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On the characteristics of titanium alloys for the aircraft applications

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Abstract

Complex aerodynamic design, high mechanical and thermal loads, extreme environmental and other service conditions produces high magnitude of dynamic stresses in various components of airframe. The magnitude and nature of these stresses further varies during different phases of flight. This governs the need to develop special materials having ability to withstand these variable stresses. Further high fuel costs, scarcity of raw material sources, need of efficiency improvements, growing demand of new aircrafts (both military and civil) and raised environmental standards (less CO_2 emission, less noise pollution, recyclability of materials, etc.) are the few factors which forced the engineers to make stronger but 'as-light-as-possible' engine, frame and other parts of aircrafts. These factors open the door for 'stronger-but-lighter' metals like titanium and its alloys for aerospace application segment. Titanium and its alloys offers a unique set of physical, mechanical, metallurgical and composite compatibility characteristics which helps the aerospace sector to meet economy, fuel efficiency and other global standards in a wide range of temperatures and other service conditions. Starting from its first application in 1950s to till date, this wonder-metal not only increases its share of presence but becomes the first choice of aircraft fabricators. This paper presents an overview of inherent mechanical and metallurgical characteristics of titanium and its alloys which makes it an ideal for the aircraft applications. A brief summary of induced stresses in aircraft critical components with advantages of titanium and its alloy to manufacture these components is also discussed.

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Keywords: Aircraft material attributes; titanium and its alloys; alloy composition; characteristics; aircraft applications

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1. Aircraft Material Requirements

Limited availability of resources (raw materials and fuels) and their continuous consumption forced the design engineers to design the aviation transportation systems giving optimum performance with minimum level of energy consumption [1]. Long term goals (such as Flightpath-2050 [2] etc.) of aviation research councils (like ACAR in Europe etc.) and raised environmental standards [3] around the globe demands improved aircraft designs. Motto to fly faster, farter, in larger aircrafts at less fueling costs is translated to complex aerodynamics with less overall weight of an aircraft. Improved design for economy of fuel and energy strives to make 'as light as possible' aircrafts. In addition to light-in-weight, the chemistry of the materials must fulfill a set of other properties like high heat capacity, toughness, oxidation resistance, thermal conductivity, strength, corrosion resistance and density etc. Possibilities to reduce the weight of aircraft component by 10% are list by [1]:

Nomenclature

α	alpha
β	beta
ω	omega
HCP	hexagonal-close-packing
BCC	body-cantered-cubic
TWCA	Teledyne Wah Chang Albany
ACAR	Advisory Council for Aviation Research
CFRPC	Carbon fibre reinforced polymer composites
STA	solution treatment and aging
YS	yield strength
UTS	ultimate tensile strength
H_2	hydrogen
MPa	Mega Pascal
RMI	RMI titanium Co.
TIMET	Titanium Metals Corporation
PW	Pratt and Whitney Co.
DAC	Douglas Aircraft Co.

(a). Reduce the component's metal density by 10%
(b). Increase the component's metal strength by 35%
(c). Increase the component's metal stiffness by 50%
(d). Increase the component's metal damage tolerance by 100%

Approach (a) is most effective approach.

1.1. General Characteristics of a material for aircraft applications

Following aspects are the behind the uncompromised selection criterion for component materials in aircrafts [4]:

- Initial cost of purchasing the new aircraft
- Costs to replace or upgrade the component materials to the latest ones
- Meeting design requirements/options of complexities of aeroengine and frames
- Pressure of high fuel consumption costs
- Level of performance in real conditions (at operational parameters)
- Power requirements from aeroengine
- Maintenance (type and costs) of aircraft parts
- Operational life of aircraft
- Reliability and safety demands
- Plan to dispose/recycle dead aircraft
- Meeting environmental issues/standards

Figure 1 details basic approaches in aircraft material selection.

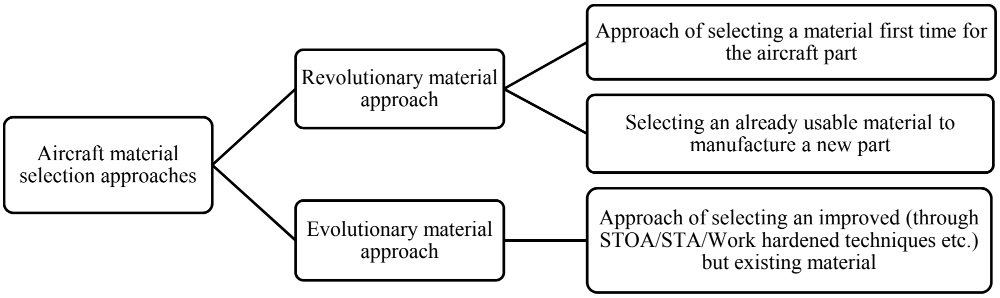

Fig. 1. Basic approaches of material selection for aircraft applications.

Characteristics required in an aerospace material are closely governed by the structure to be made, its design, type of loading and the service environmental conditions in which the structure to be worked. In Figure 2 authors summarizes basic factors and properties to select a material fir aircraft design.

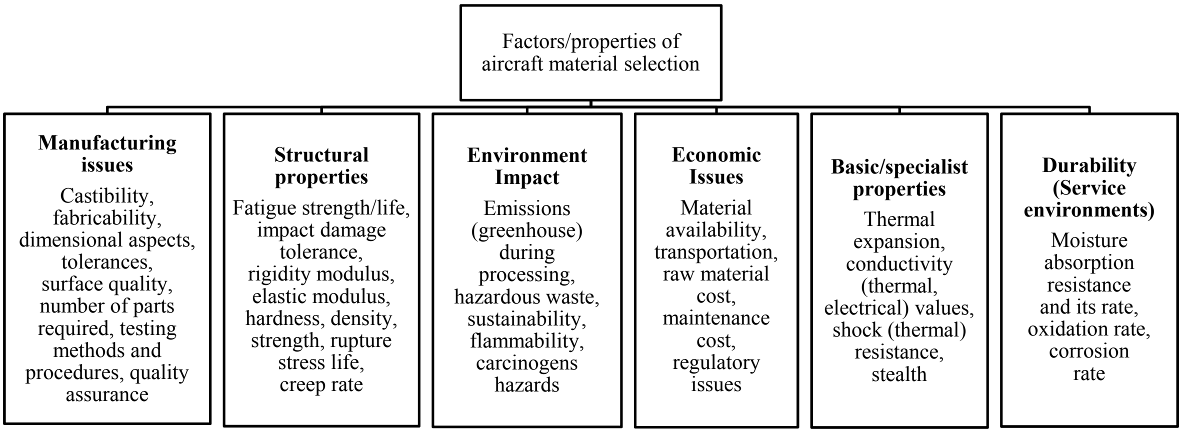

Fig. 2. Basic factors and properties of a material for aircraft applications.

In general total ‘take-off-weight’ of an aircraft is composed of about 5-7% weight of engine, 7-12% weight of fuselage and 8-14% weight of wings [4]. Due consideration is needed while selecting a weight-efficient material to manufacture the engine and other structural components of the aircraft. Authors summarize the general properties of a material for aircraft applications in table 1.

Selecting a material with above listed properties (or most of these) and maintain these during (for the whole life of component of aircraft) is always a difficult job. Aerospace engineers have to pick suitable material from about 120000 competitive materials (65000 metals, 10000 ceramics and 15000 plastics, wood, composites etc.) [4] to manufacture a part. However, only 0.05% (of total 120000 materials) are suitable (in respect of needed properties) for aerospace components [4].

2. Titanium and its alloys

With 4.51 g cm^{-3} density, titanium is ranked as ninth most abundant element in earth’s crest [7]. This light metal also have the honor to be the fourth most plentiful structural material available after aluminum, iron, and magnesium [8]. Ti-alloys, a class of chemically very similar but physically different materials, exhibits both hcp and bcc structures.

Table 1: Material properties with their necessities in aircraft components

Property	Necessities of Aircraft components
High strength and stiffness requirement with ability to carry aerodynamic and dead structural loads	• Intense static and dynamic landing loads on the components of landing gear during take-off and standing situations • Shell-type-structures of wings, empennage and fuselage generally subjected to compressive and buckling stresses • During landing, compound loading (body-loads and surface-loads) on aircraft's structure produces severe torsion, shear and bending stresses • During take-off, tailplane load coupled with wing-box load in fuselage results in severe bending stresses in fuselage • During flight, both the crown and bottom part of fuselage subjected to tensile and compressive stresses respectively. • Rolling and turning of aircraft produces high magnitude of shear and twisting stresses respectively along the fuselage. • Much stiff material is always obliged for aircraft's wings as they are facing reversal (of tensile and compressive) stresses during resting and in-flight moments • Pressurization, during flight, causes severe bending in fuselage components • Wing angle (dihedral) produces high compression on fuselage • High stiffness need for corrugated sheets (in wings) to face regular compression and tension • Caps of I-shaped-spars are under stern bending of wings • Stern compressive forces on nacelles (due to high engine wieight)
Good fracture toughness	• heavy landing and static loads
Good fatigue endurance/strength	• Superior fatigue resistance if titanium replaces aluminium in fighter aircraft's frame and bulkhead • To resist variability in loading at the moments of wind gusting and unavoidable turbulences etc. • Military aircrafts faces numerous manoeuvrings during wars and practice sessions • High fatigue occurs in fuselage skin material due to cyclic depressurization and pressurization • Five out of ten failures in gas-turbine engine's components are due fatigue failures [5] [6].
High thermal strength	• To withstand about 1500°C temperature in jet engines
Good corrosion resistance	• Flights in hot and freezing temperature conditions • Working with corrosive fluids (body paint strippers, jet fuels and lubricants)
Good impact strength (damage tolerance) properties	• The movement the bird strikes the aircraft, damage resistance is the key property • During take-off moments, fluttering debris may strike the leading edges of aircraft • Intense landing load on components of landing gear during take-off and resting moments
Good durability	• For the entire design life of aircraft (typically 8000-to-4000 and 30000-to-60000 journey hours for military aircraft and commercial airliners respectively)
Light-in-weight	• Usually airframe has major share of upto 40% of total weight of any aircraft. Light weight material will definitely reduce this burden
Good Fabricability	• Welding and riveting in airframe
Cost	• Initial Cost of purchasing new aircraft • Maintenance cost
Lead time	• Less lead time (easy machining) from raw material to finished component

Allotropy of both hcp and bcc structures widen the range of mechanical properties and hence scope of Ti-alloys in aircraft industry. At 1155 K, allotropic adaptation from α-hcp (low temperature) to β-bcc (high temperature) provides base to titanium alloys to offer wide range and variety of properties. Further (a) grouping (type and content) of alloying elements (b) their effect on physical behavior of possible phases (c) effect on mechanical behavior of possible phases (d) stability of phases are the four base reasons for manipulation in properties. In addition to (a)(b)(c)(d) reasons, processing routes, treatments methods and welcome by metallurgy (particularly of β-alloys) to develop compositions having superior properties are enough to satisfy the needs of aeroengines, airframe attachments and components [9].

2.1 Titanium as candidate in aircraft applications

Good specific strength (except few composites) and its variation in a wide range with alloys' possible chemical compositions broaden their utilization in wing boxes, undercarriage components, fuselage parts, airframe attachments etc.

Table 2: Titanium properties and their rational in aircraft component applications

Property	Rationale/Description
Strength to weight ratio with extraordinary flexibility	• 40% lesser density than that of steel • titanium weighs about 56% of weight of steel • 50% lesser modulus than that of steel replacing steel for spring manufacturing in aircrafts
Application/working temperature	• Nearly 600°C temperature of nozzle, plug and engine components [10]. • Embrittlement of materials due to O_2 contamination at engine temperature • Cryogenic temperature of rocket engines and impellers • At 270°F, aluminum looses its strength but titanium does not
Space constraint	• In 737, 757 fitting of landing gear beams possible with titanium only
Good ballistic resistance	• 15-35% less weight armor of titanium is equally strong (due to good ballistic resistance) with its counterpart made of steel
High galvanic compatibility	• Carbon and titanium are electrochemically compatible with each other which prevents galvanic corrosion
Galvanic Ti—Composites compatibility	• Among all competitor aerospace metals, titanium offers highest compatibility with CFRPCs [11] • Thermal expansion coefficient and stiffness of titanium matched with CFRPCs
High thermal conductivity	• Enormous heat production in aeroengine demands quick release; titanium is suitable for the post
Low expansion coefficient	• this property make possibility for titanium to combine with glass, ceramics and composites in aerospace applications
Corrosion resistance	• Titanium's ability to make oxide film (natural) prevents from environmental (oxidizing mineral acids, chemicals, water, inorganic salt solutions etc.) attacks • Oxide film also prevents cavitations and abrasion (due to dense air flow) during flight • Landing gear (made up of titanium) needs less maintenance due to excellent corrosion resistance; therefore cost reduction • Negligible pitting (in almost all service conditions) in parts made from titanium is advantageous compared to competitor metals
Cost	• Titanium's per kg cost is more than its competitor metals (due to its extraction and melting complexities) • Titanium ingots are costly (almost six times more pricey) to produce as compare to aluminum ingots [12]. • When cost-of-reliability, density corrected and life cycle costs are taken economics of titanium proved it as most economic option in aerospace sector [13].
Good weldability and joining by diffusion bonding:	• Some Ti-alloys can be easily joined through diffusion bonding or welding [4]; thereby reduces the number of mechanical fasteners (screws, bolts, rivets) in comparison with assemblies made up from aluminium alloys. • Weldments of Ti maintains its strength giving almost 100% weld joint efficiency for a negligible lose of durability and fracture toughness [14].

Titanium resists exfoliation, stress corrosion and other corrosion forms far better than aluminium alloys, steels etc. Titanium resists the attack of these corrosion agents by forming and maintaining oxide surface layer in application environments. Whereas on one hand the ability of titanium to retain its strength in enormous hot conditions replaces polymer-fiber composites, on the other hand, its property of being light in weight replaces counterpart materials (nickel alloys, steels) for high temperature/load applications. Candidature of Ti and its alloys for aerospace applications are based on following aspects (table 2):

Early, in 1950s, with the use to manufacture few parts in PW's J57 aeroengine for B52 bomber, titanium is the quickest noticed material in aerospace industry. To the next in 1952, firewalls and nacelles of DC-7 aircraft (product of DAC) was the second application of titanium in aerospace industry. Since then the unique attributes of this 'Cold-war-metal' appreciably increases its' demand in aircraft industry. Thermal stability of Ti-alloys extends their use in airframes subjected to frequent aero-kinetic heating.

2.2. α Titanium Alloys

Quantity (wt%) of α-stabilizer alloying elements in α-Ti alloys divides it into two classes i.e. super-α-alloys and near-α-alloys. Inherent properties of α-Ti alloys like ductility and resistance to creep in hotter environments are always welcomed for aeroengine parts. Super-α-alloys (containing > 5 wt% of alloying element) composed only α-Ti grains. Ti-5Al-2.5Sn alloy belongs to this class. Near-α-alloys contain β-stabilizers (< 2 wt %) dispersed among large volume of α-Ti grains. Solid solution hardening, work hardening (rolling, extrusion and other such plastic forming processes), grain size refinement etc. strongly affects the strength of α-Ti alloys. Plastic forming processes can even double the tensile strength of these alloys. Presence of aluminium (upto 9%) in the valence shell of Ti stabilizes the α-phase thereby rapidly increases its tensile strength. Adding more aluminium (> 9%) has adverse effect on ductility and fracture toughness. Important reason for the use of α-Ti alloys in aeroengine parts is their ability to retain strength during most heat treatment processes. Both thermal stability and thermal-aging resistance of α-Ti alloys does not allow appreciable change in mechanical properties during working in hotter conditions for long duration. In the following sections inherent characteristics and aircraft applications of these α-Ti alloys will be discussed.

2.2.1. CP-Ti

In addition to low specific strength the moderate yield strength (normally in between 170-480 MPa) of CP-Ti restricts its use for the aero-structural and engine parts [4]. Presence of small traces of atomic O_2 and Fe as impurities in CP-Ti have both advantageous and disadvantageous effects as on the one hand these impurities improves ultimate tensile strength (CP-Ti with 0.01% O_2 content have 250 MPa and 0.2-0.4% O_2 content have about 300-450 MPa), on the other hand these impurities reduces creep resistance, thermal stability and ductility of the material. Properties like good toughness and strength at cryogenic temperatures (below -220°C) favors the use of CP-Ti for making fuel tanks to store H_2 (in liquid form) in space vehicles.

2.2.2. Ti-3Al-2.5V

Developed in 1950's, this ductile alloy of good toughness, exhibits YS and UTS equals to 483 MPa and 620 MPa respectively. Both YS and UTS of this cold workable alloy can be enhanced upto 830 MPa and 910 MPa respectively by STA treatment. However STA reduces its elongation from 15% at normal temperature to 11% after STA. High pressure ducting tubes of aircraft made up of Ti-3Al-2.5V saves 40% weight when compared to tubes made up of 21-6-9 steel. Cold workable characteristics of Ti-3Al-2.5V alloy made it feasible to replace CP-Ti in fabrication of aircrafts' honeycomb core. Acceptable corrosion resistance, good weldability and ability to fabricate into seamless tubes favors its' use in aircraft hydraulic tubing.

2.2.3. Ti-5Al-2.5Sn

Good stability of Ti-5Al-2.5Sn welded joints offer oxidation resistance upto 1000°F temperature which makes Ti-5Al-2.5Sn suitable for fabrication of blades for jet and steam turbines [15]. Ti-5Al-2.5Sn is difficult to forge. Forged Ti-5Al-2.5Sn exhibits YS and UTS typically equal to 758 MPa and 792 MPa respectively. Without any notable effect on elongation value the annealing of Ti-5Al-2.5Sn plate increases its YS and UTS upto 779MPa and 827MPa respectively. Inherent capability of Ti-5Al-2.5Sn alloy to retain its ductility and fracture toughness upto cryogenic temperatures makes it possible to use this alloy to store H_2 (in liquid form) in turbo pump of space vehicles.

2.2.4. Ti-8Al-1Mo-1V

In 1960s, metallurgists succeed to develop Ti-8-1-1 alloy which, because of more aluminium content, offers more Young's modulus than all α+β alloys. American-supersonic airplane was the first to use Ti-8Al-1Mo-1V in its structure. Its' heat resistance capability upto 400°C made it a unique material to manufacture compressor blades. A normal temperature, Ti-8-1-1 elongates upto 10% and yields at 930 MPa [16]. However, its' less corrosion resistance restricts its extensive use.

2.2.5. Ti-6-2-4-2 and Ti-5.5A1-3.5Sn-3Zr-1Nb-0.25Mo-0.3Si

540°C temperature of gas turbine engine requires much stronger, creep resistant and tougher material to manufacture its part/components. Ti-6-2-4-2 forged bar (with UTS equals to 999 MPa and YS equals to 930 MPa) posses and retains all these characteristics upto 540°C. Jet-engine parts i.e. rotors, discs and blades are manufactured from Ti-6-2-4-2 alloy.

960 MPa yield strength of Ti-5.5A1-3.5Sn-3Zr-1Nb-0.25Mo-0.3Si is almost double than that for counterpart Al-alloys. RB211-535-E4 engine of Boeing 757 aircraft utilizes Ti-5.5A1-3.5Sn-3Zr-1Nb-0.25Mo-0.3Si alloy to manufacture its spacers, blades and compressor discs. This alloy with enhanced strength through β-STA treatment [17] withstands 540°C temperature of aircraft engine.

2.3. α+β Titanium Alloys

Adding α-stabilizers (in between 2-6%) and β-stabilizers (in between 6-10%) during formation of grains of α-Ti and β-Ti at normal temperature forms the most favorable class of titanium alloys (α+β-Ti) for aircraft component manufacturers. Fracture toughness, excellent creep strength, ductility of α+β titanium alloys are superior to α-Ti alloys. Tensile strength and fatigue resistance of these alloys are superior to β-Ti alloys. Grain boundary strengthening, solid solution hardening, work hardening and to the most β-Ti grains precipitation hardening improves strength of α+β-Ti-alloys. Thermal aging transforms some Ti-β-phase to ω precipitates and Ti-α-phase thereby improves strength of this class of Ti alloys. Thermal aging (at 480-650°C) can double its proof strength compared to simple annealed alloy. In the following sections inherent characteristics and aircraft applications of these α+β Ti alloys will be discussed.

2.3.1. Ti-6Al-4V

About 80-90% volume of total titanium used in airframe parts (skin panels, stiffeners, wing boxes, spares etc.) is made up of Ti-6Al-4V alloy. This alloy have also major share by volume in jet engine parts (60% of total titanium consumed) and airframes (80-90% of total titanium consumed). Cooler parts and fan of compressor, blisk of *F-35 Lightening-II* fighter and other parts working below 300°C made up of Ti-6Al-4V. Impact strength needed (to withstand bird striking) in cockpit windows is often provided by forged Ti-6Al-4V. In helicopters (BK117 and BK105) forged Ti-6Al-4V is extensively used in rotor heads.

2.3.2. Ti-6Al-2Sn-2Zr-2Mo-2Cr + Si

RMI, in 1970s, developed Ti-6Al-2Sn-2Zr-2Mo-2Cr + Si alloy. This alloy is known for its superplastic formability, thermal stability and oxidation resistance. Presence of 0.15% Si further improves its creep resistance. Its' deep hardenability with UTS and YS equal to 1069 MPa and 1034 MPa respectively (annealed conditions) make it useful to make aft fudelage, engine mounts, wing structures and bay bulkhead of F/A-22 raptor fighter aircraft. Recently this alloy is restructured for Lockheed F-22 raptor.

2.3.3. Ti-6-2-4-6 and Ti-5AI-2Sn-2Zr-4Mo-4Cr

Exceptional creep resistance and capacity to resist heat upto 450°C temperature made Ti-6-2-4-6 a unique choice for aeroengine components. STA components of Ti-6-2-4-6 can be elongated upto 10% with yield strength of 1105 MPa.

In 1970s, USA metallurgists succeed to develop Ti-5AI-2Sn-2Zr-4Mo-4Cr alloy of tensile strength and yield strength of 1250 MPa and 1150 MPa respectively. Excellent fracture toughness, superior crack propagation resistance and capacity to resist heat upto 350°C recommends this alloy for damage tolerance design of shaft and fan as a single unit in aircraft.

2.4. β Titanium Alloys

R.I. Jaffee [18] was the first who categorized β-Ti alloys as a distinct class of Ti-alloys. Initial research efforts in this direction developed Ti-13V-11Cr-3Al alloy which offered high strength (1276 MPa) but inconsistent response to heat treatment. Adding isomorphous β-stabilizers (Hf, V, Ta, Cr, Nb, Mo etc.) to cooling Ti metal, with the purpose to resist martensitical decomposition of β-phase, shifts β→α+β transformation boundary towards room temperature. Inherent properties of β-Ti alloys like extraordinary fatigue resistance and high tensile strength are always welcomed for heavily loaded structural parts. Microstructural alterations in β-Ti alloys through heat treatment regimes offers verity in their mechanical properties [19] [20] to suit for airframe components. When subjected to STA, all the Ti-β-alloys (except Ti-3Al-8V-6Cr-4Mo-4Zr) lead to develop dispersed secondary α-precipitates which improves their tensile strength. In aircraft industry, Ti-15V-3Al-3Sn-3Cr, Ti-10V-2Fe-3Al, Ti-5Al-5V-5Mo-3Cr-0.5Fe, Ti-15Mo-3Al-3Nb-0.2Si, Ti-3Al-8V-6Cr-4Mo-4Zr are the six Ti-β-alloys in continuing use till date [21][22][23] since their inception as written in Table 3.

In the following sections inherent characteristics and aircraft applications of these β-Ti alloys will be discussed.

2.4.1. Ti-10V-2Fe-3Al Alloy

TIMET, in 1974, filed a patent for the chemical composition of its newly developed titanium alloy Ti-10V-2Fe-3Al with exceptionally high fracture toughness, ductility and tensile strength [28] [29]. Initial performance of this alloy was checked by making landing gear of Boeing 777 through forging applications [21]. Except outer and inner cylinders, all the components of landing gear were made from Ti-10V-2Fe-3Al alloy [30]. Without compromising the desired strength of these components, a total reduction of 270 kg weight was achieved in aircraft [31]. Later on in 1980, its exceptional properties (UTS = 1240 MPa, Kic = 44 Mpa√m, etc.) forced the design engineers to recommend its applications in Boeing 757 airframe as well as future aircraft designs [32]. Table 3 shows that dominating share of V (9.0-11.0 wt.%) and Fe (1.6-2.2 wt.%) makes these constituents as prominent β-stabilizers. Presence of Fe makes it possible to manage microsegregation and promotes hardenability of this alloy. Al (2.6-3.4 wt.%) catalyses hardening reaction by providing necessary α-phase whereas oxygen (0.13 wt.%) maintains the fracture toughness at optimum strength levels needed in aerospace applications [28] [33].

2.4.2. Ti-15V-3Cr-3Al-3Sn Alloy

In 1970, Air Force supported a project to develop a titanium alloy for coldworking applications to manage repair works [34]. Lockheed and TIMET, during experimentation, lowers the chromium level to the minimum to develop cold rolled coils and sheets of Ti-15V-3Cr-3Al-3Sn alloy. During its first application, more than hundred parts (both non structural and structural) of Rockwell-B1B bomber were fabricated and tested successfully. Excellent formability of this alloy results in net savings in fabrication cost when compared with its competitor alloys [35]. In 1990s, Ti-15V-3Cr-3Al-3Sn alloy replaced CPTi material in ducting tubes of Boeing 777 and the results were net savings of 63.5 kg weight of Boeing airframe [21][36]. Ti-15V-3Cr-3Al-3Sn springs are of less weight (upto 70%), less volume (upto 50%) and more corrosion resistant than that of steel springs.

2.4.3. Ti-3Al-8V-6Cr-4Mo-4Zr Alloy

In 1960s, RMI titanium production company took an assignment to develop Ti-3Al-8V-6Cr-4Mo-4Zr alloy as a substitute to Ti-13V-11Cr-3Al alloy for airplane frames and components. Without compromising hot and cold workability, physical and mechanical properties etc., RMI reduced chromium content to minimize segregation tendency of Ti-3Al-8V-6Cr-4Mo-4Zr alloy [37]. Excellent deep hardenability (in more than 150 mm section size), good corrosion resistance, light weight and superior strength offered by this alloy cannot break the barrier of its limiting production (of about 1% of total Ti production) due to its high initial cost and special attention involved in melting and fabrication. Traditionally melted under plasma arc melting [38] and processed by hot working processes (extrusion, rolling, gorging etc.) at above 795°C, Ti-3Al-8V-6Cr-4Mo-4Zr alloy possesses good forgability and deep hardenability. Solution treatment of Ti-3Al-8V-6Cr-4Mo-4Zr alloy at 790-925°C for about one hour followed by suitable method of cooling (in normal air, in forced air or water quenching etc.) increases strength of this alloy [39]. Further suitable aging treatment (at 470-620°C for 4-12 hours) after solution treatment affects its mechanical properties. Ti-3Al-8V-6Cr-4Mo-4Zr exhibits many metastable phases such as α phase, β phase, β′ phase, ω phase, $(Ti,Zr)_5Si_3$ and $TiCr_2$ etc. [37]. When put to applications in fasteners, fittings and landing gear coiled actuation springs of aircraft, Ti-3Al-8V-6Cr-4Mo-4Zr offers improved corrosion resistance and about 70% weight reduction when compared with same components manufactured from conventional 17-4PH steel [31].

2.4.4. Ti-15Mo-3Al-3Nb-0.2Si Alloy

TIMET, in 1988, developed Ti-15Mo-3Al-3Nb-0.2Si alloy with unique properties like foil-producability, extraordinary strength with environmental degradation resistance etc. and ability to maintain these properties at high temperatures [40]. Produced through triple VAR, this alloy is generally available to aerospace industries in solution heat-treatment condition with only β-structure (single phase). After forging, cold rolling process can reduce its thickness less than 4mm for direct use in aircraft parts [41]. Excellent cold-formability and good response to aging treatments (without quick workhardening) makes it possible for compressive loads to reduce the Ti-15Mo-3Al-3Nb-0.2Si alloy part to 80%. During these compressions part does not lose its inherent properties and any sort of crack initiations etc. [23]. After its first application with MMCs in NAP program [40], number of components of both military and civil aeroengines' exhausting parts like plug and nozzle arrangement of Rolls-Royce Trent-400 engine on Airbus-A340 and Boeing 777 were manufactured [42]. Practically 164 kg weight of Boeing 777 aircraft was reduced when parts made up of Inconel-625 alloy ware replaced with Ti-15Mo-3Al-3Nb-0.2Si alloy [36]. In another application, thrust reverser inside wall of CFM leap 1B engine of Boeing 737-MAX aircraft performs better when made up of Ti-15Mo-3Al-3Nb-0.2Si alloy material.

2.4.5. Ti-5Al-5Mo-5V-3Cr Alloy

Late 1990s was the time aerospace industry felt need of a material with improved processability and in-work performance as compare to Ti-10V-2Fe-3Al alloy [43]. VSMPO made compositional alterations (decreased Fe wt. content and increased Cr wt. content) in the base material Ti-5Al-5V-5Mo-1Cr-1Fe and developed Ti-5Al-5Mo-5V-

3Cr alloy having more uniformity in microstructure as well as macrostructure. This new alloy has added advantages like more hardenability and ultimate strength compared to conventional Ti-10V-2Fe-3Al alloy and Ti-5Al-5V-5Mo-1Cr-1Fe alloy. Further the limited Fe content (wt.%) in Ti-5Al-5Mo-5V-3Cr minimizes segregation chances. Thermomechanical processing and heat treatment types affect α and/or β phases in microstructure and mechanical properties of this alloy [44]. Aging treatment at low temperatures affects uniformity of α-distributions and hence mechanical characteristics of this alloy [45]. In Russian aircrafts, number of components like landing gear parts, lift devices and fuselage parts the common applications of Ti-5Al-5Mo-5V-3Cr alloy. Forgings of Ti-5Al-5Mo-5V-3Cr fulfill the requirements of landing gear and airframe of Boeing-787 [46]. Parts made from Ti55531 (a version of Ti-5Al-5Mo-5V-3Cr with added 1wt.% Zr) are commonly used in Airbus 380 aircraft [47].

2.4.6. Ti-35V-15Cr Alloy

In 1980s, failures were noted in exhaust nozzle assembly (made up of conventional Ti alloys) due to high thermal stresses of combustion in Pratt and Whitney F-119 engine of F22-Raptor [48] [49]. TWCA developed a stable β alloy with compositional elements; V (35 wt.%) and Cr (15 wt.%) [50]. It took almost five years to mature this alloy [49]. There is no effect of aging treatment towards α-precipitation in Ti-35V-15Cr; alloy maintains its stability and retains β-phase without quenching. Presence of Cr in higher wt.% helps to absorb thermal energy upto 'heat of fusion' [50] [51]. Presence of V stabilizes β-phase and strengthens the solid solution of Ti-35V-15Cr whereas carbon makes carbonitrides [52]. Ti-35V-15Cr alloy offers extraordinary resistance to thermal burning in aircraft's exhausting system. This alloy maintains its strength at extreme temperature conditions though the recommended temperature is upto 540°C [48]. In the past decades, China and UK investigated a lot on burn resistant alloys by making metallurgical alterations through the addition of Al and C contents [30][53][54].

3. Summary and Future Work

This article addresses the basic attributes/characteristics of Ti-alloys and their aircraft (airframe and engine) component applications. CP-Ti and commonly used Ti-alloys of three classes (α) (α+β) (β) are discussed. Authors summarize the discussion in following bulleted points:

- Since inception in 1950s, considerable research in the metallurgical and thermomechanical processing of titanium alloys made it possible to increase their in-service temperature limit from 300°C to near 600°C.
- Moderate specific strength of Ti-alloys does not recommend their use to design airframe parts where stiffness is the prime requirement.
- High resistance to creep and oxidation offered by near alpha alloys are the key reason for their suitability at elevated temperature applications.
- Good formability characteristic increases the share of CP-Ti in airframes. Corrosive environment in aircraft lavatories and kitchen demands the use of CP-Ti. Heat resistance and strength attributes favors the use of Ti-alloys in engine.
- Presence of Mo, Ta, Nb or V etc. alloying elements hampers the ductility of metastable β alloys at high strength levels.
- Hardening rate and segregation in welded parts are the major drawbacks which limit the weld-ability of metastable β alloys and hence use of welded titanium parts in aircraft.
- Boeing of USA and Airbus of Europe (leader in aircraft manufacturing) forecasted increasing percentage share of Ti-alloys per plane and to the overall in aircraft industry in coming years.

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