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LETTER

Grain Growth Kinetics of TB18 Titanium Alloy

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Abstract: The β grain growth behavior of a novel high strength TB18 titanium alloy was investigated through the variation of β grain size in TB18 titanium alloy under the conditions of different temperatures and holding times. Results show that the heat treatment temperature and holding time have significant effects on the β grain growth of TB18 titanium alloys. The β grain size is increased with increasing the solution temperature and holding time. Besides, the coarsening temperature of TB18 alloys is 920 °C. The grain growth exponents and grain growth activation energy were calculated by Beck equation and Arrhenius equation, respectively. The grain growth exponent n is 0.13~0.26 for the TB18 alloys. The grain growth activation energy of the TB18 alloy is 34.27~60.58 kJ/mol.

Key words: titanium alloy; β heat treatment; grain size; grain growth activation energy

Metastable β alloys are widely used in aerospace due to their excellent comprehensive properties of strength, toughness, and plastic properties[1,2]. In recent years, in order to meet the need of high strength and high fracture toughness of aerospace industry, the novel high strength-toughness titanium alloys attract much attention and are used as large aeronautical structures to replace superhigh strength steel. TB18 (Ti-5Al-5Mo-5V-6Cr-1Nb-0.5Fe) titanium alloy[3] is a new high-strength and high-toughness titanium alloy with near-β structure. Compared with other near-β titanium alloys, such as Ti-1023 and Beta21S alloys, the TB18 alloy possesses optimal combination of strength, toughness, and hardening ability.

Nowadays, the damage-tolerance design has become an important design criterion for safe service of titanium alloy application in the aerospace field. In order to achieve the high toughness, β heat treatment is used to obtain high fracture toughness for titanium alloys. Grain size of alloys after β heat treatment is also an important factor to determine the mechanical properties[4-7]. Hence, it is necessary to understand the grain growth behavior before adjusting the process parameters. In this research, the β grain growth kinetics of TB18 titanium alloy was investigated. The results provided a better understanding for the evolution of β grains as well as a significant guidance for the design of heat treatment.

1 Experiment

The TB18 alloy was hot-forged into billet of 400 mm in diameter and then melted by Western Superconducting Technologies Co., Ltd for the experiments. The chemical composition of TB18 alloy billet is 4.2wt% Al, 4.72wt% Mo, 5.72wt% Cr, 1.06wt% Nb, and balance Ti. The β transus temperature (T_β) of TB18 alloy is (800±5) °C. The billet microstructure was observed by optical microscope (OM, OLYMPUS PMG3), as shown in Fig.1. It can be seen that the billet microstructure consists of a large amount of fine

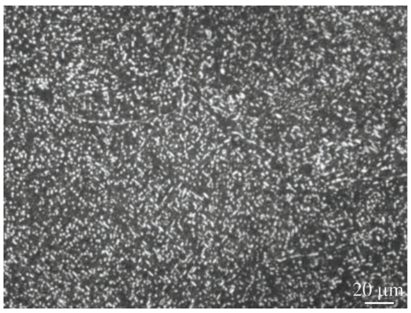

Fig.1 OM microstructure of TB18 alloy billet

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equiaxed or short-bar α phase and a small amount of transformed β phase.

The cubic specimens were cut from the billet by electrical discharge, then furnace-heated at 840, 880, 920, 960, and 1000 °C for holding time of 0.5, 2, 4, 8, and 10 h, and finally water-quenched. The specimens were then metallographically polished and chemically etched by the Kroll's reagent[8] to observe the grain microstructure. The grain size was determined by cut-off point method according to GB/T6394-2002[9] by Image-Pro Plus software.

2 Results and Discussion

2.1 Effect of solution temperature and holding time on uniformity of β grain size

The microstructures of the specimens after heat treatment at different temperatures for 0.5 h are shown in Fig.2. According to Fig.2, the equiaxed β single phase grains are formed and the β grains become coarser with increasing the solution temperature. However, the grain growth rate is different at different solution temperatures. The β grain sizes are similar in the specimens after solution treatment at 840~920 °C. The grains begin to grow obviously when the temperature exceeds 960 °C. The microstructures of the specimens after solution treatment at 840 and 1000 °C for different holding time are shown in Fig. 3. The slow grain growth rate of TB18 specimens can be observed with increasing the holding time from 2 h to 10 h during the solution treatment at 840 °C.

To assess the grain size variation, the relationships of average β grain size with temperature and holding time are shown in Fig. 4. As shown in Fig. 4a, the β grain size is increased with increasing the solution temperature. The grain growth is significantly increased when the solution temperature exceeds 920 °C. Furthermore, the grain growth rate reaches the maximum when the TB18 specimen is solution-treated at 1000 °C. Therefore, the coarsening temperature of TB18 alloy is 920 °C. The grain size difference of the specimens solution-treated at 1000 and 920 °C (ΔD_1) is significantly larger than that at 920 and 840 °C (ΔD_2), as shown in Fig.4b. which is closely associated with the diffusion rate of the Mo and Nb solid solutions. Rapid diffusion leads to the rapid migration of grain boundaries and thus the rapid grain growth. When the alloy is solution-processed at low temperature, the diffusion rate of the solution atoms is very slow, which has a pulling effect on the grain boundary and inhibits the grain growth. When the temperature is higher than 960 °C, the solid solution atoms have enough activation energy to migrate, and then the migration of grain boundaries is accelerated, thus resulting in the acceleration of grain growth.

Meanwhile, the β grain size is increased with prolonging the holding time, as shown in Fig.4b. It is found that the grain growth occurs at a very fast rate when the holding time ranges from 0.5 h to 2 h, and its rate is basically stable with further prolonging the holding time from 2 h to 10 h.

2.2 Grain growth kinetics

It is well known that the driving force for grain growth is the energy associated with the decrease in grain boundary area[10]. In pure metals and stable solid solution alloys, the kinetics of normal grain growth can be described by the Beck equation[11,12], as follows:

$$D-D_0=Kt^n \quad (1)$$

where D and D_0 are the instantaneous and the initial average grain sizes, respectively; t is the holding time; K is a parameter depending on material and temperature; n is the grain growth exponent.

In the research, D_0 is assumed to be zero because it is much smaller than D. So D_0 can be neglected. Therefore, Eq.(1) can be simplified as follows:

$$D=Kt^n \quad (2)$$

In logarithmic form, Eq.(2) can be expressed as follows:

$$\ln D=\ln K+n\ln t \quad (3)$$

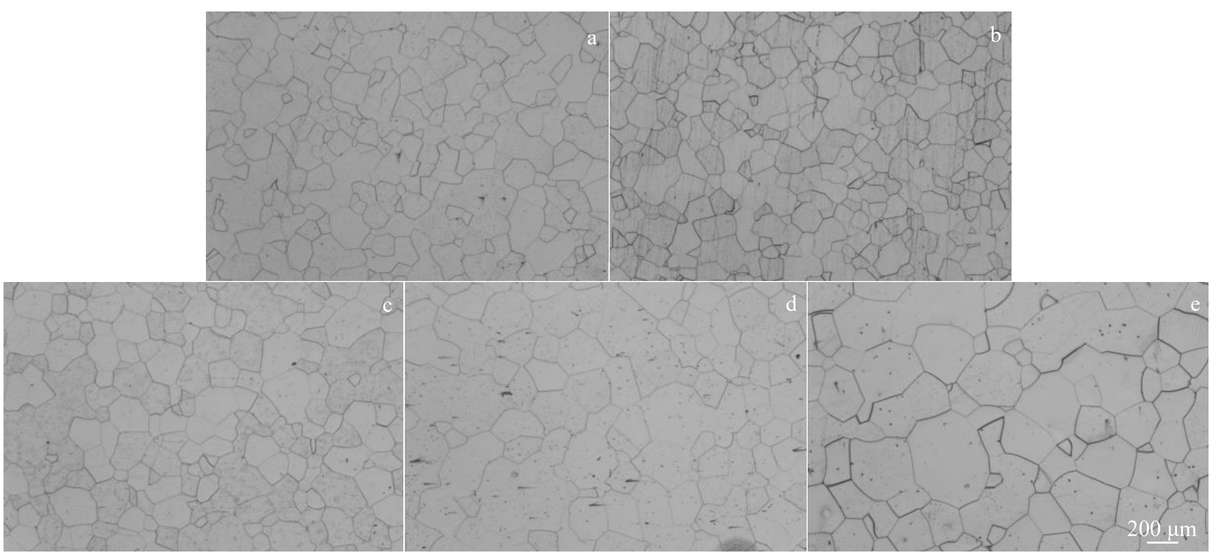

Fig.2 Microstructures of TB18 alloy specimens after solution treatment at different temperatures for 0.5 h: (a) 840 °C, (b) 880 °C, (c) 920 °C, (d) 960 °C, and (e) 1000 °C

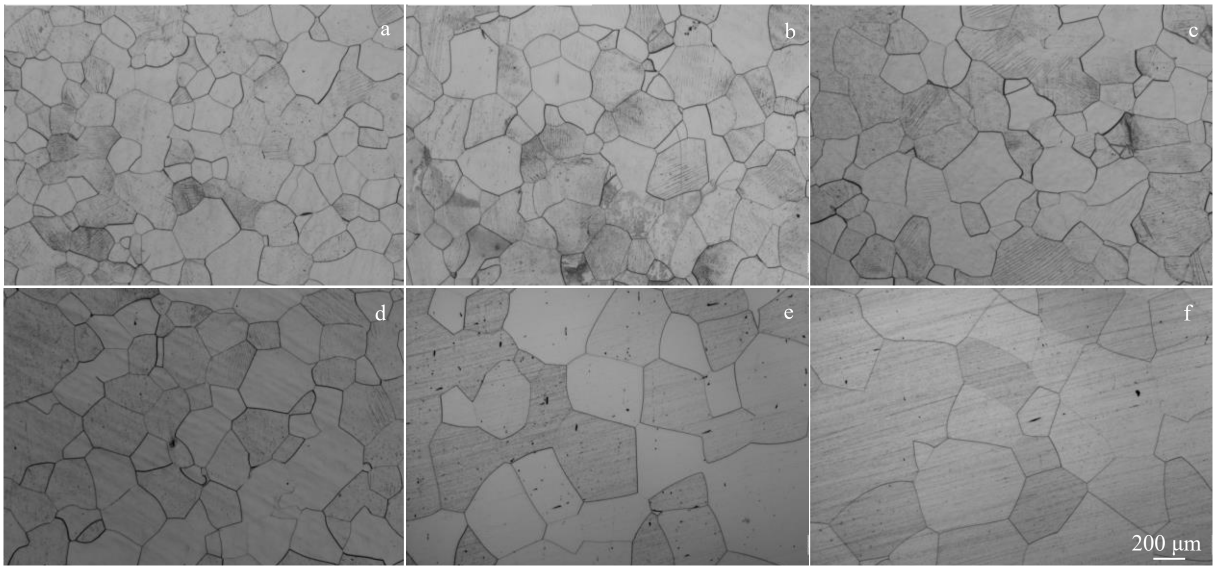

Fig.3 Microstructures of TB18 alloy specimens after different solution treatments: (a) 840 °C/2 h, (b) 840 °C/4 h, (c) 840 °C/8 h, (d) 840 °C/10 h, (e) 1000 °C/2 h, and (f) 1000 °C/10 h

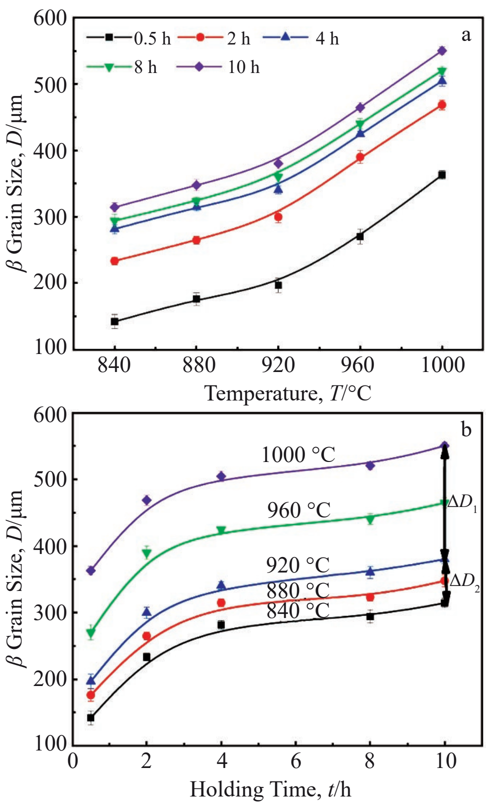

Fig.4 Relationships of β grain size with temperature (a) and holding time (b)

The relationship between ln$D$ and ln$t$ can be obtained by linear fitting analysis based on the test data, as shown in Fig.5. It can be seen that ln$D$ has a good linear relationship with ln$t$ at different solution temperatures. In addition, the β grain growth exponent n at different solution temperatures can be obtained as 0.13~0.26, which is lower than the n value of pure titanium (0.5) [13]. This is ascribed to different influencing parameters of grain growth, such as solute drag, texture, free surface effect, and dislocation substructure[14].

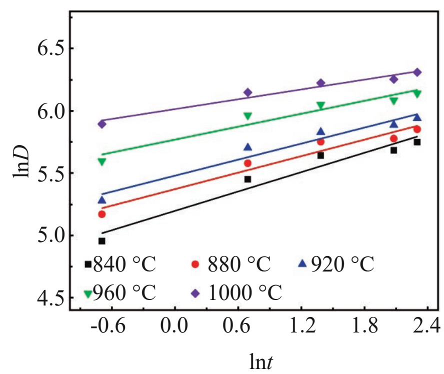

Fig.5 Relationship between ln$D$ and ln$t$ of TB18 alloys after solution treatment at different temperatures

Therefore, the kinetics of β grain growth can be modeled with a modified equation[15], as follows:

$$D^m - D_0^m = Gt \quad (4)$$

where m=1/n; G is the grain growth rate constant depending on treatment temperature. Thus, G can be expressed in an Arrhenius form, as follows:

$$G = A\exp(-Q/RT) \quad (5)$$

where A is a material constant, Q is the activation energy for grain growth, R is the gas constant of 8.314 J/mol, and T is the absolute temperature.

Fig. 6 shows the relationships between ln$G$ and T^{-1}. Thus, the activation energy of grain growth for TB18 alloy is 34.27~60.58 kJ/mol, which is 20%~30% of the diffusion activation energy of β titanium alloy (166 kJ/mol) [16]. It is inferred that the grain boundary migration of the TB18 alloy depends on the short-circuit diffusion at the grain boundary. Due to the

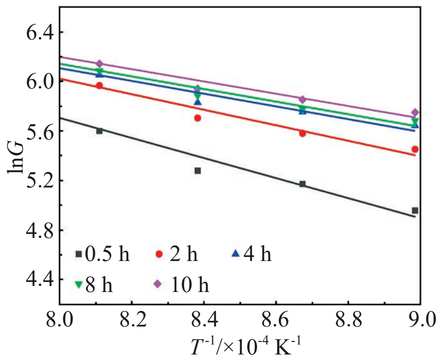

Fig.6 Relationship between ln$G$ and T^{-1} of TB18 alloys after solution treatment for different holding times

high defect density and high atomic mobility at the grain boundary, the migration energy barrier is low.

3 Conclusions

1) The β grain size of TB18 titanium alloy is increased with increasing the solution temperature and holding time. The grain growth increases significantly when the solution temperature exceeds 920 °C. The coarsening temperature of TB18 alloy is 920 °C.

2) The grain growth exponent n is 0.13~0.26, and the activation energy for β grain growth is 34.27~60.58 kJ/mol.

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TB18钛合金晶粒长大动力学

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摘　要：通过TB18钛合金在不同温度和保温时间的条件下β晶粒尺寸的变化，研究了新型超高强TB18钛合金β晶粒的长大行为。结果表明，加热温度及保温时间对TB18钛合金β晶粒长大行为具有重要影响：β晶粒尺寸随加热温度及保温时间的增加而增加，且920 ℃为合金的粗化温度。通过Beck公式计算了晶粒长大参数，采用Arrhenius公式计算了晶粒长大激活能。TB18钛合金β晶粒长大指数n为0.13~0.26，β晶粒长大激活能为34.27~60.58 kJ/mol。

关键词：钛合金；β热处理；晶粒尺寸；晶粒长大激活能

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