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High-temperature deformation and grain-boundary characteristics of titanium alloys with an equiaxed microstructure

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Abstract

The high-temperature deformation behavior of single-phase α (Ti–7.0Al–1.5V), near-α (Ti–6.85Al–1.6V), and two-phase (Ti–6Al–4V) titanium alloys with an equiaxed microstructure was examined, and the results were compared within the framework of an internal-variable theory of inelastic deformation. For this purpose, load-relaxation and tension tests were conducted at various temperatures. Stress–strain-rate curves obtained by load-relaxation tests for the three alloys were well described by the equations for grain-matrix deformation and grain-boundary sliding. With respect to boundary strength, the internal-strength parameter (σ^*) for α–α boundaries was found to be ∼2 times higher than that for α–β boundaries. The friction stress parameter (Σ_g) of boundaries was the highest in the single-phase α alloy and the lowest in the two-phase (α + β) alloy. This indicates that grain-boundary sliding occurs preferentially at α–β interfaces rather than at α–α boundaries.

Keywords: Ti–6Al–4V; Phase volume fraction; Grain-matrix deformation; Grain-boundary sliding; Internal-variable theory

1. Introduction

Two-phase titanium alloys deform heterogeneously, thus making the prediction of microstructural changes during hot-working challenging [1–4]. Previously, a number of efforts have focused on constitutive modeling and the analysis of plastic flow particularly for Ti–6Al–4V, which is the most widely used titanium alloy [5–10]. However, accurate models for such two-phase system are still limited because the microstructural features (i.e., grain size, phase volume fraction, phase morphology, crystallographic texture, and grain- or phase-boundary characteristics) controlling deformation are very complex compared to single-phase materials [11,12]. Because these factors are interdependent, it is not easy to determine their discrete effects on the overall deformation behavior. For example, special care should be taken to quantify the characteristics of grain- or phase-boundaries (i.e., α–α, β–β, and α–β), including boundary strength and friction stress between adjacent grains or phases. The nature of grain- or phase-boundaries is critical to the overall flow behavior because it greatly effects (1) slip transmission via the passage of individual dislocations and (2) friction stress between adjacent grains or phases, which is important especially for high-temperature creep or superplasticity. Obviously, these characteristics are different for different types of phase- and grain-boundaries. Knowledge pertaining to such variations would thus be very useful to obtain a better understanding of the evolution of microstructure, cavitation, and crystallographic texture [13]. Although significant research has been conducted to determine the broad effect of grain- or phase-boundary characteristics on plastic deformation, little *quantitative* information is available related to the strength or friction stress for grain- or phase-boundaries in two-phase alloys such as Ti–6Al–4V.

To help in understanding the relation between the micromechanisms of deformation and observed plastic-flow response, Chang and Aifantis [14] formulated a physically based plasticity theory utilizing the concept of internal-state variables instead of the conventional macroscopic (phenomenological) variables. In this approach, inelastic deformation is considered as a dislocation-glide process giving rise to an internal strain, and a plastic strain. Using this theory, the overall high-temperature deformation behavior of many alloys (Al, β-CuZn, Ti–6Al–4V, etc.) was successfully described, and their boundary

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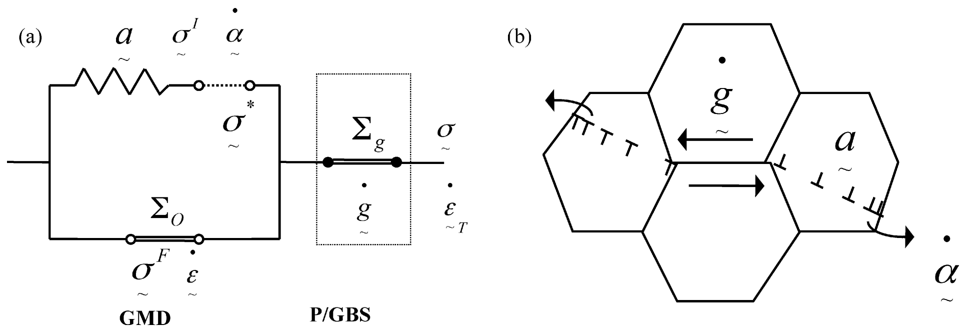

Fig. 1. Internal-variable model for the description of high-temperature deformation: (a) rheological model and (b) topological model [18].

characteristics were analyzed [15–18]. However, there remain some uncertainties with regard to the application of the theory to alloys such as Ti–6Al–4V because the approach is formally applicable to only single-phase materials. Hence, research to verify whether the inelastic deformation theory can be extended to two-phase materials would be beneficial [19,20]. To this end, the present work was undertaken to clarify the individual effects of α–α and α–β boundaries in Ti–6Al–4V on deformation at high temperature within the framework of the internal-variable theory. The effect of β–β boundary area was not considered because its fraction is very small (less than ∼5%) at the temperatures of interest (650–815 °C). In addition, β–β boundaries tend to be low angle in nature and thus do not act as strong dislocation barriers nor slide readily [8,17]. For the purpose of comparison, the state-variable model was also applied to single phase and near-α Ti alloys; the composition of the alpha phase in these alloys was chosen to be similar to that of the α-phase in Ti–6Al–4V.

2. Internal-variable theory of inelastic deformation

In the internal-variable theory of inelastic deformation, rheological and topological models (Fig. 1) are used to quantify grain-matrix deformation (GMD) and grain-boundary sliding (GBS). The model represents that GBS is mainly accommodated by a dislocation process. For the model shown in Fig. 1, the following kinematic relations among the rate variables can be derived:

$$\sigma = \sigma^{\mathrm{I}} + \sigma^{\mathrm{F}} \tag{1}$$

$$\dot{\varepsilon}_{\mathrm{T}} = \dot{a} + \dot{\alpha} + \dot{g}, \tag{2}$$

in which $\dot{\alpha}$ and $\dot{g}$ denote the plastic strain rates due to dislocation glide and GBS, respectively. The variables σ^{I} and σ^{F} are the internal stress due to the long-range interaction among dislocations and the friction stress due to the short-range interaction between a dislocation and the lattice, respectively. At high-temperature, σ^{F} is, in general, very small as compared to σ^{I}, and the internal-strain rate $\dot{a}$ is considered zero for load-relaxation tests performed under steady-state conditions because the amount of dislocations accumulated is almost identical to that of dislocations emitted through obstacle. Experimentally, the steady-state is defined as the strain level which shows steady-state flow stress.

Therefore, it is sufficient to describe the constitutive relation at high temperature by $\dot{\alpha}$ and $\dot{g}$ elements (Fig. 1).

The constitutive relation for the plastic strain rate $\dot{\alpha}$ can be formulated as a kinetic equation for the mechanical activation process of the leading dislocation by the internal stress. For uniaxial tension, the scalar relation is expressed in the form similar to that suggested by Hart [21], i.e.:

$$\frac{\sigma_{\alpha}^{*}}{\sigma^{\mathrm{I}}} = \exp\left(\frac{\dot{\alpha}^{*}}{\dot{\alpha}}\right)^{p} \tag{3}$$

$$\dot{\alpha}^{*} = \nu^{\mathrm{I}}\left(\frac{\sigma_{\alpha}^{*}}{G}\right)^{n^{\mathrm{I}}} \exp\left(-\frac{Q_{\alpha}^{\mathrm{I}}}{RT}\right), \tag{4}$$

in which p and n^{I} are material constants, and σ_{α}^{*} and $\dot{\alpha}^{*}$ denote the internal-strength variable and its conjugate reference strain rate, respectively. Eq. (4) represents an activation relation for dislocations at grain boundaries, with ν^{I} denoting jump frequency, Q_{α}^{I} activation energy, and G an internal modulus.

GBS can be represented as stress-induced viscous flow under a frictional drag and permanent process like plastic stain (α). Thus, the following scalar relation between the applied stress and the GBS rate can be derived:

$$\frac{\dot{g}}{\dot{g}_{0}} = \left[\frac{\sigma - \Sigma_{\mathrm{g}}}{\Sigma_{\mathrm{g}}}\right]^{1/M_{\mathrm{g}}} \tag{5}$$

$$\dot{g}_{0} = \nu^{\mathrm{g}}\left(\frac{\Sigma_{\mathrm{g}}}{\mu^{\mathrm{g}}}\right)^{n^{\mathrm{g}}} \exp\left(-\frac{Q^{\mathrm{g}}}{RT}\right). \tag{6}$$

in which M_{g} and n^{g} are the material constants, and Σ_{g} and $\dot{g}_{0}$ are the static friction stress and its conjugate reference rate for GBS, respectively. Eq. (6) also represents a thermally activated process of GBS, with Q^{g} denoting the activation energy for GBS.

3. Materials and experimental procedure

3.1. Materials

Three different titanium alloys were used in the present work to quantify the boundary strength and friction stress of each grain- or phase-boundary (i.e., α–α or α–β) on constitutive response at elevated temperatures. One was plate material of Ti–6Al–4V received from VSMPO Corporation, Russia; its chemical composition (in wt.%) was Ti–6.3Al–4.1V–0.21Fe–