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Friction characteristic of micro-arc oxidative Al_2O_3 coatings sliding against Si_3N_4 balls in various environments

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Abstract

The alumina ceramic coatings were prepared on 2024Al alloy by micro-arc oxidation (MAO) technique. The phase structure of the MAO Al_2O_3 coating was determined using X-ray diffraction. The thickness and micro-hardness of the MAO Al_2O_3 coatings was measured using eddy current thickness equipment and micro-hardness tester. The friction property of MAO Al_2O_3 coatings sliding against Si_3N_4 ceramic balls were investigated in air, water and oil by a ball-on-disk tribo-meter, and the worn surfaces of the MAO Al_2O_3 coatings were observed using scanning electron microscope (SEM). The results showed that the MAO Al_2O_3 coatings mainly contained α-Al_2O_3 and γ-Al_2O_3 phase. The micro-hardness of the polished MAO coatings was HV1740±87. With an increase in normal load and sliding speed, the friction coefficient in air increased from 0.74 to 0.87, while decreased from 0.72 to 0.57 in water and 0.24 to 0.11 in oil. This indicates that the fluid lubrication could improve the friction behavior of the MAO Al_2O_3 coatings. The worn surfaces' observation indicated that the wear mechanism of the MAO Al_2O_3 coatings changed from abrasive wear in air to mix wear in water, and became microploughing wear in oil.

Keywords: Aluminum alloy; Micro-arc oxidation; Friction; Lubrication

1. Introduction

Aluminum alloys possess high strength-to-weight ratio, good ductility, and are often used in automotive and aerospace industries. However, as far as the tribological machine parts are concerned, the poor wear-resistance of aluminum alloys in air and water decreases the service life of machine components [1]. Therefore, it is imperative to enhance their wear-resistance to further increase their service life in various environments. Ceramic coatings are well known to improve the wear resistance of machine parts [2–6]. However, due to the elastic or plastic deformation of aluminum alloy under mechanical loading, the thin hard coatings via PVD methods often exhibit limited tribological performance [2–6]. Recently, the micro-arc oxidation (MAO) process technique can form a thick aluminum oxide and other oxide ceramic coatings on aluminum alloys by plasma discharging in an aqueous electrolyte solution on aluminum surface under high voltage [7–13]. The MAO coatings have exhibited better mechanical properties as compared with anodic oxide coatings and plasma spray ceramic coatings, and then can be applied to many industrial fields, such as automotive, aerospace, medicine and textile engineering, etc [14].

Previously, many scientists have paid more attention to looking for good MAO parameters [15–20] to obtain high quality MAO Al_2O_3 coatings on aluminum alloys. But for the MAO Al_2O_3 coatings' tribological properties, the friction and wear properties of the MAO coatings against different mating materials have already been investigated in air [9,10,14,16,21–24]. In fact, lots of machine parts made of aluminum alloys are performed in various environments such as water and oil. Under lubrication condition, the presence of sub-micrometer, surface-connected porosity in the MAO coatings is beneficial to obtaining low friction and good wear resistance [25]. However, the

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Table 1
Chemical composition of 2024 aluminum alloy

Element	Si	Fe	Cu	Mn	Mg	Al
Content(wt.%)	<0.50	<0.50	3.8–3.9	0.3–0.9	1.2–1.8	Balance

tribological properties of MAO coatings in water and oil have not yet studied in detail. Therefore, the purpose of this paper is to investigate the friction and wear characteristic of MAO Al_2O_3 coatings in air, water and oil and discuss the influence of ambient environment on the wear mechanism of MAO Al_2O_3 coatings.

2. Experimental procedure

2.1. Materials and specimens

The extruded aluminum alloy 2024Al was used as a substrate. The chemical composition and mechanical properties of 2024Al were shown in Tables 1–2. The disk specimens (ø30 mm×4 mm) were gotten via machining 2024Al alloy bars. The uniform thickness of all specimens was ensured by grinding less than 0.1 mm of tolerance from both sides of the disk surface. One side of disc was polished to remove the grinding damage and any surface irregularities. The surface roughness of the polished surface was 0.1 µm.

2.2. MAO coatings deposition

Prior to MAO coating deposition, the disk samples were degreased in a water solution with 10 vol.% H_2SO_4 at 60–80 °C for 5 min, and washed with distilled water. An aqueous solution of electrolyte was prepared with chemically pure 10 g/L Na_2PO_3, 8 g/L Na_2SiO_3 and some additives. Alumina ceramic coatings were synthesized using a MAO unit which consists of an insulted electrolyte bath and a high voltage power supply generating saw tooth pulses with the maximum voltage amplitude of about 1.5 KV and maximum frequency of 3 KHz. One output of the power supply was connected with a stainless steel bath, and another with a specimen was immersed into electrolyte. The MAO Al_2O_3 coatings were deposited on 2024 Al for 30 min. A constant current density 5 A/dm^2 on specimen's surface was adjusted by voltage control during processing. The electrolyte temperature was kept below 50 °C. After the MAO Al_2O_3 coatings deposition, the samples were ground and polished to the surface roughness of 0.6–0.8 µm (R_a) using SiC ground paper, and then ultrasonically cleaned in acetone for 20 min.

Table 2
Mechanical properties of 2024 aluminum alloy

Materials	Yield strength	Maximum strength	Elongation	Microhardness
	σ_s (MPa)	σ_b (MPa)	δ(%)	$HV_{0.01}$
2024 Al	267.9	545.5	17	170

2.3. Microstructure, thickness and microhardness of Al_2O_3 coatings

The MAO Al_2O_3 coatings' topography was observed by using QUANTA 2000 scanning electron microscopy (SEM) (FEI, USA) and their structure were determined by D8-Advance X-ray diffraction (XRD) (Bruker, Germany). The coatings' thickness was measured by using MINITEST1100 eddy current thickness gauge. The coatings' micro-hardness was measured at 4.9 N for 10 s by a digital micro hardness tester (HXD-1000TM, China). The micro-hardness measurement was repeated for three times, and the micro-hardness value in here was the mean value of micro-hardness for three times.

2.4. Friction tests

Prior to wear test, Si_3N_4 balls with diameter of 4 mm were ultrasonically cleaned in acetone for 15 min and then dried in air. The wear experiments were performed using ball-on-flat tribo-meter (UMT-2, CETR, USA, Fig. 1) at room temperature in air, distilled water and sewing machine oil. The normal load was in the range of 5–10 N, and the sliding speed varied in the range of 0.05–0.15 m/s. The distilled water and oil was added onto rubbing surfaces using an injection-tube. The friction coefficients were obtained directly from the above-mentioned tribo-meter's computer. After testing, the three-dimensional and sectional morphologies of wear tracks on the MAO Al_2O_3 coatings were determined using a MicroXAM™ non-contact optical profilometer (ADE Phase-Shift, USA), and the wear track of MAO Al_2O_3 coatings were observed by SEM (FEI, USA).

3. Results and discussion

3.1. Microstructure, thickness and micro-hardness of MAO Al_2O_3 coatings

Fig. 2 shows the microstructure and XRD spectrum for the MAO Al_2O_3 coatings. As seen in Fig. 2(a), the coatings' surface exhibited crater-mouth like traces and was covered with many plasma discharge products. When a plasma discharge appeared,

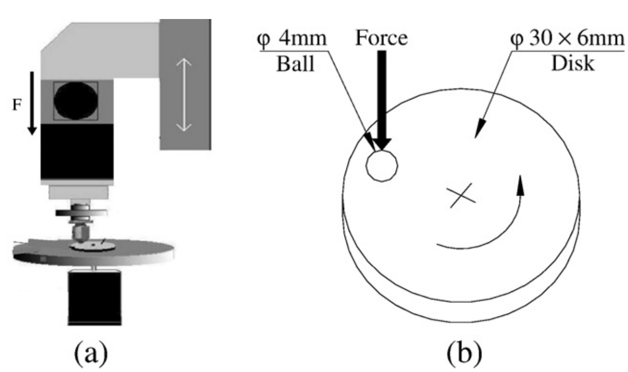

Fig. 1. Schematic diagram of ball-on-disk for UMT-CETR tribo-meter.