Article citation info:
Wróblewski P, Bratkowski P. Effect of using a combination of coatings on reducing structural defects in the working area of the combustion chamber and on the energy efficiency of a reciprocating internal combustion engine. Combustion Engines. 0000;XXX(X):xx-xx. https://doi.org/10.19206/CE-207651

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Effect of using a combination of coatings on reducing structural defects in the working area of the combustion chamber and on the energy efficiency of a reciprocating internal combustion engine

ARTICLE INFO

Received: 4 March 2025
Revised: 12 June 2025
Accepted: 27 June 2025
Available online: 28 July 2025

This article has reviewed the latest test results in the use of multi-layer thermal coatings in the combustion chambers of piston combustion engines. The work emphasized mainly their role in reducing the structural defects of thermal materials and their impact on improving the energy efficiency of engines. Two, three, or more layers of thermal coating systems reduce the consumption of material in areas undergoing the highest thermal load. Initially, significant disadvantages such as microcracks, corrosion and erosion of working components of engine combustion chambers have been excluded. This construction approach using multi-layer coatings leads to an increase in durability and reliability of piston internal combustion engines. This reduces the costs of engine operation.

The article compares various experimental and simulation results for different thermal coating systems. Companies such as ceramics, metal oxides, and nanostructural composites were analyzed. The authors emphasize in this work the increasing interest in these coatings in order to achieve a significant reduction of fuel consumption and greenhouse gas emissions. The conditions for the correct heat conduction, maintenance of thermal stability, and the ability to self-heal the coating in extreme conditions were analyzed in great detail. The summary and detailed analysis of the current state of knowledge in this area is certainly very valuable for engine designers and technologists in the automotive industry.

Key words: *thermal barrier coatings, multilayer coatings, structural defect reduction, energy efficiency, reciprocating internal combustion engines*

1. Introduction

Modern reciprocating internal combustion engines achieve high effective power through high rotational speed of the engine crankshaft and high value of mean effective pressure in the working chamber of the engine. The energy requirements imposed on modern engines necessitate new research into the use of materials for thermal and anti-wear coatings. The search for new solutions enforces studies on the possibility of applying multilayer coatings in the engine chamber. Such solutions allow for limiting the phenomenon of thermal microcrack formation, erosive and corrosive damage [15]. The use of these coatings also enables achieving higher thermal efficiency of internal combustion engines. This article presents a summary of the most important experimental and simulation studies on the use of multilayer coatings in internal combustion engines, significantly loaded mechanically and thermally. Most current research focuses on single-layer coatings. There are very few experimental studies involving piston components of internal combustion engines directed at multilayer coating systems. The authors point to the potential of this solution and the need for further research and analysis.

Preliminary studies on the possibility of using coatings as a thermal barrier included thick ceramic layers applied by plasma spraying or flame spraying [29]. In such configurations, it was often shown that these coatings, when applied to components of a reciprocating internal combustion engine, have limited crack resistance under dynamic temperature changes, e.g., in the engine combustion chamber [33, 35]. In contrast, very thin coating layers applied using these methods on turbine surfaces or deposited using PVD, CVD, and ion implantation methods exhibit better wear resistance. This allows for better thermal insulation, greater control over the coating structure, and its surface roughness. Coatings with a thickness greater than (> 0.5 mm) have significant disadvantages: low resistance to mechanical damage, reduced volumetric efficiency due to high thermal expansion, limited ability to form an oil film at elevated temperatures, and limited applicability in spark-ignition engines (in certain operating conditions, they cause knocking combustion). The research results presented in this study indicate very diverse problems related to the use of these coatings.

Some studies report up to an 8% increase in engine power and a 9% reduction in fuel consumption [46]. In other words, increased fuel consumption is observed, attributed to prolonged combustion time in the combustion chamber, dependent on the fuel dose [41]. This study proposes adjusting the fuel injection timing to counteract this effect. Moreover, the limited ability of ceramic coatings to radiate in the infrared range reduces their effectiveness in lowering radiative heat transfer, which accounts for 40% of the total heat flux in compression-ignition engines [9]. Results for spark-ignition engines appear more consistent, with some studies reporting a 6% reduction in fuel consumption. The same studies report increased hydrocarbon emissions due to the surface structure of the coatings [10, 20].

The main problem is the repeatability of results in different testing environments. In a comparative study [16], fatigue tests on six coatings conducted in three laboratories produced divergent results. The discrepancy in test results was attributed to different test conditions and the varying surface structure of the selected coatings. These studies demonstrate how strongly the geometry of the coatings and their chemical composition depend on engine operating parameters, such as combustion temperature, crankshaft rotational speed, and hydrodynamic pressure between selected kinematic pairs of the engine.

In response to these limitations, recent studies have shown that multilayer coatings with appropriate thickness and layer distribution of selected cooperating coatings can form systems with good mechanical and thermal properties. Proper selection of layers allows for meeting complex functional parameters. This primarily concerns the function of thermal insulation and the prevention of microcracks. Such complex systems of various coatings enable the formation of a highly efficient structure operating within the combustion chamber area, which translates into increased durability of the main piston mechanism of the internal combustion engine. Moreover, appropriate control of coating thickness and thermodiffusion parameters allows for the adjustment of their functional parameters to the operating conditions of selected components of the reciprocating internal combustion engine. Advanced numerical models presented in this study confirm the behavior of selected coatings under extreme engine operating conditions. These actions allow for the adoption of appropriate strategies in engine design. The literature review shows that multilayer coating systems are becoming increasingly advanced and are capable of meeting ever more demanding engine operating conditions.

Despite research challenges related to limitations in reproducibility and the application of various coatings, these systems offer a wide range of solutions aimed at achieving high engine power, reduced fuel consumption, and lower emissions of harmful exhaust substances [30]. Future research should focus on long-term durability tests under real engine operating conditions and should include studies on further improvement of materials and coating deposition technologies. In particular, this should concern the area of the engine combustion chamber.

2. Thermal loads of internal combustion engines

Computer simulation of the engine work cycle, combined with models of unknown heat exchange in individual components, can be used to forecast the temperature of the combustion chamber surface with and without insulation coating. Such a model was presented at work [47]. In the case of a combustion chamber with an insulation layer, two basic issues are distinguished [47]: the average temperature of the insulated element increases with the coating thickness and the amplitude of cyclical temperature fluctuations around this average is almost the same for thin and thick layers; In fact, the highest difference between peak and minimal values occurs for the thinnest tested layer (0.5 mm).

Thermal capacity, thermal conductivity, and thermal expansion are three key thermophysical features that determine the properties of the TBC coating. The heat capacity (C) expresses the amount of energy needed to increase the temperature of the material by one degree. It is primarily shaped by vibrations and rotation of atoms, electrons' transitions between energy levels, and changes in atom position. In porous materials, which contain less solid substance per unit of volume, heating or cooling occurs faster than in non-porous materials. In insulation, where rapid temperature changes are important, low thermal capacity is crucial. In most cases, thermal capacity is not a fixed value – it depends on the temperature, pressure, and volume. The thermal capacity at a constant pressure (C_P) and a constant volume (C_V) is most often considered. The change in internal energy along with a change in temperature at a constant volume is described by the C_V, while at constant pressure – C_P [47].

Thermal conductivity (K) determines how quickly heat flows through the material and is expressed in W/(M×K). This size depends on the energy stored in the material (i.e. the volume of heat capacity C), on heat carriers (electrons or phonons), and the heat wave distortion. The lower C, the speed of the media (V), and the average free road (λ), the lower the thermal conductivity. In ceramics, the range of values K can be very different, and at the same time, it should not be assumed that all ceramics conduct heat worse than metals. The highest K values are observed in dense, well-ordered structures, while the introduction of admixtures or foreign atoms reduces conductivity by distracting phonons [40].

In crystalline ceramics, the main mechanism of heat transport is vibrations of the crystalline network (Phonons), and the average free path (λ) decreases as the temperature increases, which increases thermal conductivity at low temperatures. However, in glass (disordered structure) λ depends less on the temperature, so the conductivity increases mainly due to increasing thermal capacity [40].

The importance of heat radiation also increases at higher temperatures. According to data at work [2], about 75% of radiation appears at frequencies above 3.1 kT/h (e.g. approx. 8.1×10^{13} Hz at 1300 K). The impact of inclusions and porosity on radiation absorption was also examined – point defects and oxygen gaps distract high-frequency network vibrations, reducing conductivity. To effectively disperse the waves with a frequency of 8.1×10^{13} Hz (at 12% porosity), spherical pores must have a radius of approximately. 0.45 µm. Additional porosity on a nanometric scale further reduces thermal conductivity, but does not affect radiation. Ultimately, low conductivity and heat capacity are desirable in ceramic barrier coatings (TBC), as well as good adhesion to the ground, high stability at elevated temperatures, and resistance to oxidation. Such rules should be strictly observed when designing coatings intended for work in piston combustion chambers of internal combustion engines.

The study [7] showed that temperature fluctuations (ΔT_s) on the surface of the engine combustion chamber are inversely proportional to the square element from the product of thermal conductivity (k), density (ρ), and specific heat (c).

$$\Delta T_s \sim \frac{1}{k\rho c}^{\frac{1}{2}} \qquad (1)$$

The next key aspect is the heat wave penetration into the material. The depth of penetration (δ) is often referred to as a distance from the surface where the amplitude of temperature fluctuations drops to 1% of the initial value on the surface, is proportional to the square element from the thermal conductivity quotient (α) to the engine speed (N), which can be saved [7]:

$$\delta \sim \left(\frac{\alpha}{N}\right)^{\frac{1}{2}} \quad (2)$$

where:

$$\alpha = \frac{k}{\rho c} \quad (3)$$

Based on the analysis, it can be stated that thin insulating coatings demonstrate significant benefits compared to thick insulating layers in multilayer coating systems. This is particularly applicable in reciprocating internal combustion engines. Owing to their low thermal inertia, they enable surfaces to respond rapidly to varying gas temperatures. Thin coatings can also be successfully applied in spark-ignition engines. In these engines, a reduction in unburned hydrocarbon emissions is observed due to the flame-quenching effect, which also leads to accelerated heating of the catalytic converter. Additional advantages of thin coatings include less friction, better immunity for erosion and corrosion, increased life of components, and greater reliability. Therefore, thin insulation coatings allow for various possibilities to improve the durability of the engine, eliminating problems associated with thicker layers of insulation coatings. In the case of multi-layer coatings, it is possible to effectively use the properties of each coating and achieve a decisive reduction of erosion consumption resulting from the propagation of the flame in the combustion chamber.

3. Tests of single-layer coatings applied to the piston bottom and the space of the combustion chamber

Based on the analysis, it can be concluded that thin thermal-barrier coatings exhibit significant advantages over thick thermal-barrier layers in multilayer coating systems. This is particularly applicable in reciprocating internal combustion engines. Thanks to their low thermal inertia, they enable surfaces to respond quickly to changing gas temperatures. Thin coatings can also be successfully applied in spark-ignition engines. In these engines, a reduction in unburned hydrocarbon emissions is observed due to the flame-quenching effect, which also leads to accelerated heating of the catalytic converter.

3.1. Metal-based coatings

In the context of piston combustion engines and their combustion chambers, metallic coatings play an important role, especially in areas with increased temperatures and exposed to combustion gases. The use of such a protective layer allows: protecting elements against corrosion, protection against temperature increases, increasing chemical resistance, surface hardening, increasing the durability of components, and reducing the friction coefficient, which helps reduce the consumption of parts of selected cinematic pairs of the engine [50]. Large heat conduction, characteristic of most metals. For this reason, metallic coatings are rarely used as insulation coatings in the chambers. The use of basic metal single-layer coatings of chromium, nickel, and molybdenum has many significant defects. These disadvantages limit the further development of these solutions for designing heat flow in the combustion chamber.

3.2. Polymer coatings

In piston combustion engines, polymer coverings are found less often directly in the combustion chamber, but they are used, e.g. in seals or anti-corrosion coatings in areas with a lower heat load. The latest research focuses on polymer coatings, which can autonomously repair their microtasus and thus prevent further corrosion of the substrate. The main idea is that during operation, when the layer is outlined or damaged, active substances are released to enable partial regeneration of the coating.

Polymer coatings can also be used in anti-corrosion protection – they are found in many industrial sectors, including tank protection [1]. In [12], a compilation of self-healing materials based on polydimethylsiloxane was presented, in which phase-separated droplets of HOPDMS and PDES undergo polycondensation catalyzed by di-n-butyltin dilaurate. In this system, the healing agent remains as separate droplets, while the catalyst is encapsulated in polyurethane microcapsules that rupture under mechanical damage, releasing DBTL. This solution enables chemical stability even in humid and high-temperature conditions. Tests using a double-supported beam method showed the recovery of a significant portion of the original crack resistance, especially after the addition of an adhesion promoter [12]. The self-healing mechanism works such that when an external factor (e.g., a crack or scratch) disrupts the capsule structure, contact occurs between the particles of the active components (previously phase-separated). As a result of the reaction, a new polymer layer is formed, filling the damage and restoring the coating's original protective properties. This significantly extends the coating's service life [13].

In the context of piston internal combustion engines and their combustion chambers, polymers are used much less frequently than metallic and ceramic coatings, mainly due to their reduced thermal resistance and lower mechanical strength compared to metals and ceramics. Nevertheless, polymer coatings are sometimes employed on components that experience lower thermal loads or serve as lubricating layers, helping to reduce friction between engine parts. While the use of these coatings in the combustion chambers of piston engines seems unlikely, combining the unique characteristics of these materials may contribute to the development of thermal coatings for engine components that are less thermally stressed.

3.3. Functional properties of ceramic coatings in the use of an engine

Ceramics are non-metallic solid materials that can have a crystalline, partially crystalline, or amorphous structure. A wide range of ceramic coatings is available on the market. These materials are characterized by very low thermal and electrical conductivity, corrosion resistance, the ability to operate at higher temperatures than most other materials, resistance to rapid temperature changes, and high wear resistance. Before applying a ceramic coating to the components of internal combustion engine chambers, it is necessary to verify the compatibility between the ceramic and the metallic substrate. One of the most important aspects is the coefficient of thermal expansion. If the difference between the thermal expansion of the coating and the substrate is too great, tensile and compressive stresses resulting from the thermal cycles of a four-stroke engine may cause cracks to develop.

3.3.1. The use of TBC coatings in automatic and spark ignition engines

Studies [45] show that the use of coatings (TBC) based on stabilized zirconia on the surface of the bottom of the piston affects the emissions of the engine and its thermal efficiency. The 100 μm thick coating was tested. However, the advantages of these coatings depend largely on the engine load and changes in operating conditions. Although the engine efficiency increased from 1.14% to 8.84% with 50% engine load, the characteristics of these changes are non-linear. These studies indicate that the given energy benefits do not necessarily have to translate into such energy gains in real conditions of the piston internal combustion engine.

The introduction of TBC coatings into the combustion engines reduces fuel consumption [45]. Fuel consumption decreases by approximately 3.38% in full load conditions, up to 28.59% at partial load (25%) of the engine. The work [45] presents a reduction in HC emissions by a value of 35.27% and a reduction of emissions by 2.7%. An increase in CO_2 emissions was observed by about 5.27%. These studies indicate an improvement in the combustion process. The work also indicates the appropriate disadvantages of emissions. Experimental research and results largely depend on the conditions of the experiment and the engine itself. Therefore, the problem should be considered on the basis of other research data in other works.

Although most of the test results indicate the great potential to use TBC coatings, the practical possibility of using them requires further research. Such tests should take into account net energy balance, material stability in the longer period of engine operation, resistance to dynamic thermal load changes, and emissions to the environment. All these activities are closely related and require experimental tests, especially in terms of the durability of coatings.

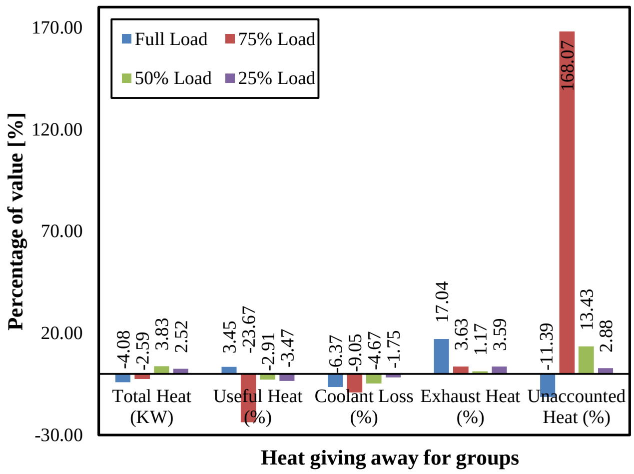

Fig. 1. Graph showing the percentage change in the application of the YSZ coating compared to no coating for various engine loads. The graph is based on selected data from the study [45]

The basic coating presented in the study [45] comprises an outer layer of zirconium dioxide (ZrO_2) partially stabilized with approximately 7% yttria (Y_2O_3). The MCrAlY (CoNiCrAlY) bond coat is applied using the HVOF method. The top coat is mainly applied by plasma spraying in an air atmosphere or by the EB-PVD method. Due to the high oxygen permeability in ceramic materials, corrosion protection relies on an intermediate layer capable of forming a dense, well-adhering oxide layer. The top coat is exposed to various types of damage caused by the penetration of foreign bodies, the effect of high temperatures that destabilize ceramic materials, and erosion induced by solid particles in the exhaust gas stream. This work suggests that the best process repeatability is achieved with the SIFCO (vapor phase) and HVOF methods; the APS method requires manual control of the coating thickness to maintain process stability. Current solutions include, among others, the use of new compositions for outer coatings (with additives of rare earth metal oxides), two-layer intermediate coatings, and the use of the HVOF spray technique [56].

In study [34], a thermal barrier coating (TBC) was applied to the cylinder head and valves of a spark-ignition engine by first removing a layer of material from the head, and then applying a 100 μm thick layer of NiCrAl (bond coat) and a 200 μm thick layer of yttria-stabilized zirconia (ZrO_2 with 8 wt.% Y_2O_3) using the atmospheric plasma spray (APS) method. The spraying specifications included a particle velocity of 500–550 mm/s, porosity of 1–8%, and a spraying distance of 100 mm. A single-cylinder Briggs & Stratton engine (10 HP, air-cooled) operating at a constant speed of 3000 rpm on gasoline and gasoline–n-butanol mixtures (GNB10 and GNB15) was used for the tests. In the engine with the TBC, a higher maximum cylinder pressure (by 2–8 bar) and a shift in the maximum heat release closer to TDC by approximately 10°CA were observed. Improved thermal insulation resulted in a reduction in specific fuel consumption (SFC) and an increase in thermal efficiency – up to 6% higher on gasoline and 7.4% higher on the GNB10 mixture compared to the uncoated engine. Better thermal insulation also led to higher exhaust gas temperatures. Emission analysis showed that, thanks to the TBC and the addition of n-butanol, the concentrations of CO and HC decreased (aided by higher combustion temperatures and the oxygen content in the fuel), whereas the concentration of NO_x increased due to the higher temperatures in the combustion chamber. Additionally, the ceramic layer protects the chamber components from damage caused by high temperatures, thereby enhancing the durability of that engine part.

In study [27], a thin ceramic coating was applied to a direct-injection diesel engine. The piston and cylinder head were coated with a 100-micrometer-thick thermal barrier coating based on yttria-stabilized zirconia, while the cylinder liner was protected with a 500-micrometer-thick coating of the same material. A reduction in fuel consumption of 6% at full load and 2600 rpm, and 3.5% at 1600 rpm, was achieved compared to a standard engine without protective coatings. These positive results were obtained thanks to the use of delayed injection timing along with high fuel injection pressure and speed. The introduction of a modern high-pressure fuel injection system enabled the desired heat release characteristics during the premixed combustion phase to be achieved. The thermal barrier coating contributed to an increased rate of heat release compared to the standard engine, confirming the quality and reliability of the obtained data relative to other studies.

In study [38], a 250-micrometer (0.25 mm) zirconia coating partially stabilized with yttria was applied to the combustion chamber surface and piston crown of an internal combustion engine. This enabled the operating temperature to increase from 350–400°C to 850–900°C and reduced heat losses to the external environment. As a result, thermal efficiency improved and the combustion process shifted from a premixed phase to diffusive combustion. The exhaust gas temperature changed from 410°C to 428°C. A significant reduction in emissions was also measured: CO lowered from 0.085% to 0.069%, HC lowered from 22 ppm to 14 ppm, and smoke levels from 4.4 to 4.13 BSU (bosch smoke unit).

3.3.2. Advanced TBC materials in automatic ignition engines

In the study [51], thermal barrier coatings (TBC) made of lanthanum zirconate ($La_2Zr_2O_7$) were applied to the piston, cylinder head, and valves of a single-cylinder diesel engine using APS plasma spray technology. The coatings had a total thickness of 500 µm, of which 150 µm was the bond coat (NiCrAlY) and 350 µm was the LZ layer. The spray process parameters included an arc current of 660 A, a primary gas (Ar) flow rate of 30 l/min, a secondary gas (H_2) flow rate of 15 l/min, a spray distance of 130 mm, and a powder feed rate of 40 g/min. The application of the TBC coatings resulted in significant energy and operational benefits. In the TBC-coated engine, fuel consumption was reduced by 4.16% for diesel, 2.9% for the B20 blend (20% biodiesel, 80% diesel), and 9.5% for B100 compared to the B100 engine without the coating [51]. At the same time, brake thermal efficiency (BTE) increased by 4% for diesel, 8.55% for B20, and 10.7% for B100 compared to the engine without the coating. CO emissions were reduced by 18% for diesel, 27.7% for B20, and 43.75% for B100, while HC emissions decreased by 11.68% for diesel, 40.98% for B20, and 62.26% for B100 [51]. However, NO_x emissions increased by 3.5% for diesel, 12% for B20, and 15% for B100 due to the higher combustion temperature of the fuel–air mixture in the combustion chamber [51]. Thanks to its low thermal conductivity (1.56 W/m·K compared to 2.5 W/m·K in PSZ) and the stability of its pyrochlore structure up to 2300°C, this material is characterized by high resistance to sintering and favorable catalytic properties, which translates into reduced HC, CO, and soot emissions [51].

The use of ceramic coatings, especially the type ($La_2Zr_2O_7$) coatings, indicates great advantages in the scope of their application on the elements of piston internal combustion engines. In diesel-powered engines, a reduction in fuel consumption is observed [28]. The tests were carried out on the components of the piston internal combustion engine after applying the coating and without applying the coating, fuel mixtures B20–B100 were used [28]. It has been shown that engines with these coatings produce a smaller amount. The coating ($La_2Zr_2O_7$) has low thermal conductivity and shows temperature stability to 2573 K [28]. Higher combustion temperature of the fuel-air mixture and catalytic properties allow the reduction of toxic exhaust components. The coating also plays a very important role [28].

Table 1. A summary of research findings regarding the application of TBC coatings in compression ignition and spark ignition engines

No.	Engine type/research object	Coating material and thickness	Application method	Key results (efficiency, fuel consumption, emissions)
[45]	Compression ignition engine, coating on the bottom of the piston	Yttria-stabilized zirconia (YSZ), thickness 100 µm	plasma spray coating	– Increase in brake thermal efficiency: +1.14% to +8.84% (at 50% load) – Decrease in fuel consumption: up to –28.59% (at 25% load) – Reduction in HC emissions: –35.27% – Reduction in CO: –2.7% – Increase in CO_2: +5.27%
[56]	General solutions for TBC coatings in spark ignition and compression ignition internal combustion engines	Surface coatings of ZrO_2–Y_2O_3 (approx. 7% Y_2O_3) + MCrAlY layers (CoNiCrAlY)	Gł. HVOF, EB-PVD, APS, SIFCO (vapor phase)	– New surface coating compositions (with additions of rare earth metal oxides) – Bilayer intermediate coatings – Superior repeatability of the SIFCO and HVOF methods – Necessity for precise thickness control in APS
[34]	Spark ignition engine (SI), single-cylinder Briggs & Stratton 10 HP	NiCrAl layer (100 µm) + ZrO_2–8%Y_2O_3 (200 µm)	APS (Atmospheric Plasma Spraying)	– Increase in maximum cylinder pressure (by 2–8 bar) – Higher thermal efficiency: up to +6% (gasoline), +7.4% (GNB10) – Reduction in SFC (specific fuel consumption) – Lower CO and HC emissions, increase in NO_x (due to higher combustion temperatures)
[27]	Compression ignition engine	ZrO_2–Y_2O_3 (100 µm on the piston and cylinder head, 500 µm on the cylinder liner)	APS (Atmospheric Plasma Spraying)	– Reduction in fuel consumption: +6% at 2600 rpm (full load) and +3.5% at 1600 rpm – Retardation of the injection timing along with high injection pressure and velocity – Higher rate of heat release compared to an engine without a coating
[38]	Compression ignition engine, coating on the combustion chamber and the bottom of the piston	Partially yttria-stabilized zirconia (250 µm)	–	At 75% rated load: – Increase in operating temperature from 350–400°C to 850–900°C – Increase in thermal efficiency (shift of combustion toward the diffusion phase) – Mitigations: CO emissions (–) 18.82%, HC (–) 36.3%, and smoke (–) 6.14%

In work [6, 39] the thermal diffusivity of modified materials is stable to a certain range of temperature. This parameter worsens with the increasing damage to the graphite coatings used in research. The use of platinum-based coatings caused more accurate test results. The thermal capacity (CP) of these materials was studied to 1400°C. In these studies, high stability for most samples was shown, except for $Eu_2Zr_2O_7$, where significant surface defects occurred. The lower value of the young module ($La_2Zr_2O_7$) partly equalizes defects in the form of thermal differences. In this way, the stress decreases, which causes less damage to the coating during engine operation.

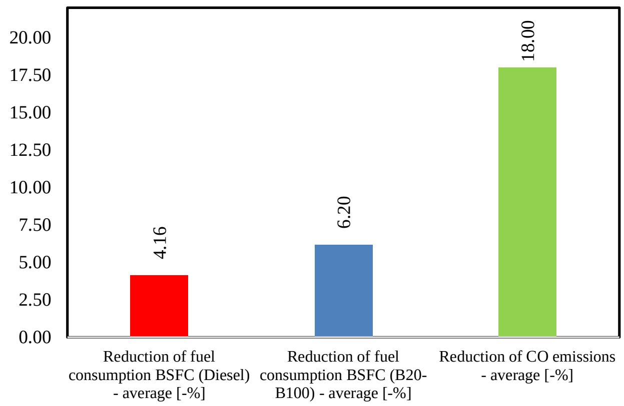

Fig. 2. The impact of $La_2Zr_2O_7$ ceramic coatings on reducing fuel consumption and CO emissions in internal combustion engines. The chart was created based on studies [6, 28, 39]

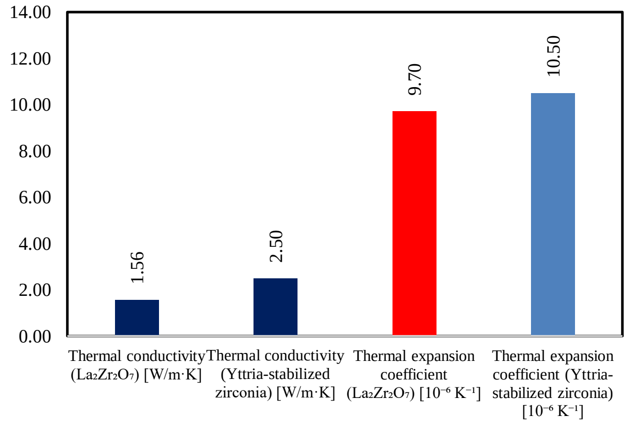

Fig. 3. The impact of $La_2Zr_2O_7$ ceramic coatings on thermal conductivity and thermal expansion coefficient in internal combustion engines. Chart created based on studies [6, 28, 39]

Similarly, the modifications described in [42] confirm the beneficial impact of coatings serving as thermal barriers on the operation of a spark ignition (SI) engine. After removing the appropriate thickness of the combustion chamber material to maintain the compression ratio, a bonding layer of NiCrAl (160 µm) and a layer of $MgZrO_3$ (320 µm) were applied to the piston, cylinder head, and valves, with the simultaneous use of an inert gas (argon) [42]. The application of TBC – with NiCrAl, $CaZrO_3$, and $MgZrO_3$ coatings on the piston, cylinder head, and valves – contributed to a change in the engine's operating parameters. In the standard engine (SE), an increase in energy efficiency of 9.93% was observed (from 81.3% at 0% Ar to 91.23% at 15% Ar), resulting from a higher mixture density and increased air mass flow [42]. However, in the TBC engine (TBCE), a decrease in efficiency of 3.89% (at 9% Ar) was noted compared to the SE, which was due to an increase in the combustion chamber wall temperature. The use of TBC also influenced fuel consumption (BSFC). In the SE, a reduction in BSFC of 17 g/kWh was measured with an increase in argon concentration from 0% to 15%, while in the TBCE, the reduction amounted to 18.2 g/kWh [42]. In the engine with TBC, the lower fuel consumption was a result of the higher combustion chamber wall temperatures, which enhanced the engine's load-bearing capacity. The maximum difference in BSFC between the TBCE and SE was 3 g/kWh in favor of the TBCE [42]. Exhaust gas temperatures decreased in both cases with increasing argon concentration. In the SE, the exhaust gas temperature dropped from 725°C (at 0% Ar) to 661°C (at 15% Ar), a decrease of 34°C [42]. In the TBCE, the exhaust gas temperature was 21°C higher compared to the SE, due to the adiabatic effect of the ceramic coatings. Regarding emissions, it was observed that introducing argon into the air mixture resulted in a 55% reduction in NO_x emissions in both the SE and TBCE compared to standard operating conditions without argon. However, NO_x emissions in the TBCE were higher than in the SE due to the higher exhaust gas temperatures and a faster combustion process. CO emissions increased with rising argon concentrations, reaching 91.2 g/kgf (at 15% Ar) in the SE, which was due to the limited availability of oxygen in the combustion process [42]. In the TBCE, CO emissions were lower because of the conversion of CO to CO_2 at higher exhaust gas temperatures. CO_2 emissions increased at lower argon concentrations (3–6%) due to greater oxygen availability, but decreased at higher argon concentrations [42]. With increasing engine speed (from 2100 rpm to 3300 rpm), an increase in exhaust gas temperature was observed in both cases; however, in the TBCE, it was on average 25°C (at 0% Ar) and 28°C (at 15% Ar) higher compared to the SE [42].

In the study [43], a CI engine with an LHR coating and one without was compared, powered by CSOME, NKOME, and diesel. The coating was applied using thermal plasma spraying, with several metal-ceramic layers on a Ni-Cr substrate. The thermal efficiency for CSOME and NKOME in the LHR engine was lower than that for diesel, and fuel consumption increased at full load. In the engine fueled by CSOME and NKOME, higher exhaust gas temperatures were recorded, along with increased emissions of unburned HC and CO. NO_x levels were also higher compared to diesel, as was smoke. The maximum cylinder pressure at partial load was highest for diesel, with a slightly lower rate of pressure increase observed for the methyl esters [43]. Thermal barrier coatings reduce heat losses, increase combustion temperatures, and improve fuel efficiency, while advanced filtration systems provide cleaner intake air, which reduces wear and stabilizes combustion conditions; together, they contribute to improved engine performance, lower emissions, and increased durability of components [27]. The use of thermal insulation in the combustion chamber raised the combustion temperature by approximately 300–350°C compared to a conventional diesel engine, which unfortunately led to higher NO_x emissions [6].

In study [52] and its co-authors, heat flow was analyzed at crank angles of 320°, 360°, and 410° for four models: the base model (without coatings), a model with a coating on the piston, one with a coating on the cylinder head and liner, and one with coatings on the piston, cylinder head, and liner simultaneously. It was demonstrated that ceramic materials (e.g., zirconia, silicon nitride) with low thermal conductivity reduce heat loss to the coolant and increase thermal efficiency. When the cylinder head and liner were insulated, heat conduction was significantly reduced, and energy transfer to the coolant was minimal. It was determined that isolating only the piston is less effective than full insulation of the piston, cylinder head, and liner. In contrast, study [58] conducted numerical investigations of an HCCI engine with catalytic combustion by coating the piston with platinum. This accelerated the ignition timing, slightly increased the maximum cylinder pressure and temperature, reduced CO and HC emissions by 9% and 4%, respectively, but increased NO_x by 5%. The indicated mean effective pressure increased by 5% and combustion efficiency by 7%. Additionally, the combustion duration was prolonged by 9%, without affecting the later phase of the process.

3.3.3. Coatings with additions of platinum and precious metals

Studies [17] showed that coating the piston of a diesel engine powered by diesel fuel with a platinum layer reduces soot emissions by 40%. However, within 8 hours of operation, the coating wore out due to poor adhesion and the formation of iron oxide deposits on the piston. In [49], a combustion engine burning methanol in a prechamber with an incandescent glow plug and a platinum mesh was described – this engine achieved low fuel consumption at light loads and lower HC emissions. Studies [24] and [25] demonstrated that coating the piston of a spark ignition (SI) engine with a Pt-Rh coating reduced unburned HC by 20%. In [27], an increase in thermal efficiency of 5–6% was achieved by using an engine with a thin thermal barrier coating. The authors of [5] reported fuel savings of 16–37%, while [54] showed an efficiency improvement of 14% under fully adiabatic conditions and 7% under partially adiabatic conditions. In [21], an improvement of 5–9% in specific fuel consumption was observed in the insulated engine compared to the standard engine. The influence of the combination of thermal conductivity and coating thickness on fuel consumption was also investigated [21]. The best results were obtained with a coating thickness of approximately 100 µm (yielding greater fuel savings), whereas thicknesses above 300 µm resulted in losses. However, thermal insulation of the engine can increase the combustion temperature by 300–350 °C compared to a conventional engine [57], which leads to a significant increase in NO_x emissions. Moreover, catalytic coatings may induce the phenomenon known as catalytic flame quenching, which negatively affects HC emissions [27].

3.3.4. Characteristics of damage and the life of coatings

Protective coatings (TBC) based on ZrO_2–Y_2O_3, applied using the APS plasma spray method, are characterized by good resistance to thermal fatigue [26]. Erosion tests complement thermal load tests, enabling additional assessment of top-layer damage caused by thermal fatigue. The greatest stress changes occur at the substrate/bond coat interface and the bond coat/top coat interface. Flame tests have been developed to simulate engine start-stop cycles, while furnace tests can be used to control the quality of the coating manufacturing process [23]. This represents an interesting alternative to bench tests using a piston internal combustion engine.

Table 2. Summary of the results of research on the use of TBC coatings in internal combustion engines

No.	TBC coating (material/ thickness)	Results (relative to the standard variant)	Key conclusions
[51]	$La_2Zr_2O_7$ (350 µm) Total TBC thickness: 500 µm	- BSFC: decrease by 4.16% (ON), 2.9% (B20), 9.5% (B100) - BTE: increase by 4% (ON), 8.55% (B20), 10.7% (B100) - CO: decrease by 18% (ON), 27.7% (B20), 43.75% (B100) - HC: decrease by 11.68% (ON), 40.98% (B20), 62.26% (B100) - NO_x: increase by 3.5% (ON), 12% (B20), 15% (B100)	– Higher combustion temperature and favorable catalytic properties ($La_2Zr_2O_7$) contribute to the reduction of CO, HC, and soot – Lower thermal conductivity (1.56 W/m·K) enables reduced heat losses – The increase in NO_x is due to the higher temperature in the chamber
[6], [28], [39]	($La_2Zr_2O_7$) and other pyrochlore TBC ($Eu_2Zr_2O_7$, $Gd_2Zr_2O_7$) with varied structural stability.	- Thermal conductivity ($La_2Zr_2O_7$): 1.56 W/m·K - Pyrochlore structural stability: up to 2300 °C (or up to 2573 K) - Thermal expansion coefficient: 9.7×10^{-6} K^{-1} ($La_2Zr_2O_7$) vs. 10.5×10^{-6} K^{-1} (YSZ) - Heat capacity (Cp) stable up to 1400°C (exception: $Eu_2Zr_2O_7$) - Lower Young's modulus reduces stresses	– Low thermal conductivity and pyrochlore stability promote thermal insulation – Matching the thermal expansion coefficient with the substrate is key – A lower Young's modulus minimizes the risk of coating cracking
[43]	(320 µm) + bonding layer (e.g., NiCrAl, $CaZrO_3$)	- Volumetric efficiency: decrease of approximately 3.89% in the TBC engine (TBCE) at 9% Ar (compared to the standard engine, SE) - BSFC: reduction of 18.2 g/kWh in TBCE with Ar increased to 15% (in SE: 17 g/kWh) - Exhaust gas temperature: in TBCE, on average 21°C higher (adiabatic effect) - NO_x emissions in TBCE are higher than in SE, but NO_x decreases with the addition of Ar	– High combustion chamber wall temperature in the TBCE reduces fuel consumption – The addition of Ar to the mixture decreases NO_x (due to less oxygen and exhaust gas cooling) but increases CO emissions – Higher exhaust gas temperature in the TBCE promotes the conversion of CO to CO_2, thereby reducing CO emissions compared to the SE

3.3.5. Issues of heat exchange in ceramic coatings

Article [36] presents the results of heat transfer studies through surfaces covered with a thin ceramic coating. The theoretical analysis showed that the ceramic coating reduces the heat flux density at a constant heat transfer coefficient. The experiments were conducted on three types of thin thermal insulation coatings: zirconium oxide (ZrO_2) partially stabilized with either yttria (Y_2O_3) or lanthana (Ln_2O_3), which were plasma-sprayed onto an aluminum alloy. The heat flux density, heat transfer coefficient, and thermal resistance of the coating were determined. It was demonstrated that heat transfer in such systems is strongly influenced by the coating's porosity, roughness, and emissivity, and that knowledge of only the coating thickness and thermal conductivity is insufficient for accurate calculations. In such cases, heat transfer must be investigated experimentally, particularly in piston internal combustion engines.

3.3.6. Popular oxides in protective coatings

Aluminum oxide (Al_2O_3) is one of the most commonly used ceramic materials in the protective coatings industry. Its high hardness, chemical inertness, wear resistance, and a melting temperature of 2072°C make it a good choice for applications in the harsh operating conditions of piston internal combustion engines. The maximum operating temperature of this material is 1650°C, which further enhances its versatility. It can be combined with TiO_2 to improve fracture toughness, although this decreases its hardness [22, 48].

In other studies, the use of Cr_2O_3 coatings is suggested. This material is characterized by high hardness, wear resistance, and chemical inertness, with a maximum operating temperature of 540°C. Its properties can be further enhanced by adding SiO_2 and TiO_2 [8, 48]. Cr_2O_3 is applied on the inner surfaces of air and gas cylinders, mechanical seals, and components in textile machinery.

Another material is LSM – $(La_{0.8}Sr_{0.2})$ $0.98MnO_3$, an advanced ceramic material used in solid oxide fuel cells (SOFC) based on YSZ electrolyte. Thanks to its thermal expansion coefficient, which is close to that of doped zirconia, and a maximum operating temperature of 1500°C, this material is indispensable for limiting the evaporation of chromite components in SOFCs, as well as for catalysts and sensors [48]. Its application in internal combustion engines is possible, but it is limited to selected components exposed to high thermal loads.

In work [48], the use of titanium oxide (TiO_2) is also suggested. Naturally occurring titanium oxide is characterized by low roughness and a dense coating structure. Its conductive properties enable its application as a conductive coating, for example, in architectural and automotive glass. With appropriate spraying parameters, both hard, dense coatings and more porous, thick layers can be achieved while avoiding cracking and delamination. The addition of Cr_2O_3 increases hardness as well as wear and corrosion resistance. TiO_2 coatings are used, among other applications, in cutting tools for CNC machines.

4. Multi-layer systems of coatings are used for combustion chambers

In thick TBC layers, a low thermal expansion coefficient (TEC) at the hot surface is essential to reduce thermal stresses and resistance to thermal shocks. However, a large TEC mismatch between the metal substrate and the coating hinders adhesion. Multilayer systems can help reconcile these opposing demands. A group of chemically compatible materials with varied TEC values and suitable thermal conductivity has been identified. Current research focuses on analyzing temperature and stress distributions within the coating to evaluate stress levels during deposition and under operational conditions. The aim is to optimize layer thicknesses to minimize operational stresses.

4.1. Multi-layered TBC coatings – concepts and materials

In the following works, the results and design ideas of multilayer TBC coatings are presented, along with the role of various materials (including intermetallic, ceramic, and metallic layers) and the need to take into account conflicting mechanical and thermal requirements.

In work [8], the use of a layered TBC MMC structure contributes to improved thermal barrier properties. Nonetheless, the high thermal conductivity of the aluminum layers limits the effectiveness of the intermetallic Fe-Al layers that form during the reactive sintering of the multilayer structure. To reduce the thermal conductivity of the aluminum layers, their reinforcement with ceramic phases of low thermal conductivity, such as YSZ (yttria-stabilized zirconia), is proposed. Such a design, consisting of intermetallic layers and Al-YSZ layers, enables the achievement of high mechanical strength and mitigates the negative impact of aluminum on the overall thermal barrier properties. Thus, the concept of a three-phase multilayer structure is justified. Enhancing the crack resistance of thermal coatings, especially under conditions of intense mechanical and thermal loading, is crucial for their durability.

In work [31], LPCS (Low-Pressure Cold Spraying) technology combined with thermal treatment enables the production of multilayer TBC coatings with excellent thermal and mechanical properties. These coatings are partly based on the addition of yttria-stabilized zirconia, aluminum, and stainless steel, combining the superior thermal insulation properties of ceramic materials with the high resistance of metals to thermal shocks. The composition of the multilayer ceramic-metal composite deposited by the LPCS method can be modified by incorporating catalytically active layers. This helps reduce the emission of harmful substances into the environment and improves the thermal efficiency of engines. Studies have shown that multilayer TBC coatings of the (Al-ZrO_2)-SHS 717 type, consisting of layers 40–50 μm thick, provide adequate insulating properties both during the spraying process and after sintering [31]. The sintering process of the Al-SHS 717 composite leads to interphase reactions and the formation of intermetallics, which results in reducing the effective thermal conductivity to about 6.0 W/mK, comparable to that of yttria-stabilized zirconia (YSZ) [31]. Depositing mixtures of Al-ZrO_2 powders causes ZrO_2 particles to fracture upon impact with the substrate, leading to the formation of a homogeneous structure with ZrO_2 particles sized 3–10 µm [31]. These coatings provide a temperature difference of about 55°C between the top surface and the substrate at a test temperature of approximately 530°C [31]. The developed TBCs demonstrate the ability to reduce thermal fatigue of component surfaces [31].

At work [3], a multi-layered coating was used to increase the strength of HFB_2 ceramic materials. Such an addition is widely used in single-layer coatings. This solution concerns the strengthening of the coating structure to avoid additional cracks. However, more advanced systems consisting of several coatings require more difficult technological procedures. Combining various ingredients, such as metals, ceramics, and intermetallic particles, allows you to obtain a coating that fulfills various functions in internal combustion engines. TBC coatings are very complex multi-material systems. These coatings must meet thermal and functional requirements. They should also achieve high hardness and bending resistance. Their appropriate design and selection of materials increase the thermal efficiency of the engine, reduce fuel consumption, and contribute to reducing the emission of harmful fumes.

Experimental studies on mechanical behavior are essential for understanding failure mechanisms. The strength of multilayer three-phase composites depends on both individual layer properties and the interactions between them. A key obstacle is the limited availability of detailed data on such structures. Current research focuses on two main strategies: metal-matrix composites and multilayer systems with enhanced barrier performance and crack resistance.

4.2. Catalytic layers in TBC and impact on the emission of toxic substances

The standard thermal-barrier coatings (TBC) with a thickness of about 300 µm presented in [11] are insufficient to achieve a significant improvement in energy efficiency and to reduce harmful exhaust emissions. In this case, selected parameters of these coatings must be enhanced. For example, in [50], the TBC material applied to the surfaces of selected engine components caused a 12% increase in exhaust-gas temperature. That study also reported a 28% decrease in CO and a 21% increase in NO_x emissions. Introducing catalytic layers into these coatings can help reduce NO_x emissions. In oxygen-deficient zones, such as a piston crown coated with a catalytic layer, the NO_x-reduction process can be supported. This process can be promoted by catalysts such as Cu-Zn/Ni-Zeolite [37], $MoSi_2/Mo_2C$, or Cr_2O_3 [4].

The temperatures prevailing in the engine working space during combustion are higher than in the exhaust gases, which increases catalyst activity. Nevertheless, the development of TBC with catalytic layers is not widely described in the literature.

4.3. Methods of manufacturing and the properties of multi-layer TBC coatings

Standard deposition methods, such as APS, HVOF, LPPS, or plasma techniques, enable precise control of coating parameters [14]. In the case of intermetallic coatings, for example, MCrAlY, controlling the thermodynamic and kinetic processes is crucial [18].

In [53], the research focused on multilayer thermal-barrier coatings (TBC) produced by APS in order to increase the durability of the coating system and improve its performance characteristics. The material used was 8% yttria-stabilized zirconia in powder form. These particles exhibited two distinct morphologies: hollow spherical particles (HOSP) and fused-and-crushed particles (FC). The powder particle diameters ranged from D10 = 6 µm to D90 = 105 µm for HOSP and to 77 µm for FC [53]. The coatings were deposited on the nickel-based superalloy Rene 80 with a NiCoCrAlY bond coat and on aluminum for mechanical and thermal measurements. Single-layer coatings (C1–C6) with thicknesses of approximately 400 µm displayed varying densities and porosities [53]. Denser coatings, such as C4, achieved a fracture toughness of K_{IC} = 2.24 MPa√m and an elastic modulus E = 35.2 GPa, whereas more porous coatings, for example, C1, exhibited K_{IC} = 1.84 MPa√m and E = 22.4 GPa [53]. Furnace cyclic tests (FCT) at 1100°C demonstrated that the single-layer coatings could endure between 600 and 800 cycles [53]. The two-layer coatings (B1–B7) with a total thickness of 300 µm were designed so that the inner layer (30–90 µm) was dense and robust, while the outer layer was porous to promote low thermal conductivity [53]. Coatings B6 and B7 showed durability beyond 1200 cycles – more than twice that of the single-layer coatings. In particular, coating B6, with an inner layer thickness of 60 µm, achieved the best compromise between durability and low thermal conductivity [53].

In studies [19] concerning 38MnSiVS5 steel, NiCoCrAlY coatings (applied via APS/HVAF) were used as the bonding layer, together with YSZ/GZO ceramics (via SPS). Additional sealing layers – both metallic and ceramic – improved tightness but reduced mechanical durability. SPS-GZO exhibited the best thermal insulation properties (thermal conductivity 0.7–0.8 W/m·K, porosity 10–15%), while APS offered high insulation efficiency but lower resistance to thermal cycling [19]. In thermal fatigue tests, SPS-GZO with ceramic sealing endured 4000 cycles, and without sealing, 6000 cycles, whereas coatings with metallic sealing suffered damage after only a few hundred cycles. These results indicate the need for a compromise between thermal insulation, durability, and resistance to thermal cycles. In studies [32], single-layer YSZ was compared with two- and three-layer GZ/YSZ coatings (applied by SPS) on Hastelloy-X and IN-738 alloys. The multilayer TBCs demonstrated lower thermal conductivity across the entire temperature range of 25–1190°C and higher durability at 1300°C (395 cycles for GZ/YSZ, 521 cycles for GZ_dense/GZ/YSZ), while single-layer YSZ survived only 43 cycles. The lower fracture toughness of GZ (1.02 ±0.11 $MPa \cdot m^{0.5}$) promoted crack formation at the GZ/YSZ interface, and the sintering of GZ led to pore closure [32]. The tetragonal phase of YSZ remained stable up to 1200°C, while the cubic phase of GZ (with a fluorite defect) was stable above 1400°C [32]. Thus, multilayer GZ/YSZ coatings offer higher durability and lower thermal conductivity under extreme conditions [32].

In work [55], residual stresses in a two-layer $La_2Zr_2O_7$/8YSZ (DCL TBC) coating applied by APS were analyzed. The coating system comprised a NiCoCrAlY bond coat (100 µm), 8YSZ (240 µm), and an LZ layer (60 µm). A finite element "birth and death element" method was used to simulate the spraying and cooling processes. The results indicated lower residual stresses in the DCL compared to a single-layer 8YSZ. The highest radial stresses were observed on the surface of the LZ, while axial and shear stresses concentrated at the interfaces' edges. Computational micro-mechanics analyses revealed that pores and microcracks locally increased the stresses but reduced them across the entire LZ layer. Overall, DCL LZ/8YSZ exhibits better resistance to residual stresses and a lower risk of cracking compared to 8YSZ, making it a promising material for high-temperature protective coatings.

Table 3. Summary of research on spraying techniques and coatings

No.	Spraying technique and coating configuration	Material	Thermal properties, cyclical durability and key conclusions
[14, 18]	Overview of techniques: APS, HVOF, LPPS, HVAF, CS. Process parameter control (gas flow, temperature, spraying speed) is crucial for the quality of the coatings. In the case of intermetallic coatings (MCrAlY), precise control of thermodynamic and kinetic phenomena is essential	Mainly MCrAlY materials (NiCoCrAlY, CoNiCrAlY), yttria-stabilized zirconia (YSZ), various single- and multilayer configurations	Standard spraying methods allow for the production of coatings with a strictly controlled microstructure. The proper selection of parameters determines the mechanical and thermal properties, as well as the durability of the coatings under high-temperature conditions
[53]	Atmospheric plasma spraying (APS). Single- and double-layer TBCs deposited on nickel-based superalloys (Rene 80) with a NiCoCrAlY bond coat. Additionally, tests were performed on an aluminum substrate (for measuring mechanical and thermal properties)	YSZ (8% Y_2O_3) in the form of powders with different morphologies: Hollow Sphere (HOSP) and Fused & Crushed (FC). Layer thicknesses: approximately 400 µm (single-layer) and 300 µm (two-layer)	Single-layer: durability of 600–800 cycles in the FCT test (1100°C). Two-layer: durability exceeding 1200 cycles (B6, B7). Coating B6 (with an inner layer of 60 µm) demonstrated the best compromise between durability and low thermal conductivity. Multilayer TBC significantly increases the number of cycles while maintaining favorable insulation properties

5. Impact of the use of multi-layer coatings on the reduction of structural defects and engine energy efficiency

Multilayer barrier coatings applied to thermally stressed components of piston engine combustion chambers offer an effective method for reducing structural defects such as cracks, erosion, and corrosion, while improving overall engine efficiency. These systems use ceramic, metallic, or hybrid layers arranged in two- or multilayer configurations, with each layer fulfilling a specific, engineered function. The following sections outline the general effectiveness and limitations of TBC coatings, along with proposals for their further development. The most common benefit of multilayer coatings is their ability to reduce heat transfer to the cooling system, thereby improving the utilization of energy from fuel combustion. Higher temperatures prevailing in the combustion chamber of reciprocating internal combustion engines lead to improved thermal efficiency. Unfortunately, this requires controlling changes in NO_x emissions. Proper material selection and layer design – using components such as YSZ, $La_2Zr_2O_7$, GZO, or MCrAlY – can significantly minimize the formation of material defects, e.g., microcracks. Two-layer or three-layer thermal-barrier coating systems allow for:

- Protection against erosion and corrosion
- Facilitation of thermal-expansion matching by means of an appropriate interlayer
- Good thermal-barrier performance while maintaining high mechanical strength (by employing differentiated surface roughness for the various layers within the system).

Such coating solutions protect not only the piston-crown structure or cylinder-head components but also improve their durability and reduce engine operating costs.

Summary

- Studies of multilayer coatings deposited on the combustion-chamber surfaces of reciprocating internal combustion engines have demonstrated their key importance in increasing thermal and mechanical efficiency, as well as in reducing emissions. The thermal barrier provided by appropriately selected coatings reduces heat losses to the cooling system. This, in turn, increases durability and resistance to erosion and corrosion under the high-temperature and medium mean-effective-pressure conditions prevailing in the combustion chamber.
- Multilayer coatings (two or three layered, etc.) effectively reduce the risk of microcracks and show high resistance to corrosion and erosion in critical working conditions of the engine. Reducing structural defects by multi-layer coatings allow you to improve thermal properties and reduce operating costs.
- TBC coatings reduce heat loss, enabling higher fuel-air mixture combustion temperatures. The cited studies showed that it is possible to reduce fuel consumption by over 10%using these systems. Higher temperatures and catalytic properties (e.g. $La_2Zr_2O_7$) reduce CO, HC and soot emissions, although they often lead to increased NO_x emissions. This is due to the higher combustion temperature, especially for a poor fuel-air mixture.
- Ceramic layers are made of materials such as YSZ, $La_2Zr_2O_7$, $Gd_2Zr_2O_7$, $MgZrO_3$, Al_2O_3, Cr_2O_3 and Multiphase Composites. More important parameters. These coatings include thermal and mechanical properties (thermal conductivity, thermal capacity, resistance to cracking, and matching thermal expansion coefficients to the ground). The intermediate layers used (e.g., McRaly) and double-layer structures help reduce residual stress. This increases the durability of coatings, especially in terms of dynamic temperature changes in the combustion process.

– The use of thicker coatings (above 0.5 mm) can cause problems with lubrication and increase the risk of premature ignition (in engines with spark plugs). Incorrect surface roughness and large differences in thermal expansion can lead to cracking of these coatings and even their detachment. In this case, higher combustion temperatures can increase the emissions of nitrogen oxides. In this case, you can modify fuel injection parameters or add appropriate catalytic layers to the multilayer coatings system (e.g. PT, RH).

– Multilayer thermal-barrier coatings (TBCs) offer an effective means of increasing the power and torque of reciprocating internal combustion engines while maintaining their durability. These coatings increase the longevity of combustion-chamber components and enhance energy efficiency. Major challenges remain the elevated NO_x emissions and the need to ensure stable mechanical properties. Multilayer thermal-barrier coating solutions represent the next step in advancing modern engine design, especially today, when high durability, excellent performance, and low exhaust emissions are paramount.

Nomenclature

APS	air plasma spraying
BSFC	brake-specific fuel consumption
CI/Diesel	compression-ignition engine
CO	carbon monoxide
CSOME	cotton seed oil methyl ester
DCL TBC	double ceramic layer TBC
EB-PVD	electron beam physical vapor deposition
FCT	furnace cycle test
HC	hydrocarbons
$La_2Zr_2O_7$	lanthanum zirconate (pyrochlore phase)
LHR	low heat rejection engine
LZ	$La_2Zr_2O_7$ (cyrkonian lantu)
MES	the method of finite elements
$MgZrO_3$	magnesium zirconate
MMC	metal matrix composite
NKOME	neem kernel oil methyl ester
NO_x	nitrogen oxides
SI	spark-ignition engine
TBC	thermal barrier coating
YSZ	yttria stabilized zirconia
ZrO_2	zirconium oxide

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