Materials Science & Engineering A 684 (2017) 456–465

Contents lists available at ScienceDirect

Materials Science & Engineering A

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

Accommodative {332}⟨113⟩ primary and secondary twinning in a slightly deformed β-type Ti-Mo titanium alloy

Xueyin Zhou[a], Xiaohu a Min[a,*], Satoshi Emura[b], Koichi Tsuchiya[b]

[a] School of Materials Science and Engineering, Dalian University of Technology, Dalian 116024, PR China
[b] Research Center for Structural Materials, National Institute for Materials Science, 1-2-1 Sengen, Tsukuba 305-004, Japan

A R T I C L E I N F O

Keywords:
Titanium alloy
Twinning
Variant selection
Strain accommodation
EBSD

A B S T R A C T

The {332}⟨113⟩ twinning microstructures in differently oriented grains were systemically examined by electron backscattered diffraction technique in a slightly deformed β-type Ti-15Mo polycrystalline alloy, and the selection of primary and secondary variants were quantitatively analyzed in terms of applied stress and strain accommodation. Primary twinning variants accompanied with their intersections and secondary twinning variants inside primary twins were easily activated in the grains. Presence of primary twinning variants in the grains with their tensile axes close to [$\bar{1}$22] and [$\bar{1}$11] directions exhibited the relatively higher contribution to macroscopic stain than those in the grains with their axes close to [011] and [001] directions. Selection of primary and secondary twinning variants not only obeyed the Schmid law with large Schmid factors from 0.3 to 0.5 but also exhibited the non-Schmid behaviors with low and negative values. The selection of twinning variants with non-Schmid behaviors was due to their high accommodative capacity to release the local internal stress concentration, which was evaluated by rotating the shear displacement gradient tensor expressed in the activated twinning variant reference frame into the accommodative twinning variant reference frame in neighboring grain or region. The occurrence of accommodative primary and secondary twinning was considered to further enhance an effectiveness of twinning deformation for the substantial strain hardening behavior of present alloy.

1. Introduction

Deformation twinning has been extensively studied not only in hexagonal-close-packed (hcp) metals with low crystal symmetry, but also in body-centered cubic (bcc) and face-centered-cubic (fcc) metals with high crystal symmetry [1–5]. As one of the fundamental plastic deformation modes, deformation twinning provides an important approach for improving the strength and ductility relationship in bulk metals and even in nanoscale metals [6–9]. Recently, β-type (bcc) titanium alloys have attracted considerable attention as promising structural and functional materials due to their diversity of deformation modes, including deformation-induced α″ (orthorhombic) martensitic transformation, deformation-induced ω (hexagonal or trigonal) phase, {332}⟨113⟩ twinning, {112}⟨111⟩ twinning and dislocation slip [10–13]. Among them, {332}⟨113⟩ twinning, as an unusual twinning mode in bcc metals since neither twinning plane nor twinning direction is close-packed, is recognized as a fundamental deformation mode in β-type titanium alloys. This typical twinning, which associates with a relatively lower β phase stability, leads to a large uniform elongation through substantial strain hardening behavior, i.e., twinning-induced plasticity (TWIP) effect for these titanium alloys [14,15].

{332}⟨113⟩ twinning was first identified in a Ti-15Mo-6Zr-4Sn (all compositions are expressed in mass%) β-type titanium alloy in the 1970s by Blackburn and Feeney [16]. Subsequently, it has been confirmed in various β-type titanium alloys, such as Ti-Mo [17,18], Ti-Nb [19,20], Ti-V [21,22] and Ti-Cr [23,24] alloys. One shear-shuffling mechanism was proposed by Crocker for this twinning, in which half of the atoms must shuffle in another direction to the ⟨113⟩ direction of twinning shear [25]. Another partial dislocation mechanism results from successive slip of 1/22⟨113⟩ partial dislocations in pairs of neighboring {332} planes accompanied by shuffling of the atoms [26,27]. Recently, a modified shear-shuffling mechanism caused by structure modulation has been proposed in terms of the magnitude of twinning shear and the complexity of shuffle [28]. Lai et al. [29] has reported a α″-assisted twinning mechanism in a Ti-36Nb-2Ta-3Zr β-type titanium alloy, in which {332}⟨113⟩ twins nucleate within progressively formed α″ martensite during deformation. Nevertheless, a special feature of {332}⟨113⟩ twins is that they easily

* Corresponding author.
E-mail address: minxiaohua@dlut.edu.cn (X. Min).

http://dx.doi.org/10.1016/j.msea.2016.12.025
Received 21 October 2016; Received in revised form 1 December 2016; Accepted 2 December 2016
Available online 07 December 2016

undergo primary twinning, twin-twin intersection, and secondary twinning inside primary twins, which has attracted much interest as a key factor to strongly affect the substantial strain hardening behavior.

One twinning plane corresponds to one shear direction in this type of {332}⟨113⟩ twinning, which corresponds to twelve possible twinning systems (variants) [30–32]. Selection of twinning variants commonly follows the Schmid law, meaning that twinning variant with highest resolved shear stress on its twinning plane and along its shear direction is activated preferentially based on the value of macroscopic Schmid factor. Macroscopically, the selection of twinning variant is considered to macroscopic strain induced by the applied stress. Hanada et al. [30] reported that {332}⟨113⟩ twinning occurs in a Ti-15Mo-5Zr single crystalline alloy with its tensile axis close to the ⟨111⟩ direction, whereas dislocation slip appears near the ⟨001⟩ and ⟨011⟩ direction. This orientation dependence of deformation modes was reasonably explained by the Schmid law. Bertrand et al. [31] has reported the selection of {332}⟨113⟩ and {112}⟨111⟩ twinning variants in a Ti-25Ta-24Nb polycrystalline alloy, and concluded that the Schmid law is a relevant parameter to determine the activated variants. On the other hand, we previously found that selection of {332}⟨113⟩ twinning variants does not always obey the Schmid law in slightly deformed Ti-15Mo and Ti-15Mo-5Zr polycrystalline alloys [32,33]. Either twinning variant with a comparatively lower positive Schmid factor or even twinning variant with negative Schmid factor is activated preferentially.

Such non-Schmid behaviors have also been reported during the formation of primary, secondary and tertiary twins in hexagonal metals such as magnesium and titanium [34–38]. They were further analyzed in terms of strain accommodation, which corresponds to the local internal stress relaxed by dislocation slip or by twinning. Local internal stress is easily produced by the interaction between twins and gain boundaries, and by the intersection between twins themselves [32,39]. It is modified to be different from the macroscopic external stress, which may stimulate the twinning variant with non-Schmid behavior to be active and suppress the formation of twinning variant with high macroscopic Schmid factor. Thus, selection of potential twinning variant based on strain accommodation can be evaluated by rotating the shear displacement gradient tensor expressed in the activated twinning variant reference frame into the accommodative twinning variant reference frame in neighboring grain or region [38]. In our previous work, the non-Schmid behaviors were quantitatively analyzed only by macroscopic Schmid factor, and were qualitatively described to some extent in terms of accommodation mechanism. However, the effect of strain accommodation on variant selection during primary and secondary {332}⟨113⟩ twinning remains unclear, which has not yet been examined quantitatively in β-type titanium alloys.

In this study, the {332}⟨113⟩ twinning microstructures in differently oriented grains were systemically investigated by electron backscattered diffraction technique in a slightly deformed Ti-15Mo β-type titanium alloy. Selection of {332}⟨113⟩ twinning variants was determined by macroscopic Schmid factors and contributions of primary twinning to the macroscopic plastic strain induced by applied stress was examined in differently oriented grains. Effect of strain accommodation through twinning shear displacement gradient tensor on selection of primary and secondary twinning variants was further analyzed for discussion of non-Schmid behaviors and their influence on strain hardening behavior.

2. Experimental procedures

2.1. Materials preparation

An approximately 1 kg ingot of Ti-15Mo alloy was prepared by cold crucible levitation melting under high purity argon gas atmosphere. After solidification, the ingot was hot forged, hot caliber rolled at 1473 K, and then homogenized at 1473 K for 10.8 ks followed by air cooling. Subsequently, a bar with a cross-sectional area of 11.8×11.8 mm^2 was produced after cold caliber rolling at room temperature. The bar was cut and hot rolled into a 4 mm plate in thickness at 1173 K [14]. The principal axes of the rolled plate are corresponding to the rolling direction (RD), the normal direction (ND) to the rolling plane, and the transverse direction (TD), which is orthogonal to both RD and ND. Tensile specimens (gage dimensions: 18 mm (l) ×4 mm (w) ×2 mm (t)) were cut out of the plate by electric discharge machining along the RD and TD, and then subjected to solution treatment at 1173 K for 3.6 ks after sealed in a quartz tube under a vacuum of 1×10^{-3} Pa, followed by water quenching for achieving a single β-phase. The oxygen content was measured as approximately 0.1 mass% after the solution treatment.

2.2. Tensile testing and microstructure characterization

Tensile testing was performed at room temperature in a tensile test machine Instron-5581 with a tensometer under an initial strain rate of 2.78×10^{-4} s^{-1}. Tensile force was applied parallel to the RD. To observe the {332}⟨113⟩ twinning microstructures in differently oriented grains at an early stage of deformation, the interrupted tensile test was carried out with the specimen stretched to a plastic strain of 5%. Note that this solution treated Ti-15Mo alloy exhibited a large elongation of 40% due to {332}⟨113⟩ twinning deformation [14]. The slightly deformed sample was subjected to mechanical-chemical polishing to obtain a smooth surface. Deformation microstructures were observed with a field-emission scanning electron microscope (JSM-7001, JEOL) equipped with an orientation imaging system for conducting the electron backscattered diffraction (EBSD) analysis with EDAX OIM analysis software.

2.3. Twinning system identification

A difference that distinguishes twinning from dislocation slip is the polarity of twinning [1]. A twinning shear is directional, meaning that a twinning shear in the opposite direction cannot produce a twin. This twinning polarity indicates that for a given crystallographic orientation, the activated twinning variants under tension are different from those under compression. The indices of 12 possible variants have been determined as follows: $(332)[11\bar{3}]$, $(323)[1\bar{3}1]$, $(233)[\bar{3}11]$, $(\bar{3}32)[\bar{1}1\bar{3}]$, $(\bar{3}23)[\bar{1}\bar{3}1]$, $(\bar{2}33)[311]$, $(\bar{3}\bar{3}2)[\bar{1}\bar{1}\bar{3}]$, $(\bar{3}\bar{2}3)[\bar{1}31]$, $(\bar{2}\bar{3}3)[3\bar{1}1]$, $(3\bar{3}2)[1\bar{1}\bar{3}]$, $(3\bar{2}3)[131]$, and $(2\bar{3}3)[\bar{3}\bar{1}1]$. To distinguish activated twinning variants within the grains based on the EBSD observations, three factors are considered together as previously reported [32,33]. (i) Trace analysis: the possible activated twinning variants can be determined by using the stereographic projection based on the identical crystallographic orientation for the ND and RD in each grain. (ii) Schmid law: the macroscopic Schmid factor (SF) is defined similarly to dislocation slip as

$$SF = \cos(\varphi)\cos(\lambda) \tag{1}$$

where, φ and λ are the angles between applied stress and direction normal to the twinning plane and twinning shear direction, respectively. The values of φ and λ are between 0° and 180°, giving Schmid factors between −0.5 and 0.5. For a comparison, twelve conventional {112} < 111 > slip systems were also used to calculate macroscopic Schmid factor. (iii) A comparison of theoretical calculated angle (θ_t) and measured angle (θ_m) between twin trace direction and tensile axis to further confirm the assignment of the twinning system by trace analysis and Schmid factor.

3. Results

Fig. 1(a) shows an EBSD inverse pole figure map for the RD, which was scanned with a step size of 1.0 µm, in the 5% strained sample, and (b) shows a {332}⟨113⟩ twin boundary and grain boundary map. {332}