APPLICATIONS OF TITANIUM ALLOYS IN AEROSPACE MANUFACTURING: A BRIEF REVIEW.

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ABSTRACT
Improvements in aircraft fuel efficiency are paralleled by an increase in the demand for titanium alloys in the aerospace industry, especially for airframes and engines. Aircraft are made of a variety of titanium materials, each one chosen for a specific purpose. Commercially pure titanium is utilized for aircraft structures where formability is necessary. Titanium alloys have been extensively used in the manufacturing of multi-part commercial and military Aircraft because of their outstanding corrosion resistance and high specific strength. Each titanium material is chosen for an aircraft based on its intended application. Commercially pure (CP) titanium is employed when building airframes because of its formability. Titanium alloys such as Ti_6Al_4V are used for engines where strength, as well as heat resistance, play a crucial role. This review article provides a concise overview of the titanium materials' current application scenario and expands on using such strategic alloys in the aerospace sector.

Keywords: Titanium alloys; Heat treatment; Aerospace industry; Mechanical properties.

1. INTRODUCTION
The production of airplanes has a strong upward tendency in the global market. According to a recent Airbus company prediction; there will be a growing need for new Aircraft through the year 2035, requiring an investment of more than $5 trillion. In this evolving scenario, numerous aviation programs have requested fuel consumption, CO_2, and NO_x emissions from aircraft operations are reduced [1]. Therefore, weight reduction is a major concern for aircraft manufacturers. In the 1960s, titanium was widely used in commercial aviation. It was essential to the development of Concorde.

In aviation, weight savings, spatial limitations, and operational temperature are all factors when selecting titanium alloys. The selection of titanium alloys in Aircraft is influenced by weight savings, available space, and operating temperature. Figure 1 shows the defense market trends and demand. The estimated worldwide defense budget for 2019 is close to $1.3 trillion, which is a marginal increase from the budget for 2018. More than half of the total estimated spending was attributed to the US, followed by non-US NATO members, China, and Russia [2]. Figure 2 shows the Global comparison of military spending in 2021 [3].

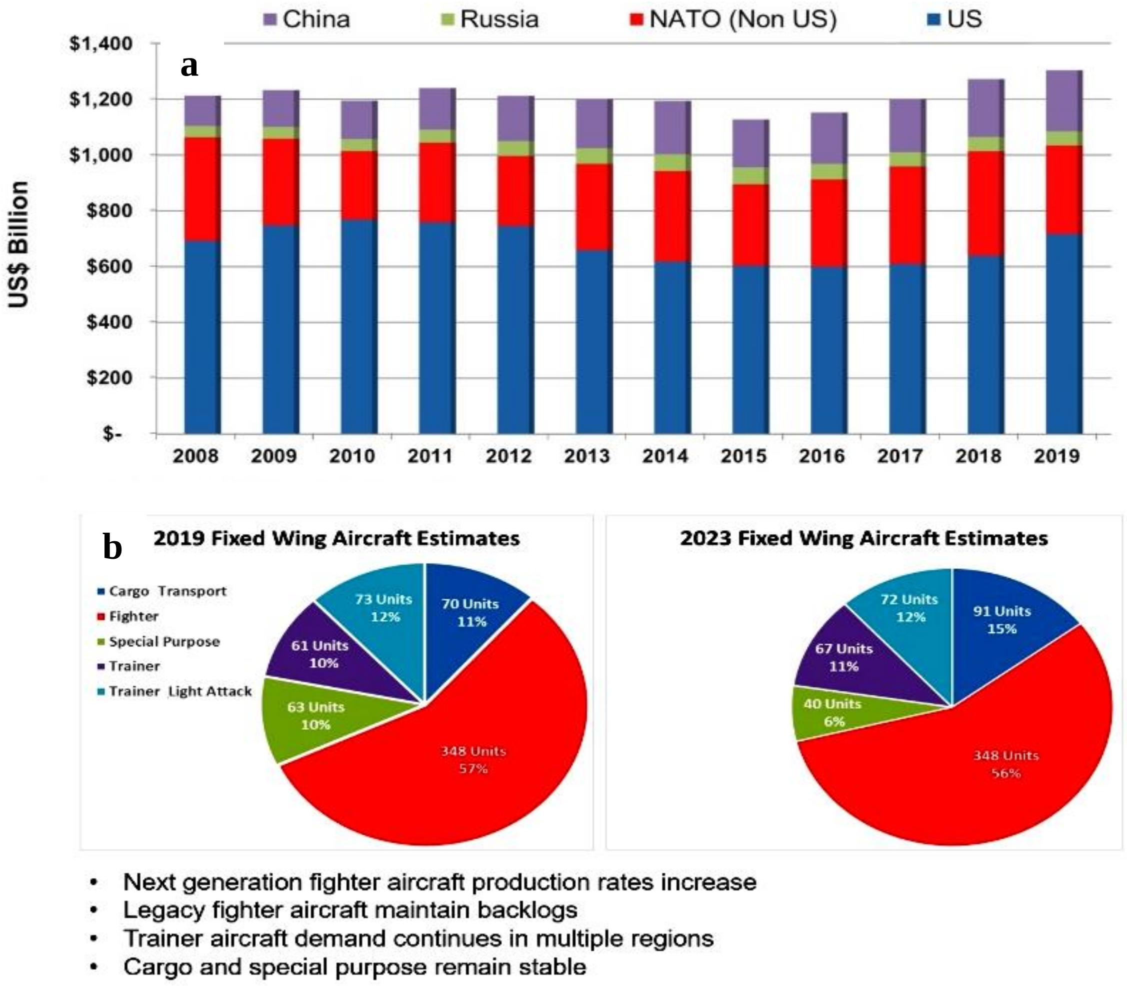

Fig. 1: (a) Defense spending and (b) Global defense aircraft trends. [2]

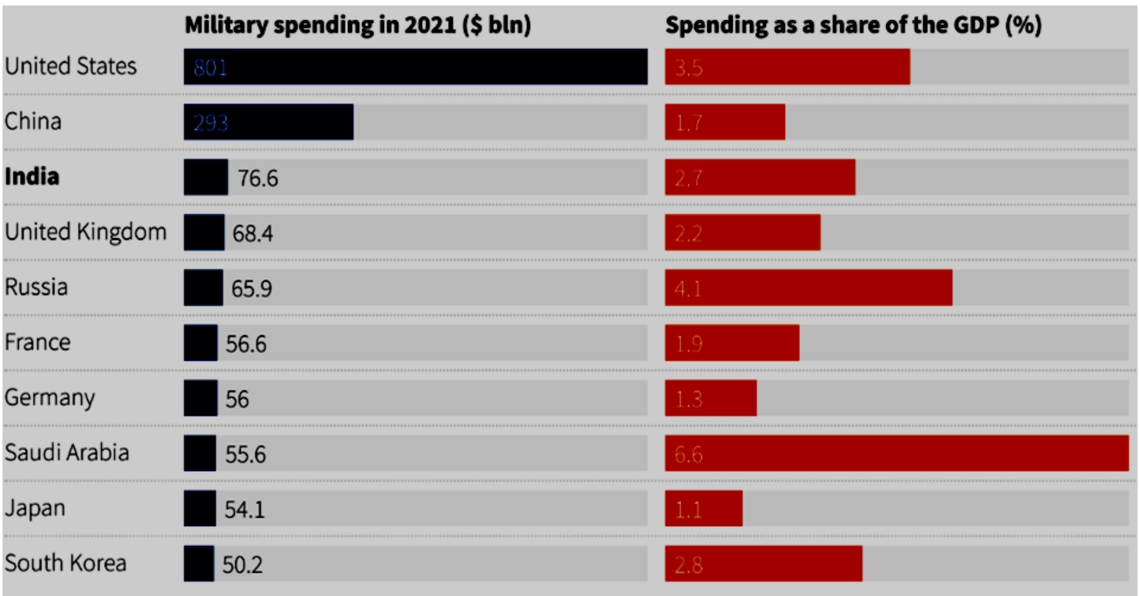

Fig. 2: Global comparison of military spending in 2021. [3]

Commercially pure and titanium alloys in industrial use are widely used for advanced aircraft applications and aero-engines as a material with lightweight (density is 60% that of steel), high strength and hardness, as well as superior corrosion resistance [4]. Many airplane parts, including the landing gear, flap tracks, springs, engine parts, pneumatic system tubes, and fuselage components, are made of titanium alloys [1]. Titanium alloys are becoming essential structural components for Aircraft. They can make up to 30-50 % of the whole structure's weight in modern Aircraft, such as the F-22 fighters, which have a weight of 41 % [5,6].

In order to decrease the amount of fuel used by airplanes, more Carbon Fiber Reinforced Plastic (CFRP) is being used in airframes and engine components lately. In a similar vein, titanium is in higher demand due to its great compatibility with CFRP in terms of corrosiveness issues and coefficient of thermal expansion [4]. Compared to aluminum, titanium is more compatible with composites in aircraft assemblies [7]. Compared to ordinary airplanes, the amount of titanium utilized in the Airbus S.A.S. A350XWB, a low-fuel consumption aircraft has increased to more than twice the amount. In addition, future aircraft demand will be steady.

For usage in aviation, several authors have evaluated various titanium alloys. Inagaki et al. [4] outlined the key features of the various titanium alloys used in the aerospace sector. Technical details on the key modern aviation titanium alloys are provided straightforwardly, connecting the alloy's properties to its intended application. However, a method for selecting materials that will satisfy the primary design requirements is not presented. Santos et al. [8] gave a detailed insight into the design specifications for these applications and a materials selection study for executive airplane interiors.

Notwithstanding, no details are given regarding using titanium alloys in airplane structural components. In this respect, several authors made significant contributions to our knowledge of the function of titanium alloys in the aircraft sector by outlining their principal strengths and weaknesses. Peters et al. [7] Notable uses for titanium alloys in Aircraft, helicopters, and spacecraft parts. Similar goals were emphasized in the report of Veiga et al. [9], which focused on the Ti6Al4V alloy's applications in the biomedical, automotive, and Aircraft industries. Henriques [10] examined the processes for producing the titanium alloys utilized in the aerospace sector. Cotton et al. [11] thoroughly examined the potential uses of β alloys in the aviation sector. More recently, Antunes et al. [1], to choose the best materials for structural aviation applications in the landing gear beam, it was necessary to investigate the relationship between the physical metallurgy of titanium alloys as well as their key characteristics. There is helpful information on the microstructure, processing, as well as characteristics relationships of numerous β alloys. Therefore, this study discusses the present state of titanium applications in aviation and methods for resolving related problems.

2. Current status of Titanium applications for Aircraft

Due to its low density, great strength, and exceptional corrosion resistance, titanium is a preferred material for aircraft applications. Over the past few decades, titanium usage has surged in both the civil and military aerospace industries. Titanium will be present in substantial quantities in even future carbon fiber composite-structured aircraft. This is due to its great strength, low Coefficient of Thermal Expansion (CTE), and chemical compatibility [7,12].

There are many different uses for titanium alloys, including in the offshore, biomedical, automotive, energy, and energy-related industries. However, its greatest market (around 80% of manufacturing) is concentrated on parts for the aerospace industry [13-15]. A new commercial aircraft's engine parts (25 wt. %) and airframe (15 wt. %) both contain titanium, see figure 3a. These values have progressively increased since titanium was initially used in the aerospace sector in the 1950s, despite the barriers to wider usage of titanium such as high manufacturing costs [14,15]. The main benefits of using titanium in the aircraft sector include weight reduction (primarily through a replacement for steel, but also as a replacement for Al alloys), corrosion resistance (replacement for Al and low alloy steels), space restriction (replacement Al alloys), and operating temperature (replacement for Al, Ni, and St alloys) [16].

Recently, TC21 Ti-alloy has been successfully developed as a structural material in aerospace applications [17, 18]. It can be utilized as a structural element, namely in the landing gear system and also in linkages between the wing and fuselage [15-18]. The usage of titanium in military Aircraft is significantly higher (20-40 wt. % in the airframe), see figure 3a. The causes are increased structural loads brought on by intense aerial operations and a less important function for cost cutting during material selection [14,15,19].

According to recent predictions from the world's major manufacturers of commercial aviation and gas turbine engines, the build rates for future next-generation goods are accelerating [5,13]. This describes the outlook for the aircraft industry's material requirements in the coming ten years: composites are expected to grow at a compound annual growth rate (CAGR) of 5.9 %, and Ti is expected to grow at a 4.4 % CAGR, while Al is expected to grow at a stable CAGR of 0.2 % [5,13]. According to the leading titanium producers, these elements suggest a persistent and favorable trend in demand for this material and, consequently, a rosy future for titanium in the aircraft sector, see figure 3b [5]. Total titanium demand for commercial engines is shown in figure 3c [20].

2.1. Titanium for Airframes

Since the 1950s, titanium has been applied to airframe construction. Fabric and timber materials were the precursors to the modern CFRP, which was developed from them through the use of aluminum alloys. Furthermore, titanium alloys have taken the role of steel-based components for areas that needed great strength (such as frames and joints), saving weight. When designing joints in an airframe with heterogeneous materials, strain from different coefficients of thermal expansion must be eliminated, as well as potential differential corrosion (galvanic corrosion). Titanium alloys with properties resembling those of CFRP have been employed more frequently lately as a result of CFRP's rise to prominence [1,4].

In fuselage applications, titanium alloys are frequently selected primarily for weight reduction, allowing for the use of the metal's high specific strength. It is frequently advantageous to use aluminum-based alloys instead of high-strength steels, even though aluminum has a lower density and steel has a higher strength. Over the past forty years, this has resulted in a rise in the use of titanium alloys in fuselages. Since titanium was first utilized in fuselages for Boeing commercial aircraft in the 1950s, figure 4 shows the steady growth of titanium used in those Aircraft. Approximately 9% of the Boeing 777's structural weight is made up of it. Similar amounts of titanium alloy applications are indicated [7,21].

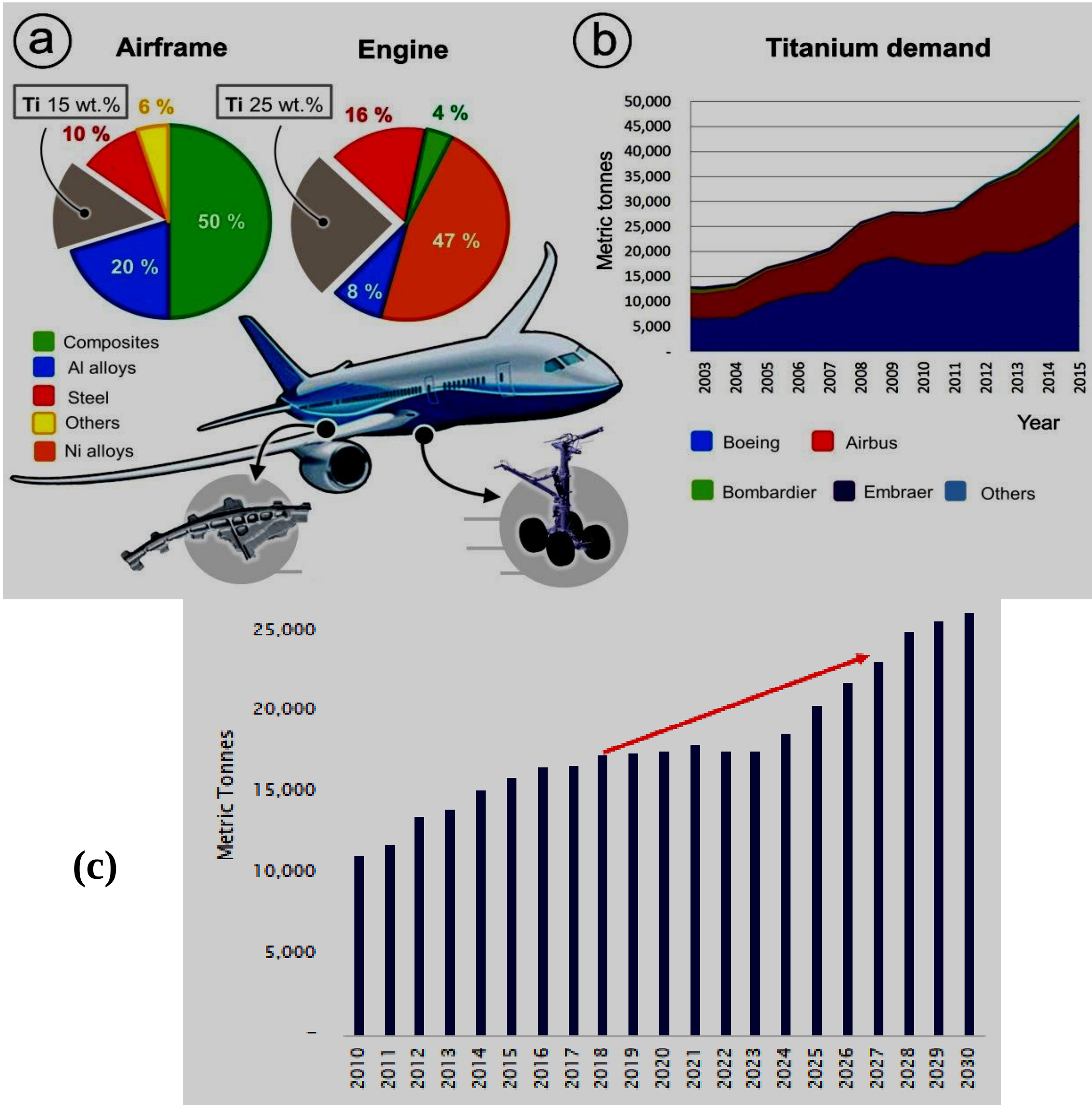

Fig. 3: (a) Material selection of gas turbine engines and airframes [5,13], (b) Trends in the previous years in the demand for titanium [5], and (c) Total titanium demand for commercial engines [20].

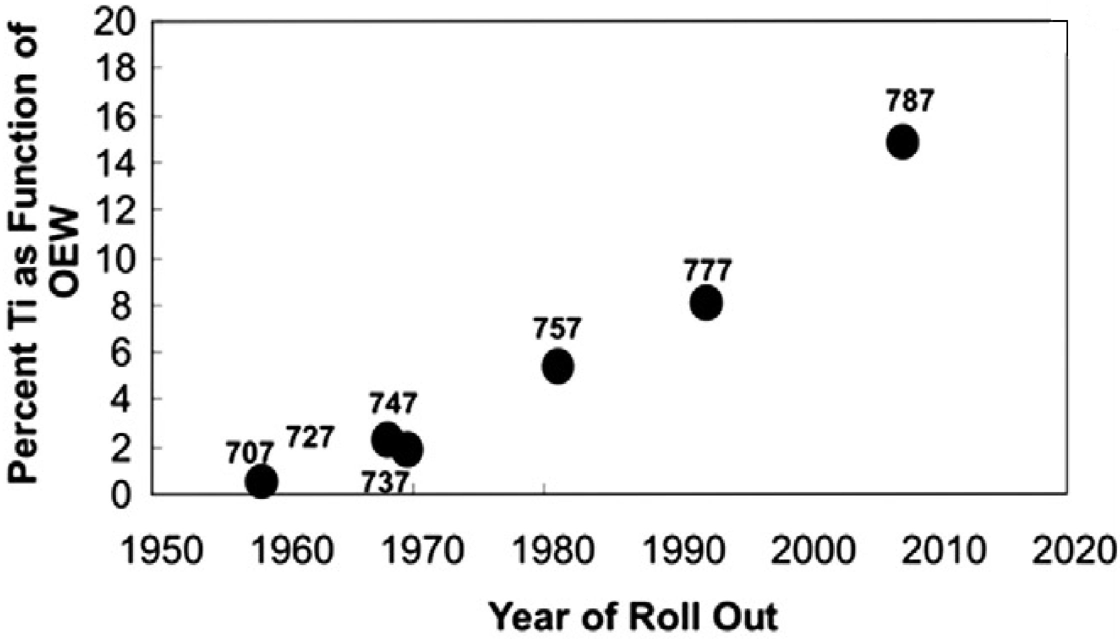

Fig. 4: Increase in applications for Ti alloys in commercial Boeing aircraft. [21]

2.2. Titanium for Engines

Commercial airplanes frequently use turbofan engines to increase combustion efficiency as well as reduce fuel consumption. The gas turbine that drives fuel combustion is located in the engine's rear part, and the fore section houses the fan blades. There are four sections in these types of turbofan engines. They are the turbine, compressor, combustion chamber, and fan, starting from the front. In the forward half portion, where the temperature is relatively low (600°C or below), titanium alloy is mostly utilized for the compressor and fan. Depending on the application, Ni or Fe-based alloy may be utilized for the combustion chamber and turbine in the rearward half portion, where temperatures are higher [4,9].

An aero engine works by the fan sucking in air, which is then squeezed further by the compressor, ignited in the combustor, and blown out and driven by the turbines. These sections are connected by shafts, which have a number of discs that hold their respective blades in place. The temperature and pressure progressively increase as air passes through the sections. Components such as the discs are subjected to high rotational speeds and hence high cyclic stresses leading to low cycle fatigue behavior and, consequently, a finite safe operating life [21-23]. Failure of such components at such high speeds makes containment difficult, and therefore, careful design is crucial. Critical factors such as the material selection, properties, processing, and machining need to be examined carefully before a component is used in these conditions.

Aero engines currently use titanium in place of steel resulting in a significant reduction in weight. Titanium alloys are selected in preference to other light alloys, such as aluminum, because they have higher yield stress, higher fatigue strength, resistance to corrosion, as well as higher temperature capability [22,23]. The rotating and nonrotating components of aviation engines are another significant application area for titanium alloys.

The gas turbine engine is where titanium alloys for aircraft are mostly used. In contemporary turbine engines, titanium makes up about one-third of their structural weight. The primary material used in engines is titanium alloys, followed by nickel-nickel superalloys. In fact, titanium alloys were present in the first jet engines that Pratt & Whitney in the United States and Rolls-Royce in England produced at the start of the 1950s. Titanium compressor discs are the first engine parts to use this material, followed by compressor blades. Modern jet engines today frequently include huge front fan blades constructed of titanium alloys. A rendering of the new Rolls-Royce Trent-900 engine that powers the Airbus A380 is seen in figure 5.

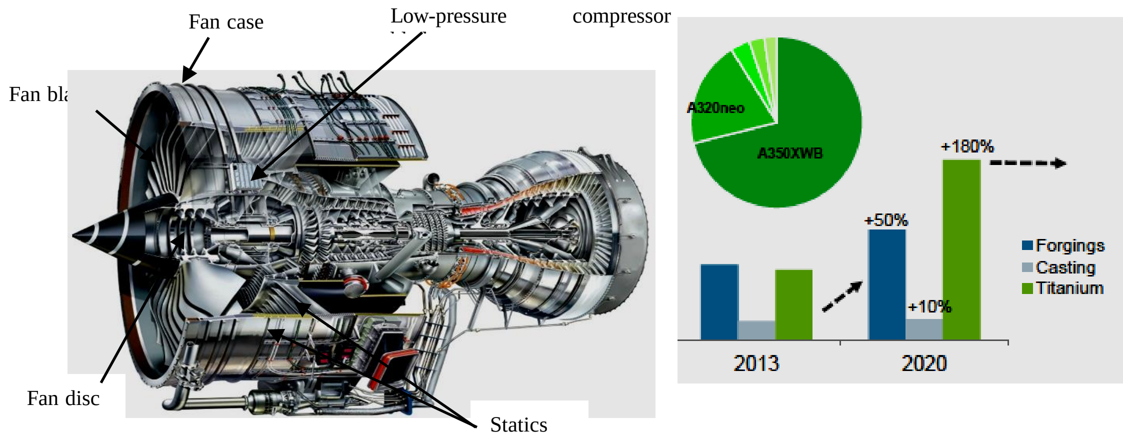

Fig. 5: Render of a Rolls-Royce Trent 900 engine used on the Airbus and demand. [4]

2.3. Properties of Titanium Used in Aircraft

The use of materials with superior fatigue strength, resistance to corrosion, crack propagation resistance, and fracture toughness can significantly lower the cost of airframe maintenance. In addition, titanium alloys are frequently employed because of their previously noted compatibility with CFRP. Table 1 [4] provides examples of titanium alloy usage for airframes based on location and substance. The design criteria for structural components in the aerospace industry have moved from static strength design to damage tolerance design, which mandates that structural components have enough residual and lifetime in the event of corrosion, fatigue, or unintentional accidents [24]. TC21 Ti-alloy, a new α+β titanium alloy, is designed to satisfy the damage tolerance [25].

For aviation engines, titanium alloys are employed for their lightweight, high specific strength as well as heat resistant characteristics. Because their strength dramatically decreases at temperatures of 200°C and above, aluminum alloys with high specific strengths are rarely employed in aviation engines. The specific strength of titanium alloys is greater than that of Ni-based alloys in the range of temperature between 500 and 600ºC, despite the fact that it degrades as the temperature increases. [1,4]

Ti-6Al-4V alloy, which has a greater specific strength and superior fatigue strength, is frequently utilized because of the low temperature surrounding fan blades [26]. To conserve weight, hollow fan blades are used in large engines with larger fan blades, while forged solid fan blades are used in medium- and small-size aircraft engines. Considered the most crucial component in terms of safety, the fan disc holds the fan blades together. As a result, titanium alloys like Ti-6Al-4V and Ti-17 (Ti-5Al-2Sn-2Zr-4Cr-4Mo) are employed because they have excellent strength and high toughness requirements. [1,4,9]

Table (1): Examples of titanium alloys used in aircraft frames. [4]

Material	Application example
Ti-6Al-4V	Fastener, wing box, and cockpit window frame
Ti-3Al-2.5V	Hydraulic pipe
Ti-6Al-3Mo- 2Sn-2Nb-2Zr-1Cr-Si (TC21)	Landing gear and Flap track
Ti-6Al-2Sn-4Zr-2Mo	Tail cone, exhaust
Ti-15V-3Cr-3Sn-3Al	Duct

3. CONCLUSION

Improvements in airplane fuel efficiency are driving up demand for titanium in airframes as well as engines. Aircraft are made of a variety of titanium materials, each one chosen for a specific purpose. Commercially pure titanium is utilized for aircraft structures where formability is necessary; titanium alloys are employed for engines where strength and heat resistance are valued highly. The use of CFRP in modern airplane structures appears to be on the rise. As a result, there is a growth in the use of titanium, and it seems that this trend will continue for some time to come.

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