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Wear failure behaviour of titanium-based oxide coatings on a titanium alloy under impact and sliding forces

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ABSTRACT

To increase the wear resistance property of a Ti alloy, a plasma electrolytic oxidation (PEO) process was used to form protective oxide coatings. The present work was mainly to study the effects of pure sliding and impact-sliding combined forces on failure behaviours of the oxide coatings with different thicknesses (10–27 μm). A recently-developed impact-sliding test method was used to investigate the combined force effects on the coatings and the uncoated substrate for comparison. In each impact-sliding cycle, the forces comprised a dynamic impact load, F_i, and a pressing load, F_p. The combined loadings were pre-set to be (F_i = 80, 130, 200 N and F_{pmax} = 200, 300, 400 N, respectively) applied by a steel ball (SI 52100). The test results show that the rough top layers of PEO coatings can cause early failure of the coatings and a large mass-loss on the counterface steel balls. For a relatively smooth coating without polishing, the porous structure can help to cushion the impact force comparing to the exposed dense inner layers of the thick coatings that were ground to have a similar surface finish. Incorporation of Si and P elements into the Ti oxide coatings may alter the surface affinity behaviour and stoichiometry of Ti oxides, causing different wear behaviours under impact and sliding forces.

1. Introduction

Titanium alloys, due to their excellent combination of low density, high strength to weight ratio, corrosion resistance and biocompatibility, are widely used in the aerospace, automotive, chemical and biomedical industries [1]. The typical examples of applications in aerospace are the landing gears of the Boeing 777, Boeing 787 and the Airbus A380 aircrafts in replacement of high-strength low alloy steels, 4340M and 4330M [1–3] and in automotive industry currently racing engine use Ti–6Al–4V for intake valves, valve retainers, connecting rods, clutch discs, transmission pressure plate and suspension coil springs [4]. Titanium and its alloys have excellent corrosion resistance towards many of the highly corrosive environments, particularly, oxidizing and chloride containing process streams [5,6]. The great corrosion resistance of titanium alloys result from the formation of highly stable, continuous, adherent and protective oxide films on the metal surface. The nature, composition and thickness of the surface oxides are depend on environmental conditions [7,8]. Corrosion may not be an issue for titanium in an aerospace environment [9,10]. However, these alloys are insufficient in tribological performances [11], characterized by high coefficients of friction, severe adhesive wear with a high tendency to seizing and low abrasion resistance, when Ti alloys slide against other engineering materials. Budinski [11] realised extensive research on tribological properties of titanium alloys and reported that Ti6Al4V has poor abrasion resistance. Masmoudi et al. [12] studied the influence of environment on friction coefficient values of Ti6Al4V alloy. There are two reasons for the inferior tribological properties [13,14]: the first is its low resistance to plastic shearing and the low work hardening; and the second reason is due to the low protection exerted by the surface oxide. The oxide is formed by high flash temperatures caused by friction during sliding. The stationary or dynamic contact loads between Ti-alloy components and other metals can cause damage to the thin oxide film and thus lose the protection.

Accelerated laboratory wear tests using test machinery are popular within the surface engineering research community. Different machinery can be used to understand the tribological behaviour of material couples. The commonly used techniques include pin-on-disc, block-on-ring, micro-abrasion and ball-on-plate impact tests [15]. Straffelini et al. [16] studied the mechanisms responsible for the wear resistance under different load and sliding speed conditions in self-mated Ti–6Al–4V disk on disk sliding test. The researchers found that in dry sliding wear the Ti–6Al–4V alloy underwent forms of oxidative wear and plastic shearing [13,17]. This is certainly a disadvantage when employing titanium alloys in kinematic linkage and dynamic load bearing applications, to the point that significant research and design efforts have been dedicated in recent years to developing coatings and surface engineering process to mitigate war and reduce friction in systems

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containing these materials. So far several well-developed methods have been utilized to enhance the surface properties of titanium alloys, such as coatings, carburizing and plasma nitriding [18]. Oxidation treatment is the most popular and effective technique to produce a relatively thick coating for the surface protection of Ti alloys [19,20]. For example, electrolytic anodising [21] and high temperature heat treatment [22] as well as other techniques such as PVD/CVD coatings are widely used by surface engineers [23] Plasma electrolytic oxidation (PEO) has been successfully used to prepare oxide coatings on Ti–6Al–4V [24–27]. This technique is based on the interaction between oxide film growing on the metal surface and spark micro-discharges, which are initiated at potentials above the dielectric breakdown voltage of the film in an aqueous electrolyte [24–26]. The use of this hard nano-structured coating is regarded as an effective practice in reducing titanium component wear [28–30]. A number of researches have been done in wear and corrosion aspects [23–26]. However, there is lack of research in wear properties of the coatings under extremely high contact stress and dynamic loading conditions.

This paper mainly focuses on studying the impact and friction wear behaviours of various PEO coatings on a Ti–6Al–4V alloy under severe testing conditions. Different current modes and treatment time were utilized during the PEO process to produce coatings of different thicknesses. An inclined impact-sliding test method was used to simulate extremely high dynamic loading conditions [31,32]. Those conditions may appear when the coated Ti–6Al–4V alloy, used for such as sliders of aircraft landing gears, accidentally suffer the combined attacks of impact and sliding forces during abnormal landing operation conditions. Although the extreme load conditions rarely exist in normal operations of, for instance, aircrafts, it is worth investigating how the coatings respond to such instances.

2. Experimental details

2.1. Sample coupon

In this study, a Ti–6Al–4V rectangular bar with a cross-sectional size of 25 mm × 25 mm was cut into pieces along its cross-sectional direction with a thickness of 7 mm each and used as substrate materials. All the sample coupons were polished progressively up to 2500 grade SiC abrasive sandpapers to obtain an average roughness $R_a \approx 1.0$ μm and then degreased in acetone ultrasonically and distilled water before dried in ambient condition (20 °C, 65% humidity). The chemical composition of the Ti–6Al–4V alloy is shown in Table 1.

2.2. PEO procedure

During the PEO treatment, the sample was connected to the power source unit as the anode by a Ti wire and a stainless steel plate as the counter cathode electrode. 18 g Na_2HPO_4 was dissolved in 3 litres of distilled water to make a 6 g/l electrolyte with a pH value around 12 [24]. 6 g/l Na_2SiO_3 was added into the electrolyte before the treatment of sample 2 (S2) and sample 3 (S3). The parameters during the PEO treatments were summarized in Table 2. Sample 1 (S1) was treated by a pulsed unipolar power source while the other two (S2 and S3) were made by a pulsed bipolar power source. All the coatings were made at the same pulse frequency, 2000 Hz.

After the PEO process, coated samples were washed carefully by soft soap solution and flushed by tap water to clean the remaining alkaline. The coating thickness was measured by a PosiTector 6000 coating thickness gauge. 8 data were collected on each coating surface to obtain an average result. The average coating thickness of each sample was listed in the 5th column of Table 2.

A Mitutoyo surface profiler SJ201P was used to measure the average roughness R_a and skewness R_{sk} on the surfaces of as-formed and polished PEO coatings. The values of R_a and R_{sk} have been reported to have significant influences on tribological properties [33,34]. Skewness R_{sk} describes the asymmetry of the height distribution histogram. If $R_{sk} = 0$, height distributions on the surface is symmetric, for example, a Gaussian like. If $R_{sk} < 0$, the surface is featured with holes and if $R_{sk} > 0$ the surface is flat one with peaks. Because all the R_{sk} values in this study were negative, a schematic of surfaces with negative skewness is shown in Fig. 1 [33,34]. In this case, the lower R_{sk} value, the more contacting areas existed between the coating and counterface steel ball.

In order to study the sliding behaviour and wear resistant of PEO-deposited TiO_2 coatings, a pin-on-disc (POD) test was carried on all of the coated samples. The test was carried out using a steel ball pin as the counterface material (AISI 52100, HRC 58-60, and 5.5 mm in diameter) in the ambient condition (40% humidity and 20 °C) under a 2 N normal load. The diameter of the circles of wear scars was 4 mm and the sliding speed was 0.075 m/s. A pure sliding was obtained by keeping the sample rotating and the counterface ball fixed. The coefficient of friction (COF) (dynamic) was automatically recorded during each test using a data acquisition system. The POD tests were firstly carried out on 3 freshly-made PEO coatings and uncoated substrate under a 100 m sliding distance. In order to minimize the effect of surface roughness to the coating performance in the tests, the outer surfaces of as-formed coatings were polished carefully to the same level of roughness to remove prominent ceramic particles. And then, the POD tests were used again under the same loading condition on the polished sample surfaces for a 300 m sliding distance. The sliding distances of as-made and polished coatings were based on the several trial tests to obtain typical failure behaviours on coating surfaces without fully worn-out of surface layer. Polished coatings have an even lower coefficient of friction comparing to as-made and uncoated ones, thus they could sustain longer sliding distance. Before the POD tests all the testing pins were degreased in acetone ultrasonically and then ethanol to remove any possible contaminations.

An inclined impact-sliding test method [31,32], which has been regarded as an effective way to study coating failures under extremely high dynamic loading conditions, was used to investigate wear behaviour of the PEO coatings under attacks of impact and sliding forces. The detailed information about the test instrument can be found from the literature [31]. With the up-and-down vertical movement of a pin driven by air cylinder, the pin first impacts the sample and then slides on the sample surface in each cycle. The impact force, F_i, and pressing force, F_p, are implemented subsequently when the pin ball contacts the coating surface through impact and then sliding. During the tests, the repetitive impact and sliding forces were applied on the coating surface by a 10-mm diameter AISI 52100 steel pin ball. In each impact-sliding cycle, the forces comprised a dynamic impact load, F_i (80 and 200 N), and a "pressing" load, F_p (with the maximum values of 200 and 400 N). The "pressing" load signifies that force which acts at the end of the sliding motion where the maximum normal load of 200 and 400 N are reached. The values of F_i and F_p were pre-determined based on trial test results, different test cycles were used to study different extents of damage, i.e., 1000 test cycles for the lowest loading condition ($F_i = 80$ N, $F_{pmax} = 200$ N), and 100 cycles for the other two loading conditions. The frequency of the test was 2.5 Hz [31].

Table 1
Chemical composition of Ti–6Al–4V in weight percent.

Element	Al	V	Fe (Maximum)	C	O (Maximum)	N	H (Maximum)	Ti	Other
Average	5.50–6.75	3.50–4.50	0.40	0.1	0.02	0.05	0.015	Balance	0.4

Table 2
Parameters of PEO procedure and thickness and roughness of coated samples.

No.	PEO treatment time (min)	Power supply mode	Current density (A/cm^2)	Thickness (μm)	Thickness-after polish (thickness decrease) (μm)	Surface roughness	Surface roughness-after polish	
						R_a	R_a	Skewness R_{sk}
1	20	Unipolar	0.08	10.8	8.8 (−2.0)	1.22	0.96	−0.67338
2	25	Bipolar	0.06/−0.05	17.8	9.7 (−8.1)	2.22	0.8	−1.32368
3	43	Bipolar	0.06/−0.05	26.9	10.6 (−13.3)	3.8	0.81	−2.23051