Effect of Base Material on Microstructure and Texture Evolution of a Ti–6Al–4V Electron-Beam Welded Joint

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Abstract The effect of base material (BM) on microstructure and crystallographic orientation evolution of a Ti–6Al–4V electron-beam welded joint was investigated. Meanwhile, the crystallographic orientation of prior β grains was studied by advanced electron backscattered diffraction data processing. The inhomogeneity of microstructure within welded joint was formed due to the different microstructures of BM. By comparing microstructure details of the welded joint, including microstructure morphology and crystallographic orientation with those of the base material, it can be found that both the microstructure morphology and crystallographic orientation of the EBW joint would be controlled by BM.

KEY WORDS: Electron-beam welding; Titanium alloys; Prior β orientation; Microstructure; Texture

1 Introduction

Electron beam welding (EBW), an advanced fusion welding technique, is widely used to join and repair thick components in aero-engine manufacturing [1–4]. EBW is highly suited for joining titanium alloys as the high vacuum inside the chamber, where the process is carried out, shields hot metal from contamination [1]. The unique high vacuum welding process can effectively prevent the dissolving of detrimental elements in atmospheric gases, such as oxygen, nitrogen, carbon and hydrogen. Moreover, the high heat intensity associated with the EBW creates a small

and narrow fusion zone (FZ), heat-affected zone (HAZ), and can be adapted for thick components [1, 4–9].

The mechanical properties of titanium alloys are primarily determined by its microstructures and textures [10, 11]. A lot of useful studies have been performed in order to clarify and improve the understanding of the evolution of microstructure occurring in EBW processing for titanium alloys [1, 3, 7, 12–14]. In addition, the researches on the microstructure and mechanical properties of EBW joint are conducted for the Ti–6Al–4V alloy [1, 4, 15–17]. These studies show the microstructure transformation in Ti–6Al–4V electron-beam welded joints. However, there are very limited studies about the texture evolution of EBW joint for the Ti–6Al–4V alloy. The texture evolution would predict and control the final weld structure, which is critical for understanding and improving the mechanical properties of EBW joints for both scientific and engineering perspectives [18].

The primary objectives of the present work are to study the effect of the base material on microstructure and texture evolution of a Ti–6Al–4V electron-beam welded joint and clarify the crystallographic orientation relations between base material and welded joint. To achieve the goal, the variations of microstructure and texture across

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different zones of EBW joints, which are closely affected by base material, were measured by scanning electron microscopy (SEM) and electron backscattered diffraction (EBSD). The difficulty associated with masking β grain structure and crystallographic orientation by $\beta \rightarrow \alpha$ phase transformation was overcome by β grain reconstruction through the Burgers orientation relationship (BOR) [19–21], which aligned the close-packed planes $\{0001\}\alpha//\{110\}\beta$ and close-packed directions $\langle 11\bar{2}0 \rangle\alpha//\langle 111 \rangle\beta$.

2 Experimental

The material used in this study was a commercial Ti–6Al–4V alloy, whose composition in weight percent was 6.03 Al, 4.02 V, 0.007 N, 0.0021 H, 0.13 O and balance Ti. Two plates with different hot working history, referred to hereafter as the “as-cast plate” and the “bimodal plate,” were selected to obtain different base materials (BM). The plates were cut from an α/β forged disk noted as bimodal plate and an ingot casting as as-cast plate of Ti–6Al–4V. The disk was forged and subsequently annealed in α/β domain by the manufacturer. Two rectangular plates with the dimension of 150 mm $\times$ 200 mm $\times$ 16 mm were welded together to make 300 mm $\times$ 200 mm $\times$ 16 mm test panel. The microstructure of the as-cast plate is a lamellar structure (Fig. 1a), consisting of colonies of α/β lamellae. The microstructure of the bimodal plate is fine-grained bimodal microstructure (Fig. 1b) formed by equiaxed primary α (α_p) grains (55%) in a matrix of secondary α (α_s) laths.

Welding experiment was conducted using a ZD150-C model electron beam welding machine with an accelerating voltage of 150 kV. The electron current of 54 mA and the welding speed of 21 mm/s were used. In this work, the reference directions were selected as follows: the welding direction (WD), the normal direction (ND) and the transverse direction (TD).

Following EBW, the specimens for microstructure examination were sectioned perpendicular to the WD. Microstructural observations were performed by optical microscopy (OM), SEM and EBSD technique. Metallographic preparation of the specimens was carried out using conventional techniques. Sample for EBSD was prepared by electropolishing in a polishing solution of 6% perchloric acid, 64% methyl alcohol and 30% butanol at -32°C using a voltage of 30 V. EBSD experiments were conducted in an Oxford-S-3400N scanning electron microscope, equipped with the HKL Channel 5 software. The orientation of prior β grains in welding joint was calculated from the secondary α orientation, measured by EBSD, using β grain reconstruction. This method combines the microstructure morphology in scanning area and EBSD

Fig. 1 SEM images of the as received Ti–6Al–4V microstructure: **a** as-cast plate, **b** bimodal plate

map to determine the prior β grain boundaries firstly, and then the β grain orientation by using an approach developed by Humbert and Gey [22].

3 Results and Discussion

The cross-sectional macrograph of the Ti–6Al–4V electron-beam welded joint is shown in Fig. 2. The shape of the welded joint is symmetric, but the microstructures between the two sides of center line are quite different. Three distinct regions can be detected in macrograph: a BM, a narrower HAZ and an FZ. However, a big differentiation of the microstructure of the zones, located on both sides of the weld joint center line, was observed. These variations could be due to the diversity of the BM. At the side of as-cast BM, the microstructure corresponds to a typical transformed- β structure consisting of the coarse β grains apparently inherited from BM in FZ and HAZ. Meanwhile, the grain size of prior β grains was not changed. The α/α' laths seem coarser in HAZ than that in FZ due to different hot working history. Microstructure characterization of the HAZ, near the bimodal BM, shows transition of

Fig. 2 Macrostructure of electron-beam welded Ti-6Al-4V joint

microstructure from a bimodal to an acicular microstructure, and a typical acicular martensite structure was formed within the β columnar grains in FZ. This variation can be attributed to the melting of the base metal during welding and different cooling rates after EBW processing.

In order to further elucidate the microstructure morphology evolution mechanism of the welded joint, more detailed microstructure morphology in welded joint was studied by SEM.

From the SEM observation shown in Fig. 3, it could be found that the intergranular structure of the prior β within FZ is identical on the both sides of the centerline. And it also can be confirmed that the columnar grains consist of plenty thin α lamellae with a thickness of $\sim 0.5 \mu\text{m}$ and a few β films at the interface of α lamellae.

In HAZ, the temperature gradually increases and finally exceeds the β phase transformation temperature with the decrease in distance to the fusion line during welding process. The inhomogeneity of microstructure within HAZ was formed due to the difference in welding thermal cycle. On the as-cast plate side, as seen in Fig. 4a–c, the lamellar α phase has gradually transformed to β phase during heating process of EBW and a much finer α lamellae structure, presented as the shape of the feather, precipitated during cooling process of the EBW. The fraction of “feathery microstructure” composed by fine transformed β within generated β lamellae was gradually increased. Meanwhile, the “feathery microstructure” gradually replaced the parent microstructure into matrix with the decrease in distance to the fusion line.

Meanwhile, the microstructure of the BM has a great effect on microstructure morphology of the HAZ. The HAZ on the bimodal plate side of the welded joint consisted of various fractions of either primary α grains or

Fig. 3 Microstructures of the FZ at the side of **a** the as-cast plate, **b** bimodal plate

“ghost” primary α grains together with original lamellar structure and/or transformed lamellar structure. In the outer part of the HAZ, where the temperature is slightly higher than $\alpha + \beta$ phase field, shown in Fig. 5a, the initial primary α grains still existed. Meanwhile, the fraction of β phase transformed from α lamellae gradually increased. Some fine α lamellae inherited from newly generated β phase were produced when the fraction of β phase increased to a certain extent. The fraction of initial lamellar structure decreased with decreasing distance to the FZ (Fig. 5b) until the child transformed microstructure gradually replaced the parent transformed microstructure in this area. Close to the FZ (Fig. 5c), the primary α grains gradually disappeared and a full lamellar microstructure was formed with decreasing distance to the fusion line.

It should be noted that the primary α grains close to the FZ had partly or fully transformed to β phase, even though traces of these grains could still be seen as a “ghost” structure (Fig. 5c). These “ghost” structures were primary α grains that were in the β phase field and possibly transformed during the welding process, but time was not sufficient to reach chemical equilibrium [4]. Thus, the areas of the “ghost” α contained more α stable elements and caused

Fig. 4 Microstructures of the HAZ at the side of the as-cast plate, **a** outer part of the HAZ, **b** middle of HAZ, **c** vicinity of FZ

Fig. 5 Microstructures of the HAZ at the side of the bimodal plate, **a** outer part of the HAZ, **b** middle of HAZ, **c** vicinity of FZ

Fig. 6 IPF maps of the zone boxed in Fig. 2: **a** zone I, **b** zone II, **c** zone III

coarse α laths produce in those areas during $\beta \rightarrow \alpha$ transformation.

The crystallographic orientations of α variants inherited from some specific areas, zones I—III marked by rectangle

in Fig. 2, crossing BM and welded joint are shown in Figs. 6, 7 and 8. At the side of the as-cast plate, the measured α texture within the zones I and II is shown in Fig. 6a, b, respectively. It could be seen that more α

Fig. 7 Local α textures in Fig. 6c: **a** far-HAZ, **b** near-HAZ, **c** FZ

variants with different crystallographic orientations were generated in HAZ and FZ than those in BM. At the side of bimodal plate, as shown in Fig. 6c, the welded joint

displayed a pronounced heterogeneous orientation distribution along different regions. The local textures of the far-HAZ, near-HAZ and FZ are represented by the $\{0002\}/\{11\text{--}20\}$ pole figure in Fig. 7a–c, respectively. It also could be seen that the main texture components are present in (0001) pole figure compared with (11–20) pole figure. Thus, the main α texture components are marked with specific names A, B, C, D, E, F, G and H with the corresponding location in (0001) pole figure in Fig. 7. The main α texture components in far-HAZ (Fig. 7a) are A and B with intensity of 6.92 and 5.23 times random, respectively. In zone located in the areas close to FZ (near-HAZ), it was obvious from Fig. 7b that the texture components A and B disappeared but the intensities of the texture component C, D, E, F and H increased from 4.79, 3.91, 3.25, 4.13 and 3.37 in Fig. 7a to 8.24, 8.08, 7.94, 6.25 and 6.95 in Fig. 7b, respectively. Meanwhile, a new texture component G with the maximum intensity of 6.12 times random was produced. It can be speculated that this texture variation was associated with $\alpha \rightarrow \beta \rightarrow \alpha$ thermal cycle as well as growth of β grains. And the texture components A and B, which disappeared, might be related to primary α grains. Comparing Fig. 7b, c, it became apparent that the zone close to FZ displayed similar texture components with FZ but significant differences in the texture intensity. The main two α texture components in FZ were G and H with intensity of 8.03 and 10.73, respectively. By comparing Fig. 7c with b, it can be found that the intensity of C, D, E and F texture components decreased.

In order to determine the high-temperature β texture, the α orientation maps were used to reconstruct the β grain

Fig. 8 EBSD maps (inverse pole figure colors relative to TD is shown in the upper right corner) of reconstructed β grains within the **a** zones I, **b** II in Fig. 2, **c** EBSD maps of reconstructed β grains of FZ and partly HAZ in the zones III in Fig. 2 and the non-reconstructed region is white, **d** IPF of reconstructed β grains in TD within FZ in **c**

structure based on the Burgers orientation relation between the β and the transformed α phases. The reconstructed β phase orientation maps, shown in Fig. 8, providing the depiction of primary β grain structures, are developed during solidification. As shown in Fig. 8a, b, all prior β gains in welded joint were inherited from original β grains in BM, although both similarities and differences in the main α texture components of BM and welded joint were found. This indicates that the growth mode for prior β grain is epitaxial growth in FZ inherited from BM, but the nucleation and growth of α/α' go through a different routine during cooling. The reconstructed β grain orientation map within FZ and partly HAZ regions for bimodal plate side is shown in Fig. 8c. A strong $\langle 111 \rangle \beta$ and a weak $\langle 001 \rangle$ fiber (presented in blue and red color in the IPF map, respectively) parallel to TD texture component with intensity of 5.15 and 1.7 times random is presented in FZ region. In HAZ region, the success reconstructed β grains also displayed $\langle 111 \rangle \beta$ /TD texture component (presented in blue color in Fig. 8c).

For duplex titanium with lamellar or bimodal microstructure, the prior β recovered from remained β during $\alpha \rightarrow \beta$ transformation with respect to the BOR. Similarly, the secondary α laths are produced within parent β with respect to the BOR during cooling. This is called “texture memory,” which has been reported widely in titanium as well as zirconium alloys [10, 23–25]. Thus, the crystallographic orientation of grains in HAZ is controlled by BM. And for the microstructure in FZ, both grain size and crystallographic orientation of prior β , via epitaxial growth, are greatly depended on the microstructure of HAZ.

4 Conclusion

In summary, both the microstructure morphology and crystallographic orientation evolution of a Ti–6Al–4V electron-beam welded joint, including HAZ and FZ, were mainly controlled by BM. In HAZ, the microstructure evolution, associated with microstructure inheritance and texture memory on the basis of $\alpha \rightarrow \beta \rightarrow \alpha$ heat treatment cycle, was greatly affected by BM directly. The FZ was

affected by BM indirectly. The morphology and crystallographic orientation of prior β grain in FZ were controlled by HAZ associated with epitaxial growth.

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