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## Experimental Investigation with Thermal Barrier Coating On Performance and Emission Of Diesel Engine

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### Abstract

*Diesel engines find vast applications in the field of transportation and power generation. The ever growing demand for energy for everyday has exerted much pressure on fuels thereby causing the fuel prices to grow and at the same time causing fuels to deplete. In order to overcome this problem the system has to be made more efficient. This is done by increasing the thermal efficiency of the system by increasing the temperature in combustion chamber up to a certain acceptable level. Higher the operating temperature higher will be the efficiency of the system. However, such higher temperatures call for enhanced temperature resistant materials to be used. These materials are called Thermal Barrier Coatings (TBC's). In this experiment tests were conducted on a single cylinder diesel engine with eddy current dynamometer whose piston and head were coated with 250 micron thickness of AMDRY 962 Nickel Chromium Aluminum Yttria Powder as thermal barrier coating. The test results of the engine coated with TBC were compared to an engine without TBC. The results obtained with the engine with thermal barrier coating were found to be better than non coated. Also emission levels were comparatively much lower except for NO<sub>x</sub> that happened to increase as temperature within combustion chamber had been increased.*

**Keywords:** Ceramic coating, plasma spray, coating method, engine performance and emission characteristics, diesel engine, plasmaspray.

### 1. Introduction

The main purpose of thermal barrier coating systems is to reduce the component metal temperature. Lower metal temperature results in reduced creep stress, lower oxidation rates, and ultimately greater component durability. Large temperature drops may allow engine manufacturers to use less exotic materials in the design of engine components or to increase the fuel efficiency of the engine by operating at higher temperatures with reduced cooling flows. The advent of high temperature, high performance ceramics has tempted engine researchers to strive for higher operating temperatures with subsequent higher engine thermal efficiency by reducing fuel consumption. The primary purpose of high temperature structural coatings is to enable components to withstand even higher temperature than they can normally and to improve component durability in engines. Here the same purpose is achieved using AMDRY 962 Nickel Chromium Aluminum Yttria Powder (Ni-Cr super alloy). It exhibits excellent mechanical and thermal properties with high chemical and hot corrosion resistance, low shrinkage, extended life and an excellent coating surface with reduced amount of degradation.

In a diesel engine the temperature inside the combustion chamber plays a huge role in determining its thermal efficiency. If the temperature of the combustion chamber is increased the thermal efficiency will automatically increase. Secondly reducing heat rejection in engines is

a possible way of reducing fuel consumption. These objectives can be achieved by TBC's. Diesel engines convert one third of fuel energy into useful work and the remaining two third is lost as waste energy through coolant and exhaust, therefore the piston crown and cylinder head of the diesel engine are coated with thermal barrier materials so that heat transfer to the surrounding can be curtailed thereby improving power output. Effectively trapping the heat within the combustion area will make the engine a Low Heat Rejection (LHR) engine (J.Rajasekaran, *et al* 2013).

The LHR means suppressing heat rejection to the coolant and recovering the energy in form of useful work. LHR engines are known to reduce engine noise, improve fuel economy, reduced noise, and higher energy in exhaust gases.

#### 1.1 Thermal Barrier Coatings (TBC)

Thermal barrier coatings are compositions of highly advanced material systems applied to working surfaces which need to withstand high temperatures. They are usually ceramic, due to the high oxidation resistance and low thermal conductivity of this material class a large number of ceramic materials have been tried and are used. (Raghavendra P. *Met. al* 2014). In an IC engine components like inlet and exhaust valves, cylinder heads, and piston crown to name a few. These coatings insulate metallic components from large and prolonged heat loads, thereby allowing them to operate at elevated temperatures while reducing oxidation, limiting the thermal exposure of structural components, hence extending service life and minimizing thermal fatigue. Modern Thermal barrier

coatings are required to not only limit heat transfer but also protect engine components from hot corrosion.

## 2 Literature Review

The research and attempts made with thermal barrier coatings were studied were made in order to bridge the gap between the objectives and scope of the project. Various researchers have used various materials and have observed a vast verity of results. The following material has helped to better understand in detail the study and build upon this project.

Naveen.P *et al.* presented the effect titanium oxide coating on the performance characteristics of the bio-diesel fuelled engine. The piston head was coated with 150  $\mu\text{m}$  Alumina-Titanium oxide ( $\text{Al}_2\text{O}_3/\text{TiO}_2$ ) plasma coating over a 60 $\mu\text{m}$  NiCrAl. Standard engine (without coating) and coated piston engine were tested at same operating conditions. The results obtained states that the brake thermal efficiency of the coated piston is increased when compared to base piston.

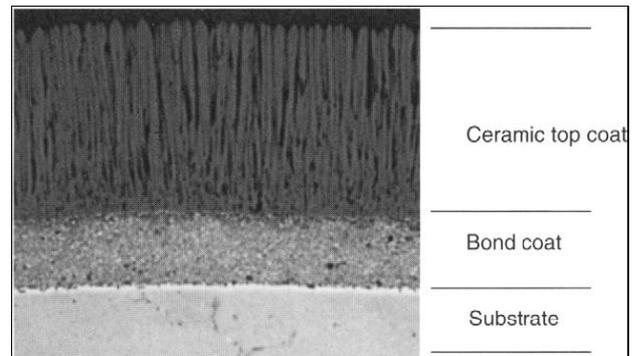
K.R.Sharma *et al.* have considered for test are Zirconia, Alumina and Chromium-Oxide coating with and without NiAl bond. They have concluded that all coated materials have higher resistance to temperature and Zirconia gives the best results in thermal shock and thermal punching experiments

C. Ramesh Kumar *et al.* have carried out the performance and emissions by coating 0.3 mm thick Alumina ( $\text{Al}_2\text{O}_3$ ) on the cylinder head, inlet and exhaust valves of a four stroke spark ignited engine fueled with E20 blend. They have concluded that partially insulated SI engine when fueled with E20 improves performance and reduces emission.

J.Rajasekaran *et al.* have selected Ytria stabilized zirconia (YSZ) which has low thermal conductivity, high thermal resistance and chemical inertness, high resistance to erosion, corrosion and high strength as a coating material for engine component. Total fuel consumption is reduced by 7% and specific fuel consumption by 6%. zirconia coated piston observed. HC emissions were reduced by 23%.CO emissions are reduced by 48% because of high temperature.

M.K.Pathak *et al.* reviewed the application of various thermal barrier coatings over the high temperature components. They have suggested making use of steel crowned articulated aluminum pistons because of reduced reciprocating mass and higher conductivity of Al-Si matrix (155 W/m-K) rather enhanced the problem of heat loss. Plasma spray coating is widely accepted technique. Yttrium stabilized zirconia the most successful ceramic top layer because of its low thermal conductivity and good phase stability

## 3. Construction of Thermal Barrier Coatings



**Fig. 1** Construction of TBC along with substrate

A typical TBC system consists of

1. The top coat, a porous ceramicinsulator.
2. The bond coat, an oxidation-resistant metallic layer between the substrate and the top coat
3. The super alloy or other material substrate that carries structuralLoad (J.A. Haynes 2000).

### 3.1 Top coat

The top coat provides thermal insulation for the substrate that lies below. Here the material is zirconia. This coating requires a material that combines low thermal conductivity and with a coefficient of thermal expansion (CTE) that is as similar to the substrate, so that generation of stresses during thermal cycling is reduced. Zirconia may exist in three solid phases, which are stable at different temperatures. At temperatures up to 1200 $^{\circ}\text{C}$ , the monoclinic phase is stable. Zirconia transforms from the monoclinic to the tetragonal phase above 1200 $^{\circ}\text{C}$  and above 2380 $^{\circ}\text{C}$  to the cubic phase. Transformation from monoclinic to the tetragonal phase has a volume decrease of 4%. This gives rise to cracks. To prevent the cracking that occurs due to volume change in the tetragonal to monoclinic phase transformation, which occurs in the the working environment stabilizers are added to the zirconia. Typically 7-9wt% yttrium oxide is used to partially stabilise zirconia. The reason for this is yttrium oxide has a suitable cation radius, similar to that of zirconium, and a cubic crystal structure. YSZ has a room temperature, grain size dependent, thermal conductivity of 2.2-2.6 W/mK (Parlak A, *et al*2003; ).

### 3.2 Bond coat:

The bond coats used can be divided in two categories:  $\text{MCrAlY}$  (where M= Co or Ni or both) and Pt-modified aluminides. In this experiment  $\text{NiCrAlY}$  is used. The bond coat protects the below substrate from oxidation and improves adhesion between the ceramic and metal. The oxygen reaching the bond coat through the top coat gives rise to oxidation. The yield and creep characteristics of the

bond coat are significant for the performance of the TBC system. These coatings were developed for use as protective coatings against hot corrosion and oxidation. When exposed to an oxidizing environment, they form a stable dense alumina layer. This alumina, often termed as thermally grown oxide, prevents further attack of the underlying material, due to its low oxygen diffusivity and its good adherence. MCrAlY bond coats are deposited by low-pressure plasma spraying and consist of two phases ( $\beta$ -NiAl and either  $\gamma$ -Ni solid solution or  $\gamma'$ -Ni<sub>3</sub>Al). Small amounts of Yttrium are added to improve the adherence to the thermally grown oxide. Yttrium additions inhibit void formation at the thermally grown oxide and bond coat interface. Furthermore, yttrium has the effect of decreasing the grain size of the thermally grown oxide and thus raises its mechanical strength. MCrAlY bond coats creep at temperatures above 800°C. At this temperature, the creep behaviour of the bond coat has a significant influence on the stress state of the TBC and thus on its failure mechanisms (VanniLughi2004).

### 3.3 Nickel based superalloys:

Nickel based super alloys can currently operate up to temperatures of 1100°C. The following properties of Nickel make it ideal to be a super alloy. It has a face-centred cubic (FCC) lattice, which has a high modulus, and low diffusivity for substitution solutes. Super alloys were conventionally produced by casting methods. However, super alloys produced by casting methods often did not exhibit consistent creep properties (Sofia A. Tsipas, 2005). This problem led to the development of directional solidification which produces castings with grains aligned in the direction of maximum stress and few grain boundaries normal to this direction. Directional solidification is achieved by ensuring that the heat during solidification of the casting is removed in a direction parallel to the desired growth direction, while a liquid/solid interface perpendicular to the solidification direction is maintained. DS results in a significant increase in the creep strength of these superalloys, relative to conventionally cast alloys, and lead to an increase in its temperature bearing capabilities.

### 4 Plasma Spray Coating

The system consists of power unit, gas supply unit, powder unit, cooling system, control unit and spraying gun. The process involves latent heat of ionized inert gas (plasma). The primary gas used to create the plasma is nitrogen (argon can also be used). The primary gas flows between the electrode and nozzle. A high voltage alternating electric arc is struck between the electrode and nozzle, which causes ionization of the gas stream.

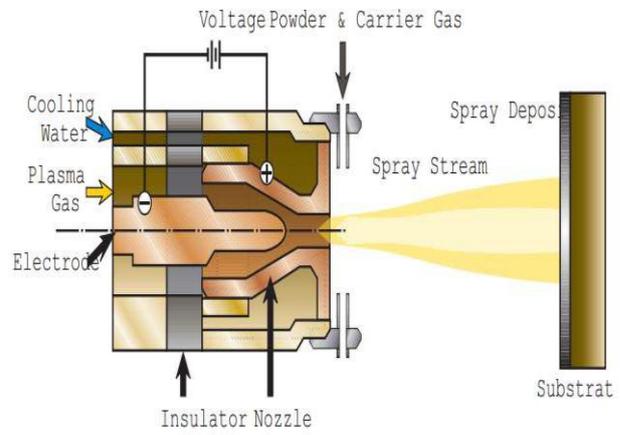


Fig. 2 Plasma spray process

### 5 Composition of TBC

Percentage by weight (%)	Ni	Cr	Al	Y	ZrO <sub>2</sub>	Y <sub>2</sub> O <sub>3</sub>
Bond coat	Bal	22	10	1	-	-
Top Coat	-	-	-	-	92	8

Table 1 Composition of bond coat and top coat

### 6 Part Preparation

The cylinder head and piston were first cleaned and degreased. In order to increase the bond strength, a bond coat was applied, comprising of NiCrAlY which acts as an intermediate layer between the substrate and the ceramic coating. This intermediate coating provides corrosion protection to the material to be coated with which is in the form of powder was fed to the machine where the molten material was further heated causing it to form plasma. Then the plasma jet was impinged on the surface and cooled in an inert gas environment thereby making it hard. This coating of AMDRY 962 is finished by grinding with a SiC wheel. An 8% yttrium-stabilized zirconium oxide material is used for the top coat because of its good thermal shock characteristics. The adhesion of the coating to the substrate is by mechanical bonding, hence careful cleaning and pre-treatment of the surface to be coated is necessary. Here the surface of the cylinder head and piston crown are coated by Yttria Stabilized Zirconium for a thickness of 250 microns by plasma spray technique. Table 2 gives the details of the parameters governing the plasma spray process.

Plasma Spray Gun series		3MB/9MB
Gases	Primary	N <sub>2</sub>
	Secondary	H <sub>2</sub>
Gas pressure	Primary (psi/bar)	50/3.45
	secondary (psi/bar)	50/3.45

Power:	Arc current (amps)	500-550
	Arc voltage (volts)	74-80
Spray rate	(lbs./hr)	8
	(g/min)	60
Spray distance	Inches	5
	Mm	125
Cooling air jet pressure (psi)		60
Deposit efficiency ( % )		65
Size(mm) Number of powder injector ports		2/2

**Table 2** Plasma spray process parameters



**Fig.3** Piston coated with TBC



**Fig 4** Cylinder head coated with TBC

**6.1 Powder Characteristics**

As the thermal barrier coating comprises of top coat and bond coat it is necessary to list the characteristics of both layers. The following tables help see and understand them clearly.

Classification	Ceramic
Chemistry	ZrO2 8Y2O3
Service Temperature *	≤ 1350 °C (2460 °F)

Melting point	2800 °C (5072 °F)
Purpose	Thermal protection
Stabilizer (weight %)	7-8
Nominal range (µm)	-75 +45
Surface Finish	450 - 600
Micro hardness	R <sub>c</sub> 30 ±5
Porosity (vol %)	10
Density (g/cc)	5.2
Thermal Expansion( 10 <sup>-6</sup> /K)	10
Thermal Conductivity(W/mK)	1.3

\*depends on type of bond coat

**Table 3** Typical characteristics of top coat

Size range(µm)	-140mesh +270 mesh (-106 +53)
Melting Point	1320°C (2408°F).
Gases	N <sub>2</sub> /H <sub>2</sub>
Thickness limit(mm)	1
Coverage(approx) m <sup>2</sup> /hr/0.1mm	4.0
Powderrequired(approx) kg/m <sup>2</sup> /0.1mm	1.1
Macro hardnessR <sub>b</sub>	90
Surface Finish R <sub>a</sub> (µm)	400-500
Bond strength (psi)	9000
Porosity (vol%)	1-2

**Table 4** Typical characteristics of bond coat

**7 Methodology**

A diesel engine is allowed to run until steady state conditions are reached the engine is loaded at 25%, 50%, 75% and 100 % of full load . All observations were made under steady state condition. All data was observed and recorded on IC engine soft software. These formed the results of the standard base engine. The piston and cylinder head were replaced with coated piston and cylinder head with a ceramic coat of 250 microns sprayed by plasma spray technique . After installation the same engine was run under steady state condition with similar loads. The performance and emission characteristics of the engine with ceramic

coated engine parts were compared to that of the standard base engine.

### 8 Experimental Procedure and engine set up

The single cylinder 4stroke diesel engine was connected to eddy current dynamometer is shown in figure 4. Dynamometer load measurement is from a strain gauge load cell and speed measurement is from a shaft mounted three hundred sixty PPR rotary encoder. Sensors for ECU is used for various temperatures, throttle position etc. Emission gas analyzers of 5 channel and smoke meter were used to measure different emissions and smoke. Fuel is fed to the injector pump under gravity. The IC engine software was used for data acquisition system. The cooling water temperature is maintained constant throughout the experimentation by controlling the flow rate of water. The engine was allowed to run till the steady state is reached. Then the engine was loaded in various loads at constant compression ratio.



**Fig.4** Experimental set up

Sr. No.	Descriptions	Specifications
1	Make	Kirloskar TV1 Engine
2	No. of cylinder	1
3	No. of stroke	4
4	Cylinder diameter	80 mm
5	Stroke length	110 mm
6	Connecting rod length	234 mm
7	Orifice diameter	20 mm

8	Dynamometer arm length	185 mm
9	Fuel	Diesel
10	Power	3.5 kw
11	Speed	1500 rpm
12	CR Range	12:1 To 18:1
13	Injection Point	0 To 20 C
14	Software	IC Engine soft

**Table 5** Engine Specifications.

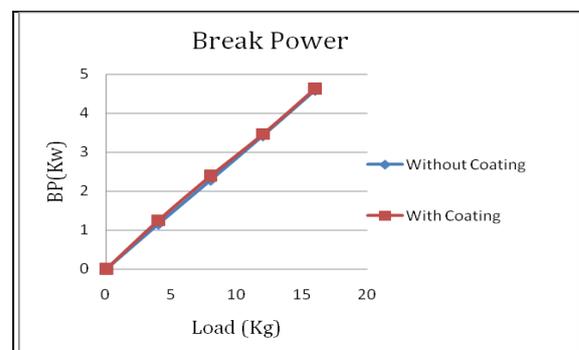
Experiment was carried out initially using an uncoated piston and cylinder head to generate the base line data. The engine was loaded at 25%, 50%, 75%, and 100 % of full load. After recording engine performance parameters at these loads the exhaust gas emissions were recorded. Smoke (opacity) was measured by smoke meter and the opacity was recorded. While keeping the fuel injector triggering pressure and fuel injection advance angle unchanged. After achieving the stable condition the observations were recorded at all above operating points. The engine piston and head were replaced with the ceramic coated piston and head and the same observations were carried out at steady state conditions.

### 9 Results and discussion

The following observations were made with the standard engine and the engine with the piston and head coated with thermal barrier coating. Various engine performance parameters were compared along with the engines emission characteristics Graphs were plotted of the same.

#### 9.1 Break Power vs. Load

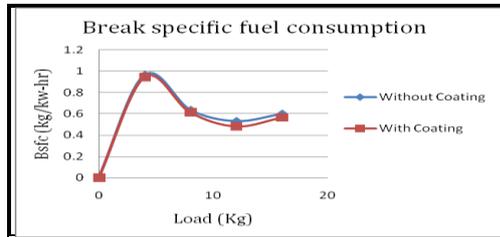
The break power of the engine with coating and without coating was compared. An increase of 2% was observed with the engine coated with TBC.



**Fig.5** Break power

#### 9.2 Break specific fuel consumption vs. Load

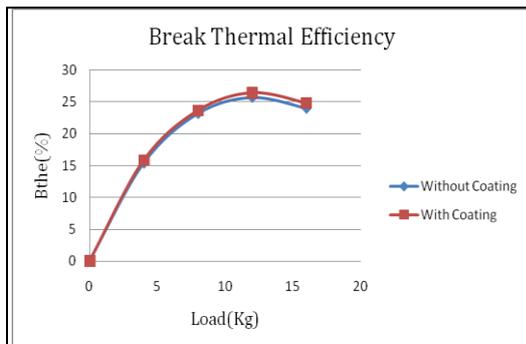
The brake specific fuel consumption was lower by 4.89 % in the coated engine as compared to the engine without TBC.



**Fig.6** Break specific fuel consumption

**9.3 Break thermal efficiency vs. Load**

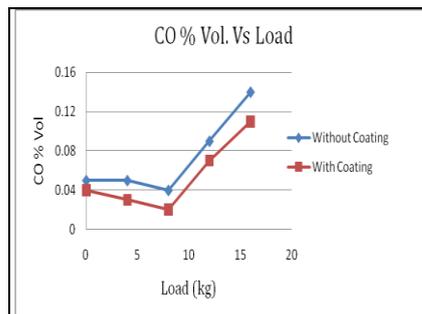
The engine with coated components was found to be higher by 2.8% as compared to that of the standard engine.



**Fig.7** Break Thermal Efficiency

**9.4 CO % volume vs. Load**

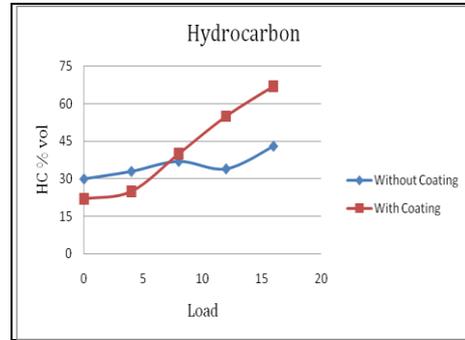
A significant reduction in emission of carbon monoxide was noticed. The carbon monoxide emissions were reduced by 21.6 % in the engine coated with TBC as compared to the standard engine.



**Fig.8** Carbon monoxide emissions

**9.5 HC % volume vs. Load**

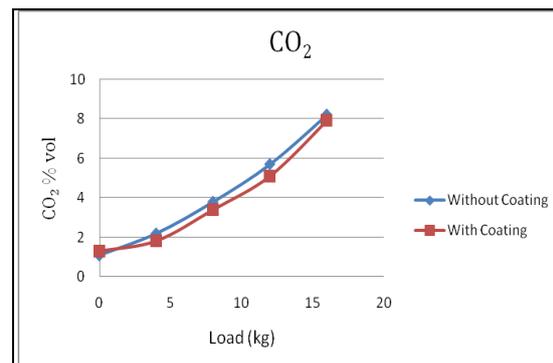
It was seen that emissions of hydrocarbon in the coated engines were lower at lower loads, however with the increase in loads the emissions go higher as compared to the standard engine.



**Fig.9** Hydro carbon emissions

**9.6 CO<sub>2</sub> emissions vs Loads**

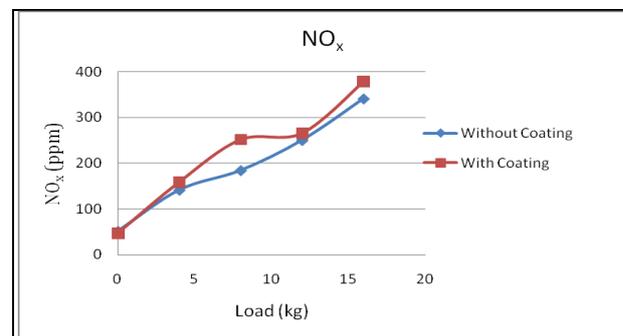
At lower loads similar amounts of emission of CO<sub>2</sub> were seen in both engines. As load increased reduction by 7% of CO<sub>2</sub> emissions were observed in the coated engine as that of the non coated engine.



**Fig.10** Carbon dioxide emissions

**9.7 NO<sub>x</sub> Vs. Loads**

Initially both engines emitted similar levels of NO<sub>x</sub> however at higher loads the engine coated with TBC showed higher levels of NO<sub>x</sub> emissions.



**Fig.11** Oxides of nitrogen emission

**Conclusion**

- In the Experimental Investigation with Thermal Barrier Coating on Performance and Emission of Diesel Engine it can be concluded that the engine performs better with thermal barrier coating.

- Brake power observed in the engine coated with TBC was 2.13 % higher than that with a standard engine.
- The brake specific fuel consumption was lower by 4.89 % in the coated engine as compared to the engine without TBC.
- The break thermal efficiency of the engine with TBC was found to be higher by 2.8% as compared to that of the standard engine.
- A significant reduction in emission of carbon monoxide was noticed. The carbon monoxide emissions were reduced by 21.6 % in the engine coated with TBC as compared to the standard engine.
- It was seen that emissions of hydrocarbon in the coated engines were lower at lower loads, however with the increase in loads the emissions go higher as compared to the standard engine
- At lower loads similar amounts of emission of CO<sub>2</sub> were seen in both engines. As load increased reduction by 7% of CO<sub>2</sub> emissions were observed in the engine with TBC as that of the non coated engine.
- Initially both engines emitted similar levels of NO<sub>x</sub> however at higher loads the engine coated with TBC showed higher levels of NO<sub>x</sub> emissions. This is justified due to rise in temperature inside combustion chamber.

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