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The construction of constitutive model and identification of dynamic softening mechanism of high-temperature deformation of Ti–5Al–5Mo–5V–1Cr–1Fe alloy

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ABSTRACT

The high-temperature deformation behaviors of Ti–5Al–5Mo–5V–1Cr–1Fe alloy were investigated through the isothermal compression experiment. The dislocation evolution in the working-hardening stage has been analyzed and the corresponding constitutive model has been constructed. The dynamic softening mechanism has been identified with the relationship between the saturated dislocation density and dynamic recrystallization (DRX) critical density. The dependence on deformation parameters has been discussed and a concept of critical strain rate $\dot{\varepsilon}_C$ has been proposed. A dynamic softening map has been designed to predict the corresponding softening behaviors under certain deformation conditions. The constitutive model based on dislocation evolution has been extended to overall deformation incorporating dynamic softening behaviors and their deviations have been explained by introducing the processing map.

1. Introduction

Ti55511 (Ti–5Al–5Mo–5V–1Cr–1Fe) is a type of near-β titanium alloy that possesses excellent mechanical properties, especially the high strength after annealing treatment, which ranks as one of the highest titanium alloys. Therefore, Ti55511 has been widely utilized to fabricate load-bearing parts in the aerospace industry like aircraft landing gears [1].

It is well-known that titanium alloys are more difficult to fabricate than other metallic materials owing to their high deformation resistance and strong sensitivity to processing parameters, such as strain ε, strain rate $\dot{\varepsilon}$ and deformation temperature T. The thermo-mechanical coupling processing has been considered as the suitable method to manufacture titanium components with desired properties because the deformation resistance always decreases with elevated temperature and required microstructures could be controlled by introducing the suitable microstructural evolution, such as dynamic recrystallization or dynamic recovery (DRV) process [2]. The constitutive relationship reflects the response of deformed materials to deformation parameters and dynamic softening behaviors determine the microstructural evolution during hot deformation. Therefore, the correlation between constitutive relationship and dynamic softening behaviors is of fundamental and technological importance in deformation mechanism research and parameter optimization.

Considerable research has been carried out on the constitutive relationship and dynamic softening mechanism for the high-temperature deformation of metal materials. Seshacharyulu et al. [3] investigated the hot deformation mechanism in extra-low interstitial (ELI) grade Ti–6Al–4V alloy and associated the thermal activation constitutive model with the processing map to analyze the globularization of the Widmanstatten microstructure. Chen et al. [4] studied dynamic recrystallization behaviors of a typical nickel-based superalloy. The recrystallized volume fraction has been estimated based on the conventional DRX kinetics model and the recrystallized grain evolution has been associated with the Zener–Hollomon parameter in the constitutive model. Momeni et al. [5] analyzed thermodynamic mechanism of subgrain expansion and shrinking at the onset of discontinuous dynamic recrystallization (DDRX) and a physical model has been proposed to describe constitutive relationship and predict DRX critical condition during hot deformation of austenitic stainless steel. Sha and Savko [6] investigated the dislocation evolution influenced by DRX during hot deformation of Ti–6Al–4V alloy and the microstructural evolution and corresponding flow characteristics have been simulated through cellular automation (CA). Poliak and Jonas [7] interpreted the critical condition of DRX according to the irreversible thermodynamics and proposed that the minimum points of

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$-\partial\theta/\partial\sigma$ curves ($\theta \equiv \partial\sigma/\partial\varepsilon$) correspond to the onset of DRX. Lin et al. [8,9] proposed a revised constitutive model to describe the relationships between flow stress, strain rate and temperature of 42CrMo steel at elevated temperatures by compensation of strain and strain rate. The static recrystallization (SRX) and metadynamic recrystallization (MDRX) behaviors have been investigated through the microstructure observation. Zhang et al. [10] combined the Arrhenius constitutive equation with the change rate of working-hardening rate ($-\partial\theta/\partial\sigma$) to investigate the high-temperature deformation behaviors of martensitic heat resistant steel and the working-hardening (WH) process; dynamic recovery, dynamic strain induced transformation (DSIT), and dynamic recrystallization have been determined by introducing the Zener–Hollomon parameter.

In this study, the high-temperature deformation behaviors of Ti–5Al–5Mo–5V–1Cr–1Fe alloy were investigated through the isothermal compression experiment. The dislocation evolution during working-hardening stage was analyzed and the corresponding constitutive model has been constructed. Dynamic softening behaviors have been identified with the relationship between the saturated dislocation density and DRX critical density and the dependence on deformation parameters has been discussed. The dynamic softening map has been designed to distinguish the dynamic softening mechanism under certain deformation conditions. Typical deformed microstructures of Ti–5Al–5Mo–5V–1Cr–1Fe alloy and power dissipation efficiency maps have been obtained to verify the identified softening mechanism. With the dynamic softening mechanism identified, the constitutive model based on dislocation evolution has been extended to overall deformation and their deviations have been explained by introducing the processing map.

2. Materials and experimental procedures

The chemical compositions (wt%) of the studied titanium alloy in the present study are as follows: Al 5.15, Mo 4.96, V 4.75, Cr 0.95, Fe 1.04, and Ti bal. The α/β transus temperature of the studied Ti–5Al–5Mo–5V–1Cr–1Fe alloy has been measured as 885 °C by using the metallographic observation method. Material parameters used in this article have been given in Table 1.

The cylindrical specimens with a diameter of 8 mm and a height of 12 mm were machined from the wrought billet. Fig. 1 shows the original microstructure of the studied titanium alloy before compression. It could be observed that the original microstructure consisted of equiaxed α grains uniformly distributing in the β matrix. The isothermal compression experiment was performed on a Gleeble-1500D thermo-mechanical simulator. Six different forming temperatures (800, 820, 840, 860, 880 and 900 °C) and six different strain rates (0.0005, 0.001, 0.01, 0.1, 1 and 10 s^{-1}) were utilized and the final deformation degree was 80%. In order to reduce friction and avoid adhesion, the tantalum foil with a thickness of 0.1 mm was used between the specimens and dies. The stress–strain data were automatically recorded by the testing system during compression. The true stress–strain ($\sigma-\varepsilon$) curves, after modifying the temperature rise, have been shown in Fig. 2. The specimens were immediately quenched by cold water to reserve deformed microstructures after each experiment. Then the deformed specimens were sliced along the compression axis section for microstructural analysis. After polished mechanically and etched in Kroll's reagent, the exposed surfaces were observed by an OLYMPUS-PMG3 optical microscope.

Table 1
Material parameters of Ti–5Al–5Mo–5V–1Cr–1Fe alloy used in this article.

Parameters	Physical meanings	Values
μ (GPa)	Shear modulus	49
υ	Poisson's ratio	0.33
b (m^{-1})[a]	Burgers vector	2.95×10^{-10}
δ (m)	Boundary thickness	3.6×10^{-16}
D_{0b} (m^2/s)	Diffusion coefficient at 0 K	
Q_{diffu} (kJ/mol)[a]	Self-diffusion activation energy	97×10^3

[a] Taken from the values of β titanium because Ti55511 is a near-β alloy.

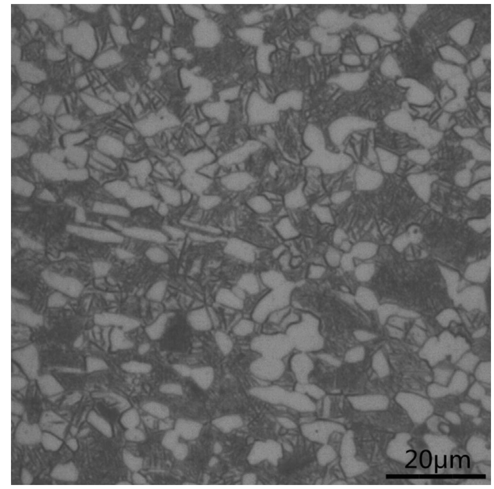

Fig. 1. Optical micrograph of the as-received Ti–5Al–5Mo–5V–1Cr–1Fe titanium alloy.

3. Modeling and analysis

3.1. Dislocation evolution and constitutive model

The evolution of dislocation density during hot deformation has been considered as a complex process controlled by dislocation multiplication and annihilation and can be assumed to be the sum of two independent terms [11]

$$\frac{d\rho}{d\varepsilon} = \left(\frac{d\rho}{d\varepsilon}\right)_+ - \left(\frac{d\rho}{d\varepsilon}\right)_- \quad (1)$$

where the first term represents the contribution of working hardening due to dislocation generation and the interaction with existing ones. The second term represents the influence of dynamic softening process caused by dislocation cancellation and rearrangement, such as dynamic recovery and dynamic recrystallization mechanism.

In the initial stage of deformation process, with the obstacles, such as dislocation forests and cellulars, not formed in the glide plane, the free path that dislocations can move is proportional to $\rho^{-1/2}$ [12]. Under this condition, a model proposed by Kocks and Mecking (K–M) could be employed to describe the dislocation evolution of the WH stage as follows [13]:

$$\frac{d\rho}{d\varepsilon} = k_1\sqrt{\rho} - k_2\rho \quad (2)$$

k_1 is a constant related to material's structural and mechanical characteristics, which determines the generation rate of dislocation density. k_1 can be calculated by [14]

$$k_1 = \frac{2\theta_{II}}{\alpha G b} \quad (3)$$

where α represents the Taylor constant equal to 0.5, θ_{II} is the slope of flow stress curve in stage II (θ_{II}–$G/200$), G is the shear modulus and b is the Burgers vector. k_2 describes the dislocation annihilation rate. Dislocation cancellation and arrangement is established through dislocation gliding, climbing and cross-slipping under