Texture in Ti60 Alloy Bars and Its Effect on Tensile Properties (Postprint)

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Abstract

Ti60 rods with diameters of 30 and 45 mm (defined as D30 and D45, respectively), which were precision forged in the $\alpha+\beta$ two-phase region, were subjected to solution+aging heat treatments at 950, 1000, and 1050 °C, and the influence of heat treatment temperature on the texture and tensile properties of the rods was investigated. The results show that in the as-forged microstructure of D45 rods, a strong fiber texture parallel to the rod axis and the <0001> or <101 0> directions of the α phase was present; after heat treatment at 950 °C, the microstructure and texture showed no significant changes. As the solution temperature increased, the <0001> fiber texture of the α phase was enhanced, while the texture density of the <101 0> fiber texture decreased. The solution temperature had little effect on the strength of the rods. In the as-forged microstructure of D30 rods, a fiber texture primarily oriented along the <101 0> direction was present; as the solution temperature increased, the <0001> fiber texture gradually strengthened, and the room-temperature strength of the rods increased significantly.

Full Text

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Abstract

Ti60 bars precision-forged in the $\alpha+\beta$ two-phase region, with diameters of 30 mm and 45 mm (designated as D30 and D45 respectively), were subjected to solution + aging heat treatments at 950, 1000, and 1050 °C to investigate the effect of heat treatment temperature on texture and tensile properties. The results show that in the as-forged D45 bars, a strong fiber texture exists with the bar axis parallel to the α-phase $<10\bar{1}0>$ direction. After heat treatment at 950 °C, the microstructure and texture show no significant changes. With increasing solution temperature, the intensity of the α-phase $<10\bar{1}0>$ fiber texture decreases. Solution temperature has little effect on the strength of the bars. In the as-forged D30 bars, the main texture is a <0001> fiber texture with the bar axis parallel to the α-phase c-axis. As the solution temperature increases, the $<10\bar{1}0>$ fiber texture gradually strengthens while the <0001> fiber texture weakens, leading to a significant increase in room-temperature strength. After heat treatment at 1050 °C, the D45 bars form transformed microstructures with <0001> and <2023> fiber textures, with maximum texture densities of 8.4 and 6.5 respectively. The D30 bars develop a strong <0001> fiber texture, which further strengthens after heat treatment at 1050 °C, while the $<10\bar{1}0>$ fiber texture weakens compared to the as-forged state.

Keywords Ti60 alloy, heat treatment, texture, tensile property

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1. Introduction

Titanium alloy microstructures can be broadly classified into three categories based on α-phase morphology: equiaxed, bimodal, and lamellar structures [?, ?, ?, ?, ?, ?]. Equiaxed structures exhibit good strength-ductility balance but poor creep resistance, toughness, and fatigue crack propagation resistance. Lamellar structures show excellent creep properties, toughness, and fatigue crack propagation resistance but inferior low-cycle fatigue performance and ductility. Bimodal structures, which lie between these two extremes, can achieve a favorable combination of tensile, fracture, fatigue, and creep properties, and are therefore adopted by most high-temperature titanium alloys [?].

Due to their excellent high-temperature mechanical properties, $\alpha+\beta$ and near-α titanium alloys have become important structural materials for aerospace hot-section components [?, ?, ?, ?]. Ti60 is a near-α titanium alloy that can be used for long-term service at 600 °C [?, ?, ?]. After deformation in the $\alpha+\beta$ two-phase region, this alloy can obtain a uniform bimodal structure through heat treatment above the finish-forging temperature, achieving a good balance between fatigue and creep properties. Heat treatment is an important means of controlling the microstructure and properties of near-α titanium alloys. According to the Burgers orientation relationship between α and β phases during phase transformation [?], i.e., $\{0001\}\alpha//\{110\}\beta$ and $<111>\beta//<11\bar{2}0>\alpha$, six differently oriented β grains will be generated during the $\alpha\rightarrow\beta$ phase transformation, and a single original β grain can form 12 differently oriented secondary α variants during cooling [?]. If each variant precipitates equivalently during the $\alpha\rightarrow\beta\rightarrow\alpha$ cycle, the texture density after heat treatment should be much lower than that before heat treatment [?]. However, during the $\beta\rightarrow\alpha$ phase transformation, β grains preferentially nucleate at retained β phase locations, causing the newly formed primary β grains to not conform to the Burgers orientation relationship with the surrounding α phase. Additionally, the selection of α-phase variants during the $\beta \rightarrow \alpha$ transformation is also influenced by the orientations of adjacent original β grains and primary α phases [**?**, **?**, **?**, **?**, **?**, **?**]. These factors make the effect of heat treatment on titanium alloy texture complex. Therefore, the texture present in titanium alloy thermomechanical processing structures not only significantly affects the mechanical properties of the as-forged material but also influences the heat treatment response.

Numerous studies have investigated the effects of heat treatment temperature on the microstructure and mechanical properties of titanium alloys [**?**, **?**, **?**, **?**]. However, with increasing performance requirements for titanium alloys, the widespread adoption of new materials, technologies, and processes, the continuous emergence of new problems during material application, and advances in research techniques, the relationship between microstructure and mechanical properties of titanium alloys remains a hot topic in current research [**?**, **?**]. Particularly, the development and refinement of electron backscatter diffraction (EBSD) technology have opened new windows for in-depth investigation of the microstructure-mechanical property relationship in titanium alloys.

Texture or microtexture in titanium alloys significantly affects properties [**?**, **?**]. Strong textures are more common in sheet materials, while textures in forgings and bars have not received much attention. Consequently, titanium alloy texture research has long focused on sheet materials. It was not until the 1980s, with the emergence of the dwell fatigue concept, that microtexture in titanium alloy forgings and bars (macrozones composed of grains with similar orientations) gradually attracted attention and has now become a research hotspot worldwide [**?**, **?**, **?**, **?**, **?**].

This work investigates two different sizes of Ti60 precision-forged bars to study the effects of heat treatment temperature on microstructure and texture, revealing the influence of texture on mechanical properties in near-α titanium alloys to provide guidance for performance optimization of high-temperature titanium alloys.

2. Experimental

The experimental Ti60 titanium alloy was prepared by triple vacuum arc remelting. The ingot had a diameter of 220 mm with a chemical composition (mass fraction, %) of: Al 5.6, Sn 3.7, Zr 3.2, Mo 0.5, Ta 1.0, Si 0.37, Nb 0.4, C 0.05, and Ti balance. The β transus temperature measured by metallographic method was 1040 °C. The ingot was initially forged in the β single-phase region to a diameter of 140 mm, then divided into two parts and precision-forged at 1000 °C to bars with diameters of 45 mm and 30 mm (designated as D45 and D30) after 2 and 3 forging passes, respectively.

Bars with a length of 70 mm were subjected to solution and aging heat treatments. Solution temperatures were 950, 1000, and 1050 °C, with a holding time of 2 h followed by air cooling to room temperature. The aging treatment consisted of holding at 700 °C for 8 h followed by air cooling.

Microstructures were observed using an Axiovert 200 MAT optical microscope (OM). The etchant for metallographic samples was a solution of HF:HNO_3:H_2O = 1:1:48 (volume ratio). Incomplete pole figures of the α-phase were measured using a D8 Discover X-ray diffraction (XRD) instrument. To investigate orientation changes of grains before and after heat treatment, EBSD analysis was performed on as-forged and two-phase region heat-treated samples. EBSD samples were prepared by mechanical and electrolytic polishing using an electrolyte consisting of 6% perchloric acid, 35% n-butanol, and 59% methanol (volume fraction). Polished samples were examined using an S-3400N scanning electron microscope (SEM) equipped with HKL-Channel5 software and an EBSD detector for acquisition and processing of crystallographic orientation data.

Tensile specimens with a gauge diameter of 3 mm and length of 15 mm were machined from the heat-treated bars. Tensile tests were conducted on a Zwick Z050 electronic testing machine at a strain rate of 1 mm/s. Elongation after fracture was measured using an extensometer.

3. Results

3.1 Microstructure

[Figure 1: see original paper] shows the as-forged microstructures of the two Ti60 bar sizes, D30 and D45. The longitudinal section of D45 bars consists primarily of equiaxed α-phase, elongated banded α, and β-transformed structures (Fig. 1a). The cross-section contains equiaxed α-phase, short rod-like α-phase, and a small amount of β-transformed structure (Fig. 1b). The longitudinal section of D30 bars consists of primary α-phase elongated along the axial direction and deformed α-laths (Fig. 1c), while the cross-section is mainly composed of equiaxed α-phase and deformed α-laths (Fig. 1d).

The longitudinal microstructures after heat treatment at different temperatures are shown in [Figure 2: see original paper]. After heat treatment at 950 °C, both D45 and D30 bars show varying degrees of α-phase spheroidization, which is more pronounced in D30 bars. After heat treatment at 1000 and 1050 °C, the microstructural differences between the two Ti60 bar sizes are minimal. Heat treatment at 1000 °C yields a bimodal structure with approximately 30% primary α-phase, while solution treatment at 1050 °C produces a lamellar structure with original β grain sizes of about 500 m.

3.2 Texture Evolution

The textures of the two Ti60 bars in the as-forged condition and after three heat treatment conditions are shown in [Figure 3: see original paper]. In the as-forged D45 bars, the main texture is a fiber texture with the bar axis parallel to the α-phase <10$\bar{1}$0> direction. With increasing heat treatment temperature, the <10$\bar{1}$0> fiber texture intensity decreases. After heat treatment at 950 and 1000 °C, the texture density with the bar axis parallel to the <10$\bar{1}$0> direction decreases slightly, while the texture density with the bar axis parallel to the crystal c-axis gradually increases. After heat treatment at 1050 °C, transformed textures of <0001> and <2023> form, with maximum texture densities of 8.4 and 6.5, respectively.

The as-forged D30 bars exhibit a strong <0001> fiber texture with the bar axis parallel to the <0001> direction. After heat treatment at 950 °C, the <10$\bar{1}$0> fiber texture weakens and a fiber texture with the bar axis parallel to the crystal c-axis appears. After heat treatment at 1000 °C, the densities of these two textures increase compared to those after 950 °C heat treatment. After heat treatment at 1050 °C, the <0001> fiber texture further strengthens and a <2023> fiber texture appears, while the <10$\bar{1}$0> fiber texture weakens compared to the as-forged state.

EBSD analysis was performed on the as-forged and two-phase region heat-treated Ti60 bars, with results shown in [Figure 4: see original paper]~[Figure 7: see original paper]. Along the bar axis, D45 bars show a texture with the bar axis parallel to the α-phase <10$\bar{1}$0> direction (Fig. 4a), while D30 bars show a strong texture with the bar axis parallel to the α-phase <0001> direction (Fig. 4b). Some equiaxed α-phase grains have their c-axis parallel to the bar axis, but the number is small, which is consistent with the results in Figs. 3a and 3b. The crystal orientation distribution maps in the radial direction (Figs. 4c and 4d) reveal significant differences in crystal orientation distribution in different regions, indicating strong microtexture.

After heat treatment at 950 °C, the microstructure and texture of D45 bars show no obvious changes ([Figure 5: see original paper]), while D30 bars show noticeable grain growth, weakened microtexture, and more uniform crystal orientation distribution. After heat treatment at 1000 °C, the microstructural differences between the two bar sizes decrease and the microtexture is significantly weakened ([Figure 6: see original paper]). As shown in [Figure 7: see original paper], the texture types and densities obtained by EBSD for bars heat-treated at 1000 °C are basically consistent with XRD results. Using Channel5 software, the textures of primary α-phase (αp) and secondary α-phase (αs) were analyzed separately, as shown in Figs. 7c~7f. In both Ti60 bar sizes, the primary and secondary α-phases have the same texture type, with the texture intensity of primary α-phase being lower than that of secondary α-phase.

In D30 bars, the texture densities of primary α-phase and secondary α-phase with c-axes parallel to the bar diameter direction are both higher than those in D45 bars. Additionally, both primary and secondary α-phases in D30 bars exhibit a <10$\bar{1}$0> fiber texture with the <10$\bar{1}$0> direction parallel to the bar axis.

During deformation in the $\alpha+\beta$ two-phase region of near-α titanium alloys, secondary α-phase within the same colony exhibits similar deformation behavior, resulting in strong microtexture in insufficiently deformed large-section bars [?, ?]. During continued deformation, grains with similar orientations in the same region maintain similar deformation behavior [?], leading to strong microtexture even in small-sized bars. During high-temperature heat treatment and subsequent cooling, α-phase recrystallization and $\beta \rightarrow \alpha$ phase transformation can generate new crystal orientations, weakening the microtexture. During precision forging, the material experiences a stress state of two compressive stresses and one tensile stress. In α-Ti deformation, prismatic, basal, and pyramidal slip systems are primarily activated [?]. With increasing deformation, the <10I0> direction gradually aligns with the bar axis, forming a <10I0> fiber texture along the axial direction.

During heat treatment, as the temperature increases, the alloy undergoes $\alpha \rightarrow \beta$ phase transformation. The β phase preferentially nucleates and grows at retained β-phase locations, during which the crystal orientation of the β phase does not change. Secondary α-phase generated during cooling has a Burgers orientation relationship with the original β grains. The presence of secondary α-phase with c-axes parallel to the bar axis indicates that the high-temperature β-phase has a <110> fiber texture with the <110> direction parallel to the bar axis. At room temperature, the retained β-phase content in near-α titanium alloys is small (volume fraction of 5%~7%), making it difficult to directly detect the crystal orientation of retained β-phase using EBSD and XRD, nor can the orientation evolution of the β-phase during high-temperature deformation be directly measured. Peck and Thomas [?] and Zhang Zhenbo [?] found that in rotary forging or extrusion of bcc metals such as Fe, Nb, W, and β titanium alloy Ti2448, the bars all develop a <110> fiber texture parallel to the bar axis, and the texture density gradually increases with increasing deformation. The stress state in bar precision forging is similar to that in rotary forging and extrusion. Therefore, it can be considered that the β-phase in near-α titanium alloys also develops the same texture type during precision forging in the $\alpha+\beta$ two-phase region, which is consistent with the crystal orientation of secondary α-phase generated after high-temperature heat treatment.

3.3 Effect of Heat Treatment Temperature on Room-Temperature Tensile Properties

[Figure 8: see original paper] shows the room-temperature tensile properties of the two Ti60 bar sizes after different heat treatments. As shown in Fig. 8a, heat treatment temperature has little effect on the yield and tensile strengths of D45 bars. After solution treatment at 1000 °C, the strength is slightly higher, with yield and tensile strengths of 1009 and 1105 MPa, respectively. Ductility decreases slightly with increasing heat treatment temperature, and drops significantly after heat treatment at 1050 °C, with an average elongation of only 6.1%. In contrast, the strength of D30 bars increases significantly with heat treatment temperature, while ductility decreases markedly. After heat treatment at 1050

°C, the average elongation is only 3.3%, but the yield and tensile strengths increase to 1086 and 1144 MPa, respectively. At a solution temperature of 1000 °C, both bar sizes achieve a good combination of tensile strength and ductility.

The macroscopic mechanical properties of polycrystalline materials are closely related to the crystal orientation distribution of grains, particularly for hexagonal close-packed α-Ti alloys where texture has a greater influence on properties. When a <0001> fiber texture exists in bars, pyramidal slip systems of the hexagonal crystal must be activated, requiring higher critical resolved shear stress and resulting in higher alloy strength. When a <10$\bar{1}$0> fiber texture exists, prismatic slip systems are activated with lower critical resolved shear stress, leading to lower strength but better ductility.

For D45 bars solution-treated below the β transus at 950 and 1000 °C, the primary α-phase content gradually decreases with increasing heat treatment temperature, while the <0001> fiber texture density increases slightly, causing a modest increase in strength and slight decrease in ductility. After heat treatment at 1050 °C, although the <0001> texture continues to strengthen, the original β grains become coarse, causing both strength and ductility to decrease.

The room-temperature tensile properties of D30 bars are more strongly affected by heat treatment temperature. After heat treatment at 950 °C, an equiaxed structure is obtained with a <10$\bar{1}$0> fiber texture, resulting in relatively low strength (yield and tensile strengths of only 948 and 1009 MPa) but the highest elongation of 16.5%. After heat treatment at 1000 °C, the <0001> fiber texture strengthens, significantly increasing alloy strength while decreasing ductility. After heat treatment at 1050 °C, the bars develop a very strong <0001> texture. Despite the coarse original β grains, the strength continues to increase significantly, reaching yield and tensile strengths of 1086 and 1144 MPa, respectively, but with elongation of only 3.3%.

In summary, the tensile properties of Ti60 bars are influenced by both microstructure type and texture, with texture having a greater effect. Selecting an appropriate solution treatment temperature to obtain a bimodal structure with α-phase c-axes parallel to the bar axis can optimize the combination of strength and ductility.

4. Conclusions

(1) The as-forged D45 precision-forged Ti60 bars with a diameter of 45 mm mainly exhibit a <10$\bar{1}$0> fiber texture with the bar axis parallel to the α-phase <10$\bar{1}$0> direction. The as-forged D30 bars with a diameter of 30 mm mainly exhibit a <0001> fiber texture with the bar axis parallel to the <0001> direction.

(2) With increasing heat treatment temperature, the intensity of the <110> fiber texture in the β-transformed structure gradually strengthens while the <10$\bar{1}$0> fiber texture gradually weakens and even disappears. This

trend is more pronounced in the 30 mm precision-forged bars.

(3) The room-temperature tensile properties of Ti60 precision-forged bars are influenced by both microstructure and texture, with texture having a greater effect. Selecting an appropriate solution treatment temperature to obtain a bimodal structure with α-phase c-axes parallel to the bar axis can optimize the balance between strength and ductility.

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