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AME HIGH TEMPERATURE DEFORMATION OF Ti6Al4V AT LOW STRAIN RATE

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ABSTRACT

A superplastic Ti6Al4V alloy has been deformed at a strain rate of 5 10^{-4} s^{-1} and at various temperatures up to 1050°C. Structural mechanisms like grain boundary sliding, dynamic recrystallization (DRX), and dynamic grain growth, occurring during deformation, have been investigated and mechanical properties such as flow stress, strain hardening and strain at rupture have been determined. DRX results in a decrease of grain size. This could be of great interest because a smaller grain size permits to lower the superplastic forming temperature. Microstructural and mechanical investigations were carried out to understand and describe the occurrence of the observed mechanisms.

Key words: Titanium alloy; dynamic recrystallization, superplasticity, grain growth

INTRODUCTION

Last decades, titanium alloys have been widely used in the aeronautical industry and for bio-medical applications. The interest in titanium and its alloys can be explained by its remarkable properties, such as a high tenacity, a good heat resistance, a particular resistance to corrosion, biocompatibility, its superplastic capacities and last but not least its interesting specific mass when compared to other high strength alloys such as steels [1]. Superplastic materials are polycrystalline solids which have the ability to undergo large strains prior to failure. Generally, the deformation temperature has to be superior to half of the melting temperature, whilst the strain rate must be between 10^{-4} s^{-1} and 10^{-2} s^{-1} [2-4]. The aeronautical grade of Ti-6Al-4V is superplastic roughly between 750°C and 950°C, and between strain rates of 10^{-4} s^{-1} and $5.10^{-3}s^{-1}$. Some authors report optimal superplasticity around 927°C [5-7]. In the present study the tensile properties and the structural evolution during deformation between room temperature (RT) and 1050°C have been investigated in a systematic way. As for the strain rate, it was decided to limit the study in a first step to a strain rate of 5.10^{-4} s^{-1} (referenced as the optimum strain rate for the superplasticity). Structural mechanisms like grain boundary sliding, dynamic recrystallization and dynamic grain growth have been investigated. Dynamic recrystallization decreases the grain size and thus allows superplasticity to occur at a lower temperature. Special attention has been given to the evolution of grain size not only as a function of temperature but also as a function of deformation.

MATERIAL AND METHOD

The material used for the current study was a commercial titanium alloy, TIMETAL® 6-4 Titanium Aero. In the as received state, it was annealed after hot and cold rolling into sheet of 1mm thickness and an initial grain size of 8 µm. In order to determine the influence of temperature on the mechanical behavior of this alloy, tests were performed on a tensile machine equipped with a furnace with three independent zones (constant temperature length 30 cm) and controlled atmosphere. Temperatures varied between room temperature and 1050°C. The tensile machine was operated at a constant true strain rate of 5 10^{-4} s^{-1}. During each test, a nitrogen gas flow was introduced in order to prevent oxidation of the sample and forming of α-case at the specimen surface. After each test, samples were quenched to room temperature by the injection of nitrogen gas inside the furnace. The method developed by Katrakova [8] was used to prepare the samples for automated Electron Backscattered Diffraction (EBSD) measurements. These measurements were carried out in a Philips XL30 microscope and analyzed with the FEI (TSL) software. Grain size measurements were performed with the mean linear intercept technique.

RESULTS AND DISCUSSION

Depending on the overall form of the tensile curves, four temperature domains with different underlying deformation mechanisms have to be considered.

RT-650°C. Fig. 1 presents the true stress-true strain curves of samples deformed in this domain. At room temperature, there is classical work hardening and the ductility is limited. With increasing temperature a gradual softening appears and the post uniform elongation increases. In this domain the microstructural changes as shown in Fig 2 are only caused by the tensile deformation. Dynamic recovery becomes more prominent with increasing temperature, but no dynamic recrystallization occurs.

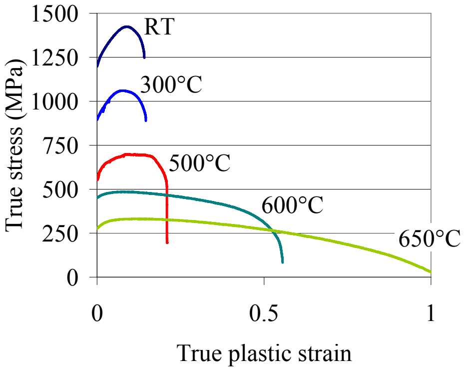

Fig. 1. True stress-true plastic strain curve of a Ti-6Al-4V flat specimen tested between room temperature (RT)and 650°C with a strain rate of 5 10^{-4} s^{-1}

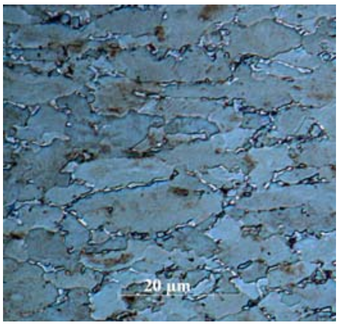

Fig. 2. Microstructure of a flat Ti-6Al-4V sample deformed at 500°C at a strain rate of 5 10^{-4} s^{-1} until 30% engineering strain. (TD is the tensile direction)

650°-750°C. In this domain the ductility is larger than at the lower test temperatures, but no "superplasticity" is observed, in the sense that no grain boundary sliding (GBS), which is typical for superplastic behavior, could be detected. In order to check this, a sample was deformed at 700°C until 100% engineering strain, then it was polished and a scratch was made on its surface. The deformation was then continued to 150% engineering strain. No discontinuities of the scratch could be observed at the intersection with grain boundaries.

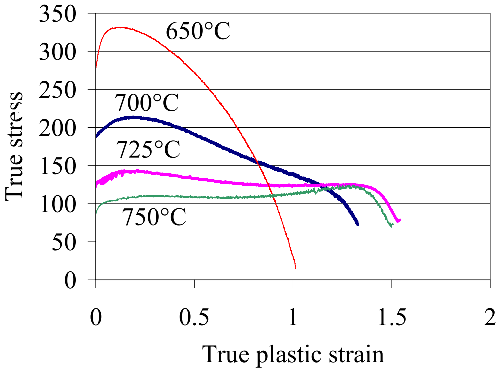

Fig. 3. True stress-true plastic strain curve of a Ti-6Al-4V flat specimen tested between 650°C and 750°C and a strain rate of 5 10^{-4} s^{-1}

The evolution of the grain size for deformation at 700 °C is shown in figure 4. A decrease in grain size of approximately 50% is observed in both the α and β phases. The decrease starts around 10% engineering strain and stops around 60%, where the grain dimensions seem to be stabilized.

Additional thermal treatments were performed to study the influence of deformation on the grain size evolution. Firstly, undeformed samples were heated to 700°C and maintained in the furnace during the same time as would be the samples during the tensile test. No variations were observed in the microstructure. Secondly, cold deformed samples were annealed during various times between 0 and 60 seconds at 700°C. None of them showed any modification of the grain size. Consequently the driving force resulting from the sample deformation seems to be necessary to trigger the grain refinement. It is very unlikely that the observed grain refinement would be due to a fast static recrystallization occurring just after the test and before quenching. Therefore we conclude that the decrease in grain size is due to dynamic recrystallization. The sample deformed for 30% exhibits a rather broad grain size distribution (Fig. 5). Some grains of the initial size (7-8µm) are present together with smaller grains (2-3µm). Samples quenched from 700°C after different degrees of deformation show that the microstructure remains equiaxed during the whole deformation. The observed phenomenon of dynamic recrystallization is quite similar with the one which was observed in commercially pure titanium by Zhu et al..[9]

750-950°C The evolution of the σ-ε curves as a function of temperature is presented in figure 6. At these temperatures, grain boundary sliding is noticed to be active and the deformation can be classified as "superplastic". The rupture strain is larger than at 700°C but the material seems to undergo a kind of hardening. This is due to dynamic grain growth. To ensure material continuity during grain boundary sliding, some accommodation mechanisms such as diffusion and dislocation climb are needed. When the grain size increases, the importance of the accommodation will also increase. On an σ-ε curve this will be translated by a raise of the flow stress.

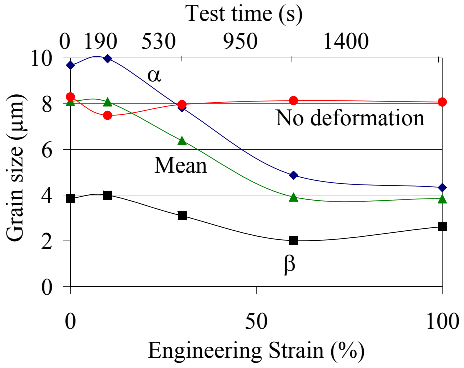

Fig. 4. Grain size evolution as a function of strain from a sample tested at 700°C.

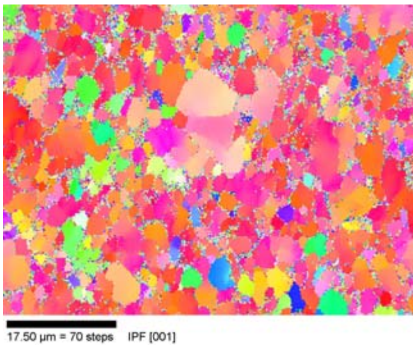

Fig. 5. Automated EBSD scan of a flat Ti-6Al-4V sample deformed at 700°C at a strain rate of 5 10-4 s-1 until 30% engineering strain

At 800°C the maximum rupture strain is obtained. The evolution of the grain size for this particular temperature is shown in figure 7. During the first part of the deformation a dynamic recrystallization occurs as in the previous temperature domain but gradually grain growth becomes more important. This grain growth is mainly dynamic: the influence of strain on grain growth was also illustrated by thermal treatments at 800°C, without deformation; only a slight variation of the grain size could be observed. Although the rupture strain starts decreasing clearly around 900-925°C, superplastic deformation is still active up to 950°C. An explanation of this decrease can be found in the evolution of grain size as a function of strain at these temperatures. At 925°C, grain growth become very pronounced in both phases, making the extent of DRX very limited and even difficult to observe (Fig. 8). Grain boundary sliding couldn't be observed directly on the deformed samples. Nevertheless the fact that the flow stress raises with increasing grain size, could be considered as an indirect but clear evidence of its occurrence.

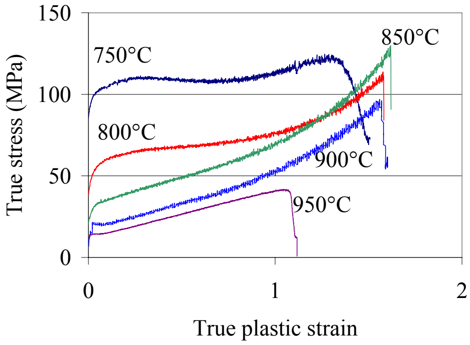

Fig. 6. True stress-true plastic strain curve of a Ti-6Al-4V flat specimen tested between 750°C and 950°C and a strain rate of 5 10^{-4} s^{-1}

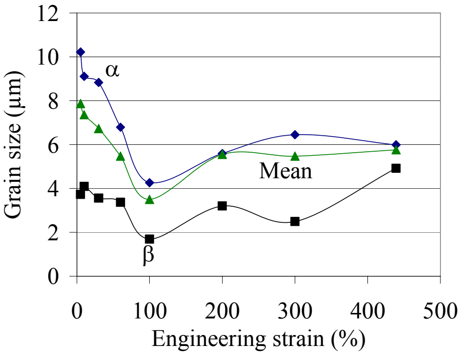

Fig. 7. Grain size evolution as a function of strain for a sample tested at 800°C

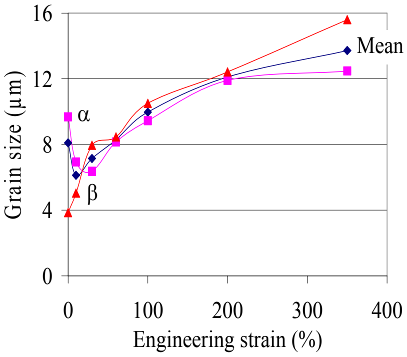

Fig. 8. Grain size evolution as a function of strain for a sample tested at 925°C

950-1050°C In this temperature domain, only DGG could be observed. The grains become too large for grain boundary sliding to occur. Another important point in this temperature interval is the proportion of β-phase. Superplastic deformation is favored by an equal amount of both the α and β phase [10-11]. At 950°C there is already 65% of β-phase and at 995°C the α-β transformation is complete. One sees that all parameters are negative for superplastic deformation: a large grain size and the predominance of the β-phase.

In literature, 927°C is presented as the optimum for superplastic deformation at a strain rate of 5 10^{-4} s^{-1} [5-7]. In this study, the superplastic deformation was effectively observed at this temperature but quite better results were observed at lower temperature. The optimum was detected around 800°C where all parameters are favorable indeed: DRX causes grain refinement and not overruled yet by DGG; temperature is high enough to allow the accommodation mechanism for the GBS to be active. From an industrial point of view, it could be reasonable to work around 700°C since rupture strain is high enough (350%) for most applications. A lower superplastic forming temperature would lead to worthwhile energy cost savings.

SUMMARY

The evolution of the mechanical behavior of Ti-6Al-4V with an initially equiaxed microstructure was investigated as a function of temperature at low strain rate. The microstructural evolution and more particularly the grain size evolution of the different phases has been determining in describing the phenomena taking place. The following conclusions are drawn from this work.

1. Between room temperature and 650°C the regime is the conventional work hardening which is increasingly counterbalanced by recovery with increasing temperature.
2. Between 650°C and 750°C dynamic recrystallization occurs.
3. Between 750°C and SP deformation is active but influenced by dynamic recrystallization and dynamic grain growth. At 800°C all parameters are optimal for superplasticity.
4. Above 950°C, dynamic grain growth is preponderant and causes, together with the increasing β phase fraction, the disappearance of superplasticity.

ACKNOWLEDGMENT

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