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Unified modeling of flow softening and globularization for hot working of two-phase titanium alloy with a lamellar colony microstructure

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ABSTRACT

In this paper, a set of physically based constitutive model coupling microstructure evolution was developed for unified prediction of flow stress and globularization evolution during hot working of two-phase titanium alloys with initial lamellar microstructure. The dislocation density variation, dynamic globularization and effect of Hall–Petch strengthening were considered in the microstructure model. The dynamic globularization was modeled by two parts: critical strain for initiation of globularization and globularization rate, both of which are function of processing conditions (temperature and strain rate); In the modeling of Hall–Petch strengthening, the dependence of Hall–Petch coefficient on processing conditions were considered and the loss of Hall–Petch strengthening with deformation process was molded. The microstructure model was implemented to a physically based constitutive model, composed of a thermally activated stress and an athermal stress, to realize the unified prediction of flow stress and globularization evolution. The material parameters were determined by calibration using the experimental flow stress and globularization fraction in isothermal compression tests through the genetic algorithm based optimization method. Based on the set of constitutive models, flow stress and globularization evolution of Ti–6Al–4V and TA15 alloys at different temperatures and strain rates were predicted. Good agreements between the experimental and computed results were obtained.

1. Introduction

Two-phase titanium alloys have been widely used to manufacture structural components in aerospace industry due to their excellent properties such as high specific strength, good thermal stability and welding performance [1]. In order to obtain desired microstructure thus getting attractive mechanical properties, the thermomechanical processing (TMP) involving a series of steps, each of which has specific microstructural goal, is usually used in the manufacture of conventional two-phase titanium alloy components. Primary hot working to produce a uniformly wrought microstructure is usually conducted in the β-phase region producing a lamellar microstructure (transformed microstructure). Although such microstructure presents high strength and fatigue crack growth resistance, the equiaxed or globular microstructure possessing a better balance of strength and ductility is often desirable for many service applications. In this regard, lamellar structure is typically broken down to obtain the desired equiaxed one through subtransus processing [2–5]. This process, commonly referred to as globularization, plays a key role in the microstructure tailoring of two-phase titanium alloys. However, the dynamic microstructure changes (such as recovery and dynamic globularization) are strongly sensitive to the processing conditions and initial microstructure. These have great influence on the deformation behavior during processing as well as the mechanical properties after deformation. Therefore, modeling the relationship among microstructure development, plastic flow and processing conditions is of significant importance to understanding the deformation behavior in depth and controlling the microstructure evolution in globularization process of titanium alloys with lamellar microstructure.

Due to its great importance in microstructure control, the globularization process of lamellar microstructure to obtain an equiaxed one has been received considerable attention. The majority of these researches have focused on the mechanisms of globularization and flow behavior during deformation [4–10]. For example, Semiatin et al. [5] investigated the dynamic globularization evolution of Ti–6Al–4V during hot working, and analyzed the strains required for initiation and completion of dynamic globularization. Shell and Semiatin [6] studied the effect of initial microstructures with different alpha plate thicknesses on dynamic globularization behavior of Ti–6Al–4V alloy. Miller et al. [7] and Semiatin and Bieler [8] studied the flow behavior

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and its dependence on the alpha platelet thickness during hot working of Ti–6Al–4V alloy with lamellar microstructure. However, limited works have been conducted on the modeling of globularization and flow stress during hot working of titanium alloys with lamellar microstructure. It has been reported that the globularization initiates at a critical strain and the globularization fraction increases with strain in a sigmoid way, thus the Avrami-type equation is often employed to depict the variation of globularization fraction with strain [11–14]. However, the critical strain and globularization are both greatly affected by processing conditions (such as temperature and strain rate) and initial microstructure. There is still a lack of general relationship between the critical strain, kinetics parameters in Avrami equation and processing conditions. Moreover, the Avrami-type description of globularization evolution in these works is independent with the flow behavior during deformation. For the prediction of plastic flow behavior, the empirical and semi-empirical regression models such as Arrhenius-type equation [15] and artificial neural network (ANN) [15,16] have been applied to model the flow behavior for lamellar starting microstructure. However, they offer less physical insight and cannot depict the coupling effect between plastic deformation and microstructure evolution. The physically-based internal state variable method, which can relate the mechanical properties of a material to its microstructure and deformation mechanism, provides a feasible way to predict the constitutive behavior and dynamic microstructure development simultaneously in hot working of metals [17–22]. However, most of these works have concerned on the hot deformation of titanium alloys with equiaxed microstructure, where dynamic globularization was not the primary microstructural phenomenon. Recently, Babu and Lindgren [23] proposed a physically founded constitutive model based on the evolution of immobile dislocation density and excess vacancy concentration for plastic deformation and globularization of Ti–6Al–4V alloy. Bai et al. [24] developed a set of mechanism-based unified elastic–viscoplastic constitutive equations to model the flow behavior of Ti–6Al–4V alloy with equiaxed microstructure, in which the flow softening caused by globularization of secondary (lamellar) alpha phase was considered. However, the initial microstructures in above two works are both a bi-modal structure with primary alpha surrounded by transformed beta (Widmanstätten structure), which is quite different from the lamellar colony microstructure. In addition, the globularization in [23] indicates the grains getting more globular caused by dynamic and static coarsening, which is similar to the globular process through coarsening in static globularization but is essentially different with the dynamic globularization of lamellar microstructure during hot deformation in physical mechanism. Thus, further work is still needed to develop mechanism-based integrated constitutive model coupling dynamic globularization model for unified prediction of flow stress and globularization evolution in hot working of two-phase titanium alloys with initial lamellar microstructure.

In this paper, a set of mechanism-based unified constitutive model coupling the globularization evolution for hot working of titanium alloys with lamellar microstructure was developed using internal state variable method. Section 2 describes the model in two aspects: constitutive modeling and microstructure modeling. The dynamic globularization and Hall–Petch strengthening were molded in the microstructure model. Applications of the unified constitutive model in two titanium alloys (Ti–6Al–4V and TA15 alloys) were given in Section 3. The results show that the integrated model developed in this paper can realize the unified prediction of flow stress and globularization during hot working of two-phase titanium alloys with initial lamellar microstructure.

2. Model description

2.1. Constitutive modeling

The flow stress model is formulated on a material volume which represents the average behavior of a large number of grains, dislocations, etc. Plastic deformation is assumed to be isotropic in this paper. The overall flow stress of a polycrystal can be expressed by [21]:

$$\sigma = M\tau \tag{1}$$

where M is the average Taylor factor of the order of 3, and the shear stress τ is computed using Taylor's assumption by which the different mechanisms act in parallel, contributing to stress separately. The total shear stress is assumed to consist of two parts [19,21],

$$\tau = \tau^* + \tau_\mu \tag{2}$$

where τ^* is the thermally activated stress needed to move dislocations through the lattice and to pass short-range obstacles. τ_μ is the athermal stress contribution from the long-range effect such as the stress field of dislocation forests and grain boundaries [21,23,25].

The thermally activated stress τ^* is given by:

$$\tau^* = \tau^0\left[1 - \left(\frac{RT}{\Delta G}\ln\frac{\dot{\varepsilon}_{ref}}{\dot{\varepsilon}^p}\right)^{1/q}\right]^{1/p} \tag{3}$$

where τ^0 is the mechanical threshold stress, or the value of the thermal stress at 0 K, ΔG is the activation energy for deformation, R is the gas constant (8.3145 KJ/mol), $\dot{\varepsilon}_{ref}$ and $\dot{\varepsilon}^p$ is the reference strain rate and applied plastic strain rate, p and q are material constants. This term represents the dependence of flow stress on temperature and strain rate. The athermal term τ_μ captures the strain hardening and grain boundary strengthening, which is given below:

$$\tau_\mu = \alpha G b\sqrt{\rho} + K_{HP}\ell^{-1/2} \tag{4}$$

where G is the shear modulus, b is the Burgers vector magnitude (2.95×10^{-10} m), ρ is the dislocation density and α is material constants. The second term in Eq. (4) is the standard Hall–Petch term, which models the slip resistance due to the barrier effect of grain boundaries, where K_{HP} is the Hall–Petch coefficient, and ℓ is the average alpha plate thickness in this paper. The Hall–Petch coefficient is dependent on microstructural phenomena, such as dislocation pileups, stress concentrations and grain boundary sources, and varies with processing conditions [8,26]. The form of K_{HP} will be discussed in Section 2.2.

2.2. Microstructure modeling

It is well known that during hot working of metals and alloys, working hardening leads to the accumulation of dislocation, while dynamic recovery annihilates dislocations. As early as 1970s, some researchers have made initial attempts to develop dislocation density based models for metal plasticity [23,27]. Bergström [28,29], Bergström and Roberts [30] developed several basic dislocation models to describe the variation of dislocation density. At about the same period, similar ideas were independently exploited by Kocks [31,32]. These models all have similar basic assumptions and ideas about dislocation density evolution processes, which basically consist of storage and recovery. Based on these initial models, Kocks and Mecking [33] developed a model (KM model) to predict the variation of dislocation density considering the working hardening and dynamic recovery, which is used in this paper and can be expressed as:

$$\frac{d\rho}{d\varepsilon^p} = k_1\sqrt{\rho} - k_2\rho \tag{5}$$