Journal of Alloys and Compounds 684 (2016) 162–170

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

journal homepage: http://www.elsevier.com/locate/jalcom

Flow and fracture characteristics of near alpha titanium alloy

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ARTICLE INFO

Article history:
Received 3 April 2016
Received in revised form
13 May 2016
Accepted 16 May 2016
Available online 17 May 2016

Keywords:
J-C model
Titanium alloy
SHTB
Triaxiality

ABSTRACT

To understand the flow and fracture behavior of near-α titanium alloy, the influence of stress triaxiality and strain rate on the failure behavior of this alloy was considered. The combined effect of strain rate, temperature and stress triaxiality on the behavior was studied by testing both smooth and notched specimens. Johnson-Cook (J-C) constitutive and fracture models were established based on high strain rate tensile data obtained from Split hopkinson tension bar (SHTB) and quasi-static tests. The Johnson Cook constitutive and fracture models have been calibrated. A modified Johnson–Cook model was established and proved to have high accuracy. The calibrated model has been validated by simulating the tension tests at various triaxialities using ANSYS autodyn software. Finite element simulations were used to predict the effective plastic strain versus triaxiality history within the deforming specimens. The fracture surfaces of specimens tested under various strain rates and temperatures were studied under scanning electron microscopy (SEM).

1. Introduction

Titanium alloys have been widely used in various fields for its exceptional properties of specific stiffness, corrosion resistance, good formability and specific strength [1]. Understanding of material characterization at high strain rates and elevated temperatures is crucial for applications such as machining, extrusion, hot forging and ballistic impacts in armour applications. It is essential to have knowledge on the mechanical behavior of near-α titanium alloy as various metals or alloys demonstrate different characteristics at different strain rates and temperatures. Presently, the compressive behavior of titanium alloys at high strain rates and elevated temperatures have been studied by many researchers [2–8]. On the whole, the available literature on the dynamic flow behavior of titanium alloys at elevated temperatures is inadequate [9–14]. Especially, on the high strain rate tensile behavior of titanium alloys, the published data is very limited. Hence, it is imperative to predict and evaluate the dynamic tensile flow behavior of titanium alloys over a wide range of temperatures.

With regard to the dynamic loading conditions of the material, the constitutive model, as a code input for simulating the material's response, will appreciably influence the accuracy of numerical results. So, it is imperative to perform the high strain rate tensile tests using Hopkinson bar system. The Johnson-cook (J-C) constitutive and fracture models [15,16] have been effectively established for various materials. J-C model constants have been generated and calibrated for different materials [17–25]. The J-C model is widely used because of the availability of the material parameters. However, J-C constitutive and fracture parameters have been developed only for few materials. The Weldox 460 E steel, OFHC Copper, Armco Iron, 4340 steel, Al-4.8Cu-1.2 Mg alloy and AA5083-H116 aluminum alloy [21–27] have been studied to evaluate the J-C constitutive and fracture parameters. Zhang.et al. [28] investigated the dynamic behavior of 7075-T6 aluminum alloy at various strain rates. A new J-C constitutive model of 7075-T6 aluminum alloy was obtained, by modifying the strain rate hardening term in the Johnson–Cook constitutive model. The damage and fracture criterion of 7075-T6 aluminum alloy was also established based on Johnson–Cook failure model. Apart from these, the researchers could not find any material for which the complete data set has been generated. Zhang.et al. [29] studied the influence of strain rate and temperature on the tension response of Ti-6.6Al-3.3Mo-1.8Zr-0.29Si alloy are systematically investigated over a wide range of strain rates, 0.001–1150/s, and temperatures, 293–573 K. J-C model was modified to describe the rate-temperature dependent deformation behavior of Ti-6.6Al-3.3Mo-1.8Zr-0.29Si alloy. The model results well matched with the experimental data.

In this paper, the effect of strain rate, temperature and stress triaxiality of near-α titanium alloy is investigated, by uniaxial quasi-static and dynamic tensile tests. A modified J-C model is established

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http://dx.doi.org/10.1016/j.jallcom.2016.05.155
0925-8388/

to correlate the relationship between the flow stress, temperature and strain rate. After evaluation of J-C strength-fracture constants tensile axisymmetric tests with various triaxialities were simulated in ANSYS autodyn. Fracture constants were validated, by comparing the experimental and numerical results.

2. Experimental methods

The alloy conforming to near-α titanium alloy composition (Ti-5.8 Al-4.0 Sn-3.5 Zr-0.7 Nb- 0.5 Mo-0.35 Si) was received, in form of rods of 20 mm diameter. Different dimensions of notch geometries were introduced to vary the stress triaxility ratio. The quasi-static tensile testing was performed according to ASTM E8/E8M-11. The quasi-static tension experiments (at a constant velocity of 4 mm/min) were done on INSTRON machine. The maximum load capacity of the machine is 50 kN. The strain rate was controlled by a cross head displacement rate. The smooth round bars and notch round bars (Fig. 1) were employed to perform quasi-static tensile experiments with universal tensile machine. A Split-Hopkinson Tension Bar (SHTB) setup was used for the high strain rate tensile tests [25]. Tensile tests were carried out at the temperatures of 25 °C, 200 °C, 400 °C and 600 °C under the different high strain rates of 500, 1000/s and 1500/s (Fig. 2). High strain rate tensile testing of titanium alloy samples of length 45 mm and diameter 10 mm was carried out using SHTB apparatus.

3. Results and discussion

The true stress-true strain curves generated at quasi-static and high strain rates under uniaxial tension are demonstrated in Fig. 2. It is observed that the dynamic tensile behavior of the near-α titanium alloy is sensitive to both the strain rate and temperature. When compared to quasi-static loadings, the strain hardening rate changes clearly at high strain rates. The flow stress increases with the increasing of the strain rate, indicative of positive strain rate sensitivity. The tensile flow behavior of this alloy is influenced by the strain rate hardening and strain hardening. The flow stress enhances with the raise in strain rate, indicative of positive strain rate sensitivity.

During the high strain rate tensile tests, the strength of near-α titanium alloy is mainly established by competing processes of strain hardening and strain rate hardening. When the material undergoes plastic deformation, the dislocation accumulates and the dislocation density increases, which causes the strain hardening.

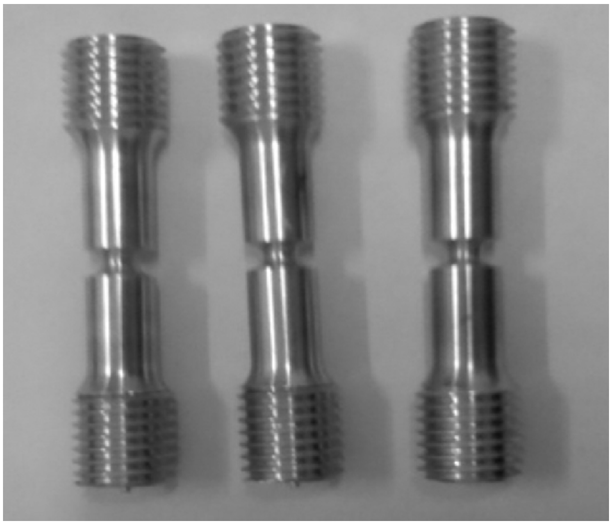
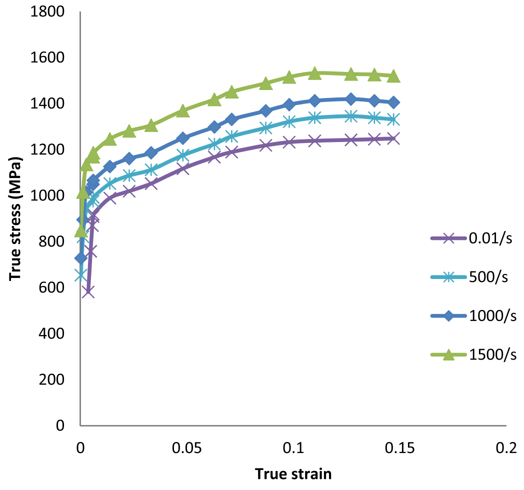
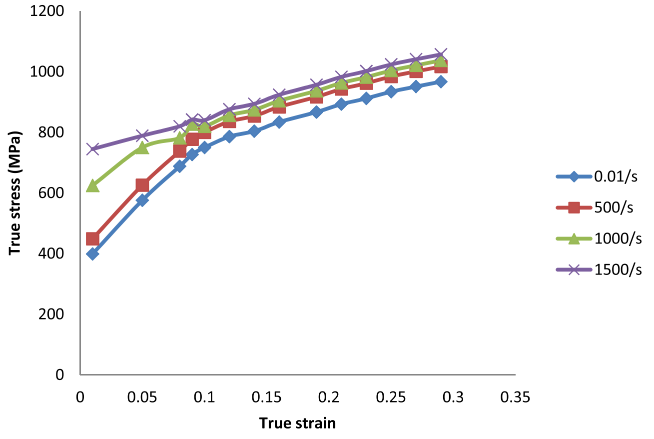


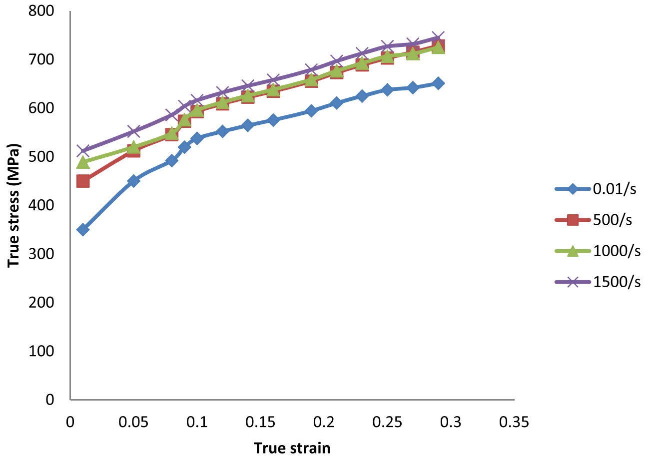
Fig. 1. Photo of the notched tensile specimen of near-α titanium alloy.



(a) 25^{0}C



(b) 400 ^{0}C



(c) 600 ^{0}C

Fig. 2. The true stress strain curves of near-α titanium alloy at various temperatures of (a) 25 °C (b) 400 °C (c) 600 °C.

3.1. Modified Johnson-Cook constitutive model

The J–C model considers isotropic hardening, strain rate