Effect of Microstructure and Texture on Tensile Properties of Ti60 Alloy (Postprint)

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Abstract

Ti60 bars of Φ30mm and Φ45mm, precision-forged in the α/β two-phase region, were subjected to solution plus aging heat treatments at 950°C, 1000°C, and 1050°C to investigate their microstructure, texture, and influence on tensile properties. The results indicate that the Φ45mm bars exhibit a strong fiber texture with <0001> and <10-10> directions parallel to the bar axis. After heat treatment at 950°C, no significant changes in microstructure or texture are observed. With increasing solution temperature, the fiber texture with the crystallographic <0001> direction parallel to the bar axis intensifies, while the intensity of the <10-10> fiber texture diminishes; however, the solution temperature exerts minimal influence on bar strength. In the Φ30mm bars, a fiber texture with the <10-10> direction parallel to the bar axis predominates. As the solution temperature rises, the texture with the crystallographic <0001> direction parallel to the bar axis progressively strengthens, leading to a significant increase in the room-temperature strength of the bars.

Full Text

Texture of Ti60 Alloy Precision Bars and Its Effect on Tensile Properties

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Abstract

Ti60 bars with diameters of 30 mm and 45 mm (designated as D30 and D45, respectively), precision-forged in the $\alpha+\beta$ two-phase region, were subjected to solution and aging heat treatments at 950, 1000, and 1050 °C to investigate the influence of heat treatment temperature on texture and tensile properties. The results show that the D45 bar exhibited a strong fiber texture in the as-forged condition, with the bar axis parallel to the direction of the α phase. Microstructure and texture changes were negligible after heat treatment at 950 °C. As the solution temperature increased, the intensity of the fiber texture gradually decreased. Solution temperature had little effect on the strength of the D45 bar. In contrast, the as-forged D30 bar primarily exhibited a fiber texture. With increasing solution temperature, the fiber texture gradually intensified, leading to a significant increase in room-temperature strength. The texture component weakened while the component strengthened. After heat treatment at 1050 °C, the D30 bar formed a strong fiber texture, with yield and tensile strengths reaching 1086 MPa and 1144 MPa, respectively, though elongation was only 3.3%.

Keywords: Ti60 alloy, heat treatment, texture, tensile property

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Introduction

Based on α-phase morphology, titanium alloy microstructures can be broadly classified into three categories: equiaxed, bimodal, and lamellar structures. Equiaxed structures exhibit good strength-ductility balance but poor creep resistance, fracture 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 widely adopted in 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 designed 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 a crucial 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., $\{\ \}\beta//\{11\bar{2}0\}\alpha$ and $<111>\beta//<\ >\alpha$, six differently oriented β grains can form during the $\alpha\rightarrow\beta$ transformation, and a single primary β grain can produce 12 different variants of secondary α during cooling. If each variant precipitates equivalently during $\alpha \rightarrow \beta \rightarrow \alpha$ cycling, the texture intensity after heat treatment should be significantly lower than before treatment. However, during the $\beta \rightarrow \alpha$ transformation, β grains preferentially nucleate at retained β locations, causing newly formed primary β grains to deviate from the Burgers orientation relationship with surrounding α phases. Furthermore, variant selection during the $\alpha \rightarrow \beta$ transformation is also influenced by the orientation of adjacent primary β grains and neighboring primary α phases. These factors render the effect of heat treatment on titanium alloy texture rather complex. Consequently, textures present in as-forged titanium alloy microstructures not only significantly affect the mechanical properties of the forged condition but also influence the alloy's response to subsequent heat treatment.

Numerous studies have investigated the effects of heat treatment temperature on microstructure and mechanical properties of titanium alloys. However, with increasing demands for performance, widespread adoption of new materials, technologies, and processes, continuous emergence of new problems during material application, and advances in research techniques, the relationship between microstructure and mechanical properties remains a hot topic in titanium alloy research. Particularly, the development and maturation of electron backscatter diffraction (EBSD) technology have opened new avenues for in-depth investigation of these relationships.

Texture or microtexture in titanium alloys significantly affects properties. Strong textures are more common in sheet materials, while textures in forgings and bars have historically received less attention, making sheets the primary focus of texture research for a long time. It was not until the 1980s, with the emergence of the dwell fatigue concept, that microtextures in titanium alloy forgings and bars—local "macrozones" composed of grains with similar orientations—gradually attracted attention and have now become a research focus worldwide.

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

Experimental Methods

The experimental Ti60 titanium alloy was prepared by triple vacuum arc remelting, producing ingots 220 mm in diameter 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, Ti balance. The β transus temperature was determined to be 1040 °C by metallographic method. The ingot was initially forged in the β single-phase region to a diameter of 140 mm, then divided into two sections and precision-forged at 1000 °C to final diameters of 45 mm and 30 mm (designated as D45 and D30) through 2 and 3 forging passes, respectively.

Bars 70 mm in length were subjected to solution and aging heat treatments. Solution temperatures were 950, 1000, and 1050 °C with a 2 h hold followed by air cooling to room temperature. Aging was performed at 700 °C for 8 h followed by air cooling.

Microstructures were examined using an Axiovert 200 MAT optical microscope (OM). Etching solution for metallographic samples was 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 diffractometer (XRD). EBSD analysis was conducted on as-forged and two-phase-region heat-treated samples to investigate orientation changes before and after heat treatment. EBSD samples were prepared by mechanical and electrolytic polishing using an electrolyte of 6% perchloric acid, 35% n-butanol, and 59% methanol (volume fraction). Polished samples were analyzed using an S-3400N scanning electron microscope (SEM) equipped with an EBSD detector and HKL-Channel5 software for data acquisition and processing.

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

Results

2.1 Microstructure Figure 1 shows the as-forged microstructures of the two Ti60 bar sizes (D30 and D45). The longitudinal section of the D45 bar consists primarily of equiaxed α phase, elongated banded α, and β-transformed microstructure (Fig. 1a). The cross-section contains equiaxed α, short rod-shaped α, and a small amount of β-transformed microstructure (Fig. 1b). The longitudinal section of the D30 bar comprises primary α elongated along the axial direction and deformed α laths (Fig. 1c), while the cross-section consists mainly of equiaxed α and deformed α laths (Fig. 1d).

The longitudinal microstructures after various heat treatments are shown in Figure 2. After treatment at 950 °C, both D45 and D30 bars exhibited varying degrees of α-phase spheroidization, more pronounced in the D30 bar. Following heat treatment at 1000 and 1050 °C, microstructural differences between the two bar sizes diminished. The 1000 °C treatment produced a bimodal structure with approximately 30% primary α, while solution treatment at 1050 °C yielded a lamellar structure with primary β grain sizes of about 500 m.

2.2 Texture Evolution and Heat Treatment Effects The textures of both Ti60 bar sizes in the as-forged condition and after three heat treatment conditions are shown in Figure 3. The as-forged D45 bar exhibits a fiber texture with the bar axis parallel to the direction of the α phase (Fig. 3a). With increasing heat treatment temperature, the intensity of the fiber texture decreases. At 950 and 1000 °C, the texture density with the bar axis parallel to the direction slightly decreases, while the texture density with the crystal c-axis parallel to the bar axis gradually increases. After heat treatment at 1050 °C, transformation textures of and form, with maximum texture intensities of 8.4 and 6.5, respectively.

The as-forged D30 bar shows a strong fiber texture. After heat treatment at 950 °C, the fiber texture weakens and a fiber texture with the crystal c-axis parallel to the bar axis emerges. At 1000 °C, the intensities of both textures increase compared to the 950 °C condition, though the fiber texture remains weaker than in the as-forged state. After heat treatment at 1050 °C, the fiber texture further intensifies and a strong fiber texture develops.

EBSD analysis of the as-forged and two-phase-region heat-treated Ti60 bars is presented in Figures 4–7. Along the bar axis, the D45 bar shows a texture with the bar axis parallel to the direction of the α phase (Fig. 4a), while the D30 bar exhibits a strong texture with the bar axis parallel to the direction (Fig. 4b). Some equiaxed α grains have their c-axis parallel to the bar axis, but in smaller quantities, consistent with the XRD results in Figures 3a and b. Crystal orientation distribution maps from the radial direction (Figs. 4c and d) reveal significant variations in orientation between different regions, indicating strong microtextures.

After heat treatment at 950 °C, the D45 bar showed negligible changes in microstructure or texture (Fig. 5), whereas the D30 bar exhibited noticeable grain growth, weakened microtexture, and more uniform orientation distribution. Following treatment at 1000 °C, differences between the two bar sizes diminished and microtextures were significantly reduced (Fig. 6). EBSD results from the 1000 °C condition (Fig. 7) show good agreement with XRD data regarding texture type and intensity. Separate analysis of primary α (α_p) and secondary α (α_s) textures using Channel5 software (Figs. 7c–f) reveals that both primary and secondary α phases exhibit the same texture type, with the texture intensity of primary α being lower than that of secondary α.

In $\alpha+\beta$ and near-α titanium alloys deformed in the two-phase region, secondary α plates within the same colony exhibit similar deformation behavior, generating strong microtextures in insufficiently deformed large-section bars. During continued deformation, grains with similar orientations in the same region maintain comparable deformation behavior, resulting in strong microtextures even in small-section bars. During high-temperature heat treatment and subsequent cooling, α-phase recrystallization and $\beta\rightarrow\alpha$ transformation generate new crystallographic orientations that weaken microtextures.

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 direction gradually aligns with the bar axis, forming a fiber texture along the axial direction. During heat treatment, as temperature increases, the alloy undergoes $\alpha \rightarrow \beta$ transformation, with β phase nucleating and growing preferentially at retained β locations without changing its crystallographic orientation. Secondary α formed during cooling maintains a Burgers orientation relationship with the original β grains. The presence of a fiber texture in secondary α implies that the high-temperature β phase possessed a fiber texture with its <110> direction parallel to the bar axis. At room temperature, near-α titanium alloys contain only a small amount of retained β phase (5-7 vol.%), making direct detection of its orientation by EBSD or XRD difficult. Studies by Peck and Thomas on Fe, Nb, W and by Zhang on β-titanium alloy Ti2448 have shown that during rotary forging or extrusion, bcc metals develop a fiber texture parallel to the bar axis, with intensity increasing with deformation. The stress state in precision forging is similar to rotary forging and extrusion, suggesting that the β phase in near-α titanium alloys develops the same texture type during $\alpha+\beta$ two-phase region forging, consistent with the orientation of secondary α after high-temperature heat treatment.

2.3 Effect of Heat Treatment Temperature on Room-Temperature Tensile Properties Figure 8 shows the room-temperature tensile properties of both Ti60 bar sizes after various heat treatments. For the D45 bar (Fig. 8a), heat treatment temperature has minimal effect on yield and tensile strength, with slightly higher strength after solution treatment at 1000 °C (yield strength 1009 MPa, tensile strength 1105 MPa). Ductility decreases slightly with increasing temperature, dropping significantly after β heat treatment at 1050 °C to an average elongation of only 6.1%.

In contrast, the D30 bar exhibits a significant increase in strength with increasing heat treatment temperature, accompanied by a notable decrease in ductility. After treatment at 1050 °C, average elongation is only 3.3%, while yield and tensile strengths increase to 1086 MPa and 1144 MPa, respectively. At 1000 °C, both bar sizes achieve a good balance of strength and ductility.

The macroscopic mechanical properties of polycrystalline materials are closely related to crystallographic orientation distribution, particularly for hexagonal close-packed α-Ti alloys where texture effects are more pronounced. When a fiber texture is present, pyramidal slip systems must be activated, requiring higher critical resolved shear stress and resulting in higher strength. With a fiber texture, prismatic slip systems operate at lower critical resolved shear stress, yielding lower strength but better ductility.

For the D45 bar solution-treated below the β transus at 950 and 1000 °C, primary α content gradually decreases with increasing temperature while fiber texture intensity slightly increases, causing modest strength enhancement and ductility reduction. After treatment at 1050 °C, although the texture continues to strengthen, the coarse primary β grains lead to simultaneous decreases in both strength and ductility.

The D30 bar shows greater sensitivity to heat treatment temperature. After treatment at 950 °C, an equiaxed structure with a fiber texture results in relatively low strength (yield strength 948 MPa, tensile strength 1009 MPa) but maximum elongation of 16.5%. At 1000 °C, enhanced fiber texture significantly increases strength while reducing ductility. After treatment at 1050 °C, a very strong fiber texture develops, and despite coarse primary β grains, strength continues to increase dramatically to 1086 MPa yield and 1144 MPa tensile strength, though elongation drops to only 3.3%.

In summary, the tensile properties of Ti60 bars are influenced by both microstructure type and texture, with texture playing the more dominant role. Selecting an appropriate solution treatment temperature to obtain a bimodal structure with α-phase c-axes parallel to the bar axis optimizes the strength-ductility balance.

Conclusions

1. The as-forged D45 precision bar (45 mm diameter) primarily exhibits a fiber texture, while the D30 bar (30 mm diameter) shows a dominant fiber texture.
2. With increasing heat treatment temperature, the intensity of the fiber texture in the β-transformed microstructure gradually increases while the fiber texture weakens and eventually disappears. This trend is more pronounced in the 30 mm diameter precision bar.
3. The room-temperature tensile properties of Ti60 precision bars are affected by both microstructure type and texture, with texture having the greater influence. Selecting a suitable solution treatment temperature to obtain a bimodal structure with α-phase c-axes parallel to the bar axis provides optimal strength-ductility matching.

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