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Study Paper

COMPARISON OF VARIOUS THERMAL BARRIER COATINGS ALONG WITH THEIR EFFECTS ON EFFICIENCIES AND FUEL CONSUMPTION BASED ON THE RESULTS OF EXPERIMENTAL LITERATURES

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The application of TBCs in engines reduces the heat transfer to the engine cooling jacket through the combustion chamber surfaces (which include the cylinder head, liner, and piston crown) and piston rings. This paper deals with the study and comparison of various coatings applied on IC engine pistons and their effects on efficiencies and fuel consumption. It is well known fact that about 30% of the energy supplied is lost through the coolant and the 30% is wasted through friction and other losses, thus leaving only 30% of energy utilization for useful purposes. There have been numerous research papers in recent years describing the theoretical benefits obtained from the use of ceramic components in reciprocating engines, but that describes practical results is very limited. This paper gives the comparison of various practical experiments on coatings in IC engines and their effects. This paper serves as a guide, i.e., collection of all coating effects from the literature for any future development in the IC engine coating industry.

Keywords: TBC, IC engines, Fuel consumption, Ceramic components

INTRODUCTION

Insulating the combustion chamber of an internal combustion engine theoretically results in improved thermal efficiency according to the second law of thermodynamics. However, this may not be the case practically due to the complex nature of the internal combustion and the mechanical and thermal limitations of the insulation material and lubricants. Thermal

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Barrier Coatings (TBCs) were used to simulate adiabatic engines with the intention not only for reduced in-cylinder heat rejection and thermal fatigue protection of underlying metallic surfaces, but also for possible reduction of engine emissions (Morel *et al.*, 1986; Miyari *et al.*, 1989; Osawa, 1991; Wong, 1995; Apticote Ceramic, 2000; and Shrirao and Pawar, 2011). TBCs were initially investigated for "adiabatic" diesel engines due to first law thermodynamic predictions of significant fuel economy improvements, reduction in heat rejection, and potential increased power density of the diesel engine. Zirconia films are ideal for various technologically important applications because of their durability, hardness, low thermal conductivity, low optical losses, etc. The reliability of the parts of the cylinder and piston have a major influence on the service life characteristics of internal combustion engines and their technical and operating indicators. A critical case concerns thermal barrier coatings, typically zirconia deposited on a metallic substrate, used in the aircraft and automotive industries as heat and wear shields of engine components. As these ceramic layers are likely to evolve when operating at high temperature (e.g., by sintering), it is needed to estimate their thermophysical properties under their usage conditions in order to predict their thermal behavior. 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 inside cylinder heat rejection.

IMPORTANCE OF THERMAL BARRIER COATINGS IN IC ENGINES

Thermal barrier coatings are duplex systems, consisting of a ceramic topcoat and a metallic intermediate bond coat. The topcoat consists of ceramic material whose function is to reduce the temperature of the underlying, less heat resistant metal part. The bond coat is designed to protect the metallic substrate from oxidation and corrosion and promote the ceramic topcoat adherence. Some advantages of thermal barrier coatings on diesel engines are below.

- Low cetane fuels can be burnt,
- Improvements occurs at emissions except NOx,
- Waste exhaust gases are used to produce useful shaft work,
- Increased effective efficiency,
- Increased thermal efficiency,
- Using lower-quality fuels within a wider distillation range,
- The ignition delay of the fuel is considerably reduced,
- The faster vaporization and the better mixing of the fuel,
- Reduced specific fuel consumption,
- Multi-Fuel capability,
- Improved reliability,
- Smaller size,
- Lighter weight,
- Decreased the heat removed by the cooling system,

- The first start of engine on cold days will be easier,
- Decreasing knocking and noise caused by combustion.

THERMAL BARRIER COATINGS FOR INTERNAL COMBUSTION ENGINES

Chrome plated cylinder liners were used in Internal Combustion (IC) Engines till 70s. Hard chromium was electroplated directly on to the bore of the aluminum cylinder. Honda cars of late 70s exclusively used this process. Kawasaki employs a process referred to as electro-fusion for the said purpose. Leading auto manufacturers such as Yamaha, Honda, and KTM utilize a technique wherein the Nikasil material is applied directly on the aluminum bore. On the liner Suzuki employs a boron composite material for the purpose. These processes are found to enable the designers to reduce the clearance between the piston and cylinder which results in enhanced power from the engine.

A Poeton Max Power, Wiscons in is considered to be the leader in the technologies related to engine cylinder plating and coatings. The company has devised a system to coat cylinders, pistons, rings and combustion chambers of IC engines with a Nickel composite loaded with ceramic particles. The process was first developed for its application in aircraft industries but later on made its way into automotive environments.

Miyari *et al.* (1989) has investigated the performance and exhaust emission characteristics of a thermally insulated single cylinder diesel engine. The cylinder head and piston crown are thermally insulated with Sintered Silicon Nitride (SSN) whereas the upper part of the cylinder liner with Partially Stabilized Zirconia (PSZ). He has shown that volumetric efficiency of engine with insulated cylinder head and liner is higher in comparison with the engine which has an insulated piston cavity. It is also examined that the gas temperature in the cylinder with insulated piston crown, cylinder head and cylinder liner is much higher than that of other types of engines such as baseline engine, engine insulated with piston crown, engine with insulated cylinder head and cylinder liner which is mainly due to formation of Nitrogen Oxide in large amount. Local insulation of combustion chamber walls with ceramics has resulted in improved engine performance with decreased volumetric efficiency. Insulation of the piston cavity, cylinder head and cylinder liner upper part together is found to reduce the emission of hydrocarbons under natural aspirated conditions at low speeds. On the other, a reduction in Brake Specific Fuel Consumption (BSFC) is reported under both naturally aspirated and turbo charged condition when the cylinder head and liner upper parts were thermally insulated with ceramics. Further insulation of the piston cavity has contributed the increased in BSFC partly due to the increase in the reciprocating mass.

Osawa *et al.* (1991) has conducted tests on coatings made on small aluminium bore of an air cooled diesel engine. He has reported that coatings possessing high thermal insulation and low friction characteristics perform best albeit with a 10% reduction in fuel consumption.

Morel *et al.* (1986) has analyzed that a significant part of the retained heat is directly

Table 1: Comparision Table

S. No.	Coating	Properties	Type of Engine Used	Effect on Efficiencies and Fuel Consumption	Advantages	Disadvantages
1.	Mullite plasma-spray technique	1) Tm = 2123 K 2) λ = 3.3 W/mK (1400 K) 3) E = 30 GPa (293 K) 4) α = 5.3 × 10^{-6}/K (293-1273 K) 5) ν = 0.25 NiCrAlY (Bond coat of TBC) 1) E = 86 GPa (293K) 2) α = 17.5 × 10^{-6}/K (293-1273 K) 3) ν = 0.3	1) Engine type Kirloskar AV1, DI 2) Stroke number-4 3) Cylinder number-1 4) Bore-80 mm 5) Stroke-110 mm 6) Compression ratio-16.5:1 7) Maximum engine power-3.7 KW 8) Maximum engine speed-1500 rpm 9) Specific fuel consumption-245 g/Kwh 10) Injection timing-20 BTDC static	1) The results showed that, increasing the brake thermal efficiency and decreasing the specific fuel consumption for LHR engine with turbocharger compared to the standard engine. 2) There was increasing the NOx emission and exhaust gas temperature for LHR engine with turbocharger. 3) However there was decreasing the CO and HC emissions for LHR engine with turbocharger compared to the standard engine.	1) High corrosion-resistance 2) Low thermal conductivity 3)Good thermal-shock resistance below 1273 K 4) Not oxygen-transparent	1) Crystallization (1023-1273 K) 2) Very low thermal expansion coefficient
2.	PZT loaded cyanate modified epoxy system (60EPCY 20PI)	1) Tensile Strength-355 MPa 2) Tensile Modulus-7.98 GPa 3) Flexural Strength-465 MPa 4) Flexural Modulus-9.5 GPa 5) Fracture Toughness-1.6 kJ/m^2s 6) Damping Factor-0.10029 7) Stiffness-62.97 N/mm	1) Engine Type Kirloskar, Vertical, Four stroke diesel engine 2) Bore Diameter-80 mm 3) Stroke Length-110 mm 4) Brake Power-3.68 kW 5) Compression Ratio-16:1 6) Speed-1500 rpm 7) Injection Type-Direct Injection 8) No. of Cylinder-1 9) Injection Pressure-210 bar	1) The coated engine has 15.89% reduced specific fuel consumption than the standard engine. 2) NOx and Exhaust Gas Temperature are increased for 60EPCY 20PI coated combustion chamber diesel engine. 3) Hydrocarbon emission was reduced by 52.1% in 60EPCY 20PI coated combustion chamber diesel engine.	1) BSFC is reduced HC emission is reduced	1) NOx is increased

Table 1 (Cont.)

S. No.	Coating	Properties	Type of Engine Used	Effect on Efficiencies and Fuel Consumption	Advantages	Disadvantages
3.	$MgZrO_3$ over a NiCrAl bond coat. $CaZrO_3$- head and valves	$MgZrO_3$ 1) Thermal Conductivity- 0.8 W/m °C 2) Thermal expansion- 8.0 1/°C 3) Density: 5600 kg/m^3 4) Specific heat-650 J/K °C 5) Poisson ratio-0.2	1) LHR engine Engine type Ford 6.0 lt. T/C, intercooling, direct injection 2) Number of strokes-4 3) Number of cylinders-6 4) Cylinder diameter-104.77 m m 5) Stroke-114.9 m m 6) Compression ratio-16.5/1 7) Maximum power-136 kW (at 2400 rpm) 8) Maximum speed-2780 rpm 9) Displacement- 5947 cm^3 10) Firing order 1-5-3-6-2-4	1) Almost 65 °C increase in the combustion gas temperature has been observed for the LHR Engine compared to the standard engine working under the same conditions. 2) The Brake Specific Fuel Consumption (BSFC) values of the LHR engine were found to be lower by about 6% than those of the standard engine. (3) The emission characteristics of the insulated engine at moderate and full loads appeared to be attractive. Particulate emissions decreased clearly in the LHR engine. These reductions were up to 40%. 4) The NOx emission levels were found to be higher by about 9% compared to those of the standard engine because of the higher exhaust gas temperatures for the LHR engine. 5) Delaying the injection timing in the LHR engine from 200 to 180 resulted in a reduction of 1-2% in the specific fuel	1) Particu- late emission is decreased BSFC is reduced	1) NOx emission is increased

Table 1 (Cont.)

S. No.	Coating	Properties	Type of Engine Used	Effect on Efficiencies and Fuel Consumption	Advantages	Disadvantages
				consumption. On the other hand, 160BTDC injection timing exhibited almost the same fuel consumption as that of the standard engine. 6) NOx emissions were observed to be lower by 11% for 180 BTDC and by 26% on average for 160 BTDC injection timings in comparison to the standard engine. 7) In terms of specific fuel consumption, considerable deteriorations have been observed for 0.38 mm of valve adjustment. 8) Reducing the valve adjustment for the LHR engine from 0.46 mm to 0.38 mm gave generally lower NOx emissions regardless of considering the injection timing. However, 0.38 mm of valve adjustment was observed to be a remarkable increase as compared to its original value (0.46 mm).		
4.	Plasma sprayed zirconia	1) Tensile Strength-355 MPa 2) Elastic Modulus-200 GPa	1) Engine Type diesel s320 2) Bore Diameter-120 mm	1) It cannot be recommended for diesel engines. The radiation from soot particles from the diesel engine flame is about five	1) PSZ coatings are recommended for SI engines.	1) Thin PSZ coatings are partially transparent to the thermal radiation and when the

Table 1 (Cont.)

S. No.	Coating	Properties	Type of Engine Used	Effect on Efficiencies and Fuel Consumption	Advantages	Disadvantages
		3) Flexural Strength-900 MPa 4) Fracture Toughness-13 MPa $m^{1/2}$ 5) Hardness-1300 Kg/mm^2	3) Stroke Length-160 mm 4) Compression Ratio-17:1 5) Speed-750 rpm	times the radiation from gaseous products and that is why the PSZ coatings may rather suitable for SI engines.	2) To ensure the optimum thermal barrier performance for either clean or heavily sooted combustion chamber surfaces, an opaque ceramic material should be considered.	ceramic is translucent its capabilities as heat barrier material and severely reduced especially in highly radiating environment of diesel flame.
5.	Cr_2O_3/MO composite coating (Marine diesel engine)	Cr_2O_3 1) Crystal structure-hexagonal 2) Density-5210 Kg/m^3 3) Hardness-2955 Kg/mm^2 4) Thermal Conductivity-9.99 to 32.94 W/mK	1) Engine type-2 cycle crosshead 2) No. of cylinders-3 3) Bore-120 mm 4) Stroke-380 mm 5) Engine output-147 kW 6) Engine speed-420 rpm 7) Max. cylinder pressure-15.7 MPa 8) Mean Effective pressure-2 MPa 9) Mean piston speed-5.32 m/s 10) No. of piston rings-comp. x4 11) Lubrication system-Cylinder Lubricator 12) Lubricant-SAE#50 TBN20 13) Lubricant rate-1.5 g/kW/hour 14) Fuel oil-Diesel oil	1) Developed piston rings and cylinder liners, coated with ceramic-metal composite by low pressure plasma spraying, proved excellent results on the wear resistant characteristics. Moreover the process developed in this study makes possible to apply stronger materials for cylinder liners.	1) Piston ring lifespan are estimated at 4 years, previously being 2 years, and cylinder liner lifespan is 25 years, previously being 12 years. This enables periodic inspection every 4 years instead of every 2 years, consequently reducing the maintenance cost for overhauling. 2) Pro1on-gation of piston ring and cylinder liner lifespan enables us to reduce the cost of spare components.	1) Peeling of coating had occurred in the Cr_2O_3 coated (not composite) cylinder liner after the 60 hours' running. Neither peeling nor scuffing occurred by usil-1 g of piston rings and cylinder liners coated witl, 1 Cr_2O_3/Mo composite by "mixed powder process". They wore about 1/10 to 1/100 of cast iron. As the result Cr_2O_3/Mo composite coating was proved having better wear resistant property and stronger coating bonding than Cr_2O_3 coating.

Table 1 (Cont.)

S. No.	Coating	Properties	Type of Engine Used	Effect on Efficiencies and Fuel Consumption	Advantages	Disadvantages
6.	Yttria stabilized zirconia	1) Tensile Strength-200 to 250 MPa 2) Fracture Toughness-18 to 15 MPa $m^{1/2}$ 3) Dilation co-efficient (20-2000 °C) 8×10^{-6} 4) Specific heat 100 °C-450 to 500 J/KgK 5) Thermal conductivity at 20 °C-2.5 to 2.8 W/mK 6) Thermal Shock resistance-400 °C 7) Young's Modulus-2*10^5 N/mm^2	1) Three-cylinder SI Daihatsu engine 2) Cylinder type-inline, arrangement mounted transversely 3) Cylinder liner type-Integral with cylinder block 4) Total displacement-993 cm^3 5) Bore-76 mm 6) Stroke-73 mm 7) Compression ratio-9.5 8) Intake and exhaust layout Cross-flow Engine dimensions (length by width by height) 566 × 530 × 636 mm 9) Engine weight-92 Kg 10) Number of piston rings Compression ring–2 Oil ring–1 11) Valve clearance [Hot] Intake-0.2 mm Exhaust-0.2 mm 12) Carburetor Type-two barrel 13) Throttle valve diameter-28, 32 mm Venturi diameter-18, 25 mm	1) The TBC, using YSZ, applied to the combustion chamber of the internal combustion engine showed some improvement in fuel economy with a maximum of up to 6% at low engine power 2) The peak cylinder pressures were increased by a magnitude of eight to ten bars in the TBC piston engine, in particular at high engine power outputs, though the exhaust gas temperatures were generally lower, indicating good gas expansion in the power stroke. 3) The unburned hydrocarbon concentrations were increased most seriously at low engine speed and/or low engine power output with a TBC piston engine. The authors suspected that this could be due to the porous quenching effect of the rough TBC piston crowns, where oxidation of hydrocarbons was Unable to be achieved by the combustion air.	1) Fuel economy increased to some extent.	1) While there was no apparent drop in micro hardness, a layer of mixed oxide formed between the YSZ top coat and nickel alloy bond coat, indicating that oxidation of the aluminum In the bond coat occurred during the engine tests.

Table 1 (Cont.)

S. No.	Coating	Properties	Type of Engine Used	Effect on Efficiencies and Fuel Consumption	Advantages	Disadvantages
				4) Sampling of cylinder pressures in the cylinders showed that the ignition point of the TBC piston engine advanced slightly relative to the baseline engine, indicating the improvement in ignitability and heat release before the top dead center, which caused the peak cylinder pressure to raise.		

converted to positive work. He has also examined that a typical highway truck engine with a practical zirconia coating able to achieve a 5% performance benefit over that of an engine cooled baseline at rated conditions.

Wong (1995) has considered different combinations of coatings with different thermal characteristics and coating thicknesses to predict the pattern of fuel consumption in IC engines. The simulation model developed by him considers the influence of transient heat transfer into and out of the combustion chamber surface throughout the entire engine operating cycle. The simulation also included an advanced liner friction model which accounts for the effects of liner surface temperatures and lubricating oil viscosity. Results of the analysis showed that all thermal barrier coating materials provided a performance benefit that is strongly dependent on the coating thickness. Most coatings for the piston and head face surfaces provided a maximum benefit at a coating thickness of 0.1mm. The predicted maximum benefit in thermal performance is found to range from 1% to 2%. It is predicted that a coating thickness of 0.5 mm in the liner would provide an optimum oil viscosity and a reduced friction with a 5% increase in performance.

ZIRCONIA CERAMICS

Zirconia ceramics have attracted much attention since their discovery, and the materials, which are very strong and tough at room temperature, can be made by control of the phases. Understanding of the phase transitions is crucial to appreciate the properties of zirconia ceramics. Zirconium dioxide (ZrO_2) has a monoclinic crystallographic structure at ambient temperatures. Upon raising the temperature, the oxide undergoes the phase transitions from monoclinic to tetragonal with a transitional temperature of 1170 °C. From tetragonal to cubic, the transition temperature is 2370 °C. At 2680 °C and above, the material melts. The transformation from tetragonal to monoclinic phase with decreasing temperature at approximately 1170 °C is quite disruptive and renders pure ZrO_2 unusable as a high-temperature structural ceramic. This disruption is caused by a 6.5% of volume expansion upon transformation from tetragonal to monoclinic phase, a change which could cause structural failure of any ceramic coating. Table 1 gives the comparison of all coatings.

CONCLUSION

Thermal Barrier Coatings (TBC) in internal combustion engine have advantages such as improved thermal efficiency and combustion, reduction in weight by eliminating cooling systems, etc. however, practical problems are faced in implementing these coatings in internal combustion engines. The problem presently faced in implementing of TBC as engine cylinder is thermal mismatch which mainly occurs due to improper adhesion and difference in thermal expansion coefficient between bond coat and cylinder materials. TBC must also withstand wear and tear. There is a need to overcome these problems for employing TBC to engine cylinder as a liner the present work is undertaken with the following main objects.

- To search a proper bond coatings and top coat materials based on composition of substrates.
- Selection of proper coatings techniques.
- Preparation of plasma sprayed coated samples for various tests.
- To check the microstructure and Topology of coating.
- To check the surface texture parameter of coating.
- To determine the bond strength of coating.
- To determine micro hardness of coating.
- To determine abrasive wear of coating.
- To determine erosion wear of coating.
- To establish the suitability of coatings for its application in internal combustion Engine as a linear.

Thus various coating materials are compared in accordance with their experimental setups, effects and the disadvantages. This paper serves as a complete reference guide for the researches who work on coatings for engine applications.

REFERENCES

1. Apticote Ceramic (2000) System, Poeton Max Power Inc., Madison WI53716.
2. Chan S H and Kho K A (2000), "The Effect of Thermal Barrier Coated Piston Crown on Engine Characteristics", *Journal of Materials Engineering and Performance*, Vol. 9, pp. 103-109.
3. Ekrem Buyukkaya and Tahsin Engin (2006), "Effects of Thermal Barrier Coating on Gas Emissions and Performance of a LHR Engine with Different Injection Timings and Valve Adjustments", *Muhammet Cerit Energy Conversion and Management*, Vol. 47, pp. 1298-1310.
4. Krzysztof Z Mendera (2000), "Effect of Plasma Sprayed Zirconia Coatings on Diesel Engine Heat Release", *Journal of*

Kones, Internal Combustion Engines, Vol. 7, pp. 382-389.

5. Masaki Tanaka, Yoshihisa Kitajima, Yasuhisa Endoh, Masaoki Watanabe and Yutaka Nagita (1993), "Ceramic-Metal Composite Coated Piston Ring and Cylinder Liner of Marine Low Speed Diesel Engine", *Bulletin of the M.E.S.J.*, Vol. 21, No. 2, pp. 19-27.
6. Miyari Y, Matsuhisa T and Ozawa T (1989), "Selective Heat Insulation of Combustion Chamber Valves for DI Diesel Engine with Ceramics", Transaction of SAE.
7. Morel T, Keribar R, Blumberg P and Fort E (1986), "Examination of Key Issues in Low Heat Rejection Engines", SAE Technical Paper-860316, DOI: 10.4271/860316.
8. Osawa K, Kamo R and Valdmanis E (1991), "Performance of Thin Thermal Barrier Coatings on Small Aluminum Block Diesel Engine", SAE Technical Paper-International Congress and Exposition, DOI: 10.4271/910461.
9. Shrirao P N and Pawar A N (2011), "Evaluation of Performance and Emission Characteristics of Turbocharged Diesel Engine with Mullite as Thermal Barrier Coating", *International Journal of Engineering and Technology*, Vol. 3, No. 3, pp. 256-262.
10. Vijaya Kumar K R and Sundareswaran V (2010), "Performance, Combustion and Emission Characteristics of PZT Loaded Cyanate Modified Epoxy Coated Combustion Chamber in Diesel Engine", *International Journal of Engineering Science and Technology*, Vol. 2, No. 7, pp. 2876-2885.
11. Wong V (1995), "Assessment of Thin Thermal Barrier Coatings for IC Engines", SAE Technical Paper-950980.