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Effect of strain rate on the tension behavior of Ti–6.6Al–3.3Mo–1.8Zr–0.29Si alloy at low temperatures

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ABSTRACT

The tension responses of Ti–6.6Al–3.3Mo–1.8Zr–0.29Si are investigated over a broad range of strain rates, 0.001–1150 s^{-1}, and initial temperatures, 213–293 K. Tensile impact and recovery tests are carried out using the split Hopkinson tension bar technique to obtain the adiabatic and isothermal stress–strain behavior of the alloy at high strain rates. Experimental results indicate that the tension behavior of the alloy is dependent on the strain rate and temperature. The value of initial yield stress increases with increasing strain rate and decreasing temperature. The isothermal strain hardening behavior changes little at different strain rates and temperatures. The adiabatic temperature rise is the main reason for the reduction of strain hardening rate during the high-rate deformation process. SEM observations of the fracture surfaces indicate that the tension specimen is broken in a manner of ductile fracture. The Zerilli–Armstrong constitutive model incorporating the effect of thermal–mechanical coupling is used to describe the rate and temperature dependent deformation behavior of Ti–6.6Al–3.3Mo–1.8Zr–0.29Si alloy. The model results are very close to the experimental data within the tested range of strain rates and temperatures.

1. Introduction

Titanium alloys, especially $\alpha+\beta$ titanium alloys, are attractive to engineering applications requiring light weight, high strength and good corrosion resistance due to their high strength-to-weight ratio, excellent corrosion resistance and good formability. Consequently, titanium alloys are commonly used in aerospace and warship components. Such alloys may be subjected to impact loadings at low or high temperatures. It is important to understand the effects of strain rate and temperature on the mechanical behavior of alloys for the structural design. Currently, the compression responses of titanium alloys such as Ti–6Al–4V at high strain rates and elevated temperatures have been reported in a large number of literatures [1–11]. Experimental investigations indicate that the compressive flow stress of Ti–6Al–4V increases with increasing strain rates and its yielding and strain hardening behavior in compression was found to be more sensitive to change in temperature than strain rate [5,9]. Little work has been done in the area of dynamic tension behavior of titanium alloys at various temperatures, though it has been found that there exists the tension–compression asymmetry for $\alpha+\beta$ titanium alloys due to their low-symmetry hcp systems [12–14].

It is well known that the strain rate has a pronounced effect on the plastic deformation of most metals and the split Hopkinson pressure bar (SHPB) is widely used to investigate the dynamic compression responses of materials at high strain rates up to $10^3\ s^{-1}$ [15]. Compared with the deformation under isothermal quasi-static loading, the deformation at high strain rates is basically adiabatic because the heat converted from the plastic work has no sufficient time to dissipate. Consequently, there is a significant temperature rise in the specimen and there exists thermal–mechanical coupling during the course of adiabatic deformation. Generally, the plastic stress–strain response of the metals subjected to high strain-rate loadings is the competition process of the strain-rate strengthening, strain hardening and adiabatic temperature rise softening effects. Uncoupling these three influences on the dynamic responses of metals is of fundamental importance for accurately predicting their plastic deformation behavior. Nemat-Nasser et al. [16,17] proposed techniques for compression recovery experiments on the SHPB system to measure the isothermal compression flow stress of metals at high strain rates.

The present paper aims to investigate the strain rate effect on the tension responses of Ti–6.6Al–3.3Mo–1.8Zr–0.29Si alloy (referred as TC11 in China) with a duplex microstructure at low temperatures ranging from 213 to 293 K. The strain rates are varied from 0.001 to 1150 s^{-1}. Moreover, the isothermal stress–strain behavior at the high strain rate is examined to accurately

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evaluate the rate dependence of initial yielding and strain hardening. Subsequently, the rate and temperature dependent constitutive model incorporating the adiabatic softening is chosen to describe the tension behavior of Ti–6.6Al–3.3Mo–1.8Zr–0.29Si within the tested range of strain rates and temperatures.

2. Material and experimental procedure

2.1. Material

The titanium alloy used in the present study was obtained as commercial forged rods, 38 mm in diameter, purchased from BaoTi Group Co. Ltd. of China. The chemical composition (in wt%) of the alloy is 6.6Al, 3.3Mo, 1.8Zr, 0.29Si, 0.07Fe, 0.01C, 0.01N, 0.004H, 0.13O and balance Ti. The samples were prepared by the following process: annealing for 2 h at 1228 K, aging for 6 h at 803 K and cooling down to the room temperature in the air. Metallographic examination of the undeformed samples reveals that the microstructure of material is duplex, containing a lamellar Widmanstatten structure dispersed between primary globular α grains, as shown in Fig. 1. The volume fraction and the average size of primary globular α grain is about 45 pct. and 10 μm, respectively.

2.2. Experimental procedure

Uniaxial tension experiments were performed at three temperatures of 213, 253 and 293 K over a wide range of strain rates from 0.001 to 1150 s^{-1}. Quasi-static tension tests were carried out at the rate of 0.001 s^{-1} on an MTS810 servo-hydraulic testing system to obtain the isothermal responses of the alloy. Dynamic tension tests were conducted at the rates of 190, 500 and 1150 s^{-1} using a modified split Hopkinson tension bar system (SHTB) to obtain the adiabatic responses of the alloy. The details on the SHTB technique and the associated measuring principle can be found elsewhere [18]. A liquid-nitrogen cooled chamber was used to create the testing temperatures between 173 and 293 K.

Due to the fact that the effects of strain rate, strain hardening, and thermal softening caused by the adiabatic temperature rise work together at high strain rates, the tensile impact recovery experiments were performed on the SHTB system to uncouple the thermo-mechanical coupling deformation behavior. The tensile incident stress pulse with short duration was generated to make the specimen deform into the plastic deformation to a certain level of plastic strain. Then the deformed specimen was unloaded and was allowed to return to its initial testing temperature. Namely, the specimen was subjected to a single loading and unloading at a high strain rate. By repeating the loading-unloading several times on the same specimen at the same strain rate, the tensile recovery experiments came into operation. The isothermal stress–strain curves at high strain rates were obtained by connecting the points associating with the initial yielding upon each loading. In the present study, the tensile recovery tests were conducted at the strain rate of 190 s^{-1} and at 253 and 293 K. The duration of the tensile incident stress pulse was chosen carefully to load the specimen to a true strain of about 1% at each incremental loading. The temperature rise in the specimen is evaluated as follows:

$$\Delta T = \frac{\gamma}{\rho C_p} \int_0^{\varepsilon} \sigma \, d\varepsilon \tag{1}$$

where σ and ε are the flow stress and the plastic strain, respectively. γ is the conversion factor of plastic work to heat. ρ and C_p are the mass density and the specific heat capacity at constant pressure, respectively.

The gage length, width and fillet radius of the dumbbell-shape plate specimen used in dynamic tension tests are 10 mm, 3.5 mm and 2 mm, respectively. The specimen thickness is 1.1 mm. The specimen geometry used in quasi-static tension tests is similar except that the gage length of 30 mm is long enough to avoid the end effects. The tension tests under each strain rate and temperature loading conditions were repeated at least three times and the good repeatability of the data was obtained.

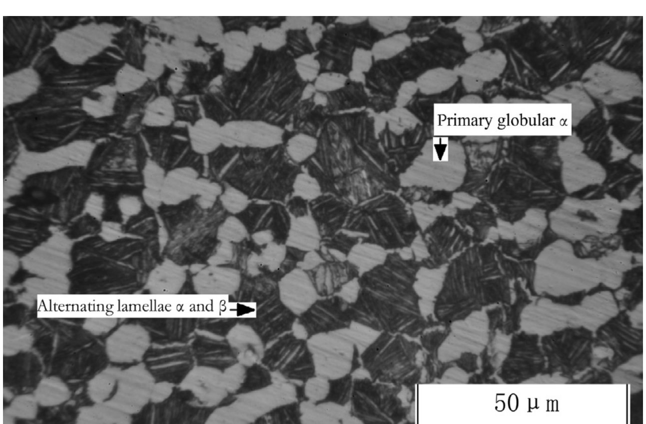

Fig. 1. Undeformed microstructure for Ti–6.6Al–3.3Mo–1.8Zr–0.29Si alloy.

3. Results and discussion

3.1. Tension responses of Ti–6.6Al–3.3Mo–1.8Zr–0.29Si alloy

Fig. 2 shows the tensile stress–strain responses of Ti–6.6Al–3.3Mo–1.8Zr–0.29Si alloy as a function of four strain rates at three initial temperatures. As presented in Fig. 2(a), the responses of the alloy at room temperature exhibit the obvious strain rate sensitivity and nonlinear elastic–plastic deformation characteristics. Since no obvious yield point can be found in the stress–strain curve, the flow stress at 0.2% plastic strain was adopted as initial yield stress. The strain rate has the positive effect on the initial yielding behavior. The values of initial yield stress for high strain rates increase obviously compared with quasi-static results, which presents a considerable strain-rate strengthening phenomenon. However, the plastic response at high strain rates is absolutely different from that at low strain rate (0.001 s^{-1}). There is little strain hardening effect in the adiabatic high-rate experiment due to adiabatically thermal softening. This observation is similar to other investigations on the compression responses of α+β titanium alloys [5,9]. The tension responses at low temperatures are shown in Fig. 2(b) and (c). At low temperatures, the strain rate also has a profound effect on the flow stress. Similar trend of reduction in strain hardening rate can be observed at high strain rates.

The effects of strain rate and temperature on the initial yield stress are shown in Fig. 3. It was seen that the initial yield stress increases with increasing strain rate at different temperatures. The values of strain-rate sensitivity parameter of $m = \delta(\ln \sigma_{0.2})/\delta(\ln \dot{\varepsilon})$ were obtained to be 0.021, 0.022 and 0.023 at temperatures of 213, 253 and 293 K within the tested rate range of 0.001–1150 s^{-1}, indicating that the strain rate sensitivity changes little with the temperature. It was also found that the initial yield stress decreases with the increase of temperature. When the temperature decreases, the yield stress increases obviously. The values of temperature sensitivity parameter of $n = \delta(\ln \sigma_{0.2})/\delta(\ln T)$ were obtained to be 0.38, 0.30, 0.31 and 0.28 at strain rates of 0.001, 190, 500 and 1150 s^{-1} within the investigated temperature range of 213–293 K. This result indicates that the temperature sensitivity of the yield stress is dependent on the strain rate. However,