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A COMPREHENSIVE REVIEW OF ADVANCED PISTON COATING MATERIALS FOR PERFORMANCE IMPROVEMENT IN I.C. ENGINES

Mahesh M. Chudasama

Lecturer, Automobile Engineering Department, Dr J N Mehta Government Polytechnic, Amreli, Gujarat, INDIA

Abstract

The rapid depletion of hydrocarbon resources has created a growing demand for enhancing the efficiency of internal combustion (I.C.) engines. As a result, engine manufacturers and the automotive industry are increasingly focusing on advanced technologies to improve fuel economy, power output, and emission control. The operational lifespan of an engine is largely determined by the durability of its critical components, especially under high-temperature conditions. To address these challenges, the application of advanced thermal barrier coatings (TBCs) has gained prominence. This study presents an experimental investigation on a partially insulated single-cylinder diesel engine, aimed at evaluating the impact of advanced piston crown coatings on engine performance and emissions. The piston crown is coated using the plasma spray method with a ceramic material composed of zirconium dioxide (ZrO_2) stabilized with 8 wt.% yttrium oxide (Y_2O_3). The results indicate a significant reduction in heat loss to the coolant and an increase in exhaust gas energy, demonstrating the effectiveness of low heat rejection (LHR) engine configurations compared to conventional diesel engines.

Key words: *Thermal Barrier coating, piston crown, diesel engine*

Introduction

Internal combustion (IC) engines are power-generating systems in which the combustion of fuel occurs directly within the engine cylinder. The high-pressure gases produced from combustion act upon the piston, converting thermal energy into mechanical work. During operation, critical engine components are subjected to extreme conditions, including elevated temperatures, high mechanical loads, and chemically aggressive environments—resulting in wear due to corrosion, oxidation, and erosion.

The service life and efficiency of IC engines heavily depend on the durability of their key components, especially those exposed to high thermal and mechanical stresses. Enhancing the longevity and performance of such components is a pressing challenge for engine manufacturers and the automotive industry. Additionally, with increasing environmental concerns and stringent emission regulations, there is a growing demand for improved engine efficiency and reduced fuel consumption.

Multiple strategies have been explored to meet these goals, such as enhancing vehicle aerodynamics, reducing component weight, and integrating hybrid powertrains. Among these, material engineering solutions—particularly the application of protective coatings—have gained significant attention. Since the early days of engine development, thermal and wear-resistant coatings have been applied to critical engine parts to improve their durability and exploit the full potential of base materials.

Modern advancements in coating technologies have led to the development of novel materials and techniques, such as plasma-sprayed thermal barrier coatings (TBCs), which offer superior thermal insulation and resistance to high-temperature corrosion. These coatings are especially relevant in the hot zones of the engine, such as the piston crown and combustion chamber, where ceramic-based TBCs help reduce heat rejection, protect metallic substrates, and improve thermal efficiency.

High-performance ceramic coatings, like those based on yttria-stabilized zirconia (YSZ) or alumina, exhibit excellent resistance to oxidation, corrosion, and thermal fatigue. The application of these coatings can significantly improve engine performance parameters such as efficiency, power output, reliability, and emissions.

This study reviews experimental investigations on the use of advanced piston coating materials in IC engines, with a focus on how such coatings influence engine performance, durability, and environmental compliance under demanding operating conditions.

Methods for Producing Thermal Barrier Coatings (TBCs)

Thermal Barrier Coatings (TBCs) are typically applied using advanced deposition techniques suited for high-performance industrial applications. The commonly employed methods include:

- **Air Plasma Spray (APS)**
  A cost-effective and widely used method that involves spraying molten or semi-molten particles onto a surface using a high-temperature plasma jet.
- **Electron Beam Physical Vapor Deposition (EBPVD)**
  This technique uses an electron beam to evaporate coating materials in a vacuum, allowing the deposition of highly controlled and columnar-structured coatings.
- **High Velocity Oxygen Fuel (HVOF) Spraying**
  In this method, coating particles are heated and accelerated in a high-pressure flame, producing dense coatings with strong adhesion and low porosity.

- **Electrostatic Spray Assisted Vapor Deposition (ESAVD)**
  A relatively low-cost, environmentally friendly technique that enables uniform coatings without the need for high vacuum systems.
- **Direct Vapor Deposition (DVD)**
  A more recent innovation, this method allows precise control of microstructure and composition, making it suitable for complex geometries and demanding thermal environments.

Materials Used in Advanced Ceramic Coatings

Advanced ceramic materials used in TBCs include both **oxide** and **non-oxide ceramics**, known for their high thermal stability, low thermal conductivity, and chemical inertness. Common materials include:

- **Oxide Ceramics:**
  - **Alumina (Al_2O_3)**
  - **Zirconia (ZrO_2)**, often stabilized with yttria (Y_2O_3)
  - **Magnesia (MgO)**
  - **Beryllia (BeO)**
  - **Yttria (Y_2O_3)**
- **Non-Oxide Ceramics and Composite Forms:**
  - **Garnets**
  - **Spinel**
  - **Mullite**

These materials are selected based on their compatibility with the operating environment of internal combustion engines, including high temperatures, thermal cycling, and corrosive exhaust gases.

Benefits of Ceramic-Coated Pistons in Compression Ignition (C.I.) Engines

Experimental investigations and finite element analysis of ceramic-coated pistons in compression ignition (C.I.) engines have demonstrated several performance improvements. The key advantages include:

- **Reduced Friction:**
  Ceramic coatings provide a smoother, more thermally stable surface, minimizing mechanical losses due to friction between the piston and cylinder wall.

- **Improved Fuel Flexibility:**
  The use of ceramic coatings allows for the combustion of low-cetane and lower-quality fuels across a broader distillation range, enhancing fuel versatility.
- **Enhanced Emission Characteristics:**
  Better combustion efficiency leads to reduced emission of pollutants such as NOx, CO, and unburnt hydrocarbons.
- **Utilization of Exhaust Energy:**
  Improved thermal insulation enables more efficient use of exhaust gases to produce useful shaft work, contributing to energy recovery.
- **Increased Effective and Thermal Efficiency:**
  Ceramic coatings reduce heat losses to the cooling system, thereby increasing the effective and thermal efficiency of the engine.
- **Shorter Ignition Delay:**
  The thermal insulation provided by the coatings shortens ignition delay, resulting in more consistent and reliable combustion.
- **Improved Fuel Vaporization and Air-Fuel Mixing:**
  Elevated surface temperatures promote faster fuel vaporization and more uniform mixing, leading to more complete combustion.
- **Reduced Specific Fuel Consumption (SFC):**
  Enhanced combustion and reduced heat losses contribute to lower fuel consumption per unit of power output.
- **Weight Reduction:**
  The use of advanced ceramic materials may contribute to an overall reduction in component weight, particularly in lightweight engine designs.
- **Lower Cooling Requirements:**
  Due to reduced heat transfer to the cylinder walls, the demand on the engine's cooling system is decreased.
- **Improved Cold Start Performance:**
  Higher combustion chamber temperatures enable easier engine starts in low-temperature conditions.
- **Reduced Engine Knock and Noise:**
  More stable combustion leads to smoother engine operation, minimizing knocking and reducing noise.

- **Extended Component Life:**
  Ceramic coatings enhance wear and thermal resistance, significantly increasing the service life of pistons and related components.

C. Application of Ceramic Coated Piston:

IC Engine– Reciprocating compressor–

II. EXISTING LITERATURE

Ashish Jashvantlal Modi and Dhiren Patel [1] investigated the performance and emission characteristics of a twin-cylinder, ceramic-coated, water-cooled compression ignition (CI) engine fueled with blends of diesel and neem biodiesel. The biodiesel was synthesized from non-edible neem oil via transesterification using methanol and potassium hydroxide (KOH) as a catalyst. The combustion chamber walls, piston crown, and valve faces were coated with magnesium zirconate ($MgZrO_3$). Experiments were conducted at medium engine speeds and varying loads to simulate urban driving conditions. Results revealed that the brake thermal efficiency of the low heat rejection (LHR) engine improved by 11–13%, while brake specific fuel consumption (BSFC) decreased by 7–12% at high loads. Additionally, the use of neem biodiesel contributed to reduced emissions of unburnt hydrocarbons and carbon monoxide, albeit with a slight increase in nitrogen oxide (NO_x) emissions.

Y. Sureshbabu and P. Ashoka Varthanan [2] studied the emission characteristics of catalytic-coated pistons and combustion chambers in a four-stroke spark ignition (SI) engine. The research evaluated various catalytic materials and concluded that copper coatings were particularly effective in reducing hydrocarbon (HC) and carbon monoxide (CO) emissions, thereby improving brake thermal efficiency. The study emphasized the need for optimizing copper coating thickness for future enhancements.

Parag C. Thanare and R. G. Telrandhe [3] conducted a finite element analysis (FEA) to investigate thermal stress distribution in piston heads with different coatings and geometries. Using Pro/ENGINEER and ANSYS, the study focused on critical regions during combustion. It was found that applying thermal barrier coatings (TBCs) reduced stress levels by 10–15%, primarily due to the lower thermal conductivity of the coating materials.

Vinay Kumar Domakonda and Ravi Kumar Puli [4] reviewed the application of TBCs in diesel engines, particularly low heat rejection (LHR) systems. They noted a modest 3–4% improvement in fuel efficiency from reduced heat losses. Additional benefits included smaller cooling systems, improved exhaust energy recovery, and enhanced combustion with biodiesel, resulting in lower emissions while maintaining performance levels similar to conventional diesel.

Helmisyah Ahmad Jalaludin et al. [5] performed an experimental study on ceramic-coated piston crowns for compressed natural gas direct injection (CNGDI) engines. Pistons made from AC8A aluminum alloy and standard CamPro pistons were coated with NiCrAl bond layers and yttria partially stabilized zirconia (YPSZ) using plasma spray techniques. Burner rig tests showed that YPSZ/NiCrAl-coated piston crowns experienced significantly reduced heat flux—up to 98% lower than uncoated crowns—demonstrating superior thermal insulation.

Nagarjuna Jana and K. Komali [6,10] conducted finite element thermal analyses of ceramic-coated diesel engine pistons using ANSYS. Their results indicated that steel pistons, due to lower thermal conductivity, exhibited higher surface temperatures than Al-Si alloy pistons. Coated pistons maintained higher surface temperatures and exhibited reduced heat loss compared to uncoated ones. Among the coatings, functionally graded materials (FGMs) outperformed single-layer and multilayer coatings—except for single-layer $MgZrO_3$ coatings, which suffered from poor adhesion and brittleness. FGMs provided better heat resistance, although increasing layer numbers reduced the overall effectiveness of the top ceramic layer.

G. Sivakumar and S. Senthil Kumar [7] analyzed the effects of yttria-stabilized zirconia (YSZ) coatings on piston crowns. Their experimental results showed that thermal efficiency increased, while BSFC was reduced by 3.38% and 28.59% at full and partial loads, respectively. Emissions of hydrocarbons and carbon monoxide were reduced by 35.27% and 2.7%, respectively, whereas carbon dioxide emissions increased slightly by 5.27%.

Sean D'Silva, Sumit Jain, and Mayur Ingale [8] compared circular and square-shaped piston heads in terms of mechanical stress and deformation using Autodesk Inventor and ANSYS. Their analysis revealed that while square pistons demonstrated favorable mechanical properties such as lower deformation and stress in some cases, they required additional cooling and maintenance. Therefore, they were deemed impractical for modern automotive applications.

M. Azadi and M. Baloo [9] reviewed the effects of TBCs on diesel engine performance and component longevity. Using a NiCrAl bond coat (150 μm) and a ZrO_2–8%Y_2O_3 top coat (300 μm), applied via plasma spraying, they observed a 12% reduction in BSFC and improvements in thermal efficiency. Notably, the use of TBCs extended engine, valve, and piston life by 20%, 10%, and 300%, respectively.

Conclusion

Research and innovation in any technical domain are only possible through a comprehensive understanding of past studies in the same field. The contributions of previous researchers serve as the foundation for future advancements. Therefore, thorough preparation prior to conducting any research must include a critical review of existing literature in related areas.

This chapter has presented an extensive review of the literature focused on piston geometry analysis and the effects of piston crown coatings on the performance of internal combustion engines. From this review, the following conclusions have been drawn:

- Coating materials with low thermal conductivity—such as copper, magnesium zirconate ($MgZrO_3$), and NiCrAl—applied to engine components like the piston and combustion chamber can significantly enhance thermal efficiency. These coatings have been shown to reduce thermal stress on the piston head by approximately 10–15%.
- Comparative analysis between square and circular piston crowns revealed that square-shaped pistons, despite occasionally showing favorable stress distributions, are unsuitable for modern automotive engines due to higher heat losses, increased cooling requirements, and maintenance challenges. Circular pistons remain superior in practical engine applications.

The literature highlights several areas where further research can contribute to improved engine performance. These include:

- Optimization of advanced ceramic coating materials and their compositions,
- Investigation of coating thickness variations and their thermal impacts,
- Design modifications of piston crown profiles to enhance heat retention and combustion efficiency.

Overall, it is evident that ceramic-coated pistons can achieve higher surface temperatures, which contributes to improved thermal insulation and enhanced overall engine efficiency.

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