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Nano-precipitation and tensile properties of Ti60 alloy after exposure at 550 °C and 650 °C

Feng Sun [a], Jinshan Li [a], Hongchao Kou [a,*], Bin Tang [a], Jianming Cai [b]

[a] State Key Laboratory of Solidification Processing, Northwestern Polytechnical University, Xi'an 710072, China
[b] Beijing Institute of Aeronautical Materials, Beijing 100095, China

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ABSTRACT

The precipitation behavior of the silicide in Ti60 alloys was studied after exposure treatments at 550 °C and 650 °C for 8 h, 50 h and 100 h, respectively. In addition to the boundary of the α plate, the dislocations and stacking faults can also be preferred as nucleation sites for the silicide in the alloy exposed at 650 °C for 50 h. The pinning effect of the silicide on dislocations was investigated by comparing the tensile properties and deformed microstructures at both room temperature and 150 °C. At room temperature, few slip bands and dislocations were observed in the deformed microstructure. Dislocations were observed around the boundary of the α plate after 100 h exposure at 550 °C, owing to the pinning effect of silicide. When the deformation temperature was raised to 150 °C, the density of slip bands and dislocations increased, and intersections of them were observed. Moreover, the pinning effect of the silicide appears to be weaker at higher tensile test at tensile testing temperatures. Accordingly, elongation of the alloy was less than 5% after exposure treatments at room temperature, but increased to above 20% at 150 °C.

1. Introduction

Recently, a near α titanium alloy Ti60 was developed to replace the superalloys. This will result in 40% weight reduction in areoengine [1,2]. The compressor disk and blade can be made from Ti60 alloy with service temperature rising up to 600 °C [3]. The excellent mechanical properties including creep resistance and ductility depend on the strengthening effect of nano-precipitations, such as ordering Ti_3Al phase and silicide [4–6]. These nano-precipitations play a role in pinning dislocations, resulting in an increase of strength and a loss of ductility [7,8]. As previously reported, the ductility of the alloy depends on the morphology and distribution of the nano-precipitations, and changes in the deformation temperature [9].

The ductility of titanium alloy increases with tensile temperature and even the superductility can be achieved [10]. More than one kind of slip system can be activated at high temperature [11]. In contrast, the ductility decreases when the motion of slip systems are limited as a result of the pinning effect of nano-precipitations [12–14]. As reported in previous studies, the ductility can be increased by increasing the tensile temperature, even for the alloy, which has almost no ductility after exposure for long period. For example, the elongation increases from 2.0% to 8.6% if the temperature is increased from room temperature to 150 °C [15]. However, it is thought that the ductility may not increase if the pinning effect is strong enough to limit the motion of dislocations, resulting in stress concentration and followed crack initiation [16–18]. The nano-precipitation of silicide precipitated during the long period exposure has rarely been investigated, although its influence on the ductility is essential to determine the performance of titanium alloys with silicon addition.

Therefore, it is important to understand the relationship between the deformation mechanism and nano-precipitations during the tensile tests. In this work, different morphology and distribution of nano-precipitations were obtained by exposure for long periods. The tensile properties of the specimens after exposure were tested at both room temperature and 150 °C, and the deformation microstructures were observed using transmission electronic microscopy (TEM). The deformation mechanism is discussed with an aim of understanding the influence of silicide on the ductility of the alloy.

2. Materials and experimental procedure

The Ti60 alloy with the nominal composition of Ti–6Al–4Sn–4Zr–0.7Nb–1.5Ta–0.4Si–0.06C (wt%) was investigated. The ingot

* Corresponding author. Tel.: +86 18092062081.
E-mail addresses: hchkou@nwpu.edu.cn, dark_sfg@126.com (H. Kou).

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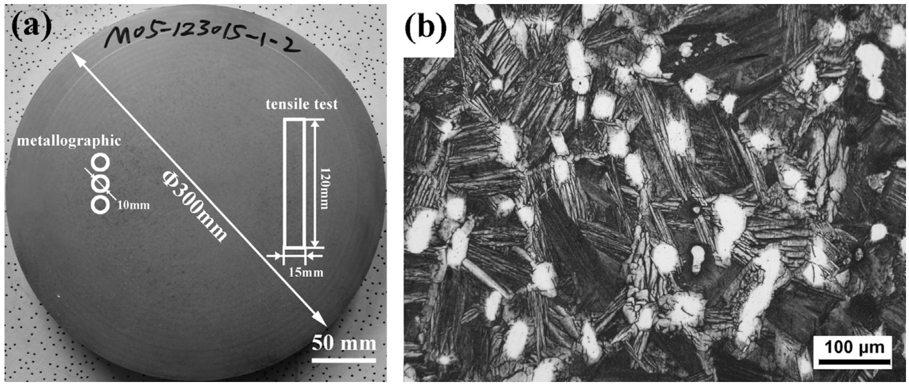

Fig. 1. Sketch of preparation of specimens (a) and initial bimodal microstructure (b) of Ti60 alloy used for the metallographic analysis and tensile test.

was forged in $\alpha+\beta$ phase field. A ⌀300 mm × 15 mm plate was cut from the cross-section of the forged bar, solution treated at 1030 °C for 120 min, and then water quenching in order to homogenize the microstructure and obtain 15% primary α phase. The plate was further aging treated at 750 °C for 120 min and then air cooled. The ⌀10 mm × 10 mm cylinders and 15 mm × 15 mm × 120 mm bars were both cut from the plate for the thermal exposure treatment, as shown in Fig. 1(a), the length of bars is parallel to the horizontal direction of the plate. The specimens had a bimodal microstructure that consisted of primary α particles and secondary acicular α plates, as shown in Fig. 1(b). The exposure experiments were performed at 550 °C and 650 °C for 8 h, 50 h and 100 h, respectively.

The oxide layer of the cylinders was removed by machining, in order to avoid the influence of oxygen on the precipitation of α_2 phase and silicide. For optical microscopy (OM) and scanning electronic microscopy (SEM) observation, the specimens were polished and then etched using the reagent ($HF:H_2O=1:15$). In order to observe the nano-precipitations using transmission electronic microscopy (TEM), foil specimens with thicknesses less than 40 μm were reduced by twin-jet electropolishing. The electropolishing was performed using a solution of 6% perchloric acid and 35% butyl alcohol in methanol at −20 °C.

The tensile properties of the 15 mm × 15 mm × 120 mm bars after exposures were measured at room temperature and 150 °C. Standard sheet tensile specimens with gauge length of 25 mm were machined from the bars for the tests according to the ASEM E8 standard. The sheet specimen had a gauge length of 6 mm width and thickness of 3 mm. The tests were carried out on the INSTRON 5985 testing system in a 50 kN screw driven corresponding to an approximating strain rate of $10^{-3}\ s^{-1}$. Before the tensile test, the surface in the gauge length was polished and etched by the reagent, which enabled OM observation of the slip bands and crack initiation after tensile deformation. Moreover, the parts near the fracture of the tensile specimens were also prepared for the TEM observation.

3. Results

3.1. Effect of temperature on precipitation behavior of silicides

The microstructures after exposure for different periods at 550 °C and 650 °C are shown in Fig. 2. At 550 °C, with an exposure period of 100 h, as shown in Fig. 2(a), (b), and (c), spherical silicide particles with diameters of 50 nm can be observed along the straight boundaries of the α plate, but none can be found inside or along the substructures including dislocations and stacking faults. When the temperate was increased to 650 °C, as shown in Fig. 2.(d), (e), and (f), elliptical silicide particles with length of 120 nm and width of 50 nm are observed along the α plate boundaries, after only 50 h exposure period. Smaller silicide particles, with diameter of 50 nm, are also observed along the dislocation inside the α plates. When the exposure period was increased to 100 h, the length and width of the elliptical silicide particles, observed along the boundary, increase to 150 nm and 70 nm, respectively. Moreover, the number of particles decreases with decreasing exposure period. Inside the α plate, large and elliptical silicide particles are observed along the stacking faults with parallel structure, whose long axes are parallel to the orientation of stacking faults. The length of these particles also increases to 150 nm, and their width is maintained at 50 nm. It is worth mentioning that, as shown in Fig. 2(i), high densities of silicide particles are parallel to the substructures inside the large bulk shape primary α phase. The length and width of the silicide particles range from 100–150 nm and 20–70 nm, respectively. These densely distributed silicide particles are rarely observed in other titanium alloys.

3.2. Tensile properties after exposure treatments at 550 °C and 650 °C

Fig. 3 shows the stress-strain curves obtained from tensile tests performed at room temperature and 150 °C. After the exposure treatment at 550 °C and 650 °C, the total strain of specimens does not exceed 5%, as a result of the tensile tests at room temperature. When the tensile temperature is increased to 150 °C, the total strain increases to above 20% as four times that of room temperature, while the ultimate strength (UTS) decreases by about 200 MPa. The ductility increase of the specimens treated at 550 °C is higher than that at 650 °C. There is a smaller decrease in the UTS of the specimens after 550 °C exposure treatment if compared to that after 650 °C exposure.

The ductility increase of the specimens exposed at 550 °C for different periods are compared in Fig. 3(a). As the period increases from 8 h to 50 h, the room temperature UTS of the specimen decreases from 1050 MPa to 1000 MPa, until the period extends to 100 h, the UTS still keeps at 1000 MPa. The total strain decreases from the maximum value of 5.2% after 8 h to about 4.7% after 50 h and 100 h. As for tensile tests the 150 °C, the UTS increases from 795 MPa after 8 h to 830 MPa after 50 h, and reaches to 850 MPa after 100 h. In contrast, the total strain decreases from 28% after 8 h to 24% after 50 h and 100 h. Compared to exposure times of 50 h and 100 h, the strengthening effect and increase of ductility are more significant for an exposure period of 8 h.

After exposure at 650 °C, in Fig. 3(b), when the exposure period increases from 8 h to 50 h, the UTS and total strains of specimens remain at 1000 MPa and 4.7% at room temperature, respectively.