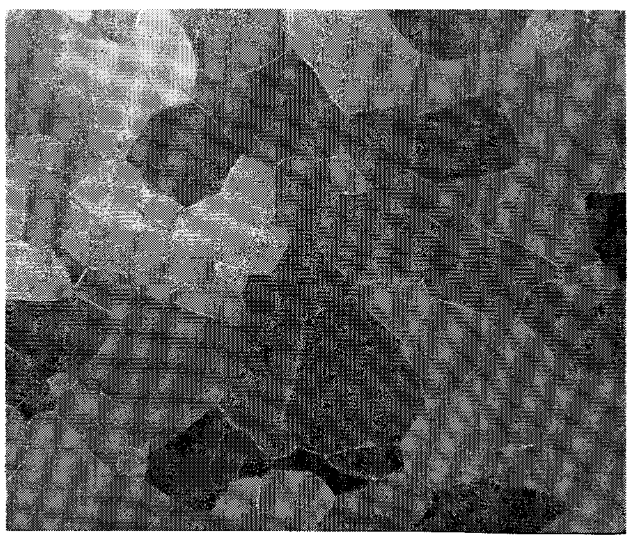


Fig. 7 Microstructure of all-beta alloy Ti-13V-11Cr-3Al, 75×.

Table 3 Tensile properties of titanium alloy structural forgings

Location	0.2% Yield strength (Y. S.) ksi	UTS, ksi	Elongation (EL.), %	Reduction of area (R. A.), %
Ti–5Al–2.5Sn 1350°F (2) air cool(AC)				
1	122.8	131.7	11.0	25.0
2	131.6	144.5	14.0	28.0
3	124.8	133.3	14.0	35.0
4	125.8	135.6	18.0	29.0
5	122.4	133.0	14.0	28.0
6	120.3	130.5	14.0	27.0
7	117.3	128.5	16.0	27.0
8	117.0	130.1	15.0	22.0
Ti–6Al–4V (0.13% O_2) 1750°F (1) water quench (WQ) + 1000°F (4) AC				
1	147.0	159.0	13.0	37.0
2	146.0	158.2	13.8	35.7
3	147.8	160.0	13.8	48.5
4	136.0	151.0	13.0	37.0
5	130.0	144.8	13.5	40.5
6	127.8	144.0	10.0	25.1
7	129.6	143.8	10.0	24.5
8	124.0	142.0	6.5	18.8
Ti–8Al–1V–1Mo 1650° (1) AC + 1100°F (8) AC				
1	137.5	143.4	18.0	29.4
2	144.1	152.7	17.0	35.4
3	139.9	151.7	21.0	35.4
4	120.9	132.1	12.0	17.1
5	116.2	126.8	8.0	24.9
6	113.6	126.2	14.0	18.5
7	117.9	130.5	12.0	15.2
8	116.8	128.1	8.0	14.2
IMI-679 1650°F (1) AC + 930°F (24) AC				
1	135.0	152.0	17.0	48.0
2	133.4	149.0	16.5	48.0
3	137.7	153.8	16.0	45.7
4	132.0	148.4	15.5	41.7
5	128.0	144.0	15.0	40.1
6	125.2	141.0	15.0	41.4
7	126.0	142.6	14.0	38.8
8	126.8	143.0	13.0	37.0

Location	0.2% Yield strength (Y. S.) ksi	UTS, ksi	Elongation, (EL.) %	Reduction of area (R. A.), %
Hylite 51 1650°F (1) AC + 930°F (24) AC				
1	173.6	187.2	14.5	41.4
2	173.0	189.0	12.5	38.2
3	167.8	185.4	12.5	36.3
9	171.4	184.8	12.0	35.7
10	169.6	183.0	12.0	38.8
Ti–6Al–6V–2Sn 1675°F (1) WQ + 1050°F (4) AC				
1	188.0	199.5	7.5	29.0
2	189.1	200.9	8.0	24.2
3	185.8	198.0	12.0	31.5
4	159.5	172.3	11.0	27.3
5	153.0	166.2	11.0	22.5
6	146.6	161.2	13.0	28.7
7	148.9	161.3	10.0	38.5
8	153.0	166.8	8.0	23.3
Ti–13V–11Cr–3Al 1335°F (1) AC + 1450°F (½) AC + 900°F (15) AC				
1	171.8	182.0	3.5	7.8
2	166.8	178.0	6.0	8.6
3	170.0	181.0	5.0	7.8
4	171.8	182.0	3.5	7.8
5	165.0	176.0	5.0	6.2
6	166.0	176.0	4.0	8.6
7	163.2	174.0	4.0	4.7
8	163.0	174.0	6.0	12.2
Ti–6Al–6V–2Sn–3.5Zr–1Cu–1Fe 1550°F (1) WQ + 1050°F (4) AC				
1	196.6	212.6	5.0	10.8
2	205.6	214.4	5.0	14.4
3	202.8	212.4	5.0	9.3
4	197.0	209.4	4.5	11.6
5	175.6	190.4	5.5	12.2
6	170.0	191.8	8.0	23.7
7	172.6	188.2	7.0	16.0
8	174.2	187.2	6.0	20.3

vantage of titanium structural forgings. The highest strength was obtained with the modified Ti–6Al–6V–2Sn. The regular Ti–6Al–6V–2Sn also shows very high strength close to the surface; however, strength falls off rapidly in both these alloys as section size increases. A drop in yield strength of 30–40 ksi is found from surface to center of a 4-in.-thick section. When section sizes are under 1 in., or where the part can be rough machined to this section size prior to heat treatment, strength levels such as those shown at the surface of these parts can be expected. Heat treated strength, however, is also a function of the amount of working and the same strength level normally cannot be expected in a 6-in. as-forged section machined to 1 in. prior to heat treatment as that which would be obtained in a 1-in.-thick as-forged section.

The Ti–13V–11Cr–3Al alloy shows good uniformity of properties from surface to center of the 4-in.-thick section; however, elongation, 3.5–6.0% at the 165-to 170-ksi yield strength level, is lower than that shown by the other alloys at

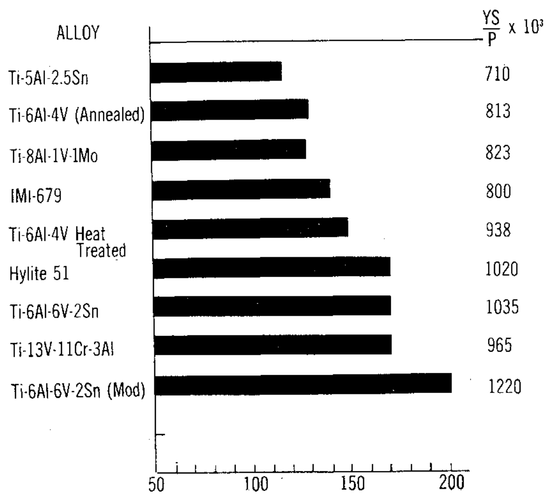


Fig. 8 Typical 70°F yield strengths: titanium alloys (1-in.-thick section).

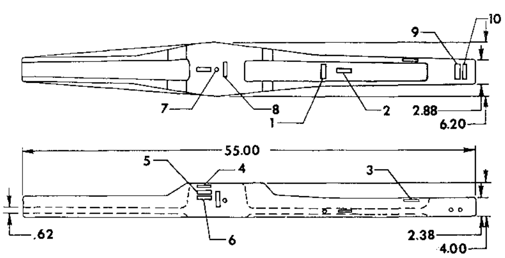


Fig. 9 Test locations airframe structural forgings.

Table 4 Notch tensile strength of titanium alloy forgings

Alloy	Smooth bar UTS, ksi	Notched strength $K_t = 4$, ksi	$\frac{NTS}{UTS}$	Notched strength $K_t = 10$, ksi	$\frac{NTS}{UTS}$	Notched time fracture, ksi
Ti–5Al–2.5Sn	130	200	1.54	205	1.58	200+
Ti–6Al–4V (ann.)	150	217	1.45	215	1.43	200+
Ti–8Al–1V–1Mo	150	225	1.50	205	1.37	180
IMI–679	150	218	1.45	220	1.46	200
Ti–6Al–4V (HT)	170	250	1.47	245	1.44	200+
Hylite 51	185	265	1.43	200	1.08	170
Ti–6Al–6V–2Sn	180	250	1.38	180	1.00	200+
Ti–13V–11Cr–3Al	175	200	1.14	210	1.31	180
Ti–6Al–6V–2Sn (Mod)	210	225	1.07	140	0.67	200+

this strength level. The Hylite 51 alloy shows good uniformity in section sizes up to approximately $2\frac{1}{2}$ in. We have not evaluated it in the full 4-in.-thick sections to date. Higher strength (180-ksi tensile yield) is possible with this composition by water quenching from solution temperature. This strength increase is, of course, accompanied by a ductility decrease.

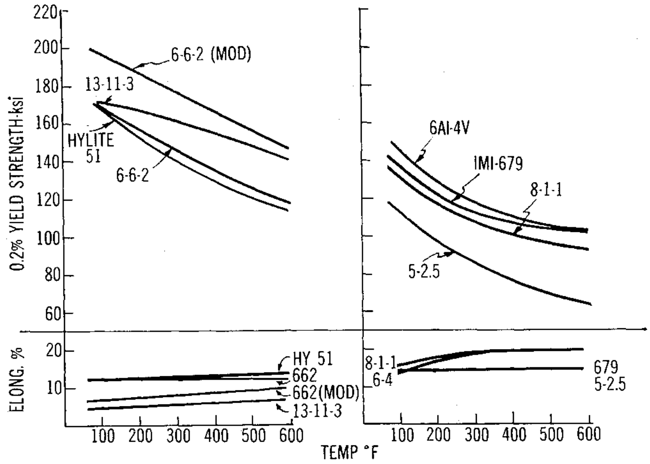


Fig. 10 Yield strength and elongation vs temperature: titanium alloys.

The tensile properties of these alloys over the range 70°–600°F are shown in Figs. 10 and 11. The modified Ti–6Al–6V-2Sn alloy showed the highest strength over the full temperature range and the others retained their same relative positions.

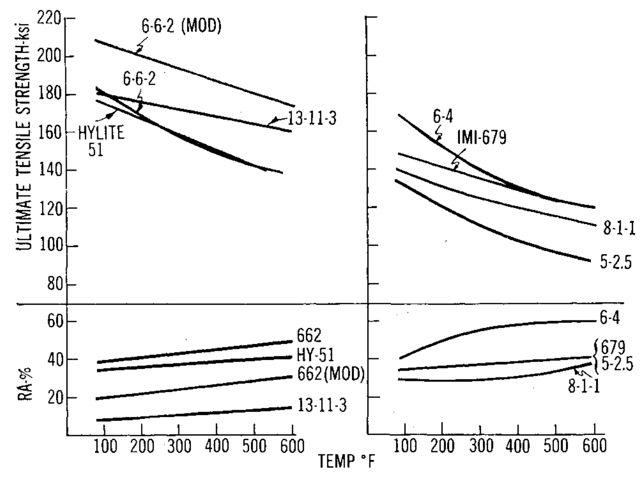


Fig. 11 Ultimate tensile strength and reduction of area: titanium alloys.

Notch tensile values and notched-unnotched ratios for all alloys at two K_t values are shown for typical yield strength levels in Table 4. Also shown are the notched-time-fracture values. In the notched-time test a notched tensile specimen ($k_t = 3.8$) is loaded at 150 ksi, held for 5 hr, then raised 10 ksi every 5 hr until failure occurs. Those values shown as 200+ indicate that no failure occurred after 5 hr at 200 ksi and the test was stopped. All alloys showed notched-unnotched ratios greater than unity at $K_t = 4$; however, at $K_t = 10$, the notched tensile strength to unnotched tensile strength ratio (NTS/UTS) of the modified Ti–6Al–6V–2Sn alloy dropped to 0.67. These values represent the average of a minimum of four specimens, two each from two different forgings in each alloy with the exception of the Hylite 51 for which only a single forging was available.

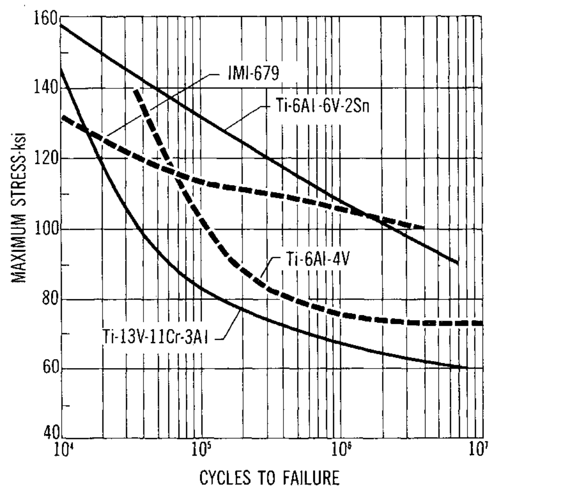


Fig. 12 70°F smooth bar fatigue properties: titanium alloy forgings, $R = 0.1$.

As an indication of fracture toughness, fatigue precracked charpy impact specimens were run on all alloys. These values

Table 5 Typical fracture toughness values of titanium alloy forgings

Alloy	0.2% Y.S., ksi	Precracked charpy W/A, in.-lb/in.^{2}	Precracked round tensile K_{Ic}, ksi-in.$^{1/2}$
Ti–5Al–2.5Sn	115	500–600	...
Ti–6Al–4V	125	1000–1180	42–46
Ti–8Al–1V–1Mo	130	1650–1810	...
IMI–679	140	150–350	33–40
Ti–6Al–4V	150	105–220	...
Hylite 51	170	80–90	...
Ti–6Al–6V–2Sn	170	250–320	29–43
Ti–13V–11Cr–3Al	170	300–400	21–27
Ti–6Al–6V–2Sn (Mod)	200	115–170	...

Table 6 Nominal composition and density of high-temperature titanium alloys

Designation	Composition, wt %							Density lb/in.³
	Al	Mo	V	Sn	Zr	Si	Ti	
Ti–7Al–12Zr	7.0	...	...	...	12.0	...	Bal.	0.165
Ti–5Al–5Sn–5Zr	5.0	...	...	5.0	5.0	...	Bal.	0.166
Ti–8Al–1V–Mo	8.0	1.0	1.0	...	...	...	Bal.	0.158
IMI–679	2.5	1.0	...	10.0	5.0	0.2	Bal.	0.175
Hylite 60	3.0	2.0	...	5.5	4.5	0.4	Bal.	0.172
Ti–6Al–2Sn–4Zr–2Mo	6.0	2.0	...	2.0	4.0	...	Bal.	0.164

with the yield strength levels of the material tested are shown in Table 5. Some K_{Ic} values obtained on fatigue precracked tensile specimen are also shown in Table 5 for comparison.

As a part of the Air Force Materials Laboratory program on large titanium forgings, Lockheed established fatigue curves on specimens cut from the forging shown in Fig. 2. Tension-tension S/N curves were generated on smooth and notched specimens of Ti-13V-11Cr-3Al, Ti-6Al-6V-2Sn, IMI-679, and Ti-6Al-4V. These curves are shown in Figs. 12 and 13. In smooth bar fatigue the Ti-6Al-6V-2Sn alloy showed the highest fatigue strength up to approximately 10^6 cycles. Beyond that point the IMI-679 alloy was superior. In notched fatigue the IMI-679 alloy had the longest life over almost the entire stress spectrum. As a part of the Air Force program, Lockheed also ran full-size forgings in a fatigue test rig to simulate actual flight conditions. Details of this test appear in the Air Force reports[5,8]; however, for comparison purposes, the cycles to failure for the parts were as follows: Ti-6Al-6V-2Sn, 150,000; Ti-6Al-4V, 160,000; and IMI-679, 270,000. An AISI-4340 steel part used as a standard also failed at 270,000 cycles; however, the 4340 part was 40% heavier than the IMI-679.

Alloys for Service to 1000°F

For engine applications, the Ti-6Al-4V alloy has been used for many years and is considered the "work horse" of the industry. More recently, the Ti-8Al-1V-1Mo and Ti-7Al-4Mo alloys have been utilized. For higher performance the aim has been to obtain an alloy that shows good creep and creep stability over 800°F. Among the alloys we have evaluated for this application are Ti–7Al–12Zr, Ti-5Al-5Sn-5Zr, Ti-8Al-1V-1Mo, IMI–679, Hylite 60, and Ti-6Al-2Sn-4Zr-2Mo. The nominal composition and density of these alloys are shown in Table 6. The IMI-679 and Ti-8Al-1V-1Mo also were on the list for lower temperature applications; however, their elevated temperature properties also make them attractive for higher temperature service. Table 7 lists weights and sizes of typical compressor wheels made in these alloys. Figures 14a and 14b show typical compressor wheel forgings. Figure 15 shows four compressor wheel configurations with test locations. Typical tensile strengths obtained on compressor wheels in these alloys from 70°–1000°F are shown in Table 8 and Figs. 16 and 17. The heat treatments used are also shown in Table 8. Some elevated temperature stress-rupture results are shown in Table 9. Al-

Table 7 Typical compressor wheel forgings produced in titanium alloys

Alloy	Wheel diam, in.	Weight, lb	Maximum section size	Minimum section size
Ti–5Al–5Sn–5Zr	31.5	662	13-in. coupling	1-in. web
Ti–7Al–12Zr	31.5	668	13-in. coupling	1-in. web
Ti–8Al–1V–1Mo	24.0	90	2-in. rim	⅝-in. web
IMI–679	29.0	450	12-in. coupling	1-in. web
Hylite 60	10.0	35	2-in. hub	¾-in. web
Ti–6Al–2Sn–4Zr–2Mo	20.0	60	2½-in. rim	¾-in. web

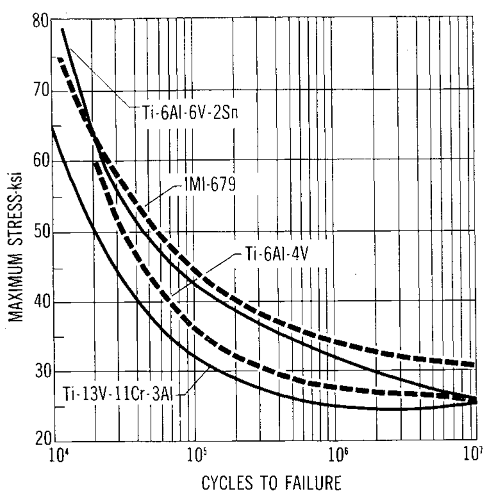
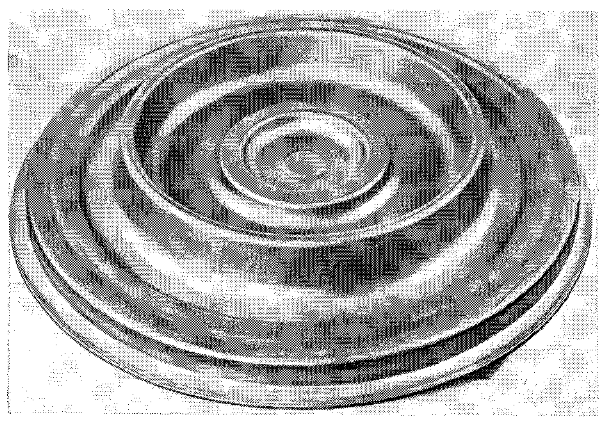
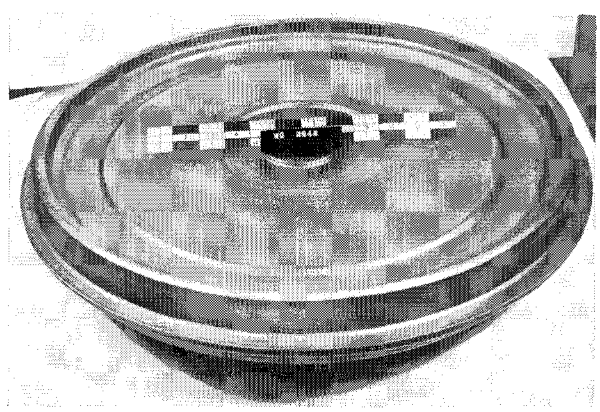


Fig. 13 70° notched fatigue properties: titanium alloy forgings; K_t = 3.0, R = 0.1.



a)



b)

Fig. 14 Typical titanium compressor wheels.

Table 8 Typical tensile properties of forged titanium compressor disks

		Test temperature															
		70°F				600°F				800°F				1000°F			
Alloy	Heat treatment	0.2% Y.S., ksi	UTS, ksi	El., %	R.A., %	0.2% Y.S., ksi	UTS, ksi	El., %	R.A., %	0.2% Y.S., ksi	UTS, ksi	El., %	R.A., %	0.2% Y.S., ksi	UTS, ksi	El., %	R.A., %
Ti–5Al–5Sn–5Zr	1650°F (4) AC	117	127	16	38	68	89	20	48	64	83	23	52	61	80	23	56
Ti–6Al–2Sn–4Zr–2Mo	1650°F (1) AC + 1100°F (8) AC	127	140	14	35	84	103	17	48	82	105	20	55	75	97	23	64
Hylite 60	1830°F (1) AC + 1020°F (24) AC	130	150	11	30	90	118	12	36	85	113	13	39	78	106	15	43
Ti–8Al–1V–1Mo	1850°F (1) AC + 1100°F (8) AC	129	141	15	30	85	107	17	43	76	97	19	50	71	88	20	58
IMI–679	1650°F (1) AC + 930°F (24) AC	137	153	14	37	120	95	15	40	82	106	15	39	79	102	16	45
Ti–7Al–12Zr	1750°F (1) AC + 1300°F (8) AC	122	133	23	34	81	102	28	41	76	95	25	44	64	90	23	48
Ti–6Al–4V	1300°F (2) AC	143	155	15	42	90	110	18	58	85	105	18	56	70	90	18	60

though the exposures are not the same for all alloys, these values are typical results and give an indication of the rupture characteristics of the alloys.

Larsen-Miller curves for 0.2% creep are shown in Fig. 18. Typical postcreep tensile results for all alloys are shown in Table 10. All of these alloys were also forged and heat treated below the beta transus, as required by most specifications, with the exception of the Hylite 60 alloy which, following the British practice, was forged approximately at the beta transus and solution treated 100°F above the transus. This results in the coarse acicular alpha structure normally associated with reduced ductility, Fig. 19. This structure has been considered undesirable in U. S. practice and in fact is the basis for rejection on some U. S. specifications. No undesirable properties were found in this investigation which were attributable to this structure in the Hylite 60 alloy.

Of the high-temperature alloy group, the compositions which appear to have the best combination of tensile strength, creep resistance and creep stability are the Ti–6Al–2Sn–4Zr–2Mo and the Hylite 60. Both of these alloys were stable up to 1000°F for the stresses and times investigated. The Ti–5Al–5Sn–5Zr alloy also showed excellent creep resistance and creep stability; however, tensile strength was significantly lower than that of the other alloys.

Table 9 Typical elevated temperature stress rupture properties of high-temperature titanium alloys

Alloy	Heat treatment	Exposure	Time to rupture, hr
Ti–8Al–1V–1Mo	1850°F (1) AC + 1100°F (8) AC	1000°F–60 ksi	45
		1000°F–60 ksi	37
Ti–5Al–5Sn–5Zr	1650°F (4) AC	1000°F–60 ksi	78
		1000°F–60 ksi	69
Ti–7Al–12Zr	1750°F (1) AC + 1300°F (8) AC	1000°F–60 ksi	396
		1000°F–60 ksi	274
IMI–679	1650°F (1) AC + 930°F (24) AC	1000°F–65 ksi	154
		1000°F–65 ksi	151
Hylite 60	1830°F (1) AC + 1020°F (24) AC	1000°F–70 ksi	255
Ti–6Al–2Sn–4Zr–2Mo	1650°F (1) AC + 1100°F (8) AC	1000°F–60 ksi	330
		950°F–70 ksi	503

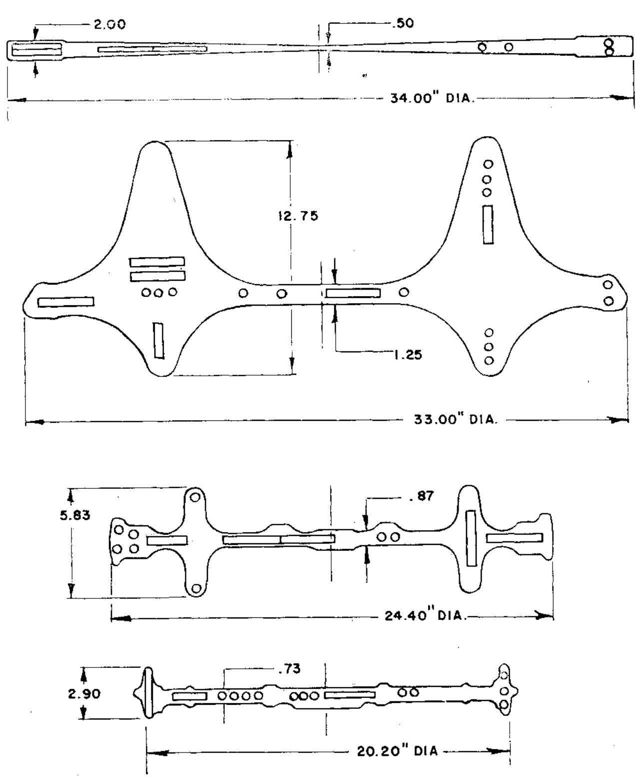


Fig. 15 Sketch of radial sections of typical titanium alloy compressor wheels indicating test locations.

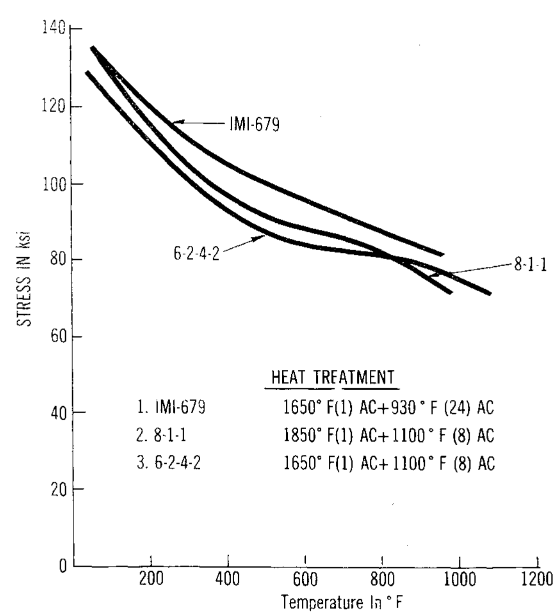


Fig. 16 Yield strength vs temperature curves of typical compressor wheel forgings in titanium alloys.

Table 10 Typical postcreep tensile results of titanium high-temperature alloys[7]

Alloy	Heat treatment	Creep exposure	0.2% Y.S., ksi	UTS, kis	EL., %	R.A., %
Ti–8Al–1V–1Mo	1850°F (1) AC + 1100°F (8) AC	None	128.8	141.2	17.0	29.2
		850°F–55 ksi–165 hr	128.8	140.9	15.0	29.5
		900°F–45 ksi–150 hr	128.0	139.9	14.0	16.1
		1000°F–25 ksi–150 hr	128.3	137.9	11.0	16.1
Ti–5Al–5Sn–5Zr	1650°F (4) AC	None	115.0	125.0	15.0	34.0
		850°F–55 ksi–150 hr	124.8	128.3	17.0	28.5
		900°F–45 ksi–307 hr	121.7	125.5	11.0	19.8
		1000°F–35 ksi–300 hr	121.7	129.0	15.0	24.7
		1100°F–15 ksi–307 hr	121.4	128.7	12.0	28.8
Ti–7Al–12Zr	1750°F (1) AC + 1300°F (8) AC	None	121.0	133.1	24.5	36.8
		800°F–60 ksi–300 hr	126.9	134.3	16.0	20.4
		900°F–38 ksi–300 hr	128.8	138.2	6.0	5.6
		900°F–35 ksi–300 hr	127.7	138.7	20.0	31.0[a]
		1000°F–30 ksi–300 hr	128.2	138.8	6.0	7.2
		1000°F–30 ksi–300 hr	127.8	139.9	20.0	30.2[a]
IMI-679	1650°F (1) AC + 930°F (24) AC	None	140.0	154.0	12.0	34.0
		850°F–65 ksi–150 hr	151.0	166.0	14.0	36.2
		850°F–65 ksi–1000 hr	145.3	156.0	14.0	28.9
		900°F–55 ksi–150 hr	142.0	157.2	12.0	22.6
		900°F–55 ksi–1000 hr	142.1	156.8	15.0	28.9
		950°F–45 ksi–150 hr	140.0	156.4	14.0	32.2
		950°F–45 ksi–1000 hr	135.5	149.2	6.0	8.7
Hylite 60	1830°F (1) AC + 1020°F (24) AC	None	133.0	150.0	11.0	32.0
		900°F–50 ksi–150 hr	145.0	162.3	14.0	29.4
		1000°F–40 ksi–150 hr	143.5	159.0	12.0	26.0
		1050°F–30 ksi–150 hr	141.4	155.5	7.0	13.1
Ti–6Al–2Sn–4Zr–2Mo	1650°F (1) AC + 1100°F (8) AC	None	126.0	141.0	13.0	32.0
		900°F–50 ksi–150 hr	134.0	143.8	19.0	39.2
		1000°F–35 ksi–150 hr	131.0	141.0	18.5	44.7
		1100°F–15 ksi—150 hr	132.0	142.0	17.0	34.1

[a] 0.025 in. removed from surface after exposure.

Forgeability

All of the alloys discussed are considered to be forgeable. The forging temperature range and a comparative rating as to crack resistance in forging are shown in Table 11. The newer high-temperature alloys are showing a trend toward decreasing forgeability with their increased elevated temperature strength. The higher strength at forging temperature also results in more rapid heat buildup at high deformation rates. Precautions must be taken with these alloys to prevent over heating in forging. With some of the lower temperature structural alloys, the lower forging temperatures and the higher pressure required can present a problem in producing the large forgings, which are under consideration by designers. The maximum size of forgings that can be produced is limited by the capacity of melting and forging equipment, and we are working at this limit in some current parts.

Other Properties

There are, of course, other properties of the subject alloys which we have not evaluated, but which may be critical for particular applications such as stress corrosion resistance, weldability and long time thermal stability. We realize the importance of these properties to individual designs, but be-

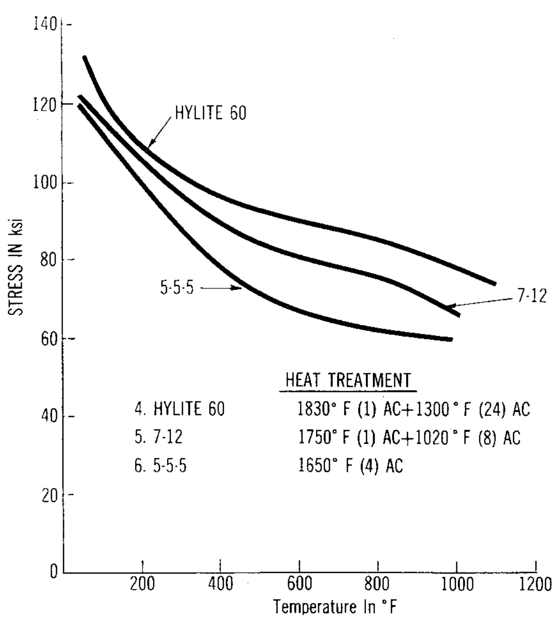


Fig. 17 Yield strength vs temperature curves of typical compressor wheel forgings in titanium alloys.

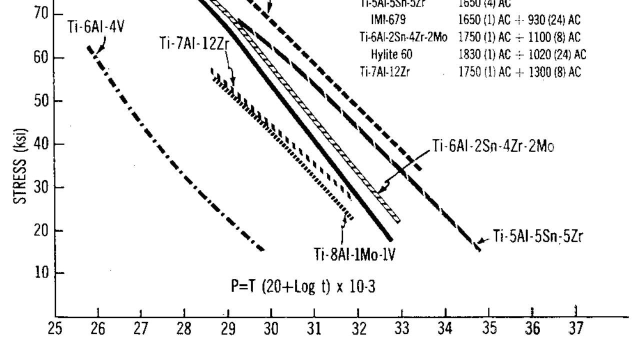


Fig. 18 Larsen-Miller plot for 0.2% plastic deformation for several titanium compressor wheel alloys.

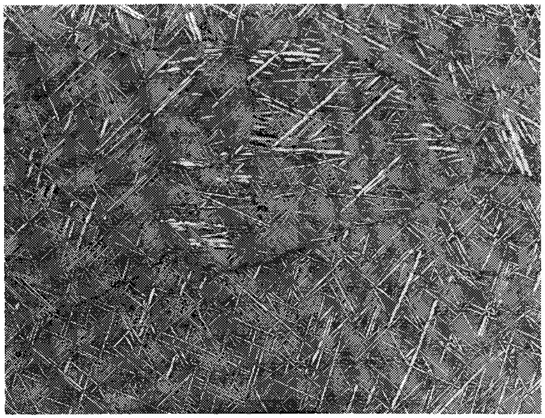


Figure 19 Microstructure of alloy Hylite 60, forged approximately at the beta transus and solution treated 100°F above the transus, 300×.

lieve that the preliminary data presented can act as a guide in alloy selection for further evaluation.

Conclusions

1) Of the titanium alloys currently available for structural application to 600°F, the Ti–6Al–6V–2Sn and modified Ti–6Al–6V-2Sn appear to be the most attractive from a strength standpoint; however, they are section size limited in heat treat response.

2) The Ti-13V-11Cr-3Al composition remains the only production alloy capable of full heat-treated strength in sections over approximately 1 in. in thickness, but ductility is relatively low.

3) The British developed alloy, IMI-679, in limited testing, shows superior fatigue resistance on both specimen and full-scale component evaluation.

4) The most promising alloys for applications over 600°F are Ti–6Al–2Sn–4Zr–2Mo and Hylite 60. Both of these alloys appear to have superior creep resistance and creep stability up to 1000°F.

5) All alloys discussed are considered forgeable and have been successfully forged in airframe and/or engine closed die forgings.

Table 11 Forging characteristics of titanium alloys[6]

Alloy	Forging range, °F	Resistance cracking
Ti–5Al–2.5Sn	1775–1850	Fair to good
Ti–6Al–4V	1650–1800	Good
Ti–8Al–1V–1Mo	1775–1850	Fair
IMI–679	1650–1725	Fair to good
Hylite 51	1750–1850	Fair to good
Ti–6Al–6V–2Sn	1575–1675	Excellent
Ti–13V–11Cr–3Al	1600–1800	Excellent
Ti–6Al–6V–2Sn (Mod)	1575–1675	Excellent
Ti–5Al–5Sn–5Zr	1700–1800	Poor to fair
Ti–7Al–12Zr	1700–1800	Fair to good
Hylite 60	1650–1750	Fair to good
Ti–6Al–2Sn-4Zr–2Mo	1675–1775	Fair to good

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