Acta Materialia 141 (2017) 285–293

Contents lists available at ScienceDirect

Acta Materialia

journal homepage: www.elsevier.com/locate/actamat

Full length article

Influence of β anisotropy on deformation processes operating in Ti-5Al-5Mo-5V-3Cr at room temperature

S. Hémery*, P. Villechaise

Institut Pprime, CNRS – ENSMA – Université de Poitiers, UPR CNRS 3346, Physics and Mechanics of Materials Department, ENSMA – Téléport 2, 1 Avenue Clément Ader, BP 40109, 86961 Futuroscope Chasseneuil Cedex, France

ARTICLE INFO

Article history:
Received 11 July 2017
Received in revised form
6 September 2017
Accepted 8 September 2017
Available online 15 September 2017

Keywords:
Titanium alloy
Slip
In situ tension test
EBSD
Anisotropy

ABSTRACT

In the past, little attention was paid to the effects of the high β fraction retained at room temperature on the deformation behavior of β metastable titanium alloys. As it significantly differs from more conventional α/β alloys, mostly constituted of α phase, a thorough investigation appears as mandatory. This is the aim of the present study through a detailed characterization of the operating deformation processes combined with an evaluation of the strain field heterogeneities. Tensile tests conducted in a scanning electron microscope coupled with markers tracking and electron back-scattered diffraction techniques enabled an in situ monitoring of the early activity of deformation systems. A major influence of the elastic anisotropy of the β phase on the highly heterogeneous deformation behavior was revealed in the elastic and plastic regimes. The underlying mechanisms controlling the onset and the development of plasticity in β metastable titanium alloys are clarified and discussed accordingly.

1. Introduction

β metastable titanium alloys are increasingly used at room temperature due to a higher strength than conventional α/β titanium alloys such as Ti-6Al-4V while maintaining high corrosion resistance and fracture toughness. Compared to α/β alloys, a refined microstructure and a high beta fraction (≈40%) are present [1]. Although the influence of the β phase on the mechanical properties is usually neglected in conventional α/β alloys, such high amounts might have significant consequences for these alloys. In particular, the body centered cubic (BCC) β phase is known to exhibit a high elastic anisotropy [2]. Hence, a heterogeneous stress field is expected and might consequently lead to heterogeneous initiation and development of the plastic activity [3].

To the authors' knowledge, the deformation processes operating in β metastable alloys have not been thoroughly characterized yet despite its prime importance for numerous aerospace applications with fatigue life as a critical design criterion. Indeed, crack initiation, accounting for most of the fatigue life in α/β titanium alloys [4], is reported to proceed on slip bands [5,6]. Although prismatic slip bands potentially lead to secondary crack initiation, fatal cracks originates from quasi-cleavage facet nucleation related to basal slip activity in the primary alpha nodules [5–8]. Nevertheless, the different composition might induce a different activation of deformation systems. Besides, interaction between neighboring nodules such as slip transmission also appear as a key parameter in α/β alloys submitted to cyclic loadings [9,10]. The microstructure of β metastable alloys being rather constituted of isolated nodules due to the low primary alpha fraction (≈20%), the studies focusing on the plasticity development and the crack initiation processes deserve to be revisited for an improved behavior understanding and prediction. Indeed, fatigue life dispersion in such alloys is reported as related to multiple crack initiation mechanisms and heterogeneous deformation in specific microstructural arrangements [11–13].

Therefore, the aim of the present work is the characterization and the identification of the deformation processes operating in Ti-5Al-5Mo-5V-3Cr. Monotonic tensile loading was used to facilitate the analysis as a recent study revealed highly similar activated deformation systems under monotonic and cyclic loadings in titanium alloys [14]. The applied procedure, based on in situ tensile tests carried out inside a scanning electron microscope (SEM), was adapted to the multiscale microstructure of the alloy. Indeed, the diameters of β grains reach several hundreds of microns while α nodules are a few microns sized precipitates. As a consequence, elastic and plastic strains were estimated using metallurgical

* Corresponding author.
E-mail address: samuel.hemery@ensma.fr (S. Hémery).

https://doi.org/10.1016/j.actamat.2017.09.023
1359-6454/

markers tracking inside single β grains while slip trace analysis was carried out to monitor the activation and the development of plastic slip in elementary elements such as α nodules. The use of the electron backscattered diffraction (EBSD) technique enabled to characterize the crystalline orientation of both α and β phases. To evidence a potential correlation between the deformation behaviors at different scales, a particular attention was paid to the crystalline orientation of the β phase and its potential consequences on the mechanical fields. Finally, additional post-mortem observations enabled to discuss the processes involved in the first plasticity development stages while considering a large number of β grains.

2. Experimental

Ti-5Al-5Mo-5V-3Cr with a bimodal microstructure composed of α_P nodules and α_S lamellas embedded in a beta matrix was used in the present work. SEM micrographs of the microstructure are shown in Fig. 1. The average nodule diameter and the surface fraction of primary α_P precipitates were estimated at about 2.5 μm and 15% respectively. The elongation, yield and tensile strengths are about 7.4%, 1181 MPa and 1240 MPa respectively according to a tensile test performed at a strain rate of 10^{-4} s^{-1}.

A dog bone shaped specimen with a gage length of 10 mm was machined for the in situ tensile test. The gage width is 2 mm and the thickness about 1 mm. A final polishing step using an OPS + 10% H_2O_2 solution was applied on the face observed in situ to enable both an easy detection of the slip traces and a successful EBSD characterization of the microstructure. SEM observations and EBSD characterizations were performed using a JEOL 6100 SEM equipped with an EBSD setup provided by EDAX. The crystalline orientation of the β phase was first characterized using the EBSD technique with a 3 μm step over the whole gage length. The corresponding inverse pole figure (IPF) map coded with respect to the tensile direction is given in Fig. 2 a. An accurate average β grain size measurement being difficult to due to the intragranular crystalline misorientations resulting from the processing steps, semi-qualitative estimations using crystalline orientation maps gives an average grain diameter about 300 μm. The orientation density function has been computed and plotted on an inverse pole figure in Fig. 2 b. The maximum being about 1.4 times random, no marked texture is noticed. All the crystalline orientation domain is thus fairly represented in the specimen gage length.

4 regions of approximately 50 × 60 μm^2 were followed in situ. These regions are located inside single β grains with different β crystalline orientations. They were selected from the IPF map of Fig. 2 a in order to study β orientations with different stiffness. As a reminder, <001> directions are usually reported as the most compliant, while <111> directions are usually reported as the stiffest. The orientation distribution of the β phase in each region is shown on an IPF in Table 1. Despite the high intragranular orientation spread inside β grains shown in Fig. 2 a, the orientation distributions reveal a low misorientation in the restricted area of the regions of interest. The crystalline orientations of the nodules contained in those regions are plotted on IPFs shown in Table 1. Highly non-uniform distributions of orientations are observed. The Burgers' orientation relationships between the α and β phases and selection of α precipitation variants might have a significant contribution to the distribution differences from one region to another [15]. Therefore, consequences might be expected on the activation of plasticity in these grains since the first slip bands are usually reported to appear in nodules rather than in lamellar colonies [14,16]. Nevertheless, crystalline orientations corresponding to high Schmid factors for basal and prismatic slip systems are present in all regions. For clarity purposes, iso-curves of Schmid factors plotted on IPFs are not recalled here but can be found in Ref. [17].

The specimen was loaded inside the SEM with a constant crosshead displacement rate of 0.02 mm min^{-1} using a Deben 5 kN tensile stage. The displacement was stopped at a target stress magnitude to observe the surface of the specimen and detect newly appeared slip traces. Beyond 800 MPa, 20 MPa steps were applied to accurately estimate the macroscopic applied stress at slip trace appearance. From 1030 MPa up to 1060 MPa, 10 MPa increases were rather used to avoid large strain increments between successive stops. The engineering stress − engineering strain at each stop is plotted in Fig. 3. At 1060 MPa (i.e. the end of the test), the total strain is about 1.4%. The corresponding plastic strain is about 0.4%. A sharp elastic − plastic transition is noticed, in agreement with the low strain hardening rates usually observed in titanium alloys [18].

The total strain in the tensile axis was estimated at each stop for the 4 regions followed in situ using markers tracking. At least 3 pairs of α_P precipitates were identified in each region and used as metallurgical markers. SEM micrographs were then processed using an in-house code to obtain the axial strain. The low spread of estimated strains given in Table 1 indicates a good accuracy of the estimation procedure (<4%). Additionally, the activated deformation systems were identified using a conventional slip trace analysis. The crystalline orientation in α_P nodules was obtained through an EBSD characterization using a 0.2 μm step. Basal, prismatic and <**a**>-type pyramidal potential slip traces were computed and compared with experimentally observed slip traces. A 5° criterion was used to dismiss slip traces with no matching theoretical slip trace. The resolved shear stress at slip trace appearance was computed using the macroscopic applied stress and the Schmid factor of the slip system identified as active. Therefore, Sachs model was employed in the present analysis [19]. The use of such assumption in this context was discussed in Ref. [20]. The CRSS was then estimated by averaging the computed resolved shear stresses at slip trace appearance. Similar procedures are now widely employed [14,16,17,21,22] although the homogeneous assumption is a rough approximation considering anisotropic materials such as titanium alloys [23].

To obtain a statistical insight about the influence of the β crystalline orientation on the deformation processes operating during the development of plasticity, post-mortem SEM observations of the deformed specimen surface were performed at the end of the test in 30 different regions. The potential relationship with the crystalline orientation of α and β phases was discussed from EBSD maps of the regions acquired using a 0.4 μm step.

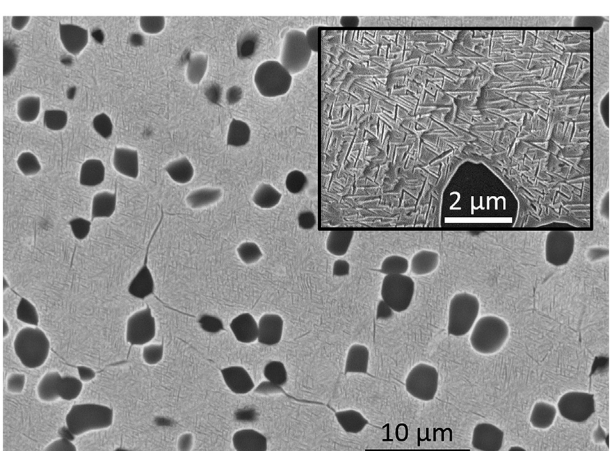

Fig. 1. SEM micrographs of the Ti−5Al−5Mo−5V−3Cr used in the present study.