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Prediction of constitutive behavior and microstructure evolution in hot deformation of TA15 titanium alloy

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ABSTRACT

A set of constitutive equations coupling microstructure evolution have been developed for hot working of a TA15 titanium alloy. Physically-based microstructure models were established for constituent phases of the material, which considered dislocation density variation, static coarsening, dynamic coarsening and strain induced grain refinement. The loss of Hall–Petch strengthening was modeled with aim to predict the flow softening. For each constituent phase, the microstructure model was implemented into a constitutive model for integrated prediction of flow stress and microstructure evolution. A visco-plastic self-consistent scheme was adopted to characterize the deformation heterogeneity from phase to phase and to predict the overall behavior of the aggregate. Model predictions, including flow stress, volume fraction and grain size of each phase, are in good agreement with experimental observations.

1. Introduction

TA15 (Ti–6Al–2Zr–1Mo–1V), a near-alpha titanium alloy with moderate room-temperature and high-temperature strength, good thermal stability and welding performance, is widely used to manufacture structure components in aeroplanes. Hot forging is the most important processing route of such alloy. During high temperature deformation of titanium alloys, significant microstructural developments may take place. Thus, hot forging changes the mechanical properties of the workpiece along with the shape. It has been recognized that by proper thermo-mechanical processing, not only the desired shape can be obtained, but also the service performance can be enhanced. Nowadays, numerical simulation, such as finite element analysis, has become an important method to optimize the hot forging process. The numerical model should accurately predict the macroscopic deformation as well as the microstructural evolution to tailor the service performance. To this end, it is necessary to develop constitutive model which quantifies the constitutive behavior and microstructural development of the material.

High temperature deformation of titanium alloys is known as a thermally-activated process. Thus, the flow stress is often predicted by the Arrhenius type of equations in Eq. (1) (e.g. [1–5]). This kind of constitutive models link the flow stress and processing parameters explicitly. However, they cannot depict the coupling effect between plastic deformation and microstructure evolution.

$$\dot{\varepsilon} = f(\sigma)\exp(-Q/RT) \tag{1}$$

Based on the extensive data obtained in experiment, the statistical models (such as the artificial neural networks) are also employed to predict the flow stress and microstructure evolution in hot deformation of titanium alloys (e.g. [6]). These models exhibit good accuracy, since they can handle the strong non-linearity between inputs and outputs. However, the statistical models offer no physical insights, and are not suitable for processes with complex history.

With further understanding of the deformation process, it is possible to establish models based on the underlying mechanism. The physically-based internal state variable methods, which describe the underlying phenomena in terms of a small number of internal state variables, have gained increasing applications in hot deformation. However, the TA15 alloy is composed of hcp alpha phase and bcc beta phase at the deformation temperatures. The two constituent phases have different properties and undergo different microstructural evolution. Besides, there may exist interaction between the two phases. Thus, accurate prediction of constitutive behavior and microstructure evolution is difficult. In recent years, efforts have been done on modeling the high temperature deformation of titanium alloys with the internal state variable method. Lin and Dean [7] developed a set of unified visco-plastic constitutive equations to predict the superplastic deformation of Ti–6Al–4V alloy, in which grain growth induced hardening is considered. However, the microstructure evolution in superplastic deformation is quite different from that in traditional hot deformation process. Zhou [8] used internal variables to characterize recrystallization induced flow softening, and successfully predict

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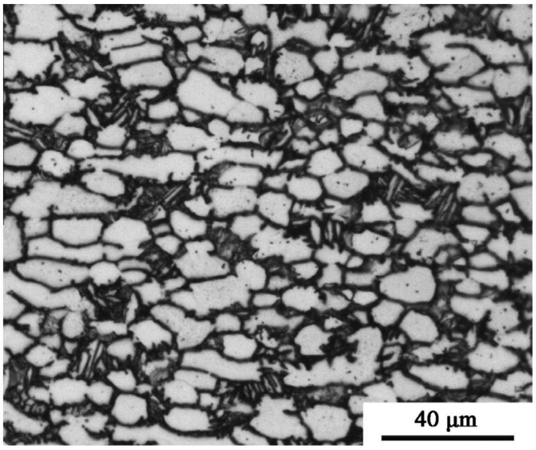

Fig. 1. Microstructure of the as-received material.

the stress–strain behavior of IMI834 alloy. However, the material heterogeneity was neglected, which oversimplifies the microstructure evolution. Picu and Majorell [9] modeled the constitutive behavior of Ti–6Al–4V alloy based on the mechanical property and microstructure evolution of each constituent phase. A similar approach was also taken by Li and Li [10] and Luo et al. [11]. These models assumed uniform strain from phase to phase, which neglected the deformation heterogeneity. A previous work by the authors [12] implemented the internal state variable method into visco-plastic self-consistent scheme to model the complex deformation behavior and microstructure evolution of two-phase titanium alloys. However, the microstructural development in alpha phase was not involved.

In the present work, isothermal compression test and quantitative metallography were employed to reveal the influence of processing conditions on microstructure parameters and the underlying mechanism. Based on the above experimental results, integrated constitutive equations were developed for each constituent phase. The constitutive equations were implemented into self-consistent scheme to predict the overall response of the material. Material constants are determined by the optimization technique.

2. Material and experiment

The material employed in the current study is a near-α TA15 titanium alloy with the chemical composition (wt.%) of 6.06 Al, 2.08 Mo, 1.32 V, 1.86 Zr, 0.30 Fe and balanced Ti, and measured β-transus temperature of 1263 K. The microstructure of the as-received material consisted of approximately 60% primary α phases within the transformed β matrix, as shown in Fig. 1.

To study the deformation behavior and microstructure evolution, cylindrical specimens of 15 mm in height and 10 mm in diameter were machined from the as-received material. Isothermal compression tests were conducted on a Gleeble-3500 thermal simulator. A thin graphite layer was placed between the specimen and die to minimize friction. The specimens were heated to the deformation temperature at a rate of 10 K/s, held for 3 min to impart thermal equilibration. The compression tests were performed at temperatures of 1133–1253 K, and strain rates of 0.001–1 s^{-1}. After the deformation, the specimens were immediately cooled to retain the deformed structure.

After the compression tests, the specimens were sectioned along the compression axis, mechanically grinded and polished, and etched with a solution of 13%HNO_3, 7%HF and 80%H_2O. Microstructural examination was performed on a LECIA DMI3000 microscope. The microstructural parameters were measured manually based on ASTM: E 112-12. For a constituent phase, the grain boundaries were picked up manually, such that each grain in the image was identified. The volume fraction of alpha phase is the area of all alpha grains divided by the total area of the image. The size of a single grain is measured to be the average length of diameters measured at 2° intervals and passing through the grain's centroid, and the aspect is the ratio between major axis and minor axis of ellipse equivalent to grain. The grain size and aspect of each phase was the average value of all grains.

3. Experimental results

The microstructure of the TA15 titanium alloy is sensitive to processing. Different kinds of microstructure morphology can be obtained under different thermo-mechanical processing routes (Fig. 2). For initially equiaxed structure, equiaxed structure or bimodal structure can be produced at temperatures below the beta transus (Fig. 2a and b). Both are composed of equiaxed alpha phases and transformed beta matrix, though the volume fraction of transformed beta is much higher in the bimodal structure, as the heating temperature is higher. The lamellar structure, which is composed of secondary alpha platelets within originally large beta grains, can be obtained at temperatures above the beta transus (Fig. 2c). In most cases, equiaxed or bimodal structures are required. Thus, only the subtransus hot working is investigated in the present work. The subtransus deformation mechanism of the TA15 alloy has been studied in a previous work [13]. It was found that the flow stress was sensitive to temperature and strain rate. For a single stress–strain curve, the flow stress reached its peak at a low strain and then decreased with further deformation. Microscopically, the initial microstructure was composed of primary equiaxed alpha phases and beta matrix in the current temperature range. Dynamic recovery was the main softening mechanism of the alpha phase, while dynamic recrystallization occurred in beta phase besides recovery [13].

The effect of deformation conditions on deformed microstructure was determined by quantitative metallography, as shown in Fig. 3. The volume fraction of primary alpha phases was determined by the deformation temperature, and close to that prior to deformation (Fig. 3a). The volume fraction would decrease at higher strain rate and larger strain, which was due to deformation heating. The variation of alpha grain size was illustrated in Fig. 3b. The alpha grain size decreased after deformation. For many metallic materials, dynamic recrystallization leads to significant grain refinement. However, dynamic recrystallization was not observed in alpha phase. Thus, it cannot account for the grain refinement in the present work. Alternatively, it was found that the imposed deformation may break down the microstructure dynamically [11,14]. The refinement of microstructure was more significant at large strains [14], which is in accordance with the present work. Therefore, strain-induced grain refinement was an important phenomenon occurred in alpha phase. The beta grain size after deformation, however, was more related to the deformation temperature than to other deformation parameters. The beta grain size increased with deformation temperature. For single phase material involving dynamic recrystallization, the recrystallized grain size is a function of Zenner–Hollomon parameter ($Z = \dot{\varepsilon}\exp(Q/RT)$ in which Q is the deformation activation energy and R is the gas constant). The recrystallized grain size decreases with Z, i.e., grain refinement is more significant at low temperature and high strain rate. However, in subtransus hot deformation of titanium alloys, the recrystallized grain size no longer depends on Z, as reported by Vo et al. [15]. In fact, the beta grain size was determined by the inter-particle spacing of alpha phase which were greatly influenced by the deformation temperature.