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Aircraft Applications of Titanium: A Review of the Past and Potential for the Future

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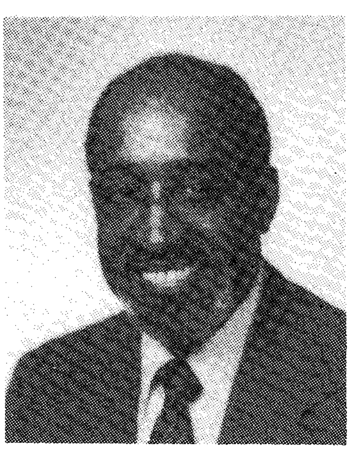
I. Introduction

IN 1791, William Gregor, English clergyman and amateur mineralogist, discovered the mineral ilmenite ($FeTiO_3$) and concluded that it contained a new element. Simultaneously, German chemist M.H. Klaproth concluded that a mineral known as rutile (TiO_2) was an oxide of a new metal called titanium, after the Titans of mythology. In 1797, Klaproth confirmed that Gregor's new element was titanium.[1] Ilmenite and rutile are the principal ores of titanium. Titanium, at 0.6%, is the ninth most abundant element in the 10-mile (16-km) outer shell of the Earth; and the fourth most abundant structural metal after aluminum, iron, and magnesium in order of decreasing abundance. The United States has abundant supplies of titanium ores, predominantly ilmenite. However, it has been more economic to import the richer rutile ore from Australia to meet domestic needs. In 1825, J.J. Berzelius extracted the metal from the ore. In 1906, M.D.A. Hunter prepared pure titanium by reducing the tetrachloride with sodium. Finally, an extractive method adaptable to commercial production was developed by William J. Kroll; and in 1946 the U.S. Bureau of Mines produced titanium by the Kroll process in 100-lb (45-kg) lots. Basically the Kroll process consists of reacting purified TiO_2 with chlorine in the presence of carbon to produce $TiCl_4$. Purified $TiCl_4$ is then reacted with magnesium in a closed retort at a temperature above the melting point of magnesium, but below that of titanium. The reaction products are $MgCl_2$ and porous titanium, called sponge. The $MgCl_2$ is leached out and electrolyzed to recover the magnesium for recycling in the titanium operation. This accomplishment started the titanium industry.

The fledgling industry received key support from the Armed Forces, particularly from the Army Materials and Mechanics Research Center (formerly Watertown Arsenal), Watertown, Mass., and from the Air Force Materials Laboratory, Dayton, Ohio. Especially important was the support given to basic research to determine phase diagrams and to define the relationships between binary alloying additions, working and thermal history, microstructure, and mechanical properties. This body of knowledge was essential to systematic alloy development and to understanding the complexities of titanium behavior and some of the problems in applying the alloys that were encountered along the way.

A brief explanation of alloying behavior of titanium may be useful in understanding the profusion of titanium commercial alloys. In the United States it is customary to name titanium alloys by their composition in weight percent, e.g., Ti-6Al-4V. The name is abbreviated by dropping the element symbols, thus Ti-6-4. Like iron, titanium is polymorphic. It solidifies in the body centered cubic crystal (bcc) form and transforms to the hexagonal close packed (hcp) form when cooled below 1620°F (882°C). The hcp phase is called alpha, and the bcc phase is called beta. Commonly used alloying additions to titanium may be divided into three groups. The first group dissolves preferentially in the lower temperature alpha phase, e.g., aluminum and oxygen. The second group dissolves preferentially in the beta phase, and stabilizes it to a degree determined by the specific element and the amount



Dr. Crossley is a recognized authority in the field of titanium metallurgy. He has been awarded five patents on titanium-base alloys, including one on the new Transage titanium alloys. Dr. Crossley has published over 40 technical papers. He is a past chairman of the Titanium Committee of the Institute of Metals Division, The Metallurgical Society of the American Institute of Mining, Metallurgical and Petroleum Engineers. He is a member of the AIAA Materials Committee. Dr. Crossley joined the Lockheed Palo Alto Research Laboratory in 1966, following ten years as Senior Metallurgist with the IIT Research Institute (formerly the Armour Research Foundation). While he was a member of Lockheed Research Laboratory, he engaged in studies to develop new lightweight alloys of beryllium-aluminum, and high-strength titanium alloys. Dr. Crossley was manager of the Producibility and Standards Department from 1974 to 1978, and manager of the Missile Body Mechanical Engineering Department, both of the Missile Systems Division, from 1978 until he assumed his present position as Consulting Engineer in April 1979. He is a Fellow of the American Society for Metals. Dr. Crossley received Ph.D. and M.S. degrees in Metallurgical Engineering and a B.S. degree in Chemical Engineering from the Illinois Institute of Technology.

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added, e.g., chromium, iron, manganese, columbium, molybdenum, vanadium, and tantalum. The third group dissolves only slightly preferentially in the beta phase; and consequently, behaves in a rather neutral way, e.g., tin and zirconium.

Additions of the first group are called alpha stabilizers; those of the second group are called beta stabilizers, and are subdivided into two groups: 1) those that form compounds with titanium, such as chromium ($TiCr_2$), iron ($TiFe_2$), manganese (TiMn), and silicon (Ti_5Si_3); and 2) those that are soluble in all proportions in the higher temperature beta phase, such as columbium, molybdenum, tantalum, and vanadium. Some compound formers, such as chromium, iron, and manganese, do so sluggishly, and their use is predicated on suppression of compound formation. On the other hand, silicon is added because the readily formed compound, Ti_5Si_3, increases resistance to elevated temperature creep.

Based upon these alloying effects, titanium alloys are divided into classes as follows: alpha, e.g., Ti-5Al-2.5Sn; near alpha, e.g., Ti-8Al-1Mo-1V; alpha-beta, e.g., Ti-6Al-4V and Ti-6Al-2Sn-4Zr-6Mo; martensitic, e.g., the Transage alloys Ti-2Al-12V-2Sn-6Zr and Ti-2.5Al-13V-7Sn-2Zr; and metastable beta (or simply beta), e.g., Ti-13V-11Cr-3Al and Ti-10V-2Fe-3Al. Alpha and near alpha alloys are not age hardenable, while all of the other groups are. Hardenability, that is, the ability to retain the metastable beta phase with decreasing cooling rate from solution heat treatment temperature, depends predominantly on the content of beta stabilizing additions. As hardenability increases, development of high strength through age hardening is attainable in increasingly heavier sections.

Titanium alloys have the strength of steels, with only 60% of their density, and have exceptionally good resistance to corrosion. Since a pound of weight saved in rotating jet engine components makes an overall weight saving in the aircraft of 4 lb, engine use is the most cost effective. Consequently, the jet engine market has been the largest for the titanium industry. The alpha phase is more creep resistant than the beta phase. Therefore titanium components subjected to the higher temperatures [up to about 900°F (500°C)] are of the alpha or near alpha alloy types. Fan stage components, which operate at the lowest temperatures, are of the age hardenable alpha-beta alloys. The martensitic and the beta alloys are cold formable in the solution heat treated condition and are more readily hot worked than the others. They are potentially useful for 1) high-strength sheetmetal structures, 2) heavy section forgings, and 3) less costly forgings.

Unlike the common structural metals, titanium, when heated to temperatures above about 600°F (260°C) dissolves oxygen at the oxide/metal interface, producing a brittle layer which must be removed. Hydrogen, if present in the furnace atmosphere as water or hydrocarbons, is also dissolved into the metal. Hydrogen can also be absorbed during aqueous solution pickling. Embrittlement may result, depending upon the amount of hydrogen present and the tolerance of the alloy. For this reason, specification limits are placed on hydrogen content.

II. Review of the Past

A. Major Milestones

The continuing position of Ti-6Al-4V as the workhorse alloy of the aerospace industry more than 25 years after its first application, qualifies its development as a major milestone in the history of titanium. The specific composition was first melted and evaluated in 1953 at IIT Research Institute under an Air Force Materials Laboratory program to develop titanium alloys for elevated temperature use.[3] As project leader of the Air Force program, I was directed by my supervisor, Harold D. Kessler, to evaluate titanium-aluminum-vanadium alloys at the 6 and 8 wt.% aluminum level. (He had already evaluated such alloys at the 2 and 4 wt.% aluminum levels under an Army-sponsored program.) Credit is also due to the late Max Hansen, who established the general plan for the basic phase diagram studies and the subsequent alloy development work.

A new alloy developed outside of a producer's laboratory is not likely to be used, no matter how promising, unless an individual representing a potential user recognizes its potential, has the courage to evaluate it, and use it if the new alloy lives up to its promise. In the case of Ti-6Al-4V, the individual was R.H. Thielemann. His selection of Ti-6Al-4V for the compressor section of Pratt & Whitney's J-57 engine is the second major milestone (see Fig. 1). This action brought the fledgling titanium industry to maturity and earned a continuing place for titanium in jet engines. The titanium version of the J-57 military jet engine weighed 443 lb (201 kg) less than its steel counterpart. Since the J-57, a number of more complex titanium alloys giving improved performance over Ti-6Al-4V have appeared in jet engines. These are near alpha and alpha-beta alloys. Examples of the near alpha alloys are IMI 679 (Ti-11Sn-2.25Al-5Zr-1Mo-0.25Si), IMI 685 (Ti-6Al-5Zr-0.5Mo-0.3Si), and Ti-811(Ti-8Al-1Mo-1V). Examples of the alpha-beta alloys are Ti-662 (Ti-6Al-6V-2Sn-1.3Cu-1.3 Fe), Ti-17 (Ti-5Al-4Cr-4Mo-2Sn-2Zr) Ti-6242 (Ti-6Al-2Sn-4Zr-2Mo), and Ti-6246 (Ti-6Al-2Sn-4Zr-6Mo). From these alloys, it may be deduced that aluminum is the best alloying friend that titanium has. It increases elevated temperature strength, decreases the rates of contamination by hydrogen and oxygen, and increases tolerance for hydrogen.

The utilization ratio (i.e., weight of mill products procured to finished weight) of titanium in jet engine components is 6:1 to 10:1, making the use of titanium forged components expensive. High material and machining costs have limited application of titanium in airframes to considerably less than optimum performance or minimum life cycle cost would dictate. However, use of titanium in airframes has grown steadily. The use of 1000 lb (454 kg) of titanium in the Convair 880 was estimated to have saved 800 lb (364 kg). More recent giant aircraft such as the Boeing 747, DC-10, L-1011, and the C5-A military transport contain more than 8000 lb (3640 kg) of titanium each. Utilization ratios for titanium in airframes vary from 50:1 for a large bulkhead forging on the F-15 fighter to 1.3:1 for sheetmetal components.

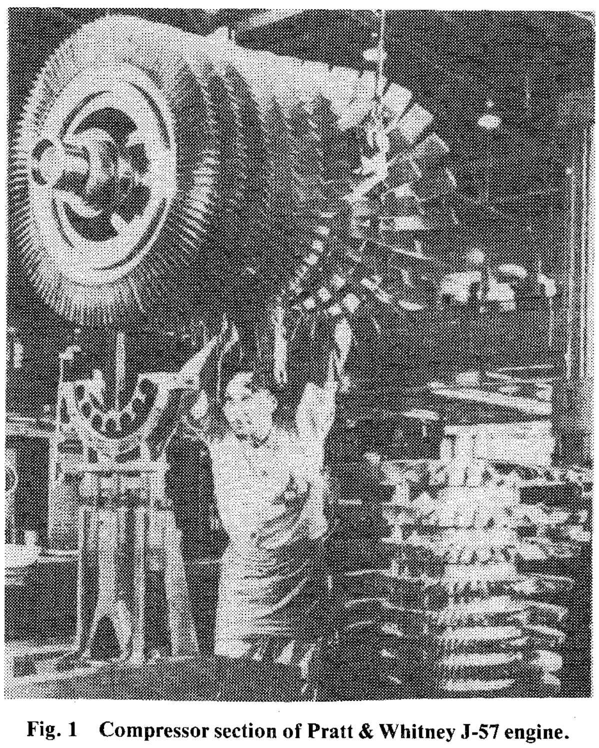


Fig. 1 Compressor section of Pratt & Whitney J-57 engine.

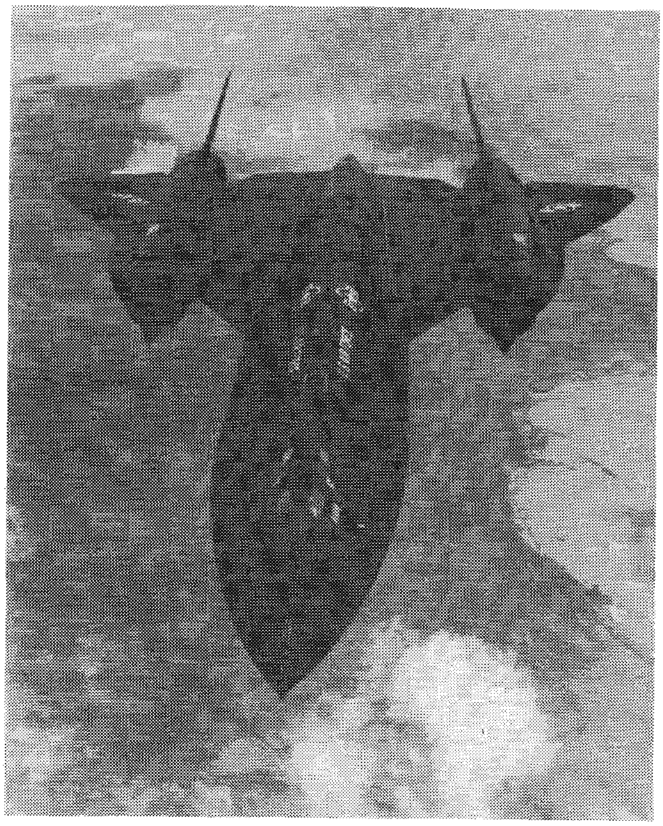


Fig. 2 Lockheed-USAF SR-71 "Blackbird" Mach 3 reconnaissance aircraft.

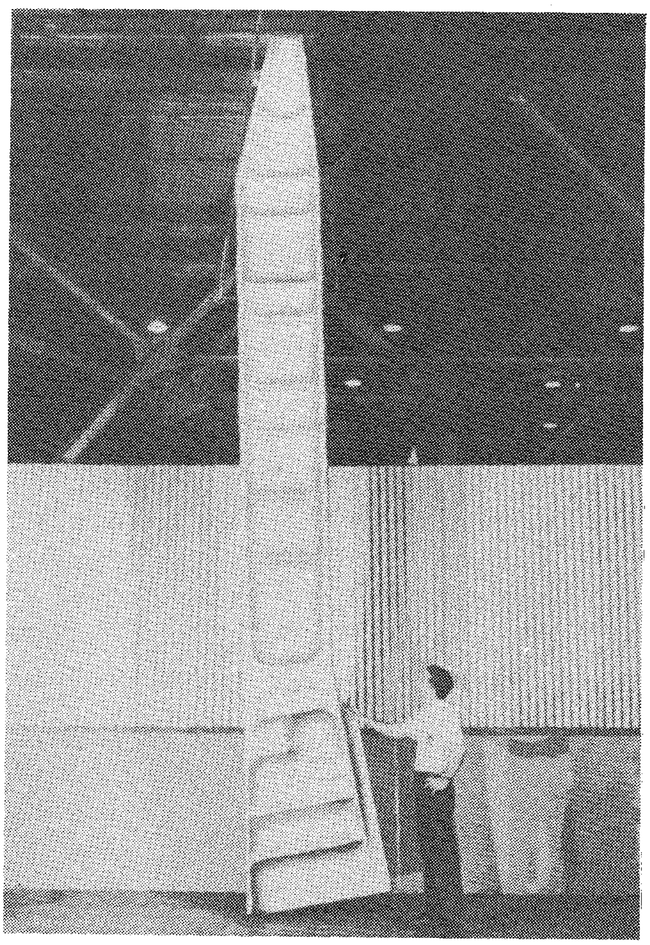


Fig. 3 Boeing 747 landing gear beam.

The use of titanium in airframes brings us to the third major milestone, the YF-12A/SR-71 reconnaissance aircraft, shown in Fig. 2. The SR-71 holds the world speed and altitude records for level flight: 2189 mph (3522 km/h) and 86,000 ft (26,212 m), respectively. The airframe is 93% titanium, and the primary alloy of construction was B 120 VCA (Ti-13V-11Cr-3Al).[4] This alloy was selected because it could be age hardened to strengths up to 200 ksi (1380 MPa), and its cold formability promised reduced fabrication costs. However, the heavily beta stabilized alloy required long aging times, initially, about 70 h. Careful control of sheet processing brought the aging time to about 40 h for maximum strength. However, overaging is accompanied by precipitation of the compound $TiCr_2$ with embrittling effects. Because of the segregation tendency of chromium and variation in the hand mill operations to produce the sheets, variation in aging response from sheet to sheet, as well as from heat to heat, was encountered. The problem was solved at considerable cost by testing samples of each sheet for formability and aging response.[4] The alloy also had poorer fatigue properties than annealed Ti-6Al-4V. During the production phase of the SR-71, the B 120 VCA alloy accounted for about 10% of titanium mill product shipments. Today it is less than 1%.

The fourth milestone is the use of two through-wing landing gear beams in the 747 aircraft. Four 4000-lb (1820-kg) Ti-6Al-4V forgings, shown in Fig. 3, are finished to the 1700-lb (773-kg) part. Two are joined to form a single main landing gear beam.

The fifth milestone is in a like vein. It is Boeing's decision to schedule into production, on the 757 aircraft, one piece main landing gear beams of the new near beta alloy Ti-10V-2Fe-3Al. Motivations for the change were reduced fabrication cost and improved performance. Use of Ti-10V-2Fe-3Al saves about 10% of the weight of its 670-lb (305-kg) Ti-6Al-4V counterpart. Ultimate tensile strength and fracture toughness requirements for the main landing gear beams are 180 ksi (1240 MPa) minimum and 40 ksi $\sqrt{\text{in.}}$ (44 MPa $\sqrt{\text{m}}$), minimum, respectively.[5]

The sixth and final milestone is the use of more than 130 Ti-6Al-4V castings in more than 25 different configurations in the Pratt & Whitney F-100 engine. The weight saved by using titanium rather than steel for these parts totals more than 30 lb (14 kg) per engine.[6]

B. Major Past Problems

This listing of major past problems is subjective, just as was the listing of milestones. The primary consideration in making the choices was the hazard the problem presented to aircraft integrity. The problems are presented in chronological order of their occurrence.

1. Hydrogen Embrittlement

During the 1950s, titanium users were shocked by the phenomenon of fracturing of titanium alloy sheet parts on aircraft that were sitting idly on the ground. Extensive and intensive investigations determined the cause to be delayed failure due to hydrogen.[7] The essential features of hydrogen embrittlement in titanium alloys may be summarized as follows.

When hydrogen content in a titanium alloy exceeds its solubility limit in the gross material or in highly localized regions, it is detrimental to mechanical properties. The detrimental effects are manifested under two basic types of loading: 1) high strain rate bending under triaxial stress, e.g., Charpy V-notch impact testing, and 2) low strain rate or static loading under uniaxial, or more complex, stress conditions. In the first case, embrittlement results from the presence of hydride particles in the microstructure. In the second case, whether or not hydride particles are observed in postfracture metallographic examination, embrittlement apparently is the result of segregation of hydrogen to sites of high triaxial stress, with subsequent precipitation of titanium hydride. Tolerance for hydrogen in titanium alloys varies widely with composition and microstructure. The delayed failure problem was solved by limiting the hydrogen content of mill products by specification, by the ascendency of Ti-6Al-4V, which has a relatively high tolerance for hydrogen, and by controlling hydrogen pickup during heat treatment, contaminated surface removal, and chemical milling operations. In heat treatment, it means vacuum or oxidizing furnace environments. In contaminated surface removal, hydrogen pickup can be avoided by employing commercially available molten salt baths, or aqueous pickling solutions appropriate to the alloy. Specifications define the requirements for established alloys. However, pickling or chemical milling solutions acceptable for Ti-6Al-4V may be detrimental to a new alloy, especially if it is significantly different in type and composition from Ti-6Al-4V. Recently, the new cold formable, age hardenable beta alloy, Ti-15V-3Al-3Cr-3Sn, was found to readily absorb hydrogen from a 10% hydrogen fluoride chemical milling solution, although the solution is in regular use for Ti-6Al-4V.[8] Because hydrogen is a beta stabilizer, pickup of 1000 ppm hydrogen caused the age hardening reaction in Ti-15-3-3-3 to be completely suppressed. Since the sheet product as received from the mill contained 350-ppm hydrogen, the importance of hydrogen control in this alloy is evident.

2. Hot Salt Stress Corrosion

In 1966, Bauer reported a surface cracking phenomenon observed in creep testing Ti-6Al-4V alloy at 700°F (370°C).[9] He attributed the cracking to a surface embrittlement phenomenon induced by oxidation. Later TIMET personnel associated surface cracking on specimens of a titanium alloy exposed to creep at 850°F (455°C) with a mottled grayish surface oxide in the pattern of fingerprints. Howard R. Frances (then of the IIT Research Institute) and TIMET personnel suspected NaCl as the causative agent. TIMET personnel immediately coated specimens of Ti-6Al-4V alloy with NaCl and exposed them at 850°F (455°C) under stress. Fractures were obtained in as little as 20 h, confirming the susceptibility of at least some titanium alloys to a delayed failure phenomenon called hot salt stress corrosion. Subsequent investigations showed that all titanium alloys were susceptible to more or less degree.

The mechanism of hot salt stress corrosion is not clearly understood. A reaction product, $TiCl_2$, appears to be involved as a causative agent.[10] While it is distressingly easy to produce cracking in the laboratory, there has been no documented flight failures, although experiments have shown that aircraft flying in marine environments collect sufficient sea salt on engine components to cause cracking under laboratory conditions.[11] Some key factors for the difference between laboratory tests and flight experience are the following: 1) NaCl is more aggressive than the more complex sea salt. 2) High velocity air flow reduces the severity of attack. 3) Cyclic exposure to temperature and stress (i.e., flight simulation) is considerably less harmful than continuous exposure. 4) In laboratory tests, conditions were generally favorable for intimate contact between the salt and clean titanium surfaces, while in-service surfaces (whether titanium or not) tend to have dirt or oxide films that may provide a barrier to salt contact. Indeed, Ti-6Al-4V compressor blades that were NaOH anodized or oxidized at 800°F (425°C) for 48 h and salted were equal in elevated temperature fatigue performance to etched, unsalted blades.[12] 5) Under simulated compressor environmental conditions, the commonly used Ti-6Al-4V alloy is creep limited and not stress corrosion limited. Shot peening compressor components to increase fatigue resistance also improves resistance to stress corrosion.[13]

Service experience with titanium alloy components has been entirely satisfactory with respect to hot salt stress corrosion. However, some precautions are in order. A new alloy capable of application at higher stresses than Ti-6Al-4V should be carefully observed for possible susceptibility under service conditions. Also, other chloride salts may be more detrimental than NaCl or sea salt. For example, a Ti-6Al-4V compressor rotor assembly failed unexpectedly during testing. Cracking occurred at almost every tie bolt where silver-plated steel bolts were in intimate contact with the disk. Analysis of the silver deposit at the crack origin revealed the presence of silver chloride. Ambient air was the apparent source of chlorine. To eliminate this threat, silver plating must not be used.[14]

3. Salt-Water Stress Corrosion

The third past problem is of continuing significance and concern. It is salt- (or sea-) water stress corrosion. It is reflected in the degradation of threshold stress intensity for crack propagation in the presence of salt water compared to air. Crack nucleation of smooth specimens of titanium alloys in salt water is difficult. Therefore the preexisting flaw (i.e., fracture mechanics) approach is taken to evaluate susceptibility. The threshold stress intensity is usually denoted K_{Iscc}.* Considerable evidence supports a conclusion that K_{Iscc} value decreases when alloying and processing factors cause or promote the appearance of the first intermediate phase in the Ti-Al system, namely, Ti_3Al. Thus increasing aluminum content above 4 wt.%, increasing oxygen content, and thermal aging in the alpha/alpha and Ti_3Al phase region lower K_{Iscc}.[15] Alloys containing 6 wt.% aluminum are borderline with respect to salt-water stress corrosion, depending upon these factors. Titanium-aluminum-base allloys have been found to have K_{Iscc} values that vary from a high of more than 90% of K_{Ic}† to a low of 19%.[16] Practically speaking, alloys that have K_{Iscc} values that are 90% or more of K_{Ic} may be considered to be immune to salt-water stress corrosion. Threshold stress intensity in the presence of salt water should be a consideration in the choice of a titanium alloy for an application that includes exposure under stress to marine environments.

4. Accelerated Fatigue Failure

The fourth and final past problem is also of continuing concern. This problem surfaced in the early 1970s when certain IMI 685 (Ti-6Al-5Zr-0.5Mo-0.25Si) large forgings service failed in fatigue with lives of less than 500 cycles, when design indicated 100,000 cycles were expected. The forgings had been solution heat treated in the beta phase field, oil quenched, and stress relieved at 580°C (1075°F) for 24 h. An intensive investigation provided the following information.[17] Because of the shallow hardenability of IMI 685 alloy, significant variation in the detailed microstructure existed throughout each forging. The extremes of these microstructures commonly encountered were what were described as "basketweave" and large colony. The basketweave structure occurred near the surface and was due to martensitic (or athermal) transformation. The large colony structure was due to nucleation and growth (i.e., diffusion dependent and hence thermally activated) transformation. The controlling microstructural element in the colony structure is packets of similarly oriented acicular alpha platlets. Fatigue test specimens having the large colony microstructure averaged only 50% of the life of specimens having the basketweave structure. This finding was for axial tests conducted under constant load amplitude, with con-

*K_{Iscc} is the threshold stress intensity [in units of ksi $\sqrt{\text{in.}}$ (MPa $\sqrt{\text{m}}$)] at which a precrack begins to grow under static tension in the presence of a medium which degrades performance compared with testing in air.

†K_{Ic} is the symbol for fracture toughness. It is the stress intensity under plane strain conditions at which a precrack loaded monotonically in tension starts to propagate. It is defined in detail in the ASTM E 399 standard.

ventional triangular wave form at 0.1 Hz frequency and stress ratio $R = 0.05$. Selected tests were run by superimposing a 5-min dwell at maximum load in order to more closely simulate actual operating conditions of the subject forgings. Under these conditions colony structure specimens had only about 2% of the life of similar specimens tested at 0.1 Hz frequency. Shorter life appears to be due to earlier fatigue crack initiation. This factor was found to be strongly related to the occurrence of heterogeneous slip, that is, the development of intense slip bands. Cracking occurred in or parallel to such slip bands. When slip band extent was broken up by reducing colony size (the extreme being a basketweave microstructure) fatigue crack initiation was inhibited. Ti-6Al-4V alloy as it is used in service has not been found to be susceptible to this phenomenon. Significantly, it is not heat treated for service applications by quenching from the beta phase field and stress relieving. The lesson here is that qualification testing must attempt to simulate both service loading conditions and microstructure. This type of phenomenon is still being investigated and the returns are not yet all in.

C. Current Problems

Major current problems concerning the application of titanium in aircraft, are cost of titanium components, and long lead times. In fall 1980, lead time for titanium forging billet was one year and lead time for titanium forgings was two years. Figure 4 shows prices of titanium sponge and of Ti-6Al-4V 8⅛-in. (206-mm) round rotating billet from 1976 to the present. Considering that it takes 16 times more energy to produce one ton of titanium sponge than it takes to produce one ton of iron ingot,[18] and considering the inflation in energy costs, the recent rapid escalations in prices of sponge and of Ti-6Al-4V billet, are not surprising. These increasing

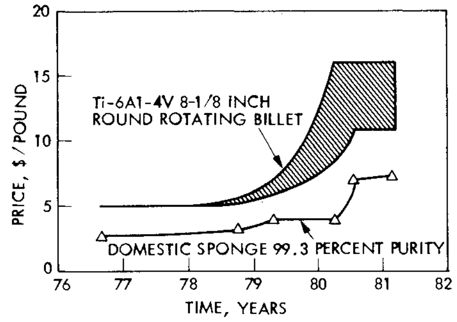


Fig. 4 Titanium sponge and Ti-6Al-4V 8⅛-in. (206-mm) round rotating billet prices from 1976.

costs should provide greater motivation to reduce buy-to-fly weight ratios. Forgings were 39% of U.S. shipments of titanium products in 1979.[18] It is in forgings that buy-to-fly weight ratios are least favorable. Users of titanium forgings commonly state their buy-to-fly weight ratios as from 5 to 1 to 10 to 1. Individual cases come to mind of much less favorable ratios. For example, a large bulkhead in the F-15 fighter aircraft is machined from a 2200-lb (1000-kg) forging to a 43-lb (20-kg) part, for a 51 to 1 buy-to-fly. Simple arithmetic suggests that reducing the buy-to-fly weight ratio of forgings alone from an assumed 7.5 to 1, to 2.5 to 1, would be the equivalent of increasing mill production of billet by 25% without investment of a single dollar in plant expansion! New alloys, new process technology, and some old process technologies newly adapted to titanium, give promise of realizing such a goal with significant reductions in component costs as well. Reduction in the cost of titanium components would have further beneficial effects. Most aircraft flying today contain less titanium than least life cycle cost, or than optimum performance would dictate. Titanium usage has been limited by high component costs that make the flyaway cost of optimum-use designs unacceptable. Reducing titanium component costs would permit greater use to improve performance and reduce life cycle cost. New alloys not only make feasible the use of certain process technologies, but offer improved performance over Ti-6Al-4V for many, if not most, airframe applications.

III. Potential for the Future

A. New Alloys

Perhaps the best way to clear the air for the discussion of new alloys, is to admit that over the past three decades a number of titanium alloys have come and gone. Some of these late and little lamented alloys are Ti-140A (Ti-2Fe-2Cr-2Mo), Ti-155A (Ti-5Al-1.4Fe-1.4Cr-1.5Mo), C-110M (Ti-8Mn), C-130AM (Ti-4Al-4Mn), Ti-5Al-3Cr, Ti-16V-2.5Al, Ti-8V-8Mo-2Fe-3Al, and Beta III (Ti-11.5Mo-6Zr-4.5Sn). It may be added that Ti-6Al-4V has earned its place as the most used titanium alloy, and there have to be compelling reasons to try a new alloy in its place. Such reasons are increasingly evident and cry out for appropriate response. The temperatures and pressures required for hot working Ti-6Al-4V makes net shape forging a losing proposition. Expensive, nickel-base alloys are required for dies, and die life (in terms of integrity of dimensions) is short. Furthermore, the shallow hardenability of Ti-6Al-4V means that heavy section parts have only moderate strength. Another reflection of the shallow hardenability of Ti-6Al-4V, is that water quenching from about 1700°F (925°C) is necessary to age harden to high strength. However, water quenching causes unacceptable

Table 1 Characteristics of new titanium alloys

Common name	Composition, wt.% V	Al	Sn	Zr	Other	Alloy type	Recommended use	Comments
Ti-6-4	4	6	...	...	...	Alpha-beta	General purpose	Weldable, shallow hardenability, and forgiving
Corona 5	...	4.5	...	...	5Mo-1.5Cr	Alpha-beta	Plate and forgings	Very high fracture toughness at moderate strength levels
Ti-10-2-3	10	2	...	...	2 Fe	Near beta	Forgings	180 ksi (1240 MPa) strength and 40 ksi $\sqrt{\text{in.}}$ (44 MPa $\sqrt{\text{m}}$) fracture toughness minima with optimized processing
Ti-15-3	15	3	3	...	3 Cr	Metastable beta	Cold formable age hardenable sheet	Fabrication costs and performance relative to Ti-6-4 being established
Transage 129	11.5	2	2	11	...	Martensitic	Cold formable age hardenable sheet	100% weld efficiency at 210 ksi (1400 MPa) demonstrated
Transage 134	12	2	2	6	...	Martensitic	Forgings, plate, and sheet; superplastic forming behavior	Exceptional resistance to fatigue. Excellent weldability superplastic behavior down to 1100°F (600°C)
Transage 175	13	2.5	7	2	1	Martensitic	Castings and forgings especially for elevated temperature use	Cast-to-size bars have exhibited superior fatigue resistance at 250 and 500°F (120 and 260°C) compared to wrought, STA Ti-6Al-4V

distortion in sheet metal parts, including superplastically formed sheet constructions. Therefore such structures are used in the annealed condition, having about 130 ksi (895 MPa) ultimate tensile strength.

The new alloys summarized in Table 1 offer improved performance over Ti-6Al-4V in one or more aspects. Ti-6Al-4V is included in the table, for it is the basis for comparison. The new alloys are Corona 5 (Ti-4.5Al-5Mo-1.5Cr), Ti-10V-2Fe-3Al, and the martensitic Transage alloys.

Corona 5 was developed to have high fracture toughness ($K_{Ic} = 100$ ksi $\sqrt{\text{in.}}$ (110 MPa $\sqrt{\text{m}}$) minimum) at an ultimate tensile strength of 135 ksi (930 MPa) minimum. It is an alpha-beta alloy like Ti-6Al-4V, but more deep hardening. It would be expected to be less weldable than Ti-6Al-4V.

Ti-10V-2Fe-3Al is a near beta alloy having good hardenability. When melted, forged, and heat treated to an optimized schedule, it has been demonstrated to meet goals of 180 ksi (1240 MPa) minimum strength with 40 ksi $\sqrt{\text{in.}}$ (44 MPa $\sqrt{\text{m}}$) minimum fracture toughness. Optimum forging requires that 80-95% of the forging reduction be done above the beta transus temperature, and the final 5-20% reduction be done 25-50°F (15-30°C) below the beta transus. This is followed by a double solution heat treatment and a single aging treatment in order to produce a controlled microstructure.[19]

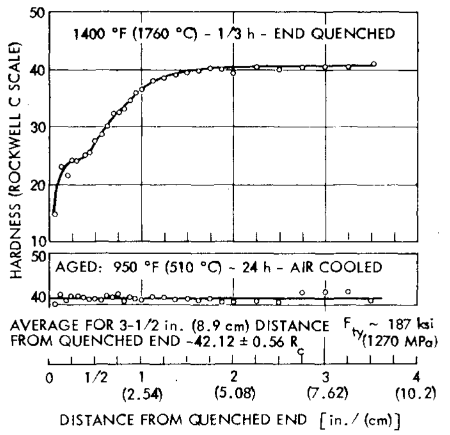


Fig. 5 Jominy hardenability curves for Transage 129 (Ti-2Al-11V-2Sn-11Zr) as end quenched and after age hardening.

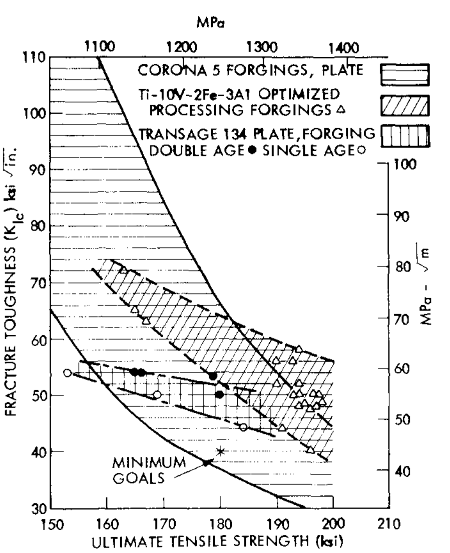


Fig. 6 Ultimate tensile strength vs fracture toughness of new titanium alloys.

The Transage alloys are a new type of titanium alloy in that they transform martensitically upon slow cooling from above their beta transus temperatures. If one considers Ti-6Al-4V to be analogous to a low alloy, high-strength steel, and near beta or metastable beta alloys to be analogous to austenitic precipitation hardenable steels like 17-7 PH, then the Transage alloys are analogous to Maraging steels. The Transage alloys have excellent weldability. Since solution heat treatment is preferably above the beta transus, the alloys have excellent welding-age hardening compatibility. Of the alloys listed in Table 1, the Transage alloys have the highest hardenability. Jominy hardenability curves for Transage 129 alloy as end quenched and after aging at 900°F (480°C) for 24 h are shown in Fig. 5. It may be noted that because of a unique age hardening mechanism, Transage alloys may age to high-strength levels in as little time as 15 min.[20] The Jominy test data lead to the expectation that Transage 129 alloy would harden uniformly throughout a bar of at least 7 in. (178 mm) in diameter.

One of the characteristics of Ti-6Al-4V that helped gain its popularity, has been described as "most fool-proof" or "most tolerant." Ti-6Al-4V contains only one beta stabilizer—vanadium. In practice, vanadium has given the least segregation problems in melting than any of the beta stabilizers. Chromium, iron, and molybdenum are more susceptible to segregation, and in practice the segregation problem increases with increasing amounts of these additions. Alloys that are solution heat treated below but close to their beta transus temperatures are susceptible to a phenomenon known as "beta fleck," which degrades ductility and toughness. It is caused by local variations in beta stabilizer content that produces variation in the beta transus temperature. The optimized process for Ti-10V-2Fe-3Al applied to the melting phase was designed to control iron distribution. Corona 5 and one of the Transage alloys have been made in heat sizes of at least 1800 lb (820 kg), thereby qualifying them in terms of commercial scale-up. However, they are newer than Ti-10V-2Fe-3Al, and there is less experience with them. Like Ti-6Al-4V, the Transage alloys have only one beta stabilizer—vanadium. Furthermore, as forgings they are preferably solution heat treated 75-150°F (40-80°C) above the beta transus, thus eliminating the possibility of beta fleck occurrence even when no more precautions in melting are taken than is done for Ti-6Al-4V.

Both cost and weight reductions are possible by substituting a new alloy for Ti-6Al-4V, in heavy section forgings. The strength vs fracture toughness relationships for Corona 5, Ti-10V-2Fe-3Al, and Transage 134 alloys are shown in Fig. 6.[19,20] A consensus appears to be developing that 180 ksi (1240 MPa) minimum ultimate tensile strength with 40 ksi $\sqrt{\text{in.}}$ (44 MPa $\sqrt{\text{m}}$) minimum fracture toughness, is a reasonable compromise of the needs for strength on the one hand, and fracture toughness on the other. These values are indicated on Fig. 6 as "minimum goals." All three alloys, Corona 5, Ti-10V-2Fe-3Al optimized processing, and Transage 134 (Ti-2Al-12V-2Sn-6Zr), demonstrate capabilities for exceeding the minimum goals, just how reliably and reproducibly remains to be seen.

The Transage alloys possess a characteristic not shared by the others that gives them additional capability to resist fracture. It is stress-induced transformation.[21,22] In the age hardened state, these alloys consist of a very fine structure of alpha, with basketweave distribution, in a beta matrix. When subjected to a high triaxial stress state, such as exists at the tip of a highly loaded crack, the beta transforms to martensite. The transformation relieves the high triaxial stress state and absorbs energy. This additional capability to resist fracture is not reflected by ASTM E 399 standard fracture toughness determinations. Load vs crack-opening-displacement (COD) curves for 1-in. (25-mm) thick compact tension specimens of Transage 129 (Ti-2Al-11V-2Sn-11Zr) and Ti-6Al-4V are shown in Fig. 7. Note that the Ti-6Al-4V specimen has a

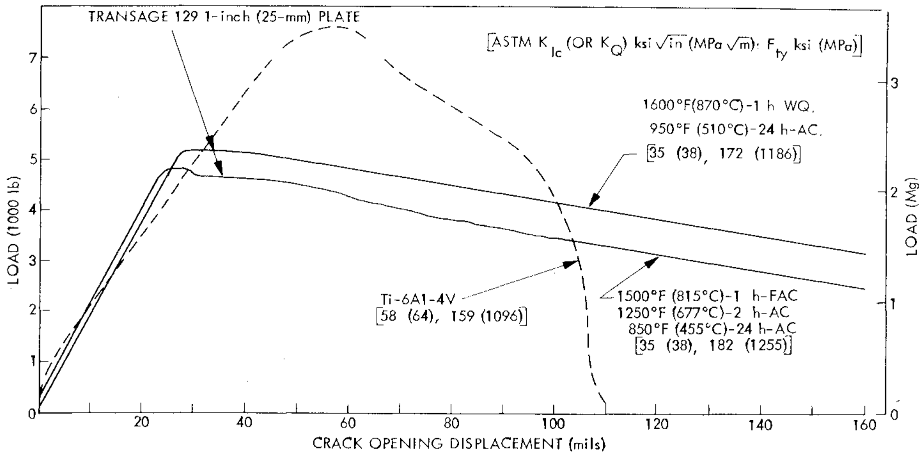
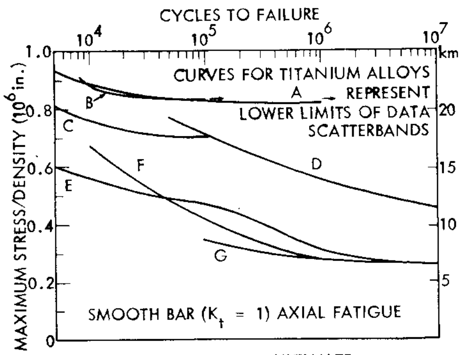


Fig. 7 Load vs crack-opening-displacement curves for 1-in. (25-mm) compact tension specimens of Transage 129 and Ti-6Al-4V alloys.



MATERIAL	ULTIMATE TENSILE STRENGTH ksi (MPa)	STRESS RATIO R
A - Ti-10V-2Fe-3Al FORGING	180 (1240) MIN.	0.05
B - TRANSAGE 134 1-in. (25-mm) PLATE	165 (1140)	0
C - Ti-6Al-4V STA FORGINGS		0
D - CORONA 5 FORGING	135 (930)	0.01
E - Ti-6Al-4V SUPERPLASTICALLY FORMED SHEET	136 (940)	0
F - ALUMINUM 7050-T73651 1-in.	71 (490)	0
G - 18 Ni MARAGING STEEL 3/4-in. (19 mm) PLATE	250 (1720)	0-0.25

Fig. 8 Smooth specimen axial fatigue strength-to-density comparison of Transage 134 alloy with high-strength structural materials (Refs. 19, 24-27).

fracture toughness value of 58 ksi $\sqrt{in.}$ (64 MPa $\sqrt{m}$) and a yield strength of 159 ksi (1096 MPa). The Transage 129 specimens have substantially lower fracture toughness values (as calculated according to the ASTM standard) and significantly higher yield strengths. According to the fracture mechanics theory, the Ti-6Al-4V specimen has a more than three time longer critical crack length than the Transage specimens. Yet, at COD of 110 mil, the Ti-6Al-4V specimen had separated into two pieces, while the two Transage specimens were carrying more than 50% of their maximum loads. This exceptional fracture resistance is the result of stress-induced transformation occurring ahead of the crack tip, and thereby controlling the rate of crack growth. The stress-induced transformation results in transformation-induced plasticity, or TRIP, as defined by Zackay et al.[23]

A strength-to-density plot comparing axial fatigue resistance of Corona 5, Ti-10V-2Fe-3Al optimized processing, and Transage 134 with other structural materials is shown in Fig. 8. Ti-10V-2Fe-3Al and Transage 134 offer

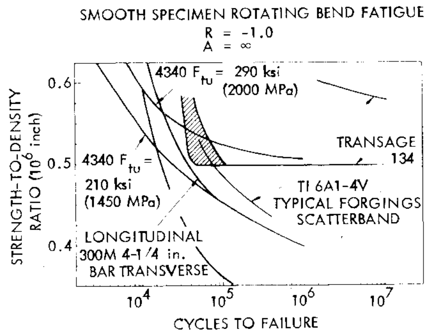


Fig. 9 Smooth specimen rotating bend fatigue strength-to-density comparison of Transage 134 with high-strength structural alloys (Refs. 25, 26).

improved performance over solution heat treated and aged (STA) Ti-6Al-4V engine forgings. Figure 9, similarly comparing Transage 134 1-in. (25-mm) plate with Ti-6Al-4V engine forgings, and 4340 and 300M steels heat treated to high-strength levels in rotating bend fatigue, indicates the potential of Transage 134 for a number of applications, including replacing 300 M for structural components in aircraft main landing gear in order to save weight. Once the aircraft is airborne, landing gear represents weight burdens, and the poor corrosion and stress-corrosion resistance of 300M, makes them high cost maintenance items, as well. Fracture mechanics type tests, i.e., K_{Iscc}, of Transage alloys, have shown no threshold crack growth in sea water at stress intensities as high as 90% (the limit of testing) of K_{Ic}. The critical crack length for threshold crack growth in salt water of the Transage alloys appears to be at least 25 times greater than that for 300M steel. Also, anodic breakdown residual potential tests (ABRPT) indicated Transage 129 alloy heat treated to 188 ksi (1295 MPa) ultimate tensile strength to have pitting corrosion resistance superior to commercially pure titanium and equal to very high purity titanium.[21] The ABRPT value of Transage 129 was determined to be 8.2 V compared to 8.1 V for very high purity titanium, values from 7.3-7.9 V for commercial purity titanium, and 6.5 V for Ti-4Al-4V alloy.[28] Because of the regular decrease in ABRPT value with increasing aluminum content, Ti-6Al-4V has an interpolated value of 5.3 V.

B. Processes

A new process, superplastic forming (with or without diffusion bonding), and several old processes adapted to titanium, offer unprecedented opportunities to reduce the costs of titanium components. This would be accomplished through the production of net or near net shapes, thereby reducing material and machining costs, and/or reducing

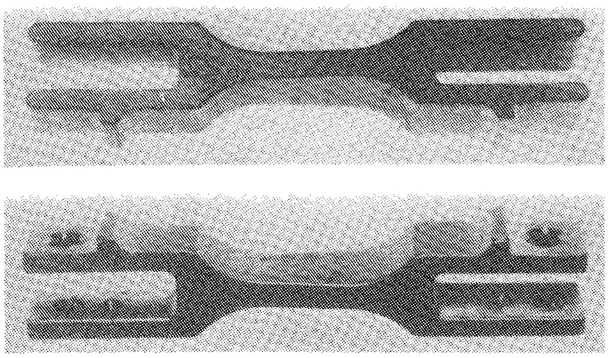


Fig. 10 Ti-6Al-4V compressor stator connecting link made from elemental powders. Left—as pressed and sintered; right—finished part.

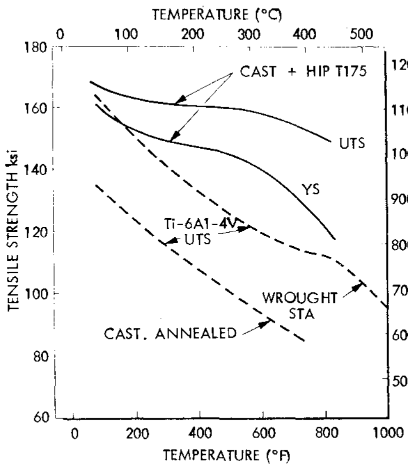


Fig. 11 Tensile strength vs temperature. Cast plus hot isostatically processed Transage 175 compared with Ti-6Al-4V in wrought solution heat treated and aged, and cast annealed conditions.

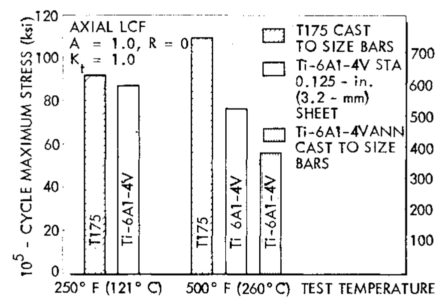


Fig. 12 Comparison of smooth bar, axial fatigue runout stresses at 10^5 cycles for cast plus isostatically processed Transage 175 at 250 and 500°F (120 and 260°C) compared with Ti-6Al-4V in wrought solution heat treated and aged, and cast annealed conditions.

assembly operations. Combining these processes with one or another of the new alloys listed in Table 1 could improve performance over Ti-6Al-4V as well.

The first of these processes is powder metallurgy. Unfortunately, contaminants have degraded the fatigue performance of powder parts to such an extent that they are considered only for static applications. An example of such a part is shown in Fig. 10. It is a compressor stator connecting link. It is of Ti-6Al-4V alloy produced from elemental powders by pressing and sintering. Pratt & Whitney expects to schedule it into production for the F-100 engine. It is a small part, but its significance is that there are more than a hundred similar parts in the F-100 engine to which this manufacturing technique could be applied for cost reductions.

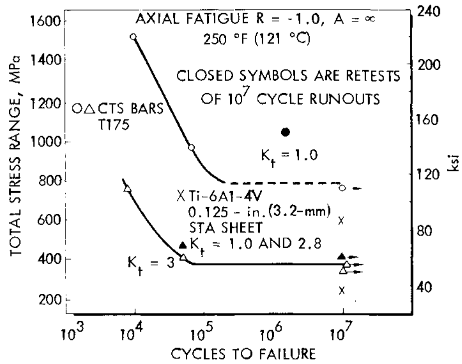


Fig. 13 Smooth and notched bar high cycle fatigue data for cast plus hot isostatically processed Transage 175 compared with wrought solution heat treated and aged Ti-6Al-4V.

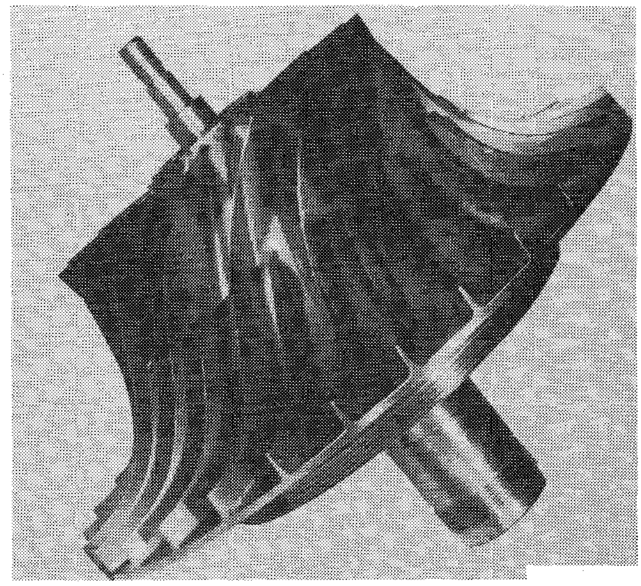


Fig. 14 Impeller being evaluated in cast plus hot isostatically processed Transage 175 alloy (Ti-2.5Al-13V-7Sn-2Zr).

The second of these processes is investment casting to net shape, especially of intricate shapes such as engine rotors and impellers, which are very costly to produce by machining forgings. The barrier to such application is that engine designers will not accept a cast rotating part in place of solution heat treated and aged or overaged wrought Ti-6Al-4V if it means reduced performance. In this regard, cast-to-size plus hot isostatically processed (HIP) test bars of Transage 175 alloy (Ti-2.5Al-13V-7Sn-2Zr) have shown superior static strength and fatigue strength at elevated temperatures, compared to STA Ti-6Al-4V 0.125-in. (3.2-mm) sheet.[29,30] These results are shown in Figs. 11-13. The results indicate a rather remarkable prospect: In time, the substitution of cast Transage 175 for forged and machined Ti-6Al-4V rotating components in engines may improve performance as well as reduce cost. Results of elevated temperature fatigue evaluations of as-cast plus HIP alpha-beta titanium alloys of greater strength and hardenability than Ti-6Al-4V are not in the open literature. However, those who are privy to such data are invited to compare the results with those for Transage 175.

A cast Transage 175 impeller of the configuration shown in Fig. 14 is currently under engineering evaluation. Three rotor designs are also scheduled to be evaluated. A key factor supporting the interest in Transage 175 castings is that they are weld repairable.

The third process, net shape or near net shape, isothermal or near isothermal forging, shows far greater promise when combined with Ti-10V-2Fe-3Al or the Transage alloys than with Ti-6Al-4V. If an alloy can be isothermally forged at temperatures not exceeding 1400°F (760°C), then relatively cheap, iron-base hot work tool steels may be used for dies, rather than costly nickel-base alloys, or molybdenum in an inert atmosphere. At these low temperatures, creep in the dies is low enough for economical die life. If practical superplasticity is defined as the strain rate sensitivity factor m, being equal to or greater than 0.25, then the Transage alloys appear to behave superplastically over a wider range of temperatures and strain rates than any other aircraft structural alloy.[31] (According to the Lee and Backofen correlation, a value $m = 0.25$ corresponds to 185% tensile elongation,[32] a value sufficient for most forming requirements.) The Transage alloys appear to behave superplastically at temperatures as low as 1100°F (595°C) and at all strain rates exceeding 10^{-5} s^{-1}. An example of this behavior in practice is shown in Fig. 15, which shows a precision forged part in Transage 129. The part was near isothermally forged from 1400°F (760°C). Metal flow time to make the part was less than 2 min. The flash resulting from the alloy flowing into the die joints is visible along the top of the forging. Also, it may be noted that the optimum shape of the workpiece is round bar, not the square bar that was actually used to make the part—see workpiece at the top of Fig. 15.

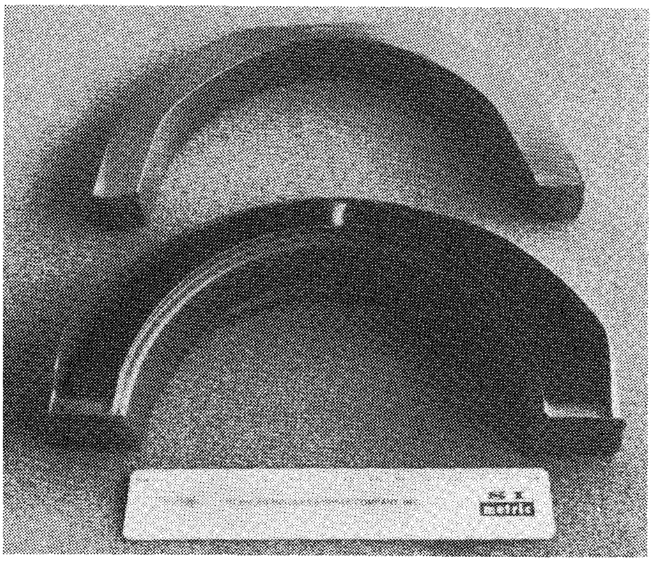


Fig. 15 Experimental net shape part near isothermally forged in Transage 129 alloy (Ti-2Al-11V-2Sn-11Zr) at 1400°F (760°C), shown with workpiece at top.

The final process of this presentation is superplastic forming, with or without diffusion bonding. Note that spot or seam welding may be used preliminary to diffusion bonding, or replace it entirely, and thereby shorten the press cycle. The potential of the process is illustrated by Fig. 16, which shows a part made by Rockwell International. The superplastically formed frame compared to the conventional sheet metal assembly, reduced the number of pieces from eight to one, and eliminated all 96 fasteners, for a cost reduction of 55% and weight reduction of 33%. Weight reductions are possible with superplastically formed parts such as this because of more efficient section stiffening by integral beads. Thus far all superplastic forming development work involving sheet constructions has been done with Ti-6Al-4V. Since the formed parts cannot be water quenched, they must be used in the annealed condition. Figure 8 shows that there is a large penalty in fatigue resistance as a consequence. By substituting a high hardenability, age hardenable alloy, it would be possible to age harden the formed part for higher strength. Superplastically formed and age hardened Ti-15V-3Al-3Cr-3Sn, Transage 134, as well as an older semicommercial metastable alloy, Ti-3Al-8V-6Cr-4Mo-4Zr, should be evaluated in fatigue for possible significant improvement over superplastically formed Ti-6Al-4V.

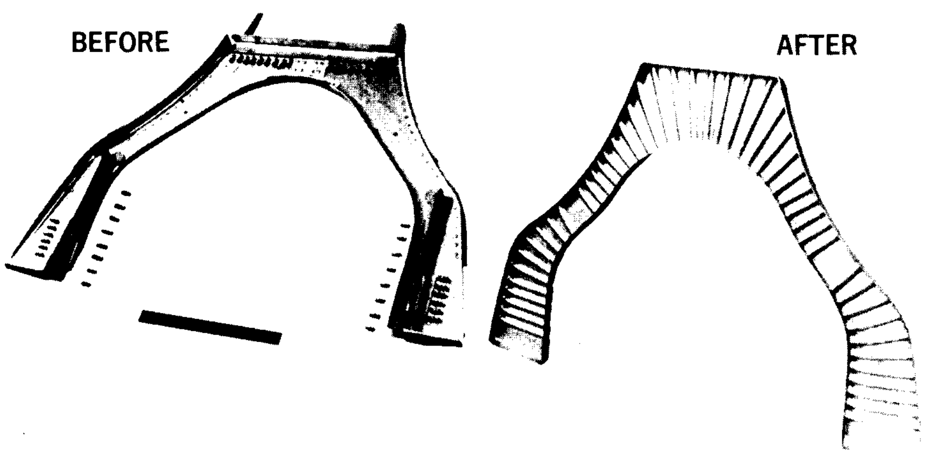
IV. Summary and Conclusions

Major milestones in the application of titanium to aircraft were 1) the invention and development of the Ti-6Al-4V alloy; 2) selection of Ti-6Al-4V for the compressor of the Pratt & Whitney J-57 jet engine; 3) the Lockheed/Air Force FY-12A/SR-71 "Blackbird" Mach 3 reconnaissance aircraft—airframe 93% titanium; 4) the four 1700-lb (770-kg) Ti-6Al-4V landing gear beam forgings in the Boeing 747; 5) the Ti-10V-2Fe-3Al landing gear beams scheduled into production for the Boeing 757; and 6) the use of more than 130 Ti-6Al-4V castings in the Pratt & Whitney F-100 engine.

Major past problems involving the use of titanium in aircraft were 1) hydrogen embrittlement; 2) hot salt stress corrosion; 3) salt-water (or sea-water) stress corrosion; and 4) accelerated low-cycle fatigue failure. Titanium alloys vary in their susceptibility to hydrogen pickup and tolerance for hydrogen. Control of hydrogen embrittlement is primarily by taking precautions in heat treating and in pickling in order to avoid or limit hydrogen pickup. Hot salt stress corrosion is very easy to produce in the laboratory, but there are no reported service failures due to this cause. Salt-water stress corrosion and accelerated low-cycle fatigue failure are highly alloy dependent. Given environmental conditions that are conducive to these failure modes, control is by alloy selection.

The major problems today are long lead times and the high cost of titanium components. Long lead time for forging billet and high costs of titanium forgings are interrelated through high buy-to-fly weight ratios. Unprecedented opportunities

Fig. 16 Superplastically formed Ti-6Al-4V frame. a) Current frame configuration—22 major fabrication operations, 8 pieces, 96 fasteners. b) Superplastic formed frame—5 major fabrication operations, 1 part, 0 fasteners: a cost reduction of 55% and a weight reduction of 33%.



now exist to reduce the cost of titanium components, and in some cases to improve performance over Ti-6A1-4V as well, by utilizing net shape or near net shape processes and new alloys, which make net shape processes considerably more attractive than when these processes are applied to Ti-6A1-4V. Currently, Ti-6A1-4V is the most used titanium alloy in aircraft. Net or near shape processes that are ready for expanded production use or first production use for titanium components are powder metallurgy; investment casting, particularly of complex geometries; isothermal or hot die forging; and superplastic forming, with or without diffusion bonding. Net shape isothermal forging is not economically feasible applied to Ti-6A1-4V. However, it is for the new alloys: Ti-10V-2Fe-3A1 and Transage 134 (Ti-2A1-12V-2Sn-6Zr) and Transage 175 (Ti-2.5A1-13V-7Sn-2Zr). Transage 175 also looks promising for cast rotating engine components. Substantially stronger superplastically formed sheet metal structures can be had by the substitution of high hardenability, age hardenable alloys, such as Ti-15V-3A1-3Cr-3Sn or Transage 134 for Ti-6A1-4V.

The new technologies can have great impact on the use of titanium in the future. For that to happen requires commitment to progress on the part of those who have the ultimate say on the choice of materials for air frames and engines and the manufacturing processes. The times require a more open minded and aggressive outlook regarding promising new processes and alloys than has been the case for the past ten years. It is time to give up the Ti-6A1-4V security blanket where opportunities exist for reducing costs and/or improving performance by choice of one or another of the new titanium alloys coupled with net shape or near net shape processes.

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