

Wear Protection of Al383/SiO₂ Metal Matrix Composites by Plasma Electrolytic Oxidation (PEO) Process

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ABSTRACT

Al383/SiO₂ metal matrix composites (MMC) was designed to increase the wear properties of the Al alloy. However, the soft Al matrix was subject to large plastic deformation under high normal load during lubricated sliding wear tests, causing detachment of the reinforced particles. To further increase the wear resistance of the MMC, in this research, Plasma Electrolytic Oxidation (PEO) process was used to form oxide coatings on the MMC. The hard and wear resistant oxide coatings protected the metal matrix during the wear tests, reducing the wear rate of MMC. The effect of both oxide coating thickness and volume content of SiO₂ particles on the wear behaviour of MMC was investigated. It was found that with a proper combination of the volume content of SiO₂ and coating thickness, the MMC exhibited high wear resistance and low friction coefficient.

INTRODUCTION

High fuel cost and the increasingly severe environmental pollution forces the automotive manufacturers to reduce the vehicle weight. Hypoeutectic Al-Si alloys were used to produce an engine block, the heaviest component in a passenger vehicle. However, due to the low wear resistance of the hypoeutectic alloys, a cast iron cylinder liner was employed to protect the Al alloys from the wear attack. Hypereutectic Al-Si alloys have been used to produce the engine blocks without the cast iron liners to further reduce the vehicle weight. The precipitated hard Si particles could isolate the contact between the piston rings and the soft Al matrix, thus greatly increased the wear resistance of the alloys. However, under high contact stress, large plastic deformation tended to occur on the soft Al matrix, which caused the Si particles detach from the matrix. Also, the

brittle Si particles were subject to fracture. The detached and fractured hard Si particles would lead to third-body wear. Moreover, due to the high manufacturing cost, the hypereutectic Al-Si alloys were only used to produce the engine blocks for the luxury cars.

Al based metal matrix composites (MMC) were designed to improve properties of Al alloys, especially wear resistance. With the addition of the reinforced materials, a transition in wear mechanism from severe wear to mild wear was observed [1, 2]. The wear rate of the composites decreased with the increasing volume content of the reinforced materials [1,2,3,4,5,6,7,8,9,10]. Like the hypereutectic Al-Si alloys, the soft Al matrix of the MMC deformed under high contact stress, causing the reinforced materials to spall from the matrix, adhere to the counterface and subsequently abrade the MMC, which caused high wear rate and friction [1]. Therefore, in order to improve the wear resistance of the composites further, it is necessary to enhance the wear resistance of the Al matrix.

Plasma Electrolytic Oxidation (PEO) process is an environmentally friendly and cost effective surface treatment technique, which can oxidize the metal surface and form wear and corrosion resistant coatings [11,12,13,14,15,16,17,18,19,20,21]. Different from the conventional anodizing process, the PEO process uses high voltage to initialize plasma discharge to produce oxide coatings in a dilute alkaline solution. The coating is composed of a porous outlayer, a dense layer and a nano-structured inner layer with grain size in the range of 50-80nm [13].

By applying the PEO process to the Al MMC, the Al matrix is oxidized to form alumina, which is hard and wear resistant. Consequently, the wear rate of the composites is expected to

significantly reduce. To protect the MMC, a thicker PEO coating is desirable. However, as its thickness increases, the coating becomes rougher and harder. The porous outlayer is subject to be worn off to form brittle particles, which may cause third-body wear. Thus, a honing process is necessary to remove the porous layer so as to reduce the wear rate and friction as well as the worn loss of the counterface material. Hence, a coating with appropriate thickness is desirable to eliminate the honing process and protect the counterface material.

In this research, SiO₂ particulate Al MMC with three volume contents of SiO₂ particles were produced by the semi-solid squeeze casting method. PEO coatings with two thicknesses were produced on each composite. The tribological properties of the coated MMC under the lubrication starvation condition were studied by reciprocating sliding wear test. The effects of coating thickness and volume contents of particles on the wear resistance of composites, the counterface volume loss and coefficient of friction (COF) were investigated.

MAIN SECTION

1. MATERIALS AND TESTING PROCEDURE

1.1. Materials

Al383 alloy (AlSi8Cu3) and SiO₂ particles were chosen as the matrix and the reinforced material to produce A383/SiO₂ particulate MMC via the semi-solid squeeze casting method. At 610°C, the SiO₂ particles were blended into the molten Al383 alloy under the protection of Ar gas. At 590°C, the liquid mixture was poured into the die. Three composites with three SiO₂ volume contents of 5%, 10% and 20%, individually, were casted and cut into small coupons (20 × 20 × 5 mm). Specimens were polished with SiC sandpapers up to 2400 Grit, rinsed and dried.

1.2. Testing Procedure

A PEO unit [14] was used to produce oxide coatings on the MMC coupons. During the PEO process, the MMC coupon acted as an anode and a stainless steel plate was a cathode. Both electrodes were connected to a pulsed DC power supply, operating at a frequency of 2 kHz and the duration time of 80% duty cycle. The specific frequency was chosen according to the dependence of coating growth rate to the current frequency [15]. The electrolyte was 8g/l Na₂SiO₃ with KOH added to balance the pH at 13. The coupons of three MMC were coated with two different coating thicknesses by adjusting the treatment time. According to the average growth rate (~1µm/min), the thickness for the thinner coating was about 3µm and 6µm for the thicker one. The sample indexes are shown in Table 1. Average surface roughness Ra of all samples was measured by Mitutoyo

SJ-201P stylus surface profiler. Reciprocating sliding wear tests were conducted on a ball-on-flat sliding wear tester at room temperature (25°C) under a starved lubrication condition. The lubricant was Motomaster® 5W-30. The MMC coupon oscillated against an AISI 52100 chrome steel bearing ball with a diameter of 5/32" under a normal load. Two normal loads 5N and 10N were applied to each coupon. The total sliding distance was 250 m. A Joel 2010 Scanning Electron Microscope (SEM) was used to observe the sample surface morphologies and wear tracks. A Buehler Omnimet optical microscope was utilized to measure the worn volume loss of the counter steel balls.

Table 1. Sample indexes

		Treatment time (minutes)		
		0	3	6
Volume contents of SiO ₂	5%	S10	S11	S12
	10%	S20	S21	S22
	20%	S30	S31	S32

2. RESULTS AND DISCUSSION

2.1. Surface Morphologies of Uncoated and Coated Samples

Fig. 1 is the SEM micrographs of the uncoated MMC coupons with three volume contents of SiO₂. The smooth spherical SiO₂ particles (diameter about 30 to 40µm) were spread in the Al383 matrix (Fig. 1 (a), (b) and (c)). The SiO₂ particles protruded from the matrix after polishing process, especially for sample S20 and S30 (Fig. 1 (b) and (c)). The SiO₂ particles of samples S10 (5% SiO₂) and S20 (10% SiO₂) were distributed more evenly in the matrix than those of sample S30 (20% SiO₂) (Fig. 1 (a), (b) and (c)). Due to the high content of the particles, during the casting process, it was difficult to mix the particles with the melt alloy. Thus, some SiO₂ particles clustered together (Fig. 1 (c)). Around the particles of the clusters, large voids were found (the insert in Fig. 1 (c)). Absorbed gas and difference in thermal expansion coefficients of Al alloy and SiO₂ particle might be the main reasons for the casting defects in sample S30.

<figure 1 here>

Fig. 2 shows the SEM micrographs of the MMC coupons coated for 3 minutes (S11, S21 and S31). The surface of the coupons consisted of smooth and relatively rough regions,

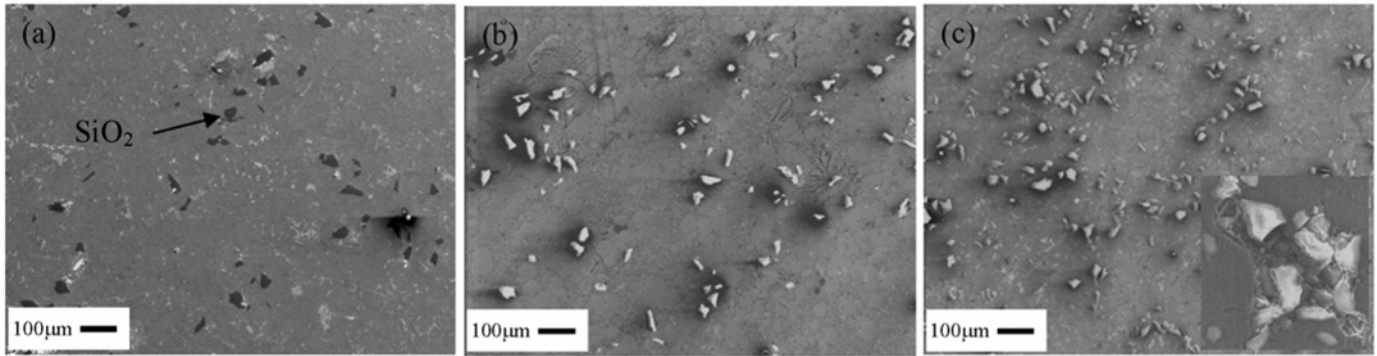


Fig. 1. SEM micrographs showing the surface morphologies of the uncoated Al383/SiO₂ MMC, (a) S10 (5% SiO₂), (b) S20 (10% SiO₂) and (c) S30 (20% SiO₂); the magnified insert showing the voids at the SiO₂ cluster.

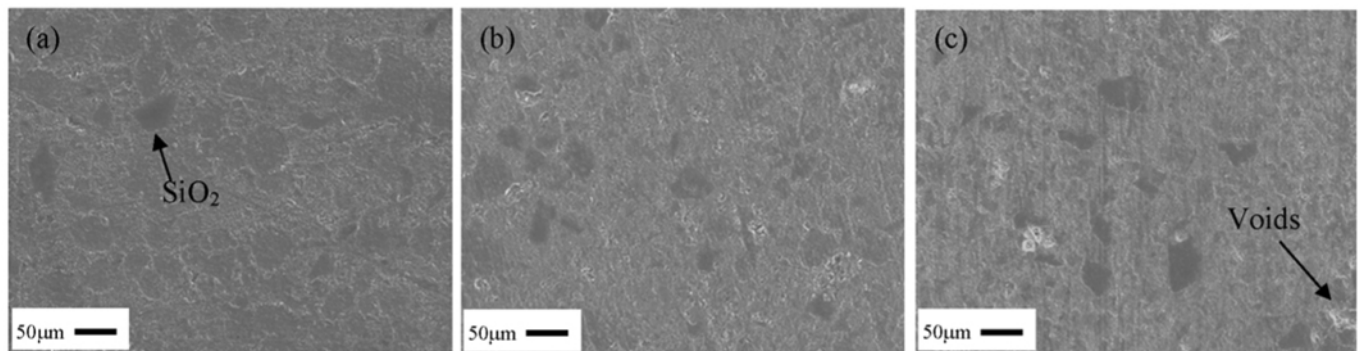


Fig. 2. SEM micrographs showing surface morphologies of Al383/SiO₂ MMC coated for 3 min, (a) S11 (5% SiO₂), (b) S21 (10% SiO₂) and (c) S31 (20% SiO₂)

corresponding to SiO₂ particles and the oxidized matrix respectively, shown in Fig. 2 (a), (b) and (c). Small projections, considered as the plasma discharge channels, were found on the Al383 matrix rather than the SiO₂ particles, as shown in Fig. 2 (a), (b) and (c). Since the plasma discharges contributed to the coating growth, the concentration of the plasma discharge channels on the matrix region indicated that the coatings more easily formed on the matrix than on the SiO₂ particles. Due to the coating growth on the Al matrix, it was found that the matrix region of coatings S11, S21 and S31 almost leveled with the SiO₂ particles (Fig. 2 (a), (b) and (c)). Also, the boundaries between SiO₂ particles and the matrix were very clear. On coating S31, the casting defects were not covered by the coating (Fig. 2 (c)).

<figure 2 here>

Fig. 3 exhibits the SEM micrographs of the MMC coupons S12, S22 and S32, which were coated for 6 minutes. Projections still concentrated on the matrix region, Fig. 3 (a), (b) and (c). Compared with the thinner coatings, the thicker coatings had larger but less projections, Fig. 3 (a), (b) and (c).

Also, the edges of the SiO₂ particles were melted and mixed with the oxidized matrix by the high temperature (up to 6000K) generated by the plasma discharges [19]. On coating S32, casting defects could still be observed, shown in Fig. 3 (c).

<figure 3 here>

The average surface roughness of all samples is listed in Fig. 4. Coatings S31 and S32 had much larger roughness than other coatings due to the casting defects in the substrates. For other coatings, the surface roughness increased with the treatment time (coating thickness). For the same treatment time, coatings had similar surface roughness.