

Investigation into Mixed and Hydrodynamic Frictions of PEO Coatings and Cast Iron

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ABSTRACT

A linerless aluminum (Al) engine block has potential to reduce the weight of an automotive engine and improve the fuel economy. However, the Al cylinder surface of an aluminum engine block is not usually strong enough to withstand the sliding wear against piston rings. A few surface processing technologies are used to protect the surface of cylinders. Among them, a thermal spraying coating, such as plasma transferred wire arc (PTWA) is already popular. Plasma electrolytic oxidation (PEO) coating is also proposed for increasing the wear resistance of aluminum-silicon (Al-Si) alloys and reducing the friction between the cylinder and piston. In this work, two different PEO coatings with a thickness of around 23 μm were prepared on an Al-Si alloy A356, and a high speed pin-on-disc tribometer was used to study the tribological behavior of the coatings at oil lubricant conditions. A cast iron sample was also used to do similar tribological tests for comparison. The coefficient of friction (COF) vs surface roughness (R_a : 0.2 - 0.8 μm) and sliding speeds (up to 6.07 m/s) were particularly studied. The results show that the COF significantly decreased with the increase of sliding speeds, and a smoother coating surface generally exhibited a lower COF and a steeper descent rate of the COF. While such observations seem true for both PEO coatings and the cast iron sample, the polished PEO coatings can have a lower COF than cast iron. The study indicates that the Al-Si alloy with PEO coatings could be further explored as a feasible solution to reduce the weight and improve the fuel efficiency of an Al engine.

KEYWORDS: PEO coating, roughness, sliding velocity, coefficient of friction

CITATION: Wang, G., Nie, X., and Tjong, J., "Investigation into Mixed and Hydrodynamic Frictions of PEO Coatings and Cast Iron," *SAE Int. J. Fuels Lubr.* 9(1):2016, doi:10.4271/2016-01-0491.

1. INTRODUCTION

Vehicles bring a lot of benefits to humanity. However, they also brought a lot of problems due to the huge amount of fuel consumption and the emission of carbon dioxide. The demand of increasing the vehicle's fleets' miles per gallon will challenge the automobile manufacturers to reduce the weight of their vehicles and frictional loss between components, along with other strategies to improve the vehicles' fuel economy [1].

A good method of reducing the vehicles' weights is to use a lighter engine block to replace the typical cast iron engine block [2, 3]. Most of the automakers prefer to use aluminum to make an engine block where cast iron liners are inserted or casted in [4]. However, the cast iron liners are heavy and lead to a few disadvantages due to the different thermal conductivity and coefficient of expansion compared with aluminum. Also, cast iron is not the best material to have a low coefficient of friction (COF) [5].

Aluminum engine blocks without liners could have been a good method to reduce weight, if the hardness of the cylinder surface made of commonly-used Al-Si cast alloys was high enough to bear the wear between the piston rings and the surface of the cylinder bore.

However, aluminum is not hard enough to bear the wear, and some additional treatments would be needed before the liners can be removed [6].

It has been practical for a thermal spray coating, for instance, plasma transferred wire arc (PTWA), to be applied to protect cylinder surfaces and improve the wear resistance [7]. PTWA is a thermal spraying process that deposits a coating on the surface of an aluminum cylinder. A single wire is used as feedstock in this system. A supersonic plasma jet melts the wire, atomizes it and propels the atoms onto the substrate [8]. The PTWA process can provide a coating with high wear resistance, and lower friction potential.

Plasma electrolytic oxidation (PEO) coating is also a promising candidate to protect the surface of aluminum cylinder. PEO process is an electrochemical surface treatment to get an oxide coating on light metals. The process employs high potentials to activate the discharges and generate the plasma to modify the structure of the oxide layers [9, 10]. This kind of coating grows both inwards and outwards from the substrate surface. PEO coatings can offer protection against wear, corrosion, and heat.

Compared with other coatings such as, PTWA, anodizing, or physical vapor deposition, PEO coating has a lot of advantages. For example, it has high adherent strength to substrate, high hardness and thickness, high corrosion resistance, high wear resistance, low environment pollution, relatively low cost, and outstanding tribological performance because of its exceptional oil retention ability [11, 12]. Additionally, the roughness and the surface topography of the PEO coating can be easily changed by changing the electrolyte composition, current, and treatment time. All of these factors can provide PEO coating with an ability to reduce the friction in tribology [13]. It is widely recognized that the energy generated by the combustion of fuel doesn't transfer to the wheels completely. Much of the energy is lost in the way of thermal loss and frictional loss. Among them, the frictional loss between the piston rings and the surface of cylinder bore accounts for more than 15% - 20% of the total vehicle power [14, 15]. Therefore, it is necessary to study the tribological properties of the PEO coatings.

The tribological properties can be affected by a number of factors, for example, the viscosity of the oil, the roughness of the counterface, the load, and the sliding velocity [16]. In this project, two critical factors are focused for study: surface roughness and sliding velocity. Roughness can considerably affect friction force and wear. The PEO coatings can be polished to have different roughness. High speed pin-on-disc tribological tests can be carried out on the coatings with different surface roughness finish. In this way, the roughness effects on the COF of PEO coatings can be studied.

The sliding velocity is another object of study in this work. The sliding velocity of the piston also always changes during work. At different sliding velocities, the piston rings and the cylinder bore will work under different lubricant conditions. At top dead center (TDC) and bottom dead center (BDC) where the sliding velocity is extremely low and the load is high, the piston rings work under boundary lubrication. At the middle of the cylinder bore where the sliding velocity of the piston is very high, the piston rings will work under mixed or hydrodynamic lubrication [17]. The Stribeck curve was first used to illustrate a relationship between COF and sliding velocity under different lubrication conditions as shown in Figure 1. In the boundary lubrication, the counterface contact is solid contact. In the hydrodynamic lubricating condition, the contact is viscous shear, and the contact is combination of these two in the mixed lubrication [18, 19].

Tribological tests are usually carried out on a low speed pin-on-disc tribometer (sliding velocity less than 1 m/s), and the whole picture of the Stribeck curve cannot be gained. The limited (low) sliding velocity can only generate a boundary oil lubricating regime. However, the tribological performance of PEO coating at mixed and hydrodynamic oil lubricating conditions is hardly known. Therefore, it is necessary to find the relationship between COF and the sliding velocity for the PEO coating at various lubricating conditions. Although a high speed reciprocating sliding test is always desired to simulate the real piston motions in an engine combustion chamber, vibration may be a problem to affect the accuracy of the test when the reciprocating speed is high. Furthermore, affordable data acquisition system requiring very high sampling rates may also be of challenge to collect the COF data of each cycle at different speeds. Thus, in this work, a

variable high speed pin-on-disc tribometer (sliding velocity goes up to 6.07 m/s) was designed to generate a boundary, mixed or hydrodynamic oil lubricating regime. The radius of the wear track can be adjusted from 0 mm to 100 mm, and the rotation sliding speed can also be changed from 0 m/s to 6.07 m/s (when the radius of wear track on sample is 50 mm). The connection between the motor and the sample holding disc is a rubber corn, and vibration is limited to an unnoticed level. A high-precision load cell is applied to collect data, and load calibration is carried out before use. The high speed pin-on-disc tribometer is shown in Figure 2.

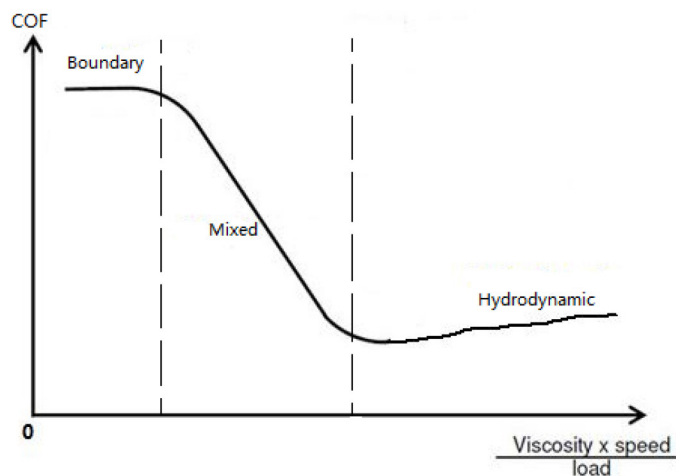


Figure 1. A typical Stribeck curve [18].

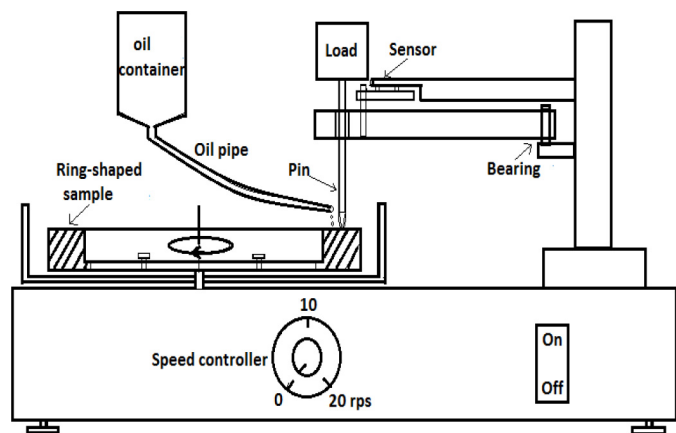


Figure 2. Schematic view of high speed pin-on-disc tribometer.

Previous studies show that the roughness and sliding velocity influence the COF of PEO coatings at the boundary lubricating condition but not that significant [20]. At a low sliding speed and thus a boundary lubrication, the COF increases, instead of decreases, when the PEO coating surface is polished from surface roughness of $R_a = 0.8 \mu\text{m}$ to $R_a = 0.5 \mu\text{m}$. Then, the COF decreases with the decrease of coating surface roughness from $R_a = 0.5 \mu\text{m}$ to $R_a = 0.3 \mu\text{m}$. Unlike the roughness effects, the COF always decreases when the sliding velocity increases even in the low speed region (sliding velocity less than 0.1 m/s) [20].

In this paper, the PEO process was applied to produce two coatings on an aluminum-silicon A356 alloy. The effects of surface roughness and sliding velocity on tribological properties at mixed or

hydrodynamic lubricant conditions were particularly studied based on these two coatings. A cast iron material was also employed to do the same tests as a reference for comparison.

2. EXPERIMENTS

In this work, A356 aluminum-silicon cast alloy was used as substrate material. The alloy was machined to have a shape of a ring with a dimension of 105 mm (outer diameter) $\times$ 78 mm (inner diameter) $\times$ 12 mm (thickness). This large diameter of the ring-shaped sample can generate high sliding velocities when the high speed pin-on-disc tribometer works at fast rotation. The top surface of the disc rings was polished to roughness equal to $R_a = 0.1 \mu\text{m}$ before a PEO coating was applied.

After the substrates were prepared, the PEO technology was used to produce two different coatings. A similar coating process has been reported in a previous publication [20]. The samples were identified by S3 and S12. A cast iron ring was also prepared to do the tribological tests as reference.

For the PEO process, the A356 aluminum alloy ring (anode) and a stainless steel (cathode) were dipped into electrolytic solutions [20]. The anode and the cathode were connected to a pulsed DC power supplier which worked at a frequency of 2 kHz and a duration time of 80% duty cycle. The current density was controlled at 0.1 A/cm^2 , and the treatment time was maintained in 20 minutes. The temperature of the solution was maintained around 300K by a tap water cooling system, as the temperature would influence the quality of the coating.

After the coatings were produced, a Mitutoyo surface profiler SJ201P was employed to measure the surface roughness and record the coating surface profiles. The coating thickness was measured using PosiTector 2000 thickness meter. The PEO coating thickness and surface roughness are listed in Table 1.

Table 1. The original PEO coating thickness and surface roughness of samples.

Samples	PEO S3	PEO S12	Cast iron
Thickness (μm)	23	21	NA
Roughness (μm)	2.58	1.89	0.28

The original roughness and topography of the two coatings were significantly different. The surface roughness of coating S3 was much higher than coating S12. The peaks were much higher and valleys much deeper on coating S3, which was supposed to be good for holding the lubricating oil on coating surface for tribological applications. During the PEO process, the degree of discharge on coating S3 was stronger than that on coating S12, which led to the rougher surface of coating S3. Cross hatches were produced on the cast iron ring disc surface to simulate a honed cylinder bore surface. The coatings were then polished to different roughness to do oil tests using the high speed pin-on-disc tribometer to find the roughness effect on friction at oil lubricating conditions. The original profile of the PEO coatings and cast iron were presented in Figure 3.

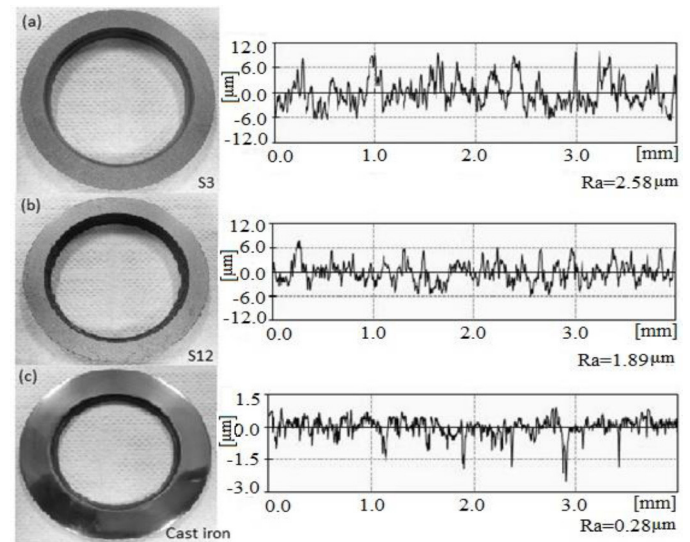


Figure 3. Original surface roughness and profiles of the PEO coatings and cast iron, (a) S3, and (b) S12, and (c) cast iron.

The oil tribological tests were carried out at a room temperature of 24°C and a humidity of around 50-60%. SAE 5W-20 full synthetic motor oil was selected to do the oil tests. An oil tube was installed in front of the pin and the oil flow rate was high enough (100 ml per-minute) to make sure that there was enough oil to form the mixed or hydrodynamic lubricating regimes at high sliding velocities. The load for the oil tribological tests was 10 N. AISI 52100 steel balls (3 mm in radius) as pins were used as counterface material. The rotation diameter of the wear track was 100 mm, and the highest rotating speed could go up to 20 rps (revolutions per second).

All the coatings and cast iron were polished to different roughness before the oil tests were carried out. The lowest roughness was around $0.2 \mu\text{m}$ after the polishing. After the polishing, the topography and thickness of the coating were significantly changed, as shown in Figure 4.

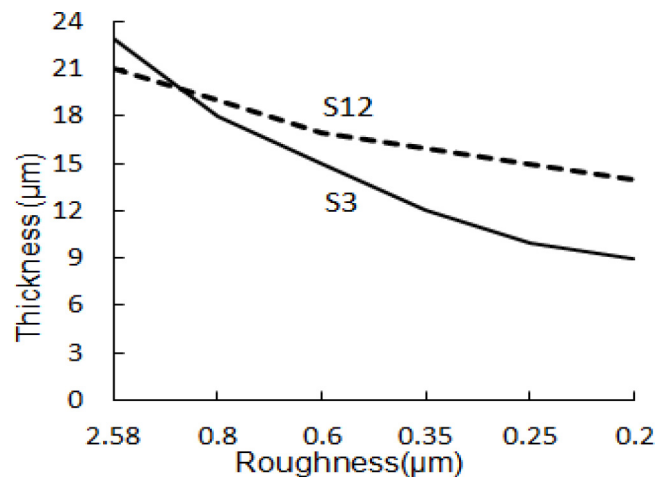


Figure 4. The relationship between roughness and thickness of coating S3 and S12.