Materials Science & Engineering A 636 (2015) 543–550

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

The effects of lamellar features on the fracture toughness of Ti-17 titanium alloy

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ARTICLE INFO

Article history:
Received 9 February 2015
Received in revised form
7 April 2015
Accepted 8 April 2015
Available online 16 April 2015

Keywords:
Fracture toughness
Ti-17
Crack propagation path
Cooling method

ABSTRACT

The effects of lamellar features on the fracture toughness of Ti-17 titanium alloy are studied in the present paper. Three cooling methods were used to prepare different lamellar features of Ti-17 titanium alloy after β forging. Then the same solid solution plus aging treatment were conducted to get the final microstructures. The results show that the microstructure with long and thick needle-like α platelets gets higher fracture toughness as well as strength than the microstructure with short rod-like α platelets. This seemingly “abnormal” phenomenon can be explained based on the theory that the fracture toughness is attributed to two major contributions, namely the crack path tortuosity (extrinsic part) and material plastic deformation along the crack path (intrinsic part). The respective contribution of the plasticity and crack path tortuosity to the fracture toughness of Ti-17 alloy are quantitatively evaluated based on the existent models proposed by previous researchers. The results show that the intrinsic contributions for the three microstructures with different lamellar features do not show a big difference. However, their extrinsic contributions are dramatically different. The microstructure which contains the longest and thickest α platelets gets the most rugged crack propagation path and moderate plasticity among the three microstructures, which results in the highest fracture toughness. Moreover, due to the nature of the near-β Ti-17 alloy, the long and thick α platelets in microstructure also get high aspect ratios, which results in high interfacial strengthening effect. Thus for Ti-17 alloy studied in the present work, the long and thick α platelets in microstructure can realize a good combination of fracture toughness and strength.

1. Introduction

In materials science, fracture toughness is a property which describes the ability of a material containing a crack to resist fracture, and is one of the most important properties in damage tolerance design concept. Thus for various kinds of materials, especially those used in aerospace industry for structural applications, fracture toughness should be regarded as an important index for material selection and component design to guarantee the safe flight [1].

Titanium alloys are widely used in the aerospace industry due to their excellent properties, such as high specific strength, good biocompatibility and corrosion resistance [2,3]. However, with the increasing demand of the fracture properties for the structural materials in aerospace industry, it tends to be increasingly difficult for titanium alloys to meet these requirements. As a result, their applications have been greatly limited. Generally speaking, two methods can be used to solve this problem. The first one is to develop a new class of titanium alloys based on the damage tolerance design concept, for example the Ti–6A1–2Zr–2Sn–3Mo–1Cr–2Nb titanium alloy designed by Northwest Institute For Nonferrous Metal Research, China [4]. The second method is to optimize the fracture toughness of the existent titanium alloys by controlling their microstructure features. It is well known that the design of a new material is a very complicated process, which needs too many verification experiments. By contrast, the second method appears to be more economic and convenient. Thus many researchers have conducted investigations on the interrelations between fracture toughness and the microstructure features for various titanium alloys [5–10]. For example, Bhattacharjee et al. [5] had investigated the influence of β grain size on the fracture toughness of Ti–10V–2Fe–3Al titanium alloy. They found that the fracture toughness of this alloy approximately follows a Hall–Petch relationship with its β grain size. Greenfield et al. [6] studied the facture

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http://dx.doi.org/10.1016/j.msea.2015.04.021
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toughness–microstructure relations for Ti–5.25Al–5.5V–0.9Fe–0.5Cu alloy, and found that the increasing grain boundary α thickness can obviously improve its fracture toughness until a critical value of 5.5 μm is reached. It is due to that thicker grain boundary α can more effectively blunt the running crack tip, which can increase the fracture resistance. Cvijović-Alagić et al. [7] found that the colony size and the aspect ratio of α phase are two main factors influencing the fracture toughness of Ti–6Al–4V alloy with lamellar structure. They thought that bigger colony size and higher aspect ratio of α platelet are more favorable to deflect the crack propagation path, which can effectively improve the fracture toughness. The research by Kwietniewski et al. [8] generally gotten a similar result with that in Ref. [7]. Richards [9] studied the fracture toughness of two α+β titanium alloys containing α platelets in transformed β matrix. He found that the highest toughness values of both alloys were associated with the finest platelet spacings and the thickest α platelets. It is explained in terms of the distance between active centers of void nucleation, which is a function of the α platelet thickness and the platelet spacing. Mitao et al. [10] found that the orientation of lamellar lath can affect the fracture toughness of γ-TiAl alloy. When the crack plane is nearly perpendicular to the lath, toughening due to crack-tip blunting results in the improved fracture toughness. However, when the crack tip is parallel to the lamellar lath, the weak interphase may not offer any resistance to crack growth and yields the lowest fracture toughness. In conclusion, the fracture toughness of titanium alloy can be greatly influenced by its microstructure features, for example the β grain size, colony size, the aspect ratio of α platelet, α platelet thickness and spacing, etc. Moreover, for different titanium alloys or the same alloy with different microstructure types, their main influencing microstructure features on fracture toughness may be variant. Thus it is essential to conduct elaborate research if the microstructure–fracture toughness relations for a given titanium alloy need to be understood.

Ti-17 titanium alloy (namely Ti–5Al–2Sn–2Zr–4Mo–4Cr), which was primarily developed by GE Aircraft Engines, is a “β-rich” α+β titanium alloy due to an 8% content of β stabilizer alloying elements including molybdenum and chromium [11]. In China, Ti-17 alloy has attracted too much attention due to its wide application in manufacturing the fan blades and compressor disks of aircraft engine [12–17]. Based on orthogonal analysis, Liu et al. [12] established a constitutive model of Ti-17 titanium alloy with lamellar-type initial microstructure during hot deformation. Li et al. [13] studied the deformation behavior of Ti-17 titanium alloy by isothermal compression at the deformation temperatures ranging from 1053 K to 1193 K. Ma et al. [15] made an investigation on the unstable flow behavior of Ti-17 alloy in α+β phase field using processing map. It can be found that the research efforts were mainly focused on the deformation behavior and microstructure evolution of Ti-17 alloy. However, a few reports concerning the microstructure–fracture toughness relations of Ti-17 alloy can be found. Thus in the present paper, the fracture toughness and the fracture mechanism of Ti-17 alloy with different lamellar features are studied. Moreover, the lamellar features which may lead to improved fracture toughness are tried to be found.

2. Materials and experimental procedures

2.1. Materials and microstructures

The as-received Ti-17 alloy bar with the size of Φ365 mm × 300 mm was supplied by AVIC Shaanxi Hongyuan Aviation Forging Company Ltd., PR China. Table 1 shows its chemical composition. The β transus temperature of this alloy was identified as 900 °C via metallographic techniques.

To prepare the experimental material with different lamellar features, the as-received bar was cut into three disks which were all isothermally forged at 930 °C with a deformation degree of about 40%. Subsequently, the three disks after β forging were cooled at room temperature by means of water quenching, air cooling and slow air cooling respectively (see Table 2). Slow air cooling means that the hot and red forging should be covered with asbestos gaskets until it became visually dark. Undoubtedly, the cooling rates of the forgings put in different cooling mediums decrease in the sequence of water quenching, air cooling and slow air cooling.

Finally, to improve the strength of Ti-17 alloy, the same solid solution plus aging treatment were conducted on the three forgings. Solid solution treatment was conducted at 800 °C for 4 h followed by water quenching to room temperature, then the aging treatment was conducted at 630 °C for 8 h followed by air cooling.

Fig. 1 shows the microstructures of Ti-17 alloy under different cooling methods. Fig. 1(a), (b) and (c) demonstrates the microstructures A, B and C respectively with low magnification (50 ×). It can be found that the three microstructures have similar β grain size, which is about 600 μm. According to the research by Gil et al. [18], the β grain size of titanium alloy can be mostly affected by the heating temperature and holding time in the β phase field. Thus it is easy to understand that the cooling rates of the forging from the β phase field do not exert too much influence on the final β grain size.

Fig. 2(a), (b) and (c) shows the microstructures A, B and C respectively with high magnification (500 ×). It can be noted that the lamellar features of the three microstructures are obviously different. Microstructure A was obtained through water quenching. It contains short rod-like α platelets, which are about 3–10 μm in length and 1–1.5 μm in thickness, as shown in Fig. 2(a). By contrast, microstructure B obtained through air cooling gets obviously longer α platelets than microstructure A, which are about 10–20 μm in length. However, the α platelets of microstructures B are slightly thinner than microstructures A, which are around 1 μm. Microstructure C obtained through slow air cooling gets the longest and thickest α platelets among the three microstructures, which are about 20–40 μm in length and around 1.5 μm in thickness. To sum up, with decreasing cooling rates after forging, the α platelet length of Ti-17 alloy keeps increasing. Besides, unlike the rod-like α platelets in microstructures A, the tail ends of the α platelets in microstructures B and C are very sharp and exhibit needle-like features. The obviously different lamellar features of the three microstructures can be attributed to the variant cooling methods after forging. As we know, Ti-17 alloy belongs to the category of near β titanium alloy, thus this alloy can retain, if quenched quickly, the whole β phase at a metastable state [19]. Therefore, during the water quenching process of the Ti-17 forging, the α phase can almost not precipitate from the β matrix. As a result, high distortion energy during deformation was stored. In the subsequent insulation stage of solid solution treatment (800 °C for 4 h), the existence of the distortion energy in the metastable β matrix

Table 1
The chemical composition (wt%) of as-received Ti-17 titanium alloy.

Ti	Al	Sn	Zr	Mo	Cr	Fe	N	O	H	C
Bal.	5.03	2.31	1.99	3.92	3.95	0.05	0.01	0.002	0.11	0.01

Table 2
The thermomechanical processes for Ti-17 titanium alloy.

	β Forging process	Cooling method after β forging	Solid solution plus aging treatment
A	930 °C, 40%	Water quenching	800 °C/4 h, WQ+630 °C/ 8 h, AC
B		Air cooling	
C		Slow air cooling	