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Adiabatic shear localization in pure titanium deformed by dynamic loading: Microstructure and microtexture characteristic

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ABSTRACT

The adiabatic shear localization characteristic of annealed pure titanium was studied by means of hat-shaped specimen and Split Hopkinson Pressure Bar system. The microstructure and microtexture of the received shear localization regions were investigated by optical microscopy (OM), electron backscatter diffraction (EBSD) technique, transmission electron microscopy (TEM) and microhardness tests. The results show that microstructure within the adiabatic shear band consists of ultrafine grains with well defined high-angle-boundaries. In the vicinity of the shear band, grains are elongated toward the shear direction, and deformation twins including $\{10\bar{1}2\}<\bar{1}011>$ and $\{11\bar{2}2\}<11\bar{2}\bar{3}>$ are frequently observed. Microhardness tests reveal that the value of Vickers hardness in the shear band is the higher than all of the outside regions due to the strengthening effect of the ultrafine grains. Microtexture analysis reveals that a stable orientation, in which the $<11\bar{2}0>$ direction tends to align with the local shear direction and the $\{10\bar{1}0\}$ plane tends to parallel to the local shear plane, develops in the shear localization region. The calculated results show that the dynamic recrystallization (DRX) can take place in the process of deformation on the basis of the rotational dynamic recrystallization mechanism.

1. Introduction

Adiabatic shear localization, which sometimes refers to adiabatic shear band, is an important damage/failure model of materials which often occurs in metallic materials during high-strain-rate deformation such as ballistic impact, penetration and explosion [1,2]. This model is generally characterized as a plastic flow instability phenomenon in the case that thermal softening arising from the adiabatic temperature rise exceeds work hardening and strain-rate hardening [3,4].

Titanium and its alloys are particularly susceptible to shear localization during dynamic loading due to the property of low heat conductivity. In the past decades, a large number of investigations have been conducted experimentally to understand the adiabatic shear localization in Ti and its alloys. Microstructural evolution of shear localization has received a great attention. Meyers et al. [5,6], Chichili et al. [7] and Yang et al. [8] investigated the microstructure of shear bands in pure titanium. The TEM observations revealed that the microstructure in the center of shear band consists of equiaxed nanocrystalline grains with low dislocation density and well defined high-angle grain boundaries. These remarkable features indicate that dynamic recrystallization (DRX) occurred in the process of adiabatic shear band formation. Li et al. [9], Murr et al. [10,11], Rittel et al. [12,13] and Peirs et al. [14] investigated the microstructure of adiabatic shear localization in a $\alpha+\beta$ titanium alloy (Ti–6Al–4V). They also reported that the shear bands contain nano-size equiaxed grains, which confirmed the occurrence of DRX, and moreover, Rittel et al. stressed that the DRX is a potential cause for adiabatic shear failure. Recently, Zhan et al. [15,16] investigated the shear band in a β-titanium alloy (Ti-6554). It was found that the outer region of the shear band consists of cell structures bounded by dislocation clusters. In the core region of the shear band, the microstructure is composed of equiaxed subgrains and dynamically recrystallized nanograins with sharp boundaries. The microstructure investigations mentioned above provide fundamental information to understand the thermal-mechanical evolution during shear localization. However, the report to understand microtexture evolution in the shear localization of titanium is still relatively rare. Only few studies [17,18] have applied the electron backscatter diffraction (EBSD) techniques to investigate the micotexture in shear bands of titanium.

In this study, the adiabatic shear localization behavior of commercially pure titanium was investigated by a Split Hopkinson Pressure Bar system and the received shear regions were systematically investigated by OM, EBSD, TEM and microhardness tests. The emphasis of the research, in particular, is on the microstructure and microtexture of titanium deformed under

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extreme conditions. Additionally, the adiabatic temperature rise in the shear band and the possibility of dynamic recrystallization are also discussed. The study advances our understanding of the adiabatic shear localization behavior of titanium under dynamic loading.

2. Experimental

An annealed commercially pure α-Ti (grade 2) plate was used in this study. The initial microstructure of the material is a typical equiaxed grains with the size of about 20 μm (as shown in Fig.1). Hat-shaped specimen (as illustrated in Fig. 2(a)) prepared along the normal direction of the annealed Ti plate, was used to produce well-controlled shear band at a high strain rate. Dynamic tests were carried on a Split Hopkinson Pressure Bar system at room temperature. Samples for microstructure characterization were cut from the deformed hat-shaped specimens along the loading axis by means of electrical discharge machining (as schematic illustrated in Fig. 2(a)). Metallographic specimen was prepared by standard mechanical polishing and then etched in a solution of 4 ml HF+20 ml HNO_3+200 ml H_2O. Microhardness tests were carried out on a Digital Microhardness Tester HVS-1000, with the load of 0.49 N and loading time of 15 s. Samples for EBSD, cut from the shear localized region, were firstly mechanical grinded by using grit paper with different particle sizes from 400 to 2000 mesh. Electrolytic polishing was finally conducted on a twin-ject polisher in a solution of 60 ml perchloric acid +360 ml n-butyl alcohol +600 ml methanol at 40 V for 90 s at −30 °C. EBSD characterization was carried out on a FEI Sirio200 scanning electron microscope system (equipped with an orientation imaging microscopy software developed by TSL) on condition of an acceleration voltage of 20 kv. Microstructure and microtexture were also analyzed by commercial available TSL-OIM Version 5.0 software. As severe deformation can cause poor Kikuchi patters and orientation noise, which may affect statistical analysis (such as microtexture analysis), every measured dots whose confidence index (CI) is lower than CI_{min} were excluded from the analysis of the EBSD data. According to Zeng et al. [19], the CI_{min} was set to 0.1 in present study.

Samples for TEM were cut out to a 500 μm foil along the loading axis, and then mechanically grinded to a thickness of 80 to 100 μm. Three-millimeter-diameter disk was punched out from the foil with great care to ensure the shear band paths went across the center of the disk, as illustrates in Fig. 2(b). Final thinning was finished by using the same method as electrolytic polishing for EBSD sample. TEM observation was conducted on a FEI TecnaiG220ST electron microscope operated at 200 kV.

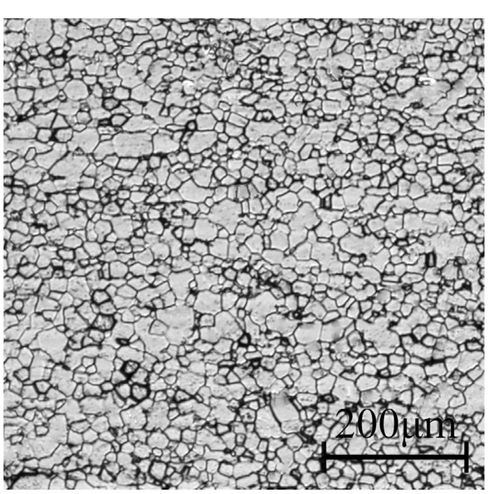

Fig. 1. Initial microstructure of specimen with equiaxed grains.

3. Results and discussions

3.1. Dynamic shear response

When the hat-shaped specimen was loaded by a Split Hopkinson Pressure Bar, the force applied to the shear region can be calculated from the signals collected by the strain gauges on the incident and transmitted bars. According to Andrade et al. [20], the shear stress, shear strain, and shear strain rate within the shear region can be calculated by the following equations:

$$\tau(t) = \frac{E_0 A_s \varepsilon_t(t)}{\pi h\left(\frac{d_i + d_e}{2}\right)} \tag{1}$$

$$\dot{\gamma}(t) = \frac{2C_0[\varepsilon_i(t) - \varepsilon_t(t)]}{W} \tag{2}$$

$$\gamma(t) = \int_0^t \dot{\gamma}(t)dt \tag{3}$$

where E_0 and C_0 are the elastic modulus and elastic wave speed in SHPB; A_s is the cross-section area of the incident bar; h and W are the length and width of the shear region, d_i and d_e denote the top and bottom diameter of the hat-shaped specimen, and $\varepsilon_i(t)$ and $\varepsilon_t(t)$ represent the strain signals of incident and transmitted pulse on the Hopkinson bars, respectively.

Fig. 3 shows the deformation process of commercially pure α-Ti during dynamic shearing at strain rate of about $3.2 \times 10^4\ s^{-1}$. The deformation process can be divided into three stages. In the first stage (a–b), the shear stress increases with the increasing shear strain due to strain hardening, excepting the short plateau formed at shear strain of 0.15–0.25 due to the balance of strain hardening and thermal softening. The shear stress reaches the maximum value of 1024 MPa at the shear strain of 0.53. In the second stage (b–c), the flow stress starts to decline as the shear strain exceed 0.53. According to the maximum stress criterion for instability deformation [21], the peak of a dynamic shear stress–strain curve often represents the onset of thermo-viscoplastic instability, after which the thermal softening exceeds work hardening and the deformation begins to localize into an adiabatic shear band. In the last stage (c–d), the flow stress keeps at a level of about 440 MPa and a new "plateau" is formed due to the competing process of work hardening and the work softening introduced by significant temperature rise. Work softening processes are microstructural changes by which dislocations realign and annihilate each other through dynamic recovery or DRX.

3.2. Microstructure characteristic and microhardness

As shown in Fig. 4, the adiabatic shear band appears on the cross section of the hat-shaped specimen, and a curved micro crack is along with it. The shear band is long and straight, and can be distinguished from the matrix by clearly boundaries. The plastic deformation is highly localized in a narrow region with its width of ~45 μm.

In order to understand the microstructural and orientation information of the shear localization, EBSD scanning (step size=0.5 μm) was employed to investigate the deformed specimen. Fig. 5 shows the EBSD micrographs of deformed regions obtained from the center of the shear band to the area which is far away from the shear band. In Fig. 5(a), the vertical is parallel to the local shear direction (SD) of the shear band, the horizontal is