Titanium alloy Ti-6242 for high temperature structural application. Static and dynamic mechanical properties and impact of ageing.

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Abstract

Increasing the efficiency of aero-engines by increasing the engines' working temperatures requires, in turn, the adaptation of the materials used in structural parts surrounding the engines. Specifically, improvement of the mechanical properties, resistances to specific operational loading conditions and good durability are required in the targeted range of temperatures. Building upon work on titanium alloys that are resistant to high temperatures—already used by engine designers—studies have been carried out to find alloy + microstructure combinations that are likely to meet structural requirements.

Guided by targeted mechanical specifications, various industrialized thermo-mechanical processes have been performed to produce Ti-6242 pancakes of different initial microstructures. For each manufacturing route investigated, the microstructure, tensile properties, crack propagation resistance and fracture toughness have been evaluated, either as-manufactured or after ageing for 5000 hours at 500°C. The different types of microstructures do not exhibit the same initial mechanical resistances, and the sensitivity of alloy Ti-6242 to high temperature ageing phenomena proves to be highly microstructure dependent. Nevertheless, among these different microstructures, some show properties that comply with targeted specifications and show interesting long duration thermal stability, which makes them promising candidates for future industrial future needs.

1-Introduction

Given the aeronautical industry's goal to lower environmental footprints through the optimization of engine efficiency, an increase of the engines' working temperature is required. This temperature increase necessitates adaptation of the materials used in the vicinity of the engines while limiting the embedded weight increase. The requirements for high working temperature applications generally lead to materials with good static properties, good resistances to dynamic loading conditions, and limited deterioration of properties due to thermal ageing phenomena. Among these materials, titanium alloys are the most suitable to comply with the aforementioned requirements and constraints.

Enabling the use of titanium alloys for higher temperature structural applications is of foremost interest in order to provide alternatives to Ti-64, which has already reached its limit service temperature. Additionally, alternatives to nickel based superalloys currently used for higher working temperatures are needed. As such, manufacturers must modify or optimize existing thermo-mechanical processes or develop new titanium alloys with enhanced properties and resistances. The targeted properties for the considered structural applications were defined in terms of tensile properties and ductility, fracture toughness (FT) and crack growth rate (CGR) in the as-received state as well as after 5000 hours of isothermal ageing at 500°C.

The considerations on which alloys are more likely to fulfil the requirements for high temperature structural applications led to the selection of near-α titanium alloys. Among the different alloys considered in these activities, alloy Ti-6242 provided the most promising results. This alloy is already used by engine suppliers to produce rotating parts such as hot section gas turbine components and high pressure compressor disks, and is, hence, known to have interesting high temperature performances [1–3].

To this end, the different types of microstructural features most likely to fulfil the specifications were determined on the basis of the collected information throughout a large literature review. Different initial microstructures and metallurgical conditions have been produced by industrial forging and heat treating operations. The selection of the initial microstructures was based on their expected range of tensile strength and ductility levels, resistances to dynamic loading conditions, and their different response to prolonged isothermal ageing.

2-Material and experiments

2.1-Material selection and manufacturing operations

The titanium alloys used in the present works were supplied by TIMET. The dimensions of the Ti-6242 billet sections used to perform the different thermo-mechanical processing (TMP) routes were 250 mm in diameter and 280 mm in length. Optimal TMP routes were first proposed on the basis of a wide literature review on links existing between mechanical resistance, microstructures and the microstructures generated during processing parameters. These optimal processing routes were then adapted to the constraints of industrial production processes.

In order to evaluate the most suitable forging parameters, ie. providing the largest suitable volume for samples machining with the most homogeneous strain levels throughout the produced pancakes, simulations were carried out on Forge™ prior to forging operations. Forgings and heat treatments were carried out by Aubert & Duval on conventional industrial equipment. The as forged and heat treated pancakes for each initial microstructure were then separated in symmetric halves, one to be characterized in the as-received state and the other one to be characterized after exposure to 5000 hours of isothermal ageing treatment at 500°C. Sampling plans were developed in order to permit the comparison of material properties with those having undergone similar thermo-mechanical histories for all stages of heat treatment.

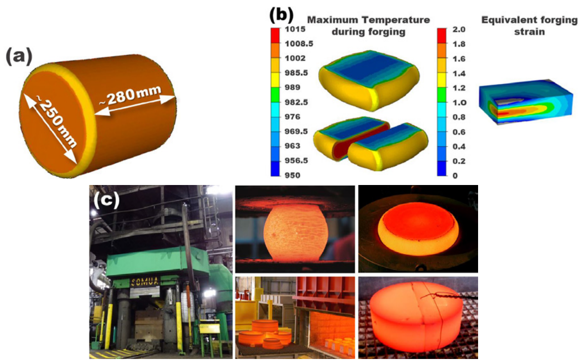

Figure 1- Process for selection of TMP routes, forging modes, and manufacturing parameters: (a) typical dimensions of initial billet sections, (b) thermo-mechanical simulations of forging of pancakes, and (c) illustration of the 22 000 kN hydraulic press used to perform forging operations, courtesy of Aubert & Duval, Pamiers.

2.2-Microscopic observations

Metallographic preparation was performed by grinding with SiC paper until 2400 grit and finished by a long polishing step with an OPS + 10% hydrogen peroxide mixture. Etching was performed using Kroll's reagent. Microstructure observations were carried out along the different main directions of the produced parts on an Olympus PMG3 optical microscope.

2.3-Mechanical tests

Mechanical characterizations were performed for the different microstructures of Ti-6242 alloy, either as-manufactured or after long time exposure to ageing temperature through tensile tests, FT and CG tests along different directions of the produced parts.

Tensile tests were carried out at both room temperature and 500°C according to NF-EN-2002-01 and NF-EN-2002-02 respectively on a screw-driven Instron™ testing machine with a constant strain rate of 0.005 min^{-1} throughout the test. Cylindrical tensile specimens 5 mm in diameter and 30 mm in length were used. Fracture toughness and crack propagation tests were carried out at room temperature on 100 kN Instron devices respectively on CTW40B20 specimens according to ASTM-E399-12 and on CTW50B12 specimens with a frequency of 10 Hz according to ASTM-E647-15.

3-Results

3.1-Generated microstructures

The different microstructures produced through the applied TMP routes were first characterized by optical microscopy in different locations in the pancakes. Various initial types of microstructures were targeted due to their respective interests regarding their resistance to different loading conditions, as well as their evolution during prolonged isothermal ageing.

The β-annealed material exhibits a fine Widmanstätten microstructure with thin α phase on the prior β grain boundaries, whereas β-forged material exhibits a slightly coarser lamellar basketweave microstructure with the local presence of α colonies and tortuous prior β grain boundaries decorated by α phase. The bimodal microstructure exhibits a large volume fraction—between 40 and 55%—of small size primary α nodules.

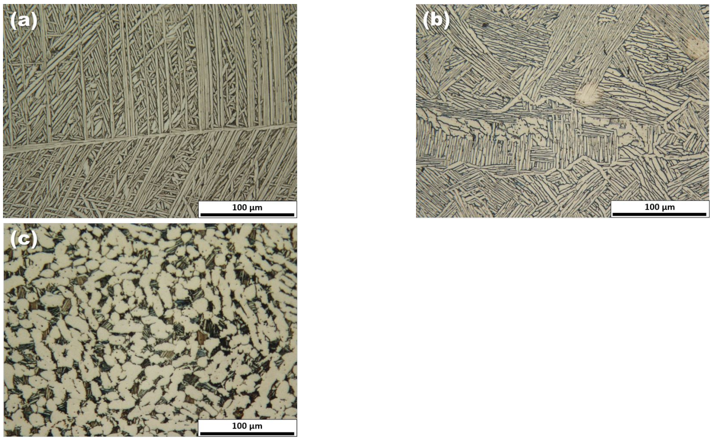

Figure 2- As received microstructures of Ti-6242 alloy after the different TMP routes applied to initial billet sections: (a) β-treated, (b) β-forged, and (c) α/β forged.

3.2-Mechanical testing results

3.2.1-Tensile tests

The tensile tests carried out on the different initial microstructures and states of ageing of Ti-6242 provided an accurate overview of the effect of isothermal ageing on the alloy's tensile properties with respect to the sampling direction and location in the pancake. Figure 3 shows the average tensile properties of ten room temperature tests for the three initial microstructures before and after long term ageing. The prolonged exposure to high temperature has nearly the same effect on the tensile strength for all microstructures. The main difference when considering the impact of ageing concerns ductility. Whereas bimodal microstructures' ductility remains nearly unaffected by long term ageing, both lamellar microstructures exhibit strong ductility reductions after exposure to 5000 hours at 500°C. The elongation to failure of β-treated and β-forged Ti-6242 alloy were reduced by 35 and 45% of their as-received values, respectively.

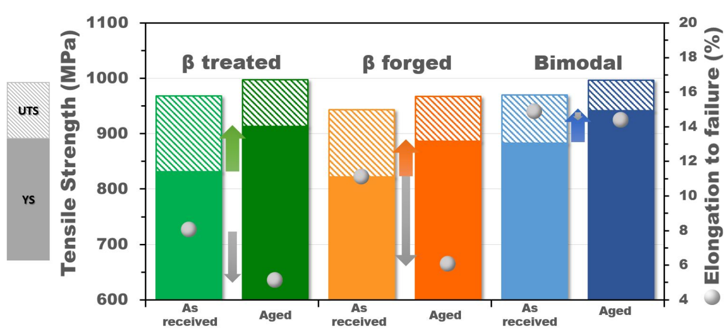

Figure 3- Tensile properties in (light colours) as received state and (dark colours) after isothermal ageing, 5000 hours at 500°C. The lower full coloured parts of the histogram correspond to yield strength while the upper dashed parts represent the ultimate tensile strength. Shadowed circles represent to the uniform elongation of the different metallurgical states.

3.2.2-Fracture toughness

FT tests were carried out on each microstructure in both the as-received state and after long term ageing and in the three main directions of the produced pancakes. The histogram in Figure 4 shows the average K_q (FT) values. As expected, long term ageing lead to a reduction in the measured fracture toughness, whose extent depended on the initial microstructure.

The as-received lamellar microstructures showed high fracture toughness values close to which was reduced to about 65 to 70 after ageing for 5000 hours at 500°C—a reduction of 25-30%. The bi-modal microstructure presented lower fracture toughness of about 50 to 60 in its as-received state, which was reduced after long-term ageing by 25 to 40% to about 35 to 40.

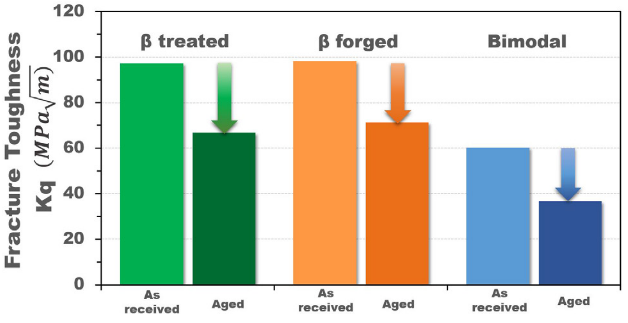

Figure 4- Average FT values in three main directions tests for the three microstructures of Ti-6242 alloy in the as-received state (light colours) and aged state (dark colours).

3.2.3-Crack growth rate

The crack propagation rates of the different microstructures were characterized in different directions of the initial pancakes both before and after long-term ageing. The impact of prolonged ageing was quite different depending on the considered initial microstructure. Both lamellar structures appeared to be moderately affected by long-term ageing, and the observed increase in crack growth rate (CGR) essentially affected these microstructures for high stress intensity factors . Bimodal microstructures were strongly impacted by long-term ageing, and they exhibited significant increases in crack propagation rates even at average stress intensity factors, reaching up to one order of magnitude faster CGR above .

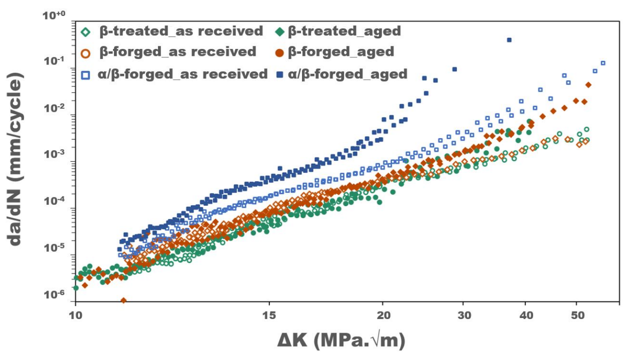

Figure 5- Crack propagation rate curves for the different initial microstructures, in their as-received state (light colours empty signs) and after isothermal ageing for 5000 hours at 500°C (dark colours full signs) : (a) lamellar microstructures, β-treated (green) and β-forged (orange), and (b) bimodal microstructures, α/β forged (blue).

4-Discussion

As expected, long term isothermal ageing impacts tensile properties to different extents as a function of initial microstructure. The bimodal Ti-6242 microstructures exhibited high tensile strength and a high ductility which was only slightly impacted by long-term ageing. In contrast, for lamellar microstructures, the material showed lower tensile strength and low ductility. Ductility was, in particular, strongly impacted by isothermal ageing and exhibited a drop of close to 45% after 5000 hours at 500°C. This reduction of ductility can be expected to have a noticeable impact on FT and CGR.

Indeed, it is known that microstructural parameters are likely to impact crack propagation in two different ways: a direct influence on unstable crack propagation through the modification of the material's ductility or a structural influence on the geometry of the crack front.

In this view, the proposed lamellar microstructures were selected to provide a compromise between FT and CG resistance. This required a microstructure with relatively fine prior β grains together with very fine and, if possible, discontinuous α_{GB} phase at prior β grain boundaries. It has been shown that for lamellar microstructures FT tends to decrease with decreasing grain size [4,5]. On the other hand, the presence of α_{GB} of sufficient thickness contributes to higher FT, but an excessive thickness is known to have a deleterious effect on fatigue crack initiation at the β/α_{GB} interfaces [6].

Under dynamic loading conditions, many elements can influence the global response of the alloy to crack propagation, among which can be mentioned: the prior β grain size, the ductility, its strain hardening capacity and the tortuosity of the path offered to propagating crack. Hence, reaching a good resistance to fatigue crack propagation generally requires moderate YS combined with high strain hardening [7,8] until failure at important strain values with minimal strain localisation.

When considering lamellar microstructures the propagating cracks are essentially deviated at α/β interfaces between α lamellae and between two α colonies [9]. Fine lamellar structures form a complex path for cracks to go through, and generally exhibit better resistance to crack propagation under cyclic loading conditions [1,10,11] than bimodal ones.

The reduction in ductility of Ti-6242 lamellar microstructures due to isothermal ageing together with the evolutions of FT and CGR suggests that ductility is not a key parameter driving these properties. Instead, both appear to be related to the crack propagation path provided by these microstructures.

The higher ductility of bimodal microstructures makes them generally less sensitive to crack initiation, but this ductility does not compensate for the lower tortuosity of the crack path, provided that their strain hardening capacity has not been enhanced by other structural optimization. This optimization would require the presence of a relatively low volume fraction of finely and evenly distributed primary α nodules throughout the alloy's microstructure. Even if the theoretical TMP routes likely to provide such a microstructure are known and feasible at the laboratory scale, the precise control of thermal parameters can be extremely hard to manage industrially. Indeed, the massiveness of a 150 kg pancake is inherently problematic given the thermal heterogeneity and the quenching kinetics that vary significantly from the skin to the bulk. Furthermore, even if tensile ductility remains nearly unaffected by long term ageing, FT and CGR are however impacted by this prolonged exposure to high temperature.

5-Conclusion

The best properties and resistances to the targeted types of loading conditions clearly proved to be the lamellar ones, obtained either by β annealing or β-forging. These lamellar microstructures fulfil targeted specifications in their as-received state and their properties remain sufficiently high despite significant decreases in ductility due to isothermal ageing after long term exposure to high temperatures. On the other hand, tensile properties of bimodal microstructures showed much lower sensitivity to thermal ageing, and their tensile ductility remained nearly unaffected by long term ageing. Nevertheless, these microstructures exhibited lower FT and higher CGR, especially for high stress intensity factors. Furthermore, even if their ductility was not impacted by isothermal ageing, they exhibited important drops in FT and CGR after 5000 hours at 500°C exposure, which makes them unlikely to fulfil the targeted properties.

To further develop titanium alloys for use in aeronautical structures at such a high temperature, it is necessary to better understand their high temperature mechanical response and durability. In the present work, the only mechanical tests carried out at working temperature were tensile tests. Although the static response of the alloy at such a high temperature, both before and after long term ageing, is important, it does not account for the coupled phenomena likely to occur during dynamic tests. Environmental effect occurring at 500°C is an important factor in several titanium alloys' loss of durability, especially when dealing with enhanced CGR due to plasticity-oxidation interactions and/or hydrogen embrittlement at the crack tip [12–19]. Hence, even if these microstructures of alloy Ti-6242 sound promising, collecting data on high temperature behaviour and quantifying the coupling effects occurring between plasticity and environment appears necessary to optimize the alloy and further develop their use for high temperature structural applications.

6-Acknowledgements

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7-References

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