Studies on Titanium Alloys for Aerospace Application

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Abstract. Since the development of the Ti54M titanium alloy in 2003, its application within the aerospace sector has gradually increased due to the combination of properties such as improved forgeability and machinability, low flow stress at elevated temperatures, and superplastic characteristics. However, for the successful exploitation of Ti54M a comprehensive understanding of its mechanical characteristics, microstructure stability, and superplastic behaviour is required.

The superplastic forming of titanium alloys is characterised by high deformation at slow strain rates and high temperatures which influence the material microstructure, and in turn, determine the forming parameters. These mechanisms make the prediction of the material behaviour very challenging, limiting its application within the aerospace industry. Even though Ti54M has been commercially available for over 10 years, further studies of its mechanical and superplastic properties are still required with the aim of assessing its applicability within the aerospace industry as a replacement for other commercial titanium alloys. Therefore, in this work a study of the mechanical and superplastic properties of Ti54M, in comparison with other commercial titanium alloys used in the aerospace industry - i.e. Ti-6AL-4V, and Ti-6-2-4-2 - is presented. The final objective of this study, carried out at the Advanced Forming Research Centre (AFRC, University of Strathclyde, UK), is to obtain material data to calibrate and validate a model capable of estimating the behaviour and grain size evolution of titanium alloys at superplastic conditions.

Introduction

Over the years the aerospace industry has played a vital role on the development and application of new materials. The current demand for reduced fuel consumption in combination with high quality manufacturing standards, is driving the aerospace engineering sector to develop new materials that can both lead to significant weight savings and withstand challenging environments, while remaining easy to manufacture.

Materials used in aerospace are required to have a range of properties depending on application, these include low density, resistance to high temperatures and to embrittlement at low temperature, high corrosion resistance and low thermal expansion. Compared with most steels and aluminium alloys, titanium alloys have higher specific strength and corrosion resistance. Titanium alloys have found increasing use on modern aircraft; they have a higher temperature stability than aluminium alloys and half the weight of most of the steels [1], in addition to good fatigue strength, crack propagation resistance and fracture toughness [2]. For example, Ti-6Al-4V, Ti-3Al-2.5V, Ti-10V-2Fe-3Al, Ti-6Al-2Sn-4Zr-2Mo and Ti-15V-3Cr-3Sn-3Al are used to manufacture frames, engine parts, hydraulic pipes, landing gear parts, track beams, exhausts, tail cones and airplane ducts [2].

The most common titanium alloy within the aerospace industry is Ti-6Al-4V (Ti-64). This α/β alloy has a good combination of mechanical properties, a wide temperature range for processing, and is highly weldable [3]. Ti-6Al-2Sn-4Zr-2Mo (Ti-6-2-4-2) and Ti-5Al-2Sn-4Mo-2Zr-4Cr (Ti-17) are used in place of Ti-64 where there is a requirement for higher temperature resistance and higher strength, respectively [2], [3]. However, the machining of these alloys remains as one of the main challenges for their application within the aerospace industry.

For aircraft engines, titanium alloys such as Ti-64 and Ti-17 are selected for their light weight, high strength, and heat resistance. For fan blades, where the working temperature is relatively low but higher specific strength, toughness and fatigue resistance are needed, titanium alloys such as Ti64 and Ti-17 are used [2], [4]. For high pressure compressor components, titanium alloys with high heat resistance, strength and fatigue resistance characteristics such as Ti-6-2-4-6 are chosen. For compressor disks, low-cycle fatigue and creep resistance characteristics are needed. Therefore, titanium alloys such as Ti-6-2-4-2 and Ti-6-2-4-6 are usually employed [2].

TIMETAL® 54M (Ti54M) is an α/β alloy which provides higher machinability than Ti-64 while maintaining equivalent mechanical properties [5]. Additionally, previous work [6], [7] has shown that Ti54M has superplastic behaviour at lower temperatures than Ti-64, which may reduce the energy consumption during forming Ti54M parts.

The objective of this work was to understand the possible applications where Ti54M could be used as an alternative material that is easier to process or where Ti54M could provide better mechanical performance. This paper provides an overview of the mechanical and superplastic properties of Ti54 compared with other titanium alloys (i.e. Ti-64, and Ti-6-2-4-2).

Background

The materials selected for the present work, Ti54M, Ti-64 and Ti-6-2-4-2, were analysed based on both their mechanical properties at room temperature and their behaviour at superplastic forming conditions. Note that the chemical composition of the alloys, detailed in Table 1, is directly related with their mechanical properties. The aluminium is a so-called α phase stabiliser. The presence of significant levels of α phase contributes to a higher strength, but reduces machinability and forgeability. Additions of vanadium and molybdenum stabilise the β phase making the alloy more workable and may facilitate precipitation hardening generating significant tensile strength [8].

Table 1 Chemical composition and mechanical properties of some titanium alloys [2], [6], [9]

	Composition (wt%)	Density (g/cm^3)	Yield Strength (MPa)	Tensile Strength (MPa)	Elongation at RT	β transus temperature (°C)
Ti54M	Ti-5%Al-4%V-0.7%Mo-0.5%Fe	4.44	845	925	10%	950±17
Ti-64	Ti-6%Al-4%V	4.43	825	895	10%	996±14
Ti-6-2-4-2	Ti-6%Al-2%Sn-4%Zr-2%Mo	4.55	860	930	10%	995±15

Ti54M - Developed by TIMET in 2003, Ti54M exhibits an improved machinability as compared to most titanium alloys while maintaining mechanical properties similar to those of Ti-64. Its yield strength is over 845 MPa, with a tensile strength over 925 MPa, and an elongation at room temperature higher than 10%. The slightly reduced aluminium content (5%) in Ti54M as against Ti-64 (6%) improves the forgeability and machinability of this alloy, addressing one of the main challenges for its industrial application. The addition of molybdenum (0.55%) promotes α grain refinement. The β phase diffusion is accelerated due to the higher content of iron (0.45%) [7].

Ti-64 - The ideal balance in the material characteristics of strength, ductility, fracture toughness, high temperature strength, creep resistance, weldability, workability, and thermal processability has enabled Ti-64 to become the preferred titanium alloy for use within the aerospace industry to date. The yield strength of the annealed material is 825 MPa or higher, its tensile strength is 895 MPa or higher, and its elongation is 10% or higher at room temperature. Ti-6Al-4V contains 6% of aluminium, which stabilizes the α phase by solid solution strengthening without causing embrittlement, and 4% of vanadium, which stabilizes the β phase and helps to refine the microstructure and strengthen the alloy [10].

Ti-6-2-4-2 - Developed in the 1960s, this heat resistant material is the most common alloy used for high temperature aircraft applications. (its heat resistance is 200°C higher than in Ti54M and Ti-64). Ti-6-2-4-2 oxidation and creep resistance can be improved by adding 0.06-0.2 wt% of Si. The yield strength of the annealed material is over 860 MPa, its tensile strength is over 930 MPa, and its elongation is 10% or higher at room temperature. The high temperature strength of Ti-6-2-4-2 makes it difficult to machine, as it tends to crush the cutting edge of the tool.

Experimental Procedure

Tensile tests of Ti54M and Ti-64 were performed at the Advanced Forming Research Centre (AFRC) of the University of Strathclyde at a specified strain rate ($1x10^{-4}$ s^{-1}) and three different temperatures within their superplastic range (785-815 °C for Ti54M and 875-925°C for Ti-64) to identify the process conditions which result in the material exhibiting the key indicators of superplastic deformation (high strain rate sensitivity, high strains and uniform deformation).

Table 2 shows the high temperature tensile test matrix for Ti54M and Ti-64 samples, which were carried out on a Zwick-Roell Z250 electro-mechanical test machine following the ASTM E2448 standard. The tests were performed within an Argon atmosphere to protect the surface from oxidation during testing. The tensile test samples, cut by EDM, had a gauge of 25 mm length, 6 mm width and 1.6 mm thickness.

Table 2 Tensile test matrix for Ti54M and Ti-64 material samples

	Strain rate (s^{-1})	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
Ti54M	$1x10^{-4}$	785°C	815°C	845°C	-	-	-
Ti-64	$1x10^{-4}$	-	-	-	875°C	900°C	925°C

Results and Discussion

Superplastic forming (SPF) of titanium alloys offers several advantages to the aerospace industry, mainly related to the possibility of producing complex shaped parts in one operation. In superplastic forming, higher values of strain rate sensitivity ($m > 0.5$) and lower temperatures are preferred. The m value is linked to the material's capacity to resist necking and provides an indicator of the material's superplastic formability. Lower process temperatures reduce the grain growth in the material, allowing for higher elongations and a reduced α case at the surface of the formed part (hence less post-processing).

The β transus temperature of Ti54M is approximately 930°C; lower than Ti-64 whose transus is typically around 1000°C. However, for Ti54M a superplastic response may be obtained at a temperature as low as 732°C [7], i.e. 100°C lower than in Ti-64. Figure 1 (a) shows the results of the high temperature tensile tests carried out on Ti54M samples. As expected, the true stress decreases with increase in temperature due to the material softening behaviour. Figure 1 (b) shows the results of the high temperature tensile tests carried out on Ti-64. Similarly to Ti54M, the true stress decreases with increase in temperature due to the material softening. The flow stress in Figures 1 (a) and (b) are similar, although the tests were done at much lower temperature for Ti54M. The reduced flow stress for the Ti54M would facilitate lower forming temperatures in manufacture, which would itself reduce heating costs, alpha case formation and likely improve tool life.

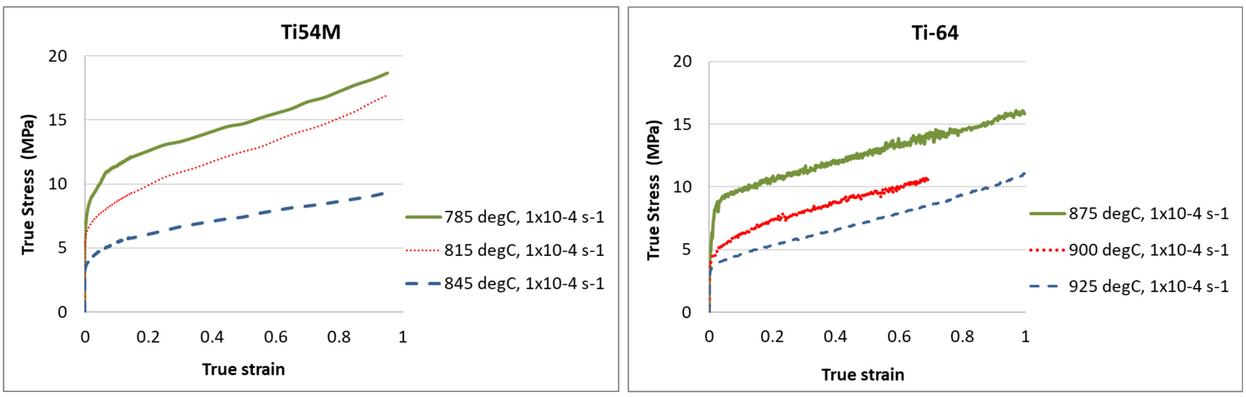

Figure 1 True stress vs true strain curves at high temperature of (a) Ti54M and (b) Ti-64

Strain rate jump tests, Figure 2 (a), were performed as per the ASTM E2448 standard, allowing the calculation of the strain rate sensitivity value (*m* value). Figure 2 (b) shows the strain rate sensitivity of Ti54M, Ti-64, and Ti-6-2-4-2 within their superplastic temperature range.

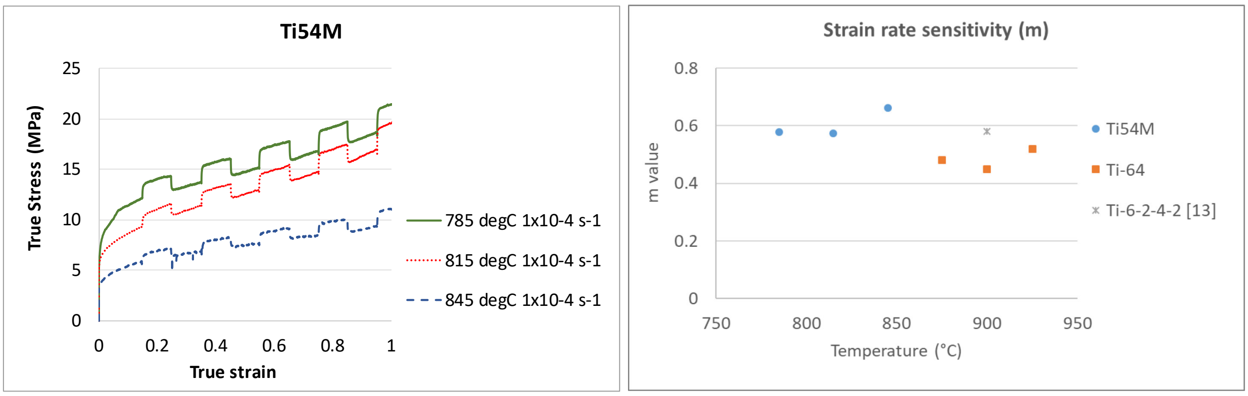

Figure 2 (a) Jump strain rate test and (b) strain rate sensitivity (*m*) at the superplastic temperature range for titanium alloys: Ti54M, Ti-64 and Ti-6-2-4-2

Ti54M shows superior superplastic forming properties than Ti-64 and Ti-6-4-2-4, i.e. at a lower temperature (below 850°C) Ti54M shows a higher *m* value while keeping same similar peak stresses as compared to Ti-64, and much lower than Ti-6-4-2-4 (over 80% difference [11]). Ti54M however exhibited a higher flow hardening at the strain rate tested.

The microstructural evolution of the material during heating and forming affects the flow stress behaviour. At the temperatures associated with superplastic forming, the titanium alloys will be in the two phase region with approximately equal volumes of both the α and β phase. Sieniawski [12] has shown that the best superplastic properties in α/β alloys are achieved for 40%-50% volume fraction of β phase. The presence of the two phases stabilises the grain size. It is considered that most of the deformation is accommodated in the β phase due to its cubic crystal structure (as against the hcp structure of the α phase) and higher diffusion rates which facilitate the recovery mechanisms operating during forming.

The β transus temperature of Ti-6-2-4-2 is approximately 996°C, which is similar to Ti-64 but higher than in Ti54M. At a lower volume fraction of β phase (approximately 20%), the strain rate sensitivity of Ti-6-2-4-2 is equivalent to that of Ti-64, i.e. approximately 0.5 [12]. However, Ti-6-2-4-2 exhibits experimentally 30% less elongation than Ti-64. At higher temperature (over 900°C), when both materials have achieved equal volumes of α/β phase, the superplastic behaviour of Ti-6-2-4-2 improves but does not reach that of Ti54 and Ti-64 [13]. Moreover, the peak stress values of Ti54M at these high temperatures are much lower than in Ti-64. It is expected that this behaviour is related with the microstructure of the material, therefore further studies of the Ti54M microstructural evolution of the material are being carried out at the AFRC.

Conclusions

The similar mechanical properties between Ti54M, Ti-64 and Ti-6-2-4-2, makes Ti54M suitable for application in the manufacture of aircraft components, where it can possibly replace Ti-64 and Ti-6-2-4-2 alloys for some applications. The potential application of Ti54M in the aerospace industry is mainly a result of its higher machinability and better weldability characteristics. However, Ti54M is still limited to applications up to the range of 315 °C. For higher temperatures, Ti-6-2-4-2 remains as a better option.

The study conducted on the superplastic behaviour of Ti54M alloy also indicated possible wider applications within the aerospace industry. With a maximum strain rate sensitivity of 0.66 versus 0.52 and 0.58 of Ti-64 and Ti-6-2-4-2 respectively, Ti54M exhibits superplastic behaviour at much lower temperature (approximately 100°C) than the main titanium alloys used in the aerospace industry. The results highlighted that the potential use of Ti54M could provide considerable energy savings during the SPF process due to the lower forming temperature required. This aspect also helps to overcome one of the limits for the wider application of the SPF technology, i.e. the use of costly high temperature resistant tools.

As the temperature increases, Ti54M exhibits lower flow stress values – between 30% - 40% lower than Ti-64 and Ti-6-2-4-2. The flow stress behaviour is related with the microstructural evolution of the material during forming. Therefore, current ongoing investigations at the AFRC on the microstructure evolution of Ti54M within the superplastic temperature range will help to further understand the behaviour of this alloy and the possibilities for its exploitation on industrial applications. The results of this work will also be used to calibrate and validate a material model that is able to predict the superplastic behaviour and grain size evolution of the material during forming.

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