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Effect of the strain on the deformation behavior of isothermally compressed Ti–6Al–4V alloy

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The deformation behavior of isothermally compressed Ti–6Al–4V alloy in the deformation temperature range from 1093 K to 1303 K, the strain rate range from 0.001 s^{-1} to 10.0 s^{-1} and the height reduction range from 20% to 60% has been investigated in depth. Effect of the strain on the flow stress, the grain size and the apparent activation energy for deformation of isothermally compressed Ti–6Al–4V alloy is analyzed. The results show that the apparent activation energy for deformation and the grain size of isothermally compressed Ti–6Al–4V alloy in the $\alpha + \beta$ two-phase region vary slightly with strain: the activation energy increases with strain after an early drop as the primary α grain size varies with strain. On the other hand, the apparent activation energy for deformation of isothermally compressed Ti–6Al–4V alloy in the β single-phase region increases firstly with the increasing of strain and then does that slightly in the strain range from 0.3 to 0.7. A processing map of the isothermally compressed Ti–6Al–4V alloy is constructed at a strain of 0.6. The processing map of isothermally compressed Ti–6Al–4V alloy exhibits that the optimal processing parameters are the deformation temperature of 1143 K and the strain rate of 0.001 s^{-1}. Meanwhile, two instability domains in the processing map of isothermally compressed Ti–6Al–4V alloy are as follows: one is in the deformation temperature range from 1093 K to 1183 K and the strain rate range from 0.011 s^{-1} to 2.02 s^{-1}, and another is in the deformation temperature range from 1243 K to 1303 K and the strain rate range from 1.0 s^{-1} to 10.0 s^{-1}.

1. Introduction

For metals or alloys, several modeling approaches, including the stress–strain curves, kinetic analysis and processing map, are widely used to characterize the deformation behavior in order to control the microstructure exactly and optimize the processing design. Applying the kinetic analysis to model the deformation behavior of alloys, the apparent activation energy for deformation is usually determined on the experimental flow stress at a series of deformation temperatures and strain rates and a certain strain. However, some investigations showed that the apparent activation energy for deformation would vary with the strain. For instance, Roberts [1] found that the apparent activation energy for deformation of austenitic 18Cr–8Ni stainless steel and M2 high-speed steel varies with the strain. Lee and Lin [2] modeled the apparent activation energy for deformation varying with the strain. Li et al. [3] found a slight effect of the strain on the activation energy for deformation of Ti–5.6Al–4.8Sn–2.0Zr alloy.

In the past two decades, processing map had been used to optimize the processing parameters in hot working of metallic materials. Sivakesavam and Prasad [4] determined the sound domain in superplastic deformation of as-cast Mg–11.5Li–1.5Al alloy through processing map. Balasubrahmanyam and Prasad [5] studied the deformation behavior of Ti–10V–4.5Fe–1.5Al alloy (a kind of β type titanium alloys) and optimized the processing parameters through processing map. Łyszkowski and Bystrzycki [6] established the processing map of Fe_3Al intermetallic alloy and obtained the instability domains of plastic deformation. Cai et al. [7] developed the processing map for a Ni-based superalloy and pointed out that the strain had a slight effect on the processing map.

Ti–6Al–4V alloy as a kind of $\alpha + \beta$ type titanium alloy has good formability, weldability and properties against corrosion, that makes it an ideal material in aviation and aerospace industries. Follansbee and Gray [8] studied the deformation mechanism of a commercial Ti–6Al–4V alloy at the solution treated and solution treated-aged conditions, and concluded that the mechanical twins occurred only at very high strain rates (~5000.0 s^{-1}) and these levels planar slip was the most dominant deformation mechanism at lower strain rates. Lee et al. [2,9] observed that the effect of deformation temperature on yield behavior of the as received Ti–6Al–4V

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Table 1
Chemical composition of the as received Ti–6Al–4V alloy (mass fraction in %).

Al	V	Fe	C	N	O	H	Ti
6.50	4.25	0.04	0.02	0.015	0.16	0.0018	Bal.

alloy was more prominent at higher deformation temperatures, but was independent of strain rates. Nemat-Nasser et al. [10] observed the dynamic recrystallization at high strain rates and also dynamic strain aging at higher deformation temperatures on a commercially hot isostatically pressed (HIP) Ti–6Al–4V alloy. Majorell et al. [11] observed that the deformation temperature sensitivity of flow stress reduced with the increasing of deformation temperature at low to moderate strain rates and moderate to high deformation temperatures on the Ti–6Al–4V alloy. Frouin et al. [12] used the ultrasonic second harmonic generation technique to determine the degree of nonlinearity and quantify the level of damage during the fatigue process of Ti–6Al–4V alloy. 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 alloys [13–16]. But, effect of the strain on the deformation behavior of isothermally compressed Ti–6Al–4V alloys is not reported in the open literature, therefore, investigations are furthermore needed so as to understand those phenomena.

In this paper, effect of the deformation temperature, the strain rate and the strain on the flow stress is analyzed to represent the mechanical behavior of isothermally compressed Ti–6Al–4V alloy, and the apparent activation energy for deformation of isothermally compressed Ti–6Al–4V alloy at different strains is calculated. And, the deformation mechanisms are clarified through the apparent activation energy for deformation of isothermally compressed Ti–6Al–4V alloy in the ($\alpha + \beta$) two-phase region and/or the β single-phase region compared to the activation energy for self-diffusion of α-Ti and β-Ti. Finally, the processing map of isothermally compressed Ti–6Al–4V alloy at a strain of 0.6 is established so as to optimize the processing parameters.

2. Experimental procedures

The chemical composition and micrograph of as received Ti–6Al–4V alloy are shown in Table 1 and Fig. 1 respectively. The starting microstructure consists of an equiaxed primary α phase (hexagonal close-packed, hcp) with about a grain size of 10.0 μm, secondary (platelet) α and a small amount of intergranular β (body-centered cubic, bcc). The heat treatment prior to isothermal compression was conducted in the following procedures: (1) heating to 1023 K and holding for 1.5 h, (2) air-cooling to room temperature. The 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 β transus temperature of Ti–6Al–4V alloy is about 1263 K and in a good agreement with those reported by Majorell et al. [11] and Semiatin and Bieler [17]. But, Bruschi et al. [18] found the β transus temperature of another Ti–6Al–4V alloy is about 1283 K, in which the β transus temperature increases 20 K compared to those in present alloy and Refs. [11,17] as being adjusted elements Al and V slightly [18]. It is well known that element Al is a β stabilizer and increases the β transus temperature, but element V is a β stabilizer and decreases the β transus temperature.

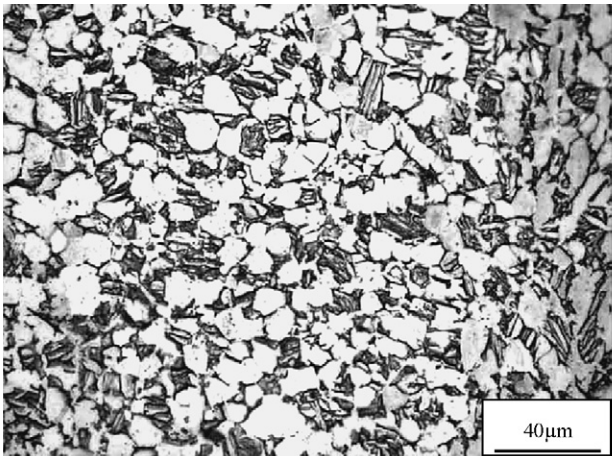

Fig. 1. Micrograph of the as received Ti–6Al–4V alloy.

To investigate the effect of processing parameters on deformation behavior of Ti–6Al–4V alloy, isothermal compressions were conducted at a Thermecmaster-Z simulator in the deformation temperature rang from 1093 K to 1303 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 reduction range from 20% to 60% with an interval of 10%. The specimens prior to isothermal compression were heated and held for 3.0 min at the deformation temperature so as to obtain a uniform deformation temperature. The strain–stress curves were recorded automatically in isothermal compression. After compression, the specimens were cooled in air to room temperature.

In order to measure the grain size of post isothermally compressed Ti–6Al–4V alloy, the isothermally compressed specimens were axially sectioned and prepared using standard metallographic techniques. And, four measurement points and four visual fields of one 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 sixteen visual fields.

3. Experimental results and analysis

3.1. Flow stress

Selected flow stress curves in the $\alpha + \beta$ two-phase region and β single-phase region of Ti–6Al–4V alloy at the strain rates and deformation temperatures are shown in Fig. 2. It could be found from Fig. 2 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 flow stress increases quickly with the increasing of strain and reaches a peak value. Then, the flow stress sharply decreases to a steady value, the steady flow occurs as the dynamic softening effect is sufficient to counteract the work-hardening effect of this alloy in the isothermal compression, as illustrated in Fig. 2(a) and (b). On the other hand, the strain affects slightly the flow stress in the β single-phase region in low strain rate range from 0.01 s^{-1} to 0.001 s^{-1} illustrated in Fig. 2(c) and (d), which represents the steady flow behavior. Wanjara et al. [19] also observed that the differences of flow softening behavior in the β single-phase region with that in the $\alpha + \beta$ two-phase region occurred in isothermal compression of near α type titanium alloy IMI834, and pointed out that it related to the microstructure evolution of near α type titanium alloy IMI834. Fig. 2(c) and (d) illustrates the slight oscillatory flow curves in the β single-phase region of Ti–6Al–4V alloy at a strain rate of 10.0 s^{-1}, in which those oscillation of stress–strain curves indicates the possibility of dynamic recrystallization, localized or unstable plastic flow of Ti–6Al–4V alloy. Similarly, the broad oscillations of flow curves in the β single-