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ScienceDirect

Acta Materialia 75 (2014) 198–211

Acta MATERIALIA

www.elsevier.com/locate/actamat

Variant selection during secondary and tertiary twinning in pure titanium

Hong Qin [a,b], John J. Jonas [b,*]

[a] College of Materials Science and Engineering, Chongqing University, Shapingba St. 174, Chongqing 400044, China
[b] Department of Materials Engineering, McGill University, 3610 University St., Montreal, QC H3A 2B2, Canada

Received 7 February 2014; received in revised form 5 April 2014; accepted 28 April 2014

Abstract

Three generations of twins were identified by electron backscatter diffraction techniques in pure titanium subjected to uniaxial compression at room temperature. Many primary contraction twins were observed as the initial texture was favourable for their formation. Numerous secondary extension twins formed within the primary contraction twins and some tertiary contraction twins within the secondary extension twins. The orientations of these three generations of twins were determined and their associated Schmid factors (SFs) were calculated. The formation of the twin variants selected in each generation and the absence of certain potential variants are explained by rotating the twinning displacement gradient tensor expressed in the twin system reference frame into the crystal reference frame of the relevant neighbouring grain. The presence of the observed secondary and tertiary twins is accounted for in terms of the ease of imposing the required accommodation strains on their neighbours. The results show that secondary twins can form even with low SFs as long as their accommodation takes place by prismatic or basal glide. However, the formation of certain second and third generation potential high SF twins was impeded when this would have required accommodation by the most difficult deformation mode: pyramidal glide.

Keywords: Schmid factor; Twinning; EBSD; Titanium; Variant selection

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1. Introduction

Mechanical twinning is generally accepted as one of the important deformation modes in hexagonal materials of low symmetry [1–7]. Over the last few decades, this mechanism has been extensively investigated in magnesium [5,8–10], and zirconium and titanium [11–14]. Such twins can either strengthen or weaken the material, depending on whether extension or contraction twins are being formed and therefore on the initial texture as well as the loading path [7,15–17]. In this way, deformation twins have pronounced effects on both the mechanical behaviour and texture evolution [14,15,18,19]. In the case of titanium, four major types of twins have been observed [20–22]: primary extension and contraction twins, and secondary extension and contraction twins. Additionally, Tirry et al. [23] have reported that tertiary twins can form in high-purity titanium under both quasi-static and dynamic compression conditions. Three generations of twins have also been reported to form in deformed magnesium [24,25].

Extension twins in Ti are of the $\{10\bar{1}2\}$ $< 10\bar{1}\bar{1} >$ type and lead to an 85° rotation of the crystal axes around a $< 11\bar{2}0 >$ direction. The flow stress generally increases when such twinning takes place [23,26,27]. Conversely, the occurrence of contraction twinning of the $\{11\bar{2}2\}$ $< 11\bar{2}\bar{3} >$ type leads to a rotation of 64° around a $< 10\bar{1}0 >$ direction and therefore to flow softening. This

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* Corresponding author.
E-mail address: john.jonas@mcgill.ca (J.J. Jonas).

http://dx.doi.org/10.1016/j.actamat.2014.04.065
1359-6454/

is because reorientation of the prismatic planes brings about an increase in the Schmid factor (SF) [28]. The new orientations may also be favourable for the formation of secondary and even tertiary twins.

The formation of primary twins generally follows the highest resolved shear stress selection rule, which means that the variant with the highest Schmid factor is the one that forms first [2,29,30]. However, many non-Schmid behaviours have also been observed, particularly during the formation of primary, secondary and tertiary twins in magnesium [24,25]. By contrast, in titanium, there is only a limited literature regarding twin variant selection. Some authors have explained the selection of primary and secondary twin variants by employing a criterion based on deformation energy and grain size [31,32]. However, the formation of a twin depends not only on the deformation energy, but also on the interaction of potential twins with their neighbouring grains [33]. In an earlier paper [34], the importance of this interaction was examined by the present authors with regard to variant selection for primary twinning. However, the effect of the accommodation strain on variant selection during secondary and tertiary twinning has not yet been investigated in titanium.

In the present study, the geometries associated with both present and absent secondary twin variants are analysed so as to determine the factors controlling their selection. Variant selection during tertiary twinning is examined along similar lines, with the result that the relative importance of the Schmid factor and the accommodation strain observed to apply during secondary twinning is shown to be valid for tertiary twin variant selection as well.

2. Experimental method

2.1. Material and experimental set-up

The material used in the present study was high-purity titanium (99.99%). The as-received material was a rolled sheet with a thickness of 10 mm. Annealing was performed at 530 °C for 1 h to produce an equiaxed grain structure with an average grain size of around 16 µm. Cylindrical samples of 8 mm diameter and 9 mm height were machined along the normal direction from the as-received plate. Uniaxial compression tests were carried out on the McGill servo-controlled MTS machine at room temperature at strain rates from 0.001 to 1 s^{-1} to a true strain of $\varepsilon = -0.3$.

The initial texture measured on the plane perpendicular to the compression direction is presented in terms of (0002) and (10–10) pole figures in Fig. 1. It can be seen that the c-axes of most of the grains were aligned along the normal direction with a spread of about 30° mostly towards the transverse direction. As a result, during compression, the formation of contraction twins was favoured in most of the grains, as their c-axes were subjected to contraction during deformation. Only $\{11\bar{2}2\} < 11\bar{2}\bar{3} >$ contraction twins (CTs) and $\{10\bar{1}2\} < 10\bar{1}\bar{1} >$ extension twins (ETs) formed during primary twinning in the current study (see Table 1), i.e. there was no evidence for the formation of $\{11\bar{2}1\} < 11\bar{2}6 >$ extension twins.

The deformed samples were sectioned along the compression direction and then subjected to metallographic preparation by grinding with up to 4000 grit SiC paper. This was followed by electrolytic polishing for 80 s in a solution of 10 ml perchloric acid and 90 ml methanol at -30 °C and 17 V. An electron backscatter diffraction (EBSD) system on a Hitachi SU-8000 scanning electron microscope equipped with a field emission gun was employed to determine the orientations of the matrix grains and all three generations of twin variants. For this purpose, an acceleration voltage of 20 kV was used, together with a working distance of 15 mm and a sample tilt angle of 70°, for the preparation of EBSD maps. Data acquisition and analysis were carried out using the HKL Channel 5 software.

2.2. Calculation of the accommodation strains

In the present work, the following deformation modes were taken into consideration: <*a*> glide on the $\{10\bar{1}0\}$ prismatic plane; <*a*> glide on the {0001} basal plane;<*c* + *a*> glide on the $\{10\bar{1}1\}$ pyramidal plane; and contraction and extension twinning of the types described above. The values of the critical resolved shear stresses (CRSSs) of the above slip systems were taken from Ref.

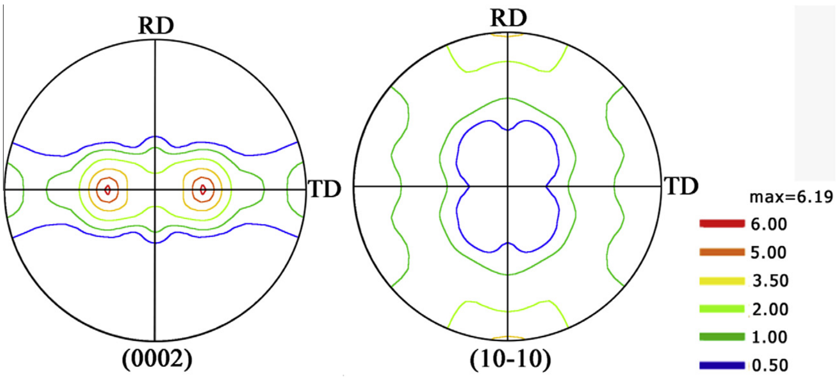

Fig. 1. Initial texture of the compression samples measured on the rolling plane (RD and TD are the rolling and transverse directions; the normal direction (ND) is perpendicular to both).