Influence of aging treatment on microstructure and mechanical properties of a new high strength TB17 titanium alloy

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ABSTRACT: Scanning Electron Microscope (SEM), Transmission Electron Microscope (TEM) and X-Ray Diffraction (XRD) were employed to investigate the influence of heat treatment conditions on microstructure and mechanical properties of a new high strength TB17 titanium alloy at aging temperature from 530°C to 620°C. The results showed that the aging temperature had a significant influence on microstructures and mechanical properties of the alloy. At aging temperature of 530 °C, the existence of lamellar secondary α phase with a size of 40nm resulted in high tensile strength above 1500MPa and acceptable elongation of 6%. The secondary α phases had a great effect on the mechanical properties of TB17 titanium alloy, i.e. the fine acicular secondary α phase contributed to quasi-cleavage fracture, while the coarse α phases lead to the ductile fracture. Finer secondary α phase could provide more α/β phase interface, which could act as the site of micro-crack nucleation and hinder the dislocation movement inside the titanium alloy, thus, a higher strength could be obtained for the TB17 titanium alloy.

1. Introduction

Titanium and titanium alloys were widely used in the aerospace, biomedical defense and sporting goods industry, owing to its high specific strength-to-density ratios, good creep and corrosion resistance. The ß titanium alloys were considered to have great potentials in the aerospace fields due to its balance between strength and ductility [1-3]. In the last decades, the application of near β titanium alloys, such as VT22, Ti-1023 and Ti-5553, are gradually increased in aerospace structural fields due to their higher strength-to-density ratios, better fatigue and crack propagation properties comparing with $\alpha+\beta$ titanium alloys [4-5]. Due to the poor ductility of β titanium alloys above 1350MPa, their applications in aerospace fields are hindered [6-7]. The optimization of mechanical properties is attributed to the adjustment of process parameters, holding time or rate of both the solution treatment and aging, which help to control the volume fraction size, morphology, and distribution of both the primary and secondary α phase. The pramary α phase can be formed during isothermal heat treatment below β - transus temperature or slow cooling from the β phase field. The secondary α phase formed by precipitated from the β phase matrix. The secondary α phase morphology, volume fraction, size and distribution have a significant effect on the mechanical properties of β titanium alloy[8-10]. Thus, it is important to invest the relations between secondary α phase and the mechanical properties of β titanium alloys.

Recently, a novel metastable β titanium alloy named TB17 titanium alloy with independent intellectual property rights has been developed. This alloy has a great potential as aerospace structure material with a strength above 1400MPa and good strength-plasticity match (elogation above 7%), the plane fracture toughness above 40MPa m^{1/2}, and high cycle fatigue can above

875MPa (R=0.1) after solution and aging heat treatment. The present work not only helps to establish the quality correspondence among microstructure and strength but also contributes to the accurate control and prediction on the process conditions for the TB17 titanium alloy to obtain the desired mechanical properties.

2. Materials and experimental procedures

The TB17 titanium alloy was melted by multiple vacuum arc re-melted (VAR) method. The ingot with Φ 220mm in diameter was first forged at β phase temperature and then hot rolled at the α/β field down to 150mm (width) ×120mm (thickness) ×L. The β transition temperature of TB17 alloy is measured as 845°C using metallographic method. Samples from the as forged materials were firstly solution treated at 825°C (below β transition temperature) for 1.5 hours in an air furnace and then followed with air cooling. Then, the sample after solution treated were undergone aging heat treatment at 530°C, 550°C, 570°C and 620°C, respectively, for 8 hours and then followed with air cooling.

The conventional optical microstructure (OM), SEM and TEM were observed. The TME observation for the rolled specimen was preformed on Tecnai G2 F30S (FEI America) under an acceleration voltage of 300KV. The XRD experiment was carried on the D8 advance apparatus (Bruker Germany). Fig. 1 shows the micrographs of the initial microstructure for TB17 titanium

(Bruker Germany) .Fig. 1 shows the micrographs of the initial microstructure for TB17 titanium alloy. The forged microstructure of the matrix consists of globular α phase particles.



Fig.1 Micrographs of the initial microstructure for TB17 titanium alloy

- 3. Results
- 3.1 Microstructure



Fig.2 Micrographs of the microstructure for TB17 titanium alloy after solution treatment (a. Optical micrograph; b. SEM micrograph)



Fig.3 X-ray diffraction patterns of TB17 titanium alloy for different heat treatment The initial microstructure of TB17 titanium alloy in a solution treatment below β transition temperature is show in Fig.2. The result presents a large number of primary α phase dispersed on the β phase matrix with a size of about 50µm. Primary α phase is short rod like with about 0.2µm in width and length inhomorogenous. The microstructure of TB17 titanium alloy during solution treatment at α + β phase temperature only consisted by α phase and β phase (Fig. 3).



Fig. 4 SEM morphology of TB17 titanium alloy solution heat-treated at 825°C and aged for 8h (a.530°C; b. 620°C)

The microstructure of TB17 titanium alloy along the transversal section after α/β solution treated at 810 °C plus aging at 530°C and 620°C are shown in Fig. 4. For the β titanium alloys, the primary α phase limit the recrystallization and growth of β phase grains. As Fig. 4 showns the primary α phase distributes at β phase grain boundary with the β grain size is only about 15µm both aging at 530°C and 620°C. It means that the primary α phase has a distinctly pinning effect on growth of β grain during solution at 820°C.





Fig. 5 TEM morphology of TB17 titanium alloy solution heat-treated at 825°C and aged for 8h (a.530°C; b.550°C; c.570°C; d. 620°C; e.530°C)

Fig. 5 shows the TEM microstructure and corresponding electronic diffraction (ED) image of TB17 titanium alloy after the α/β solution treatment aging range from 530°C to 620°C, respectively. The aging temperature has a great effect on the size of acicular α phase. During aging at 530 °C, the size of acicular α precipitates in the β matrix is about 0.25µm in length and 0.04µm in width, the microstructure is homogenous, and the aging temperature raise to 570°C, the lamella of secondary α phase were not grew up obviously, while during aging at 620°C, the inhomogeneous microstructure formed, and the secondary α phase is about 0.95µm in length and 0.125µm in width. Electronic diffraction image demonstrate that secondary α phase have Burgers relation with β phase matrix (Fig. 5e).

3.2 Mechanical Properties

Fig.6 shows the variation of mechanical properties of TB17 titanium alloy at various aging temperature. Comprehensively, the TB17 titanium alloy has a quite excellent combination of strength and ductility at the aging temperature from 530°C to 620°C. The strength level decrease from 1500 MPa to 1250 MPa and excellent ductility increase from 6.8% to 15.0% in elongation. The change of mechanical properties might be affected synthetically by primary α phase morphology, fraction and secondary α phase, and it will be discussed in chapter 4.



Fig. 6 The effect of aging temperature on the tensile properties at room temperature of TB17 titanium alloy

Fig.7 shows the nominal engineering stress-strain curves of TB17 titanium alloy at different aging temperature. At both aging temperature of 530° C and 620° C, the characteristics of stress-strain curves is similar and can be divided into three stages, i.e. plastic deformation stage (stage I), yield stage (stage II), and fracture stage (stage III). The stress-strain curve at aging temperature of 620 °C has longer yield stage and fracture stage comparing with that of 530 °C. The alloy presents higher ultimate tensile strength at aging temperature of 530 °C comparing to that of 620 °C.



Fig.7 Nominal engineering stress-strain curve of TB17 titanium alloy at different aging temperature

3.3 Fracture Analysis

Fig.8 shows the room temperature tensile fracture microstructure with different aging temperature. At aging temperature of 530°C, the fracture contains large amounts of dimple and tear ridge (Fig. 8a), which acts as pale-type and tear-type fracture, and presents the characteristics of both quasi-cleavage and ductile fracture, and also the crack path is straight as shown in Fig. 10a. With the aging temperature raising to 620°C, fracture morphology contains deep dimples (Fig.8b), with lots of core particles at the bottom of the deep dimple, which has the characteristics of ductile fracture, and the crack path is zigzag.



Fig.8 SEM micrographs showing fracture surface of TB17 titanium alloy at different aging temperature (a.530°C; b.620°C)



Fig.9 SEM micrographs showing crack path profile of TB17 titanium alloy at different aging temperature (a.530°C; b.620°C)

4. Discussion

As Fig.3 shows the microstructure of TB17 titanium alloy during aging temperature ranged from

530°C to 620°C only consisted by α phase and β phase, thus, the change of mechanical properties mainly caused by lamella secondary α phase parameter. There are two main processes of metastable β phase titanium alloys precipitation, nuclear and grow up [11]. Aging at lower temperature, there are much more nucleation for higher driving force but lower atomic diffusion rates, thus fine and uniform secondary α phase formed. Aging temperature raised from 530°C to 570°C, the lamella of secondary α phase grew up from 40nm to 55nm with the ultimate tensile strength decreased 50MPa while the elongation without obvious changes. However, aging at higher temperature, the lower driving force and higher atomic diffusion rates dominate the precipitate process, the coarse and non-uniform secondary α phase formed. During aging temperature raised from 570°C to 620°C, the lamella of secondary α phase coarsen from 55nm to 125nm with the ultimate tensile strength decreased about 250MPa and elongation increased about 7%.



Fig.10 The schematic diagram of crack propagation of TB17 titanium aooly

The lamella of secondary a phase have significant effect on fracture behavior of TB17 titanium alloy. Generally, the interfacial energy is weaken than that of α or β matrix, the α/β phase interface act as the potential site of crack under static stress. During aging at 530°C, the fine and uniform increased much α/β phase interface which provide more site of nucleation and the stress concentration dispersed, thus the much energy were absorbed during the micro-cracks nucleation process and delay the plastic deformation zone, the higher ultimate tensile strength achieved[12-13]. Continue to load, the core of micro- crack expand and the yield area formed in front of the crack tip. The micro plastic zone formed during this stage[14]. As Fig. 10 shows if crack cross the fine and uniform secondary a phase, the straight and crack path formed. Some crack cannot pass through part of secondary α phase which have lower orientation factor instead expand along with cleavage plane, thus the cleavage edge formed(Fig.8a). During aging at 620°C, the coarse and non-uniform secondary α phase intensively impede the motion of dislocation. The stress concentration at α/β phase interface lead to the TB17 titanium alloy enter the yield stage much more early (Fig. 6). During this stage the dislocation easier slip in β phase for body-centered cubic (bcc) lattice structure and longer effective expand distance[15-16], thus the deeper dimple formed and the crack path more zigzag (Fig.10b).

4 Conclusions

1. TB17 titanium alloy has a great potential as aerospace structure material with a strength above 1500MPa and good strength-plasticity match (elongation 6.8%) after solution and aging heat treatment.

2. The aging temperature of TB17 titanium alloy has a great influence on secondary α phase thickness, for eample, after 530°C aging, the thickness of lamellar of secondary α phase is 40nm, while aging temperature rises to 620°C, lamellar α phase coarse to the thickness of 125nm.

3. There are two freture mechanisms of TB17 titanium alloy for various secondary α phase morphology: fine and uniform secondary α phase contributes to quasi-cleavage fracture, while the course and nou-uniform α phase leads to the ductile fracture.

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