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Effect of strain rate on the tension–compression asymmetric responses of Ti–6.6Al–3.3Mo–1.8Zr–0.29Si

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ABSTRACT

An experimental investigation is performed to explore the tension–compression asymmetry of Ti–6.6Al–3.3Mo–1.8Zr–0.29Si alloy over a wide range of strain rates. A split Hopkinson bar technique is used to obtain the dynamic stress–strain responses under uniaxial tension and compression loading conditions. Experimental results indicate that the alloy is a rate sensitive material. Both tension yield strength and compression yield strength increase with increasing strain rate. The mechanical responses of the alloy have the tension–compression asymmetry. The values of yield strength and subsequent flow stress in compression are much higher than that in tension. The yield strength is more sensitive to change with strain rate in tension than compression. The difference of the yield strength between tension and compression increases with the increase of strain rate. The tensile specimen is broken in a manner of ductile fracture presenting characteristic dimples, while the compressive specimen fails in a manner of localized shearing failure.

1. Introduction

Titanium alloys, especially two-phase α/β alloys, are attractive structural materials due to their high specific strength, excellent corrosion properties and good formability. These alloys are widely used in engineering applications not only requiring light weight and high strength (such as aerospace components) but also involving high-rate loadings (such as foreign-object impact and high-speed machining). The dynamic properties of α/β titanium alloys such as Ti–6Al–4V have been received more attention in the past years and it has been found that the alloys have a positive strain rate sensitivity. For example, Follansbee and Gray investigated the compressive behavior of Ti–6Al–4V at temperatures between 76 and 495 K and strain rates between 0.001 and 3000 s^{-1} [1]. Majorell et al. presented the results of the compressive deformation of Ti–6Al–4V in the temperature range 650–1340 K and under constant strain-rate loading ranging from 10^{-3} to 10 s^{-1} [2]. Nemat-Nasser et al. [3] and Khan et al. [4,5] investigated the compressive thermomechanical responses of Ti–6Al–4V at elevated temperatures and high strain rates of up to 10^3 s^{-1}, and proposed constitutive models to describe the adiabatic deformation behavior of the tested alloy. Zhang et al. conducted compression tests on the α/β titanium alloy TC11 at strain rates ranging from 0.001 to 10 s^{-1} [6]. Furthermore, it has been known that the fracture behavior of titanium alloys subjected to high-rate compressive loadings is related to the localized shearing failure. For example, Silva and Ramesh reported the rate-dependent deformation and fracture behavior of Ti–6Al–4V using compression and torsional Kolsky bars [7]. Lee and Lin studied the compressive plastic deformation and fracture mechanism of Ti–6Al–4V at high strain rates and various temperatures [8]. Wagoner Johnson et al. [9] and Liu et al. [10] performed the compression tests on the Ti–6Al–4V alloys with different microstructures at strain rates over the ranges of 0.1–1000 s^{-1} and 10^{-3}–10^4 s^{-1}, respectively. Ramesh reviewed results of high-strain-rate deformation and dynamic failure studies on Ti–6Al–4V and discussed the observations of adiabatic shear localization [11].

In addition, experimental investigations under quasi-static loading conditions indicate that the alloys with the hexagonal close-packed crystal structure have the tension–compression asymmetry, including deformation performances, damage patterns and failure mechanisms in tension and compression [12,13]. Luntz et al. conducted the tension and compression tests on the Titanium 6–6–2 alloy at strain rates ranging from 10^{-4} to 10^0 s^{-1} [14] and Fundenberger et al. examined the yield strength of the α/β titanium alloy TA6V in tension and compression [15]. They found that the values of yield strength in compression for two alloys are obviously greater than that in tension. Neeraj et al. studied the creep behavior of two alloys, Ti–6Al–2Sn–4Zr–2Mo and Ti–6Al, and a

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dramatic asymmetry between tension and compression was observed [16]. It is necessary to achieve a fundamental understanding of the tension–compression asymmetry in α/β titanium alloys at high strain rates. However, the high-rate tensile behavior of titanium alloys is reported little due to technique difficulties [17,18]. Sarsfield et al. conducted the tension and compression tests on cylindrical specimens at quasi-static (10^{-4} s^{-1}), medium (10^2 s^{-1}) and high (10^3 s^{-1}) rates of strain in ambient environment and observed the obvious tension–compression asymmetry in three titanium alloys, Ti64, Ti550 and Ti6246 [19].

The purpose of the present paper is to investigate the tension and compression responses of Ti–6.6Al–3.3Mo–1.8Zr–0.29Si over a wide range of stain rates. Split Hopkinson bar technique is utilized to perform the uniaxial tension and compression tests at high strain rates. The stress–strain behavior and failure mode are examined to evaluate the strain rate effect on the tension–compression asymmetry in the α/β titanium alloys.

2. Experimental procedure

2.1. Material

The chemical composition (in wt%) of the α/β titanium alloy used in the present investigation was 6.6Al, 3.3Mo, 1.8Zr, 0.29Si, 0.07Fe, 0.01C, 0.01N, 0.004H, 0.13O and balance Ti. The alloy was supplied by Baoji Titanium Industry Company in China in the form of 38 mm forged rods. The samples were subjected to annealing and cooling processes as follows: annealing for 2 h at 955 °C, aging for 6 h at 530 °C and cooling down to the room temperature in the air. As shown in Fig. 1, metallographic examination for the undeformed alloy reveals that the duplex microstructure was obtained, containing a lamellar Widmanstatten structure dispersed between primary globular α grains.

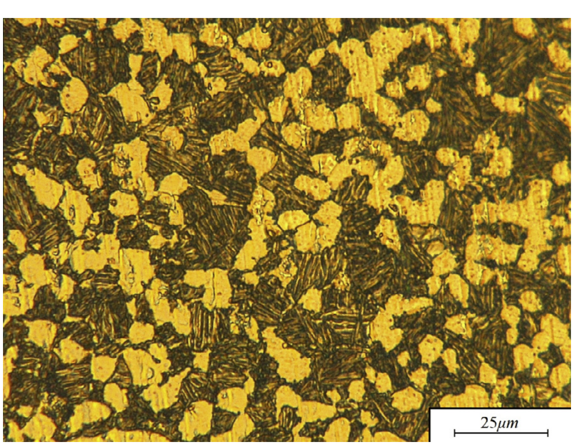

Fig. 1. Microstructure of the undeformed alloy.

2.2. Tension and compression tests

Quasi-static tension and compression tests were carried out on MTS809 and MTS810 testing machines respectively at ambient temperature and at a constant strain rate of 0.001 s^{-1} [20,21]. For tension tests, dumbbell-shape flat specimens with 3.5 mm in gage width, 30 mm in gage length and 1.1 mm in thickness were used. The cylindrical specimens in compression tests were 8 mm in diameter and 20 mm long. All specimens were prepared by electro-discharge machining parallel to the axial direction from rods of the alloy.

Split Hopkinson bar systems were employed to conduct the high strain-rate tension and compression tests at ambient temperature. The schematic diagram of the testing facility is shown in Fig. 2. Dynamic tension tests were achieved using the split Hopkinson tension bar apparatus, which comprises an impact system, a prefixed short metal bar, an incident bar and a transmitted bar [22]. The tensile incident pulse was produced by the deformation of the prefixed metal bar due to the impact between the hammer and the impact block. The amplitude and duration of the incident pulse can be effectively controlled by adjusting the length and diameter of the prefixed metal bar and the impact velocity of the hammer. The role of the prefixed metal bar (made of Ly12cz aluminum alloy, Chinese brand, strain-rate insensitive material) is not only the pulse producer but also the low-pass mechanical filter due to its plastic deformation. The tension specimen was connected to the incident/transmitted bars using adhesive connection. Dynamic compression tests were conducted on the split Hopkinson pressure bar apparatus. A copper pulse shaper was utilized to reduce the wave oscillation due to the direct impact between the striker and the incident bar. The specimen was sandwiched between the incident and transmitted bars. Strain gage signals, incident pulse ε_i, reflected pulse ε_r and transmitted pulse ε_t measured from strain gages on the incident/transmitted bars, were recorded as a function of time. According to the one-dimensional elastic wave propagation theory and the assumption of stress equilibrium in the specimen ($\varepsilon_i + \varepsilon_r = \varepsilon_t$), the engineering stress, σ_e, strain, ε_e, and strain rate, $\dot{\varepsilon}_e$, in the specimen can be derived as follows [23].

$$\sigma_e(t) = \frac{EA}{A_s}\varepsilon_t(t) \tag{1}$$

$$\varepsilon_e(t) = \frac{2C_0}{l_s}\int_0^t [\varepsilon_i(\tau) - \varepsilon_t(\tau)]d\tau \tag{2}$$

$$\dot{\varepsilon}_e(t) = \frac{2C_0}{l_s}[\varepsilon_i(t) - \varepsilon_t(t)] \tag{3}$$

where C_0 (=E/ρ, E and ρ are the Young's modulus and density of the incident/transmitted bar, respectively) is the longitudinal wave velocity in the bar. A is the cross-sectional area of the incident/transmitted bar. A_s and l_s are the cross-sectional area and gage length of the specimen, respectively.

Dynamic uniaxial tension tests at strain rates of 210 s^{-1}, 450 s^{-1} and 940 s^{-1} on the investigated alloy were performed at ambient temperature. The tensile specimen was machined to a dumbbell-shape plate with 3.5 mm in gage width, 10 mm in gage length and 1.1 mm in thickness. Dynamic uniaxial compression tests at strain rates of 500 s^{-1}, 1500 s^{-1} and 2500 s^{-1} were conducted at ambient temperature. The compressive specimen was machined to a cylindrical disk with 5 mm in diameter and 4 mm in thickness.

3. Results and discussions

The engineering stress versus strain curves obtained under uniaxial tension at quasi-static and high rates of strain are shown in Fig. 3. It can be seen that the tensile response of the alloy is sensitive to the strain rate. The flow stress increases rapidly when the strain rate is increased from 0.001 to 210 s^{-1}. The 0.2% tension yield strength of the alloy is 930 MPa at a strain rate of 0.001 s^{-1} and increases to approximately 1250 MPa at a strain rate of 210 s^{-1}. The strain hardening rate changes obviously at high strain rates when compared with that under the quasi-static loadings and the reduced strain hardening phenomenon was observed at high strain rates. Similar results were found by Macdougall and Harding in tensile tests at a rate of 2000 s^{-1} for Ti–6Al–4V alloy on cylindrical specimens [17]. The compressive responses of the alloy as a function of strain rate are shown in Fig. 4. The flow stress at all levels of strain increases obviously with increasing strain rate.