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Quasi-static and dynamic forced shear deformation behaviors of Ti-5Mo-5V-8Cr-3Al alloy

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ABSTRACT

The mechanical behavior and microstructure characteristics of Ti-5Mo-5V-8Cr-3Al alloy were investigated with hat-shaped samples compressed under quasi-static and dynamic loading. Compared with the quasi-static loading, a higher shear stress peak and a shear instability stage were observed during the dynamic shear response. The results showed that an adiabatic shear band consisting of ultrafine equiaxed grains was only developed in the dynamic specimen, while a wider shear region was formed in the quasi-static specimen. The microhardness measurements revealed that shear region in the quasi-static specimen and adiabatic shear band in the dynamic specimen exhibited higher hardness than that of adjacent regions due to the strain hardening and grain refining, respectively. A stable orientation, in which the crystallographic {110} planes and < 111 > directions were respectively parallel to the shear plane and shear direction, developed in both specimens. And the microtexture of the adiabatic shear band was more well-defined than that of the shear region in the quasi-static specimen. Rotational dynamic recrystallization mechanism was suggested to explain the formation of ultrafine equiaxed grains within the adiabatic shear band by thermodynamic and kinetic calculations.

1. Introduction

Adiabatic shear band (ASB) is an important deformation mode that intensive deformation localizes in a narrow band when metal deformed under dynamic loading [1]. It is generally recognized that the formation of shear band is a result of the effect of thermal softening exceeding that of strain and strain rate hardening [2,3]. With the formation of the shear band, the bearing capacity of structural material would decrease sharply and even lead to a catastrophic failure because cracks always nucleate and propagate within the ASB [3–5]. Meanwhile, the investigation on quasi-static experiment contributes to a better understanding of the dynamic deformation, and low strain rate deformation is frequently involved during the processing and application of metallic material. Thus, much attention has been paid to exploring the mechanical behavior and microstructure development in various metals and alloys during quasi-static and dynamic deformation. Some experimental and simulation studies [4–6] have revealed that the shear stress is related to the strain rate and the dimensions of hat-shaped specimen. The mechanical curve of hat-shaped specimen deformed under quasi-static loading presents a continuous hardening characteristic, and yet a stress collapse would take place on dynamic shear response. It has been reported that titanium and its alloys are very susceptible to form ASB during dynamic deformation due to their poor thermal conductivity [7,8]. Numerous studies on titanium and its alloys have revealed that the microstructure of ASB consists of ultrafine equiaxed grains, which is a result of dynamic recrystallization [8–13]. Based on this remarkable feature and an extremely short deformation time, a new mechanism named as rotational dynamic recrystallization (RDRX) was proposed by Meyers et al. [14]. It has also been reported that a well-developed shear band would not be formed under the dynamic condition, but the shear localization is more pronounced in the dynamic specimen than that in the quasi-static specimen [15]. Grains adjacent to the ASB represent a special orientation variation that the crystallographic {110} planes and < 111 > directions respectively tend to parallel to the shear plane and shear direction in Ta and Ta-W alloys [16] and stainless steel [17] (body-centered cubic structure metals). Dougherty et al. [18] indicated that the grains within the ASB in steel show three type orientations: {112} < 111 > , {110} < 111 > and {110} < 001 > . These well-defined simple shear texture formed in the dynamic specimen implies that dislocation slip in the {110} and {112} planes along the < 111 > directions. Additionally, Bhattacharyya et al. [19] reported that the deformation texture appears sharper for dynamic specimen compared with quasi-static specimen at large strains (> 1.0). Thus, the strain rate is an important factor to affect

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the mechanical property, microstructure and microtexture development of metals. Ti-5Mo-5V-8Cr-3Al alloy is a kind of typical metastable beta titanium alloy, which would experience different strain rate deformations during its service lifespan. However, the research on the mechanical response, microstructure and microtexture characteristics of beta titanium alloys deformed under quasi-static and dynamic forced shear conditions is still scanty.

In this paper, we investigated the forced shear deformation behaviors of Ti-5Mo-5V-8Cr-3Al alloy under quasi-static and dynamic conditions, and focused on the deformed microstructure and microtexture features. Additionally, the thermodynamic and kinetic calculations were performed to verify the RDRX mechanism. The findings in this work advance our understanding of the force shear deformation behaviors of Ti-5Mo-5V-8Cr-3Al alloy under quasi-static and dynamic loading.

2. Experimental

The forged Ti-5Mo-5V-8Cr-3Al alloy plate with dimensions of 200 mm×80 mm×60 mm was kept at the temperature of 1203 K (930 °C) for 55 min, and subsequently the thick sheet was hot-rolled from 60 to 12 mm, yielding a cumulative rolling reduction of 80%. The initial microstructure of hot-rolled Ti-5Mo-5V-8Cr-3Al alloy plate is shown as the 3D view in Fig. 1, where strip grains were observed in the hot-rolled plate. The tested hat-shaped specimens, whose dimensions are shown in Fig. 2(a), were fabricated with loading axis paralleling to the normal direction of the titanium alloy plate.

The quasi-static (~10^{-3} s^{-1}) and dynamic (~10^4 s^{-1}) forced shear deformation were performed by an Instron apparatus and a SHPB system at room temperature. Specimens for microstructure characterization were cut from the deformed hat-shaped samples along the loading axis by means of electrical discharge machining. The sectioned surfaces for metallographic observation were polished to a mirror finish and then etched with 2 ml HF+15 ml HNO_3+83 ml H_2O. Vickers microhardness was obtained using an HVS-1000 Microhardness Tester with a load of 50g and a dwell time of 10 s. Specimens for electron backscatter diffraction (EBSD) measurement were prepared by mechanical polishing and electro polishing using a solution of 60 ml $HClO_4$+360 ml $CH_3(CH_2)_3OH$+600 ml CH_3OH on Automatic Twin-Jet-Electro polishing device at 75 V and −30 °C. EBSD observations of the electrolytic polishing region (Fig. 2(b)) were carried out on a FEI Sirio200 scanning electron microscope system with an acceleration voltage of 20 kV. Microstructure and microtexture were also analyzed by available commercial TSL-OIM Version 5.0 software.

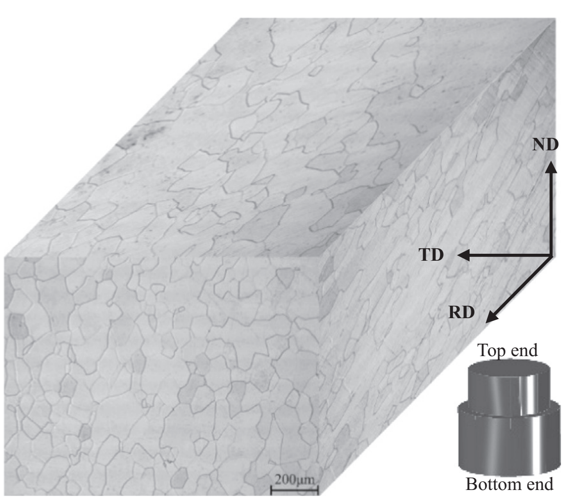

Fig. 1. Microstructure of the initial hot-rolled Ti-5Mo-5V-8Cr-3Al alloy plate. ND, RD and TD respectively stand for the normal direction, rolling direction and transverse direction of the hot-rolled plate.

3. Results and discussions

3.1. Shear stress-shear strain curve

According to Longère et al. [4], the shear stress (τ) and shear strain (γ) of quasi-static and dynamic forced shear deformation can be calculated by the following equations:

$$\tau = \frac{F}{S_{shear}} \tag{1}$$

$$\gamma = \frac{\Delta L}{W_{shear}} \tag{2}$$

$$S_{shear} = \frac{\pi}{\cos\alpha}\frac{D+d}{2}\sqrt{(\frac{D-d}{2})^2 + H^2} \tag{3}$$

$$\alpha = \arctan\frac{D-d}{2H} \tag{4}$$

where F is the load applied on the specimen, ΔL is the relative displacement of the top and bottom end. S_{shear} and W_{shear} are the section area and width of the shear region, respectively. D and d are top and bottom diameter of the hat-shaped specimen, respectively. α is the angle between shear direction and loading axis. H is the shear region height.

The shear stress-shear strain curves of Ti-5Mo-5V-8Cr-3Al alloy during quasi-static deformation at the strain rate of approximately 1.0×10^{-3} s^{-1} and dynamic deformation at the strain rate of approximately 6.3×10^4 s^{-1} are shown in Fig. 3. The compression displacements (ΔL) in these two tests are the same. Therefore, the shear strain (γ) of the dynamic deformation was larger than that of the quasi-static deformation because the width of the shear region (W_{shear}) in the dynamic specimen was smaller. The two curves are quite different, except for a similar elastic region. The shear stress of quasi-static sample increased with the increasing strain after the yield point due to the strain hardening, but the rate of strain hardening decreased gradually. The dynamic curve can be divided into three stages as the denoting point (a, b, c, d) in Fig. 3. In the first stage (a-b), the shear stress increased with the increasing shear strain. In the second stage (b-c), the shear stress started to decline with the increasing shear strain. Hence, the shear stress (point b) reached the maximum value of 960 MPa at the shear strain of 0.61. According to the maximum stress criterion for instability deformation [20], the point b represented the onset of unstable deformation, after which the deformation began to localize into an ASB. In the third stage (c-d), the shear stress varied slightly and a “plateau” was formed due to the competing process of the work hardening and the thermal softening introduced by significant rising temperature.

3.2. Microstructure characteristic and microhardness

An enlarged optical micrograph of the shear region (Fig. 2) in the quasi-static and dynamic specimen was respectively shown in Fig. 4(a) and (b). As marked in Fig. 4, the left ends were the top ends of the hat-shaped samples and the right ends were the corresponding bottom ends. As shown in Fig. 4(a), the plastic deformation of quasi-static specimen mainly occurred in a broad region named as shear localization region. The grains within this region were deformed and elongated toward the shear direction (SD), while those outside the region basically kept the original features. It should be also noted that groups of band structures (denoted by some white arrows) located in some grains. In beta titanium alloys, generally, the thin bands are formed due to the dislocation slip [21]. The shear localization region can be preliminary identified as the region between two black dashed lines and its width was approximately 600 μm. Additionally, the distribution of bands revealed that the inhomogeneous deformation within the shear region. The grains of the bottom end experienced more shear deforma-