

# Review on Advanced Alternative Thermal Barrier Coatings (TBC's) Materials in Low Heat Rejection Engines

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## Abstract

This paper presents a general overview about the previous research efforts into Low Heat Rejection Engine (LHRE) concept. Many researchers have carried out a large number of studies on low heat rejection engine concept. Some of them are experimental work and many are theoretical studies. In the most of the case low heat rejection engines almost all theoretical studies predict improved performance but many experimental studies show different picture to incorporate various systems of ceramic materials in intermittent combustion engines, and on the use of ceramics in these engines is presented. The use of Thermal Barrier Coatings (TBCs) to increase the combustion temperature in diesel engines has been pursued for over 20 years. These TBCs provide the potential for higher thermal efficiencies of the engine, improved combustion and reduced emissions. The purpose of this paper is to explain TBC materials like YSZ, Mulite, Sic/Sic and the advanced search of alternative TBC materials. And also various advanced coating techniques like plasma spray and EB-PVD.

## Keywords

Thermal Barrier Coatings, Low Heat Rejection Engine, YSZ, Mulite, Sic/Sic, plasma spray and EB-PVD

## I. Introduction

Present research on internal combustion engines is mainly focused on decreasing costs of the engines and fuel consumption and also the technological innovation studies are in focus. In this connection, Ceramic coating applications in internal combustion engines grow rapidly. Ceramic coatings applied to diesel engine combustion chambers are aimed to reduce heat which passes from in-cylinder to engine cooling system. Engine cooling systems are planned to be removed from internal combustion engines by the development of advanced technology ceramics. One can expect that engine power can be increased and engine weight and cost can be decreased (Gataowski, 1990; Schwarz et. al. 1993). Coating combustion chamber with low heat conducting ceramic materials leads to increasing temperature and pressure in internal combustion engine cylinders. Hence, an increase in engine efficiency should be observed.

Quick ignition delay in ceramiccoated diesel engines due to increased temperature after compression because of low heat rejection. More silent engine operation can be obtained considering less detonation and noise causing from uncontrolled combustion. Engine can be operated at lower compression ratios due to shortened ignition delay. Thus better mechanical efficiency can be obtained and fuel economy can be improved.(Büyükkaya et. al., 1997).

Another important topic from the view point of internal combustion engines is exhaust emissions. Increased combustion chamber temperature of ceramic coated internal combustion engines causes a decrease in soot and carbon monoxide emissions. When increased exhaust gases temperature considered, it is obvious

that turbocharging andconsequently total thermal efficiency of the engine is increased.

Low heat conduction and high resistant material leads to thermal barrier coated engines also known as low heat rejection engines. TBCs are becoming increasingly important in providing thermal insulation for LHR engine components. For such an engine the insulating material must possess high chemical stability, low thermal conductivity, low specific heat, high strength, high fracture toughness, high compression strength ,high thermal shock resistance, low friction and wear resistance, high temperature capability, high expansion coefficient and chemical inertness for high resistance to erosion and at all temperature ranges. Among those properties, thermal expansion coefficient and thermal conductivity seem to be the most important. In this study materials which are favorable to achieve low heat rejections are consider.

Table 1: Comparison of Energy Distribution Between Conventional and Ceramic Coated Engine

S. No.	Type of Energy	Conventional Engine	Ceramic coated engine
1	Useful energy	32%	48%
2	Exhaust energy	36%	35%
3	Coolant energy	34%	17%

The selection of TBC materials is restricted by some basic requirements:

1. High melting point,
2. No phase transformation between room temperature and operation temperature,
3. Low thermal conductivity,
4. Chemical inertness,
5. Thermal expansion match with the metallic substrate,
6. Good adherence to the metallic substrate and
7. Low sintering rate of the porous microstructure.

The number of materials that can be used as TBCs is very limited. So far, only a few materials have been found to basically satisfy these requirements. Progression of temperature capabilities of Ni-based super alloys and TBCs materials for the past 50 years is depicted in fig. 1. The red lines indicate progression of maximum allowable gas temperatures in engines, with the large increase gained from employing TBCs. Based on a diagram from the late Professor Tony Evans.

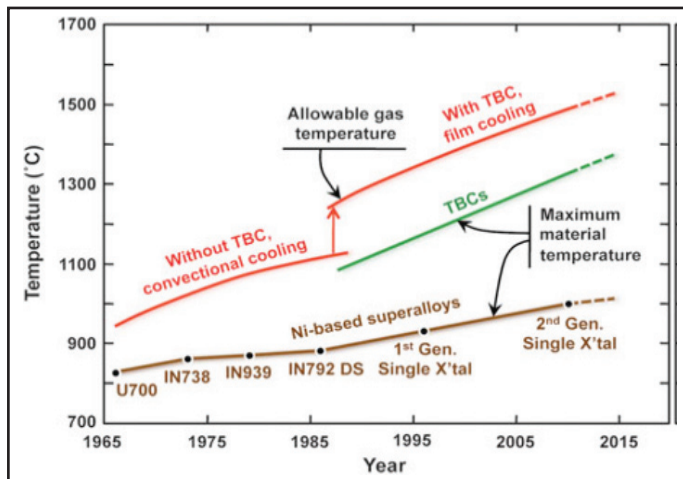


Fig. 1: Progression of Temperature Capabilities of Ni-based Super Alloys and TBCs Materials for the Past 50 Years

## II. Topcoat ceramics

Thermal barrier coatings typically consist of four layers: the metal substrate, metallic bond coat, thermally grown oxide, and ceramic topcoat. The majority of TBCs in use today are  $ZrO_2$ -based having a composition containing  $\sim 7$  wt%  $Y_2O_3$  (7YSZ). Originally, this ceramic was selected empirically based on its low thermal conductivity, high melting point, resistance to sintering, a demonstrated manufacturing capability for depositing it with constant composition, and long life in the resulting TBCs [1,2-4]. Unlike the cubic  $ZrO_2$  used in oxide fuel cells, oxygen sensors, and fake diamonds, which have higher  $Y_2O_3$  content, 7YSZ is a metastable tetragonal phase ( $t'$ ). 7YSZ has been shown to have unusually high fracture toughness due to Ferro elastic toughening [6-7]. Unlike other transformation-toughened  $ZrO_2$ -based ceramics, so-called "ceramic steels," [8] used in bearings, cutting tools, and knives, the toughness in 7YSZ does not arise from the martensitic transformation (an irreversible and diffusionless collective movement of atoms) from the tetragonal to monoclinic phase but rather from reversible ferroelastic domain switching from one tetragonal variant to another when stressed [6-7]. Also, unlike transformation toughening, Ferro elastic toughening can operate at high temperatures, typical of those at engine temperatures. High fracture toughness in TBCs is important not only for resisting impact and erosion but also spallation.

## III. Bond-coat Alloys

In many respects, the most stringent constraints are imposed on the bond coat. Its primary function is to provide a reservoir from which Al can diffuse to form a protective  $\alpha$ - $Al_2O_3$  TGO while maintaining cohesion with the TBC without reacting with it. Mechanics modeling [9] indicates that, ideally, the TGO should remain elastic to the highest temperatures and not creep to prevent "rumpling" [10-11] or cavitation on thermal cycling [13] that can, in turn, lead to the development of local separations at the TBC interface [12]. At the same time, it has to operate at the highest temperature possible to minimize the amount of air used to cool the vanes and blades, without reacting with the underlying superalloy and melting. This presently implies that the maximum bond-coat temperature cannot be allowed to exceed  $\sim 1150^\circ C$ . Currently, there are two main bond-coat alloys in use, a Ni-rich nickel aluminide and a compositionally more complex MCrAlY (M=Ni, Co+Ni, or Fe) alloy. While these are very different alloys metallurgically, the challenges are similar, as described in the article by Pollock et al.: how to minimize deformation at intermediate and operating

temperatures, how to minimize interdiffusion with the underlying superalloy to prevent the formation of brittle intermetallics, and how to deliver critical elements in addition to Al, such as Hf and Y, to the growing TGO to minimize its inelastic plastic deformation under thermal cycling.

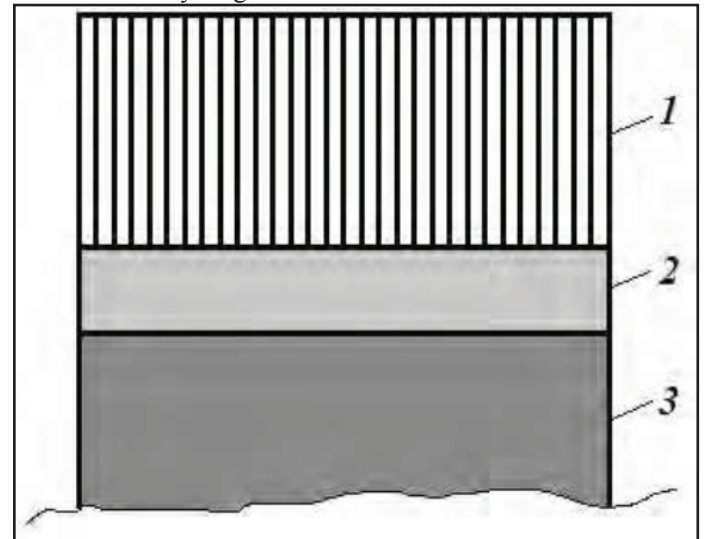


Fig. 2: Thermal barrier coating system: 1 – ceramic coating  $ZrO_2$ -8% $Y_2O_3$ , 2 – bond coating MCrAlY, 3– superalloy.

## IV. Advanced Technology Ceramics

### A. YSZ

The most widely used TBC material is YSZ, zirconia containing 6–8 wt%  $Y_2O_3$  (equivalent to about 3.4–4.5 mol%), which is produced in a metastable tetragonal phase ( $t'$ ). Alloying zirconia with yttria is necessary to avoid the disruptive monoclinic to tetragonal phase transformation that would otherwise cause mechanical breakdown of the zirconia; however, it also reduces the thermal conductivity by creating point defects that scatter phonons. The introduction of  $Y^{3+}$  as an aliovalent dopant on the  $Zr^{4+}$  site is compensated by vacant oxygen sites. Interestingly because of the similarity in atomic mass between the  $Y^{3+}$  and  $Zr^{4+}$  ions, the oxygen vacancies are primarily responsible for reducing thermal conductivity.

A physical picture of thermal transport in solids is given by propagating lattice waves, known as phonons. Scattering of these waves off of each other, as well as off of the defects in the crystal lattice, impedes energy flow and pronounces itself as a thermal resistivity. Although models for the reduction in thermal conductivity from point defects based on this physical picture describe the basic mechanisms well, 3 molecular dynamics simulations reveal a more complex situation in YSZ. Interestingly, the physics is very similar in off-stoichiometric fluorite-structured  $UO_2$ , the dominant fuel system for nuclear fission reactors. These studies show that with increasing defect concentration, the thermal conductivity transitions from that characteristic of a crystalline material to that characteristic of an amorphous solid. This transition can be described in terms of the structure of the vibrational modes of the system. These can be classified as propagons (normal phonon modes that are delocalized with well-defined momentum and polarization), diffusons (delocalized like phonons, but no longer possessing well-defined polarizations), and locons (strongly localized modes). While the vibrational modes in a crystalline solid are essentially all propagons, the vibrations in amorphous materials contain diffusons ( $\sim 93\%$  of all modes in

a-Si); these modes are far less efficient heat carriers. In both YSZ and  $\text{UO}_2$ , propagon modes only appear at the low-frequency end of the spectrum ( $<2$  THz), while locons are concentrated at the high end ( $>26$  THz). In the case of YSZ, complete transition to amorphous-like heat transport dominated by the diffusons takes place at about 24 YSZ (24% yttria): further increase of the Y<sub>2</sub>O<sub>3</sub> content does not affect the structure of the vibrational spectrum. These molecular dynamics simulations indicate that more detailed exploration of the different forms of phonons in other complex oxides should be especially insightful.

A further route to optimizing the performance involves the addition of paired dopants, such as  $\text{Nd}_2\text{O}_3$  (or  $\text{Gd}_2\text{O}_3$ ) and  $\text{Yb}_2\text{O}_3$  (and/or  $\text{Sc}_2\text{O}_3$ ), into the  $\text{ZrO}_2$ - $\text{Y}_2\text{O}_3$  system, which segregate into 5–100 nm defect clusters and can reduce the thermal conductivity by about 20–40%, compared with the baseline  $\text{ZrO}_2$ - $\text{Y}_2\text{O}_3$  ceramics. Meanwhile, these thermodynamically immobile defect clusters can significantly enhance the sintering resistance of the coating at high temperatures.

### B. Mullite

Mullite ( $3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$ ) is an attractive engineering ceramic, only stable intermediate phase in the alumina-silica binary system. Due to its harsh formation conditions involving high temperature and low pressure, mullite rarely exists in nature. It emerges at the contact of superheated magma intrusions with  $\text{Al}_2\text{O}_3$ -rich sediments, as on the Island of Mull (Scotland), where the name mullite comes from. The resulting synthetic mullite composites can be classified into three categories according to the technical routes: sintered-mullite, fused mullite and chemical-mullite. It has excellent high temperature and chemical stability at temperature as high as  $1500^\circ\text{C}$ . In addition, mullite has low thermal conductivity of  $0.06 \text{ W cm}^{-1} \text{ K}^{-1}$ , good thermal shock resistance, coefficient of thermal expansion close to SiC-based ceramics ( $4.7 \times 10^{-6}$  for SiC and  $5.05 \times 10^{-6}$  for mullite). It has been found that mullite coating is superior to  $\text{ZrO}_2$  protective coating in preventing diesel

### C. SiC/SiC

SiC/SiC matrix composite is a particular type of ceramic matrix composite (CMC) which have been accumulating interest mainly as high temperature materials for use in applications such as gas turbines, as an alternative to metallic alloys. CMCs are generally a system of materials that are made up of ceramic fibers or particles that lie in a ceramic matrix phase. In this case, a SiC/SiC composite is made by having a SiC (silicon carbide) matrix phase and a fiber phase incorporated together by different processing methods. Outstanding properties of SiC/SiC composites include high thermal, mechanical, and chemical stability while also providing high strength to weight ratio.

### V. The Search for Alternative TBC Materials

In seeking potential new TBC materials, it makes sense to explore other refractory materials. However, since there are numerous crystal structures known to the mineralogical and crystal-chemistry communities, and each can be formed from several different elements, there are literally thousands of possible compounds to search. Faced with this complexity, initial attempts have focused on exploring oxides with structures related to zirconia. More recently, the search has been broadened by using insights from atomistic simulations and crystal chemistry.

### A. Fluorite Oxides

A natural place to look for other TBC materials is among fluorite-structured materials. The obvious candidates include  $\text{HfO}_2$ ,  $\text{CeO}_2$ , and  $\text{ThO}_2$ ;  $\text{UO}_2$  and transuranic fluorite structured oxides are precluded for obvious reasons. Also, although doped ceria exhibits comparable thermal conductivity, it is not a practical choice because of volatilization. Measurements on both  $\text{HfO}_2$  and  $\text{ThO}_2$  are similar to those on monoclinic  $\text{ZrO}_2$ .

However, recent research has shown that co-doping zirconia and hafnia can result in reductions in thermal conductivity. The most intriguing observations have been made on co-doping YSZ with a mixture of one trivalent ion larger than  $\text{Y}^{3+}$  and another trivalent ion smaller than  $\text{Y}^{3+}$ , while still preserving the metastable zirconia structure [19]. Similarly, reductions in thermal conductivity have been reported [20] for compositions in which some of the  $\text{Zr}^{4+}$  is replaced with  $\text{Hf}^{4+}$ . While the measurements have been made on porous coatings rather than dense materials, hence the contribution to the low thermal conductivity from porosity is unknown, the results indicate that these materials warrant further investigation.

### B. Pyrochlore Oxides

Since the fluorites do not offer any other viable candidate materials, attention has turned to the pyrochlores,  $\text{A}_2\text{B}_2\text{O}_7$ , because several zirconate pyrochlores have lower thermal conductivity than YSZ [18]. This class of materials is also of fundamental interest because of the close relationship between the fluorite and pyrochlore structures (Fig. 5). The pyrochlore unit cell may be viewed as eight fluorite unit cells, each of which contains, on average, a single oxygen vacancy. The close relationship between the fluorite and pyrochlore structures is well illustrated by the yttria-zirconia system. The pyrochlore  $\text{Y}_2\text{Zr}_2\text{O}_7$  is actually unstable to the disordered fluorite material  $(\text{ZrO}_2)_2\text{-Y}_2\text{O}_3$ , i.e. heavily doped YSZ. However, replacing the  $\text{Y}^{3+}$  ion with larger ions, such as  $\text{La}^{3+}$  or  $\text{Gd}^{3+}$ , results in a stable pyrochlore structure up to at least  $1500^\circ\text{C}$ . Likewise, replacement of the  $\text{Zr}^{4+}$  ion by a smaller ion, such as  $\text{Ti}^{4+}$  or  $\text{Mo}^{4+}$ , also stabilizes the pyrochlore structure. The pyrochlores are also attractive because many are refractory up to temperatures well in excess of  $1500^\circ\text{C}$  and thermally stable. Moreover, they can be formed from a wide range of cations, since the A site can have a notional charge of  $3+$  or  $2+$  and the B site cation can have a valence of either  $4+$  or  $5+$ . Consequentially, there can be extensive intermixing of different ions on the same crystallographic sites.

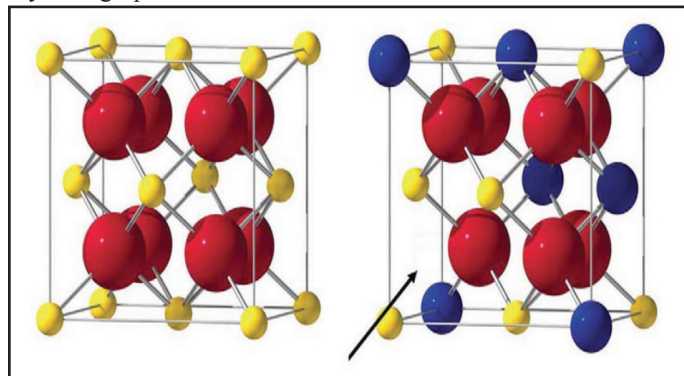


Fig. 4: The Unit cell of the high-temperature cubic phase of zirconia has the fluorite structure, with O ions shown in red and the smaller Zr ions shown in yellow. (b) One-eighth of the unit cell of the pyrochlore,  $\text{A}_2\text{B}_2\text{O}_7$  structure, with the oxygen in red, the  $\text{B}^{4+}$  ions in yellow, and the  $\text{A}^{3+}$  ions in blue.

### C. Other oxides

Apart from the fluorites and pyrochlores, many other oxide compounds have been proposed as candidate low conductivity materials. These include the garnets ( $Y_3Al_xFe_{5-x}O_{12}$ ) [22], monazite ( $LaPO_4$ ) [23], and the magnetoplumbite lanthanum hexaaluminate ( $LaMgAl_{11}O_{19}$ ) [24]. While they all have rather low thermal conductivity ( $< \sim 3$  W/mK), none offer the prospect of compositions with lower conductivity than the pyrochlore zirconates.

In contrast to these other classes of oxide, the perovskites,  $ABO_3$ , comprise a class of crystal structures that can accommodate a wide variety of different ions in solid solution, including ions with large atomic mass. Many compositions are stable to very high temperatures. Although some members exhibit rather low thermal conductivity at high temperatures, none has yet been found to have conductivity as low as the zirconate pyrochlores. One explanation is that the perovskite structure is more rigid, as the octahedra are corner sharing. Several that appear promising on the basis of their mean molecular weight unfortunately undergo phase transitions at intermediate temperatures. For instance,  $SrZrO_3$  transforms from orthorhombic to pseudo-tetragonal at about  $730^\circ\text{C}$ , accompanied by a change in volume [26]. However, one hopeful development in the area of perovskites is a recent report of very low thermal conductivity in a coating made of a layered perovskite with Ruddlesden-Popper structure [25]. While fully dense materials have not been studied, the very wide range of potential compositions in this class of crystal structure and the possibility of forming a variety of other layered structures, there is plenty of scope for further work on perovskite.

Table 2: TBC materials and their characteristics [27]

Material	Advantages	Disadvantages
YSZ	1. High thermal expansion co-efficient $10 \times 10^{-6} \text{C}^{-1}$ 2. Low thermal conductivity $2 \text{ W m}^{-1} \text{ K}^{-1}$ 3. High melting point $2800^\circ\text{C}$	1. Sintering above $1473 \text{ K}$ 2. Phase transformation $1443 \text{ K}$
Mullite	1. High corrosion resistant 2. Low thermal conductivity 3. Not oxygen transparent	1. Crystallization ( $1023\text{--}1273 \text{ K}$ ) 2. Very low thermal expansion-coefficient
$MgZrO_2$	1. Low thermal conductivity $2 \text{ W m}^{-1} \text{ K}^{-1}$ 2. High fracture toughness 3. High Young's Modulus	1. Low Melting point $1600^\circ\text{C}$ 2. Very low thermal expansion-coefficient
Silicates	1) Cheap, readily available 2) high corrosion-resistance	1. decomposition into $ZrO_2$ and $SiO_2$ during thermal spraying 2. very low $\alpha$
$Al_2O_3$	1) high corrosion-resistance 2) high hardness 3) not oxygen-transparent	1. phase transformation ( $1273 \text{ K}$ ) 2. high $\lambda$ 3. very low $\alpha$

Table 3: Properties of TBC materials

Material	Properties
$ZrO_2$	$T_m = 2973 \text{ K}^{29}$ $D_{th} = 0.43 \times 10^{-6} \text{ m}^2 \text{ S}^{-1} (1273 \text{ K})^{30}$ $A = 2.17 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1} (1273 \text{ K})^{31}$ $E = 21 \text{ GPa} (1373 \text{ K})^{28}$ $\alpha = 15.3 \times 10^{-6} \text{ K}^{-1} (1273 \text{ K})^{32}$ $\nu = 0.25^{28}$
3YSZ	$T_m = 2973 \text{ K}^{33}$ $D_{th} = 0.58 \times 10^{-6} \text{ m}^2 \cdot \text{s}^{-1} (1273 \text{ K})^{27}$ $\lambda = 2.12 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1} (1273 \text{ K})^{27}$ $C_p = 0.64 \text{ J} \cdot \text{g}^{-1} \cdot \text{K}^{-1} (1273 \text{ K})^{27}$ $\alpha = 11.5 \times 10^{-6} \text{ K}^{-1} (293\text{--}1273 \text{ K})^{27}$
Mullite	$T_m = 2123 \text{ K}^{35}$ $\lambda = 3.3 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1} (1400 \text{ K})^{28}$ $E = 30 \text{ GPa} (293 \text{ K})^{36}$ $\alpha = 5.3 \times 10^{-6} \text{ K}^{-1} (293\text{--}1273 \text{ K})^{37}$ $\nu = 0.25^{28}$
NiCrAlY (bond coat of TBC)	$\alpha = 15.4 \times 10^{-6} \text{ K}^{-1} (293\text{--}1273 \text{ K})^{34}$

## VI. Thermal Barrier Coating Techniques

### A. Plasma Spray Coating

Plasma is a dense gas which has equal number of electron and positive ion and generally named as fourth state of the matter. This method has two primary priorities; It can provide very high temperatures that can melt all known materials and provides better heat transfer than other materials. High operating temperature of plasma spray coating, gives opportunity to operate with metals and alloys having high melting points. Also using plasma spray coating in inert surroundings is another positive side of the method. Oxidation problem of the subject material is reduced due to inert gas usage in plasma spray such as argon, hydrogen and nitrogen. All materials that are produced in powder form and having a specific grain size can be used in this method (Yaşar, 1997; Geçkinli, 1992).

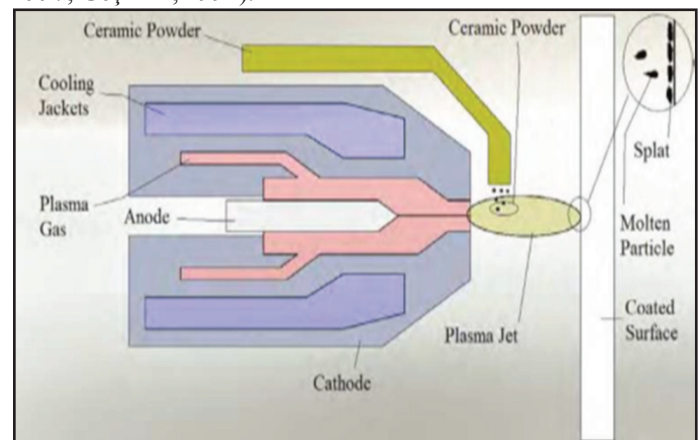


Fig. 4: Plasma Spray Gun [41]

### 1. Plasma Spray Coating Applications

Jet engines literally contain hundreds of components that are plasma spray coated. A commonly used coating in jet engines is produced with yttria partially stabilized zirconia (YSZ). This coating provides high temperature protection to components that

are exposed to combustion gases. The thermal protection allows the component to last longer and run at higher temperatures, which improves the system's overall performance efficiency.

**B. The EB-PVD Process**

The electron beam-physical vapor deposition (EB-PVD) process has overcome some of the difficulties associated with the CVD, PVD, and metal spray processes. In the EB-PVD process, focused high-energy electron beams generated from electron guns are directed to melt and evaporate ingots, as well as to preheat the substrate inside the vacuum chamber.

Mass production EB/PVD systems are equipped with one central coating chamber incorporating two electron beam guns and a reservoir of zirconia ceramic for the coating process. Preheating chambers are connected on either side of the coating chamber. Each preheating chamber allows the connection of up to two alternately actuated parts loading chambers. Each loading chamber is equipped with a carrier and drive system for the parts to be coated. This system carries the parts from the loading position to the preheating station and finally to the coating position. In the coating position, parts can be rotated, tilted or both at the same time, matching the part geometries and the specified coating thickness distribution requirement. Vacuum valves are installed between the coating and heating chambers. This allows the coating of parts loaded from the left side of the machine, while at the same time the next lot of parts is preheated in the right side heating chamber. As soon as the coating process is finished, the left side parts are moved out to the unloading station while the just preheated parts from the right side are moved into the coating chamber for coating. During the coating process, the left side parts are unloaded and replaced by new parts, which are then moved into the preheating position. The modular design of the EB/PVD coating system offers the possibility to install up to four loading chambers for the highest productivity requirement, two loading chambers for medium-size capacity or only a single loading chamber for pilot production or a small-size capacity requirement as needed by repair and overhaul shops today.

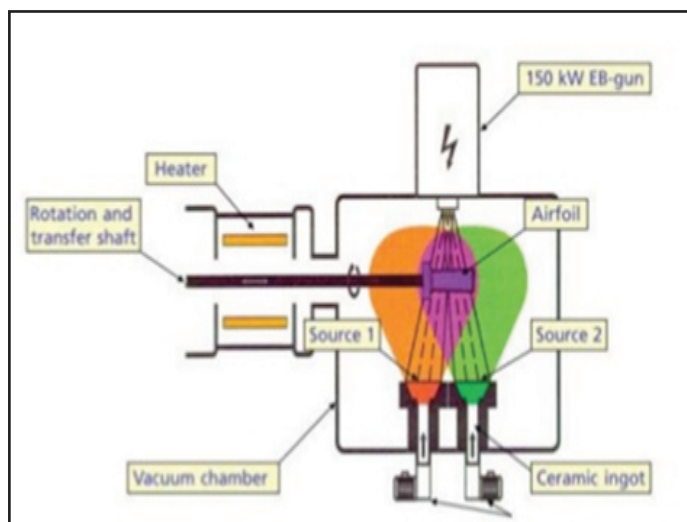


Fig. 5: Electron beam-physical Vapor Deposition(EB-PVD)(4)

**1. Advantages of EBPVD**

The deposition rate in this process can be as low as 1 nm per minute to as high as few micrometers per minute. The material utilization efficiency is high relative to other methods and the process offers structural and morphological control of films. Due to the very high deposition rate, this process has potential industrial

application for wear resistant and thermal barrier coatings in aerospace industries, hard coatings for cutting and tool industries, and electronic and optical films for semiconductor industries and thin film solar applications.

**2. Applications of the EB-PVD Process**

The versatility of the EB-PVD process is very wide and new varieties of coatings and materials continue to be developed. Some successful applications of the EB-PVD and ion beam-assisted EB-PVD processes are given below.

Table 4: Properties of TBCs produced by plasma spray and EB-PVD processes

Properties	EB-PVD	Plasma sprayed
Thermal Conductivity (W/mK)	1.5	0.8
Surface roughness (um)	1.0	10
Adhesive strength (MPa)	400	20-40
Young's modulus (Gpa)	90	200
Erosion Rate (Normalized to EB-PVD)	1	7
Microstructure	Columnar	laminated

**C. Powder Flame Spray Coatings**

In this method, micro-pulverized powder alloys are sprayed to target surface in oxyacetylene flame by oxygen vacuum. It is called cold coating because flame temperature is about 3300 oC and target surface is about 200 oC during coating process. Adherence is mechanical. Coating layer thickness is changed 0,5 to 2,5 mm according to shape of work piece. Using highly alloyed and self lubricant NiCrBSi materials as coating powder and making materials which are not produced in rod or wire shapes possible for coating are the main advantages of this method. Powder flame spray systems are proper for spraying primarily ceramics and metals and cermet's (metals and ceramic oxide alloys) as coating materials. Bearing supports, axle and shaft pivots, compressor pistons, cam shafts, bushes, rings and sleeves, hydraulic cylinders and pistons can be coated by this very method

**D. Wire Flame Spray Coatings**

Wire flame spray coating method is applied by spraying a wire shaped metal which has a melting point below flame temperature to coated surface. It can be used for metal spray materials and metal surfaces. Coating material wire is molten by oxygen and gas fuel flame after passing from the coating gun nozzle. Acetylene, propane and hydrogen are used for gas fuel. Relatively low equipment costs, high spray speeds and adjustment property according to wire diameters are the advantages of this system. Lower coating intensity and adherence strength comparing with other methods can be told as disadvantages of the method. Bearing supports, hydraulic piston pins, various bearings, shafts, wearing surfaces of axles, piston segments, synchromesh, crank shafts, clutch pressure plates can be coated with wire flame spray coating systems.

## VII. Over Past Researchers

Table 5: Investigators Over Researchers

Investigator	Type of TBC coatings	Technique	Result
Kazuhide Matsumoto*, Yoshiyasultoh, Tsuneji Kameda[65]	$Y_2O_3$ -HfO <sub>2</sub> (7.5YSH)	Electron-beam physical vapor deposition	1.The result of sintering behavior obtained by heating tests at 1300 and 1400 °C, it was considered that the thermal durability for the 7.5YSH coating was improved upto about 100 8C in comparison with the 8YSZ coating.
G. Sivakumar, S. Senthil Kumar[62]	Yttria Stabilized Zirconia (YSZ)	Plasma spray technique	1.The TBC coated engine shows better Brake thermal efficiency and better BSFC compared to the baseline engine. 2.Brake thermal efficiency is improved at all loads and speed conditions in the TBC coated engine. The improvement is ranging from 1.14% to a maximum of 8.84% at 50% of full load condition. 3.TBC coated engine reduces the specific fuel consumption by 3.38% and 28.59% at full load and 25% of the full load conditions, respectively when compared to the baseline engine.
S B Patond, S A Chaple, P N Shrirao, P I Shaikh[64]	3Al <sub>2</sub> O <sub>3</sub> .2SiO <sub>2</sub> (mullite) (Al <sub>2</sub> O <sub>3</sub> = 60%, SiO <sub>2</sub> = 40%) top coat NiCrAlY bond coat	Plasma spray technique	1.This insulation coating exhibits the brake specific consumption very close to conventional engine with deviation by about 1.76% higher at full engine load. 2.The LHR engines are exhibiting a higher rate of heat release compared with conventional engine
E. K. Arthur <sup>1,*</sup> , E. Ampaw <sup>1</sup> [63]	(Y <sub>2</sub> Si <sub>2</sub> O <sub>7</sub> / 3Al <sub>2</sub> O <sub>3</sub> .2SiO <sub>2</sub> /Yb <sub>2</sub> Si <sub>2</sub> O <sub>7</sub> )	plasma spraying	1.TBC coated engine reduces the specific fuel consumption by 5% and 30% at full load and 28% of the full load conditions, respectively when compared to the baseline engine.
S. Tailor <sup>1</sup> , R. M. Mohanty and P. R. Soni[64]	Al-SiC	plasma spraying	1.Coatings with a sol-gel silica coated SiC reinforcement increase the wettability of the SiC by molten aluminium giving rise to a more continuous coating. 2.The minimum porosity of 1% has been achieved.
P.N. Shrirao et.al [37]	mullite (Al <sub>2</sub> O <sub>3</sub> 60 % SiO <sub>2</sub> 40%).	plasma spraying	1. 2.18 % decrease on specific fuel consumption. 2. 12% increase on exhaust gas temperature
L. Wang, X.H. Zhong, Y.X. Zhao, S.Y. Tao, W. Zhang, Y. Wang, X.G. Sun[40]	YSZ/NiCoCrAlY	atmospheric plasma spraying (APS)	1.Thermal barrier coatings (TBCs) with excellent performance is to find an optimized coating structure with high thermal insulation effect and low residual stress.
Shchan et.al [39]	yttria stabilized zirconia (YSZ)	plasma spraying	1.Improvement in fuel economy upto 6 % at low engine power is reported. The peak cylinder pressure is reported to be increased by a magnitude of 8 to 10 bars in TBC piston engine
Roberi Vassen et.al [38]	yttria stabilized zirconia (YSZ) bottom coat pyrochlores or perovskites are used as top coat layers.	plasma spraying	1.To reduce the radiative heat transfer through the TBC.
E. Garcia et al (2009)	Mullite and mullite/ZrO <sub>2</sub> -7wt.%Y <sub>2</sub> O <sub>3</sub> coatings	Two powder processing routes Spray Drying (SD)	1.The powder morphology was correlated to the in-flight particle characteristics and splat morphology to gain insight about into the influence of powder characteristics on the coating formation.

### VIII. Fuel Consumption

Numerous investigators have modeled and analyzed the effects of in-cylinder thermal insulation on fuel consumption. The level of improvement that has been predicted ranged from 2 to 12 %. Kamoetal. [43] Test results indicate that coatings on the cylinder liner bore produced a reduction in fuel consumption while coatings on the piston and cylinder head-face surface were more effective in reducing heat rejection. Uzan et al. [42] reported 2% decrease in the engine specific fuel consumption with TBCs. Murthy et al. [44] indicate that LHR engine showed deteriorated performance at recommended injection timing and pressure and improved performance at advanced injection timing and higher injection pressure, when compared with conventional engine (CE). At peak load operation, brake specific fuel consumption (BSFC) decreased by 12%.

Thring [45] stated that comparison of SFC between baseline and LHR engine should be done carefully, because reducing the heat rejection affects other engine operating parameters such as volumetric efficiency, air-fuel mixing and etc., which in turn affect fuel consumption. Hence it is felt that, comparison between the two engines should be made at same engine operating conditions and same engine operating parameters. In general, it has been reported that fuel consumption of, naturally aspirated LHR engine is in the range of 0 to 10% higher, turbocharged LHR engine in the order of 0 to 10% lower and turbo-compounded LHR engine in the order of 0 to 15% lower, when compared with the conventional cooled engine.

### IX. Engine Efficiency

#### A. Volumetric Efficiency

The volumetric efficiency is an indication of breathing ability of the engine. It depends on the ambient and operating conditions of the engine. Reducing heat rejection with the addition of ceramic insulation causes an increase in the temperature of the combustion chamber walls of an LHR engine. The volumetric efficiency should drop, as the hotter walls and residual gas decrease the density of the inducted air. As expected all the investigations such as Thring [45], Assanis et al. [46], Gatowski [47], Miyairi et al. [48], and Suzuki et al. [49], on LHR engine show decreased volumetric efficiency. The deterioration in volumetric efficiency of the LHR engine can be prevented by turbo-charging and that there can be more effective utilization of the exhaust gas energy.

#### B. Thermal Efficiency

The improvement in engine thermal efficiency by reduction of in-cylinder heat transfer is the key objective of LHR engine research. Much work has been done at many research institutes to examine the potential of LHR engines for reducing heat rejection and achieving high thermal efficiency. Researchers such as Thring [45], Alkidas [50], Havstad et al. [51], Moore et al. [52], and many others have reported improvement in thermal efficiency with LHR engine. They attribute this to in transfer reduction and lower heat flux. However investigations of others such as Cheng et al. [53], Woschni et al. [54], Dickey [55] and some others report that thermal efficiency reduces with insulation. They all attribute this to an increase in the convective heat transfer coefficient, higher heat flux (increase in-cylinder heat transfer) and deteriorated combustion. The in cylinder heat transfer characteristics of LHR engine are still not clearly understood. Thus the effect of combustion chamber insulation on reducing heat rejection and hence on thermal efficiency is not clearly understood as on date. Hoag et al. [56],

Sudhakar [57], Yoshimitsuetal.[58], and Yonushonis [59] have reported improvement in the reduction of fuel consumption and in the thermal efficiency of LHR engine.

The effects of ceramic coating on the performance of the diesel engine were investigated by Taymaz [60, 61]. The combustion chamber surfaces, cylinder head valves and piston crown faces were coated with ceramic materials. The layers were made of CaZrO<sub>3</sub> and MgZrO<sub>3</sub> and plasma coated onto the base of the NiCrAl bond coat. The ceramic-coated research engine was tested at the same operation conditions as the standard (without coating) engine. The results showed that the increase of the combustion temperature causes the effective efficiency to rise from 32% to 34% at medium load and from 37% to 39% at full load and medium engine speeds for ceramic-coated engine while it increases only from 26% to 27% at low load. The values of the effective efficiency are slightly higher for the ceramic-coated case as compared to the standard case (without coating).

### X. Conclusion

In this review paper, various types of coating materials have been discussed among them the yttria stabilized zirconia is most widely used for TBC application in LHR engines and also optimizing the performance involves the addition of paired dopants, such as Nd<sub>2</sub>O<sub>3</sub> (or Gd<sub>2</sub>O<sub>3</sub>) and Yb<sub>2</sub>O<sub>3</sub> (and/or Sc<sub>2</sub>O<sub>3</sub>), into the ZrO<sub>2</sub>-Y<sub>2</sub>O<sub>3</sub> system. Thermal conductivity is another key element for the TBC performance. A lower thermal conductivity TBC lowers the substrate temperature and/or reduces the TBC thickness, which improves the performance and life of LHR engines. In this paper, the advantages and disadvantages of several materials for use as thick thermal barrier coatings in diesel engines were reviewed. In this paper show that APS and EB-PVD are most valuable techniques for deposition of TBC coatings on substrates.

Future demand of working in high temperatures in high speed engines and gas turbines with resistance to corrosion and erosion can be achieved by TBC's. YSZ, Mullite, Sic/Sic based Thermal barrier coatings have strong technological potential and rapid industrial growth is expected over the next decade. The objectives of improved thermal efficiency, improved fuel economy and reduced emissions are attainable, but much more investigations under proper operating constraints with improved engine design are required to explore the full potential of Low Heat Rejection engines.

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