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ARTICLE

Lamellar Features and Mechanical Properties of Ti5321 Alloy at Different Cooling Rates of BASCA Treatment

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Abstract: The effects of three cooling rates on lamellar morphology and mechanical properties for Ti5321 alloy under β-annealing with subsequent slow cooling and aging (BASCA) heat treatment were studied. The results show that the cooling rates play a decisive role in the α lamellar size formed with slow cooling process after β zone solution. The lamellar size of Ti5321 alloy keeps increasing with the decrease of cooling rate, and the growth rate of lamellar in the length direction is much faster than that in the thickness direction. With the increase of cooling rate, the strength of the alloy will increase, but the fracture toughness will decrease. The cooling rate of 0.5 ºC /min in this experiment is the optimal cooling way. The ultimate tensile strength of the alloy treated with this rate can exceed 1200 MPa with an excellent fracture toughness ($K_{IC}\geqslant$65 MPa·m$^{1/2}$).

Key words: Ti5321 alloy; β heat treatment; mechanical properties; lamellar morphology

Beta titanium alloys are widely used in aerospace industry due to their excellent properties, such as high strength-to-mass ratio, deep hardening potential and inherent ductility[1-3]. In recent years, some beta titanium alloys, Ti-5553, Ti-1023, TC21, etc. have found many applications in airframe as important structural components because of their high strength and damage tolerance properties[4-6]. A new high strength titanium alloy named after Ti5321 has been designed and developed in Northwest Institute for Nonferrous Metal Research in China[7].

As we all know, high strength materials are highly sensitive to damage. It is difficult to solve the contradiction between strength and damage tolerance only depending on alloy composition design. Heat treatment has a great influence on the properties of β titanium alloys. Different microstructures could be obtained by different heat treatments. Titanium alloys with lamellar structure have higher fracture toughness and lower fatigue crack propagation rate than the alloys with equiaxed structure.

At present, β-annealing with subsequent slow cooling and aging heat treatment (named BASCA[8]) is employed for beta titanium alloys to obtain lamellar microstructure. The objective of the present work is to study the influence of different cooling rates of BASCA treatment on microstructure and mechanical properties for Ti5321 titanium alloy. It is helpful to formulate the BASCA treatment process and optimize the properties of Ti5321 titanium alloy.

1 Experiment

The Ti-5321 alloy used in this study is a hot-forged billet with sectional dimension of 80 mm. The microstructure of the as-received material consists of equiaxed primary α grains with an average size of 1~3 μm and retained β phase (Fig.1). The nominal composition (wt%) of this alloy is 5.02 Al, 3.0 Mo, 2.99 V, 2.04 Cr, 2.02 Zr, 1.37 Nb, 1.01 Fe, 0.0011 H, 0.064 O, 0.004 N and the balance Ti. The β transus temperature (T_β) for the alloy is (860±5) ºC.

In order to study the influence of cooling rate on lamellar characteristic and mechanical properties, only one solution temperature was used in present work. The

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BASCA treatment processes mainly consisted of high temperature solution at β phase field, subsequent slow cooling to a certain temperature of 760 ºC with different cooling rates, and then ageing at 620 ºC for 6 h, air cooling. β high temperature solution can control the size of the original β grain. Different lamellar morphologies were obtained under different cooling rates after β solution treatment. The ageing treatment determines the strengthening effect of secondary α phase[9]. Various heat treatments employed in present work is listed in Table 1.

The tensile tests were carried out on the Instron 5985 testing machine, following the ASTM E8 standard[10]. Fracture toughness tests were conducted by an MTS810 fatigue testing machine, in accordance with ASTM standard E-399[11]. The fatigue crack propagation rate experiments were performed by a test with a load ratio R=0.1 on an MTS810 fatigue testing machine. The Olympus MG3 optical microscope (OM) and JSM-6700 scanning electron microscope (SEM) were used to observe the microstructure and the fatigue crack propagation route. The phase compositions was identified by Rigaku D/max-RB X-ray diffractometer.

2 Results and Discussion

2.1 Lamellar morphology

The specimen 1 was treated at 880 ºC followed by water quenching. Fig.2 shows the optical microstructure and XRD pattern of specimen 1 only after solution treatment. It is a fully β equiaxed grains with an average size of around 100 um, as shown in Fig.2a. Only β phase is obtained after β solution followed by water quenching, as shown in Fig.2b.

Fig.3 shows the microstructures of specimens at different cooling rates and water quenched after reaching prespecified temperatures. It can be found that α phase nucleated and grew up during the cooling process. However, the morphology of obviously different α lamellar can be seen under three cooling rates. At the fastest cooling rate of 1 ºC/min, more fine needle-like α platelets with 5~10 μm in length and 0.5~1 μm in thickness are precipitated not only at grain boundaries but also inside, as shown in Fig.3a. While at the cooling rate of 0.5 °C/min, obviously longer α platelets with average length of 15~20 μm and slightly wider thickness of around 1.5 μm can be obtained. When the cooling rate is further reduced to 0.25 ºC/min, the longest and thickest α platelets can be got, which was 40~50 μm in length and around 2 μm in thickness. To sum up, the lamellar size of Ti5321 alloy would increase with the decrease of cooling rates after β solution treatment. Besides, the growth rate of lamellar in the length direction is much faster than that in the thickness one.

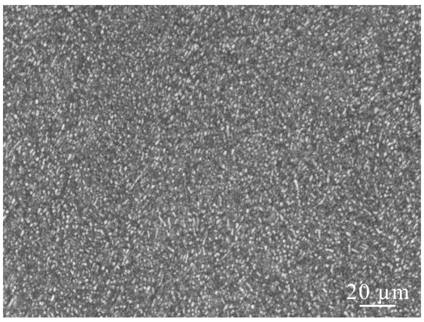

Fig.1 Original microstructure of the alloy billet

Table 1 BASCA treatment processes

Specimen	Solution treatment	Aging treatment
1	880 ºC/1 h WQ	-
2	880 ºC/1 h FC(1 ºC/min) to 760 ºC/1 h WQ	620 ℃/6 h AC
3	880 ºC /1 h FC(0.5 ºC/min) to 760 ºC/1 h WQ	620 ℃/6 h AC
4	880 ºC/1 h FC(0.25 ºC/min) to 760 ºC/1 h WQ	620 ℃/6 h AC

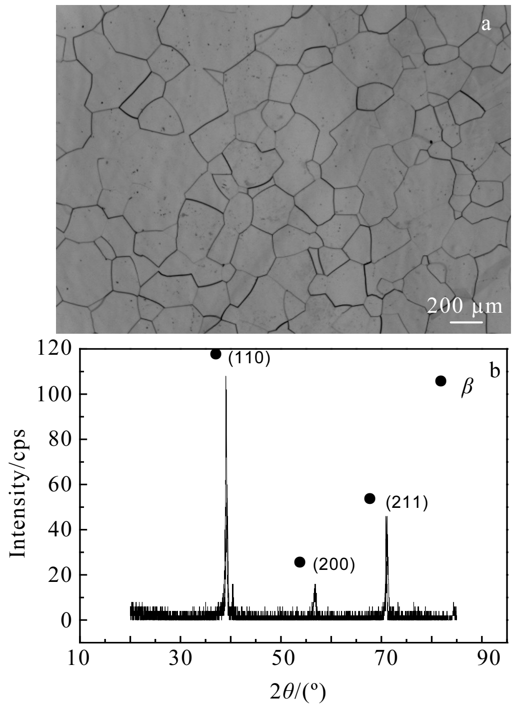

Fig.2 Optical microstructure (a) and XRD pattern (b) of specimen 1

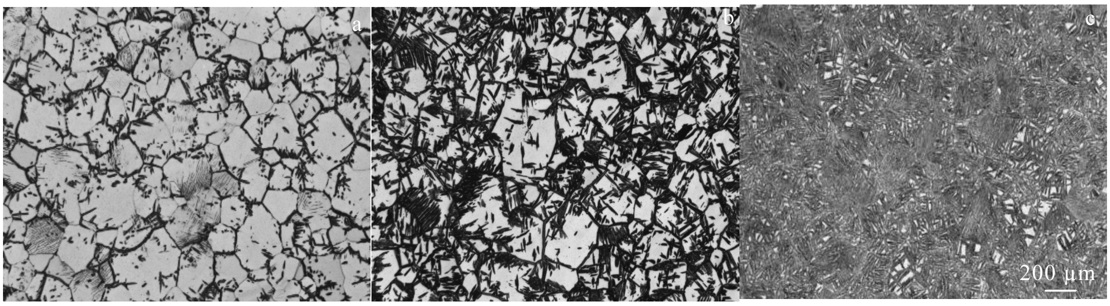

Fig.3 OM images of Ti-5321 alloy cooled at different rates: (a) 1 ºC/min, (b) 0.5 ºC/min, and (c) 0.25 ºC/min

Fig.4 is the SEM morphologies of Ti-5321 alloy after BASCA treatments. Residual beta phase (white area in Fig.3) is a metastable phase, which would provide favorable precipitation conditions for secondary α phases in subsequent aging process. It can be seen from Fig.4 that abundant small secondary α lamellar could precipitate and fill in the whole β grains after aging treatment, which could lead to a significant increase in strength by preventing the dislocation from free gliding effectively[12]. The morphology of the three specimens varies noticeably, and the size of secondary phase becomes bigger with the decrease of cooling rate.

2.2 Mechanical Properties

Table 2 demonstrates the tensile properties and fracture toughness of Ti5321under different BASCA heat treatments. The curve of da/dN vs. ΔK at stable speed expansion stage and linear regression analysis of three specimens in double logarithmic coordinates are shown in Fig.5. It can be found that the strength of specimen 2 is significantly higher than that of specimen 4, the ultimate tensile strength of the former and the latter is 1320 MPa and 990 MPa, respectively. Specimen 3 has moderate ultimate tensile strength of about 1210 MPa, which is between specimen 2 and specimen 4. The reason is mainly attributed to the precipitate strengthening of secondary α phase during aging process. According to Orowan strengthening mechanism[13], the smaller the size of secondary α phase, the more obvious the strengthening effect within the range of effective strengthening sizes.

When comparing the damage tolerance property of three specimens, specimen 4 are obviously better than specimen 2 and specimen 3. The fracture toughness K_{IC} of specimen 4 exhibits the largest values of about 102 MPa·m$^{1/2}$, with the indication of an excellent fatigue crack propagation rate for the alloy, as shown in Fig.5 (red curve). On the contrary, the fracture toughness K_{IC} of specimen 2 is merely 35 MPa·m$^{1/2}$, and fatigue crack propagation rate is also the highest (as shown in Fig.5 grey curve). Similarly, specimen 3 has moderate comprehensive properties, which are between specimen 2 and specimen 4.

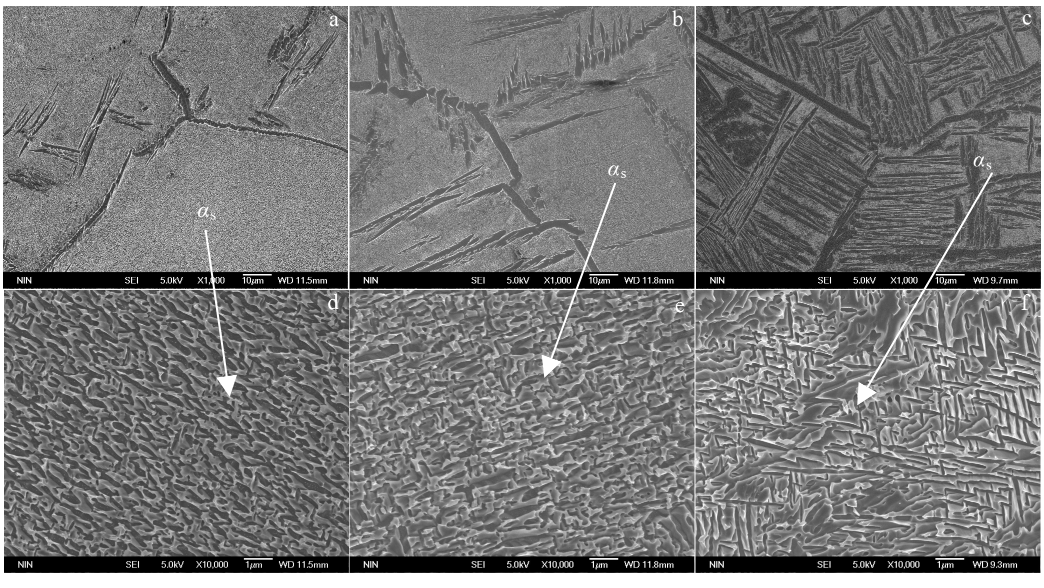

Fig.4 SEM images of Ti-5321 alloy after different BASCA treatments: (a, d) specimen 2, (b, e) specimen 3, and (c, f) specimen 4

Table 2 Mechanical properties of the alloy after BASCA treatment

Specimen	UTS/ MPa	YS/ MPa	EL/ %	RA/ %	K_{IC} /MPa·m$^{1/2}$
2	1320	1270	6.0	17	35
3	1210	1120	9.0	26	68
4	990	910	16.0	36	102

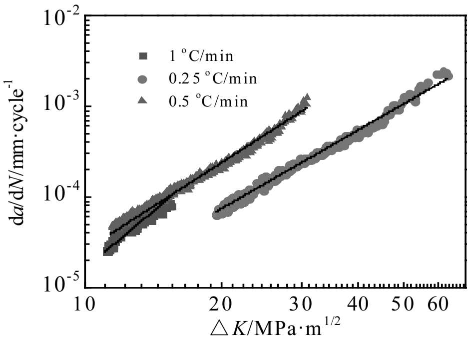

Fig.5 da/dN~ΔK curves of different BASCA treatments

Fig.6 shows the crack propagation paths and surface morphologies of three specimens after fracture toughness tests. Fig.6a, 6b and 6c show the crack propagation paths of the three specimens. It can be found that specimen 2 has the flattest crack propagation path among the three specimens, which shows no obvious fluctuation. On the contrary, a "zig-zag" shape fracture trace can be found in specimens 4 (the red arrows marked in Fig.6f). This indicates that the specimen can possess relatively higher plasticity than specimen 2 and 3, which is consistent with the results shown in Table 2.

More detailed fracture surface morphologies of three specimens are shown in Fig.6d, 6e and 6f. For specimen 2, some small flat cleavage facets and shallow dimples are distributed on the fracture surfaces, which are usually considered as brittle fracture. However, for specimen 3 and specimen 4, not only larger dimples but also some secondary cracks are distributed on their fracture surfaces (as shown in Fig.6e and 6f). In addition, deep secondary crack can be found on the fracture surface for specimen 4, as shown in Fig.6f. According to the research by Shi[4], the creation of secondary crack requires additional energy, which will lead to the increase of fracture toughness for titanium alloys.

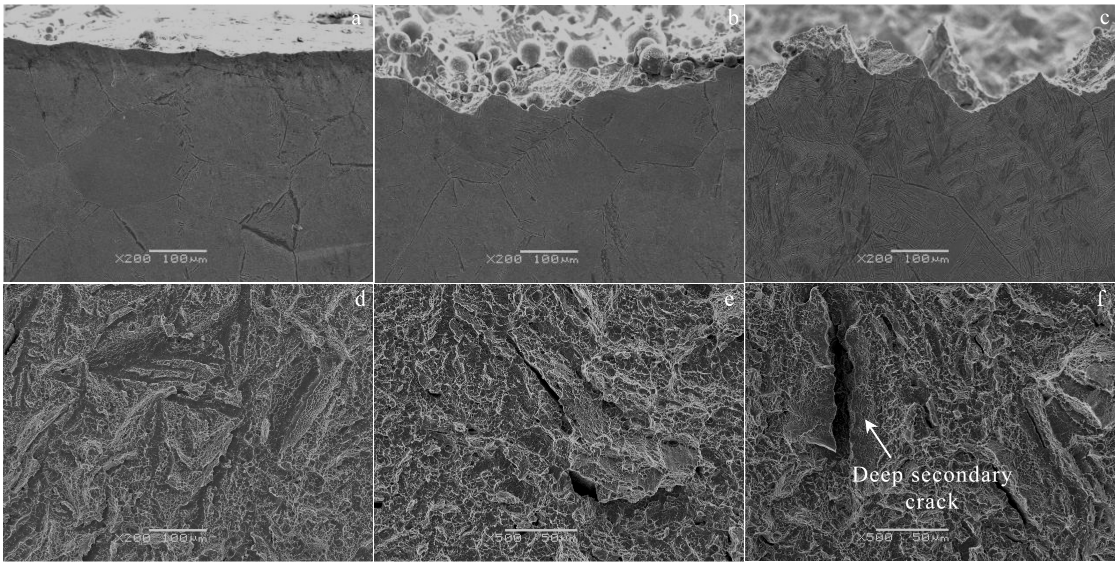

Fig.6 SEM images of specimens after fracture toughness tests: (a, d) specimen 2, (b, e)specimen 3, and (c, f) specimen 4

3 Conclusions

1) For Ti5321 alloy under different BASCA treatment, the cooling rates play a decisive role in the α lamellar size formed at slow cooling process after β zone solution. The lamellar size of Ti5321 alloy increases with the decrease of cooling rate, and the growth rate of lamellar in the length direction is much faster than that of the thickness direction.

2) With the increase of cooling rate, the strength of the alloy will increase, but the fracture toughness will decrease. The ultimate tensile strength for the alloy with the cooling rate of 0.5 ºC/min can exceed 1200 MPa with an excellent fracture toughness ($K_{IC} \geqslant 65$ MPa·m$^{1/2}$), which is the optimal cooling way in this experiment.

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Ti5321 钛合金 BASCA 处理不同冷却速度下的片层形态和性能研究

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摘　要：为了研究冷却速度对新型高强韧钛合金 Ti5321 显微组织和力学性能的影响，研究了 Ti5321 合金在不同 β 固溶缓冷时效处理（BASCA）处理后的组织和力学性能。结果表明，Ti5321 合金 β 区固溶后缓慢冷却过程中冷却速率对 α 片层尺寸有决定性影响。片层尺寸随着冷却速率的减小而增大，片层在长度方向的生长速率远快于厚度方向。同时，随着冷却速度的降低，合金的强度降低。但损伤容限特性显示出强度的反向趋势。当冷却速度为 0.5 ℃/min 时，合金抗拉强度超过 1200 MPa、同时具有良好的断裂韧性（K_{IC}≥65 MPa·m$^{1/2}$）。

关键词：钛合金；β热处理；力学性能；片层特征

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