

High-temperature deformation behavior of Ti60 titanium alloy

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ABSTRACT

Isothermal compressions of near- α Ti60 alloy were carried out on a Gleeble-3800 simulator in the temperature range of 960–1110 °C and strain rate range of 0.001–10.0 s^{−1}. The high-temperature deformation behavior was characterized based on an analysis of the stress–strain behavior, kinetics and processing map. The flow stress behavior revealed greater flow softening in the two-phase field compared with that of single-phase field. In two-phase field, flow softening was caused by break-up and globularization of lamellar α as well as deformation heating during deformation. While in the single-phase field, flow softening was caused by dynamic recovery and recrystallization. Using hyperbolic–sine relationships for the flow stress data, the apparent activation energy was determined to be 653 kJ/mol and 183 kJ/mol for two-phase field and single-phase field, respectively. The processing map exhibited two instability fields: 960–980 °C at 0.3–10 s^{−1} and 990–1110 °C at 0.58–10 s^{−1}. These fields should be avoided due to the flow localization during the deformation of Ti60 alloy.

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1. Introduction

Near- α titanium alloys, such as IMI685 [1] IMI829 [2], IMI834 [3] and Ti-1100 [4] alloy, are extensively used in jet engines as compressor discs and blades because of their light weight and superior fatigue and creep properties at elevated temperatures up to 600 °C compared with steels and nickel alloys [5–7]. Ti60 [8] alloy is another new near- α high-temperature titanium alloy developed on the basis of IMI834. Compared with IMI834 alloy, more Si element is added to the Ti60 alloy to improve the creep performance further at the servicing temperature of 600 °C. A small amount of Ta and C elements are added to improve its heat-resistant and widen ($\alpha + \beta$) phase field, respectively [9]. Like other high-temperature titanium alloys, Ti60 alloy also possesses excellent heat resistant properties at high temperature. Furthermore, as a potential candidate of materials for compressor disks, Ti60 alloy has received considerable attention in China.

It is well known that the deformation processing “window” for titanium alloys is quite narrow as compared to aluminum alloys or steels. Furthermore, the evolution of microstructures is very sensitive to process parameters such as temperature, strain rate and strain [10]. Therefore, careful process control and profound knowledge of the influence of processing parameters on hot working behavior are important for the manufacturing of titanium alloys.

Weiss and Semiatin [11] have reviewed high-temperature deformation mechanisms and microstructure control of IMI685, IMI834 and Ti-1100 titanium alloys during thermo-mechanical processing. The deformation behavior of IMI834 alloy in the temperature range of 950–1125 °C and strain rate range of 0.001–1 s^{−1} has been investigated by Wanjara et al. [10]. The results showed that the flow softening in $\alpha + \beta$ phase field was greater than that of β field in which a yield point phenomenon occurred at high strain rates. Liu and Baker [7] reported that the stress–strain curves of IMI685 alloy obtained in β phase field were typical of dynamic recovery, no dynamic recrystallization occurred during the forging. However, there is little work focusing on the hot deformation behavior of Ti60 alloy.

The objective of this study is to investigate the influence of process parameters on the flow stress behavior of Ti60 alloy, and to perform constitutive modeling of hot working process in both the $\alpha + \beta$ and β phase field. The approach of processing map has been adopted to understand the mechanisms during high-temperature deformation, and to optimize hot forming process for Ti60 alloy.

2. Experimental procedures

Ti60 alloy (Ti–5.8Al–4.0Sn–3.5Zr–0.4Mo–0.4Nb–1.0Ta–0.4Si–0.06C, wt.%) used in the present work was received in bar form with a diameter of 250 mm. The β transformation temperature of this material was measured to be 1049 °C by metallographic observations. The as-received Ti60 alloy bar had been subjected to a large number passes of forging in the $\alpha + \beta$ phase field. Finally, a homogenous microstructure was obtained which consisted of

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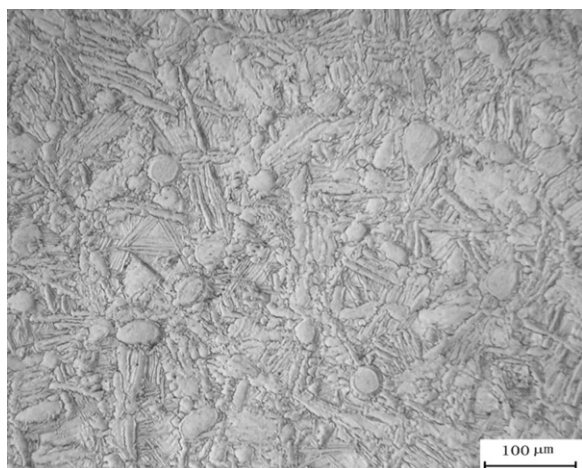


Fig. 1. Initial microstructure of Ti60 alloy in the forged condition.

approximately 25% equiaxed alpha within a fine transformed β matrix, as shown in Fig. 1. Cylindrical specimens were electro-discharged machined from the bar with 8 mm in diameter and 12 mm in height.

Hot compression tests were carried out in the temperature range of 960–1110 °C with 30 °C intervals and strain rate range of 10^{-3} – 10 s^{-1} on a Gleeble-3800 simulator. Thermocouples welded in the middle surface of the specimens to measure the actual temperature. Specimens were heated to the test temperatures with a heating rate of 5 °C/s, held for 5 min and then deformed up to 60% height reduction under constant strain rate. In order to preserve the microstructure at high temperatures, the compressed samples were water-quenched immediately after compression tests. To reduce die friction and get uniform deformation, the ends of the specimens were coated with graphite powder, and a foil of tantalum was placed between the faces of the specimen and the anvils. Deformed specimens were sectioned parallel to the compression axis and prepared for metallographic examination using standard procedures. The microstructure of the specimens was studied using an optical microscope (OM) Leica DFC320.

3. Results and discussion

3.1. Stress–strain behavior

The shape of stress–strain curves indicates some features that help in identifying the mechanism of hot deformation. Typical true stress–strain curves at 990 and 1080 °C for different strain rates are shown in Fig. 2a and b, which are representative of the behavior below and above the transformation temperature, respectively. The curves indicate that the flow stress increases with increasing strain rate and decreasing temperature. At strain rate of 0.001 s^{-1} , the curves are of steady-state type in which the flow stress remains nearly constant with increasing strain. Such steady-state curves indicate that the mechanisms of softening are sufficiently fast to balance the rate of work hardening and mechanisms like dynamic recrystallization, super-plasticity deformation or dynamic recovery are suggested [12,13]. However, when the strain rate is larger than 0.001 s^{-1} , all curves exhibit flow softening behavior in which the flow stress reaches a peak at a critical strain and then decreases with further straining. Furthermore, there is a significant difference in the flow softening behavior of the stress–strain curves observed for deformation in the $\alpha + \beta$ phase field compared with that of β phase field. For deformation in the β phase field, the flow stress appears to reach a steady-state value at strain of 0.6, but the steady-state conditions are not observed in the $\alpha + \beta$ phase field. In addition, at

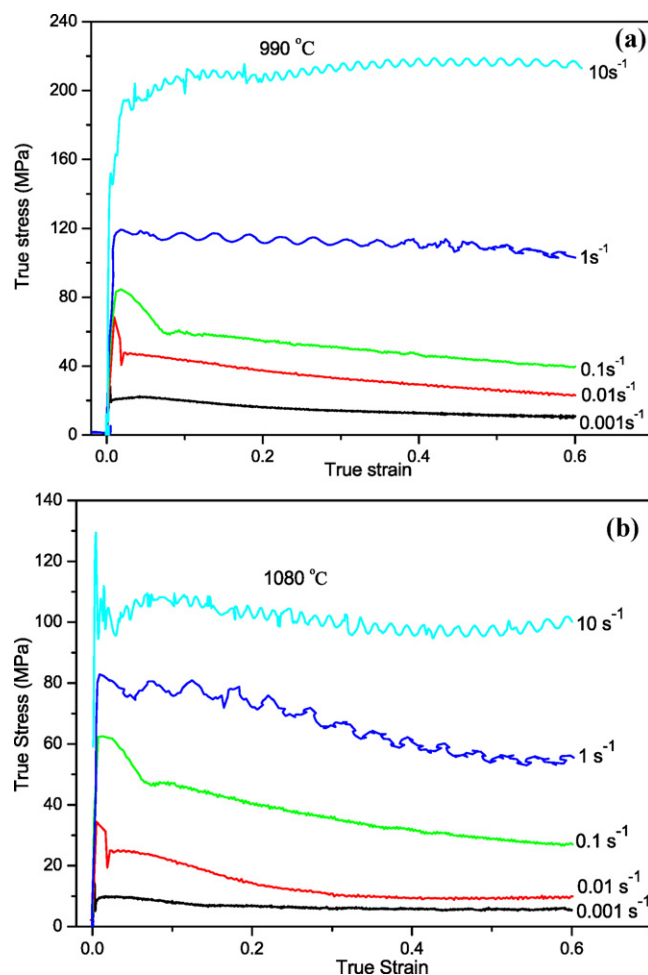


Fig. 2. Flow stress curves of Ti60 alloy deformed at (a) 990 °C and (b) 1080 °C.

higher strain rates ($\geq 1.0 \text{ s}^{-1}$), the curves display significant oscillation in both the β phase and $\alpha + \beta$ phase field which indicates dynamic recrystallization, unstable deformation, or cracking [12]. Similar oscillatory behaviors have been reported in other titanium alloys at higher strain rates [12,14,15].

3.1.1. Flow softening behaviors

In order to evaluate the extent of flow softening during the deformation, the softening of flow stress ($\Delta\sigma = \sigma_p - \sigma_{0.6}$) with increasing deformation temperature for various strain rates are shown in Fig. 3. The values of the stress corresponding to the strain of 0.6 are considered as the steady-state stress. It is clear that the extent of softening in the $\alpha + \beta$ phase field is greater than that of β phase field. Furthermore, the extent of softening maintains basically constant above the β transformation temperature at a certain strain rate. The variation in extent of softening with increasing temperature is the result of microstructural changes, such as the grain size, the number of dislocations, the volume and composition of the phase, and so forth. In addition, the curves in Fig. 3 indicate that the strain rate has a significant effect on the extent of softening of Ti60 alloy. As observed from these curves, the extent of softening increases with increasing strain rate from 0.001 to 0.1 s^{-1} . However, it decreases with increasing strain rate when the value of strain rate is over 0.1 s^{-1} .

Previous reports suggest that the flow softening may be attributed to the globularization of lamellar structures, deformation heating, and flow instability due to flow localization, or microcracking [14,16,17]. For Ti60 alloy, the low thermal conduc-

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