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Effect of β (110) texture intensity on α-variant selection and microstructure morphology during β→α phase transformation in near α titanium alloy

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ABSTRACT

In the present work, we investigated the texture evolution as well as the role of the β texture intensity on the α-variant selection and microstructure morphology during the α→β→α phase transformation in Ti60 alloy. Different microstructures and textures were obtained through forging the Ti60 bars into diameters of 45 mm denoted as D45 and 30 mm as D30. Subsequently, small samples with the same size cut from both bars were heat-treated above the β transus followed by furnace cooling and air cooling. We found that the β texture intensity, cooling rate, and variant selection affect both the texture intensity and microstructure morphology of the transformed α phase. The high temperature β phase exhibits stronger (110) parallel to axial direction fiber texture in the β annealed D30 bar than that for the D45 bar. A basketweave microstructure was found in the β annealed D45 bar after air cooling whereas a coarse α colonies populated by fine α lamellae formed in the D30 bar. For furnace cooled samples, the α texture is stronger than that in the air cooled sample in D45 bar whereas the intensities of the textures are very similar to air cooled sample in the D30 bar. The influence of the β texture intensity and variant selection on the α texture evolution were studied by comparing the four experimental results and simulation data. The effect of α variant number in a β grain on α texture intensity, base on variant selection, and the effects of β texture intensity on microstructure morphology are discussed.

1. Introduction

Titanium alloys generally have hexagonal close-packed (HCP) structure (i.e., α phase) at low temperature whereas they exhibit body-centered-cubic (BCC) structure (i.e., β phase) at high temperature. The transformation between the α phase and the β phase is normally governed by the Burgers orientation relationship (BOR) [1–5]: {0001}α//(011)β and [11–20]α//<1–11>β. Based on the BOR as well as the symmetry of the BCC and HCP structures, six possible β variants with different orientations may form in an α grain during α→β transformation and twelve possible α variants in a β grain during β→α transformation [6–8]. Obviously, if all the variants occur with equal probability, the final α texture should be weaker than the initial one after α→β→α heat cycle [9–13]. However, many experiments demonstrated that this is not always the case. For example, the β texture may not fit BOR with the originally α phase in Ti-6Al-4V during α→β phase transformation [3]. Although the transformed α texture always follows the BOR with the parent β phase, the amount of the measured α transformation texture (variants) normally does not agree quantitatively with the predicted α transformation texture [10]. This phenomenon could be ascribed to variant selection.

Variant selection mechanism in titanium alloys during β→α phase transformation has been interpreted as follows [10,14,15]: (1) stress generated by the phase transformation strain due to the volume change; (2) untransformed remnant α phase at the boundaries of the β phase act as nuclei during β→α phase transformation; (3) formation of grain boundary α phase at the beginning of the β→α phase transformation with optimum characteristic for nucleation of low temperature phase. According to Obasi et al. [10,11], the first two mechanisms are unlikely to be true because the α phase has disappeared and the β phase is very soft in β phase field. Bhattacharya et al. [14] reported that, in the case of neighboring β grain with a common <110>$_\beta$ pole (within 10°), the c-axis of the transformed α orientates along the common <110>$_\beta$ pole. They also demonstrated that the grain boundary of these special β

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grain pair exhibits less nucleation energy, resulting in early α phase forming during cooling. The variant selection plays an important and dominant role in respect of texture evolution. More recently, Obasi et al. [10–13,16] reported that the degree of the variant selection dominance during β→α phase transformation is related to the β grain growth and the β texture component, which are influenced by the hot working process. The results showed that some special β texture components may produce more β grain pairs, which having a common <110>$_\beta$ pole, and, consequently, promote the formation of α texture after β→α phase transformation. Beside, the geometrical direction of the α laths is related with theirs crystallographic orientation [17,18]. Stanford et al. [19] have observed that the number of α variants formed on the side of the β/β boundary is also affected by the crystallographic orientation relationship between the prior β grains. Thus, the morphology of lamellar microstructure is assumed to be associated with the parent β orientation as well as the β texture.

At present, although some researchers have studied the influence of the variant selection on the texture evolution in titanium alloys, the influence of β texture intensity on the variant selection and the transformed α texture intensity as well as microstructure evolution have not been clarified. To address this, in the present work, two Ti60 bar with different β texture intensity in (110) pole figure were selected. In-house thermomechanical processing was carried out to achieve similar microstructure of the 2 bars upon both air and furnace cooling. The texture evolution of the α phase during α→β→α phase transformation were measured by XRD and EBSD. The experimental results are compared with those from calculation and simulation to show that the role of the variant selection in the texture evolution and microstructure morphology during β→α phase transformation in titanium alloy.

2. Material and experimental method

The material used in the present study was Ti60 titanium alloy with a composition (in wt.%) of 5.6Al, 3.7 Sn, 3.2 Zr, 0.5 Mo, 0.4 Nb, 1.0 Ta, 0.37 Si, 0.05 C, balance Ti. The β transus temperature is about 1040 °C. The ingot casting was broken down at 1060 °C from the diameter of 220 mm to 140 mm. Then the bar was cut in the middle and then forged at 1000 °C to 45 mm (D45) and 30 mm (D30) in diameter with two and three forging steps, respectively. Samples were cut from D45 and D30 bars with dimensions of 30 mm in diameter and 20 mm long. Two samples, which were cut from different bars, were heated to the fully β phase field at 1050 °C for 100s and subsequently air cooled (~800 °C/min in the range of 1050-900 °C) to room temperature. Using similar approach, slowly cooled samples were produced by furnace cooling with an approximate rate of 8 °C/min.

To observe the optical metallography, mid-sections of the β heat-treated samples were prepared by conventional grinding/polishing procedures and etched in 2% HF, 8% HNO3 and 90% H2O (Kroll's reagent) for 20s. Laboratory X-ray diffraction was used to determine the α texture evolution during α→β→α transformation. Small slabs were cut from the center of the sample, including original and β annealed samples, with dimensions of 15 mm in diameter and 10 mm long and prepared by traditional method for XRD texture analysis. XRD tests were performed using a Bruker D8 Discover XRD Instrument, and three incomplete pole figures ($\alpha \le 70°$), i.e. (0001), (10-10) and (10–11), were measured. The orientation distribution functions (ODFs) were calculated using WIMV method from the measured pole figures after background and defocusing correction. The recalculated pole figures based on the corrected ODFs were plotted using TEXEval V2.0.

In order to understand the detailed grain orientation evolution during the β→α transformation, the electron backscatter diffraction (EBSD) was carried out. The EBSD samples were mechanically polished followed by the electro-polishing in the solution of 5% perchloric acid, 35% butanol and 60% methanol at approximately −35 °C for 60s with an applied potential of 30 V. An Oxford-S-3400N Scanning electron microscope (SEM), equipped with HKL channel 5 software, was used for EBSD data acquisition and analysis. A step size of 2 μm was used and performed on an area of 1.2 × 1.2 mm^2 in the middle of the samples. The number of the prior β grains was 25–35 in each sample. Taking the transformed α texture measured by EBSD, the texture of the high temperature parent β phase was reconstructed manually. The prior β grain boundaries were determined by combining the microstructure morphology in scanning area and EBSD map. Then the β grain orientation was determined by using Burgers orientation relation between the parent and daughter phases.

In order to understand the influence of the β texture intensity and cooling rate on texture intensity evolution of the transformed α phase, the reconstructed β orientations and four groups simulated data with different intensity in (110)$_\beta$ were used to study the variant selection during β→α transformation. Meanwhile, predicted α texture based on the high-temperature β texture assuming equal variant selection was used to understand the influence of the variant selection for 2 bars with different intensity of prior β.

3. Results

3.1. Microstructure and texture of as-received material

Optical micrographs of the original D45 and D30 bars are shown in Fig. 1. The two bars show largely different microstructures due to different deformation strains. The microstructure of the D45 bar (Fig. 1a and b) is composed by the equiaxed α phase, deformed α lamellae and a few secondary α phase which are formed during β→α transformation after forging. For D30 bar (Fig. 1c and d), the marbling like microstructure was composed by the equiaxed α and the broken α lamellae in transversal direction of the bar. Meanwhile, the elongated α phase is seen in the longitudinal direction. The above microstructural features indicate that the actual deformation temperature gradually decreases during the forging process. For the D45 bar, the finish forging temperature fell in the lower α/β phase field. For the D30 bar, the finish forging temperature was below the α/β phase field and large deformation was undertaken under the α/β phase field.

The α textures of material before annealing are presented by {0001} and {10-10} pole figures in Fig. 2. The texture components of the D45 bar are relatively complex (Fig. 2a), the c-axis are either concentrated around axial direction (AD) or distributed around radial directions (RDs), perpendicular to the AD, of the bar. At the same time, the {10-10} poles are distributed around RDs or parallel to AD, respectively. The maximum intensities are 2.7 and 2.6 times of the random intensities in the {0001} and {10-10} pole figures, respectively. The main texture component of the D30 bar is quite simple (Fig. 2b). The c-axis of α phase is distributed around RDs and the {10-10} fiber parallels to AD. The maximum intensity is about 5.5 times of the random intensity in {10-10} pole figure.

3.2. Microstructure and texture after β annealing

Fig. 3 shows the fully transformed microstructure obtained after β heat treatment at 1050 °C for 100s. The prior β grains, surrounded by continuous grain boundary α, can be easily identified. The size of the prior β grain is 200–250 μm for four different samples. For the air cooled samples, a basketweave α microstructure is found within the prior β grain in the β annealed D45 bar (Fig. 3a) whereas, in the D30 bar (Fig. 3c), coarse α colonies are populated by the fine α