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Pre-processing related recrystallization behavior in β annealing of a near-β Ti-5Al-5Mo-5V-3Cr-1Zr titanium alloy

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ABSTRACT

Recrystallization behavior of Ti-55531 alloy in β annealing is explored for grain refinement during primary hot working. Four typical pre-processing conditions were adopted to characterize the diverse processing routes of primary hot working: deformation and annealing in the two-phase region, deformation of globularized structure in two-phase region, deformation of lamellar structure in two-phase region and deformation in single β region. The microstructure evolution in β annealing was quantified by Optical Microscopy (OM), Electron Backscattered Diffraction (EBSD), X-ray diffraction (XRD) and quantitative metallography. The results indicate that the nucleation mode of static recrystallization is determined by the size and distribution of substructures prior to annealing which is related to pre-processing route. The uniform substructures in as-deformed globularized structure produce a higher fraction of low angle grain boundaries after full recrystallization. Fine β recrystallized structure can be obtained when β recrystallization is accompanied by α-to-β phase transformation.

1. Introduction

Near-β titanium alloys possess excellent mechanical properties and high strength-to-weight ratios [1–3]. In addition, they exhibit a relatively good workability owing to the low β transus temperature compared to the typical (α + β) titanium alloys and the α titanium alloys [4]. Therefore, they are widely used in the aerospace industry [5–8]. Ti-5Al-5Mo-5V-3Cr-1Zr (Ti-55531) is a relatively new near-β titanium alloy based on Russian alloy VT22 [9–12], with high tensile strength ($\delta_b \geq 1200$ MPa), good fracture toughness ($K_{IC} \geq 55$ MPa·m$^{1/2}$) and well hardenability (≥250 mm) et al. [13]. This high-strength alloy is particularly suitable for the manufacturing of large-scale integral structural applications in the aerospace industrial field such as bogie beams in aircraft landing gear.

Thermomechanical processing is required for titanium alloys to tailor the mechanical properties along with shaping [14]. Commonly, the hot working of titanium alloys consists of a primary hot working to transform ingots into semi-product with specific microstructure and a secondary hot working which shapes the semi-product into products [15]. The primary hot working aims to refine the coarse as-cast β grains and globularize the α lamellae. β grain refinement significantly enhances the ductility and fatigue life of final forgings [2]. Furthermore, it will can weaken the micro texture and improve the performance of ultrasonic flaw detection [16]. For instance, the tensile elongation of the β-CEZ alloy (β titanium alloy) was increased from 1% to 21% with no obvious change on yield stress by the reduction of β grain size from 400 μm to 60 μm [2].

β grain refinement is usually achieved by recrystallization in hot deformation and subsequent annealing. The near-β titanium alloys exhibit strongly dynamic recovery owing to the bcc crystal structure of β phase, which inhibits dynamic recrystallization during hot deformation. Moreover, the deformation temperature of near-β alloys is often relatively low due to the low β transus temperature. Thus, it is difficult to achieve completely homogeneous recrystallized structure solely by hot deformation. Previous experimental work by Fan et al. found that the dynamic recrystallized fraction for a coarse grained Ti-55531 alloy was no more 20% after deformation in the β phase field [16]. However, Warchomicka et al. [4] found that α phase was completely transformed into β phase and fully static recrystallization of the β phase was achieved after holding for 900 s at 843 °C. Semblanet et al. [17] also concluded that full recrystallization would be achieved within some minutes for the deformed Ti-17 titanium alloy during β annealing and the subsequent grain growth was slow with the increase of holding time. Thus, static recrystallization (SRX) plays more important role in grain refinement of near-β titanium alloys.

The static recrystallization of β phase is affected by the hot working parameters, including initial microstructure, strain, strain rate, deformation temperature and heat treatment temperature et al. Fan et al. [15] reported that the recrystallized grain size was more affected by strain and initial grain size than by strain rate. Semblanet et al. [17]

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found that finer microstructure would be obtained with increasing strain. The effect of deformation temperature of two-phase region on changing law of microstructure of TC18 titanium alloy was studied by Liu et al. [18]. They concluded that equiaxed β grains were obtained in β annealing after (α + β) forging. Moreover, the size of β recrystallized grains increased with the increase of the deformation temperature. Fan et al. [19] found that the microstructure of Ti-7333 alloy solution treated at supertransus region showed equiaxed β grains and the size of β grains increased with the increase of the solution treatment temperature and solution treatment time. The results by Ghaderi et al. [20] indicated that each large β grain was homogenously recrystallized into finer β grains in β annealing after hot rolling. They also concluded that the onset of β recrystallization corresponded to the massive dissolution of α precipitates. These investigations are useful to understand the microstructure evolution in β annealing for Ti-55531 titanium alloy. However, titanium alloy shows a diverse microstructure during primary hot working, which is closely related to the α-β phase transformation. It is manifested as different morphologies, sizes and volume fractions of α phase at different processing routes. The static recrystallization behavior in subsequent β annealing is greatly affected by the microstructures under various pre-processing conditions, which needs a profound study.

The present work was to analyze recrystallization behavior of hot worked Ti-55531 titanium alloy in β annealing under different pre-processing conditions. Thus, hot compression and annealing at 865 °C for different times were carried out. EBSD was used to investigate the evolution of substructures. Transmission Electron Microscope (TEM) was used to characterize β recrystallization at the early stage of holding. XRD was applied to analyze the evolution of texture. The results are useful for guiding the microstructure control in the primary hot working of Ti-55531 titanium alloy.

2. Material and Procedures

The Ti-55531 titanium alloy with chemical composition (wt%) of 5.39Al, 4.80Mo, 4.95V, 2.90Cr, 1.09Zr, 0.32Fe, 0.014C, 0.007N, 0.11O and Ti (balance) was prepared in this paper. The as-received Ti-55531 alloy was a hot forged bar followed by a final heat treatment in the two-phase region, which consisted of ~20% (volume fraction) equiaxed primary α grains with an average grain size ~2 μm (Fig. 1(a)). The measured β-transus temperature was 845 °C.

Generally, the primary hot working of titanium alloy is composed of (α + β) deformation, β deformation and heat treatment. It is difficult to achieve grain refinement through single large deformation in the (α + β) phase region or β phase region. The combination of deformation and heat treatment can refine the microstructure effectively. A typical “high-low-high” processing route is most commonly used to refine the β grains during the primary working of titanium alloy. The first “high” refers to forging above the β transus (β working) so as to break the as-cast microstructure. The “low” means forging below the β transus ((α + β) working), which aims to provide sufficient stored energy for subsequent hot working. Finally, the workpiece is reheated to β phase region to recrystallize. The β grain refinement is achieved by the static recrystallization (SRX) in β annealing after (α + β) working. However, diverse and complicated microstructures after deformation, including the different morphology, different size and different volume fraction of α phase will significantly affect the recrystallization behavior of β phase in subsequent β annealing. Thus, it is necessary to study the effect of different initial microstructures obtained by different pre-processing conditions on β recrystallization. And four typical initial microstructures were employed in the present work. The initial microstructure A (MA) shown in Fig. 1(a) was the as-received microstructure (referred as globularized microstructure), which was obtained through a combination of deformation and annealing in the two-phase region. The initial microstructures B (MB) and C (MC) were the (α + β) deformation of globularized microstructure (Fig. 1(b)) and as-transformed microstructure (Fig. 1(c)) at temperature of 775 °C, strain rate of 0.1 s^{-1} to height reduction of 50%, respectively. The initial microstructure D (MD) was the β deformation of as-transformed microstructure (Fig. 1(d)) at temperature of 865 °C, strain rate of 0.1 s^{-1} to height reduction of 50%. The as-transformed microstructure (lamellar microstrucutre) was obtained by solution heat treatment at 900 °C for 60 min following furnace cooling to 570 °C at a rate of about 1 °C/min and then holding for 120 min before a final furnace cooling to room temperature. The average β grain size was about 420 μm, whose

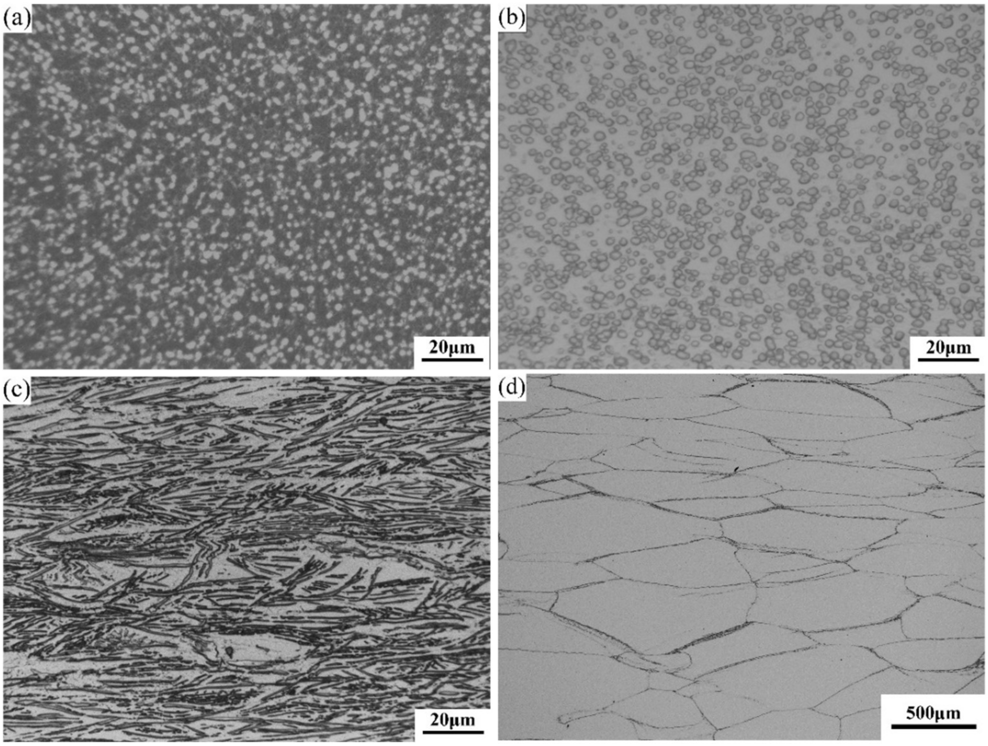

Fig. 1. Typical microstructures obtained by different pre-processing routes: (a) the as-received microstructure; (b) the (α + β) deformation of as-received microstructure; (c) the (α + β) deformation of lamellar microstructure; (d) the β deformation of lamellar microstructure.