

Thermal Barrier Coating System and Different Processes to apply them- A Review

Shubham Barnwal¹, B.C.Bissa²Student Scholar, Dept. of Mechanical Engineering, RCOEM, Nagpur, Maharashtra, India¹Assistant Professor, Dept. of Mechanical Engineering, RCOEM, Nagpur, Maharashtra, India²

ABSTRACT: The depletion of fossil fuels and their increased cost has driven the attention towards energy security. The energy security can be moderately achieved by improving the efficiency of energy producing equipments. Thermal Barrier Coatings (TBCs) are refractory metal compounds deposited on substrate to reduce thermal loss and to protect components from high temperature. In this paper, a review about Thermal Barrier Coatings and different types of thermal spray processes involved for applying coatings is presented. (TBCs) are composite overlay of bond coat and ceramic topcoat on a substrate. Thermal sprayed coatings are extremely effective at increasing the component's life and value, further TBC decreases machinery down-time, and improve performance in a wide variety of applications.

KEYWORDS: Thermal Barrier Coatings (TBCs), Thermal Spray Coating Techniques.

I. INTRODUCTION

The trend in mechanical engineering has long been depicted by conflicting requirements: on one hand, customers want increasingly compact and lightweight parts while on the other hand, more stringent requirements are being imposed on engineered parts in terms of performance, reliability, and service life. Moreover, customers insist on reducing energy consumption and the use of ecologically safer coolants, lubricants and similar consumables in the smallest possible quantities. Extreme requirements must be fulfilled by the components and component surfaces of machines with key functions, whose failure would cause considerable downtime expense. The same applies to systems built for longevity and/or high operating reliability. One decisive criterion for the reliability and longevity of precision components is their frictional behaviour; it is largely determined by the properties of their surfaces. Accordingly, great importance is associated with the wide range of surface treatment methods which increases the wear resistance of parts and reduces friction.

Coatings: A coating is basically a covering which is applied to the surface of an object, usually referred to as the substrate. The application of coating can be decorative, functional, or both. The coating itself may completely cover the substrate, or it may only cover parts of the substrate. Paints and lacquers are coatings that have dual uses of protecting the substrate and being decorative, although artist's paints are used only for decoration, and the paint on large industrial applications are presumably only for the function of preventing corrosion. Some functional coatings are applied to change the surface properties of the substrate, such as adhesion, wet ability, corrosion resistance, or wear resistance. Coating can range from a simple brush for painting a wall, to some very expensive machinery which is used for applying coatings in the industry.

Thermal Barrier Coatings: Thermal barrier coatings (TBCs) are highly advanced material systems mostly applied to metallic surfaces, such as gas turbine or aero-engine parts which operate at elevated temperatures, as a form of exhaust heat management. The purpose of these coatings is to insulate components from large and prolonged heat loads by using thermally insulating materials which can sustain an appreciable temperature difference between the load-bearing alloys and the coating surface. TBCs basically consist of four layers: the metal substrate, metallic bond coat, thermally grown oxide, and ceramic topcoat.

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 9, September 2015

II. NEED OF THERMAL BARRIER COATINGS

A thermal sprayed coating effectively increases the component's life and value, decreases machinery down-time, and improves performance in a wide variety of applications. Thermal spraying can provide thick coatings as well as thin coatings. Thermal barrier coatings (TBC) can also be used to improve reliability and durability of hot section metal components and are also helpful in enhancing engine performance and thermal efficiency in diesel engines. As the combustion chamber temperatures of ceramic-coated engines are higher than those of uncoated (base engine) engines, it may be possible to use a fuel with a large distillation range and lower quality fuels. TBCs consist of a ceramic topcoat and a metallic intermediate bond coat due to which they are considered as duplex systems. The topcoat consists of ceramic material whose function is to reduce the temperature of the underlying, less heat resistant metal part. The bond coat protects the metallic substrate from oxidation and corrosion and also promotes the ceramic topcoat adherence.

Bond Coating: Bond Coating is a thermal sprayed coating applied to provide a 'key' for subsequent build-up coats of a different material. It gives adhesion between coating and substrate, the thermal barrier bond strength depends on the process and material used. Some sprayed materials adhere strongly to clean smooth surface. They are adherent over a wide range of conditions and a thin layer can serve as an 'anchor' for materials sprayed on top. Interface of super alloy (substrate) and ceramic coating (TBC) plays a most important role in resisting failure. This interface is usually produced from different types of bond coating (BC). Based on variation of temperature of service exposure/experiment, every metallic constituent plays different roles to transform to lower state of energy. As a result, the respective effects are reflected to substrate and bond coat, with increasing periods of exposure. The depletion of valuable constitutions results in loss of thermo mechanical properties.

Properties of Coating Materials

The coating material should have the following properties:

1. **Low thermal conductivity:** The material used for coating should resist almost or complete heat transfer to the substrate.
2. **High thermal stability:** The coated material should be able to sustain very high temperature. It should have very high melting point so that base or substrate material could be protected from high temperature corrosion.
3. **High wear resistance:** The coated material should have oxidation and corrosion resistant property. It can be achieved by properly heat treating the coated material.
4. **Hardness:** The coated material should possess optimum range of both micro and macro hardness.
5. **Good adhesive property:** The coated material should be well adhered to the substrate. So that bonding strength will be excellent.

III. MATERIALS FOR TBC

The selection of TBC materials is restricted by some basic requirements. They are high melting point, low thermal conductivity, chemical inertness, no phase transformation between room temperature and operation temperature, thermal expansion match with the metallic substrate, low sintering rate of the porous microstructure and good adherence to the metallic substrate. So far, only a few materials have been found to basically satisfy these requirements.

1. **Zirconates:** The main advantages of zirconates are their low sintering activity, low thermal conductivity, high thermal expansion coefficient and Good thermal cycling resistance. The problem is its high thermal expansion coefficient which results in residual stress in the coating, and due to which delamination of coating occurs. Some materials in this category; e.g. $\text{BaO}\cdot\text{ZrO}_2$, $\text{SrO}\cdot\text{ZrO}_2$, and $\text{La}_2\text{O}_3\cdot 2\text{ZrO}_2$, undergoes phase transformation or become non-stoichiometric during heating.
2. **Yttria Stabilized Zirconia:** 7-8% Yttria stabilized Zirconia has high thermal expansion coefficient, high thermal shock resistance and low thermal conductivity. Disadvantages of Yttria stabilized Zirconia are phase transformation at 1443^0 K and sintering above 1473^0 K , corrosion and oxygen transparent.
3. **Alumina:** It has very high hardness and chemical inertness. Alumina has relatively high thermal conductivity and low thermal expansion coefficient compared with Yttria stabilized Zirconia. Even though alumina alone is not a good thermal barrier coating candidate, its addition to Yttria stabilized Zirconia can increase the hardness of the

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 9, September 2015

coating and improve the oxidation resistance of the substrate. The disadvantages of alumina are high thermal conductivity, low thermal expansion coefficient and its phase transformation at 1273⁰K.

4. **Garnets:** Polycrystalline garnet ceramics are used in different applications due to their unique properties. Particularly YAG (Y₃Al₅O₁₂) is a good choice for many high-temperature applications, due to its excellent high temperature properties and phase stability up to its melting point (1970°C). Other advantages which make YAG a candidate as a TBC are their low thermal conductivity and its low oxygen diffusivity. Although the thermal conductivity value is almost same as Zirconia, the thermal expansion coefficient is lower.

IV. DEGRADATIONS OF THERMAL BARRIER COATING

In thermal barrier coating degradations occur because of

1. Failure of bond coat by cracks and top coat penetration.
2. Thermally grown oxide formation in voids and porosity.
3. Open interfaces and thermally grown oxides.
4. No significant rumpling of ceramic coating after thermo mechanical fatigue.
5. Crack penetration in bond coat and sometimes through ceramic coat and,
6. The coat does not respond to comparative creep phenomenon and produces thermal shielding to inhibit rumpling by reducing plastic deformation and bending elastic strain.

Effects of corrosion and erosion

The protective coating produces thermal shielding and chemical reaction protection to substrate. In-service interfacial oxides resist oxidation of substrate from diffusing species of environment. The corrosion-erosion phenomenon in this case plays either exogenously from the environment or endogenously from the substrate. Environmental degradation of petrochemical components is due to reactive contamination of gases consisting of low oxygen, sulphur, carbon, sodium sulphate, sodium chloride and vanadium compounds. At low temperatures environmental variation arising from liquid compound deposition of sodium sulphates and nitrates on coated surface, the variations of interfacial pH of respective metal/coating and corroding deposition to gaseous media increase the corrosion rate. The corrosion rate is high in the presence of liquid deposition than gas-metal/coating surface reaction. Concentrations of desirable elements perform the following functions. Aluminium forms alumina layer, Yttrium improves adherence property of alumina, platinum and precious elements like Rhodium and Palladium reduce other elemental depletion. The undesirable elements like Sulphur and Boron reduce alumina adhesion and increase oxide pit formation. In the presence of boron, incomplete transformation of silicon to silica forms low melting silicate compounds within interfacial oxide layer. This disrupts the strength of interface even at lower temperatures. Coating degradation takes place by thermally induced stress arising from differences in coefficient of thermal expansion, in-situ scale thickness variation, thermal fatigue, and loads in service. Occurrence of both erosion and corrosion limits the rate of reaction by either corrosion enhanced erosion or erosion enhanced corrosion phenomenon.

V. INTRODUCTION TO THERMAL SPRAY PROCESSES

Thermal spraying is a general term to describe all methods in which the coating is formed from melted or semi-melted droplets. In thermal spraying, the material is in the form of powder, wire or rod which is fed into the flame produced by a spray gun, where it melts and the formed droplets are accelerated towards the substrate which is to be coated. The thermal and kinetic energy of the flame can be produced either by burning mixtures of fuel gas and oxygen or by using an electrical power source.

Based on the energy source, thermal spray methods can be divided into a few main groups:

1. Plasma spray methods (APS, VPS, LPPS),
2. Combustion Flame Spray Methods (FPS, FWS)
3. High velocity oxy/air - Fuel methods (HVOF/HVAF),
4. Arc spray methods
5. Cold gas methods (CGS).

Since coating is built up from flattened, fast solidified droplets the velocity plays an important role. For the obtained density of the lamella structured coating, temperature of the flame has a strong effect on the suitable materials to be sprayed. Ceramic coatings are mainly manufactured by using Atmospheric plasma spray method, while temperature sensitive materials, such as cermets, are more preferably sprayed by methods with a lower flame temperature. Figure 1 presents the typical operation ranges for various systems.

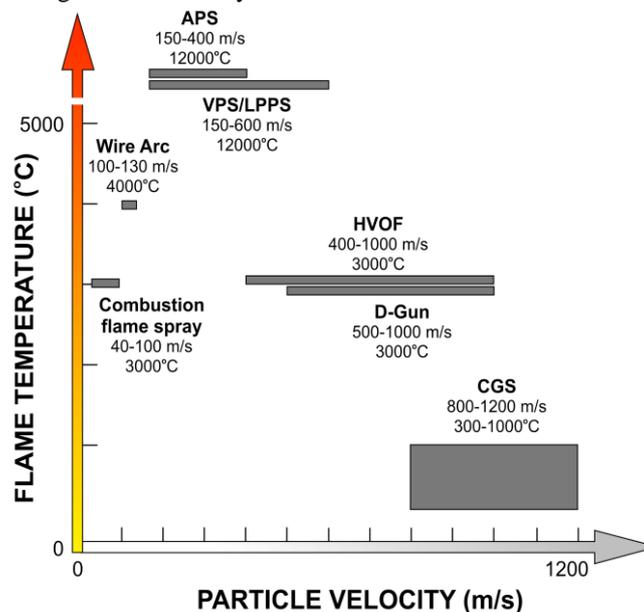


Figure1. Typical flame temperature and particle velocity operation ranges for various thermal spray systems. [6]. For example, at a temperature of 3000° C, the particle velocity for HVOF spray system varies from 400-1000 m/s. Similarly, flame temperature for different systems can be correlated.

Depending factors

1. **Powder size:** As powder size decreases, the hardness, wear resistance increases.
2. **Process and Feedstock:** Thickness and bond strength of coating depends upon on the process and feedstock.
3. **Particle Velocity:** Greater the Particle Velocity more will be the adhesive property and more bond strength.
4. **Flame Temperature:** More the Flame Temperature, more fine the coating appears.

For example: Ceramic coatings are mainly manufactured by using Atmospheric Plasma Spray method, while temperature sensitive materials, such as cermets, are more preferably sprayed by methods with a lower flame temperature.

VI. MAJOR THERMAL-SPRAY COATING PROCESSES

1. **Plasma spray:** Uses a plasma-forming gas (typically argon or nitrogen) as both the heat source and propelling agent for the coating material. A high voltage arc struck between an anode and cathode within the gun ionizes the gas, which is then forced through a convergent/divergent nozzle. As the gas exits the nozzle, it reverts to its natural state, liberating large amounts of heat. Powdered coating material is injected into the hot gas stream, where it is melted and projected at high velocity onto a prepared substrate.

Advantages: Coatings are dense and strongly bonded to the substrate. In general, they have higher integrity and perform better than coatings applied by other thermal-spray processes.

2. **Wire flame spray:** Applies coatings of any metal that can be drawn into a wire. It has a melting point below that of a combustion flame. Drive rolls feed the wire through a flame-spray gun to its nozzle where the wire is melted in an oxygen/fuel-gas (oxy fuel) flame after which compressed air atomizes the metal and projects it onto the prepared surface.

Advantages: Best choice for all-purpose spraying. Coatings can be applied rapidly and at low cost.

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 9, September 2015

3. **Electric-arc spray:** It applies metal coatings in wire form. Push/pull motors feed two electrically charged wires through the spray gun. When their tips touch at the gun head, an arc is created which melts the wires at temperatures above 3,980 °C after which compressed air atomizes the molten metal and projects it onto a prepared surface.

Advantages: It can spray up to a large area and can also apply thick coatings. Its built-in flexibility permits tailoring of coating characteristics, such as hardness and surface texture.

4. **High-Velocity Oxy-fuel (HVOF):** It uses high-velocity combustion of mixtures of oxygen and a fuel gas to heat and propel semi-molten-to-molten powdered materials. The sprayed particles impact the substrate with extremely high kinetic energy and with negligible oxidation of the coating material.

Advantages: Compared with other thermal spray processes, the HVOF method produces coatings that have the highest bond strength and lowest porosity. Coatings also have low internal stresses, which allow thick layers to be deposited, and fine as sprayed surface finishes. HVOF is well suited to producing high-quality tungsten and chromium-carbide coatings.

The comparison of plasma sprayed and HVOF sprayed oxide ceramic coating using Yttria-stabilized Zirconia (YSZ), Alumina (Al_2O_3), and Chromia (Cr_2O_3) as coating materials are shown in figure 2.

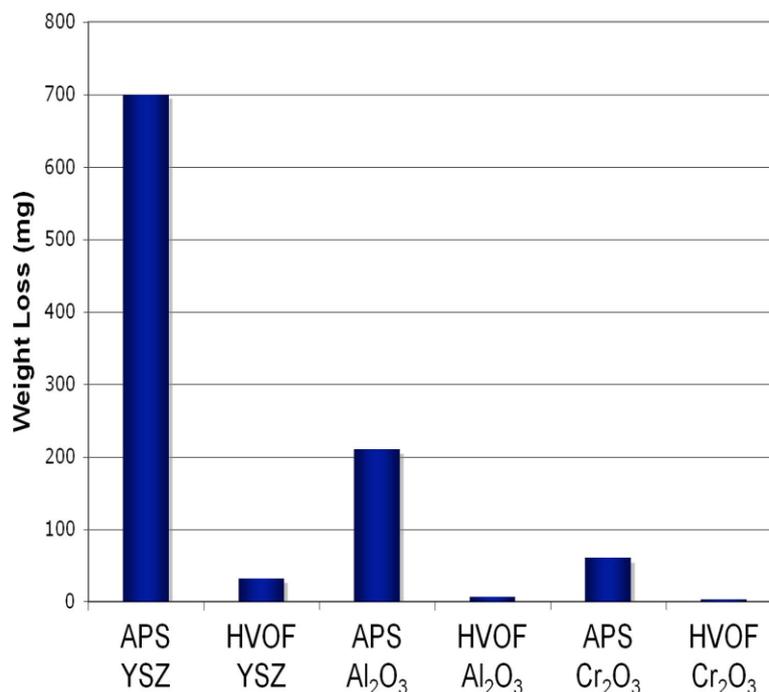


Figure 2. Comparison of abrasive wear resistance of ‘plasma sprayed’ and ‘HVOF sprayed oxide ceramic’ coatings using Yttria-stabilized Zirconia (YSZ), alumina (Al_2O_3), and chromia (Cr_2O_3) as coating materials [6].

The figure 2 shows the comparison of weight loss in milligrams for different coating film materials if applied by APS or HVOF spray processes.

COMPARISON OF WEAR RESISTANT COATINGS

Generally it is recognized that the wear resistance properties of HVOF coatings are superior to their APS counterparts. HVOF sprayed coatings have improved density and less pores and cracks than the APS sprayed. It has been found out by measuring in a standardized rubber wheel abrasion test that the abrasion wear resistance of the coatings is improved more than tenfold when the coating is made by HVOF spraying. This difference is more than 15 times with Alumina and Chromia coatings where the spray parameters have been optimized. The HVOF Zirconia coatings perform more

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 9, September 2015

than 20 times better than the corresponding APS coatings. It must be noted though that the reference value for comparison is for Thermal Barrier Coating (TBC), where maximum density is not aimed. However, the results show that HVOF spraying of ceramics can be an effective method to produce dense, well-adhered ceramic coatings with good environmental protection capability. This can be attributed mainly to the lower porosity and improved cohesion of the ceramic coating structure when produced by HVOF techniques. The comparison of different spray processes based on the different coating types and their property are shown in table 1.

Table 1. Comparison of major thermal-spray coating processes

Property	Coating type	Wire flame spray	Powder flame spray	Electric arc	Plasma spray	HVOF
Bond strength [Mpa]	Ferrous.	14	28	41	34+	62
	Non	21	21	41+	34+	70
	Ferrous	-	69+	-	-	62
	Ceramics	-	14-34	-	21 +	-
	Carbides	-	34-48	-	55-69	83+
Hardness [HRC]	Ferrous	35	35	40	40	50
	Non	40	20	80 HRB	40	55
	Ferrous	-	30-60	-	-	60
	Ceramics	-	50-65	-	50-70	-
	Carbides	-	50-60	-	50-60	65
Coating thickness limitation [mm]	Ferrous.	1.25-2.5	1.25-2.5	1.25-2.5	1.25-2.5	1.25-2.5
	Non	1.25-5	1.25-5	1.25-5	1.25-5	2.5-5
	Ferrous	-	0.4-2.5	-	-	1.25
	Ceramics	-	0.4	-	0.4	-
	Carbides	-	0.4	-	0.4	0.6

VII. FUTURE OF THERMAL COATINGS

The search for low thermal conductivity materials for thermal barriers is only just beginning. The innumerable range of chemical compositions of all refractory oxides and minerals precludes a purely Edisonian approach in identifying compositions; it is simply too time consuming and costly. Improved thermal barrier coatings (TBCs) will make maximum utilization of future gas turbines and will enable it to operate at higher gas temperatures. Considerable effort is being invested, therefore, in identifying new compositions which will help in improving the performance even better than the current industry standard, Ytria-stabilized Zirconia (YSZ). The most rapid progress will probably only be made by using a combination of intuition about crystal structures and atomic-level simulations to guide experiments.

VIII. CONCLUSION

This paper presents the review of different factors which affect the thermal coating process. It is observed that the need of TBCs and advantages of applying it on different components. Thermal barrier coating leads to improved life of implements and increases performance of hot section. Bond coat plays an important role in providing thermal-physical-chemical-mechanical compatibility between ductile substrate and ceramic topcoat. In most cases spallation is a dominant mode of failure. Undesirable elements increases interfacial activity and reduce the life of coating. The improvements in the properties of coatings are mainly due to mismatch at interface, decrease in thermal conductivity, and porosity, which lower the absorption of corrosive chemicals at the interface.

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 9, September 2015

REFERENCES

1. Ravikumar T, Kiran K, Ravichandra V Koti, Chetan Appasab Chougale, "Alternative Thermal Barrier Coatings for CI Engines", IJRAT, Vol. 2, No.5, pp.350-355, May 2014
2. K.N.Balan, Manimaran.S, B.R.Ramesh Bapu, A.John Rajan,"Enhancement of surface property by thermal spray coating technique", 10th IRAJ International Conference, Tirupati, India, pp.29-31, October 2013
3. B. Goswani, A.K.Ray, and S.K.Sahay,"Thermal barrier coatings for gas turbine application", (CSIR) Jamshedpur,pp.73-92, December 4, 2003
4. M. Hetmańczyk, L. Swadźba, B. Mendala, " Advanced materials and protective coatings in aero-engines application" , JAMME, Vol.24 Issue 1, pp.372-381, September2007
5. Masaki Tanaka , Yoshihisa Kitajima , Yasuhisa Endoh, Masaoki Watanabe, Yutaka Nagita , "Ceramic-metal Composite Coated Piston Ring and Cylinder Liner of Marine Low Speed Diesel Engine" M.E.S.J., Vol. 21, No.2, pp.77-85, October 1993
6. Maria Oksa,Erja Turunen,Tomi Suhonen,Tommi Varis and Simo-Pekka Hannula, "Optimization and Characterization of High Velocity Oxygen-fuel Sprayed Coatings: Techniques, Materials, and Applications" , MDPI Journal, pp.17-52, September 2011
7. David R. Clarke, Simon R. Phillpot, "Thermal barrier coating materials" Materials today, pp.22-29, June 2005
8. Prakash C. Patnaik , Xiao Huang, Jogender Singh, "State of the Art and Future Trends in the Development of Thermal Barrier Coating Systems", In Innovative Missile Systems, pp. 38-1 – 38-20. Meeting Proceedings RTO-MP-AVT-135, Paper 38. Neuilly-sur-Seine, France: RTO, May 2006

BIOGRAPHY



Shubham Barnwal, is a student Scholar at Department of Mechanical Engineering, Shri Ramdeobaba College of Engineering and Management, Nagpur. He is actively involved in research projects related to automobiles and has contributed in BAJA-2015, a vehicle design and development projects by SAE INDIA. He is presently working on portable personal cooling systems for people working in hotter zones.



Prof. B. C. Bissa is working as Assistant Professor, Department of Mechanical Engineering, Shri Ramdeobaba College of Engineering and Management, Nagpur. He is actively involved in research projects related to I.C. Engines and Automobiles. He has guided several students for BAJA and SUPRA, vehicle design competitions by SAEINDIA as a faculty advisor and presented several research papers in journals and conferences.