Materials and Design 31 (2010) 741–748

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

The variation of strain rate sensitivity exponent and strain hardening exponent in isothermal compression of Ti–6Al–4V alloy

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ARTICLE INFO

Article history:
Received 4 August 2009
Accepted 30 September 2009
Available online 4 October 2009

Keywords:
Titanium alloy
Isothermal compression
Strain rate sensitivity exponent
Strain hardening exponent
Grain size

ABSTRACT

The deformation behavior in isothermal compression of Ti–6Al–4V alloy is investigated in the deformation temperatures ranging from 1093 K to 1303 K, the strain rates ranging from 0.001 s^{-1} to 10.0 s^{-1} at an interval of an order magnitude and the height reductions ranging from 20% to 60% at an interval of 10%. Based on the experimental results in isothermal compression of Ti–6Al–4V alloy, the effect of processing parameters and grain size of primary α phase on the strain rate sensitivity exponent m and the strain hardening exponent n is in depth analyzed. The strain rate sensitivity exponent m at a strain of 0.7 and strain rate of 0.001 s^{-1} firstly tends to increase with the increasing of deformation temperature, and maximum m value is obtained at deformation temperature close to the beta-transus temperature, while at higher deformation temperature it drops to the smaller values. Moreover, the strain rate sensitivity exponent m decreases with the increasing of strain rate at the deformation temperatures below 1253 K, but the m values become maximal at a strain rate of 0.01 s^{-1} and the deformation temperature above 1253 K. The strain rate affects the variation of strain rate sensitivity exponent with strain. Those phenomena can be explained reasonably based on the microstructural evolution. On the other hand, the strain hardening exponent n depends strongly on the strain rate at the strains of 0.5 and 0.7. The strain affects significantly the strain hardening exponent n due to the variation of grain size of primary α phase with strain, and the competition between thermal softening and work hardening.

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1. Introduction

Ti–6Al–4V alloy as a kind of $\alpha + \beta$ type titanium alloy has good formability, weldability and properties against corrosion, which makes it an ideal material in aviation and aerospace industries. In the past several decades, high temperature deformation behavior of this alloy was continuously paid attention and reported in the open literature due to the benefits of extended formability. Follansbee and Gray [1] reported the deformation mechanism of a commercial Ti–6Al–4V alloy in a solution treated (ST) and a solution treated and aged condition (AG), and concluded that the mechanical twins occurred only at high strain rates ($\sim$3000.0 s^{-1}) and planar slip was the most dominant deformation mechanism at lower strain rates. High temperature deformation and fracture behavior of Ti–6Al–4V alloy were studied by Lee and Lin [2–4]. Semiatin and Bieler [5] investigated the effect of alpha platelet thickness on the plastic flow of Ti–6Al–4V alloy with a transformed microstructure. Nemat-Nasser et al. [6] observed the dynamic recrystallization at high strain rates and dynamic strain aging at higher deformation temperatures on a commercially hot isostatically pressed (HIP) Ti–6Al–4V alloy. Majorell et al. [7] observed that the deformation temperature sensitivity of flow stress of Ti–6Al–4V alloy reduced with the increasing of deformation temperature at low to moderate strain rates and moderate to high deformation temperatures. Moreover, some experimental investigations had been carried out in order to evaluate the performances, yield behaviors and constitutive models at different loading conditions on the commercial Ti–6Al–4V alloy [8–10].

It is well known that the strain rate sensitivity exponent m is important in determining the tensile ductility of superplastic material. Moreover, the m values are related to the deformation mechanisms of material [11,12]. Therefore, many researchers had used different methods to measure the strain rate sensitivity exponent m [13–19]. Subsequently, some investigators reported that the m values varied with the processing parameters and the microstructural variables. For instance, Romhanji et al. [20] investigated the effect of deformation temperature on the strain rate sensitivity exponent m of high strength Al–Mg alloy sheet and at higher deformation temperatures observed that the m values increased with the increasing of deformation temperature. Picu et al. [21] studied the deformation behavior of a commercial aluminum alloy AA5182-O, and found the strain rate sensitivity exponent m was determined as a function of deformation temperature and plastic

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doi:10.1016/j.matdes.2009.09.055

strain. The effect of deformation temperature, strain rate and strain on the strain rate sensitivity exponent *m* was studied by Lee et al. [22] and Chiou et al. [23]. del Valle and Ruano [24] investigated the effect of grain size on the strain rate sensitivity exponent *m* of Mg–3Al–0.75Zn alloy, and observed the strain rate sensitivity exponent *m* increased strongly with the decreasing of grain size below 15 μm. On the other hand, the strain hardening exponent *n* reflecting the work-hardening effect of material is also an important parameter in plastic deformation, since the *n* values control the amount of uniform plastic strain which the material can undergo before strain localization, necking and failure [25]. So a number of efforts were previously made to study the strain hardening exponent *n* [26–29]. For instance, Lee and Lin [4] studied the effect of deformation temperature on the strain hardening exponent *n* of Ti–6Al–4V alloy, and pointed out the strain hardening exponent *n* decreased rapidly with the increasing of deformation temperature. Antoine et al. [30] studied the influence of a Ti–IF steel grade microstructure on the strain hardening exponent *n* and established an empirical formula to predict the *n* values. However, no detail descriptions about the effect of processing parameters and grain size on the strain rate sensitivity exponent *m* and the strain hardening exponent *n* of Ti–6Al–4V alloy are reported in the open literature. Therefore, investigations are furthermore needed so as to model the deformation behavior in isothermal compression of Ti–6Al–4V alloy.

In this paper, the effect of deformation temperature and strain rate on the peak and steady flow stress is analyzed to represent the deformation behavior in isothermal compression of Ti–6Al–4V alloy. On the basis of the stress–strain curves in isothermal compression of Ti–6Al–4V alloy, the strain rate sensitivity exponent *m* and the strain hardening exponent *n* are calculated. And, the effect of processing parameters and grain size on the strain rate sensitivity exponent *m* and the strain hardening exponent *n* is investigated in isothermal compression of Ti–6Al–4V alloy.

2. Experimental

2.1. Experimental material

As-received bar stock of Ti–6Al–4V alloy is 90 mm in diameter. The chemical composition (wt.%) of the alloy used in this investigation is as follows: 6.50 Al, 4.25 V, 0.16 O, 0.04 Fe, 0.02 C, 0.015 N, 0.0018 H and the bal. Ti. The beta-transus temperature for this alloy was determined to be 1263 K via a technique involving heat treatment followed by optical metallography, which was in a good agreement with those reported by Semiatin [5] and Majorell [7]. The optical micrograph of as-received Ti–6Al–4V alloy is shown in Fig. 1. It is seen from Fig. 1 that the microstructure at room temperature is composed of an equiaxed primary α phase with about a grain size of 10.0 μm, secondary (platelet) α and a small amount of intergranular β.

2.2. Experimental procedures

Cylindrical compression specimens have 8.0 mm in diameter and 12.0 mm in height, and the cylinder ends were grooved for retention of glass lubricants in isothermal compression of Ti–6Al–4V alloy. The isothermal compressions were conducted at a Thermecmaster-Z simulator in the deformation temperatures ranging from 1093 K to 1303 K at an interval of 20 K, the strain rates of 0.001 s^{-1}, 0.01 s^{-1}, 0.1 s^{-1}, 1.0 s^{-1}, and 10.0 s^{-1}, and the height reductions of 20%, 30%, 40%, 50%, and 60%. After isothermal compression, the specimens were cooled in air to room temperature. In order to measure the grain size of primary α phase in isothermal compression of Ti–6Al–4V alloy, the specimens were axially sectioned and prepared using standard metallographic techniques. And, four measurement points and four visual fields of each point in the different deformation regions were chosen. The grain size was measured at an OLYMPUS PMG3 microscope with the quantitative metallography SISC IAS V8.0 image analysis software, and the primary α grain size was calculated by the average value of 16 visual fields.

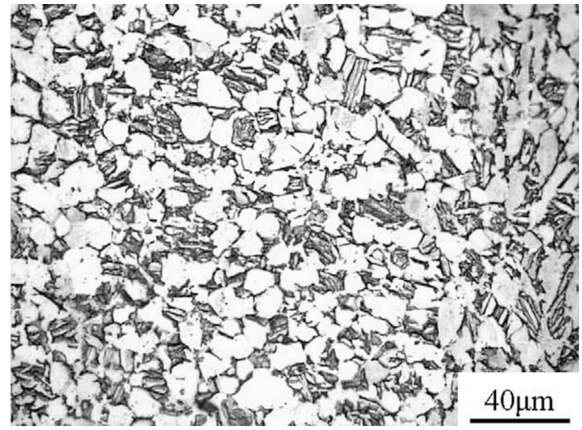

Fig. 1. Optical micrograph of as-received Ti–6Al–4V alloy.

3. Results and discussion

3.1. Flow stress

The selected flow stress–strain curves in α + β two-phase region and β single-phase region of Ti–6Al–4V alloy at different strain rates and deformation temperatures are shown in Fig. 2. In both cases, isothermal compression behavior exhibits a peak flow stress at a very low strain followed by extensive flow softening whose softening rate is higher at low strains and considerably less at higher strains. This phenomenon is related to the fact that the dominant deformation mechanism is due to slip of dislocations at low strains. Thus, the dislocation density increases quickly with the increasing of plastic strain. Then, the softening effect plays an important role in dislocation density evolution with the further increasing of strain, which leads to the flow stress sharply decreases to a steady value when the dynamic softening effect is sufficient to counteract the work-hardening effect in isothermal compression of Ti–6Al–4V alloy. In addition, it can be seen that the flow stress decreases with the increasing of deformation temperature at a constant strain rate, and increases with the increasing of strain rate at a constant deformation temperature.

Fig. 3 shows the peak and steady flow stress in isothermal compression of Ti–6Al–4V alloy. The peak flow stress firstly decreases with the increasing of deformation temperature, and then it reaches an apparent plateau at a deformation temperature about 1243 K, as illustrated in Fig. 3a. In the plateau region, the peak flow stress varies slightly with the deformation temperature. And the decreasing degree is relatively small at low strain rate (0.001 s^{-1}) but increases with the increasing of strain rate, this indicates that the peak flow stress tends to be strain rate dependent over all of the deformation temperatures. On the other hand, the steady flow stress in isothermal compression of Ti–6Al–4V alloy, as presented in Fig. 3b, exhibits essentially similar characteristics in deformation behavior as the peak flow stress.

3.2. Strain rate sensitivity exponent

In present study, the strain rate sensitivity exponent *m* is determined using the following expression [31]

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