Materials Science and Engineering A 528 (2011) 3130–3133

Contents lists available at ScienceDirect

Materials Science and Engineering A

journal homepage: www.elsevier.com/locate/msea

Effects of microstructure on the adiabatic shearing behaviors of titanium alloy

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ARTICLE INFO

Article history:
Received 4 November 2010
Received in revised form 9 December 2010
Accepted 16 December 2010
Available online 23 December 2010

Keywords:
Adiabatic shear
Titanium alloy
Adiabatic shear sensitivity

ABSTRACT

The effects of microstructure on the adiabatic shearing behaviors in the Ti-1300 alloy were investigated by means of the split Hopkinson pressure bar (SHPB) with hat-shaped specimens. Shear bands were developed in both Ti-1300 alloys with β phase and α + β lamellar microstructures during a forced dynamic shear deformation. The microstructures have a significant influence on the adiabatic shearing behaviors of Ti-1300 alloy. The critical strain for the initiation of shear bands in α + β lamellar microstructure is less than that in β phase microstructure. The α + β lamellar microstructure experiences more extensive microscopic damage than β phase microstructure. Therefore, the α + β lamellar microstructure is more susceptive to adiabatic shear localization deformation than β phase microstructure at the same strain rate.

1. Introduction

Adiabatic shear band (ASB) is a narrow band-like region where plastic shear deformation is highly localized. In recent years, the SHPB technique is extensively used to investigate adiabatic shearing behaviors of many materials, such as titanium and titanium alloy [1–4], stainless steel [5–8], aluminum alloy [9], copper alloy [10], tantalum [11] and monel alloy [12].

Due to the properties of low heat conductivity and high adiabatic shearing sensitivity, ASB was easily observed in titanium and titanium alloys [1,2,13]. Dynamic recrystallization and phase transformation phenomena were observed in the shear bands of titanium and its alloys [2,14]. Minnaar and Zhou [1] analyzed dynamic shear failure resistance of Ti–6Al–4V and several steel alloys. Odeshi et al. [15,16] investigated adiabatic shearing and its effect on fracture behavior at high strain rate. It was shown by Xue et al. [13] that the shear bands are the preferred sites for nucleation, growth, and coalescence of voids and are precursors to failure. Martinez et al. [17] and Murr et al. [18] investigated the crack initiation and growth in the shear bands. Teng et al. [19] studied numerically the formation and propagation of cracks within adiabatic shear bands. Yang et al. [20] found that the coalescence of microcracks formed the crack within shear bands. Liu et al. [3,21] investigated the influences of microstructure and strain rate on adiabatic shearing behaviors and the correlation of shear band with fracture.

Ti-1300 alloy is a super high strength titanium alloy which is developed by Northwest Institute for Non-ferrous Metal Research. The microstructure of Ti-1300 alloy is single and equiaxed β phase after solution above the transformation point, and the granular and needle α phase in β matrix after solution below the transformation point. The microstructure is primary α phase in both grain boundary and grain interior, and short rod-like secondary α phase in β matrix by aging after solution below the transformation point [22]. The formation of ASB is an important dynamic damage and fracture mechanism of materials. The shear bands are preferred sites for nucleation and coalescence of microvoids/microcrack. When the microcrack grows to macrocrack, the shear band becomes a "fast" channel of fracture, and finally leads to low toughness fracture of materials [23]. The adiabatic shearing behaviors of Ti-1300 alloys with different microstructures are different under the same loading condition. In present work, two different heat treatments are involved to produce Ti-1300 alloys with β phase and α + β lamellar microstructures. The effects of microstructure on adiabatic shear sensitivity were investigated by means of the SHPB technique.

2. Experimental procedure

The material used in this study was Ti-1300 alloy, which was subjected to two different heat treatments to obtain β phase and α + β lamellar microstructures. The β phase microstructure (Fig. 1(a)) was obtained by solid solution at 880 °C/1 h followed by water cooling, while the α + β lamellar microstructure (Fig. 1(b)) by solid solution at 760 °C/1 h followed by air cooling, then aged at 520 °C/4 h followed by air cooling. The α + β lamellar microstructure consists of α phase in β matrix.

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0921-5093/$ – see front matter
doi:10.1016/j.msea.2010.12.068

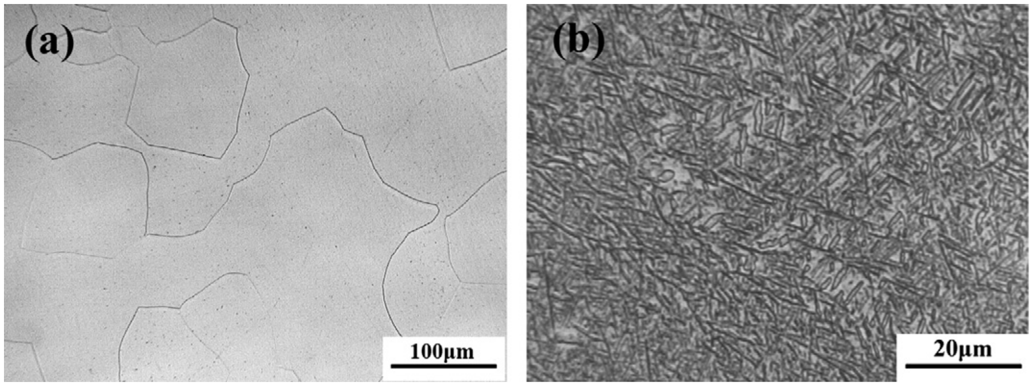

Fig. 1. Optical microstructure of Ti-1300 before testing: (a) β phase and (b) α + β lamellar microstructure.

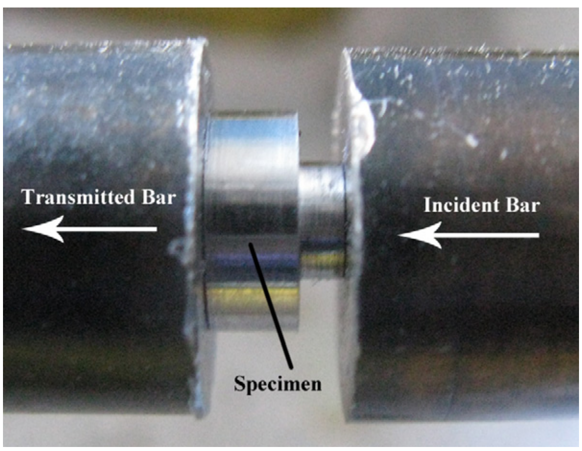

Fig. 2. Hat-shaped specimen between Hopkinson bars.

The SHPB was used to test dynamic mechanical properties and shear deformation of the two alloys. The details and principles of this facility have been discussed in Refs. [3,8,24]. The length of the incident and transmitted bars is 1 m. The diameter of all the bars is 14.5 mm. The hat-shaped specimens were used to generate a forced shear section between the incident and transmitted bars (Fig. 2). Fig. 3 schematically illustrates the forced shear configuration and the hat-shaped specimen. The combination of the forced shear stress and the high shear strain rate at the shear section facilitates the formation of adiabatic shear bands.

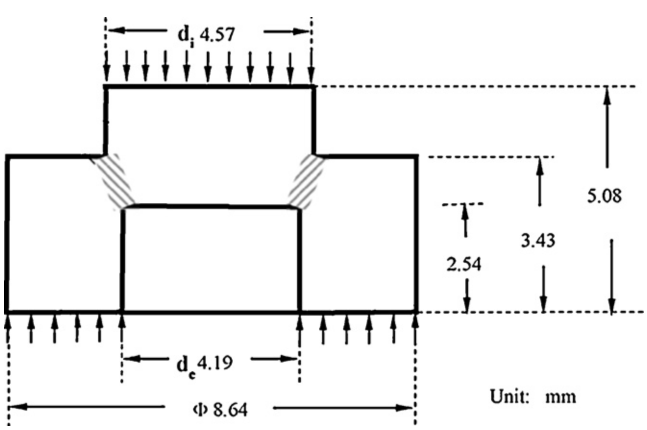

Fig. 3. Schematic configuration of the hat-shaped dynamic shear specimens and loading condition.

The specimens for investigation were cut from the hat-shaped specimens by means of an electrical discharge machine. The chemical attack for Ti-1300 alloy was a solution of HF 1 ml, HNO_3 3 ml, and H_2O 10 ml. The metallographic analysis was made by means of POLYVAR-MET optical microscope (OM) and SIRION200 field emission scanning electron microscope (SEM).

3. Results and discussion

In the SHPB test, the loading period of shock wave T could be calculated according to the equation:

$$T = \frac{2L_0}{C_0} \tag{1}$$

where L_0 is the length of the striker bar, 200 mm, and C_0 is the velocity of longitudinal wave in the maraging steel, 4756 m/s. So the loading period T is calculated to be 84 μs.

The shear stress τ, strain γ, strain rate $\dot{\gamma}$ and true strain ε in the shear band can be calculated as following [24,25]:

$$\tau(t) = \frac{E_0 d_i^2 e_t(t)}{L(d_i + d_e)} \tag{2}$$

$$\dot{\gamma}(t) = \frac{2C_0 e_r(t)}{W} \tag{3}$$

$$\gamma(t) = \int_0^t \dot{\gamma}(t)dt \tag{4}$$

$$\varepsilon = \ln\sqrt{1 + \gamma + \frac{\gamma^2}{2}} \tag{5}$$

where E_0 is the elastic modulus of the maraging steel, $e_r(t)$ and $e_t(t)$ are the experimentally measured strain of reflected and transmitted stress pulse on the Hopkinson bars, L and W are the length and width of the shear band, d_i and d_e are the geometrical parameters of the hat-shaped specimens (Fig. 3).

Strain rate–time curves and true shear stress–strain curves obtained from the SHPB tests at strain rates of $4 \times 10^5\ s^{-1}$ and $6 \times 10^5\ s^{-1}$ are shown in Figs. 4 and 5, respectively. The solid lines are for β phase microstructure, and dotted lines for α + β lamellar microstructure. The phenomenon, stress decreases sharply during the loading time, indicates that adiabatic shear localization deformation takes place [23]. From the stress–strain curves, it could be seen that adiabatic shear deformation happened in both microstructures at the tested strain rates.

The critical strain for the initiation of shear bands in α + β lamellar microstructure is less than that in β phase microstructure (Table 1). In addition, stress decreases more sharply in α + β lamellar microstructure than that in β phase microstructure. Therefore,