Study on Plastic Deformation Zone of Titanium Alloy

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Abstract: During the crack propagation, crack tip contains stress odd singularity and has specific yield range. As the cycling loading continuing, the crack grows in the plastic zone. So the plastic zone is crucial to crack propagation action. In this paper, the crack propagation route was observed in different microstructures, the deformation characteristic of plastic zone was analyzed for equiaxed structure and lamellar structure. The results show that crack propagation path is more straighter in equiaxed structure than that in lamellar structure. There were more tiny cracks near the crack surface in the lamellar structure during the crack growth, which shows that lamellar structure has a bigger plastic zone during the deformation. The plastic deformation need absorb the energy, which hinders the crack propagation.

1. Introduction

With the developments of fracture mechanics and damage tolerance theory, the damage tolerance design concept is widely accepted in aerospace structure material. The damage tolerance properties are tested mainly by fracture toughness (KIC) and crack propagation rate (da/dN). Some studies [1-6] have shown that lath morphology of the titanium alloys can obtain lower crack propagation rate and higher fracture toughness. TC4-DT is an α+β titanium alloy with moderate strength and high damage tolerance, it has preferable fracture properties comparing to other Ti grades thus it widely used in manufacture flight frame members with superior properties [7]. Fatigue crack propagation mechanism has been more studied, which mainly focuses on studying the effect of microstructure on crack propagation path. Fracture process of most materials need overcome surface energy and plastic deformation energy, that is, cracks need to overcome the plastic deformation in crack tip to split the material during the crack propagation. There is a plastic zone near the crack tip, and the area of the plastic zone means that how much energy can be absorbed when the crack moves forward. In the process of the crack propagation, crack tip contains stress singularity and has specific yield range, the crack propagation occurs in the plastic zone, so the plastic zone is crucial to crack propagation action. Currently, the research about crack deformation plastic zone is insufficient to fully understand the fracture properties of TC4-DT [8-13]. In this paper, fatigue crack propagation behavior was assessed at room temperature, and plastic deformation zones in different microstructures were studied.

2. Experimental procedure

The TC4-DT alloy used in this study was produced by double-melt in consumable electrode vacuum furnace into a cylindrical mold of 460mm in diameter, hot-forged in the β phase field, and finally forged to a square bar of 80 mm×80 mm×L in the (α+β) phase field, followed by air-cooling to room temperature. The beta transus temperature of the alloy was (980±5)°C. Its chemical composition (mass fraction %) is 6.08Al, 4.19V, 0.06Fe, 0.11O, 0.009C, 0.005N and the remaining is titanium. The tensile
specimens were made by wire electrical discharge machining from the bar with a gauge length of 25 mm and a diameter of 5 mm. The normative T–L specimens are used for a da/dn test, and the thickness of the specimens is 12.5 mm. The specimens were solution-treated and aged with two different parameters, the corresponding morphology and performances are shown in Table 1. microstructure of equiaxed and the lamellar could be obtained in different conditions, as shown in Fig. 1. Fatigue tests were performed on a fatigue test machine of MTS-810 under maximum load control of 5KN at R=0.1 and frequency of 15HZ. A light microscope of OLYMPUS PMG3 was used to observe the microstructures, the fracture surface of the specimens and the crack propagation route after fatigue tests were observed using a scanning electron microscopy.

Table 1 Parameters of solution treated and aged condition

| No. | Treated conditions | Microstructure | Rp0.2 /MPa | A/% | Z/% | KIC /MPa.m$^{1/2}$ | Da/dN |
|-----|------------------|----------------|------------|-----|-----|---------------------|------|
| 1   | 950℃/1h. AC+550℃/4h. AC | Equiaxed       | 868        | 15.5 | 51  | 75.8 | $1.53 \times 10^{-9}(\Delta K)^{1.99}$ |
| 2   | 1000℃/1h. AC+550℃/4h. AC | Lamellar       | 823        | 9    | 20  | 81.8 | $1.08 \times 10^{-11}(\Delta K)^{4.99}$ |

3. Results and discussion

3.1. Crack growth route in different microstructures

The crack growth paths of the different microstructures are shown in figure 2. As shown in figure 2a, the crack growth route is smooth in equiaxed structure, and there are few branches. Cracks directly spread through equiaxed α grain when meet equiaxed α phases, and a small number of transformed β structure can’t hinder fatigue crack growth, so less energy was absorbed, which leads to a higher crack spread rate. While crack growth path in lamellar structure is zigzag. Fatigue crack extends forward along zigzag, as shown in figure 2b. The main crack produces branches to form secondary cracks and extend forward during the crack propagation. Moreover, secondary cracks can generate more tiny cracks, which absorb the fracture energy, leading to the slow crack propagation under the cyclic loading. The lamellar structure has coarse initial β grains and continuous α phase on initial β grain boundary, lamella α cluster is formed in the β grain. The cracks can only pass through the α bundling which is parallel to the crack propagation orientation, as shown in figure 2c. Orientation of every α bundling is different, so cracks cease and are obliged to change orientation when spread to bundling boundary, which lead to more-zigzag expansion path, coarser fracture surface, and more energy consumption. In addition, the main crack generates branches to release the concentrated stress in crack tip of the Widmanstatten structure, that is, secondary crack forms at an angle to main crack and crack tip meets more resistances during the propagation, which can consumes more energy, so the fatigue crack growth properties of lamellar structure is superior comparing to the equiaxed structure.

![Figure 1. Optical micrograph of equiaxed and lamellar structure](image1.jpg)
The fatigue crack is produced in the process of local plastic deformation, and it propagates following two stages under the condition of cyclic stress, as seen in figure 3. Dislocation glide is the most important role in the first stage and its feature is that, the crack growth plane is parallel to the orientation of maximum resolved shear stress and crack growth is limited in the scale of two grains on surface. In the second stage of crack growth, fatigue crack will change the direction of extension surface to be perpendicular to the direction of maximum tensile stress, and display the feature of crack growth on normal stress. Large numbers of tiny cracks can be seen at an angle of 45 degree to external stress on the surface of fatigue-damaged specimen, which occurs from different persistent slip bands, and grows through dislocation slipping, one of them grows to become main crack and lead to fracture.

3.2. Theoretical analysis of plasticity region
During the crack propagation, crack tip contains stress singularity and has specific yield range, that is the plastic deformation zone. A tiny plastic zone is formed in crack tip when the stress reaches the yield limit of the material at the front of cracks, which releases the stress. Figure 4 shows the stress distribution of small plasticity zone ahead of I-type crack.
Without considering the work hardening, effective stress $\sigma_y$ in the Y direction is equal to $\sigma_{ys}$, that is, the material yields and the crack tip occurs the plastic deformation. In fact, the plastic deformation redistributes stress and the plastic area are concentrated more close to the front of the crack. So the size of the plastic zone on plane strain condition is smaller than that on actual condition. Plastic deformation feature near crack surface can reflect deformation status in crack tip place. In this paper, deformation feature near crack surface is observed by optics microscope and crack tip plasticity region in lamellar structure is studied during crack propagation. The result displays bigger plastic deformation region near crack surface in lamella structure, and with the crack length increasing, the plastic deformation range and deformation degree increase gradually.

Figure 5. The plastic deformation near crack surface in lamellar structure

Figure 5 shows surface crack, which are produced by plastic deformation. When the fatigue crack length is 1mm, the depth of the surface crack is 40 $\mu$m, and when the crack length is 4.5mm, the depth of the surface crack is 440 $\mu$m. In the equiaxed structure, the smaller plastic deformation range is found near crack surface. The fatigue cracks propagate and loop around or cut through $\alpha$ phase when cracks meet equiaxed $\alpha$ grains, as seen in figure 6. Comparing to equiaxed structure, fatigue crack tip creates larger plastic deformation zone in the lamellar structure.

Figure 6. Crack propagation in bi-modal structure

3.3. Discussion
Fatigue crack tip plastic region can be divided into the one-way region and the cyclic plastic region, on the condition of cycling loading plane strain, the dimension of crack tip plastic zone is described by the equation (1) [14, 15].

$$Rc = \frac{1}{3\pi} \left( \frac{\Delta K}{2\sigma_y} \right)^2$$

(1)

In the equation, $\sigma_y$ is yield strength, and $\Delta K$ is stress intensity factor range. In this paper, the test was on the condition of cyclic loading. When crack length is 1mm, $\Delta K$ is corresponding 12.75 MPa.m$^{1/2}$, and width of plastic region is 6.5$\mu$m; when crack length is 4.5mm, $\Delta K$ is corresponding 22MPa.m$^{1/2}$, and width of plastic region is 20$\mu$m. Therefore, the dimension of plastic region by theory calculation is
much smaller than actual measure one. Equation (1) is suitable for ideal elastic-plastic material and takes no account of the effect of microstructure and stress slack on plastic region. In addition, plastic deformation ahead of cracks makes stress to redistribute and leads to the plastic region amplify on the horizontal cyclic loading, and forms plastic deformation material layer. As seen in equation (1), the dimension of plastic region is influenced by yield strength, which is 823MPa in lamellar structure and is 868MPa in equiaxed structure. In the same stress intensity factor range, the difference of plastic region range from two microstructures is only 8% by theoretical calculation, but the difference is much bigger than 8% in the actual measure result. The morphology and property parameters also affect the results beyond the yield strength. Feature of plastic region is related to the plastic deformation characteristic of the material. For material toughness, crack propagation caused by cycling loading can be thought as local deformation process in the slipping band near crack tip and the forming of new crack surface by cutting. Therefore, microscopic model of fatigue crack propagation is depended on slipping feature under the specific condition of microstructure and stress level. The research [16] shows that the HCP structure and the BCC structure have respectively different sliding system in titanium alloy, and have a specific orientation relationship. In the lamellar structure, $\alpha/\beta$ phase has the same direction in adjacent bundling, and slipping is easy to start. In addition, the dimension of grain and colony is much bigger in the lamellar structure, and the interaction of more slip systems makes coordination deformation zone bigger, which leads to the larger crack tip plastic region. While fatigue crack initiates along slip band on the surface in the equiaxed structure, the slip band is not continuous under the microscope. Moreover, there is dense void at the $\alpha/\beta$ boundary in the slide bands, which is due to the small equiaxed grain and no orientation relationship between them, thus sliding distance is shorter and slip is easy to be hindered by phase boundary. To keep the strain coordination of many grains, it is necessary to move more slip systems, and crack propagates along the consistent phase boundary with the slip line to interact with the deformation between adjacent phases. Since the slip system is in smaller range near crack surface, it leads to smaller crack tip plastic zone.

4. Conclusion
1. The microstructure characteristic has big effect on crack propagation path. The crack propagation path is more linear in equiaxed structure than that in lamellar structure.
2. There were more tiny cracks near the crack surface in the lamellar structure, which shows that lamellar structure has a bigger plastic zone during the deformation. This plastic deformation absorbs the cracking energy and hinders crack propagation.

References
[1] T Seshacharyulu, S C Medeiros, J T Morgan, et al 2000 Mater. Sci. Eng. A 279 289-299
[2] V Sinha, W O Soboyejo 2001 Mater. Sci. Eng. A 319-321 607-612
[3] G Lütjering 1998 Mater.Sci.Eng. A 243 32-45
[4] G Lütjering 1999 Mater. Sci.Eng. A 263 117–126
[5] R Filip, K Kubiak, W Ziaja, J Sieniawski 2003 J. Mater.Proces. Technol 133 84–89
[6] Sh K Li, B Q Xiong, S X Hui, W J Ye, Y Yu 2007 Mater. Sci. Eng. A 460–461 140–145
[7] D C James, P C Larry, R P Herry 2002 Adv. Mater. Process. 160 25-8
[8] Sh K Li, B Q Xiong, S X Hui, W J Ye, Y Yu 2008 Mater. Characterization 59 397-401
[9] K Sadanandaa, A K Vasudevanb 2005 Int. J. Fatigue. 27 1255–1266
[10] K Sadananda 2005 Int. J. Fatigue 27 1255-1266
[11] T Goswami 2003 Mater. Des. 24 423-433
[12] J Ding, R Hall, J Byrne 2005 Int. J. Fatigue 27 1551-1558
[13] S Shademan, V Sinha 2004 Mech. Mater. 36 161–175
[14] G R Irwin 1960 (Proceedings of the Seventh Sagamore Ordnance Materials Conference New York VI) 63-78
[15] J R.Rice 1967 (Fatigue Crack Propagation ASTM STP 415 Philadelphia ASTM) 247-312
[16] S Suri, G B Viswanathan, T Neeraj, D H Hou, M J Mills 1999 Acta. Mater. 47 1019-1034