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Unified modeling of work hardening and flow softening in two-phase titanium alloys considering microstructure evolution in thermomechanical processes

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ABSTRACT

One of the most critical aspects in understanding the deformation behavior of two-phase titanium alloys subjected to thermomechanical processes (TMPs) lies in being able to describe the flow stress accurately. To this end, in this study, initially, hot tension tests were conducted on a two-phase Ti-6Al-2Zr-1Mo-1V alloy. It was observed that the flow stress at a given temperature and strain rate exhibits work hardening, followed by flow softening. Flow softening occurs at the peak strain, where the maximum stress is observed; peak strain decreases with increasing temperature and decreasing strain rate. Variations in peak strain are more obvious at low temperatures and high strain rates. Later, the microstructure of the alloy was analyzed and the results show that work hardening and flow softening are caused by dynamic recrystallization (DRX). The DRX volume fraction was found to exhibit an increasing trend and discontinuous dynamic recrystallization (DDRX) was observed at increasing temperature and decreasing strain rate. With respect to microstructure evolution, a unified model consisting of a thermally activated stress component and an athermal stress component was developed. In the athermal stress term, dislocation density and the Hall-Petch effect were used to describe the work-hardening and flow-softening behavior. In the case of the dislocation term, the DRX effects were modeled considering the critical strain for DRX initiation and the DRX rate, which are both temperature-and strain rate-dependent. In the Hall-Petch effect term, the dependence of the Hall-Petch coefficient on the processing conditions was considered and the loss of Hall-Petch strengthening with deformation was modeled. Using the proposed model, the work-hardening and flow-softening behavior and microstructure evolution in Ti-6Al-2Zr-1Mo-1V alloys subjected to TMP were predicted. A good agreement could be observed between the experimental and predicted results. This study provides a solution for modeling work-hardening and flow-softening behavior and helps us understand the deformation behavior of two-phase titanium alloys subjected to TMP.

1. Introduction

Two-phase titanium alloys are widely used to manufacture structural components in aerospace and aviation industries because of their good thermal stability and welding ability [1–3]. Generally, due to the poor formability of titanium alloys at room temperature, they are manufactured using thermomechanical processes (TMPs) [4]. During the TMP of two-phase titanium alloys, the process conditions (viz., deformation degree, strain rate, and temperature) affect microstructure evolution (phase transformation, lamellar globalization, grain coarsening, and recrystallization nuclei and their growth) [5–8]. Depending on their microstructure, titanium alloys exhibit different flow behaviors, which in turn affect the deformation behavior of the alloys during TMP [9,10]. Therefore, to better understand the deformation behavior of two-phase titanium alloys during TMP, modeling their flow behavior, while taking the microstructure evolution into account, is necessary.

With regard to their importance in controlling the deformation behavior, the microstructure evolution and flow behavior of two-phase titanium alloys subjected to TMP have been investigated by

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many researchers in the past. For the two-phase titanium alloys with different initial microstructures, Semiatin et al. conducted several investigations to study the dynamic recrystallization (DRX) and globularization behaviors [11–14]. Liu et al. [15] investigated Ti-6Al-2Zr-1Mo-1V (TA15) alloys with an initially equiaxed microstructure during TMP and observed the occurrence of DRX. Poorganji et al. [16] investigated the initial microstructure effects of two-phase titanium alloys on DRX. They observed that refining the interlamellar spacing and colony size of the (α + β) lamellar structure by quenching after β-solution formation promotes DRX and the formation of an ultrafine-grained α structure. He et al. [17] analyzed the effects of temperature, strain rate, and strain on the DRX behavior of TA15 alloys and found that discontinuous dynamic recrystallization (DDRX) occurs at high temperatures and low strain rates. Considering the microstructure evolutions in two-phase titanium alloys, their flow behavior during TMP was also investigated. Semiatin et al. observed the flow softening behaviors in the TMP [11–14]. Yang et al. [18] investigated the tensile flow behavior of TA15 alloys at elevated temperatures. They observed that the flow stress initially increased to a maximum value (peak), which was termed as work hardening. After this peak value, the flow stress dropped slowly due to flow softening caused by DRX. Zhang et al. [19] observed the flow behavior of TC4 with different initial microstructures and found that flow stress exhibits work-hardening and flow-softening behavior due to the occurrence of DRX. Xiao et al. [20] analyzed the effects of temperature and strain rate on the work hardening and flow softening of a TC4 alloy. They observed that with increasing temperature and decreasing strain rate, the work-hardening stage decreased. These reports suggest that the flow stress of two-phase titanium alloys subjected to TMP mainly exhibits work hardening and flow softening, which vary with the processing conditions. Thus, to describe flow stress accurately, the work-hardening and flow-softening behavior needs to be analyzed accurately.

Thus far, much work has been done on the constitutive modeling of titanium alloys subjected to TMP. Quan et al. [21] predicted the flow stress of TA15 alloys using a BP neural network method based on compression tests. Their results indicated a very good correlation between the experimental and predicted flow stress values, including work hardening and flow softening. Yuan et al. [22] investigated the hot compression behavior of TC4 alloys and established a constitutive model using multiple nonlinear regressions, while considering work hardening and flow softening. Xiao et al. [20] conducted hot tensile tests on TC4 alloys and used an Arrhenius-type model to characterize work hardening and flow softening. Kotkunde et al. [23] conducted a comparative study on modified Johnson-Cook and Arrhenius-type constitutive models to predict the flow behavior of TC alloys at elevated temperatures. The results showed that the Arrhenius-type model fared better in predicting the work-hardening and flow-softening behavior. Clearly, all the above-described models are either empirical or semi-empirical and could accurately predict the work-hardening and flow-softening behavior of two-phase titanium alloys subjected to TMP. However, they offer less physical insight and cannot depict the coupling effect between flow stress and microstructure evolution.

In contrast to empirical and semi-empirical models, physical property-based internal state variable methods provide a feasible way to predict the flow stress and microstructure simultaneously for two-phase titanium alloys subjected to TMP [24]. For example, Luo et al. [25] developed an internal state variable (ISV) model to describe the flow behavior of TC4 alloys during TMP by coupling the grain size, volume fraction, and dislocation density. Fan et al. [26] developed an ISV model to predict the flow behavior of each individual phase in TA15 alloys, which exhibit DRX under hot-working conditions. Gao et al. [27] developed a set of physical property-based constitutive models to predict the flow stress and globularization during the hot working of two-phase titanium alloys with initial lamellar microstructures. However, in these models, only the flow-softening behavior was predicted, while the work-hardening behavior was neglected. Besides this, the existing models were established based on compression tests, which are mainly used for TMPs under compression. While for the TMPs under tension, like sheet metal forming process, the existing models might not be suitable as the flow behavior and microstructure evolution are quite different between compression and tension [17,18,20]. Thus, to describe the flow stress accurately under different deformation conditions, further work is needed to develop a physical property-based constitutive model that can describe both the work-hardening and flow-softening trends in tension-dominated TMP.

To this end, a unified constitutive model, which can predict the work-hardening and flow-softening behavior of two-phase titanium alloys during TMP, was established in this study after taking the microstructure evolution into account. Firstly, hot tension tests were conducted on a two-phase titanium alloy to investigate its work-hardening and flow-softening behavior and microstructure evolution. Later, on the basis of microstructure evolution, a set of unified constitutive equations that can capture the work-hardening and flow-softening behavior was developed. Finally, the ability of the developed model to describe the work-hardening and flow-softening behavior and microstructure evolution was validated.

2. Experimental

In the present study, a two-phase TA15 alloy received from Baotai Group Co., Ltd. in the form of round bar was used. The chemical composition of the titanium alloy is listed in Table 1. The microstructure of the as-received alloy consists of an equiaxed primary phase within a transformed β phase (secondary α phase and β phase), as shown in Fig. 1. The transformation temperature of the α/β phase is 1263 K [28].

Isothermal hot tension tests were conducted on a SANS CMT 5205 electrical test machine equipped with a furnace (temperature

Table 1
Chemical composition of the Ti-6Al-2Zr-1Mo-1V alloy used in this study.

Element	Ti	Al	Mo	Zr	V	Fe	Impurity
Content (wt.%)	Matrix	6.1–6.5	0.9–1.2	1.9–2.2	0.8–1.3	0.25	<0.3

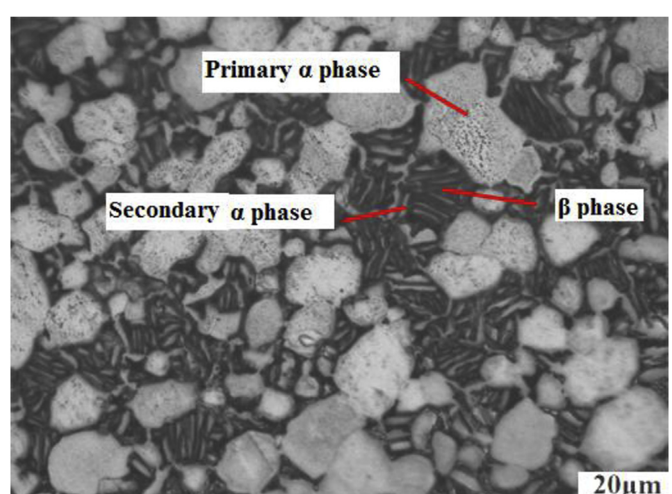

Fig. 1. Initial microstructure of the TA15 alloy.