Erosion behavior and damage evolution of Ti-6Al-4V aero-engine titanium alloy

Y Q Li¹, X D Wang¹, C B Long², Z P Sun³, X L Wei¹ and L C Zhou¹,4

¹ Science and Technology on Plasma Dynamics Laboratory, Air Force Engineering University, Xi'an, Shaanxi, 710038, China
² School of Advanced Materials and Nanotechnology, Xidian University, Xi'an, Shaanxi, 710071, China
³ School of Materials Science and Engineering, Chang’ an University, Xi’an, Shaanxi, 710061, China

E-mail: happyzlc@163.com

Abstract. This paper studies sand- and dust-erosion damages of aero-engine titanium alloy blades, and associated damage mechanism was discussed with the simulation of actual dust environment. The abrasion test of TC4 titanium alloy was carried out by high-speed erosion equipment. The roughness, micro-damage morphology, and stress distribution of titanium alloy were characterized by the roughness tester, SEM and XRD residual stress gauges, respectively. The results show that the erosion rate of titanium alloy matrix increases with the erosion time, while its roughness does not vary significantly. However, the roughness and residual compressive stress sharply rise with erosion rate. As the erosion time progresses, the surface morphology exhibits cutting wear, and the worn surface center starts to peel off.

1. Introduction
Titanium alloys are widely used in aircraft engine parts due to their good heat resistance, high specific strength, good corrosion resistance, non-magnetic properties, and other advantages [1-4]. Most of advanced aircraft engine compressor blades are made of titanium alloys [5], but their high hardness implies their poor wear capacity [6-8]. This is critical for dust- and sand-polluted environment, which is very topical for China, where the sand-affected area exceeds 50% [9,10]. Sustained impacts and wear appear on front blades of compressors contacting numerous solid particles in the high-speed air flow, which results in severe erosion and causes curl deformation, chord length decrease, thickness reduce and other damage [11], and this severely affects the operational performance, safety and reliability of aircrafts [12-14].

The erosion issues have been studied for a long time and covered by numerous erosion theories. In 1958, Finnie [15] proposed a micro-cutting theory. When a particle impacts a surface, it creates a crater. Other particle impacts make the crater larger and also pile up materials around the crater, the piled up materials are eventually removed by continued particle impacts. In 1963, Bitter [16] proposed a deformation wear theory, which divided the erosion wear into deformation wear and cutting wear. In 1973, Tilly [17] suggested a two-stage erosion mechanism, the second stage of erosion is caused by impacting particles which break up into small fragments, the damage of erosion is proportional of the particle kinetic energy and fragmentation degree, and the total erosion wear is the sum of two-stage erosion. In 1981, Hutchings [18] proposed a low-cycle fatigue theory of metal materials when impacted...
vertically by spheres. In recent years, multiple erosion models and theories have been permanently developed based on in-depth studies [19-20], and comprehensive description of erosion damages has been achieved. The erosion behavior is known to be influenced by particle characteristics, erosion angle, speed, time, environmental temperature, and microstructure of matrix materials [21-22]. However, the available erosion theories fail to predict material performance under such complex conditions quite accurately.

In this paper, the effects of sand erosion angle, time and speed on titanium alloy are synthetically considered as reference to natural sand and dust environment, and the erosion damage evolution is studied. The sand motion speed as high as 185 m/s is adopted, and the comparison between high-speed and low-speed erosions is carefully carried out. This has important strategic significance to enhance the anti-erosion performance of the engine and environmental adaptability of the helicopter, to improve the viability of aviation aircrafts and meet future military development needs.

2. Experimental

TC4 (Ti-6Al-4V) titanium alloy was used as the experimental material. TC4 belongs to α+β type titanium alloy, and its composition and mechanical properties at room temperature are listed in tables 1 and 2, respectively. Samples with the size of 50 mm × 20 mm × 4 mm were prepared by wire cutting using electrical discharge machining (EDM). Coarse grinding, fine grinding, polishing, acetone ultrasonic cleaning, and drying were carried out before erosion. The main component of the experimental sand is SiO₂, which basic parameters are shown in table 3. The diameters of sand particles vary in the range of 60~800μm, while most of them fit within the size of 100 ~ 250μm.

Sand erosion experiment is conducted with self-developing high-speed erosion test, the residual stress is measured with X-ray stress analyzer (X-350A). The erosion surface morphology of TC4 is characterized with 3D optical microscope. The cross-sectional microstructure of the erosion region is observed with scanning electron microscope (SEM, JSM-6700F), the surface roughness before and after erosion is obtained with surface morphology (Talysurf 5P-120).

| Element | Ti | Al | V | Fe | C | N | H | O |
|---------|----|----|---|----|---|---|---|---|
| Content | Balanced | 6.06 | 3.92 | 0.3 | 0.013 | 0.014 | 0.0014 | 0.15 |

| σ₀.2/MPa | σₚ/MPa | δ/% | ψ/% |
|-----------|--------|-----|-----|
| 983 | 1027 | 18.5 | 20.1 |

| Density (g/cm³) | Hardness (Hv₀,₁) | Refractivity | Melting temperature (℃) |
|----------------|-------------------|--------------|-------------------------|
| 2.65 ~ 2.66 | 1161 | 1.6 | 1650±50 |

3. Results and discussions

3.1. Influences of erosion time and erosion angle

Figure. 1(a) shows mass loss rate of TC4 titanium alloy under different erosion angles and erosion time with the sand motion speed of 185m/s. At the erosion angle is 30°, the mass loss rate of TC4 alloys increases with erosion time due to a declining growth. With an angle of 60°, this rate increases from 1.87 to 2.18 mg/min and then remains unchanged. It is observed that higher mass loss rate is achieved
by lower angle impact after a 10 min erosion. As seen in figure 1(b), the surface roughness of TC4 increases dramatically as the erosion time reaches 2 min. This surface roughness under 30° is \(\sim 3.78\ \mu m\) and then slightly increases to \(\sim 4.66\ \mu m\) as the erosion time increases to 10 min. At the erosion angle of 60°, the TC4 titanium alloy shows higher roughness, and the above two values are \(\sim 5.01\) and \(5.26\ \mu m\), respectively. This is primarily attributed to the fact that more serious deformation occurs at higher erosion angles. Therefore, severe plastic deformation yields a rougher surface.

The effects of erosion angle and erosion time on residual stress of TC4 titanium alloy are shown in figure 1(c) and 1(d), where the experimental results are extracted from the erosion center and erosion edge, respectively. In general, the residual compressive stress first increases and then decreases with the erosion time. The TC4 titanium alloy shows larger compressive stress measured at high erosion angle within the entire region for assessment, and the resultant reduction of residual compressive stress is caused by the peeling-off of the alloy matrix. With an erosion angle of 60°, the maximum compressive stress at the erosion center and edge are 746 MPa (at 2 min) and 675 MPa (at 5 min), respectively.

![Figure 1.](image)

**Figure 1.** (a) Mass loss rate at different erosion angle and time, (b) Roughness at different erosion angles and times. Residual stress of TC4 surface at different erosion angles and times: (c) erosion center, (d) erosion edge.

Figure 2(a) shows the surface morphology under different erosion angles and erosion times with the sand motion speed of 185 m/s. It can be seen that the erosion pits increase and the damage increases as erosion time progresses. Figure 2(b) and 2(c) show the microstructure at different erosion angles, i.e., 60 and 30°. At the erosion angle of 30°, it is mainly plough wear and abrasive wear. A longer impact time correspond to higher residual stresses, the hardening effect of the matrix is increased and the wear slows down. Due to the reduction of difference in hardness between the sand and matrix, abrasive wear turns into adhesive wear, as shown in figure 2(d). The compositional analysis of erosion surface was conducted by EDS, the atomic percent of the adhesion was determined as 12.68Si-74.26O-6.41Ti-6.65Al, and the adhesion with bright contrast was identified as SiO\(_2\) based stoichiometric ratio, which is the main component of sand. Mass adhesion of sand promotes the reduction of damage, surface roughness and residual stress. When the erosion angle is 60°, the impact is obviously strong and the residual stress increases. With the increase of erosion time, the repeated impact fatigue from the sand
causes the matrix to peel off and expose new material, and then there are decreases of residual stress and surface roughness, more evident erosion damage is caused than that with the erosion angle of 30 °.

**Figure 2.** Morphology of TC4 surface under different erosion conditions (a−c) and the EDS analysis of the adhesion (d). (a) 60°, 185m/s, 2min, (b) 60°, 185m/s, 5min, (c) 30°, 185m/s, 5min.

3.2. Influence of erosion rate
When the erosion angle is 60 ° and the erosion time is 5 min, the mass loss rates with the sand motion speed of 85 and 185m/s are 0.262 and 2.17 mg/g, respectively (table 4). Distinctly, the latter (high-speed erosion) is 7.28 times than that of the former (low-speed erosion).

**Table 4.** The mass loss rates at sand speeds of 85 and 185m/s.

| Sand speed (m/s) | 85   | 185  |
|------------------|------|------|
| Erosion rate (mg/g) | 0.262 | 2.17 |
Figure 3. Roughness at erosion angle of 60° for sand speeds of 85 and 185 m/s.

Figure 3 shows the surface roughness after 5 min erosion with the sand speeds of 85 and 185 m/s. The surface roughness of substrate TC4 alloy is 0.079 μm, and a rise to 2.689 μm is obtained after erosion with sand speed of 85 m/s, which is increased by 20 times. Interestingly, this value increases dramatically to 5.117 μm when the sand speed is 185 m/s.

The effect of different sand speeds on the residual stress field of the titanium alloy matrix is displayed in figure 4, which reveals that the residual stress in the center of erosion pit reached -821.5 MPa at sand motion speed of 85 m/s. However, this value decreased to -663.5 MPa under a high-speed erosion of 185 m/s, which is related to fatigue spalling of the titanium alloy matrix. Around the erosion pit edge, the residual stress reached -252 MPa when at the speed of 85 m/s. Because the fatigue spalling was not pronounced, the accumulation of stress expressed an increase in residual stress to -677.7 MPa under high-speed erosion.

Figure 4. Residual stress of TC4 surface at erosion angle of 60° at 85 and 185 m/s.

Figure 5 shows the evaluation of surface morphology at different sand speeds after a 5 min erosion with the erosion angle of 60°. It can be seen that the area of erosion spit is small under the condition of low-speed erosion, and there is little exfoliation of the matrix alloy caused by impact fatigue. Under the condition of high-speed erosion (figure 5b), the crater is deep and large, the length and depth of the plough are increased, materials pile up around the crater. In the center of the crater, the surface substrate is no longer visible. Under repeated impact, continuous fatigue spalling makes the surface roughness and the mass loss rate is increased. Meanwhile, the exposure of a new matrix results in the decrease of the residual stress in the surface layer.
3.3. Discussion of erosion mechanism

Based on the experimental investigations, the mechanism of erosion evolution is discussed, and the erosion of titanium alloy is subdivided into three zones, namely the edge of the erosion, the transition region and the center of the erosion. Figure 6 shows the macroscopic observations of the erosion surface under different conditions, and the three zones of each sample are schematically indicated. The characteristics of each zone are discussed below.

The first zone (the crater edge):

When the erosion angle is 30°, it is mainly abrasive wear in the erosion edge. As erosion time progresses, the surface roughness and residual compressive stress increases gradually. When the hardening effect of the matrix is significant, the wear will become less.

When the erosion angle is 60°, it is mainly the plough wear by the sharp and high-speed sand in the erosion edge, the residual compressive stress, the roughness and the mass loss rate increase accordingly. With the prolongation of erosion time, when the hardening of the matrix reaches a certain level, the impact and wear fall in a decline.

The second zone (the transition region):

When the erosion angle is 30°, with the rise of erosion sand, the wear, roughness and residual stress further increase. In the process of wear, the erosion sand interact with the matrix alloy, and some sand particles are embedded in the matrix to form adhesion, the brittleness of this part is higher than that of original matrix, it is repeatedly impacted and peeled in subsequent sand dust erosion. The hardening
effect of matrix is remarkable by massive erosion, the hardness difference between sand and matrix is diminished.

When the erosion angle is 60°, there is a very small contact area between sharp sand and the matrix, this led to plough wear; while correspondingly larger the contact area from regular sand caused impact. The impact depth is obviously positive correlation with erosion rate. Higher speed erosion intensifies the plough wear and cutting wear. Quantities of impact craters and cutting surfaces are formed. Simultaneously, the matrix is embedded with plenty of sand in the inaction progress of high-speed sand and soft alloy matrix.

The third zone (the erosion center):

When the erosion angle is 30°, the wear, roughness and residual stress gradually increase with the explosion of erosion sand. The matrix has obvious hardening effect under repeated abrasion of sand and dust, fatigue spalling occurred by subsequent erosion impact.

When the erosion angle is 60°, the hardening effect, the residual stress and stress concentration enhanced with the explosion of erosion sand. At the concentrated areas of stress, fatigue cracks are induced by impact, the exfoliation of matrix alloy is very severe. Higher speed erosion would bring more obvious impact fatigue, rough surface and deep crater. Under the impact of subsequent sand dust, the exposed fresh matrix repeats the process of “impact-fatigue-spalling”.

Accordingly, the impact fatigue is significant under the condition of high-speed erosion, regardless of the erosion angle and erosion time. By low-speed erosion, the wear becomes evident with the erosion angle of 30°, while the impact fatigue is prominently featured with the erosion angle of 60°, the macroscopic comparison of the surface at low-speed erosion under different erosion angle is shown in figure 7.

![Figure 7. Macroscopic comparison of the surface at low-speed erosion with different erosion angles. (a) 85m/s, 30°, 10min, (b) 85m/s, 60°, 10min.](image)

4. Conclusion

The erosion behavior of Ti-6Al-4V alloy were investigated by varying angles from 30° to 60°, sand motion speeds from 85 to 185m/s for 2, 5, and 10 min, respectively. Based on the macroscopic comparison, microstructure observation, mass loss calculation, roughness determination and analysis of residual stress distribution, the main conclusions can be drawn:

1. As the time increases, the residual stress on the substrate surface first increases and then decreases, while there has been consistent growth for the mass loss rate and roughness over erosion time.

2. At the same erosion angles and times, the mass loss rate and roughness sharply rise with the sand motion speed (up to 20 times). Compared to erosion times and angles, the speed is the main factor affecting the erosion behavior.

3. In the area close to the erosion boundary, plough wear is induced by sharp and high-speed sand particles. Between the erosion boundary and its center, there are many impacting sand particles adhered to the erosion surface. In the erosion center, the matrix with sand adhesion results in the erosion spalling under the action of substantial sand impact. The exposed fresh surface occurs, with impact hardening
and flaking by continuous sand impact. Some craters come into being, and this causes a significant increase of erosion rate and surface roughness.

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