Application of ceramic coating for combustion chamber equipments of IC engine: A Review

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Abstract— **The internal combustion engine is a heat engine that converts chemical energy of fuel into thermal energy by means of combustion with air inside the engine and this thermal energy gets converted into mechanical energy to the crankshaft, which is the output of the engine, through piston and connecting rod. 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. In a standard engine, a large percentage of energy is wasted through the cooling and exhaust system.**

So, to minimize these losses the combustion chamber parts (piston crown, inlet valves, exhaust valves and cylinder head) were coated with ceramic materials without changing the original dimensions. Tests were conducted and comparison is done between coated and uncoated engines. Many authors/researchers have made one step ahead by using bio-diesel or by altering the injection timing. Their results have showed improved engine performance and emission characteristics. Zirconia and Alumina is considered to be the most suitable material for ceramic coating. Plasma spray coating is widely accepted technique.

Index Terms—**Ceramic coating, plasma spray coating method, engine performance and emission characteristics. .**

I. Introduction

The internal combustion engine is a heat engine that converts chemical energy of fuel into thermal energy by means of combustion with air inside the engine. This thermal energy raises the pressure and temperature of the gases inside the combustion chamber and this high pressure and temperature gas expands against the piston then through connecting rod to the crankshaft, which is the output of the engine. The crankshaft, in turn, is connected to flywheel and then to the propeller shaft to transmit the mechanical energy to the desired end use. Applications include, automobile, truck, locomotive, marine vessel etc. Other applications include stationary engines to drive generators, pumps etc**.**

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. In a standard engine, a large percentage of energy is wasted through the cooling and exhaust system. By thermally insulating the engine's piston crown, valves and cylinder head which improve the combustion process and reduce the heat energy losses through the exhaust gases, by this the performance increases and emission reduces. Then it can be harnessed to increase the power output of the system, thus by raising the thermal efficiency and decreasing specific fuel consumption [11].

In the combustion chamber the flame front does not travel uniformly throughout the combustion process. Irregular spread of the flame front in the combustion chamber forms negative effects such as flame collisions and knocking. Therefore the combustion chamber parts or elements are exposed to extreme temperatures and thermal shocks. This is one the reasons that ceramics are seen as a alternative for combustion chamber parts because of its high corrosion resistance and high melting points. By application of ceramic coating the base material or substrate are not damaged, and the lifetime of these parts increases. [24]

The LHR concept is based on suppressing heat rejection to the coolant and recovering the energy in form of useful work. Some important advantages of LHR engines are improved fuel economy, reduced engine noise, higher energy in exhaust gases and multi-fuel capability of operating low cetane fuels. [6] The petroleum crisis and the subsequent increase in the cost of fuels, the improvement of fuels and the improvement of fuel economy of the I.C Engines has become a high priority to the researchers. Numerous investigations have modeled and analyzed the effects of in-cylinder thermal insulation. Reducing heat rejection in reciprocating engines is a possible way of reducing fuel consumption. [8]

In this literature review we are going to see the various efforts taken by the researchers by using several coating methods, varying injection timings and also making use of biodiesel blends to improve the IC engine performance and emission characteristics.

II. LITERATUTRE SURVEY

P.M.Pierz [1] make use of a finite element analysis to analyze these thermal barriers i.e Zirconia and Mullite coating. Aluminium alloy piston containing 12% Si and small addition of copper, magnesium and nickel were coated with Zirconia and Mullite coating with thicknesses, 0.40mm

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and 1.5mm.The outcome of this study suggested that primary cause of coating failure is proposed to be low cycle fatigue resulting from localized yielding when coating is hot and in compression.

Adnan Parlak et al. [2] have conducted test on single cylinder, indirect injection Ricardo E6-MS/128/76 type diesel engine. Cylinder head, valves and piston were coated with MgO–ZrO_2 layer of 0.35 mm thickness over a NiCrAl bond coat of 0.15 mm thickness. They have found that in LHR diesel engine there is a reduction on the NOx emissions with about 40% and BSFC with about 6% compared to standard engine when injection timing was retarded to 34^0 crank angle before top dead centre to that of standard engine (38^0 CA BTDC).

Ekrem Buyukkaya et al. [3] have made the comparison between standard engine and LHR (low heat rejection) engine. $MgZrO_3$ was employed as coating material for diesel piston and $CaZrO_3$ for the cylinder head and valves. Pistons were coated with a 350 μm thickness of $MgZrO_3$ over a 150 μm thickness of NiCrAl bond coat. On the basis of results they have concluded that approximately 65^0C increase in combustion gas temperature for LHR engine. The BSFC for LHR engine is reduced by about 6% and reductions in particulate emissions were up to 40% as compared to standard engine. In LHR engine NOx emissions level were found to be increased by about 9% because of higher exhaust temperatures. Later NOx emissions were improved by delaying the injection timings from 20^o to 18^o and were observed to be lower by 11% and by 26% on average for 16^o BTDC injection timings in comparison to the standard engine.

Ekrem Buyukkaya et al. [4] performed thermal analyses on both conventional (Aluminium silicon alloy and steel) diesel pistons and pistons coated with MgO-ZrO_2 material by means of using a commercial code, namely Ansys. Piston is coated with a 350 μm thickness of $MgZrO_3$ over a 150 μm thickness of NiCrAl bond coat. The result showed that by means ceramic coating, strength and deformation of the materials are improved and maximum surface temperature of the steel piston is higher approx. 14% than the AlSi alloy one.

Ekrem Buyukkaya and Muhammet Cerit [5] have conducted an experimentation on low heat rejection (LHR) turbocharged direct injection diesel engine to study the effects of injection timing on nitrogen oxide (NO*x*) emissions. The cylinder head and valves were coated with a 350 μm thickness $CaZrO_3$ over a 150 μm thickness NiCrAl bond coat and $MgZrO_3$ were used as piston coating material. The results showed that the BSFC and NO*x* emissions were reduced 2% and 11%, respectively by retarding the injection timing. Optimum injection timing for the LHR engine was obtained through decreasing by 2^0 BTDC.

Can Hasimoglu et al. [6] has experimented on LHR turbocharged DI engine for improving engine performance when biodiesel (produced from sunflower oil) is used as an alternative fuel. The cylinder head and valves were coated with plasma sprayed yttria stabilized zirconia ($Y_2O_3ZrO_2$) with a thickness of 0.35mm over a 0.15mm thickness of NiCrAl bond coat. The results showed that specific fuel consumption and the brake thermal efficiency were improved and exhaust gas temperature before the turbine inlet was increased for both fuels in the LHR engine.

NG Ka Jun et al. [7] have quantified the friction and wear characteristics of TiC coatings on piston and rings. Photography, Scanning Electron Microscopy (SEM) imagery, and x-ray diffraction of the piston and rings were considered to compare the coating durability. For TiC coated rings the Ra is reduced by approximately 44% in 5 hours of operation as compared to standard zinc phosphate coating by 75%.

Palaniswamy E. and Manoharan N. [8] have evaluated the performance of IC engine by applying thermal barrier coating i.e. Partially Stabilized Zirconium on piston crown and combustion chamber with a thin film of 250 micron. AVL5 Gas analyzer is used to measure the particulate matter, oxides of nitrogen, smoke density, hydrocarbon and carbon monoxide in the exhaust gases. The result stated thermal barrier coating promotes better energy recovery and reduction in HC, CO and PM emissions.

Hanbey Hazar [9] have performed experiment using diesel engine in which cylinder head, exhaust and inlet valves were coated with MgO–ZrO_2, to a thickness of 0.35 mm over a 0.15 mm thickness of NiCrAl bond coat, by the plasma spray method. The piston surface was coated with 0.35 mm of ZrO_2 over a 0.15 mm layer of NiCrAl bond. Tests were performed on the uncoated engine, and then repeated on the coated engine using diesel and biodiesel (canola methyl ester).They have found significant improvement in engine power and decrease in specific fuel consumption, as well as significant improvements in exhaust gas emissions and smoke density for all test of fuels used in coated engine when compared with standard engine.

Hanbey Hazar and Ugur Ozturk [10] have done the experimentation in which cylinder head, piston, exhaust and inlet valves of the diesel engine used were coated with Al_2O_3/TiO_2, which is a ceramic material, to a thickness of 250 mm over 50 mm thickness of NiAl bond coat, by using the plasma spray method. The effects of corn oil methyl ester that produced by the transesterification method, and No. D2 fuel's performance and exhaust emission's rate were studied by using equal in every respect coated and uncoated engines. A decrease in engine power and specific fuel consumption, as well as significant improvements in exhaust gas emissions (except NOx), were observed for all test fuels used in the coated engine compared with that of the uncoated engine.

A.P. Sathiyagnanam et al. [11] evaluated performance, combustion and emission characteristics of thermal barrier coated DI diesel engine plus fuel additives. The plasma spray coating technique has been used to coat the cylinder head, valves and piston crown with ZrO_2 /Al_2O_3 about 150/150 microns. The additives are added to neat diesel fuel, by volume and they are in the ratio between 0.5% to 2.0% with the intervals of 0.5%.The experimental results indicates that due to thermal barrier coating the thermal efficiency has been slightly improved and fuel additive with 1.0% shows better performance than other concentration. NOx emmision was found less about 500ppm as compared to standard engine. By combination of fuel additives and TBC, NOx emission was further reduced by 100 ppm.

M. Cerit et al. [12] have numerically performed thermal analysis for both standard and coated pistons by using

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commercial code, namely ANSYS. Also, experimentally test were conducted on a single cylinder, water cooled SI engine for both standard and coated cases. Piston top was coated with Al bond coat and 0.35 mm ceramic $MgZrO_3$ layers. Analysis results showed that the surface temperature of the coated piston part was increased up to 100 ^{0}C, which leads to an increase in air fuel mixture temperature in the crevice and wall quenching regions. Thus, cold start HC emissions considerably decrease compared to the standard engine without any degradation in engine performance. Maximum decrease in HC emissions was 43.2% compared to the standard engine.

P. Lawrence et al. [13] have investigated the performance and emission characteristics of diesel engine using Zirconia as a thermal barrier coating and ethanol as a sole fuel. By using plasma spray method, the cylinder head, valve and piston of the test engine were coated with a partially stabilized Zirconia of 0.5 mm thick. Necessary modifications were done to run the diesel engine with ethanol. The engine's performance was studied for both wet ethanol and diesel with and without Zirconia coating.It has been found that the brake thermal efficiency was increased up to 1.64% for ethanol with coating and there was a significant reduction in the specific fuel consumption. The NOx, CO and HC emissions in the engine exhaust decreases with coating.

P Lawrence et al. [14] have studied the engine performance and exhaust emissions for both wet ethanol and diesel with and without Zirconia coating. It has been found by the application of Zirconia coating power output and brake thermal efficiency has been increased. In case of emissions CO & unburned HC are reduced but greater reduction of NOx due to coating because of nitrogen is absorbed by Zirconia.

C. Ramesh Kumar and G. Nagarajan [15] have carried out the performance and emissions by coating 0.3 mm thick Alumina (Al_2O_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.

Vinay Kumar Domakonda and Ravi Kumar Puli [16] reviewed the research on low heat rejection engines. They have concluded that the objectives of improved thermal efficiency, improved fuel economy and reduced emissions are achievable but there is a need to improvise under proper operating constraints with improved engine design are required to explore the full potential of Low Heat Rejection engines.

Naveen.P et al. [17] presented the effect titanium oxide coating on the performance characteristics of the bio-diesel fuelled engine. The piston head was coated with 150 *μ*m Alumina-Titanium oxide (Al_2O_3/TiO_2) plasma coating over a *60μ*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. Also biodiesel H30 giving higher thermal efficiency when compared to other biodiesel blends and pure diesel. The specific fuel consumption is lower for the coated piston when compared to base piston. Biodiesel blend H30 at high loads and blend H20 giving better results at low loads.

Hüseyin Aydin [18] used different blends of cottonseed and sunflower oils with petroleum based diesel fuel. The piston surface, exhaust and intake valves of test engine were coated with a ZrO_2 layer and thickness of coating layer was 200 µm. Comparisons were made between blends of cottonseed, sunflower oil blends and diesel fuel and in coated and uncoated diesel engines. Experimental results showed that power and torque were increased with simultaneous decrease in fuel consumption (bsfc). Furthermore, exhaust emission parameters such as CO, HC, and Smoke opacity were decreased. Also, sunflower oil blends presented better performance and emission parameters than cottonseed oil blends.

Helmisyah Ahmad Jalaludin et al. [19] have used plasma spray method to coat yttria partially stabilized zirconia (YPSZ) with bonding layer NiCrAl onto AC8A aluminum alloy CNGDI piston crowns and normal CamPro piston crowns in order to minimize thermal stresses. They have performed experimentation using, a) CamPro and CNGDI piston crown surface coated with thicknesses between 100 to 150 µm of bond coat NiCrAl. b) CamPro and CNGDI piston crown surface coated with thicknesses between 100 to 150 µm of bond coat NiCrAl and 300 to 350 µm of YPSZ topcoat. The performance of the coating against high temperature was tested using a burner rig. The result showed that the average heat flux of YPSZ/NiCrAl coated piston crown exhibited 98% lower than the uncoated piston crowns.

Vinay Kumar. D et al. [20] have conducted a experimental work on a single cylinder diesel engine whose cylinder head, valve faces and piston top surface were coated with Lanthanum zirconate with a thickness of 350 microns over NiCrAlY with thickness of 150 microns. A number of experiments were conducted on the engine with and without coating using diesel and biodiesel fuels (Pongamia Pinnata oil). Experimental results showed improved engine efficiency and reduced emissions with thermal barrier coating.

K.R.Sharma and Debasish Das [21] 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.

Hanbey Hazar and Ugur Ozturk [22] have carried out investigation of LHR (low heat rejection) 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 piston and valves were coated with thickness of 250 µm using an atmospheric plasma spray method and NiAl (50 µm thickness) was employed as bond layer. Coated and uncoated surface were tested under same operating conditions. Scanning electron microscope (SEM) and optical microscope were used to examine the coating surface.The results showed that atmospheric plasma spray method is the most appropriate technique. Increased surface resistance and a high performance thermal barrier is observed by application of ceramic coating on the surface of combustion chamber components. The mechanical lifespan of base materials and fuel consumption were successfully improved. Wear, operational delays, renewal of equipment, delays caused by

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servicing and repairs were also reduced by the application of thermal barrier coating.

J.Rajasekaran et al. [23] have selected Yttria 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. Standard engine and coated piston engine were tested under same operating conditions. Exhaust gas analyzer and smoke meter were used to measure the exhaust emissions. The result stated that application of zirconia coating have increased the brake thermal efficiency and mechanical efficiency by the average value of of 9% and 25% respectively. Total fuel consumption is reduced by 7% and specific fuel consumption by 6%. zirconia coated piston observed reduction in NOx emissions by 14% and unburned HC emissions were reduced by 23%.CO emissions are reduced by 48% because of high temperature.

Nitesh Mittal et al. [24] carried out experimental investigation in which the cylinder head and valves were coated with a 0.1mm thickness of NiCrAl bond coat. Zirconium dioxide (ZrO_2) with 8% by weight of Yttrium Oxide (Y_2O_3) was deposited over the bond coat to a thickness of 0.2mm by plasma spray method. Performance and emissions test were carried out using single cylinder SI engine when fueled with two different blends of butanol and gasoline. Two different fuel blends containing 10% and 15% by volume of butanol in Gasoline are tested on an engine dynamometer using the uncoated and ceramic coated engines. They have concluded that combination of ceramic coated engine and butanol gasoline blended fuel has potential to improve the engine performance.

M.K.Pathak et al. [25] reviewed the application of various thermal barrier coatings over the high temperature components. They have suggested making use of steel crowned articulated aluminium 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.

Mr.Shailesh Dhomne et al. [26] revealed that NiCr+Ce coating improves brake thermal efficiency of SI engine and also reduces the emissions of carbon and hydrocarbons in the exhaust gases.

III. Conclusion

By using different thermal barrier coatings authors/researchers have achieved significant improvement in performance and emission characteristics of IC engines. Plasma spray coating method was considered to be the most widely accepted and appropriate method. Alumina and Zirconia is the widely accepted ceramic materials for thermal barrier coating. The coating material and its thickness needs to optimized. There is a need to study the long term durability of thermal barrier coating under high pressure and temperature of the IC engine. There is a need to take care of exhaust emissions, especially NOx.

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