A Review on Thermal Barrier Coating on Piston of I.C Engine

K. Aruna Prabha*, Putha Prasad Kumar, K. Balashowry, S. Swetha, Priyadarsini Morampudi

Department of Mechanical Engineering, VNR Vignana Jyothi Institute of Engineering and Technology, Hyderabad, Telangana, India, 500090
arunaprabha_k@vnrvjiet.in

Abstract. Pistons are vital components of internal combustion (IC) engines and are used in various vehicle types. The high temperatures produced in an IC engine can cause major thermal strains. Reduced efficacy of the piston crown resulting from inadequate heat dissipation mechanism would affect the piston's performance time and mechanical efficiency of the engine. The piston absorbs the heat produced during combustion, therefore reducing the general engine efficiency. The cooling system distributes this extra heat in part, and high-temperature insulating materials help to further lower heat output. Acting as such insulating layers, thermal barrier coatings (TBCs) greatly lower heat transmission to important engine components. Using TBCs on engine parts not only lessens specific fuel consumption but also lessens thermal stress and improves engine efficiency. Among the several TBC materials—7-8% Yttria-stabilized Zirconia (YSZ), mullite, Al_2O_3, AlSi, and NiCrAl have proven that they increase efficiency, fuel economy, and CO and HC emissions into the air. Components include the piston head, cylinder liner, and intake and exhaust valve seating, and cylinder head can be TBCs. In experimental research, YSZ and zirconium oxide (ZrO_2) have shown very interesting results among these coatings, as they offer the best balance of thermal insulation and performance enhancement. The findings and results from various literature demonstrates how thermal barrier coatings (TBCs) can improve the longevity and efficiency of IC engines, which in turn contributes to the expansion of profitable automotive engineering.

Keywords: Thermal Barrier Coatings, Piston, Engine Efficiency, IC Engines, Materials.

1 Introduction

Reducing fossil fuels on the planet compelled us to concentrate on alternative fuels and propulsion systems with optimal engine characteristics. The creation of heat barrier coatings is one such effort. By reducing the rate at which heat moves from the cylinder walls to the cooling water, the thermal barrier layer improves combustion in the combustion chamber. The engine efficiency, rate of heat release, and peak pressure rose with the rising combustion chamber inner temperature. Acting as a heat-resistant medium, the ceramic coating shields the substrate from thermal stresses and shocks. CO and HC emissions clearly show how important ceramic coatings are in the emission reduction. Examining several studies, it has been shown that the pistons and

B. S. Babu et al. (eds.), *Proceedings of International Conference on Advanced Materials, Manufacturing and Sustainable Development (ICAMMSD-2024)*, Advances in Engineering Research 257,
https://doi.org/10.2991/978-94-6463-662-8_73

the walls of the combustion chambers absorb most of the heat produced in the case of an internal combustion engine. This directly reflects the heat loss to the piston and surrounding walls. This lowers the produced power and so influences internal combustion engine performance [1][2]. Thermal barrier coatings help us resolve this issue. The coated piston will maintain the necessary temperature in the combustion chamber. This will lessen the heat loss toward the piston which would ignite the un burning gases, thereby reducing the contaminated exhaust emissions [3].

Thermal barrier coatings, which are extremely complex material systems, are used to protect gas turbines parts, pistons of diesel engines etcfrom high temperatures. Three layers define thermal barrier coatings. Their substrate is metal their metallic bond coat is the top coat that is, the ceramic layer. The bond coat forms a link between the top coat and metallic substrate. Metallic substrates and bond coats employ various alloys and metals. Desired for having a very low conductivity while nevertheless staying stable under nominal working conditions, the third coat is the ceramic top coat: zirconia (ZrO_3), mullite ($3Al_2O_3$-$2SiO_2$), and alumina (Al_2O_3). This layer primarily generates the temperature gradient of the thermal barrier coating. Selection of the ceramic coat depends much on characteristics like thermal conductivity and thermal coefficient of expansion. Engineers use thermal barrier coatings to enhance engine performance and yield while also strengthening the hot sections of metal components. Thermal barrier-covered engine components include pistons, cylinder heads, cylinder sleeves, and exhaust valves. Low-heat-loss engines use thermal barrier coating. [4] Industry produces thermal barrier coatings using a variety of methods like EBPVD (electron beam physical vapor deposition), APS (Air Plasma Spray), Electrostatic Spray-Assisted Vapor Deposition (ESAVD), Explicit Vapor Deposition. The physical velocity of electron beam deposition is actually, a ceramic coating with a layer structure as a thermal barrier coating. It not only lessens thermal fatigue but also shields the underlying metal from corrosion and oxidation. It enhances engine performance and helps raise operating temperatures. It significantly extends the life of the covered section.

2 Literature

Thermal barrier coatings (TBCs) are essential for protecting metallic engine components from extreme heat. Key qualities for selecting TBCs include a high melting point, stability across thermal cycles, low thermal conductivity, chemical resistance, and compatibility in thermal expansion with the metal substrate. Strong adhesion to the substrate and a low rate of sintering within the coating's microstructure are also critical [5]. Materials like Mullite, 7-8% Yttria-Stabilized Zirconia (YSZ), Al_2O_3, AlSi, and NiCrAl are commonly used. TBCs are applied to reduce heat rejection in IC engines, allowing for greater fuel efficiency by retaining more heat within the combustion chamber, which results in better overall combustion conditions and a shorter ignition delay. Sivakumar et al., explored the benefits of applying Yttria-Stabilized Zirconia to a piston crown. Their findings indicated a substantial decrease in brake-specific fuel consumption (up to 28.3%), HC emissions (up to 35.2%), and CO emissions (up to 2.72%). They also noted a reduction of 5-10% in heat loss to the cooling system when compared to uncoated engines [6]. In a separate study, Nittesh Mittal et al., examined a low-heat-rejection SI engine using a 100 µm NiCrAl bond coat topped with a 200 µm layer of ZrO_2 on the cylinder head and valves. This coating setup advanced the combustion process, raising peak cylinder pressure, improving brake thermal efficiency, and increasing NOx emissions, while CO and HC emissions declined. The engine efficiency rose by 7.4%, and specific fuel consumption decreased due to higher combustion temperatures in the coated engine [7]. Research by Kamo et al., applied a 100 µm YSZ coating to the piston and cylinder, and a thicker 500 µm YSZ layer on the cylinder liner, resulting in a 5-6% increase in fuel efficiency [8]. Winkler's et al., study spanning ten years showed that ceramic coatings effectively reduce emissions and improve combustion efficiency in diesel engines [9-10]. Kamo et al., further observed that coating the piston and cylinder head surfaces effectively reduced heat rejection, while coating the cylinder liner improved fuel economy [11]. Buyukkaya's findings demonstrated that combining TBCs with optimized injection timing could reduce brake-specific fuel consumption by 1-8% [12]. Advantages of TBCs for Diesel Engines:- Compatibility with low-cetane fuels- Emission reduction (except for NOx)- Effective use of exhaust gases for power- Enhanced effective and thermal efficiency- Wider range of fuel types- Decreased ignition delay, better fuel vaporization and mixing- Lower specific fuel consumption- Multi-fuel adaptability and improved reliability- Smaller, lighter engines- Reduced cooling system load- Easier cold starts- Lowered knocking and noise during combustion [13]. Due to its excellent thermal insulating properties, partially stabilized zirconia (PSZ) is one of materials which is widely used for thermal barrier coatings (TBC) on engine components particularly on pistons. The component temperature can be reduced up to 100°C by applying PSZ due to its dramatic reduction of heat transfer to the piston crown. This decrease is achieved by increasing the engine thermal efficiency, leading to a 10 increase in engine power output and a 11% decrease in fuel consumption. Furthermore, TBCs can also enhance engine operating life by as much as 20% and extend the life of critical components such as valves by as much as 300%. Moreover, the coating has 20–50% less harmful particles and contaminants emissions and also has 3 dB lower engine noise and 15% lower oil consumption. The benefits of improved performance and cost efficiency are demonstrated by the 20% decrease in operating expenses that goes hand in hand with these changes. An analysis of the piston crown's heat and flux distribution before and after coating offers important information on how well PSZ TBCs work to maximize engine performance and particular fuel usage.

3 Methodology

The current study employs experimental analysis, which includes coated pistons, to investigate the impact of thermal barrier coatings (TBCs) on engine performance. To guarantee the accuracy of the coating parameters, the initial phase of the investigation involves modeling the piston in a CAD tool like SolidWorks. The purpose of this research is to evaluate a variety of coating methods for pistons and cylinder walls to enhance their thermal resistance and durability. Plasma spray coating is preferred procedure due to its ability to create a durable insulation layer on piston surfaces using heat-resistant materials. The study also demonstrates how TBCs enhance heat retention and reduce heat stress in the combustion chamber by analyzing flux and heat distribution using ANSYS. The performance testing on a two-stroke, one-cylinder, air-cooled gasoline engine to assess the effect of ZrO_2 and TiO_2 coatings on the piston is evaluated. The results demonstrate that TBCs enhance thermal efficiency and fuel economy by optimizing engine performance and specific fuel consumption. This research demonstrates the critical role of TBCs in reducing heat loss and enhancing efficiency. Furthermore, it demonstrates that the integration of plasma spray coating, computer-aided design, and thermal analysis has the potential to enhance engine's reliability.

4 Experimentation, Design and Modelling Study

4.1 Piston Coating Methods

Flame Spraying, Spray and Fuse, Chemical Vapor Deposition (CVD), and HVOF Thermal Spray.

The most popular method aside from these is the Plasma Spray Coating Technique as seen in figure 1. Plasma spraying produces a high-energy plasma discharge using a cannon with two electrodes that helps to deposit a great range of metallic and ceramic materials. Development of unique properties in this coating process is made possible by plasma, a condition of matter in which the energy levels of electrons, ions, and large particles are in balance. Plasma spraying is first a flexible method suitable for many kinds of ceramics, metals, and their mixtures. Second, it preserves the original composition without change by helping alloys and mixed ceramics made of materials with quite differing vapor pressures to be deposited. Thirdly, it helps to generate homogeneous coatings with constant thickness and composition, therefore raising the quality of the finished good. Additionally produced by the technique are tiny microstructures devoid of columnar flaws and distinguished by equiaxed grains, which support the strength and longevity of the coating. Moreover, plasma spraying allows great deposition rates without requiring significant equipment capital expenditures. This approach also has great versatility as it can be utilized in air, inert atmospheres at low and high pressures, and even underwater, therefore allowing it to be applied in a range of settings [14].

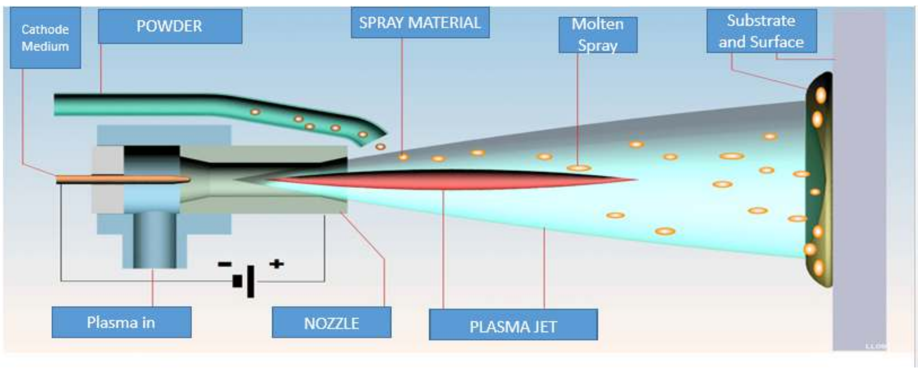

Fig. 1. Plasma Spraying

5 Study on Effect of Thermal Barrier Coating on Piston

Heat losses through the piston are reduced when it is coated. When compared to an uncoated piston, engine efficiency rises when the heat and flux distribution on the piston crown yields low values. Engine performance is often enhanced by this energy savings. Additionally, it affects fatigue lifetime and reduces weight by eliminating cooling systems, among other things [15], which enhances brake thermal efficiency and reduces fuel consumption.

5.1 Findings through analysis and modelling

By all means, CAD software can be used to represent the geometry determined for piston design, it is been modelled for further analysis purpose. The Finite Element Analysis (FEA) program can compute heat transfer through a piston. This work uses ANSYS 15.1 to investigate the piston model, both with and without a Thermal Barrier Coating (TBC) of Yttria-Stabilized Zirconia (YSZ). Applying the coating to the piston crown at different thicknesses helps one to evaluate its thermal effects. Operating circumstances have the piston crown heated to 600°C while convection occurs on the remaining surfaces using a film coefficient of 0.0002 W/mm²°C and an ambient temperature of 29°C. These requirements call for the evaluation of piston functioning using ANSYS 15.1, a powerful FEA tool. The FEA investigates the impact of coating thickness on thermal behavior on both YSZ-coated and untreated pistons. Based on previous studies [16][17], this study offers a perspective on the potential enhancement of engine efficiency and component longevity due to the increased thermal resistance of pistons under high-temperature conditions, which is attributed to the presence of TBC layers. The piston's thermal barrier coating helps reduce the heat losses passing through it. When the heat and flux distribution on the piston crown yields low values instead of an uncoated piston, engine efficiency rises. Typically, this conserved energy enhances the engine's performance. It also influences the fatigue lifetime and advantages of weight loss by eliminating cooling systems, etc. [15], improving brake thermal efficiency, and lowering fuel consumption.

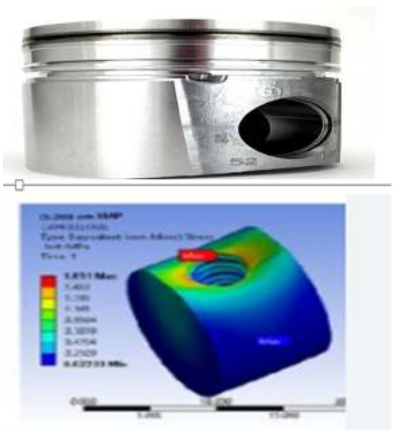

Fig. 2. Temperature distribution of uncoated coated piston [16][17]

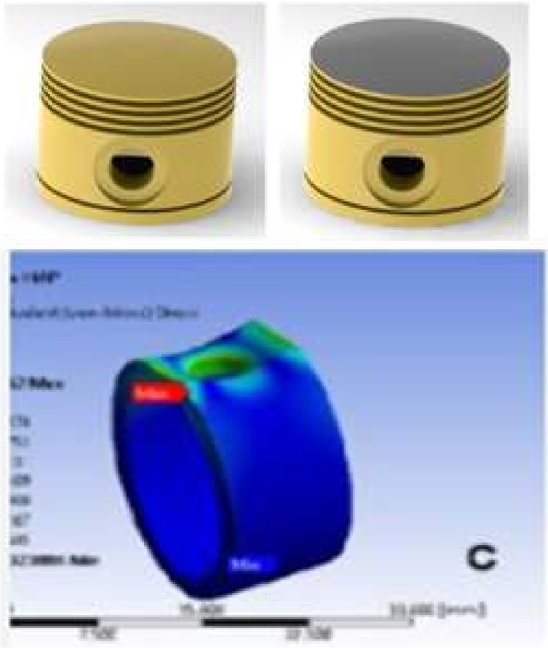

Fig. 3. Temperature and heat flux distribution of 0.2mm coated piston [17][24]

Figure 3 shows the findings of a finite element analysis performed on a piston crown that was exposed to 600°C on its uncoated surface and to a lower temperature on its covered surface. As the amount of coating increases, the temperature at the piston crown surfaces decreases. The results show that, in comparison to the uncoated piston, the piston with the YSZ coating on the piston crown has a lower temperature and heat flow at the top land, which lowers the amount of heat lost through the piston (see figure 2).

5.2 Findings from experimentation and theoretical calculations

To conduct an engine performance test, prior to the experiment, all switches were ensured in "off" position for operational safety. The engine was started by a control switch beside interval CT coil and later the mains supply was switched ON. The level of the lubricating oil in the sump was checked so as to ensure sufficient lubrication for an easy running. To minimize engine wear and improve performance consistency, a 50:1 gasoline-2T oil mix was introduced into the fuel tank. To prepare the fuel system starting from the petrol cock below the gas tank and put in a burette for constant supply of petrol. The cam switch for the load engaging system was confirmed as off before kick-starting the engine. The engine was then permitted to stabilize at a nominal operating speed of 1500rpm. Thereafter, the changeover switch was positioned to generator mode which allowed for the engine to be loaded for testing [19].

The calculations use generator efficiency, voltage, and current to calculate the engine's brake power (BP). The amount of fuel used, its specific gravity, and the amount of time needed for consumption are the factors that determine the mass of fuel consumed (mf). While indicated power (IP) is determined by adding up BP and frictional power (FP), specific fuel consumption (SFC) is computed by dividing m f(fuel consumption) by BP,. IP, fuel characteristics, and calorific value are used to calculate various efficiency levels, such as mechanical efficiency (*h*ηmech), brake thermal efficiency (η bth), and indicated thermal efficiency (η ith) [24]. Using variables like manometer readings, orifice area, and discharge coefficients, airflow analysis determines the actual volume of air (Va) entering the cylinder. The engine's swept volume, or Vs, is calculated [20].

5.3 Study & Discussions on Experimental Findings

The following table shows the change in different efficiencies depending of the material used as TBC.

Table 1. Efficiency for Different Thermal Barrier Coatings Materials [18].

Data	Al Alloy	ZrO_2	TiO_2
Brake Thermal Efficiency	10.329%	12.223%	11.137%
Indicated Thermal Efficiency	24.604%	29.136%	26.278%
Mechanical Efficiency	41.980%	41.953%	42.381%
Volumetric Efficiency	47.663%	51.816%	49.783%
Air-Fuel Ratio	10.575	13.264	11.611

The following graphs show the change in efficiency and performance for different material used as thermal coatings.

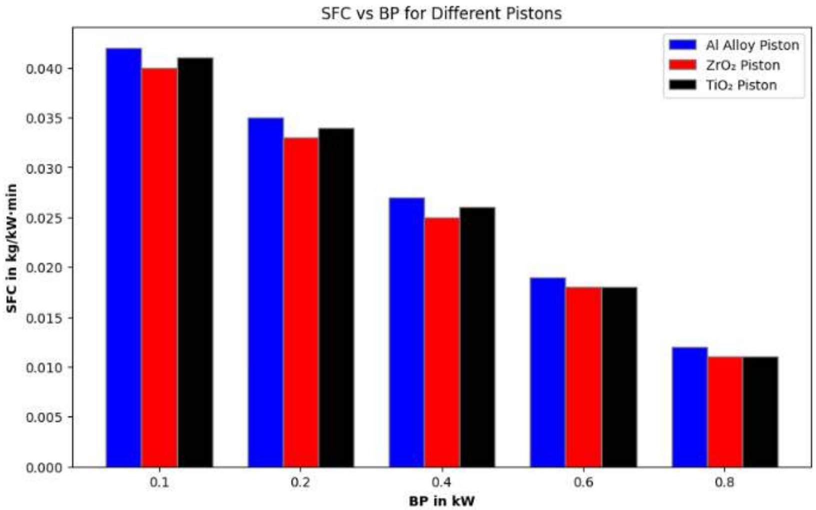

Fig. 4. Specific Fuel Consumption vs Brake Power [5]

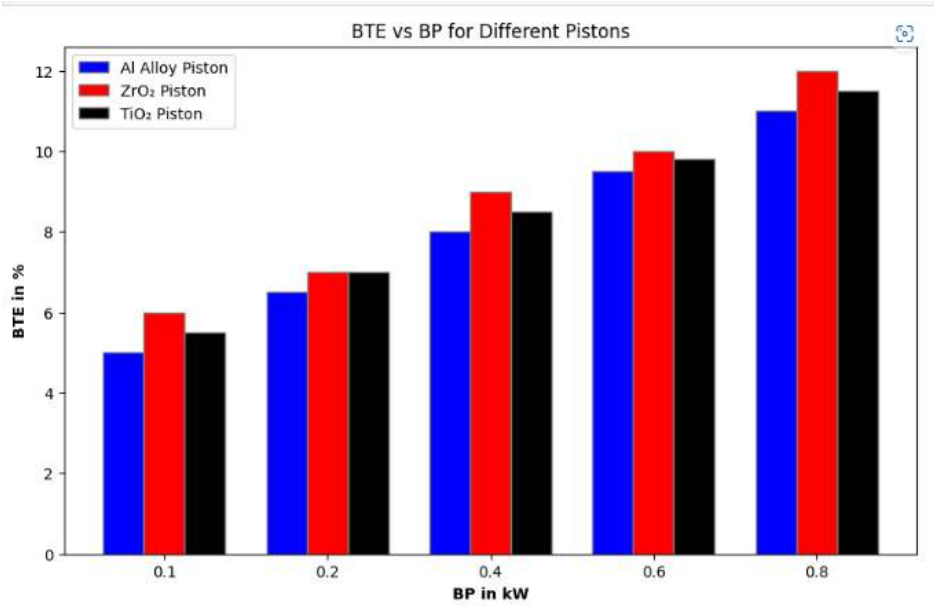

Fig. 5. Brake Thermal Efficiency vs Brake Power [5]

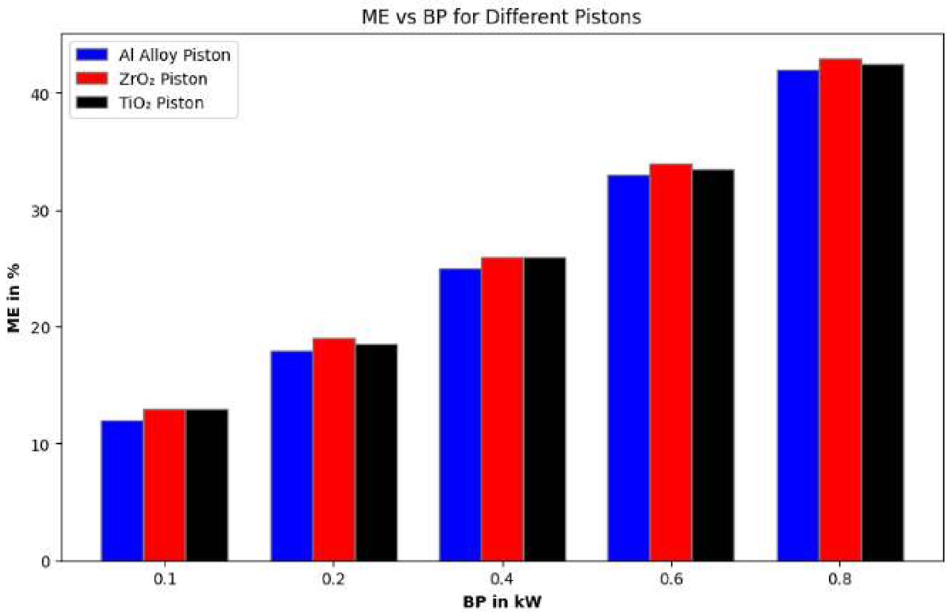

Fig. 6. Mechanical Efficiency vs Brake Power [5]

This paper figures out how much fuel titanium dioxide (TiO_2) and zirconium doxide (ZrO_2) coated pistons use, as well as their brake thermal efficiency, indicated thermal efficiency as seen in figure 5, mechanical efficiency as seen in figure 6, and volumetric efficiency as seen in figure 4. Under different engine loads and varying engine speeds (1000 to 4500 rpm), measurements of engine speed, load torque, engine power, fuel consumption, exhaust gas temperature, and gas emission concentration were recorded [23].

These results can be clearly interpreted from the above study of experimental, theoretical analytical calculations. Further the tabular and graphical results confirm the same [22]. Thermal Barrier Coatings has generally increased brake thermal efficiency, indicated thermal efficiency, and volumetric efficiency over typical Al alloy pistons but total fuel consumption has decreased. Over TiO_2 and Al alloy pistons, ZrO_2 (Yttria-stabilized Zirconia) performs better. Comparatively, pistons covered with ZrO_2, and pistons covered with TiO_2 revealed that the former produced superior outcomes than the latter. The ZrO_2 coated piston outperforms the TiO_2 coated piston in terms of efficiency and performance. The range of 1% to 2% defined the variation in efficiency between TiO_2 and ZrO_2 covered pistons. When compared with a TiO_2 coated piston, the engine with a ZrO_2 coated cylinder likewise demonstrates improved fuel economy [21].

6 Conclusions

Coatings, known as thermal barrier coatings (TBCs), to the critical components in the combustion chamber, such as pistons and cylinder liner, have resulted in a significant improvement of thermal and mechanical efficiency. These enhancements are characterized by increased engine performance metrics, such as as specific fuel consumption reduction. Different coating methods are used for TBC deposition, including Chemical Vapor Deposition (CVD), Physical Vapor Deposition (PVD), Flame Spraying, Spray and Fuse, and High-Velocity Oxy-Fuel (HVOF) Thermal Spray processes. Among these, Plasma Spray Coating is the most widely used method for TBC applications.

Experimental studies of the impact of TBCs on engine performance in an internal combustion engine have been encouraging, with zirconium oxide (ZrO_2) being one of the most effective materials. Coatings of zirconium oxide (ZrO2) and titanium dioxide (TiO2) have been shown to reduce the specific fuel consumption by 1%. Other highly efficient TBC material Yttria-Stabilized Zirconia (YSZ) is also described, which possesses the properties of high thermal insulation and high strength.

The use of TBCs allows engineers to maximize product performance, reduce downtime and associated maintenance costs, maximize energy efficiency, and reduce production costs. This versatile technology finds applications across various industries, including automotive manufacturing, making it an invaluable tool for improving efficiency and sustainability.

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