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Crystallographic orientation evolution during the development of tri-modal microstructure in the hot working of TA15 titanium alloy

Pengfei Gao, Yang Cai, Mei Zhan*, Xiaoguang Fan, Zhenni Lei

State Key Laboratory of Solidification Processing, School of Materials Science and Engineering, Northwestern Polytechnical University, P.O. Box 542, Xi'an, 710072, PR China

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ABSTRACT

The crystallographic orientation evolution and its dependence on processing parameters during the development of tri-modal microstructure of titanium alloy were studied by the thermal-mechanical processing tests and electron backscatter diffraction (EBSD) examination. It is found that the development of tri-modal microstructure undergoes two stages: firstly, bimodal microstructure consisting of equiaxed α (α_p) and transformed β matrix (β_t: a mix of secondary α phase (α_s) and β phase) is formed after first-stage near-β forging; then, the tri-modal microstructure consisting of α_p, lamellar α phase (α_l) and β_t are obtained after the following heat treatment. The equiaxed α in final tri-modal microstructure does not follow the Burgers orientation relationship (OR) with β phase. Its crystallographic orientation is hardly influenced by the hot processing parameters. The lamellar α in tri-modal microstructure is right the undissolved secondary α of bimodal microstructure (obtained after first step) during the heating process of the second step. Both of them keep the Burgers OR with β phase, however, the dissolution of secondary α present selectivity to some extent making the variant selection degree of lamellar α greater than that of secondary α. The variant selection degree of lamellar α in tri-modal microstructure decreases with increasing the cooling rate, deformation degree and strain rate of near-β forging. The secondary α in tri-modal microstructure is precipitated from β phase and obeys the Burgers OR with β phase during the cooling process of the second step. The existing lamellar α plays a strengthening role in the variant selection during its precipitation. While the cooling rate, deformation degree and strain rate of near-β forging show limited effect on the probabilities of each type of misorientation and variant selection degree of secondary α.

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1. Introduction

Titanium alloys are widely used in aeronautic, energy and biomedical industries because of their high specific strength, superior creep resistance, good thermal stability and excellent corrosion resistance [1,2]. TA15 (Ti-6Al-2Zr-1Mo-1V) alloy, for example, is a representative near-α titanium alloy. It is usually used to form the load-bearing structural components under severe working conditions, thus very high requirements are put forward on the microstructure and mechanical properties during the hot forming process [3]. Generally, five kinds of microstructure morphologies, including equiaxed microstructure, bimodal microstructure, basket weave microstructure, lamellar microstructure and tri-modal microstructure, can be obtained under different hot working conditions of titanium alloys. Among them, the formation of tri-modal microstructure is highly desirable due to its favorable combination of strength, ductility, fracture toughness and fatigue life [4,5]. This microstructure consists of equiaxed α phase (α_p), lamellar α phase (α_l) and transformed β matrix (β_t: secondary α phase (α_s) and β phase). In addition to the microstructure morphology, the microstructure parameters (such as the volume fraction, size and distribution) and crystallographic orientation of each constituent phase are also essential for the mechanical properties. But it is quite challenging to control the tri-modal microstructure in a precise way because it was found to be very sensitive to the hot working conditions.

By now, many studies have been conducted on the fabrication methods for tri-modal microstructure and also the relationships between the processing parameters and microstructure parameters. It was proposed that the tri-modal microstructure could be

* Corresponding author.
E-mail address: zhanmei@nwpu.edu.cn (M. Zhan).

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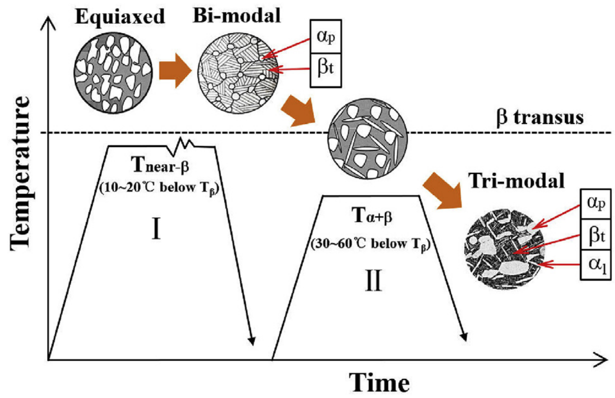

Fig. 1. Typical processing schedule for obtaining tri-modal microstructure.

obtained by a two-step thermo-mechanical processing (TMP) at near-β temperature range (10–20 °C below β-transus temperature (T_β)) and a lower temperature range (30–60 °C below T_β) sequentially [4–8], as shown in Fig. 1. The key influencing factors (including deformation temperature, deformation degree and strain rate) for the parameters of each constituent phase (including volume fraction, average grain size and aspect ratio) and the corresponding quantitative influence rules are also revealed [6–8]. Moreover, a prediction model was established to correlate the tri-modal microstructure parameters and processing conditions based on the microstructure evolution phenomena [9]. These studies provide theoretical and practical insights into the control of the tri-modal microstructure parameters. As for the effects of microstructure parameters on mechanical properties of tri-modal microstructure, Lei et al. [10] quantitatively analyzed the nano-hardness of three constituent phases and micro-hardness of integrated tri-modal microstructure under different processing conditions. Gao et al. [8] found that the contents of equiaxed α and lamellar α of tri-modal microstructure both play great roles in the yield strength, ultimate tensile strength and reduced area. However, the crystallographic orientation characteristics of each constituent phase in tri-modal microstructure and their effects on the mechanical properties have not been studied yet. Recent studies [11–13] suggest that the slip system activation and gliding transmission across phase boundaries during deformation of titanium alloy are strongly dependent on the crystallographic orientation of α and β phases. And then these phenomena play a decisive role in the plastic deformation, damage behavior and final mechanical properties [14–16]. Therefore, it is of great importance to reveal the evolution mechanisms of crystallographic orientation during the development of tri-modal microstructure.

In recent years, the crystallographic orientation characteristics of titanium alloys in various forming processes have attracted increasing attention. Yang et al. [17] and Zhao et al. [18] investigated the effect of thermal history on the crystallographic orientation of α variants and β phase of Ti-6Al-4V alloy during additive manufacturing through selective laser melting. Ghosh et al. [19] compared the crystallographic orientation features of commercially pure titanium developed by different rolling modes (unidirectional rolling and multi-step cross rolling) and annealing treatments. Dong et al. [20] characterized the micro-texture components and variant selection of α phase in a hot-rolled near β titanium alloy Ti-7333. They found that the acicular α variants in β matrix hold the Burgers orientation relationship (OR) with β matrix and the dislocations in β matrix have a significant selection effect on α variants. It has also been found that the shear strain in surface area and dynamic recrystallization have significant effects on the crystallographic orientation of β titanium alloy during hot rolling process [21–23]. Furthermore, the influences of annealing temperature in α+β two-phase field on the crystallographic orientation evolution a Ti60 alloy rolled billet were investigated [24]. Chen et al. [25] comparatively studied the grain orientation uniformity of Ti-17 titanium alloy under different hot deformation modes, including the compression, axial upsetting and drawing, and the relationships between grain orientation evolution and deformation parameters were revealed.

These earlier works suggest that the crystallographic orientation evolution of titanium alloy is strongly dependent on the phase transformation $\alpha \rightleftarrows \beta$ and deformation mode during hot working. In addition, the variant selection of α variants during $\beta \rightarrow \alpha$ phase transformation is a very critical phenomenon and has great effect on the final crystallographic orientation, thus which has become a research focus in recent. The informed studies indicate that the variant selection of α variants is mainly related to the following four aspects: (1) the elastic strain energy generated by the $\beta \rightarrow \alpha$ transformation. Humbert et al. [26] have proposed that the variants with minimum elastic strain energy are preferentially nucleated. (2) The selective formation of grain boundary α phase at the beginning of $\beta \rightarrow \alpha$ phase transformation. It has been reported that the number and type of α variants formed on β/β boundary is greatly affected by the orientation relationship between the prior β grains, and the degree of variant selection is related to the β texture and grain size [27–29]. (3) The role of pre-existing defects within β phase in the variant selection. Qiu et al. [30] found that the dislocations within β phase govern the variant selection of α phase in both of its nucleation and growth stages, and the effects change with the dislocation type. (4) The primary α precipitate impacts the subsequent α nucleation through the autocatalysis effect. It is found that the stress field around a pre-existing α lamellae is largely nonuniform, which will produce different interactions with various α variants and thus lead to the variant selection [31]. However, the reported works are mainly focused on the crystallographic orientation evolution of lamellar or bimodal microstructure obtained by one-step thermo-mechanical processing. For the tri-modal microstructure, both of the formation process and constituent phases are more complex. It needs two steps TMP, and each constituent phase (equiaxed α, lamellar α and transformed β matrix) produces at different stages. Thus, the crystallographic orientation evolution of tri-modal microstructure is more complicated than that in the lamellar and bimodal microstructure. Therefore, it is urgent to investigate the crystallographic orientation evolution and its dependence on processing parameters during the hot working of titanium alloy for tri-modal microstructure.

In this paper, the crystallographic orientation evolution and its dependence on processing parameters during the development of tri-modal microstructure are systematically studied by the thermal-mechanical processing tests and electron backscatter diffraction (EBSD) examination. In section 2, the material and detailed experiment schemes to obtain tri-modal microstructure are described. In section 3, firstly, the crystallographic orientation evolution of equiaxed, lamellar and secondary α phases of tri-modal microstructure are analyzed step by step in its typical development process. Here, the crystallographic orientation features mainly include the Burgers OR between α and β phases, variant types and texture. Then, the effects of processing parameters on the crystallographic orientation of tri-modal microstructure are investigated. The results will provide a better understanding of the mechanism in crystallographic orientation evolution and also provide technical guidance for the control of tri-modal microstructure during hot working of titanium alloys.

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