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Development of advanced coating for enhancing performance of internal combustion engine

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By
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Development of advanced coating for enhancing performance of internal combustion engine

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ABSTRACT

Government has mandated all the automakers to increase their vehicle fleet miles per gallon average (MPG) to mitigate the global warming effects. Automakers have to find ways to reduce vehicle weight and frictional loss between powertrain components to increase the MPG, a higher MPG can help to reduce the vehicle fuel consumption and emissions. One popular approach is to remove the cast iron cylinder block liners and replace them with a lighter more thermally efficient material to reduce engine weight and enhance engine performance with higher power output or higher fuel efficiency.

In this work, electrolyte jet plasma oxidation (EJPO) coating was the first time to be applied on engine cylinder bore and other components to enhance engine performance, reduce weight and cost. EJPO coating is a kind of aluminum oxidation coating which has high hardness, high corrosion resistance, low coefficient of friction (COF) and good thermal properties. Lab tribology tests and thermal investigation showed EJPO coating had 65% lower COF than cast iron and 50% lower than plasma transfer wire arc (PTWA) coating, and better thermal properties. EJPO coated 2.0 L and 5.0 L engines were tested and compared with cast iron liner engine and PTWA coated engine.

EJPO coated 2.0 L engine passed Break-in test, Power test and 100 hours engine fatigue test. Compared with cast iron liner 2.0 L engine, EJPO coated 2.0 L engine had higher power output, especially at speeds lower than 3000 rpm and speeds higher than 5000 rpm. EJPO coated 2.0 L engine block reduced weight around 6.4% and reduce cost around 17.5%. EJPO coated 5.0 L engine passed Break-in test, Power test and vehicle

durability test. Compared with PTWA coated 5.0 L engine, the EJPO coated 5.0 L engine had higher power output at speeds lower than 3000 rpm and the EJPO coated camshaft bores, piston crown and cylinder head dome enhanced the performance more at high speeds. EJPO coated 5.0 L engine block reduced weight around 2% and reduce cost around 9% compared with PTWA coated one.

EJPO coating's lower COF and thermal swing property contributed to the higher engine performance. Lower COF helped to reduce engine friction loss, and the thermal swing property helped to reduce the engine heat loss without heating up the intake air temperature.

EJPO coating process and honing process parameters for 2.0 L and 5.0 L aluminum engine blocks were developed and the engine cylinder bore coating thickness, coating roughness, and piston to bore clearance were found in this work. EJPO coating is a potential candidate material for internal combustion engine to enhance performance, reduce weight, cost and increase the MPG in the future.

Keywords: EJPO, cast iron, PTWA, COF, weight reduction, temperature swing, engine, Dynamometer, vehicle durability, wear resistance, corrosion resistance, engine performance.

DEDICATION

I would like to dedicate this dissertation to my parents and my family for their unconditional love, support and encouragement.

I would like to dedicate this dissertation to my advisors Dr. X. Nie and Dr. J. Tjong for their support and guidance in my research career.

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I would like to thank Ford Motor Company's Powertrain Engineering Research & Development Center for their assistance with the EJPO coating facilities, engine assembly and engine tests.

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LIST OF ABBREVIATIONSAND SYMBOLS

CO_2	Carbon Dioxide
MPG	Mile per Gallon
COF	Coefficient of Friction
EJPO	Electrolyte Jet Plasma Oxidation
PEO	Plasma Electrolyte Oxidation
PTWA	Plasma Transferred Wire Arc
DLC	Diamond-Like Coating
EDS	Energy Dispersive Spectroscopy
SEM	Scanning Electron Microscopy
Rk	Core roughness depth
Rpk	Reduced peak height
Rvk	Reduced valley depth
TDC	Top dead center
EFT	Engine Fatigue Test
PCM	Powertrain Control Module

1. Chapter 1 Introduction

1.1 Background

The carbon dioxide (CO_2) produced from burning gasoline and diesel fuel in automotive engines is contributing to global climate change [1]. Global warming effects force the automakers to reduce the carbon oxide emission and enhance engine performance to increase the fuel economy. Achieving an acceptable trade-off between fuel economy/exhaust emissions and engine performance is one of the biggest challenges.

Research showed that increasing the MPG from 25 to 35 would save 1.8 billion barrels of oil over the lifetime of the cars sold from 2012 to 2016. It would also reduce the emissions by 900 million tons, which is equal to shutting down 194 coal plants [2]. Thus, the governments stepped in and requested the automakers to enhance engine performance and reduce emissions. They set the MPG target between 47 and 62 by 2025.

The development of lightweight aluminum engines is the most significant development in the automotive industry. More and more aluminum parts are being used on modern passenger vehicles to reduce weight. However, aluminum has its own limitations such as low wear resistances, low Young's modulus, low tensile strength and low hardness. All these limitations will prevent the application of aluminum on moving or sliding components, for example cylinder bore, bearing, and valve and so on. Inserting cast iron liners in aluminum engine block is an excellent solution for modern lightweight aluminum engine.

Replacing the cast iron engine block with the aluminum engine block with cast iron liners has enhanced engine performance and fuel economy significantly. It also reduced the weight by 45% compared with cast iron engine block, which helped to reduce vehicle rolling resistance thereby increased the MPG [3]. The design of cast iron liner conjunction with aluminum engine block worked perfectly until the government required the automakers to increase the MPG and reduce emissions. Figure 1-1 shows the cast iron engine block and the aluminum engine block.

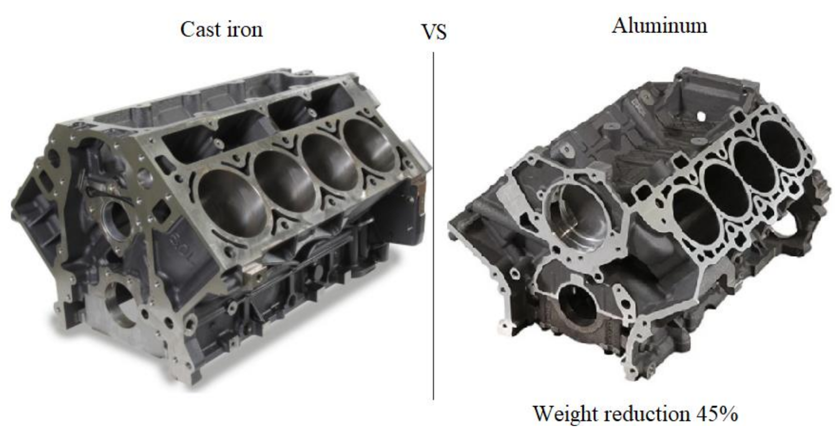

Figure 1-1. Cast iron engine block and aluminum engine block [3]

Cast iron liners are low-cost, durable, and easy to manufacture, which are critical for mass production. However, cast iron liners have their own inherent disadvantages that limit the improvement of the engine performance including weight, size, thermal conductivity, friction, and thermal expansion difference between cast iron and aluminum.

The different thermal expansion could cause the liner distortion, and the distorted liner could lead to more fuel and oil consumption thereby more emissions. Besides, it needs a heavy and big cooling system to cool down the engine, which will increase vehicle weight and rolling resistance [4]. All these disadvantages will limit the engine's performance and improvement.

One of the ways to enhance engine performance and fuel economy is to remove the cast iron liners from the aluminum engine block and replace them with a lighter, lower friction and more thermal efficiency material. Cast iron liners are a very cost-effective solution for mass production, to replace them with other more efficient material is not an easy change because of the cost and the effectiveness. However, to increase performance and reduce emission, this action should be a necessity.

To be an alternative material for cast iron, it must meet the cylinder block functional requirements. Internal combustion engine has high temperature, high pressure and high shearing load on cylinder bore surface. The replacement material must have high wear and scuff resistance and good tribological properties. The porosity level of the running surface must be below 1% and the maximum pore size must be below 500 microns to maintain good oil retention and low coefficient of friction (COF) [5]. The material should also have corrosion resistance since the sulfur contents in the fuel.

Besides, the engine cylinder bore replacement material must have low COF. The mechanical friction loss accounts for more than 15% of the total engine power, however, the friction between the piston ring and cylinder bore accounts for over 45% of the total friction loss as shown in Figure 1-2. Thus, the alternative material should have low COF to reduce the friction loss thereby enhancing engine performance [6].

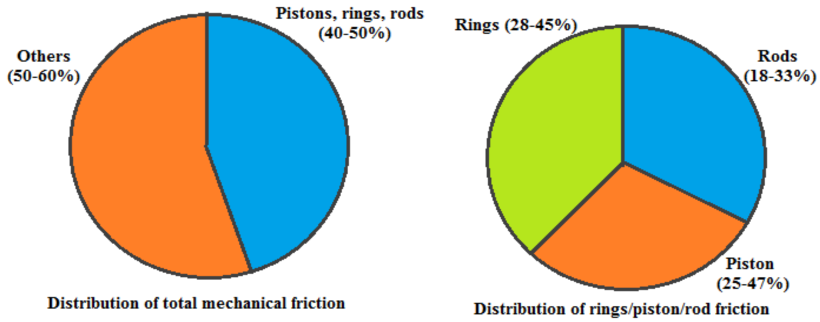

Figure 1-2. Engine friction distribution [6]

Electrolyte Jet Plasma Oxidation (EJPO) coating is also a kind of Plasma Electrolyte Oxidation (PEO) coating, which is characterized as hard, dense, wear-resistant, corrosion resistant and well-adhered oxide coating for metals like aluminum, magnesium, titanium and so on. The principle of PEO and EJPO coating fabrication is same; however the treatment processes are different. As shown in Figure 1-3, traditional PEO process needs immerse the parts or component in electrolyte which require high power supply if the coated part is huge, and mask is needed if local treatment required. EJPO process uses spray nozzle to do the whole surface and local treatments without mask and can coat any shape of the surface. EJPO process can reduce power requirement and save the mask design cost.

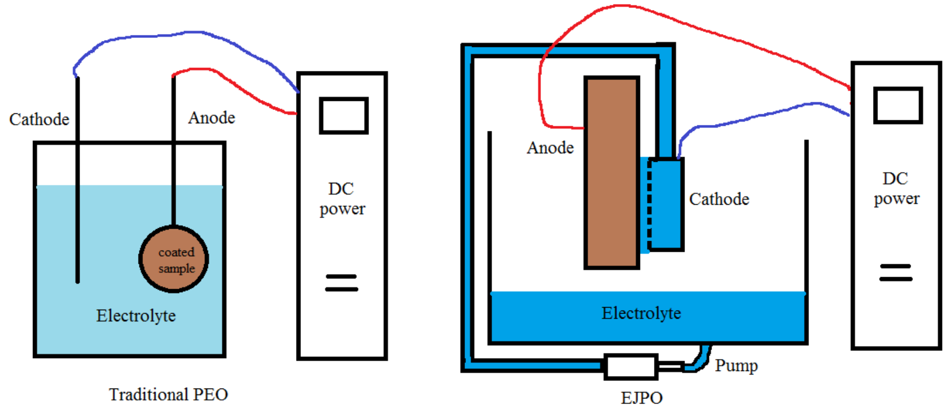

Figure 1-3. Comparison between PEO and EJPO process

Different from PEO coating, EJPO coating has special elements to help reducing the COF which are added in electrolyte. EJPO coating has a higher porosity to enhance the oil retention ability which also helps to reduce the COF. The porous structure of the EJPO coating can also help to enhance the thermal management in the applied locations. EJPO coating is a potential material for engine cylinder bore. A surface and cross-section view of the EJPO coating is shown in Figure 1-4.

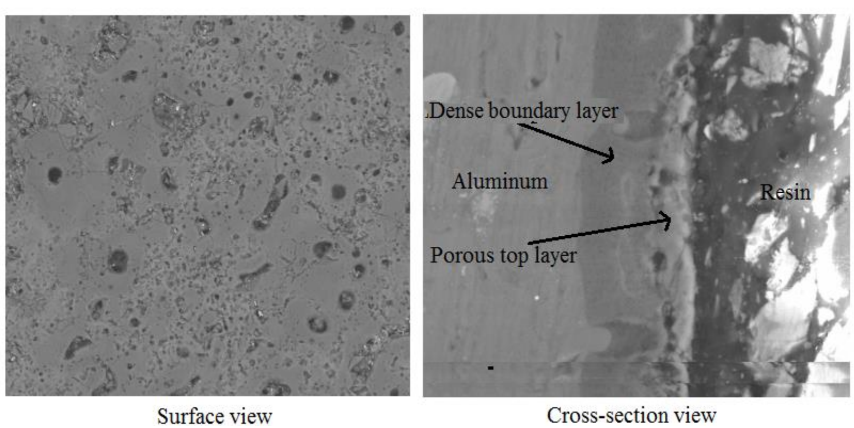

Figure 1-4. Surface and cross-section view of the EJPO coating

In this work, the properties of the EJPO coating will be investigated and the coating honing process will be studied. The EJPO coating will be applied on aluminum engine cylinder bore and other components to enhance engine performance for fuel economy and weight and cost reduction. Engine dynamometer and vehicle tests will be carried out to evaluate the engine performance and coating durability compared with cast iron liner engines and Plasma Transfer Wire Arc (PTWA) coated engines.

The advent of the battery electric vehicle affects the internal combustion engine's market, however, the small displacement engine for hybrid vehicle and high displacement engine for heavy duty vehicle will stay on the market for a long time. This work will focus on the EJPO coating fabrication and testing on 2.0 L and 5.0 L engines.

1.2 Objectives

This work focused on the preparation and test of the EJPO coated engine cylinder bore and other auto components including piston crown, camshaft bore, and cylinder head dome. The properties of the EJPO coating and the performance of the EJPO coated engines were investigated and evaluated. The following objectives were aimed to be achieved:

1. To investigate the EJPO coating's processes, microstructures and properties including hardness, corrosion resistance, tribological behavior and thermal management

performance, specially focus on the COF and evaluate the COF between EJPO coating, cast iron and PTWA coating.

2. To study the EJPO coating process and honing process effects on the coating's microstructure and surface morphologies of the EJPO coated aluminum engine cylinder bore.

3. To build-up a prototype linerless aluminum engine with EJPO coating and demonstrate its advantages including lighter weight, lower cost and a better engine performance compared with cast iron liner engine and PTWA coated engine.

4. To optimize and summarize the EJPO coating fabrication and honing process parameters for 2.0 L and 5.0 L aluminum engine blocks.

1.3 Dissertation Outline

This dissertation includes a total of fifteen chapters:

In Chapter 1, a brief introduction was provided with the objectives and the outline of this dissertation.

In Chapter 2, a literature review related to this study was carried out. Background knowledge of parameters that affect the engine performance, alternative materials for the engine cylinder bore, and a brief introduction of the EJPO coating. A proposed methodology was also introduced.

In Chapter 3, a few critical properties of the EJPO coating were investigated.

In Chapter 4, the #1 EJPO coated 2.0 L engine was prepared and tested. Two kinds of EJPO coatings were deposited on the cylinder bores. The objective of this test was to screen out a suitable EJPO coating for the combustion environment. The #2 EJPO coated 2.0L engine was prepared and flex brush honed for engine Break-in test.

In Chapter 5, the #3 EJPO coated 2.0 L engine was prepared and tested for engine performance. In this work, diamond stone machine honing process was studied, and the engine performance was compared with cast iron liner engine. EJPO coated engine had better performance at engine speeds below 3000 rpm and speeds higher than 5000 rpm. The#4 EJPO coated 2.0 L engine was prepared with bigger cylinder bore size and tested. The #4 EJPO coated 2.0 L engine passed Break-in, Power, Engine Fatigue, and Post power tests, and a summary of the EJPO coated 2.0 L engine work was provided.

In Chapter 6, the #1 EJPO coated 5.0 L engine was prepared with coating on cylinder bore only and tested. The EJPO coated engine passed Break-in and Power tests. Power performance was compared with PTWA coated engine. The #2 EJPO coated 5.0 L engine was fabricated with coating on cylinder bore, camshaft bore, piston crown and cylinder head dome and tested. This engine passed Break-in, and Power test. The engine performance of the #2 engine was compared with the #1 engine and PTWA coated engine.

In Chapter 7, piston temperature test was carried out to investigate the thermal insulation property of the EJPO coating in combustion conditions. Templugs were used and installed on EJPO coated pistons and uncoated pistons to measure the temperatures and do the comparison.

In Chapter 8, the #3 EJPO coated 5.0 L engine was prepared with coating on cylinder bore, camshaft bore, piston crown and cylinder head dome for engine durability test. After the test, cylinder bore distortion was investigated with torque plates.

In Chapter 9, the #4 and #5 EJPO coated 5.0 L engines were prepared with coating on cylinder bore, camshaft bore, piston crown and cylinder head dome. Engines were installed on the cars for vehicle durability tests.

In Chapter 10, a summary of the research work and future work was provided.

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2. Chapter 2 Literature review and proposed methodology

Engine performance can be enhanced in many ways. However, balancing the engine performance and fuel economy & emission is a challenge. Cost is another factor that affects the decision of changes in design for mass production. Among the best approaches to enhance engine performance are to reduce engine friction, increase engine thermal efficiency, and reduce weight. Most automakers work on engine friction, weight, and thermal efficiency to enhance engine performance, fuel economy and reduce emissions.

2.1 Engine friction effects on engine performance

Internal combustion engine has a lot of moving parts inside the engine and all these moving parts produce friction. Some of the frictions are constant and some of the frictions are variable when the engine speed and load change. All these frictions contribute to engine power loss or efficiency loss.

A general estimation of the friction in fired internal combustion engine is shown in Figure 2-1, the mechanical friction accounts for 4-15% of the total fuel energy consumption of the engine or 10-30% of the output power loss. However, in some extreme and idling conditions, the mechanical friction loss accounts for much more. At idling condition, there is no net output power, and all the energy is used to overcome the frictions [1].

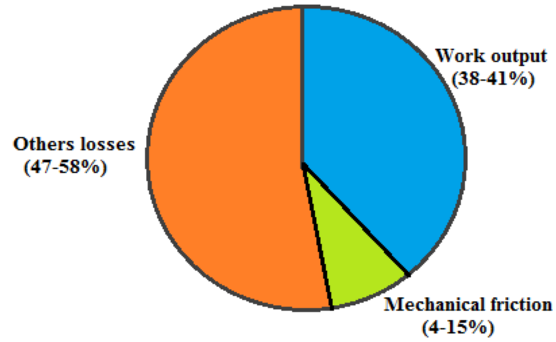

Figure 2-1. Energy distribution of fired engine [1]

As engine speed or load increases, the mechanical friction percentage will decrease because of the hydrodynamic lubrication is formed. At the hydrodynamic lubrication condition, there is an oil film formed between the rubbing parts and the oil film helps to reduce the friction [2]. Thus, at a low speed and low load condition, mechanical friction consumes about 30% of the output power. At a high speed and high load condition, the mechanical friction takes up about 10% of output power [3].

Among the mechanical frictions, the portion of piston ring friction is up to 50%. A distribution of the mechanical frictions is shown in Figure 2-2. Piston assembly includes piston, piston rings, piston pin, connecting rod and bearings. There are three main frictions in the piston assembly system: piston skirt, piston rings, and connecting rod bearings [4]. 50-68% of the friction comes from the piston rings rubbing.

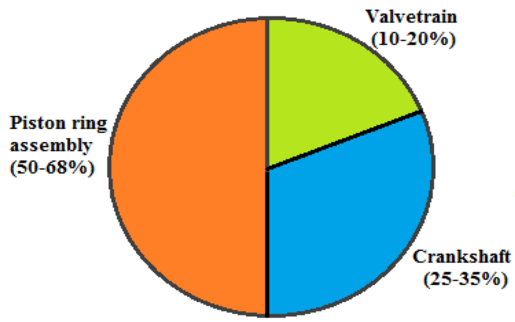

Figure 2-2. Distribution of mechanical friction in engine [3]

Several factors affect the piston ring friction including oil, piston ring coating & design, and cylinder bore material & honing patterns etc. More details will be reviewed as follows:

2.1.1 Oil effects on the friction

The main function of motor oil is to reduce friction and wear on moving parts and clean the engine from sludge and detergents. It also improves sealing of piston rings, and cools the engine by carrying heat away from moving parts. Additives are added to the oil to improve the oil functions. Motor oils also have different viscosity, and thin oils reduce friction in engines and help engines start quickly during cold weather. Thick oils are better at maintaining film strength and oil pressure at high temperatures and loads [4].

Synthetic oil is more chemically engineered than conventional oil, so its molecules are more uniform in shape and size, with fewer impurities. Using synthetic oil can help to reduce friction by 5% or more [4]. Dr. Guojun Liu is a professor in the Department of

Chemistry of Queen’s University and an expert in polymer synthesis developed Nano scale polymer particles dispersed in motor oil to help reduce friction. The test results showed the Nano particles were able to reduce friction by 55% more [6].

Using synthetic oil or oil with special additives can help to reduce the friction more. In this work, 5W-30 full synthetic oil was used to do tribology tests.

2.1.2 Piston ring coating effects on friction

The piston is the main component that delivers mechanical energy through reciprocating motion. The piston ring pack includes two compression rings and one oil control ring. The main functions of the ring pack are sealing the combustion chamber to prevent the high-pressure gas from leaking into the crankcase which is a waste of power, controlling oil lubrication between cylinder wall and piston rings, transferring heat from piston to cylinder wall then finally to the cooling system.

The piston ring front face rubs on cylinder wall and generates friction and heat. Different treatments can be used on piston ring to reduce friction, for example, DLC coating, Nitrided coating, polished Nitrided coating, and Mn-Pho’s coating. Lab bench test and single cylinder test showed that the DLC coated ring and polished Nitrided ring can help to reduce the friction by 17-25% [7]. In this work, Molybdenum coated and Nitrided rings were used to do the test.

Figure 2-3. Single cylinder test [6]

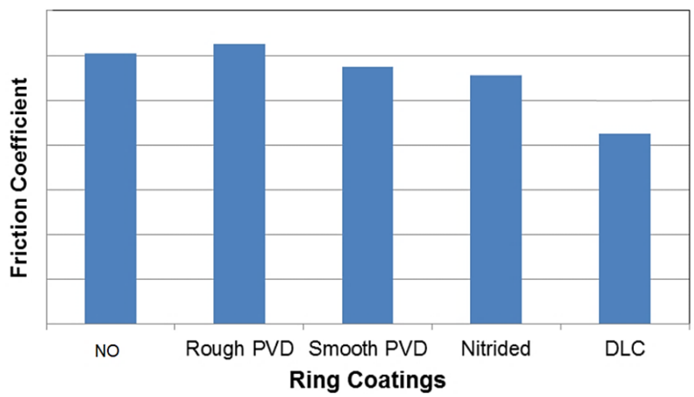

Figure 2-4. Friction results for different coatings [6]

2.13 Cylinder bore material, surface finish effects on friction

For a reciprocating engine, piston rings travel on the cylinder bore surface and generate friction and heat. The cylinder bore material, surface finish, honing pattern and cylindricity all affect the friction between piston rings and cylinder bore significantly.

Nowadays, most of the production engines use aluminum engine block conjunction with cast iron liners. Cast iron liners are low-cost, durable and easy to manufacture, but the tribological properties are not perfect and have some inherent disadvantages in weight, size, thermal conductivity, and thermal expansion. All these disadvantages will cause the liner distortion and increase the fuel and oil consumption, and emissions [7]. Four most promising ways to replace the cast iron liners and improve the tribological properties of the cylinder bores include hypereutectic aluminum silicon alloy cylinder bore, fiber or particle reinforced aluminum matrix composite cylinder blocks or liners, thermal spray coatings on the cylinder bore, or electrochemical deposited coatings on the cylinder bore. All these alternative materials have lower COF than cast iron, however not all of them are successfully in production due to high cost, complicated manufacture, or sulfur corrosion.

Plasma Transferred Wire Arc (PTWA) coating is a kind of thermal spray coating, which is characterized for its high wear resistance, light weight, low COF and better thermal conductivity. Ford Motor Company applied the PTWA coating on its 5.0 L engine to replace the cast iron liners for weight and friction reduction. Ford Motor Company has announced vehicle weight reduction can improve fuel economy by 40% by 2020 to meet the new CAFE standards [8]-[9]. Replacing cast iron liners with PTWA coating can reduce 8.5 pounds' weight. Based on Ford study, the PTWA coated bore can help to reduce friction by 6.8% with cylinder head compared with the aluminum engine block with cast iron liners. The friction reduction would increase to 14.1% without the cylinder head installed. The weight and friction reduction can help to increase the fuel economy by 5% [10]. Except Ford, BMW and Nissan also use the PTWA coating for their productions. A typical PTWA process and coating cross section pattern are shown in Figure 2-5.

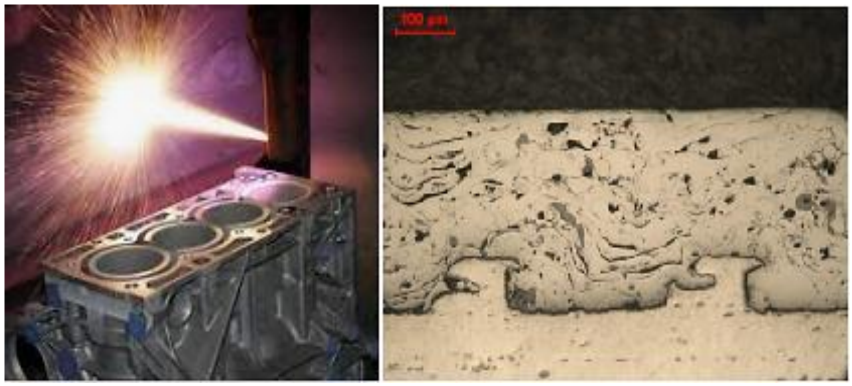

Figure 2-5. PTWA coating spray and coating cross section view [9]

Diamond-Like Coating (DLC) is a hard film made of carbon that has diamond-like properties. It has super wear resistance and low COF. Reciprocating rig and fired engine tests were carried out under lubricated condition at constant oil temperature of 120 ℃. The test result showed that DLC coating could reduce friction by 19%, and the fired engine test showed that the DLC coating could help to reduce the fuel consumption by 2.5% [11].

Nissan developed mirror bore coating for its PR25DD engine to reduce friction and weight. The mirror coating thickness is 0.2 mm which is 1/100 of the thickness of the cast iron liner. The mirror coating can help to reduce weight by 1.5 Kg. The mirror bore coating improves the oil retention ability of the bore surface and helps to reduce the friction by 5% compared with the cast iron liners [12]. Figure 2-6 shows a cross section view of the cylinder bore with cast iron and mirror coating. Figure 2-7 shows a comparison of friction between cast iron and mirror bore coating.

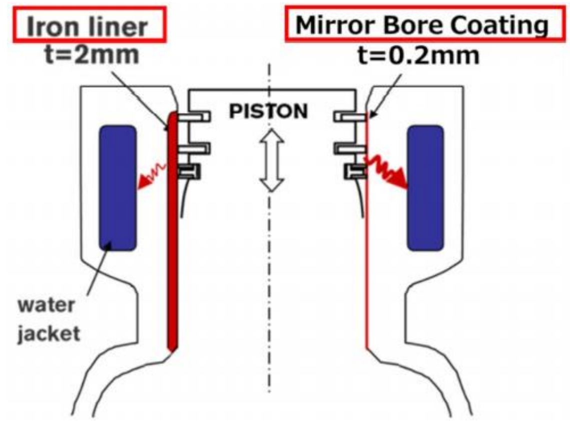

Figure 2-6. Cross section view of the bore with cast iron and mirror coating [12]

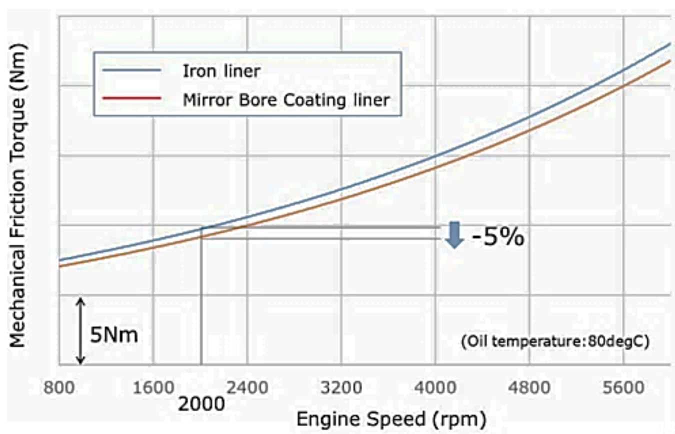

Figure 2-7. Comparison of friction between cast iron and mirror coating [12]

In conclusion, reducing engine friction can help to enhance engine performance. There are many ways to reduce engine mechanical frictions including oil additives, piston ring coating, cylinder bore coating, honing pattern and so on. In this work, EJPO coating will be used as alternative bore material to replace cast iron liner. The low COF of the EJPO coating should help to reduce friction and enhance engine performance.

2.2 Weight effects on engine performance and fuel economy

Vehicle weight affects the vehicle rolling resistance, and rolling resistance affects the engine fuel economy or affects the engine output efficiency. The lighter vehicle weight will help to reduce the vehicle rolling resistance waste and enhance engine output efficiency. Every 100 pounds taken out from the vehicle and the fuel economy is increased by 1-2 percent [13]. In this work, the EJPO coating will be used to enhance engine performance to making more output power to increase fuel economy and rolling distance or MPG.

2.2.1 Hypereutectic Al-Si linerless engine block

Commercial grade hypereutectic Al-Si alloys range from 12% to 20% or more in silicon concentration [14]. The high concentration of silicon can give hypereutectic Al-Si alloy high hardness to be used as engine block material. However, the silicon particles in the aluminum must be distributed uniformly on the cylinder bore surface, otherwise failure may happen on the part where no silicon particles are distributed. The work principle of the hypereutectic Al-Si linerless engine block is the piston ring rides on a combination of lubricant and the primary silicon particles in the aluminum, so the chemical etching is needed on the cylinder bore surface to explode the silicon particles [15]. A typical work principle of hypereutectic Al-Si cylinder bore is shown in Figure 2-8.

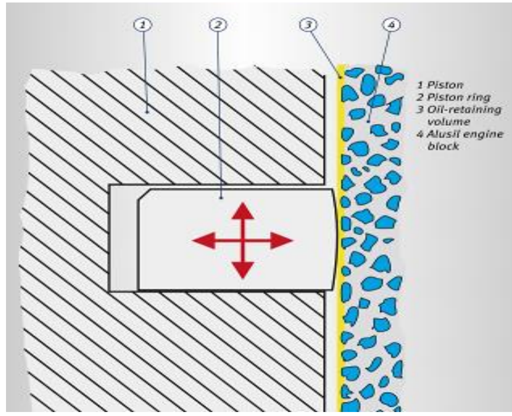

Figure 2-8. Work principle of hypereutectic Al-Si cylinder bore [14]

Mercedes, Audi, Porsche, BMW, VW and Mercury Marine all use hypereutectic Al-Si alloy to make engine blocks. The hypereutectic Al-Si alloy engine block or liners can help to reduce weight significantly. The thermal conductivity of the hypereutectic Al-Si alloy is 400% higher than cast iron, it can help to transfer the heat evenly and easily [16]. Besides, it also helps to reduce the cooling load therefore to reduce the weight of the engine cooling system. Uniformly transferring the heat from the combustion process enables the manufacturers to design for higher operating temperatures which increases engine power and reduces emissions. Engine fuel economy can be increased by 6-8% [17]. However, this technology didn’t stay on market for long because of the high tooling cost and the difficulty of casting the silicon uniformly on the cylinder bore surface.

2.2.2 Metal matrix composite (MMC) liner or block

Metal matrix composites (MMC) consisting of either continuous or discontinuous fibers in a metal result in a material with combinations of very high specific strength and modulus. The reinforcement fibers can be a multitude of different materials, the most common being silicon carbide, a ceramic. Aluminum MMC is much stronger at elevated temperatures, so it can be used as engine block material [18]. Aluminum MMCs are light-weight materials compared with cast iron. Replacing cast iron liners with aluminum MMC can also reduce huge weight [19].

Toyota used their all-aluminum cylinder block with an MMC cylinder bore for the seventh generation Celica sports car sold in the US starting in 2000. Figure 2-9 shows the 2ZZ-GE's engine block with the MMC liners for cylinder bore surface [20].

Figure 2-9. 2ZZ-GE's engine block with MMC liners [20]

Toyota found that an MMC lined cylinder block would allow them to decrease the distance between cylinder bore diameters to 5.5 mm for the 2ZZ-GE to increase the piston bore diameter and decrease the piston stroke. The MMC bore material has a higher young's modulus, higher tensile strength at elevated temperature. The Toyota 1.8 L 2ZZ-GE engine with MMC liners was able to make 26.17% more horsepower and 4.65% more torque than the 1ZZ-FE engine that uses cast iron liners [20]. The total engine reduces weight around 20% and the reduction of the weight results in a reduction of fuel consumption around 5% to 7%. [21]. If the MMC reinforcement particles are not evenly distributed throughout the cylinder bore surface, the piston rings can wear away the softer aluminum matrix material and the engine will lose compression. This is the main reason to prevent the MMC from wholly replacing cast iron liners.

In conclusion, vehicle weight affects the vehicle rolling resistance and fuel economy significantly or in other words the weight affects engine's output efficiency significantly. All the engineers are working hard to remove the weight even by 1 pound. Replace cast iron liners with a 20 um thick EJPO coating can reduce the engine weight significantly.

2.3 Temperature swing effects on engine performance

Temperature swing coatings have recently been of great interest to automotive researchers for their potential to insulate internal combustion engines, reduce cooling requirements, and increase efficiency. Ceramic coated engines studied in the 1980s caused constantly high temperature on combustion wall surface during the whole combustion cycle including the intake stroke. This resulted in an increase in NOx, Soot, and occurrence of engine knocks, and decrease in volumetric efficiency and combustion efficiency [22]. On the other hand, thermal swing coating on the combustion chamber walls leads to a large fluctuation in surface temperature. In this case, the surface temperature with this insulation coating follows the transient gas temperature, which helps to decrease the heat loss with the prevention of heating the intake air temperature and reduce the NOx and Soot [23].

The cylinder wall temperature swing is caused by the lower heat conductivity and lower heat capacity of the coating. This temperature swing is desired in gasoline engines to reduce the heat transfer from cylinder wall to the combustion gas and can eliminate engine knocks. Usually, porous coating has the temperature swing function [22]. A comparison of cylinder wall temperature with material of traditional metal, thick heat insulation ceramic, and proposed thermal swing coating was shown in Figure 2-10.

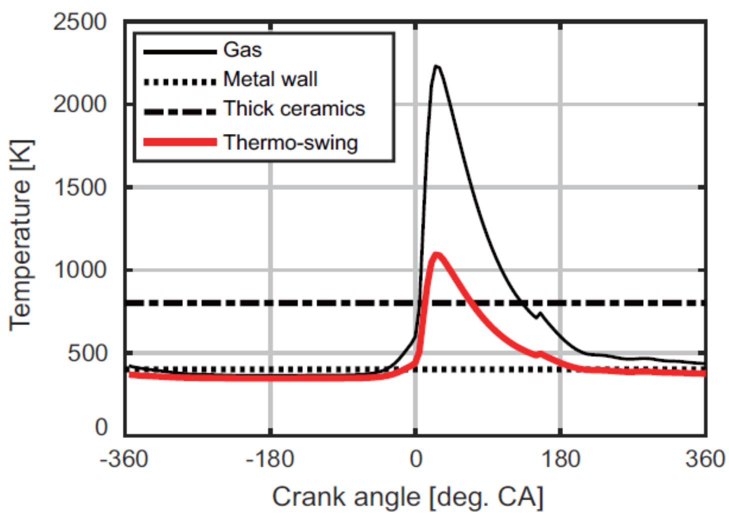

Figure 2-10. Transient gas and piston/cylinder wall temperature in dependence of different coating material in entire engine cycle [22]

Usually, cast iron or aluminum alloy are used as engine cylinder wall material and their thermal conductivity is in the range of 55 to 150 W/mK and the volumetric heat capacities in the range of 2400 to 3400 J/m^{3}K [24]. The surface temperature of the metal cylinder wall is kept constant at a lower level during the entire combustion cycle as shown in Figure 2-10. The temperature difference between the metal cylinder wall and the working as is relatively large, which will cause a higher heat loss as shown in Figure 2-11. This kind of heat loss will reduce the engine thermal efficiency [24].

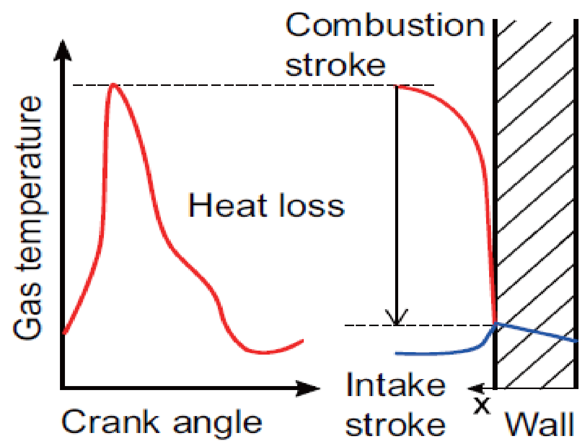

Figure 2-11. Schematic view of in-cylinder transient gas temperature profile and metal wall temperature profile [22]

For the traditional thick thermal insulation coated engine, the combustion heat will be kept in the combustion chamber and the cylinder wall temperature will keep at a higher level during the entire engine combustion cycle as shown in Figure 2-10. The high combustion chamber temperature will reduce the volumetric efficiency [21], and the occurrence of engine knocks will also be increased [22]. The reduced volumetric efficiency will reduce engine power output [23] and the engine knocks will increase the possibility of the engine components failure [24]. The temperature difference between the heat insulation ceramic wall and the working gas is shown in Figure 2-12. As shown in the figure, the temperature difference and heat loss are small, but the high combustion temperature can reduce volumetric efficiency and introduce engine knocks.

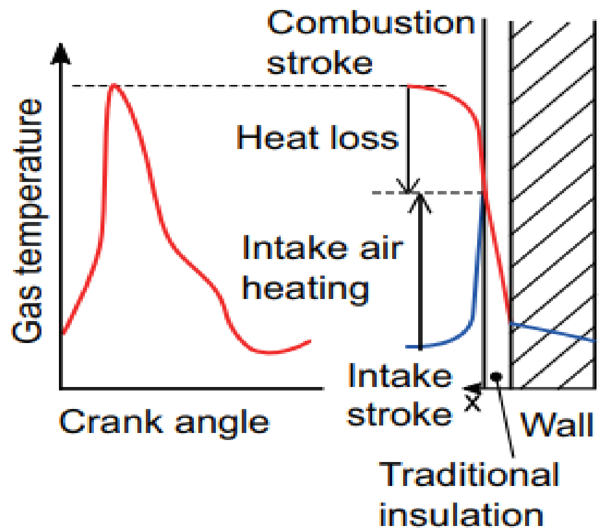

Figure 2-12. Schematic view of in-cylinder transient gas temperature profile and heat insulation wall temperature profile [22]

However, for the new temperature swing coated cylinder wall, the temperature of the cylinder wall changes following with the transient gas phase temperature as shown in Figure 2-10. The temperature difference between thermal swing wall and the transient gas is dynamic and relatively small. The temperature difference between thermal swing wall and transient gas are shown in Figure 2-13. As shown in the figure, the thermal swing coating has a lower surface temperature during the intake stroke and a higher temperature during the combustion stroke, and the temperature difference is relatively small at combustion stroke. This thermal swing property can help to reduce the heat loss without heating up the intake air temperature [25]. This dynamic temperature change can help to increase engine thermal efficiency without engine knocks.

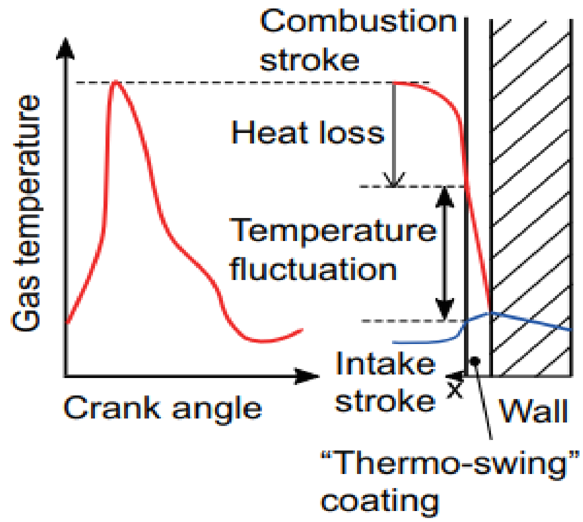

Figure 2-13. Schematic view of in-cylinder transient gas temperature profile and thermal swing wall temperature profile [22]

EJPO coating is a kind of porous ceramic coating. A three-dimensional transient finite element analysis (FEA) thermal model was developed and proved EJPO coating has thermal swing properties by Dr. Nie's group in the University of Windsor. It was found that EJPO coating has temperature swing properties and both coating thickness and thermal conductivity could significantly affect the bore surface temperature and temperature fluctuation behaviors at the different crank angles. A possible selection of the parameter combination of coating thickness and thermal conductivity would provide a high-quality thermal swing coating for the cylinder bores to improve internal combustion (IC) engine efficiency [24]. Figure 2-14 shows the temperature variations of the cylinders made of different materials including grey cast iron, CGI, A356, A390, A356 with a cast iron liner, A356 with a PTWA-coated cylinder bore (coating thickness of 150 µm), and A356 with a EJPO-coated cylinder bore (coating thickness of 20 µm). Figure 2-15 shows temperature variation involving two thermal conductivities and two coating thicknesses (20 and 60 μm) [24].

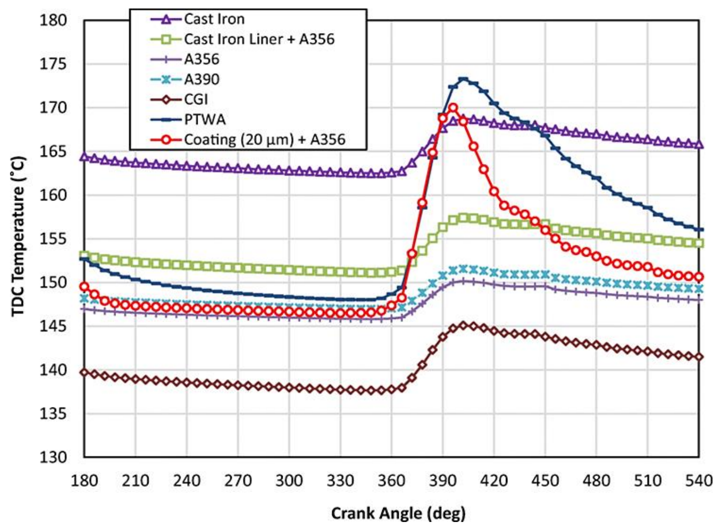

Figure 2-14. Temperature variations of the cylinders made of different materials including grey cast iron, CGI, A356, A390, A356 with a cast iron liner, A356 with a PTWA coating (150 μm), and A356 with a EJPO coating (20 μm) [24]

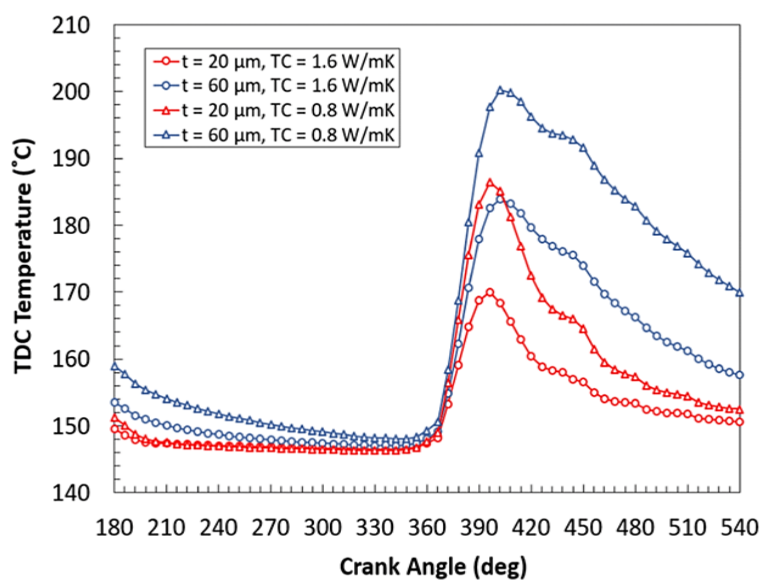

Figure 2-15. Temperature variation involving two thermal conductivities and two coating thicknesses (20 and 60 μm) [24]

As Figure 2-14 shows, the EJPO coating has better temperature swing property than other materials at crank angle 400 degrees and the temperatures of top dead center (TDC) are lower at other crank angles which is better to pull the spark timing forward to make more power and avoid the engine knocks. Figure 2-15 shows that a thicker EJPO coating with a lower thermal conductivity has a better thermal swing property. However, the residual heat in chamber is also higher. The higher residual heat in the combustion chamber will heat up the intake air temperature and increase the occurrence of engine knocks [24]. In this work, the EJPO coating thickness is around 20 ums to 30 ums. This coating thickness allows EJPO coating to have the temperature swing function and also has less residual heat in combustion chamber. It will help to reduce heat loss without heating up the intake air temperature and reduce the chance of engine knocking. Besides, the thinner coating will also help to reduce the fabrication cost.

Keronite performed single cylinder engine tests with temperature swing coated pistons, comparing their performance with uncoated and anodized pistons. The test results showed that the temperature swing properties of PEO coating provided at least a 3-5% fuel consumption reduction under part load conditions [25].

In conclusion, temperature swing property is desired in internal combustion engines especially gasoline engines. The porous thermal swing coating on the cylinder wall can reduce the heat flux from the wall to the working gas during intake stroke and can reduce engine knocks. EJPO coating is a porous low thermal conductivity PEO coating, and it was proved to have the temperature swing property in simulation and Keronite engine test. Thus, applying the EJPO coating on the engine cylinder wall could help to enhance the engine performance by its temperature swing function.

2.4 Current engine block design and limitation

In the past, the automakers replaced the cast iron engine block with the aluminum engine block for weight reduction. Replacing cast iron with aluminum can help to reduce the engine weight by 45% for gasoline engines [26]. However, the aluminum is soft and doesn't have good tribological properties for the engine cylinder wall. The aluminum surface needs to be replaced or modified to meet the surface engineering and combustion requirements. Historically, the solution was to sleeve or cast in the cast iron liners to meet the required surface characteristics. The cast iron liners meet the cylinder bore requirements, and have the characteristics with low-cost, durable and easy to manufacture. This solution was good for mass production for a long time until the government required the automakers to increase the vehicle MPG and reduce emissions [27]. New solution or new materials are needed to increase the engine performance or fuel economy.

Cast iron liners also have their own inherent disadvantages in weight, size, thermal conductivity, differential thermal expansion and recyclability [28]. The different thermal expansion coefficients of gray cast iron and aluminum can cause deformation of the liner and increase oil and fuel consumption. The different thermal conductivity between cast iron and aluminum also needs a larger cooling system to cool down the engine, which will increase the weight of the vehicle [29].

New materials with light weight, good tribological properties and better thermal management are desired to replace the cast iron liners.

2.5 Engine cylinder block requirements

Internal combustion engine cylinder blocks must satisfy several functional requirements including surface profile and finish, high corrosion and wear resistance, etc. During the combustion process, the engine produces high pressure, heat and shearing load. The cylinder block bore surface material must have high wear resistance and be capable of withstanding high pressures on the order of 100 to 200 bar [30]. The porosity level of the running surface material must be below 1% and the maximum pore size must be below 500 microns [31]. The cylinder bore materials also must have corrosion resistance because of the sulfur contents in the fuel. This sulfur contents will promote the wear or scuffing on cylinder bore surface if the bore material is not corrosion resistant [32]. Another important requirement for cylinder bore material is the coefficient of friction. Friction between the cylinder bore surface and the piston rings has a major impact on the efficiency of an engine’s powertrain. Friction loss accounts for over 40% of the total vehicle power loss and more than half of that power loss can be attributed to the frictional loss between piston rings and cylinder bores [33]. Thus, a lower coefficient of friction is also required for the cylinder bore material.

The engineering materials used to manufacture the cylinder bore product must have high strength, modulus of elasticity, wear resistance, scuffing resistance, corrosion resistance and low COF.

2.6 PTWA coating process and properties

PTWA coating is a kind of thermal spray coating. Thermal spray coating deposition technology is a way to offer an effective thick or thin coating upon the surface to change the properties of the surface [34]. Thermal spray process sprays a stream of particles, metallic or nonmetallic on the prepared substrate and the particles are flattened to form splats. With several layers of these splats the coating formed on the substrate [35]. The main use of thermal spray coating technologies is offering a protective surface with properties of wear resistance, corrosion resistance, thermal insulation and electrically conductive [36]. A typical thermal spray process is shown in Figure 2-16.

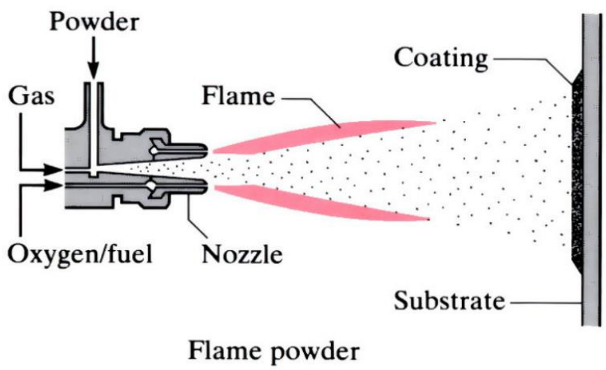

Figure 2-16. Thermal spray process [36]

Plasma transferred wire arc (PTWA) coating process for engine cylinder bore was developed to increase fuel efficiency, reduce overall vehicle weight as well as improve engine efficiency by reducing internal friction losses by Flame-Spray Industries and Ford Motor Company [37]. It is a wire based rotating spray process with combination of plasma spray process and twin wire arc spray process. A constant current power supply with an arc voltage of 100–120 V and a current of 60–100 A is used to generate plasma from the cathode to the wire [38]. This power melts the tip of the wire and then the high-pressure plasma gas together with the atomizing gas strips the molten wire tip to particles. Thereby a bunch of finely atomized particles is created, which are accelerated towards the substrate at high speed by gases which are usually Ar, H_2, He, or N_2 [39].

A typical PTWA spray head schematic drawing and a PTWA spray process on engine block is shown in Figure 2-17. Due to the high speed of the spray particles of 100–130 m/s, a very dense coating with the porosity of less than 2% can be fabricated by the PTWA system [40].

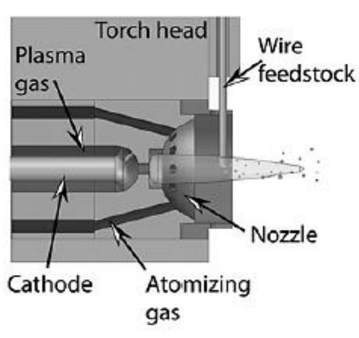

Figure 2-17. PTWA spay head and PTWA spray process on engine block [40]

Due to the high speed of the spray particles, very dense coatings can be fabricated with the PTWA system. Coatings applied onto the wall of cylinder bore should have bond strength value of more than 30 MPa which is the minimum required value [41]. Thus, a pre-treatment of the cylinder bore surface is needed to increase the coating bonding force. A surface roughing process is developed to machine slots on cylinder bore substrate and these slots can enhance the mechanical interlocking of substrate and coating [42] – [43]. A typical cross-section view of the PTWA coating is shown in Figure 2-18.

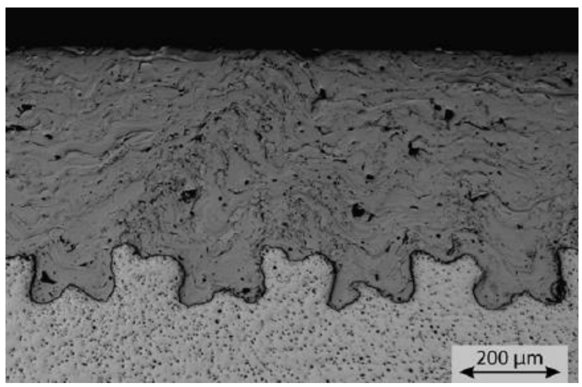

Figure 2-18. Cross section view of PTWA coating [42]

The PTWA coating process for engine cylinder bore has four steps including machining the cylinder bore to a certain diameter, roughing the cylinder bore surface to increase the bonding force between coating and substrate, spraying the coating on the pre-treated cylinder bore surface, and finally hone the coating surface to meet the tribological requirements. The honed PTWA coating has the properties of light weight, high hardness, wear resistance, corrosion resistance and good tribological properties because of the controllable porosity.

Ford Motor Company's study showed Ford engine with PTWA coated liners had better performance and the friction tests were also carried out with a stripped-down engine. The friction tests showed that the friction of the engine with cylinder head was 6.8% below the values measured from the standard engine with liners made from grey cast iron. Without the cylinder head, the friction was 14.1% lower compared to the standard engine [44].

Ford Motor Company has applied PTWA coating technology on its 5.0 L production engine. This PTWA coated 5.0 L engine can help to reduce weight by 8.5 pounds, reduce friction by 6.8% and increase fuel economy by 5% [45]. PTWA coating is a successful replacement material for cast iron liners.

2.7 EJPO process introduction and coating properties

EJPO coating process is a plasma-enhanced anodizing process for deposition of ceramic coatings on metal surface in aqueous solutions or electrolytes. Figure 2-16 shows a layout of the typical EJPO coating equipment, which includes DC power supply, electrolyte, cathode, anode and cooling or blending system [46]. The EJPO coated part will work as anode, a plate of graphite or the stainless-steel will work as cathode. Both cathode and anode need to be immersed in the electrolyte and the power supply needs to be a pulsed DC power to provide the energy for the EJPO process [47].

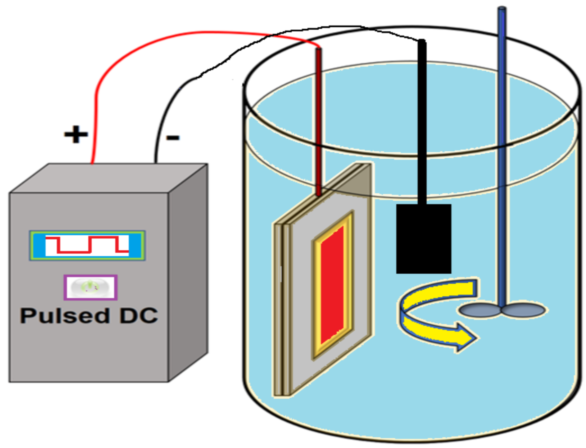

Figure 2-19. Schematic illustration of the EJPO equipment layout [46]

The EJPO process is quite similar to the classic anodization, but a much higher voltage (~250-750 V) is applied. Therefore, the dielectric breakdown occurs, and numerous micro plasma discharges are formed on the anode surface [47]. During the classic anodization process, a thin oxide layer on the metal can be formed by continuous transportation of ions through the electrolyte. However, in the EJPO process, the metal and oxygen atoms or ions are generated simultaneously by the hot plasma and then combined to form the dense oxide [48]-[51]. This mechanism promotes the ceramic coatings to grow with higher thickness and hardness. The physical-chemical reactions in the EJPO process are strongly enhanced by the plasma discharge events. Therefore, the physical-chemical reactions at the anode surface are complicated and accompanied with extensive gas liberation, acoustic emission and optical emission [52]. To meet the requirements of various engineering applications, a lot of research focus on characterization and optimization of the EJPO coating properties including tribological properties [53]-[58], corrosion resistance [59]-[64], photocatalytic efficiency [65]-[71], bioactivity [72]-[79] and thermal properties [80]-[85]. EJPO coating has been applied in industry more and more, especially in space and automotive industries.

The surface morphology and microstructure of the EJPO coating can be affected by many parameters including composition of electrolyte, current mode, substrate materials, processing time and so on. Electrolytes contain silicates and phosphates, which promote strong metal passivation, and are most widely used for the EJPO process. These constituents decrease the breakdown voltage and increase the coating growth rate by integrating SiO_3^{2-} into the coatings [86]-[89]. Coatings with mullite phase have been deposited on the aluminum alloys by EJPO treatment with electrolyte containing sodium silicate and can be useful for thermal management application since they have very low thermal conductivities [90]-[92].

EJPO coatings have been reported to possess high hardness, good corrosion and wear resistance, excellent adhesion to the substrate, high thermal shock resistance and low thermal conductivity. EJPO coating has high hardness since the coating contains mainly α-Al^2O^3 and γ-Al^2O^3. The hardness range of EJPO coatings has been reported as 900-2000 HV [93]-[97]. The wear resistance of the EJPO coating is also high because of the high coating hardness. The high wear resistance property allows the EJPO coating to be applied on moving joint of surface to reduce wear. EJPO coating also has high corrosion resistance because of the inner dense layer of the coating, and this property usually be used to protect the surface of the magnesium or aluminum [98]-[100]. The EJPO coating has much lower thermal conductivity compared with metal, and the thermal conductivity can be as low as 0.8 W/(m•K) on magnesium [101]-[102]. This low thermal conductivity can be used as thermal insulation to change the system thermal management.

EJPO coating is a new desired material for engine cylinder walls that has high hardness, high corrosion resistance, low COF, light weight and temperature swing properties. All these coating properties can help to enhance engine performance for fuel economy and emission reduction. In this work, EJPO coating will be applied on engine cylinder wall and other components for engine performance and durability enhancement.

2.8 Proposed methodology

The properties of EJPO coating on aluminum will be investigated including hardness, corrosion resistance, coefficient of friction and thermal insulation.

Flex brush honing and diamond stone honing process will be studied on the EJPO coated aluminum engine blocks.

2.0 L and 5.0 L engine blocks and other components including piston, camshaft bore, and cylinder head dome will be EJPO coated, and tested to evaluate the engine performance and durability.

Piston temperature test will be carried out to investigate coating's thermal insulation property at the combustion condition.

Vehicle durability test will be carried out on EJPO coated 5.0 L engines to investigate the coating's durability.

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3. Chapter 3 EJPO coating properties investigation

3.1 EJPO coating hardness investigation

EJPO coating is also a kind of ceramic coating or oxide coating, and it is an oxide converted from its substrate material same as PEO process. In this work, the EJPO process applied on aluminum and the coating is mainly aluminum oxide. In the EJPO coating, it contains crystalline phase corundum (α-Al_2O_3), so the hardness is high. As a result, mechanical properties of the coating such as wear resistance and toughness are enhanced. Figure 3-1 shows a typical SEM- EDX analysis from an EIPO coating that contains α-Al_2O_3.

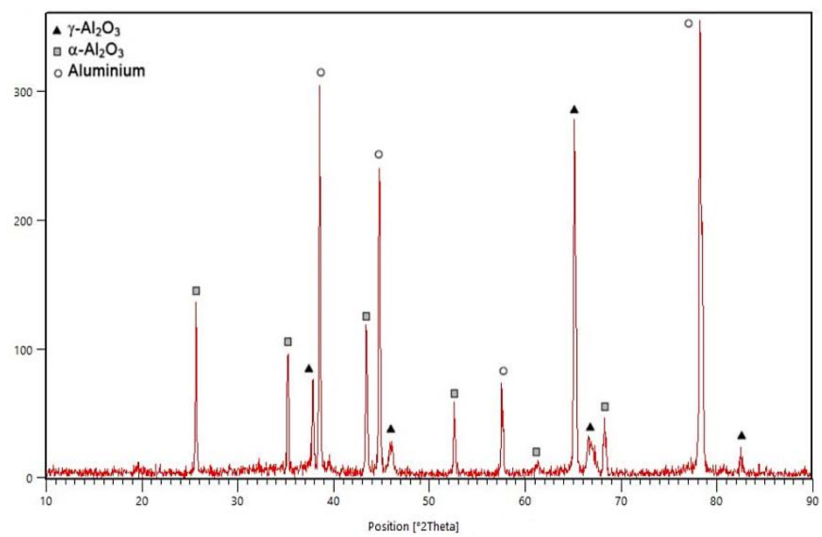


Figure 3-1. SEM-EDX analysis on EJPO coating [1]

A small EJPO coated aluminum sample (A390) was polished to roughness around 0.3 um and the coating thickness was around 15 ums. This coating roughness is similar to the cast iron liner roughness. A Vickers hardness tester was used to test the hardness of the coated sample. The load was set up as 10 grams, and the hardness was compared with the aluminum without coating. The hardness test results showed the hardness of the EJPO coated sample was 439HV10, and the hardness of the uncoated sample was 70HV10. The surface hardness was improved significantly by applying the EJPO coating. This hardness test was carried out on the 20 um coating surface, so the harness was relatively lower. If the coating was thick enough, or tested on the cross section coating surface, the hardness would be higher than 1000HV10. Figure 3-2 shows the Vickers hardness tester and the micro dent on the coating.

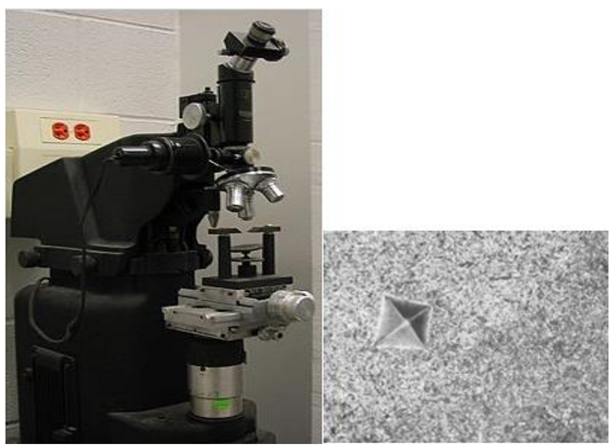


Figure 3-2. Vickers hardness and micro dent

The Rockwell hardness test was also carried out on the EJPO coated sample, the coating thickness was 15 um, and the roughness was 0.3 um. The Rockwell hardness of the coated sample was 59 compared with the reference brass hardness 55. The dent on the coated sample was investigated using SEM, the picture showed there was no crack and peel off on the dented coating, which meant the adhesion force of the coating was very strong. Figure 3-3 shows the Rockwell hardness tester and the SEM image of the dent on the coating.

Figure 3-3. Rockwell hardness tester and SEM image of dented coating

The Vickers and Rockwell hardness tests show the EJPO coating has high hardness and strong coating adhesion which means the EJPO coating has high wear and scuff resistance and has the potential to be used as a new material for combustion cylinder wall. High wear and scuff resistance are the basic combustion functional requirements.

3.2 EJPO coating corrosion resistance investigation

EJPO coating is also a high corrosion resistant coating which can help to protect the substrate material from corrosive environment. In this work, the corrosion resistance of EJPO coating was measured by the Potentio-dynamic polarization equipment. The electrolyte used in the corrosion test was 0.5 mol/L sulfur acid solution, since the combustion chamber has sulfur content. The corrosion resistance of EJPO coating was compared with cast iron. Figure 3-4 shows the Potentio-dynamic polarization equipment. Figure 3-5 shows the test results.

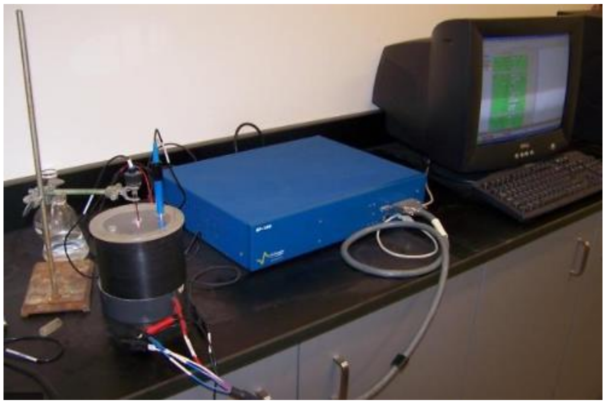


Figure 3-4. Potentio-dynamic polarization corrosion tester

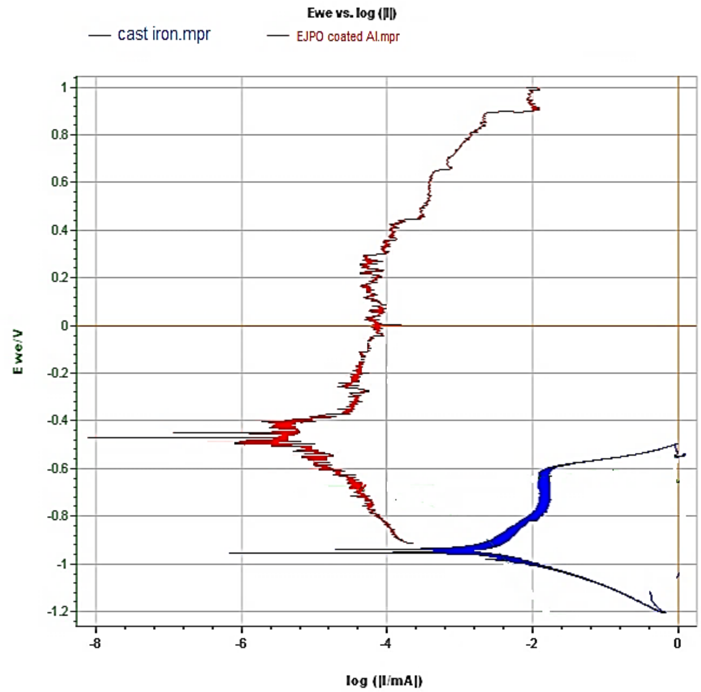


Figure 3-5. Potentio-dynamic polarization behavior of EJPO coating and Cast iron

The corrosion resistance can be calculated by the following formula:

$$R_p = \frac{\Delta E}{\Delta i_{app}} = \frac{\beta_a \beta_c}{2.3 i_{corr} (\beta_a + \beta_c)}$$

Where βa and βc are the Tafel slops of the anodic and cathodic reactions respectively. The calculated corrosion resistance of EJPO coating was 7.05 x 10^6 Ω, while the corrosion resistance of cast iron was 2.16 x 10^3 Ω. The corrosion resistance of EJPO coating is much higher than cast iron, so the EJPO coating is more corrosion resistant to sulfur acid solution. Figure 3-6 shows the cast iron and EJPO coated samples after corrosion test. As shown on the tested samples, cast iron had much more corrosion on the tested area.

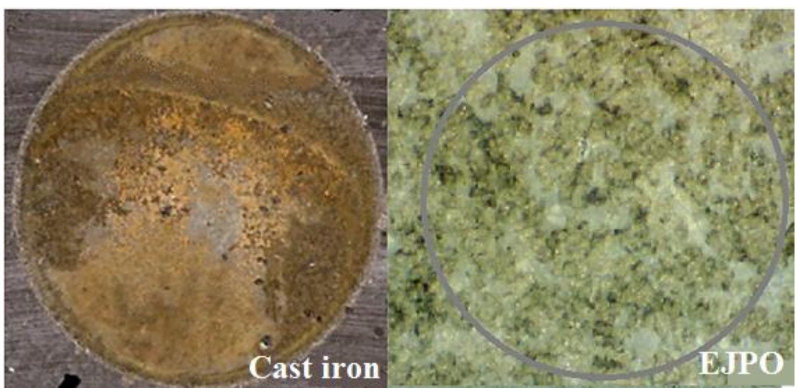


Figure 3-6. Cast iron and EJPO coated aluminum samples after corrosion test

The Potentio-dynamic polarization corrosion tests show that EJPO coating has higher corrosion resistance than cast iron. Combustion chamber has heat, humidity, sulfur contents which is very corrosive for metals. The high corrosion resistance property of EJPO coating will help to protect the cylinder wall from the corrosive combustion environment.

3.3 COF of EJPO coating

Coefficient of friction is a dimensionless scalar value which describes the ratio of the force of friction between two contacting materials. At the same load condition, the COF is the main factor to affect the friction.

In this work, a high speed tribometer was used to measure the COF. Ring shape EJPO coated sample, PWTA sample and a cast iron sample were used to do the tribological tests for COF comparison. The reason for comparing EJPO coating with cast iron and PTWA coating is that the performance of EJPO coated engine will be compared with aluminum engine with cast iron liners and PTWA coating.

The diameter of the ring sample was 110 mm and the test load was 10 N. The surface roughness of the tested samples was around 0.3 um and full synthetic 5W-30 oil was used as lubrication and AISI 52100 steel balls were used as counter face material. The tests were carried out at room temperature and the tribometer speed was increased from 0 m/s to 6 m/s steadily. Figure 3-7 shows the high speed tribometer. Figure 3-8 shows the EJPO coated, cast iron and PTWA coated samples.

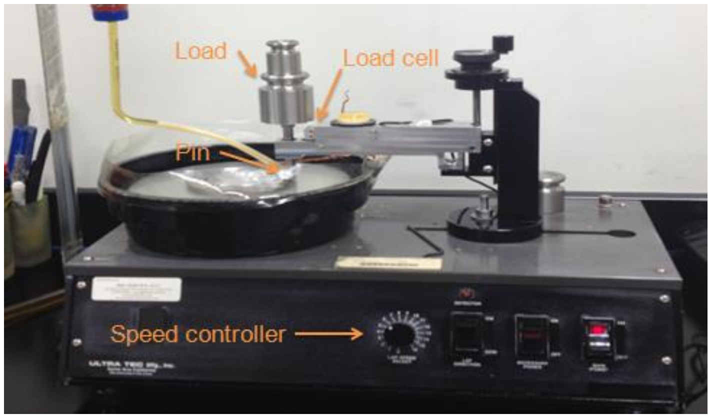


Figure 3-7. High speed pin-on-disc tribometer

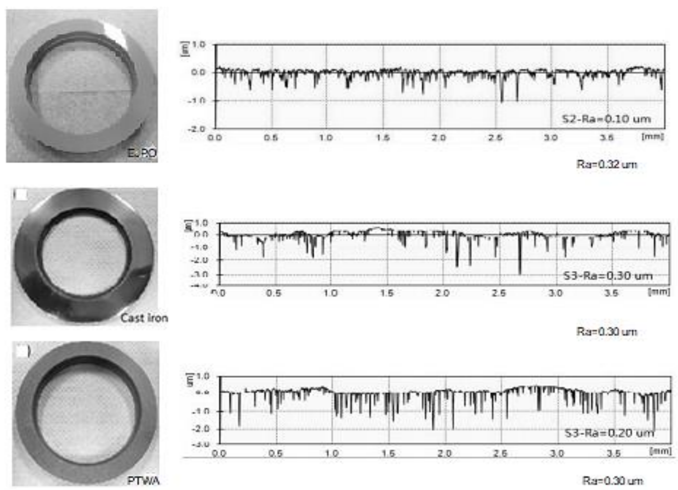


Figure 3-8. EJPO coated, Cast iron and PTWA coated samples

As shown in Figure 3-8, the surface roughness of the tested samples was measured, and the Mr2, Rvk also were measured to calculate the oil retention volume. The oil retention volume equation is shown below:

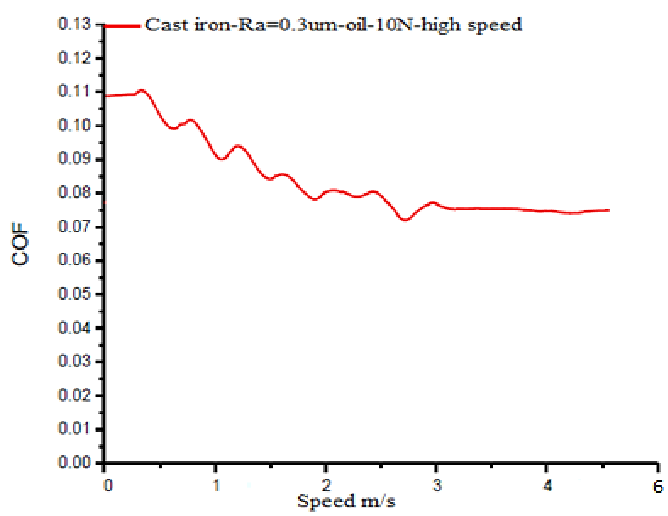
$$Vo = \frac{(100 - Mr2)}{200} \cdot Rvk$$

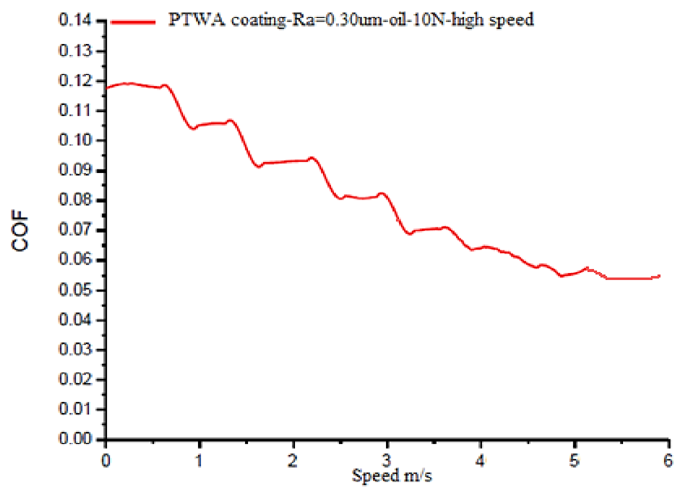
The measured parameters are shown in Table 3-1:

Table 3-1. Surface measurements of cast iron, PTWA, and EJPO

Sample	Ra(um)	Rpk(um)	Rvk(um)	Rk(um)	Mr1(%)	Mr2(%)	Oil volume
Cast iron	0.30	0.39	0.96	0.80	9	86	0.0672
PTWA	0.30	0.27	1.28	0.94	7	88	0.0768
EJPO	0.32	0.18	1.32	0.90	5	85	0.0990

As shown in Table 3-1, EJPO had higher oil retention volume than PTWA coated and cast iron samples. All three samples had similar roughness, but a higher Rvk value would increase the oil retention volume. The porous structure of the EJPO coating increased the Rvk value. A higher oil retention volume would help to reduce the COF at oil lubricated condition. The test results are shown in Figure 3-9.





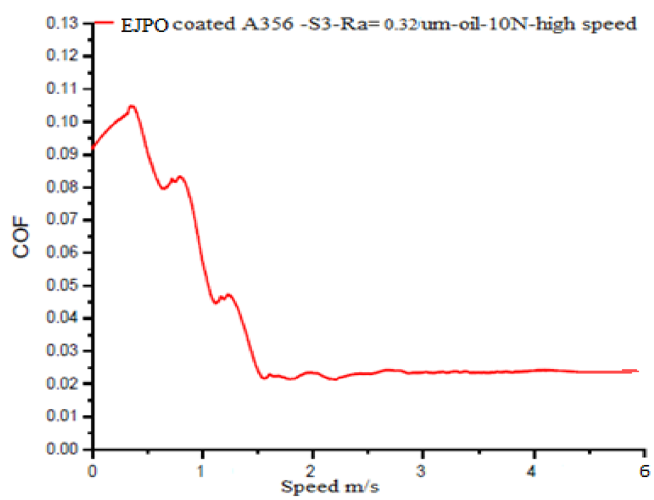


Figure 3-9. COF obtained from high speed tribotest on cast iron, PTWA and EJPO

The test results show that the Stribeck curve was formed when the speed increased. The EJPO coating had the highest COF drop rate at mixed lubrication and lowest COF at hydrodynamic lubrication. The hydrodynamic lubrication was formed at a much lower speed on the EJPO coating. The lowest COF of cast iron obtained in the test was 0.072, the lowest COF obtained on PTWA coating was 0.050, and the lowest COF obtained from EJPO coating was 0.025. At the same test condition, the COF of EJPO coating was 65% lower than cast iron and 50% lower than PTWA coating.

After the test, the surfaces of the tested samples were investigated using a microscope. The microscope images showed all the tested surfaces were intact and no scratches or wear on them, which meant the EJPO coating and PTWA coating were wear resistant as cast iron. Also, the wears on the counterface balls were measured and the wears were quite similar. The EJPO coating was wear resistant but didn't consume counter face material. Figure 3-10 shows the surface images of tested samples, and the measurements of the counter face balls.

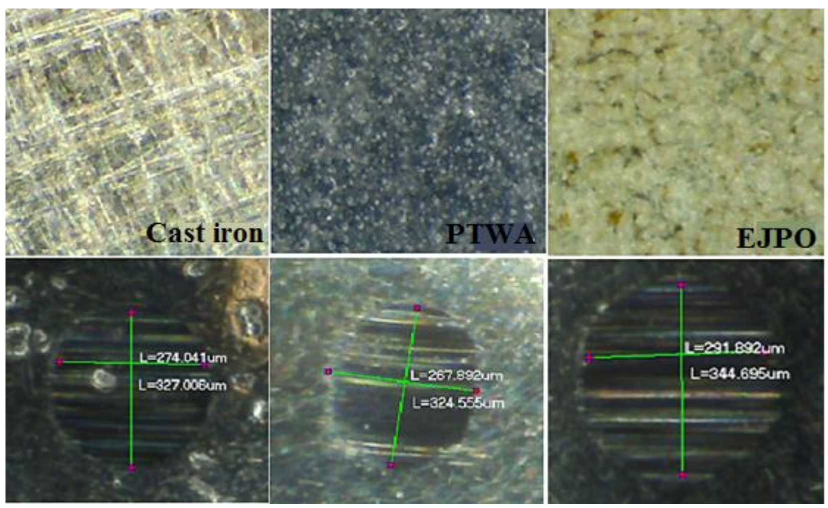


Figure 3-10. Microscope images of tested samples and counter face ball measurements

In conclusion, COF was affected not only by Ra but also Rvk. Surface with similar roughness and a higher Rvk would help to increase oil retention volume and reduce COF at lubrication conditions. EJPO coating had a much lower COF at same test condition because of the higher oil retention volume. SEM investigation showed EJPO coating had high wear resistance. The tribological test also showed EJPO coating had a much higher

COF drop rate when the sliding speed increases which meant the EJPO coating can have low friction at low speeds. Thus, the low COF of EJPO coating has the potential to help reduce the friction between piston ring and cylinder wall and enhance the engine performance.

3.4 EJPO coating thermal property investigation

EJPO coating is a low-heat-conductivity and low-heat-capacity coating which can protect the light metal from heat and has thermal swing property to change the engine cylinder wall temperature significantly. It is shown that the surface temperature with such an insulation coating follows the transient gas temperature, decreasing the heat loss while preventing the heating of intake air to enhance engine performance [2]. Prof. Nie and his group also found that EJPO coating has thermal swing properties and both coating thickness and thermal conductivity could significantly affect the bore surface temperature and temperature fluctuation behaviors at the different crank angles. A possible selection of coating thickness and thermal conductivity can improve internal combustion (IC) engine efficiency significantly [3]. The thermal insulation property of the EJPO coating can also help to enhance engine thermal efficiency.

In this work, the thermal insulation property of EJPO coating was measured using the experimental setup shown in Figure 3-11. The tested sample was surrounded by insulation material which was encased in an aluminum guard shell. This setup could help to reduce the radial heat from the surrounding environment. A heater was installed at the bottom and two standard grade K-type thermocouples were used to measure the temperature below and above the tested sample. It took around one hour to get the temperature steady and measured. The temperatures were compared between coated and uncoated samples and the results were shown in Figure 3-12.

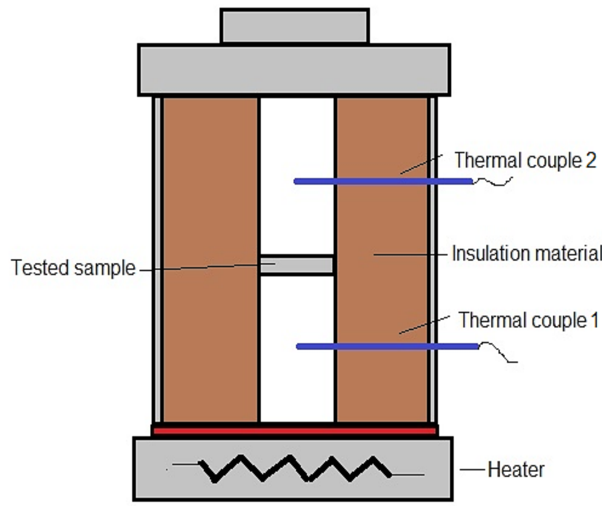


Figure 3-11. Experimental setup for thermal insulation investigation

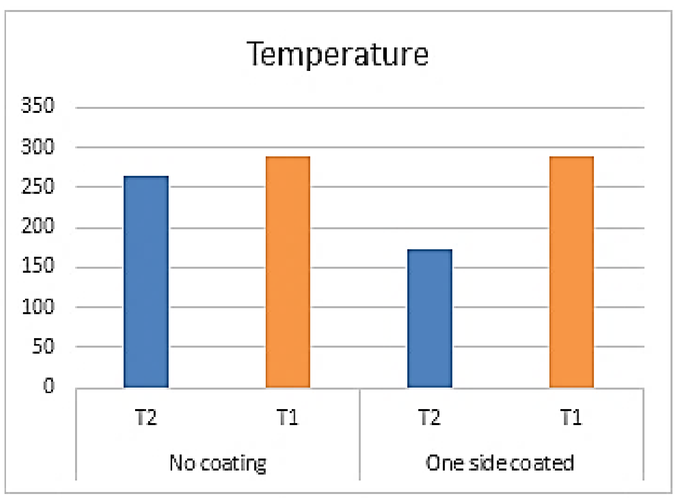


Figure 3-12. Temperature measurement below and above tested samples

As shown in Figure 3-12, the EJPO coating could reduce the temperature of T2 significantly, which proved that the EJPO coating could insulate heat efficiently.

An air-cooled thermal shock test was also carried out to test coating's adhesion after thermal expansion and contraction. An EJPO coated aluminum sample was heated up by a flame torch for 10 seconds, and cooled by dry air for 20 seconds, repeated 100 times and the tested sample was investigated by microscope to check if any interfacial spallation had occurred. The test setup is shown in Figure 4-13 and the microscope images of the coating after test is shown in Figure 3-14.

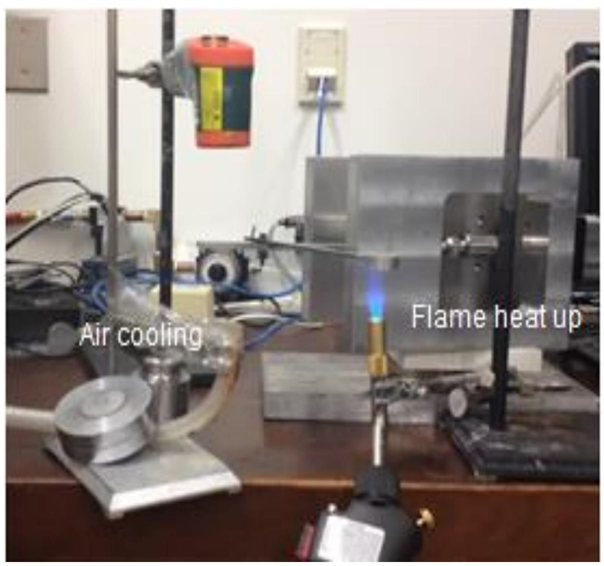


Figure 3-13. Air-cooled thermal shock test setup

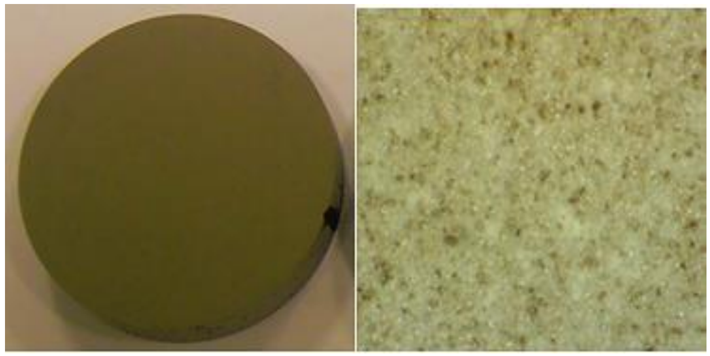


Figure 3-14. EJPO coating surface images after thermal shock test

As shown in Figure 3-14, the microscope images showed that the coating was intact and no cracks or interfacial spallation happened. The EJPO coating had strong adhesion and thermal stress to anti thermal expansion and contraction, and this thermal property promoted the EJPO coating to be applied on combustion engine cylinder wall.

In conclusion, the thermal insulation test and thermal shock test showed that the EJPO coating had good thermal insulation and strong thermal stress properties, and these properties could promote the EJPO coating's application in combustion environment.

3.5 Flex honing study on EJPO coated aluminum liner

An EJPO coated aluminum liner was used to study the flex honing process. Prof. Nie invented a spray head to coat the aluminum liner. The head sprayed the electrolyte on the inner surface of the liner and rotated to cover the entire surface. The plasma arc happened between the rotating spray head and aluminum liner and the coating was fabricated on the inner surface of the liner. After the EJPO process, the coating thickness and roughness were measured, and the data showed the EJPO spray process could generate a uniform coating on the liner surface. The original coating thickness was 30 um and the original coating roughness was around 1.9 um. An EJPO coated aluminum liner is shown in Figure 3-15.

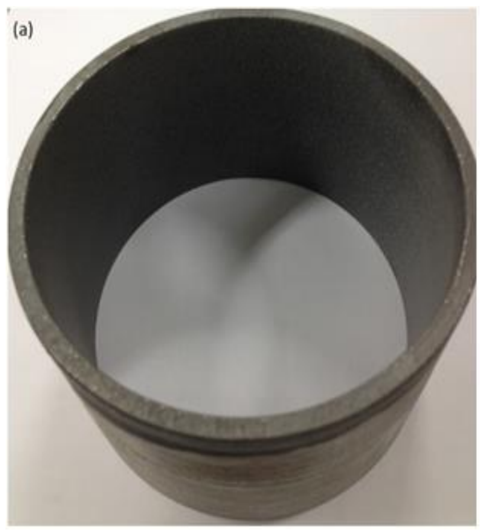


Figure 3-15. EJPO coated aluminum liner

Flex honing brushes were used to hone or polish the coating to get the desired roughness and thickness. The material of the beads on the honing bush was silicon carbide. Different grits of the brushes were used including 400 Grit, 600 Grit, 800 Grit and 1200 Grit and 5W-30 oil was used as honing lubricant. The rougher honing brush was used first to remove the rougher and loose top layer of the coating, and then fine honing brushes were used to modify the coating surface roughness. A dial bore gage was used to measure the liner bore size and a surface profile meter was used to measure the coating roughness every five honing stokes. Figure 3-16 shows the flex honing process and bore size measurement.

Figure 3-16. Flex brush honing and bore size measurement

The flex honing process and measurements are shown in Table 3-2, this honing study was trying to get the desired coating roughness and thickness with the required cylinder bore size. Figure 3-17 shows the roughness and thickness changes during the honing.

Table 3-2. Flex honing process and measurements

Grits		400	600	800	1200
Strokes	0	20	30	30	50
Roughness(um)	1.42	0.8	0.6	0.45	0.35
Thickness(um)	23	18	15	14	12
Bore size(cm)	87.454	87.464	87.47	87.472	87.478

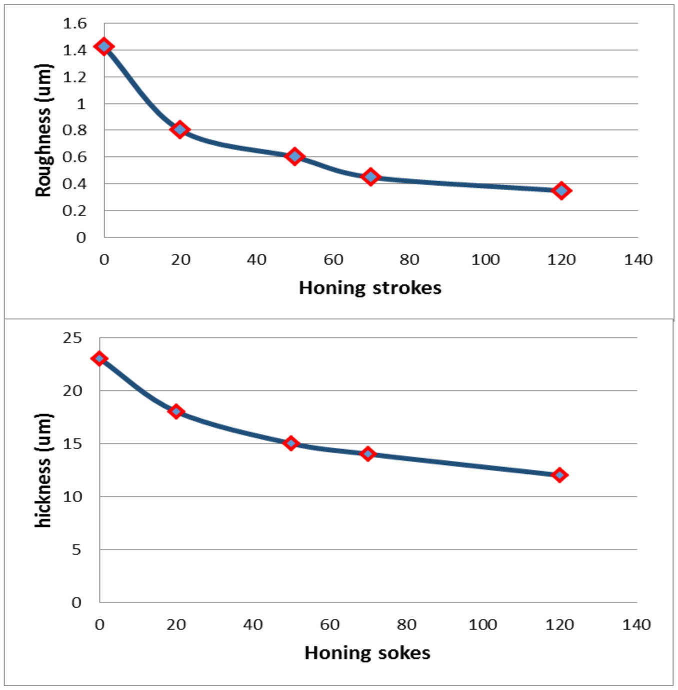


Figure 3-17. Roughness and thickness changes during honing

As shown in Figure 3-17, the coating had a high roughness with a higher thickness, when the coating was honed thinner, and the coating roughness decreased because of the less porosity on the inner dense layer. During the honing process, the honing strokes were recorded to remove 5 um of coating thickness using different grit honing. The honing brush grits and strokes are shown in Table 3-3.

Table 3-3. Honing brush grits and strokes during honing

Coating thickness removal	5 um	5 um	5 um	5 um	5 um
Grit	240	400	600	800	1200
Strokes	8	20	30	50	80

According to Table 3-3, the liner honing process can be applied on EJPO coated engine cylinder bore and the coated cylinder bore can be honed to required size with desired roughness and thickness.

In conclusion, the aluminum liner could be uniformly coated by the EJPO rotating spray head. Flex honing study showed the EJPO coated liner could be honed to desire roughness and thickness with required bore size. The EJPO coating process and the flex brush honing process for the aluminum liner can be applied on the EJPO coated engine cylinder bores.

4.6 Conclusions

The Vickers and Rockwell hardness tests showed the EJPO coating had high hardness and strong coating adhesion which promoted the EJPO coating to meet the engine cylinder bore surface hardness requirement. The Potentio-dynamic polarization corrosion tests with 0.5 mol/L sulfur acid solution showed that EJPO coating had higher corrosion resistance than cast iron and could be applied on cylinder bore to anti sulfuric corrosion. The high speed tribological test showed that EJPO coating had much lower COF than cast iron and PTWA coating, which could help to reduce the engine friction if the EJPO coatings were applied on cylinder bore surface. The thermal insulation test and thermal shock test showed that the EJPO coating had good thermal insulation and strong thermal stress properties which proved the EJPO coating could be applied in engine combustion chamber to improve the thermal management. EJPO coating fabrication and honing study on aluminum liner showed the EJPO coating could be fabricated on liner uniformly and could be honed to the target surface roughness with desired coating thickness, and these processes can be applied on the engine cylinder bore.

All the EJPO coating properties tested or studied showed that the EJPO coating had the potential to meet the combustion functional requirements and has the potential to enhance engine performance by reducing engine friction and enhancing engine thermal efficiency.

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2. Y. Wakisaka, M. Inayoshi, K. Fukui, H. Kosaka, Y. Hotta, A. Kawaguchi, N. Takada, Reduction of heat loss and improvement of thermal efficiency by application of "temperature swing" insulation to direct-injection diesel engines, SAE Int. J. Engines, 2016.

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4. Chapter 4 Effects of coating and honing process on wear of the engine cylinder bore

EJPO coating's porosity, hardness, surface topography and other properties can be affected by changing the current density, electrolyte, treatment time, and temperature during the coating process. A proper EJPO coating process or coating parameters are needed to fabricate an advanced coating for the aluminum cylinder bore.

The honing process is a critical step for a fired engine test, since the engine needs perfect geometry, size, straightness, roundness, surface finish to run, otherwise failure will happen. A proper honing process is needed to hone the engine cylinder bore to standard size with desired coating surface finish and thickness.

EJPO coating and honing process on aluminum liner were studied and these processes could be applied on aluminum engine cylinder bores. In this work, an aluminum linerless 2.0L engine block was EJPO coated, flex honed and tested to select a proper coating for the 2.0L engine aluminum cylinder bores.

4.1 Effects of coating process on the wear of the 2.0 L engine cylinder bores

4.1.1 EJPO coating process for a 2.0 L aluminum linerless engine block

EJPO coating process was studied and tested on the #1 linerless aluminum 2.0 L engine block. The EJPO coatings' properties can be changed for different applications during the coating process, in this work, a wear resistant EJPO coating with good tribological properties is desired for the aluminum cylinder bore. Two kinds of EJPO coatings were fabricated on the #1 2.0 L engine block and tested to select one functional coating for this project.

Flex brush honing was used to hone the coated cylinder bore to the specific diameter with tolerance for piston and cylinder bore's thermal expansion. Before the EJPO coating fabrication, the aluminum cylinder bores had to be honed bigger to leave space for the EJPO coating and the piston to bore clearance. After honing, the EJPO coated bore will be honed to standard size with desired coating thickness and piston to bore clearance. In this work, the desired coating thickness was 20 ums, and the desired piston to bore clearance was around 25 ums. The aluminum cylinder bores were honed 28 um bigger than the standard bore size to make room for coating growth. A flex brush honed 2.0L aluminum engine block is shown in Figure 4-1.

Figure 4-1. Flex brush honed linerless 2.0 L aluminum engine block

After the aluminum engine block was honed and cleaned, it was set up on the EJPO coating machine for the coating fabrication. During the EJPO coating process, the plasma discharges generated a large amount of heat, and the heat would affect the coating quality. To reduce the EJPO process temperature, an aluminum top plate was used to cover the engine block cylinder deck and process water was used to cool down the engine block by going through the engine coolant channels. Figure 4-2 shows the cooling system for the EJPO coating process.

Figure 4-2. Engine cooling system for EJPO coating process

The EJPO coating process took 20 minutes for each cylinder bore to get 35 ums coating thickness, because a lower current was used to reduce the process heat. The process water temperature was not cold enough to take away the heat efficiently, so a lower current density and a longer treatment time were needed. If the process water was cold enough, the treatment time could be reduced significantly. Each cylinder bore consumed 15 Kwh electricity power during the coating process, and the whole engine block consumed 60

Kwh electricity power. Based on local mid-peak power rate, the EJPO treatment cost for each cylinder bore would be 1.65 dollars, which was a competitive cost compared with the 2 dollars each cast iron liner. The EJPO coated 2.0L engine block could help to reduce the cost by 17.5%. The weight of EJPO coated engine block was measured and compared with the engine block with cast iron liners and the EJPO coated engine block could reduce weight by 3.96 pounds or 6.4%.

In this work, two kinds of EJPO coatings were fabricated on this 2.0 L engine block and tested to select one coating that worked better at the combustion conditions. Cylinders 1 and 2 were coated with coating S3, and cylinders 3 and 4 were coated with coating S12. The coating S3 and coating S12 were fabricated by using different electrolytes, thus coating S3 and coating S12 had different porosity, hardness and different elements in the coatings. These two coatings were tested and compared on the 2.0 L engine test. The EJPO coated 2.0 L aluminum engine block is shown in Figure 4-3.

Figure 4-3. EJPO coated 2.0 L aluminum engine block with two kinds of coatings

After all the cylinder bores were coated, the engine block was taken out from the coating machine and washed. The coating thickness and roughness were measured to make sure the coating thickness and uniformity were good.

The coating thickness measurement showed all the cylinder coatings had similar thickness close to 35 ums. The coating thickness checks are shown in Table 4-1.

Table 4-1. EJPO coating thickness check after 20 minutes' treatment

Cylinders	Cylinder 1	Cylinder 2	Cylinder 3	Cylinder 4
Thickness(um)	35	36	34	34

The cylinder bore diameters were measured before and after EJPO coating process, this measurement could be used to calculate how much coating grew inside and outside of the aluminum surface. The cylinder bore diameter measurements are shown in Table 4-2.

Table 4-2. Cylinder bore diameter measurements before and after coating process

Cylinders	Cylinder 1	Cylinder 2	Cylinder 3	Cylinder 4
Size before coating(mm)	87.574	87.582	87.581	87.578
Size after coating(mm)	87.526	87.532	87.530	87.526
Difference(um)	48	50	49	48
Coating grow inside(um)	11	11	9.5	10

As shown in Table 4-2, the EJPO coating grew almost 1/3 inside of the aluminum substrate.

4.1.2 Flex brush honing process for a EJPO coated 2.0 L engine block

The flex brush honing process was carried out after the measurements were completed. During the honing process, the coating thickness, bore size and roughness were measured frequently to make sure the EJPO coated bores were honed to standard size with desired thickness and roughness. Different grits of honing brushes were used to hone the coated bores, and the 0.5 um aluminum powder was used to do the final polish. The honing details are shown in Table 4-3.

Table 4-3. EJPO coating flex honing parameters

Brush grit	240	400	600	800	1200	0.5um Powder
Honing strokes	10	10	20	30	50	50

After the final powder polish the EJPO coating thickness was around 20 ums, the surface roughness was around 0.35 um for coating S12 and 0.7 um for coating S3, and the cylinder bore diameter was 87.560 mm. The flex honed cylinder bore, and the roughness are shown in Figure 4-4 and Figure 4-5.

Figure 4-4. Flex brush honed cylinder bore

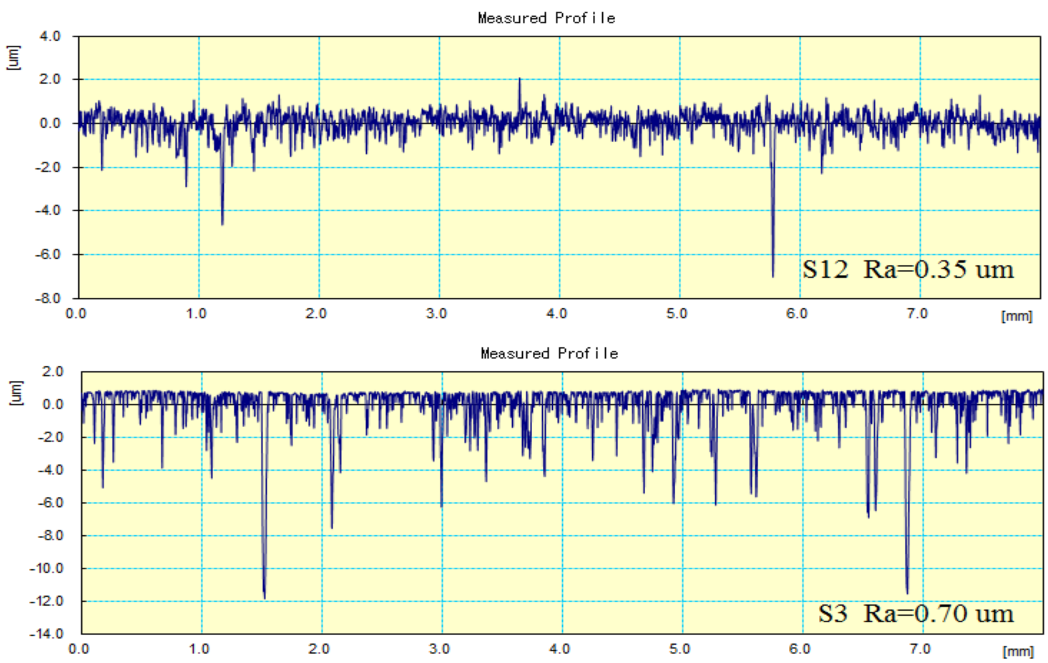


Figure 4-5. Flex brush honed cylinder bore roughness

As the surface profile shown in Figure 4-5, coating S3 had higher roughness because of the coating had more deep pores on the coating which were good for a higher oil retention volume. Coating S12 had smoother surface because of the less porosity of the coating.

The piston size was 87.535 mm, and the piston to bore clearance was 25 ums, which was in the range of the required clearance tolerance. The honed engine block was ready to be assembled as an engine.

4.1.3 EJPO coated 2.0L engine test and tear down analysis

This engine block was assembled as an engine and scheduled to run the engine Break-in test. In the Break-in test, the EJPO coated engine ran 2 hours' low load steps up to 3000 rpm, and ran 3000 rpm full load for 3 hours, and then ramp up to 5000 rpm with full load for another 3 hours. After the Break-in test completed, the engine was torn apart to check the coating conditions. The tested EJPO coated engine is shown in Figure 4-6.

Figure 4-6. EJPO coated engine after Break-in test

As shown in Figure 4-6, the coatings in cylinders 1 and 2 were intact, and the coatings in cylinders 3 and 4 were scuffed. This Break-in test proved that the coating S3 worked better in the combustion environment. The bore diameter, coating roughness and the coating thickness were measured after the test. Compared with measurements before the test, it showed that there was no obvious difference for the coating S3 in cylinder 1 and 2.

One piece of cylinder bore bridge was cut off from the tested engine block for further investigation including wear resistance, hardness and oil retention volume. A reciprocating tribological test was carried out to test the coating wear resistance, Vickers hardness test was carried out to check the coating hardness and a MITUTOYO profilometer was used to measure the surface profile and calculated the oil retention volume.

The Vickers hardness test showed the coating S3 had a higher hardness, which was 376HV10 compared with 290HV10 of coating S12. The oil retention volumes were also calculated and coating S3 had higher oil retention volume than coating S12. The surface roughness measurements were shown in Table 4-4.

Table 4-4. Surface roughness and oil retention volume of coating S3 and S12

Coating	Ra	Ry	Rz	Rq	Rpk	Rvk	Rk	Mr1	Mr2	Oil retention Volume
S3	0.34	4.97	4.97	0.55	0.19	1.24	1	6%	85%	0.093
S12	0.32	4.61	4.61	0.58	0.39	0.96	0.8	9%	86%	0.0686

The SEM pictures showed the coating S3 had higher porosity than coating S12. The surface morphology is shown in Figure 4-7.

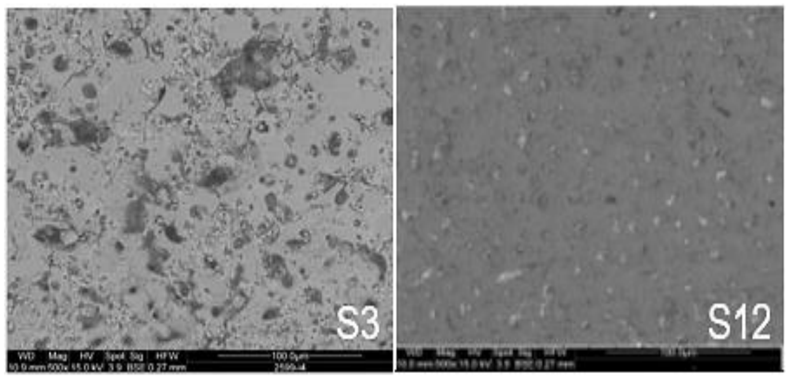


Figure 4-7. Surface morphology of coating S3 and S12

A reciprocating tribometer was used to carry out the coating wear resistance test. The tribological tests were carried out at a room temperature of 24 ^{o}C and a humidity of around 50-60%. SAE 5W-30 full synthetic motor oil was used to do the tribological tests. 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 test continued to run for ten thousand loops and the coatings were investigated and compared using microscope. The coating surface morphologies are shown in Figure 4-8.

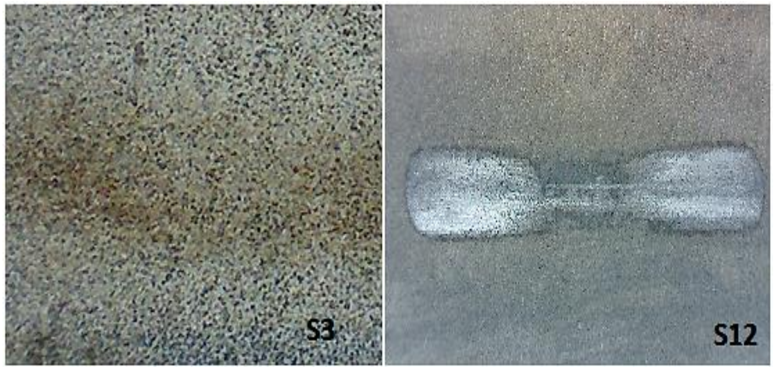


Figure 4-8. Coating surface morphologies after wear resistance test

As shown in Figure 4-8, there was no wear or scuff on coating S3, however, some wear showed up on the coating S12. This tribological test proved coating S3 had a higher wear resistance than coating S12.

4.1.4 Conclusions

In conclusion, EJPO coating process could produce uniformed coating on the cylinder bore, and the cost was 17.5% lower compared with cast iron liner. EJPO coated 2.0 L engine block could reduce weight by 3.96 pounds or 6.4% compared with the engine block with cast iron liners. Flex brush honing could hone the EJPO coated bore surface to desired roughness and thickness. The engine Break-in test showed coating S3 worked better in combustion environment and coating S12 was scuffed after the Break-in test. The coating hardness test, reciprocating tribological test, and surface profile measurements all showed EJPO coating S3 had a higher wear resistance and oil retention ability. EJPO coating S3 was selected as candidate coating for the next engine block to run the performance and durability tests.

4.2 Effects of the flex brush honing on the wear of the EJPO coated cylinder bores

4.2.1 EJPO coating S3 fabrication for the 2.0 L engine block

The #1 EJPO coated 2.0 L engine test proved that EJPO coating S3 was harder and had higher wear resistance. EJPO coating S3 was used to coat the #2 2.0 L engine block. The #1 engine test also showed cylinder 1 and 2 coating were intact which meant the cylinder bore diameter, piston to bore clearance, coating roughness and coating thickness worked on the 2.0 L engine block. The #2 2.0 L engine treatments would be same as the cylinder 1 and 2 of the #1 2.0 L engine.

The aluminum engine block cylinders were machined and honed to 30 um bigger than the standard bore size to make room for EJPO coating growth. The honed aluminum bore roughness was less than 1um, and the engine block was washed and dried before coating fabrication process. The flex honed aluminum engine block was shown in Figure 4-9.

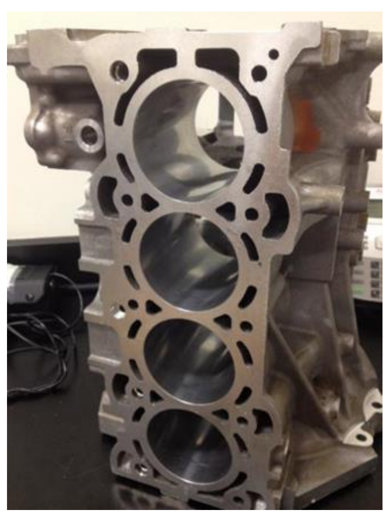


Figure 4-9. Flex brush honed aluminum engine cylinder bore

After the engine block was honed and cleaned, it was set up on the EJPO coating machine for the coating process. During the EJPO coating process, the plasma discharges generate a large amount of heat, and the heat affects the coating quality. Same as the #1 engine block, an aluminum top plate and process water were used to cool down the engine block. Figure 4-10 shows the engine cooling system for the EJPO coating process.

Figure 4-10. Engine cooling system for EJPO coating process

The EJPO coating treatment took 25 minutes, and a higher current density was applied to increase the coating thickness to 42 ums. The dense layer of the coating would be increased, and the coating bonding would also be enhanced. The coating thickness measurement showed all the cylinder coatings had thickness close to 42 ums. The coating thickness checks are shown in Table 4-5.

Table 4-5. EJPO coating thickness check after 25 minutes' treatment

Cylinders	Cylinder 1	Cylinder 2	Cylinder 3	Cylinder 4
Thickness(um)	41	42	41	43

The original coating roughness was measured, and it was around 3.6 ums. The surface profile of the original coating was shown in Figure 5-3, and it showed the pores on the coating were deeper because of the higher current density.

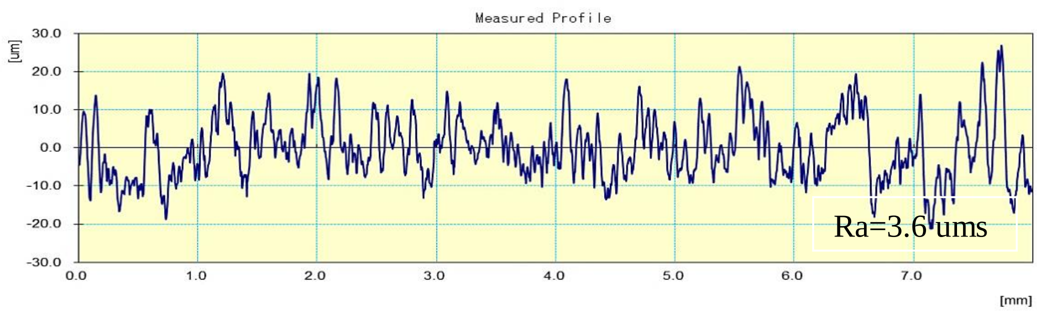


Figure 4-11. Original coating surface profile

4.2.2 Flex brush honing for the EJPO coated 2.0 L engine block

Flex brush honing was used to hone the EJPO coating on the cylinder bores. The coating roughness was honed to around 0.7 um, and the coating thickness was honed to around 20 ums with the target bore diameter 87.555 mm. Different abrasives of honing brushes were used to reduce the coating roughness during the honing process. The coating honing process is shown in Figure 4-12 and the honed cylinder bores are shown in Figure 4-13.

Figure 4-12. Flex brush honing process

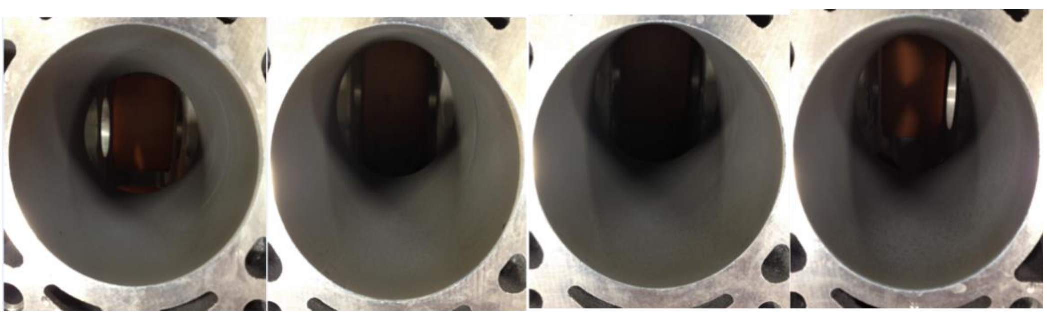


Figure 4-13. Flex brush honed cylinder bores

After flex brush honing, the engine block was washed and dried. The cylinder bore diameters, coating roughness, coating thickness and piston to bore clearance were measured. The measurements are shown in Table 4-5.

Table 4-5. EJPO coating and cylinder bore measurements

Cylinders	Bore size(mm)	Roughness(um)	Thickness(um)	Clearance(um)
Cylinder1	87.555	0.71	21	24.5
Cylinder2	87.556	0.73	22	25
Cylinder3	87.557	0.69	23	25.5
Cylinder4	87.556	0.74	21	24

The measurements showed all the parameters met the requirements; however, the surface profile showed the cylinder bore was not straight. The cylinder bore had a wave shape. At that time, flex brush honing was the only available honing source and efforts were made to hone the bore as good as possible. The surface profile is shown in Figure 4-14.

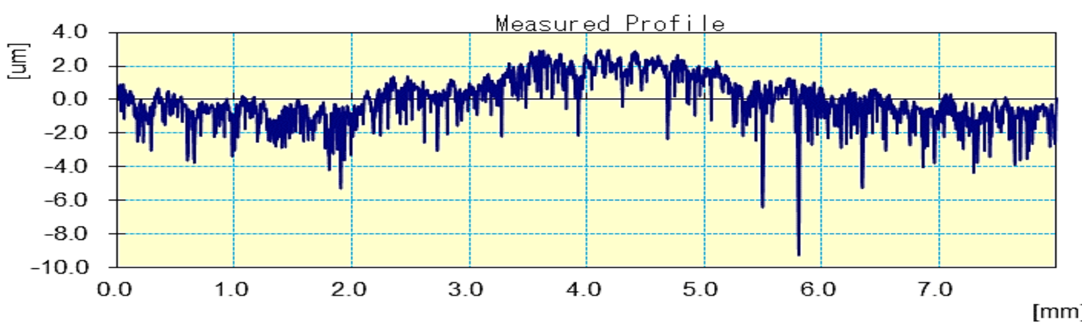


Figure 4-14. Surface profile of the flex honed coating

4.2.3 EJPO coated 2.0 L engine test and tear down analysis

The Flex honed #2 2.0 L engine block was assembled and scheduled to run an 18 hours' dynamometer Break-in test.

The test started at low speed and low load and ended up with high speed and full load. Figure 4-15 showed the Break-in speed and load.

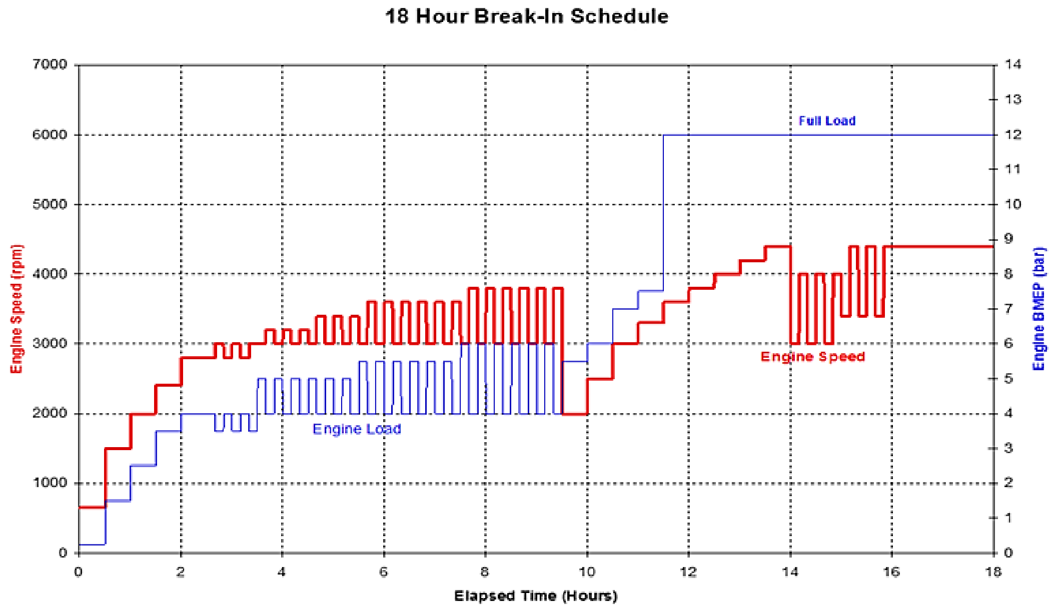


Figure 4-15. Eighteen hours' engine Break-in test

After the 18 hours' Break-in test, cylinder borescope checks were performed. The checks showed the coatings were intact but showed non-uniform patterns. Some parts of the cylinder bore coating had light color and some parts had dark color. The engine was torn down to investigate the coatings' conditions. The tear down analysis proved that the coatings were intact, but the cylinder bore not straight and had wave shaped surface. The coating pictures were taken and shown in Figure 4-16.

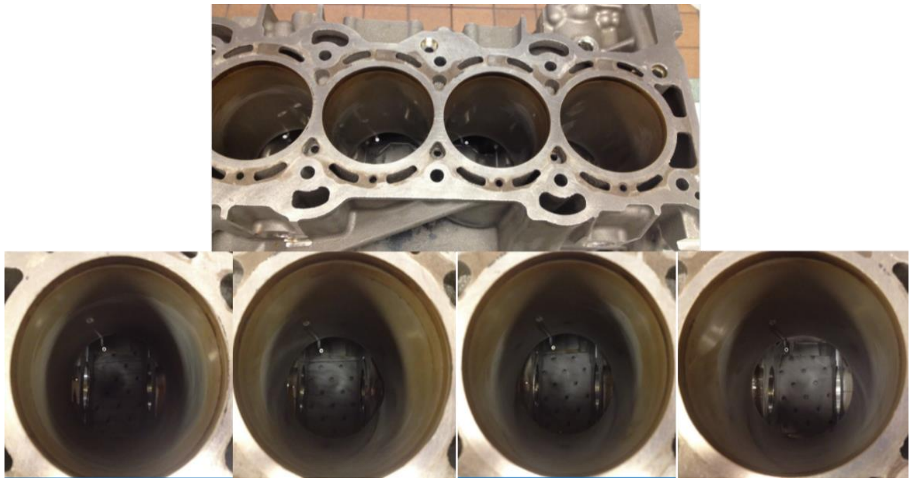


Figure 4-16. Wave patent wear on the coating after Break-in test

As shown in Figure 4-16, the light color areas were the high spots where the coatings were rubbed more by piston rings. The dark areas were the low-lying area where piston rings rubbed the coating lightly. The wave shape cylinder bore was supposed to be developed during the aluminum cylinder bore honing process.

Before the EJPO coating process, the aluminum cylinder bores were honed bigger to make room for coating growth. In this work, flex honing brushes were used to do the honing. Aluminum was a kind of soft material, when the applied honing force was not even on the aluminum surface, the honed surface would present uneven shape.

Flex honing brush has a lot of silicon carbide balls on the elastic bars, the elastic bars have same length and the pressure force on each ball should be same. However, during the honing process, the brush was sliding in and out the cylinder bore, and some parts of the silicon carbide balls were squeezed together and the honing force on the cylinder bore was higher and more materials were removed. In this case, the wave shaped aluminum cylinder bore was formed. Figure 4-17 shows the flex honing brush in cylinder bore and a wavelike cylinder bore.

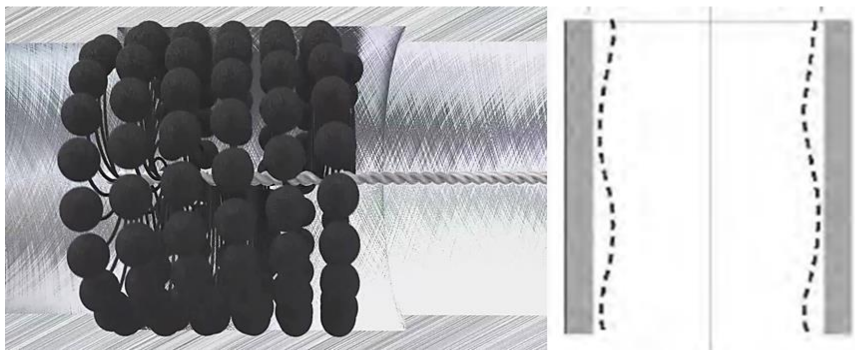


Figure 4-17. Uneven distribution of honing force on Si-C beads and wavelike bore after honing

Flex honing brush might work well on hard materials like cast iron, but not very well on soft aluminum materials. A better honing resource or tool was desired to hone the aluminum cylinder bores round and straight.

4.2.4 Conclusions

In conclusion, the #2 2.0 L engine block was EJPO coated with coating S3, flex brush honed, and assembled as engine to run the engine test. The engine passed the 18 hours Break-in test. After the test, the cylinder bore showed non-uniform patterns. Engine was torn down and showed coatings were intact, but the cylinder bores were not round and straight. The uneven cylinder bore surface was developed during the flex brush honing process on the aluminum bore and a better honing source was required to hone the cylinder bore round and straight.

5. Chapter 5 Machine honing and engine tests for a 2.0 L EJPO coated engine

The #2 EJPO engine test showed the flex honing brush couldn't hone the aluminum cylinder bore round and straight and a better honing source was desired. Compared with flex brush honing, stone machine honing can provide better straightness and roundness. For the aluminum cylinder bore honing, silicon carbide stones were used, and for the ceramic EJPO coating honing, diamond stones were used. The stone machine honing was studied and tested on the #3 2.0 L engine block.

5.1 Machine honing process study on a 2.0 L engine block

Using silicon carbide stone to hone the aluminum cylinder bore was studied and the aluminum bore could be honed straight, besides, the aluminum bore surface roughness could be honed lower than 0.5 um by using the fine stones. A used EJPO coated engine block was used to practice and learn the EJPO coating honing process. During the EJPO coating honing process, the bore diameter, coating thickness and roughness were measured frequently to guarantee both coating thickness and roughness were in desired range. Faster stroke and light honing force were used to make the coating smooth and without removing too much coating for each honing. Two kinds of diamond stones were used to hone the coating, one coarse stone and one fine stone. 10 um top loose coating was removed by the coarse stone and 10 um inner dense coating was removed by the fine stone. After the fine diamond stone honing, the EJPO coating had mirror finish surface, and straightness and roundness were improved significantly.

After learning the stone machine honing, the #3 2.0 L engine block was coated and honed by diamond stones. The EJPO coating treatment was the same as the #2 engine block. The honing head with two honing stones was used during the machine honing. The stone machine honing process is shown in Figure 5-1.

Figure 5-1. Diamond stone honing process

After diamond stone machine honing, the EJPO coating had mirror finish surface. The diamond honed #3 engine block is shown in Figure 5-2.

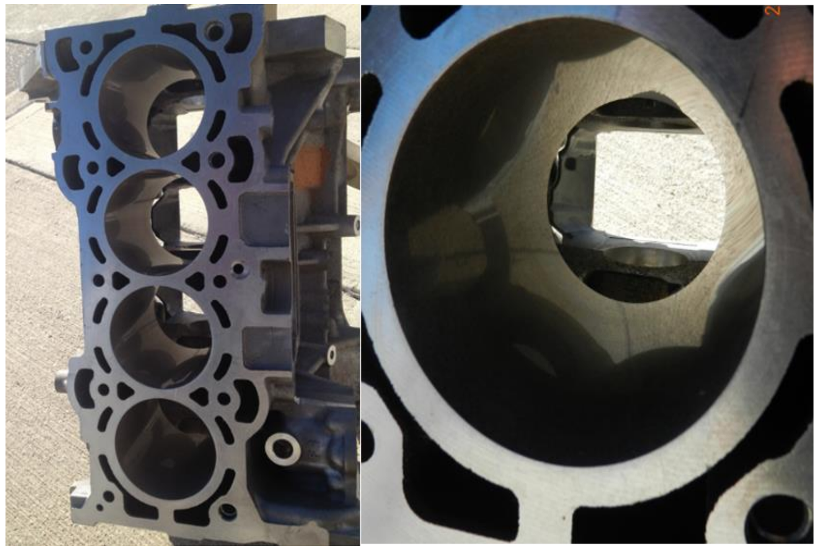


Figure 5-2. Mirror finished cylinder bores after diamond stone honing

After the #3 engine block was diamond honed, the block was sent to do the Coordinate Measuring Machine (CMM) measurements. This measurement could check bore size, roundness and straightness. A CMM roundness check is shown in Figure 5-3 and straightness check is shown in Figure 5-4.

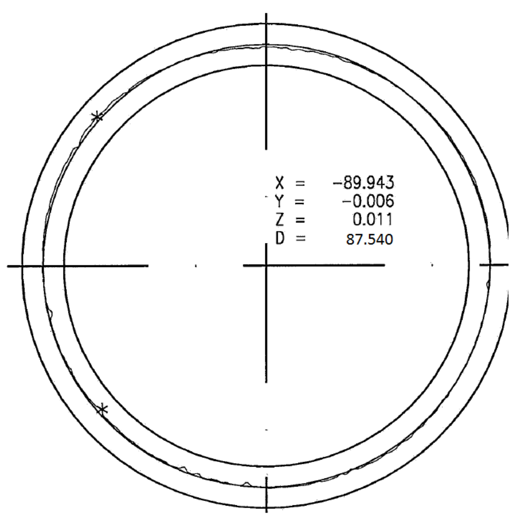


Figure 5-3. CMM cylinder bore roundness and bore size check for #3 EJPO coated block

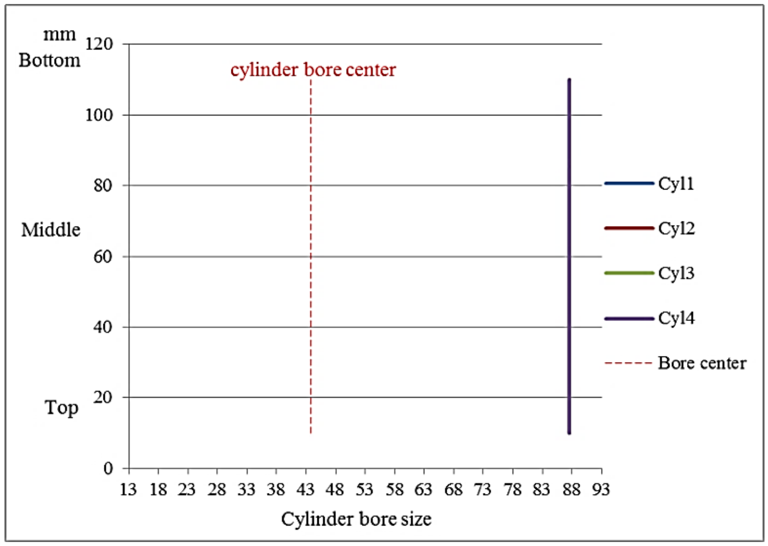


Figure 5-4. CMM cylinder bore straightness and bore size check for #3 EJPO coated block

As shown in Figures 5-3 and 5-4, the roundness was not perfect due to the two stones honing head, but the roundness and straightness were improved significantly compared with flex brush honing.

The cylinder bore diameter, piston size, piston ring end gap were measured and the piston to bore clearance was calculated. The measurements and the calculation are shown in Table 5-1.

Table 5-1. #3 engine cylinder bore, piston size and clearance measurements

Cylinder#	Bore size(mm)	piston skirt Size(mm)	piston top ring end gap(mm)	piston 2nd ring end gap(mm)	piston to bore clearance(um)
Cylinder 1	87.542	87.517	0.381	0.864	25
Cylinder 2	87.539	87.514	0.381	0.864	24.5
Cylinder 3	87.538	87.512	0.381	0.889	26
Cylinder 4	87.537	87.513	0.381	0.864	24

The honed EJPO coating thickness was also measured. The coating thickness is shown in Table 5-2.

Table 5-2. #3 engine EJPO coating thickness after honing

Cylinder	Cylinder 1	Cylinder 2	Cylinder 3	Cylinder 4
Thickness(um)	21	22	20	21

As shown in Table 5-2, the coating thickness was the desired thickness after honed the cylinder bore to target size.

The honed EJPO coating roughness was also measured (Ra=0.70 um) and the coating oil retention volume was calculated. The coating surface profile is shown in Figure 5-5, and the profile showed the cylinder bore straightness was improved significantly.

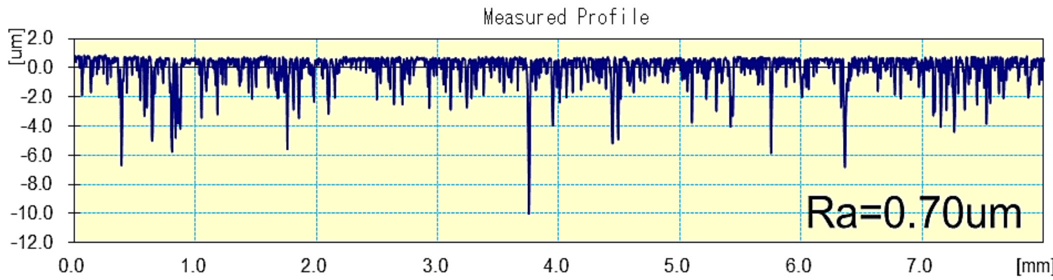


Figure 5-5. Diamond honed EJPO coating roughness and profile

The EJPO coating oil retention volume was calculated, and it was 0.19 um^3/um^2.

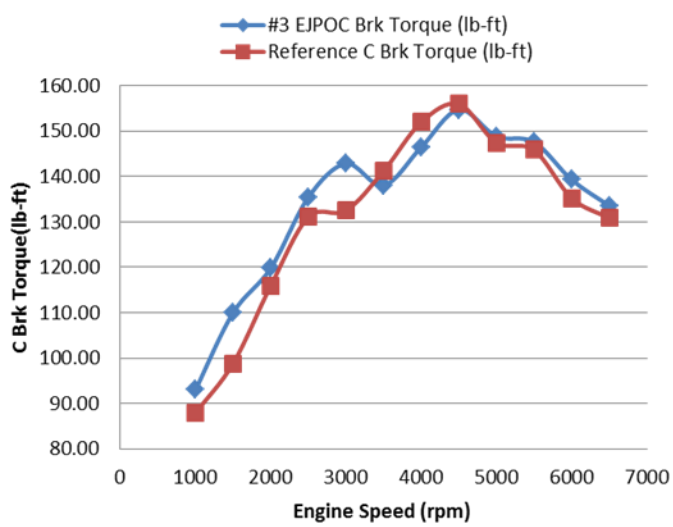
5.2 Engine tests of the machine honed 2.0 L engine

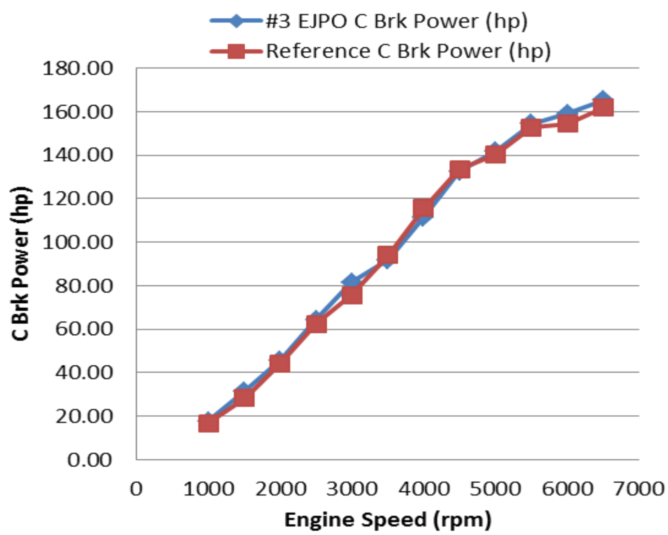
All the measurements met the requirements and the diamond honed #3 engine was scheduled to run 8 hours Break-in test first. After Break-in test, the cylinder bores were checked by using cylinder borescope. The borescope check showed the cylinder bore coatings were smooth and intact. The borescope pictures are shown in Figure 5-6.

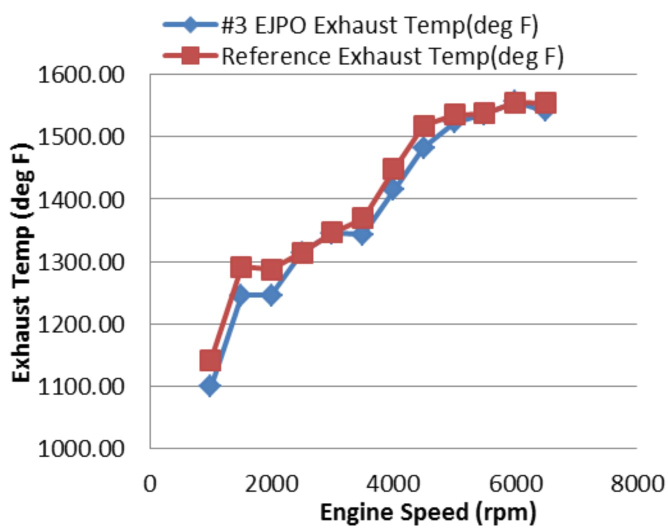
Figure 5-6. Cylinder borescope pictures after Break-in test

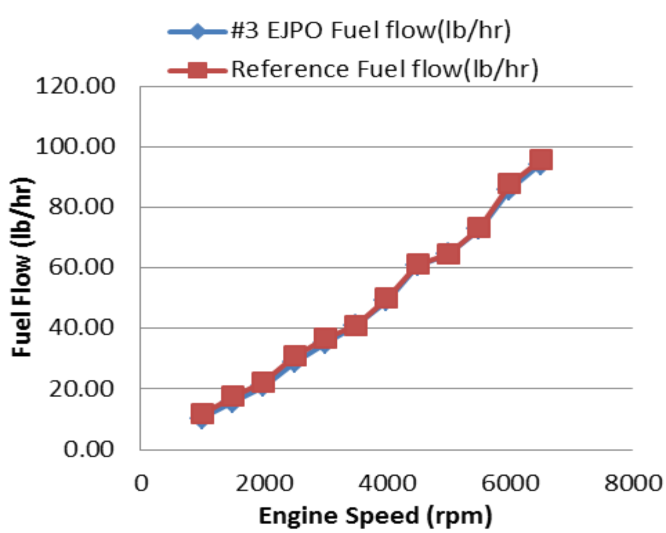
5.2.1 Engine Power test of the machine honed 2.0 L engine

Since the coatings' conditions were good, the engine continued to run a Power test. The Power test was designed to generate the engine performance map. During the Power test, each engine speed step kept running for 2 minutes, and the data acquisition frequency was 1 second. 120 data points were averaged for each point in the plot. The EJPO coated engine performance data were used to compare with the performance of the regular cast iron liner engine, and then evaluated the capability of EJPO coating for engine performance enhancement. Some of the EJPO Power test data and the stock engine Power test data are shown in Figure 5-7.




#3 EJPO C Brk Power (hp)
Reference C Brk Power (hp)
C Brk Power (hp)
180.00
160.00
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0
1000
2000
3000
4000
5000
6000
7000
Engine Speed (rpm)


#3 EJPO Exhaust Temp(deg F)
Reference Exhaust Temp(deg F)
Exhaust Temp (deg F)
1600.00
1500.00
1400.00
1300.00
1200.00
1100.00
1000.00
0
2000
4000
6000
8000
Engine Speed (rpm)


#3 EJPO Fuel flow(lb/hr)
Reference Fuel flow(lb/hr)
Fuel Flow (lb/hr)
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0
2000
4000
6000
8000
Engine Speed (rpm)

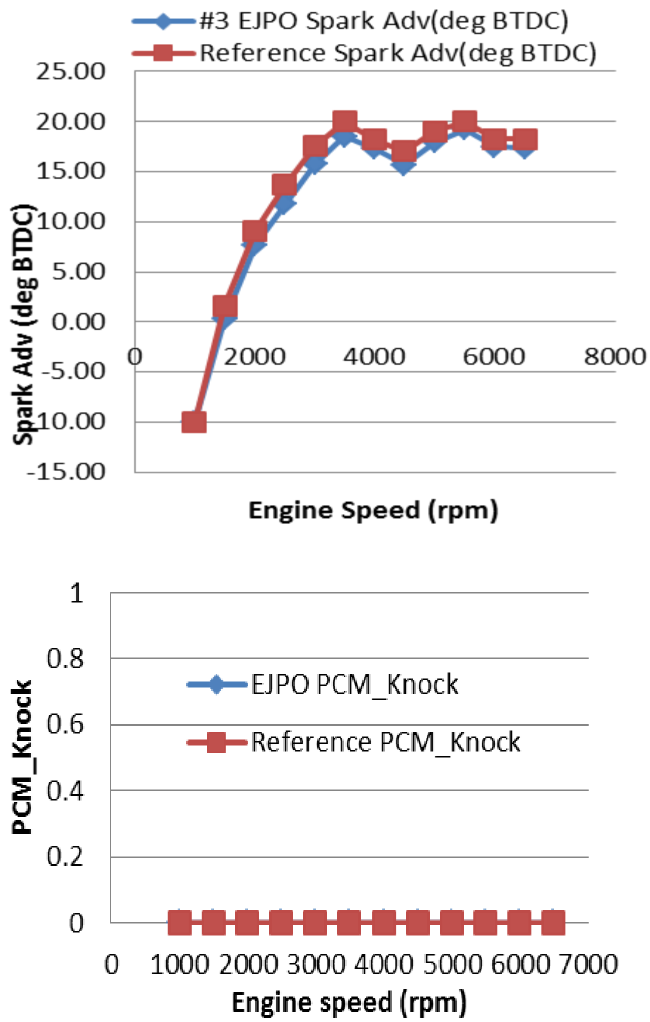


Figure 5-7. EJPO coated engine Power data compared with the stock engine

As shown in Figure 5-7, EJPO coated engine made more Torque and Power at speeds lower than 3000 rpm and speeds higher than 5000 rpm. The highest engine torque enhancement was 11.29% at 1500 rpm. Fuel consumption was almost the same and even less at some speeds, but EJPO coated engine had higher power output, which helped to reduce the fuel consumption and emissions to do the same work.

The EJPO coated engine had lower exhaust temperature and had smaller coolant in and out temperature difference which meant EJPO coated engine has less heat loss. The temperature swing property of EJPO coating helped to keep more heat in combustion chamber to do work.

The EJPO coated engine had retarded spark timing at all the speeds which indicated the combustion chamber temperature of the EJPO coated engine was higher. The engine knock sensors detected the potential of the engine knocks and retarded the spark timing to get rid of the engine knocks. The temperature swing function of the EJPO coating also helped to reduce engine knocks. The retarded spark timing would reduce engine power, however EJPO coated engine had higher power output at some speeds because of the lower COF and higher fuel or thermal efficiency.

Compared with the stock cast iron liner engine, EJPO coated engine made better performance at speeds lower than 3500 rpm and higher than 5000 rpm. The comparison data is shown in the following tables.

Table 5-3. Engine torque comparison between EJPO coated and stock engines

Speed(rpm)	EJPO (lb-ft)	Stock (lb-ft)	Enhancement %)
1000	92.98	87.89	5.79
1500	109.96	98.80	11.29
2000	119.17	115.88	3.35
2500	135.37	161.03	3.31
3000	142.81	132.47	7.80
3500	137.96	141.17	-2.27

Speed(rpm)	EJPO (lb-ft)	Stock (lb-ft)	Enhancement %)
4000	146.42	151.91	-3.61
4500	154.69	155.93	-0.79
5000	148.82	147.40	0.96
5500	147.57	145.81	1.21
6000	139.26	135.21	2.99
6500	133.52	130.81	2.07

Table 5-4. Engine power comparison between EJPO coated and stock engines

Speed(rpm)	EJPO (HP)	Stock (HP)	Enhancement %)
1000	17.70	16.75	5.69
1500	31.40	28.22	11.29
2000	45.61	44.13	3.35
2500	64.44	62.37	3.30
3000	81.57	75.69	7.76
3500	91.94	94.07	-2.27
4000	111.51	115.70	-3.61
4500	132.54	133.57	-0.77
5000	141.68	140.30	0.98
5500	154.53	152.66	1.22
6000	159.09	154.47	2.99
6500	165.24	161.89	2.07

As shown in Tables 5-3 and 5-4, the highest performance enhancement was 11.29% at 1500 rpm. At speeds 3500 rpm, 4000 rpm and 4500 rpm, the EJPO coated engine had worse performance, after 5000 rpm the EJPO coated engine made better performance again. Two main reasons to enhance the engine performance were lower engine friction and higher thermal efficiency.

The previous lab tribological tests proved the EJPO coating had lower COF than cast iron, so the friction between EJPO coated cylinder wall and piston rings should be smaller than that between cast iron cylinder wall and piston ring. The COF comparison between EJPO coating and cast iron is shown in Figure 5-8.

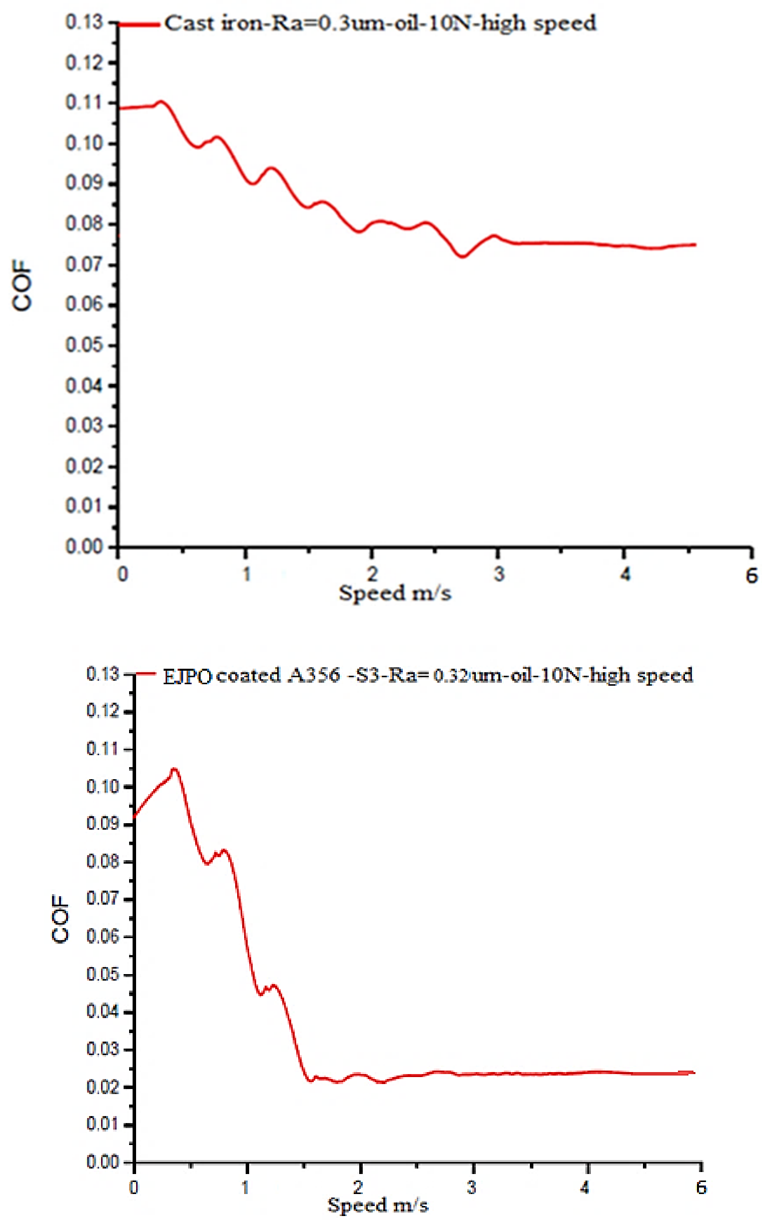


Figure 5-8. COF comparison between cast iron and EJPO coating

The lower friction between cylinder wall and piston rings made a contribution to a higher engine performance. The COF of EJPO coating was a typical Stribeck curve. When the sliding speed increased, the boundary, mixed and hydrodynamic lubrication formed and the COF of EJPO coating dropped significantly. Compared with the COF of cast iron, the COF of EJPO coating could reduce to the lowest value with a much lower speed.

Corresponding to EJPO coated engine performance, at speeds lower than 3500 rpm, the boundary and mixed lubrication formed, the COF was much lower than the cast iron, thus the EJPO coated engine made higher performance. When the speed increased between 3500 rpm and 4500 rpm, might be the hydrodynamic lubrication formed and the COF of EJPO coating increased at these speeds. The EJPO coating had higher COF and worse performance at these speeds because of the lubrication, surface profile and temperature influences. After 4500 rpm, the combustion temperature increased and the piston and cylinder bore expansion might change the clearance between the piston ring and cylinder wall, and this changed lubrication condition and affected the COF. The engine combustion was complicated, and the COF between piston ring and cylinder wall was one of those parameters that affect engine performance. The thermal efficiency effects on engine performance were introduced next.

Another reason for EJPO coated engine making higher performance was the higher thermal efficiency. Toyota motor company’s research and experiments show the low thermal conductivity and low thermal capacity coating has temperature swing function and can help to reduce the heat loss during combustion without heating up the intake air temperature [1]. The temperature swing illustration is shown in Figure 5-9.

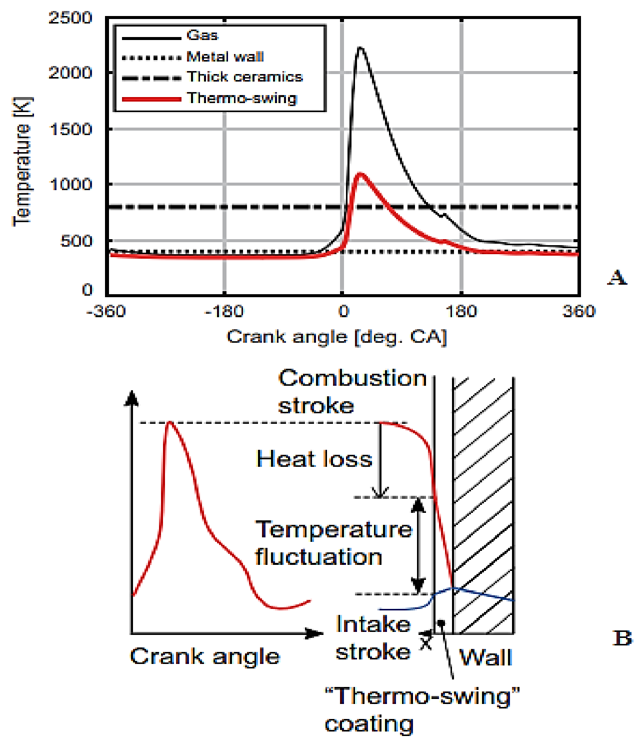


Figure 5-9. Function of the temperature insulation coating in cylinder [1]

As shown in Figure 5-9-A, tradition normal cylinder wall temperature stays at low temperature during the whole combustion cycle, cylinder wall temperature of traditional insulation stays at high temperature during the whole combustion cycle, while the wall temperature of the temperature swing insulation coating fluctuates during the combustion cycle.

Heat loss in combustion chamber is the temperature difference between the combustion gas temperature and the cylinder wall temperature ΔT as shown in Figure 5-9-B. ΔT in normal cylinder will be high, because the constant low cylinder wall temperature. ΔT in traditional insulated cylinder will be small because the high cylinder wall temperature, however, knocks will happen since the constant high temperature in cylinder. ΔT in temperature swing insulated cylinder is small without heating up the intake air temperature, so there will be no knocks. Thus, temperature swing insulation coating can help to reduce the heat loss without heating up the intake air temperature thereby increasing the engine thermal efficiency.

Prof Nie's group also developed a three-dimensional transient finite element analysis thermal model to investigate the thermal behavior of EJPO coated cylinder bores. The study found that a possible selection of EJPO coating thickness and thermal conductivity could provide a thermal swing property to improve engine efficiency [2]. A simulation of temperature swing function of EJPO coating is shown in Figure 5-10.

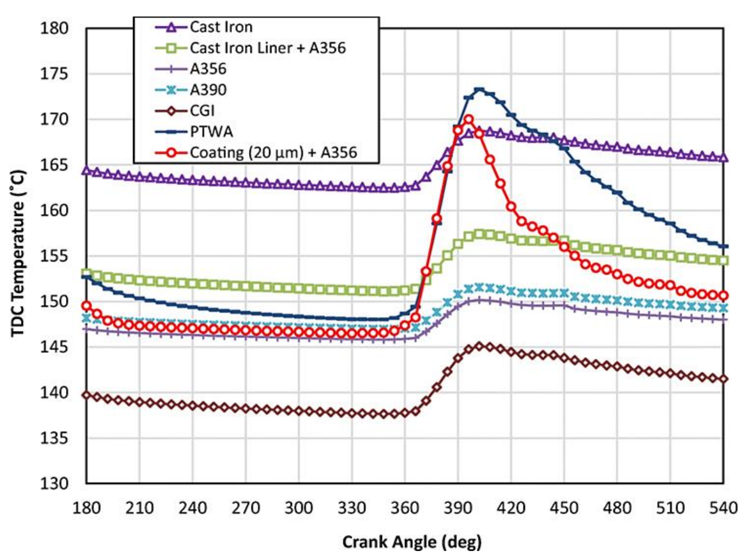


Figure 5-10. Temperature swing function of EJPO coating [2]

In this simulation study, the 20 um EJPO coating had good temperature swing function. So, during the Power test, the temperature swing function of EJPO coating helped to increase the engine thermal efficiency.

Data in Figure 5-7 also showed the EJPO coated engine had a similar amount of fuel to generate the same amount of heat, it had lower exhaust temperature and lower coolant heat loss, which meant more heat was used to do the work. The thermal efficacy was increased to enhance engine performance. The fuel consumption, exhaust temperature, and coolant temperature comparison are shown in the following tables.

Table 5-5. Fuel consumption comparison between #3 EJPO coated and stock engines

Speed(rpm)	EJPO (lb/h)	Stock (lb/h)	Reduction (%)
1000	11.22	11.71	1.26
1500	15.69	17.51	1.04
2000	21.84	22.26	2.35
2500	30.86	30.92	0.66
3000	35.95	36.63	0.46
3500	41.06	41.12	1.41
4000	49.24	49.91	1.35
4500	60.68	61.12	0.72
5000	64.61	64.58	0.03
5500	72.74	73.17	0.05
6000	85.95	87.8	2.1
6500	94.27	95.27	1.5

Table 5-6. Exhaust temperature comparison between #3 EJPO coated and stock engines

Speed(rpm)	EJPO (lb/h)	Stock (lb/h)	Reduction (%)
1000	1099.3	1141.5	3.69
1500	1245.3	1291.3	3.56
2000	1246.1	1286.8	3.16
2500	1314.1	1314.3	0.02
3000	1345.4	1346.9	0.11
3500	1343.8	1369.6	1.88
4000	1415.4	1448.3	2.27
4500	1482.6	1517.7	2.31
5000	1523.4	1535.0	0.76
5500	1536.7	1537.3	0.04
6000	1556.8	1554.9	0.12
6500	1542.1	1553.9	0.76

Table 5-7. Coolant temperature in & out difference comparison between #3 EJPO coated and stock engines

Speed(rpm)	EJPO (lb/h)	Stock (lb/h)	Reduction (%)
1000	9.17	10.9	15.83
1500	7.2	8.48	15.1
2000	6.6	7.45	11.33
2500	6.65	7.09	6.17
3000	6.46	6.52	1.01
3500	6.34	6.47	1.9
4000	6.33	6.79	6.78
4500	6.7	6.77	1.09
5000	6.54	6.31	-3.71
5500	6.65	6.25	-4.83
6000	6.34	5.98	-5.95
6500	6.12	5.82	-5.08

During the dynamometer test, the test cell ambient temperature, engine oil temperature, and engine coolant out temperature were controlled at constant level. As shown in Tables 5, 6 and 7, the EJPO coated engine and stock engine had similar fuel consumption which meant the heat generated by the engines were similar, however the EJPO coated engine had a lower exhaust temperature and lower coolant heat loss. That meant the EJPO coated engine had less heat loss and more heat was used to make power especially at speeds lower than 3500 rpm.

The engine thermal efficiency can be calculated by using engine power and fuel flow rate, the formula is shown as follows:

Thermal efficiency= Actual Power (KW) / (Fuel Flow (g/s) * LHV (KJ/g))

LHV=42.9 KJ/g.

The comparison of engine thermal efficiency between cast iron liner engine and EJPO coated engine is shown in Table 5-8.

Table 5-8. Thermal efficiency comparison between EJPO coated 2.0 L engine and cast iron liner 2.0 L engine

Speed (rpm)	EJPO			Stock			Increment (%)
	Power (kw)	Fuelflow (g/s)	Thermal (%)	Power (kw)	Fuelflow (g/s)	Thermal (%)	
1000	13.21	1.29	23.90	12.50	1.47	19.75	20.99
1500	23.43	1.98	27.62	21.05	2.21	22.24	24.22
2000	34.02	2.63	30.20	32.92	2.80	27.36	10.37
2500	48.07	3.64	30.81	46.53	3.90	27.84	10.67
3000	60.85	4.40	32.21	56.47	4.62	28.52	12.93
3500	68.59	5.17	30.90	70.18	5.18	31.58	-2.13
4000	83.19	6.20	31.25	86.31	6.29	31.99	-2.30
4500	98.87	7.65	30.14	99.64	7.70	30.16	-0.05
5000	105.7	8.14	30.26	104.7	8.14	29.98	0.95
5500	115.3	9.17	29.32	113.9	9.22	28.79	1.83
6000	118.7	10.83	25.54	115.2	11.06	24.28	5.21
6500	123.3	11.88	24.19	120.8	12.06	23.34	3.63

As shown in Table 5-8, the EJPO coated 2.0 L engine had higher engine thermal efficiency at speeds lower than 3000 rpm, and at speeds higher than 5000 rpm. The highest thermal efficiency enhancement was 24.22% at 1500 rpm. The thermal efficiency enhancement shown in the Power test was engine output or performance enhancement. The thermal swing function of EJPO coating enhanced thermal efficiency and enhanced thermal efficiency enhanced engine performance.

Thus, the lower COF and temperature swing function of EJPO coating helped to enhance the engine performance.

5.2.2 Engine fatigue test of the machine hone 2.0 L engine

After the Power test, the #3 engine was scheduled a service to check the engine's leak down and compression. This check could help to evaluate the conditions of the cylinder bores. If the service data were good, the engine would continue to run the Engine Fatigue Test (EFT). The compression and leak down checks is shown in Table 5-9.

Table 5-9. #3 EJPO coated engine service check

Service	Cylinder 1	Cylinder 2	Cylinder 3	Cylinder 4
Compression(psi)	191	192	190	189
Leak down (%)	6	5	4	6

The service checks showed the engine was healthy and no scuffs were on the cylinder bores. The #3 EJPO coated engine was scheduled to run EFT test to test the honing effects on coating durability. One cycle of the EFT test lasts 3.5 hours, and 40 cycles were set up in the test. After one cycle EFT test, the data was processed to check engine performance. Part of the data is shown in Figure 5-11.

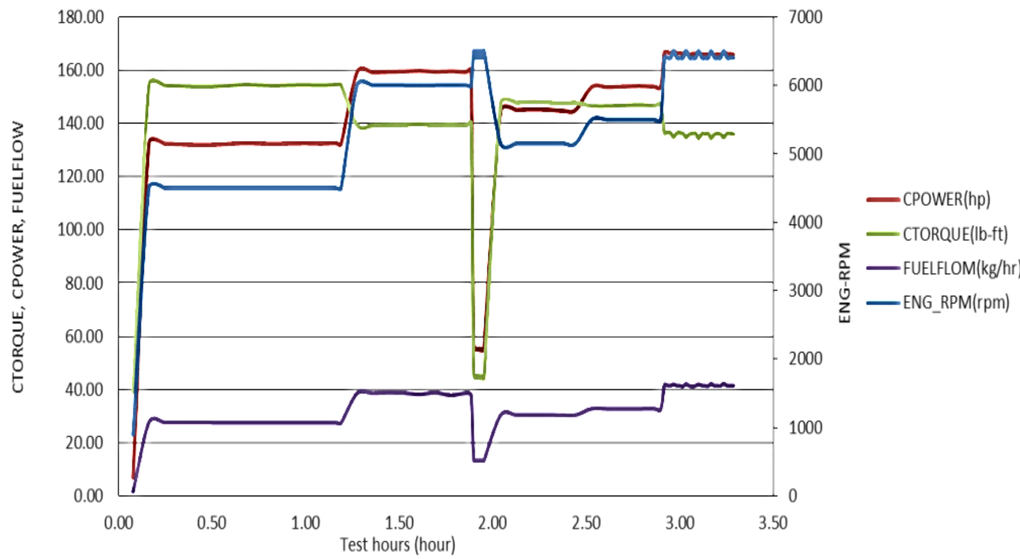


Figure 5-11. Part of the one cycle EFT data

The one cycle EFT data showed the engine made good power and torque at different steps.

A cylinder borescope check was performed to check the coating's condition after one cycle of EFT test. The borescope check found cylinder one had some scuffs on top of the cylinder bore. These scuffs might cause the engine failure during the EFT test, so the test was hold and the engine was torn down to investigate. The cylinder bores are shown in Figure 5-12.

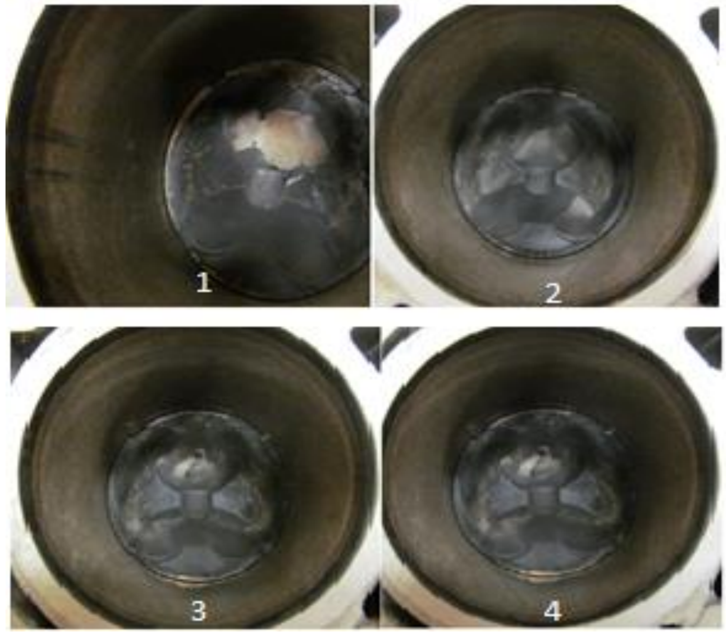


Figure 5-12. Cylinder bore coatings after one cycle EFT test

The cylinder one had scuffs on top of the cylinder bore. The pistons were also inspected after the tear down. Found #1 piston had scuffs on the piston top land which meant the clearance between piston and the top part of cylinder bore was tight. The #1 piston is shown in Figure 5-13.

Figure 5-13. Scuffed cylinder one piston

A bigger piston to bore clearance was necessary to avoid the coating scuff and pass the EFT test.

5.2.3 Conclusions

In conclusion, the #3 EJPO coated 2.0 L engine block was prepared same as the #2 engine. Diamond stone honing was learned and applied to hone the #3 engine block; the diamond honed coating had mirror finish. #3 EJPO coated 2.0 L engine passed Break-in test, Power test, and one cycle of EFT test. During Power test, EJPO coated engine had better performance at speeds lower than 3000 rpm and at speeds higher than 5000 rpm because of the low COF of the EJPO coating and temperature swing function of the EJPO coating. The highest engine performance enhancement was 11.29% at 1500 rpm. The lower friction and higher thermal efficiency enhanced engine performance. Cylinder one piston top land touched the top of the cylinder bore, and a bigger piston to bore clearance was needed.

5.3 Engine tests of the machine honed 2.0 L engine with bigger bore size

5.3.1 Machine honing the 2.0 L engine with a bigger bore size

The #3 EJPO coated 2.0 L engine test failed after the first cycle of EFT test because of the tight piston to bore clearance. A bigger piston to cylinder bore clearance was needed to pass the EFT test. The #4 EJPO coated 2.0 L engine block was prepared and diamond stone honed with a bigger piston to bore clearance for the engine tests.

The #4 EJPO coated 2.0 L engine block was treated same as the #3 engine block, and the cylinder bore diameter was diamond honed 5 ums bigger than the #3 engine block. The diamond honed #4 engine block is shown in Figure 5-14.

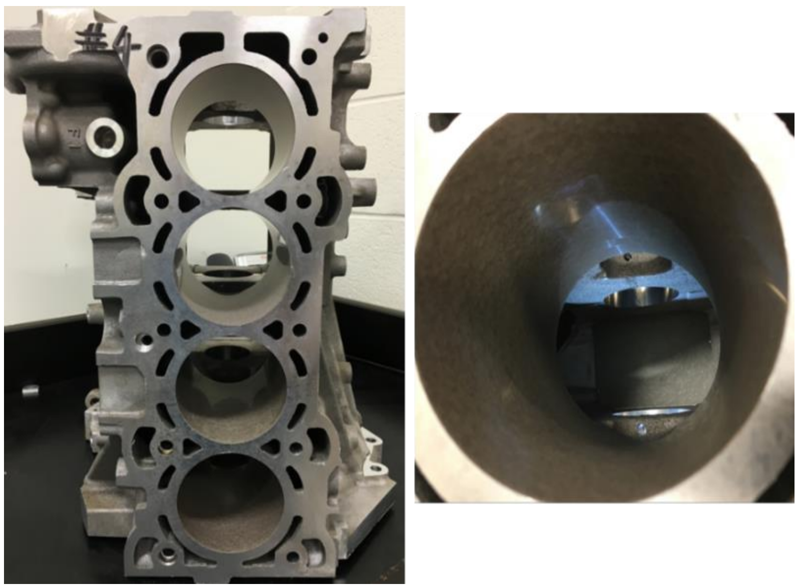


Figure 5-14. Diamond stone honed #4 engine block and mirror finished surface

The bore size, roundness and straightness were checked by CMM machine and were good. The pistons were measured, and the clearance was calculated to make sure the clearance was 5 ums bigger than the #3 engine block. The measurements are shown in Table 5-10.

Table 5-10. #4 engine block cylinder diameter, piston and clearance measurements

Cylinder #	Location	Piston size(mm)	Cyl bore size(mm)	Clearance(um)
1	top	87.489	87.518	29
	mid	87.490	87.52	30
	bot	87.491	87.522	31
2	top	87.490	87.518	28
	mid	87.491	87.52	29
	bot	87.488	87.519	31
3	top	87.487	87.518	31
	mid	87.489	87.521	32
	bot	87.490	87.520	30
4	top	87.483	87.515	32
	mid	87.482	87.511	29
	bot	87.482	87.512	30

The coating thickness was also measured at three locations including top, middle and bottom to make sure the coating thickness was uniform. All the coating thicknesses were a little bit higher than 20 ums. The measured coating thickness is shown in Table 5-11.

Table 5-11. #4 engine block coating thickness after diamond honing

Cylinder bore	1	2	3	4
Thickness Top(um)	23	22	23	21
Thickness Middle(um)	23	22	23	21
Thickness Bottom(um)	21	21	22	20

The coating surface roughness was also measured and it was around 0.72 ums. The measured coating surface profile is shown in Figure 5-15.

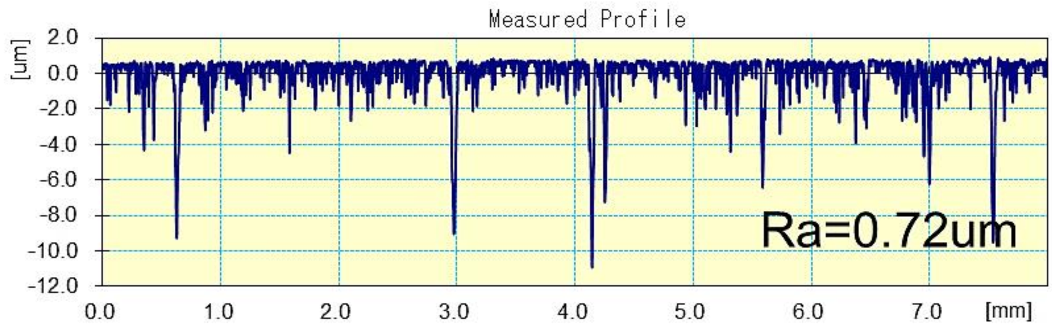


Figure 5-15. Surface profile of the diamond honed EJPO coating

The oil retention volume was calculated and it was 0.16 um^3/um^2.

5.3.2 Engine tests of the 2.0 L engine with bigger bore size

All the EJPO coating parameters, cylinder bore size and clearance met the requirements and the engine block was assembled to run dynamometer engine tests. The #4 EJPO coated engine passed the Break-in test, and Power test. After the Power test, the coatings' conditions were checked by using borescope.

The cylinder borescope checks showed the coatings were smooth and intact after Power test. The borescope pictures are shown in Figure 5-16.

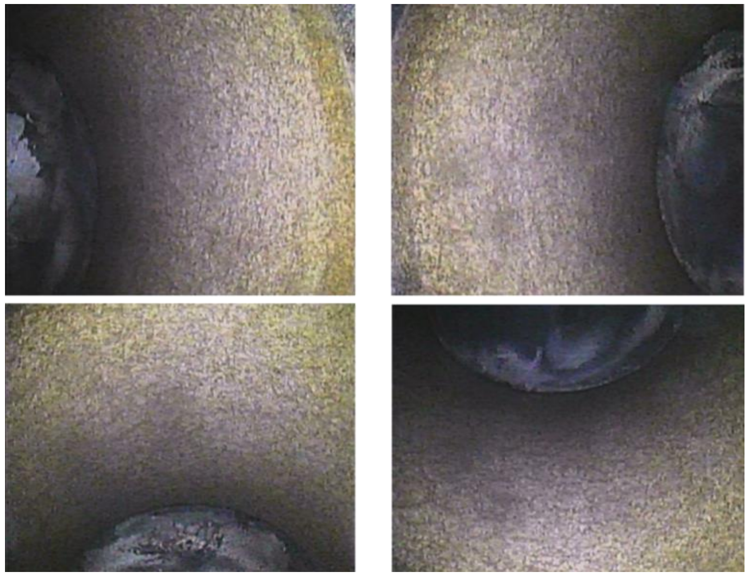
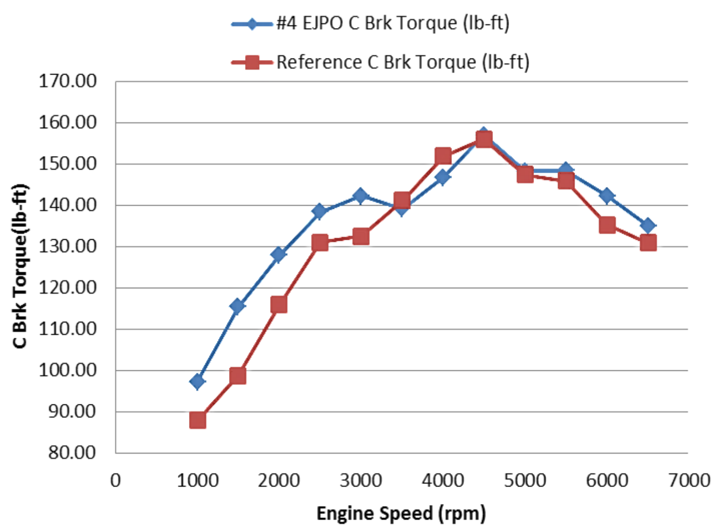


Figure 5-16. Cylinder bore pictures after Power test

The Power test data was processed and compared with the reference stock engine with cast iron liners to investigate the engine performance. Part of the engine performance data are shown in Figure 5-17.



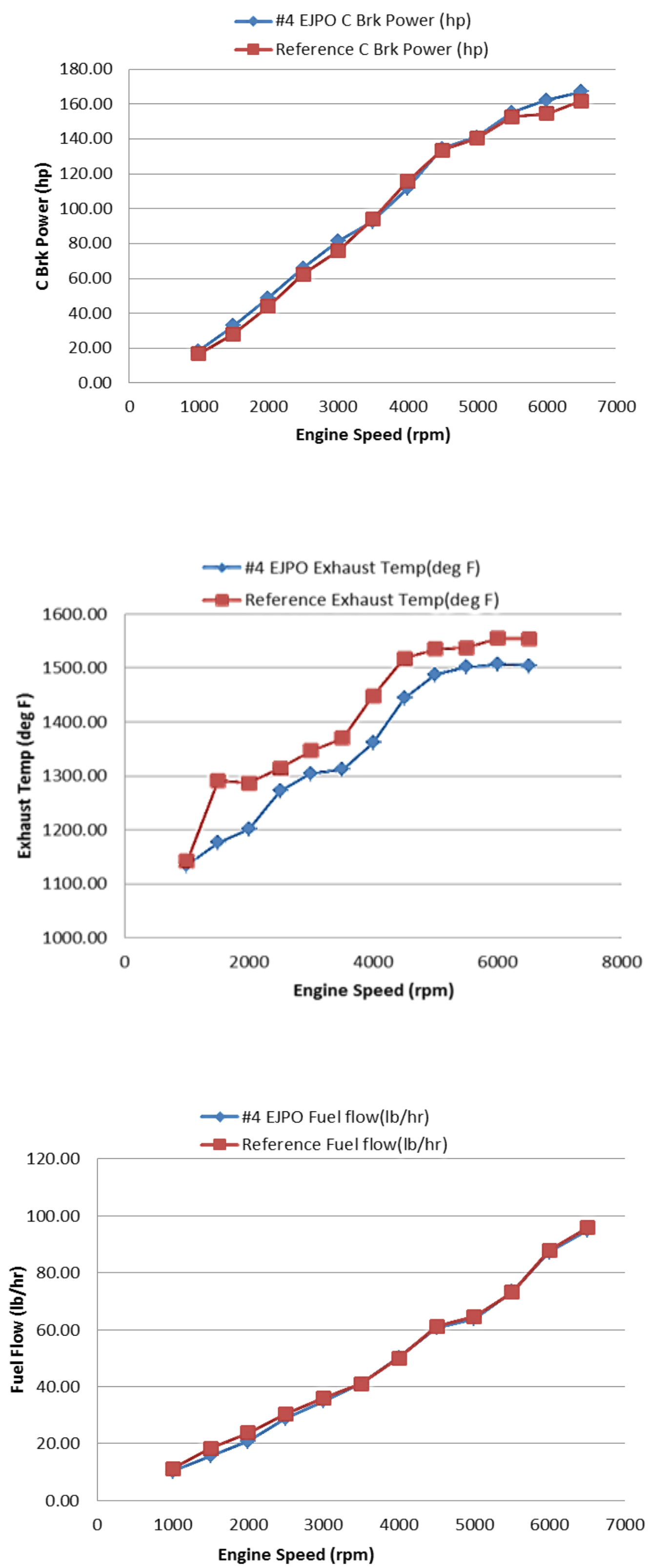


Figure 5-17. Part of engine performance data compared with reference data

As shown in Figure 5-17, the #4 EJPO coated engine performed quite similar to #3 EJPO coated engine. The #4 EJPO coated engine made higher Power and Torque at low speeds (lower than 3000 rpm) and higher speeds (higher than 5000 rpm), also had similar even less fuel consumption and lower exhaust temperatures. The two main factors to enhance engine performance were lower COF and higher thermal efficiency of the EJPO coating (temperature swing and thermal insulation properties) which were talked about in Chapter 5.2.1.

Both #3 and #4 EJPO coated 2.0 L engines reacted similarly and had better performance which meant the EJPO coating indeed has the benefits to enhance engine performance, besides the EJPO coating process was repeatable and cost-effective.

After the Power test was completed, the engine service was performed to check engine's health. The service data showed the engine was healthy and able to run the EFT test. The service data is shown in Table 5-12.

Table 5-12. #4 Engine service data after Post Power test

Service	Cylinder 1	Cylinder 2	Cylinder 3	Cylinder 4
Compression(psi)	193	191	189	192
Leak down (%)	5	5	6	6

After service the #4 EJPO coated engine was scheduled to run a 100 hours EFT test. The engine passed the EFT test and some of the EFT data are shown in Figure 18.

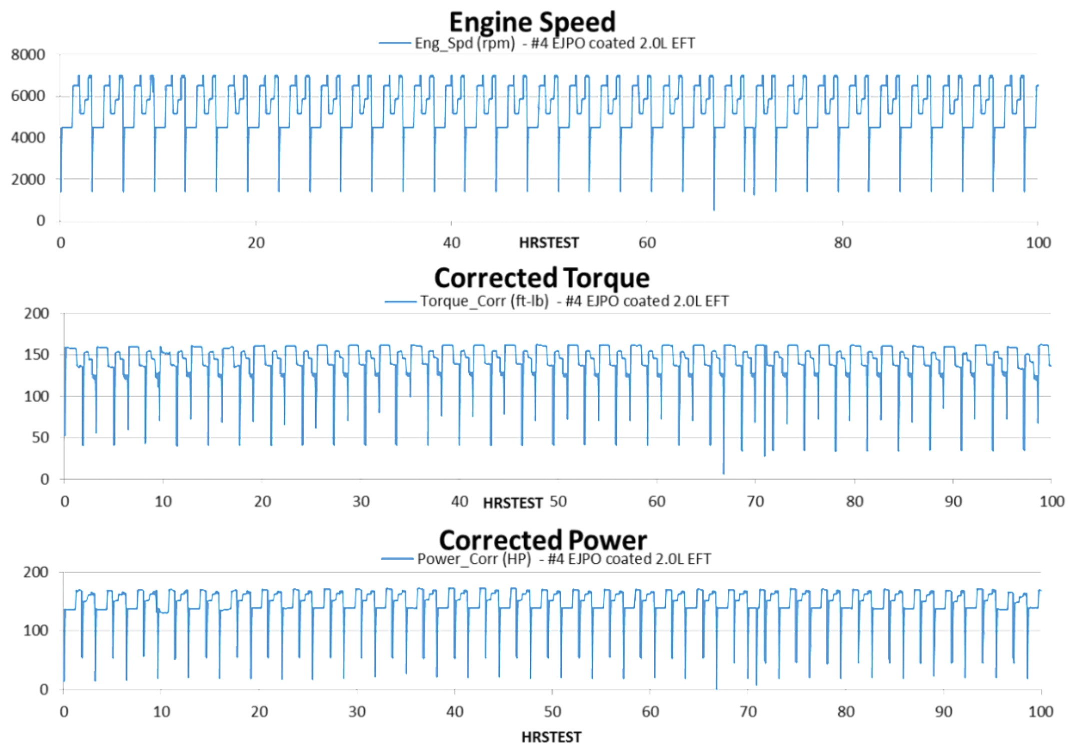
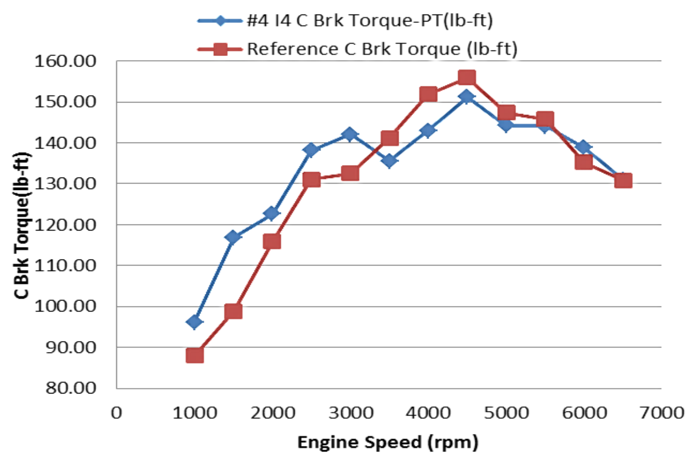
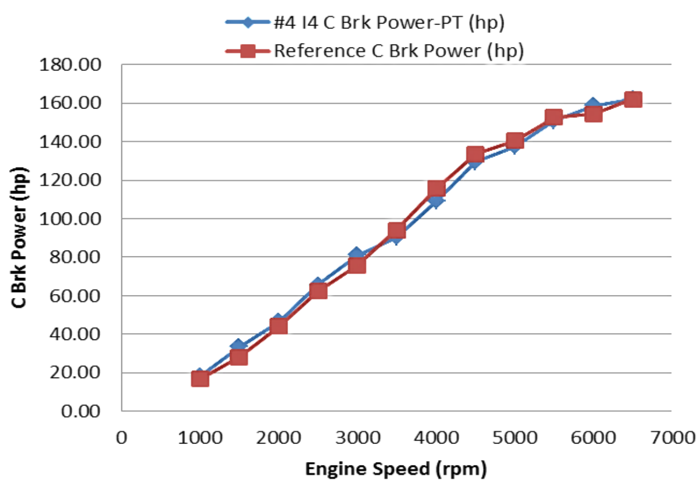


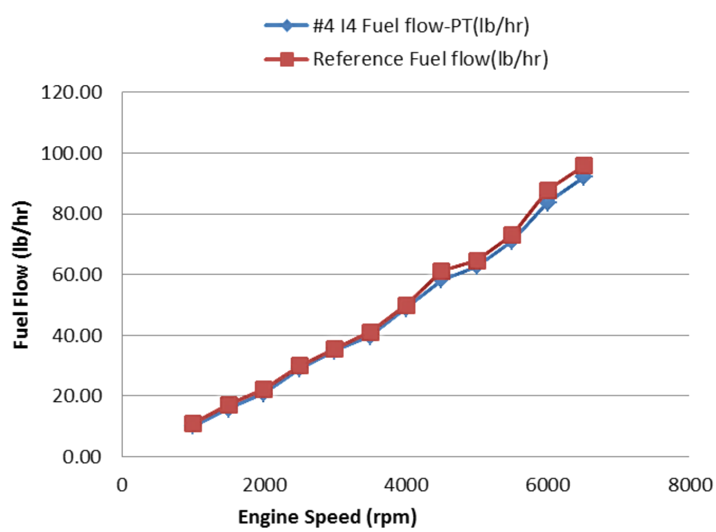
Figure 5-18. Part of the 100 hours EFT test data

The EFT data showed the engine made stable peak Power and peak Torque during the 100 hours EFT test which meant the engine was healthy and the EJPO coating had high wear resistance and durability.

After the EFT test, the #4 EJPO coated engine was scheduled to run a Post Power test to check engine performance after the EFT test. The post Power test showed engine made similar Power and Torque with the Power test. The Post Power test data was processed and compared with reference engine. Part of the data is shown in Figure 5-19.


#4 I4 C Brk Torque-PT(lb-ft)
Reference C Brk Torque (lb-ft)
C Brk Torque(lb-ft)
160.00
150.00
140.00
130.00
120.00
110.00
100.00
90.00
80.00
0
1000
2000
3000
4000
5000
6000
7000
Engine Speed (rpm)


#4 I4 C Brk Power-PT (hp)
Reference C Brk Power (hp)
C Brk Power (hp)
180.00
160.00
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0
1000
2000
3000
4000
5000
6000
7000
Engine Speed (rpm)


#4 I4 Fuel flow-PT(lb/hr)
Reference Fuel flow(lb/hr)
Fuel Flow (lb/hr)
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0
2000
4000
6000
8000
Engine Speed (rpm)

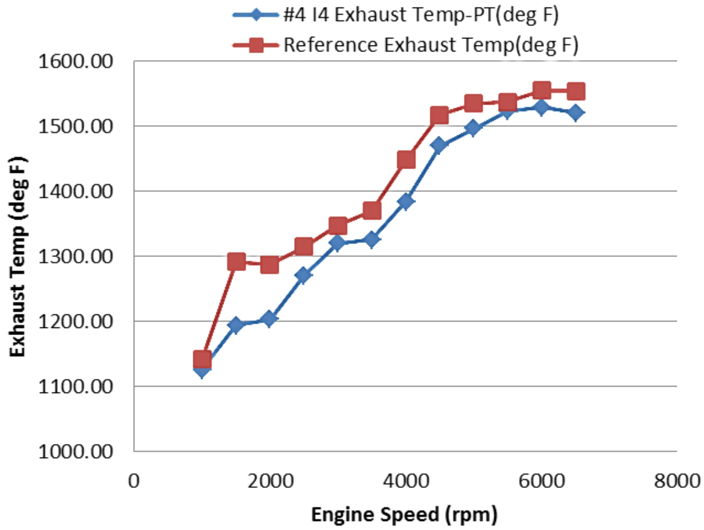


Figure 5-19. Post Power test data compared with reference data

As shown in Figure 5-19, the EJPO coated engine still performed better after the 100 hours EFT test. All the data from #3 EJPO coated engine Power test and #4 EJPO coated engine Power and Post Power tests showed EJPO coated engine could make higher engine performance at some speed ranges than the stock engine with cast iron liners. The performance evaluation and data analysis were talked about in Chapter 5.2.1.

Post service checks were performed after Post Power test, the service data showed engine had similar compression and leak down compared with the beginning checks. The postal service data is shown in Table 5-13.

Table 5-13. #4 Engine service data after Post Power test

Service	Cylinder 1	Cylinder 2	Cylinder 3	Cylinder 4
Compression(psi)	198	191	187	196
Leak down (%)	7	7	6	6

The #4 EJPO coated engine was torn down to check coating and measure cylinder bore diameter, coating thickness and roughness. The cylinder bore coatings were all smooth and intact, the engine block is shown in Figure 5-20.

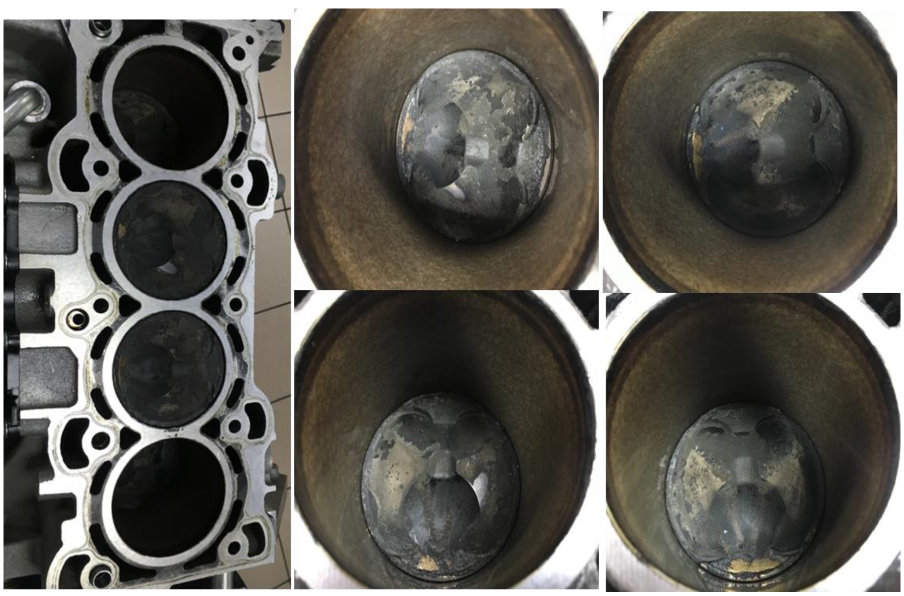


Figure 5-20. #4 EJPO coated engine torn down pictures after dynamometer test

The cylinder bore size, piston size, piston to bore clearance, coating thickness and coating roughness were measured and are shown in Table 5-14, Table 5-15 and Figure 5-21.

Table 5-14. #4 EJPO coated engine bore size and clearance measurements after dynamometer tests

Cylinder	Location	Piston size (mm)	Cyl bore size (mm)	Clearance (um)	Original clearance(um)
1	top	87.492	87.52	30	29
	mid	87.495	87.529	34	30
	bot	87.497	87.529	32	31
2	top	87.494	87.524	30	28
	mid	87.495	87.526	31	29
	bot	87.491	87.523	32	31
3	top	87.492	87.524	32	31
	mid	87.496	87.528	32	32
	bot	87.495	87.528	33	30
4	top	87.486	87.518	32	32
	mid	87.485	87.518	33	29
	bot	87.485	87.516	31	30

Table 5-15. #4 EJPO coated engine coating thickness after dynamometer tests

Cylinder bore	1	2	3	4
Thickness Top(um)	22	21	22	21
Thickness Middle(um)	22	21	22	21
Thickness Bottom(um)	21	21	21	20

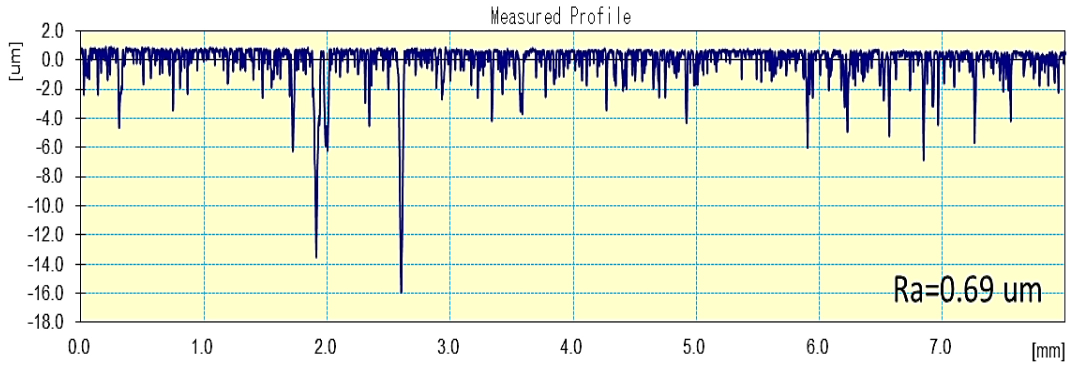
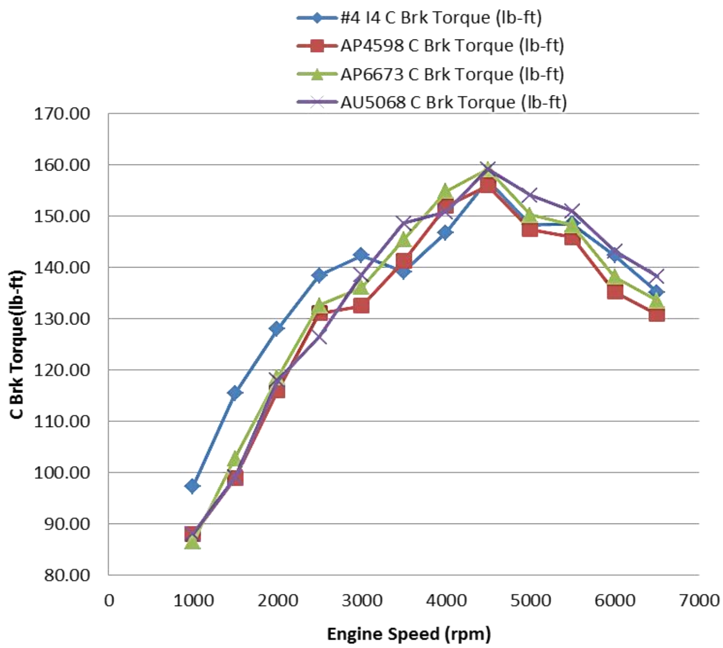


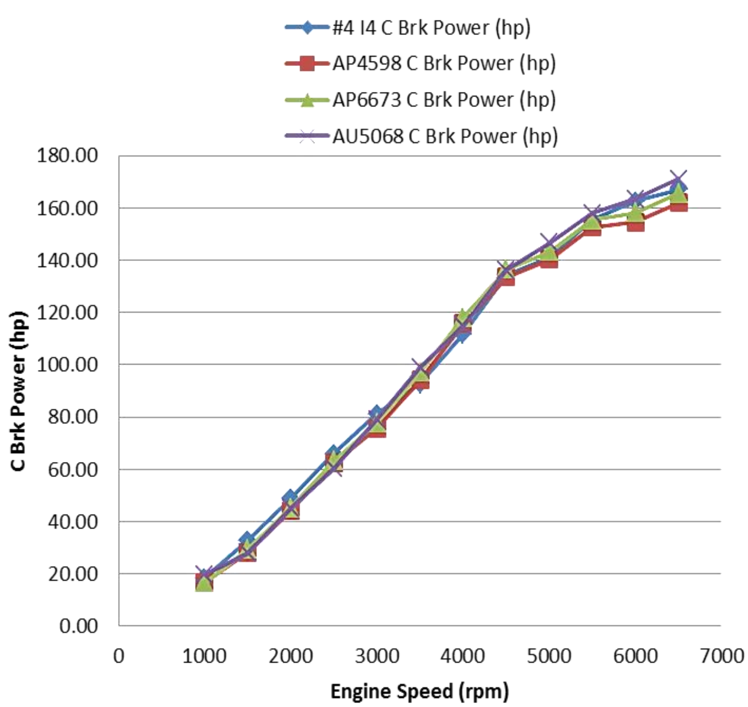
Figure 5-21. #4 EJPO coated engine coating roughness after dynamometer tests

All the measurements showed the EJPO coated bore size, piston to bore clearance, coating thickness and coating roughness didn't change obviously which meant the EJPO coating had high wear resistance and durability. The EJPO coating is a good candidate material to replace the traditional cast iron liners.

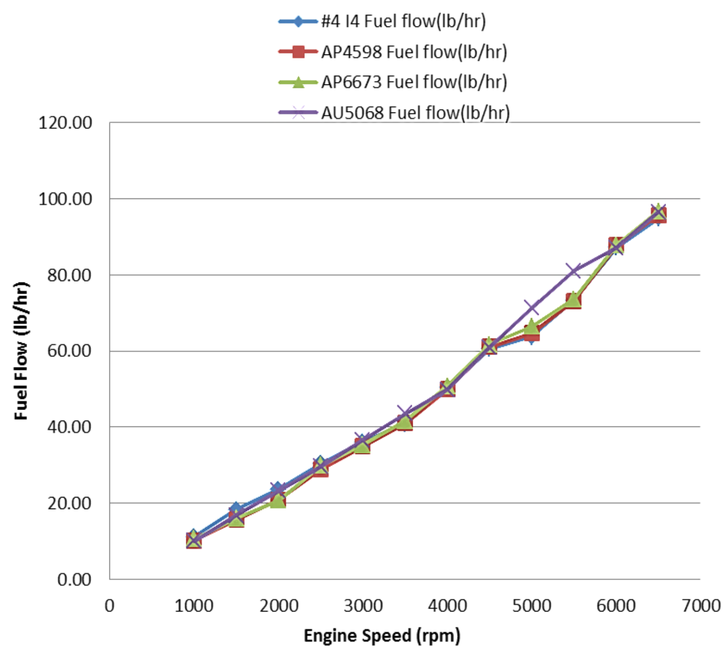
In order to prove the EJPO coating can enhance engine performance, the engine performance data of EJPO coated engine were compared with more other reference engines. The comparison showed the EJPO coated engine had a better performance than all other reference stock engines. The performance comparison data are shown in Figure 5-22.



#4 I4 C Brk Torque (lb-ft)
AP4598 C Brk Torque (lb-ft)
AP6673 C Brk Torque (lb-ft)
AU5068 C Brk Torque (lb-ft)
C Brk Torque(lb-ft)
170.00
160.00
150.00
140.00
130.00
120.00
110.00
100.00
90.00
80.00
0
1000
2000
3000
4000
5000
6000
7000
Engine Speed (rpm)



#4 I4 C Brk Power (hp)
AP4598 C Brk Power (hp)
AP6673 C Brk Power (hp)
AU5068 C Brk Power (hp)
C Brk Power (hp)
180.00
160.00
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0
1000
2000
3000
4000
5000
6000
7000
Engine Speed (rpm)



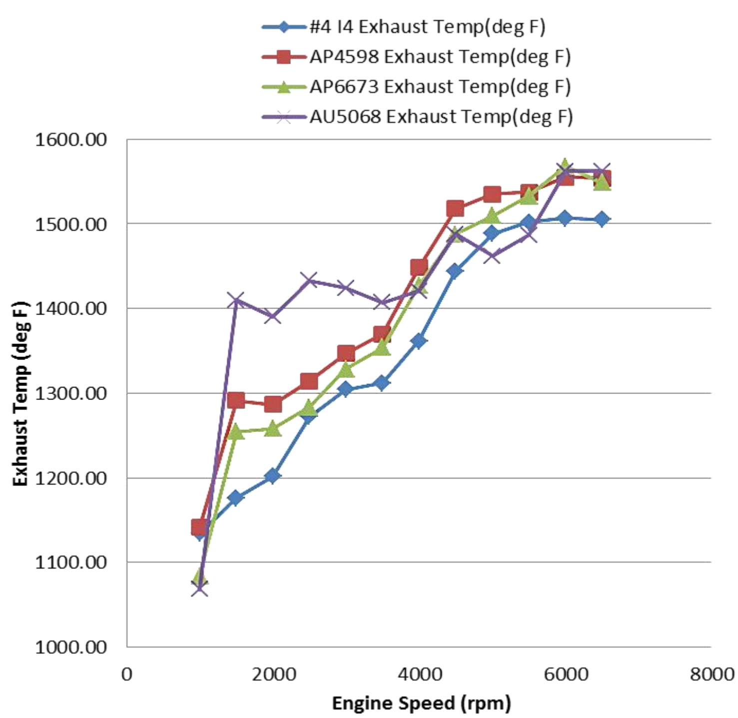


Figure 5-22. EJPO coated engine performance data compared with other stock reference engines

5.3.3 Conclusions

In conclusion, the #4 EJPO coated 2.0 L engine block was prepared same as the #3 engine. Diamond stone honed the cylinder bore size 5 ums bigger than the #3 engine block. The #4 EJPO coated 2.0 L engine passed Break-in test, Power test, 100 hours EFT test and Post Power test. During Power and Post Power test, EJPO coated engine had better performance at speeds lower than 3000 rpm and at speeds higher than 5000 rpm because of the low COF of the EJPO coating and temperature swing function of the EJPO coating. The lower friction and higher thermal efficiency enhanced engine performance. Cylinder bore size, coating thickness and roughness measurements after dynamometer tests showed EJPO coating had high wear and scuff resistance and the coating thickness and cylinder bore size changes were minor. Engine performance data comparison between EJPO coated engine and other reference engines proved EJPO coating could enhance engine performance especially at lower speeds.

5.4 Summary of the EJPO coated 2.0 L engine work

In the beginning of this work, the properties of EJPO coating including hardness, COF, thermal insulation were studied and tested in the lab. The EJPO coating was proved to have a higher hardness, lower COF and better thermal insulation. These properties made EJPO coating a possible candidate to be applied in the combustion engine to enhance engine performance. The corrosion resistance of the EJPO coating also promotes the EJPO coating to work with the biofuel in the future.

Flex brush honing process was studied on the EJPO coated aluminum liner and 2.0 L engine. The flex brush honing could the EJPO coating to the required roughness with the desired coating thickness. The flex brush honed engine test showed the flex brush honing couldn't provide a good cylinder bore roundness and straightness. Diamond stone machine honing was studied on EJPO coated 2.0 L engine block, the CMM measurement and the engine test showed the diamond stone machine honing could improve the cylinder bore roundness and straightness significantly, also mirror finished cylinder bore surface could be obtained.

The #1 EJPO coated 2.0 L engine test proved that EJPO coating S3 was harder than EJPO coating S12 and could meet the combustion functional requirements. EJPO coating S3 was selected to be used in this project.

The #2 EJPO coated 2.0 L engine test proved that flex brush honing could not provide a straight and round bore finish. A better honing source was needed. Diamond stone honing was introduced and learned. The diamond stone honing could provide a better straightness, roundness and a mirror finish surface. Diamond stone honing was selected to be used to hone the future EJPO coated engine blocks.

The #3 EJPO coated 2.0 L engine test proved that EJPO coating S3 and diamond stone honing worked well in combustion engine. Also, the Power test proved that EJPO coated engine had a better performance than regular stock cast iron liner engine especially at speeds lower than 3000 rpm and speeds higher than 5000 rpm. The highest engine performance enhancement was 11.29% at 1500 rpm. The lower COF and temperature swing property of EJPO coating helped to enhance the engine performance. The #3 EJPO coated engine failed at the end of the first cycle of EFT test, the piston to bore clearance was small at the top part of cylinder one. 5 ums more clearance was needed.

The #4 EJPO coated 2.0 L engine test proved that 30 ums piston to cylinder bore clearance was needed for engine durability test. This engine passed Break-in, Power, 100 hours EFT, and Post Power tests. The Power and Post Power test data showed EJPO coated engine had a better performance same as #3 EJPO coated engine. After tests the engine was torn down for analysis, the coating appearance, thickness, roughness measurements proved the coating didn't have obvious changes before and after the dynamometer engine tests. The measurements proved that EJPO coating had high wear resistance and high durability.

The #4 EJPO coated 2.0 L engine passed performance and durability tests, and base on this, the EJPO coating and honing parameters were learned and developed for the 2.0 L engine including EJPO coating S3 electrolyte, diamond stone machine honing process, piston to bore clearance (30 um), coating roughness (Ra<0.8 um, Rvk<2.0 um), and coating thickness (20 um). These parameters could be used as reference for the future EJPO coated 2.0 L engine.

Compared with 2.0 L cast iron liner engine, the EJPO coated 2.0 L engine can help to reduce weight by 3.96 pounds (6.4%) and reduce cost around 17.5%.

References

1. Hidemasa Kosaka, Yoshifumi Wakisaka, Yoshihiro Nomura, Concept of "Temperature Swing Heat Insulation" in Combustion Chamber Walls, and Approprite Thermal-Physical Properties for Heat Insulation Coat, SAE Int. J. Engine 6-1:142-149, 2013.

2. Xinwei Shen1 & Xueyuan Nie1 & Jimi Tjong2, Effects of electrolytic jet plasma oxidation (EJPO) coatings on thermal behavior of engine cylinders, Heat and Mass Transfer 55-n6, 9/6/2019.

6. Chapter 6 EJPO coating deposition and performance test for 5 .0 L engines

One of the ways to improve an automobile's fuel economy and efficiency by reducing vehicle weight, friction loss and increasing thermal efficiency simultaneously is to remove the cast iron cylinder liners and replace them with a lighter, low friction and more thermally efficient material.

Plasma Transferred Wire Arc (PTWA) coating is a kind of thermal spray coating and implemented by Ford Motor Company to spray the engine cylinder bore. The PTWA process melts or heat softens a material to particles, and the particles are propelled by a jet of process gases against the substrate [1]. Coating quality is determined by its porosity, oxide content, macro and micro-hardness, bond strength and surface roughness.

The PTWA coating reduces friction between the piston rings and the cylinder bores allowing the engine to build rotational speed quicker so that the motors produce more power. It also helps to reduce weight by 8.5 pounds on Ford's 5.0 L engine block compared with the traditional aluminum block with cast iron liners. The Fuel economy has also been increased by 5% over the old version engine [2]. PTWA coated engine is a successful production and continues up to now.

In the EJPO coated 2.0 L engine tests, it proved the EJPO coating was also a candidate material for the combustion engine cylinder bore. However, the EJPO coating's performance on a higher displacement engine which had higher combustion temperature, pressure, speed and higher cylinder bore distortion was never known, and it was interesting to compare the engine performance, weight, and manufacture cost between EJPO coated engine and PTWA coated engine. In this work, EJPO coating was applied on the 5.0 L engine cylinder bores to compare the weight, friction, engine performance and cost with the PTWA coated engine.

6.1 Properties comparison between EJPO coating and PTWA coating

6.1.1 Weight comparison

The coating thickness and the weight of the engine block with cast iron liner, PTWA coating and EJPO coating were measured and compared. The EJPO coating had the thinnest coating thickness and lowest weight. The pictures of the three kinds of engine block are shown in Figure 6-1, and the measurements are shown in Table 6-1.

Figure 6-1. Engine blocks with cast iron liners, PTWA coating, and EJPO coating

Table 6-1. 5.0 L engine block weight and coating thickness measurements

Engine blocks	Cast iron liner	PTWA	EJPO
Weight(lbs.)	96.9	88.4	86.6
Thickness(um)	2000	220	20

As shown in Table 6-1, the thinner EJPO coating could help to reduce the weight 1.8 pounds which was 2% weight reduction compared with PTWA coated engine block.

Weight affects the vehicle rolling resistance then affects the vehicle Mile per Gallon (MPG). Replacing cast iron liners with PTWA coating can reduce the weight by 8.5 pounds. The thickness of EJPO coating is 1/10 of PTWA coating thickness, which can help to reduce the weight by another 1.8 pounds (2%). This weight reduction can help to improve the MPG and fuel efficiency.

6.1.2 Cost comparison

PTWA coating is thermal spray coating, and the coating process consumes electricity power, feedstock material, plasma gas (Ar, H_2, He, or N_2), and the plasma torch needs maintenance or replacement. All these materials and maintenance will compose the cost of the PTWA coating process.

EJPO coating process is an electrical plating process, and it uses electricity power and electrolyte to generate the oxidation coating on metals. In the coating process, it consumes electricity power but not electrolyte. The main cost of the EJPO coating process is the cost of the electricity power.

Compared with PTWA coating process, the EJPO coating process can save cost around 9%.

6.1.3 PTWA and EJPO coating friction comparison

The Coefficient of Friction (COF) of PTWA and EJPO coatings was studied in lab tribological test. The EJPO coated ring-shape samples were prepared and polished to different surface roughness (Ra from 1.0 um to 0.3 um) and Rvk which affect the oil retention volume of the coating. The PTWA coating had a lower porosity, so the roughness was around 0.3 um.

In this work, the COF of EJPO coating with different surface roughness were tested and compared with the COF of PTWA coating. The triboligical tests were carried out under the same conditions. A high-speed pin-on-disc tribometer which is shown in Figure 6-2 was used to do the tribology test.

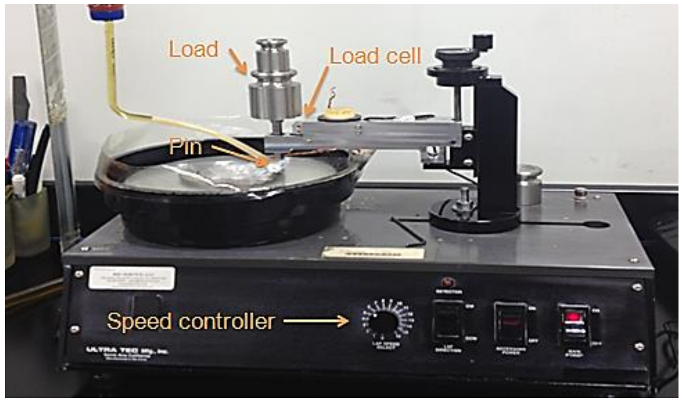


Figure 6-2. High speed pin-on-disc tribometer

Test results showed the COF Stribeck curve was formed during the high-speed tribology test. The COF of EJPO coating dropped much faster and earlier than PTWA coating when the sliding speed increased. At hydrodynamic lubrication EJPO coating had 50% lower COF than PTWA coating. The lowest COF of EJPO coating was 0.025, while the lowest COF of PTWA coating was 0.05 at hydrodynamic lubrication. The test results are shown in Figure 6-3.

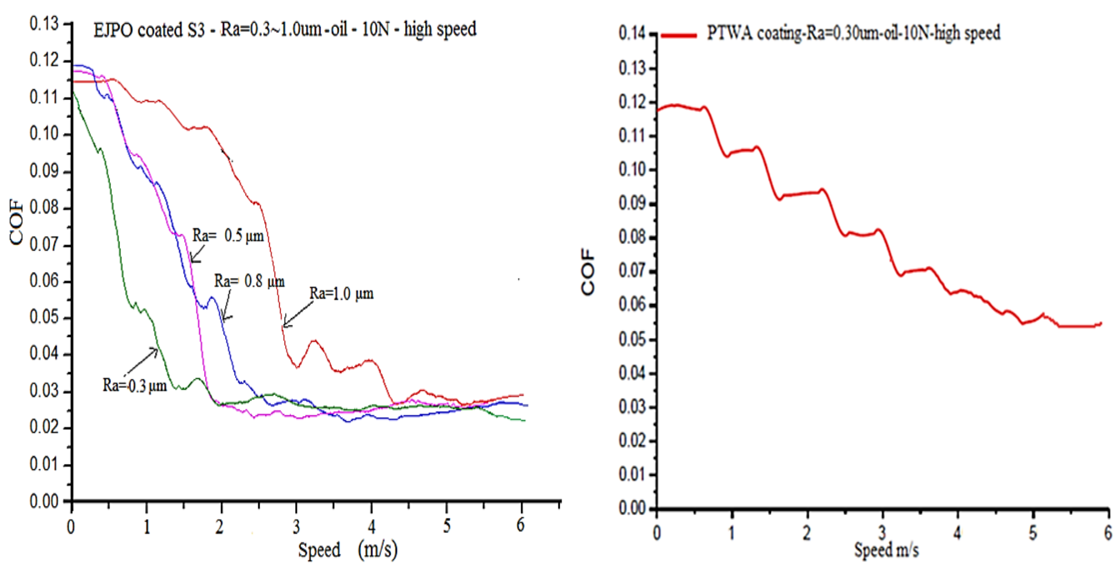


Figure 6-3. COF comparison between EJPO and PTWA coatings

As shown in Figure 6-3, the EJPO coating had much lower COF than PTWA coating even with the higher surface roughness at hydrodynamic lubrication. Besides, all the EJPO coatings with different roughness had higher COF drop rate than PTWA coating. Thus, during cylinder bore honing process, the EJPO coating roughness lower than 1.0 um would be good enough to have a better tribological property than PTWA coating.

Coating the surface with a higher oil retention volume would help to reduce the COF. In this work, the porosity of EJPO coating was increased during EJPO coating process to increase the oil retention volume. The oil retention volumes of EJPO and PTWA coatings were measured and shown in Table 6-2.

Table 6-2. Oil retention volume of EJPO and PTWA coating

Coating	Ra(um)	Rvk(um)	Mr2(%)	Vo(um3/um2)
EJPO	1.0	2.7	72	0.38
	0.8	2.1	71.5	0.31
	0.5	1.8	86.7	0.21
	0.3	1.6	83.7	0.13
PTWA	0.3	1.4	86	0.098

As shown in Table 6-2, all the EJPO coatings with different roughness had higher oil retention volume than the PTWA coating, and the high oil retention volume helped to build up the oil film between piston ring and cylinder wall to reduce the COF.

One piece of honed EJPO coated cylinder bore and a piece of honed PTWA coated cylinder bore were used to do the SEM analysis. The coating surface morphology of two kinds of coatings was investigated. The SEM images of the coating surface are shown in Figure 6-4.

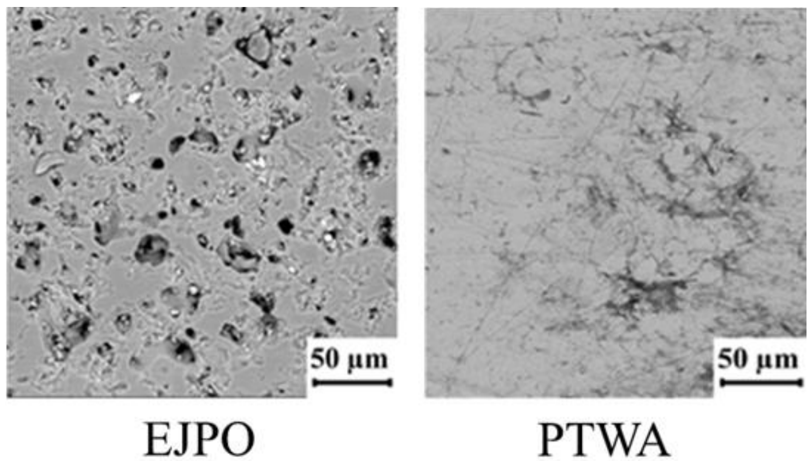


Figure 6-4. Surface morphology of the honed EJPO and PTWA coatings

As shown in Figure 6-4, EJPO coating had much higher porosity than PTWA coating. The surface roughness parameters in Table 6-2 were used to calculate the oil retention volume using the following formula:

$$V_0 = R_{vk}\,(100 - M_{r2})/200$$

Where V_0 is the oil retention parameter ($\mu m^3/\mu m^2$), R_{pk} 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.

$$\text{EJPO: } V_o = (100\text{-}75) \times 1.6/200 = 0.20\ \mu m^3/\mu m^2$$
$$\text{PTWA: } V_o = (100\text{-}86) \times 1.4/200 = 0.098\ \mu m^3/\mu m^2$$

EJPO coating had a much high oil retention volume, which was beneficial to reduce the engine friction loss and enhance engine performance.

6.1.4 Thermal swing function

In chapter 2, the literature review indicated that both EJPO and PTWA coatings had temperature swing function. The coating thickness affects the thermal swing function, the thicker coating has better temperature swing function, but the residual temperature in the combustion chamber is also high which is not desired, since the high residual temperature will reduce volume efficiency and also will heat up the intake air temperature and introduce knocks. The simulation showed EJPO coating had better temperature swing function and lower residual temperature with a thickness between 20 um and 30 um. In this way, the EJPO coating could help to reduce heat loss to cylinder wall without heating up the intake air temperature and enhance engine thermal efficiency.

In this work, EJPO coating was honed to 20 ~ 30 um thick to have a better thermal swing function with a lower residual heat.

6.1.5 Challenges

Compared to the 2.0 L I4 engine, EJPO coating and testing the 5.0 L V8 engine is challenging. The combustion temperature, pressure, peak engine speed and cylinder head torque are much higher than the I4 engine. The high combustion temperature and the high cylinder head torque will increase the aluminum cylinder bore distortion much more. To reduce this cylinder bore distortion or make the coating works with the distortion is challenging. The comparison of test conditions between I4 and V8 is shown in Table 6-3.

Table 6-3. Engine parameters between I4 and V8 engine

Displacement (L)	Speed (rpm)	No fire compression (psi)	Exhaust Temp (F)	Head bolt torque
2.0	6500	190	1400	35Nm+225degree
5.0	7400	315	1600	75Nm+240degree
Increment	13.80%	65.80%	14.30%	214%

As shown in Table 6-3, the 5.0 L cylinder head bolt torque is much higher. The EJPO coating is very thin and has no liner support, the higher cylinder head torque together with the higher combustion temperature will cause huge cylinder bore distortion. A better honing process to improve cylinder bore roundness and straightness or a stronger coating can help to reduce the EJPO coating failure in high displacement engine.

6.1.6 Conclusions

The weight of the EJPO coated and PTWA coated 5.0 L engine blocks were measured and compared. PTWA coating thickness was around 220 ums and EJPO coating thickness was around 30 ums. The thinner coating thickness helped the EJPO coated engine block reduce 1.8 pounds' weight, which was 2% weight reduction. Weight reduction can help to reduce the vehicle rolling resistance and increase fuel efficiency.

Compared with PTWA coating process, the EJPO coating process can save cost around 9%.

The COF of EJPO coating and PTWA coating were tested and compared and EJPO coating had much higher COF drop rate when speed increased and had 50% lower COF at hydrodynamic lubrication with surface roughness lower than 1.0 um, compared PTWA coating with a 0.3 um surface roughness which is production surface roughness. The oil retention volumes of both coatings were calculated and compared, EJPO coating had higher oil retention volume than PTWA coating with all the surface roughness lower than 1.0 um. After the EJPO coated cylinder bore honed, the coating would have better tribological properties when surface roughness was lower than 1.0 um. Lower COF can help to reduce the engine friction loss and thereby enhance engine performance.

High combustion temperature, high compression and high cylinder head bolt torque can increase the cylinder bore distortion for 5.0 L engine block.

6.2 EJPO coating deposition on 5.0 L engine cylinder bore and performance test

6.2.1 EJPO coating and honing process for 5.0 L engine block

The #1 EJPO coated 5.0 L engine block was fabricated with coating on cylinder bores. The aluminum cylinder bores were honed to 40 um bigger to make room for the coating growth. Coarser stones were used to hone to aluminum bore bigger and 800 Grit stone was used to finish the bore surface. The honed aluminum engine block is shown in Figure 6-5.

Figure 6-5. Oversize honed aluminum engine block

After honing, the aluminum engine block was washed, dried and installed on the EJPO coating machine for EJPO treatment. The EJPO coating process took 20 minutes and coating thickness grew up to 50 ums with a higher current density. The original coating roughness was around 3.8 um. Thickness meter and surface profile meter were used to check the coating uniformity, the EJPO coating thickness and roughness were similar all over the bore. The EJPO coated #1 engine block is shown in Figure 6-6.

Figure 6-6. EJPO coated #1 5.0 L engine block

Diamond stones were used to hone the #1 EJPO coated 5.0L engine block. There were two steps for honing the EJPO coated cylinder bore. First, a rough honing stone was used to remove the top loose coating by 10 um. Second, a fine honing was used to do the mirror finish honing. After the honing, the coating thickness was around 30 um and the cylinder bore size was honed to standard size, which made the piston to bore clearance was around 30 um. In this honing process, the two parameters used to control the honing process were coating thickness and coating roughness. The coating thickness must be around 30 um and the coating surface roughness had to be lower than 1.0 um and the Rvk should be less than 2.0 um.

The honing parameters and measurements are shown in Table 6-4.

Table 6-4. #1 EJPO coated engine honing parameters and measurements

Cylinder	cyl1	cyl2	cyl3	cyl4	cyl5	cyl6	cyl7	cyl8
Thickness(um)	26	28	27	30	32	28	26	29
Ra(um)	0.69	0.62	0.78	0.86	0.89	0.77	0.87	0.79
Rvk(um)	1.6	1.8	1.5	1.7	1.8	1.4	1.5	1.6
Mr2(%)	81	77	75	78	82	75	75	76
Bore size(mm)	93.017	93.019	93.018	93.016	93.011	93.015	93.018	93.018
Piston size(mm)	92.976	92.986	92.986	92.986	92.981	92.984	92.987	92.987
Clearance(mm)	0.031	0.033	0.032	0.030	0.030	0.031	0.031	0.031

The surface profiles of the honed #1 EJPO coated and PTWA coated cylinder bores are shown in Figure 6-7.

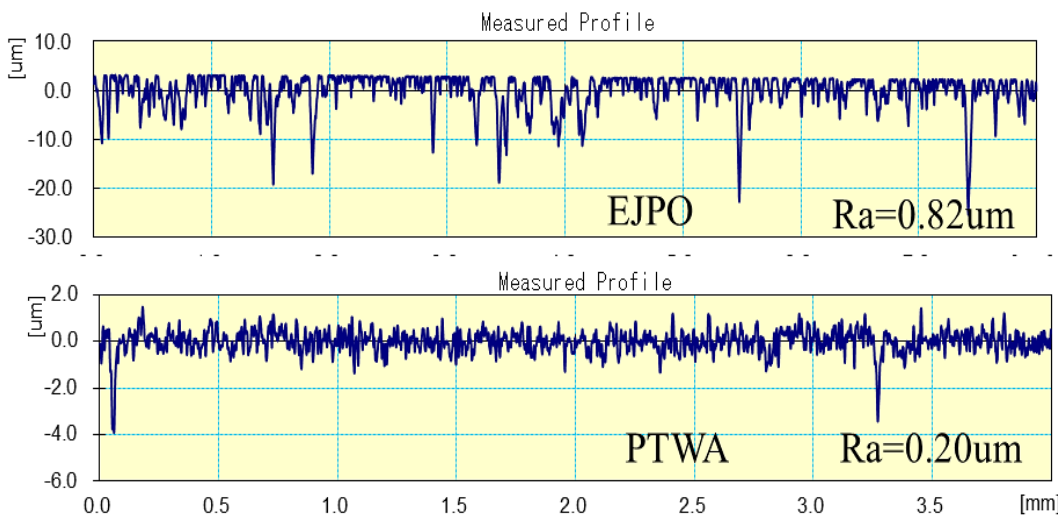


Figure 6-7. Surface profiles of the honed #1 EJPO coated and PTWA coated cylinder bore

As shown in Figure 6-7, the honed EJPO coated bore had a higher roughness with more deep pores and the honed PTWA coated bore had a lower roughness with less deep pores. This surface difference would make a big difference on the oil retention volume of the cylinder bore. In order to get a higher oil retention volume to reduce friction, the porosity of EJPO coating was increased during the EJPO coating process. The higher porosity would increase the surface roughness but would get higher oil retention volume with desired Rvk.

6.2.2 EJPO coated 5.0 L engine performance test

After the measurements were completed, the #1 EJPO coated engine was assembled to run 8 hours Break-in test and Power performance test. During the tests, no parameters were fixed like the spark timing, air fuel ratio, and fuel flow, the engine was running by its own control.

The power test data were used to do the engine performance comparison between EJPO coated engine and PTWA coated engine. Power data showed EJPO coated engine made higher torque and power at speeds lower than 3000 rpm, and lower output at higher speeds. The selected power test data are shown as follows:

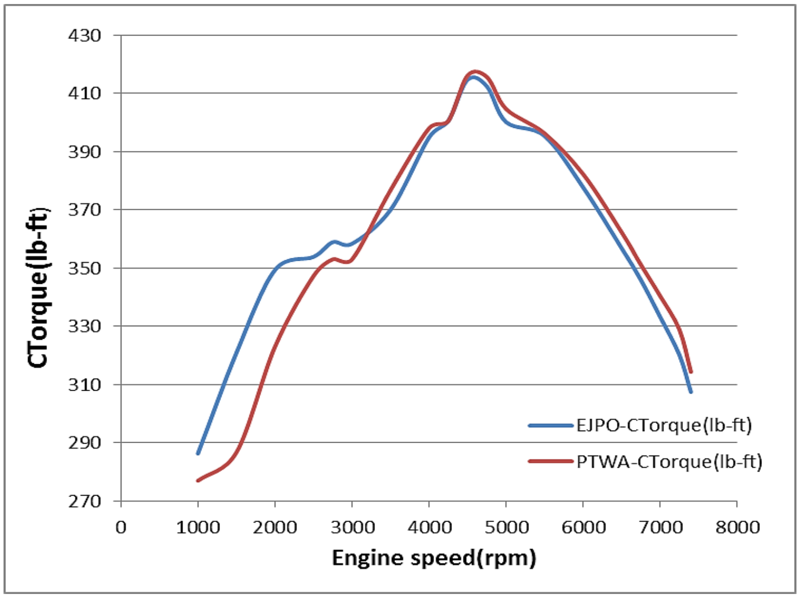


Figure 6-8. Corrected torque comparison between #1 EJPO and PTWA engines

Table 6-5. Corrected torque data from #1 EJPO and PTWA engines

Speed(rpm)	EJPO C-Torque (lb-ft)	PTWA C-Torque (lb-ft)	Increment (%)
1000	286	277	3.38
1500	321	287	11.95
2000	349	323	8.14
2500	354	347	1.88
2750	359	353	1.67
3000	358	353	1.53
3500	370	377	-1.80
4000	395	398	-0.78
4250	401	401	0.00
4500	415	416	-0.34
4750	412	416	-0.77
5000	400	405	-1.11
5500	395	396	-0.23
6000	378	382	-1.19

Speed(rpm)	EJPO C-Torque (lb-ft)	PTWA C-Torque (lb-ft)	Increment (%)
6500	357	362	-1.51
6750	346	351	-1.49
7000	333	340	-2.11
7250	320	329	-2.64
7400	307	314	-2.19

EJPO coated engine made higher torque at speeds lower than the 3000 rpm, the highest output enhancement was 11.95% at 1500 rpm. After 3000 rpm, EJPO coated engine made less torque than PTWA coated engine, and the highest output decrement was 2.64% at 7250 rpm.

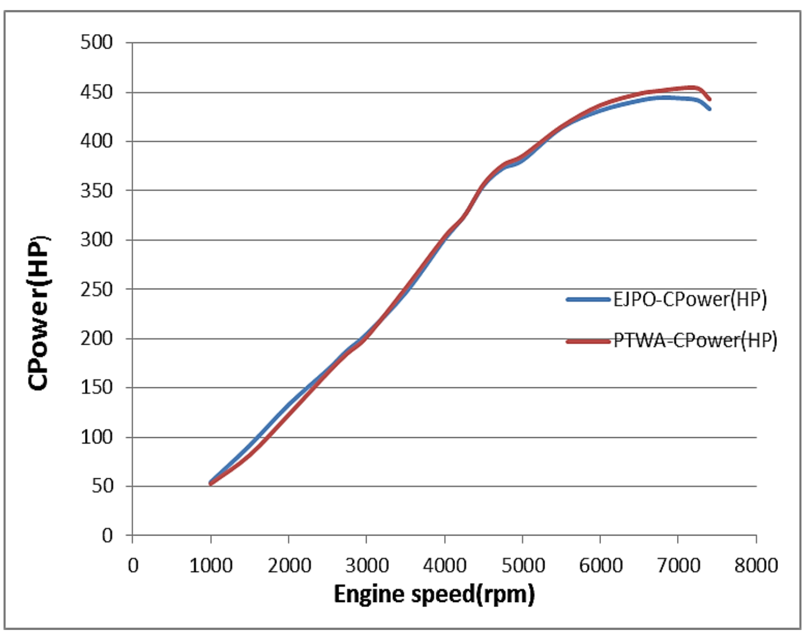


Figure 6-9. Corrected power comparison between #1 EJPO and PTWA engines

Table 6-6. Corrected power data from #1 EJPO and PTWA engines

Speed(rpm)	EJPO C-Power (HP)	PTWA C-Power (HP)	Increment (%)
1000	54	53	3.19
1500	92	82	12.06
2000	133	123	8.25
2500	169	165	1.87
2750	188	185	1.64
3000	205	202	1.48
3500	247	251	-1.84
4000	301	303	-0.84
4250	324	324	-0.05
4500	355	357	-0.40
4750	373	376	-0.82
5000	381	385	-1.15
5500	414	415	-0.27
6000	432	437	-1.22
6500	442	449	-1.54
6750	445	451	-1.52
7000	444	454	-2.14
7250	442	454	-2.68
7400	433	443	-2.23

The power output trend was similar to the torque output, since the power was calculated using the torque by the equation of Power = Torque x RPM / 5252. The highest power enhancement was 12.06% at 1500 rpm, and the highest power decrement was 2.68% at 7250 rpm.

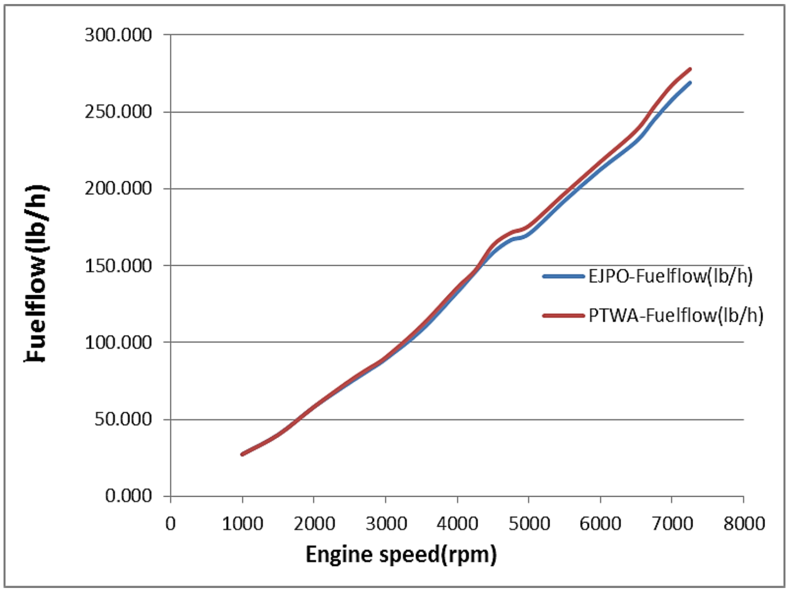


Figure 6-10. Fuel flow comparison between #1EJPO and PTWA engines

Table 6-7. Fuel flow data from #1EJPO and PTWA engines

Speed(rpm)	EJPO Fuelflow (lb/h)	PTWA Fuelflow (lb/h)	Increment (%)
1000	54	53	3.19
1500	92	82	12.06
2000	133	123	8.25
2500	169	165	1.87
2750	188	185	1.64
3000	205	202	1.48
3500	247	251	-1.84
4000	301	303	-0.84
4250	324	324	-0.05
4500	355	357	-0.40
4750	373	376	-0.82
5000	381	385	-1.15
5500	414	415	-0.27

Speed(rpm)	EJPO Fuelflow (lb/h)	PTWA Fuelflow (lb/h)	Increment (%)
6000	432	437	-1.22
6500	442	449	-1.54
6750	445	451	-1.52
7000	444	454	-2.14
7250	442	454	-2.68
7400	433	443	-2.23

Fuel flow data showed the EJPO coated engine had higher fuel consumption than PTWA engine at speeds lower than 1500 rpm, and other speeds had lower fuel consumption.

Fuel injection is a main factor that affects the engine output. In this work, the fuel injection or fuel flow was not fixed, and the engine powertrain control module (PCM) controlled it. PCM monitored the engine combustion conditions and made the adjustment.

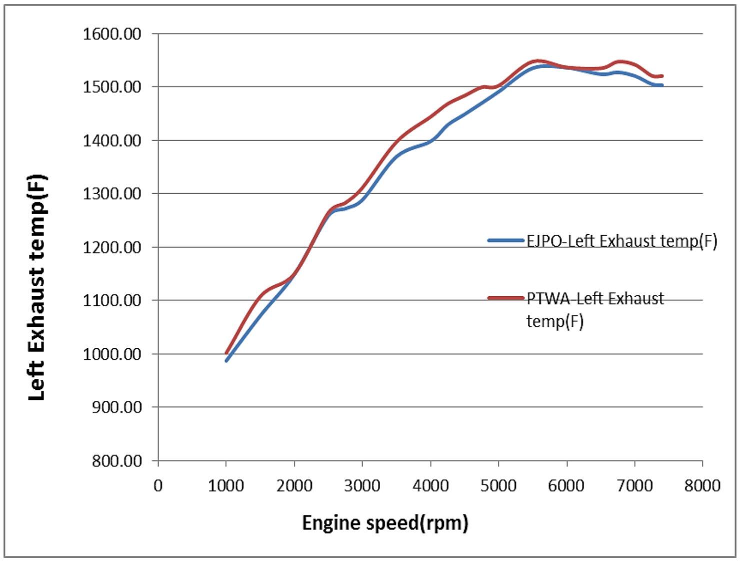


Figure 6-11. Left exhaust temperature comparison between #1 EJPO and PTWA coated engines

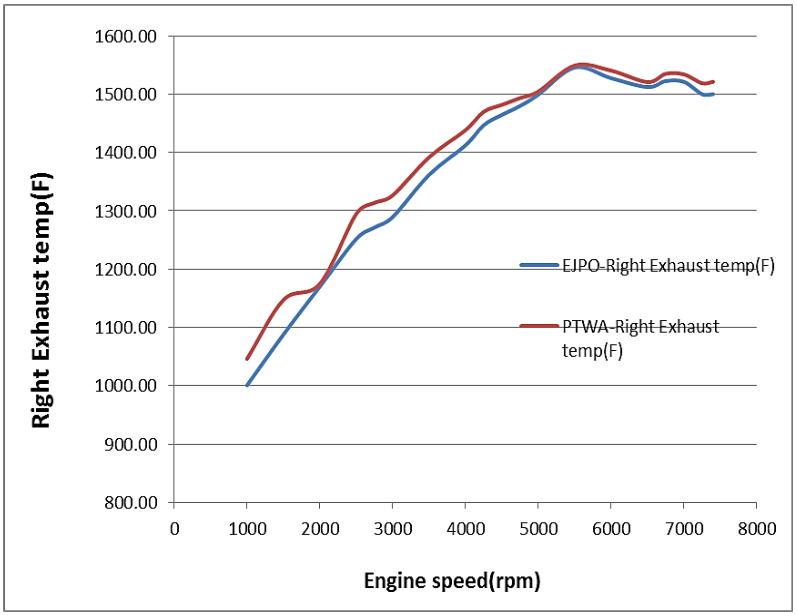


Figure 6-12. Right exhaust temperature comparison between #1 EJPO and PTWA coated engines

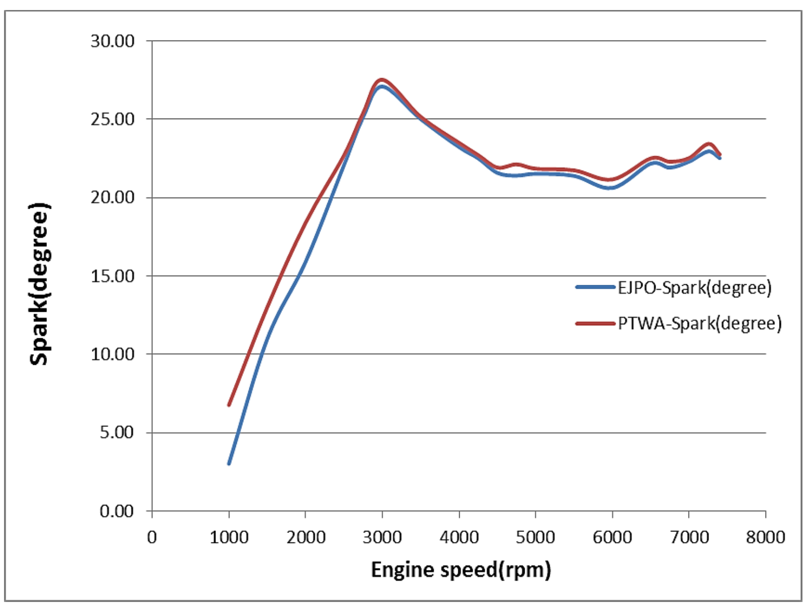


Figure 6-13. Spark timing comparison between #1 EJPO and PTWA coated engines

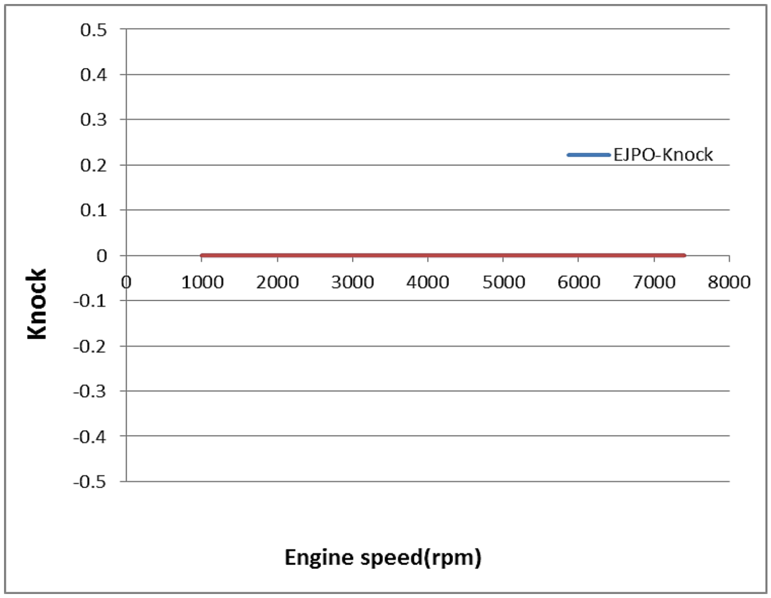


Figure 6-14. Engine knockl comparison between #1 EJPO and PTWA coated engines

During the power test, there was no knock happened. EJPO coated engine had lower exhaust temperature than PTWA coated engine and had retarded spark timing at all speeds. The PCM and knock sensor detected the potential knock and retarded the sparking timing to avoid the engine knocks. The retarded spark timing would reduce the engine power output. In this power test, even with retarded spark timing, the EJPO coated engine still made higher power at speeds lower than 3000 rpm. This higher power output should be gained from the lower friction and better thermal management. The engine friction was tested by dynamometer motoring friction test and the thermal efficiency was calculated based on the fuel flow and power output.

After the Power test, the dynamometer motoring friction test was performed on both EJPO coated and PTWA coated engines. This friction test used the dynamometer to motor the unfired engine and measure the resistant torque, the more negative the torque was, the higher friction the engine had. The measured dynamometer motoring torque and the comparison plot are shown in Figure 6-15 and Table 6-8.

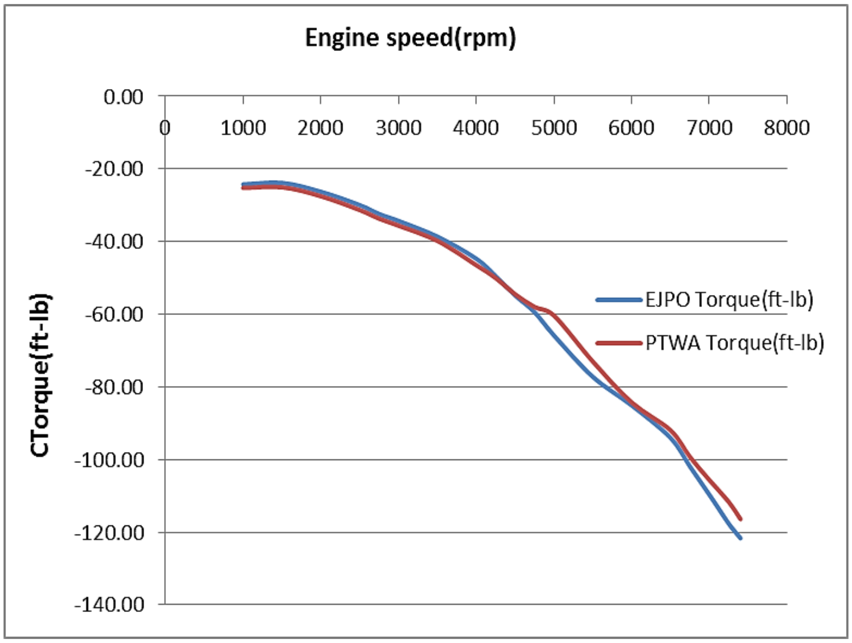


Figure 6-15. Results of the dynamometer motoring friction test

Table 6-8. Dynamometer motoring friction torque from #1 EJPO and PTWA coated engines

Speed(rpm)	EJPO friction torque (ft-lb)	PTWA friction torque (ft-lb)	Increment (%)
7400	-121.65	-116.39	-4.51
7250	-117.65	-111.70	-5.33
7000	-109.67	-105.62	-3.83
6750	-101.87	-99.26	-2.63
6500	-94.04	-91.96	-2.26
6000	-85.09	-84.29	-0.95
5500	-77.23	-73.02	-5.77

Speed(rpm)	EJPO friction torque (ft-lb)	PTWA friction torque (ft-lb)	Increment (%)
5000	-65.82	-60.35	-9.05
4750	-59.43	-58.00	-2.47
4500	-54.82	-54.50	-0.59
4250	-49.57	-50.05	0.96
4000	-44.73	-46.47	3.74
3500	-38.64	-39.79	2.88
3000	-34.34	-35.60	3.54
2750	-32.43	-33.67	3.69
2500	-29.97	-31.31	4.29
2000	-26.28	-27.50	4.42
1500	-23.85	-25.03	4.70
1000	-24.26	-25.21	3.78

As shown in Figure 6-15 and Table 6-8, at speeds lower than 4500 rpm, the EJPO coated engine had less motoring torque, which meant the EJPO coated engine had less friction at those speeds. Speed higher than 4500 rpm, the EJPO coated engine had higher friction than PTWA coated engine. Compared with the PTWA coated engine, the highest friction reduction was gained at 1500 rpm, which was 4.70%.

The engine’s thermal efficiency was also calculated based on fuel consumption and power output. It was calculated using the following formulas:

Engine thermal efficiency = Power (KW) / Input fuel energy (KW)

Input fuel energy = Fuel flow (g/s) x LHV (KJ/g)

(In this work, LHV=42.9 kJ/g)

The calculated thermal efficiencies of EJPO and PTWA coated engines are shown in Table 6-9.

Table 6-9. The thermal efficiency calculation and comparison between #1 EJPO and PTWA coated engines

Speed (rpm)	EJPO			PTWA			Increment (%)
	Power (kw)	Fuelflow (g/s)	Thermal efficiency (%)	Power (kw)	Fuelflow (g/s)	Thermal efficiency (%)	
1000	41	3.44	27.94	39	3.44	26.65	3.12
1500	68	5.05	31.58	61	5.04	28.22	11.91
2000	99	7.33	31.55	92	7.34	29.12	8.34
2500	126	9.33	31.40	123	9.47	30.35	3.46
2750	140	10.28	31.77	138	10.43	30.81	3.12
3000	153	11.26	31.60	150	11.38	30.81	2.57
3500	184	13.62	31.47	187	13.98	31.25	0.71
4000	224	16.74	31.23	226	17.09	30.84	1.26
4250	242	18.38	30.65	242	18.51	30.45	0.64
4500	265	19.97	30.93	266	20.58	30.13	2.65
4750	278	21.01	30.86	280	21.60	30.27	1.96
5000	284	21.50	30.79	287	22.17	30.22	1.92
5500	309	24.24	29.69	310	24.82	29.07	2.14
6000	322	26.79	28.00	326	27.42	27.69	1.11
6500	329	29.09	26.39	334	29.99	26.00	1.49
6750	331	30.87	25.03	337	31.93	24.58	1.86
7000	331	32.51	23.74	338	33.72	23.40	1.48
7250	330	33.90	22.66	339	35.02	22.54	0.53
7400	323	34.69	21.70	330	35.62	21.62	0.40

As shown in Table 6-9, the EJPO coated engine had higher thermal efficiency through all the speeds. The highest thermal efficiency increment was gained at 1500 rpm, which was 11.91%.

The engine friction test showed the EJPO coated engine had less friction at speeds lower than 4500 rpm, and the thermal efficiency analysis showed the EJPO coated engine had higher thermal efficiency at all speeds. However, the EJPO coated engine only had higher power output at speeds lower than 3000 rpm. The internal combustion was very complicated and combined components friction, combustion temperature, thermal efficiency, spark timing and other factors, the EJPO coated engine only made higher power output at speeds lower than 3000 rpm.

After the engine tests were completed, the EJPO coated engine was removed from the test cell and torn down to check the coating conditions. The tested cylinder bore pictures are shown in Figure 6-16.

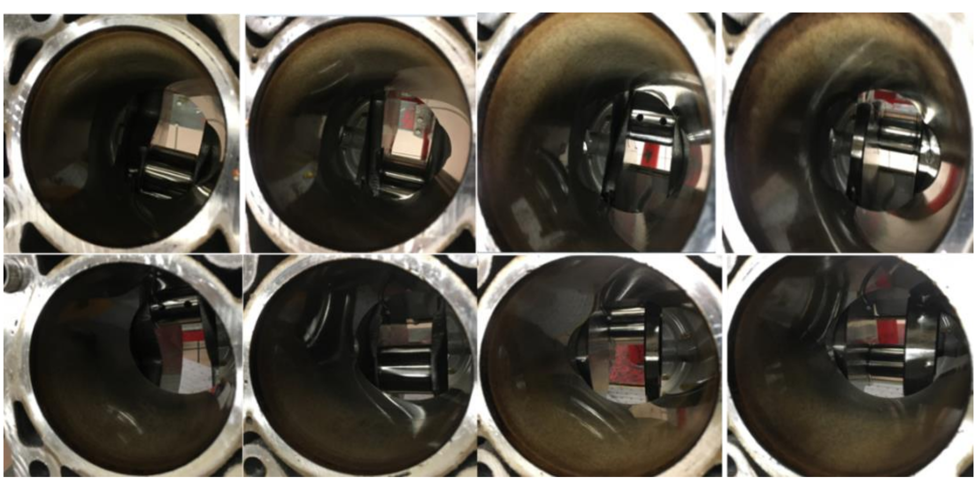


Figure 6-16. #1 EJPO coated cylinder bore after Break-in and Power tests

The tear down pictures showed the EJPO coated cylinder bores were shinning and smooth, no scuffs were on the coating. The coating thickness, surface roughness and piston to bore clearance worked for the 5.0 L engine, and these parameters would be used as reference for the future 5.0 L engine block coating and honing process.

The tear down investigation also found there were some minor wear signs on the camshaft journal and camshaft bore surface. There was no bearing between the camshaft journal and camshaft bore. The camshaft and camshaft bore are shown in Figure 6-17.

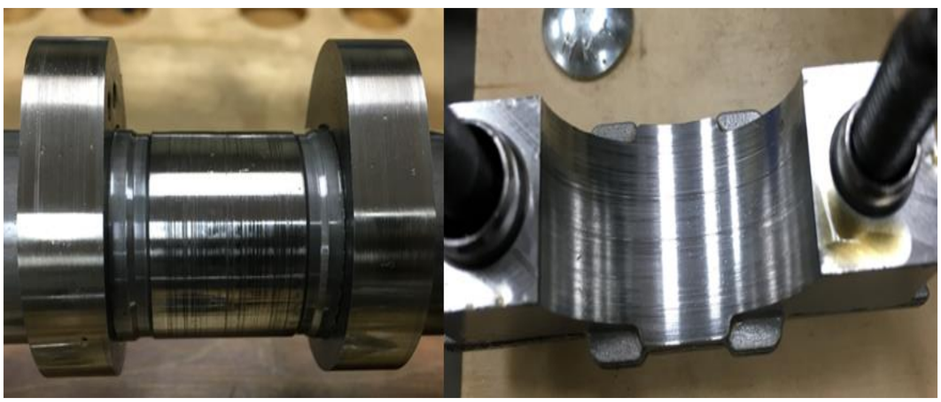


Figure 6-17. Camshaft and camshaft bore after Break-in and Power test

As shown in Figure 6-17, both camshaft journal and camshaft bore had minor wear signs. These minor wears might increase the friction between camshaft and camshaft bore. However, the PTWA coated engine also had these minor wears and never caused any problem or failure.

For research purpose EJPO coating can be applied on the camshaft bore surface to increase the surface hardness and reduce wear and friction. A special mask and spray head were designed and manufactured for the camshaft bore EJPO coating process. The EJPO coated camshaft bore would be tested on #2 EJPO coated engine.

6.2.3 Conclusions

The EJPO coated engine passed 8 hours dynamometer Break-in test and Power test. During the Power test, EJPO coated engine had better performance at speeds lower than 3000 rpm. The highest performance enhancement was at 1500 rpm, which was 11.95%.

The engine friction was tested by using the dynamometer motored the unfired engine. The results of the engine friction test showed EJPO coated engine had less friction at speeds lower than 4500 rpm compared with PTWA coated engine, the highest friction reduction was at 1500 rpm, which was 4.70%.

The engine thermal efficiency was calculated by using fuel consumption and power output, the calculation showed EJPO coated engine had higher thermal efficiency at overall speeds compared with PTWA coated engine. The highest thermal efficiency increment was at 1500 rpm, which was 11.91%.

During the Power test, the knock sensors and the PCM controlled the engine and retarded the spark timing at all speeds to avoid the engine knocks. The retarded spark timing would reduce the engine power output, but the lower coating friction and the better temperature swing property helped EJPO coated engine made higher power output at speeds lower than 3000 rpm. This engine performance enhancement is good for the vehicle daily drive which engine speed is lower than 3000 rpm most of the time.

After the tests, some minor wears were found on the camshaft bores and camshaft journals, the aluminum camshaft bores could be EJPO coated to reduce wear and friction.

6.3 Performance test on the fully coated combustion chambers of a 5.0 L engine

The #2 EJPO coated 5.0 L engine block was fabricated with EJPO coating on cylinder bores, camshaft bores, piston crown and cylinder head dome. The EJPO coatings on the cylinder bore and camshaft bore were used to reduce friction, and the EJPO coatings on the piston crown and cylinder head dome were used to enhance the engine thermal efficiency. The #2 EJPO coated engine was used to run Power performance test and compared with PTWA coated engine and #1 EJPO coated engine.

6.3.1 Performance comparison between EJPO and PTWA coated engines

The #2 5.0 L engine block was coated and honed same as #1 EJPO coated engine block. The coating thickness was around 30 um, the piston to bore clearance was around 30 um, coating surface roughness was around 0.8 um. The honing results are shown in Table 6-10.

Table 6-10. #2 EJPO coated engine block honing results

Cylinder	cyl1	cyl2	cyl3	cyl4	cyl5	cyl6	cyl7	cyl8
Thickness(um)	29	30	27	30	28	28	27	28
Ra(um)	0.71	0.72	0.76	0.77	0.81	0.79	0.80	0.72
Rvk(um)	1.6	1.8	1.9	1.9	2.0	2.0	2.1	1.7
Bore size(mm)	93.020	93.020	93.020	93.019	93.015	93.019	93.019	93.023
Piston size(mm)	92.988	92.989	92.980	92.987	92.984	92.986	92.988	92.983
Clearance(mm)	0.032	0.031	0.030	0.032	0.031	0.033	0.031	0.030

The honed EJPO coated engine block, and other EJPO coated components are shown in Figure 6-18.

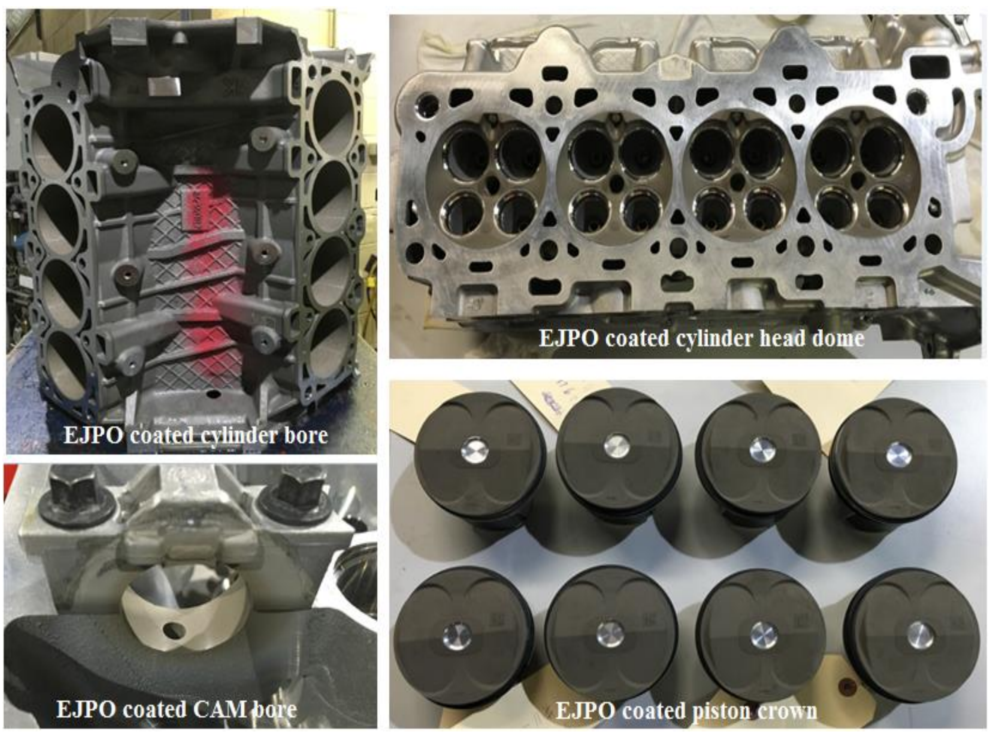


Figure 6-18. Honed EJPO coated engine block and EJPO coated camshaft bore, cylinder head dome, and piston crown

The #2 EJPO coated engine was assembled with cylinder bore coating, camshaft bore coating, piston crown coating and cylinder head dome coating, and scheduled to run dynamometer Break-in test and Power performance test. The Power test data was used for engine performance analysis compared with PTWA coated engine. Some of the Power comparison data are shown in the following figures and tables.

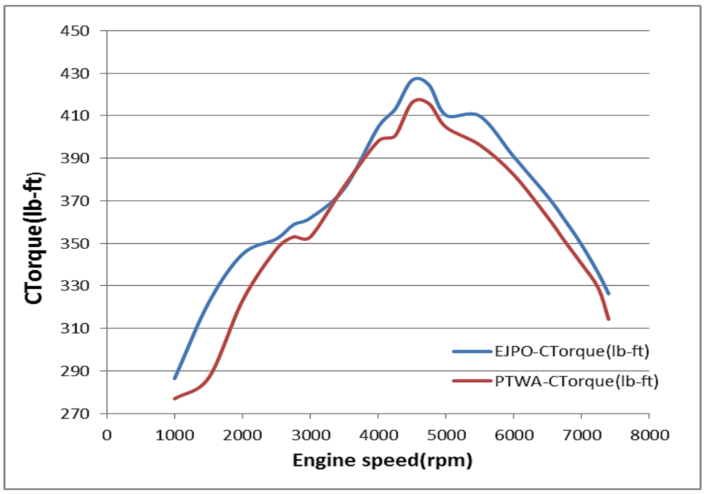


Figure 6-19. Corrected torque comparison between #2 EJPO and PTWA engines

Table 6-11. Corrected torque data from #2 EJPO and PTWA engines

Speed(rpm)	EJPO C-Torque (lb-ft)	PTWA C-Torque (lb-ft)	Increment (%)
1000	286	277	3.44
1500	322	287	12.33
2000	345	323	6.76
2500	352	347	1.38
2750	359	353	1.62
3000	362	353	2.53
3500	376	377	-0.29
4000	405	398	1.65

Speed(rpm)	EJPO C-Torque (lb-ft)	PTWA C-Torque (lb-ft)	Increment (%)
4250	413	401	3.11
4500	427	416	2.53
4750	425	416	2.13
5000	410	405	1.38
5500	410	396	3.43
6000	391	382	2.23
6500	372	362	2.69
6750	361	351	2.85
7000	349	340	2.64
7250	336	329	2.13
7400	326	314	3.82

EJPO coated engine made higher torque at all speeds except at 3500 rpm where EJPO coated engine made 0.29% lower torque than PTWA coated engine. The highest torque enhancement was 12.33% at 1500 rpm.

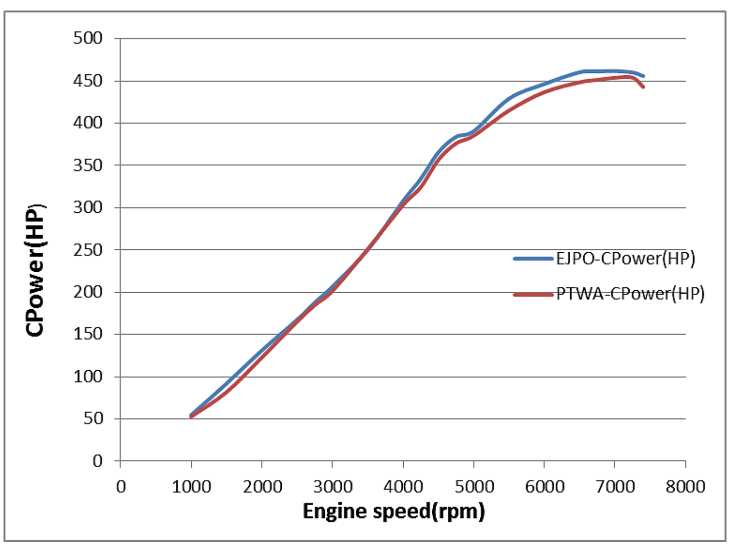


Figure 6-20.Corrected power comparison between #2 EJPO and PTWA engines

Table 6-12. Corrected power data from #2 EJPO and PTWA engines

Speed(rpm)	EJPO C-Power (HP)	PTWA C-Power (HP)	Increment (%)
1000	55	53	3.57
1500	92	82	12.35
2000	131	123	6.75
2500	168	165	1.33
2750	188	185	1.60
3000	207	202	2.49
3500	250	251	-0.36
4000	308	303	1.56
4250	334	324	3.07
4500	366	357	2.48
4750	384	376	2.08
5000	391	385	1.34
5500	429	415	3.39
6000	446	437	2.21
6500	460	449	2.65
6750	461	451	2.22
7000	462	454	1.76
7250	460	454	1.32
7400	456	443	2.93

The power output of the EJPO coated engine was similar to torque, and the highest power enhancement was 12.35% at 1500 rpm.

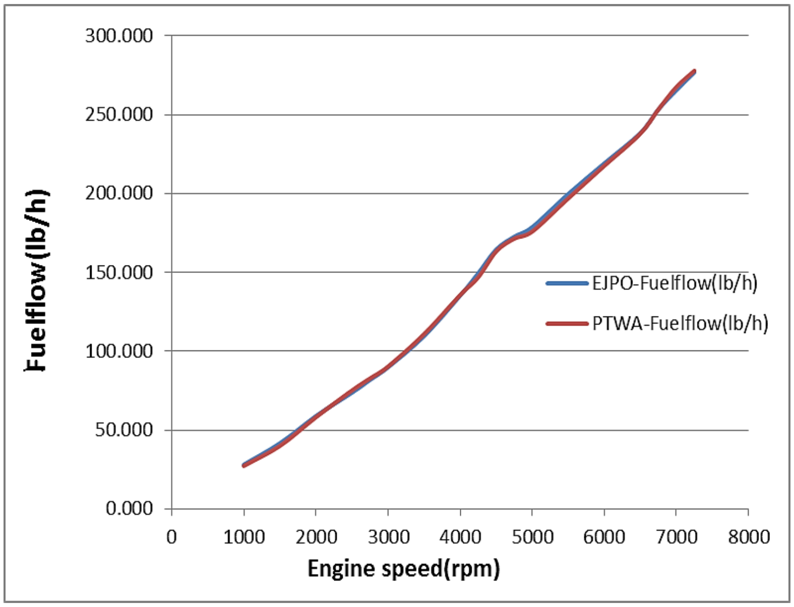


Figure 6-21. Fuel flow comparison between #2 EJPO and PTWA engines

Table 6-13. Fuel flow data from #2 EJPO and PTWA engines

Speed(rpm)	EJPO Fuel flow (lb/h)	PTWA Fuel flow (lb/h)	Increment (%)
1000	28.087	27.288	2.92
1500	41.670	40.002	4.17
2000	58.962	58.257	1.21
2500	73.837	75.183	-1.79
2750	81.899	82.809	-1.10
3000	89.871	90.298	-0.47
3500	109.704	110.946	-1.12
4000	135.292	135.654	-0.27
4250	149.425	146.907	1.71
4500	164.567	163.369	0.73
4750	172.631	171.415	0.71
5000	178.728	175.963	1.57
5500	199.786	197.008	1.41

Speed(rpm)	EJPO Fuel flow (lb/h)	PTWA Fuel flow (lb/h)	Increment (%)
6000	219.157	217.630	0.70
6500	238.362	237.991	0.16
6750	253.378	253.378	0.00
7000	265.596	267.596	-0.75
7250	276.923	277.923	-0.36
7400	280.689	282.689	-0.71

Fuel flow data showed the #2 EJPO coated engine had similar fuel consumption with PTWA engine, and higher fuel flow at speeds lower than 2000 rpm, and speeds between 4250 rpm and 6500 rpm. Fuel flow affected power output and higher fuel flow would make higher power output. In this work, fuel flow was not fixed, and it was adjusted by the engine PCM itself.

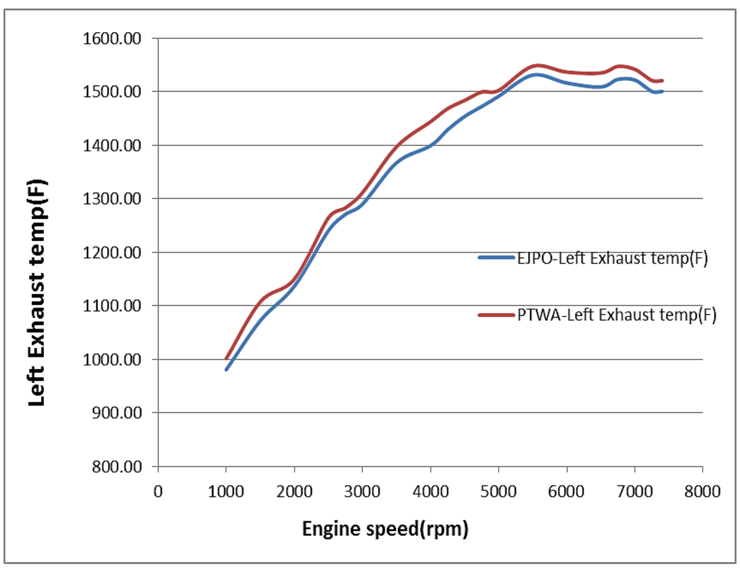


Figure 6-22. Left exhaust temperature comparison between #2 EJPO and PTWA engines

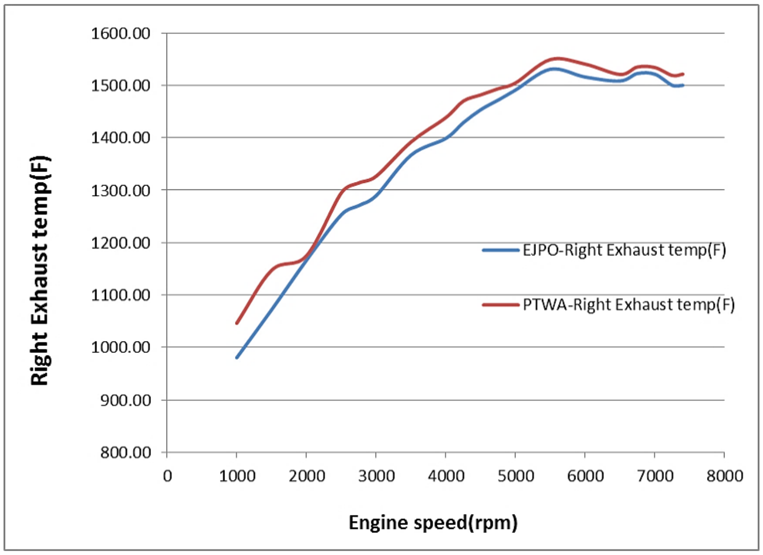


Figure 6-23. Right exhaust temperature comparison between #2 EJPO and PTWA engines

Compared with PTWA coated engine, EJPO coated engine had lower exhaust temperatures on both sides. The heat in the exhaust gas is a waste of energy, and the lower exhaust heat waste is desired to get a higher thermal efficiency.

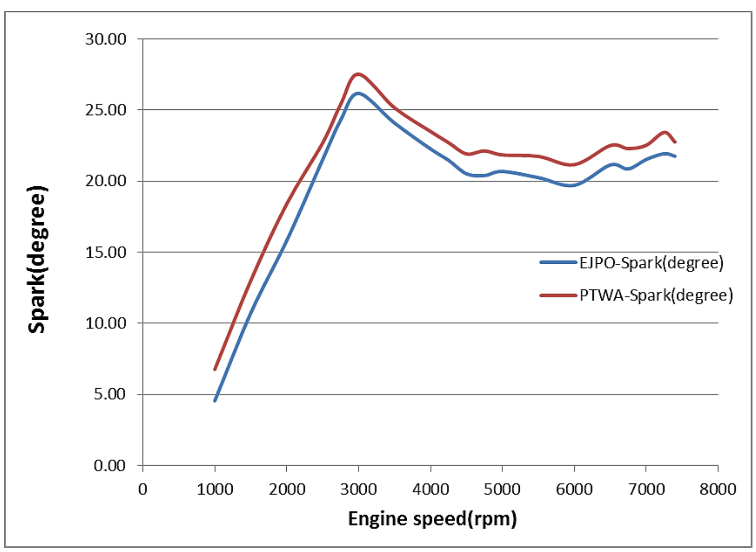


Figure 6-24. Spark timing comparison between #2 EJPO and PTWA engines

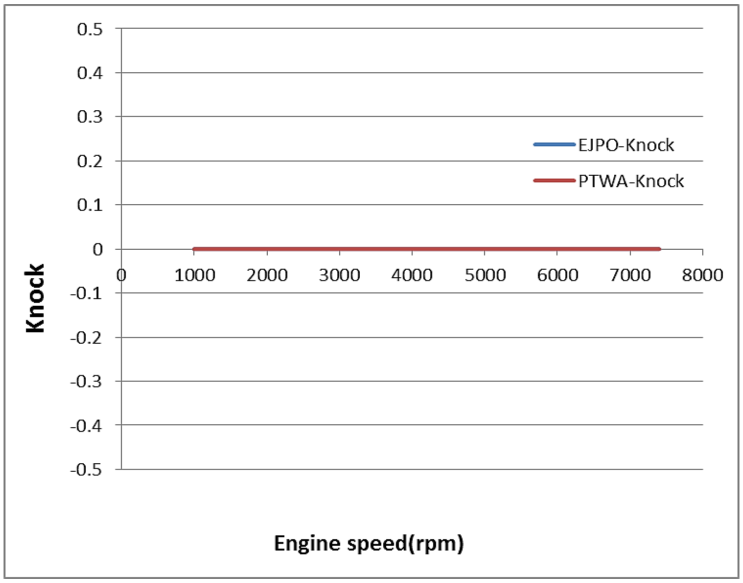


Figure 6-25. Engine knock comparison between #2 EJPO and PTWA engines

Similar to #1 EJPO coated engine, there was no engine knock happened during the Power test, and spark timing was retarded at all speeds. Retarded sparking timing helped to reduce the knock, but also reduced the engine power output theoretically.

After the Power test, the engine friction test was carried out on the dynamometer by motoring the unfired engine. The more negative the torque was, the higher friction the engine had. The measured dynamometer motoring torque and the comparison plot are shown in Figure 6-26 and Table 6-14.

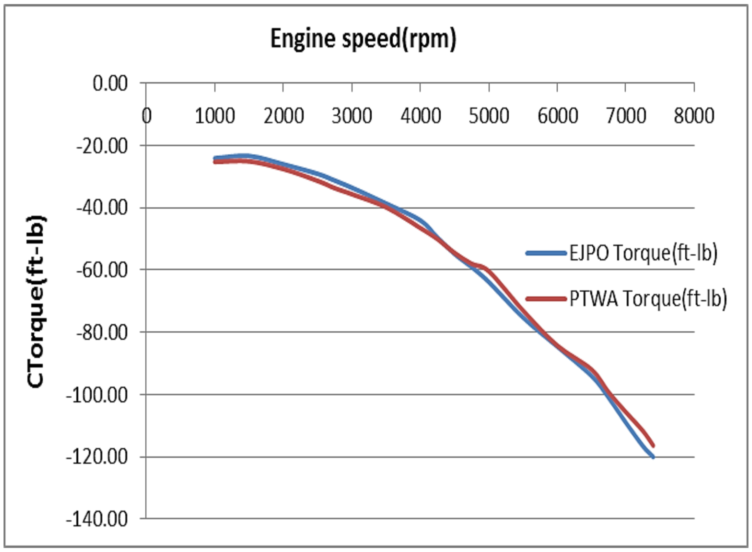


Figure 6-26. Results of the dynamometer motoring friction test

Table 6-14. Dynamometer motoring friction torque from #2 EJPO and PTWA coated engines

Speed(rpm)	EJPO motoring torque (ft-lb)	PTWA motoring torque (ft-lb)	Increment (%)
7400	-120.05	-116.39	-3.14
7250	-116.55	-111.70	-4.34
7000	-109.00	-105.62	-3.20
6750	-101.00	-99.26	-1.76
6500	-94.00	-91.96	-2.22
6000	-84.59	-84.29	-0.36
5500	-75.23	-73.02	-3.03
5000	-63.82	-60.35	-5.74
4750	-59.03	-58.00	-1.78
4500	-54.82	-54.50	-0.59
4250	-49.57	-50.05	0.96
4000	-44.03	-46.47	5.24
3500	-38.64	-39.79	2.88

Speed(rpm)	EJPO motoring torque (ft-lb)	PTWA motoring torque (ft-lb)	Increment (%)
3000	-33.54	-35.60	5.79
2750	-31.23	-33.67	7.25
2500	-29.07	-31.31	7.17
2000	-26.02	-27.50	5.37
1500	-23.35	-25.03	6.70
1000	-24.06	-25.21	4.57

As shown in Figure 6-26 and Table 6-14, #2 EJPO coated engine had lower friction at speeds lower than 4250 rpm and had higher friction at other speeds. The highest friction reduction was 7.25% at 2750 rpm. Compared with #1 EJPO coated engine, #2 EJPO coated engine had lower friction.

Thermal efficiency was also calculated using the same method as #1 EJPO coated engine. The thermal efficiency of #2 EJPO is shown in Table 6-15.

Table 6-15. Thermal efficiency of the #2 EJPO coated engine

Speed (rpm)	EJPO			PTWA			Increment (%)
	Power (kw)	Fuelflow (g/s)	Thermal efficiency (%)	Power (kw)	Fuelflow (g/s)	Thermal efficiency (%)	
1000	40.72	3.54	26.82	39.32	3.44	26.65	0.63
1500	68.55	5.06	31.59	61.01	5.04	28.22	11.94
2000	97.98	7.33	31.13	91.70	7.34	29.12	6.89
2500	125.0	9.27	31.45	123.4	9.47	30.35	3.59
2750	140.1	10.28	31.77	137.9	10.43	30.81	3.10

Speed (rpm)	EJPO			PTWA			Increment (%)
	Power (kw)	Fuelflow (g/s)	Thermal efficiency (%)	Power (kw)	Fuelflow (g/s)	Thermal efficiency (%)	
3000	154.1	11.32	31.73	150.4	11.38	30.81	2.98
3500	186.7	13.82	31.49	187.4	13.98	31.25	0.76
4000	229.7	17.05	31.41	226.2	17.09	30.84	1.83
4250	249.3	18.83	30.86	241.8	18.51	30.45	1.33
4500	272.7	20.74	30.65	266.1	20.58	30.13	1.73
4750	286.3	21.75	30.68	280.5	21.60	30.27	1.36
5000	291.2	22.02	30.84	287.4	22.17	30.22	2.06
5500	320.1	25.12	29.70	309.6	24.82	29.07	2.16
6000	332.9	27.61	28.10	325.8	27.42	27.69	1.49
6500	343.3	30.03	26.65	334.5	29.99	26.00	2.49
6750	344.1	31.93	25.12	336.6	31.93	24.58	2.22
7000	344.4	33.46	23.99	338.4	33.72	23.40	2.53
7250	343.1	34.89	22.92	338.6	35.02	22.54	1.69
7400	340.0	35.37	22.41	330.3	35.62	21.62	3.67

#2 EJPO coated engine had higher thermal efficiency than PTWA coated engine, especially at 1500 rpm which was 11.94% higher than PTWA coated engine. #2 EJPO coated engine had higher power at high speeds and higher thermal efficiency.

6.3.2 Performance comparison between EJPO coated engines

The Power test data were compared between #1 and #2 EJPO coated engine and shown in the following figures and table.

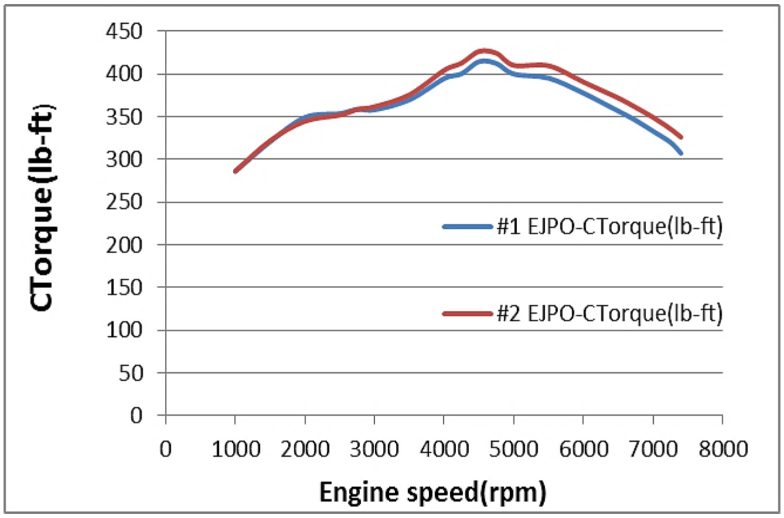


Figure 6-27. Torque comparison between #1 and #2 EJPO coated engines

As shown in Figure 6-27, the #2 EJPO coated engine made higher torque at higher speeds, the highest toque increment was 6.15% at 7400 rpm.

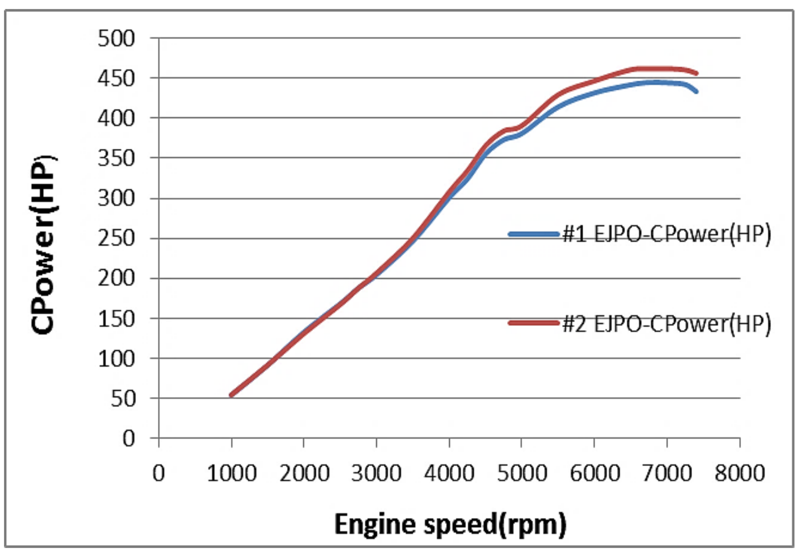


Figure 6-28. Power comparison between #1 and #2 EJPO coated engines

Similar to torque, the #2 EJPO coated engine had 5.28% power increment at 7400 rpm.

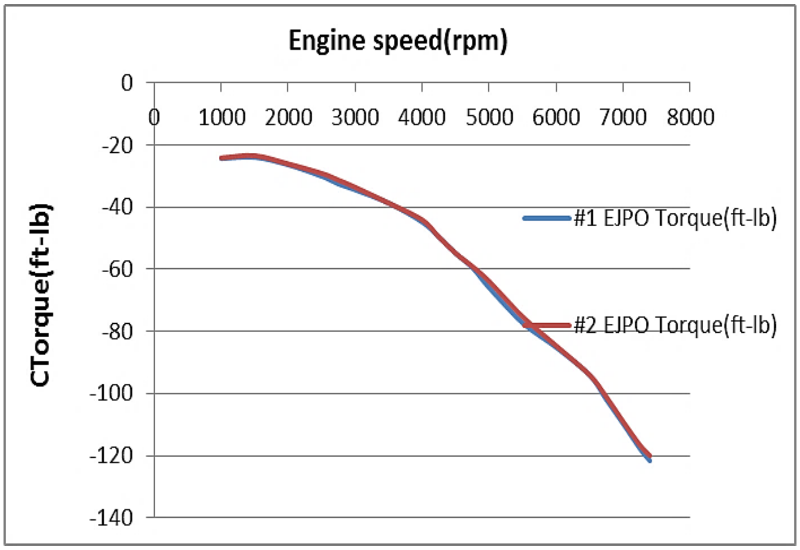


Figure 6-29. Engine friction comparison between #1 and #2 EJPO coated engines

As shown in Figure 6-29, the #2 EJPO coated engine had lower friction at most of all the speeds, the highest friction reduction was 3.70% at 6500 rpm.

The enhancement of torque, power, friction and thermal efficiency of # 2 EJPO coated engine are shown in Table 6-16.

Table 6-16. Torque, power, friction and thermal efficiency increment of #2 EJPO coated engine compared with #1 EJPO coated engines

Speed(rpm)	Power increment (%)	Torque increment (%)	Friction reduction (%)	Thermal efficiency increment (%)
1000	0.37	0.05	1.32	-2.41
1500	0.27	0.34	0.93	0.02
2000	-1.39	-1.27	0.61	-1.34
2500	-0.53	-0.49	0.85	0.13

Speed(rpm)	Power increment (%)	Torque increment (%)	Friction reduction (%)	Thermal efficiency increment (%)
2750	-0.03	-0.04	0.04	-0.04
3000	1	0.99	0.59	0.40
3500	1.5	1.54	2.59	0.05
4000	2.41	2.45	3.04	0.57
4250	3.12	3.12	0.67	0.69
4500	2.89	2.88	-0.01	-0.89
4750	2.93	2.92	-0.01	-0.59
5000	2.52	2.53	1.56	0.14
5500	3.67	3.67	0.00	0.01
6000	3.46	3.46	2.33	0.38
6500	4.25	4.26	3.70	0.98
6750	3.79	4.40	3.00	0.35
7000	3.99	4.86	0.99	1.04
7250	4.11	4.90	2.10	1.15
7400	5.28	6.15	0.82	3.26

The #2 EJPO coated engine made higher power and torque, lower friction and higher efficiency at most speeds. Camshaft bore coating helped to reduce friction. Piston and cylinder dome coating helped to increase thermal efficiency.

After all the tests were completed, the #2 EJPO coated engine was torn down, the tear down pictures are shown in Figure 6-30.

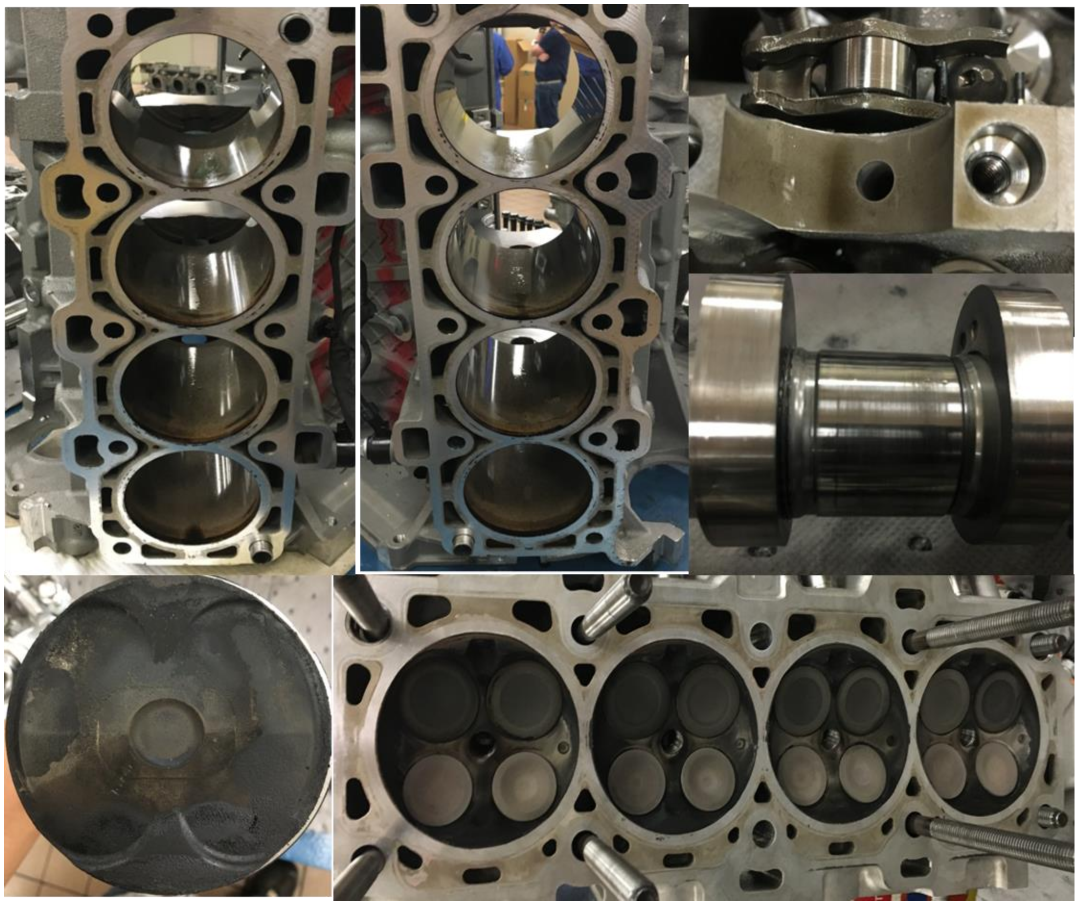


Figure 6-30. #2 EJPO coated engine tear down pictures after test

The tear down pictures showed the #2 EJPO coated cylinder bores were smooth and intact, the camshaft bore coatings were smooth and intact, the wear on the camshaft was reduced, the EJPO coatings on the piston crown and cylinder head domes were intact.

6.3.3 Conclusions

In conclusion, EJPO coating was applied on cylinder bore, camshaft bore, piston crown, and cylinder head dome to reduce friction and increase thermal efficiency for the #2 engine. The #2 EJPO coated engine passed 8 hours' Break-in and Power tests. The Power test data was compared with PTWA coated engine and the #1 EJPO coated engine.

Compared with PTWA coated engine, the #2 EJPO coated engine made higher performance at all speeds, especially higher at speeds lower than 3000 rpm. The highest torque increment was 12.33% at 1500 rpm.

Compared with #1 EJPO coated engine, the #2 EJPO coated engine made higher performance at speeds higher than 3000 rpm. The highest power increment was 5.28% at 7400 rpm. The EJPO coating on the camshaft bore could help to reduce the friction more and the EJPO coating on the piston crown and cylinder head dome could help to increase the engine thermal efficiency more.

The #2 EJPO coated engine tear down analysis showed all the coatings were good and intact after test, the coating fabrication and honing processes worked for 5.0 L engine.

References

1. Walton, Charles F., Coating of Castings. Metals Handbook 9th Ed. Vol. 15 – Castings. Pp. 563.

2. Ford, Matthew, Fisher, Matthew. “Method for Coating Combustion Engine Cylinders by Plasma Transferred Wire Arc Thermal Spray”, MSE 121, 4/30/2010.

7. Chapter 7 Piston temperature test for EJPO coated piston

7.1 Temperature plugs instrumenting

The #2 EJPO coated 5.0 L engine test data showed the engine made higher performance at all speeds during the Power test compared with the #1 EJPO coated 5.0 L engine. The EJPO coated components for #1 and #2 engines were different. The #1 EJPO coated 5.0 L engine had coating only on wall of the cylinder bore, and the #2 EJPO coated 5.0 L engine had coating on wall of cylinder bore, camshaft bore, piston crown, and cylinder head dome. The EJPO coated locations of the #1 and #2 5.0 L engine are shown in Table 7-1. The EJPO coated parts are shown in Figure 7-1.

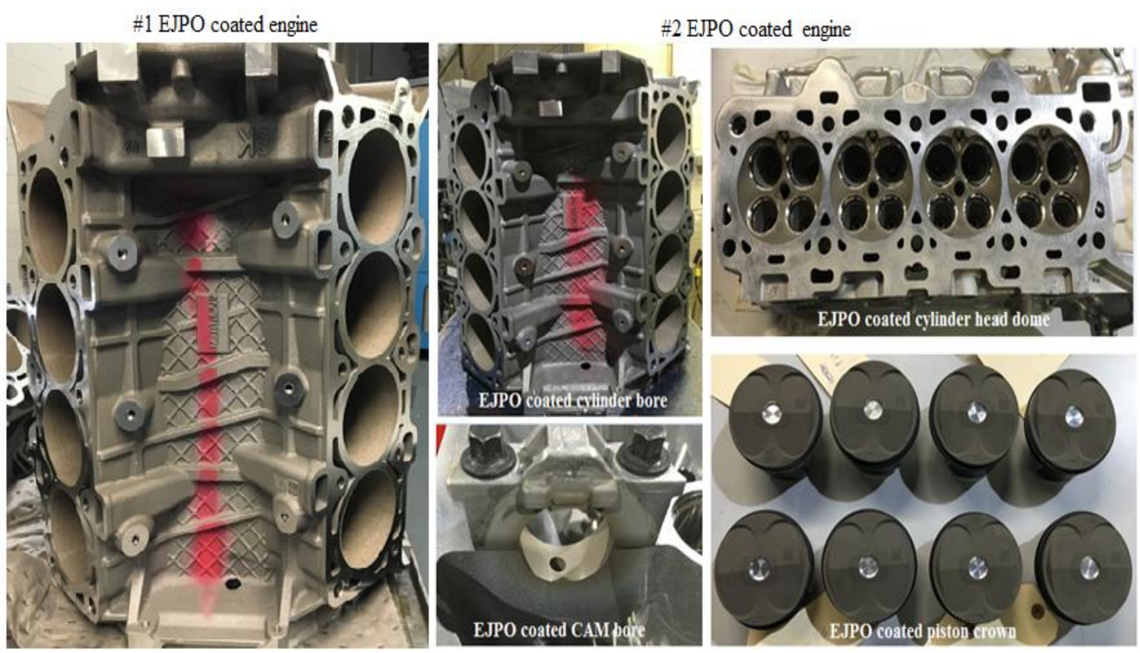


Figure 7-1. EJPO coated parts on #1 and #2 5.0 L engines

Table 7-1. EJPO coating application location on #1 and #2 EJPO coated engines

Coating location	Cylinder bore	Camshaft bore	Piston crown	Cylinder dome
#1 EJPO engine	Yes	No	No	No
#2 EJPO engine	Yes	Yes	Yes	Yes

During the Power test, the #2 EJPO coated engine made higher power output at all speeds, especially at high speeds. The engine torque and power comparisons between #1 and #2 EJPO coated engine are shown in Figure 7-2 and Figure 7-3.

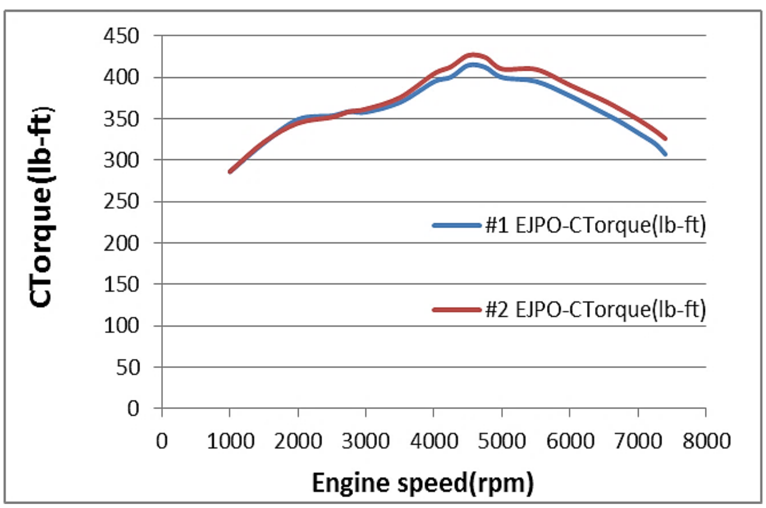


Figure 7-2. Torque comparison between #1 and #2 EJPO coated engines

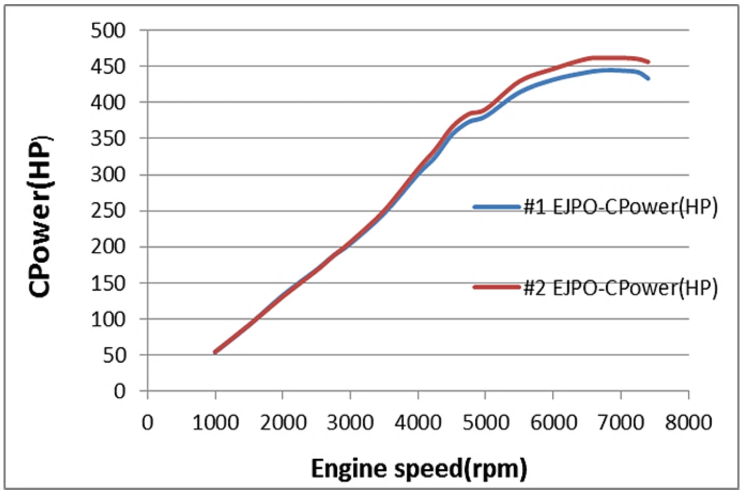


Figure 7-3. Power comparison between #1 and #2 EJPO coated engines

The #2 EJPO coated 5.0 L engine made higher Power and Torque at most of the engine speeds compared with #1 EJPO coated 5.0 L engine, especially at high engine speeds. The engine friction comparison between #1 and #2 EJPO coated 5.0 L engine is shown in Figure 7-4.

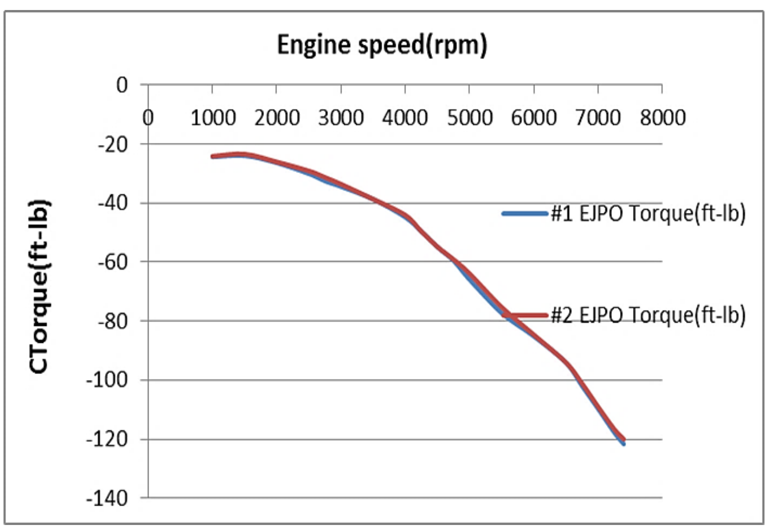


Figure 7-4. Engine friction comparison between #1 and #2 EJPO coated engines

As shown in Figure 7-4, the #2 EJPO coated engine had lower friction at most of the speeds, the highest friction reduction was 3.70% at 6500 rpm. The higher engine performance of the #2 EJPO coated 5.0 L engine was enhanced by a lower friction from camshaft bore coating and higher thermal efficiency from EJPO coated piston and cylinder dome compared with #1 EJPO coated 5.0 L engine. EJPO coating has high hardness and low COF which can help to protect the aluminum camshaft bore and reduce friction. The tested camshaft bores with and without EJPO coating and camshafts are shown in Figure 7-5.

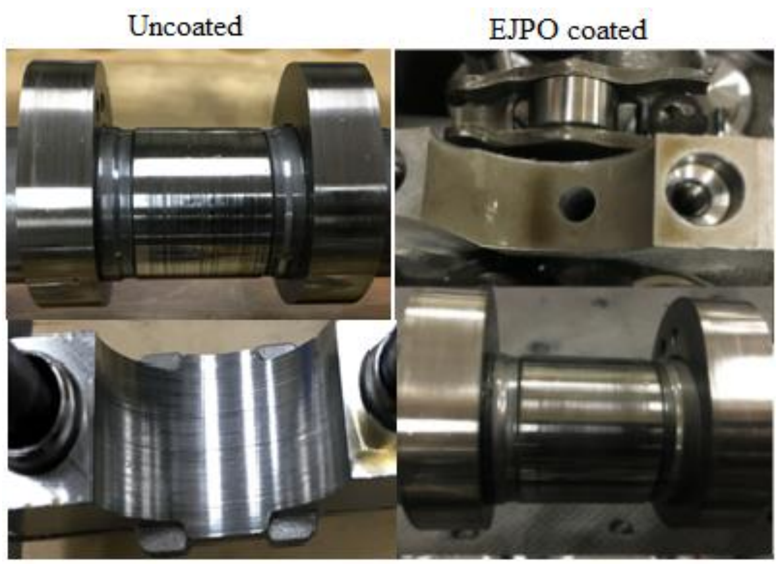


Figure 7-5. Tested camshaft bore and camshaft with and without EJPO coating

As shown in Figure 7-5, the surface condition of the camshaft bore, and camshaft was improved significantly and there were no scratches on camshaft bore and minor wear on camshaft. This improvement could help to reduce the friction and enhance engine performance.

Another factor helped to enhance the #2 engine performance was the higher engine thermal efficiency. In Chapter 3, the thermal barrier function of the EJPO coating was tested in the lab using the equipment designed and fabricated by Prof. Nie's group. The test result showed the EJPO coating could help to block heat and had thermal insulation function. However, the temperature fluctuation and combustion pressure of the engine combustion are quite different from the lab test condition, it is necessary to investigate the coating's thermal insulation property in the combustion environment.

In this work, the templugs instrumented 3.5 L engine pistons were available at that time and used to do the piston temperature test to test the thermal insulation of the EJPO coating on the piston crown.

Templug is a temperature sensitive steel screw and is used for measuring the maximum temperature in locations that are difficult to use traditional thermal couples. Usually, the templugs are used in the engine moving parts, turbine blades, and other moving components. The tested part can be any kind of material.

The templug can be installed at a location where temperature needs to be measured by drilling and tapping. The principle of the templug is thermal softening of the hardened steel. A master calibration curve was developed by Shell to determine the maximum temperature. The maximum temperature is determined by the time of exposure and the measured hardness [1].

The EJPO coating mask for the 3.5 L piston was designed and fabricated, and the 3.5 L piston crown was EJPO coated. Both EJPO coated and uncoated pistons were instrumented with templugs and installed in engine and tested. The EJPO coated piston and uncoated piston are shown in Figure 7-6.

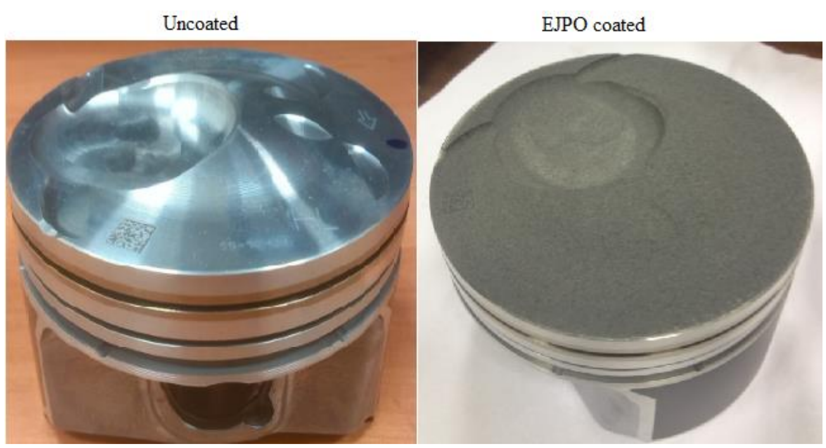


Figure 7-6. EJPO coated piston and uncoated piston

The templugs were installed on four locations including piston top land, under crown, behind top groove, and above pin hole. The templug instrumented piston is shown in Figure 7-7. The instrumented pistons were installed in engine and tested in 3.5 L engine.

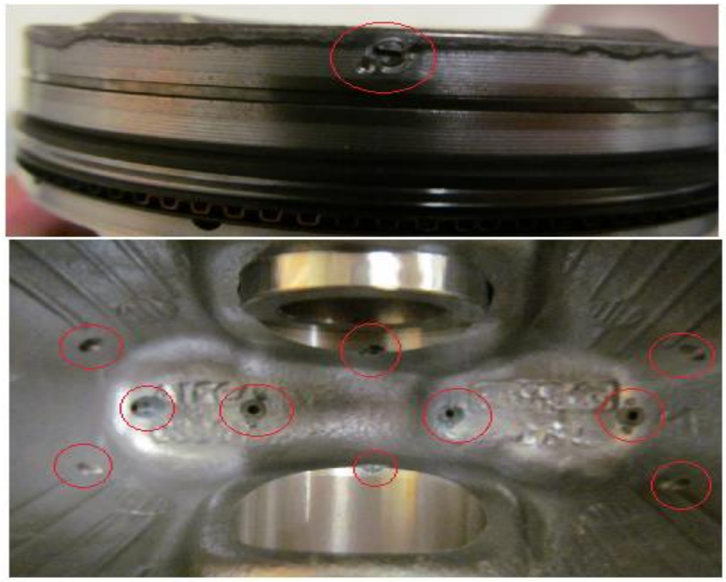


Figure 7-7. Templug instrumented piston

7.2 Piston temperature test and results

The EJPO coated and uncoated instrumented pistons were installed in the engine and ran 10 hours' constant speed and load engine test. After the test, the pistons were taken out and sent out for temperature analysis. The pistons were cut apart and templugs were removed to do hardness analysis. The dissected piston is shown in Figure 7-8. The measured and calculated temperatures including average and maximum at different locations are shown in Table 7-2. And the temperature plots are shown in Figure 7-9.

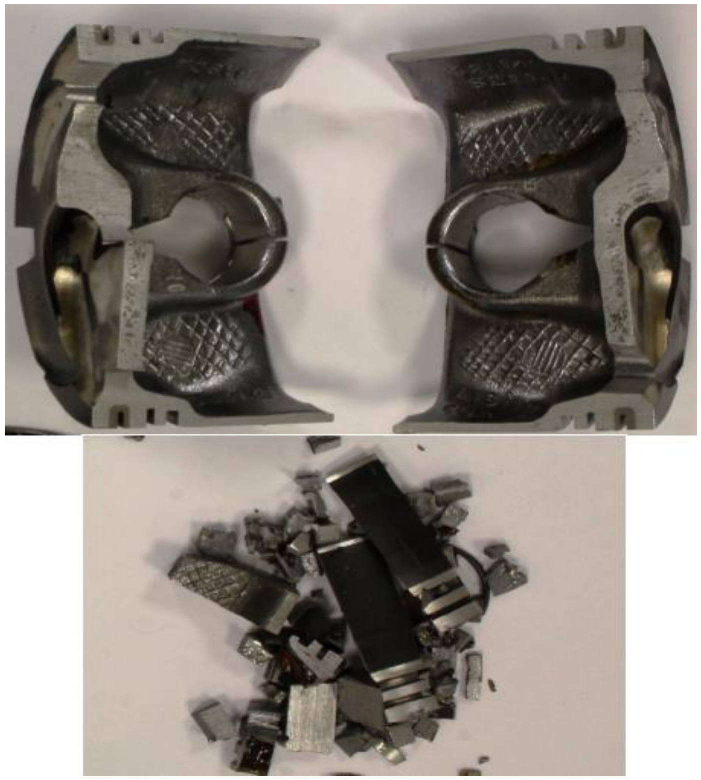


Figure 7-8. Dissected piston after test

Table 7-2. Measured and calculated temperature at different locations

Location	Uncoated average	Coated average	Uncoated max	Coated max
Top land	282.0	282.0	287.0	287
Under crown	270.2	268.7	287.5	285
Behind top groove	255.3	246.0	277.0	264
Above pin holes	251.5	250.5	255.5	255

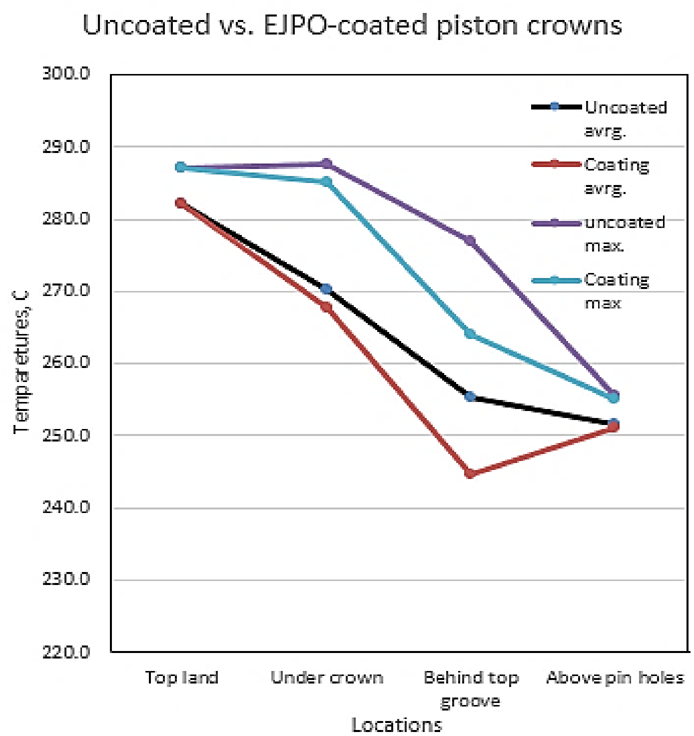


Figure 7-9. Average and maximum temperature at different locations

As shown in Table 7-2 and Figure 7-9, the average and the maximum temperature of the EJPO coated piston were lower than the uncoated piston, especially under the crown and behind top groove locations. However, at the top land location the temperature was same, because there was a gap between the piston top land and the cylinder wall and the coating couldn't block the combustion heat to the top land. Other's locations' temperatures showed EJPO coating could block the heat from the combustion chamber to the piston. This thermal barrier function could help to reduce the heat loss from piston to engine oil, thereby could increase thermal efficiency.

The piston crown coating was also observed by using SEM after the piston temperature test. The SEM picture of the test piston coating is shown in Figure 7-10.

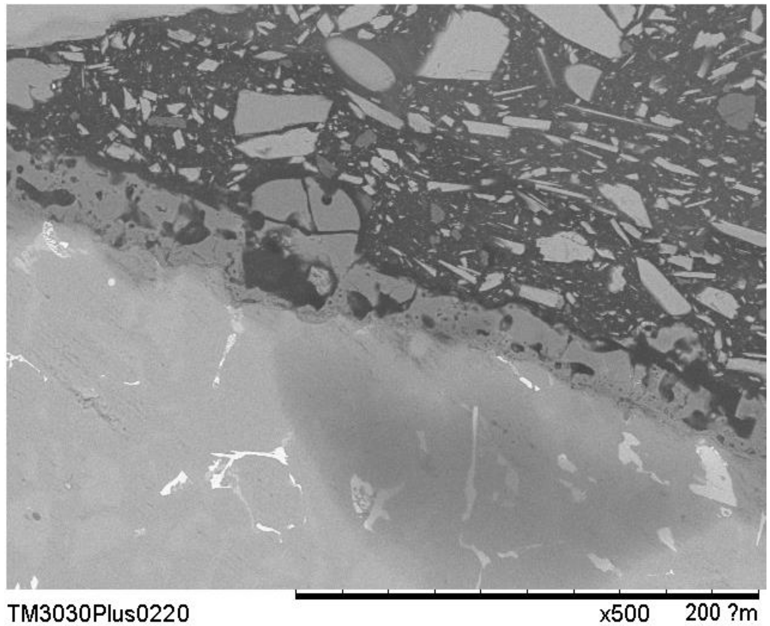


Figure 7-10. SEM image of the EJPO coating on piston crown

As shown in Figure 7-10, after the piston temperature test, the EJPO coating was still intact. The SEM image showed the EJPO coating had high porosity. This porous structure could help to increase the coating's thermal insulation property. The EJPO coating porosity can be controlled or modified during the coating process by changing the DC power parameters or electrolyte additives. To get better thermal insulation, a higher coating porosity is desired.

7.3 Conclusions

In conclusion, the EJPO coated engine with EJPO coated piston crown, EJPO coated cylinder dome, and EJPO coated camshaft bore had higher engine performance. The engine friction was reduced by coated camshaft bore, and thermal efficiency was increased by applying coating on piston crown and cylinder dome. The piston templug temperature test showed the EJPO coating on the piston crown could help to reduce the heat loss from piston to the engine oil. The SEM investigation showed the EJPO coating had porous structure and could help to increase the coating's thermal insulation property. The thermal insulation functions of the piston coating could help to increase the engine thermal efficiency thereby enhancing engine performance.

References

1. TEMPPLUG user information guide, version 4, 2013.

8. Chapter 8 Low load durability test on a EJPO coated 5.0 L engine

The #3 EJPO coated engine was prepared to do a 100 hours low load durability test to test the coating and honing process effects on coating durability, and it was fabricated same as the #2 EJPO coated engine. The #3 EJPO coated engine had coating on cylinder bore, camshaft bore, piston crown and cylinder head dome. The cylinder bore coating thickness was 30 um, and the piston to bore clearance was 30 um. The coated parts are shown in Figure 8-1.

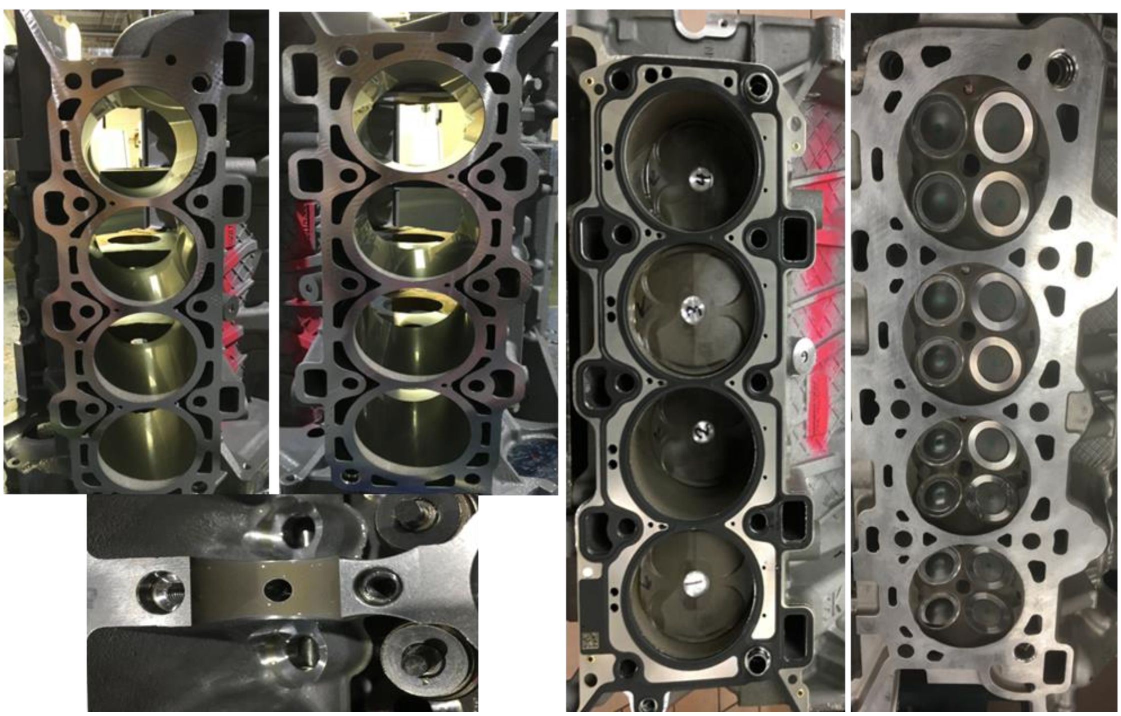


Figure 8-1. EJPO coated parts on the #3 EJPO coated engine

8.1 100 hours durability test on EJPO coated 5.0 L engine

The #3 EJPO coated engine was assembled and scheduled to run a 100 hours' low load durability test. The test was set up to run 2000 rpm with 50% pedal and 4000 rpm with 70% pedal. The purpose of this test was to test the durability or wear resistance of the EJPO coating in combustion conditions.

The #3 EJPO coated engine passed the 100 hours' low load durability test. Parts of the data are shown in Figure 8-2.

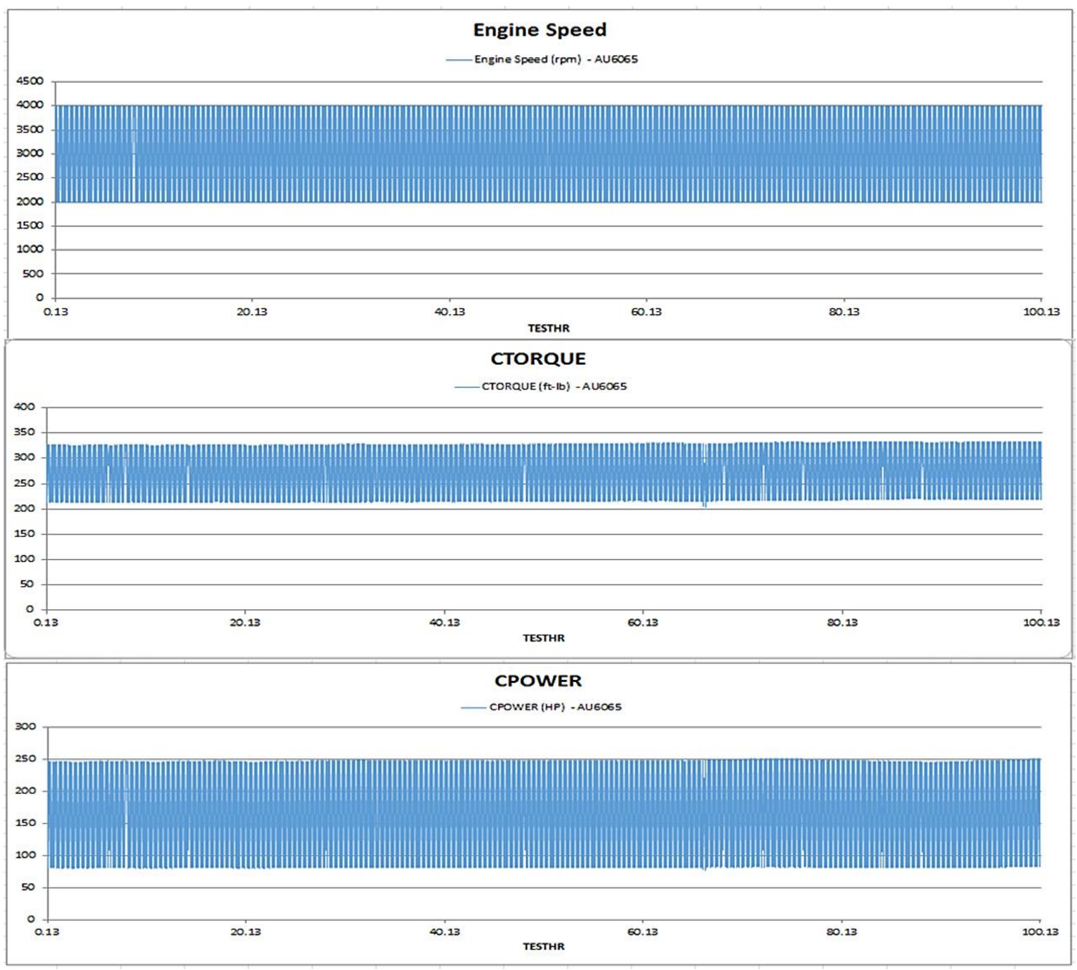


Figure 8-2. Torque and Power data from the 100 hours low load durability test

As shown in Figure 8-2, during the 100 hours' durability test the engine peak torque and peak power maintained at same level, which meant the engine was healthy and all the EJPO coated parts worked as they should be.

After the 100 hours' low load durability test was completed, the #3 EJPO coated engine was torn down to check the coating conditions. All the coatings were intact and smooth on cylinder bore, camshaft bore, cylinder head dome and piston crown. However, some black marks were found on some of the cylinder bores. The cylinder bores with black marks are shown in Figure 8-3.

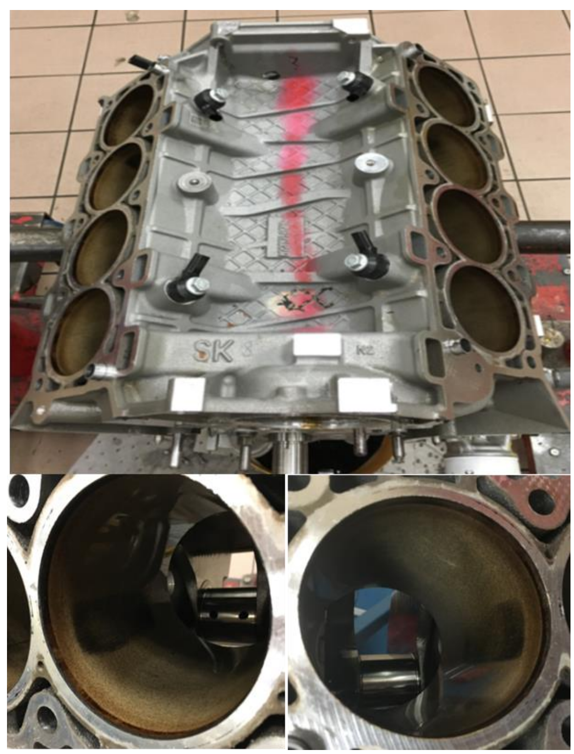


Figure 8-3. Cylinder bores with black marks after test

As shown in Figure 8-3, the black marks were on the cylinder bridge area between cylinder bores. The black marks looked shining and smooth. The surface profile measurement also showed the black mark area was flat and no scratches or scuffs, and the surface roughness of the black mark area was smoother than the original roughness (Ra = 0.76 um). The surface profile of the black area is shown in Figure 8-4. Cross section and surface images were taken and shown in Figure 8-5.

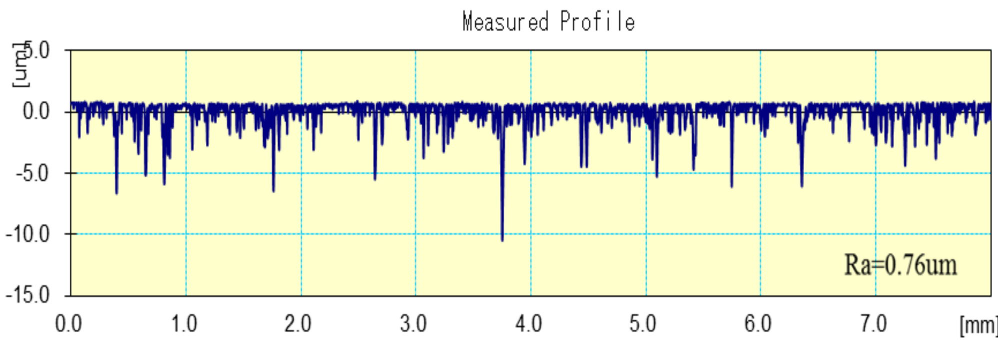


Figure 8-4. Surface profile of the black mark area

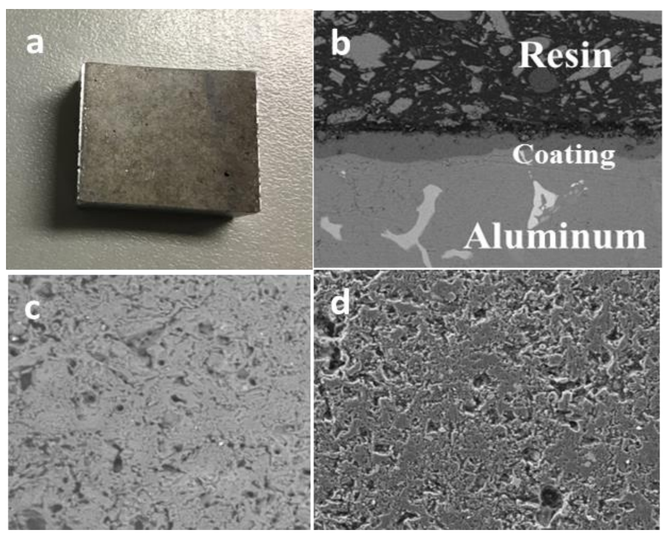


Figure 8-5. Cross sectional and surface images of the cylinder bore piece with black mark, a: cut piece, b: cross section image, c: good coating surface image, d: coating with black mark surface image

Figure 8-5-b showed the cross-section image of the coating, the coating was still bonding well with the aluminum and there were no cracks on the coating. Figure 8-5-c showed the normal light color coating. Figure 8-5-d showed the black marked coating surface, the image showed there was no scuff on the surface.

EDX analysis showed the main content of black stuff on the coating was carbon. The EDX result is shown in Figure 8-6.

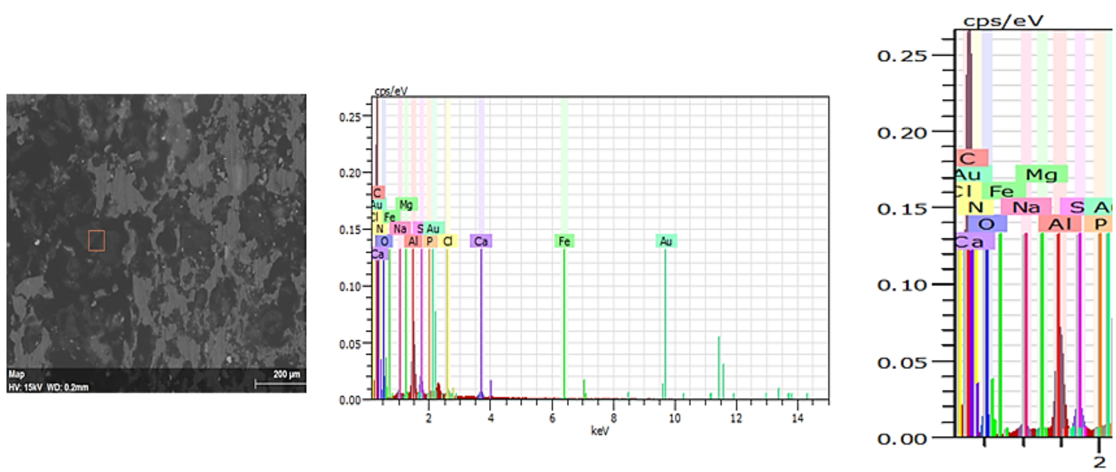


Figure 8-6. EDX analysis of the black coating (main content of the black coating was carbon)

The black mark on the cylinder bore bridge area also indicated the piston to bore clearance of the area was smaller and the black carbon was built up from the burnt oil or overheated oil. There was no liner supporting the aluminum cylinder bore, the cylinder bore distortion should reduce the piston to bore clearance after cylinder head installed and torqued. A torque plate analysis was necessary to investigate the cylinder bore distortion.

8.2 Cylinder bore distortion investigation with torque plates

A pair of cylinder head torque plates were manufactured and used to study the cylinder bore distortion after cylinder head torque applied. The torque plates were made from the 5.0 L cylinder heads, the thickness of the torque plate was same as the cylinder head. After torque applied, the cylinder bore distortion should be same as the assembled engine. The torque plates are shown in Figure 8-7.

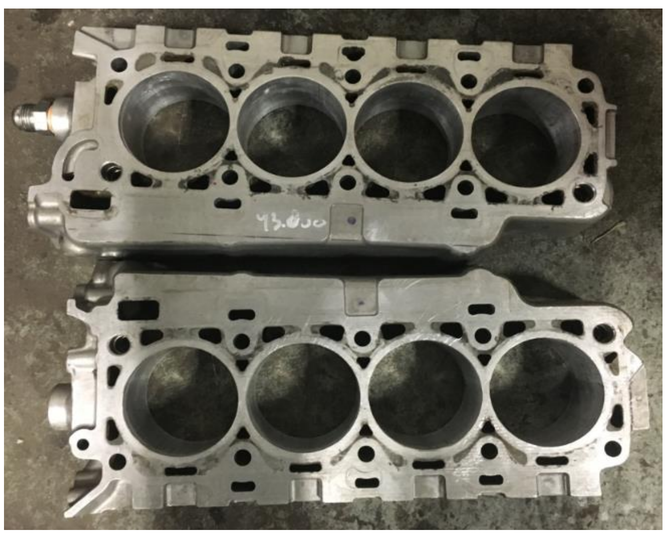


Figure 8-7. Cylinder torque plates made from 5.0 L cylinder heads

The EJPO coated engine block was honed to 93.020 mm without the torque plates, the cylinder bores were measured and showed round shape. After that, the torque plates were installed and torqued. The cylinder bores were measured with the torque plates, the cylinder bore size and shape changed after the torque plated installed. The crankshaft direction of the cylinder bore shrunk and the piston skirt direction of the cylinder bore expanded. As shown in Figure 8-8, the crankshaft direction was defined as 0 and 180 degrees' direction, the piston skirt direction was defined as 90 and 270 degrees' direction. The cylinder bore measurement and distortion is shown in Figure 8-9.

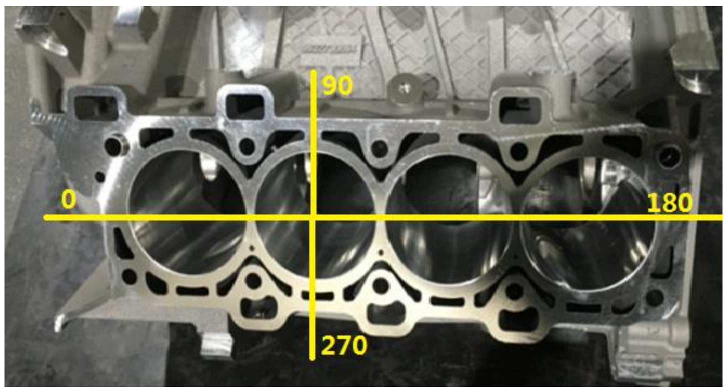
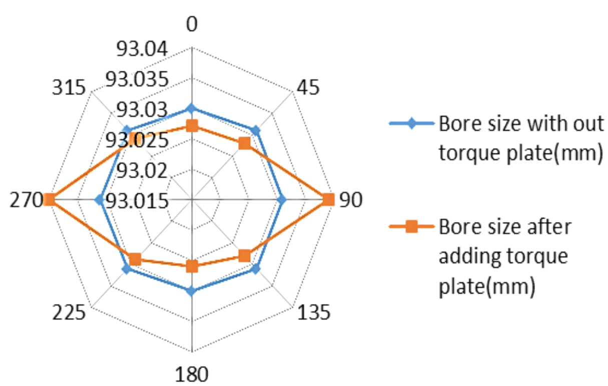


Figure 8-8. Definition of the cylinder bore direction



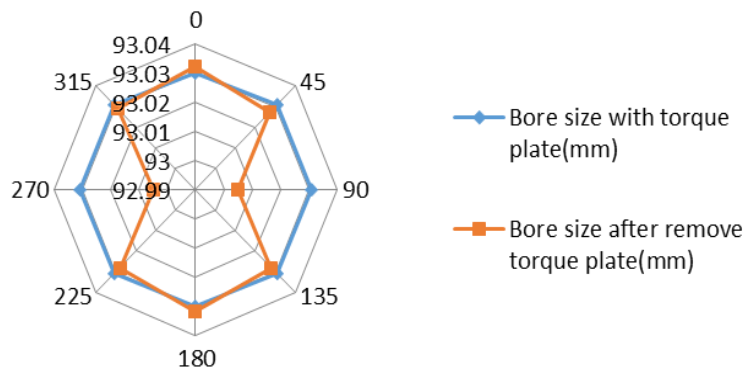
Location	0	45	90	135	180	225	270	315
Bore size with out torque plate(mm)	93.02	93.021	93.021	93.02	93.02	93.021	93.021	93.021
Bore size after adding torque plate(mm)	93.017	93.019	93.029	93.019	93.016	93.019	93.03	93.02
Change(mm)	0.003	0.002	-0.008	0.001	0.004	0.002	-0.009	0.001
Percentage(%)	0.003225	0.00215	-0.0086	0.001075	0.0043	0.00215	-0.00968	0.001075

Figure 8-9. Cylinder bore size and the cylinder bore distortion after torque plate installed

As shown in Figure 8-9, the cylinder bore was round shape before the torque plate installed. After the torque plate installed, the cylinder bore size reduced at the crankshaft direction, which was the main cause of the reduction of the piston to bore clearance at crankshaft direction. The reduced clearance created more heat between piston ring and cylinder wall and black carbon marks were built up. To reduce the distortion affects, the cylinder bore had to be honed bigger at crankshaft direction, however, the bigger clearance at piston skirt direction would cause piston slap knocking. So, honing the cylinder bore bigger without the torque plate installed was not a good solution.

Another method to get a better cylinder bore roundness and clearance with cylinder head installed was honing the EJPO coated bore with cylinder head torque plates installed. In this work, the EJPO coated 5.0 L engine block was installed with cylinder head torque plates, torqued and honed to 93.020 mm. The honing process and the cylinder bore size measurements are shown in Figure 8-10 and 8-11.

Figure 8-10. Honing process with torque plates installed



Location	0	45	90	135	180	225	270	315
Bore size with torque plate(mm)	93.02	93.021	93.021	93.021	93.02	93.021	93.021	93.021
Bore size after remove torque plate(mm)	93.022	93.017	92.995	93.018	93.022	93.018	92.995	93.019
Change(mm)	-0.002	0.004	0.026	0.003	-0.002	0.003	0.026	0.002
Percentage(%)	-0.00215	0.0043	0.027951	0.003225	-0.00215	0.003225	0.027951	0.00215

Figure 8-11. Cylinder bore size measurements with and without torque plate

As shown in Figure 8-11, the cylinder bore roundness and bore size were good with the torque plate installed, which meant the cylinder bore would keep the same shape after the engine was assembled. The measurements also showed the bore distortion and size changed after removed the honing torque plate, the piston skirt direction shrunk, and the crankshaft direction expanded. This bore size change and distortion was opposite with the honing without torque plate. Thus, honing the cylinder bore with torque plate is the good solution to keep the cylinder bore round and straight after the engine is assembled.

In this work, the honing machine used two stones honing head, which was not good for soft material like aluminum to get a better roundness. After the pressure applied on the honing stone, the cylinder bore would change to oval shape especially at the cylinder bridge location as shown in Figure 8-12.

Figure 8-12. The cylinder bridge deformed when the honing pressure was applied using two stones honing head

The cylinder bridge part was pressed out, and the material would be removed less than other area, so the roundness of the bore was not good and the clearance at cylinder bridge area was smaller. A honing head with more honing stones (4 or more) is also a good choice to improve the honing results.

8.3 Conclusions

In conclusion, #3 EJPO coated 5.0 L engine passed 100 hours low load durability test, however some black marks were found at the cylinder bore bridge area. SEM and EDX analysis showed the black mark on the cylinder wall was mainly carbon. Torque plate honing analysis showed the cylinder bore deformed after torque applied, the piston skirt direction expanded, and the cylinder bridge area shrunk. This cylinder bore distortion reduced the piston to bore clearance at the cylinder bridge area and produced black carbon mark on the tight area. A honing head with 4 or more honing stones or honing with torque plate could help to improve the honing results and reduce the cylinder bore distortion.

9. Chapter 9 Vehicle durability tests on a EJPO coated 5.0 L engines

9.1 Vehicle durability test on 5.0 L engine with thinner coating

The #4 EJPO coated engine was prepared for the vehicle durability test and treated same as the previous #3 EJPO coated engine blocks. The #4 EJPO coated engine had coating on cylinder bore, camshaft bore, piston crown and cylinder head dome. This EJPO coated engine block was honed to a thinner coating thickness with bigger piston to bore clearance. The cylinder bore coating thickness was around 20 um, and the piston to bore clearance was around 45 um. The coated block and honed bore are shown in Figure 9-1.

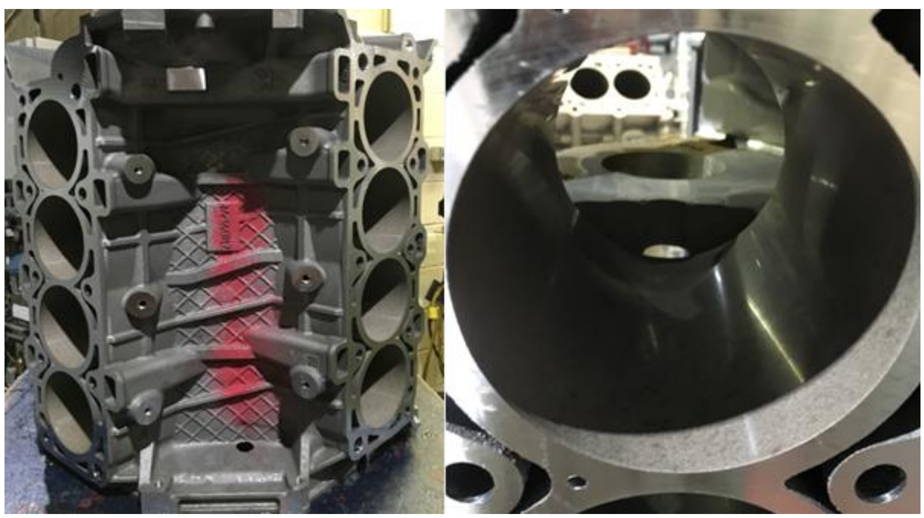


Figure 9-1. #4 EJPO coated and honed engine block

After the #4 EJPO coated engine block was honed, the cylinder bore size, coating thickness, coating roughness, and piston to bore clearance were measured and shown in Table 9-1.

Table 9-1. #4 engine block measurements after honing

Cylinder	Cyl1	Cyl2	Cyl3	Cyl4	Cyl5	Cyl6	Cyl7	Cyl8
Bore size(mm)	93.019	93.021	93.019	93.017	93.021	93.015	93.019	93.017
Piston size(mm	92.976	92.975	92.975	92.972	92.977	92.971	92.973	92.974
clearance(mm)	0.043	0.046	0.044	0.045	0.044	0.044	0.046	0.043
Thickness(um)	21	23	22	21	19	16	17	22
Roughness(um)	0.76	0.80	0.75	0.77	0.78	0.72	0.75	0.81

The #4 EJPO coated engine block was assembled and ran the 8 hours Break-in test. After the Break-in test, the cylinder bores were checked by using the cylinder bore scope. The cylinder bore coating images are shown in Figure 9-2.

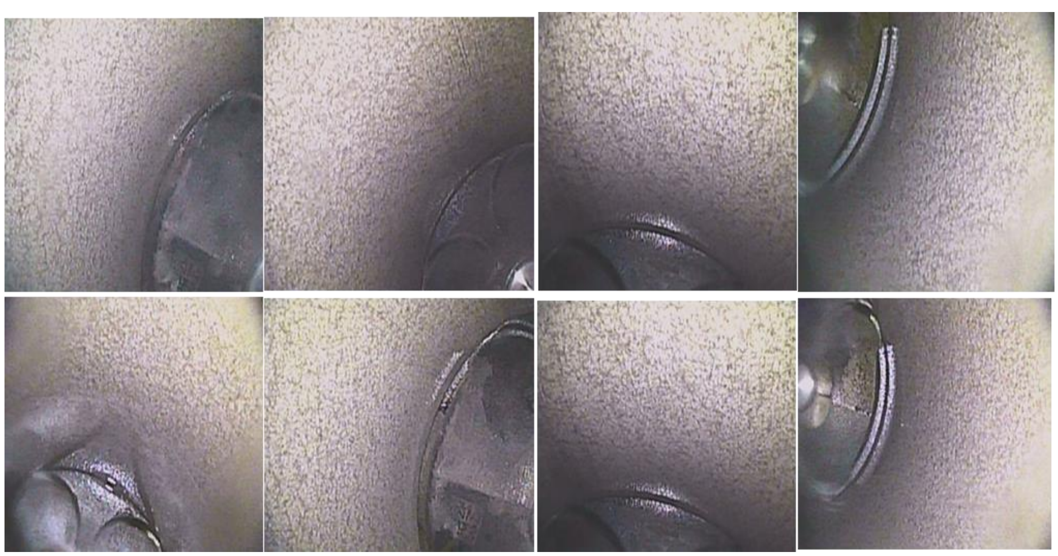


Figure 9-2. Cylinder bore images after Break-in test

The cylinder bore scope images showed the coatings were intact and smooth. Then the #4 EJPO coated engine was sent to Detroit for vehicle durability test. The #4 EJPO coated engine was installed on the Ford Mustang car and ran the vehicle durability test. The car ran the durability test for one and a half years at different test conditions, after accumulated certain mileage, the #4 EJPO coated engine was removed from the car and torn down. The cylinder bore coatings are shown in Figure 9-3.

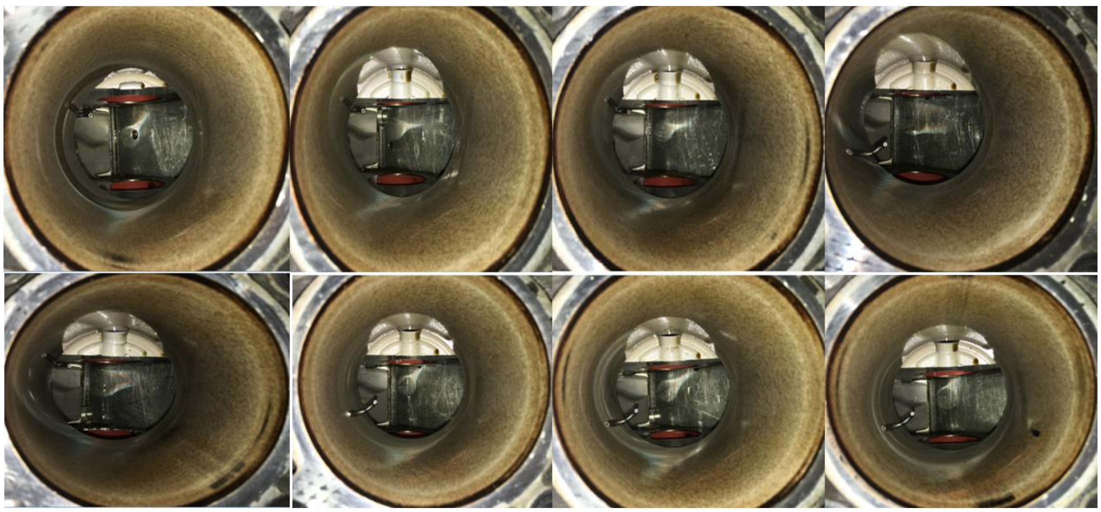


Figure 9-3. #4 engine block bore coatings after vehicle durability test

As shown in Figure 9-3, the cylinder bore coatings were all intact and smooth after the vehicle durability test. Some small black marks were found on the very top of some cylinder bores, which were similar to the black marks on the #3 engine block. The black marks were smooth and shining, they were carbon build up, not scratches.

The EJPO coatings on the camshaft bores and piston crown were also good and intact. The coatings are shown in Figure 9-4.

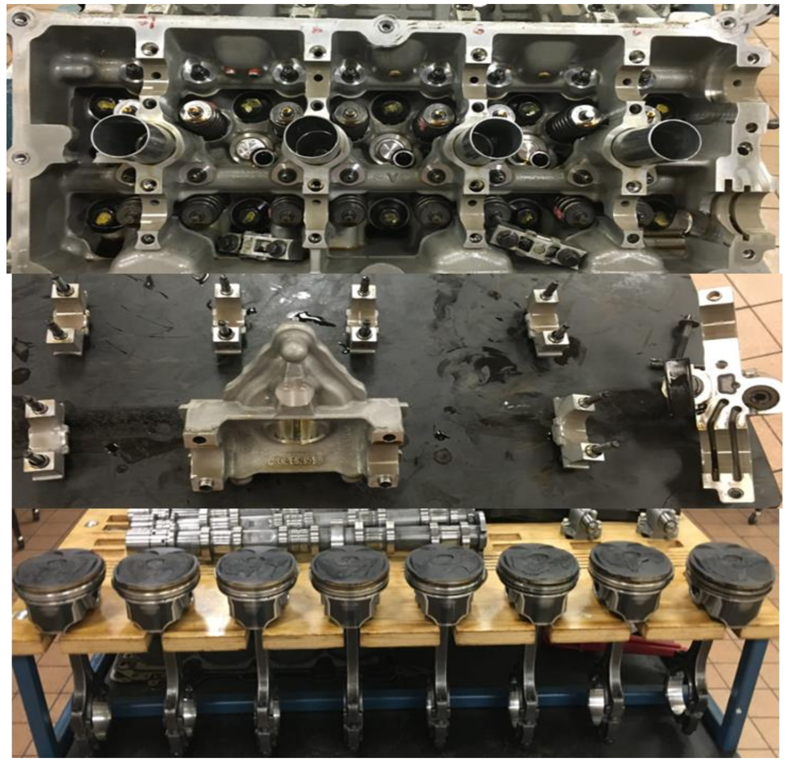


Figure 9-4. EJPO coated camshaft bores and pistons after vehicle durability test

The cylinder bore coating roughness was measured and the surface profile is shown in Figure 9-5.

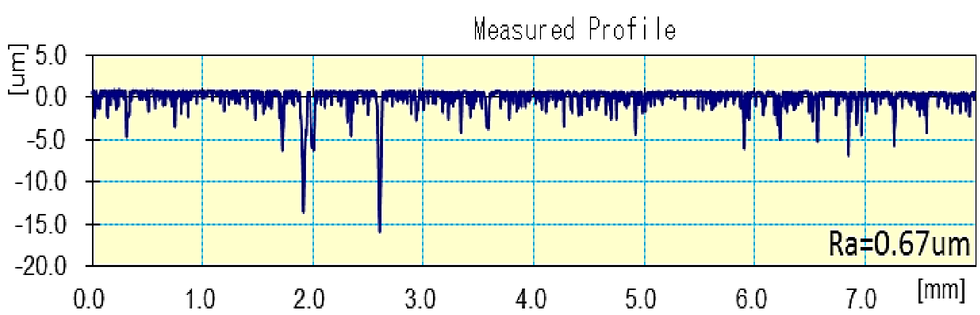


Figure 9-5. Surface profile of cylinder bore coating after vehicle durability test

Compared with the original surface roughness, after the test the surface roughness reduced a little bit. The carbon might fill up the pores on the coating surface and reduced the surface roughness.

The cylinder bore size, coating thickness, piston size and piston to bore clearance were measured and shown in the following tables.

Table 9-2. #4 EJPO coated 5.0 L cylinder bore measurement

Cylinder	Cyl1	Cyl2	Cyl3	Cyl4	Cyl5	Cyl6	Cyl7	Cyl8
Before test bore size (mm)	93.019	93.021	93.019	93.017	93.026	93.015	93.019	93.017
After test bore size(mm)	93.025	93.025	93.025	93.026	93.036	93.026	93.030	93.027
Increment(mm)	0.006	0.004	0.006	0.009	0.010	0.011	0.011	0.010

Table 9-3. #4 EJPO coated 5.0 L coating thickness measurement

Thickness	Original(um)	After test(um)	Decrement(um)
Cy1	21	19	2
Cy2	23	21	2
Cy3	22	20	2
Cy4	21	20	1
Cy5	19	18	1
Cy6	16	15	1
Cy7	17	15	2
Cy8	22	20	2

Table 9-4. #4 EJPO coated 5.0 L piston size measurement

Piston size	Original(mm)	After test(mm)	Decrement(mm)
Cy1	92.976	92.971	0.005
Cy2	92.975	92.969	0.006
Cy3	92.975	92.973	0.002
Cy4	92.972	92.970	0.002
Cy5	92.977	92.971	0.006
Cy6	92.971	92.970	0.001
Cy7	92.973	92.970	0.003
Cy8	92.974	92.973	0.001

Table 9-5. #4 EJPO coated 5.0L piston to bore clearance measurement

Clearance	Original(mm)	After test(mm)	Increment(mm)
Cy1	0.043	0.054	0.011
Cy2	0.046	0.056	0.01
Cy3	0.044	0.052	0.008
Cy4	0.045	0.056	0.011
Cy5	0.044	0.060	0.016
Cy6	0.044	0.056	0.012
Cy7	0.046	0.060	0.014
Cy8	0.043	0.054	0.011

As shown in the above tables, the coating thickness, bore size and piston to bore clearance changes were minor, especially the coating thickness, which was only 1 or 2 um change, which meant the EJPO coating was hard and durable. The combustion heat and cylinder head torque should also cause the cylinder bore distortion and size change. All these changes were minor and acceptable.

9.2 Vehicle durability test on 5.0 L engine with thicker coating

The #5 EJPO coated engine was prepared for the vehicle durability test and treated the same as the previous #4 EJPO coated engine blocks. The #5 EJPO coated engine had coating on cylinder bore, camshaft bore, piston crown and cylinder head dome. This EJPO coated engine block was honed to a thicker coating thickness with smaller piston to bore clearance. The cylinder bore coating thickness was around 30 um, and the piston to bore clearance was around 35 um. The coated block and honed bore are shown in Figure 9-6.

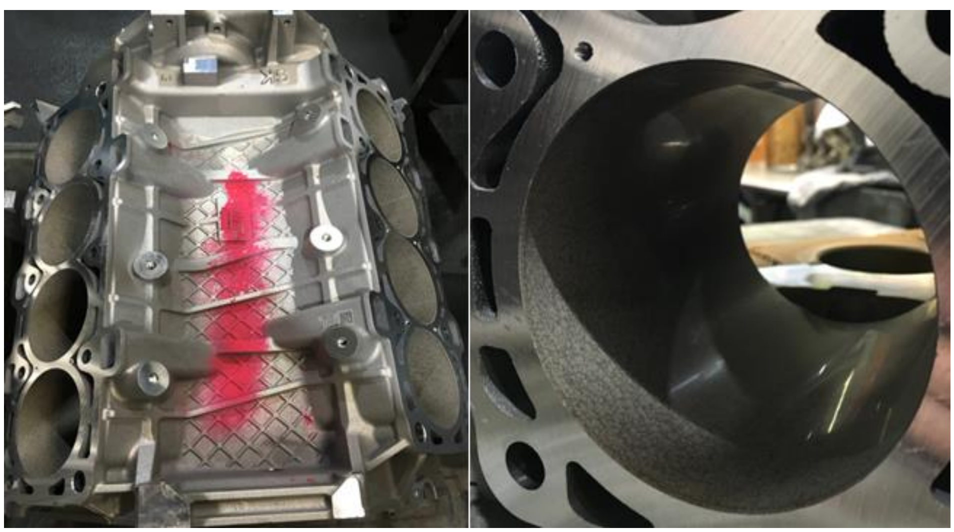


Figure 9-6. #5 EJPO coated and honed engine block

After the #5 EJPO coated engine block was honed, the cylinder bore size, coating thickness, coating roughness, and piston to bore clearance were measured and shown in Table 9-6.

Table 9-6. #5 engine block measurements after honing

Cylinder	Cyl1	Cyl2	Cyl3	Cyl4	Cyl5	Cyl6	Cyl7	Cyl8
Bore size(mm)	93.015	93.014	93.012	93.011	93.011	93.012	93.010	93.015
Piston size(mm	92.977	92.980	92.979	92.975	92.974	92.978	92.975	92.971
clearance(mm)	0.038	0.034	0.033	0.036	0.037	0.034	0.035	0.034
Thickness(um)	31	30	32	31	29	27	28	29
Roughness(um)	0.80	0.79	0.82	0.81	0.78	0.79	0.79	0.80

The #5 EJPO coated engine block was assembled and ran the 8 hours Break-in test. After the Break-in test, the cylinder bores were checked by using the cylinder bore scope. The cylinder bore coating images are shown in Figure 9-7.

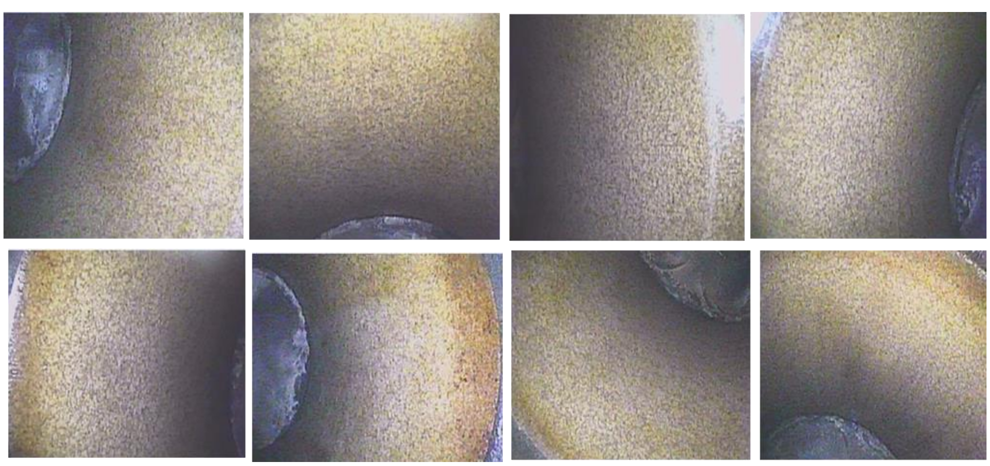


Figure 9-7. Cylinder bore images after Break-in test

The cylinder bore scope images showed the coatings were intact and smooth. Then the #5 EJPO coated engine was sent to Europe for vehicle durability test. The #5 EJPO coated engine was installed on the Ford Mustang car and ran the vehicle durability test. The car ran the durability test for one and a half years at different test conditions, after accumulated certain mileage, the #5 EJPO coated engine was removed from the car and torn down. The cylinder bore coatings are shown in Figure 9-8.

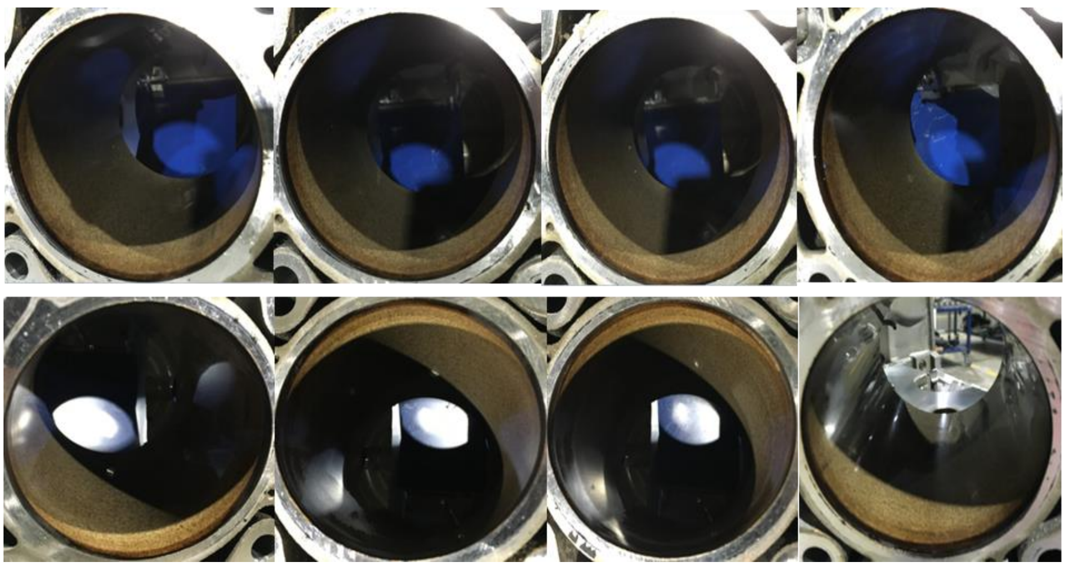


Figure 9-8. #5 engine block bore coatings after vehicle durability test

As shown in Figure 9-8, the cylinder bore coatings were all intact and smooth after the vehicle durability test. Different from the #4 EJPO coated engine, the #5 engine block didn’t have black marks on the cylinder bore which meant the cylinder bore distortion was less than the #4 engine block. Comparing #4 and #5 engine tests, it proved the engine block with 30um coating thickness and 20 um piston to bore clearance worked better.

The thicker coating could help to insulate the heat and reduce cylinder bore distortion better.

The EJPO coatings on the camshaft bores and piston crown were also good and intact. The coatings are shown in Figure 9-9.

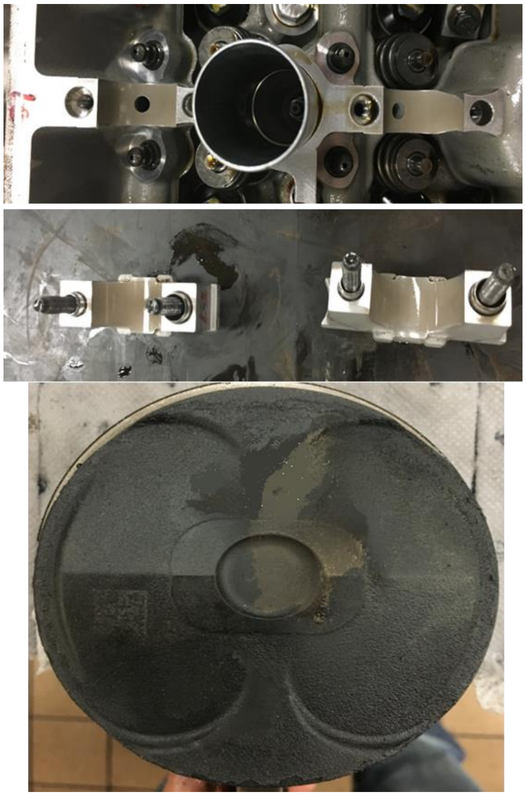


Figure 9-9. EJPO coated camshaft bores and pistons after vehicle durability test

The cylinder bore coating roughness was measured and the surface profile is shown in Figure 9-10.

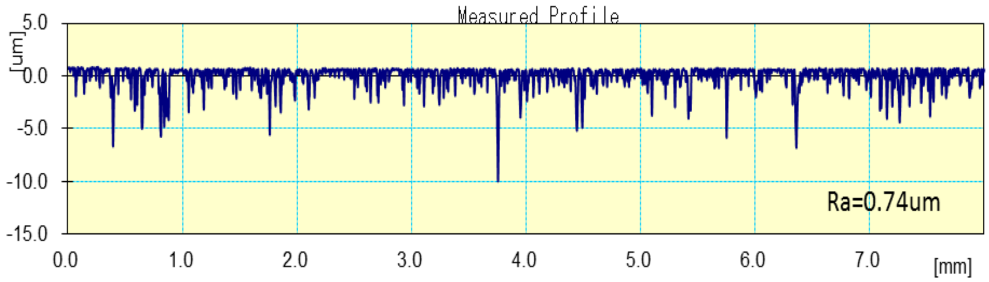


Figure 9-10. Surface profile of cylinder bore coating after vehicle durability test

Compared with the original surface roughness (Ra=0.8 um), after test the surface roughness reduced a little bit. The carbon might fill up the pores on the coating surface and reduced the surface roughness.

The cylinder bore size, coating thickness, piston size and piston to bore clearance were measured and shown in the following tables.

Table 9-7. #5 EJPO coated 5.0 L cylinder bore measurement

Cylinder	Cyl1	Cyl2	Cyl3	Cyl4	Cyl5	Cyl6	Cyl7	Cyl8
Before test bore size (mm)	93.015	93.014	93.012	93.011	93.011	93.012	93.010	93.015
After test bore size(mm)	93.020	93.019	93.016	93.016	93.015	93.016	93.016	93.022
Increment(mm)	0.005	0.005	0.004	0.005	0.004	0.004	0.006	0.007

Table 9-8. #5 EJPO coated 5.0 L coating thickness measurement

Thickness	Original(um)	After test(um)	Decrement(um)
Cy1	31	30	1
Cy2	30	28	2
Cy3	32	30	2
Cy4	31	29	2
Cy5	29	27	2
Cy6	27	25	2
Cy7	28	26	2
Cy8	29	27	2

Table 9-9. #5 EJPO coated 5.0 L piston size measurement

Piston size	Original(mm)	After test(mm)	Decrement(mm)
Cy1	92.977	92.971	0.006
Cy2	92.980	92.976	0.004
Cy3	92.979	92.975	0.004
Cy4	92.975	92.970	0.005
Cy5	92.974	92.971	0.003
Cy6	92.978	92.974	0.004
Cy7	92.975	92.972	0.003
Cy8	92.971	92.966	0.005

Table 9-10. #5 EJPO coated 5.0 L piston to bore clearance measurement

Clearance	Original(mm)	After test(mm)	Increment(mm)
Cy1	0.038	0.049	0.011
Cy2	0.034	0.043	0.009
Cy3	0.033	0.041	0.008
Cy4	0.036	0.046	0.010
Cy5	0.037	0.044	0.007
Cy6	0.034	0.042	0.008
Cy7	0.035	0.044	0.009
Cy8	0.034	0.046	0.012

As shown in the above tables, the coating thickness, bore size and piston to bore clearance changes were minor, especially the coating thickness, which was only 1 or 2 um change, which meant the EJPO coating was hard and durable. The combustion heat and cylinder head torque should also cause the cylinder bore distortion and size change. All these changes were minor and acceptable. However, compared with #4 EJPO coated engine block, the cylinder bore size changes of the #5 block were less. The thicker coating might help to reduce the heat transfer from combustion chamber to aluminum cylinder wall, and then reduced the cylinder bore distortion.

9.3 Conclusions

In conclusion, the #4 and # 5 EJPO coated engines passed 8 hours Break-in test and one and a half years' vehicle durability test. The tear down analysis showed the EJPO coating was intact and durable, and worked in the combustion engine.

EJPO coated engine with 30 um coating thickness and 35 um piston to bore clearance worked better and had less bore distortion.

10. Chapter 10 Conclusions and Future Works

10.1 General conclusions

Applications of Nano–ceramic oxide coatings for engine cylinder bore and other automotive components, from fabrication to characterization tests, are reported. Traditional aluminum engine block with cast iron liner worked fine until the government mandated that automakers raise their fleet MPG average. Cast iron liner has its inherent disadvantages in weight, size, friction, and thermal management. Replacing cast iron liners with EJPO coating, which has lower weight, COF, and better thermal properties, is a possible approach to enhance engine performance and thereby to increase the MPG. EJPO coating has been fabricated on 2.0 L and 5.0 L aluminum engine cylinder bores and other components to enhance engine performance. The EJPO coating properties, coating fabrication process, coating honing process and the EJPO coated engine tests were studied and carried out in this work. The main conclusions of the above studies can be summarized as follows:

- EJPO coating property investigation showed the EJPO coating had high hardness, high adhesion, high corrosion resistance, high wear resistance, low COF and good thermal properties. These desired EJPO coating properties had the potential to meet the engine cylinder functional requirements. Lab tests showed EJPO coating had 65% lower COF than cast iron and 50% lower than PTWA coating, and better thermal properties.

- Electrolyte spray head and coating mask were used to fabricate the coating on the desired locations and the EJPO coating could be applied on engine cylinder bore uniformly. Flex brush honing couldn't hone the cylinder bore round and straight, but the diamond stone machine honing could hone the cylinder bore round and straight. Two steps diamond stone machine honing was developed to hone the EJPO coated bore to desired surface roughness with desired coating thickness. The coarse stone was used to remove the top 10 um thick coating, and the fine stone was used to do the mirror finish honing.

- EJPO coated 2.0 L engine block reduced weight around 6.4% compared with cast iron liner engine block, and reduced cost around 17.5%. EJPO coated 5.0 L engine block reduced weight around 2% and reduced cost around 9% compared with PTWA coated engine block.

- EJPO coated 2.0 L engine passed Break-in, Power, 100 hours Engine Fatigue test, and Post Power tests. The cylinder bore coatings were smooth and intact after all the tests. The Power test showed the EJPO coated engine made higher performance at speeds lower than 3000 rpm and higher than 5000 rpm, the highest power enhancement was 11.29% at 1500 rpm compared with the engine with cast iron liners. EJPO coating's lower COF and thermal swing properties helped to enhance the engine performance. This engine performance enhancement was good for the vehicle daily drive, which engine speeds were lower than 3000 rpm, to reduce fuel consumption and emissions.

- EJPO coated 5.0 L engine passed Break-in, Power, 100 hours low load Engine Fatigue test, and vehicle durability tests. The Power test showed the EJPO coated 5.0 L engine made higher performance at speeds lower than 3000 rpm and highest enhancement was 12.06% at 1500 rpm compared with PTWA coated 5.0 L engine. EJPO coated piston crown, cylinder head dome and camshaft bore helped to enhance the engine performance at all the speeds during the Power test. The coating on camshaft bore helped to reduce the friction more and the coatings on piston crown and cylinder head dome helped to increase the engine thermal efficiency more.

- Piston temperature test showed EJPO coating on the piston crown could help to block the heat transfer from combustion chamber to piston and reduce the heat loss from piston to the engine oil. The SEM investigation showed the EJPO coating had porous structure and could help to increase the coating's thermal insulation property. The thermal insulation functions of the piston coating could help to increase the engine thermal efficiency thereby enhancing engine performance.

- Engine torque plate analysis showed the cylinder head torque caused the cylinder bore distortion and reduced the clearance between cylinder bridges. A better honing equipment or torque plate honing were needed to reduce he cylinder bore distortion.

- Critical parameters for 2.0 L EJPO coated engine were found including piston to bore clearance (30 um), coating roughness (Ra<=0.8 um, Rvk<2.0 um), and coating thickness (20 um). Critical parameters for 5.0 L EJPO coated engine were found including piston to bore clearance (35 um), coating roughness (Ra<=0.8 um, Rvk<2.0 um), and coating thickness (30 um).

10.2 Future work

- EJPO coating process needs automation and the cooling system needs to be upgraded to have higher cooling efficiency.

- EJPO coating honing process needs to be improved to reduce the cylinder bore distortion.

- Dynanometer engine fatigue test and engine global thermal test need to be carried out to test the EJPO coating performance at extreme load and temperature conditions.

- More performance tests need to be carried out with transducers instrumented for more combustion analysis.

- EJPO coating and honing parameters for racing engines need to be developed.

APPENDICES

1. EJPO coating machine

EJPO coating machine consists three main parts including power supply system, coating fabrication system, and electrolyte cooling system. A full view of the EJPO coating machine is shown in Figure 1.

Figure 1. Full view of the EJPO coating machine

The power unit is a pulse reverse DC power supply unit which can supply a 212 ampere effective DC current at 550 volts, and a 480 ampere pulse current at 700 volts. The DC power unit is shown in Figure 2.

Figure 2. Pulse reverse power supply

The coating fabrication system includes a multi ways adjustable electrolyte spray head, engine block or component mounting base, and electrolyte circulation line. A close view of the EJPO coating system is shown in Figure 3. The EJPO coating system can treat different shapes of surface. Some of the EJPO coated parts are shown in Figure 4.

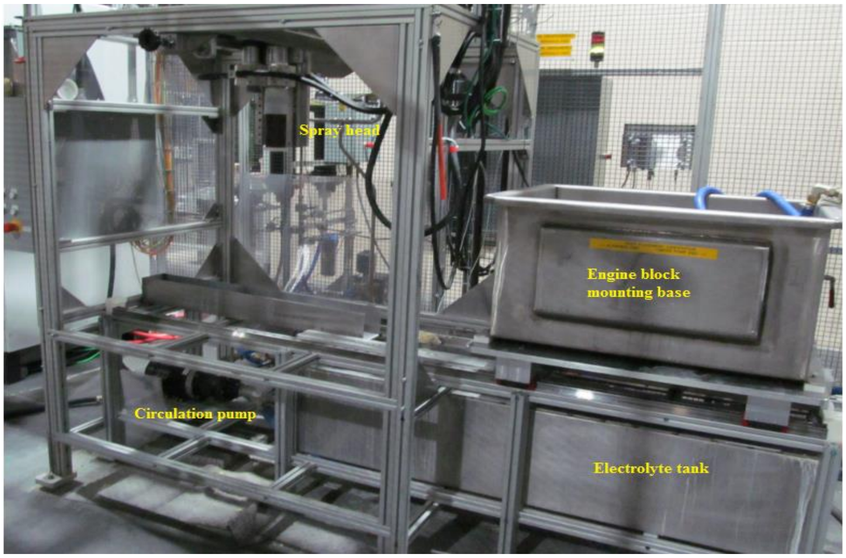


Figure 3. EJPO coating fabrication system

Figure 4. EJPO coated parts

EJPO electrolyte cooling system uses process water cooled cooper coil to cool down the electrolyte. EJPO coating process generates a lot of heat, and the heat affects the coating quality. The electrolyte needs to be cooled to fabricate high quality coating. The cooling system needs to be updated, since the process water is not cold and efficient enough. The cooling system is shown in Figure 5.

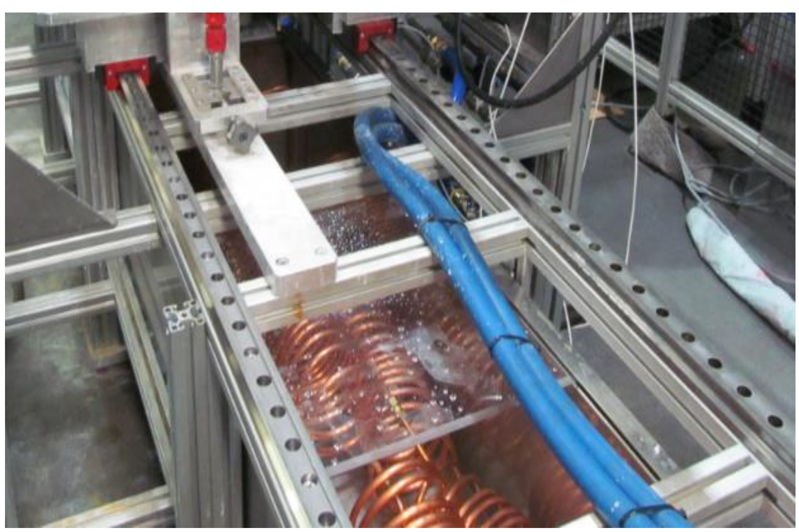


Figure 5. EJPO electrolyte cooling system

2. EJPO coating power control parameters

EJPO coating process used pulse reverse DC power, and used current control mode. The duty cycle of the current was 50%, the negative current was 50% of the positive current. The frequency of the current was 1000 Hz. The DC current was set at 150 A, and the treatment time was around 30 minutes. The voltage went up to 550 V at the end of the coating process. A full cycle of the DC current waveform is shown in Figure 6.

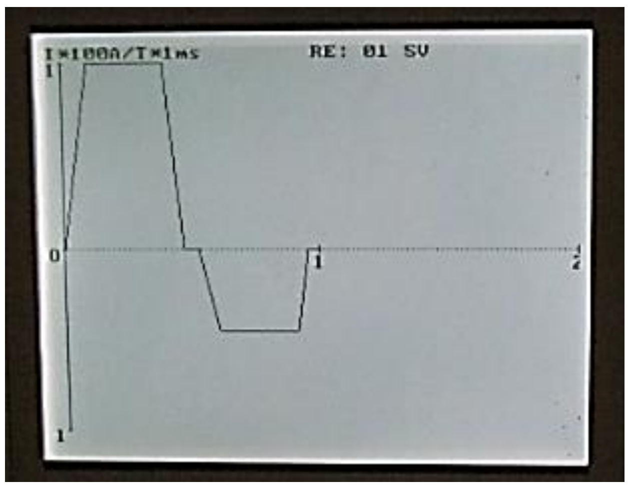


Figure 6. Waveform of the DC current duty cycle

3. Electrolyte

The electrolyte was silicate base electrolyte with additives including molybdate and phosphate to help to reduce coating COF and increase coating adhesive force.

4. Weight

Cast iron liner 2.0 L engine block weighs 61.96 lbs, and EJPO coated 2.0 L engine block weighs 58 lbs. The EJPO coated 2.0 L engine block reduces weight 3.96 lbs (6.4%) compared with cast iron liner 2.0 L engine block.

PTWA coated 5.0 L engine block weighs 88.4 lbs, and EJPO coated 5.0 L engine block weighs 86.6 lbs. The EJPO coated 5.0 L engine block reduces weight 1.8 lbs (2%) compared with PTWA coated 5.0 L engine block. The weights of the EJPO coated 2.0 L and 5.0 L engine blocks are shown in Figure 7.

Figure 7. Weights of EJPO coated 2.0 L and 5.0 L engine blocks

5. Cost

During the EJPO coating fabrication process, there is no electrolyte consumption and the electrolyte can be used for long time if it is sealed properly. Thus the main cost of the EJPO coating process is electricity power.

To cast, machine and insert a cast liner in aluminum engine block costs 1.98 $, and EJPO coats an aluminum cylinder bore costs 1.65 $ which consumes 15 kWh electricity power at a rate of 0.11 $/kWh.

The PTWA coating process consumes electricity power, feedstock wire, Argon gas, and torch maintenance. The cost of a PTWA coated bore is around 1.81 $. The EJPO coating process can save cost around 9%.

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