Analysis of the effect of fretting wear on key structural components of TB6 titanium alloy with actual failure cases

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Abstract: As the main metal structure materials, titanium alloys have been widely applied in aerospace and other military industries. Titanium alloy develops on the way of high performance and functionalization. Compared with other materials, titanium alloy has high surface integrity and high fretting damage sensitivity. In this paper, the failure case of TB6 high strength titanium alloy key structural parts is taken as the breakthrough point to analyze the effect of surface fretting wear damage on its performance. The appearance inspection, macro and micro morphology observation and energy spectrum analysis were carried out, and the microstructure examination and hardness test were also adopted. The results showed that the fracture property of lug of TB6 high strength titanium alloy was fatigue fracture, and the fretting wear damage of the inner surface of lug hole was the main reason for the fatigue crack initiation. This case is a typical example of titanium alloy structure failure due to fretting wear, which provides reference for the prevention of the recurrence of such faults.

1. Introduction

Titanium alloys, as the main metal structure materials, have been widely applied in aerospace and other military industries. With the rapid development of the military industry, the requirement for titanium alloy products is higher and higher. Titanium alloy develops on the way of high performance and functionalization[1]. Compared with other materials, titanium alloy has high surface integrity and high fretting damage sensitivity. The results show that the microdynamic damage of the titanium alloy used in aerospace is very serious. The study shows that the fatigue life of the titanium alloy is reduced by 20%~50% because of the fretting effect, and the ratio of microdynamic damage to the structural damage of the titanium alloy is as high as 90%[2,3].

TB6 titanium alloy is a typical near beta titanium alloy made on the basis of the successful Ti-1023 titanium alloy developed in 1970s in the United States. The strength, toughness and forging ability of the alloy are much better than any other titanium alloy. TB6 titanium alloy is used in some advanced civil aircraft landing gear structures, external support beams, and some military helicopter horizontal rotor system structures in the United States and Europe[4]. TB6 titanium alloy is also widely used in the main rotor hub system of our helicopter. Because of the development of high strength and high
toughness, the fretting wear sensitivity of TB6 titanium alloy has not aroused enough attention in the industry. This state is more easily ignored and brings serious safety hazards to aircraft flight.

The lug (TB6 titanium alloy) and bolts (steel) of the central parts of a key structural component fractured during the fatigue test. In this paper, the appearance inspection, macro and micro morphology observation and energy spectrum analysis of the lug and bolt were carried out, and the microstructure examination and hardness test were also adopted, finally fracture properties and failure cause of the lug were determined. The case provided reference for the prevention of the recurrence of such faults.

2. Test process and results

2.1. Macroscopic observation

The fracture macroscopic appearance of the lug and bolt were shown in figure 1 and figure 2. The lug’s 1# fracture was relatively flat and has obvious fatigue characteristics, the fatigue area was larger. The lug’s 2# fracture was rough, the height difference was great, and the macroscopic fatigue characteristic was not obvious. Thus, the fatigue crack initiation of the 1# fracture was prior to the 2# fracture. The bolt fracture surface had obvious fatigue characteristic. Parallel to the axis of the bolt, the fatigue zone was light gray, flat and exquisite. Two sides of the fatigue zone were two inclined planes, 45 degrees angle to the axis of the bolt, which was a transient zone.

There was obvious fretting wear damage on the inner surface of two lug fractures, especially the microdynamic damage phenomenon near the fracture source area showed more serious, particularly curling feature was visible partly. Lug’s fretting wear morphology was shown in figure 3.

Figure 1. Fracture morphology of lug and bolts
2.2. Microscopic observation of lug fractures

1# and 2# fracture’s radiation characteristics were obvious, and morphology of each region was shown in figure 4 and figure 5 respectively. Two fracture’s source regions were in the same basic position, originated from the inner surface of the circular hole, which located at the corner of the outer side about 2mm away. Source region presented obvious characteristics of friction damage at high magnification. Two fracture’s transient zones were characterized by dimple fracture samely.

Two fracture’s fatigue spreading area showed obvious differences. 1# fracture fatigue spreading area was flat, and the fatigue band was obvious and fine. The measured mid and late strip spacing were about 0.92μm and 1μm respectively. The transient zone was characterized by dimple fracture. The fatigue crack growth depth was about 13mm. The side surface near the source area presented serious fretting wear, which damaged the surface integrity of the titanium alloy. It's remarkable that this damage was very unfavorable to the device use. 2# fracture fatigue crack propagation depth was about 3mm, whose expansion area was much smaller. Meanwhile we can see that the fatigue strip spacing was wider. From above comprehensive analysis, we can conclude that 1# fracture presented earlier beginning of failure.

Energy spectrum analysis of 1# fracture source area and side surface showed that O element was high in source area, and contained a certain amount of Cu element. The higher O element is also observed in the fretting wear area of the side surface. It can be seen that the surface oxidation corrosion occurred on titanium alloy substrate, which is a characteristic feature of the fretting damage of titanium alloy[5,6]. The results of energy spectrum analysis on the source and side surface were shown in table 1.
Figure 4. Lug’s 1# fracture microscopic morphology

Figure 5. Lug’s 2# fracture microscopic morphology

Table 1. The results of energy spectrum analysis on the source and side surface.

|       | O   | Al  | Ti    | V    | Fe  | Cu  |
|-------|-----|-----|-------|------|-----|-----|
| source area | 32.06 | 1.61 | 51.51 | 5.96 | 1.25 | 7.61 |
| side surface | 33.10 | 1.60 | 57.31 | 6.76 | 1.22 | -   |

2.3. Microscopic observation of bolt fractures
The bolt fracture microscopic morphology was shown in figures 6. The bolt fracture originated from its surface, showing the characteristic of line source. There was no metallurgical defect in the source area under high magnification. The fatigue crack growth depth was about 3.4mm, and the fatigue strip and secondary cracks were visible in the extension area. The fatigue strip spacing was about 1.25μm. The transient fracture zone was characterized by dimple morphology.

Figure 6. Bolt’s fracture microscopic morphology

2.4. Metallographic examination
The metallographic specimen was intercepted at the lower side of the lug plate. After the grinding and polishing, the discontinuous long strip of primary alpha phase along the original grain boundary was
visible, and the fine short strip or the equiaxed alpha phase can be seen in the crystal. Metallographic structure of the lug was shown in figures 7, no obvious abnormalities were found.

![Metallographic structure of the lug](image)

Figure 7. Bolt’s fracture microscopic morphology

2.5. **Microhardness testing**

Microhardness testing was carried out on the lug near the fracture and off the fracture. Results showed that microhardness of each region was uniform, which matched the technical requirements. The test results were shown in table 2.

| Region                     | Mean \(N\) 1 | Mean \(N\) 2 | Mean \(N\) 3 | Mean \(N\) value | Requirements |
|----------------------------|--------------|--------------|--------------|------------------|--------------|
| Near the fracture          | 336          | 346          | 342          | 341              | ≥320         |
| Far from the fracture      | 334          | 343          | 339          | 339              |              |

3. **Analysis and discussion**

According to the results of fracture observation, the fracture of lug and bolt all showed fatigue characteristics. The fracture properties of lug and bolt were fatigue fracture.

The fatigue crack growth depth of lug’s 1# fracture was far greater than that of the bolt, and the distance between the fatigue strip was slightly smaller than that of the bolt. Therefore, the fatigue expansion life of the 1# lug fracture was estimated to be far greater than the extended life of the bolt. Therefore, 1# lug fatigue crack should be sprouted first.

Through the analysis of the fracture of 1# lug, we find the following characteristics:

1. The crack source of the 1# lug fracture was not in the chamfering part of the structural stress concentration, but originated from the inner surface of the circular hole and was about 2mm from the lateral chamfer.

2. No metallurgical defects were found in the source area.

3. There were serious wear marks on the side surface of the source area.

The above analysis showed that the fretting wear damage of the inner surface of lug hole was the main reason for the fatigue crack initiation. This case is a typical example of titanium alloy structure failure due to fretting wear.

The fretting damage performance of titanium alloy is poor, which is mainly related to its electronic layer, crystal structure and thermal conductivity. Titanium activity is very high, it is easy to combine with other elements, and it is easy to oxidize during the wear process. Titanium alloy is six square structure, the slip system of \([1 \ 0 \ 0]\) surface is easy to move and adhesion failure comes. Also the thermal transmission ability of titanium alloy is poor, which causes the titanium alloy to occur fretting damage easily. The fretting wear of titanium alloy is mainly caused by two kinds of failure
mechanisms: fretting wear and fretting fatigue. To fretting damage, many mechanisms have been proposed by scholars at home and abroad, such as the initiation mechanism of contact cracks in micro convex bodies\(^7\sim^9\).

For many years, multiple fracture failures occurred during the test of TB6 titanium alloy lug. The result of analysis showed that the direct cause of lug was that the internal surface of the bushing had a more serious fretting wear, which destroyed the integrity of the surface. The fatigue strength and fatigue life were greatly reduced. For many years, around the fretting wear of TB6 titanium alloy, the macro analysis and micro details control were used to carry out in-depth study. A number of anti fretting wear measures had been put forward\(^{10,11}\), and the structure had been improved effectively. The ratio of the rotor system to the test required by the test had been improved, but it still failed to reach to the preconceived state. At present, we are studying the influence of the complex stress form on the fretting wear of the lug. From the complex stress form, the mechanism of the fretting wear of the titanium alloy is studied and the follow-up achievements will be further reported.

4. Conclusion

With the increasing application of titanium alloys, the cognitive fretting wear of titanium alloys will gradually increase. It is not limited to the single stress form, but the study on the mechanism and influence factors of titanium alloy fretting wear in the form of actual stress state (such as multi axis complex stress) will be further studied. It is believed that in the near future, titanium alloys will make greater progress to meet the needs of industrial development and aerospace.

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