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Collaborative behavior in α lamellae and β phase evolution and its effect on the globularization of TC17 alloy

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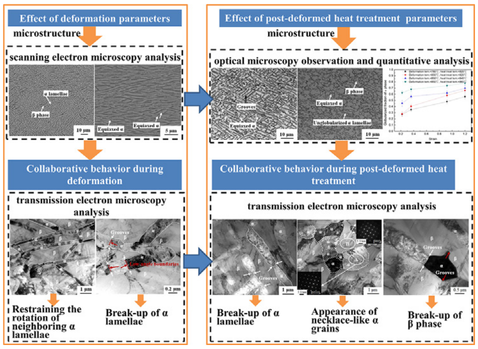
HIGHLIGHTS

- An increase in strain and subsequent heat treatment temperature enhances the globularization of TC17 alloy.
- Collaborative evolution between interleaved α lamellae promotes the globularization of α lamellae.
- The low-angle boundaries in the β grain interiors promote the appearance of necklace-like α grains during heat treatment.
- The globularized mechanisms of TC17 alloy include groove splitting, fault migration and substructure rotation.

GRAPHICAL ABSTRACT



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ABSTRACT

The globularization behavior of the basketweave microstructure in TC17 alloy is quantitatively analyzed during deformation and subsequent heat treatment. Collaborative behavior in the α lamellae and β phase evolution are proposed to affect globularization based on the transmission electron microscopy (TEM) and high-resolution electron backscatter diffraction (EBSD) observations as follows: (i) the interleaved α lamellae restrain the rotation of neighboring α lamellae and promote the formation of low-angle boundaries (LABs) and grooves, and then (ii) the β phase has a positive effect on facilitating the complete separation of α lamellae during deformation. During heat treatment, (iii) the formation of the LABs in the β grain interiors accelerates the appearance of necklace-like α grains, and (iv) the α lamellae promotes the break-up of β phase while the β phase has a positive effect on facilitating the complete separation of α lamellae. In other words, Collaborative behavior in α lamellae and β phase evolution promotes the globularization of TC17 alloy containing a basketweave microstructure. Except for the boundary splitting and termination migration, the mechanism of substructure rotation also participates in the globularization of TC17 alloy containing a basketweave microstructure, which is different to that of the alloys containing a colony microstructure.

1. Introduction

Titanium and its alloys are widely used for several areas like aerospace and biomedical applications due to their high strength-to-weight ratio, good mechanical properties, excellent corrosion resistance and biocompatibility [1–5]. This material is often deformed or heat-treated in the $\alpha + \beta$ phase field or in the β phase field to require goal microstructure with desired mechanical properties. For instance,

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Basketweave or colony microstructure of two phase titanium alloys is generally processed in the $\alpha + \beta$ phase field via hot working [6,7] to purposely destroy microstructure features, produce the desired globular one and require a better balance of strength and ductility. Thus, the kinetics and mechanisms of globularization in two phase titanium alloys containing a colony microstructure have received considerable attention due to their great technological importance [8–12].

For instance, Semiatin et al. [13] revealed that the strains for the initiation of dynamic globularization were 0.75–1.0, and the globularization was nearly completed after reaching strains of 2.0–2.5 for most cases during hot working of Ti-6Al-4 V containing a colony microstructure. Mironov et al. [14] showed that the kinking process of α colonies was closely linked with the development of shear bands during warm working of Ti-6Al-4 V containing a colony microstructure. Warwick et al. [15] showed that the α (0002) texture initially softened and the colony α became kinked during rolling at 950 °C, but the globularization of the colony α resulted in further texture strengthening during the heat treatment of Ti-6Al-4 V alloy. Zeng et al. [16,17] investigated the effect of isothermal forging and subsequent heat treatment on the microstructure evolution for Ti17 alloy with a lamellar colony structure, and established its kinetic modeling of dynamic globularization. Much prior work has also showed that the mechanisms of dynamic globularization of two phase titanium alloys containing a colony microstructure involves groove/boundary splitting [18,19]. This process includes the formation of intraphase α/α boundaries and the subsequent diffusional penetration of the β phase along these boundaries, finally leading to break-up of the colony α lamellae. Intraphase α/α boundaries may evolve from the recovered substructure, dynamic recrystallization, or the formation of localized shear bands within/across individual α lamellae. Related work has shown that the mechanisms of static globularization in two phase titanium alloys containing a colony microstructure involves groove/boundary splitting and fault migration or termination migration [20]. This reference [20] pointed out that the termination migration consisted of the transfer of mass from the curved surfaces of the lamellar terminations to the flat surfaces of the lamellae, and its driving force was provided by curvature difference between the lamellar terminations and the flat lamellar interfaces.

Although previous work has provided a broad insight into the mechanisms of both dynamic and static globularization in two phase titanium alloys containing a colony microstructure, relatively little attention focused on the detailed mechanisms of microstructure evolution in two phase titanium alloys containing a basketweave microstructure. Specially, the collaborative behavior in the α lamellae and β phase evolution has received little attention in the open literature. While the collaborative behavior in the α lamellae and β phase evolution has little influence on the mechanisms of globularization in two phase titanium alloys containing a colony microstructure since the α lamellae are parallel, these become important in basketweave microstructure. Main reason is that the interleaved α lamellae may have a profound effect on the rotation of α lamellae, dislocation density, the formation of LABs and even grooves during deformation, while the formation of the LABs in the β grain interiors during deformation may accelerate the appearance of necklace-like α grains during heat treatment.

In the present work, TC17 (Ti-5Al-2Sn-2Zr-4Mo-4Cr) alloy containing a basketweave microstructure is obtained. This alloy as a kind of “beta-rich” $\alpha + \beta$ titanium alloy has high strength, superior toughness and deep hardenability, which makes it an ideal material in aviation and aerospace industries [7]. The object of the present work is to correlate the desirable microstructure and processing parameters. For this purpose, the globularized fraction (i.e. including dynamic and static globularization) of α lamellae is measured via quantitative metallography. In addition, the effects of collaborative behavior in the α lamellae and β phase evolution on the rotation of α lamellae, the formation of LABs and even grooves, the complete separation of α lamellae or β phase, and the formation of necklace-like α grains by the substructure rotation are analyzed thoroughly. Characterization techniques include optical microscopy (OM), scanning electron microscopy (SEM), transmission electron microscopy (TEM) and high-resolution electron backscatter diffraction (EBSD).

2. Material and experimental procedures

2.1. Material

As-received material used in the present study was TC17 alloy with a basketweave microstructure. Chemical composition (in wt%) of the as-received TC17 alloy was shown in Table 1. The β transus temperature of this material was approximately 905 °C.

Fig. 1 showed an optical micrograph taken from a longitudinal section of the as-received TC17 alloy. An initial basketweave microstructure was observed in which the α lamellae were interleaved. Here, the secondary α phase was light and the β phase was the dark constituent. The secondary α phase exhibited three types of morphologies: (i) α precipitation in β/β grain boundaries, marked with a red arrow, was termed as α_{GB}; (ii) α Widmanstätten developed from β/β boundaries or from α_{GB} in parallel colonies, marked with a black arrow, was termed as α_{WGB}; and (iii) α Widmanstätten precipitation in the intragranular area that formed a basketweave microstructure, marked with a white arrow, was termed as α_{WM} [21]. In addition, the basketweave microstructure had a grain boundary α-layer with a thickness of 1.3 μm.

2.2. Isothermal compression and heat treatment

Isothermal compression at Northwestern Polytechnical University (NWPU) was conducted using a Gleeble-3500 simulator. The specimens with a diameter of 8.0 + 0.05 mm and a height of 12.0 + 0.05 mm were heated at a controlled rate of 10 $°C \cdot s^{-1}$ through Electrical Resistance Heating (ERH), and held for 5 min at the deformation temperature to establish a uniform temperature in the specimens. Isothermal compression was performed at the deformation temperatures of 780 ± 1 °C, 820 ± 1 °C and 850 ± 1 °C, with strains of 0.22 ± 0.01, 0.36 ± 0.01, 0.92 ± 0.01, 1.20 ± 0.01, at a strain rate of 1.0 s^{-1}. A S type thermocouple was welded on the surface of the specimens to measure the temperature during deformation, and graphite powder was put between the specimens and the anvils to reduce die friction. After isothermal compression, the specimens were water quenched to room temperature, and the flow stress-strain curves at different total strains were compared to confirm the reproducibility. If one of these curves was not overlapped, duplicate or triplicate samples at this condition were compressed to improve the reproducibility.

Following compression, some deformed specimens were heat-treated using a KSL-1400XA4 box type furnace. These specimens were heated to a certain temperature at a controlled rate of 8 $°C \cdot min^{-1}$, and were held for 1 h and then allowed to air-cool to room temperature. The heating temperature was in the range of 760–860 °C with an interval of 20 °C. Fig. 2 showed the schematic of isothermal compression and heat treatment sequences.

Table 1
Chemical composition of TC17 alloy (wt%).

Al	Sn	Zr	Mo	Cr	Fe	C	N	O	H	Ti
5.12 ± 0.03	2.03 ± 0.02	2.10 ± 0.03	4.04 ± 0.02	3.94 ± 0.06	0.10 ± 0.004	0.012 ± 0.001	0.007 ± 0.001	0.12 ± 0.01	0.007 ± 0.001	Bal.