# Aeronautical Industry Requirements for Titanium Alloys

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**Abstract**. The project presents the requirements imposed for aviation components made from Titanium based alloys. A significant portion of the aircraft pylons are manufactured from Titanium alloys. Strength, weight, and reliability are the primary factors to consider in aircraft structures. These factors determine the requirements to be met by any material used to construct or repair the aircraft. Many forces and structural stresses act on an aircraft when it is flying and when it is static and this thesis describes environmental factors, conditions of external aggression, mechanical characteristics and loadings that must be satisfied simultaneously by a Ti-based alloy, compared to other classes of aviation alloys (as egg. Inconel super alloys, Aluminum alloys).For this alloy class, the requirements are regarding strength to weight ratio, reliability, corrosion resistance, thermal expansion and so on. These characteristics additionally continue to provide new opportunities for advanced manufacturing methods.

## 1. Introduction

To properly construct and maintain any equipment, especially airframes is vital to understand the uses, strengths, limitations, and other characteristics of this structural metals [1,2]. In aircraft may result in the loss of equipment and lives if is not taken into consideration the maintenance and repair, the substitution of inferior materials or even a slight deviation from design specification [3]. The finest craftsmanship can be readily erased by the use of unsuitable materials. For a specific repair job the selection of the correct material demands familiarity with the physical properties of various metals.

## 2. Properties of Metals

In the aircraft maintenance the general properties of metals and their alloys are the primary concern [5]. These terms are explained in this thesis to be able to establish a basis for further discussion of structural metals.

### *2.1. Brittleness*

When a metal permits only a small amount of deformation without shattering we say it is a brittle material. Such a metal can break or crack without modifications in the shape. Structural materials are many times exposed to shock loads and this is why this characteristic is not advantageous. Examples of brittle materials are the cast iron and aluminum and sometimes some very hard grades of steels.

### *2.2. Density*

The weight of a unit volume of a material is named density. To determining the weight of a part before actual manufacture can be used the specified weight of a material per cubic inch, in aircraft work. In order to maintain the proper weight and balance of the aircraft when choosing a material to be used in the design of a part is important to have into consideration the density.

### *2.3. Ductility*

The property of a metal that can be permanently drawn, twisted or bent into different shapes without breaking is named ductility. For metals used in making wire and tubing this property is essential.

In aircraft industry, it is better to use ductile metals due to an ease of forming and also they are more resistant to shock loads and other types of failure. This is why the aluminum alloys are preferred for the fuselage and wing skin, for the cowl rings and for the extruded components such as the spars, bulkheads and also the ribs. Another material with a high ductility used in aircrafts is chrome molybdenum because it can be formed into shapes. Another property similar to ductility is malleability.

### *2.4. Elasticity*

The property that allows a material to come back to the original shape and dimension after a tension which caused the modification has been removed is called elasticity. Elasticity is one of the most important properties because knowing it, components that don't have a permanent deformation when the load is removed can be designed. Each material has an elastic limit. When the tension is greater, the deformations will be permanent. In the aeronautical industry, the components are conceived in such a way that that the maximum tolerances at which they will be exposed will not stress these components further than their elastic limit. An example of component where this property can be observed is a spring.

### *2.5. Electric and heat Conductivity*

The ability of a material to conduct heat or electricity is called conductivity. Metals are generally good conductors of heat and electricity. Heat conductivity at metals is an important characteristic since during the welding it is valuable to know the amount of heat necessary for good fusion. In order to eliminate the radio interference, aeronautical engineers must consider the electrical conductivity of a metal in conjunction with bonding.

### *2.6. Fusibility*

The property of a metal to turn into liquid phase after heat is applied is called fusibility. Welding is an example of process where the metals are fused together. The temperature of fusion for steels is about 1426°C and the temperature of fusion for most aluminium alloys is around 590°C.

### *2.7. Hardness*

The ability of a material to resist abrasion, penetration, cutting action, or permanent distortion is named hardness. We can increase this ability in the case of steel and certain aluminum alloys, by cold working the metal and by heat treatment[6,7].

Usually the parts with structural character are formed while they are soft and afterwards thermal-treated to obtain hardness properties in such a way that the finished shape could be retained. The metals properties of hardness and the strength are usually directly related.

### *2.8. Malleability*

A metal can be called malleable when is pressed into various shapes without cracking, is hammered or rolled. The metal that is worked into curved shapes, such as cowlings, fairings, or wingtips this property is necessary. An example of a malleable metal is copper.

### *2.9. Strength*

Strength is an important material property. Is the ability of a material to resist deformation and to resist stress without breaking. The strength of the material is affected by the type of load or stress applied.

### *2.10. Thermal Expansion*

The contraction and expansion of a metal as reaction to changes in temperature is the property of thermal expansion. After a metal has been heated, it will grow its dimensions. After cooling it down, the dimensions will shrink. The tolerances generated by this phenomenon must be taken into account while designing aircraft parts.

### *2.11. Toughness*

The property of a material to be resistant to tearing or shearing and also to stretching and other deformation without damaging is called toughness. It is another very important property for a material used in aeronautics.

## 3. Titanium and Titanium Alloys

Titanium was first discovered by an English priest named Gregot. In 1825, a rudimentary separation process for the titanium was first performed. Enough quantity of pure titanium was obtained until 1906 for a study to begin. After the first study, the Kroll process was developed in 1932. Titanium sponge was first made by the United States Bureau of Mines as early as 1946. The melt process was developed four years after this and today the usage of this metal is very spread. Titanium has applications in many industries and there are high commercial orders for this material and its alloys for all kinds of components such as tools, fixtures, pumps and screens, mostly due to a high resistance to corrosion of titanium. In the aeronautical industry, titanium is used for the skin of the fuselage, for the engine components, for firewalls, for frames and other parts such as ducts, fasteners and fittings [4].

Other parts made from titanium are compressor disks, blades and vanes, spacer rings, bolts, housings for turbines and many others [7].

The visual aspect of titanium is similar to the stainless steel. To quickly distinguish titanium the spark test can be performed. During the burst, the titanium will generate a white brilliant trace. Another quick way to identify titanium is by wetting it and drawing a line on glass with it. The effect will be a dark line similar to the one traced by a pencil. When it comes to some of the most important properties, such as elasticity, strength to high temperatures and density, the titanium is between steel and aluminum. Titanium has a low coefficient of thermal expansion and also a low conductivity but a relatively high melting point, ranging from 1500°C to 1730°C. The most important physical aspects regarding titanium is that it is a light, corrosion resistant and strong material, with a density 60% bigger than aluminums but half of the stainless steel density. The properties for high temperatures are not great due to a high melding point and thus, for example the yield strength will rapidly decrease at temperatures higher than 430°C.

The avidity of titanium for nitrogen and oxygen increase once the temperature is above 500°C and thus making the metal brittle if a long contact is maintained , the metal becomes brittle and loses its value.

At high temperatures of up to 1650°C, titanium has its credit in applications where the strength is not a primary concerning aspect. Such requirements are for the firewall of the aircraft.

The magnetic character of titanium is nonmagnetic and in comparison with stainless steels, the electrical conductivity of titanium is similar. The harness values for most titanium alloys are high.

By the heat treatment, the titanium and its alloys don't achieve the high level of hardness as some steel heat treated alloys.

In the recent period, a new type of titanium alloy has been developed with triple treatable ability. Before this, the only method of forming that could be achieved was first heating and afterwards rolling the material. There is still the possibility that before treating the titanium for hardness to form the new obtained alloy in a soft condition.

The stabilizing elements which are used to produce titanium alloys are Iron, Molybdenum and Chromium. These alloys will be quenched and age hardened. The increase of ductility is also a consequence of adding these elements.

Steel and Aluminum have a lower fatigue tolerance than titanium does.

The hardness of Titanium is inversely proportional to the purity of the alloy. By chemical analysis, distinguishing between the unalloyed titanium or diverse grades of commercially pure titanium is not an efficient method. In conclusion, the mechanical characteristics of the material are the ones which are used at determining the grades.

### *3.1. The Designations of Titanium*

In order to provide a advantageous and transparent way for characterizing all the titanium alloys, a classification was established and thus, three categories were proposed: A-B-C because there are three kinds of crystals which are determined by titanium and its alloys: A (alpha), B (beta), and C (combined alpha and beta) with the following properties:

- The alpha alloys — all around characteristics; good weldability; in both hot and cold conditions, they are strong and tough. Good corrosion resistance.
- The beta alloys —very good ductility and ability to bend; in hot and cold conditions the alloys are strong, but the contamination is problematic because these alloys are susceptible.
- Alpha + beta alloys— these alloys are strong in cold and warm condition, but, nevertheless, weak at high temperatures; the bendabilityis good; moderate resistance to corrosion; the forging properties are very good but these alloys represent a compromise for performances.

There are two ways of manufacturing the titanium in order to use it commercially: it can have commercial purity or it can be alloyed. The yield strength of the titanium and its alloys can varry from 380 MPa to 760 MPa. This material has a generic scope, and is manufactured in processes where moderate to severe forming apply. Occasionally, titanium and its alloys are used in nonstructural parts for aircraft design for multiple applications which require a high corrosion resistance. One of this applications is tubing with its fittings. Other applications for the titanium are due to the fact that it has a good weldability and where a high stress resistance is required in high temperature environments.

### *3.2. Resistance to Corrosion for Titanium*

Titanium has a very good resistance to corrosion. A shielding surface layer is generating the corrosion resistant behavior, being made of stable oxide or chemically absorbed oxygen. Due to the existence of the oxygen and its agents, the layer is created. The character of the titaniums corrosion is uniform. A tiny proof of pitting exist and also forms of localized attack. The titanium and its alloys are not usually subjected to corrosion fatigue, stress corrosion galvanic or intergranular corrosion. These materials have an equal or larger resistance to corrosion than stainless steel grades.

Experimentally, it was determined that the titanium and its alloys tend to polarize readily when attacked with acids or saline solutions. This leads to a lower current flow in corrosion and galvanic cells. At the surface of titanium, there are corrosion currents and metallic couples which are restricted in a natural way. It is an effect which offers a good protection to many chemicals and also, the titanium and its alloys can be used in combination with other elements without the worry of the galvanic effect on eachother.

### *3.3. The Heat Treating of Titanium and its alloys*

The reasons why titanium and its alloys need heat treatment are:

- The elimination of the tensions which have accumulated after forging
- To anneal the material subsequently to forging or to offer a high level of ductility for the plastic deformation processes.
- Improving the strength by thermal hardening

*3.3.1. Tension Relieving.* Usually, the tension relieving is used to eliminate stress concentrations consequential as of forming of titanium forged products.

This heat treatment has a range of temperatures which start at 343°C and go up to 538°C. The exposure in time is different from a rather thin plate which takes a few minutes to more than an hour for larger parts. One representative cure of stress relieving is at 480°C for half an hour, being subsequent to an atmospheric cooling. Pickling in solution with acid character is an easy solution to remove the discoloration or scales formed on the exterior of the treated metal. The percent of nitric acid which is recommended is aprox. 10 – 20% and up to 30% hydrofluoric acid. Room temperature is indicated for the operation.

*3.3.2. Complete Annealing.* The toughness and ductility are properties which can be obtained at room temperature for titanium and its alloys by annealing. Other obtained properties are the structural and dimensional stability at a high range of temperatures and also enhanced machinability properties.

A complete anneal is necessary to prepare the material for supplementary operations. This step of the treatment is carried to completion at a range of 650°C – 900°C. The exposure time at the high temperature can start from 1/4h and up to multiple hours, build upon parameters such as the dimensions and also the magnitude of the forging which is to be done. Generally, such a treatment is performed at 700°C for one hour, with subsequent atmospheric cooling. After the complete annealing treatment a caustic descaling process is mandatory because the treatment produces usually enough scale and so a sodium hydride salt bath must be provided.

*3.3.3. Temperature Hardening.* Pure titanium is not possible to be thermal treated, unlike the alloyed state, where the aeronautical industry alloys benefit by an increase of strength by thermal treating but this property comes most of the times with a compromise for the ductility. To have the highest properties, the recommendation is to perform a water quenching process at a temperature of 800°C and afterwards another heating up to 480°C with a time of 8h.

*3.3.4. Casehardening.* Special applications indicate the usage of titanium and its alloys due to the elements fast assimilation of other gases such as oxygen and nitrogen but also carbon. These can be absorbed at relatively low temperatures. The processes of carburizing, nitriding and carbonitriding are being used at the production of water-resistant case of 3 μm to 5 μm in depth.

## 4. Mechanical properties of Titanium Alloys

### *4.1. Tensile properties*

Profitable (over 99% purity) grades of titanium poses a ultimate tensile strength of about 434 MPa, which is equal to that of common, low-grade steel alloys, but with a much lower density. Titanium has a density 60% higher than aluminums, but with properties which make it more than twice as strong as the most general used 6061-T6 aluminium alloy. Some titanium alloys achieve tensile strengths of over 1400 MPa. Nevertheless, when heated above 430°C titanium loses its strength. The tensile properties of the most used titanium alloys in aeronautics is presented in figure 1.

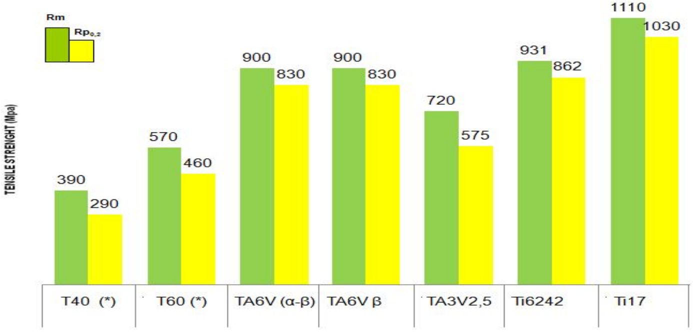

**Figure 1**. Titanium alloys ultimate and yield tensile strength.

### *4.2. Fracture toughness properties*

In materials science, fracture toughness is a property which describes the ability of a material containing a crack to resist fracture, and is one of the most important properties of any material for many design applications, especially in the field of aeronautics. Figure 2 describes the fracture toughness for titanium alloys. A large scatter band is noticeable.

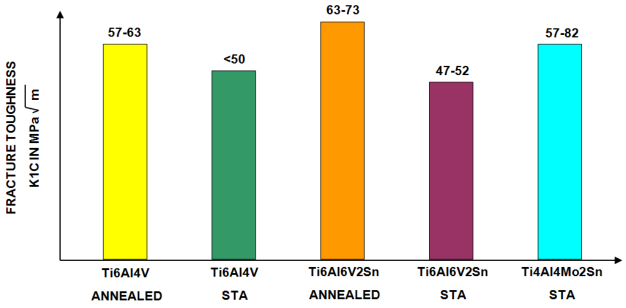

**Figure 2**. Fracture Toughness for Titanium Alloys.

### *4.3. Fatigue properties*

Titanium isn't as hard as some grades of heat-treated steel, it is non-magnetic and has a low coefficient of electrical and heat conductivity. Precautions must be taken in order to machine titanium, because the material might gall unless sharp tools and proper cooling methods are used. The titanium structures have a fatigue limit that guarantees longevity in some applications, similar to steel structures. The fatigue requirements in aeronautics for the Ti-6Al-4V alloy is described in table 1 for the annealed forged state, for the Alpha-Beta

Hot Isostatically Pressed and Annealed state and for the β Annealed Forging state.

**Table 1**. Fatigue requirements.

| State of the alloy | The curve of the test results, calculated in accordance with EN 6072, shall not lay below the reference curve defined by the following data: | |
|---|---|---|
| | σ max (MPa) | Number of cycles |
| annealed forged state | 410 | $1x10^4$ |
| | 270 | $1x10^5$ |
| | 185 | $1x10^6$ |
| Alpha-Beta<br>Hot Isostatically Pressed<br>and Annealed state | 400 | $3x10^4$ |
| | 285 | $1x10^5$ |
| | 230 | $1x10^6$ |
| β Annealed Forging state | 410 | $1x10^4$ |
| | 270 | $1x10^5$ |
| | 185 | $1x10^6$ |

### *4.4. Crack propagation properties*

A occurrence in fatigue loading where the crack remains in a closed position is crack closure , even if on the material some external forces are present. A crack can be opened during this process, beyond a stress with a certain limit.

Phase transformation during the propagation of the crack and the plastic deformation of the material are some of the factors which contribute to this phenomenon and thus, the surface of the crack can present traces of corrosion, due to a fluid presence inside the crack which is amplified by a rough quality of the surface inside the crack. By diminishing the speed of the crack rate, a longer life for the material is gained.

A wide range of fatigue data can be explained by the effect of the crack closure. This is the standard analysis for the effects of load ratio. Almost all the fatigue prediction models use it. Nevertheless, predicting such effects of crack closure in laboratory conditions is not quite possible.

The crack propagation requirements in aeronautics for the Ti-6Al-4V alloy is described in table 2 for the annealed forged state, for the Alpha-Beta Hot Isostatically Pressed and Annealed state and for the β Annealed Forging state.

**Table 2**. Crack propagation requirements.

| State of the alloy | The crack propagation rates shall not be greater than the following data: | |
|---|---|---|
| | $\Delta K$ (MPa$\sqrt{m}$) | da/dN (mm/cycle) |
| annealed forged state | 15 | 1,5x10$^{-4}$ |
| | 20 | 3,5x10$^{-4}$ |
| | 30 | 8x10$^{-4}$ |
| Alpha-Beta Hot Isostatically Pressed and Annealed state | 15 | 1x10$^{-4}$ |
| | 20 | 3x10$^{-4}$ |
| | 30 | 1,3x10$^{-3}$ |
| | 40 | 3x10$^{-3}$ |
| β Annealed Forging state | 15 | 4x10$^{-5}$ |
| | 20 | 1,5x10$^{-4}$ |
| | 30 | 7x10$^{-4}$ |
| | 40 | 1,5x10$^{-3}$ |

## 5. Industry specifications for Titanium alloys

A list of specifications which state requirements for titanium alloys is shown in table 3.

**Table 3**. Specifications for titanium alloys.

| Material | ASTM | | AMS | German WL | British BS | French AIR |
|---|---|---|---|---|---|---|
| C.P.Ti | ASTM 265 | Grade 1 | AMS 4902 | 3.7024 | BS TA1 | AIR 9182 T-35 |
| | | Grade 2 | AMS 4900 | 3.7034 | BS TA2 | AIR 9182 T-40 |
| | | Grade 3 | AMS 4901 | 3.7064 | BS TA6 | AIR 9182 T-65 |
| Ti3Al2.5V | ASTM 338 Grade 8 | | AMS 4944 | 3.7194 | | |
| Ti6Al4V | ASTM 265 Grade 5 | | AMS 4911 | 3.7164 | BS TA10 | AIR 9182 T-A6V |
| Ti4Al4Mo2Sn | | | | 3.7184 | BS TA51 (IMI 550) | AIR 9183 T-A4DE |
| Ti6Al6V2Sn | MIL-T-9047 (Ti6-6-2) | | AMS 4978<br>AMS 4979 | 3.7174 | | |

## 6. Conclusions

Having a relatively low density, titanium is a low-weight material, with good resistance to corrosion which indicate it in structural applications. Titaniums mechanical properties can be increased by allowing with other elements and through heat treatment processes. The titaniums ratio for strength to weight is first-class, it also has a low thermal expansion coefficient. Titanium has good oxidation resistance at intermediary temperatures. The weldability and toughness of titanium are good.

Through many application of titanium and its alloy, one with the most importance is the aerospace industry. With a large number of customers from this industry, it is directly linked with the economy of manufacturing this material. Due to a high demand, progress is made and better aeroplanes are manufactured. The higher demand of titanium is on the rise. In the aeronautical industry, many parts are manufactured from titanium, such as frames, engine components and others. The titanium performances provides the manufactures with what they desire in order to have the best designs. Since the jet propulsion engines and also the parts of the frame need to resist a wide range of temperatures from belo 0°C and up to 600°C, the titaniums high temperature performances are ideal. Parts of the engine which are manufactured of titanium are the blades , discs, caings and shafts. Due to such characteristics and applications, and the inter-dependence between the titanium and the aerospace industry, the market for this material should be strong in the years to come.

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