An Investigation of the Microstructure and Oil Retention of Electrolyte Jet Plasma Oxidation (EJPO) Coating

Nasim Bahramian, Sina Kianfar, Joshua Stroh, Dimitry Sediako, and Jimi Tjong

Abstract Next-generation automotive engines demand new materials and technologies to meet efficiency mandates regarding energy conservation and emission reduction. Replacing heavy ferrous metals with lightweight aluminum (Al) alloys can considerably improve fuel efficiencies in the transportation sector. However, most Al alloys suffer from poor tribological characteristics, which urged original equipment manufacturers to develop advanced materials for high friction applications like cylinder blocks. Recently, there has been a growing trend to produce coatings with high-temperature strength and wear resistance. These coatings are deposited on an Al substrate of linerless engine blocks using various technologies, including Electrolytic Jet Plasma Oxidation (EJPO). The present study investigates the coating's microstructure, surface roughness, and oil retention and compares the latter with the oil retention of the Plasma Transferred Wire Arc (PTWA) coating which is currently used in cylinder block applications. The results revealed higher roughness ($R_a = 0.86\ \mu m$) and oil retention ($V_0 = 0.356\ \mu m^3/\mu m^2$) of the EJPO coating than the PTWA one ($R_a = 0.34\ \mu m$, $V_0 = 0.041\ \mu m^3/\mu m^2$).

Keywords Surface modification and coating · High-temperature material · Characterization · Linerless Al engine block

Introduction

To combat climate change and global warming, many governments have introduced energy conservation and fuel consumption mandates within various industries. For instance, in the automotive sector, weight reduction has been one of the most promising approaches to address the new demands [1, 2]. Replacing heavy ferrous

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metals with lightweight aluminum (Al) alloys, particularly in powertrain components, is an effective solution toward this goal. However, Al alloys suffer from poor tribological characteristics and insufficient high-temperature strength, which are both required for applications such as engine blocks. To tackle this challenge, a common approach is to embed cast-in iron (Fe) liners in the cylinder bores to protect them from the harsh conditions that are present inside the combustion chamber. However, during the manufacturing of Al engine blocks with cast-in Fe liners, the mismatch of thermal expansion/contraction coefficients between the Al cylinder wall and the Fe liner leads to the development of unwanted residual stresses [3, 4]. These stresses can cause distortion and premature failure of engine blocks while under in-service loadings [5–7]. Another approach is to use press-fit Fe liner, as opposed to cast-in Fe liner, which lowers the maximum magnitude of tensile stress and changes the stress mode from purely tensile to mostly compressive [8]. However, the reduced interface area between the liner and the cylinder wall results in a lower thermal conductivity, adversely affecting the engine's efficiency [9, 10].

Nowadays, there has been a growing trend toward manufacturing linerless engine blocks with advanced coating materials as alternatives to the Fe liners [11]. These coatings are to possess specific characteristics, protecting the Al part from the severe conditions in the combustion chamber. Other than high-temperature strength, as well as wear and corrosion resistance, the cylinder wall surface must also have sufficient oil retention. Oil retention is the ability of a surface to retain enough oil to prevent scuffing of the poor-lubricated area, such as the exposed surface of the cylinder wall when the piston is at Top Dead Center (TDC). Among various coating technologies, Plasma Transferred Wire Arc (PTWA) is a steel-based coating process that offers improved thermal conductivity and lower mass as compared to Fe liners [12, 13]. Previous studies showed that the tribological characteristics and strength of the PTWA coating are sufficient for engine block applications [14]. However, due to its dense structure (i.e., low open-porosity level), the PTWA coated cylinder wall requires post-processing honing to provide the surface with sufficient oil retention. The additional post-processing time, accompanied by the mechanical bonding between the coating and substrate (i.e., Al alloy cylinder wall), urged OEMs to find a more promising coating technique for next-generation internal combustion (IC) engines.

Plasma Electrolyte Oxidation (PEO) is an environmentally friendly and cost-effective coating technique that demonstrates considerable promise in applications subjected to severe wear, corrosion, and elevated temperatures [15–17]. PEO is a plasma-assisted coating generated by electrochemical conversion of the lightweight metal surface to a hard and well-bonded ceramic film. For instance, during PEO coating on an Al component, the Al part is immersed in an electrolyte bath while being subjected to high voltages, leading to numerous local plasma discharges on the metal surface and gradual formation of an alumina coating [18–20]. While the PEO technique is highly applicable for coating the external surfaces of a metallic component, its application is limited if certain areas of the external surface must remain uncoated. In these cases, the uncoated area would be covered from electrolyte, giving rise to additional post-processing cost and time. To overcome this challenge, a novel

coating method called Electrolyte Jet Plasma Oxidation (EJPO) is being developed, with a similar coating mechanism as PEO but a different configuration in applying the electrolyte [21]. In the EJPO coating process, the electrolyte is directly sprayed onto the locations of interest for the coating, allowing it to coat only the selected regions of the complex component. Therefore, EJPO coating has a great potential to provide a forever solution for using lightweight metals in broader applications such as aerospace, railway, and automotive powertrain. Despite numerous studies on the application of PEO on simple geometries, there is a lack of microstructural investigation on the EJPO coating applied to complex geometries.

This study conducts a microstructural characterization on the cylinder wall of an EJPO coated engine block. The coatings' morphology and phase composition are investigated using Scanning Electron Microscopy (SEM) and Electron Disperse X-ray Spectroscopy (EDS). In addition, surface roughness profiles were measured for an EJPO and a PTWA coated engine blocks. The roughness data were, then, used to perform a comparative study between two coatings to evaluate their oil retention characteristics.

Experimental Procedure and Results

Microstructural characterization was performed on a cylinder cut obtained from a V8 engine block coated with the novel EJPO technique. Field Emission Scanning Electron Microscope (FE-SEM, Tescan Mira3 XMU) operating at an accelerating voltage of 15 kV was utilized to evaluate the surface and cross-section morphologies of the coatings. Before SEM examination, the EJPO samples were sputter-coated with gold due to the low electrical conductivity of aluminum oxide. Oxford Instruments Aztec data acquisition and processing software with an 80 mm^2 Oxford EDS detector were used for the composition analysis of the coatings and corresponding substrates.

As mentioned in the previous section, oil retention is one of the crucial surface characteristics to be considered in cylinder block applications as it is a direct measure for preventing scuffing in poor-lubricated areas. In this study, surface roughness parameters were first measured using a Mitutoyo SJ-410 Series surface roughness tester, as shown in Fig. 1. Then, the roughness parameters were used in the following formula to calculate the oil retention.

$$V_0 = R_{vk} \frac{100 - M_{r2}}{200} \qquad (1)$$

where V_0 is the oil retention parameter ($\mu m^3/\mu m^2$), R_{vk} is the proportion of profile valleys below core roughness, and M_{r2} is the lower intersection point of the core roughness datum line with bearing ratio curve. The terminology and parameters are based on ASME B46.1–2009 [22].
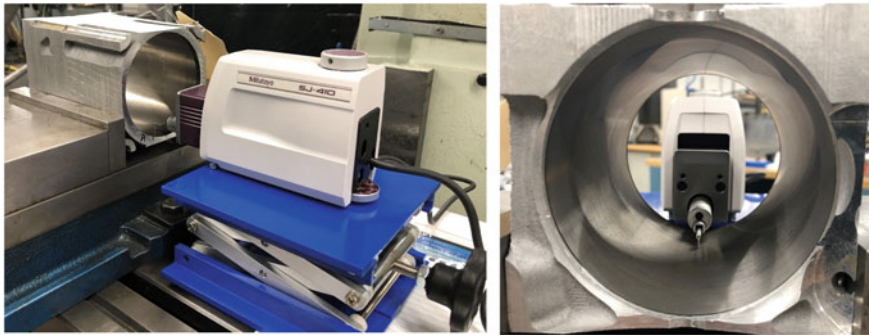
Fig. 1 Surface roughness measurement set-up

Microstructure of EJPO Coating

SEM observations of the EJPO cross-section indicate that the coating consists of three layers, as shown in Fig. 2. The outer layer is exposed to the electrolyte and is subjected to a high cooling rate and rapid solidification, leading to having a porous amorphous structure [23]. A relatively high amount of silicon (Si) content (20%) can also be observed in this layer due to electrolyte constituent interaction with the coating during plasma discharge. Being under a complex cooling rate during coating formation, the intermediate layer is dense and more likely to have a nanocrystalline structure. Due to its dense structure, this layer plays a vital role in improving the coating's thermal conductivity. Furthermore, compared to the outer region, a dramatic reduction in

Fig. 2 EDS phase analysis on EJPO coating's three layers across the cross-section
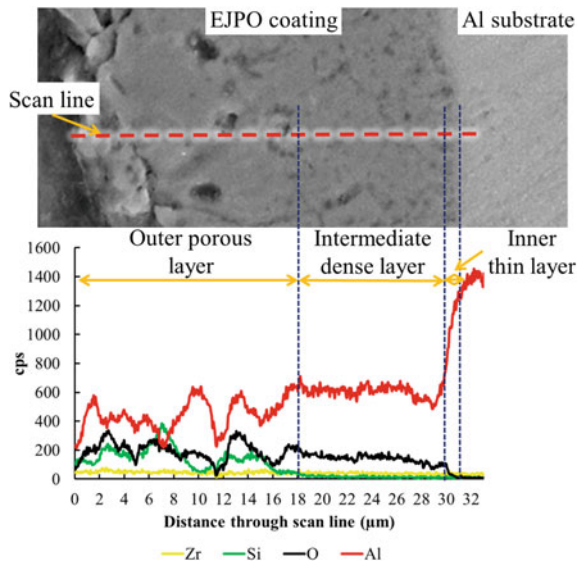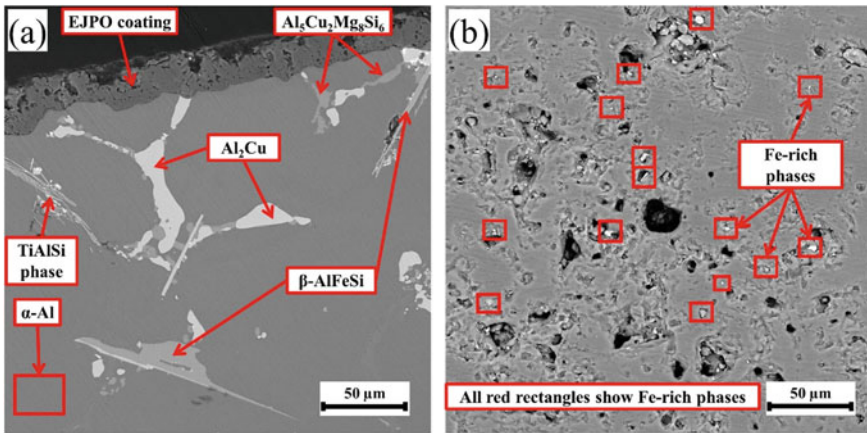
Fig. 3 Intermetallic phase at the Al substrate boundary reaching to coating/substrate interface

Si content can be seen toward this layer. Finally, there is a thin alumina film, 1–2 μm, where a sharp drop toward zero occurs in the oxygen level, accompanied by a simultaneous growth in the Al content.

Figure 3a depicts the SEM micrographs of the coating cross-section where the substrate intermetallics (such as β-AlFeSi) were occasionally observed to be present at the coating/substrate interface. A phase composition analysis on the coating surface (Fig. 3b) also reveals the presence of intermetallic elements (like Fe) in the outer layer of the coating. These observations suggest that the intermetallic elements can participate in conversion of the substrate into the oxide layer during plasma discharges. The previous study on PEO coating also confirmed the impact of substrate phases on the coating microstructural composition [24].

In addition, the elevated levels of oxygen diffusion into the Al substrate were observed occasionally in the vicinity of the coating/substrate interface (Fig. 4). This can adversely affect the substrate hardness, which shows the necessity for further investigation of the mechanical properties of the Al component.

Roughness Measurements and Oil Retention

Figures 5 and 6 depict the roughness profiles obtained from EJPO and PTWA coated cylinder cuts using a Mitutoyo profilometer. The results indicate that the EJPO coating has a high roughness value (i.e., $R_a = 0.86$ μm, average from ten measurement), which is more than twice the roughness value achieved from the honed surface of the PTWA one ($R_a = 0.34$ μm). The SEM micrographs of the surfaces of both coating also reveal a much greater level of porosity in the EJPO coating.
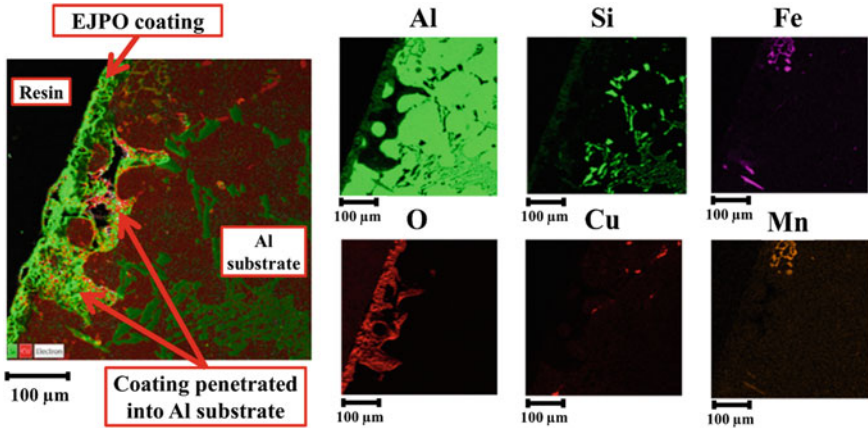
Fig. 4 SEM micrograph showing the oxygen diffusion in the Al substrate
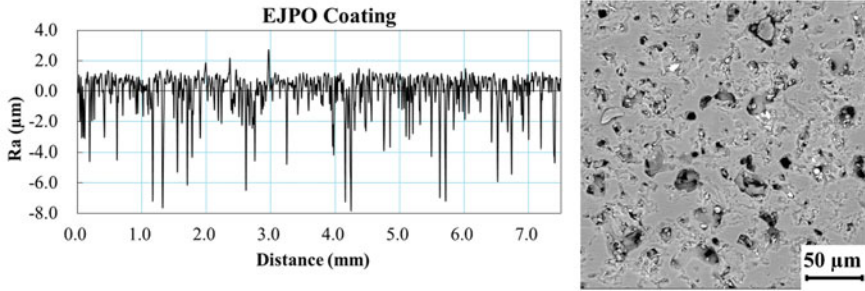

Fig. 5 Roughness profile and surface micrograph of EJPO coating representing the coating's porosity level
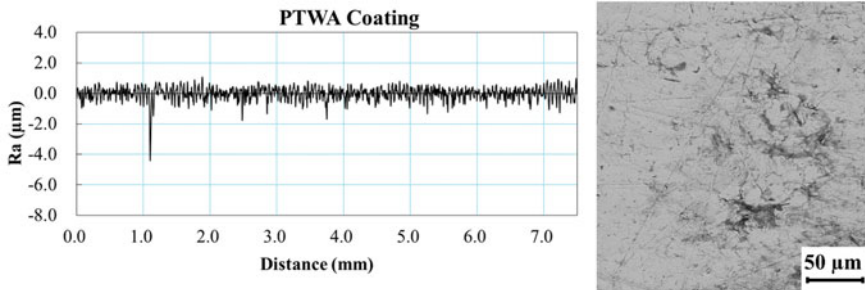

Fig. 6 Roughness profile and surface micrograph of PTWA coating representing the coating's porosity level

Table 1 Roughness and oil retention data for PTWA coating

	Measurement points									
	1	2	3	4	5	6	7	8	9	10
R_a (μm)	0.318	0.322	0.309	0.311	0.402	0.303	0.327	0.424	0.319	0.310
R_{vk} (μm)	0.693	0.703	0.632	0.683	0.791	0.517	0.754	0.878	0.687	0.652
Mr_2 (%)	90.568	88.201	89.592	86.753	82.272	88.336	89.936	90.528	88.580	87.640
V_0 ($\mu m^3/\mu m^2$)	0.033	0.041	0.033	0.045	0.070	0.030	0.038	0.042	0.039	0.040

Table 2 Roughness and oil retention data for EJPO coating

	Measurement points									
	1	2	3	4	5	6	7	8	9	10
R_a (μm)	0.892	0.996	0.907	0.884	0.703	0.709	0.992	0.849	0.817	0.894
R_{vk} (μm)	3.245	4.355	2.906	2.858	2.571	2.446	4.339	2.842	2.909	2.997
Mr_2 (%)	76.216	79.752	73.707	73.160	77.347	77.813	80.344	73.840	80.536	78.667
V_0 ($μm^3/μm^2$)	0.386	0.441	0.382	0.384	0.291	0.271	0.426	0.372	0.283	0.320

Tables 1 and 2 represent the roughness data that are used to calculate (see Eq. 1) the oil retention (V_0) of both surfaces. The results indicate that the average oil retention of the EJPO coating is 0.356 $\mu m^3/\mu m^2$, which is about nine times more than for the PTWA coating (0.041 $\mu m^3/\mu m^2$). Since the oil retention has a crucial impact on the coating's ability to prevent severe wear and friction at TDC, there is a potential that the EJPO coating may perform superiorly, as compared to the PTWA coating.

Conclusion

In this study, a microstructural analysis was performed on a novel coating technique, known as Electrolytic Jet Plasma Oxidation that was applied to the cylinder bore of a V8 engine block. Then, the surface roughness and oil retention of the coating were measured and compared to the values obtained from a PTWA coated block. The following conclusions may be drawn from this study:

(1) The EJPO coating consists of three layers, each with distinct features. The outer layer, as shown in the SEM micrograph, is primarily amorphous since it is cooled and solidified rapidly; however, the dense intermediate layer is exposed to a complex cooling rate, increasing the possibility of having nanocrystaline structure. The thin inner layer has no porosity and show consistent thickness (~2 μm) along the coating/substrate interface.
(2) The surface roughness measurements of the EJPO and PTWA coatings revealed that the EJPO coating had a surface roughness that was nearly 3 times greater (i.e., 0.86 versus 0.34 μm, respectively) than for PTWA. As a result, the EJPO coating has a calculated oil retention that is approximately 9 times higher (i.e., 0.356 $\mu m^3/\mu m^2$ versus 0.041 $\mu m^3/\mu m^2$, respectively).
(3) The SEM micrograph of the EJPO coating cross-section indicated the occasional elevated oxygen diffusion in Al substrate. Therefore, further research on the effect of the coating on the Al substrate mechanical properties such as hardness is recommended.
(4) The present study provides a better understand of the microstructural characteristics of the novel EJPO coating. In addition, the notable increase in oil retention provides good evidence that the EJPO coating may perform superiorly in engine applications, as compared to PTWA. Thus, it is important to continue examining the EJPO coating, focusing on its thermal conductivity and wear resistance.

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