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The microstructure characterization of adiabatic shearing band in Ti-17 alloy at high strain rates and elevated temperatures

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ABSTRACT

The effect of process variables on flow response and microstructure evolution during high velocity deformation of Ti-17 with a colony alpha preformed microstructure was established using the Split Hopkinson Pressure Bar (SHPB). The testing was conducted on samples with prior-beta grain sizes of 400 μm at strain rates of 2000–6000 s^{-1}, test temperatures of 293–973 K. All flow curves exhibited a peak stress followed by a moderate flow softening which can be rationalized by the occurrence of the adiabatic shearing band (ASB) in this alloy. The ASBs could be divided into two types, "white" ASBs (deformation band) and "dark" ASBs (recrystallization band). In addition, the equiaxed beta grains with diameters of 3–5 μm in the "dark" ASBs could not be explained by the sub-grain rotation dynamic recrystallization (RDR) mechanism using the traditional calculation method of temperature rise. Therefore, a modified equation for calculating temperature rise was used to determine the temperature in the ASBs, and the recalculated results of RDR kinetics equations have the excellent agreement with the microstructure observations.

1. Introduction

Ti-17 alloy is a kind of near beta titanium alloy of high strength, high toughness and high harden-ability. In China, it has received considerable attention from aviation industry as a potential candidate of materials for manufacturing the dual-property blisk [1]. During the manufacturing and subsequent service lives of such alloy, high-speed loading is sometimes inevitable, such as high-speed cutting, foreign-object impact, ballistic impact, etc. [2–4]. Therefore, the research on the flow response and microstructure characterization of Ti-17 alloy at high strain rate was essential to obtain the excellent performance.

In macro mechanics, the flow response at high strain rates and elevated temperature is a complicated process resulting from the interaction of temperature, strain and strain rate. The high temperature reduces the internal resistance of dislocation movements and results in plastic flow, while a high strain and a high strain rate tend to block dislocation, leading to work hardening [4–6]. As a consequence, it is significantly challenging for studying the flow response of these alloys. Lee et al. [7] investigated the mechanical behavior of Ti-15Mo-5Zr-3Al alloy deformed at various strain rates and temperatures. It was reported that the mechanical behavior of the alloy was highly sensitive to both strain rate and temperature, and the flow stress curves presented an initial work hardening followed by flow softening. Li et al. [8] employed SHPB to study the dynamic mechanical behavior of pure titanium and found a linear strain hardening at high strain rate ($\sim$1000 s^{-1}). Through the above mentioned analysis, it is important to research the effect of process variables on flow response, which laid the foundation for studying the microstructure characterization of Ti-17 alloy at high strain rates and elevated temperatures.

In microstructure characterization, titanium and titanium alloys were more prone to develop adiabatic shear bands (ASBs) under high strain rate loading due to their low thermal conductivity and high strength [9–13]. Much attention have been paid to the ASB because of the extreme thermomechanical history and complex ultrafine microstructure in the narrow shear localization regions, and the mechanisms within the ASB have become the focus in these years. Considering a near beta titanium alloy, Yang et al. [14] investigated the microstructure and the phase transformation within the ASB by means of TEM (Transmission Electron Microscope) and the results showed that the elongated sub-grains with the width of 0.2–0.4 μm have been observed in the shear band boundary. Wang et al. [15] found the ASB in Ti-3Al-5Mo-4.5Al alloy was a "white" band of width about 13 μm by SEM and phase transformation was used to explain for this. Meyers et al. [16] found the shear band consisted of equiaxed grains with diameters of micron size and suggested the dynamic recrystallization may dominate in many kinds of alloys. However, Hines et al. [17] found that the kinetics of the existing recrystallization models were inadequate to explain the observed grain sizes, with the

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kinetics being several orders of magnitude slower than the deformation time or the cooling time of the shear bands. Then he proposed that mechanically-driven sub-grain rotations could assist recrystallization at very high strain rates. On this basis, many researchers proposed the sub-grain rotation dynamic recrystallization (RDR) mechanism [18–23]. Three stages [18–23] could describe the process of RDR: the first stage was the rearrangement of the homogeneous distribution of dislocations into elongated dislocation cells due to the dynamic recovery. As the misorientation increases, these cells become elongated sub-grains secondly. The last stage was the formation of the geometrically-necessary boundaries referred to the rotation of the sub-grains to different directions. As the RDR explained the formation of fine equiaxed grains within ASBs in many alloys, the relevant information will guide the current work in this study.

Although many investigations have been carried out for flow response and microstructure characterization of titanium alloys at high strain rates, the theories are less systematic and the relationship between the microstructure and macro-behavior is also not clear. Especially for Ti-17 alloy, little work on the microstructure changes under high-speed loading was investigated. This would limit its application in aerospace engineering. Consequently, systematically examining, evaluating the mechanical properties and microstructure characterizations of such alloy at a wide range of strain rates and temperature loading conditions are essential. Accordingly, the purpose of the present paper was to utilize Split Hopkinson Pressure Bar (SHPB) apparatus to investigate the flow response of Ti-17 alloy at the strain rates between 2000 s^{-1} and 6000 s^{-1} and temperatures ranging from 293 K to 973 K. The microstructural evolution of the Ti-17 alloy during high strain rate deformations was observed through SEM as well as OM and the correlation between the microstructure evolution and flow response behavior was analyzed.

2. Materials and experimental procedure

The material used in the present study was Ti-17, consisting of 5.12Al, 2.03Sn, 2.10Zr, 4.04Mo, 3.94Cr, 0.10Fe, 0.012C, 0.007N, 0.007H, 0.12O, and balance Ti (in wt%). The beta transus temperature of this alloy was measured of 1163 K by metallographic method. The bar with a diameter of 75 mm and length of 180 mm was forged to the height reduction of 50% at 1188 K followed by air cooling to obtain the basket weave microstructure, as shown in Fig. 1. As seen from Fig. 1, the initial alloy had a lamellar microstructure with 400 μm grain size and 20–30 μm length, about 0.5 μm thick alpha lamellae. Then the cylindrical specimens with a diameter of 5 mm and length of 4 mm were machined by wire-electrode cutting. The surfaces of specimen were carefully ground to make sure a close contact between the specimen and the pressure bars of the SHPB apparatus during impact testing..

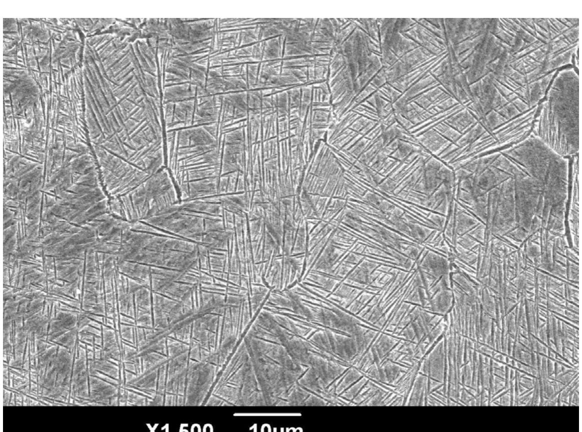

Fig. 1. SEM micrograph of the initial microstructure of the Ti-17 alloy.

SHPB apparatus was employed to perform the high-speed impact at the strain rates of 2000 s^{-1}, 4000 s^{-1}, 6000 s^{-1} and deformation temperatures of 293 K, 573 K, 773 K, and 973 K, respectively. The details and principles of SHPB apparatus have been discussed in Refs. [24–26]. The diameters of the incident bar and the transmitted bar are both 14.5 mm. Besides, the diameter and the lengths of the striker bar are 200 mm and 1 m, respectively. In addition, the loading period of shock wave t during the SHPB test could be calculated according to the equation:

$$t = 2L_0/C_0 \tag{1}$$

where L_0 is the diameter of the striker bar, and C_0 is the velocity of longitudinal wave in the martensitic steel (4756 m/s). Therefore, the loading period t is calculated to be 84 μs. During the impact, a data acquisition system was applied to record and replay the original pluses, by which the stress, strain and strain rate can be calculated. After the impact, the specimens were air cooled.

Following the tests, the samples were recovered and mounted and then were prepared by grinding, polishing, and etching in a solution of H_2O 20 ml, HF 2 ml, and HNO_3 6 ml. OM and SEM were employed for the metallographic analysis.

3. Results and discussion

3.1. Flow stress behavior

True stress-true strain curve reflects the relations of flow stress and deformation condition, meanwhile, it can also reveal the microstructure evolution and mechanical properties changes in parts. The strain-stress curves of Ti-17 alloy at various strain rates and temperatures are shown in Fig. 2. The intense oscillations can be obviously observed in the curves at high strain rates due to the technical limitations of the SHPB apparatus [27]. Obviously, the flow stress decreases with the increasing of temperature, but increases with the increasing of strain rate, as shown in Fig. 2. The similar results of the curves were also observed in other alloys [6]. The reason can be described that higher strain rate accelerate the multiplicity of dislocations, leading to dislocation tangles which could retard the movement of dislocations and eventually results in higher flow stress, whereas higher temperature will supply dislocations with sufficient thermal energy to help them overcome dislocation tangles and causes lower flow stress [28,29]..

All flow curves exhibited a moderate flow softening, and the flow softening degrees under different deformation conditions are shown in the Fig. 3. For simplicity, linear approximation is used to fit the flow stress softening curves, the slope of the best-fit line is considered as the flow softening degree. It can be seen that the flow softening degree is more sensitive to the strain rate than temperature, as shown in Fig. 3. The curves indicate that the flow softening degree increases with the increasing of strain rate, because the flow instabilities of the metals or localized plastic deformation increases with the increasing of the strain rate. When the localized deformation reached a relatively high point, the adiabatic temperature rise could induce the formation of adiabatic shearing band (ASB), flow softening or even losing loading capacity could occur since it needs to absorb substantial energy for nucleation, growth and expansion [30,31]..

In the present study, ASB-induced flow stress softening takes place as well. Since the test involves a variety of temperatures and strain rates, some typical microstructures are selected for analysis