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Review Article

THERMAL BARRIER COATINGS MATERIAL SELECTION, METHOD OF PREPARATION AND APPLICATIONS - REVIEW

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The desire to reach higher efficiencies, lower specific fuel consumption and reduced emissions in modern engines has become the primary focus of engine researches and manufacturers over the past three decades. Ceramic coating is a solution to such problems as they provide good thermal barrier properties for designers. In the design of adiabatic engines, reducing in-cylinder heat rejection requires very special thermal barrier coatings on the engine combustion chamber. Partial Thermal barrier coating (TBC) on the top surface of the piston is considered as a solution for reduction of unburned Hydrocarbon (HC) emission produced by incomplete combustion with respect to crevice volume when engines start. The TBC on the top piston surface decreases the thermal conductivity and increases the unburned charge oxidation, so that the metallic substrates will be exposed to lower peak temperature thereby reducing the thermal stress in engine components. Also thermal barrier coatings on other elements of combustion chamber of internal combustion engine offer advantages including fuel efficiency, multifuel capacity and high power density. Therefore, thermal barrier coating (TBC) technology is successfully applied to the internal combustion engines, in particular to the combustion chamber [1].

Keywords: Thermal Barrier Coatings, Yttria Stabilized Zirconia, Electrostatic Spray Assisted Vapour Deposition, Hot corrosion, High Velocity Oxygen Fuel process.

INTRODUCTION

General

Heat engines are based on considering various factors such as durability, performance and efficiency with the objective of minimizing the life cycle cost. For example, the turbine inlet temperature of a gas turbine having advanced air cooling and improved component materials is about 1500°C. Metallic coatings were introduced to sustain these high temperatures. The trend for the most efficient gas turbines is to exploit more recent advances in material and cooling technology by going to engine operating cycles which employ a large fraction of the maximum turbine inlet temperature capability for the entire operating cycle (A Parlak and V Ayhan, 2007).

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Thermal Barrier Coatings, as the name suggests are coatings which provide a barrier to the flow of heat. Thermal Barrier Coatings (TBC) performs the important function of insulating components such as gas turbine and aero engine parts operating at elevated temperatures. Thermal barrier coatings (TBC) are layer systems deposited on thermally highly loaded metallic components, as for instance in gas turbines. TBC's are characterized by their low thermal conductivity, the coating bearing a large temperature gradient when exposed to heat flow. The most commonly used TBC material is Yttrium Stabilized Zirconia (YSZ), which exhibits resistance to thermal shock and thermal fatigue up to 1150°C. YSZ is generally deposited by plasma spraying and electron beam physical vapour deposition (EBPVD) processes. It can also be deposited by HVOF spraying for applications such as blade tip wear prevention, where the wear resistant properties of this material can also be used. The use of the TBC raises the process temperature and thus increases the efficiency.

Structure of TBC

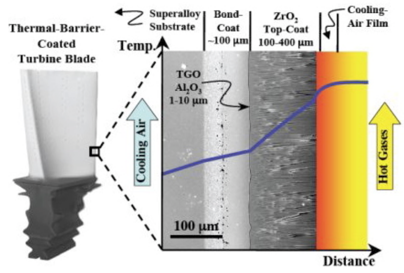
Modern TBC's are required to not only limit heat transfer through the coating but to also protect engine components from oxidation and hot corrosion. No single coating composition appears able to satisfy these multifunctional requirements. As a result, a coating system is being used (Bose S, 2007). Researchers have led to a preferred coating system consisting of three separate layers to achieve long term effectiveness in the high temperature, oxidative and corrosive use environment for which they are intended to function.

First, a thermally protective TBC layer with a low thermal conductivity is required as the outer layer to maximize the thermal drop across the thickness of the coating. This layer is also called the top coat. This coating is likely to have a thermal expansion coefficient that differs from the component to which it is applied. This layer should therefore have a high in-plane compliance to accommodate the thermal expansion mismatch between the TBC and the underlying nickel super alloy component. In addition, it must be able to retain this property and its low thermal conductivity during prolonged environmental exposure. A porous, columnar, 100-200 µm thick, yttria stabilized zirconia (YSZ) layer is currently preferred for this function.

Second, an oxidation and hot corrosion resistant layer is required to protect the underlying turbine blade from environmental degradation. This layer is required to remain relatively stress free and stable during long term exposure and remain adherent to the substrate to avoid premature failure of the TBC system. It is important that it also provide an adherent surface for the TBC top coat. Normally, the thin (< 1 µm), protective aluminium rich oxide which is thermally grown upon the bond coat is utilized for this purpose (M Cerit *et al*., 2011.)

Since the aluminium content of modern nickel based super alloy is not typically high enough to form a fully protective alumina scale, an aluminium rich layer (bond coat) is applied onto which the thermally grown oxide may get deposited. A ~100µm thick layer of either a low sulphur platinum aluminide or MCrAlY (where M is Ni or Co) is utilized for this purpose. Either low pressure plasma spray (LPPS) or pack cementations are used to apply the bond coat.

Figure 1: Layer Structure of Thermal Barrier Coating on a Turbine Blade



The thermally generated oxide layer is required to protect the substrate from oxidation and hot corrosion. The choice of base material (Co or Ni) is dependent on the primary corrosion mechanism, but as engine temperatures increase, the trend is towards CoNiCrAlY compositions. Cr and Al are present in the MCrAlY composition because they form highly tenacious protective oxide scales, whilst Y promotes formation of these stable oxides. MCrAlY coatings may be applied by a number of processes including:

- Physical vapour deposition (PVD) [8].
- Low pressure (LPPS), vacuum plasma (VPS) or air plasma spraying (APS).
- High velocity oxy-fuel (HVOF) spraying.

PVD and VPS offer high quality in terms of minimal oxidation of the coating during the deposition process, but are the most expensive. Approvals have been granted for the use of APS and HVOF coatings on certain components with significant cost savings. It is common for MCrAlY coatings to be deposited onto components pre-coated with Al, PtAl or Cr, which have been produced by vapour deposition techniques or diffusion processes.

Characteristics of TBC

There are certain characteristics that a good Thermal Barrier Coating should satisfy. They are listed as follows:

- High melting point: The coating should be having high melting point so that it can withstand high operating temperatures without melting away.
- Low thermal conductivity: The coating should have very low thermal conductivity so that it produces a considerable drop in temperature across the coating.
- Low density: The coating material should be having low density and weight in order to reduce the payload.
- High thermal shock resistance [4].
- Resistance to oxidation and chemical environment: The coating material should protect the underlying metal from oxidation and corrosion.
- High surface emissivity: The coating should have high emissivity so that a major portion of the incident heat is emitted away.
- Resistance to mechanical erosion: The coating should provide resistance towards the mechanical erosion caused due to the various particles present in the exhaust gas coming from the combustion chamber.
- High coefficient of thermal expansion: The coating material should have a coefficient of thermal expansion which is higher than that of the substrate so that it will not crack or fail when it is subjected to high temperatures.

Design Options for TBC

Some of the innumerable design options with regard to TBC are given below:

Fuel Flexibility

Corrosion resistance [5]

Alternative fuels

No derating for heavy fuels

Availability and Reliability

Corrosion / Erosion resistance

Lower metal temperature

Lower transient thermal stress

Efficiency

Reduce coolant flow

Increase the turbine inlet temperature

Capital cost

Easily cast super alloy

Simplified cooling

The options stressed above depend on the application of TBC. For aircraft turbines, emphasis has been placed on efficiency, durability and capital cost. For example, calculations have shown that the application of 1 mm oxide coating to the first two stages of an aircraft gas turbine can reduce cooling air consumption by 6.1% yielding a net thrust specific fuel consumption improvement of 1.3%. Alternatively, metal temperature and transient thermal stresses can be reduced significantly with more than a four-fold improvement in blade life.

For stationary gas turbines and diesel engines, emphasis has been placed on fuel flexibility and durability. In some cases, ceramics are more corrosion resistant than potential metallic coated materials, thus permitting firing with minimally processed fuels. They also result in lower metal temperatures; improve creep and thermal fatigue resistance of the substrate metal.

For small aircraft and land vehicles on IC engines, efficiency improvement has been emphasized.

Material Selection

Yttria stabilized zirconia has become the preferred TBC layer material for gas turbine engine applications because of its low thermal conductivity, k and its relatively high thermal coefficient of expansion (compared to many other ceramics). This reduces the thermal expansion mismatch with the high thermal expansion coefficient metals to which it is applied. It also has good erosion resistance which is important because of the entrainment of high velocity particles in the engine gases. The low thermal conductivity of bulk YSZ results from the low intrinsic thermal conductivity of zirconia and phonon scattering defects introduced by the addition of yttria. These defects are introduced because yttria addition requires the creation of O²? vacancies to maintain the electrical neutrality of the ionic lattice. Since both the yttrium solutes and the O^{2-} vacancies are effective phonon scattering sites the thermal conductivity is decreased as the yttria content is increased. YSZ has a room temperature, grain size dependent, thermal conductivity of 2.2-2.6 W/mK in the densest form. Adding porosity further reduces k and can improve the in-plane compliance (Parlak A, *et al*., 2003; Chan S, H, 2001; Srinivasan K K, 2010; Uzun A, 1999; Taymaz I, 2005; Chan S H and Khor K A, 2000; Buyukkaya E *et al*., 2006; Barbezat G, 2006).

METHODS TO PRODUCE TBC

As stated earlier the Thermal Barrier Coatings can be produced in industries by the following methods:

(i) Air Plasma Spray (APS)

(ii) Electron Beam Physical Vapour Deposition (EBPVD)

(iii) High Velocity Oxygen Fuel (HVOF)

(iv) Electrostatic Spray Assisted Vapour Deposition (ESAVD) and

(v) Direct Vapour Deposition (DVD)

The EBPVD and APS processes are widely used in industries whereas HVOF, ESAVD and DVD processes are less frequently used. Two processes are explained below.

Electrostatic Spray Assisted Vapour Deposition (ESAVD)

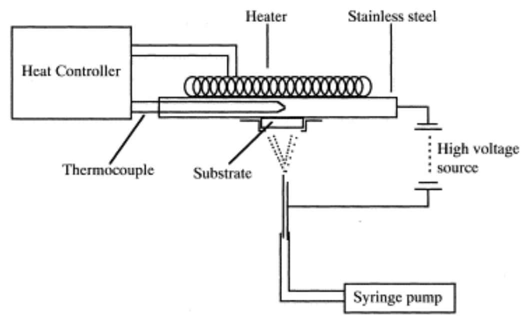
Principle

ESAVD is the process of producing coating on a heated substrate by spraying chemical precursors through an electric field. It is a non- line-of-sight-process. The electric field helps to direct the chemicals on to the substrate and initiate the chemical reaction. This leads to the formation of an adherent coating with the correct chemical and physical characteristics, together with the desired microstructure.

Process

The ESAVD process involves the spraying of atomized, charged droplets containing carefully formulated mixtures of coating precursor material through an electric field, in an otherwise ambient environment, towards a mildly heated substrate. Careful control of process conditions in the spray reaction zone (i.e. zone between spray nozzle and substrate) allows the appropriate chemical reactions to occur. These include evaporation/decomposition of aerosol droplets and formation of intermediate reactants that undergo chemical reactions in the vicinity of the heated surface of the substrate. This leads to the formation of an adherent coating with the correct chemical and physical characteristics, together with the desired microstructure. ESAVD enables the use of a simple aerosol type precursor delivery system to be combined with the vapour phase based coating of Chemical Vapour Deposition. ESAVD is a non-line-of-sight process, and therefore able to coat complex geometries, the electric field helps to ensure that a very high proportion of the precursor ends up on the substrate via electrostatic attraction. (Boehman A L, 1997).

Figure 2: Schematic of ESAVD Process



The unique spray reaction zone is a distinct environment that enables the chemical vapour deposition to occur unhindered. This means that coatings normally applied in dedicated reactors using moderate to high vacuums, and hence expensive vacuum systems, can now be applied in open atmosphere. The resulting deposition equipment is simple to construct and can be maintained easily with minimum equipment downtime, requiring a relatively low capital investment.

Features

- The equipment is simple to construct and can be maintained easily with minimum equipment downtime, requiring a relatively low capital investment.
- This coatings which were normally applied in dedicated reactors using moderate to high vacuums, and hence expensive vacuum systems, can be applied in open atmosphere.
- The use of electrostatics also ensures that ESAVD is a 'non-line-of-sight' process and can therefore be used to coat either flat surfaces or complex 3D geometries, e.g. hip implants, engine components and curved windscreens.
- Produces coatings with variable thickness at variable deposition rates depending on the conditions.

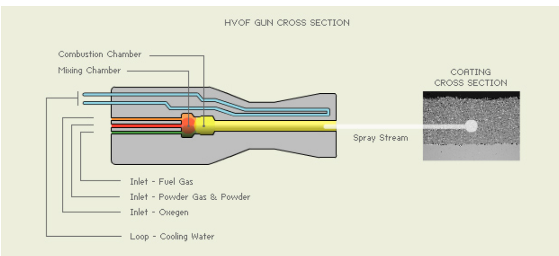
- Uniformity and microstructure can be precisely controlled to produce very high standard coatings, whether involving a dense coating onto a porous substrate or a porous coating onto a dense substrate.
- The electric field directs the precursor to the substrate, thereby minimizing losses to the surroundings, unlike other Chemical Vapour Deposition process. When ESAVD is optimized over 90% of the precursor will end up on the substrate.

High Velocity Oxygen - Fuel (HVOF)

Principle

The High Velocity Oxygen Fuel (HVOF) process is a subset of flame spray process. There are two distinct differences between conventional flame spray and HVOF. HVOF utilizes confined combustion and an extended nozzle to heat and accelerate the powdered coating material. Typical HVOF devices operate at hypersonic gas velocities, greater than MACH 5. The extreme velocities provide kinetic energy which help produce coatings that are very dense and very well adhered in the as-sprayed condition.

Figure 3: Cross Section of an HVOF Gun



Equipment

The HVOF gun has three different inlets for the fuel gas, ceramic powder and for oxygen. The three components are mixed in the mixing chamber and subjected to combustion in the combustion chamber. This combustion product is made to flow through a nozzle and directed on to the substrate to form the coating.

Process

In High Velocity Oxygen Fuel process, oxygen and a suitable fuel (acetylene, propylene, propane or hydrogen) is fed into a gun where it undergoes combustion to produce a high pressure flame. Ceramic powder is also fed into it axially. This melts the powder, which is then passed through a nozzle to increase it's velocity. This process produces dense strong coatings.

Features

HVOF is commonly used to produce very wear resistant coatings such as cermets (ceramic and metal mixes) like tungsten-carbide cobalt. Coatings of this type have wear resistance similar to sintered carbide materials. Since HVOF produces very dense coatings (porosity levels less than 0.5%), it can be used to produce very good corrosion resistant coatings from materials such as Inconel, Stellite, stainless steel and ceramics.

Applications

HVOF coatings can be incorporated into the design of complex components such as high-tech medical devices used for performing complex surgeries, to simple components such as bolts used in agricultural combines. Combines process incredible amounts of crops during harvesting. The wear created by the crop going through the machine can be extreme and in those cases the bolts that are used to attach critical internal components are coated with carbide materials to greatly extend the life of the bolt. The improved bolt assures the component that the bolt is holding remains attached.

APPLICATIONS OF TBC

Direct vapour deposition is mainly used for producing coatings on complex surfaces. It is capable of producing coatings on internal surfaces of machine parts which cannot be attained by other methods.

Turbine Blade Applications

Thermal barrier coatings have been extensively used to protect the internal surfaces of the combustion chambers in aircraft gas turbines (Ekrem Buyukkaya *et al*., 2006). Due to their low absorptivity and low thermal conductivity, such coatings yield a substantial reduction in metal temperature.

In turbines, the demands placed on TBC are far more stringent than in the combustor. The high convective heat fluxes encountered in the turbine results in large thermo mechanical stress in ceramic coatings under both transient and steady state conditions. The average and high metal temperature on the hot spots of the turbine range from 50 to 100°C higher than in the combustor. This places great demand on the environmental resistance of the bond coat. At these high surface temperatures, plasma sprayed coatings are subjected to process such as sintering and phase changes.

Earlier, thermal barrier coatings for turbine blade applications involved calcia and magnesia stabilized Zirconia and nichrome (Ni-20Cr) bond coats (all compositions are in weight percent). The first major advance was the identification of $ZrO_{2-}12Y_2O_3$ / Ni-16Cr-6Al-0.6Y system (Felicia M Pitek and Carlos G Levi, 2007. This new generation TBC offered superior durability compared to the oxide coat mentioned above. The bond coat operating temperature limit for this system is 850 to 900°C a significant improvement attributed to the improved environmental resistance of NiCrAlY.

CONCLUSION

Thermal barrier coating is actually a ceramic coating, which is having a layer structure. It not only reduces thermal fatigue but also protects the underlying metal from oxidation and corrosion. It helps to increase the operating temperature and also improves the engine performance. The life of the coated part is increased to a great extent.

The currently used coating material (yttria stabilized zirconia) is capable of providing considerable protection for the existing engines, but in future, more powerful engines will be developed and there is a need for a better coating material (Chan S H and Khor K A, 2000).

Various methods like plasma spray technology, electron beam physical vapour deposition etc. have significantly improved the reliability of TBC turbines, diesel engines and other heat engines. Processing improvement in the control and development of TBC are required. Further study on the mechanisms controlling coating adherence and degradation in clean and dirty environments, the effects of coating composition and structure on coating properties and correlation of models of engine tests are necessary to obtain thermal barrier coating that have even better tolerance to high temperature and thermo-mechanical stresses.

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