Numerical investigation of ceramic coating on piston crown using Finite Element Analysis

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Abstract

The main purpose of this research is to analyze the effect of ceramic coating on piston to improve the thermal efficiency along with reduction in emission of engine. In this study, the surface of a piston in a diesel engine is coated with Zirconia material with depth of 100 microns using plasma-spray technique. The temperature distribution is subsequently analyzed by Finite Element Analysis method which is carried using ANSYS. An experimental work is conducted to detect the change in engine characteristics with the influence of functionally graded coating material. The experimental setup was constructed and results were obtained for thermal efficiency, Performance and emissions. The obtained results were compared between uncoated and Zirconia coated piston. Validations between the experimental and analysis reports were made and the values were matched proving the potential application of using this project in real time scenario. It also aims in converting a conventional engine into a low heat rejection (LHR) Engine.

Keywords: *Ceramic coating, Plasma spray coating method, Engine performance and Emission characteristics.*

1. Introduction

In case of Internal Combustion Engines, most of the heat generated during combustion process is absorbed by piston. This is direct heat loss to the piston. This reduces Indicated Power and in turns the performance of Internal Combustion Engine. Engine coating with a ceramic thermal barrier can be applied to improve reliability and durability of engine performance and efficiency in diesel engines. In a conventional diesel engine, about 30% of the total energy is rejected to the coolant and it was reported that the engine coating may be a good solution. Main advantages of the engine coating concept were such as improved fuel economy, reduced hydrocarbon, smoke and carbon monoxide emissions, reduced noise due to lower rate of pressure rise and high energy in the exhaust gases. Thermal barrier coatings are generally applied on the cylinder head, piston and valves by plasma spray method. Coating these parts with ceramic also limits the negative effects of wear, friction, heating, corrosion and oxidation. It was also reported in a theoretical diesel cycle analysis that more the heat transfer decreases, the less energy will be lost, thus increasing the work output and the thermal efficiency. In another study, with engine coating an increase in engine power and decrease in specific fuel consumption, as well as significant reduction in exhaust gas emissions and smoke density have been addressed in comparison to the uncoated engine. Using the coated piston, the required temperature in the combustion chamber will be maintained. This will reduce the heat loss to the piston. This reduction in the heat loss will be used to burn the unburnt gases there by reducing the polluted exhaust gases.

Functionally graded materials are of widespread interest because of their superior properties such as corrosion, erosion and oxidation resistance, high hardness, chemical and thermal stability at cryogenic and high temperatures. These properties make them useful for many applications, including Thermal Barrier Coating (TBC) on metallic substrates used at high temperatures in the fields of aircraft and aerospace, especially for thermal protection of components in gas turbines and diesel engines. Thermal barrier coatings have been successfully applied to the internal combustion engine, in particular the combustion chamber in order to simulate adiabatic changes. The objectives are not only for reduced in-cylinder heat rejection and thermal fatigue protection of underlying metallic surfaces, but also for possible reduction of engine emissions and brake specific fuel consumption. The application of TBC reduces the heat loss to the engine cooling-jacket through the surface exposed to the heat transfer such as the cylinder head, liner, piston crown and piston rings. The insulation of the combustion chamber with ceramic coating affects the combustion process and, hence, the performance and exhaust emissions characteristics of the engines improve. On the other hand, the desire of increasing the thermal efficiency or reduce fuel consumption of engines leads to the adoption of higher compression ratios, in particular for diesel engines, and reduced in-cylinder heat rejection. Both of these factors cause increased mechanical and thermal stresses of materials used in combustion chamber.

The application of TBC to the surfaces of these components enhances high temperature durability by reducing the heat transfer and lowering temperature of the underlying metal. Typical TBCs failure is by spalling of the ceramic top coat from the bond coat. There are many factors that influence the overall performance of coatings and cause spalling of the coating. However oxidation and thermal mismatch are identified as two major factors influencing the life of the coating system. The coatings are permeable to the atmospheric gases and liquids resulting in the oxidation of the bond coat and spalling of the coating. The functionally graded coatings were used to reduce the mismatch effect. Therefore the thermal expansion and interfacial stresses are an alternative approach to conventional thermal barrier coatings.

Experimental and Computational Investigations on Piston coated externally scavenged S.I. Engine by two stroke engines have a drawback of more fuel consumption & more exhaust emission, as compared with four stroke engines [1]. Combined effects of Thermal Barrier Coating and blending with Diesel fuel on usability of Waste Plastic Oil in Diesel Engines by the possibility of using waste plastic pyrolysis oil-diesel blends in a thermally insulated diesel engine has been experimentally investigated [2].

Experimental investigation of performance and combustion characteristics on a single cylinder Low Heat Rejection (LHR) engine using diesel and multi-blend biodiesel a nano ceramic Al2O3 was used as a coating material in the low heat rejection engine concept [3]. Effect of Thermal-Barrier Coating plus Fuel Additive for Reducing Emission from D.I Diesel Engine in internal combustion engines, approximately one third of the total fuel input energy was converted into useful work and two-third has been lost through exhaust gas and cooling system [4]. Experimental investigation of heat losses in a ceramic coated diesel engine, the quest for increasing the efficiency of an internal combustion engine has been going on [5]. Thermal barrier coatings are most commonly stabilized zirconias such as Yttria- Stabilized Zirconia (YSZ), but other ceramics like Silicon Nitride (SN) have been used. Thermal conductivities (k) have ranged from less than 0.5 W/mK to 10 W/mK and thickness has ranged from 0.1 mm to 4.5 mm. Ceramic coatings can be applied by a variety of methods, although thermal spraying techniques such as plasma spray are the most common. A bonded layer with a Coefficient of Thermal Expansion (CTE) in between that of the Thermal Barrier Coating (TBC) and metal substrate is typically used to improve coating adhesion.

2. Finite Element Analysis

2.1 Modeling and Grid generation

Thermal barrier coatings can be applied in the IC engine to insulate combustion chamber surfaces. The coatings can be applied to the entire combustion chamber or to select surfaces like the piston crown or valves. In this study the TBC coating is applied on the piston crown. Model of the piston and coating layer constructed using solid works modeling software. Description of the piston parts & piston coatings are shown in table 1 & 2 and respective models are shown in Fig. 1 & 2. Piston model was imported to ANSYS software were tetrahedral grids are generated and displayed in Fig. 3.

TABLE I. PISTON SPECIFICATION

Coating material	Zirconium
Coating thichness	100 micron
Method used for coating	Plasma Spray Technique

TABLE II. PISTON COATING SPECIFICATIONS

Dia of piston	87.4 mm
Shank length	110 mm
No. of ports	5
Pin dia	14 mm
No. of piston rings	2
Thickness of piston ring	mm

2. 2 Boundary condition and meshing:

- Type of Analysis – Thermal Analysis – Steady State
- Temp at Robin Boundary Conditions -Top Surface = 873K
- Convection Film Co efficient – 1500 W/Sq mC
- No of Nodes – 39009
- No of Elements – 48102

International Journal of Scientific Engineering and Applied Science (IJSEAS) – Volume-2, Issue-4,April 2016
ISSN: 2395-3470
www.ijseas.com

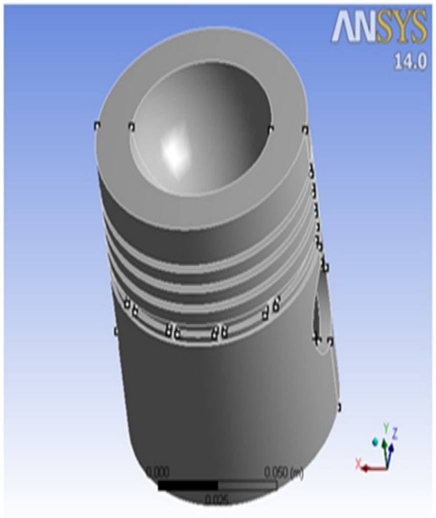

Fig .1. Uncoated piston model

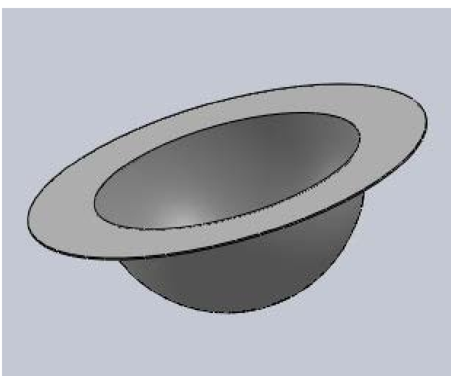

Fig. 2. Coating layer

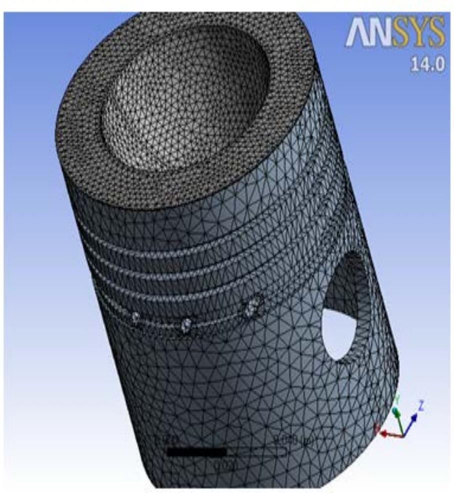

Fig.3. Meshed piston model

Some of the additional heat energy in the cylinder can be converted into useful work, increasing power and efficiency. Reducing heat transfer also increases exhaust gas temperatures, providing greater potential for energy recovery with a turbocharger or possibly a thermoelectric generator. Additional benefits include protection of metal combustion chamber components from thermal stresses and reduced cooling requirements. A simpler cooling system would reduce the weight and cost of the engine while improving reliability.

The temperature distributions on conventional and Zirconium coated piston with Al alloy are shown in the figure. The maximum temperature value is determined as 558.98°C at the combustion chamber of conventional piston. The maximum temperature value of ceramic coating piston is determined as 650°C at the combustion chamber of coated piston .The combustion chamber has relatively larger heat transfer area compared to the other areas. Since the combustion chamber surface has been coated circumferentially with relatively very low conduction coefficient material, the heat transfer was reduced considerably to it. The surface temperature of the piston with Al alloy is found to improve approximately 14% via ceramic coating.

2.3 Experimental Procedure

The plasma generator consists of a circular anode usually of copper and a cathode of thoriated tungsten. The cathode is made of graphite in a water stabilized torch. A strong electric arc is generated between anode and cathode. This ionizes the flowing process gases into the plasma state. Now, powdered feedstock material is injected into the plasma jet. Plasma jet will melt the material and propel it onto the work piece surface. Atmospheric plasma spraying is carried out using a Sulzer Metco F4 gun operating at power levels up to 50 kW. A gas mixture of hydrogen and argon is used as a plasma gas. The argon gas is also considered as a carrier gas for the feedstock material injection. Compressed air is used as the cooling gas during plasma spraying.

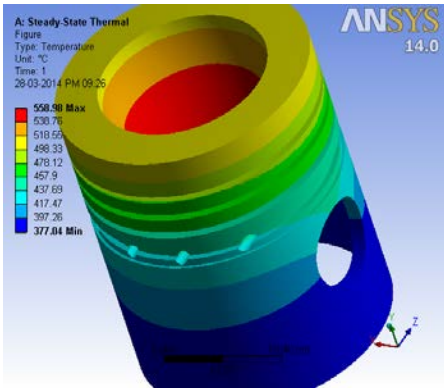

Fig. 4. (a) Temperature distribution for uncoated piston

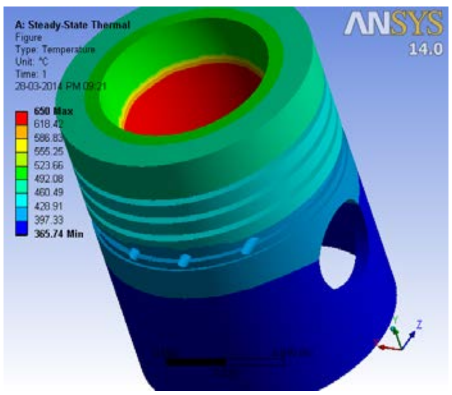

Fig. 4.(b). Temperature distribution for coated piston

TABLE III: PLASMA SPRAYING PARAMETERS

Sl. No	Parameters	Value
1	**Current (A)**	490
2	**Voltage (V)**	60 – 70
3	**Powder feed (g/min)**	40-50
4	**Spray distance**	76.2 - 127 ± 10 % mm
5	**Particle velocity (m/s)**	Up to 450
6	**Arc Temperature (0C)**	16,000
7	**Particle size (µm)**	14.5 – 45
8	**Inert gas flow rate**	
	a.)Argon (lit/min)	100– 200 ± 5%
	b.)Hydrogen (lit/min)	100 ± 5%

Fig. 5. Test engine

3. Result And Discussion

3.1 Performance analysis of coated piston

The performance characteristics of Zirconium coated piston diesel engine was investigated and compared with standard engine is displayed in figures (6- 17). The results obtained from the experiments conducted on the engine are discussed. Maximum brake thermal efficiency of uncoated piston is 32.98%. Maximum brake thermal efficiency of coated piston is 38.87%. Because of zirconium oxide coating 5.89% of brake thermal efficiency improved. Maximum indicated thermal efficiency of uncoated piston is 44.38%.Maximum indicated thermal efficiency of coated piston is 55.52%.Because of zirconium oxide coating 11.14% of indicated thermal efficiency improved. of indicated thermal efficiency improved.

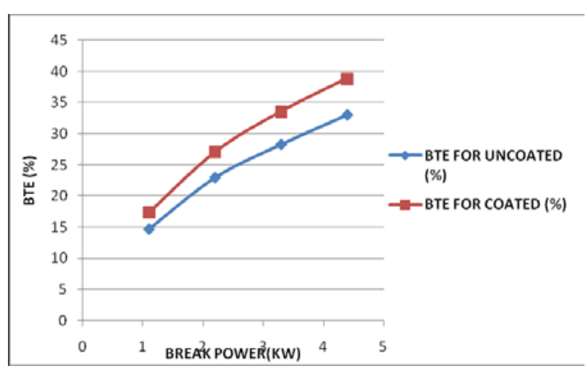

Fig. 6. Comparison of brake thermal efficiency

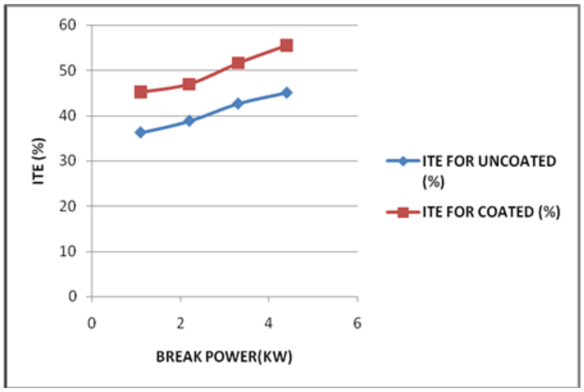

Fig. 7. Comparison of indicated thermal efficiency

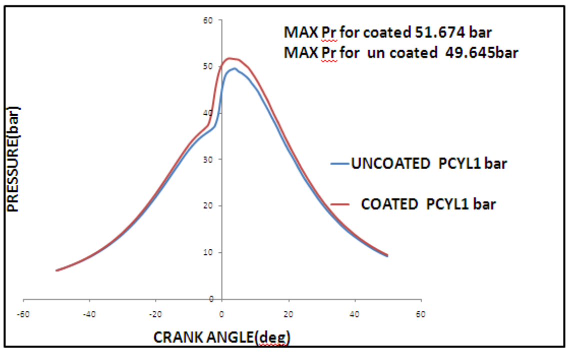

Fig. 8. Pressure vs crank angle for 25% load

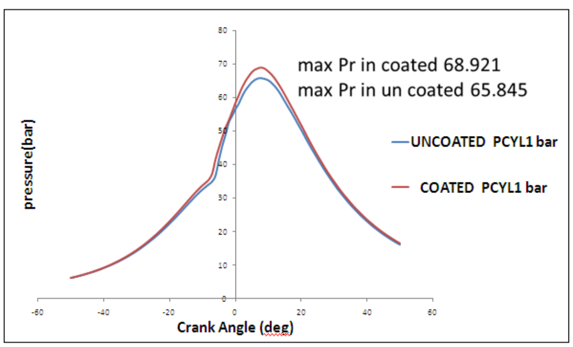

Fig. 9. Pressure vs crank angle for 100% load

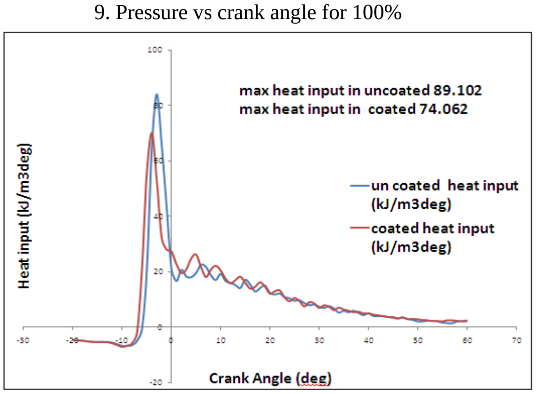

Fig. 10. Heat input vs crank angle for 25% load

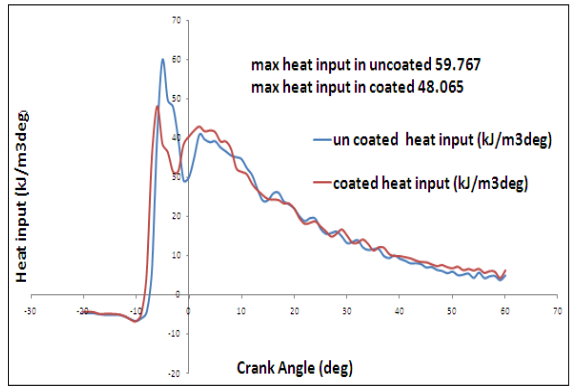

Fig. 11. Heat input vs crank angle for 100% load

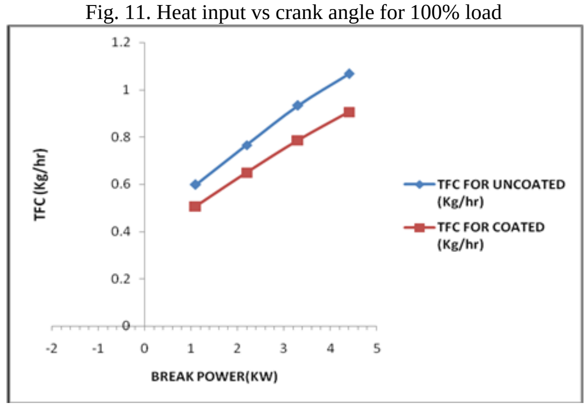

Fig. 12. Comparison of TFC

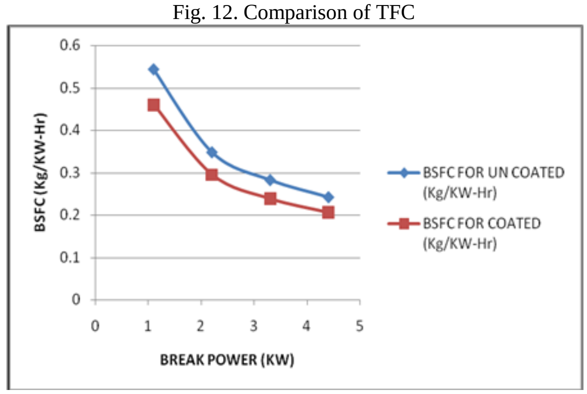

Fig. 13. Comparison of BSFC

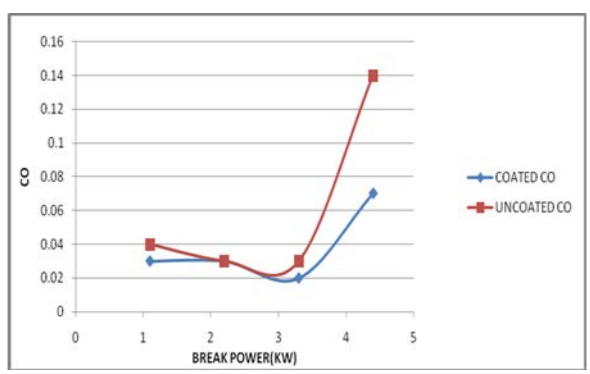

Fig. 14. Comparison of CO

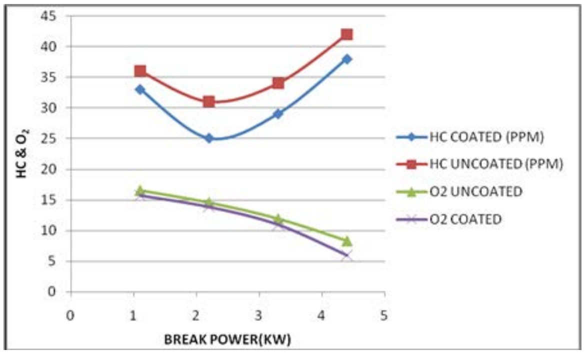

Fig. 15. Comparison of HC & O_2

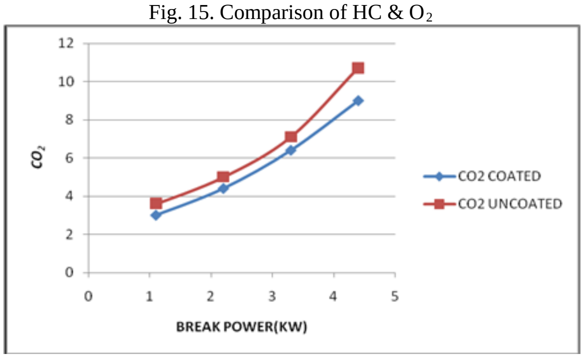

Fig. 16. Comparison of CO_2

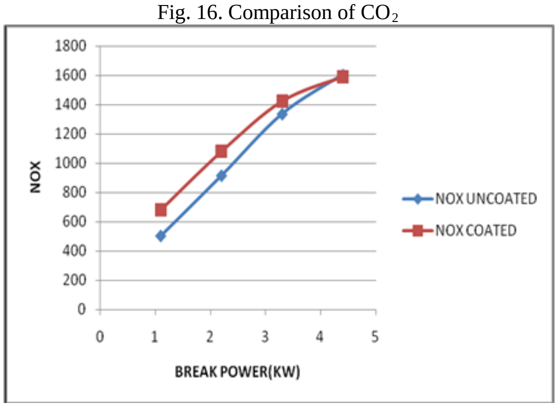

Fig. 17. Comparison of NO_X

Conclusion

From the FEA results, the maximum temperature value of the coated piston was shown at the piston's combustion chamber. Therefore, this area must be coated intensively. The maximum surface temperature of the coated piston with material which has low thermal conductivity has improved approximately by 14%. Because of reduced heat losses, efficiency will improve. According to the experimental results, brake thermal efficiency and indicated thermal efficiency have improved by 5.89% and 11.14% respectively. This result shows that the reduction in the cooling load of system is also obtainable. From the experimental results, maximum brake thermal efficiency of uncoated piston is 32.98%. Maximum brake thermal efficiency of coated piston is 38.87%. Because of zirconium oxide coating, brake thermal efficiency has improved by 5.89%. Maximum indicated thermal efficiency of uncoated piston is 44.38%. Maximum indicated thermal efficiency of coated piston is 55.52%. Because of zirconium oxide coating, indicated thermal efficiency has improved by 11.14%.

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