A REVIEW ON THERMAL BARRIER COATINGS ON GAS TURBINE ENGINE BLADES AND VANES

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Abstract:

Thermal barrier coatings are used to protect blades and vanes in the hot sections of gas turbines. They consist of a thick porous ceramic layer deposited on a alumina forming metallic bond coat in contact with the nickel- based super alloy substrate. They are designed to prolong the components lifetimes or to increase gas temperature, and therefore efficiency. In service, the structure and composition of the various layers evolve, due to sintering of the ceramic layer, oxidation of the bond coat, and inter diffusion phenomena with the substrate. As a result, the properties of each layer are affected, as is the interfacial toughness. These evolutions, combined with applied external stresses, may lead to bond coat rumpling, crack formation at the bond coat/ceramic interface and the ceramic layer may eventually spall off. In addition to these intrinsic degradation modes, interactions with the environment can accelerate the system degradation. This paper reviews the before researches about barrier coatings and discuss about the future implementations by considering present approaches.

Key words; Thermal barrier coatings, Materials used for barrier coatings, Efficiency of gas turbine.

Introduction

Thermal barrier coatings (TBC) are highly advanced materials systems usually applied to metallic surfaces, such as on gas turbine or aero-engine parts, operating at elevated temperatures, as a form of exhaust heat management. These coatings serve to insulate components from large and prolonged heat loads by utilizing thermally insulating materials which can sustain an appreciable temperature difference between the load-bearing alloys and the coating surface.[1] In doing so, these coatings can allow for higher operating temperatures while limiting the thermal exposure of structural components, extending part life by reducing oxidation and thermal fatigue. In conjunction with active film cooling, TBCs permit working fluid temperatures higher than the melting point of the metal airfoil in some turbine applications.

What is meant by exhaust gas management and how it is related to Thermal barrier coatings?

2. LITERATURE REVIEW

It is known that the efficiency of internal combustion diesel engines changes %38-42. It is about %60 of the fuel energy dismissed from combustion chamber. To save energy, combustion chamber component are coated with low thermal conduction materials. In this paper, give an eye to thermal barrier coating and ceramic materials which are used for making low heat released engines.

The quantity of the energy acquired from the fuel is not an intended level because of the factors in the combustion chamber of the engine. Some of the factors are, design of the combustion chamber, lack of adequate turbulence in the combustion chamber, poor oxygen at the medium, lower combustion temperature, compression ratio and advance of injection timing. It is thought that combustion temperature is the one of the most important factor among the aforementioned factors. All of the hydrocarbons cannot be reacted with oxygen chemically at the during combustion time. With this aim, coating combustion chamber components with low thermal conductivity materials becomes a more important subject at these days. For this reason, combustion chamber components of the internal combustion engines are coated with ceramic materials using various methods.

The efficiency of most commercially available diesel engine ranges from 38% to 42%. Therefore, between 58% and 62% of the fuel energy content is lost in the form of waste heat. Approximately 30% is retained in the exhaust gas and the remainder is removed by the cooling, etc. More than 55% of the energy

Which is produced during the combustion process is removed by cooling water/air and through the exhaust gas. In order to save energy, it is an advantage to protect the hot parts by a thermally insulating layer. This will reduce the heat transfer through the engine walls, and a greater part of the produced energy can be utilized, involving an increased efficiency.

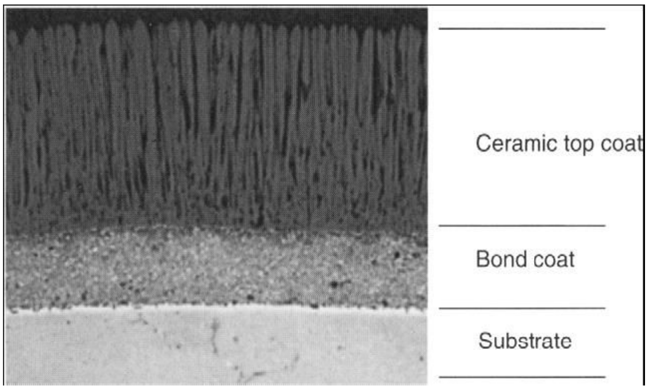
The major promises of thermal barrier coated engines were increased thermal efficiency and elimination of the cooling system. A simple first law of thermodynamics analysis of the energy conversion process within a diesel engine would indicate that if heat rejection to the coolant was eliminated, the thermal efficiency of the engine could be increased.

Thermal barrier coatings were used to not only for reduced in-cylinder heat rejection and thermal fatigue protection of underlying metallic surfaces, but also for possible reduction of engine emissions.

Thermal insulation brings, according to the second law of thermodynamics, to engine heat efficiency improvement and fuel consumption reduction. Exhaust energy rise can be effectively used in turbocharged engines. Higher temperatures in the combustion chamber can also have a positive effect in diesel engines, due to the ignition delay drop and hardness of engine operation.

2.2 INTRODUCTION TO THERMAL BARRIER COATINGS

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 [5]. A thermal barrier application is shown in figure 1.



In a diesel engine almost %30 of the fuel energy is wasted due to heat losses through combustion chamber components. For that reason, lots of research activity has focused on applying thermal barrier coatings to diesel engines. Figure 2 shows a cross-sectional view of the diesel engine combustion chamber and points out the components that might be effectively coated with thermal barrier coatings.

In figure 2, 1 indicates piston head, 2 indicates cylinder liner, 3 indicates seating of intake valve, 4 indicates seating of exhaust valve, 5 indicates cylinder head, 6 indicates intake valve and 7 indicates exhaust valve.

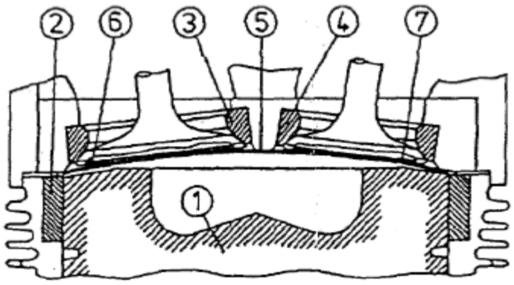


Figure 2. Potential thermal barrier coated components in a diesel engine combustion chamber

The design of the thermal barrier coatings and the environment in which it operates impose restrictions on the materials of construction. Table 1 lists some of the property requirements of the ceramic coating of the thermal barrier coating system.

2.3 MATERIALS FOR THERMAL BARRIER COATING

The selection of thermal barrier coating materials is restricted by some basic require- ments. They are high melting point, no phase transformation between room temperature and operation temperature, low thermal conductivity, chemical inertness, thermal expansion match with the metallic substrate, good adherence to the metallic substrate and low sintering rate of the porous microstructure. So far, only a few materials have been found to basically satisfy these requirements. There are some ceramics which are used for thermal barrier coating below.

Zirconates

The main advantages of zirconates are their low sintering activity, low thermal conductivity, high thermal expansion coefficient and good thermal cycling resistance. The main problem is the high thermal expansion coefficient which results in residual stress in the coating, and this can cause coating delamination

Yittria Stabilized Zirconia

%7-8 yittria stabilized zirconia has high thermal expansion coefficient, low thermal conductivity and high thermal shock resistance. Disadvantages of yittria stabilized zirconia are sintering above 1473 K, phase transformation at 1443 K, corrosion and oxygen transparent [22].

Mullite

Mullite is an important ceramic material because of its low density, high thermal stability, stability in severe chemical environments, low thermal conductivity and favorable strength and creep behavior. Compared with yittria stabilized zirconia, mullite has a much lower thermal expansion coefficient and higher thermal conductivity, and is much more oxygen-resistant than yittria stabilized zirconia. The low thermal expansion coefficient of mullite is an advantage relative to yittria stabilized zirconia in high thermal gradients and under thermal shock conditions. However, the large mismatch in thermal expansion coefficient with metallic substrate leads to poor adhesion. The other disadvantage of mullite is crystallization at 1023-1273 K [21, 22].

Alumina

It has very high hardness and chemical inertness. Alumina has relatively high thermal conductivity and low thermal expansion coefficient compared with yittria stabilized zirconia. Even though alumina alone is not a good thermal barrier coating candidate, its addition to yittria stabilized zirconia can increase the hardness of the coating and improve the oxidation resis- tance of the substrate. The disadvantages of alumina are phase transformation at 1273K, high thermal conductivity and very low thermal expansion coefficient [22].

Spinel

Although spinel has very good high temperature and chemical properties, its thermal expansion coefficient prevents its usage as a reliable choice for thermal barrier coatings [21].

Forsterite

The high thermal expansion coefficient of forsterite permits a good match with the substrate. At thicknesses of some hundred microns, it shows a very good thermal shock resistance [21].

To meet tough automotive competition and stringent government regulations, more efficient engine components, improved engine oils, and high performance coating materials have been developed within the automotive industry. The efficiency of most commercially available diesel engine ranges from 38% to 42%. Therefore, between 58% and 62% of the fuel energy content is lost in the form of waste heat. More than 55% of the energy which is produced during the combustion process is removed by cooling water and through the exhaust gas. The quantity of the energy acquired from the fuel is not an intended level because of the factors in the combustion chamber of the engine. Some of the factors are, design of the combustion chamber, lack of adequate turbulence in the combustion chamber, poor oxygen at the medium, lower combustion temperature, compression ratio and advance of injection timing. It is thought that combustion temperature is one of the most important factors among the above mentioned factors. All of the hydrocarbons cannot be reacted with oxygen chemically during combustion time. With this aim, coating the combustion chamber components with low thermal conductivity materials becomes a more important subject at these days. For this reason, combustion chamber components of the internal combustion engines are coated with ceramic materials using various methods. Temperature resistant materials leads to thermal barrier coated engines also known as low heat rejection engines. Thermal barrier coated engines can be thought as a step to adiabatic engines. To achieve this aim, ceramic is a preferred alternative. Thermal barrier coating is mostly done by ceramic coating of combustion chamber, cylinder heads and intake/exhaust valves.

If cylinder walls are intended to be coated, a material should be selected which has proper thermal dilatation and wear resistance. Some ceramic materials have self-lubrication properties up to 8700C. Exhaust gas temperature changing between 400-600 0C for conventional diesel engines while it is between 700-900 0C for thermal barrier coated engine. Low Heat Rejection (LHR) engines aim to utilize the maximum energy or we can save the energy by reducing the heat lost to the coolant. This will reduce the heat transfer through the engine walls, and a greater part of the produced energy can be utilized, involving an increased efficiency. The diesel engine with its combustion chamber walls insulated by ceramics is referred to as LHR engine. Thermal barrier coatings (TBC) are used to improve reliability and durability of hot section metal components and enhance engine performance and thermal efficiency and elimination of the cooling system in diesel engines. Because the combustion chamber temperatures of ceramic-coated engines are higher than those of uncoated base engine engines, it may be possible to use a fuel with a large distillation range and lower quality fuels. 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.

Thermal barrier coatings (TBC): The most common coatings currently used in high temperature engine applications are stabilized zirconia due to their very low thermal conductivity and a coefficient of thermal expansion which is higher than the vast majority of insulating ceramics. Coating thicknesses used in engine applications have varied from 0.1mm to 4.5mm, with thicker coatings theoretically providing greater resistance to heat flux. The most common way of applying these coatings has been through plasma spraying which has been used to apply coatings both selectively to specific engine components (i.e. valves, cylinder head, piston crown) and to the entire combustion chamber. The primary challenges posed by thermal barrier coatings within engine environments stem from their durability. Due to their low coefficients of thermal expansion (CTE) in comparison to the metallic substrates upon which they are applied, ceramic TBCs are prone to cracking, spalling and eventual failure resulting from the cyclic thermal stresses created by the temperature differential between the coating and the substrate. In an attempt to alleviate these problems, new nano-structured ceramic and metal-based TBCs with CTEs more comparable to typical metallic substrates have been studied, with some promising results. The increased surface temperatures in a TBC-coated combustion chamber may also result in the degradation of engine lubricants, while decreasing the volumetric efficiency of the engine due to heating of the intake charge. As will be discussed, the higher temperatures may also have significant effects on combustion and thus engine emissions. Though not currently used in production engines, a great deal of research has been conducted studying the use of TBCs in both compression and spark ignition engines as a means of managing heat losses. In the following, a brief overview of the available work in the two research areas is given.

2.4 TBCs in Diesel Engines:

The vast majority of research studying the use of TBCs in diesel engines was in the development of the adiabatic engine. The premise of this technology was to reduce heat losses from the combustion chamber to a minimum by applying thick plasma-sprayed ceramic coatings throughout the combustion chamber. The goal was to maximize the amount of energy extracted from each cycle by reducing losses, which would ultimately lead to improved fuel efficiency and reductions in cooling requirements for the engine. Though many studies on this topic showed significant reductions in heat loss, increases in efficiency and reduced fuel consumption, some unexpected results were also encountered. Morel et al. conducted multiple studies in a single cylinder turbocharged diesel engine analyzing the feasibility of the low heat rejection engine. In each of these studies, the piston crown, cylinder head and valves were coated with 1.25mm of plasma sprayed zirconia. In-cylinder surface temperature measurements demonstrated that the peak and average heat flux decreased by up to 50% with the introduction of the TBC in comparison to the baseline, uncoated engine. Similar decreases in heat transfer were seen by Cheng et al. in their heat transfer study of an uncoated exhaust valve placed in a diesel engine whose piston and remaining valves were coated in 1.52mm of plasma sprayed zirconia. Decreases in heat flux amplitude between 10% - 30% and increased surface temperatures of up to 200K with respect to an uncoated engine were seen. Assanis saw an 80% decrease in peak heat flux when comparing ceramic-coated to uncoated plugs and temperature increases on the order of 150K for the coated plugs.

Thus, the potential for TBCs as a means of reducing engine heat transfer is evident. However, other researchers had findings contradicting these claims of improved efficiency and decreased heat transfer. Using heavily insulated pistons in diesel engines, both Woschni et al. saw increases in peak heat flux of up to 100%, which they attributed to the increase in heat transfer coefficient with increasing surface temperatures. They credited this temperature dependence to a reduction in thermal boundary layer thickness due to increased surface temperatures which allowed for closer interaction of the flame with the piston surface. In addition, attributed increases in fuel consumption and decreased thermal efficiency seen in their low heat rejection engine experiments to degraded combustion. It was concluded by various authors that in order to extract maximum benefits from the introduction of ceramic coatings, combustion quality must be optimized by making appropriate changes to the injection timing. Studies have also been conducted using thin ceramic TBCs (<1mm) as opposed to the much thicker coatings originally implemented in the adiabatic engine studies. Thin coatings have been shown to reduce the negative effects associated with thicker coatings such as poor mechanical reliability, decreased volumetric efficiency due to excessive heating of the intake charge and poor tribological behavior due the significantly higher surface temperatures.

2.5 ADVANTAGES OF THERMAL BARRIER COATINGS FOR DIESEL ENGINES

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,

CHAPTER-3

Emissions

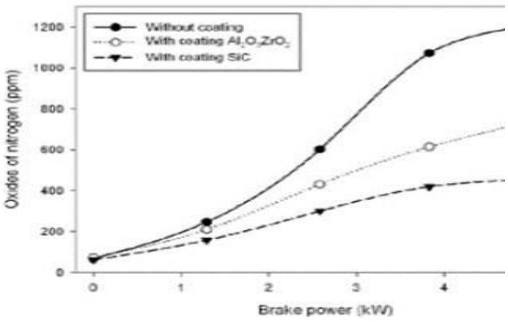
- **3.1 Unburned Hydrocarbon and Carbon Monoxide Emission:** In this section, the unburned hydrocarbon (UHC) and carbon monoxide (CO) emissions are investigated. The emission of unburned Hydrocarbon from the LHR engines is more likely to be reduced because of the decreased quenching distance and the increased lean flammability limit. The higher temperatures both in the gases and at the combustion chamber walls of the LHR engine assist in permitting the oxidation reactions to proceed close to completion. Most of the investigations show reduction in HC level [34]. Also many investigations indicate lower level of CO emissions. They attribute this to high gas temperature and combustion chamber walls. The reduced level of pre-mixed combustion in the insulated engine decreases the initial production of CO and the higher temperatures during diffusion combustion accelerate the oxidation of CO.
- **3.2 Nitrogen Oxides and Smoke:** Nitrogen oxides (NOx) are formed by chain reactions involving Nitrogen and Oxygen in the air. These reactions are highly temperature dependent. Since diesel engines always operate with excess air, NOx emissions are mainly a function of gas temperature and residence time. Most of the earlier investigations show that NOx emission from LHR engines is generally higher than that in water-cooled engines. This could be due to

higher combustion temperature and longer combustion duration. indicate that Smoke levels increased by 16% and NOx levels by 34% with LHR engine at an injection timing of 32°BTDC and an injection pressure of 270 bars, in comparison with CE (conventional engine) operating at an injection timing of 27°BTDC, and an injection pressure of 190 bars indicate NOx emissions were obtained below those of the base engine by 11% for 18°BTDC injection timing. The Investigation of reports an increase in the LHR engine NOx emissions and concluded that diffusion burning is the controlling factor for the production of NOx. Almost equal number of investigations report declining trend in the level of emission of NOx, For example Ramu et al. showed that the combined effect of thermal barrier coating plus fuel additive shows better performance and simultaneously reduces the smoke and NOX emission. Fig. 3 shows the emission of NOx against brake power of the standard engine and TBC engine. The result shows that NOx emission is significantly reduced in the coated engines. The main cause in lowering NOx emission is due to late combustion, because of change in the delay period. Due to the effect of delay period, the heat release diagram centroid shifts away from TDC, as a result of drop in pressure rise during combustion. Since the peak pressure rise is lower for the above reason, assuming the same value of mass, the peak gas temperature may also be lower near TDC, resulting reduced NOx formation. The same trend in observed by during their experiments. They found lower NOx level for a LHR engine than the standard engine. It is found that approximately 500 ppm NOx emission reduced for ZrO2-Al2O3 coated engine at maximum brake power. Further it is found that SiC coated engine reduces the NOx emission about 800 ppm at maximum brake power against the standard engine.

CHAPTER-4

Engine efficiency

- **4.1 Volumetric Efficiency:** The volumetric efficiency is an indication of breathing ability of the engine. It depends on the ambient and operating conditions of the engine. Reducing heat rejection with the addition of ceramic insulation causes an increase in the temperature of the combustion chamber walls of an LHR engine. The volumetric efficiency should drop, as the hotter walls and residual gas decrease the density of the inducted air. As expected all the investigations such as Gatowski , Miyairi et al. on LHR engine show decreased volumetric efficiency. The deterioration in volumetric efficiency of the LHR engine can be prevented by turbo-charging and that there can be more effective utilization of the exhaust gas energy.



.The amount of nitrogen oxides against the brake power

4.2 Thermal Efficiency: The improvement in engine thermal efficiency by reduction of in-cylinder heat transfer is the key objective of LHR engine research. Much work has been done at many research institutes to examine the potential of LHR engines for reducing heat rejection and achieving high thermal efficiency. Researchers such as Havstad et al. ,Moore et al. Morel et al, and many others have reported improvement in thermal efficiency with LHR engine. They attribute this to in transfer reduction and lower heat flux. However investigations of others such as Cheng et al. , Woschni et al., Furuhama et al. Dickey and some others report that thermal efficiency reduces with insulation. They all attribute this to an increase in the convective heat transfer coefficient, higher heat flux (increase in in heat transfer) and deteriorated combustion cylinder heat transfer characteristics of LHR engine are still not clearly understood. Thus the effect of combustion chamber insulation on reducing heat rejection and hence on thermal efficiency is not clearly understood as on data.

4.3 Objective

The performance of internal combustion engines should be improved depending on some technological requirements and rapid increase in the fuel expenses. On the other hand, the improvements in engine materials are forced by using alternative fuels and environmental requirements. Therefore, the performances of engine materials become increasingly important. For improving the performance of engine, thermal barrier coatings (TBCs) are a promising step forward. In this experimental study, alumina – (40 %) titania and nickel - chromium are used as the thermal barrier materials. The purpose of using these materials is to reduce the heat loss from engine. TBCs are done by atmospheric plasma spraying technique. Engine working conditions are maintained constant before and after coating. The results showed a reduction in specific fuel consumption. CO and HC emissions are slightly more than the conventional coated diesel engine at low and medium loads but lesser at higher loads whereas NOx is reduced.

Diesel engines are more fuel efficient than other fuelled engines because of the high calorific value of diesel. The leading role of diesel engines in both transport and agriculture sector is because of its good fuel economy and lower running cost. However, diesel engines can only convert one third of fuel energy into useful work and the remaining two third is lost as waste energy through coolant and exhaust. The piston crown and cylinder head of diesel engines are coated with thermal barrier materials to reduce heat transfer to the coolant and also to improve the power output along with an increase in the exhaust energy .

The transfer of heat occurs through the combustion chamber elements, like valves, piston surfaces and liners. Ceramic coatings, with low thermal conductivity, on the combustion chamber surfaces, keep the heat in the chamber and hence increase the temperature . Engines operating on higher temperatures can only be more efficient than the present engines available. Ceramics with high temperature resistance may offer an excellent coating surface with reduced amount of degradation and extended life.

The primary purposes of high temperature structural coatings are to enable high temperature components to operate at even higher temperature and to improve component durability of engines. Al-Ti and Ni-Cr are characterized by excellent mechanical and thermal properties with high chemical and corrosion resistance, low shrinkage on curing and the ability to be processed under a variety of conditions.

SPRAYING

5.1 Thermal spraying :

Thermal spraying techniques are coating processes in which melted (or heated) materials are sprayed onto a surface. The "feedstock" (coating precursor) is heated by electrical (plasma or arc) or chemical means (combustion flame).

Thermal spraying can provide thick coatings (approx. thickness range is 20 micrometers to several mm, depending on the process and feedstock), over a large area at high deposition rate as compared to other coating processes such as electroplating, physical and chemical vapor deposition. Coating materials available for thermal spraying include metals, alloys, ceramics, plastics and composites. They are fed in powder or wire form, heated to a molten or semimolten state and accelerated towards substrates in the form of micrometer-size particles. Combustion or electrical arc discharge is usually used as the source of energy for thermal spraying. Resulting coatings are made by the accumulation of numerous sprayed particles. The surface may not heat up significantly, allowing the coating of flammable substances.

Coating quality is usually assessed by measuring its porosity, oxide content, macro and micro-hardness, bond strength and surface roughness. Generally, the coating quality increases with increasing particle velocities.

Several variations of thermal spraying are distinguished:

- Plasma spraying
- Detonation spraying
- Wire arc spraying

- Flame spraying
- High velocity oxy-fuel coating spraying (HVOF)
- Warm spraying
- Cold spraying

In classical (developed between 1910 and 1920) but still widely used processes such as flame spraying and wire arc spraying, the particle velocities are generally low (< 150 m/s), and raw materials must be molten to be deposited. Plasma spraying, developed in the 1970s, uses a high-temperature plasma jet generated by arc discharge with typical temperatures >15000 K, which makes it possible to spray refractory materials such as oxides, molybdenum.

5.2 Plasma spraying

In plasma spraying process, the material to be deposited (feedstock) — typically as a powder, sometimes as a liquid, suspension or wire — is introduced into the plasma jet, emanating from a plasma torch. In the jet, where the temperature is on the order of 10,000 K, the material is melted and propelled towards a substrate. There, the molten droplets flatten, rapidly solidify and form a deposit. Commonly, the deposits remain adherent to the substrate as coatings; free-standing parts can also be produced by removing the substrate. There are a large number of technological parameters that influence the interaction of the particles with the plasma jet and the substrate and therefore the deposit properties. These parameters include feedstock type, plasma gas composition and flow rate, energy input, torch offset distance, substrate cooling, etc.

Deposit properties

The deposits consist of a multitude of pancake-like 'splats' called lamellae, formed by flattening of the liquid droplets. As the feedstock powders typically have sizes from micrometers to above 100 micrometers, the lamellae have thickness in the micrometer range and lateral dimension from several to hundreds of micrometers. Between these lamellae, there are small voids, such as pores, cracks and regions of incomplete bonding. As a result of this unique structure, the deposits can have properties significantly different from bulk materials. These are generally mechanical properties, such as lower strength and modulus, higher strain tolerance, and lower thermal and electrical conductivity. Also, due to the rapid solidification, metastable phases can be present in the deposits.

Applications

This technique is mostly used to produce coatings on structural materials. Such coatings provide protection against high temperatures (for example thermal barrier coatings for exhaust heat management), corrosion, erosion, wear; they can also change the appearance, electrical or tribological properties of the surface, replace worn material, etc. When sprayed on substrates of various shapes and removed, free-standing parts in the form of plates, tubes, shells, etc. can be produced. It can also be used for powder processing (spheroidization, homogenization, modification of chemistry, etc.). In this case, the substrate for deposition is absent and the particles solidify during flight or in a controlled environment (e.g., water). This technique with variation may also be used to create porous structures, suitable for bone ingrowth, as a coating for medical implants. A polymer dispersion aerosol can be injected into the plasma discharge in order to create a grafting of this polymer on to a substrate surface. This application is mainly used to modify the surface chemistry of polymers.

5.2.1 Variations

Plasma spraying systems can be categorized by several criteria.

Plasma jet generation:

- direct current (DC plasma), where the energy is transferred to the plasma jet by a direct current, high-power electric arc
- induction plasma or RF plasma, where the energy is transferred by induction from a coil around the plasma jet, through which an alternating, radio-frequency current passes

Plasma-forming medium:

- gas-stabilized plasma (GSP), where the plasma forms from a gas; typically argon, hydrogen, helium or their mixtures
- water-stabilized plasma (WSP), where plasma forms from water (through evaporation, dissociation and ionization) or other suitable liquid
- hybrid plasma - with combined gas and liquid stabilization, typically argon and water

Spraying environment:

- air plasma spraying (APS), performed in ambient air
- controlled atmosphere plasma spraying (CAPS), usually performed in a closed chamber, either filled with inert gas or evacuated
- variations of CAPS: high-pressure plasma spraying (HPPS), low-pressure plasma spraying (LPPS), the extreme case of which is vacuum plasma spraying (VPS, see below)
- underwater plasma spraying

Another variation consists of having a liquid feedstock instead of a solid powder for melting, this technique is known as Solution precursor plasma spray

5.3 Vacuum plasma spraying

Vacuum plasma spraying (VPS) is a technology for etching and surface modification to create porous layers with high reproducibility and for cleaning and surface engineering of plastics, rubbers and natural fibers as well as for replacing CFCs for cleaning metal components. This surface engineering can improve properties such as frictional behavior, heat resistance, surface electrical conductivity, lubricity, cohesive strength of films, or dielectric constant, or it can make materials hydrophilic or hydrophobic.

The process typically operates at 39–120 °C to avoid thermal damage. It can induce non-thermally activated surface reactions, causing surface changes which cannot occur with molecular chemistries at atmospheric pressure. Plasma processing is done in a controlled environment inside a sealed chamber at a medium vacuum, around 13–65 Pa. The gas or mixture of gases is energized by an electrical field from DC to microwave frequencies, typically 1–500 W at 50 V. The treated components are usually electrically isolated. The volatile plasma by-products are evacuated from the chamber by the vacuum pump, and if necessary can be neutralized in an exhaust scrubber.

In contrast to molecular chemistry, plasmas employ:

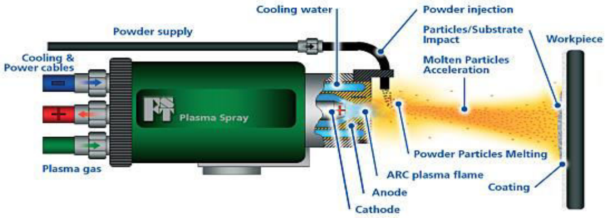
- Molecular, atomic, metastable and free radical species for chemical effects.
- Positive ions and electrons for kinetic effects.

Plasma also generates electromagnetic radiation in the form of vacuum UV photons to penetrate bulk polymers to a depth of about 10 µm. This can cause chain scissions and cross-linking.

Plasmas affect materials at an atomic level. Techniques like X-ray photoelectron spectroscopy and scanning electron microscopy are used for surface analysis to identify the processes required and to judge their effects. As a simple indication of surface energy, and hence adhesion or wettability, often a water droplet contact angle test is used. The lower the contact angle, the higher the surface energy and more hydrophilic the material is.

5.4 Changing effects with plasma

At higher energies ionization tends to occur more than chemical dissociations. In a typical reactive gas, 1 in 100 molecules form free radicals whereas only 1 in 10^6 ionizes. The predominant effect here is the forming of free radicals. Ionic effects can predominate with selection of process parameters and if necessary the use of noble gases.



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 gasses 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 was used as the cooling gas during plasma spraying

Plasma spraying parameters

Sl.	Parameters	Value
1.	Spray gun	3 MB
2.	Nozzle	GH
3.	Current (A)	490
4.	Voltage (V)	60 – 70

5.	Powder feed (	40-50
6.	Spray distance	76.2 - 127 ± 10 %
7.	Particle velocity (	Up to 450
8.	Arc Temperature (0C)	16,000
9.	Particle size (μm)	14.5 – 45
10.	Inert gas flow rate	
	a.)Argon (l/min)	100– 200 ± 5%
	b.)Hydrogen	100 ± 5%

Coated piston and cylinder head

RESULTS AND DISCUSSION

The performance and Emission characteristics of Al-Ti and Ni-Cr coated piston crown and cylinder head diesel engine was investigated and compared with standard engine. The results obtained from the experiments conducted on the engine are presented in Figure 3 to Figure 7.

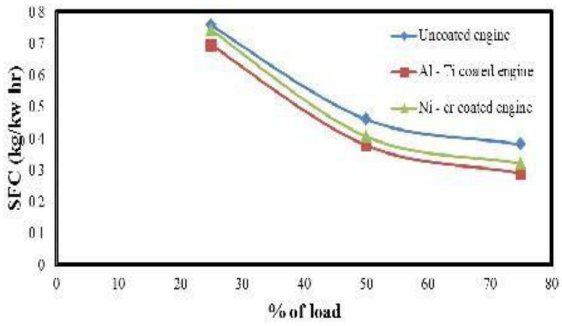


Figure 3: Comparison of Specific Fuel Consumption for different loads.

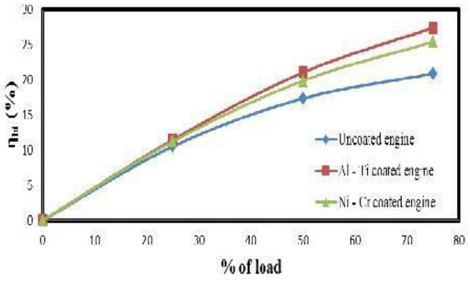


Figure 4: Comparison of Brake Thermal Efficiency for different loads.

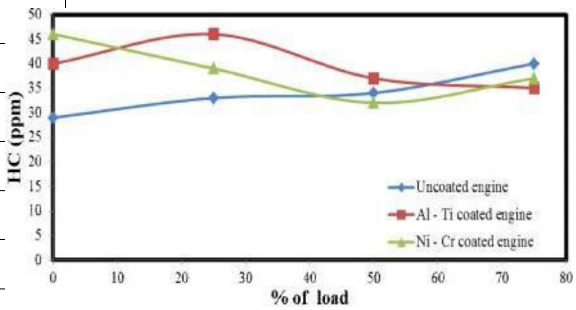


Figure 5: Comparison of Hydrocarbon emission for different loads.

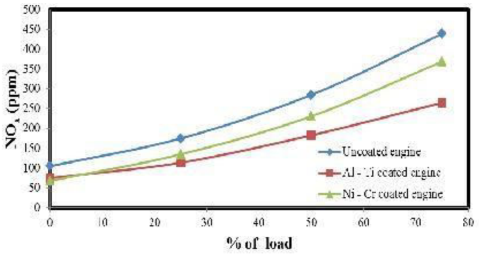


Figure 6: Comparison of Oxides of Nitrogen emission for different loads.

Figure 3 shows the variations of specific fuel consumption of standard engine and compared with Al-Ti and Ni-Cr coated piston crown and cylinder head. The specific fuel consumption is reduced by 16.6% for Al-Ti coating and 9.86% for nickel chromium coating compare to standard engine. Complete combustion of fuel inside the cylinder may reduce the amount of fuel consumed. T. Hejwowski and A. Weroński (2002) stated that specific fuel consumption for a coated engine decreases by 15– 20%.

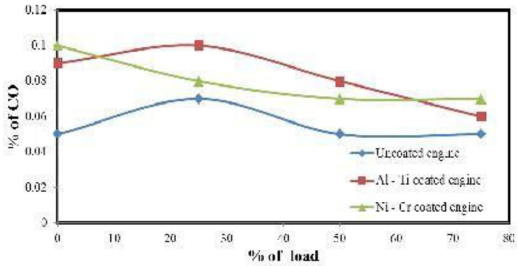


Figure 7: Comparison of carbon monoxide emission for different loads.

The variation of brake thermal efficiency with load for engine operating on Al-Ti and Ni-Cr coated engine and standard engine is shown in figure 4. It is significant that modified engine has higher efficiency than that of base line engine. Reduced thermal loss might be the reason for the improvement in brake thermal efficiency. The maximum brake thermal efficiency obtained for engine operating on Al-Ti coated and standard engine are 20% and 14.26 % respectively. Ilker Turgut Yilmaz (2010) also stated that break thermal efficiency for coated engine improved by 20-25%.

Figure 5 shows the comparison of hydrocarbon emission for different loads. Combustion chamber temperature is inversely proportional to HC emission. So HC is slightly more than the conventional diesel engine at low and medium loads and lesser at high loads . Modified engine HC emission is lower by around 10 % at full load condition.

Figure 6 indicated the variation of oxides of nitrogen with load for Al-Ti and Ni-Cr coated and standard engine. NOx is generated mostly from nitrogen present in air and also from fuel. The inherent availability of nitrogen and oxygen in the fuel accelerates the formation of NOx. NOx formation is directly proportional to the combustion temperature. In Al-Ti and Ni-Cr coated engine, the NOx level is reduced by 40 and 20 % respectively. Reduced combustion chamber temperature due to lower fuel consumption might be the reason for lower NOx levels.

The measured CO emissions for Al-Ti and Ni-Cr coated engine and standard engine are shown in Figure 7. The reduction in CO emission is due to complete combustion and CO emission is slightly more than the conventional and nickel chromium diesel engines at low and medium loads and lesser at high loads.

CONCLUSION

A conventional contemporary diesel engine is converted into Al-Ti and Ni-Cr coated diesel engine. SFC and emissions were measured to determine the performance and emission characteristics of the engine. The following conclusions can be drawn from the experimental results.

Al-Ti coated diesel engine shows better specific fuel consumption compared to conventional and Ni-Cr coated diesel engine which is 16.6% lower than the standard engine. NOx emission from Al-Ti coated engine is lower by 40 % than the standard engine. Results show increase in brake thermal efficiency after coating.

With the results obtained it is clear that the coated engines are optimum for low and medium load conditions and more suitable for high load conditions when compared to standard engine.

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