Review of ceramic materials that used as a thermal barrier in diesel engine pistons

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Abstract. The diesel engines is used in many industrial applications in addition to that in cars. In this type of engine the fuel-air mixture will burn behind the piston inside the cylinder and will produce high temperature. Developing diesel engines to be more efficient, less fuel consumption, low gas emissions, and high performance that has been pursued for more than two decades. Increased combustion temperature can enhance engine power and efficiency while lowering specific fuel consumption and CO emission rates. Ceramic thermal barrier coatings have been identified as the most promising method for achieving these goals. Due to the abundance of materials and technologies, it is necessary to understand the best material suitable for depositing and the techniques required to complete the process. Many researchers have studied a wide range of materials like ZrO₂, Al₂O₃, mullite, YSZ, and forsterite to develop suitable systems that use thermal barrier coatings. Additionally, many techniques such as EB-PVD and ASP have been developed to meet the requirements of these systems. This paper will examine the materials and technologies that can be used to improve internal diesel engine performance.

1. Introduction

Thermal barrier coatings (TBCs) are a multi-layer coating system with a distinct function for each layer. The topcoat layer, which is deposited on the intermediate layer, provides thermal insulation and is composed of ceramic materials with low thermal conductivity. The second layer is a bond coat, which is an intermediate layer that is applied directly to the metal surface. which protects the metal substrate from oxidation and enhances adhesion between topcoat and substrate surface It's either a diffusion aluminide, like platinum aluminide or an overlay coating, typically NiCoCrAlY.[1]

Thermal barrier coating systems (TBCs) are broadly used in gas turbine engines for power generation, marine, aero-engine, and diesel engine applications to reduce the surface temperature of the combustion chamber and the hottest component.[2] The majority of the heat generated during the combustion process is transferred to engine components via the piston in internal combustion engines.
Engine coating with a ceramic thermal barrier can be used to improve the reliability and durability of diesel engine performance and efficiency. Thirty percent of total energy is lost to coolant, and it was concluded that engine coating may be a good solution.[3] Fuel energy must be converted to kinetic energy at the fastest possible rate to achieve better engine performance. The use of low heat-conducting ceramic materials to coat combustion chambers causes an increase in temperature and pressure in internal combustion engine cylinders. As a result, increased engine efficiency should be observed.[4]

This review article aims to provide an overview of ceramic thermal barrier materials that can be deposited on IC engines and related coating technologies.

2. TBCs materials

The ceramic topcoat insulates the substrate beneath it from heat. The material used as a topcoat should have the following basic properties:

1. Low thermal conductivity
2. High melting point
3. Phase stability.

Because of its low thermal conductivity, relatively high CTE, and adequate toughness, 6–8 wt. percent YSZ is the most commonly used topcoat material. Other ceramics used as TBC materials besides YSZ include mullite, Forsterite, Al2O3, TiO2, CeO2+YSZ, La2 Zr2O7, Spinel, pyrochlore, and perovskites[2] several topcoat materials have been reviewed for diesel engine applications over the decades. Most of these materials will be explained in this paper.

2.1. Zirconia (ZrO2)

Zirconia is available in three crystal structures. They are Monolithic (m), tetragonal (t), and cubic (c). Between room temperature and 1170°C, the monolithic structure is stable, but above 1170°C, it transforms into a tetragonal structure. The tetragonal structure is stable up to 2379°C, after which it transforms into a cubic structure.[4] A metastable tetragonal phase is formed as a result of rapid cooling during the coating processes. When heated to high temperatures, the tetragonal phase
decomposes into a two-phase mixture of the tetragonal and cubic phases via diffusion. When the tetragonal phase later converts to the monoclinic phase, the coating may spall due to volume change. However, The tetragonal phase in a diesel engine is expected to be stable at relatively low temperatures.[6]

2.2. **Mullite (3Al2O3.2SiO2)**
Mullite is a compound of SiO2 and Al2O3 with a composition (3Al2O3.2SiO2). It has a much lower thermal expansion coefficient and higher thermal conductivity than yttria-stabilized zirconia, as well as being much more oxygen resistant. Mullite's low thermal expansion coefficient is an advantage over yttria-stabilized zirconia. Engine tests conducted with both materials show that the mullite coating in the engine lasts significantly longer than the zirconia coating. Mullite is a great TBC material alternative to zirconia especially for applications like diesel engines, where surface temperatures are lower than in gas turbines.[7]

2.3. **Alumina (Al2O3)**
Alumina is extremely hard and chemically inert. When compared to yttria-stabilized zirconia, it has a higher thermal conductivity and a lower thermal expansion coefficient. Coating hardness can also be increased by spraying an outer layer of alumina onto YSZ coatings [5]. Because of its low oxygen diffusivity, alumina develops gradually at elevated temperatures so that it was designed to act as a barrier -Al2O3 layer in between the bond coat and the topcoat.[6]

2.4. **Forsterite**
The high coefficient of thermal expansion of the forsterite allows better coordination with the substrate. With a thickness of hundreds of microns, it exhibits excellent thermal shock resistance.[5]
It is particularly useful for low loss dielectrics and in designs where the coefficient of thermal expansion must match the metal-ceramic bond[8]. Because of its good CTE can be used as a bond coat in multilayer TBCs system.

2.5. **Lanthanum zirconate (LZ, La2Zr2O7)**
Lanthanum zirconate (LZ, La2Zr2O7) has pyrochlore-structured ceramic, which has fracture toughness that is close to YSZ, and its thermal conductivity at higher temperatures is approximately 20% less than that of YSZ. Lanthanum zirconate has a thermal expansion of 9.1 10–6 K–1 at 30–1000°C, which is lower than that of YSZ and may result in higher stresses in the coating due to a larger thermal expansion mismatch with other layers in the TBC system. Thermal cycling studies of LZ and YSZ/LZ coatings, on the other hand, have yielded encouraging results. As a result, in diesel engine applications, this should not be a problem.[6]

3. **COATING PROCESS**
Coatings are applied using a variety of methods that have been categorized into gaseous state processes, solution-state processes; molten or semi-molten state processes, and solid-state processes depending on the physical states in which they are applied. Physical vapor deposition (PVD) is one of the gaseous state methods.
Air plasma spray and EB –PVD is the most commonly used techniques in the deposition of thermal barrier coatings, as described below

3.1. **Air plasma spray**
Air plasma spray (APS) deposits a ceramic topcoat in one of two morphologies. With sub-critical horizontal micro cracking between individual splat layers, a "low density" coating has an even spacing of pores and voids ranging from 20 micros to nano-scaled. Coating density usually varies from 80 to
86 percent of the theoretical value. Figure 2 displays cross-section optical and SEM images of a typical low-density coating[9].

Air plasma spray (APS) for ceramic coatings is the same as that for metallic coatings, with the exception that ceramic materials have higher melting points, which needs some modifications. The feedstock material, in the form of powders, is introduced into the higher temperature zone of the plasma using a carrier gas.

The powder's particle size is typically between 10 and 40 microns. Larger particles tend to melt partially. Particles smaller than 10 microns, on the other hand, are unable to reach the plasma and are trapped in the cooler periphery. The majority of the bonding between the coating material and the substrate is mechanical. The adhesion mechanism is provided by the interconnecting of the depositing particles with the substrate roughness features[1].

![Figure 2: Cross-section of APS low density TBC, containing approximately 15% porosity. Two different magnifications are shown to reveal the “macro” and “micro” structure of the coating.](image)

The plasma jet melts the particles and accelerates them towards the substrate. On contact, the molten particles flatten and form splats. A lamellar coating forms when more splats touch the surface. During the solidification of the splats, cooling rates can reach 105 Ks–1, resulting in lateral solidification and grain growth that is primarily perpendicular to the substrate. Factors such as shadowing by previously deposited particles and splat curling caused by surface tension and thermal expansion mismatch stresses because of intersplat pores and cracks. For APS coatings with typical microstructure, the porosity creates some lateral strain compliance[6].
Fig 3. The surface of an ASP YSZ coating, showing how a molten particle has flattened on impact [6].

3.2. Electron beam–physical vapor deposition (EB-PVD).

The microstructure of electron beam–physical vapor deposition (EB-PVD) coatings is columnar, with inter-columnar pores that allow for lateral strain compliance. EB-PVD coatings are frequently used on mechanically loaded components. The coated component is preheated before being placed in a vacuum chamber, where electron beams impact and evaporate ceramic ingots. At speeds of 4–10 µm min–1, the vapor is deposited onto the substrate, combined with a balanced amount of oxygen. This is a costly coating process that can not be used for many of the alloys used in diesel engine components due to high deposition temperatures of about 1000°C, which result in melting or undergoing phase transitions.[6]

Fig 4. Columnar structure of a TBC fabricated by EB-PVD technique[6].

4. Air plasma spray AGAINST EB-PVD

The ceramic topcoat is commonly deposited using electron beam physical vapor deposition (EB–PVD) and APS or any modified version of any of them. Some deferent features are owing to each technique will summarize here[10].

1. The preheating of the substrate is not mandatory in the air plasma spray process but it is compulsory in using electron beam physical vapor deposition.
2. In electron beam physical vapor deposition, the coating deposition rate is lower compared to that of the plasma spraying process.
3. The microstructure of the coatings formed by the two processes shows some deference.
4. The coating deposited by the APS process has a lamellar morphology; on the other hand, the coating deposited with the EB PVD process has a columnar morphology.
5. Porosity and defects in the form of minor cracks are a characteristic feature of the APS deposited coating that plays a crucial role in reducing the thermal conductivity of the topcoat layer.
6. The layers are coated by the APS technique are thicker than those in EB-PVD.

5. CONCLUSION

Thermal barrier coatings have been approved for their effectiveness in improving many components that operate at extremely high temperatures. These applications include power turbine engine blades and vanes, aero-engines, and many diesel engine components such as pistons, liners, cylinder heads, and intake and exhaust manifolds.

The mean goal of using the thermal barrier coating in diesel engines is to improve the efficiency and performance of engines. The many research achieved on diesel engine elements showed that deposition of ceramic material as topcoat not only reduces heat transferred from the combustion chamber to the engine body, but it also insulates the metal substrate from oxidation and corrosion.

It aids in raising the operating temperature and improving engine performance. The life of the coated part is significantly extended.

The best ceramic material may be used as thermal barrier coating in diesel engines does not need to have high thermal and mechanical properties like in turbine engines. Mullite, forsterite, alumina, and spinel can focus on developing, utilizing, and innovating new coating types.

For their advanced coating features, with engine design and manufacturing development, the two most commonly used technologies in thermal barrier coating are EB-PVD and Air plasma spraying. They need to be easier and more variable to produce coatings that meet new engine requirements.

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