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Adiabatic shear localization in a near beta Ti–5Al–5Mo–5 V–1Cr–1Fe alloy

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ABSTRACT

Adiabatic shear localization plays an important role in the deformation and failure of near beta Ti–5Al–5Mo–5 V–1Cr–1Fe alloy used in aircraft's gear at high rate deformation. Hat shaped specimens with different nominal shear strains are used to induce the formation of an adiabatic shear band under controlled shock-loading experiments. When the nominal shear strain is about 0.68, unstable shear deformation of the alloy emerges after the true flow stress reaches 1100 MPa, the first vibration peak during the split Hopkinson pressure bar testing, and the whole process lasts about 62 μs. The microstructures within the shear band in the Ti–5Al–5Mo–5V–1Cr–1Fe alloy are investigated by means of optical microscopy, scanning electron microscopy and transmission electron microscopy. Phase transformation occurs in the shear band when the nominal shear strain increases to 0.68. A number of equiaxed grains with sizes 50–200 nm and alpha″-phase are in the center of the shear band. Kinetic calculations indicate that during the deformation process, the recrystallized nanosized grains can be formed in the shear band by way of the subgrain boundaries rotation, and the alpha″ phase transformation start after the subgrain boundaries rotated to 30°.

1. Introduction

Near-beta titanium alloy (Ti–5Al–5Mo–5V–1Cr–1Fe) used in aircraft structural applications, especially in the landing gear components for their low density and high strength, often experiences high velocity deformation during processing and application in aircraft [1,2]. Adiabatic shear localizations (frequently also denoted as adiabatic shear bands) are observed in it when subjected to dynamic loading due to the properties of low heat conductivity and high adiabatic shearing sensitivity. Adiabatic shear band is an important precursor for dynamic failure and has been widely studied for many years [3–5]. The microstructure within shear bands observed in post-deformation observations provides some information to understand the thermal–mechanical evolution during shear localization. It has been found that the microstructure of adiabatic shear bands is different in various materials. In the earlier studies, two types of the shear band characterized as deformed band and transformed band according to the appearance observed by optical microscope. Phase transformation is considered to occur in the transformed bands because of the white-etching characteristic. It is now recognized that a broad range of structural alterations is possible in transformed bands: dynamic recrystallization [6–9], phase transformation [10,11], amorphization [12]. There are many different phase transformations in titanium alloys when processed at high strain rates. The most general phase transformation is that of beta-Ti to alpha-Ti. However, it may be difficult to happen for this allotropic transformation under an off-balance condition of chemistry, strain or temperature. Some transitional stages then are necessary for this transformation. The microstructural characterization of the shear band in near beta-Ti alloy investigated by Yang et al. [13], have suggested that the ω (althermal) phase can be formed from parent beta-Ti within the shear band. Xu et al. [14] have revealed that alpha″-martensitic phase transformation occurs in the shear bands in Ti–6Al–4V. Wang et al. [15] observed that grains with beta phase are recrystallized into grains with alpha″ structure in a Ti–3Al–5Mo–4.5V alloy with two-phase (alpha–beta) microstructure. This is additional evidence that phase transformation can occur in conjunction with recrystallization. Wan et al. [16] proposed that the microstructure of the shear band in the Ti–6Al–4V alloy changed with cutting speed, that is, the deformed band can change to a transformed band. In our previous work [17], we investigated the deformed shear band in

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fine-grain-sized near beta titanium alloy and its dynamic recrystallization in the shear band. However, the phase transformation in the shear band in the near beta titanium alloy is yet not clear.

In the present work, we investigate the localized plastic deformation of near beta Ti–5Al–5Mo–5V–1Cr–1Fe alloy under controlled dynamic compressive loading. The aims of this paper are to report observations of the microstructure in the shear band at the different nominal shear strains, especially the phase transformation, and to discuss the dynamic recrystallization and the phase transformation in the shear band in near beta Ti–5Al–5Mo–5V–1Cr–1Fe alloy.

2. Experimental

The hat-shaped specimens were used to produce an adiabatic shear band in the near beta Ti–5Al–5Mo–5V–1Cr–1Fe alloy at high strain rate (see our previous work, Ref. [17].

Nominal shear strain is equal to the shear displacement divided by the thickness of the shear region [18].

$$\gamma_{\text{nominal}} = \frac{\text{shear displacement}}{\text{shear zone thickness}} \tag{1}$$

Five specimens tested with nominal shear strains (γ_{nominal}) of 0.09, 0.39, 0.56, 0.68 and 0.87 are called as H1, H2, H3, H4 and H5, respectively, as shown in Table 1. The dynamic compression of hat shaped specimens was conducted using a Split Hopkinson Pressure Bar (SHPB) at 293 K. Details of the SHPB technique have been described elsewhere [17].

The shear stress, the strain rate, the shear strain and the true stress applied to the shear zone in the specimen was calculated from data collected by the strain gauges on the incident and transmitted bars, as the following equations [19,20].

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

$$\dot{\gamma} = \frac{2C_0\left[(\varepsilon_i(t) - \varepsilon_t(t)\right]}{s} \tag{3}$$

$$\gamma = \frac{2C_0 \int_0^t \left[(\varepsilon_i(t) - \varepsilon_t(t)\right]dt}{s} \tag{4}$$

$$\sigma = 2\tau \tag{5}$$

where E_0 and C_0 are elastic modulus and elastic wave speed in the split Hopkinson pressure bar; A_s is the cross section area of the bar; h and s are the thickness of deformed section and the width of the shear band; d_i and d_e are the geometrical parameters of the hat-shaped specimen; $\varepsilon_r(t)$ and $\varepsilon_t(t)$ are the experimentally measured strains of reflected and transmitted stress pulse on the split Hopkinson pressure bars, respectively.

Culver [21] introduced a simple relation between the true strain (ε) and the shear strain (γ) expressed as Eq. (6).

$$\varepsilon = \ln\sqrt{1 + \gamma + \frac{\gamma^2}{2}} \tag{6}$$

The samples for investigation were cut from the hat-shaped specimens by electrical discharge machining. The sectioned surfaces were polished and etched by 1 ml hydrofluoric acid+3 ml nitrate+80 ml water. Optical microscopy (OM) was performed with POLYVAR-MET. Scanning electron microscopy (SEM) observations were carried out with a FEI Quanta-200 scanning electron microscope operated at 20 kV. The samples were reduced to a thickness of about 0.06 mm by polishing, and then the foils were perforated upon the shear band by electro-polishing in solution of 300 ml methanal+175 ml 1-butanol+30 ml perchloric acid at 243 K. Fig. 1 shows the low-magnification OM image of the transmission electron microscopy (TEM) disk clearly delineating that the shear band is located at the center of the perforated region. Such optical examination was deemed essential to remove any ambiguity of the precise location being examined. TEM observations were performed using a Tecnai G^2 F20 transmission electron microscope operated at 200 kV.

Table 1
Specimens with nominal shear strains for dynamic testing.

Experimental numbers	Shear displacement (mm)	Shear zone thickness (mm)	Nominal shear strain $\gamma_{\text{nominal}} = \frac{\text{shear displacement}}{\text{shear zone thickness}}$
H1	0.1	1.07	0.09
H2	0.4	1.02	0.39
H3	0.6	1.08	0.56
H4	0.7	1.03	0.68
H5	0.9	1.04	0.87

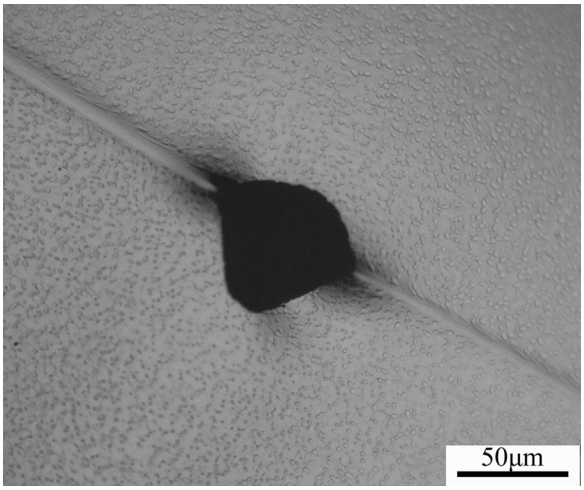

Fig. 1. Low-magnification optical microscope image of the TEM disk.

3. Results and discussion

3.1. Mechanical responses of the specimens

Fig. 2(a) shows the relationship between voltage pulse and loading time at the SHPB experiment. The strain rate during shear deformation can be calculated from the relationship between voltage pulse and loading time at the controlled dynamic testing (Fig. 2(a)) and Eq. (3), as shown in Fig. 2(b). Thus, the specimen H4 (γ_{nominal}=0.68) was tested at the strain rate about $2.5\times10^5\ s^{-1}$. The adiabatic shearing deformation starts from the first peak value of the strain rate to the last loading stress peak [19]. Therefore, it is found that the shear deformation process of H4 (γ_{nominal}=0.68) lasts for about 62 mocroseconds (μs).

The true flow stress and true strain curves of H3 (γ_{nominal}=0.56) and H4 (γ_{nominal}=0.68) tested by split Hopkinson pressure bar can be obtained using Eqs. (2)–(6), as shown in Fig. 2 (c). At the beginning of the shear localized deformation, the true flow stress increases with the true strain due to strain hardening and strain rate hardening, and the true flow stress for specimen H4 (γ_{nominal}=0.68) reaches the maximum value of about 1100 MPa where the strain is about 1.35. Beyond the maximum flow stress,