EXPERIMENTAL INVESTIGATION OF THERMAL BARRIER ($8YSZ-TiO_2-Al_2O_3$) COATED PISTON USED IN DIRECT INJECTION COMPRESSION IGNITION ENGINE

by

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Thermal barrier coatings are becoming increasingly important in providing protection from high temperature degradation for heat engine components and allow further increase in engine temperatures for higher efficiency. The main objective of this research work is to experimentally investigate the air plasma sprayed yttria stabilized zirconia with addition of titanium oxide and aluminum oxide thermal barrier coating on Al-13% Si piston material. The mechanical properties of the coated and uncoated samples were comparatively analyzed. The test revealed that hardness values of coated samples are ten times higher than the hardness values of uncoated samples. The microstructure and surface morphology of the coating were evaluated by scanning electron microscopy. The de-lamination behaviour of thermal barrier coating was evaluated by thermal cycle test. Finally, the performance test of the coated and uncoated engine was evaluated with the same engine operating conditions. The brake thermal efficiency is increased by 5.99%. The brake specific fuel consumption was decreased by 0.06 kg/kWh, in TBC engine with 8YSZ + + Al_2O_3 + TiO_2. The CO and HC was greatly decreased in thermal barrier coating engine. There was the greater reduction of NO_x is observed due to coating because of nitrogen has absorbed by zirconia.

Key words: *$8YSZ-TiO_2-Al_2O_3$ coating, thermal barrier, plasma spraying, thermal cycle test, scanning electron microscopy, engine performance, emission test*

Introduction

Thermal barrier coatings (TBC) are commonly applied to substrates to insulate them thermally so as to allow for higher operating temperature. The desire to increase thermal efficiency or reduce fuel consumption of engines makes it tempting to adopt higher compression ratios, in particular for Diesel engines, and reduced in cylinder heat rejection [1, 2]. The energy conversion efficiency of internal-combustion engines, such as gasoline engines and Diesel engines, is only ~30% because there are exhaust loss (~30%), thermal loss (~30%), and mechanical loss (~10%). If the thermal loss is reduced by applying a TBC, the energy conversion efficiency is considered to be improved by ~10% [3]. The TBC have been identified as a means of reducing heat flux from the combustion chamber. Various studies analyzing TBC feasibility in both compression and spark ignition engines have been conducted, and though they were generally shown to have beneficial effects on engine performance [4].

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The Diesel engine has more advantages than the standard engine, such as better fuel economy and lower CO and HC emissions, although there are high smoke and NO_x emissions. Exhaust gas emissions from Diesel engines have become a serious problem to the researchers. Therefore, a method of reduction of gas emission is needed. Among the pollutants, nitrogen oxides NO_x, smoke, and particulate matter in the environment are presently the most critical problems for Diesel engine manufacturers [5].

One such ceramic used for TBC is zirconium dioxide (ZrO_2). Upon heating zirconia to typical engine inlet temperatures, the material undergoes successive phase transformations, passing from monoclinic (m) to tetragonal (t) to cubic fluorite (c) phases. The (m) to (t) transformation induces a 3-5% volume change, which can lead to cracking and brittle fracture in service. In order to circumvent this phase change, yttria (Y_2O_3) is added as a dopant to stabilize the zirconia and fully or partially retain the (t) phase to lower temperatures. Due to the high fracture toughness, thermal shock resistance and ionic conductivity of yttria stabilized zirconia (YSZ), it is also used for oxygen sensors and solid oxide fuel cells, in addition to TBC [6, 7].

Early engine tests demonstrated that two-layer coating systems consisting of a layer of zirconia-yttria ceramic over a layer of a MCrAlY alloy had the potential to survive in the engine environment. The MCrAlY alloy layer, which is often called the bond coat, is typically applied by either low-pressure plasma spraying or by air plasma spraying, while the zirconia-yttria layer is typically applied by air plasma spraying. Typical coating thicknesses for aircraft gas turbine applications are 0.13 mm bond coat thickness and 0.25 mm ceramic layer thickness [8, 9]. Thermal sprayed alumina-titania coatings are typically applied to structural materials or machinery for protection against abrasive and erosive wear, cracking, spallation, and corrosion. Alumina was incorporated in YSZ to enhance the abrasion wear, oxygen diffusion, and thermal resistances of conventional YSZ coatings [10].

Nanotechnology and structured coatings would be expected to increase life of ceramic coating is very longer, showed superior mechanical properties of crack resistance, adhesive strength, spallation resistance, abrasive wear resistance, and sliding wear residence Lower component structural temperatures will results in greater durability to increase of engine life [11].

In this work, the engine performance and emission characteristics of $Al_2O_3 + TiO_2 + 8YSZ$ plasma spray coated piston were studied. Additionally, the micro hardness, adhesion strength, and thermal cycle test of the thermal barrier coated Al-Si alloy specimen were evaluated.

Experimental method

Materials for plasma spray coating

Aluminum alloy (Al-13%Si) pistons material used as the substrate material. The top layer of TBC was made of 20% Al_2O_3, 20% TiO_2, and 60% yttria stabilized zirconia (8YSZ) by plasma spray coating with a thickness of 250 μm, and the bond coating is made of Co-Ni-Cr-Al-Y with thickness of 100 μm, (tab. 1).

Table 1. Thickness of sprayed coatings

Coating layer	Material	Thickness
Substrate	(Al-13% Si)	5 mm
Bond coat	Co-Ni-Cr-Al-Y	100 (μm)
Top coat	$TiO_2 + Al_2O_3 + 8YSZ$	250 (μm)

Micro hardness test

Vickers micro hardness tester is shown in fig. 1. The hardness values of the coated and uncoated samples were determined using a micro indenter (THV-1M, micro Vickers hardness tester) with a Vickers tip for a load of 3 N.

Figure 1. Vickers micro hardness tester

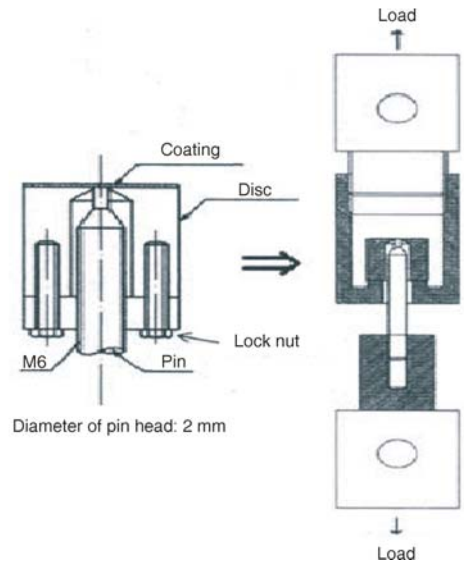

Figure 2. Tensile pin test

Adhesion strength test

Adhesion strength of the sprayed coatings was evaluated using a tensile pin test. Figure 2 shows the schematic diagram of the tensile pin test set-up.

Thermal cycle test

The test specimen dimension is 10 mm × 10 mm × 5 mm. In thermal cycle test the specimen was successively placed inside the electrical furnace at the temperature of 803 K for 5 minute and cooled in water bath for 10 seconds. The test was completed in 100 cycles. Every 10 cycles the surface of the coating was inspected for evidence of the coating spallation [12].

Engine test set-up

The pictorial view of the engine test set-up is shown in fig. 3. The single cylinder 4-strokes Diesel engine set-up was done and the specifications of engine were noted in tab. 2. The engine was run at constant rpm and the performance calculation has been done by using obtained readings. The performance of engine was compared with the standard readings of that engine by the piston before coating.

Figure 3. Pictorial view of engine test set-up

Technical specifications

Calibrated burette is used for fuel intake measurement. Orifice meter fitted to the air inlet tank with water manometer for air intake measurement. Multi-channel digital temperature indicator used for measure the temperature at various points.

Table 2. Technical specification

Engine	Water cooled 4-stroke direct injection Diesel engine
Cylinder	Vertical twin cylinders with individual cylinder head
No. of cylinder	1
No. of strokes	4
Engine power	5.2 KW engine
Speed	1500 rpm
Compression ratio	17.5:1
Cooling type	Water cooling
Electrical dynamometer	7.5 KW capacity alternator coupled to the engine with load bank. (With ammeter and volt meter)

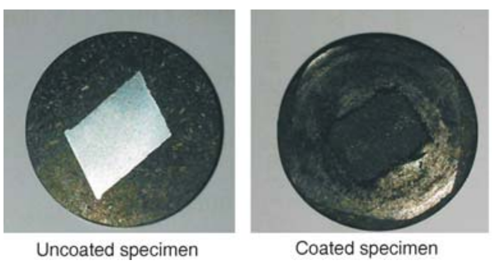

Figure 4. Samples for micro hardness test

Exhaust gas calorimeter to measure heat carried away by exhaust gas. Exhaust gas analyzer and smoke intensity measuring device are used to analyze the amount of emissive particles and the amount of smoke intensity.

Result and discussion

Vickers micro indentation test were conducted to characterize the hardness of the coating.

Figures 4 and 5 shows the samples and results of vickers micro hardness test. The test was repeated three times for each sample under same condition. The test revealed that, measured hardness values of coated specimen are ten times higher than the hardness values of uncoated specimen. This is because the addition of Al_2O_3 and TiO_2 with YSZ can increase the hardness of the coated substrate.

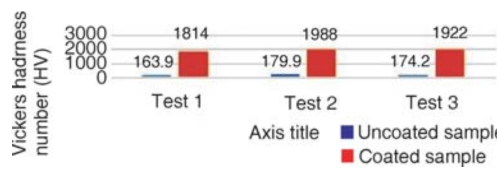

Figure 5. Result of viskers micro hardness test

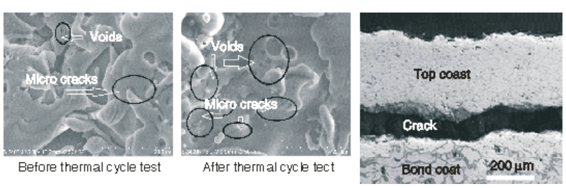

Figure 6. The SEM image of TBC coating

The adhesion strength of coating was evaluated by tensile pin test. The measured values of adhesion strength of the (8YSZ-TiO_2-Al_2O_3) coated specimen was 64, 65, and 67 MPa.

Figure 6 shows the scanning electron microscopy (SEM) image of coated samples for before and after thermal cycle test. From the thermal cycle test, after 100 cycles some micro cracks and voids were found on the surface and interface of the coating. The cracks and de-lamination were occurred due to the phase transformation of (t) phase to (m) phase of zirconia at temperature variation form high temperature to low temperature in thermal cycle test.

The combustion chamber insulation with 350 μm thickness is applied on the piston crown using atmospheric plasma spraying coating with different composition such as 8%YSZ + + Al_2O_3 + TiO_2 (60% + 20% + 20%). Over a thickness of Co-Ni-Cr-Al-Y bond coat. The thermal barrier coated piston engine was compared with the standard engine. The prepared specimen's dimensions 10 × 10 × 5 mm with similar coating surface were examined by means of SEM and energy dispersive X-ray (EDX) spectroscopy analysis. Figure 7 shows the coated and uncoated specimens of piston crown.

Scanning electron microscope analysis

Properties of the piston top coated with TBC and bond coat were analyzed by using SEM and EDX. The coating thickness achieved for both plasma sprayed top coat of 8YSZ + Al_2O_3 + TiO_2 and bond coating of Co-Ni-Cr-Al-Y were at the thickness of 350 μm, where optimum compositional and structural conditions of the coating component were analyzed. The micrograph of fracture surface of the 8YSZ + Al_2O_3 + TiO_2 coated pistons crown samples are shown in fig. 8, and the structure exhibited particles of both materials were deformed on impact during plasma spraying process and melted on piston crown surface. The overall performance of coating was helpful to identify the micro cracks, oxidation, thermal mismatch, and porosity are compared. When comparing these defects of Al_2O_3 with Co-Ni-Cr-Al-Y bond coating at the piston, it is observed bigger dense splat and a few of bigger voids. Which in turn showed lower porosity compared with coating material. The structure of surface shows fine particles with a lot of small voids which shows high porosity causes increase in thermal cycling life of the coating [13].

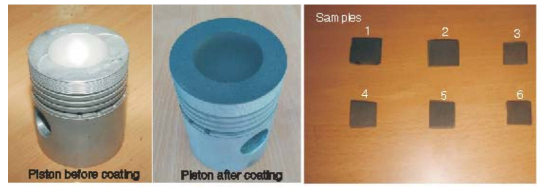

Figure 7. Piston before and after coating and coated samples

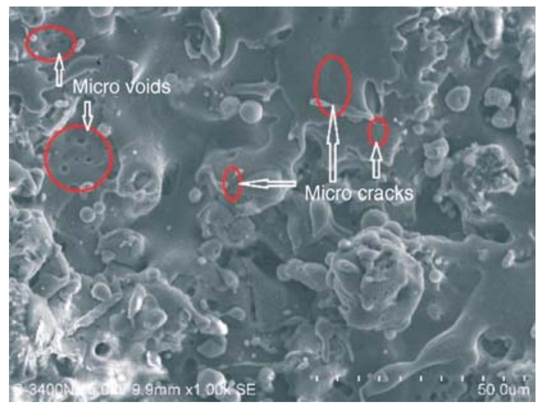

Figure 8. The SEM micrographs of Al_2O_3 + TiO_2 + + 8YSZ coated surface

The structure of the top layer of Al_2O_3 + TiO_2 + 8YSZ layer exhibited high porosity, number of small voids, oxides inclusion, unmelted particles, and cracks of micro size. High porosity characteristics of Al_2O_3 + TiO_2 + 8YSZ contributed to the brittleness of the structure. The coating was still perfect and adhered to the bond coat. A significant difference was observed between the microstructures of the coating material and bond coating. This might be a reason on low thermal conductivity that leads to heat transfer reduction [14]. This is maybe the reason for poor thermal efficiency and in this condition of several micro cracks the heat will be lost through the cracks of the coated part of the engine. This will spoil the purpose of coating.

Energy dispersive X-ray spectroscopy analysis

The effect of EDX are investigated and taken from the microstructure given in for TBC coat and bond coating is shown in figs. 9 and 10. It Illustrate the composition consisting of Co-Ni-Cr-Al-Y phases in the matrix made up of 8YSZ + Al_2O_3 + TiO_2 composite phase predominantly. Oxygen is observed in the matrix. It

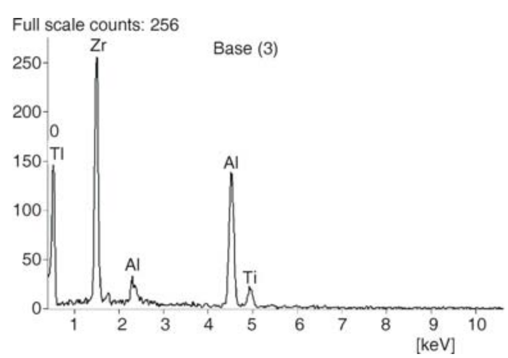

Figure 9. The EDX analysis of Al_2O_3 + TiO_2 + YSZ coated surface

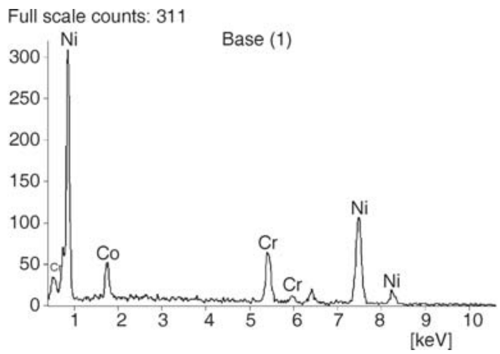

Figure 10. The EDX analysis of Co-Ni-Cr-Al-Y bond coated surface

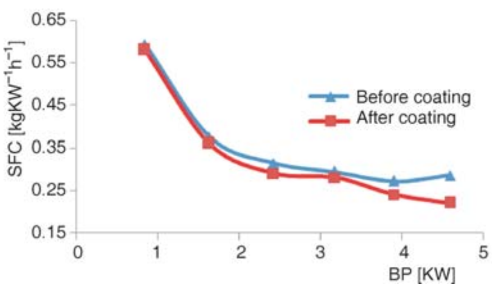

Figure 11. Effect of engine break power on specific fuel consumption

can be seen from figs. 9 and 10 that some oxygen is present in the composition in the coating. The oxygen is probably imported from the air atmosphere to the coating during the process, because the coating process has been carried out in air atmosphere without any vacuum.

The performance parameters of the engine after TBC has been measured and the efficiencies of these engines also increased a little much.

Effect of engine break power on specific fuel consumption

The variation of brake specific fuel consumption (BSFC) with brake power with varying load for coated and uncoated engine is presented in fig. 11. It was decreased sharply with increase in engine load for both coated and uncoated engine. From fig. 11, the BSFC decreasing for TBC coated piston when compared to uncoated engine. This is because of increased temperature of the piston crown which increases the temperature of cylinder gas and wall, which results higher temperature in combustion chamber. The combustion conditions become more favorable which results shortening ignition delay time in coated engine affects the both chemical and physical reactions positively, It is believed that this situation contributes to decrease BSFC when compared to uncoated engine. From the graph BSFC of thermal barriers coating engine compared to uncoated engine. For 8YSZ + Al_2O_3 + TiO_2, the BSFC is decreased by 0.06 kg/kWh.

Effect of engine break power on brake thermal efficiency

The variation of the brake thermal efficiency (BTE) with break power of engine for both uncoated and thermal barrier coated engines is shown in fig. 12. It is clear that the BTE of the thermal barrier coated piston increased when compared with the uncoated engines. The ceramic coating has low thermal conductivity which enhances higher operating temperature of the engine. The efficiency was increased due to the reduction in heat transfer from the gas to the wall during the combustion or expansion. The variation of BTE in TBC engine depends upon the thermal conductivity of the material. For 8YSZ + Al_2O_3 + TiO_2, the BTE is increased by 5.99%

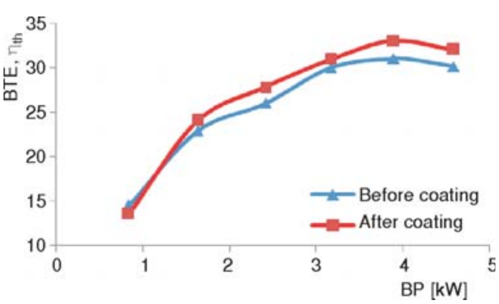

Figure 12. Effect of engine break power on BTE

Effect of engine brake power on unburned HC

From fig. 13 It is clear that, the unburned HC emissions are reduced when engine is run with coated piston. The unburned HC emissions are slightly higher when the engine runs without the coating.

The main reason for this reduction in the unburned HC emissions is that at high temperatures the engine will have sufficient amount of oxygen which mixtures with the HC emissions. As a result of this, the HC will split into H and C which mixes with O_2 thereby reducing the HC emissions.

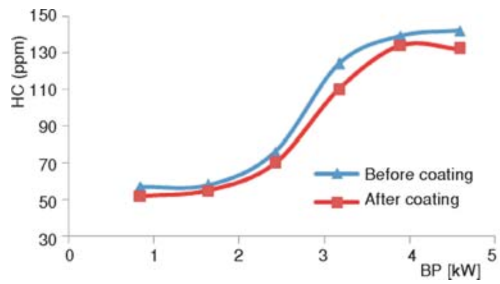

Figure 13. Effect of engine break power on unburned HC

Effect of engine brake power on CO

The variation of CO emissions with brake power is shown in fig. 14, for uncoated and TBC engine. It can be observed from the results that thermal barrier coating in piston crown decreasing CO when compared with uncoated engine. The CO is decreased after the coating due to the complete combustion. The CO, which arises mainly due to incomplete combustion, is a measure of combustion in efficiency. Generally oxygen availability in diesel is high so at high temperature carbon easily combines with oxygen and reduces the CO emission. For 8YSZ + Al_2O_3 + TiO_2, the CO is reduced by 4.8% of volume.

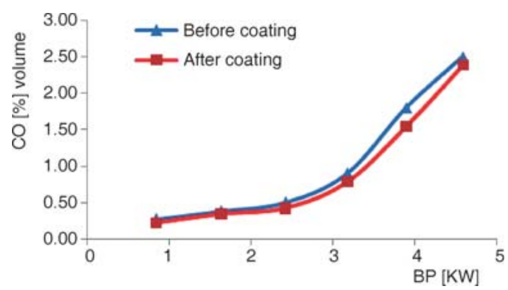

Figure 14. Effect of engine break power on CO

Effect of engine brake power on NO_x

The variation of NO_x with break power is shown in fig. 15, for uncoated and thermal barrier coated engines. The NO_x emissions are mainly a function of gas temperature and residence time. Most of the earlier investigations show that NO_x emission from low heat rejection engines is generally higher.

This is due to higher combustion temperature and longer combustion duration. But the present investigation, an increased reduction of NO_x was observed due to coating because nitrogen is absorbed by zirconia [15]. Generally the availability of oxygen in diesel is high, so at high temperatures, nitrogen is easily combines with oxygen. But availability of nitrogen is very less due to coating and therefore forms less NO_x.

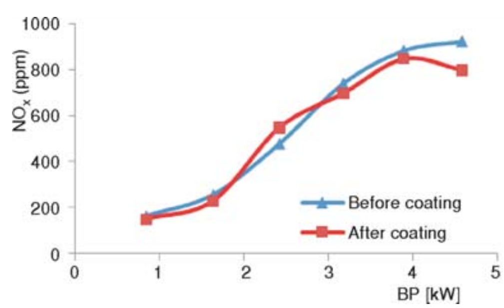

Figure 15. Effect of engine break power on NO_x

Conclusions

The mechanical properties of the coated and uncoated samples were comparatively analyzed. The test revealed that hardness values of coated sample are ten times higher than the hardness values of uncoated samples. The measured values of adhesion strength of the ($8YSZ-TiO_2-Al_2O_3$) coated specimen was 65 ±2 MPa. After 100 thermal cycles cracks and spallation were found on the surface and interface of the coating.

The BTE was increased in TBC engine mainly depends upon the thermal conductivity of the material. For $8YSZ + Al_2O_3 + TiO_2$, the BTE is increased by 5.99%. The BSFC was decreased in TBC engine. For $8YSZ + Al_2O_3 + TiO_2$, the BSFC is decreased by 0.06 kg/kWh. The CO and HC was greatly decreased in TBC engine. There was the greater reduction of NO_x is observed due to coating because of nitrogen has absorbed by zirconia.

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