1-1-2010

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Journal of Physics: Conference Series **240** (2010) 012022 doi:10.1088/1742-6596/240/1/012022

Effect of microstructural morphology on the mechanical properties of titanium alloys

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Abstract. Different morphologies of α+β microstructures were obtained in a commercial Ti-6Al-4V alloy by cooling at different rates from the single β-phase region into the two phase region. The effect of such morphologies on mechanical properties was studied using hot compression tests in a Gleeble thermomechanical simulator. A variety of complex morphologies could be obtained since the cooling rate has a significant influence on the β to α phase transformation and the resulting morphological development. While most of the β phase transformed to colonies of α at high cooling rates, it was possible to obtain a complex mixture of α colonies, grain boundary α and lamellar structure by decreasing the cooling rate. These complex morphologies each exhibited distinctive mechanical properties and characteristic dynamic phase transformation behaviour during deformation as a function of strain rate.

1. Introduction

Titanium alloys exhibit mechanical and physical properties which fit aerospace applications in which light weight, good wear and corrosion resistance are required and provide significant economic benefit in these applications. However, these unique properties are strongly affected by the chemical composition, microstructure, deformation and heat treatment history. Ti-6Al-4V (Ti64) as the most popular α+β titanium alloy used in the aerospace industry, has attracted significant research interest and an enormous amount of work has been done regarding the improvement of its mechanical properties through heat treatment, hot deformation or a combination of these processes. Much of the research centred on improving the microstructure and attaining appropriate mechanical properties. Earlier work has shown that the initial microstructure such as the fraction of α and β phases, the morphology and thickness of α-lathes as well as the size of α colonies (i.e. the geometrical arrangement of α and β-phases) have significant effects on the mechanical properties of the Ti64 alloy. For example, Lütjering [1] has shown that among the all microstructural characteristics, the α colony size has the most significant influence on the mechanical properties. It has furthermore been shown that parameters such as the cooling rate from the β- phase field, the initial β grain size and the presence of interstitial impurities (oxygen and carbon), can affect the geometrical arrangement within the microstructure of the Ti64 alloy. The cooling rate seems to be one of the most important parameters affecting microstructural development. Whereas slow and intermediate cooling rates lead to nucleation and growth of α-lamellae into the initial β grains through a diffusion controlled process, higher cooling rates render a martensitic transformation [1, 2].

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The influence of different initial microstructures on the mechanical properties of a variety of α+β titanium alloys containing a single morphology, has been extensively studied [3, 4]. However, the case is more complicated when a mixture of different morphologies with different responses to hot deformation exists in the initial structure. The present project was therefore designed to study the effect of cooling rate, from the single β-phase into the two-phase α+β region, on the geometrical arrangement of the constituent phases and in addition, to determine the effect of the resulting arrangements on the mechanical properties of a commercial Ti64 alloy.

2. Experimental procedure

12.7 mm diameter rods of commercially available Ti-6Al-4V alloy (0.06% C, 0.2% Fe, 0.15% O, 5.8% Al, 4.1% V and balance of Ti) were used in this study. Samples for the compression tests, 12.7mm diameter and 19 mm in length were cut from the as-received rods. Hot compression tests were carried out in a Gleeble 3500 thermomechanical simulator. Samples were heated to 1323 K at a rate of 5 Ks^{-1} and held for 180 s, aiming to achieve a single phase β microstructure. To achieve different morphologies of α+β structures from this initial β phase, samples were cooled to 1073 K at different cooling rates (10, 5, 2, 1 or 0.5 Ks^{-1}). Following cooling to 1073 K, some samples were directly quenched in water to study the microstructural development as a function of cooling rate. While other samples were deformed at a strain rate of 1 s^{-1} or 0.1 s^{-1} followed by water quenching to assess the influence of cooling rate on the resulting mechanical properties. Microstructural development was studied by optical and scanning electron microscopy following standard metallographical practice.

3. Results and Discussion

Figure 1 shows the microstructure of Ti64 samples after soaking at 1323 K and cooling to 1073 K at different rates. The microstructure developed by cooling at a rate of 5 ks^{-1} consists of colonies of α within the prior coarse β-grains of about 350 μm (Figure 1a). On some selected β grain boundaries α-plates nucleated and grow towards the β-grain interior (acicular α). This acicular structure of α was presumably formed during cooling from the β transition temperature to 1073 K. Also, a thin layer (<1 μm) of grain boundary α (GB-α) was observed in some regions of prior β-grain boundaries. By decreasing the cooling rate to 2 Ks^{-1}, the microstructure changed to a mixture of α-colonies, α-lamellas with an average size of 40 μm and α-plates (i.e. acicular-α) of 1 μm thick as well as some GB-α (Figure 1b). Slower cooling caused the formation of even more complex structures consisting of large lamellar-α, acicular-α, GB-α as well as some large equiaxed or elongated α-grains (Figures 1c and d). The thickness of both the acicular and GB-α phases is increased by decreasing the cooling rate. Figure 2 shows the influence of cooling rate on the thickness of α-phase as measured from SEM images. It is clear that a decrease in the cooling rate from 10 to 0.5 ks^{-1} leads to an increase in the thickness of GB-α from 1 μm to more than 10 μm. Figure 1 shows that the volume fractions of both morphologies of α are also increased by decreasing the cooling rate. It stands to reason that during slow cooling, more time is available for the diffusional transformation of β to α leading to an increase in the size and volume fraction of the different α- morphologies.

These experiments clearly demonstrated that a wide range of microstructures with different morphologies and sizes of α-plates can be brought about by changing the cooling rate and it is expected that these different morphologies can not only influence the mechanical properties of the as-quenched specimens but perhaps more importantly, have a determining effect on the mechanical properties following hot deformation. To further probe this premise, hot deformation tests were carried out at different strain rates and examples of typical shapes of flow curves are shown in Figure 3. The flow curves show a rapid increase to the peak followed by a continuous flow softening beyond the peak. The peak stress as a function of cooling rate (i.e. different microstructures) is superimposed in Figure 2. At both strain rates, an increase in the cooling rate leads to an increase in peak stress up to a cooling rate of 2 Ks^{-1} and then remains constant. Lütjering [1] has shown that for a fully lamellar structure, the flow stress remain constant at cooling rates between 1 $Ks^{-1}$and 100 Ks^{-1}, and only at cooling rates higher than 100 Ks^{-1} a rapid increase in flow stress is observed due to a decrease in the α-colony size. The present work has shown that at cooling rates between 2 Ks^{-1} and 5 Ks^{-1}, where most of the microstructure is consists of α-colonies (Figure 1a and b), the flow stress is essentially constant (Figure 2) in agreement with Lütjering. However, a gradual decrease in cooling rate below 2 Ks^{-1} leads to a rapid decreased in peak stress. Figures 1c and d, confirm that the microstructure following slow cooling comprise a complex mixture of different α-phase morphologies. It is well known that these different morphologies have different strengths and deform by different mechanisms. Colonies of α are expected to have the highest strength due to their unique orientation. By contrast, β-layers are very soft at high temperature while grain boundary-α should be softer than α-colonies, but will be harder than the equiaxed α-phase. Therefore, mixtures of these phases in the initial microstructures result in complex mechanical behaviour upon further deformation at high temperature. Moreover, dissimilarity between the restoration mechanisms of the different α-morphologies during hot deformation will lead to even more complex mechanical response. While a kinking process, which has less effect on stress, is proposed for the restoration process of α-colonies [5], it is expected that lamellar and GB-α will be restored by dynamic recovery and recrystallization. These proposed phenomena were studied in more detail by analyzing the as-deformed microstructures.

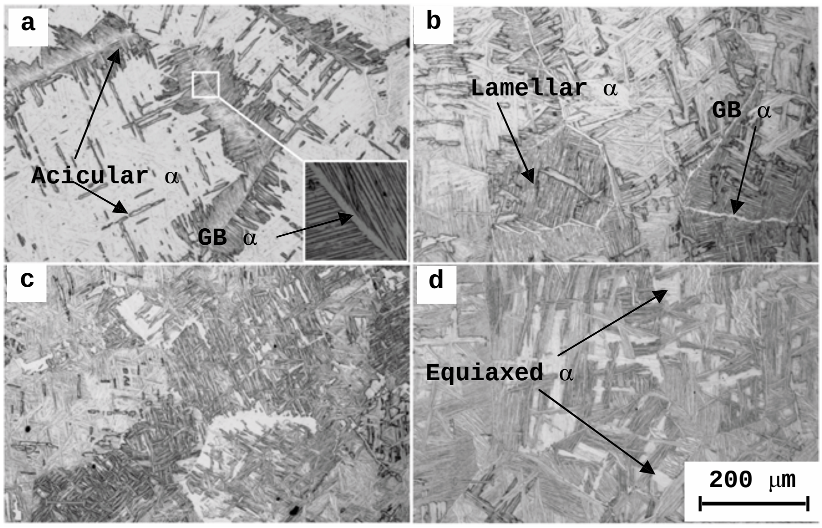

Figure 1: Microstructure of Ti64 alloy after re-heating to 1323 K and cooling to 1073 K at different cooling rates **a)** 5 Ks^{-1}, **b)** 2 Ks^{-1}, **c)** 1 Ks^{-1} and **d)** 0.5 Ks^{-1}

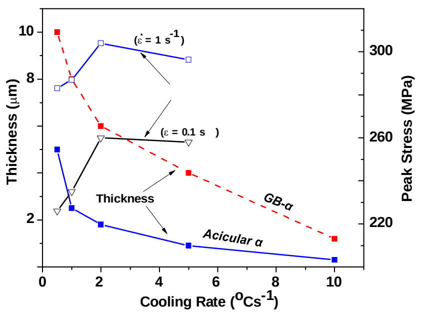

Figure 2. The thickness of α-phases and peak stress as functions of cooling rate

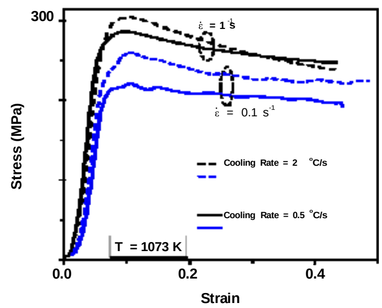

Figure 3. The flow curves of samples deformed at 1073 K at different strain rates

Figure 4 shows the optical microstructure of samples with different initial microstructures resulting from different cooling rates to 1073 K and then isothermally deformed at a true strain of 0.5. While the lamellar α-structure globulized, the grain boundary and equiaxed-α phases were plastically deformed and elongated (pancake structure) along the direction of deformation. The result of globularization is a massive decrease in the average grain size of the α+β structure and the effect of this globularized structure on mechanical properties as shown in Figure 3 is a decrease in the flow stress (a continuous softening in flow stress). The influence of globularization of the lamellar structure on decreasing the flow stress is clear for samples cooled at low rates. As these samples have more and larger α-lamellar phase, the globularization of this phase caused a significant decrease in the flow stress (Figure 2). The GB-α and equiaxed grains of α showed a different restoration mechanism compared to lamellar-α. A trace of dynamic recrystallization was frequently observed in these α morphologies by the formation of small grains in the vicinity of the initial grain boundaries (Figure 4c) and it is reasonable to assume that the occurrence of such a dynamic recrystallization is the main reason for decrease in peak stress in slow cooled samples since they contain a larger fraction of GB and equiaxed α.

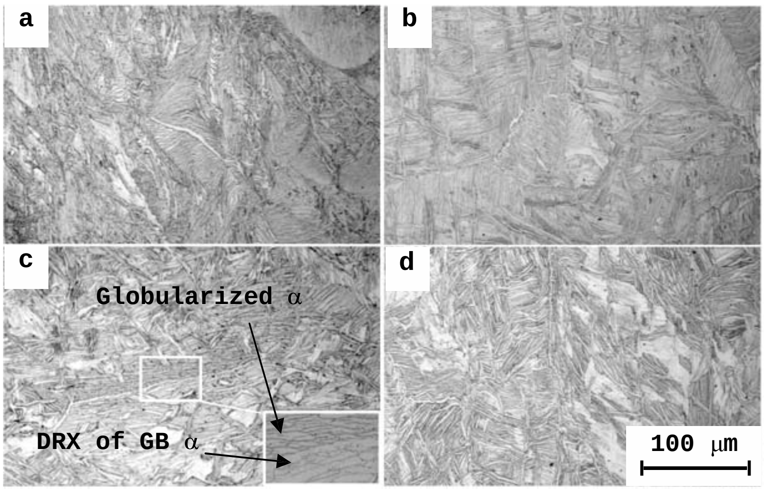

Figure 4: The microstructure of Ti64 alloy deformed at 1073 K after cooling at different rates of **a)** 5 ks^{-1}, **b)** 2 ks^{-1}, **c)** 1 ks^{-1} and **d)** 0.5 ks^{-1} ($\dot{\varepsilon} = 1s^{-1}$)

An interesting observation is the presence of multiple peaks in the flow curves following deformation at low strain rates (Figure 3). This phenomenon has been observed during the hot deformation of steel under very low strain rates and/or very high temperatures and has been attributed to the occurrence of discontinuous dynamic recrystallization [6]. However, more accurate analyses of deformed microstructures are necessary to verify that discontinuous dynamic recrystallization is responsible for the appearance of multiple peaks in the present case.

4. Conclusions

A wide variety of simple and complex microstructures were obtained following cooling of a commercial Ti-6Al-4V alloy from the single β-phase region to the α+β region after different cooling rates. Different initial microstructures responded differently to hot deformation. While, lamellar structures globularized, grain boundary-α and equiaxed α-grains deformed plastically. Also, traces of dynamic recrystallization were observed following hot deformation in microstructures containing grain boundary α-phase.

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