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Formation of equiaxed α phase in Ti-5Al-5Mo-5V-3Cr alloy deformed by high-pressure torsion

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ABSTRACT

Formation of ultrafine equiaxed α phase particles was observed in Ti-5Al-5Mo-5V-3Cr (mass%) alloy after aging of samples deformed by high-pressure torsion (HPT) while acicular α phase was observed in undeformed samples. Burgers orientation relationship was obeyed between equiaxed α and β phases. The numerous nucleation sites and enhanced diffusivity in HPT processed samples due to high density of dislocations promoted the nucleation of and growth of α phase at the early aging stage. The segregation of β stabilizers near the α/β interfaces retarded the growth of α phase during aging, leading to equiaxed α phase with ultrafine particle size.

1. Introduction

In recent years, metastable β-Ti alloys are increasingly used due to their unique combination of high strength-to-density ratio, excellent hardenability and good corrosion resistance [1–3]. Among them, Ti-5Al-5Mo-5V-3Cr (Ti-5553, mass%) alloy with promising mechanical properties is used for the thick forging applications in landing gear components [4,5]. This alloy exhibits a wider processing window and a better deep-hardenability than its predecessor Ti-10V-2Fe-3Al alloy [4–6]. It also exhibits a higher strength and a better high-cycle fatigue property compared with Ti-6Al-4V alloy which is the most widely used Ti alloy [7]. However, the mechanical performance of this alloy is very sensitive to its microstructure, especially the α phase precipitates, which can vary substantially as a function of thermomechanical processing. The volume fraction, particle size, distribution and morphology of α phase are considered as important microstructural parameters which can influence the mechanical properties [8–10]. Therefore, in order to improve the mechanical properties, it is essential to critically understand the formation process of α phase.

The nucleation sites for α phase include the prior β grain boundaries, secondary phase such as ω phase [11,12] and dislocations [13]. A high density of dislocations can promote the formation of α phase with a fine particle size and a uniform distribution which is desirable for attaining high strength [14]. Severe plastic deformation by high-pressure torsion (HPT) is considered as an effective method to introduce a high density of dislocations [15]. Some previous studies showed that the introduction of severe plastic deformation resulted in the formation of ultrafine equiaxed α phase instead of coarse acicular α phase upon aging [16–19]. The crystallographic orientation relationship between α phase and β phase is well known as Burgers orientation relationship, which is described by $\{0001\}_\alpha // \{011\}_\beta$ and $\langle <11\bar{2}0\rangle_\alpha // \langle 111\rangle_\beta$ [20]. Zafari et al. [19] studied the formation of α phase in HPT deformed Ti-5553 alloy after aging at 873 K for short time of 30 s and 120 s. It was reported that Burgers orientation relationship was obeyed at the nucleation stage of α and equiaxed α with incoherent interfaces was developed later as a result of grain growth. In the present research, a series aging was carried out on HPT deformed Ti-5553 alloy at 923 K from 0.3 ks to 360 ks to investigate the grow process of equiaxed α phase. STEM-EDS analysis showed a segregation of β-stabilizers (Mo V and Cr elements) near the equiaxed α/β interface, which could reduce the growth rate of α phase. In addition, much

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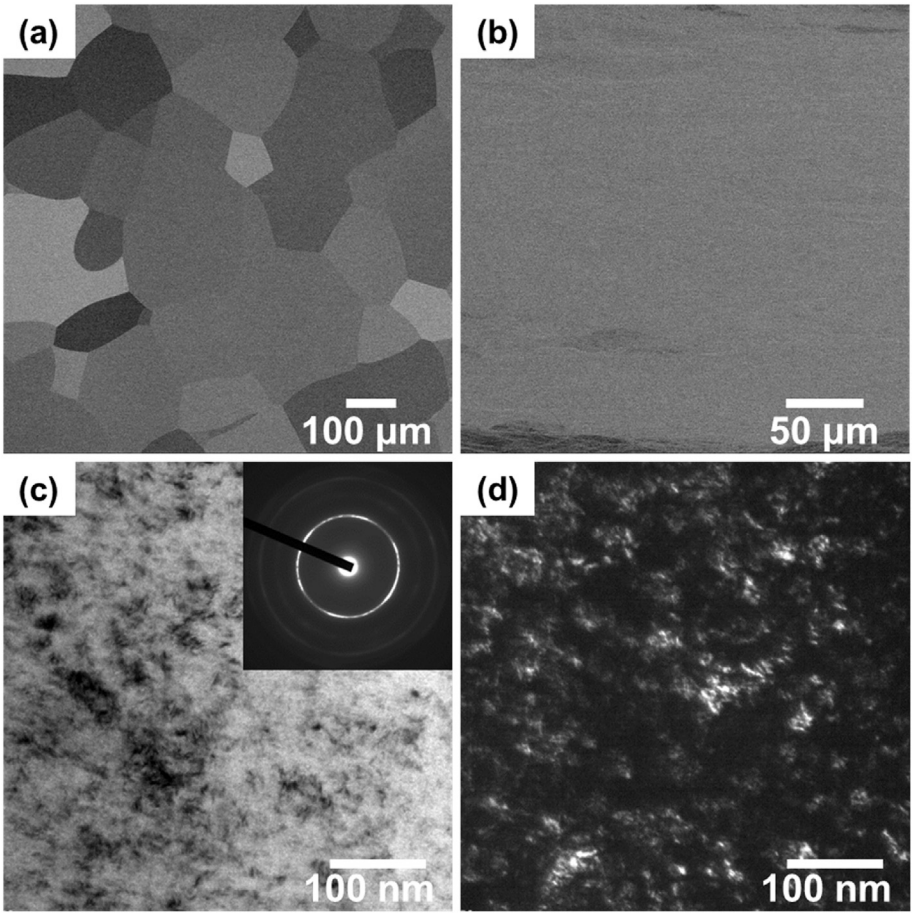

Fig. 1. BSE-SEM images of Ti-5553 alloy: (a) after ST and (b) after HPT of 10 revolutions; and TEM images of Ti-5553 alloy after HPT of 10 revolutions: (c) BF image and (d) DF image.

more detailed analyses by t-EBSD and TEM showed that Burgers orientation relationship was still maintained between equiaxed α phase and β phase after substantial grain growth.

2. Experimental

An ingot of Ti-5553 alloy was prepared by cold crucible levitation melting (CCLM). The analyzed chemical composition is Ti-5.04Al-5.14Mo-4.91V-3.04Cr (mass%). After hot forging and rolling at 1473 K, a bar of the alloy was cold swaged to a diameter of 10 mm. The bar was solution treated (ST) above the β transus temperature (1129 K) at 1273 K for 3.6 ks in an Ar atmosphere, followed by water quenching. Subsequently, HPT processing was performed at room temperature on discs of 10 mm in diameter and 0.85 mm in thickness for 10 revolutions under a compressive pressure of 5 GPa and at a rotation speed of 0.2 rpm. The ST samples and HPT samples were isothermally aged at 923 K in an Ar atmosphere, followed by water quenching. The aging time ranged from 0.3 ks to 360 ks.

Backscattered electron (BSE) observations were carried out on the cross-sections of the samples mounted in resin by using scanning electron microscopy (SEM, JEOL JSM-7001F, 20 kV). Based on the BSE images, the particle size and the volume fraction of α phase were measured by the image analysis software. More than 200 α particles were selected for the quantitative analysis on the particle size and at least 5 BSE images were selected for the quantitative analysis on the volume fraction. Thermodynamic calculations by Pandat software (Version 8.2, CompuTherm, LLC, USA) were done to predict the equilibrium volume fraction and equilibrium chemical composition of α phase in Ti-5553 alloy aged at 923 K. Microstructural characterization was also carried out using transmission electron microscopy (TEM, JEOL JEM-2100 or 2800, 200 kV) and scanning transmission electron microscopy equipped with dual energy dispersive X-ray detectors (STEM/EDS, JEOL JEM-2800, 200 kV). The detectors have a larger area of 100 mm^2, allowing an accurate analysis. Disk samples (3 mm in diameter) for TEM and STEM analysis were cut from the median plane of the disk and thinned to perforation using a Gatan precision ion polishing system. Transmission electron backscatter diffraction (t-EBSD) observation was also carried out on the TEM sample. The t-EBSD data were obtained by use of a Sigma Zeiss SEM equipped with a TSL Orientation Imaging Microscopy (OIM) EBSD system. Special specimen holder was used to set the specimen at a tilt angle of 40° from the horizontal plane. The working distance (WD) was set to 5 mm and the accelerating voltage was 30 kV. The step size of t-EBSD was 20 nm. The quantitative analysis on the composition of α phase was carried out by electron probe microanalysis (EPMA, JEOL JXA-8900F) at a voltage of 15 kV and a probe current of 10 nA. At least 10 α particles were chosen in each sample. The analyzed spot size was around the order of 0.1 μm in diameter.

3. Results

Fig. 1(a) shows a BSE-SEM image of the Ti-5553 alloy after ST at 1273 K for 3.6 ks. The sample was found to be in a single β phase with an average grain size of around 220 μm. Fig. 1(b) shows a BSE-