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ARTICLE

Friction and Wear Behavior of Micro Arc Oxidation Coatings on Magnesium Alloy at High Temperature

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Abstract: A ceramic coating was formed on AZ91D magnesium alloy by micro arc oxidation technology in aqueous solution containing silicate and phosphate. The phase composition, surface, cross-sectional and wear tracks morphologies of the coating were analyzed by XRD, SEM and Laser Scanning Confocal Microscope (LSCM), respectively. UMT-3 High Temperature Tribometer was used to study the friction and wear behaviors of coating within 150 °C. The results show that the coatings' mean friction coefficient firstly increases with the temperature increasing. When the ambient temperature exceeds 100 °C, it begins to reduce. The wear rate of the coating is much lower than that of magnesium alloy substrate, and it declines as temperature goes up. The results indicate that the micro arc oxidation coating has excellent wear resistance particularly at high temperature. Through the analysis of grinding cracks' micro-structure at the load of 2 N, the main wear mechanism of these coatings at different temperatures is all abrasive wear.

Key words: magnesium alloy; micro arc oxidation; high temperature; friction and wear behaviors

Magnesium alloys research focuses on auto parts in energy saving and emission reduction fields due to their low density, high specific strength and high energy attenuation coefficient. While the poor wear resistance and corrosion resistance of magnesium alloys owing to their low hardness and high chemical activity restrict their wide application in auto industry[1-4].

In recent years, micro arc oxidation (MAO) has been widely used in magnesium alloys surface modification. It is a potential technology that can effectively improve magnesium alloys' wear resistance and corrosion resistance [5-7]. The process is that in the electrolyte of certain composition, using magnesium alloy as the anode, stainless steel container as the cathode, one applies pulse high voltage and high current between the electrodes; then the magnesium alloy surface produces micro arc discharge, and a kind of oxide ceramic coating with good adhesion, excellent corrosion resistance and wear resistance in situ grows in the surface[8,9].

At present, many researchers have studied the friction and wear performances of micro arc oxidation coatings on magnesium alloys at room temperature [10-15], but the wear performances at higher temperature are rarely reported. According to a Ref.[16], magnesium alloys crystal sliding trend becomes active and their mechanical strength declines when temperature exceeds 450 K (about 150 °C), so they are usually used that temperature. Therefore the present work was undertaken to investigate the coatings' friction and wear properties within the condition of 150 °C and could provide experimental and theoretical bases for the applications of the coatings at higher temperature.

1 Experiment

AZ91D magnesium alloy, whose chemical composition was given in Table 1, was used as substrate material. The size of samples were all *Φ*50 mm×2 mm. Before micro arc oxidation, the samples were drilled at first and then were polished with 180#~800#CW waterproof abrasive papers and cleaned using acetone ultrasonic for 15 min. At last the samples were washed with deionized water and dried with a drier. MAO process was carried out with a MAO device (DSM35F) invented by Harbin University of Technology. The samples and stainless steel container were used as anode and cathode,

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Table 1 Nominal chemical composition of AZ91D (wt%)

Al	Zn	Mn	Si	Cu	Ni	Mg
9.5	0.90	0.40	≤0.05	≤0.025	≤0.001	Bal.

respectively. The electrolyte was prepared by dissolution of reagent grade chemicals of sodium silicate (10 g/L), sodium phosphate (10 g/L), sodium hydroxide (8 g/L) and some additions. With a constant current mode, the current density, frequency, duty cycle and process time were 20 A/dm^2, 800 HZ, 20% and 15 min, respectively. The electrolyte's temperature was kept below 20 °C with a cooling system.

Tribological properties of coatings at high temperatures were investigated by a ball-on-disc high temperature tribo tester (UMT-3). The experiments were conducted with a Si_3N_4 ball with the diameter of 9.5 mm in sliding contact. The tests were implemented at room temperature, 75, 100, 125 and 150 °C under a load of 2 N at the speed of 200 r/min and in dry sliding condition. The wear tracks radius of magnesium alloy and the coatings were 5 mm and the tests were performed for 10 min. The wear tracks morphologies and wear volume of magnesium alloy and coatings were observed and calculated, respectively by the Laser Scanning Confocal Microscope (LSM700). The wear rate was calculated using $K=V/FL$ equation, where K is the value of wear rate, V is the worn volume, F is the normal load, L is the total length of wear track.

The phases of magnesium alloy and coatings before and after tribological tests were analyzed through X-ray diffractometer equipment (X'PertPro) with a Cu Kα radiation source. The scanning angle was 10°~80°. The morphology of surface, cross section and wear tracks were observed by a scanning electron microscope (SEM-VEGA3) and the composition of coating and wear debris was analyzed by Energy Disperse Spectroscopy (EDS).

2 Results and Discussion

2.1 XRD analysis

XRD patterns for magnesium alloy and the coating are shown in Fig.1. The coating is mainly composed of MgO phase (Periclase, syn) and Mg_2SiO_4 phase (Forsterite, syn) compared with the XRD pattern of magnesium alloy. From Fig.1, magnesium phase appears in the XRD pattern of the coating as the coating is thinner. The process of micro arc oxidation produces high energy, making the surface of substrate molten, and the molten magnesium alloy could react with oxygen and silicate ions in the discharge channel, forming MgO phase and Mg_2SiO_4 phase respectively. Those phases could effectively improve the hardness of magnesium alloy. According to the elementary composition in Table 2, O and Mg elements are the main elements in the coating. While the elements of Na, Si, P and F are mainly from the electrolyte.

2.2 Morphology and microstructure of the coating

The surface and cross-section morphology of the coating are shown in Fig.2. Fig.2a reveals that the surface morphology of the oxidation coating is rough and porous. These special features are formed during the following process. A thin passive oxidation layer is formed on the substrate surface after the initial period, which is a breakdown under the action of arc discharge that is produced by high voltage. In addition, the arc discharge action produces high energy that could make the substrate molten and the molten substrate react with oxygen and silicate ions in the discharge channel. The product is sprayed to the surface owing to the high pressure in the discharge channel and then it is quickly cooled down when contacted with the cold electrolyte, eventually forming the porous morphology. There are still some microscopic cracks between those micro-holes. Because these holes are full of bubbles which are ionized with a large amount of energy and high internal stress, resulting in a reduction of material strength and thus causing the cracks[17]. The coating and the substrate are closely combined with each other and the combination mode is metallurgical bonding. The coating could be obviously divided into two layers. The outer layer is looser with more defects while the inner layer is denser

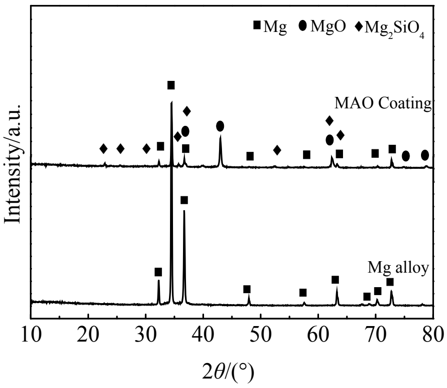

Fig. 1 XRD patterns of MAO coating and magnesium alloy

Table 2 Main elementary composition of coating on Mg alloy

Element	O	Mg	Na	Si	P	F
Content/wt%	34.12	34.96	5.42	5.88	1.85	3.16

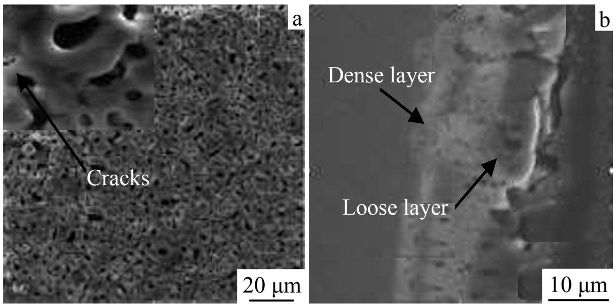

Fig.2 Surface (a) and cross-sectional (b) morphology of MAO