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Microstructure and mechanical properties of high strength as-cast Ti-15-3 alloy①

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[Abstract] The effects of heat treatment and solidification cooling rate on the microstructure and mechanical properties of as-cast Ti-15-3 alloy prepared by induction skull melting method were investigated. Results show that the microstructure of as-cast Ti-15-3 alloy changes from the features of simplified and larger size of beta grains to finer grain size with increasing solidification cooling rate. After solution treatment and different ageing treatment, alpha phase precipitates in grains interior as well as in grain boundaries. Due to the modification of the precipitate phase, the tensile strength and elongation of the alloy are improved simultaneously. A good combination of the values of 1.406 GPa of σ_b and 4.5% of δ was obtained, which will be satisfied the use of this kind of alloy in critical areas.

[Key words] cast Ti-15-3 alloy; solidification cooling rate; heat treatment; microstructure; mechanical properties
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1 INTRODUCTION

Titanium alloys have received appreciated attentions in the fields of aircraft, aerospace, and others owing to their excellent mechanical properties, especially the high specific strength. With regards to lower the mass of aircraft and improving their suitability for transportation, an important class named beta titanium alloys are developed to meet the requirements of the above situations[1,2]. As the results of good properties combination of higher specific strength, elastic modulus and elongation, the alloy Ti-15V-3Cr-3Sn-3Al(Ti-15-3) has become a potentially selective material to be used among those beta type alloys[3]. From Ref.[4], it is known that the alloy Ti-15-3 has good workability at room temperature and suitable for cold working. Unfortunately, the high processing cost and drawbacks of low plasticity and high deformation force of the alloy have made it difficult to produce complex and thin-walled components that are being the keynotes for aero applications[5]. In order to reduce the processing cost and reach the flexibility of shaping Ti-15-3 alloy, the technique of precision casting has been involved in the field. But due to the large beta grain size and lower mechanical properties under casting condition, the usage of the as-cast Ti-15-3 alloy is limited. Because of the strengthen effects of heat treatment on the beta type titanium alloys, the Ti-15-3 alloy can somewhat be strengthened to the extent of high level of the mechanical properties. The investigations on the effects of heat treatment on titanium alloys have been carried out by America and the former Soviet Union[6,7]. As it is pointed out that, after heat treatment, the matrix precipitates alpha phase in grain interior and at grain boundaries as well. The appearance and distribution of alpha phase improve the mechanical properties of the alloy dramatically[8]. The purpose of this article is to investigate the effect of different solidification cooling rates and heat treatment on the microstructure and mechanical properties of the alloy in order to find an efficient measurement to further improve the mechanical properties of the alloy.

2 EXPERIMENTAL

The experimental raw materials came from spongy titanium, vanadium-aluminium master alloy, high-purity aluminium block, chrome powder and tin block. Then they were melted in an induction skull melting furnace according to the nominal composition of the alloy which composed of 15%V, 3%Al, 3%Cr, 3%Sn, and the balance Ti. The total mass of the charge was 18 kg. The pouring parameters were set as the speed of 200 r/min for rotating table and the pouring temperature of about 1750 ℃. In order to study the effect of different solidification cooling rates on the solidification microstructure and mechanical properties of the alloy, the molten alloy were centrifugally pouring into a step metal mould with the gauge of 235 mm in length, 100 mm in width, and 50 mm, 25 mm, and 10 mm in thickness respective-

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ly. The samples for the analyses of microstructure and mechanical properties of the alloy came from the step specimen.

The samples for heat treatment was solute treated at 800 ℃ for 20 min and then water cooling as well as the treatment of different ageing temperatures and times with air cooling. The microstructure of the alloy was studied with optical microscope and TEM. The morphology of fractures after tensile test was also investigated by SEM. The mechanical properties were tested in model Instron 1186 electric tensile machine.

3 RESULTS AND DISCUSSION

3.1 Effect of solidification cooling rate on microstructure of alloy

The microstructure of the alloy after solidification is shown in Fig. 1. The equiaxed beta grain is found with a few of gas and shrinking holes in grain interior and at grain boundaries as well. The secondary phases with black color were confirmed as a non-equilibrium solidification structure. With increasing solidification cooling rate, the grain size becomes smaller. The grain size is small where attached to the inner surface of mould or positions with smaller casting size because of the action of chilling effect of mould inner surface and smaller casting size on the alloy. Compared with the thin section, the middle and thick section have less difference in grain size.

3.2 Effect of solidification cooling rate on mechanical properties of alloy

Table 1 has shown the effects of different solidification cooling rates on the tensile properties of the alloy. With increasing solidification cooling rate, the tensile strength of the alloy increases. At the same time the elongation of the alloy is improved. The increase of strength and elongation attributes to small grain size[9]. Compared with the thin section, the middle and thick section has less difference in tensile properties.

Table 1 Tensile properties of Ti-15-3 alloy at different positions of step casting

Position	Thickness / mm	Estimate solidification cooling rate / (℃·s^{-1})	σ_b / MPa	δ / %
Thick	50	3.50	725	17.0
Middle	25	5.70	730	18.5
Thin	10	9.10	870	21.0

3.3 Microstructure of alloy after heat treatment

At the normal condition the single beta microstructure for the alloy can be obtained by air cooling and water cooling. After solution treatment and different ageing treatments, acicular alpha phase is observed at grains interior as well as in grain boundaries. A good combination of strength and elongation can be achieved with proper heat treatment.

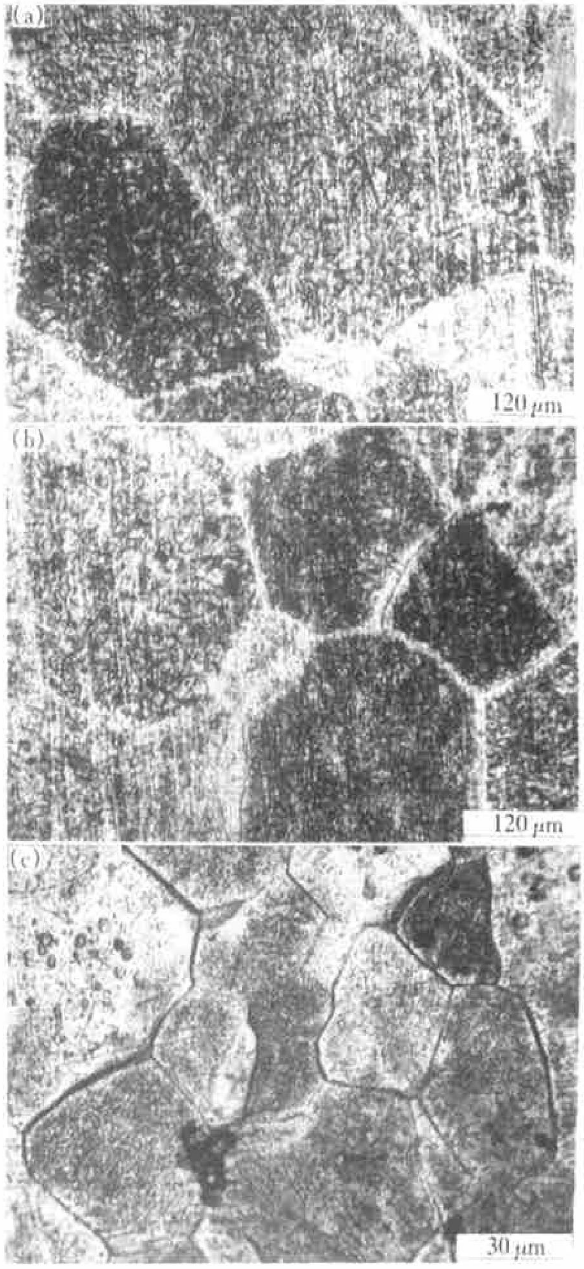

Fig. 1 Solidification microstructures of Ti-15-3 alloy at different positions of step casting
(a) —Thick area; (b) —Middle area; (c) —Thin area

Figs. 2(a) and (b) show TEM image of the alloy aged at 450 ℃ and 650 ℃ for 8 h. With increasing ageing temperature, the acicular alpha phases become coarse. There exists incoherent corresponding relationship between the alpha phase and matrix[10].

Fig. 2(c) shows alpha phases precipitate at grain boundaries. The angles between the grain boundaries and alpha phases were estimated about 30°. The reasons for the easy precipitation of alpha phases at grain boundaries can be interpreted as low nucleation energy and the segregation of alloying element at grain boundaries due to the inadequate solution

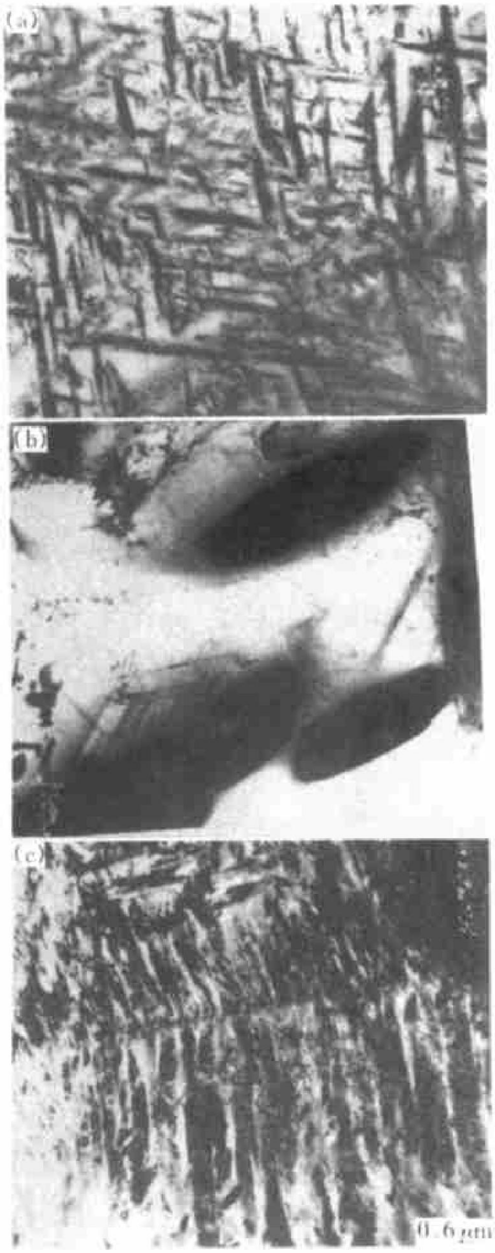

Fig. 2 Effect of ageing temperature on microstructure of Ti-15-3 alloy
(a) —450 ℃, 8 h; (b) —650 ℃, 8 h;
(c) —Alpha phases precipitate at grain boundary

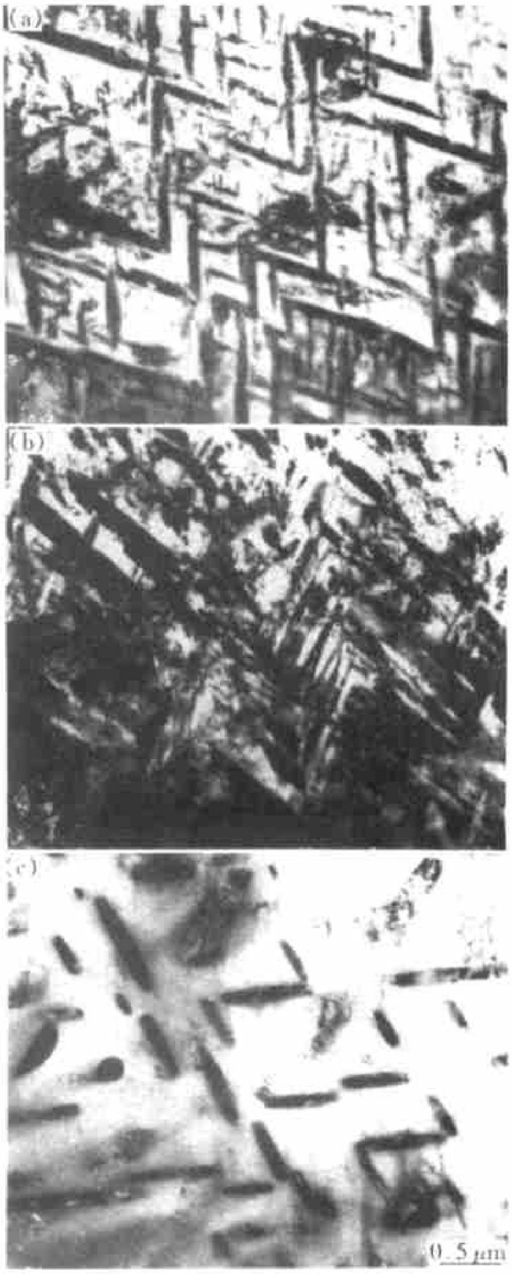

Fig. 3 Effect of ageing time on microstructure of Ti-15-3 alloy
(a) —450 ℃, 6 h; (b) —450 ℃, 24 h;
(c) —Duplex aged at 450 ℃ 6 h, 650 ℃ 8 min

treatment. The large quantity of precipitates at grain boundaries was responsible for the brittleness of the alloy.

Figs. 3(a) and (b) present TEM image of the alloy aged at 450 ℃ for 6 h and 24 h. With increasing ageing time, the alpha phases become coarser. The volume fraction of the alpha phase increases simultaneously.

Fig. 3(c) present the comparison of TEM image of the alloy with duplex ageing treatment. The alpha phases became coarser with a longer distance between alpha precipitates after duplex aged.

3.4 Mechanical properties of alloy after heat treatment

Fig. 4(a) demonstrates the change of mechanical properties of the alloy aged at different temperatures for 8 h. With increasing ageing temperature, the tensile strength and yield strength decrease and elongation increases. The direct reasons for the change ofmechanical properties of the alloy is the size, quantity and distribution of alpha phases in the matrix. With raising ageing temperature, the alpha phases become coarse that leads to the more easiness for dislocations to cross the precipitation during the test process so that the strengthening action of the alpha phase lessens which will cause the lower strength and higher elongation of the alloy. When the ageing temperature is 450 ℃, σ_b equals to 1.406 GPa. While the ageing temperature is 650 ℃, σ_b equals to 905 MPa. Compared with the strength,

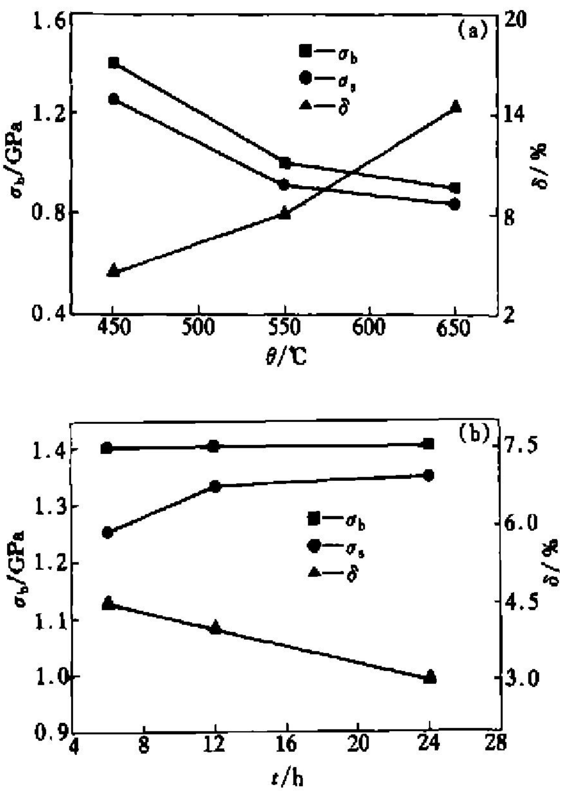

Fig. 4　Effect of ageing temperature (a) and ageing time (b) on tensile properties of Ti-15-3 alloy

the elongation of the alloy has different change trends. The elongation is from 4.5% (450 ℃) to 14.4% (650 ℃).

Fig. 4(b) demonstrates the change of mechanical properties of the alloy aged at 450 ℃ for different times. With increasing ageing time, the tensile strength and yield strength increase a little with the decrease of elongation. With prolonging the ageing time, the distance between the precipitations become nearly that leads to the more difficulty for dislocations to cross the precipitations during the test process, which cause the higher strength and lower elongation.

Fig. 5 shows the fracture morphology of the alloy aged at 450 ℃ and 650 ℃ for 8 h. It has shown that the fracture is intergranular characterized by dimples. Although the fractures are intergranular, the relatively smaller grain sizes maybe the better explanation of the high elongation.

When the alloy is duplex aged, the strength decreases with increase of elongation. σ_b has been cut down by 386 MPa. The elongation has been improved by 3.5%. The longer distance between the precipitations after duplex aging is responsible for the lower strength and higher elongation.

3.5　Effect of solidification cooling rate on mechanical properties of alloy after heat treatment

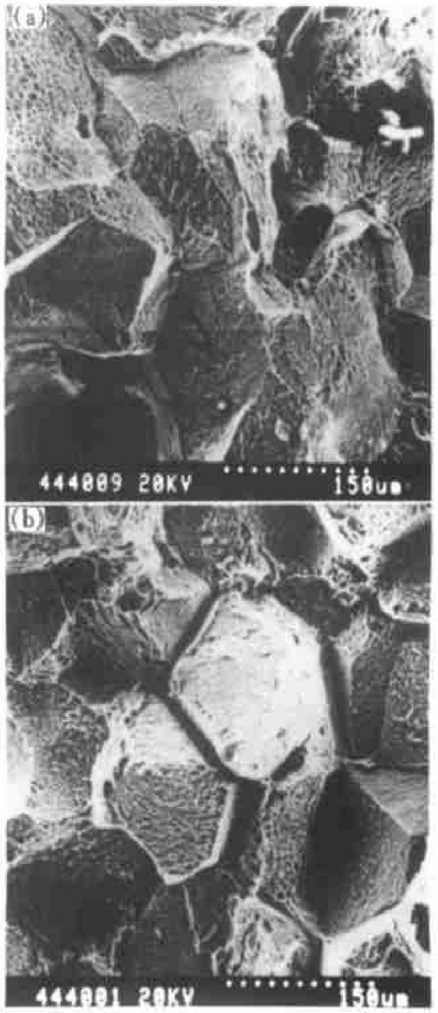

Fig. 5　Fracture morphologies of Ti-15-3 alloy for different ageing temperature
(a) —450 ℃; (b) —650 ℃

Fig. 6 presents the mechanical properties of the alloy which locate in the middle and thick section after heat treatment. The samples were solute treated at 800 ℃ for 20 min and then ageing at different temperatures for 8 h. The tensile strength of the alloy from both the middle and thick section decreases with the increase of elongation when the ageing temperature increases. As a whole the tensile

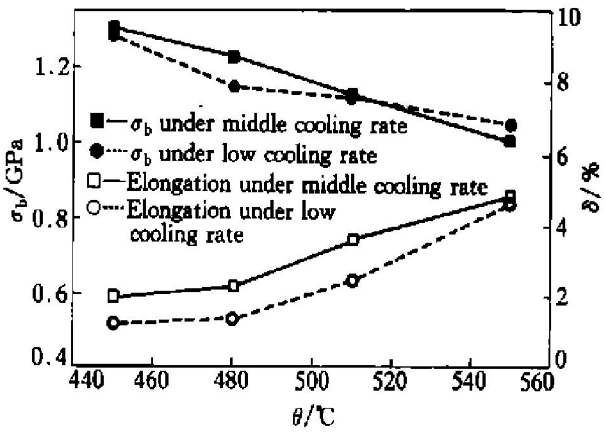

Fig. 6　Effect of solidification cooling rate on tensile properties of Ti-15-3 alloy after heat treatment

strength and elongation of the alloy from middle section are higher than that from the thick section. But aged at or above 510 ℃ for 8 h, the tensile strength of the alloy from middle section is lower than that of the thick section.

This unexpected behavior can be explained by means of model which incorporate the contribution of the grain boundaries to and the grain interior to the tensile strength[8].

The contribution of the grain boundaries to σ_s can be expressed by the well known Hall-Petch relationship

$$\sigma_s = \sigma_i + k_L d^{-1/2} \quad (1)$$

where σ_i is the friction stress opposing to dislocation motion, k_L is a constant, and d is the grain diameter.

The contribution of the grain interior to precipitates (τ) maybe expressed by the Orowan equation modified by Ashby[11].

$$\tau = Gb/2\pi(D-l)\ln l/r_0 \quad (2)$$

where G is the shear modulus, b is the burgers vector and $r_0 = 4b$, D is the distance between precipitates, l is the thickness of the precipitates. When considering the tensile yield strength it is possible to assume that for a polycrystalline material $\tau = 1/2\sigma$. The combined contribution of grain boundaries and the precipitates in the grain interior is

$$\sigma_s = \sigma_i + k_L b^{-1/2} + Gb/\pi(D-l)\ln l/r_0 \quad (3)$$

Increasing the grain size would decrease the yield strength, but would also cause larger precipitate density in the grain interior, which result in a smaller distance between precipitates. Compared with the small grain size, the contribution of precipitates in the grain interior to the tensile strength is the dominating factor for the large grain size. When aged at or above 510 ℃ for 8 h, the tensile strength of large grain size has exceeded the small one due to the relatively stronger strengthening action of the precipitates in the grain interior.

4 CONCLUSIONS

1) The microstructure of the alloy after solidification is the equiaxed beta grain with a few of gas and shrinking holes in grain interior and grain boundaries as well. With increasing solidification cooling rate, the size of grain becomes smaller, the tensile strength and yield strength of the alloy increase. At the same time, the elongation of the alloy is improved.

2) With increasing ageing temperature and also prolonging of ageing time, the acicular alpha phase becomes coarse. The volume fraction of the alpha phase increases simultaneously. The alpha phase becomes coarse after duplex aged.

3) With increasing ageing temperature, the tensile strength and yield strength decrease and the elongation increases. With increasing ageing time the tensile strength and yield strength increase a little and the elongation decreases. After the alloy is duplex aged, the strength decreases and the elongation increases.

4) The tensile strength and elongation of the alloy from middle section are higher than that from the thick section in general. A good combination of the values of 1.406 GPa of σ_b and 4.5% of δ are obtained, which will be satisfied the usage of this kind of alloy in critical areas.

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