An experimental investigation of surface behavior of Al_2O_3-TiO_2 coated parts of a diesel engine

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***Abstract*— This study examined the effects of Al_2O_3-TiO_2 surface coating on the combustion chamber components of a diesel engine. The piston surface, cylinder head, exhaust and inlet valves of a single cylinder, four-stroke diesel engine were coated with Al_2O_3-TiO_2 (87-13) oxide based ceramic composite. The surface coating was applied to a thickness of 250 µm using an atmospheric plasma spray method. NiAl (50 µm thickness) was employed as bond layer for the piston and the valves. Coated and uncoated surfaces were tested under the same conditions for 150 hours. After testing, the surface treatments were examined using a scanning electron microscope (SEM) and optical microscope. According to test results, coated samples have showed fewer deformations, wear lines and less erosion in comparison to uncoated samples. A positive effect was also observed on the cylinder bore and piston rings. The results indicate that coating the pistons and valves with oxide based ceramics contributed to increasing the mechanical lifespan of the samples.**

***Index Terms*— Abrasion, cylinder line, diesel engine, plasma spray, piston surface**

I. INTRODUCTION

Friction and wear phenomena represent serious problems within sliding mechanical systems. By the most widely known definition, wear is the result of a deformation mechanism on the material surface. Due to the physical and chemical effects on the material surface, deformation and cracks begin at the micro structural level, before developing and causing particles to break away from the surface. Particularly within automotive applications, wear and the mechanisms related to wear cause mechanical damage, losing operation and equipment, necessitate renewal of equipment, and result in loss of time for servicing and repair work. Consequently, such issues impose large economic losses [1].

When the sliding parts of an internal combustion engine are investigated in conformance with tribological behavior, the wear phenomenon occurs as a casual connection. Friction, adhesive and corrosive environments are unavoidable within internal combustion engines. In such cases, the use of a protective surface layer will be the most effective way of minimizing damage and protecting the substrate surface [2].

In internal combustion engines, the energy cycle occurs within the combustion chamber. The components of the combustion chamber are defined as the cylinder bore, piston, piston head, piston rings and valves. These components are subject to a number of mechanisms of wear, including acids that occur after combustion, high temperature, high pressure, sulphur, relative humidity in air and gas atmosphere, and particles vacuumed through inlet valves. The cylinder bore and piston rings are subjected to particularly high levels of friction, high thermal pressure, and corrosive media. Because of these conditions, wear seems on these surfaces relatively. Abrasion occurs on the sliding surfaces due to friction between compression segment and cylinder bore. High loads on the cylinder surface lead to wear lines and micro cracks. The deformation movement then continues until the particles break away from the surface [3].

Many different technologies and coating processes, including plasma spraying, have been used in combustion engine applications, to improve the surface defection, increase the surface quality and increase performance after burning.

In plasma spray processes, the artificial plasma is formed by achieving high temperatures. Plasma is formed inside the plasma gun by generating a high voltage arc between the water-cooled copper anode and thorium cathode. During this event, the plasma gases such as Ar, H_2, N_2 and He are passed through the high voltage arc. The neutral positions of the plasma gases in the electrical arc degenerate as a result of dissociation, ionization and recombination there occurs a high temperature of up to 20,000 K. The gases having gone so high temperatures expand as radially and axially. The supersonic expansion is reached by the gases passed through the narrow way of nozzle. Coating powders are fed by the Ar carrier gas which has been passed from the plasma beam. The powders melted in ionize gas sprayed on the substrate which is prepared before. The powders hit to the surface which are melted or half melted flatten, or turn into the shape of lamellar and hardens

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because of the sudden cooling. (10^{-6} ºC/s) [4,5]. Figure 1 shows cross section of plasma spray gun and formation of plasma.

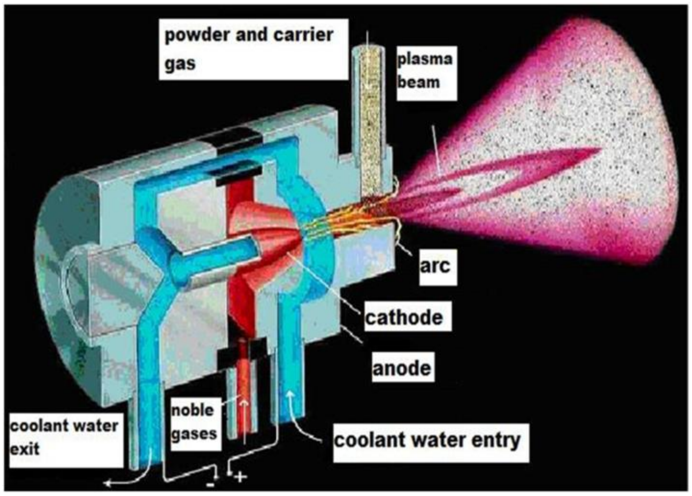

Figure 1. Cross Section of Plasma Spray Gun and Formation of Plasma [2].

Due to their physical and chemical properties, the use of ceramic-based composites in this plasma spray process produces a coating on the material surface that is highly wear-resistant and acts as a thermal barrier. Engines that have a thermal barrier coating applied are called low heat rejection (LHR). The low heat rejection (LHR) engine concept is based on minimizing heat transfer to the coolant system and recovering the energy in the form of useful work. Insulating the combustion chamber parts reduces heat transfer between the gas within the cylinder and the cylinder line [6-11].

By reducing lost energy and eliminating the need for a conventional cooling system, this engine system can dramatically improve overall performance and could potentially result in 50% volume and 30% weight reductions in the entire propulsion system [12,13].

Current low heat loss engine designs, although not fully adiabatic, particularly minimize heat losses during normal running of the engine, reduce the load on the cooling system and the power consumed by it, and consequently increase the efficiency of the engine [14].

The investigations about engine material and design carry on fast to achieve improvements in fuel consumption and reduce exhaust emissions. Part of this research field involves insulating the combustion chamber parts using ceramic coatings. Coating some components within the combustion chamber with low heat conductive material increases the combustion temperature, resulting in more efficient combustion and reduced emissions [15].

In this study of a diesel engine, the piston outside surface, exhaust and inlet valves were coated with Al_2O_3-TiO_2 ceramic material using an atmospheric plasma spray process; the effects of this applied thermal barrier on the coated samples were examined

II. MATERIALS AND METHODS

The tests were performed on the single cylinder, four-stroke, direct injection, air-cooled diesel engines; one engine was standard and the other had thermal coating applied to combustion chamber components. Technical specifications of the engine are given in Table 1. Only the surfaces of the piston, exhaust and inlet valves that face the combustion chamber were been coated. Surface material (chipping) of the components was removed in proportion to the thickness of the coating applied in order to retain the standard compression ratio in the cylinder head, piston, exhaust and inlet valves Considering that the compression ratio of this engine will change as a result of the fact that cylinder head, piston, exhaust and inlet valves have been coated in 250 µm thickness, and standard compression ratio has been obtained by adding double seal. Thus, both engines were configured to the same compression ratio. The plasma spray parameters used in the study are given in Table 2. Coated and uncoated parts in engines were run constantly for a period of 150 hours.

The first surface coating layer is a 50 µm thick (NiAl) bond layer and the main coating is a 250 µm layer of Al_2O_3-TiO_2 (87-13). When considering the experimental characteristics of wear resistance, surface treatment, high thermal shocks and tensions, the ceramic based material Al_2O_3-TiO_2 was identified as the most appropriate surface coating.

According to Lugscheider [16], oxide based ceramics are successfully used for wear applications because of their toughness and high melting temperatures. The toughness of coating materials varies according to the use of carbide, metal or oxide based ceramics. For oxides based on ceramics (Al_2O_3), the toughness scale ranges between 1200 HV0.3 and 1600 HV0.3

Al_2O_3-TiO_2 composite coatings consist of a matrix of Al_2O_3 and a second Al_2O_3-TiO_2 phase called reinforcement. The function of the matrix is to distribute the stresses homogeneously inside the composite material. The function of the second phase in the coating is mostly to provide mechanical reinforcement [17,18].

It is well known that the adhesion strength of alumina–titania composite coatings increases with increased titania content [19].

The surface analyses of coated and uncoated samples were done with an optical microscope and a scanning electron microscope (SEM). After the experimental processes, the surface treatments of coated and uncoated samples were estimate. Throughout the experiments, No. 2D diesel fuel is used. To achieve effective and objective results from the experimental research, SEM and optical pictures were taken from the same zone of samples reciprocally.

Type of engine	6LD 400 Lombardini
Stroke	4
Number of cylinder	1
Bore/stroke (mm)	86/68
Maximum engine power (kW)	6.25 (3600 1/min)
Fuel type	Diesel
Type of injection	Direct injection
Compression of injection (kg/cm^2)	200
Type of coolant	Air
Compression ratio	18:1
Maximum engine speed (min^{-1})	3600

Table1. Test Engine Specifications

Power (kW)	40
Arc current (A)	500
Arc voltage (V)	60-62
Used gases	Ar-H
Spray distance (mm)	75
Coating thicknesses (µm)	50µm NiAl + 250µm Al_2O_3-TiO_2(87-13)
Gas flow for Ar (psi)	80
Gas flow for H (psi)	15
Type of plasma gun	3 MB Metco
Nozzle size (mm)	7,35
Powder/ carrier gas flow rate	30/30
Powder feed rate (kg/h)	4.1

Table2. Plasma Spraying Parameters

III. RESULTS AND DISCUSSIONS

Optical microstructures of the cross section of plasma sprayed coatings are given in Figure 2. When the coated piston surface and the two coating layers are examined, it is seen that the NiAl bond layer is completely penetrated over the piston outer surface. The role of the NiAl bond layer is to provide adhesion strength for the subsequent main layer. As seen in Figure 2, the Al_2O_3-TiO_2 layer shows strong adhesion to the NiAl bond layer. The bond between the layers is seen clearly and uniformly. When the running time is considered, the deformation that occurred across the Al_2O_3-TiO_2 coating surface, is minimal compared to the uncoated components. This is an important indication of the protective effect of the surface coatings and is the main focus of the study.

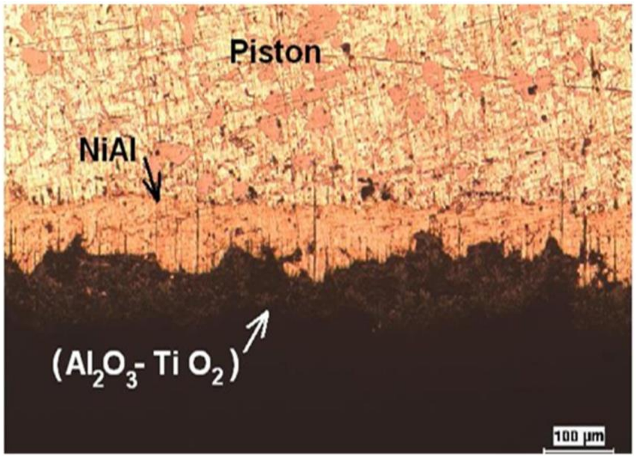

Figure2. Optical Image of Coated Piston Cross-Section after Running

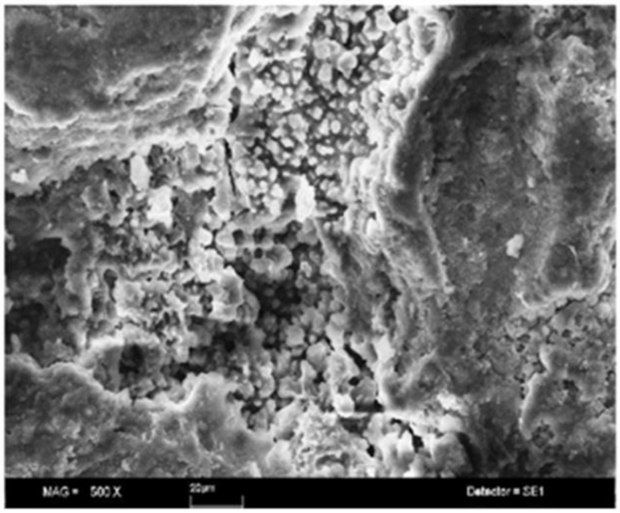

Figure 3. a. SEM Image of Uncoated Piston Surface (After Running)

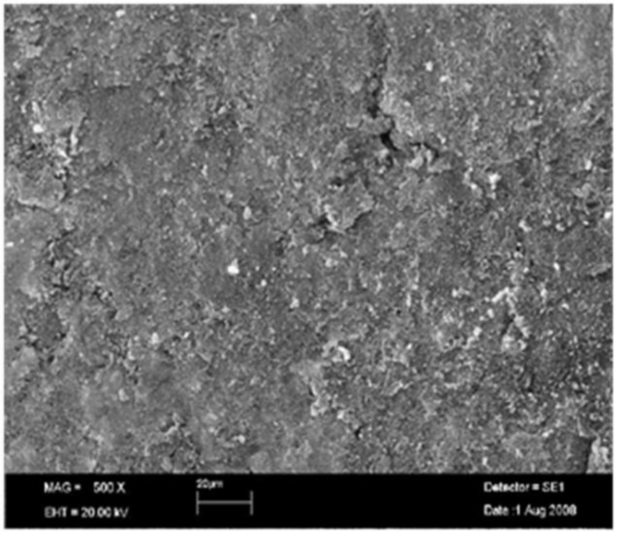

Figure 3. b. SEM Image of Coated Piston Surface (After Running)

As seen in Figure 3a, there are large bounded and deep cavities over the uncoated piston surface. When the combustion phenomena are considered, the piston's outer surface was exposed to the negative physical and chemical effects of burning. Because of the high temperature, pressure and constant thermal loads, corrosive and adhesive abrasion occurs over the faces of materials, which cause the cavities observed on the surface of the piston. In addition, it is thought that, the sulphur that is formed after combustion can cause the corrosive deformation. Fig. 3.b shows that the surface of the coated piston has a more uniform structure than the uncoated piston. It can be seen that the coated piston has few deformations and that micro cracks have not appeared across the surface. It can also be seen that there are fewer pores and wears on the face. It is possible to say that the differences observed between the coated and uncoated pistons are due to the oxide-based layer, which has a high melting point and high thermal resistance. At the same time, local deformations, cavities and cracks were not formed because of the role of the matrix phase in Al_2O_3 which distributes stresses homogeneously inside the composite material.

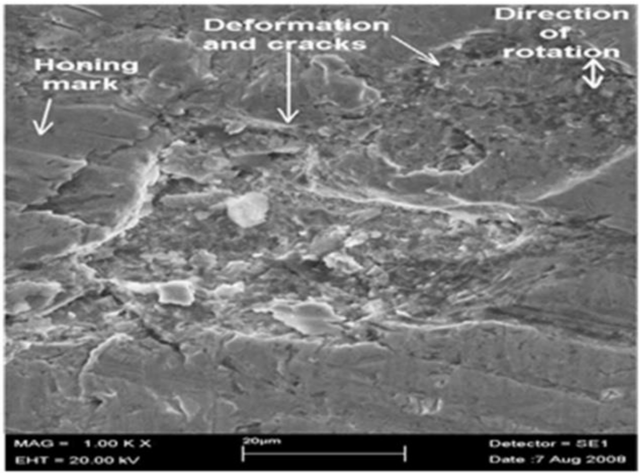

Figure 4.a. The SEM Image of Cylinder Close to the Upper Side Zone (x1000µm) (After Running with Uncoated Parts)

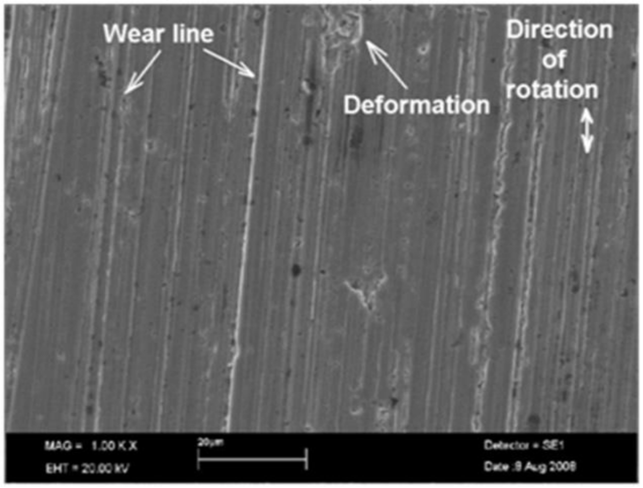

Figure 4.b. The SEM Image of Cylinder Close to the Upper Side Zone (x1000µm) (After Running with Coated Parts)

When both of the materials that are piston and cylinder line, investigated as characteristic of tribology, it is seen that the cylinder bore is subjected to the highest wear. As seen in Fig. 4.a of the surface of the cylinder line shows large bounded, deep deformations, cracks and wear lines toward to the direction way are observed. These deformations can be explained as the result of combustion (high temperature, high pressure, vibration), and the products of electrochemical reactions, such as sulphur and corrosive media factors. Also it is foreseen that by the effect of high temperature and pressure there can occur cativations over the surface of cylinder line by the result of explosion of gas calicles. But it is seen in Fig. 4.b the SEM image of cylinder bore. When the SEM images of cylinder bore are analyzed, it has a much more uniform structure and less surface porosity then the uncoated cylinder. The coated cylinder also has relatively narrow deformation bounds compared to the uncoated sample. This can be explained by reduced level of heat that is transferred to the cylinder bore due to the thermal barrier effect of the surface coating. Also, due to a more efficient combustion process, the coated components exhibit reduced oxidation within the cylinder bore.

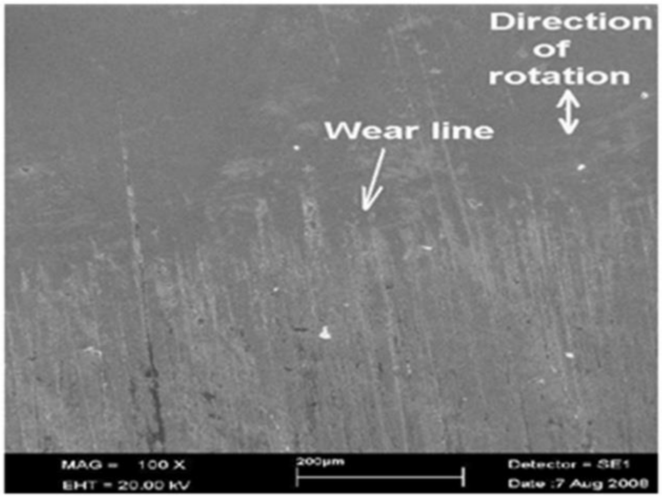

Figure 5.a. The SEM Image of Compression Ring (After Running with Uncoated Parts)

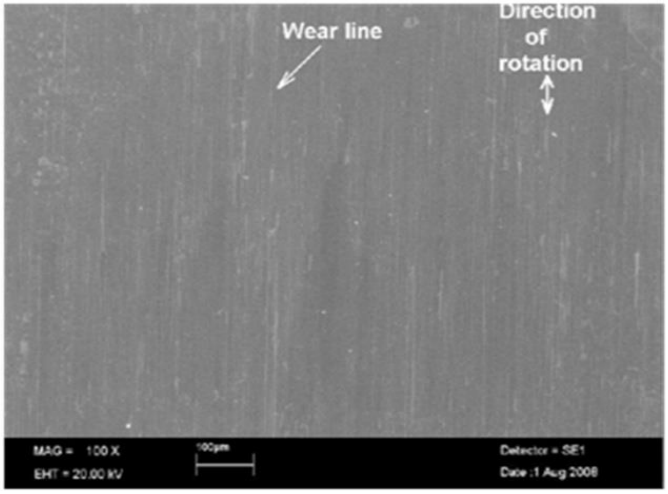

Figure 5.b. The SEM Image of Compression Ring (After Running with Coated Parts)

Friction occurs between the cylinder bore and piston rings and they are also subjected to the negative effects of the combustion process. These conditions involve high temperature, high pressure and corrosive media, similar to the faces of combustion chamber parts. Fig. 5.a shows an SEM image of the uncoated piston ring, in which it is seen that there are dense wear lines. It is considered that the wear lines can occur due to the particles from the cylinder bore by the effect of friction between the piston rings and cylinder bore. This conclusion is supported by the evidence of cavities, damage across the surface and the particles which are dislodged by the effect of wear. Fig. 5.b. shows the coated piston ring. When the surface characteristics are examined, it is seen that the coated component has a more uniform and more regular surface structure.

IV. CONCLUSIONS

1. When the operating conditions and the surface characteristics of combustion chamber components of diesel engines and are considered, atmospheric plasma spray is the most appropriate technique for applying protective surface coatings.
2. The application of a metal oxide coating to the surface of combustion chamber components provides increased surface resistance and a high performance thermal barrier.
3. The mechanical lifespan of the base materials were successfully increased by the application of ceramic coatings
4. Bond layer components provide effective adhesion durability over the substrate layer.
5. Increased thermal insulation of the combustion chamber reduces heat transfer between the sliding faces, thereby allowing the engine to operate more efficiently and reducing fuel consumption.
6. The coating process contributes to reducing many undesired phenomena such as wear, operational delays, renewal of equipment, delays caused by servicing and repairs.

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