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Observation of fretting fatigue cracks of Ti6Al4V titanium alloy

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Abstract: Using a test system developed in laboratory, the fretting fatigue mechanism of Ti6Al4V alloy has been studied, with analyses of fracture morphology and composition. The results show that fretting fatigue source area is semi-elliptical and occupies a small proportion of the total fracture surface. The area is relatively flat and smooth and shows traces of friction. With the increase of contact pressure, the depth of the source region first increases rapidly and then stabilizes, but the fatigue strength decreases rapidly and then stabilizes. Fretting causes severe oxidation of the surface. In the interface between the source and the fatigue propagation zone, the contents of O and Fe drop sharply.

Keywords: fracture mechanics/fracture behavior/fatigue; titanium alloys; electron microscopy; grains and interfaces; characterization

1 Introduction

Ti6Al4V titanium alloy is widely used in aviation engine tenon connection, bolting and other structures. In these connection structures, particularly between the engine compressor blade root and disc tongue and groove, due to vibration loading and the nature of the structure, fretting damage is prone to happening, seriously reducing fatigue properties, and is thus a huge safety risk. Titanium has poor friction performance. During friction of titanium alloy material with itself or with other materials, transferring of material is prone to happening, causing fretting fatigue damage [1]. Especially in the high-cycle fatigue, crack initiation and initial propagation account for most of the fatigue life. Fretting damage has a greater effect on fatigue properties. Many researchers have carried out in-depth study of fretting fatigue of Ti6Al4V titanium alloy [2-14], but due to the limitations of observation means, the study of fatigue crack initiation region was not thorough. There is little quantitative analysis, and the material fretting fatigue mechanism is not fully revealed. The background of the present

study is the fretting fatigue damage of tenon and mortise blade, bolts and other aviation products. Using a fretting fatigue test system designed and developed in-house, the effect of the presence of fretting on fatigue properties of titanium alloy Ti6Al4V has been analyzed. The effect of contact pressure on fretting fatigue strength has been studied. The aim is to provide a theoretical guidance for failure analysis in the practical application in the field of aviation titanium fretting environment.

2 Experimental

2.1 Test material, equipment, parameters and program

Hot-rolled Ti6Al4V titanium alloy bars were used for fretting fatigue damage study. The composition of the material is given in Table 1. The initial microstructure of the as-received alloy is shown in Fig. 1. The treatment process was heating for 2 h at 950 °C, water quenching followed by heating for 6 h at 540 °C, air cooling.

Table 1 Chemical composition of Ti6Al4V titanium alloy

Element	Al	V	O	N	C	H	Fe	Ti
wt.%	6.3	4.16	0.2	0.004	0.002	0.006	0.16	balance

Fig. 1. Initial microstructure of the as-received alloy.

General fatigue and fretting fatigue tests were carried out using a QBG-100 computer controlled high-frequency tension and compression fatigue testing system manufactured by Changchun Qianbang Test Equipment Co., Ltd (Fig. 2). The schematics of the plain fatigue and fretting fatigue test specimens are shown in Fig. 3. The schematics of fretting pads are

shown in Fig. 4. The edge was not artificially machined to have roundness. The surface was polished to be flat so that the contact area can be as large as possible. Because the fretting pad has sharp contact edges, the contact pressure profile will not be uniform along the contact width (i.e., along the specimen axis). If it is perfectly sharp, the pressure (stress) becomes singular at each contact edge in theory. Of course, it cannot be so because the pad must be machined and thus it has a finite corner radius value even if it is very small. Then, the geometry becomes so-called a ‘rounded punch’. In this case as well, the maximum pressure must be much higher than the average pressure values. The pressure profile influences the direction of the fretting fatigue crack, fatigue life as well as other features of fretting fatigue cracking behaviour. On the other hand, such a non-uniform contact pressure distribution will be inevitable in practice, so the test data obtained here will have more practical use. In other words, the contact pressure values are calculated from the contact force divided by the contact area in the present experiment. The material of fretting pads is the 30CrMnSiA steel, which has the minimum properties of yield strength 835 MPa, tensile strength 1080 MPa, elongation 10%, and reduction of area 45%. The fretting fatigue test rig was calibrated per ASTM E1012-12.

Fig. 2. Fretting fatigue testing system. (a) Photograph of experiment rig; (b) schematic drawing of experiment rig.

A Phenom ProX SEM with energy spectrometry made by the Dutch company Phenom-World was used to observe the fatigue fracture surface morphology and to analyze its chemistry. The surface roughness was measured using a fracture surface topography contours test equipment made by Shanghai No. 1 Optical Instrument Plant (Model SPA-1). The fracture profile topography acquisition method is illustrated in Fig. 5. The broken line in Fig. 5a is the path of data acquisition. In general, a fretting fatigue crack initiates at (or near) the contact edges, grows inward obliquely to some extent and further grows perpendicular to the far field fatigue load, and eventually a final catastrophic failure takes place when it is observed from the specimen surface (not a fracture surface). Observations in the present work agree with this. As shown in Fig. 5b, along the direction of crack propagation as shown by arrow in both Figs. 5a and 5b, the crack propagates for approximately W along the plane perpendicular to the specimen axis at an angle to this plane. After this initial propagation path, the further propagation is on the plane perpendicular to the specimen axis. W is the distance of crack propagation along the fracture surface. Values for W were measured on the surface profile of fracture morphology under different contact pressure. Under each contact pressure, a minimum of three sets of data were collected.

Fig. 5. Data acquisition schematic. (a) Fracture morphology, where the width of the specimen is 4 mm and the long dimension of the specimen is 7 mm, as given in the right diagram in Fig. 3; (b) fracture profile topography acquisition results.

2.3 Fatigue source depth measurement

Scanning electron micrographs of fretting fatigue specimens under different contact pressure were obtained, using a same magnification. Measuring from the fatigue specimen surface area as a starting point, to the intersection of the source region and the fatigue propagation as the end, the length of the longest straight line is the depth value H of the fatigue source region. The depth value H of the source region after fatigue fracture at different contact pressure was measured. It includes the crack length of oblique portion of the plane perpendicular to the specimen axis (W in Fig. 5b) as explained in detail in section 2.2. This will be shown later.

3 Results and discussion

3.1 Fatigue fracture morphology and composition analysis

Fig. 6 shows the plain fatigue S-N curve and the fretting fatigue S-N curve when $F = 10$ MPa. The fretting fatigue strength is 271 MPa, only 40% of the plain fatigue.

Fig. 6. S-N curves. (a) Plain fatigue; (b) fretting fatigue ($f = 81-85$ Hz, $F = 10$ MPa).

Fig. 7 shows fretting fatigue fracture surface morphology of the Ti6Al4V titanium alloy. As can be seen, fretting fatigue fracture consists of three principal areas: fatigue crack source region (I), crack propagation zone (II) and finally the short-break zone (III). The source region occupies the smallest proportion of the entire area of fatigue fracture.

As can be seen from Fig. 7b, in fretting fatigue, fatigue crack source is from the surface area of fretting fatigue damage specimen, unlike plain fatigue (Fig. 7a) where fatigue initiation is at a sharp corner (bottom right in this case) on the sample surface. It can be seen from Fig. 7c that, compared to the fatigue propagation area, fatigue crack initiation area is darker and has a generally semi-oval shape. As can be seen from Fig. 7d, fatigue crack initiation zone has obvious signs of delamination during friction due to the low fatigue crack growth rate in the source region and the crack being subjected to repeated extrusion and friction. The fracture is flatter than the propagation region. The fatigue crack propagation area shows many cleavage facets and is very different in morphology from the fatigue crack initiation region. There is no intermediate transition zone, which shows that when the fatigue crack reaches the propagation stage, the growth rate is rapidly increasing. Due to the presence of cleavage facets, fatigue crack propagation area looks brighter.

Fig. 7. Fatigue fracture surface morphology of Ti6Al4V titanium alloy. (a) Overall plain fatigue fracture morphology; (b) overall fretting fatigue fracture morphology ($F = 10$ MPa, $f = 76$ Hz, $N = 656200$); (c) fretting fatigue source region (low magnification); (d) fretting fatigue source region (high magnification).

Linear spectrum analysis was carried out from the source region along the direction of fretting fatigue crack propagation, as shown in Fig. 8. As can be seen, the content of each element component jumps at the interface from the source to the propagation of fatigue. The content of O and Fe sharply decreases, while the Ti, Al and V contents increase. This is because, in the initial stages of fatigue crack growth, fretting operation generates small debris containing Fe and O. The debris under the effect of vibration enter the growing crack. Due to the cycling load, the two open sections have friction with the wear debris. Because of slow growth of cracks in the source region during fretting fatigue, the wear debris containing Fe and O are attached to the surface area in the source of fatigue fracture over the long friction process. Into the propagation area, fatigue crack growth rate increases rapidly. There is no longer friction action of the fatigue fracture surface with wear debris. With the decrease in Fe and O rich debris beyond the source region, of course we would mainly see the base Ti6Al4V alloy again, evidenced by the Ti, Al and V increase. The total composition will of course always be 100%, so reduction in Fe and O will have to correspond to increase in other elements. The increasing of Ti, Al and V contents is relative to the decreasing of Fe and O contents.

In this paper, reference to the fretting fatigue crack growing slowly in the source region is relative to the crack growing in the propagation region. It is generally known that the crack growth rate in the contact stress influencing region (i.e., early stage of fretting fatigue crack growth) is comparatively higher so that the fatigue life is consumed considerably in that region contrary to the plain fatigue crack growth behaviour. In this research, the crack growth rate is not measured. It remains for our future work to draw a crack growth rate curve to confirm the slow crack growth in the source region.

Fig. 8. (a) Interface area from fretting fatigue source area to the propagation area and (b) composition profile along the dashed line shown in (a), in the Ti6Al4V titanium alloy. In (b), the vertical axis shows the percentages of elements. The curves indicate the variation trend.

3.2 Effect of contact pressure on the fracture surface and the fatigue source region

Comparing fretting fatigue fracture morphology of the Ti6Al4V titanium alloy specimens under different contact pressure, it is found that the main difference lies in the different fatigue fracture morphology of the source region. This indicates that during the fretting fatigue process, the effect of the contact pressure is mainly through the influence on the initiation of the source region to change the fatigue strength of the fretting fatigue specimen. Fig. 9 shows SEM photographs of the fatigue fracture source region of the Ti6Al4V titanium alloy fretting fatigue specimens under different contact pressure. Under different contact pressure, the fatigue source region has similar characteristics, but there is a difference in its depth. Adibnazari and Hoepfner [15] and Nakazawa et al. [16] studied the influence of contact pressure on life for varied materials. They found that life is decreased firstly with the increase of contact pressure, and then remains unchanged. With the increasing of contact pressure, the friction force increases, and the driving force of crack initiation and propagation increases. However, the friction force is proportional to the contact pressure to a certain extent. The friction force would not increase continuously along with the contact pressure. This may be because the contact pressure profile is not uniform along the contact width. The maximum pressure is higher than the average pressure values used. With the increase of the average contact pressure, the non-uniformity of the contact pressure profile will decrease, as

the loose contact part will be pressed into better contact. So, with the increase of the average contact pressure above a certain level (10 MPa), the maximum pressure remains almost constant. This maximum pressure determines the fretting fatigue strength. Nakazawa et al. have studied austenitic stainless steel and come to similar conclusions [17].

The variation in the depth of the source region, measured as described in the beginning of section 2.3, with the fatigue contact pressure is shown in Fig. 10. As can be seen from the figure, the relationship between the depth of the source region and the fatigue contact pressure is opposite to the relationship between fatigue strength and the contact pressure, when the contact pressure is smaller than 10 MPa. With the increase of contact pressure, the depth of the fatigue source zone increases rapidly, and fretting fatigue strength of the alloy has a corresponding rapid decrease. When the contact pressure is greater than 10 MPa, with continuing increase in the contact pressure, there is minor change in the depth of the fatigue source region. Meanwhile, the alloy fretting fatigue strength also remains stable. The saturation behaviour observed when the contact pressure exceeded 10 MPa has the same explanation as given in the last part of the last paragraph. We have studied fretting fatigue in another titanium alloy and have found that the fretting fatigue life also remains stable when the contact pressure exceeds a certain value [18].

The fracture surface profile at different contact pressure is shown in Fig. 11. When the contact pressure is 0 (normal fatigue), the fracture plane is approximately perpendicular to the principal stress direction. When the contact pressure is greater than 0 (fretting fatigue), the initial crack direction has a component parallel to the principal stress direction. This is because under the conditions of fretting fatigue, the friction force by the fretting pad on the surface of the sample causes uneven forces on the initial crack. With the crack length increasing, the effect of the frictional force on the propagation direction gradually reduces to zero. Then, the crack propagates perpendicular to the direction of the principal stress. Note that different scales are used in the horizontal and the vertical axes, to magnify the vertical displacement, so the angle to the contact surface (or perpendicular to it) is not the visual angle seen in the figure. It can be calculated with the data in the figure however. As explained in Fig. 5, W values reflect the effect of the depth of friction. Fig. 12 shows the relationship between the depth of the friction effect and the contact pressure. With an increase in contact pressure, the effect zone depth increases rapidly. When the contact pressure reaches 10 MPa, the affected zone depth reaches a maximum, steady value.

Fig. 9. Surface morphology of the source region of fretting fatigue fracture surface of Ti6Al4V titanium alloy under different contact pressure. (a) $F = 3$ MPa, $N = 2463600$; (b) $F = 5$ MPa, $N = 859600$; (c) $F = 7$ MPa, $N = 764500$; (d) $F = 10$ MPa, $N = 656200$; (e) $F = 20$ MPa, $N = 807900$; (f) $F = 45$ MPa, $N = 1560400$.

Fig. 10. Depth variation of the fatigue source region and fretting fatigue strength under different contact pressure. The scatter of the fretting fatigue strength data measured in 8-12 tests for each contact pressure may be expressed in standard deviations, which are 22, 16, 30, 37, 10, 9 MPa for the contact pressure of 3, 5, 7, 10, 20, 45 MPa, respectively.

Fig. 11. Fracture surface profile under different contact pressure.

Fig. 12. Effects of exposure to pressure on the affected area depth.

4 Conclusion

The fretting fatigue strength of Ti6Al4V titanium alloy is 271 MPa under 10 MPa contact pressure, which is 40% of plain fatigue strength. The effect of contact pressure on the fracture surface and the fatigue source region was studied. The depth of the source region of fretting fatigue in the Ti6Al4V titanium alloy increases rapidly when the contact pressure increases to 10 MPa. With further increase in the contact pressure, the source depth of fretting fatigue is maintained at a stable value of about 250 μm .

The damage in the fretting zone is mainly fatigue delamination. The composition suddenly changes from source region to propagation region. O and Fe contents decrease sharply and the Ti content increases.

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