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Effectiveness of Materials as Thermal Barrier Coating for I.C. Engines – A Review

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ABSTRACT

This review article analyses the research articles submitted for past one decade in various combinations of materials in thermal barrier coated engines. Thermal insulation materials have a major impact on the efficiency of automotive engines. More efficiency is expected to increase the operating temperature. This paper examines the different aspects and applications of the thermal insulation materials. The system has an impact on fuel consumption, fuel efficiency, and pollution content and fatigue life of an engine components. The thermal insulationon the top layer of the piston decreases thermal conductivity that increases the unburned oxidation of fuel, decreasing in thermal tension of the engines by exposing the metal substrates at low peak temperature. The article discusses the performance, merits and de-merits of TBC.

Keywords – Thermal barrier coatings; LCR Engine; Ceramic materials; Emission control

1. Introduction

In the automotive sector, a number of research programs are currently underway to reduce engine fuel consumption and pollution. This design is based on a rapid increase in fuel costs and a lower production of fuel due to high quality and environmental concerns, and the application of the thermal barrier (TBC) coating increases with lower heat-refusal diesel engines. Ceramic coatings offer the potential for increased engine heat efficiency, longer lifespan and increased strength of engine components. Thermal barrier coatings provide the opportunity to reduce particulate emissions Thermal barrier coatings reduce significant amounts of hydrocarbons [1-8]. Figure 1, shows the thermal barrier coatings models in IC engine. Several simulation experiments have been carried to evaluate the efficiency of the thermal coated engine. [9-11].These simulations expect an increase in thermal efficiency of LHR engines in standard cooled engines.In most cases, turbocharged, high-speed, multi-cylinder diesel engine simulations are common [12-13]. The fuel economy ranges from 3% to 15%.The diesel engine is known as an LHR engine consisting of a ceramic shielded combustion ventricle wall [13]. Majority scientists conclude such separation reduces heat flow, improves thermal output and improves waste energy [14]. Therefore, some experimental studies have shown almost no improvement in heat efficiency, in contrast to the above-mentioned [15]. Exhaust emissions have deteriorated in comparison to conventional water-cooled engines [16]. Due to ceramic insulation in the combustion bay the temperature will rise constant, though wide range of distillation and lower-quality fuel can be used [15-16]. The ceramic material is made at top coat, which is designed to increase the thermal resistance of the metal structure [17]. The bond coat has been designed to prevent oxidation and corrosion of the metal substrate and to promote ceramic adhesion to the top coat [18]. It is less beneficial to use reduce therejection of heat in combustion engines, therefore turbocharged engines are more efficient. In addition to producing an improved output with a large number of loads, it is important to have an appropriate turbocharger. [19]. In past one decade of experimentation in the field of TBC have been recorded in diesel engines to reduce automotive emissions and improve fuel efficiency [20].The next few parts of the study will discuss the impact on ceramic coatings approach of fuel usage, emissions (e.g. NO, smoke, HC and CO), engine performance, themal disclosure, deflection area, and wear and tear life [21-22].Many research indexed and analysed on impact in ceramic insulated combustion chamber on fuel usage [23]. The degree of change measured varied from 4% to 11%. Test findings indicate that the cylindrical boring bore covers resulted in a decrease in fuel usage, whereas the piston coating and the cylindrical head surface were more efficient in minimizing heat discharge [24]. Examination of unmarked hydrocarbon (UHC) and carbon monoxide (CO) emissions is underway [25-26]. Pollutants of uncombusted hydrocarbons from ceramic coated engines are more likely to decrease due to decreased quenching distance and increased maxillary inflammation [26]. Higher temperatures in the LHR engine gasses and the walls of the combustion chamber help to close the oxidation reactions. Most studies have shown a lowering of HC levels [27]. Table 1, shows the specifications of ceramic coating. A number of studies also point to lower carbon emissions [27-28]. They are responsible for the high temperature of the gas chamber and the walls [28]. The reduced level of pre-mixed combustion reduces the emission output of carbon monoxide and increases heat to accelerate the oxidation of carbon monoxide during diffusion combustion [29].

2. Materials Used for Thermal Barrier Coating In Engine

Some of the basic requirements limit the choice of composites combination for the ceramic coatings [30]. Beacuse the melting point of some ceramic materials , do not transform the phases between ambient and combustion temperature, minimal heat conductivity, chemical imbalance, thermal distribution of the metal composites, good metal substrate for adhesion and lower porous microstructure frittage rate [31]. Till to date, only a few materials have essentially met these requirements [32]. Table 2, shows the Properties of TBC materials

2.1 Zirconia

Yttria Zirconia Stabilizer (YSZ), which is commonly used ceramic coat materials as it works well within high-temperature areas such as automotive engines and gas propulsion units. The column microstructures of the YSZ covering provide a good resistance to friction and cover adhesion [31-32]. It also has a high corrosion tolerance of Na_2SO_4 and V_2O_5 [33]. Owing to splitting in the surface, YSZ may be used for long-lasting usage at a minimal working temperature (< 1500 K) [34].

Zirconia has a slight frictional effect, weak thermal distribution, high coefficient of thermal expansion and equal heat resistance for cycling. The main issue is the high thermodynamic coefficient, which adds to the remnants pressure on the layer and can be enable the layer to be de-laminated [35-38]

2.2 Mulliet

Mullite is a significant ceramic material due to its low density, strong thermal resistance, robustness under harsh chemical conditions, less thermodynamic distribution, attractive bonding ability and crunchiness. It is a combination of silicon oxide and alumina oxide with a chemical compounding of Al_2O_3. SiO_2 [39]. Compared to YSZ, mullite is significantly smaller than YSZ, with much more oxygen-resistant thermospheric expansion and better thermal conductivity. Mullite is an excellent alternative to zirconia in the variation of surface temperature which is comparatively less in both automotive engines and gas propulsion system [40]. Engine experimentation with both materials shows that the aluminium silicate coated on the engine as longer in life than zirconia. In thermal cycling life, mullites are much shorter than the 1285 K YSZ. This material solidifies at 1030–1285 K with a molar volume compression which causes fracture and weaker in bonding papmeter [41]. This aluminium silicate is the most best medium for the silicate substratum because its thermodynamical expansion coefficient is same to that of the SiC substratum. [42]

2.3 Alumina

This is extremely difficult and chemically inert. It has a comperatively high thermal conductivity and low thermal expansion coefficient compared other composite materials [43]. Although it alone is not a perfect ceramic material for the coating process, the addition of zirconia stabilized yittria may increasing the toughness of the surface and increase the oxidation power of ceramic material [44]. Aluminum (Al_2O_3) is the soluble component of all aluminum oxides. It is very durable and chemically inert. The study has shown that the durability and bond strength can be improved with the composition of a constant amount of alumina in YSZ [45]. 8YSZ + Al_2O_3 coating has a significantly longer shelf life than YSZ alone [46].

2.4 Aluminium-Silicon

AlSi is commonly used to improve modulus, termperature and friction resistance. The ceramic material composition for coating of the substrates is (AlSi) (12% wt) [47]. These coatings were tested in an AlSi matrix alloy with a homogeneous distribution of SiC. They also grow nano-crystals which lead to high durability and low wear [48].

2.5 Nickel-Chromium-Aluminium

Ceramic layers may be used using a number of techniques, but plasma is the most popular thermal spraying strategy [49]. The CTE bonding layer between the TBC and the metal substrates is usually used to strengthen the adhesion of the coating [50]. Essentially, it gives the TBC a bond coat. These materials help to create a strong link between the soil and the base of the board. The requisite covers are adhesive material, longevity at working temperature. [51]

2.6 Other Materials

Table 3, shows the merits and demerits of different ceramic materials. Numerous researchers use the above-mentioned TBC coating materials primarily for IC engine applications in the analysis of test work. However, several other TBC products are also available and could be useful for different applications. It's time to study those issues. As mentioned above, TBC goods have their own advantages and drawbacks. Additional TBC resources are being developed to counter this. [52-54]

3. Coating Methodologies

The thermal barrier coating is the primary method. TBC are used to increase the durability, strength of high tempered engine parts and, optimize engine efficiency and output. The elements of the thermal barrier coated engine contain pistons; cylindrical head seal and exhaust valves. In ceramic coated automotive engines the loss of heat is highly eliminated. [55-58]

3.1 Electron Beam Physical Vapor Deposition (EBPVD)

Due to the increasing durability of the coating produced compared to other deposition processes, the TBC deposition process has been advantageous. In this method the evaporation is the application of ceramic coated covering parts of engines [59]. The EB-PVD TBC has a micro structured columnar which provides exceptional resistance to thermal shock and mechanical stress. This figure shows the EB-PVD process diagram of the coating chamber [60]. The EB-PVD process is carried out by vaccum pumping unit in the chamber, a manipulator (horizontally placed), a water-cooled container and evaporating ceramic ingot [61]. Electrons are produced by source (electron) beam gun that directly affect the ceramic coating on the top layer of the sink and bring the layer to a temperature that is high enough to generate steam. The steam generates a cloud of vapor condensing the substrate and forming a coating [62].The horizontal manipulator in the center of the vapor cloud makes it possible to change the height of the chamber [63]. During the coating process, oxygen or other gasses are blown into the vapor cloud to stimulate the stochiometric reaction of the ceramic. An over-source heater or electron beam weapon may be used to heat the substrate, which keeps the substrate at the desired temperature [64].

3.2 Air Plasma Spray (APS)

The plasma pistol is placed between the copper anode and the tungsten throated cathode. A gas is injected into the annular vacuum, which is often a mixture of argon and hydrogen [65]. The DC electrical arc is connected to two electrodes to start the process [65-66]. The arc produces gas ionization, which allows gas atoms to release electrons and becomes positive ions. The electrons move at a high velocity towards the anode while the ions migrate through the cathode [66]. The atoms and molecules of neutral gas are in conflict with the electrons and atoms on the lane [67].Electrons and atoms collide on their way with neutral gas atoms and molecules. The electric arc therefore continuously transforms the gas into plasma (a mixture of high-energy ions and electrons) [67-68]. The plasma is electrically neutral with exceptionally high temperatures. Plasma (mostly emitted by free electrons) is converted into thermal energy during collisions between ions, electrons, and atoms [68]. Plasma can therefore produce temperatures of around 110K [68-69]. Hot gas exits the piston at high speeds. The substance in the powder is distributed in a plasma plume [69].The powder particles on the ground are dissolved and pushed by the hot air. As individual molten particles come into contact with the substrate surface, they crack, cool, and solidify [70]. These splats are slowly formed by the coating [70-71]. Gradients of the radial temperature of the plasma feathers

[71]. If the particles passing through the central plasma core appear to be smoking, overheating, or even vaporizing, they do not smell the particles floating around the periphery [72].It will have an effect on the final coating structure, which may contain slightly faded or infused particles [72-73]. The coating can contain voids, oxidized particles and parts that are not molten. Such results can be useful depending on the specifications of the coating [73].

4. **Multi Layered Coating**

A small TEC is ideal for a thick TBC to minimize heat-induced stresses on hot layer and thermal shock exposure [73-74]. Broad TEC unevenness with the metal substrate reduces the adhesion to the coating [74]. A multilayer framework will be generated. Enable the requirements to be fulfilled on the contrary [75]. A collection of chemically compatible products, providing a variety of TECs and appropriate thermal conductivity, has been established [75-76]. Coupled analysis of temperature and stress distribution increasing multi-layer coating width to assess the degree of stress in the coating and under operational conditions [76].

5. **Impacts of coating in Engine performance**

5.1 Volumetric Efficiency

The engine's breathing power is indicated by a volumetric output [77]. This efficiency is based on the ambient conditions and the engine working condition [78]. Decreasing the rejection of heat by adding ceramic insulation results in rise in temperature at the combustion chamber wall of the ceramic coated engine [78-79]. As the air densities are reduced by the high temperature in combustion chamber, the volumetric efficiency should be reduced [80].The volumetric efficiency is as estimated from all LHR engine investigations. The volumetric output failure of the LHR engine can be reduced by using boost and utilizing exhaust gas resources more effectively. [81]

5.2 Thermal Efficiency

It is the actual calculation of the output by converting chemical energy into the form of useful work energy by the engine. The main aim of the LHR engine is to improve the thermal performance by increasing the in-cylinder heat transfer [82]. Several research institutes have worked hard to explore the capacity of LHR engines to reduce heat rejection and achieve good thermal efficiency [83].Thermal efficiency decreases with insulation [84]. All of these are responsible for increasing the coefficient of conductivity of heat transfer, increasing the flow of heat and degraded combustion [84-85]. The heat transfer coefficient at combustion chamber of LHR engine need to be decreased [85]. At currently period, there is no simple understanding on the impact of cylindrical chamber which is insulated for thermal discharge and thermodynamic performance. [86]

6. **Impact on fuel consumptions**

Many researchers have developed and experimented the impact of ceramic coated engine on fuel consumption [86-87]. Reduction in fuel in the TBC engine increased [87]. The degree of change figures ranged from 4% to 20%. That is how the channels are partitioned [88]. Insulation of components in the chamber was supposed to be a more effective way to reduce heat loss and fuel consumption [89].The study indicates a reduction in fuel usage, which is linked to a decline in pressure as the wall temperature increases [90]. He also found out that fuel usage is not measuredly enhanced based on the thermodynamics involved [90-91].

7. **Impact on Emission**

7.1 Unburned Hydrocarbon

Considering the decreasing the distance of fuel spary will be improved lean in flammability, ceramic coated engines are more likely to reduce the emission of uncombustable hydrocarbon. The higher temperatures in the LHR engine's gases as well as in the combustion chamber walls help to enable the oxidation reactions to continue near completion. Most investigations show lowering of HC levels [92-95].

Various research reports also indicate that CO emissions are smaller [96]. This is due to the improved combustion area of gas temperatures and walls [97]. In the insulated engine, low pre-mixed combustion levels decreased CO performance and higher temperatures enhanced CO oxidation during diffusion combustion.[99]

7.2 Nitrogen oxide

Nitrogen and oxygen chain reactions are produced by oxides of nitrogen [100]. These chemical balanced ractions are not based on temperature difference [101]. The diesel based automotive engines often run with huge amount of oxygen, the main feature of NOx pollution is the gas temperature and its lifespan [49]. A lot of recent research has shown that the NOx rates of LHR engines are usually higher than those of water and air cooled engines. This may because of high rise in temperature and increase in burning time [102].The rise in pollution from NOx in LHR engines was inferred, and the concentration of burning in the normal mechanism for the output of NOx [102-103].A decreasing increase in the amount of complaints into the amount of NOx pollution [103].

7.3 Smoke

LHR engines may be expected to emit less smoke and particulate matter than normal engines due to factors such as increase in high temperature at combustion chamber and increase in temperature of air in the engine [103]. Past studies suggest that smoking and particulate matter rates have risen in certain cases and reduced in others.High combustion temperatures and heavy turbulence produced by the squish inverted to maximize soot oxidation have made this possible [104]. Research at SWRI, however, shows a higher level of flame burning smoke. This is the result of a loss of oil regulation at higher temperatures. The consequences of this are increased gasoline consumption [103-104]. Smoke and particulate production is also responsible for factors such as less ignition cycle time, unbalance mixture of air-fuel [105].

factors such as less ignition cycle time, unbalance mixture of air-fuel [105].

8. **Conclusion**

This article addressed the benefits and disadvantages of specific products used as thermal barrier coatings in diesel engines. A multi-layer method is a practical alternative to satisfy opposing surface requirements. The thickness of the various components must be adjusted in such a way as to reduce friction under operational conditions.Table 4, shows the Comparison of best experimental results of low heat rejection (LHR) engine.

Thermal barrier coating technology has resulted in significant changes in thermal and mechanical quality and other engine output metrics, such as the specific use of fuel, and minimizes exhaust pollution in various engine combustion zone components such as piston and cylinder liner. This paper highly communicates the different aspects, effects, and major applications of ceramic coating for piston, combustion chamber and other engine parts. This article is also a complete reference document for researchers on the basis of coatings for engine applications. In fact, the thermal barrier coating is a ceramic coating with a plate structure. It not only reduces heat fatigue, but also prevents the base metal from oxidation and corrosion. This helps to increase the running temperature and engine efficiency. Various methods, such as plasma spray technology, physical vapor deposition of electron beams, etc., have significantly improved the safety of TBC turbines, diesel engines and other heaters.

In this case, fuel intaked by the engine is comperatively lower, engine efficiency and combustion effectiveness are gradually incraesed, polluted content is reduced and the life of engine components such as the combustion chamber and piston is improved as the surface temperature is reduced by 100 ° C and the temperature gradient and the thermo-mechanical stresses are reduced substrates.

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FIGURE

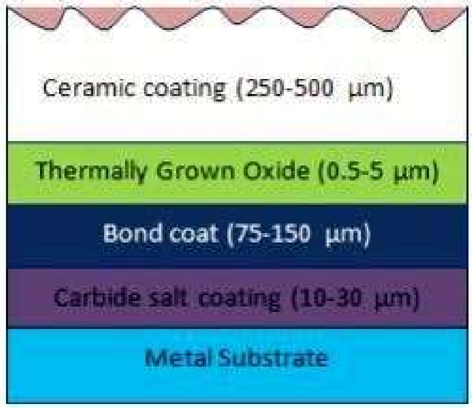

Fig 1 Thermal Barrier Coatings Models in IC Engine

TABLES

Parameters	Values
Particle velocity	400–500 mm/s
Oxide content	1–2%
Porosity	1–8%
Powder feed rate	40 g/min
Current	550 A
Voltage	86 V
Spray distance	100 mm
Torch nozzle diameter	5.2 mm

Table 1 Specifications of ceramic coating [106]

S.No	Materials	Properties
1	ZrO_2	T_m=2973 K[7] D_{th}=0.43x10^{-6}m^2 s^{-1} ʎ=2.17 W m^{-1} K^{-1} E=21 GPa α=15.3x10^{-6} K^{-1} v =0.2510
2	3YSZ	T_m=2973 K[12] D_{th}=0.58x10^{-6} m^2 s^{-1} ʎ=2.12 W m^{-1} K^{-1} C_p=0.64 J g^{-1} K^{-1} α=11.5x10^{-6} K^{-1}
3	Mullite	T_m=2123 K[14] ʎ =3.3 W m^{-1} K^{-1} E=30 GPa α=5.3x10^{-6} K^{-1} v=0.2510
4	Al_2O_3	T_m=2323 K[9]

		D_{th}=0.47x10^{-6} m^{2} s^{-1} ʎ =5.8 W m^{-1} K^{-1} E=30 GPa α=9.6x10^{-6} K^{-1} v=0.2610
5	CeO_2	T_m=2873 K9 D_{th}=0.86106 m^{2} s1 C_p=0.47 J g1 K1 ʎ =2.77 W m^{-1} K^{-1} E=172 GPa (293 K)10 α =13106 K^{-1} v =0.27

Table 2 Properties of TBC materials [107]

Material	Advantage	Disadvantage
7-8 YSZ	1. High thermal expansion coefficient 2. Low thermal conductivity 3. High thermal shock resistance	1. Sintering above 1473 K 2. Phase transformation 3. Oxygen-transparent
Mullite	1. High corrosion-resistance 2. Low thermal conductivity 3. Good thermal-shock resistance 4. Not oxygen-transparent	1. Crystallization (1023-1273 K) 2. Very low thermal expansion coefficient
Alumina	1. High corrosion-resistance 2. High hardness 3. Not oxygen-transparent	1. Phase transformation 2. High thermal conductivity 3. Very low thermal expansion coefficient
YSZ+CeO_2	1. High thermal expansion coefficient 2. Low thermal conductivity 3. High corrosion-resistance 4. High thermal-shock resistance	1. Increased sintering rate 2. CeO_2 precipitation 3. CeO_2-loss during spraying
Silicates	1. Cheap, readily available 2. High corrosion-resistance	1. Decomposition into ZrO_2 and SiO_2 during thermal spraying 2. Very low thermal expansion coefficient

Table 3 TBC materials and their characteristics [107]

Investigator(s)	Test model	Thickness of coating	Operational constraints	Performance of LHR engine compared to standard engine
Bakan E et al [1]	Single cylinder, direct injection diesel engine [1]	500 μm and 1000 μm [1]	Constant load and various speeds for both [1]	10% improvement in BSFC; on average 15% increase NOx. [1]
Bernard, B et al [18]	Single cylinder, two stroke diesel engine [18]	500 μm [18]	Constant BMEP and various speeds for both [18]	5% decrease BSFC; 3% increase exhaust gas temperature. [18]
Zhou, F et al [26]	Turbocharged	600 μm [26]	Constant air/fuel	9.2% increase HC

	diesel engine [26]		ratio and different speeds for both [26]	emission; NOx emissions don't change; 1.7%improvement BSFC [26]
Gao, L et al [51]	Turbocharged heavy duty and light duty engines [51]	Different levels of insulation [51]	Constant peak pressure and air/fuel ratio for both [51]	Thermal efficiency increased with the level of insulation at all loads for both heavy and light engines; brake thermal efficiency improves 8% which groves to 13% with Rankine bottoming cycle for truck engine [51]

Table 4 Comparison of best experimental results of low heat rejection (LHR) engine [108]