Effect of micro-arc oxidation coatings with different thickness on high cycle fatigue performance of Ti-6Al-4V titanium alloy

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Abstract: Micro-arc oxidation (MAO) coatings with 2 μm, 5 μm and 10 μm in thickness were produced on Ti-6Al-4V titanium alloy by MAO treatment, and the effect of coating thickness on the high cycle fatigue property was investigated. The microcopies and phases of coatings were analyzed by scanning electron microscopy (SEM) and X-ray diffraction (XRD) techniques. The results indicated that the coatings were mainly composed of anatase TiO₂. The MAO process generated micro pits at the substrate surface. The micro pits played a role of the notches, which induced the crack initiation during fatigue loading. The fatigue life of samples decreased with the increase of coating thickness. The micro pits were the main factor for the decrease of the fatigue life.

1. Introduction
Ti-6Al-4V titanium alloy is an attractive structural material, which has successfully and widely been utilized in aerospace, chemical, marine and biomedical industries due to optimized mechanical properties, excellent corrosion resistance and favorable biocompatibility. However, titanium alloys intrinsic poor wear resistance and low hardness restrict the use of the base material under friction condition. Enhancing wear resistance of titanium alloy components is still an open question [1-3]. Many various surface modification methods, such as physical vapor deposition, chemical vapor deposition, thermal spraying, and plasma nitriding have been applied. Among them, MAO technique is one of the most effective methods, which is generally applied to provide chemical stability ceramic coatings aiming at improving the surface properties of the light metal (Al, Mg and Ti alloy). Some studies have showed that MAO technique is a dominant choice in producing high hardness, superior abrasive resistance and desirable biocompatibility coating on titanium alloys surface.

It is well known that fatigue fracture is an important structural failure in aircraft components subjected to axial loading. In this work, the effect of coating thickness on high cycle fatigue performance was evaluated, and the fatigue failure mechanism of coated substrate materials was analyzed.

2. Experimental

2.1 Materials
The nominal chemical composition (wt. %) of Ti-6Al-4V alloy employed in this work was: 6.11 %Al, 4.4 %V, 0.17 %O and Ti balance. The samples for high cycle fatigue test were obtained from an annealed rod of 20 mm in diameter. The corresponding microstructure was composed of the equiaxial
α-phase and intergranular β-phase which was depicted in figure 1. The basic mechanical properties were listed in table 1. The fatigue sample geometry was given in figure 2.

![Figure 1: Optical micrograph of annealed Ti-6Al-4V alloy](image1.png)

Table 1: Mechanical properties of Ti-6Al-4V alloy

| Ultimate tensile strength (MPa) | Yield strength (MPa) | Elongation (%) | Reduction in Area (%) |
|---------------------------------|----------------------|----------------|-----------------------|
| 1006                            | 928                  | 17             | 46                    |

![Figure 2: Dimension of high cycle fatigue testing sample](image2.png)

2.2 Characterization of coating

The MAO coating was obtained on the smooth fatigue samples by a self-manufactured MAO device. The coating thickness was 2μm, 5μm, 10μm, respectively. The surface and cross-sectional morphologies of the coating were observed by SSX-550 SEM. Figure 3 illustrated the surface morphologies of the MAO coating with different thickness. The coating surface was characterized by countless micro-pores, which were formed during the micro-arc discharge process. The MAO technology generated many electronic sparks on the surface of samples, a micro pore formed when a spark extinguished. The spark and pore size was depended on the current density and oxidation time [4, 5]. The thicker the coating was, the bigger the diameter of pores was. The phases of MAO coating were analyzed by Rigaku D/max 2500PC XRD. The phases were mainly composed of anatase TiO2 and a small portion of rutile TiO2. XRD pattern of MAO coating was illustrated in figure 4.
Figure 3 SEM surface morphologies of various thickness of MAO coating on Ti-6Al-4V alloy (a) 2μm, (b) 5μm, (c) 10μm

Figure 4 X-ray diffraction pattern of MAO coating (a) 2 μm, (b) 5 μm, (c) 10 μm

Figure 5 presented the SEM cross-sectional images of coated samples for various thicknesses. No transition layer existed between substrate and coating. Excellent bonding strength with the substrate was obtained by in-situ formed MAO coating. The substrate/coating interface was a zigzag shape. With the increase of coating thickness, the interface was more zigzag.
2.3 Fatigue tests

Uniaxial high cycle fatigue tests were carried out using a sinusoidal constant amplitude load of frequency 120 Hz and stress ratio $R=0.1$ at room temperature by PLG-100C fatigue testing machine. The maximum stress of 750 MPa was applied. It was identified that MAO obviously reduced the fatigue life of Ti-6Al-4V alloy under the consistent loading conditions.

3. Results and discussions

The fatigue life decreased with the increase of coating thickness. The samples fractured at $4.0 \times 10^4$, $3.3 \times 10^4$ and $2.5 \times 10^4$ cycles, respectively. The zigzag substrate/coating interface was responsible for the decrease of the fatigue life. The MAO process increased the roughness of the substrate material surface, which generated micro pits at the substrate surface. In some very tiny regions, the MAO coating at the micro pits overgrew into the substrate. The micro pits played a role of the notches, which served as the stress concentration area during fatigue loading [6-7]. The stress concentration at the notch sites induced the fatigue crack initiation. Figure 6 illustrated that the substrate/coating interface was considered as a piece of circular arc, and the segment between two endpoints was the chord length. The notch depth and the arc radius were measured and calculated respectively, which results was given in table 2. When a notch was shallow, the formula was applied as follows [8]:

$$k_i = 1 + 2\sqrt{\frac{t}{r}}$$

$t$-notch depth, $r$-notch curve radius. According to this approximation, $k_i$ for a shallow notch was a function only of $t$ and $r$.

Based on the analysis above, the value of $k_i$ increased with the coating thickness. The notch sensitivity of the coated samples increased simultaneously. The fatigue crack nucleated on the substrate surface at the tips of the notch regions preferentially, and then propagated into the substrate material to fracture, so the fatigue life decreased distinctly.
Table 2 Notch parameters by measure and calculation

| Coating thickness (µm) | Notch depth t (µm) | Arc radius r (µm) | Stress concentration factor $k_t$ |
|-----------------------|--------------------|-------------------|----------------------------------|
| 2                     | 3.12               | 10.17             | 2.10                             |
| 5                     | 1.78               | 3.96              | 2.34                             |
| 10                    | 17.59              | 2.01              | 6.92                             |

Fig.6 Schematic diagram of notches in the substrate/coating interface with various coating thickness (a) 2µm, (b) 5µm, (c) 10µm

4. Conclusions
Micro arc oxidation coating was mainly composed of anatase TiO$_2$. The coating/substrate interface was more zigzag with the increase of the coating thickness. The micro pits formed at the substrate surface and induced the stress concentration, which was the leading factor for the decrease of the fatigue life. The fatigue crack initiated at the substrate surface, propagated into the substrate. The fatigue life decreased with the coating thickness. The high cycle fatigue life was $4.0\times10^4$, $3.3\times10^4$, $2.5\times10^4$ cycles, respectively.

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