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Hot deformation behavior and microstructure evolution of TC4 titanium alloy

SUN Sheng-di(孙圣迪), ZONG Ying-ying(宗影影), SHAN De-bin(单德彬), GUO Bin(郭 斌)

School of Materials Science and Engineering, Harbin Institute of Technology, Harbin 150001, China

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Abstract: The hot deformation behavior of Ti-6Al-4V (TC4) titanium alloy was investigated in the temperature range from 650 °C to 950 °C with the strain rate ranging from 7.7×10^{-4} s^{-1} to 7.7×10^{-2} s^{-1}. The hot tension test results indicate that the flow stress decreases with increasing the deformation temperature and increases with increasing the strain rate. XRD analysis result reveals that only deformation temperature affects the phase constitution. The microstructure evolution under different deformation conditions was characterized by TEM observation. For the deformation of TC4 alloy, the work-hardening is dominant at low temperature, while the dynamic recovery and dynamic re-crystallization assisted softening is dominant at high temperature.

Key words: TC4 titanium alloy; flow stress; hot tension; microstructure

1 Introduction

Titanium and titanium alloys have been widely used in aviation, spaceflight, weapons and so on as structural materials due to low density, high specific strength and high corrosion resistance[1−3]. However, it is difficult for titanium alloys to deform because of their poor deformability, high resilience and low plasticity[4−6], which limits the application of titanium alloys. CUI et al[7] carried out isothermal hot compression tests in the temperature range from 750 °C to 900 °C and strain rate range from 0.001 s^{-1} to 10 s^{-1} for implant biomedical Ti-6Al-7Nb alloy. The stress−strain curves were characterized by flow softening and the optimum hot deformation condition was obtained. STAPLETON et al[8] discussed the evolution of intergranular lattice strains in a textured, forged bar sample of the $\alpha+\beta$ Ti-6Al-4V (TC4) titanium alloy using in situ X-ray diffractometry. SHANG et al[9] studied the influence of heat treatment temperature on the textures in a new Ti-Al-Mo-V-Fe-B titanium alloy thin sheet by means of orientation distribution function. They concluded that the heat treatment temperature should be higher than transition temperature of β phase in order to change the texture of α phase in $\alpha+\beta$ titanium alloy. GONG et al[16] found that the temperature and strain rate had significant effects on the tensile behavior of TC21. However, most of the previous studies were carried out in the compressive stress states, while few studies were focused on the hot tension behavior of the titanium alloys[11−16]. In addition, many components of titanium alloy were processed and deformed under tensile stress. So, it is significant to study the hot tension behavior of titanium alloy to determine the formation process.

In this work, the effects of deformation temperature and strain rate on the flow stress and microstructure evolution of hot-rolled TC4 alloy sheet before and after tension were investigated. The deformation mechanism was revealed.

2 Experimental

The experimental material was hot-rolled TC4 alloy sheet (1 mm in thickness) which was equiaxial two-phase alloy with a chemical composition (in mass fraction) of 5.5%−6.75% Al, 3.5%−4.5% V, <0.45% Fe, <0.24% O, <0.12% C, <0.07% N and balance Ti.

To investigate the hot deformation behavior and microstructure evolution in the $\alpha+\beta$ region, the hot tensile tests were carried out at a temperature ranging from 650 °C to 950 °C with 100 °C intervals and at a strain rate ranging from 7.7×10^{-4} s^{-1} to 7.7×10^{-2} s^{-1}. The specimens were heated with a heating rate of 10 °C/s and soaked for 3 min at the deformation temperature before the hot tension. When the true strain reached 0.4, the experiment was terminated. Tensile specimens with a gauge section of 4.4 mm×1.4 mm×8 mm were prepared

Corresponding author: SUN Sheng-di; Tel: +86-451-86412043; E-mail: sunshengdi2005@163.com
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from the above sheet by electro spark wire-electrode cutting. Phase constitutions were characterized by X-ray diffractometry, which were performed using an X-ray diffractometer employing Cu K_α radiation at room temperature using a step scan procedure (0.02° per 2θ step and 0.5 s count time per step) on a Japan RIGAKU D/MAX−2200 automated powder diffractometer. Microstructures of the composites were observed by a CM12 transmission electron microscopy (TEM). The specimens for TEM observation were thinned by ion milling.

3 Results and discussion

3.1 Hot tension behavior

The hot deformation of titanium alloy at $\alpha+\beta$ phase field behaves complicated because it includes the concurrent deformation process of α and β phases as well as the $\alpha\rightarrow\beta$ phase transformation process. Variations of the flow stress with test temperature and strain rate are shown in Fig.1. It is found that when the strain rate is kept constant, the flow stress decreases gradually with increasing the hot deformation temperature. When the strain rate is 7.7×10^{-2} s^{-1}, the flow stress almost decreases linearly with the increase of the deformation temperature. When the temperature is below 800 °C, the flow stress decreases sharply with increasing the deformation temperature, whereas the flow stress decreases slowly with increasing the deformation temperature when the temperature is above 800 °C. This is due to the fact that the impact of work-hardening vanishes when the strain rate is below a critical value, resulting in the fact that the flow stress is determined by the activated energy. Experiments prove that work-hardening is dominant before the flow stress reaches the peak value. The effect of work-hardening on TC4 alloy is obvious at low temperatures. While at high temperatures, the deformation softening predominates, which is controlled by the dynamic recovery. When the deformation temperature is higher than 850 °C, the flow stress increases with increasing strain until reaching the peak value, followed by a constant until fracture. At 900 °C, the flow stress peak is below 25 MPa. The deformation is mainly controlled by dynamic re-crystallization at high deformation temperature.

The true stress−true strain curves under different strain rates at 750 °C are shown in Fig.2. It is found that the tensile strength increases with increasing the strain rate. In addition, when the strain rate is higher than 7.7×10^{-3} s^{-1}, the specimens fracture before the strain reaches 0.25, which indicates that the TC4 alloy has poor deformability at high strain rate. The higher the strain rate is, the poor the hot tensile deformability is. This indicates that the strain rate plays an important role in the hot deformation process of TC4 alloy.

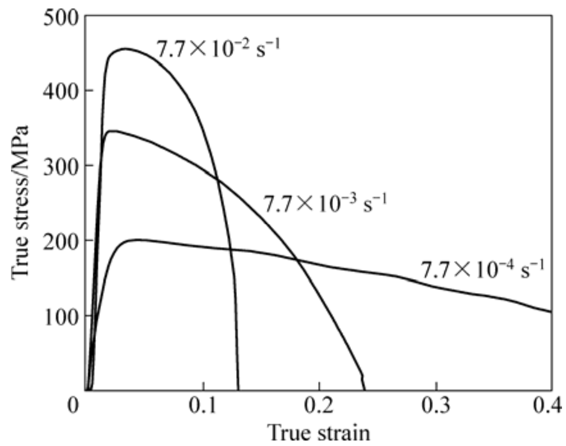

Fig.2 True stress−true strain curves of TC4 alloy deformed under different strain rates at 750 °C

3.2 Phase constitution

XRD patterns of TC4 alloy deformed until fracture at different temperatures under strain rate of 7.7×10^{-3} s^{-1} are shown in Fig.3. TC4 alloy will transform from α-phase

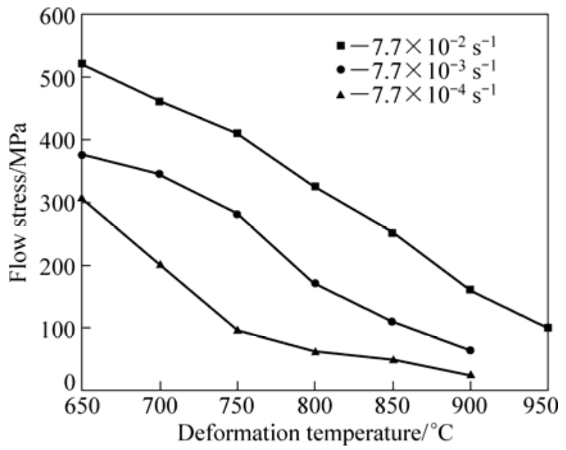

Fig.1 Variation of flow stress with deformation temperature and strain rate

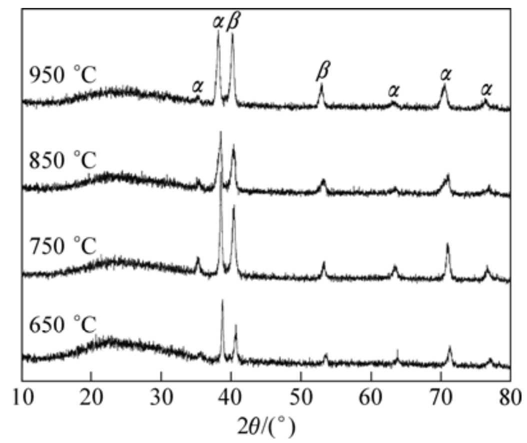

Fig.3 XRD patterns of TC4 alloy deformed at different temperatures under strain rate of 7.7×10^{-3} s^{-1}

into β-phase at about 882 °C. At low temperature (about 650 °C), α-phase of TC4 alloy is the main phase, and β-phase is the minor phase. However, at high temperature (about 950 °C), high content of β-phase in TC4 alloy is detected by XRD, indicating that α-phase of received TC4 alloy is transformed into β-phase. The content of β-phase of TC4 alloy increases with increasing hot-deformation temperature. According to Fig.3, it can be concluded that higher hot-deformation temperature is beneficial for the formation of β-phase of TC4 alloy. At 950 °C, rapid volume fraction increase of β phase entails that the deformation is controlled by dynamic recovery under strain rate of 7.7×10^{-3} s^{-1}. There is no obvious effect of strain rate on the phase transformation of TC4 alloy, so the XRD patterns of TC4 alloy deformed at different strain rates are not given.

3.3 Microstructure evolution

The microstructure of the TC4 alloy during hot tension is strongly influenced by temperature and strain rate. TEM images can provide more information of material microstructures in details. TEM images of TC4 alloy deformed until fracture at different temperatures under the constant strain rate of 7.7×10^{-3} s^{-1} are given in Fig.4.

The phase boundaries are clear when the hot-deformation process is executed at 650 °C under constant strain rate (nearly 7.7×10^{-3} s^{-1}), as shown in Fig.4(a). Many dislocations are kept in the specimen deformed at low temperatures. So, this possibly implies that it is difficult to counteract residual dislocation under low strain rate at 650 °C. More dislocations are formed in the hot-deformation process at 750 °C (as shown in Fig.4(b)). The diffraction patterns of α-phase and β-phase of TC4 alloy are illustrated in Fig.4(c). It is easy to find obviously elongated grains of α-phase and β-phase of TC4 alloy in Fig.4(d), indicating that it is beneficial for TC4 alloy material to form long plate grain under low strain rate and high hot-deformation temperature. This result agrees with the characteristic of the stress−strain curves of TC4 alloy (Fig.1). The high hot-deformation temperature will improve the deformability of TC4 alloy.

4 Conclusions

1) The hot-deformation temperature has an obvious effect on the phase composition, while the strain rate has no effect on phase constitution in the low hot-deformation

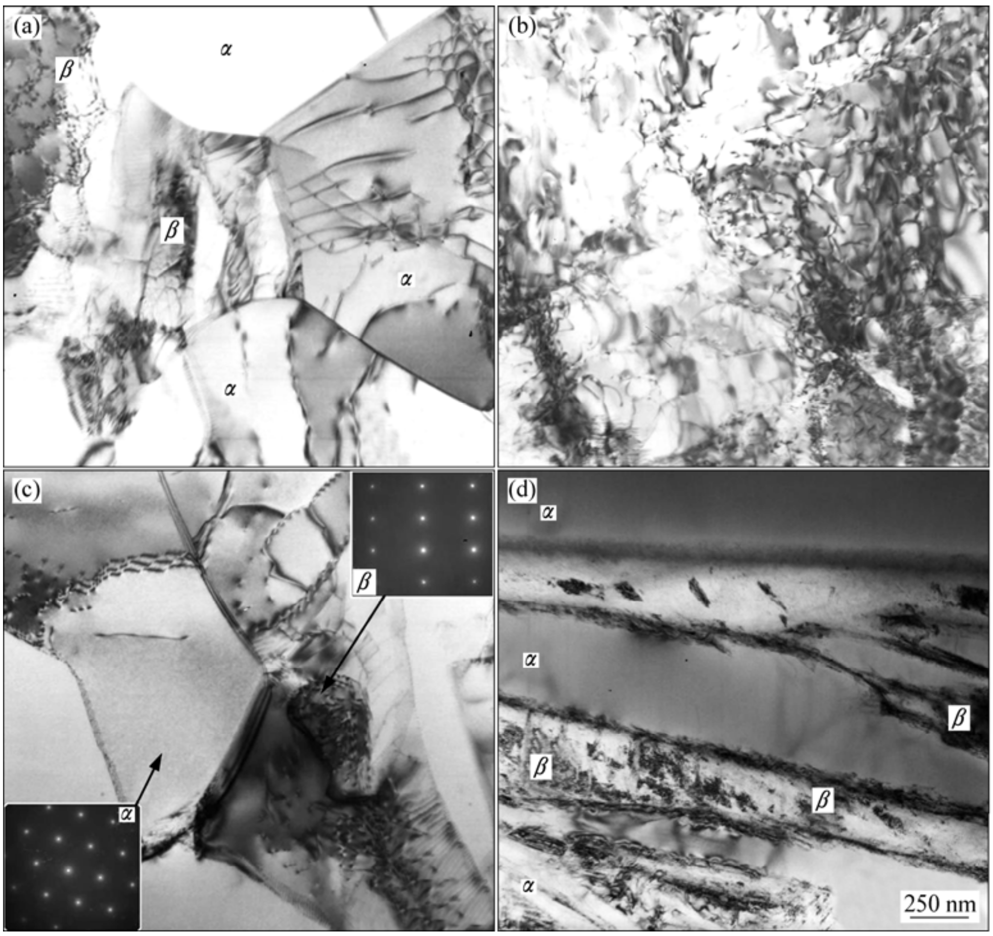

Fig.4 TEM images of TC4 alloy at different temperatures under strain rate of 7.7×10^{-3} s^{-1}: (a) 650 °C; (b) 750 °C; (c) 850 °C; (d) 950 °C

temperature. The high hot-deformation temperature is beneficial for the formation of β-phase of TC4 alloy.

2) The softening mechanism is dynamic recovery and dynamic re-crystallization. It is beneficial for TC4 alloy to form long plate grains under low strain rate and high hot-deformation temperature according to the microstructure analysis.

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