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Influences of deformation strain, strain rate and cooling rate on the Burgers orientation relationship and variants morphology during $\beta \rightarrow \alpha$ phase transformation in a near α titanium alloy

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ABSTRACT

High temperature compression deformation studies of Ti–6Al–2Zr–1Mo–1V titanium alloy in full β phase region with different strains/strain rates and then with subsequent varied cooling rates were performed to understand the microstructure evolution. Crystal orientation information and microstructure morphology of all tested samples were investigated by electron backscatter diffraction (EBSD) measurements. The crystal orientations of prior high temperature β grains were estimated by reconstructing the retained β phase at room temperature. The theoretical crystal orientations of all possible α variants within an investigated prior β grain were calculated according to the Burgers orientation relationship (OR) between parent and product phase. The calculated and experimental results were then compared and analyzed. The influences of deformation strain, strain rate and cooling rate on the Burgers OR between prior β matrix and precipitated α phase were investigated. Full discussions have been conducted by combination of crystal plasticity finite element method (CP-FEM) grain-scale simulation results. The results indicate that external factors (such as deformation strain, strain rate and cooling rate) have a slight influence on the obeying of Burgers OR rule during $\beta \rightarrow \alpha$ phase transformation. However, strain rate and cooling rate have a significant effect on the morphology of precipitated α phase.

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1. Introduction

Titanium and titanium alloys are preferentially used in the aerospace sector, chemical industry, medical engineering, and leisure sector because of their high specific strength and excellent corrosion resistance [1]. Titanium alloys are classified as α, near α, $\alpha+\beta$, and β alloys according to their position in a pseudo-binary section through a β-isomorphous phase diagram [2]. TA15, whose nominal chemical component is Ti–6Al–2Zr–1Mo–1V, is one of the typical near alpha titanium alloys and is widely used in aerospace industry owing to its excellent thermal stability and low fatigue crack growth rate [3].

The general production process of titanium alloys includes melting, casting, forging, and subsequent heat treatments. However, due to high yield stress and relatively low elastic modulus, most of titanium alloys (including TA15) are difficult to deform at room temperature. Therefore, their fabrication and forming operation are usually carried out at elevated temperatures, such as $\alpha+\beta$ forming (at temperature of 30–100 °C below the β-transus), β deforming (at temperature above the β-transus). For TA15 titanium alloy, whose microstructures cannot be significantly manipulated by traditional heat treatment, thermomechanical processing was usually adopted to get the desired usable shape and control the microstructure [4]. Moreover, local transformation from prior body-centered cubic (bcc) β phase to hexagonal close-packed (hcp) α phase of TA15 titanium alloy is generally governed by the Burgers orientation relationship [5]: $\{1\,1\,0\}_\beta // \{0\,0\,0\,1\}_\alpha$, $\langle 1\,1\,1\rangle_\beta // \langle 1\,1\,\bar{2}\,0\rangle_\alpha$. The special Burgers OR also has a significant effect on texture inheritance and crystallographic variant selection during the $\beta \rightarrow \alpha$ phase transformation [6–9].

As reported in many research works [1,2,10], the microstructures have a substantial influence on the in-service and mechanical properties of titanium alloys. Generally, the lamellar microstructures exhibit excellent fracture toughness and high fatigue crack propagation resistance but low resistance to fatigue crack nucleation and poor plasticity. Even for lamellar microstructure, its mechanical properties are dramatically sensitive to microstructural parameters such as the size of α colonies, the ratio of width and length and the crystallographic orientation distribution [11].

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In view of the above, influence of the processing parameters on the evolution of subsequent microstructure morphology, texture inheritance, and variant selection in these alloys, becomes a main research focus. The influences of deformation rate on the microstructure morphology were investigated by Seshacharyulu and Dutta [12]. Their research results reveal that the prior deformation rate has a significant influence on the morphology of transformed α: lamellar α grains formed at low strain rate (less than $10^{-1}\ s^{-1}$) and coarse equiaxed α grains formed at high strain rate (1–100 s^{-1}) [12]. The influences of strain and strain rate on the β → α phase transformation kinetics, including the nucleation sites, nucleation numbers and growth rates of the α precipitations during subsequent cooling, were fully studied by a calculation model developed by Da Costa Teixeira et al. [13]. It is reported that, when an external field exists, such as a prior strain field induced by compression ($\varepsilon = -1.4$) in α + β phase field of TIMETAL 834 alloy, the Burgers OR between the primary α (α_p) and the retained β phase (β_r) was respected only up to 30–60% with a tolerance of 10° [14]. Some studies also indicate that elastic anisotropy could be decisive factor for the variant selection and has a relationship with the sharp textured regions called macrozones [15]. At the same time, Kato et al. [16] has observed that the stress always plays an important role in the early stage of α to β phase transformation process. On the other hand, some authors pointed out that the significant variant selections can occur during bcc to hcp phase transformation even if no external field is imposed [17].

Most of the early research work was focused on the morphology, growth direction and orientation selection of α lamellae or colonies during the deformation or heat treatment process. However, a clear understanding of the influence of the external factors on the respecting of Burgers OR between α and β phases during phase transformation is still not available. In the present work, the compression deformation tests with different strains/strain rates and different subsequent cooling rates were carried out on TA15 titanium alloy at 1050 °C. Based on the results obtained with different test parameters, the influences of deformation strain, strain rate, cooling rate on the obeying of Burges OR were analyzed. Finally, full discussions were conducted by combination of CP-FEM simulation results at grain-scale.

2. Experimental

2.1. Material and sample preparation

TA15 titanium bar stock having a chemical composition of 6.47 wt% Al, 1.59 wt% Zr, 1.45 wt% Mo, 1.91 wt% V, 0.038 wt% Fe and titanium balance was used in the present study. The β-transus temperature was around 993 °C. The as-received material was subjected to β forging at 1050 °C and was subsequently annealed at 600 °C for 4 h. The microstructure of the used alloy consisted of coarse primary α phase and residual β phase (less than 10 vol.%).

Cylindrical specimens of 5 mm diameter and 10 mm height for hot compression tests were machined from the mentioned bar stock.

2.2. Compression test

Uniaxial compression tests were carried out on a computer controlled servo-hydraulic testing machine (INSTRON 8501) equipped with induction heating apparatus and cooling systems. The compressive strain, strain rate and heating/cooling rate were exactly controlled by the testing machine during the test. All tests were conducted under the vacuum conditions. The test details are listed in Table 1. All test were performed at 1050 °C (∼60 °C above β transus) which was achieved with 10 °C/s heating rate and deformation was started after 2 min holding at this temperature.

Table 1
The test no. and detailed test parameters in the present work.

Test no.	Strain	Strain rate (s^{-1})	Cooling rate (°C/s)
A	–	–	5
B	0.8	1	5
C	0.1	1	50
D	0.8	10	1

2.3. EBSD measurement

The deformed specimens were sectioned along compression axis into two equal halves. The sectioned surface was then prepared for scanning electron microscopy (SEM) and electron backscatter diffraction (EBSD) measurement using standard grinding and polishing techniques. A mixture of colloidal silica (OP-S, 90 vol.%) and H_2O_2 (10 vol.%) was used as a polishing solution during the final polishing process.

EBSD data acquisition was carried out on a JEOL 6500F scanning electron microscope equipped with an EBSD system developed by EDAX/TSL®. The Kikuchi patterns were indexed automatically in real time and the results were analyzed by the same software EDAX-TSL OIM®. In order to facilitate comparison, the central area of each prepared surface was selected to carry out EBSD measurement.

3. Results

3.1. Influence of deformation strain

The result of orientation image microscopy (OIM) with a scanning step size of 0.2 μm of sample A, which has not be subjected to any deformation, is shown in Fig. 1(a). The microstructure very clearly shows the presence of α lamellae along with a small fraction of residual β phase. These lamellae are 3–5 μm thick and 50–70 μm long in size. Some of lamellae even cross the whole prior β grain. The α colonies, which are composed of several parallel α lamellae sharing similar crystal orientation, nucleate preferentially at β grain boundaries and grow into the β grain interior until they impinge with other colonies, as seen in Fig. 1(a). The occurrence of similar microstructure was also observed in the previous studies [6,8,9,12,13,18].

We can easily deduce that there is an equiaxed prior β grain (marked as "Grain A", see Fig. 1(a) and (b)) in the center of the measured region from the distribution of grain boundary α lamellae. The sketch of the reconstructed β grain boundaries at high temperature has been plotted according to the residual β phase orientations and grain boundary α lamellae, as shown in Fig. 1(b). The reconstructed microstructure indicates that the microstructure at 1050 °C consists of equiaxial β grains of roughly 100–120 μm in size.

As mentioned in the introduction, the Burgers OR should be generally maintained during the transformation between the β phase and α phase. Owing to the cubic symmetry, 24 hexagonal variants of α should be obtained. Actually, taking both the cubic and hexagonal symmetries into consideration, there are only 12 distinct variants [5]. But here, our study revealed the presence of only 7 distinct variants in the marked "Grain A". Two possible reasons can account for the observed results. Firstly, the preferred selection of variant exists during the formation process of α lamellae even there in the absence of external influence [17]. Secondly, Fig. 1 gives only a 2 dimensional (2D) section; therefore, some information on other variants in real 3 dimensional (3D) spaces may be lost. However, our research objective is to study whether the Burgers OR is well

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