



Strain rate sensitivity and strain hardening exponent during the isothermal compression of Ti60 alloy

J. Luo*, M.Q. Li

School of Materials Science and Engineering, Northwestern Polytechnical University, Xi'an 710072, PR China

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ABSTRACT

In this paper, the flow stress was investigated in detail during the isothermal compression of Ti60 alloy. The strain rate sensitivity and the strain hardening exponent of Ti60 alloy were calculated based on the flow stress–strain curves. The results showed that the softening effect in the $\alpha + \beta$ two-phase region was more significant than that in the β single-phase region due to the change in the deformation heat of the alloy. An initial yield drop was observed at or above 1273 K and in the strain rate range of $0.1\text{--}10.0\text{ s}^{-1}$. The β phase became the continuous phase above 1273 K, which led to little temperature dependence of flow stress. The maximum m value of 0.34 occurred at 1253 K and a strain rate of 0.001 s^{-1} during the isothermal compression of Ti60 alloy. The strain rate sensitivity at a strain of 0.7 and a strain rate of 10.0 s^{-1} decreased with increasing deformation temperature after a peak value. And the m values decreased with increasing strain rate. This phenomenon could be reasonably explained based on the microstructure evolution during the isothermal compression of Ti60 alloy. The strain hardening exponent increased with increasing deformation temperature at the strain rates of 0.001 s^{-1} , 1.0 s^{-1} and 10.0 s^{-1} . The variation of strain hardening exponent with strain was observed to be dependent on the strain rate and the deformation temperature.

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1. Introduction

In recent years, a series of commercial near- α titanium alloys, such as IMI685 alloy, IMI834 alloy, TIMETAL-1100 alloy, Ti600 alloy and Ti60 alloy were designed for a service temperature of at least 873 K. High temperature deformation behavior of these alloys was continuously paid attention and reported in the open literatures due to the benefits of extended formability. For example, Weinem et al. [1] investigated the microstructure evolution and the mechanical properties of TIMETAL-1100 alloy after different thermomechanical treatments. The results showed that the yield strength of TIMETAL-1100 alloy was lower for the fine-grained lamellar structure than for the coarse-grained structure. Wanjara et al. [2,3] studied the effect of processing parameters on the flow stress and the microstructure evolution during the isothermal compression of IMI834 alloy, and proposed the constitutive equations using an Arrhenius-type hyperbolic-sine relationship. Zhou [4] described the effect of average grain size on the flow behavior of IMI834 alloy by introducing internal variables to characterize the phenomenon of flow softening. The deformation behavior and the processing map of IMI685 alloy were investigated during

the isothermal compression [5–7]. Moreover, many experimental investigations had been carried out in order to evaluate the flow behavior, the microstructure evolution and the constitutive equations of Ti600 alloy at different hydrogen contents [8–12].

Ti60 alloy as a near- α type titanium alloy has excellent combination of mechanical and physical properties, i.e., good strength, good fatigue resistance and creep resistance characteristics at a service temperature of 873 K, that enables this alloy to be one of the most important high temperature materials to fabricate engine parts such as blades and discs in the aviation and aerospace industries. Xiong et al. [13,14] investigated the corrosion behavior of Ti60 alloy with an aluminide, TiAlCr and enamel coatings in moist air containing NaCl vapor at 973–1073 K, proposed that the enamel coating could protect Ti60 alloy from corrosion due to high thermochemical stability and matched thermal expansion coefficient with substrates of Ti-base alloys during corrosion. Li et al. [15] characterized the high temperature deformation behavior of Ti60 alloy based on an analysis of the stress–strain behavior, kinetics and processing map. Subsequently, Li et al. [16,17] refined grain of Ti60 alloy using thermohydrogenation treatment and equal-channel angular pressing. Luo et al. [18] modeled the constitutive relationships and microstructural variables of Ti60 alloy during high temperature deformation by using a fuzzy set and artificial neural network (FNN) technique with a back-propagation learning algorithm. Although many studies have been focused on this alloy, the effect of

* Corresponding author. Tel.: +86 29 88460465; fax: +86 29 88492642.

E-mail addresses: luojiao@nwpu.edu.cn, schjiaozi@163.com (J. Luo).

Table 1
Chemical composition of the as-received Ti60 alloy (mass fraction in %).

Al	Sn	Zr	Mo	Si	Nd	Ti
6.62	5.14	1.82	0.54	0.36	0.85	Bal.

processing parameters on the strain rate sensitivity and the strain hardening exponent of Ti60 alloy was not discussed. Therefore, additional studies are necessary to model the deformation behavior during the isothermal compression of Ti60 alloy.

The objective of present study is to reveal the variations of the strain rate sensitivity and the strain hardening exponent with processing parameters during the isothermal compression of Ti60 alloy. To reach this objective, isothermal compression is carried out in order to investigate the flow behavior of Ti60 alloy. The effect of processing parameters on the strain rate sensitivity and the strain hardening exponent is analyzed and detail explanation is given with the help of the microstructure evolution of Ti60 alloy.

2. Experimental

2.1. Material

In this study, an as-received bar stock of Ti60 alloy with an 18.0 mm diameter was used. The chemical composition and a micrograph of this alloy are shown in Table 1 and Fig. 1, respectively. Fig. 1 shows that the typical alloy microstructure at room temperature is composed of equiaxed primary α phase with a grain size about 6.0 μm and a small amount of intergranular β . The INCA ENERGY 350 energy dispersive X-ray spectrometer (EDX) analysis reveals that the dark particles marked with white arrows are Nd-rich rare earth phase. The heat treatment prior to isothermal compression was conducted in the following procedures: (1) heating to 1263 K and holding for 2 h, (2) air-cooling to room temperature, (3) heating to 973 K and holding for 2 h, and (4) air-cooling to room temperature. The beta-transus temperature for this alloy was determined to be 1303 K via a technique involving heat treatment followed by optical metallography. Jia et al. [19] found that the β transus temperature of another Ti60 alloy was about 1318 K. The increase in the β transus temperature was attributed to the slight change of alloy elements.

2.2. Experimental procedures

The cylindrical compression specimens of Ti60 alloy were 8.0 mm in diameter and 12.0 mm in height. The cylinder ends

were grooved for retention of glass lubricants. A series of isothermal compressions were carried out using the Thermecmaster-Z simulator at the deformation temperatures ranging from 1173 K to 1333 K, strain rates of 0.001, 0.01, 0.1, 1.0 and 10.0 s^{-1} , and height reductions of 50%, 60%, and 70%. The specimens were heated for 3 min to obtain a uniform deformation temperature prior to isothermal compression. The flow stress–strain curves were recorded automatically during the isothermal compression. After isothermal compression, the specimens were cooled in air to room temperature. To examine the microstructure, the specimens were axially sectioned and prepared using standard metallographic techniques. The grain size and volume fraction of phase were measured using an OLYMPUS PMG3 microscope with the quantitative metallography SISC IAS V8.0 image analysis software.

3. Results and discussion

3.1. Flow stress

A series of flow stress–strain curves during the isothermal compression of Ti60 alloy at different deformation temperatures and strain rates are shown in Fig. 2 and Fig. 3, respectively. It is observed from Fig. 2 that the flow stress increases with increasing strain, reaches a peak at a critical strain, and then decreases to a steady value because the dynamic softening is sufficient to counteract the work-hardening of the material during the isothermal compression. As illustrated in Fig. 2, the overall shapes of flow curves are dependent on the deformation temperature and the strain rate. Firstly, it can be seen that the softening effect in the $\alpha + \beta$ two-phase region is significantly different from those in the β single-phase region. In the $\alpha + \beta$ two-phase region, the softening effect is more significant for all tested strain rates, and a steady flow is observed up to a strain of 0.7, as illustrated in Fig. 2(a)–(g). In contrast, the softening effect in the β single-phase region is relatively low. The flow stress in the β single-phase region appears to be the steady flow behavior at a small strain, which implies that the effect of strain on the flow stress is negligible, as shown in Fig. 2(h)–(j). The noticeable softening phenomenon in the $\alpha + \beta$ two-phase region may be attributed to the adiabatic heating generated during deformation, which raises the actual temperature of the specimens and also the proportion of soft β phase. Similarly, Wanjara et al. [3] also observed that flow softening behavior in the β single-phase region appeared to be significantly different from the deformation behavior in the $\alpha + \beta$ two-phase region. Secondly, the overall shapes of flow curves at or above 1273 K and at high strain rates ranging from 0.1 s^{-1} to 10.0 s^{-1} are significantly different from those at low deformation temperatures and low strain rates. An initial yield drop is observed at or above 1273 K and at high strain rates ranging from 0.1 s^{-1} to 10.0 s^{-1} , followed by flow softening whose softening rate is higher at low strains and considerably less at high strains. This yield drop phenomenon is related to the fact that high strain rates promote less time for recovery processes and higher local stress concentrations due to dislocation pile-up [20]. Similarly, an initial yield drop was reported previously for the deformation processes of IMI834 alloy at 1303 K and strain rates ranging from 0.1 s^{-1} to 1.0 s^{-1} [2]. The occurrence of yield drop phenomenon in IMI834 alloy was rationalized through existing static and/or dynamic deformation theories. Moreover, it is also seen from Fig. 2 that the flow stress greatly increases with increasing strain rate at a set deformation temperature. In other words, the flow stress is sensitive to the strain rate during the isothermal compression of Ti60 alloy. Main reason is that the rate of dislocation generation increases with increasing strain rate. The tangled dislocation structures hinder the dislocation movement, leading to an increase

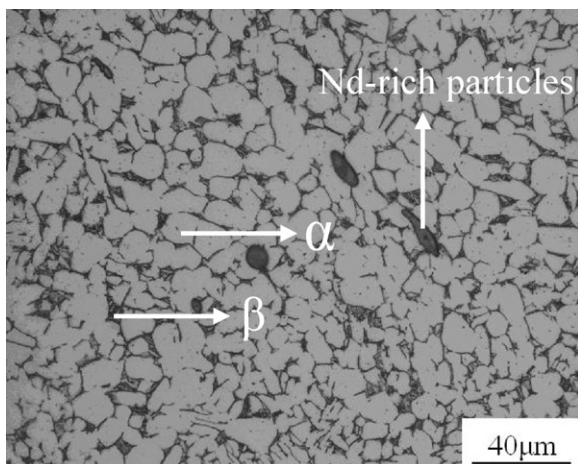


Fig. 1. Optical micrograph of the as-received Ti60 alloy.

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