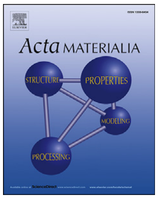
Acta Materialia 136 (2017) 402–414

Contents lists available at ScienceDirect

Acta Materialia

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



Full length article

Micromechanical behaviour of a two-phase Ti alloy studied using grazing incidence diffraction and a self-consistent model

Y. Zhao [a], S. Wroński [b], A. Baczmański [b, *], L. Le Joncour [a], M. Marciszko [c], T. Tokarski [c], M. Wróbel [d], M. François [a], B. Panicaud [a]

[a] ICD-LASMIS, Université de Technologie de Troyes (UTT), UMR CNRS 6281, 12 rue Marie Curie, CS 42060, 10004, Troyes, France
[b] AGH- University of Science and Technology, Faculty of Physics and Applied Computer Science, al. Mickiewicza 30, 30-059, Krakow, Poland
[c] AGH- University of Science and Technology, Academic Centre for Materials and Nanotechnology, al. Mickiewicza 30, 30-059, Krakow, Poland
[d] AGH- University of Science and Technology, Faculty of Metals Engineering and Industrial Computer Science, al. Mickiewicza 30, 30-059, Krakow, Poland

ARTICLE INFO

Article history:
Received 21 March 2017
Received in revised form
9 June 2017
Accepted 9 June 2017
Available online 10 June 2017

Keywords:
Elasto-plastic deformation
Polycrystalline material
Self-consistent model
Grazing incidence angle
X-ray diffraction

ABSTRACT

The mechanical behaviour of each phase in two-phase titanium Ti-18 was studied at room temperature under a low strain rate tensile test until fracture. Due to its selectivity, the X-ray diffraction method was applied for *in-situ* tensile test to analyse the behaviour of each phase in the direction perpendicular to the loading force. In addition, the biaxial stress states of the initial sample, as well as those of the sample during the tensile test, were determined using multi-reflection grazing incidence X-ray diffraction (MGIXD). The experimental data were compared with the prediction of an elasto-plastic self-consistent model in order to study slips on crystallographic planes and mechanical effects occurring during plastic deformation.

1. Introduction

Due to a high strength-density ratio, as well as excellent chemical and mechanical resistance, titanium is widely used in industrial applications. At low temperatures, titanium crystallises in a hexagonal close-packed (hcp) structure called α-phase. Above its transus temperature (882± 2 °C), it is transformed into a stable body-centered cubic (bcc) structure referred to as β-phase.

The elasto-plastic deformation of titanium alloys is determined by the activation of slips and the twinning process occurring in each phase of the material, as well as intergranular and interphase interactions in polycrystalline aggregates. In the case of bcc crystals (β-phase) the pencil glide, i.e. the slip systems: $\{011\}\langle 11\bar{1}\rangle$, $\{112\}\langle 11\bar{1}\rangle$ and $\{123\}\langle 11\bar{1}\rangle$ are active during plastic deformation [1]. A greater number of glide systems occur in the hexagonal hcp lattice than in the cubic structure. The prismatic slip system P $\langle a\rangle$: $\{\bar{1}100\}\langle 11\bar{2}0\rangle$ is the main active system, while the basal B $\langle a\rangle$: $\{0002\}\langle 11\bar{2}0\rangle$, pyramidal Π_1 $\langle c+a\rangle$: $\{\bar{1}011\}\langle 11\bar{2}3\rangle$ and pyramidal Π_1 $\langle a\rangle$: $\{\bar{1}101\}\langle 11\bar{2}0\rangle$ systems are considered secondary in the α-phase of Ti [1–7]. Mechanical twinning, the other mechanism of the plastic deformation can occur in the α-phase, however in two-phase titanium alloys this phenomenon is suppressed by oxygen and aluminium components and in this case the twins can appear only after some deformation by slip (e.g. in Ti-6Al-4V for deformation above 4% [1,8]).

As a selective and non-destructive method, the diffraction method applied here for *in-situ* tensile test is particularly useful in analysing the evolution of phase behaviour during elastic and elasto-plastic deformation. This experimental technique enables determination of the average elastic strain for grain subsets situated inside the gauge volume defined by diffraction condition. The measurements are carried out using selected *hkl* reflections for different directions of the scattering vector with respect to the sample during tensile/compression tests or cycling loading [5,6,9–17]. In the case of multiphase polycrystalline materials, the measurement of separate diffraction peaks enables independent investigations of the behaviour of each phase [10–17].

The results of experiments are usually then compared with the predictions of micromechanical models in order to interpret the observed evolution of lattice strains during deformation [5,6,9–14].

---

[*] Corresponding author.
E-mail address: Andrzej.Baczmanski@fis.agh.edu.pl (A. Baczmański).

http://dx.doi.org/10.1016/j.actamat.2017.06.022
1359-6454/

Heretofore, many studies have concerned the identification of initial critical resolved shear stress (CRSS) and parameters of work hardening models characterising crystallographic slips, as well as analysis of the twinning phenomenon occurring in single- or two-phase materials. The measurements are generally done using the transmission method during an *in-situ* tensile/compression test; the lattice strains are determined in the direction of the applied load and in the transverse direction. To accomplish this, radiation with a low rate of absorption in the studied material must be used; therefore the most suitable techniques for such experiments are the neutron [5,6,9–11,14,15] and high-energy synchrotron diffraction methods [12,13,16,17].

Two-phase titanium alloys were investigated using the neutron [14,15], synchrotron [16,17] as well as classical diffraction methods [18]. Using diffraction during *in-situ* tensile test the values of CRSS in both phases were determined by comparing self-consistent model with measured lattice strains [14–17]. Moreover, a very good agreement of measured and model lattice strains characterising anisotropic intergranular stresses within α-phase was found in Ti–6Al–4V alloy [15,16]. In the above cited works [14–17] the single crystal elastic constants (SECs) of both phases were determined in different two-phase titanium alloys. The measurements performed for different alloys showed similar values of SECs for α-phase [19], while in the case of β-phase elastic properties of crystal depend strongly on alloying components as well as on the thermal treatment. It should be also stated that due to low coherent neutron scattering of titanium, and/or a small content of a given phase, the lattice strains were measured only for one reflection in β-phase [15,16] or not measured in α-phase [14]. Therefore in these works the information about one of the studied phases was limited. The most representative data concerning elasticity of β-phase (3 reflections) as well as β-phase (7 reflections) were obtained using high-energy synchrotron diffraction for *in-situ* tensile test performed for aged and forged Ti–10V–2Fe–3Al alloy [17]. It was found that the SEC of β-phase are very different after two thermal treatments, while α-phase do not change significantly. Also, the standard Cu Kα X-ray radiation was used to determine SEC of β-phase from lattice strains for Ti-17 alloy subjected to applied load [18]. However, in this work the properties of α-phase as well as plastic behaviour of the sample were not studied.

Contrary to previous experiments conducted with neutron or high-energy synchrotron radiation, the present paper proposes an original diffraction method for study of elasto-plastic behaviour of two-phase Ti alloy, performed in reflection mode on a laboratory diffractometer. Due to the excellent coherent scattering of X-rays by titanium and a significant content of both phases, sufficient diffraction intensity was registered for large diffraction patterns containing reflections from both β- and α-phases, even in the case of strongly textured sample. Thanks to the use of the multi-reflection grazing incidence X-ray diffraction (MGIXD) technique [20–28], not only the lattice strains but also the mean stresses in each phase, i.e. the stress partitioning between phases, were determined experimentally. In the present work the SEC given in Table 1 were used in model prediction and to calculate stresses in both phases. In the case of β-phase different sets of elastic constants found in literature were verified.

Table 2

The chemical composition in weight percentage of TIMETAL-18 (T-18) alloy.

Al	Mo	V	Cr	Fe	O	C	N	Ni	Ti
5.5	5.0	5.0	2.3	0.8	0.15	<0.1	<0.1	<0.1	Balance

The measured lattice strains as well as the mean phase stresses were also successfully compared with the predictions of an elasto-plastic self-consistent (EPSC) model [11,29] based on Eshelby's inclusion scheme.

2. Material characterisation and experimental techniques

The experiments were carried out on the newly developed high-strength titanium alloy TIMETAL 18 (called Ti-18) produced by the TIMET company (Exton, Pennsylvania, USA) and received as a quarter of an ingot, with a diameter of 250 mm. This ingot was prepared by means of vacuum arc remelting, then forged and rolled below the beta transformation temperature equal to 1136 K. Subsequently, the material was processed by means of solution heat treatment at a subtransus temperature (1089 K) for 2 h, then air-cooled. Finally it was treated by precipitation hardening at 894 K for 8 h (aging) and then air-cooled. The chemical composition of the studied alloy is shown in Table 2.

The characteristic bi-modal microstructure of Ti-18 alloy consists of uniformly distributed equiaxed primary α_p-phase grains and lamellar secondary α_s-phase inclusions embedded in β-phase matrix (cf. Fig. 1). The α_p grains are transformed from β-titanium due to sub-transus solution treatment treatment, while the lamellar α_s inclusions appear during the precipitation hardening process [30]. The volume fraction of α-phase estimated from SEM images is equal to 45% ± 5%.

To determine microstructures of initial and fractured (deformed) samples the Transmission Kikuchi Diffraction (TKD) method [31,32] was used. TKD methodology offers much better spatial resolution in comparison with standard EBSD technique, therefore the orientation maps acquired with a step of 20 nm allowed us to determine reasonable images for α_s lamellas (acquisition parameters were set according to [32]). The results of TKD analysis, in the form of raw data without any map cleaning procedures, are shown in Fig. 2. As expected for small sample strain E_{11} of about 4.5%, no significant differences between the initial and deformed samples are observed and no twins were found in both phases of the studied Ti-18 alloy. The inverse pole figures (IPF) maps show homogenous lattice orientation in β-phase as well as within α_p precipitates. Analysis of the image quality (IQ) maps shows that the worse quality of Kikuchi patterns (dark shade of gray) were obtained for α_s precipitates possibly due their small size (both α and β phases are present in the gauge volume studied by TKD) or possibly due to higher density of defects.

A PANalytical X'Pert MPD diffractometer using not filtered Cu

Table 1

Single crystal elastic constants (SEC) for α and β titanium, using the Voigt convention.

Phase	Material	c_{11} (GPa)	c_{12} (GPa)	c_{44} (GPa)	c_{13} (GPa)	c_{33} (GPa)	Zener factor A	Reference
α (hcp)	-	162	92	47	69	181	–	[19]
β (bcc)	Ti-17	174	116	41	$= c_{12}$	$= c_{11}$	1.4	[18]
	Ti–6Al–4V	138	108	51			3.4	[15]
	Ti–10V–2Fe–3Al (forged)	140	128	50			8.3	[17]
	Ti–10V–2Fe–3Al (forged and aged)	165	118	45			1.9	[17]