Aero-engine applications: present and future

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ANNOTATION
Titanium-based materials play an important role in the design of gas turbine aero-engines. Initially, research activities have been concentrated on developing conventional alpha-beta and near-alpha alloys with improved specific strengths and higher temperature capability. Relationships between microstructures and mechanical properties have been studied extensively. More recently, a particular emphasis has been put on process modelling with the objectives of obtaining the adequate microstructure according to the required mechanical resistance in forged products and reducing the scatter of mechanical properties. Efforts have been directed towards the development of metallurgical models enabling to predict those properties. This last point will be discussed in detail.

Owing to the requirements of the aerospace industry for increased performance, new types of advanced materials are under development: gamma titanium aluminides and continuous fibre-reinforced titanium matrix composites. Recent technical progress and barrier issues to be addressed are presented.

Key words: high strength titanium alloys, process modelling, gamma titanium aluminides, titanium matrix composites, aero-engines applications.

1. INTRODUCTION

Conventional titanium alloys remain excellent candidates for aero-engines critical parts, such as disks and blades owing to their high strength to weight ratios [1]. Due to the complexity of microstructures and phases they present, which generate specific mechanical properties, a compromise is looked for between high resistance/medium temperature alloys (beta-metastable grades) and high temperature/medium resistance alloys (near-alpha grades). In the last ten years, little effort has been focused towards the development of new grades in western countries. However, the increase in performances in modern aero-engines inducing large amplitude cycled loads coupled to higher operating temperatures has made necessary the availability of a titanium alloy associating the advantages of the aforementioned two classes. In the last decade, several valuable titanium alloys have been developed in Russia for aeronautical applications, among which BT25Y revealed quite attractive with regard to the above requirements [2].

Another important trend of development in the use of titanium alloys for aero-engines manufacturers concerns the ways to obtain reduction cost in the implementation of those materials. Turboengine compressors disks are high added value components and a comprehensive mastery in the whole course of process conditions is actively sought: the adjustment of processes modelling enable to achieve this objective.

Demands of the aerospace industry for higher thrust levels, lighter weights and increased efficiency has led to considerable research efforts being directed towards the development of new types of structural materials: gamma titanium aluminides and continuous fibre reinforced titanium-based composites (TMCs).

As compared with near-alpha alloys, gamma titanium aluminides offer the unique advantages of a very high stiffness, improved specific strengths (tensile and creep) and a better oxidation and burning resistance. Potential applications of these materials are high pressure compressor blades, casings and even low pressure turbines blades in place of nickel base superalloys.

Metal matrix composites are one of several classes of advanced materials which are expected to play a significant role in the development of future aerospace applications. Due to the availability of high performance continuous fibres, these composites exhibit much improved properties, in terms of specific strengths and stiffness at room and elevated temperatures, compared to unreinforced structural materials. Among metal matrix composites, TMCs are of particular interest for critical rotating parts in aero-engines.
2. PRESENT STATUS

2.1. INTEREST OF BT25Y ALLOY

The alpha/beta forged Russian alloy BT25Y (Ti-6%Al-2%Sn-3.5%Zr-3.5%Mo-1%W-0.2%Si) has been compared in the 450-550°C temperature range to Ti-6242 alloy, both alpha/beta and beta processed, which is commonly used today for high pressure compressor disks in turboengines [3], and to reference high temperature (IMI 834) and high resistance (Ti-17) alloys.

The static resistance, yield strength and ultimate tensile strength, has been investigated up to 600°C: a higher resistance of about 100MPa is observed in comparison with Ti-6242 and IMI 834 (Fig. 1). In fact, the static resistance of BT25Y is close to the level of the beta-metastable titanium alloys exhibiting the highest values such as Ti-17. It is worth to notice that the rupture elongations remain elevated (> 20%) at all temperatures.

Low cycle fatigue strength is a property of the utmost importance for disks. It has been evaluated through strain controlled tests at 450 and 550°C (R = 0, frequency 1Hz). The results are plotted in Figures 2 and 3 and evidence the higher resistance (about 10 to 15%) in alternated pseudo stress E\(\Delta\varepsilon\) for \(10^5\) cycles of BT25Y as compared to the best Ti-6242 (alpha/beta processed at 450°C and beta processed at 550°C).

The high cycle fatigue resistance (repeated tensile load, frequency 100Hz) is slightly better than that of reference alloys as shown in Table 1.

As far as creep is concerned, BT25Y in the alpha/beta processed condition is quite comparable to Ti-6242 alpha/beta at 500°C but significantly less resistant than Ti-6242 beta. At 550°C, the difference between the two alloys is still more important. Nickel content could be suspected to have a detrimental effect on creep strength [4]: in the investigated BT25Y, the Ni content is about 70ppm which is lower than the 100ppm critical value and so cannot be put forward as an explanation for the observed moderate creep resistance of BT25Y. Optimisation of thermomechanical treatments, and especially beta processing, could allow to improve the creep resistance but fatigue strength could be affected consequently, which would decrease the interest of the alloy and a compromise would be once more necessary.

In conclusion, BT25Y shows excellent mechanical properties, in the alpha/beta processing route, with regard to static and fatigue resistance when compared to usual high temperature alloys. This material can be considered as one of the best titanium alloys between 450 and 550°C, and therefore a quite attractive grade for manufacturing disks and blades which are to operate within that temperature range. Nevertheless, the limited creep resistance above 500°C needs to be considered: according to the specific applications, it may remain acceptable for short durations but if creep mechanisms are operating to some extent, this relative weakness may forbid the use of this alloy. Finally, other properties such as ageing response and oxidation behaviour are to be assessed before implementation of this material in turboengines.
Figure 2. Low cycle fatigue behaviour at 450°C of BT25Y and Ti-6242 alloys.

Figure 3. Low cycle fatigue behaviour at 550°C of BT25Y and Ti-6242 alloys.

Table 1. High cycle fatigue resistance ($2 \times 10^7$ cycles) at high temperature of titanium alloys for disk application.

<table>
<thead>
<tr>
<th></th>
<th>BT25Y</th>
<th>Ti-6246 α/β</th>
<th>Ti-6246 β</th>
<th>IMI 834</th>
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<tbody>
<tr>
<td>450°C</td>
<td>210</td>
<td>180</td>
<td>190</td>
<td>-</td>
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<tr>
<td>550°C</td>
<td>220</td>
<td>-</td>
<td>210</td>
<td>200</td>
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2.2. PROCESSES MODELLING DEVELOPMENT

Turboengine manufacturers have been concerned for years in the processes cost reduction and quality improvement [5]. With regard to titanium alloys forged parts, these two objectives are to be reconciled and one favourite way to take up such a challenge is to develop numerical models enabling to account for the consecutive stages of the process [6]: alloy melting, ingot transformation through forging, heat treatment and associated microstructure evolution. For the turboengine designer, the ultimate issue of this development will be in the prediction of the mechanical properties in all the areas of critical components. Some examples of the benefits of forging and heat treatment modelling, in reference to the aforementioned objectives, are presented hereafter.

The first one deals with the isothermal forging of a Ti-6-4 fan disk. It was observed that undesirable folds may appear in zones of thickness variations. The material flow in the whole part during forging can be calculated through the finite elements code FORGE 2 [7] and the folds are well predicted (Fig. 4). Subsequent modifications of the dies geometry have allowed to eliminate those defects by means of computation. This
procedure is much less expensive than full scale tests and in that case, a significant quality improvement has been achieved at a limited cost.

Figure 4. Optimisation of isothermal forging in a Ti-6-4 fan disk.

The titanium alloys microstructural evolutions during thermomechanical treatments are other important concerns to be addressed. The mechanical properties are heavily influenced by the microstructures [8] and many experimental attempts and simulations have been carried out to obtain reliable microstructures after forging [6] and heat treatments [9]. The main difficulty lies in the determination and the quantification of the relevant microstructural parameters. For instance, in beta processed Ti-17 alloy, the beta recrystallized grains zone is a parameter worth of investigation since it may influence the fatigue resistance. A mathematical model is under development to predict the extent of the recrystallized zone in a forged part, from the processing data (deformation speed and temperature) and the stress-strain state as determined by the rheological code FORGE 2. A minimisation of the recrystallized volume in a Ti-17 compressor disk is achievable with adequate forging conditions which are determined by computation, as shown in Figure 5. Thus, the optimised processing route can be used rapidly by the forge workshop with a small number of iterations.

Figure 5. Simulation of recrystallized zones in a Ti-17 compressor disk.

The last example concerns a quantitative alpha microstructure determination during the continuous cooling stage of the β-CEZ alloy. The morphology of the alpha phase is known to have a strong effect on both fatigue crack initiation and propagation [8]. A nucleation-growth model has been proposed [10] with the aim of predicting the various alpha morphologies: along the grain boundaries (αGB), growing perpendicular to the grain boundaries
(αWGB) and inside the grains (αWI). The model fits rather well with experimental data regarding the temperatures where the above various alpha phases are observed (Fig. 6). The next step will consist in introducing a mechanical effect in the model to simulate the cooling operation after forging. An optimisation of the final microstructure in a disk corresponding to the desired associated mechanical properties is expected through this simulation.

In conclusion, the development of modelling in the forging operations of titanium alloys disks has progressed greatly in recent years. Valuable results have already been obtained and significant improvements in mults or dies shapes through computations have been achieved. The prediction of subsequent microstructures is available under well defined specific conditions and the final aim to associate mechanical properties might be reached. Important efforts are still needed both for a comprehensive understanding of the phenomena and their simulation. However, it seems reasonable to view a whole control of the thermomechanical process of forging titanium alloys disks within a few years: the compromise between time for adjustment, cost and quality will be then completed.

![Figure 6. Comparison between calculated and experimental transformation temperatures in the β-CEZ alloy as a function of the cooling rate.](image)

**3. FUTURE TRENDS**

**3.2. GAMMA TITANIUM ALUMINIDES**

The most extensive research activities in alloy development have been conducted on two-phase (TiAl + Ti₃Al) gamma TiAl alloys. The microstructure consists of 75-95% of the tetragonal TiAl phase having the L1₀ structure, the remainder being the aluminium rich Ti₃Al phase with the DO₁₉ structure. Gamma alloys are typically based on aluminium concentrations in the range 46-49 at.%. They also contain at least one ductilizing element and other elements which improve oxidation and creep. One example of this class of alloys is Ti-48Al-2Cr-2Nb which has been developed by General Electric. New generation gamma alloys are studied currently aiming to provide improved properties and higher temperature capabilities. Their composition can be expressed by the following formula [11]:

Ti-(46-47)Al-2Cr-(2-5)Nb-(0.2-1.2)W,Hf-(0.2-0.8)B,C,Si
Gamma alloys are processed by conventional methods, including casting, ingot metallurgy and powder metallurgy [12]. Recently, a new generation of castable gamma alloys has been developed at ONERA, based on the role of solidification paths [13]. While most of the alloys previously studied solidify through the alpha phase showing an as-cast microstructure characterised by the presence of columnar alpha grains in which all the gamma lamellae are formed perpendicularly to the axis of these grains, the alloys that have been developed solidify through beta. In that latter case, the initial beta grains are divided into differently oriented colonies of alpha laths in which gamma lamellae are subsequently formed. As a consequence, beta-solidified alloys exhibit much weaker texture and smaller grain size than alpha-solidified alloys such as Ti-48Al-2Cr-2Nb. Preliminary mechanical tests conducted on the new alloys indicate that they show a reasonable room temperature tensile ductility, together with an excellent high temperature creep strength.

It has been established that the microstructure and mechanical properties of gamma alloys very much depend on thermomechanical and heat treatment conditions. There are three main typical microstructures: duplex, fully lamellar (FL) and near lamellar (NL). The duplex structure consists of fine equiaxed gamma and lamellar alpha two + gamma grains whereas the fully lamellar structure is composed of coarse grains with parallel alpha two + gamma colonies. The near lamellar structure can be described as the refined preceding one.

The influence of the above microstructures on mechanical properties of gamma alloys can be summarised as follows: coarse-grained fully lamellar microstructure exhibits poor tensile ductility and strength, especially at room temperature, but relatively good fracture toughness and excellent creep resistance. Duplex microstructure shows moderate tensile ductility and strength at room and elevated temperature but low fracture toughness and creep resistance (Fig. 7). The optimum balance between fracture toughness, creep resistance on one side and tensile ductility/strength on the other side is expected for fine-grained fully lamellar microstructures with small gamma grains on the boundaries of lamellar grains [12].

Since several years, the research has entered the component design stage. Potential applications are compressor inlet casing and interstage casing in the place of conventional titanium alloys owing to the better burning resistance of gamma alloys. Significant mass savings can be achieved in the case of combustor and turbine casings which are made of nickel base superalloys. The same advantage will be obtained by replacing high pressure compressor vanes sectors and blades made of steel or superalloy today. Also, gamma alloys could be used for low pressure turbine nozzles and blades in civil engines: an example of a cast SNCEMA component is shown in Figure 8.

![Figure 7](image-url)  
**Figure 7.** Relations between room temperature tensile properties and microstructure/grain size in gamma alloys [12].

![Figure 8](image-url)  
**Figure 8.** Low pressure turbine nozzle segment (Ti-48Al-2Cr-2Nb alloy).
3.3. TITANIUM MATRIX COMPOSITES

3.3.1. Fibres

The reinforcement phase should possess high specific mechanical properties (modulus, tensile strength) up to 1000°C at least. Also, it should be both thermally and mechanically (expansion coefficient mismatch) stable with the titanium-based matrix.

There is a limited range of commercially available fibres. Most of them are large diameter SiC monofilaments produced by chemical vapour deposition (CVD). Silicon carbide offers the advantages of high strength at elevated temperature, good thermal stability and oxidation resistance. Two types of SiC fibres are produced: the ones manufactured by Textron (SCS-6, SCS-Ultra) have a carbon core (33 µm in diameter) whereas those fabricated by DERA-Sigma (SM 1140+) and ARC (Trimarc) have a tungsten core (13 µm in diameter). Thermal stability of SiC fibres with a carbon core is superior to the ones with a tungsten core: silicon carbide reacts with tungsten above 1000°C with the formation W2Si and WC and this reaction induces a decrease in the tensile properties of the monofilament [14]. All SiC fibres possess a protective coating to avoid any chemical interaction with the matrix during fabrication of the composite or service conditions. This coating mainly consists of carbon which has a thickness (3 to 5 µm) and a structure varying with the fibre.

The tensile strength of SiC monofilaments varies between 3.5 and 4 GPa generally. However, a significant improvement has been obtained recently at Textron by modifying CVD parameters for the deposition of SiC onto the carbon core and a tensile strength of 6.2 GPa has been reached [15].

3.3.2. Matrices

The most widely used titanium alloys in initial studies on TMCs were Ti-6-4 and Ti-15-3. However, the increased operating temperature of advanced aeroengines requires matrices with improved high temperature properties and near-alpha alloys are of interest for that reason. Several compositions have been considered: Ti-6242, Ti-1100 and IMI 834. The best candidate appears to be Ti-6242 although its creep performance is not as good as the one of the two other alloys. Indeed, matrix cracking has been observed in the as-consolidated condition in composites made with Ti-1100 and IMI 834 alloys [16,17]. It has been shown that this cracking phenomenon results from the combined effect of the microstructure of the alloy and thermal residual stresses at the fibre/matrix interface [18].

The first significant activity on continuously reinforced titanium aluminide composites was performed on the SCS-6/Ti-24Al-11Nb system. The Ti-24Al-11Nb alloy is mainly composed of the alpha two phase and it was shown that the properties of the composite are limited by the characteristics of that phase. These limitations include low ductility, chemical incompatibility with the carbon-rich coating of the SCS-6 fibre, poor creep resistance, inadequate transverse properties and environmental embrittlement when exposed to oxygen at elevated temperature [19,20].

Orthorhombic titanium aluminides represent the best alternative to alpha two alloys at the present time. These new materials possess a better room temperature ductility and improved high temperature specific strengths (tensile, creep). The matrix compositions of interest range from Ti-(21 to 25)Al-(17 to 27)Nb.

3.3.3. Fabrication routes

The manufacture of TMCs is difficult because of the high melting point and the extreme chemical reactivity of titanium-based alloys. Therefore, processing of composites is limited to solid state routes at a maximum temperature around 1000°C. Various fabrication methods have been developed with the objective of producing high quality and cost effective components. These methods differ in the way in which the fibre and the matrix are assembled before consolidation. The consolidation is performed in a temperature range where the matrix exhibits good formability, or even superplastic behaviour. The different routes are usually termed as foil/fibre/foil, plasma spray coating and physical vapour deposition (PVD) coating. Details of these processes are described below.

The foil/fibre/foil route consists of the consolidation of alternately stacked layers of alloy foil (80-120 µm thick) and fibre mat made of aligned monofilaments. The fibre mat is produced either by weaving with a wire or ribbon, or the fibres are held in place with a fugitive organic binder which is outgassed before the final consolidation [21,22]. This process can be only applied to titanium alloys that possess a good formability and that can be obtained in the form of foil at a reasonable cost, i.e. beta-metastable, alpha-beta and some near-alpha alloys. Figure 9 gives an example of a 12 ply SM 1140+/Ti-6242 composite manufactured at SNECMA. Attempts have been made to produce titanium aluminide foil by chemical milling of sheet or pack rolling but these techniques are too expensive. It should be mentioned that an alternative to the foil is the use of a titanium alloy wire or of a powder matrix, whereby the powder is mixed with an organic binder and the resulting slurry is cast into a thin tape.

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Vacuum plasma spraying is used to manufacture TMCs monotapes. Metallic powders of 20-100 µm are fed continuously into the plasma where they are melted and propelled at high velocity onto a single layer of fibres wound on a drum. The monotapes thus obtained are subsequently cut, stacked and hot pressed to form a fully dense TMC component [23,24]. The quality of the monotapes very much depends on the care that has been taken to avoid gas contamination (oxygen, nitrogen) and superficial fibre damage due to the impact of molten droplets.

The PVD processes that have been developed can be subdivided into two categories: electron beam evaporation and deposition (EBED) [25-27] and sputter techniques [28,29]. In both processes, SiC fibres are precoated with a thick layer of matrix before consolidation into a bulk composite. The matrix material is provided entirely by the coating, thus avoiding the expensive alloy product forms such as foil or powder required for the aforementioned methods. The main advantage of these processes, as compared with other fabrication routes, is the attainment of a very uniform fibre distribution with no fibres touching. Furthermore, the fibre volume fraction in the finished composite can be controlled by the thickness of the coating. Also, as each fibre is surrounded by matrix material, handling and consolidation are less damaging to the reinforcement than other processes.

Among the different sputter techniques, the triode sputtering route has been developed at ONERA for the manufacture of TMCs [29]. As compared with the EBED route, it offers the possibility to use any matrix alloy with a precise control over the chemical composition of the coating on the fibre; different conventional (Ti-6-4, Ti-6242, IMI 834) and intermetallic (Ti-22Al-27Nb) alloys have been deposited with success. Figure 10 is a transverse optical micrograph of a SM 1140+/Ti-22AI-27Nb orthorhombic titanium aluminide composite manufactured at ONERA.

Figure 9. Transverse optical micrograph of a SM 1140+/Ti-6242 composite manufactured by the foil/fibre/foil route.

Figure 10. Transverse optical micrograph of a SM 1140+/Ti-22AI-27Nb composite manufactured by the ONERA processing route.

3.3.4. Applications

Potential applications of TMCs are advanced aero-engines where their high temperature properties are very attractive. Recognising that the structural limits of more conventional aerospace materials have been reached, engine designers have turned to TMCs as a way to increase performance-to-weight capability. Many engine components using TMCs have been demonstrated (compressor and turbine blades, shafts, vanes, nozzles, casings, actuator rods) but the most significant of which are compressor disk replacements where the potential weight savings due to improved specific properties are the greatest. The increase in mechanical properties allows radical changes in the design of the component. The conventional disk and blade arrangement is replaced by a fibre-reinforced bladed ring, also called bling, which exploits the longitudinal strength of the composite to carry the very high hoop stress. Studies have shown that, compared to a conventional disk and blade assembly, a bling of this type could provide a weight saving of up to 50% in advanced engine compressors. This does not take into account effects on other associated components due to the reduction in core engine rotation mass. A SM 1140+/Ti-6242 reinforced bling manufactured at SNECMA is illustrated in Figure 11.
4. CONCLUSION

The Russian alloy BT25Y exhibits excellent mechanical properties when compared to usual high temperature titanium alloys for disk and blade applications. Its tensile strength is higher than those of Ti-6242 and IMI 834 in the temperature range 20-600°C and its fatigue resistance is better than the one of Ti-6242 at 450 and 550°C. Today, rather than developing new grades, the main efforts of titanium alloys end-users in aerospace industry are aimed at mastering all the processes involved in disks manufacturing, especially microstructures in regard of mechanical properties, both for cost reduction and reliability concern. In that way, the modelling of thermomechanical treatments has progressed greatly in recent years. The material flow during processing can be calculated in order to obtain homogeneous microstructures according to the required mechanical properties in forged products.

Both technical and economical barrier issues are to be addressed for the introduction of gamma titanium aluminides and TMCs in aero-engines. One main technical issue to the wide spread application of gamma alloys remain their low ductility up to 600°C as enough plasticity is necessary to achieve damage tolerance in service. Also, mechanical properties are sensitive to small variations in the concentration of some alloying elements and the close control of the chemical composition may be difficult to attain in production ingots.

With regards to TMCs, recent manufacturing techniques have improved the quality of the products. However, scaling up of the fabrication processes and NDE testing are issues still to be addressed. Besides, a thorough understanding of mechanical damage mechanisms must be established in order to develop life prediction models.

From an economical point of view, efforts are required to reduce the cost production of these advanced materials, especially TMCs, in order to enable their implementation in future aero-engines.

5. LITERATURE