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ARTICLE

Hot Deformation Behavior and Processing Map of Ti-6Al-3Nb-2Zr-1Mo Titanium Alloy

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Abstract: The isothermal compression tests were performed over the ranges of temperatures 820~1060 ºC and strain rates 0.001~1 s^{-1} on a Gleeble-3800 simulator. The constitutive equation of Ti-6Al-3Nb-2Zr-1Mo alloy has been established to describe the changing rule of flow stress with the strain rate and deformation temperature. The apparent activation energies have been calculated to be 764.71 kJ/mol in the dual phase region and 126.94 kJ/mol in the single phase region. The processing maps have been constructed based on the dynamic material model (DMM) and the Prasad's instability criterion at strains of 0.4 and 0.7. The maps exhibit a stable domain in the temperature range of 840~1060 ºC and strain rate range of 0.001~0.1 s^{-1} with two peaks in power dissipation of 51%, occurring at 940 ºC/0.001 s^{-1} and 880 ºC/1 s^{-1}, respectively. The high efficiency values of power dissipation indicate dynamic recrystallization (DRX)/globalization in these fields. Based on the constructed processing maps, the optimal hot processing window of this alloy corresponds to the temperature range of 840~1060 ºC and the low strain rate range of 0.001~0.1 s^{-1}. The microstructures of the specimens deformed at different conditions were analyzed and connected with the processing map. It is found that in processing of the alloy at 820 ºC and a higher strain rate (≥1 s^{-1}) an instability deformation will take place easily.

Key words: Ti-6Al-3Nb-2Zr-1Mo alloy; constitutive equation; processing maps; microstructure

Titanium alloys are widely used in light-weight high-temperature structure due to their excellent mechanical properties at high temperature, low density and high specific strength and corrosion resistance[1,2]. High temperature titanium alloys are attracted to be used as components under a long-term load at the high temperature up to 600 ºC. In previous pioneering work, a number of titanium alloys regarding this kind performance have been studied concerning hot deformation behavior, microstructure evolution and processing parameters optimization, such as IMI834[3], IMI685[4], Ti60 alloy[5,6] and Ti6242 alloy[7]. In the present study, Ti-6Al-3Nb-2Zr-1Mo alloy is a high temperature near-alpha titanium alloy developed in China, and mainly used for preparation of ship piping system because of its outstanding strength, weld-ability and corrosion resistance. So far, the increasing attention has been received with respect to Ti-6Al-3Nb-2Zr-1Mo titanium alloy by many material scientists. In the previous studies, the efforts were mainly focused on the microstructure, the properties and applications of this alloy. The effect of element addition ways on the microstructure and the performance of P/M Ti-6Al-3Nb-2Zr-1Mo was investigated by Huang et al[8], and the conclusion was that the sintered alloy made by proper element addition ways had much higher strength and lower plasticity than the forged. Wen et al[9] studied the mechanical properties, the microstructure and impact property of this alloy at five different annealing temperatures, and the best annealing schedule was obtained.

In general, the quality of a large structural part depends

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on the cogging, forging and following heat treat processes. Consequently, the forging quality of Ti-6Al-3Nb-2Zr-1Mo alloy essentially relies on its microstructure, which is highly associated with the hot working condition of the titanium alloy[10]. Unfortunately, little work has been conducted concerning hot deformation behavior for Ti-6Al-3Nb-2Zr- 1Mo titanium alloy. Therefore, it is necessary to carry out the present investigation. Thus the present work was mainly focused on the hot deformation behavior of the Ti-6Al-3Nb-2Zr-1Mo titanium alloy based on experimental results in isothermal compression tests, the processing maps of this alloy were constructed in order to analyze the instability region, and the optimum condition for plastic deformation procedure of the Ti-6Al-3Nb-2Zr-1Mo alloy was found out.

1 Experiment

The starting microstructure of the alloy as shown in Fig.1 is typical duplex microstructure, which consists of equiaxed, lamellar *α* and inter-granular *β*. The *β*-transus temperature for the alloy was measured to be approximately 995 ºC by optical metallographic.

Compressive specimens with 8 mm in diameter and 12 mm in height were prepared from the forged billet of Ti-6Al-3Nb-2Zr-1Mo alloy, and then hot compression tests were conducted by a Gleeble-3800 simulator. Concentric grooves with a depth of 0.1 mm were made on the tops and the bottoms of the specimen to minimize the friction. Thermal couples were welded in the middle surfaces of the specimens to monitor the actual temperatures of the specimens. Before starting isothermal compression, all specimens were heated at a rate of 15 ºC/s to the target temperature and held for 5 min to homogenize the temperature distribution. Subsequently, the compressed samples were quenched to room temperature immediately in water to preserve the microstructure during hot temperatures. Finally, the compressive specimens for microstructure observation were sectioned parallel to the compression direction, and the cut surfaces were prepared with standard methods. Metallographic observation was carried out on an Olympus-PMG3 optical microscope.

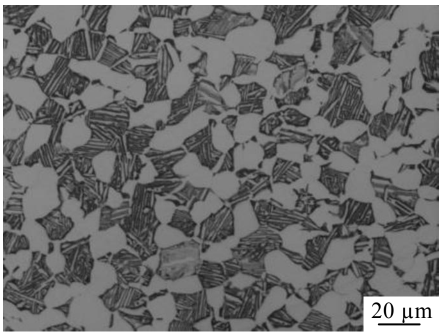

Fig.1 Starting microstructure of Ti-6Al-3Nb-2Zr-1Mo alloy

2 Results and Discussion

2.1 Hot deformation behavior

The dependence of flow stress on the strain for each compressing specimen was obtained after the isothermal compression tests. Typical flow stress-strain curves of Ti-6Al-3Nb-2Zr-1Mo alloy obtained at various strain rates (0.001, 0.01, 0.1 and 1 s^{-1}) and deformation temperatures of 820 and 1000 ºC with height reduction of 60% are shown in Fig.2. The characteristics of the flow curves presented by the alloy at several strain rates and deformation temperatures can be markedly summarized as follows: in the *α*+*β* phase field (820 ºC, Fig.2a), the flow stress curves exhibit flow softening behavior, and the higher the strain rate, the more remarkable the softening. However, in the single *β* phase field, the flow stress remains steady state as the true strain increases. From the aspect of softening mechanism, such feature means that the rate of work hardening is quickly balanced by dynamic recrystallization or dynamic recovery [11]. Moreover, significant oscillations are observed in both the *α*+*β* dual phase and single *β* phase region, which indicate flow localization, dynamic recrystallization and grain boundary cracking[12], and the related characteristic was studied by researchers in other titanium alloy[13,14].

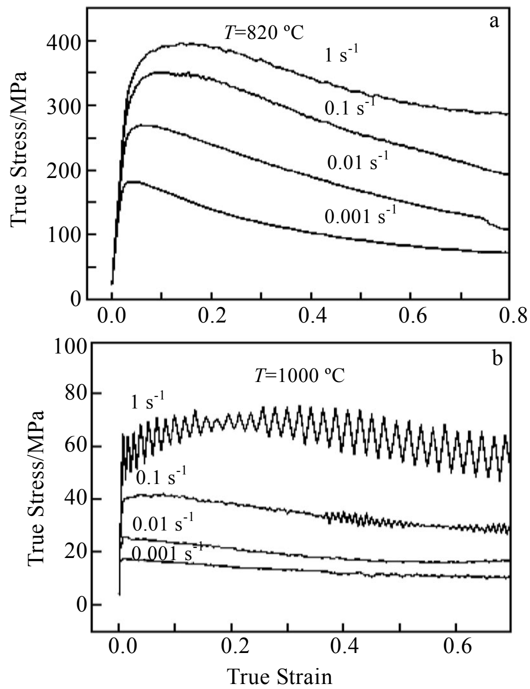

Fig.2 True stress-strain curves obtained from compression tests at different deformation temperatures: (a) 820 ºC and (b) 1000 ºC