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MATERIALS NOTE 129

ACCESSION OF TITANIUM AS AN AIRCRAFT MATERIAL—A CURRENT VIEW

by

H. R. CHIN QUAN

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SUMMARY

A brief account is given of the metallurgy, alloy development, fabrication and property characteristics of titanium alloys for aircraft structural applications. A detailed list of alloy compositions is appended and a general bibliography of titanium references included.

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16. *ABSTRACT*

A brief account is given of the metallurgy, alloy development, fabrication and property characteristics of titanium alloys for aircraft structural applications. A detailed list of alloy compositions is appended and a general bibliography of titanium references included.

CONTENTS

1. INTRODUCTION

For airplane and engine applications, the higher specific strength and superior properties of titanium and its alloys at above-ambient temperatures offer many advantages over the more traditional aluminium alloys and steels. Tables 1 and 2 compare some of the more important physical and mechanical properties of titanium and the 6Al 4V alloy with those of 7075 aluminium alloy and D6 AC steel. The advantages of titanium alloys have long been recognized but, only recently, have they been used more extensively to provide the increased structural and mechanical performance required of modern aircraft. While titanium alloys were used in aircraft during the late 1950's and steadily found increased application during the 1960's, the long-predicted boom in titanium usage has not yet eventuated. Two important factors have been the lack of accrued long-term service experience and the unique difficulties in fabricating titanium alloy components. The practical influences of these factors are being avoided by restricting service application (and research evaluation) to a very small number of alloys and by developing innovative and improved fabrication techniques. These approaches have enabled acceptable performance-to-cost benefits to be attained.

TABLE 1.

Melting point and density of Titanium, compared with Iron, Aluminium and Magnesium.

Metal	Melting Point °C	Density (g/cc)
Titanium	1680	4·54
Iron	1535	7·86
Aluminium	660	2·70
Magnesium	650	1·74

TABLE 2

Principal mechanical properties of Titanium, T1-6A1-4V compared with aluminium alloy 7075 and D6AC steel.

Alloy	YS (MPa)	UTS (MPa)	Elongation (%)
Titanium: commercially pure	340	440	25
6Al/4V	1100	1200	10
Aluminium: 99·5%	35	80	47
7075-T6	460	520	11
Steel: low carbon	200	360	30
D6AC	1400	1500	10

2. GENERAL CHARACTERISTICS

Titanium is the ninth most abundant element in the earth's crust and the fourth most common of the structural metals (after aluminium iron and magnesium). Because a considerable amount of energy is required to extract titanium from its oxide ore minerals (rutile and ilmenite) the development of the new industry lagged until the introduction of the Kroll process (1941) which allowed large-scale production of titanium. This process involves a two-stage pyrometallurgical chemical reaction at 850°C which reduces titanium tetrachloride in the presence of magnesium, and yields 99·5% pure titanium. Sodium is often now substituted for magnesium, to improve efficiency.

Titanium is a silvery-grey paramagnetic metal whose density (see Table 1) falls between aluminium and steel. In alloy form it possesses twice the strength of aluminium alloys, five times the strength of magnesium alloys and is stronger than some alloy steels. On a specific strength basic, savings in weight of 40% may be achieved by replacing steel with titanium alloy.

A wide variation in physical and mechanical characteristics may be obtained by alloying titanium with other elements, including oxygen, aluminium, vanadium, tin, zirconium, manganese, molybdenum and copper. The high melting point (1680°C) of titanium leads to the retention of good tensile and creep properties up to 500°C, well above that for aluminium and magnesium alloys.

Titanium is extremely reactive and instantly forms a thin coherent surface oxide film when exposed to air. This passive film is mechanically very strong and chemically stable and provides high resistance to most types of corrosion. Moreover, the film reforms immediately if broken by impact or abrasion although at high temperatures (>650°C), the metal dissolves its oxide and these passivating effects are lost. However, this dissolution of the oxide does facilitate the diffusion-bonding of titanium parts (sect 6.2) which is becoming of great significance in aircraft construction.

3. BASIC METALLURGY OF TITANIUM

Titanium exists in two crystal forms, alpha and beta (α,β). Alpha titanium has a close-packed hexagonal structure which transforms to the beta, body-centred cubic structure at 885°C (1625°F). The various alloying elements added to titanium can be classified according to their effect on the $\alpha+\beta$ transformation temperature. Commonly, the "commercially-pure" grades contain oxygen, which increases the transformation temperature and thus the alpha range, and hence is referred to as an interstitial alpha-stabilizer. The extensive solid solubility of oxygen permits strengthening by solid-solution effects, increasing the UTS from 170 MPa to 500 MPa. Lowering oxygen contents to extra low interstitial (ELI) levels (0·10–0·13%) considerably improves the fracture toughness but with some loss in yield strength. However, at very low oxygen (VLO) contents (less than 0·08%) the reduced yield strength levels are unacceptable for aircraft applications. Other interstitial alpha-stabilizers are hydrogen and nitrogen; these must be held to very low levels to avoid serious loss of ductility.

Aluminium is the major substitutional element capable of stabilizing the alpha form of titanium. Further solid-solution strengthening of alpha titanium is obtained when tin and zirconium are added jointly with aluminium.

Many of the transition metals e.g. vanadium, niobium, molybdenum and tantalum form isomorphous solid solutions and lower the α to β transition temperature when added to titanium and are thus beta-stabilizers. Other beta-stabilizers which form eutectoids with titanium, are chromium, manganese, iron, cobalt, nickel, copper and silicon. Tin and zirconium, which only marginally lower the $\alpha+\beta$ transition temperature, are regarded as being effectively neutral. Titanium alloys containing various combinations of these alloying elements are thus either single or two phase (α or β) or ($\alpha+\beta$). Certain definable properties are ascribed to each type.

Alpha alloys are weldable with good ductility and high creep strength at elevated temperatures, while beta alloys are heat-treatable, stronger and easier to fabricate. The two-phase alloys have intermediate properties.

TABLE 3

Comparative Properties of Single and Two-Phase Titanium Alloys

Phases Present	Strength	Ductility	Heat-treatable	Weldability
Alpha	Moderate	Good	No	Excellent
Alpha + Beta	Stronger	Moderate	Yes	Good
Beta	Strongest	Low	Yes	Poor

The single-phase alpha structure occurs in commercially pure titanium, and in alloys with over 5% aluminium and minor quantities of beta-stabilizing elements. However, there is an upper limit to the total amount of alpha-stabilizing elements above which a short-range ordering reaction may cause a significant loss of ductility. To avoid this situation, an empirical stability/ordering parameter is invoked whereby aluminium + $\frac{1}{3}$ (tin) + $\frac{1}{6}$ (zirconium) + $\frac{1}{10}$ (oxygen) + 4 (silicon) must remain less than 8 weight percent.

The two-phase ($\alpha+\beta$) structure is usual when no more than 5 weight percent of beta stabilizers and up to 8 weight percent of aluminium is present. Further additions of beta stabilizers produce a single-phase beta structure at room temperature. The mechanical properties of titanium alloys usually depend on the relative amounts of each phase present, as well as on variables which affect the distribution of the phases (e.g. composition, thermal history and heat-treatment).

3.1 Commonly Used Alloys

Commercially pure titanium has the highest ductility, combined with high corrosion-resistance (better than most titanium alloys). Oxygen additions confer moderate tensile strength, with the most common grades possessing UTS of 280, 380 and 480 MPa (40, 55 and 70 ksi).

The alloy 5% Al-2·5% Sn is the best established of the alpha alloys and exhibits good weldability, medium strength and good elevated temperature creep properties, but it is not heat-treatable. It is used only in the annealed condition and has very high fracture toughness at room and elevated temperatures.

The alloy 8% Al-1% Mo-1% V is the best-known of a series of super alpha (or lean β) alloys, designed to retain the excellent weldability of alpha alloys but with improved elevated temperature tensile strength and creep resistance, superior to other commonly available alpha or alpha-beta alloys. This alloy is stable to 500°C (950°F) and has the highest tensile modulus and lowest density of any commercial titanium alloy.

The alloy 6% Al-4% V, an alpha-beta type, is well-known as a general purpose structural alloy for aircraft and space vehicle use and may be heat-treated to a wide range of strength levels. In its fully aged condition, it is suitable for highly stressed welded structures and exhibits good stability to 400°C (750°F). This alloy accounts for over half of titanium alloy production, but is one of the most difficult to fabricate among annealed titanium alloys, being essentially hot working due to its composition.

The alloy 6% Al-6% V-2% Sn is a beta-rich, alpha-beta type, and sacrifices weldability (compared with 6Al 4V titanium) for higher annealed strength (15 percent > 6Al 4V) and improved heat-treatment response (generally, two-phase alloys retain weldability if the beta content is below 20 percent).

The alloy 3% Al-13% V-11% Cr is a metastable beta alloy combining high formability with high room-temperature strength (UTS up to 1320 MPa or 200 Ksi), but relatively low creep resistance at elevated temperatures.

Although there are over one hundred and sixty different alloys, 90 percent of usage involves the commercially pure grades and the five specific alloys mentioned above.

4. SPECIFICATION DESIGNATIONS OF TITANIUM ALLOYS

Titanium alloys are best designated by their chemical composition. A comprehensive list of commercial and developmental titanium alloy compositions is arranged in Appendix 1. Alloys having related compositions fall together and may be compared; in addition, the list has been subdivided into the generic alloy types (e.g. alpha, super alpha, alpha-beta and beta alloys) as their alloy phase characteristics given in Table 3 will broadly apply.

The designations employed by national standards organizations, trade societies and supply companies are largely arbitary but some become widely recognized through common usage. Hence, it may be useful to describe the format of some of these systems relating to aeronautical use.

4.1 United Kingdom Specifications

Within their "Aerospace Series" specifications, the British Standards Association denotes titanium alloys with the prefix TA. Currently titanium alloys range from TA 1 to TA 55 e.g. the alloy 6% Al–4% V is denoted by BS. TA 10, TA 11, TA 12, TA 13, depending on the product form (sheet, rod etc).

DTD specifications (Directorate of Technical Development) are issued by the Ministry of Defence. Here, titanium alloys are included in a grouping known as "Aerospace Materials and Processes" (DTD series 1–999 and 5000–5999). The alloy 6% Al-4% V is denoted by DTD 5303, 5313 and 5323, depending on the product form.

Imperial Metals Industries (UK) a major titanium supplier, uses a three-digit designation, preceded by their initials e.g. IMI 318 denotes the alloy 6% Al–4% V.

4.2 United States Specifications

The Society of Automotive Engineers (SAE), within their "Aerospace Material Specifications" series, use a four-digit designation. Current titanium alloys range from AMS 4901 to AMS 4998 and ten of these denote 6% Al–4% V, in various conditions.

The American Society for Testing and Materials (ASTM) place titanium alloy specifications, together with other non-ferrous metals, in one group prefixed by the letter B. The main titanium alloy specifications are B265, 348, 367 and 381 again depending on the product form.

Military Specifications (Mil. Spec) for titanium alloys are designated numerically, but are scattered throughout the main body of some ninety-thousand specifications e.g. Mil-F-83142 denotes the specification "Forging, Titanium Alloys for Aircraft and Aerospace Applications". The prefix letter (F) has no particular significance, it is simply derived from the first letter of the title. Other titanium alloy specifications, which all have the prefix "Mil-T-" are, 9046, 9047, 46035, 46038, 81556 and 81915. The prefix "Mil-STD-" denotes a separate series, called "Military Standards" with the alternative prefix "MS", replacing "MIL-STD" in more recent issues.

The Unified Numbering System (UNS), introduced jointly in 1975 by SAE and ASTM, provides a means of correlating various nationally used numbering systems for all types of metals and alloys. The format consists of a letter, followed by five digits. Titanium alloys appear as part of a group called "Reactive and Refractory Metals and Alloys" and are prefixed R5 xxxx e.g. the alloy 6% Al–4% V is UNS R5640 X, the final figure in this case, indicating purity levels.

Major US producers use company identification symbols, e.g. MMA 6510 of Martin Marietta Aluminium (Titanium Division) for 6% Al–4% V and RMI 6Al/4V from RMI Co. (formerly Reactive Metals), or simply nominal compositions e.g. Ti–6Al/4V from Timet (Titanium Metals Corporation of America). Crucible Inc. uses a three-part code; firstly, a letter, A, B or C denoting an alpha, beta or two-phase alloy respectively; then a number indicating the minimum tensile yield strength; followed by suffix letters to indicate alloying elements. Thus C120 AV denotes 6% A–4% V alloy.

4.3 French Specifications

AECMA (Association of European Manufactures, Paris, France) use the format Ti P·XX for titanium alloy designations e.g. Ti P·63 denotes the 6% Al–4% V alloy.

AIR NORMS (Regulations AIR, Paris, France) use a prefix T, followed by a letter code, indicating principal alloying elements and often integers indicating the amount of each element e.g. T-A6V denotes the alloy 6% Al-4% V. This element code, which also applies for aluminium alloys (prefixed by A) is given alphabetically as follows:

A = aluminium
C = chromium
D = molybdenum
E = tin
G = magnesium
K = cobalt
M = manganese
N = nickel
S = silicon
U = copper
V = vanadium
W = tungston
Z = zinc
Zr (or ZR) = zirconium

A major supplier, Pechiney-Ugine-Kuhlman (PUG Group, Paris, France) uses a similar notation to AIR Norms, but with the prefix UT, instead of T.

4.4 German Specifications

Luftfahrt Werkstoffe (Aircraft Material and Aircraft Industry), or LW numbers for titanium alloys use the format 3·7XXX e.g. LW 3·7164 denotes the 6% Al-4% V alloy. The prefix "LW" is often substituted by "BWB", in Britain.

DIN (German Standards) take the form 178XX, such as DIN 17851 for 6% Al-4% V alloy.

DIN Werkstoffe designations, which are subdivisions of general DIN specifications, appear as DIN 3·7XXX.

5. SERVICE PROPERTIES OF TITANIUM AND ITS ALLOYS

5.1 Corrosion and Oxidation

Titanium is a highly reactive metal and forms a thin protective film of oxide whenever it is exposed to air or other environments containing available oxygen. This film gives titanium its excellent corrosion resistance. The most protective films on titanium are usually developed when water, even in trace amounts, is present. However, when titanium and its alloys are exposed to strongly oxidizing environments in the absence of moisture, the film formed is *not protective* and rapid oxidation may take place e.g. titanium is quite resistant to wet chlorine (1% moisture) but is readily attacked by dry chlorine. Generally, titanium and its alloys show exceptionally high resistance to atmospheric corrosion in industrial and marine environments, and to sea water. They are also highly resistant to strong oxidizing acids, salt solutions and moist oxidizing gases. For long-time service, the upper temperature limit for titanium in hot air is about 700°C, while 1200°C is possible in short-time applications e.g. fire walls surrounding jet engines. A lower temperature limit is minus 250°C, when ELI grades are used for maximum toughness.

When passivated with its protective oxide film, titanium is the more noble metal in galvanic couples with all structural alloys except monels and stainless steels. In most environments, the potential of passivated titanium is similar to that of stainless steels. Thus, less noble metals, such as aluminium alloys, carbon steels and magnesium, may suffer accelerated attack when coupled with titanium, particularly where large cathodic areas of titanium material are coupled to the latter metals in aggressive environments.

Attack is prevented or minimized in most cases by protective paints and other treatments. However, titanium alloys are generally less corrosion-resistant than commercially pure titanium.

Two dangerous environments for titanium are (i) red-fuming nitric acid which, in the presence of water and nitrogen dioxide, may produce a pyrophoritic explosion, and (ii) liquid oxygen which can detonate on impact. In turbine engines, titanium fires have occurred where parts of compressor blades ignited due to overheating in direct rubbing contact, or as a consequence of mechanical failure or foreign object damage.

Titanium alloys may undergo cracking through processes involving liquid-metal embrittlement, hydrogen damage or fatigue damage. Mercury, gallium, and molten cadmium cause rapid cracking (liquid-metal embrittlement) of stressed titanium alloys. Silver, in the form of silver-plated steel bolts in contact with titanium alloys, has caused cracking at temperatures above 340°C. These possibilities are recognized in various specifications, e.g. MIL-STD-1568 prohibits cadmium-plating of titanium parts or their use in direct contact with other cadmium-plated parts or tools, while MIL-S-5002 prohibits silver-plating on, or in contact with, titanium.

Precracked titanium alloys are susceptible to stress-corrosion cracking in salt solution. This susceptibility appears to increase with increasing aluminium and tin content (alpha stabilizers) and decrease with increasing amounts of molybdenum, vanadium and niobium (beta stabilizers). Most titanium alloys are also susceptible to hot-salt stress-corrosion at temperatures above 320°C. The alpha alloys are apparently more susceptable than alpha-beta alloys e.g. alloy 8Al-1V-1Mo is very susceptible, while alloys 6Al 4V, 6Al 6V 2Sn and 3Al 13V 11Cr are moderately so; one of the most resistant is 4Al 3Mo 1V alloy, though variations in heat-treatment affect the reactivity of many alloys. However failures of this type in service applications have been rare.

5.2 Fatigue and Fracture

Fatigue strength and fracture toughness are two important mechanical properties. Both depend on many interrelated metallurgical factors i.e. no single factor shows dominant control over fatigue properties. Titanium exhibits greater sensitivity to more of these factors than other metals, such as steel and aluminium and, thus, the scatter in fatigue data is more severe. Interstitial elements are an important factor. Generally, higher oxygen contents improve strength and fatigue properties but decrease fracture toughness. However, other interstitials (nitrogen, carbon and hydrogen) are detrimental. These contaminants are readily absorbed, especially by beta alloys, during hot working and heat treating and this factor may account for part of the wide scatter in fatigue properties. Titanium alloys containing a large proportion of alpha phase show marked anisotropy in fatigue properties. These property variations occur because the hexagonal crystal structure of the alpha phase is susceptible to the development of strong crystal textures during rolling, forging and extrusion processes. Environment does not appear to have a major effect on crack initiation in titanium but can appreciably affect crack propagation at low rates of cyclic loading. In general, fatigue strength decreases with increasing temperature, usually in proportion to tensile strength. Normal atmospheric endurance limits lie within the range 0·5 to 0·65 times the ultimate tensile strength, although stress-raisers (notches, rough surfaces, fretting-see later) may reduce this factor appreciably. Most coatings lower the fatigue strength, the exceptions being certain oxide or anodized coatings. Generally, the best fatigue properties are obtained in fine grained alpha-beta alloys containing a relatively high proportion of alpha phase.

Rates of fatigue crack growth in and fracture toughness of, titanium alloys are sensitive to micro-structural differences induced by diffirent fabrication processes and heat-treatments. The fracture toughness of alpha-beta alloys is highest in solution-treated alloys which contain a low proportion of alpha phase (10–25%) distributed in an acicular rather than an equiaxed form throughout the beta matrix. However, these alloys possess lower toughnesses than the high values developed in the meta-stable beta alloys.

5.3 Fretting Damage

Titanium and its alloys are particularly sensitive to contact damage, a characteristic which may lead to "fretting fatigue" and a subsequent serious reduction in strength. Fretting itself is a form of wear which occurs when two metal surfaces, pressed together by an external static load, are subject to a transverse cyclic loading so that one contacting face is cyclically displaced relative (and parallel) to the other face. It is characterized by extremely small relative displacements of the contacting surfaces (less than 0.1 mm) and often the small fragments of metal which break off lead to surface pitting, accelerated by the oxidation products which usually provide harder and thus more abrasive particles. Fretting fatigue occurs when fretting takes place in metal under dynamic loads. Fretting damage in titanium alloys can reduce fatigue life by almost a factor of eight, compared with a reduction factor of about three for similar damage in aluminium alloys.

Considerable efforts are made to minimize fretting in titanium alloys. Anti-fretting agents, such as oils and greases, appear to act by reducing metal-metal contact, by absorbing the fretting movement, by spreading and reducing the local severity of the damage, and by excluding the atmosphere. Other solutions to the problem include plasma spray deposition of tungsten carbide, thermal diffusion of nickel and chromium electroplating, and induced compressive stresses by shot or glass-ball peening.

Titanium alloys may be anodized but, unlike aluminium, the films do not adhere strongly and may exhibit friability. Nevertheless, anodizing does assist in the adhesion of subsequently applied organic coatings containing molybdenum disulphide to reduce fretting. Tough adherent films are theoretically possible and could (in future) provide a basis for other anti-fret overlays. Usual treatments, in decreasing order of effectiveness, are:

(*a*) Anodize, for antigalling and wear resistance.

(*b*) Apply metallic coatings (cadmium or zinc prohibited, silver over nickel is acceptable) plus paint or resin coating.

(*c*) Paint or resin coating with faying edges sealed.

(*d*) Bare metal with faying edges sealed, in contact with metals other than manganese, zinc or cadmium.

Generally, where there is a choice of treatments, a higher level treatment is preferred for the more active metal, and an alternative treatment for the less active metal, as the more active metal is likely to undergo more corrosion initially.

5.4 Creep Properties

Creep in titanium alloys is not significant unless the temperature exceeds 400°C, or design stresses exceed 90% yield. Under these conditions, alpha (hexagonal close-packed) alloys are more creep-resistant than beta (body-centred cubic) alloys. Moreover, since the hexagonal structure is strongly anisotropic, control of crystal texture allows optimization of such properties in preferred directions.

6. MANUFACTURING PROCESSES FOR TITANIUM AND ITS ALLOYS

6.1 Conventional Processing

Most structural applications of titanium alloys have been in aircraft and space vehicles. Factors influencing material selection are cost, service temperatures, loads and part configurations. Relative to titanium alloys, aluminium alloys currently enjoy large advantages in both material and processing costs. Hence, the utilization of aluminium alloys has been optimized around its excellent formability and machinability, while avoiding its rather poor (especially for high strength alloys) weldability. Thus, aluminium structures commonly contain numerous detail parts which are mechanically fastened together in a variety of ways, with larger structures being extensively machined. These established design and manufacturing processes are not suitable for titanium alloys, nor can they be successfully adapted. The development of more efficient processing options for titanium requires continual appraisal of its physical characteristics and advanced methods are discussed in section 6.2.

Titanium is relatively difficult to form, roll and extrude and difficult to machine and drill. Moreover, the chemical reactivity of titanium allows it to react rapidly at high temperatures with oxygen, nitrogen and constituents in cutting tools, thus contributing to seizing, galling and abrasion during machining. Titanium also has relatively low thermal conductivity which causes very high temperatures at tool tips. The machinability of commercially pure titanium can be considered to be similar to that of the austenitic stainless steels but differences in composition and hardness, of other titanium alloys, give rise to large variations in machinability.

The formability of titanium alloys is also similar to stainless steels. Most titanium alloys are either hot-formed or cold-preformed and hot-sized. The high notch-sensitivity of titanium often leads to cracking or tearing, especially in cold-forming. Galling and springback variations and a tendency to shrink cause greater problems with titanium than with stainless steels. Purer grades of commercially pure titanium, containing less oxygen, are more formable. Heating titanium alloys improves formability and reduces springback but contamination is a severe problem at higher temperatures.

Hydrogen absorption, which may embrittle some titanium alloys is usually removed by vacuum-annealing. The other main practical contamination problem is exposure to air at temperatures greater than 650°C. The brittle surface layer, formed by oxygen diffusion, is removed by pickling, grinding or machining. Forging conditions are similar to steels but more energy is required per part and the working (forging temperatures) range is narrower.

Despite the above disadvantages, titanium alloys have inherent strength, toughness and high-temperature advantages over other metals, e.g. the upper temperature limit for the utilization of aluminium alloys (about 180°C) precludes their application in areas subject to engine-heating and to aerodynamic heating at supersonic speeds.

6.2 Advanced Processing Techniques

To compete on a cost basis, new, efficient processing options have been utilized for producing titanium parts. The common objective in methods such as superplastic-forming, diffusion-bonding, hot isostatic-pressing and isothermal forging, is to provide near net-shape component forms, thereby minimizing the number of individual details, reducing assembly costs and minimizing metal removal costs.

Titanium alloys become superplastic under given conditions of microstructure, temperature and pressure, exhibiting tensile elongations of up to 1000 %. Under these conditions it will flow into die cavities and undertake the precise configuration of the die. Titanium will also diffusion-bond to itself* under conditions very similar conditions to those for superplastic forming-thus, conditions can be optimized to enable both processes to proceed together in a combined forming and bonding operation, which can markedly reduce recurring fabrication costs.

Materials utilization is also improved by compacting titanium powders in inert atmospheres by hot isostatic pressing and isothermal forging techniques to produce near net shape titanium forgings. Conditions for hot isostatic pressing include compacting spherical pre-alloyed titanium powder in an autoclave, usually at 100 MPa pressure for two to three hours, at a temperature just below the beta transus. In isothermal forging, titanium preforms are forged in heated dies; minimal heat loss allows time to fill die details, resulting in near net shapes.

7. CURRENT AND FUTURE TRENDS FOR TITANIUM USAGE

Titanium usage in present day aircraft, both military and civil, appears to have stabilized. Amongst other factors, increasing usage into the 80's has been forestalled by the cancellation of the B1 strategic bomber and the US-SST supersonic transport (mainly titanium) projects. Nevertheless, strong demand continues in military aircraft, where titanium forms important areas of the airframe, such as main spars, landing gear struts and areas subject to engine-heating, as well as various engine components (Table 4). On the civil side, aluminium remains the predominant airframe material, as improved aluminium alloys and new thermal treatments are being developed and used in preference to more costly titanium alloys. Consequently the percentage of titanium in civil airframes remains low e.g. Boeing 747 (4%), 767 (2%), Douglas DC10 (3%), Airbus A300B (6%—wing weight). A notable exception is the Lockheed L1011 where 14% of the structural weight is titanium. Titanium levels in civil transport aircraft engines however, have grown (up to 20-25%) in common with military aircraft engines. In general, the projected usage of about 30% in future aircraft appears well-founded and achievable, with military aircraft leading the way.

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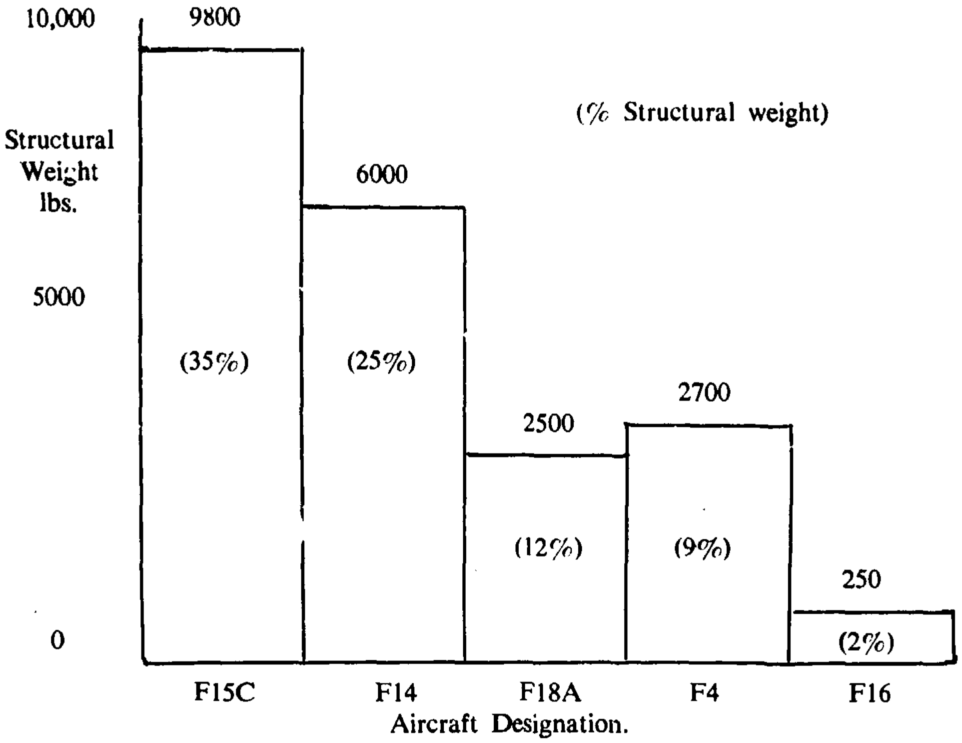
* "Self-fluxing" characteristic arises as the oxide film is dissolved in titanium at elevated temperature in inert atmospheres.

Table 4. Titanium usage in Military Airframes.



Despite considerable improvements in the strength/fracture toughness properties, and service experience, with 6Al–4V alloy, it is predicted that a greater range of titanium alloys will be employed in the future. Many of the newer alloys (Fig. 1) are eminently suitable for the processing options to be introduced into future aircraft and already some current production programmes have been modified to allow these processing options to be phased in. Creep and oxidation resistance is being steadily improved, with significant gains in the newer alloys (Fig. 2).

Challenges to titanium usage are maintained with aluminium alloy and steel developments. A new series of aluminium alloys have appeared with stricter controls on minor (impurity) element levels (Fe + Si) e.g. 2224, 2324, 7010, 7050, 7150, 7475 with new aging tempers T73 and T76 or RRA (a retrogression and reaging of T6 temper without sacrifice in strength which may be applied to 7075). These alloys and heat-treatments are far more resistant to stress-corrosion cracking than the widely used 7075–T6 aluminium alloy.

The development of aluminium-lithium alloys, with 12–15% reduction in conventional aluminium alloy density and increased elastic modulus, offers the possibility of very much higher strength-to-weight ratio for aircraft structural application. However, with aircraft speeds above mach 2.2, aerodynamic heating imposes temperature limitations on the utilization of aluminium alloys. Replacement by titanium allows potential speeds of mach 3.0 or more (the US–SST, a largely titanium aircraft, had a projected speed of mach 2.7 to 3.0)

The challenge of steel comes with the development of alloys such as AF 1410, combining high strength and high fracture toughness with good corrosion resistance. This steel (14% Co, 10% Ni, 2% Cr, 1% Mo, 0·16% C, 0·15% Mn) exhibits far greater specific strength and toughness than 6Al–4V titanium and until recently*, a much lower cost. While newer improved titanium alloys are available, the cost disadvantages would remain. However, for titanium, there is considerable potential for making further gains in powder-processing, in novel fabrication technology, and in more efficient materials utilization, to continue the strong growth in titanium usage.

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* The strategic importance, supply and high cost of cobalt has curtailed further development of this steel.

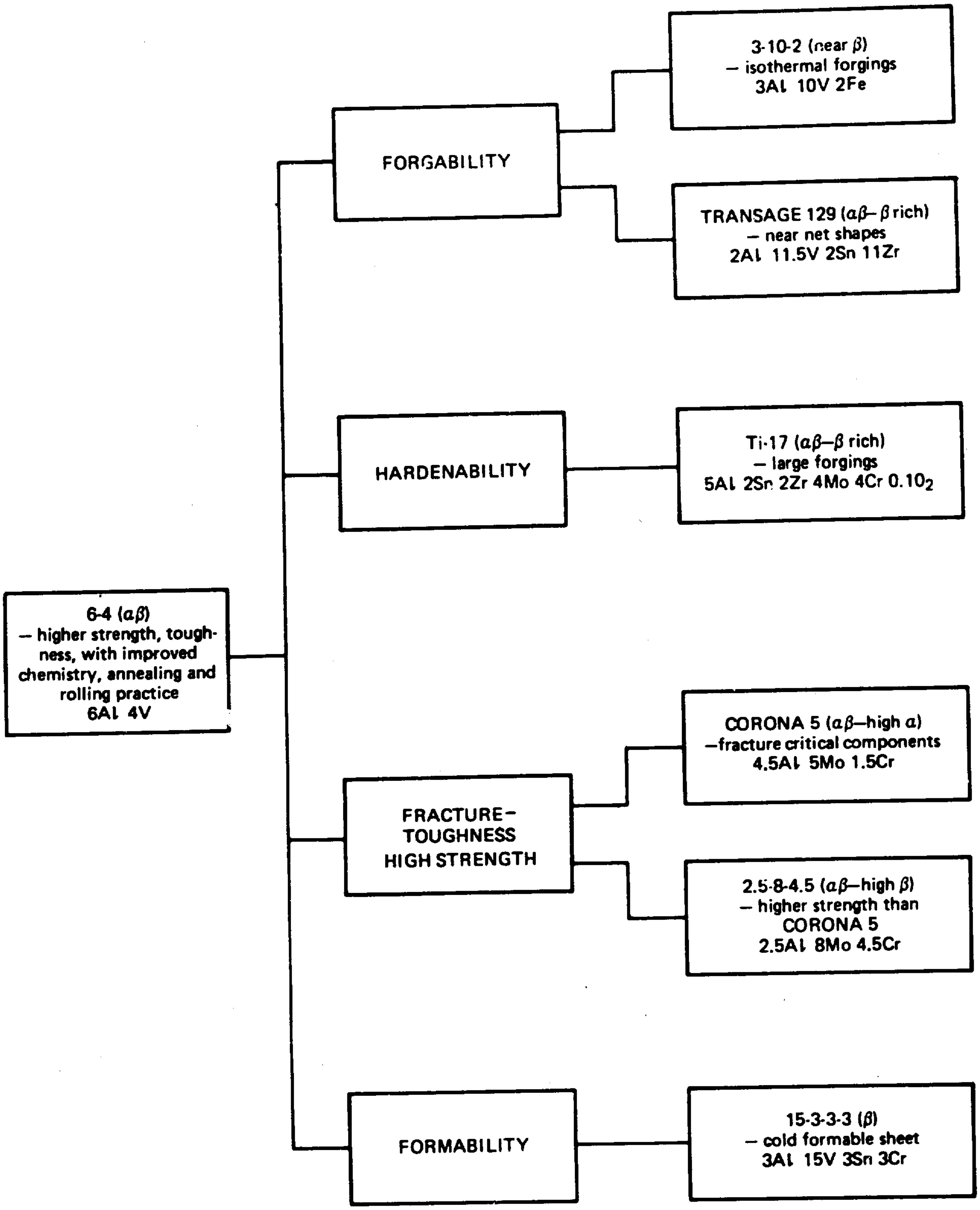

FIG. 1: ALLOY DEVELOPMENTS I – STRUCTURAL MATERIALS

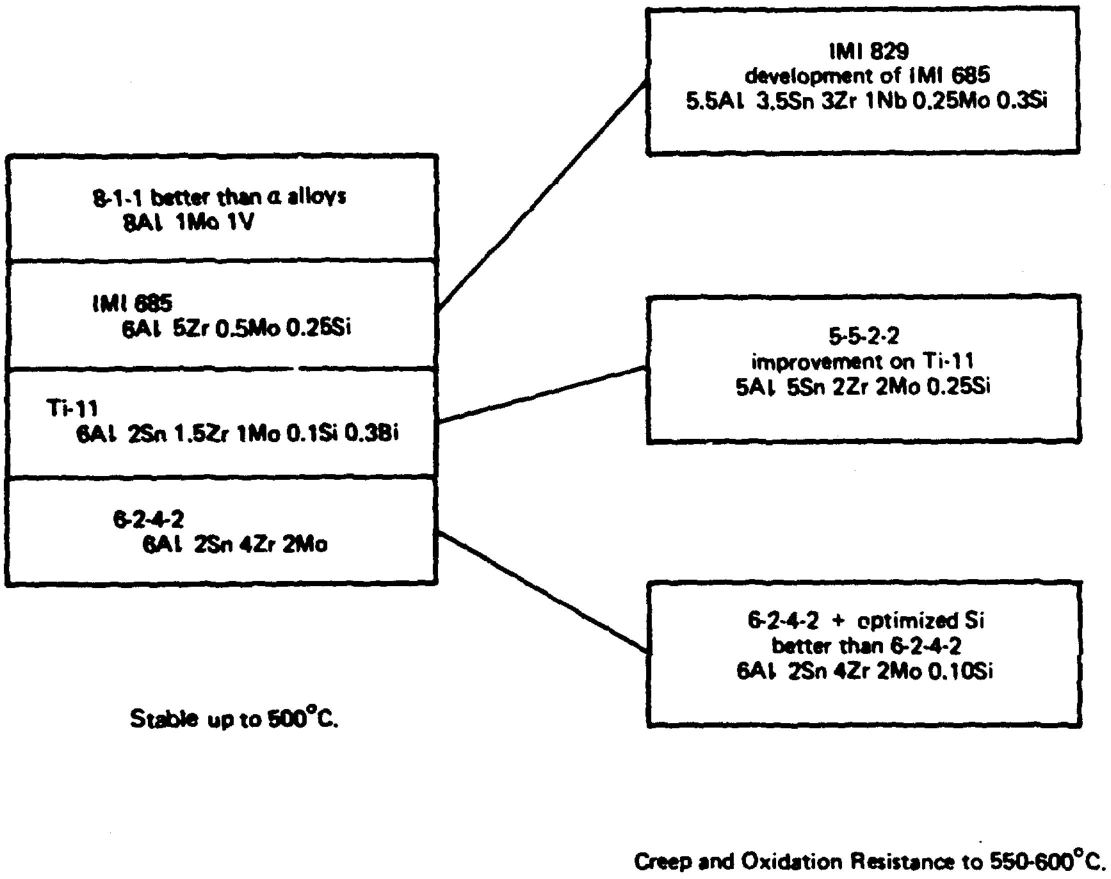

FIG. 2: ALLOY DEVELOPMENTS: II ENGINE MATERIALS (all $\alpha\beta$ – high α)

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APPENDIX I

Titanium Alloy Compositions

The following one hundred and sixty-five chemical compositions are classified in an alphanumeric sequence with more important alloying elements, such as Al, V, Mo, etc., leading the classification.

The division into alloy types indicates the predominant crystal structure and hence certain physical properties (see Table 3). This division is somewhat arbitrary as final heat treatments may, in some cases, determine the phases present.

Alpha Titanium Alloys

Common Name	Weight Percent														Other Elements
	Al	V	Mo	Sn	Zr	Mn	Cr	Fe	Cu	Pd	Nb	Ta	Si	W	
Commercially Pure Grades (IMI 125, 130, 155, 160) 4															99·0 Ti
3															99·2 Ti
2															99·5 Ti
1															99·6 Ti
	3														
	3			6	5								0·5		
	4·5			2·5											
	5														
	5			2	5										
IMI 317	5			2·5											
	5			5	5										
	5				2										
	5												0·5		
	6			1											
	6			2·5											
	7				12										
	7											1			
	7										2	1			
	8										2	1			
							2								
IMI 230							2·5								
IMI 115										0·15					
										—0·20					
										0·15					
										—0·25					
										0·15					
										—0·30					
											4·5				
												5			
															1·0–2·0 Ni

Super Alpha (lean beta) Alloys

Common Name	Weight Percent														Other Elements
	Al	V	Mo	Sn	Zr	Mn	Cr	Fe	Cu	Pd	Nb	Ta	Si	W	
	0·8					0·8									
	1					1									
IMI 679	2·25		1	11	5								0·2		
	3		0·5	6	5								0·4		
	5		0·8	5	2								0·5		
	5		1	6	2								0·2		
	5		2	5	2								0·25		
IMI 829	5·5		2·5	3·5	3						1		0·35		
	6	0·5	0·5	2	4										
	6	1		4											
	6	1			4										
	6	1	0·7		5		0·3						0·2		
	6	1	1	2											
	6		0·5										0·5		
IMI 685	6		0·5		5								0·25		
	6		0·8								2	1			
	6		0·8								1	2			
	6		1		6										
	6		1		11								0·15		
Ti 11	6		1	2	1·5								0·1		0·35 Bi
	6		2	2	4								0·1		
	6·5	1			5						3				
	6·5	1	1		2										
	7	1	1												0·5 Co
	7			2							3				
8·1·1	8	1	1												
	8	1	1												0·5 Co

Alpha-Beta Alloys

Common Name	Weight Percent														Other Elements
	Al	V	Mo	Sn	Zr	Mn	Cr	Fe	Cu	Pd	Nb	Ta	Si	W	
	1					1·5									
	1·5					1·5									
	2		4		4										
	2		7·5												
	2					1·5									
IMI 315	2					2									
	2·3		4·6	11·2											
	2·5		4			2							0·5		
IMI 680	2·5		4			11							0·25		
	3	2													
3-2·5	3	2·5													
	3		2	6	5								0·4		
	3		3		3										
	3					1·5									
	3					3		3							
	3						*	*					*		* total 1·5%
	3						5								
	3						5	3							
3·10·2	3	10						2							near-beta
4·1·3	4	1	3												
	4	1	3										0·2		
	4	2													
IMI 550	4			2		4							0·5		
IMI 551	4			4		4							0·5		
	4					1·5									
IMI 314	4					4									
	4							4·5							
	4										4				
	4										4				0·1 Re
	4·25					1·5									
	4·5	3·5													
Corona 5	4·5		5				1·5								
	4·5						*	*					*		* total 1·5%
	5	2	2	2											
	5	5	5				1	1·3							near beta
	5		1				1·5	1·5							
	5		1·2				1·4	1·4							
	5		2	5	2								0·25		
Ti 17	5		4	2	2		4								near-beta
	5		4	5	2								0·25		
	5				5								0·3	1	
	5						2·75	1·25							
	5						3	1							

Alpha-Beta Alloys (Continued)

Common Name	Weight Percent														Other Elements
	Al	V	Mo	Sn	Zr	Mn	Cr	Fe	Cu	Pd	Nb	Ta	Si	W	
	5·2	5·5						0·9	0·5						
	5·5	4													
	6		2												
	6	2	2	2											
	6	3	1												
6–4 (IMI 318)	6	4													
	6	4		2											
	6	4											0·2		
	6	4													3 Co
	6	5	1	2	3		1	1	1						
	6	5	5	2	4										
	6	6		2				0·5	0·5						
	6	6		2				1	1						
	6	6		2·5				0·5	1						
6·6·2	6	6		2											
	6	6		2	6										
	6	6		2	6			0·5	0·5						
	6		0·5										0·5		
	6		1	2	5								0·25		
	6		1				1·5	1·5							
6·2·2·2·2	6		2	2	2		2						0·25		
	6		2												
	6		2		4		2	1					0·2		
IMI 700	6		4		5				1				0·2		
6·2·4·6	6		6	2	4										
	6		6	4	4										
	6				1·5	1·5									
IMI 684	6				5								0·2	1	
	6·5		3·5										0·25		
	6·5		3·5	2									0·25		
	6·5	1			5										
	7	0·5	1·5												
	7	1	1												
	7		2·5												
	7		3												
	7		4												
	7			2							3				
			0·3												0·8 Ni
			1·5		2·5										
			2				2	2							
						3	3	3							
						7									
						8									

Beta Alloys

Common Name	Weight Percent														Other Elements
	Al	V	Mo	Sn	Zr	Mn	Cr	Fe	Cu	Pd	Nb	Ta	Si	W	
	1	8						5							
Transage 129	2	11		2	11										near-beta
	2	16		4			15								
	2·5	4·5	5												near-beta
	2·5	5	5				1·3	1							near-beta
	2·5	8	10												
	2·5		4				7								
	2·5		8				4·5								
	2·5		10				6								
	2·5	16													
	2·9	15													
	3	6	4		4		6								
	3	7	3·5				10								
	3	8	2				4	2							
Beta C	3	8	4		4		6								
	3	8	4		6		6								
3·8·8·2	3	8	8					2							
	3	8	8		4		6								
	3	8		4	1		7								
	3	12·5													
3·13·11	3	13					11								
15·3·3·3	3	15		3			3								
	3		7				5·5	3							
	3		7·5				11								
	6		12												
			10	5·4											
			11	3	8										
			11	5											
			11	5	5										
			11·5												
Beta III			11·5	4·5	6										
IMI 205			15												
			15		5										
			32												
			32								1·5				

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