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Deformation behavior of Ti−5Al−2Sn−2Zr−4Mo−4Cr alloy with two initial microstructures during hot working

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Abstract: The effects of initial microstructure on the flow stress, strain rate sensitivity (m), strain hardening exponent (n), apparent activation energy (Q) for deformation of Ti−5Al−2Sn−2Zr−4Mo−4Cr alloy were investigated using isothermal compression tests. Results show that the alloy with Widmanstätten alpha plates shows a higher peak stress and flow softening. Additionally, the alloy with equiaxed primary alpha exhibits an early yield drop at or above 810 °C and at strain rates of 0.1−5.0 s^{-1}. In the strain range of 0.5−0.7, m of the alloy with equiaxed primary alpha is found to be larger at 0.01 s^{-1} and lower deformation temperatures. This phenomenon could be reasonably explained based on the microstructure evolution. The strain has a significant effect on n of the alloy with Widmanstätten alpha plates, which is attributed to platelet bending/kinking and dynamic globularization of α phase. In the strain range of 0.15−0.55, Q of the alloy with Widmanstätten alpha plates is larger.

Key words: titanium alloy; isothermal compression; flow stress; microstructure evolution; dynamic globularization

1 Introduction

The mechanical properties of material are closely related to its final microstructure features (i.e., grain size, volume fraction of phase, phase morphology) [1]. The final microstructure is dependent on the various microstructure characteristics inherited from the initial microstructure morphology and processing parameters during hot forming. Therefore, an increased understanding of the relationship among the initial microstructure morphology, processing and microstructure evolution is particularly critical for sustaining further improvements in performance and reliability of material. Recent research has reported the effects of the initial microstructure, deformation temperature and strain rate on the deformation behavior and microstructure evolution during hot forging of AZ91 magnesium alloy [2], 2219 aluminum alloy [3], 45 steel [4], Ti−10V−2Fe−3Al titanium alloy [5,6]. In particular, a significant difference of flow softening between different initial microstructures was observed in the shapes of the flow stress−strain curves, which can be reasonably explained by microstructure evolution. For instance, JACKSON et al [6] noted that near-β alloy Ti−10V−2Fe−3Al with a high aspect ratio of Widmanstätten α platelets produced more significant flow softening than that with globular primary α, which was attributed to the breaking up of the Widmanstätten α platelets. However, it is not easy to determine the concrete effect on the deformation behavior because various microstructure characteristics are interdependent.

Ti−5Al−2Sn−2Zr−4Mo−4Cr alloy (a "β-rich" α+β titanium alloy) is characterized by high strength, excellent corrosion resistance, superior fracture toughness and significant hardenability, which makes it an ideal material in the aviation and aerospace industries. In the past several years, the deformation behavior of this alloy has been examined extensively due to the benefits of its extended formability [7−9]. However, the effect of the initial microstructure on the deformation behavior of the alloy has not been reported. Therefore, this study aims to clarify the deformation characteristics of a "β-rich" α+β titanium alloy in the α+β two-phase region with different initial microstructures.

In this study, two initial microstructures are firstly obtained by changing the heating treatment processes. Secondly, the effects of the initial microstructure

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and processing parameters (i.e., deformation temperature, strain rate and strain) on the flow stress, the strain rate sensitivity (m), the strain hardening exponent (n) and the apparent activation energy for deformation (Q) were analyzed and detail explanation is given with the help of the microstructure observations during isothermal compression of Ti−5Al−2Sn−2Zr−4Mo−4Cr alloy.

2 Experimental

2.1 Material

In this study, a piece of bar stock alloy with a diameter of 50.0 mm was used. The chemical composition (mass fraction, %) of this alloy was as follows: 5.12 Al, 2.03 Sn, 2.10 Zr, 4.04 Mo, 3.94 Cr, 0.10 Fe, 0.012 C, 0.007 N, 0.007 H, and 0.12 O with balance Ti. The β transus temperature for this alloy was determined to be 905 °C by a technique involving heat treatment followed by optical metallography [10]. A three-stage heat treatment (840 °C, 1 h + air cooling + 800 °C, 4 h + water quenching + 630 °C, 8 h + air cooling) was performed on the alloy, and a SEM image of the alloy with equiaxed microstructure (AB) is shown in Fig. 1. The microstructure AB consists of equiaxed primary α phase (grain size ~3.29 μm) and elongated primary α phase (feret ratio ~5.52) and a small amount of β-transformed phase (grain size ~2.37 μm). The volume fraction of α phase for the alloy was examined using quantitative metallography image analysis software and was found to be near 34.9%.

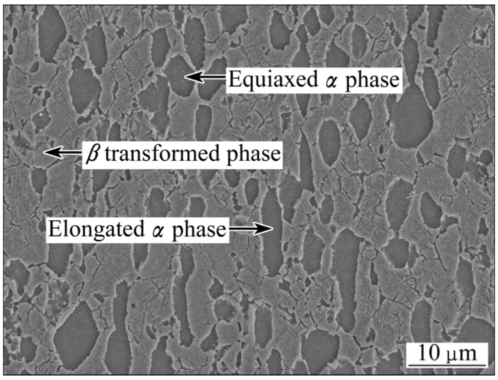

Fig. 1 SEM image of Ti−5Al−2Sn−2Zr−4Mo−4Cr alloy at room temperature (microstructure AB)

To obtain a transformed microstructure (B), this alloy underwent a heat treatment of 910 °C for 20 min with a furnace cool to room temperature. SEM image of the transformed Ti−5Al−2Sn−2Zr−4Mo−4Cr microstructure at room temperature is shown in Fig. 2. The lamellar microstructure (B) has a prior-β grain size of approximately 260 μm. The β grains contain a high volume fraction of Widmanstätten α plates with a high feret ratio. The thickness of α lamellae in microstructure B is 0.24 μm.

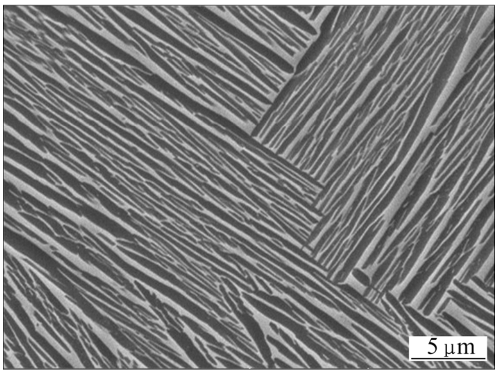

Fig. 2 SEM image of transformed Ti−5Al−2Sn−2Zr−4Mo−4Cr microstructure at room temperature (microstructure B)

2.2 Procedures

Cylindrical compression specimens were 8.0 mm in diameter and 12.0 mm in height. A series of isothermal compression tests of the alloy with microstructures AB and B were conducted on a Gleeble−1500 simulator at deformation temperatures of 770, 790, 810, 830, 850 and 870 °C, strain rates of 0.01, 0.1, 1.0 and 5.0 s^{-1}, and strains of 0.5, 0.7 and 0.9. The specimens were heated and held for 5 min at the given deformation temperature to establish a uniform temperature throughout the specimens. Flow stress−strain curves were recorded automatically during isothermal compression. After isothermal compression, the specimens were cooled in air to room temperature, and the specimens were axially sectioned, electropolished and chemically etched in a solution of 10 mL HF, 15 mL HNO_3 and 75 mL H_2O. The grain size and volume fraction of each phase were measured using quantitative metallography image analysis software (Image-Pro Plus 6.0), and the grain size and volume fraction were calculated by the average value of sixteen visual fields.

3 Results and discussion

3.1 Flow stress

Figure 3 shows the flow stress−strain curves of Ti−5Al−2Sn−2Zr−4Mo−4Cr alloy with two initial microstructures. It is observed that the overall shapes of the flow curves are dependent on the deformation temperature, strain rate and initial microstructure. At a deformation temperature of 770 °C (Fig. 3(a)), the flow stress of two initial microstructures (i.e., microstructures AB and B) firstly increases with increasing strain, reaches a peak value at a critical strain, and then gradually decreases to a steady value. There is a smooth transition from yield to steady state at a deformation temperature of 770 °C, irrespective of the strain rate and initial microstructure. However, an early yield drop of the alloy with microstructure AB is observed at or above 810 °C and at higher strain rates ranging from 0.1 to