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Microstructural evolution and mechanical properties of Ti−5Al−5Mo−5V−3Cr alloy by heat treatment with continuous temperature gradient

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Abstract: A new high throughput heat-treatment method with a continuous temperature gradient between 600 and 700 °C was utilized on the Ti-5553 alloy (Ti−5Al−5Mo−5V−3Cr, mass fraction, %). The temperature gradient was induced by the variation of the axial section of sample, which was heated by the direct current. The variation of continuous cooling rates on the treated sample was realized by using the end quenching method. The microstructural evolution and mechanical properties under different heat treatment conditions were evaluated. The results show that the pseudo-spinodal decomposition of the alloy occurs at (617±1) °C, and the size of the precipitated α phase is around 300 nm. Moreover, the highest microhardness is obtained after the heat treatment at the pseudo-spinodal decomposition temperature for 4 h. These indicate that the high throughput method is efficient and fast to determine the phase transformation temperature and corresponding microstructural evolution of alloys.

Key words: Ti−5Al−5Mo−5V−3Cr alloy; high throughput method; pseudo-spinodal decomposition; temperature gradient; microstructure; mechanical properties

1 Introduction

Near-β titanium alloys, which can be quenched to room temperature and retain a full β phase microstructure, are wildly used in structural applications. Ti-5553 alloy (Ti−5Al−5Mo−5V−3Cr, mass fraction, %) is one kind of new near-β titanium alloys with excellent hardenability and reduced sensitivity of hot working variables [1]. It has gradually replaced Ti−10V−2Fe−3Al and Ti−6Al−4V in the applications of landing gear of Boeing-787 and Airbus-A380 airplanes. However, the optimization of mechanical properties, such as balancing strength, toughness, ductility and fatigue resistance, is dependent on very careful control of the thermo-mechanical processing parameters. A little change in processing parameters can induce very different precipitation microstructures and properties [1−3]. For near-β titanium alloys, the high strength is usually controlled not only by the β phase itself, but also largely by the distribution of the fine-scaled α precipitates [4]. IVASISHIN et al [5] studied three near-β titanium alloys, TIMETAL-LCB, VT22 and Ti-15-3-3-3 (Ti-15-3), and found that only fine plate-like α lathes contribute to high strength. It is most likely that the fine α phase induces a large number of α/β interfaces, which hinder the movement of dislocations.

Recently, a new non-classical strengthening mechanism in β-Ti alloys called pseudo-spinodal decomposition has been discovered [6]. The mechanism favors thermodynamically in the transformation of β phase into fine α phase without compositional change but involving compositional fluctuations [7,8]. The microstructure, presenting a chessboard nanowire structure, is very sensitive to temperature as well as alloy composition [9]. This decomposition was observed in other alloys like Co−Pt [10], Ti−Nb−Al [11] and even in some oxide ceramics [12−14]. In Ti alloys, the pseudo-spinodal decomposition of Timetal 21S alloy (Ti−15Mo−3Al−2.7Nb−0.3Si, mass fraction, %) was studied. The results indicated that the pseudo-spinodal decomposition became active at 550 °C, leading to a drastic increase in the density of intragranular α precipitates. Ti-5553 alloy was also studied by NAG et al [8], and the temperature of pseudo-spinodal decomposition was found to be between 600 and 650 °C. However, the exact

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temperature was not determined yet. Therefore, there are also some uncertainties in the pseudo-spinodal decomposition of Ti-5553 alloy. Firstly, it is very time-consuming in observing the microstructural change of the alloy aged at very small temperature intervals in order to determine the accurate temperature for the pseudo-spinodal decomposition. Secondly, since the mechanical properties are largely dependent on the size and volume fraction of α phase, it is very important to systematically study the microstructural evolution in the pseudo-spinodal decomposition. Currently, there have been some high throughput methods for studying the compositional designs and microstructural evolution of alloys. These methods can also be used to optimize process parameters in a time-saving and efficient way. AFONSO et al [15] utilized the end quenching test to obtain different cooling rates of Ti−20Nb alloy. The variation of cooling rates leads to different microstructures and mechanical properties.

In this work, a new high throughput heat treatment method was developed. In this method, a temperature gradient was exerted on the samples. Each section of the sample represented a heat treatment condition, and the microstructural evolution in the whole temperature range can be conveniently studied by using a single sample. The method was used to study the pseudo-spinodal decomposition of Ti-5553 alloy, in order to determine the accurate decomposition temperature and to build up the relationship between the heat treatment parameters and the precipitation of α phase.

2 Experimental

2.1 Material preparation

The forged Ti-5553 alloy used in the present work was provided by Baogang Company, China. The chemical composition of the alloy is shown in Table 1.

Table 1 Chemical composition of Ti-5553 alloy (mass fraction, %)

Al	Mo	V	Cr	Fe	O	N	Ti
5.57	4.97	4.93	3.05	0.49	0.145	0.02	Bal.

Small circular truncated cone sample with the length of 40 mm shown in Fig. 1(a) was cut from the Ti-5553 alloy bar by spark erosion, and then encapsulated in quartz tube under the protection of pure argon. The sample was heated to 1000 °C for 1 h to produce a full β-phase microstructure with equiaxed grains. After that, the sample was equipped on the Gleeble3180 thermal mechanical machine and then heated by the direct current, and the local heat was dependent on the electric resistance of the Ti-5553 alloy, shown as follows:

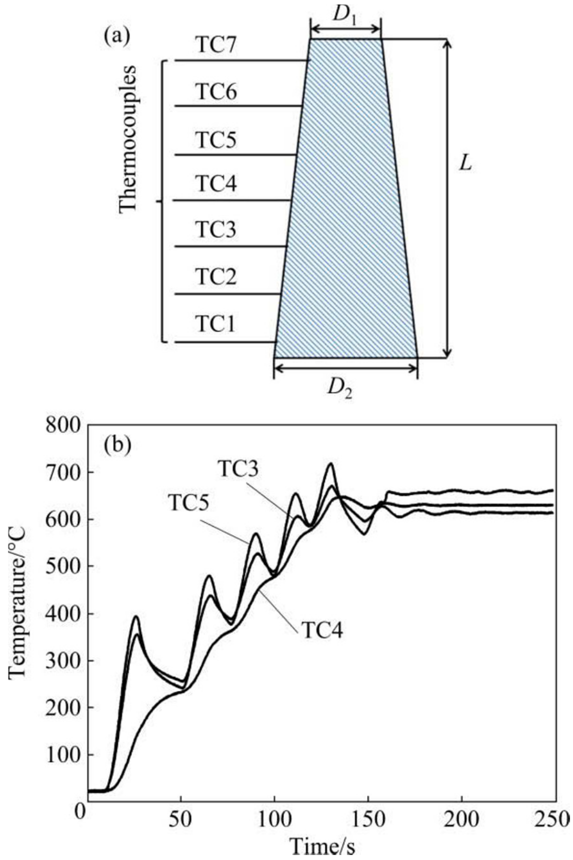

Fig. 1 Schematic illustration of sample for high throughput heat-treatment method (a) and temperature change with heating time measured by thermocouples (b)

$$Q=I^2Rt \quad (1)$$

where Q denotes the thermal energy, I is the current, R represents the resistance of the Ti-5553 alloy and t is the time. The resistance of the alloy is decided as follows:

$$R=\frac{\rho L}{s} \quad (2)$$

where ρ is the electrical resistivity of Ti-5553 alloy, L and s denote the length and the cross-sectional area of the sample, respectively, and ρ is a function of temperature which can be defined by

$$\rho=\rho_0(1+\alpha T) \quad (3)$$

where ρ_0 is the electrical resistivity at 0 °C, α denotes the coefficient of resistance to temperature and T represents the temperature. Finally, the thermal energy can be described according to the above equations as

$$Q=\frac{I^2\rho_0(1+\alpha T)Lt}{s} \quad (4)$$

So, it is clear that the energy received through the current thermal effect at different positions is dependent on the cross-sectional area of the sample. The change of the cross-sectional area is continuous, leading to the