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ARTICLE

Relationship between Mechanical Properties and Microstructure in a New High Strength β Titanium Alloy

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Abstract: A new high strength titanium alloy containing elements Cr, Fe, Mo, W and Al was designed in order to achieve an excellent combination of ultra-high strength and good fracture toughness. Both the α/β and β heat treatment were introduced to study the effect of microstructure on mechanical properties of the alloy. The result shows that the alloy with α/β solution plus aging treatment is composed of mixture microstructures including a few equiaxed or short billet-like primary α phase and fine lamellar secondary α phase. The alloy has an excellent combination of ultra-high strength and good fracture toughness. The corresponding tensile strength exceeds 1400 MPa and fracture toughnesses K_{IC} is up to 50.7 MPa m$^{1/2}$. Compared with the alloy after α/β heat treatment, the alloy with β region heat treatment presents representative Widmanstatten structure which has higher fracture toughnesses and lower strengths than the bimodal microstructure.

Key words: microstructure; high strength titanium alloy; mechanical property

β titanium alloys have been widely used in aerospace and automotive applications due to their higher strength-to -density ratio enhanced processing characteristics, excellent strength/toughness combination and superior corrosion resistance [1-5].

For structural materials, the strength and toughness are considered to be important properties for material selection and component design [6]. It is well known that the optimization of mechanical properties (strength, toughness and ductility, etc) is achieved by controlling the microstructure for titanium alloys [7]. There have been numerous studies about microstructure and mechanical properties. For example, S. Osovski et al [8] studied the effects of material properties and microstructure features on crack growth resistance when the fracture mechanism is room temperature grain boundary ductile fracture. Li Yang et al [9] had discussed the relationship between microstructure and mechanical properties of aged Ti-1300 alloy. G. Srinivasu et al [10] researched the interrelationships between rolling and solution treatment temperature, microstructures and mechanical properties.

A new β titanium alloy which contains the β stabilizing elements Cr, Fe , Mo, W and the α stabilizing element Al was designed by Northwest Institute for Nonferrous Metal Research (NIN) in China. The molybdenum equivalent of the new alloy is about 13 according to the composition and the empirical equation. Its design is to achieve an excellent combination of ultra-high strength and good fracture toughness. In the present paper, two heat treatments were carried out to prepare different microstructures of the alloy. The tensile properties and fracture toughness with two different microstructures were studied, and the fracture mechanism of the alloy was analyzed.

1 Experiment

The alloy used in this research was a forged billet with 80 mm in length of side from which cuboid specimens (11 mm

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×11 mm × 70 mm for tensile test and 52 mm ×50 mm × 25 mm for fracture toughness test) were cut linearly. Fig.1 shows the microstructure of the alloy billet. The microstructure consists of primary α phase (white particle in Fig.1) surrounded by transformed β phase (black zone in Fig.1). The transus temperature (T_β) of the material obtained by examination of microstructure is (880 ±5) ℃.

To achieve the desired microstructure, two heat treatments were applied on the microstructure. One was solution treatment at 900 ℃ for 2 h followed by furnace cooling (FC) to temperature of 400 ℃ and then air cooling (AC). The other was solution treatment at 850 ℃ for 1 h followed by air cooling and then aging at 600 ℃ for 6 h and f air cooling. The experimental scheme was given in Table 1. Tensile tests were performed in air at room temperature using Instron 1196 testing. The tensile specimens had gauge dimensions of 5 mm (diameter) and 50 mm (length). Fracture toughness tests were conducted using standard CT (compact tension) specimens with dimensions of about 50 mm × 48 mm × 20 mm in accordance with ASTM standard E-399[11] using an MTS810 fatigue testing machine. Microstructure was observed using a microscope of OLYMPUSPM-G3. Fracture surfaces of the specimens after the fracture toughness tests were observed using a scanning electron microscopy SEM-JSM6460.

2 Results and Discussion

2.1 Microstructure and mechanical properties

Representative material microstructures taken from different heat treatment are shown in Fig.2. It can be seen that microstructures of the two specimens are obviously different. The microstructure of specimen A is a mixed microstructure which contains equiaxed or short billet-like primary α and lots of secondary α phase. SEM micrograph (Fig.2b) demonstrates the shape of secondary α is fine lamellar structure with 200~300 nm in length. While the microstructure of specimen B is representative Widmanstatten structure, in which the intracrystalline α colony size ranges from 100 μm to 300 μm and the width of grain boundary α is approximately 5 μm.

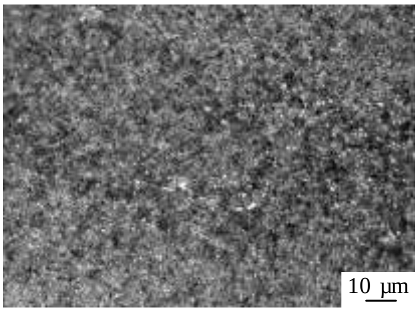

Fig.1 Original microstructure of the alloy billet

Table 1 Heat treatment schedule

Specimen	Heat treatment
A	850 ℃/1 h, AC + 600 ℃/6 h, AC
B	900 ℃/2 h, FC 400 ℃, AC

Table 2 displays the average tensile properties and fracture toughness of the alloy. It can be found from Table 2, the ultimate tensile strength of specimen A can exceed 1400 MPa with an excellent fracture toughness, and its K_{IC} is 50.7 MPa·m$^{1/2}$. Compared with other high strength titanium alloys (Ti-5553, TB10 etc[12,13]), the new alloy exhibits the better optimization of ultra-high strength and high fracture toughness. By contrast, specimen B gets clearly lower strengths value than specimens A, and its ultimate tensile strength is merely 1041 MPa. The strengthening in α/β heat treatment is attributed to the fine dispersion secondary alpha led to a high resistance against dislocation movement [14]. The fracture toughness of a material generally exhibits a reverse trend to the strength [15]. The fracture toughness of specimen B shows the larger values of K_{IC}=103.6 MPa·m$^{1/2}$. These differences clearly indicate that fully-lamellar α colonies exhibit greater toughness compared with the mixed microstructure. This theory agrees with the research by Ghosh et al [16,17].

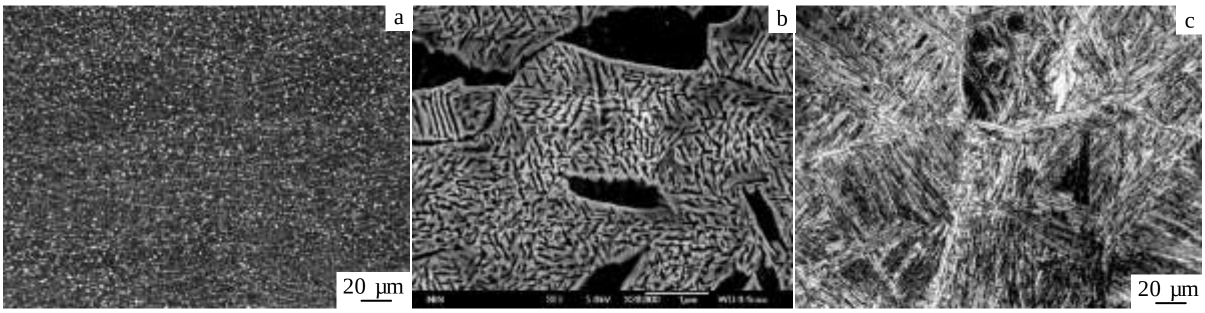

Fig.2 OM (a, c) and SEM (b) microstructures of specimen A (a, b) and specimen B (c)

Table 2 Mechanical properties of the alloy

Specimen	UTS/ MPa	YS/ MPa	EL/ %	RA/ %	K_{IC}/ MPa·m$^{1/2}$
A	1407	1346	10.5	45	50.7
B	1047	1016	19.5	37	110.4

2.2 Fracture morphology characteristics

It is necessary to investigate the fracture morphology characteristics of the alloy in order to explain the different effects of two microstructures on the fracture toughness. Fig.3 exhibits microscopically morphologies of the fracture toughness specimens A and B. It can be found that these fracture surfaces of the two specimens have obvious difference in characteristic. The fracture surface for specimen A is relatively flat with large secondary crack, but the fracture surface of specimen B is obviously rougher and some ravines can be observed on its fracture surface. The roughness of the fracture surface corresponds in general to the degree of the crack deflection [18].

The crack propagation routes of specimens A and B at high magnification are shown in Fig.4. Compared to lower fracture toughness specimen A, the crack propagation route of specimen B is branched and zigzag. For microstructure of specimen B, the crack will change its direction when crack traverses the grain boundary alpha layers or different direction intracrystalline α colonies which enhance the crack deflection effect and thus increase crack path tortuosity[19]. These processes require additional energy and result in increased fracture toughness of the material.

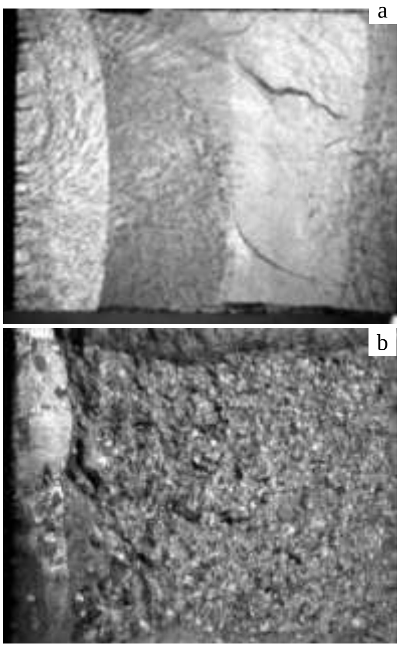

Fig.3 Fracture morphologies characteristics of specimen A (a) and specimen B (b)

Fig.5 shows the fracture surfaces of specimens A and B at high magnification using SEM. It can be found that there still exist great differences of the fracture mechanisms between the two specimens. The fracture surfaces of specimen A is of ductile intercrystalline crack character, while specimen B shows ductile transcrystalline fracture, separation surface appears at coarse β grain boundaries and there exist microcracks besides primary β grain boundaries which will lead to stress release, thus increasing the toughness[20].

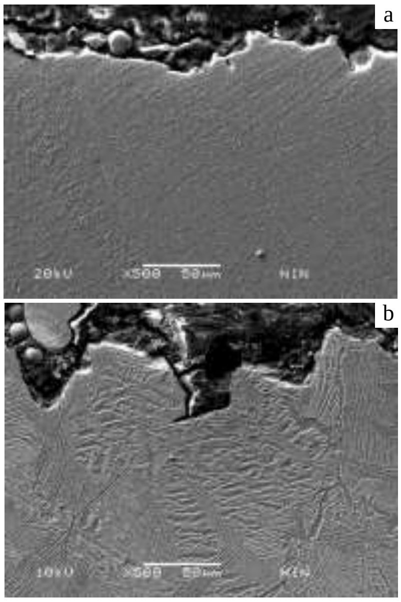

Fig.4 Crack propagation paths of specimen A (a) and specimen B (b)

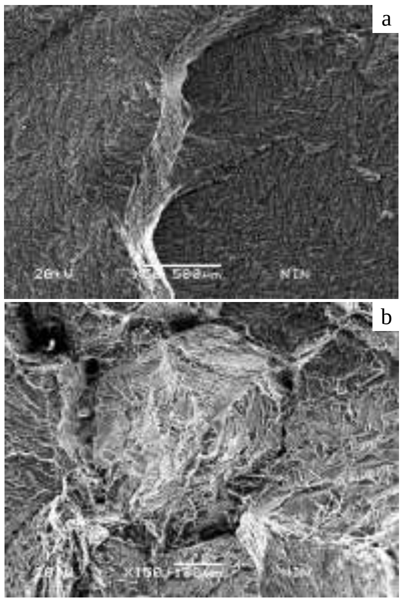

Fig.5 Fracture surfaces of specimen A (a) and specimen B (b)

3 Conclusions

1) For the new high strength β titanium alloy studied in present work, the microstructure with α/β region solution treatment plus aging treatment is composed of a few equiaxed or short billet-like primary α phase and fine lamellar secondary α phase, while the alloy with β region solution treatment and slow cooling to low temperature presents representative Widmanstatten structure.

2) The microstructure of Widmanstatten structure has higher fracture toughnesses and lower strengths than the bimodal microstructures. Various fracture mechanisms change from transcrystalline in Widmanstatten structure to intergranular in mixed microstructures.

3) Compared with other high strength titanium alloys, the new alloy with α/β solution plus aging treatment has excellent combination of ultra-high strength and good fracture toughness. The corresponding tensile strength is about 1400 MPa and fracture toughnesses K_{IC} is 50.7 MPa m$^{1/2}$.

References

1 Zhang Yaowu, Kent Damon, Wang Gui *et al*. *Journal of the Mechanical Behavior of Biomedical Materials*[J], 2015, 207: 218

2 Li Chenglin, Mi Xujun, Ye Wenjun *et al*. *Journal of Alloys and Compounds* [J], 2013, 523: 30

3 Chen Yuyong, Du Zhaoxin, Xiao Shulong *et al*. *Journal of Alloys and Compounds* [J], 2014, 588: 592

4 Huang Liguo, Chen Yuyong. *Materials and Design*[J], 2015, 110: 117

5 Chen Jun, Chang Hui, Li Hui. *Acta Metallurgica Sinica*[J], 2002, 38(S): 108 (in Chinese)

6 Fan J K, Li J S, Kou H C *et al*. *Materials Characterization*[J], 2014, 93: 99

7 Guo Ping, Zhao Yongqing, Zeng Weidong. *Rare Metal Materials and Engineering*[J], 2015,44(S): 277 (in Chinese)

8 Osovski S, Srivastava A, Williams J C *et al*. *Acta Materialia* [J], 2015, 67: 178

9 Li Yang, Wei Qiang, Ma Chaoli *et al*. *Chinese Journal of Aeronautics*[J], 2009, 535: 539

10 Srinivasu G, Natraj Y, Bhattacharjee A *et al*. *Materials and Design*[J], 2013, 323: 330

11 Prasad Kartik, Sarkar Rajdeep, Kamat S V *et al*. *Materials Science and Engineering A*[J], 2011, 529: 74

12 Fanning J C. *Journal of Materials Engineering and Performance*[J], 2005, 788: 791

13 Zhang Zhu, Hui Songxiao, Liu Wei. *Chinese Journal of Rare Metals*[J], 2004, 221: 225 (in Chinese)

14 Li Chenglin, Mixujun, Yewenjun *et al*. *Materials Science and Engineering A*[J], 2013, 578: 103

15 Peng Xiaona, Guo Hongzhen, Wang Tao *et al*. *Materials Science and Engineering A*[J], 2012, 533: 55

16 Kwietniewski C, dos Santos J F, da Silva A A M *et al*. *Materials Science and Engineering A* [J], 2006, 417: 49

17 Cvijovic′-Alagic′ I, Gubeljak N, Rakin M *et al*. *Materials and Design* [J], 2014, 870: 880

18 Shi Xiaohui, Zeng Weidong, Shi Chunling *et al*. *Journal of Alloys and Compounds*[J], 2015, 748: 755

19 Shi Xiaohui, Zeng Weidong, Zhao Qinyang. *Materials Science and Engineering A*[J], 2015, 636: 543

20 Lei Wang, Mitsuo Niinomi, Shiro Takahashi *et al*. *Materials Science and Engineering A* [J], 1999, 263: 319

一种新型高强 β 钛合金力学性能和显微组织的关系研究

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摘 要：研究了一种新型 Ti-Al-Cr-Mo-W 系高强、高韧 β 钛合金显微组织与力学性能的关系。结果表明，相变点之下固溶时效处理得到的含有等轴或短棒状初生 α、细小片层次生 α 的混合组织的强度超过 1400 MPa ，断裂韧性达到 50.7 MPa m$^{1/2}$，该性能表明合金与同类高强钛合金相比具有更优异的强-韧性匹配。β 区固溶缓冷处理得到的魏氏组织相比于混合组织具有较低的强度和较高的韧性。

关键词：显微组织；高强钛合金；力学性能

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