Subsurface Facet-fisheye Induced Failure of Titanium Alloy under Very High Cycle Fatigue

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Abstract. Very high cycle fatigue test under pulsating tension was performed to investigate the subsurface failure mechanism of a titanium alloy. A peculiar region, called “facets cluster zone (FCZ)”, is located at the center of fisheye. The slip-like patterns on facet surface, coalescence of nanoscale cracks and growth of microcracks in the maximum shear stress plane are observable. Combined with the evaluation of stress intensity factors at crack tips, the subsurface failure processes are summarized as: (a) localization of plastic strain, (b) occurrence of slip lines, (c) nucleation of microcracks, (d) coalescence and growth of microcracks, (f) occurrence of the FCZ, (g) formation of fisheye and (i) unstable crack growth until final fracture.

1. Introduction

Very high cycle fatigue (VHCF) associated with microscale deformation-induced failure of materials has been a topic of growing interest, because fatigue failures in the VHCF regime beyond $10^7$ cycles have been widely found in materials that were assumed to be operating at the stresses below conventional fatigue limit [1]. One of the things that we focus in the VHCF regime is the change of failure mode from the surface to the subsurface [2, 3]. Because of this change, some researchers [4, 5] believe that there is no conventional fatigue limit in many metals and alloys such as high-strengthen steels, titanium alloys, high-temperature alloys, irons, etc. According to the X-ray analysis, generally internal metallurgical defects such as non-metallic inclusions or pores can be easily the source for cracks to develop in the VHCF regime [2-4]. And, a propagating circular crack shaped like a fisheye can be observable. Sometimes, a fine granular area (FGA) [2] can occur around the inclusion. Some models or methods have been used to explain its formation mechanism [5]. However, for the titanium alloys with non-defect induced failure, the subsurface failure mechanism and related mechanical condition are not yet well understood [6, 7]. In this study, in order to ensure the long-term safety of mechanical components or parts, we therefore investigate the subsurface failure processes with crack nucleation and early growth for a titanium alloy subjected to the VHCF loading.

2. Materials and Method

The investigated material is a TC11 titanium alloy. Its chemical composition (mass percentage) is: 6.3Al, 3.4Mo, 1.68Zr, 0.23Si, 0.10O, 0.05Fe, 0.0006C, 0.0006N and balance Ti. The specimens were...
first machined into the shape of hourglass with a certain amount of grinding margin, and then heat-treated as: (1) 950 °C × 1 h, air cooled and (2) 530 °C × 6 h, air cooled. The microstructure observed by scanning electron microscope (SEM) consists of about 37% α grains and 63% β grains.

The pulsating tension fatigue test was performed by using an electromagnetic resonant testing machine at the frequency of 100 Hz in open environment at room temperature. The testing cycles were ranged from $10^6$ cycles to $10^9$ cycles.

3. Results and Discussion

3.1. Subsurface Failure

The $S$–$N$ (stress – number of cycles) data exhibit the continually descending trend without conventional fatigue limit. Based on the observation of SEM and the analysis of energy dispersive X-ray spectrometer, failures are all caused by inhomogeneous microstructures. Figure 1(a) shows a typical fracture surface, on which the fisheye, unstable growth zone and momentary fracture zone are all distinguished. A peculiar bright region shown in Figure 1(b) occurs at the center of fisheye, and some flat facets are found within this region. The morphology of facet is given in Figure 1(c). This region is named as “facets cluster zone (FCZ)”. From the viewpoint of small crack growth, the maximum stress intensity factors around the facet, FCZ and fisheye, $K_{max-f}$ $K_{max-FCZ}$ and $K_{max-FE}$, are given by [8, 9]

$$K_{max-f or FCZ} = 0.5\sigma_{max} \sqrt{\pi area_{f or FCZ}} \tag{1}$$

$$K_{max-FE} = \frac{2}{\pi} \sigma_{max} \sqrt{\pi area_{FE}}$$

Where $\sigma_{max}$ is the applied maximum stress, $\sqrt{area_{f or FCZ}}$ is the size of facet or FCZ and $\sqrt{area_{FE}}$ is the size of fisheye. The values of $K_{max-f}$ are in the range of 1.17-1.44 MPam$^{1/2}$ and tend to decrease with the increasing of life $N_f$, as showed in Figure 1(d). This means that small crack effect contributes to the fracture of facet. Moreover, the values of $K_{max-FCZ}$ and $K_{max-FE}$ are respectively in the limited ranges of 5.17-5.77 MPam$^{1/2}$ and 9.51-11.06 MPam$^{1/2}$, as shown in Figure 1(d). Each of them keeps a constant, regardless of life. Combined with previous studies [2, 10], $K_{max-FCZ}$ and $K_{max-FE}$ can be regarded as the threshold values controlling the stable and unstable crack growth, respectively.

![Figure 1](image_url)

Figure 1. (a) Typical fracture surface ($\sigma_{max}$=650 MPa, $N_f$=90,199,000 cycles), (b) FCZ, (c) Facet and (d) $K_{max-FCZ}$, $K_{max-FE}$ and $K_{max-f}$ vs. $N_f$.

3.2. Observation using FIB

The focused ion beam (FIB) was used for site specific milling on fracture surface. For the fracture surface given in Figure 2(a), two sites including the site within FCZ and the site outside FCZ within fisheye are chosen. The milled microscopic holes are shown respectively in Figs. 2(b) and 2(c).
Along the base line that is tangent to the edge of facet within the FCZ, the milling direction, i.e. the change of width $W$, is shown Figure 3(a). A number of slip-like patterns on facet surface are found. It is verified that the slip related to dislocation movement plays a role in the formation of facetted crack. With the increasing of $W$, the different morphologies on the inner wall of hole can be observable. When $W=4 \mu m$, a large grain surrounded by small grains is found in Figure 3(b). The strain discontinuity inevitably occurs on the interface between them. When $W=8 \mu m$, a few of deformed grains that contact the fracture surface are observed in Figure 3(c). When $W=10 \mu m$, two embedded microcracks I & II occur in Figure 3(d). It seems that there is no coalescence between them in Figure 3(e). The length of crack II is only about hundreds of nanometers. When $W=12 \mu m$, a microcrack III shown in Figure 3(f) is inclined with respect to the loading direction. When $W=13.2 \mu m$, the growth of microcrack III along about $45^\circ$ is identified in Figure 3(g). This means that the microcracks easily blocked by the grain boundary tend to grow in a plane of maximum shear stress. Furthermore, the coalescence of microcracks I & II is found. For the FIB milling within fisheye, however, besides the propagating secondary cracks shown in Figure 3(h) with $W=5 \mu m$ and non-deformed grains shown in Figure 3(i) with $W=15 \mu m$, no microcracks can be found below the fracture surface from $W=0 \mu m$ to $W=15 \mu m$. 

**Figure 2.** (a) FIB sampling, (b) Milled hole within FCZ and (c) Milled hole within fisheye
3.3. Failure Modeling

Before loading, a number of dislocations can exist in the crystal structure, as shown in Figure 4(a). Under loading, due to the difference of mechanical properties between softer α grains and harder β grains, the large or small stress concentration, i.e. the localization of plastic strain, can occur on the interfaces, as shown in Figure 4(b). On some grains oriented in the maximum shear stress plane, slip lines or bands can preferentially occur, as shown in Figure 4(c). In these stages, $K_{\text{max}}$ is still smaller than the threshold value governing local microstructurally small crack, $\Delta K_{\text{th,l}}$. As cycling continuous, more slip lines occur and continue to thicken. Especially at their intrusions, they will become the sources for crack nucleation. As a result, a few microcracks are formed, as shown in Figure 4(d). Some of them will discontinuously grow along the maximum shear stress plane and mutually coalesce. When the crack crosses the entire grain, the facet is formed, shown in Figure 4(e). Meanwhile, $K_{\text{max}}$ will exceed $\Delta K_{\text{th,l}}$, governed by the microstructure. When the progressive development of microcracks, followed by the fracture of α-grains, spreads to a given region, and a circular crack, i.e. the FCZ, is formed, as shown in Figure 4(f). Note that $K_{\text{max}}$ reaches the threshold value controlling macrocrack growth, $\Delta K_{\text{th,o}}$. Herein, this threshold value is $K_{\text{max,FCZ}} = 5.52 \text{ MPa m}^{1/2}$. From then, the mechanics will dominate the growth of crack instead of the microstructure. The formed macrocracks will propagate at a stable rate in Paris region, as shown in Figure 4(g). When the fisheye is fully formed, the subsequent crack will grow in an unstable manner until fracture, and $K_{\text{max}}$ is larger than the threshold value controlling unstable growth $\Delta K_{\text{th,u}}$, i.e. $K_{\text{max}} \geq K_{\text{max,FE}}$, as shown in Figure 4(h).
Figure 4. (a) Microstructure with α and β grains $(K_{\text{max}} < \Delta K_{\text{th-L}})$, (b) Localization of plastic strain $(K_{\text{max}} < \Delta K_{\text{th-L}})$, (c) Occurrence of slip lines $(K_{\text{max}} < \Delta K_{\text{th-L}})$, (d) Nucleation of microcracks $(K_{\text{max}} > \Delta K_{\text{th-L}})$, (e) Coalescence and growth of microcracks $(K_{\text{max}} > \Delta K_{\text{th-L}})$, (f) Formation of FCZ $(\Delta K_{\text{th-L}} < K_{\text{max}} \leq \Delta K_{\text{th-s}})$, (g) Formation of fisheye $(\Delta K_{\text{th-s}} < K_{\text{max}} \leq \Delta K_{\text{th-u}})$ and (h) Unstable crack growth $(\Delta K_{\text{th-u}} < K_{\text{max}})$

4. Conclusions
In summary, the technique of FIB was used to study the non-defect induced crack nucleation and propagation behavior of titanium alloy in the VHCF regime. The subsurface failure processes are divided as: (a) Localization of plastic strain, (b) Occurrence of slip lines, (c) Nucleation of microcracks, (d) Coalescence and growth of microcracks, (f) Occurrence of the FCZ, (g) Formation of fisheye and (i) Unstable crack growth until fracture.

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6. References
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