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Titanium Alloys for High Temperature Applications – A Review

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ABSTRACT

The development of energy efficient gas turbine engines with high thrust-to-weight ratios has increased the need for more titanium static and rotating engine components because of the high property-to-density ratio of these alloys. In the last 20 years advances in alloy development and microstructure control have made commercially available a family of high temperature titanium alloys which can operate at temperatures as high as 590°C (1100°F). The relationships between high temperature properties and alloy chemistry, processing, resulting microstructures and protective coatings will be discussed, and applications of these alloys in aerospace systems will be highlighted.

INTRODUCTION

The development of supersonic military aircrafts after World War II initiated an intensive research effort to develop new structural alloys which could withstand the demanding operational conditions of both airframes and gas turbine engines /1/. The use of titanium alloys in critical components, where more conventional aluminum alloys or steels were not suitable, contributed to the development of Mach 3 class military aircrafts. In aerospace applications conventional aluminum alloys are only usable to about 150°C (300°F). The most commonly used titanium alloy – Ti-6Al-4V – can be used up to 300°C (580°F) which places it in a high temperature alloy category as compared to conventional aluminum alloys. However, the need for higher temperature applications in the hot sections of high Mach airframes and in gas turbine engines required higher temperature titanium alloys capable of being used at well above 300°C (580°F). Recent skyrocketing increases in jet fuel cost intensified the development of more fuel-efficient engines, making titanium a desirable choice in even hotter engine sections. Today, the useful temperature range of titanium alloys which are commercially available or in the last stages of introduction is 590°C (1100°F) /2/. This class of alloys, which is based on near alpha compositions, could lead to compressor sections of future advanced commercial engines built almost entirely from titanium alloys /3/. Further work in the area of alloy development, process optimization, and improved oxidation resistance by coatings /4/ can lead to an additional increase of the temperature range which will allow the use of these alloys in the low pressure turbine section of gas turbine engines /3/ for further increase in fuel efficiency.

ALLOY DEVELOPMENT

Existing high temperature titanium alloys are based on high alpha phase volume fraction morphology. Most structural titanium alloys are two phase alloys. Those rich in beta phase will have, after proper aging, higher room temperature strength, while alloys rich in alpha will demonstrate better high temperature capability. Table 1 lists high temperature titanium alloy compositions which were developed or are available today in the Western industrial world markets in the order of their introduction. These alloys contain a minimum of 5 wt.% of aluminum which is a strong alpha phase stabilizer with some weak alpha stabilizing additions of Sn and beta stabilizing Zr and Mo, added mainly for solid solution strengthening. Since the introduction of IMI-685 in 1969, silicon is also added to the newer high temperature alloys which further increases the high temperature creep resistance by interacting with dislocation motion /5, 6/.

TABLE 1. Temperature Range and Chemical Composition of Near Alpha High Temperature Titanium Alloys, Listed in the Order of Introduction

Alloy Designation	Year of Introduction	Useful Temperature Range, °C (°F)	Chemical Composition, wt.%						
			Al	Sn	Zr	Mo	Nb	V	Si
Ti-811	1961	400 (750)	8	–	–	1	–	1	–
Ti-6246	1966	450 (840)	6	2	4	6	–	–	–
Ti-6242	1967	450 (840)	6	2	4	2	–	–	–
IMI-685	1969	520 (970)	6	--	5	0.5	–	–	0.25
Ti-5522S[a]	1972	520 (970)	5	5	2	2	–	–	0.2
Ti-11[a]	1972	540 (1000)	6	2	1.5	1	–	–	0.1 (0.3Bi)
Ti-6242S	1974	480 (900)	6	2	4	2	–	–	0.1
IMI-829	1976	580 (1080)	5.5	3.5	3	0.3	1	–	0.3
IMI-834[a, b]	1984	590 (1100)	NA	NA	NA	NA	NA	NA	NA

[a] Not yet used commercially.

[b] Exact mechanical property data and alloy chemistry are not yet publicly available.

It was recognized in the early stage of titanium alloy development /7/, that an addition of Al increases tensile and creep strengths and moduli. The maximum allowable content was set at 9 wt.% due to its embrittling effects. After studying the creep and tensile properties of then known Ti quarternary systems, Rosenberg /8/ arrived at an empirical formula:

$$\%\mathrm{Al} + 1/3\%\mathrm{Sn} + 1/6\%\mathrm{Zr} + 10\%\mathrm{O}_2 \leqslant 9\% \qquad (1)$$

as a criterion which he stated should be used to design high temperature Ti alloys. It should be noted that all commercial alloys presently in service still meet this requirement. Moderate amounts of the beta stabilizers such as Mo and Nb, which are added to enhance tensile properties at the lower temperature range, do not violate this rule.

It is generally accepted that the minimum creep rate, ϵ_m can be expressed by the empirical equation /9/:

$$\epsilon_m = AD_0 \exp(-Q/RT)(\sigma/E)^n(\gamma^{3.5}/L^2) \qquad (2)$$

where

D_0 = Diffusion constant
Q = Activation energy of diffusion
σ = Applied stress
E = Young's Modulus
γ = Stacking fault energy
L = Grain size
A = Constant
n = Constant (4 to 5)
R = Gas constant
T = Absolute temperature

Since the service temperature range of commercial titanium alloys is low relative to their melting point (T_m), the role of diffusion in creep deformation is small, and therefore main considerations should be paid to optimize the elastic modulus and grain size (and perhaps the stacking fault energy). It is believed that at the temperature range of 0.3 to 0.4 T_m, cross-slip of screw dislocations plays a major role in creep /10/. Below 0.3T_m, where conventional titanium alloys are most frequently utilized, dislocation intersection processes control the creep mechanism /9, 11, 12/.

Si addition is of great significance to creep resistance (Figure 1) as the Si interaction with dislocations impedes their motion by an atmosphere drag /13/. By comparison with other alloy systems, it is possible that a small amount of Si will reduce the stacking fault energy of the dislocations in the alloy /13, 14/, and consequently the mobility of the dislocations under stress will be restricted during cross-slip. Figure 2 exhibits silicide precipitation in IMI-829 after 300 hr 590°C (1100°F) creep-exposure at a stress of 210 MPa (30 ksi) indicating that Si has interacted with dislocations both as a precipitate and in an "atmosphere" mode /5/. This dislocation slip restriction is used in formulating the newer commercial alloys /15, 16/ which normally contain from 0.1% to 0.3% of Si (Table 1).

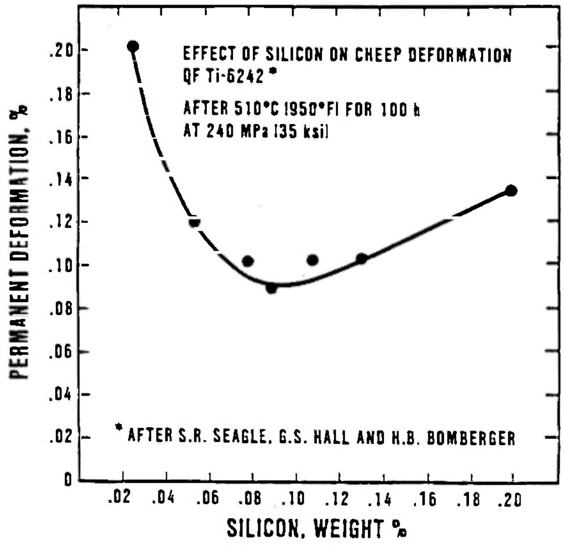

Fig. 1. Effect of minor silicon addition on the creep strength of Ti-6242 /16/.

TABLE 2. Minimum Creep Rate of Textured Ti-6Al-4V Plate /17/

Orientation	Stress, MPa	ksi	Temperature °C	°F	Minimum Creep Rate, mm/mm/hr	Young's Modulus x 10^{-6} at Temperature, MPa	psi
Longitudinal	345	50	480	900	7×10^{-5}	0.075	10.9
	241	35	540	1000	1×10^{-4}	0.064	9.3
Transverse	345	50	480	900	7×10^{-6}	0.109	15.8
	241	35	540	1000	1×10^{-5}	0.096	13.9

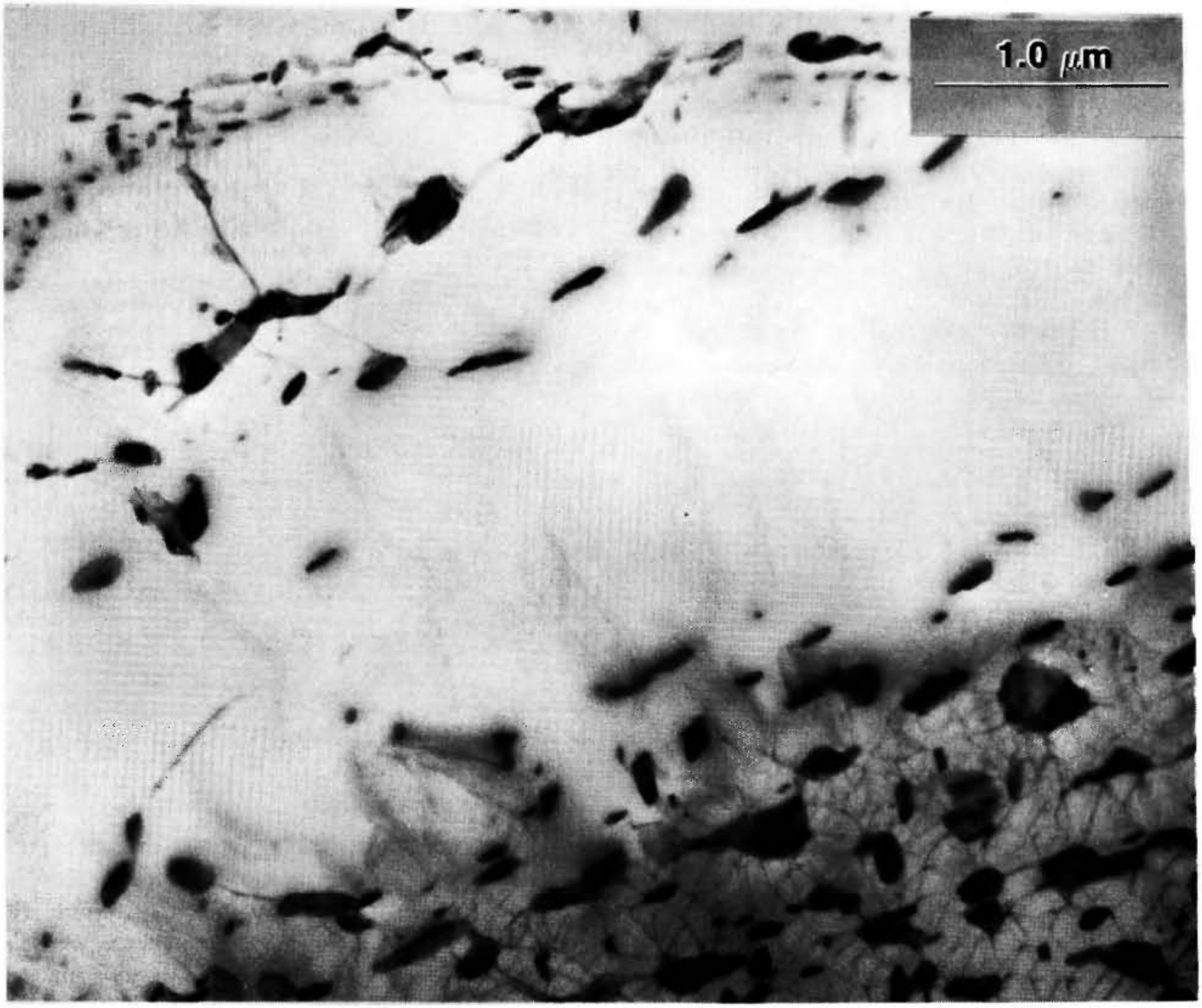

Fig. 2. TEM photomicrograph of IMI-829 after creep deformation showing titanium silicides.

It should also be noted from Equation 1 that an increase in modulus will increase creep strength. It was demonstrated that the creep resistance along the transverse direction in a highly basal textured Ti-6Al-4V is much higher than along the perpendicular direction /17/ (Table 2).

To illustrate the commercial development of high temperature titanium alloys in recent years, the creep temperature required for 0.2% strain at 415 MPa (60 ksi) stress of various key alloys is plotted in Figure 3 against the year of introduction.

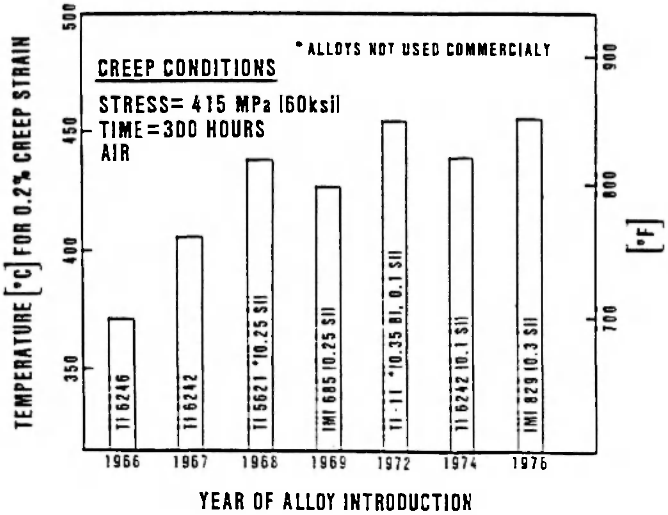

Fig. 3. The temperature required for 0.2% creep strain (at 415MPa after 300 hr) vs. the year of introduction for several key high temperature titanium alloys.

The current temperature limit of the near alpha alloy class is 590°C (1100°F) /2/ (Table 1). To push this limit higher, one approach is to develop creep resistance alloys based on fine dispersion of the α_2 phase (Ti_3Al) in an alpha titanium matrix (the $\alpha + \alpha_2$ alloy class) /18/. Although α_2 is generally considered to have an embrittling effect on titanium alloys, it has been demonstrated that niobium /19/ or niobium and other beta stabilizing elements /20/ can be used to improve the ductility of $\alpha + \alpha_2$ alloys. A further increase of the Al content results in intermetallic (Ti_3Al and TiAl) matrix alloys which also have good high temperature properties /21, 22/. However, due to the experimental nature of these works a detailed discussion is beyond the scope of this review.

MICROSTRUCTURE AND MECHANICAL PROPERTIES

The important high temperature properties for aerospace related applications of titanium alloys are: tensile strength, creep, fatigue and fatigue crack propagation resistance, fracture toughness, hot salt stress corrosion cracking, and oxidation resistance. Titanium is used in gas turbine engines mainly because of its high strength-to-density ratio at a wide range of temperatures. The 0.2% yield stresses of some of the alloys listed in Table 1 are plotted in Figure 4 as a function of temperature in comparison to the nickel base INCONEL 718 and IN-100 alloys. To demonstrate the structural efficiency of titanium alloys, the yield stress of the nickel base alloys is also plotted on a density corrected basis (when the density of Ti-6242S is taken as 1) showing the advantage of the titanium alloys. The increased use of titanium in hotter sections of gas turbine engines is usually done at the expense of nickel base alloys which have both high temperature strength and oxidation resistance. For this reason the titanium alloy data in Figures 4 and 5 are compared to some of the most commonly used nickel base alloys /23/. The titanium alloy yield stress values in Figure 4 were obtained from alloys heat treated to microstructure conditions most suitable for rotating engine compo-

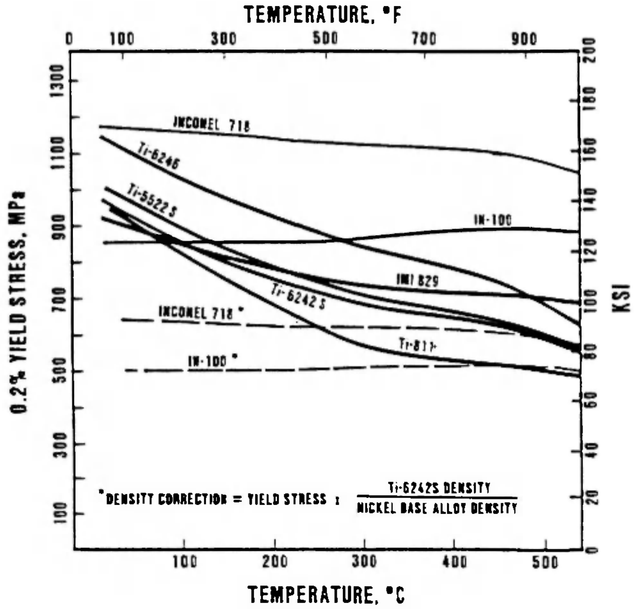

Fig. 4. Comparison of 0.2% yield stress of some high temperature titanium alloys to nickel base INCONEL 718 and IN-100 alloys. The density corrected data of the nickel base alloys (based on Ti-6242S density) are also plotted.

nents. These microstructures typically offer a good combination of tensile strength and ductility, low cycle fatigue strength, and creep resistance.

The creep strengths of some of the alloys are plotted in Figure 5 at 0.2% permanent strain as creep stress against the Larson-Miller parameter (K) which combines creep temperature and time. This plot demonstrates the creep strength advantage of the IMI-829 alloy and is also compared to the creep strength of the nickel base alloy INCONEL 718. It should also be noted that in near alpha and alpha + beta titanium alloys the creep strength will greatly increase by heat treating or processing the material above the beta transus temperature, which results in a lenticular alpha structure (Figure 6a). In contrast, an equiaxed alpha structure (Figure 6b), the result of hot working and subsequent heat treatment both in the alpha + beta phase field, has lower creep resistance which is demonstrated in Figure 7 /24/.

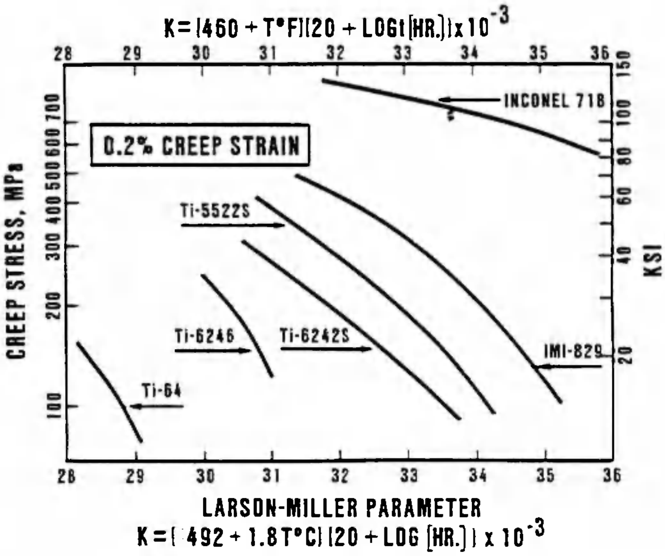

Fig. 5. Creep strength comparison of some high temperature titanium alloys and nickel base INCONEL 718 based on the Larson-Miller parameter.

The beta processed lenticular alpha structure is also a desirable microstructure for an improved fracture toughness /24/ and fatigue crack growth resistance /25, 26/. However, this microstructure is not desirable for high temperature strain control low cycle fatigue (LCF) strength as shown in Table 3 /27/. It was found that cracks prematurely initiated along the surface connected lamellar interfaces, possibly the result of enhanced oxidation along the planar phase boundaries

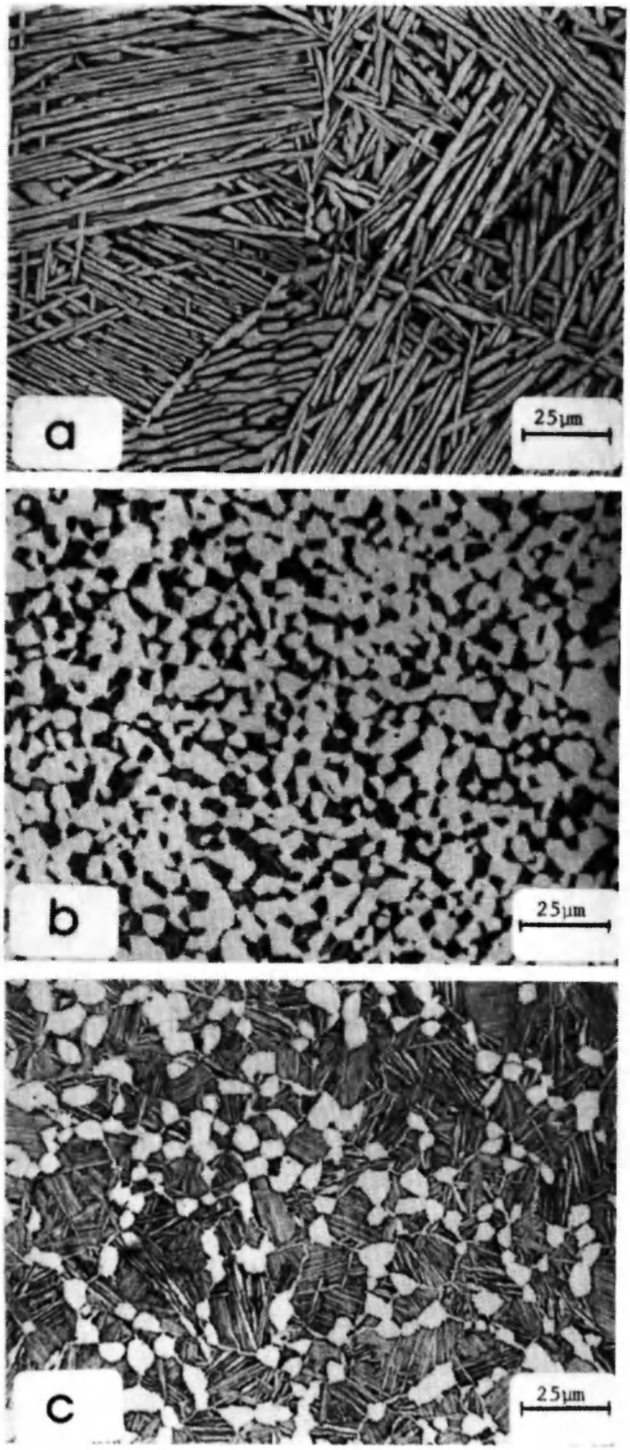

Fig. 6. Microstructures of Ti-6242 (a) beta solution treated (lenticular structure); (b) alpha+beta worked and alpha+beta solution treated (primarily equiaxed alpha structure); and (c) alpha+beta worked and solution treated slightly below the beta transus temperature (low volume fraction of equiaxed alpha in lenticular alpha matrix).

/28/. When the high temperature LCF tests of a lenticular structure alloy were conducted in vacuum, a significant increase in strength was obtained /29/.

TABLE 3. Strain Control Low Cycle Fatigue Life of Ti-6242S at 480°C (900°F) /27/

Test Frequency, cpm	Total Strain Range, %	Number of Cycles to Failure: Lenticular Structure	Number of Cycles to Failure: Equiaxed Alpha Structure
0.4	1.2	1,196	10,500[a]
10	1.2	3,715	31,000[a]
0.4	2.5	273	722
10	2.5	353	1,166

[a] Run out test.

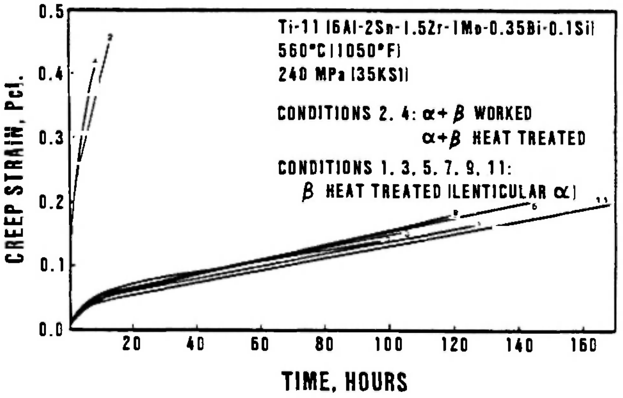

Fig. 7. Comparison of creep curves (strain vs. time) of lenticular alpha microstructure and equiaxed microstructure conditions in Ti-11 alloy /24/.

The advantage of the equiaxed alpha structure for LCF strength is demonstrated in Figure 8 which plots the total strain range versus the number of cycles to failure for lenticular transformed beta and for alpha + beta microstructures of two alloys. In gas turbine engine compressor disc applications, the high temperature strain control LCF is becoming an important design criterion. As a result, to achieve a good balance between creep and LCF resistance /16/, a duplex structure consisting of about 30 vol.% equiaxed alpha phase combined with lenticular alpha (Figure 6c) is currently used for many elevated temperature rotating components /30/. Because a large proportion of the alpha is lenticular the creep strength is good (Figure 7), while the LCF life is better than those shown in Table 3 and Figure 8 for the fully lenticular alpha structure. The effect of the alpha phase morphology on the various mechanical properties is summarized in Table 4.

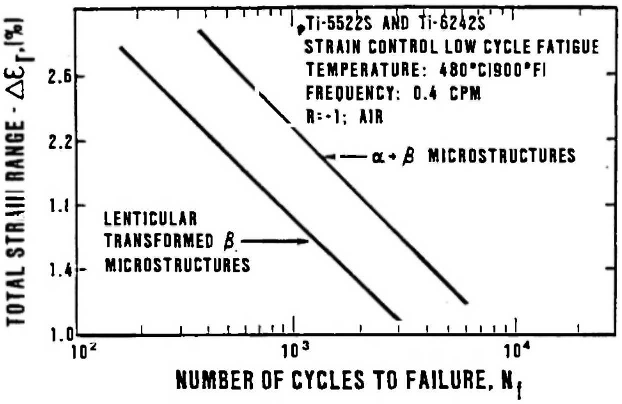

Fig. 8. Strain control low cycle fatigue average life curves of lenticular and equiaxed alpha structures in Ti-5522S and Ti-6242S alloys /27/.

OXIDATION RESISTANCE

The present maximum service temperature of the most advanced high temperature alloys (Table 1) is 590°C (1100°F). This is mainly because above this temperature the material loses its creep strength, even with silicon additions, and severe surface oxidation takes place. Any increase in the temperature range of titanium alloys will have to solve these two problems.

The main problem with conventional oxidation resistance coatings of titanium is the high reactivity of the coating material with the alloy substrate. These lead to surface embrittlement, which causes severe degradation to such surface related properties as low and high cycle fatigue /31/. High temperature coatings were developed on a U.S. Air Force program /4, 32/ and were based on ion plating of ductile noble metals like gold or platinum. It was found that the 1 micron thick ion plating provided good surface adherence without degrading fatigue properties /33/. Due to the high coat ductility, it remained uncracked even after relatively large creep strains, and provided an effective protection /32/. Air exposure surface oxidation rates in Ti-6242 are shown in Table 5 in terms of mg cm^{-2}h^{-1} after 500 hr.

TABLE 4. Property Ranking Summary of Alpha + Beta Titanium Alloys Based on Their Alpha Phase Morphology

Alpha Morphology	Mechanical Properties Tensile Strength	Tensile Ductility	Creep Strength	Fracture Toughness	H.T. LCF	FCIR[a]	FCPR[b]
Equiaxed	NE[c]	High	Low	Low	High	High	Low
Lenticular	NE	Low	High	High	Low	Low	High

[a] FCIR = Fatigue Crack Initiation Resistance

[b] FCPR = Fatigue Crack Propagation Resistance

[c] NE = No significant effect

TABLE 5. 500 Hour Weight Gain of Ti-6242 Alloy in Air

Ion Plating Materials	Exposure Temp., °C (°F)	Weight Gain Rate, mg cm^{-2} h^{-1}
No coating	590 (1100)	6.9×10^{-2}
Gold	430 (800)	2.2×10^{-4}
Gold	480[a] (900)	2.6×10^{-3}
Platinum	590[a] (1100)	1.2×10^{-3}
Tungsten/platinum	650 (1200)	3.3×10^{-4}
Tungsten/platinum	700[a] (1300)	$1.7 \quad 10^{-3}$

[a] Highest temperatures under which no spelling or loss of the coating was detected after 500 hr.

This table demonstrates that an effective long range oxidation protection can be provided to existing high temperature alloys up to 590°C (1100°F) by platinum ion plating. However, with the use of tungsten as a primer and platinum as a secondary coat, it is possible to extend this range up to 700°C (1300°F). The difference between coated and uncoated Ti-6246 compressor blades with and without platinum ion plating after 500 hr at 590°C (1100°F) is shown in Figure 9.

It was also found that the Pt ion plating greatly improves the creep resistance of the conventional high temperature titanium alloys /4, 32/ and comparison between the creep curves of uncoated Ti-6242 in vacuum and air, and platinum ion plated alloy in air is shown in Figure 10. The mechanisms involved in the increase of creep strength of alpha + beta titanium alloys under vacuum or coating are discussed elsewhere /4/. It was also found that Au coating can suppress fretting /34/ which is one of the limiting factors for using titanium components in contact with other titanium components (like Ti blades and the mating Ti compressor disc dovetail slots) above 400°C (750°F), a temperature at which most dry film lubricants decompose /35/.

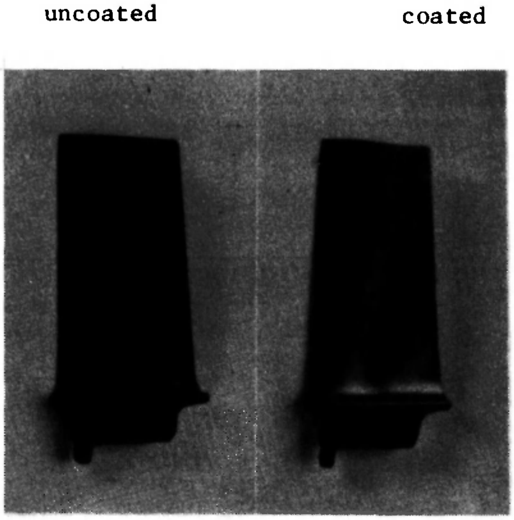

Fig. 9. Uncoated and platinum ion plated Ti-6246 alloy compressor blades after an air oxidation test at 590°C for 500 hr. The platinum-coated blade retained its original metallic luster after the test.

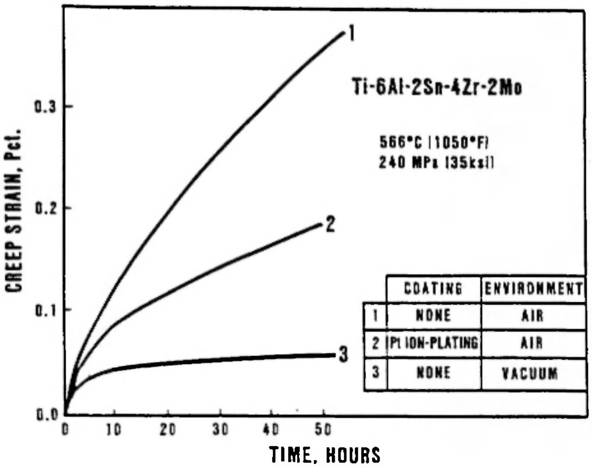

Fig. 10. Creep curves at 240MPa (35ksi) of Ti-6242 in air (curve 1) and in vacuum (curve 3), and of Ti-6242 with platinum ion plating in air (curve 2) at 566°C (1050°F) /32/.

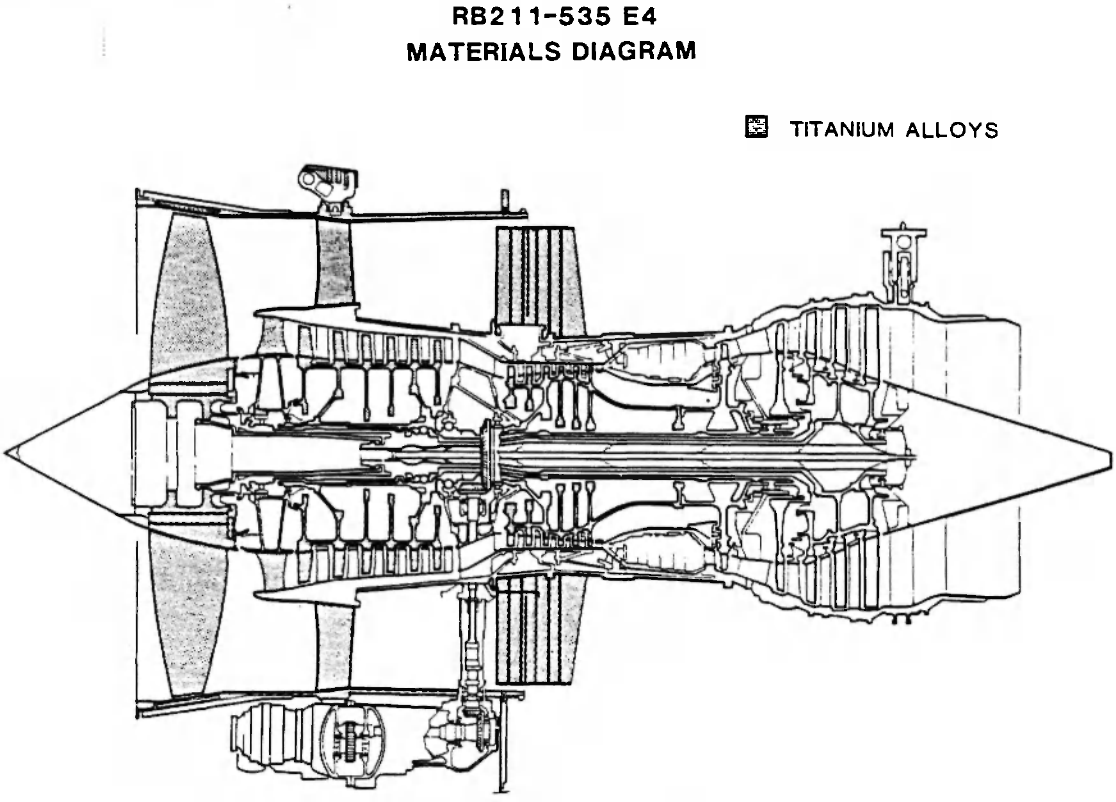

Fig. 11. Cross section of the Rolls-Royce RB-211-535-E4 aircraft gas turbine engine showing the usage of titanium (courtesy of Rolls-Royce).

APPLICATIONS

Because of the high tensile and fatigue strength-to-density ratios, titanium alloys are extensively used in rotating and static gas turbine engine components. The drive to utilize more titanium alloys is increasing with the need for more fuel efficient engines with lower engine weight and especially for rotating components which result in the highest fuel savings. Figure 11 shows a section view of the Rolls-Royce RB-211-535-E4 fuel efficient engine which is being installed in the new Boeing 757 airliner. This engine includes more titanium alloy components than any other commercial or military gas turbine engine. This is also the first engine to use the new high temperature alloy IMI-829 (Table 1). The shaded areas in this figure highlight the major titanium alloy components.

Generally speaking, high temperature titanium alloys produced by close die forging, which gives the highest integrity products, are used for rotating components, especially in the inner compressor stages where the temperatures and pressures are higher. IMI-829 is used in the RB-211-535-E4 engine in the 4th, 5th, and 6th compressor stage discs and in the 2nd, 3rd, and 4th stage blades. All other RB-211 class engines and the smaller RB-199 class engines have IMI-685 rotating components. In future engines there are plans to use advanced high temperature titanium alloys also in the low pressure section of the turbine /3/. U.S. made and U.S. designed engines of similar class use Ti-6246 and Ti-6242S (Table 1) alloys extensively for rotating components. The biggest advantage of using titanium lies in reducing the weight of the blades. The lighter blades reduce the disc stresses, which allows thinner disc sections. This results in a further reduction in the disc weight since it has to carry less of its own rotary weight. By replacing steel blades with titanium alloy blades, a 44% reduction in blade weight and 20% reduction in disc weight is realized due to the lower blade weight /35/.

Less critical non-rotating components like compressor cases are also made of titanium. Where the temperatures are below 315°C (600°F), more conventional alloys like Ti-6Al-4V could be used. Since hot isostatically pressed titanium castings offer many properties like creep, fatigue crack growth resistance and tensile strength almost as good as forged products /36/, they are used extensively in most advanced engines like the 135 kg (300 lb) Ti-6Al-4V Fan Frame for the G.E. CF6-80C aircraft gas turbine engine shown in Figure 12.

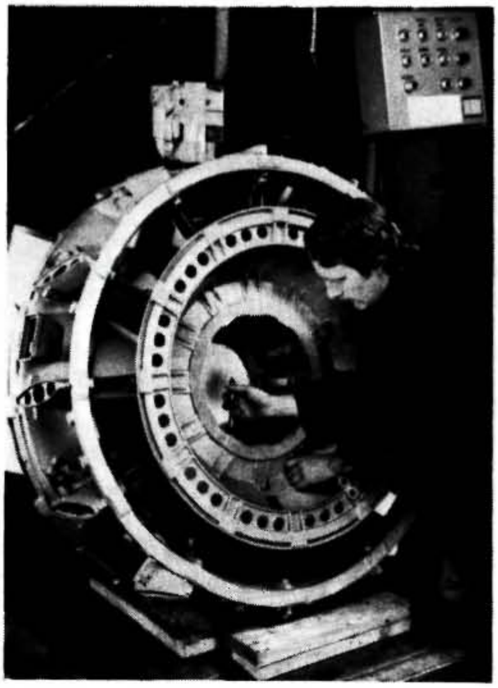

Fig. 12. 135kg Ti-6Al-4V cast Fan Frame for the General Electric CF6-80C gas turbine engine produced by the investment casting method (courtesy of Precision Castparts Corp.).

Other applications for high temperature titanium alloys are in airframe hot sections of high performance aircraft, which are typically located around the engine, in the duct system of vertical/short take off and landing (V/STOL) planes, and in the wing leading edges of high Mach planes. Recently, some applications were also found in intake and exhaust valve assemblies for racing car engines /37/.

SUMMARY

Commercially available high temperature titanium alloys are of the near alpha class. The high volume fraction of alpha with additions of solid solution strengthening elements and minor additions of silicon provide the capability of these alloys to perform up to 590°C (1100°F). Due to the favorable property-to-density ratio titanium alloys have found many applications in gas turbine engine components resulting in substantial weight and, consequently, fuel savings.

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