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Crystal plasticity modeling of a near alpha titanium alloy under dynamic compression

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ABSTRACT

The purpose of this study is to describe the dynamic behavior of near alpha titanium alloy at elevated temperatures using Crystal plasticity and other models. Three constitutive models: Johnson-Cook (J-C), Zerilli–Armstrong (Z-A), Cowper-Symonds (C–S) and J-C fracture models are established. Experimental results observed that material displayed strain rate sensitivity at various strain rates. The generated model constants have been incorporated into finite element code. Finite Element simulations of tensile tests under different strain rates have been performed using Autodyn software. A crystal plasticity model is established and shows that it can predict the stress strain response under dynamic loading conditions. The developed crystal plasticity model was implemented in the ABAQUS code to simulate high strain rate compression and showed good agreement. Subsequently, a Charpy impact test on specimen has also been simulated. The fracture surfaces of specimens tested under quasi static state at various temperatures were studied under scanning electron microscopy (SEM).

1. Introduction

Titanium alloys have replaced different steels in various engineering applications, owing to their superior mechanical properties and low density to strength ratio. Broad investigation on high strain rate behavior at elevated temperatures is significant for uses in field of armour, biomedical and machining operations [1–8]. The materials in these applications are typically subjected to strain rates in the order of 10^2–10^4/s. In numerical simulation point of view, flow behavior of materials under dynamic situations is imperative to build constitutive models. The characterization of metals at high strain rates and temperatures is governed by hardening and softening principles. Many researchers [5–8] have proposed a range of constitutive models, accounting the combined effects of strain, strain-rate and temperature on the flow stress. Overall, the published literature on the flow behavior of beta titanium alloys under dynamic loading conditions is inadequate.

The crystal plasticity theory [9–17] proposed in the early nineties, with a comprehensible physical basis. Since Crystal plasticity (CP) has become so powerful tool for assessing the deformation behavior at large strain rates and strains, this can be incorporated into finite element (FE) for obtaining the simulated deformation behavior under these conditions.

The aim of the present study is to determine the flow behavior of the near alpha titanium alloy under various strain rates and temperatures using the crystal plasticity and other constitutive models. In this work, quasi-static and high strain rate compression tests were carried out on titanium alloy. A crystal plasticity model is established and demonstrates that the model can evaluate stress strain response under different strain rates. This model is implemented in ABAQUS/Explicit code.

2. Experimental methods

The near alpha titanium alloy, with the composition, Ti-5.75Al-4.0Sn-3.5Zr-0.7Nb-0.5Mo-0.33Si, was used in the present study. This alloy is solution treated at 1020 °C for 2 h and then oil quenched. The solution treated microstructure has been aged at 700 °C for 2 h. Microstructure of the alloy consists of primary α (~12 vol.%) in transformed β matrix is shown in Fig. 1. Etchant used for etching the alloy is Kroll's etching reagent containing distilled water 100 ml, hydrofluoric acid 1–3 ml and nitric acid 2–6 ml for microstructural examination.

Low strain rate tests were performed on Instron machine. A Split-Hopkinson Pressure Bar (SHPB) setup was used for the high

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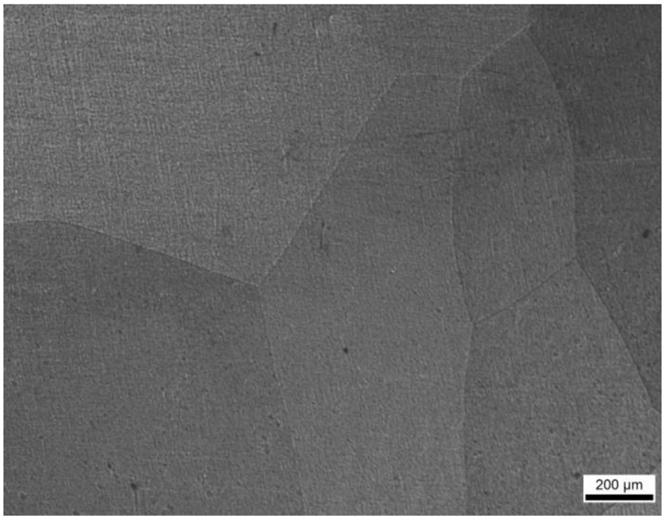

Fig. 1. Optical micrograph of titanium alloy.

strain rate compression tests. Cylindrical specimens of various dimensions were made as per ASTM: E209 standard. Compression tests were carried out at the temperatures of 25 °C, 200 °C, 400 °C and 600 °C under the different strain rates of 0.01–3500/s (Fig. 1). The Charpy impact tests were carried out in a Zwick–Roell make system.

3. Results and discussion

3.1. Plastic deformation mechanism and microstructure study

The compressive stress–strain curves for near alpha titanium alloy at various temperatures are shown in Fig. 2. For a given temperature, the flow stress raises as the strain rate goes up owing to the proliferation of dislocations. Elevated strain rates and lower temperatures promote energy accumulation due to short duration of time. Usually, at high strain rates the dominant deformation mechanism is dislocation slip or twinning. As per dislocation dynamics, the flow stress consists of two components of thermal and athermal nature. The thermal part is controlled by shot-range barriers such as the intersection of dislocations. A higher strain rate can increase speed of dislocation pile-up, leading to the tangle

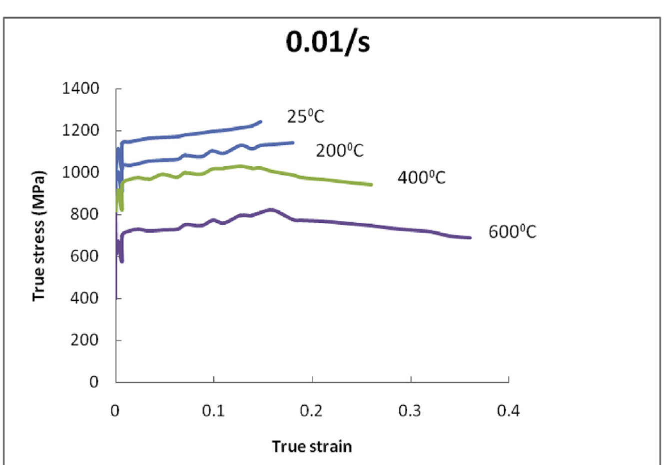

Fig. 2. The true stress strain curves of titanium alloy at various temperatures.

formation which will suppress the dislocation movement. Therefore, the flow stress increases with increasing strain rate while decreases with increasing temperature. The athermal flow stress is controlled by long-range resistance due to grain boundaries and precipitates. The large improvement of flow stress at high strain rates is attributed to a transition from a thermally activated mechanism to a dislocation drag mechanism. The optical micrographs of titanium alloy after high strain rate compression are shown in Fig. 3. The influence of temperature on microstructural evolution can be observed from these microstructures. Dynamic recrystallization (DRX) occurs at a low strain rate, but almost no such phenomenon is found at a higher strain rate [18–21]. At high strain rates, DRX formation tendency is less, since dislocations won't find enough time to consume or generate. This is because the fact that at higher strain rates, adiabatic deformation heat is generated due to insufficient deforming time during hot working and the low thermal conductivity of titanium alloy.

Fig. 4 shows the tensile fracture surfaces at various strain rates and temperatures. The fracture surfaces predominantly contain dimples. Based on these observations, tensile failure mainly involves void nucleation, growth and coalescence. The fracture surface, at low strain rates has few faceted surfaces which possesses micro dimples. It is clear that the titanium alloy displays mixed mode fracture consisting of ductile dimples interspersed with faceted fracture surfaces. At high strain rates transgranular fracture is observed with well developed dimples.

3.2. The crystal plasticity model of near alpha titanium alloy

Considering the plastic deformation to occur due to slips on well defined crystallographic planes, for finite deformations, the total deformation gradient F is decomposed into elastic and plastic parts as suggested in Refs. [9–11].

$$F = F^{*}F^{p} \tag{1}$$

It is to be noted that in the above expression F^{*} contains deformation gradients due to both elastic stretching and the lattice rotation, while F^{p} denotes the deformation gradient due to plastic deformation only. As suggested in Ref. [9] the constitutive equation for stress in the crystal can be expressed as

$$T^{*} = C\left[E^{*}\right] \tag{2}$$

where C is the fourth-order elasticity tensor reflecting the inherent anisotropy of the single crystal, T^{*} and F^{*} are a pair of work conjugate stress and strain measures defined using the elastic deformation gradient, F^{*} as;

$$T^{*} = \frac{1}{2}\left\{F^{*T}F^{*} - 1\right\} \tag{3}$$

The strain tensor ε is split into two components [13]: the elastic strain tensor ε_e and the plastic strain tensor ε^{p}_{slip}, i.e.,

The elastic strain tensor ε_e can be determined by Hooke's law:

$$\varepsilon = \varepsilon_e + \varepsilon^{p}_{slip} \tag{4}$$

where σg is the stress tensor and C is the fourth-order elastic tensor.

$$\varepsilon^{e} = C^{-1} : \sigma^{g} \tag{5}$$

The plastic strain produced by dislocation slipping is estimated from the given formulae: