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Scientific Outcomes on Thermal Barrier Coating: A Review

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Abstract: *An extensive literature review on the Thermal Barrier Coatings (TBC'S) has been done with the motive to build and add-on a strong foundation and understanding of the abovesaid coating technology. This paper mainly discusses the important findings reported by the researchers on the functionally graded coatings, applied to the Internal combustion engine and in the allied engineering fields. The research findings are centric towards the pros and cons in the related field of TBC viz. coating techniques, coating microstructure, microhardness, microporosity, tribology, and corrosion but not limited to. This article may help the researchers and scientists to extend their knowledge and apply the important findings prudently in the field of engineering sciences and technology.*

Key Words: *Thermal Barrier Coatings, Temperature, Microhardness, Temperature etc.*

1. A REVIEW:

There are several research works reported on microstructural studies of coating applied on the different substrates. It has been noticed, during the spraying process, the thermal cyclic effect during the coating process has a detrimental effect on the microstructure of the coating. Giovanni Di Girolamo [1] has prepared zirconia-based lanthanum zirconate, and ceria-yttria-stabilized zirconia (CYSZ), and carried out several studies such as microstructure formation, thermal and mechanical properties. This investigation has helped the other researchers to develop multilayer thermal barrier coatings. In their research, they observed that there would be enhanced phase stability for the surface, which is made up of CYSZ and $La_2Zr_2O_7$ at and above 1300°C when compared with YSZ coating. It has also observed that the specific heat capacity is also affected due to sintering at this high temperature. Gurusamy [2] developed the zirconia, alumina, and composite thermal barrier coating made up of a mixture of zirconia and alumina on a stainless-steel substrate by varying the spray parameters. He studied the microstructure, porosity, and hardness. He found that if the quantity of the alumina increases, the porosity of the coating decreases, and hardness value increases. With the rise in the volume of alumina in the composite mixture, it increases the hardness value from 1083Hv to 1371Hv, whereas porosity decreased from 33.7% to 7.65%, and wear weight loss decreased from 8.38 to 1.49 mg/cm^{2}h, but bond strength decreases from 112.2kgf/cm^2 to 64.5kgf/cm^2. Jing Wu [3] and Tilmann Beck [4] used the APS technique for their coatings and which contains nanostructured ceramic YSZ coating. In their research, they have compared this nanostructured coating with the conventional YSZ coating. The porosity found to be increased by 25% in the nanocoating than the traditional coating, which might be due to the increase in the inter splat gap in nanostructured powder coating. In their research, it has also noticed that the thermal conductivity of nanostructured coatings decreased to 0.8-1.1 W/mK, which is 40% lower than the conventional coating. There is an increase in the life of about 500 cycles in APS coating than traditional YSZ coating techniques. Jianguo Zhu [5] studied the thermal barrier coating of YSZ material to determine the porosity, microstructure, and coating's hardness. In their study, they found that there will be a decrease in the porosity with an increase in temperature. Their study found that this decrease in the porosity at elevated temperature may be due to the grain growth and crack closeness. Sung-Hoon Jung [6] mentioned that the bi-layered Yb-Gd-YSZ with a buffer layer of high purity 8YSZ showed better performance than the 8YSZ topcoat alone. In their research, they found that thermal behavior performance improved when the thickness of the topcoat increases up to 4times of the coating thickness from 200µm-800µm.

Ningning Hu [7] prepared the plasma sprayed YSZ coating on the aluminum alloy to study the surface morphology, pores, and cracks on the coating material and discussed the relationship between the thermal conductivity and grain boundary density. In their work, they noticed that the big angle crack would have a significant effect on the heat diffusion at both the low temperature (25°C) and at a high temperature (1200°C). N. P. Padture [8] mentioned an innovative method called solution precursor plasma spray (SPPS) for zirconia-based thermal barrier coating and found a noticeable improvement in thermal cycle life than the conventional YSZ. In their work, they found a new innovative SPPS process. The TBCs have the absence of splats, evenly spaced vertical cracks, a porous microstructure with the nanometre-sized grains, most desirable and required property such as low thermal conductivity and improved thermal life cycle of the coating. Amol D. Jadhav [9] prepared the 7YSZ thermal barrier coating using both atmospheric plasma spray and solution precursor plasma spray (SPPS) technique and found a reduction in the thermal conductivity in the SPPS method. He developed the analytical model with the help of an object-oriented finite element (OOF) to capture the effect of real microstructures on the coating's thermal conductivities. Z. Kavaliauskas [10] studied the influence of plasma nozzle jet temperature for making a dense microstructure through the YSZ coating technique. The temperature between 3000°C- 3350°C, the cubic crystal orientation has formed; at this temperature, an excellent dense and proper microstructure for thermal barrier coating has developed, and with the increase in temperature, the nature of crystalline tendency decreases. In their work, they found the profoundly influencing parameter on the performance of the thermal barrier coating is the coating powder's properties and the plasma process temperature. They proposed from their work, the best plasma process temperature region will be between 3200°C-3350°C. P Sokołowski L [11] yttrium/ceria stabilized zirconia coating by suspension plasma spraying technique on the stainless steel substrate and studying thermal conductivity and thermal diffusivity properties by varying the spray distance and gun speed. They found the thermal diffusivity in the range of 0.23 to 0.49 × 10−6 m2/s and the thermal conductivity about 0.5 W/ (m K). C Batista [12] developed an 8YSZ APS thermal barrier coating subjected to the CO_2 laser glazing process with the different process parameters such as track overlapping and beam scanning speed and found the reduction in the surface roughness of the coating. Robert Vaßen [13] prepared the thermal barrier coating for suspension plasma spray (SPS) and produced a unique microstructure that is not provided by the conventional method. In SPS considerably smaller size of the droplet, disintegrated at plasma jet and reduced the pores and led to the dense coating on the substrate. R A Miller [14] studied the thermal barrier coating by a physical vapor deposition method (PVD) for aircraft airfoils and the aircraft turbine section. S Sampath [15] studied the rapid solidification of the coating. They studied ultrafine grains, and metastable microstructure found to form at a high velocity. Hongbo Guo [16] used the crushed powder of 8%YSZ coating and showed an effect on the mechanical properties. He mentioned that the microstructure and thermal conductivity are very much sensitive among all the spray parameters. In their work, they observed that the high segmentation crack density would influence the heat treatment may moderately increase the reduction in Young’s modulus of the thermal barrier coating and strength. R Taylor [17] has critically evaluated the zirconia powder and their properties and suitability for the thermal barrier coating and found a more stable form of zirconia powder. Ashish Ganvir[18] examined the specimens prepared from the axial suspension plasma spraying (ASPS) and found the distribution of pore size in terms of submicron and nanoscale. He compared the coating characteristics with the other coating method, such as electron beam physical vapor deposition. He found that the coating prepared by the ASPS has the following advantages viz. reduced vertical intersplat, thermal diffusivity, and thermal conductivity. Paweł Sokołowski [19], Soha A [20] prepared a thermal barrier coating using two plasma spraying gun SG-100 of Praxair and Triplex of Oerlikon Metco. They used yttria-stabilized and calcia stabilized zirconia powder and studied the properties of the coating and found the thermal barrier coating produced by the Triplex of Oerlikon Metco having the uniform microstructure and the porosity of the coating when compared with the other gun. Qinghe Yu [21] doped the nanostructure Al_2O_3 with YSZ and developed the coatings with the help of atmospheric plasma spraying. He studied the coated specimens for microstructure and phase composition with the help of SEM, TEM, and XRD. He observed that after doping, the coefficient of thermal expansion of YSZ is decreased to 10.928 x 10-6 /K. Further addition of Al_2O_3 leads to a decrease in thermal conductivity, and life is increased to1000 cycles at 1100°C. In any thermal barrier coating, the coating's durability mainly depends on the type of topcoat materials used.

Generally, in most of the thermal barrier coatings, the topcoat material used is Yttria-stabilized zirconia. Emine Bakan [22] reviewed many papers on different thermal barrier coatings and discussed some new methods such as suspension plasma spraying and its importance in the coating techniques. Dapeng Zhou [23] developed the thermal barrier coatings by the new process of spraying called axial suspension plasma spraying and found columnar structures in the coating. Here the thermal cycle test of the coatings is weaker than the APS coatings. The spray parameters are also considered for the coating characteristics and found that bond coat roughness and standoff distance played an essential role in the coating lifetime. From the above work, it has found that the standoff distance influences the coating's roughness as the standoff distance increases the roughness of the bond coat decreases. An increase in standoff distance deteriorates the performance of the coating. There is a chance of liner worn out due to the piston's movement over cylinder liner. It is of prime importance that the coating inside the cylinder liner should withstand the heat and have excellent wear resistance. Several researchers have studied the improvement in the wear resistance of thermal barrier coating. Kristina [24] deposited the ceramic coating on the stainless-steel substrate using an atmospheric plasma spray coating technique. She coated yttrium stabilized zirconia and studied its tribological behavior. The worn-out surfaces are examined under SEM and found that Alumina-Zirconia having composition 15wt. % and 85wt. % have better wear properties than at unlubricated conditions. In her next research [25], the structural and tribological characteristics of zirconia and alumina-based ceramic coating explained. She found a drastic improvement in the mechanical properties with lubricated underwater conditions. Rajarathnam [26] studied the microstructure and abrasive wear properties of the AISI1040 steel surface with Cr_2O_3 ceramic materials. Here better wear properties observed for ceramic coating containing 85% Al_2O_3. The microcracking increased in some cases due to the increase in microhardness value on the coating after the wear. N Krishnamurthy [27] studied the alumina and yttria-stabilized zirconia composite coatings deposited by a plasma spraying technique on the Al6061 substrate. He has observed that coatings' wear has been affected by microstructure, roughness, porosity, and topcoat thickness. The coefficient of friction increases, which attributed to the three-body abrasion. D. M.Kennedy [28] carried out erosion, impact, and dynamic wear tests on coated and uncoated samples. In their investigation, they found that the testing method applied mainly affects the wear rate. Simulation models created and data obtained from this correlated with the experimental results Boneche [29] discussed the effect of intensity of plasma spraying and particle size on wear properties. The samples subjected to SEM and XRD characterization. The coating exhibits excellent property when the plasma intensity is 625 A. Samples also tested for erosion wear and noticed that erosion rate is more at 90° angle of impact [30].

S Dallaire et al. [31] have done some exciting experiments, where they sealed aluminum phosphates over chromium oxide coating. There is an increase in the hardness of 200 to 300HV. The abrasion and wear resistance also increased with this method. The coating showed excellent corrosion resistance when kept at the acidic and alkaline environment for 30 days. P Ctibor [32] further studied the formation of pores by these techniques. He mentioned that one should be careful in the selection of spray parameters for these techniques. From the extensive investigation, they found that there was an improvement in the properties of coatings when they subjected to the annealing process.E. Erzi [33] prepared the plasma sprayed thermal barrier coatings on the Al 6063 substrate. 8% YSZ material is used as a topcoat and Ni-Cr-Al as a bond coat. Wear and coefficient of friction conducted on the prepared sample. Vickers's hardness value found for coated samples were 266 HV3 ± 5, friction coefficients measured to be between 0.101-0.218. N.Krishnamurthy [34] studied the plasma sprayed coatings on cast iron substrate and developed a relationship between the different properties such as surface roughness, porosity, and thickness of the coating. He observed that the coefficient of friction highly influenced by the load than the other coating parameters. He further prepared the two types of thermal barrier coatings on the Aluminium substrate and conducted the erosion test. Results showed that alumina coatings have more erosion resistant than $ZrO_2$5CaO coatings. N.Krishnamurthy [35] prepared the thermal barrier coating consists two topcoat layers, which is made up of pure alumina and calcia partially stabilized zirconia, in between the topcoat and substrate there will be two bond coat which made up of Metco 446 and Metco 410. Measured the coating thickness, porosity, microhardness, and coating density, and conducted adhesion tests and solid particle erosion tests. In their research they found following observations i) density of Al_2O_3 is 2.48-2.67 g cm-3 and for calcia stabilized zirconia is 6.78-6.96 g cm-3 ii) the highest value of adhesion strength 15MPa was obtained for $ZrO_2$5CaOcoatings iii) Al_2O_3 coatings having 1100 to 1180 HV is harder than the $ZrO_2$5CaO iv) erosion wear was more at 45° angle of impact. J. J. Coronado [36] studied the effect of grain size during the abrasion wear and found that the abrasive grain size will affect the wear mechanism. Abdul Rahim Mahamad Sahab [37] studied the bond strength or adhesion strength by varying plasma spray parameters such as current, powder flow rate, and standoff distance. In their investigation, they found an increase in bond strength when the current increased from 550A to 650 A and powder flow rate from 22.5g/min to 26g/min. P. Kulu [38] prepared the tungsten carbide-cobalt (WC-Co) coating with the help of a detonation gun and studied the wear property and effect of hardness of materials on the wear. R. Westergard [39] studied many plasmas sprayed specimens prepared by axial and radial injection plasma spray systems with different process parameters such as powder type, nozzle size, and varying percentages of hydrogen and energy input. The resistance of the coating increases with the increase in hydrogen content and nozzle size. The abrasion and erosion wear rates are reduced by 10 to 20% when hydrogen gas supply and nozzle size increased. Also, the medium-sized precursor coating powder was advantageous because of the high grain size or very small grain size on coating quality compared with alumina coating. Hyo-Sok [40] developed the thermal barrier coatings of 5% calcia stabilized zirconia,8% yttria-stabilized zirconia, 20% yttria-stabilized zirconia and alumina-zirconia composite topcoat on cast iron and steel substrates. In their work, they have studied the wear characteristics. During the wear, there is a plastic deformation which influenced the Coefficient of friction and wear rate. Maozhong Yi [41] studied the wear properties for abradable coating materials such as M307, M310, M313 and M601 (METCO 307-75% Ni:25% graphite, METCO 310-57% Al:8% Si:35% graphite, METCO 313-40% Al, 5.5% Si: 45.5% graphite,9% organic binder and METCO 601-40% polyester,60% Al-Si alloy). He found that M313 possesses good readability when compared with other types of coatings. X. Nie[42] prepared the alumina coating on Aluminium substrate BS Al 6082 by using the electrolytic plasma technique. They are subjected to abrasive wear and corrosion test and found that the specimen prepared by the electrolysis process exhibits excellent wear and corrosion resistance property.

2. CONCLUSION:

It can be summarized that thermal barrier coatings in an internal combustion engine possess advantages such as improved thermal efficiency and combustion, reduction in weight with the elimination of the cooling system, and so on. However, several practical issues have to examined while implementing these coatings in internal combustion engines. A significant amount of research activities have carried out to achieve TBCs in different parts of the IC engine. The survey of the published literature indicates that, at present, TBCs applied to combustion chamber components of IC engines such as piston crown, valves, cylinder cover, and cylinder liners. However, the extended applications of TBC to cylinder liners have not realized practically. The cylinder liner is one of the vital segments of an IC engine that experiences severe wear and tear because of the sliding movement of the piston. Also, the hot gases produced due to the combustion of air-fuel mixture inside the cylinder develop thermal stresses in the liner. The problem presently faced in the implementation of TBC as an engine cylinder liner is a thermal mismatch that mainly occurs due to improper adhesion and difference in thermal expansion coefficients between the bond coat and cylinder material. There is a need to conquer these issues for its compelling usage to the liner of the engine cylinder.

Conflict of Interest: The authors confirm that this article content has no conflict of interest.

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