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Transformation mechanism and mechanical properties of commercially pure titanium

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Abstract: In order to establish the rolling process parameters of grade-2 commercially pure titanium (CP-Ti), it is necessary to understand the transformation mechanism and mechanical properties of this material. The $\beta\rightarrow\alpha$ transformation kinetics of the grade-2 CP-Ti during continuous cooling was measured and its hot compression behavior was investigated using Gleeble-1500 thermal mechanical simulator. Dynamic CCT diagram confirms that cooling rate has an obvious effect on the start and finishing transformation and microstructures at room temperature. The critical cooling rate for β-phase transforms to α phase is about 15 °C/s. When the cooling rate is higher than 15 °C/s, some β phases with fine granular shape remain residually into plate-like structure. The plate-like α phase forms at cooling rate lower than 2 °C/s, serrate α phase forms at medium cooling rates, about 5−15 °C/s. The flow stress behavior of grade-2 CP-Ti was investigated in a temperature range of 700−900 °C and strain rate of 3.6−40 mm/min. The results show that dynamic recrystallization, dynamic recovery and work-hardening obviously occur during hot deformation. Constitutive equation of grade-2 CP-Ti was established by analyzing the relationship of the deformation temperature, strain rate, deformation degree and deformation resistance.
Key words: commercially pure titanium; phase transition; mechanical properties; flow stress

1 Introduction

The practice shows that a rolling process has higher billet productivity and lower energy consumption than forging process. Its production cost is 1/3 that of forging billet[1−3]. Titanium ingots still have been bloomed on the forging hammer in China, while the process is widely operated on mill in America, Japan and Russia[4−5]. Thus, our products are lack of competitive ability on the international and domestic market. It is urgent to replace forging by rough rolling ingots of titanium and its alloys. Rolling process is a different plastic deformation from forging process, the forming temperature range and deformation degree of rolling process as well as the cooling mode after finish rolling is distinguished from hot forging. Before rolling titanium ingots, it is necessary to study the transformation mechanism and mechanical properties of titanium and its alloys. The $\beta\rightarrow\alpha$ transformation kinetics of titanium and titanium alloys is important in determining their microstructure[6−9], and the relationship of strain and stress is applied to calculate hot rolling forces in various reduction amounts in hot rolling process[10−13]. The $\beta\rightarrow\alpha$ transformation kinetics of commercially pure titanium (CP-Ti) during continuous cooling was measured by KIM and PARK[6], but the phase transformation temperatures were not measured during continuous cooling after compression. ZHOU et al[14] investigated the tensile deformation behavior of CP-Ti at 700, 750 and 800 °C at cooling rates of 4.5, 12 and 45 mm/min, simultaneously. CHEN et al[15] analyzed microscopic mechanisms underlying the dynamic tensile behaviors of a commercially pure titanium at different temperatures (298−973 K) and strain rates (10^{-3}−1 400 s^{-1}). NASSER et al[11] studied mechanical properties and deformation mechanisms of a CP-Ti in compression test at a temperature range of 77−1 000 K and strain rates of 10^{-3}−8 000 s^{-1}. However, the phase transformation temperature and mechanical properties depend on factors such as composition, processing regime and cooling rate. In this work, transformation temperatures of grade-2 CP-Ti were

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measured by thermal mechanical simulation tests and its flow stress were investigated in hot compression using a Gleeble-1500 thermal mechanical simulator.

2 Experimental

2.1 Materials

Table 1 lists the composition of grade-2 CP-Ti investigated in this study. The alloy was mold cast into an ingot with dimensions of *d*1 040 mm×2 400 mm. It is important to note that this material contains a significant amount of Fe as an impurity. The middle part of the ingot was machined into bar specimens with dimensions of *d*8 mm×15 mm using an electro-discharge machine.

Table 1 Chemical composition of steels (mass fraction, %)

Fe	Si	C	H	O	N	Ti
≤0.30	≤0.15	≤0.10	≤0.05	≤0.15	≤0.05	Bal.

2.2 Experimental procedure

2.2.1 Dynamic continuous cooling transformation (CCT) diagram

The start and finishing transformation temperatures of grade-2 CP-Ti were measured in continual cooling procedure. Thermal mechanical simulation tests were carried out on a Gleeble 1500 thermal simulator. Round specimens were compressed and continually cooled at various cooling rates. Specimens were heated at a heating rate of 10 °C/s up to 950 °C and held for 10 min, then cooled at 5 °C/s to 930 °C, these specimens were hot compressed with a true strain of 0.6 and at a strain rate of 10 s^{-1}. Finally, these compressed specimens were treated by cooling process. The cooling rates were 0.5, 1, 2, 5, 7, 10, 15 and 20 °C/s, respectively. Schematic diagram of measuring dynamic CCT was shown in Fig.1. The microstructure of these specimens were observed with optical microscopes after they were mechanically polished and chemically etched, CCT diagrams were constructed for each heat by analyzing the dilation curves and metallographic examination of the specimens.

2.2.2 Flow stress

Hot compression tests were carried out on a Gleeble 1500 thermal simulator. Specimens were heated to 950 °C at a rate of 10 °C/s and held for 2 min, then cooled at a rate of 5 °C/s to 900，850，800，750 and 700 °C, respectively and held for 2 min. These specimens were hot compressed with a true strain of 0.6 and strain rates of 3.6, 10, 30 and 40 mm/min, respectively. After that, these compressed specimens were cooled by water spraying to room temperature. The schematic diagram is shown in Fig.2.

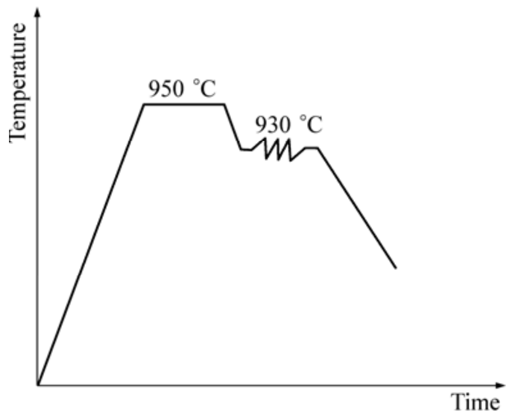

Fig.1 Schematic diagram of measuring dynamic CCT

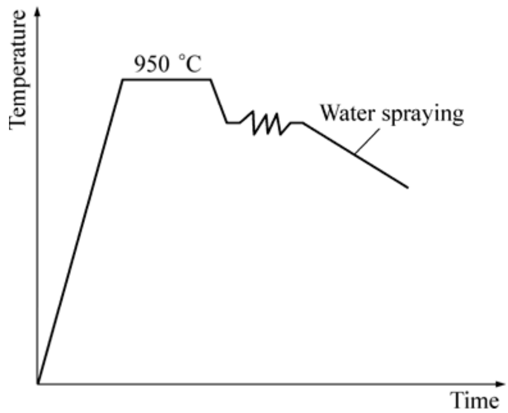

Fig.2 Schematic diagram of hot compressed test

3 Results and discussion

3.1 Dynamic CCT diagram

Dynamic CCT diagram of experimental materials is given in Fig.3. When cooling rate is down to 0.5 °C/s, the start and finishing temperature of the *α*-*β* transformation are 885 and 874 °C, respectively. And when cooled over 1 °C/s, the start temperature is between 886 and 890 °C and the finishing temperature is between 833 and 868 °C which increases with increasing

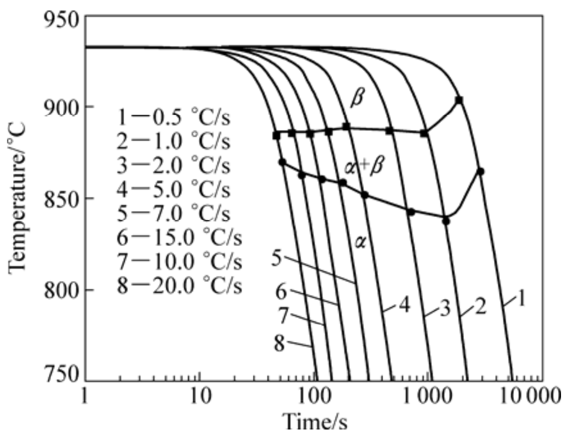

Fig.3 Dynamic CCT diagram of alloys deformed at 930 °C

cooling rate. The transformation temperatures in this paper are different from those in Ref.[6].

The continuous cooled microstructure of the experimental material is shown in Fig.4. It is found that cooling rate has a great effect on the microstructure of CP-Ti. The microstructures are mainly composed of lamellar α phase. When the cooling rate is lower than 15 °C/s, the grains trend fine with increasing cooling rate. When the cooling rate is up to 15 °C/s, some residual β phases with fine granular structure change into lamellar structure, and the amount increases with the increasing cooling rate.

Plate-like α phase forms in lower cooling rates of 0.5, 1 and 2 °C/s, as shown in Figs.4(a)−(c). The results

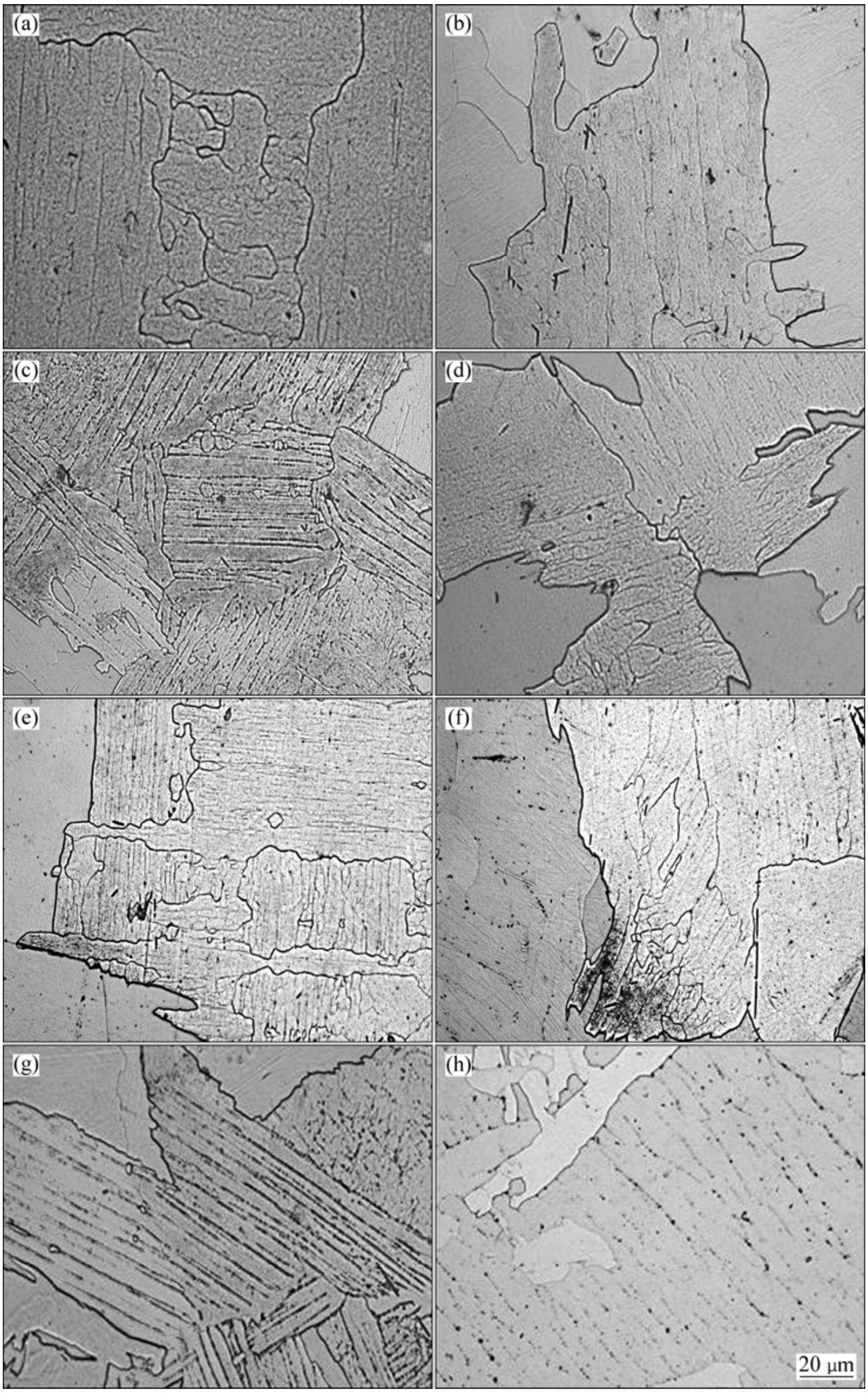

Fig.4 Optical micrographs of alloys at different cooling rates: (a) 0.5 °C/s; (b) 1 °C/s; (c) 2 °C/s; (d) 5 °C/s; (e) 7 °C/s; (f) 10 °C/s; (g) 15 °C/s; (h) 20 °C/s

show that the morphology is almost coarse plate-like structure containing a little amount of strip-like phase, which is more at 2 °C/s than at 1 °C/s. All the microstructures change from plate-like to serrate when cooling rate increases from 5 to 10 °C/s, no residual β phase remains, which is shown in Figs.4(d)−(f). Net-like α phase appears when cooling rate is higher than 15 °C/s.

Different morphologies are compared in Figs.4(f)−4(g) and Figs.5(a)−(c). Fig.5 presents dark field images corresponding to the bright field images in Fig.4. When the cooling rate is less than 15 °C/s, β-phase almost transforms to α phase, which is the reason that residual β-phase grains can not be observed in dark field image in Fig.5(a). However, when the cooling rate is up to 15 °C/s, β-phase does not completely transform to α phase, some of it remains in lamellar structure which is composed of strips and fine granules shown in Fig.4(g). Residual β-phase is represented by white fine granules distributed in a narrow and long belt shown in dark field images of Fig.5(b). When the cooling rate is up to 20 °C/s, the lamellar structures disappear as shown in Fig.4(h). A lot of residual β-phase with white fine granules in linear form are observed in Fig.5(c). Residual β-phase grains increases with the increase of cooling rate.

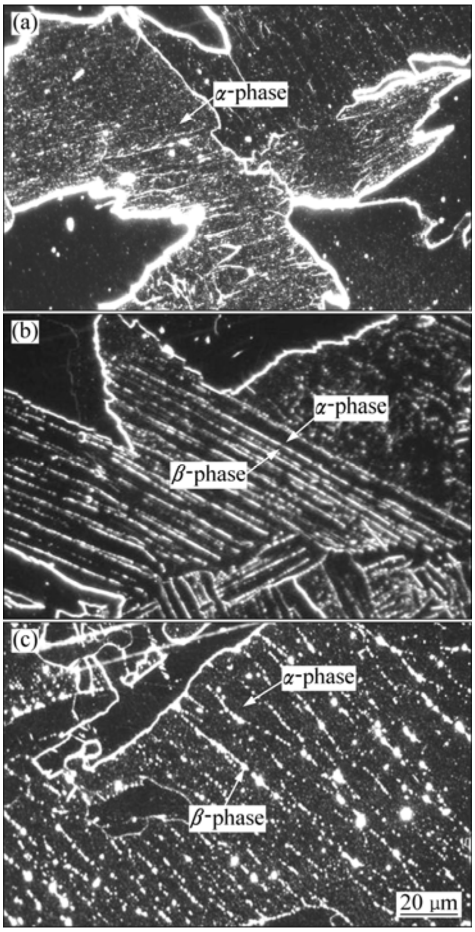

Fig.5 Optical micrographs of alloys at different cooling rates: (a) 0.5 °C/s; (b) 15 °C/s; (c) 20 °C/s

3.2 Flow stress

The true stress—strain curves resulting from the hot compression tests at 700, 750, 800，850 and 900 °C and the strain rates of 3.6, 10, 30 and 40 mm/min are shown in Figs.6(a)−(d). The flow stress of grade-2 CP-Ti is strongly dependent on the temperature and strain rate, and displays obvious differently with strain, strain rate and temperature. At the same strain rate and strain, the flow stress and stress peaks of grade-2 CP-Ti decrease significantly with the increase of temperature. As shown in Fig.6, the flow stress obtained at 700 °C is higher than those obtained at the other four higher temperatures. When the deformation is performed at strain rates of 3.6, 10, 30 and 40 mm/min and temperature of 900 °C, the flow stress exhibits a slight transitional drop indicating dynamic recrystallization behavior. However, at 700 °C, the true stress—strain curves show work-hardening characteristic without any peaks. At 750, 800 and 850 °C, the flow stress shows a steady-state flow at strain rates of 3.6, 10, 30 and 40 mm/min. The results show that only dynamic recovery occurs during hot deformation of CP-Ti in the temperature range.

Figs.6(a)−(d) also reveal the strain rate sensitivity of grade-2 CP-Ti. At the same temperature, the flow stress increases with increasing strain rate. For instance, at 700 °C and strain rate of 3.6 mm/min, the steady flow stress is 78 MPa, in contrast, the steady flow is 120 MPa at a strain rate of 40 mm/min at the same temperature. It can be concluded that the work-hardening effect is obvious at lower temperature. In the middle temperature range of 750，800 and 850 °C, the stress—strain curves show dynamic recovery behavior. And dynamic recrystallization behavior occurs in deformed grade-2 CP-Ti at 900 °C.

The stress—strain data obtained from the compression tests under different strain rates and temperatures can be used to determine the material constants of the constitutive equations which are generally employed to set up models for deformation response in the working process of metals. For this purpose, using the obtained experimental data, the constitutive equation derived by WEI et al[16] is introduced to describe the plastic deformation behavior of pure titanium at constant strain rates ranging from 3.6 to 40 mm/min and at temperatures between 700 to 900 °C.

The constitutive equation can be written as

$$\sigma = C\varepsilon^n \dot{\varepsilon}^m \exp\left(\frac{\beta}{T}\right) \tag{1}$$

where C is the constant concerning with stress; ε is the strain; $\dot{\varepsilon}$ is the strain rate; σ is the flow stress; T is the absolute deformation temperature; β is the coefficient concerning with temperature; m is the strain rate sensitivity coefficient and n is the strain hardening exponent.

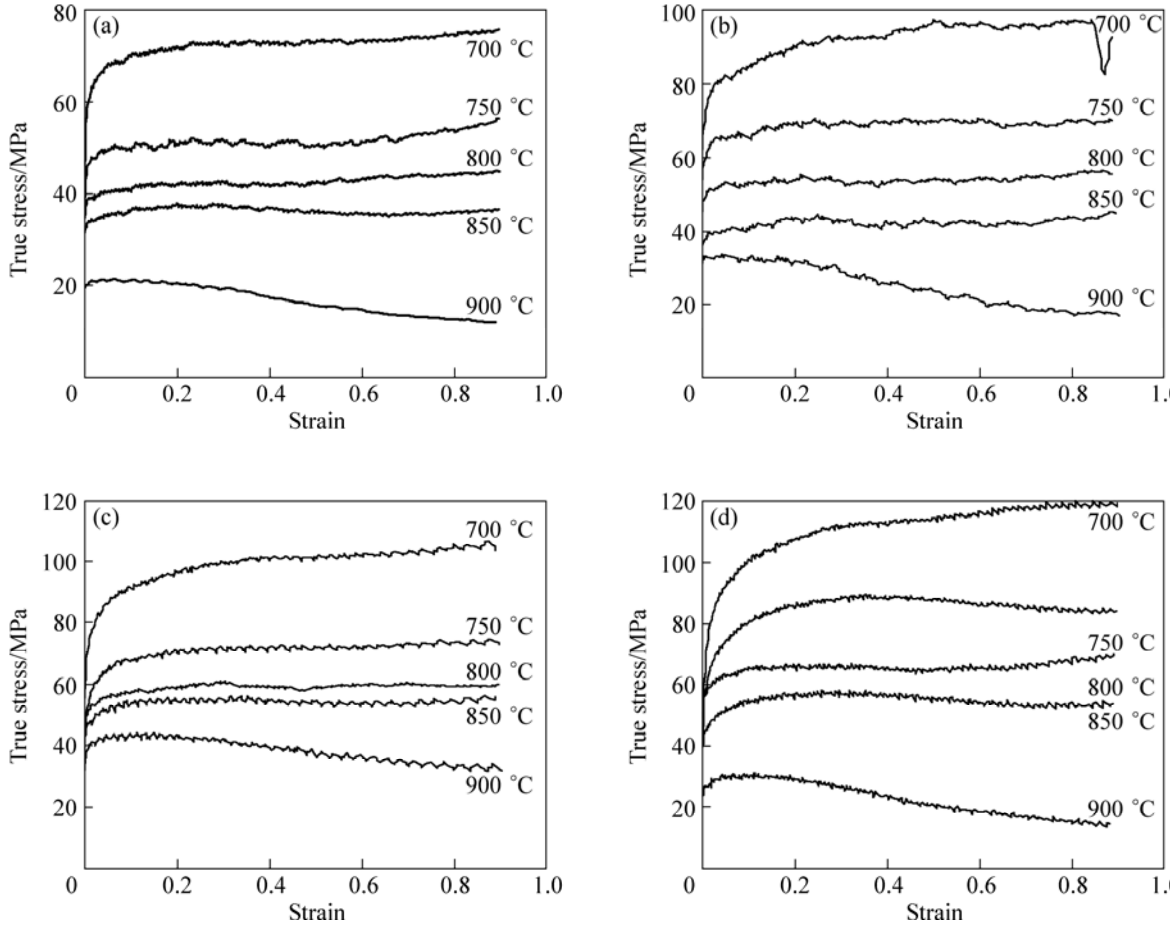

Fig.6 True stress—strain curves of alloys at different strain rates: (a) 3.6 mm/min; (b) 10 mm/min; (c) 30 mm/min; (d) 40 mm/min

Constitutive equation of grade-2 CP-Ti for high temperature is gained by computing every parameter of the constitutive equation models. Then constitutive equation for grade-2 CP-Ti during hot compression is shown as

$$\sigma = 0.255\varepsilon^{0.00032}\dot{\varepsilon}^{0.171876}\exp\left(\frac{6446.771}{T}\right) \quad (2)$$

4 Conclusions

1) Dynamic CCT diagrams confirm that cooling rate has an obvious effect on the start and finishing transformation and microstructures at room temperature. The cooling rate of 15 °C/s is a critical point at which β phase transforms completely to α phase. When cooling rate is up to 15 °C/s, some residual β phase remains in α phase. Plate-like α phase forms at cooling rates lower than 2 °C/s, serrate α phase occurs at medium cooling rates, from 5 to 10 °C/s. Net-like α phase appears after cooling rate is higher than 15 °C/s.

2) There are three deformation patterns of grade-2 CP-Ti at a temperature range from 700 to 900 °C. Dynamic recrystallization occurs at 900 °C, dynamic recovery takes place at middle temperature range from 750 to 850 °C, and the work-hardening phenomenon occurs at a lower temperature of 700 °C.

3) The constitutive equation of grade-2 CP-Ti is established by analyzing the relationship of the deformation temperature, strain rate, deformed degree and deformation resistance.

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