© Universiti Tun Hussein Onn Malaysia Publisher's Office

IJIE

Journal homepage: http://penerbit.uthm.edu.my/ojs/index.php/ijie
ISSN : 2229-838X e-ISSN : 2600-7916

The International Journal of Integrated Engineering

Development and Adhesion Strength of Plasma-Sprayed Thermal Barrier Coating on the Cast Iron Substrate

Haridasa Nayak[1*], N Krishnamurthy[2], Shailesh R A[3]

[1]Department of Mechanical Engineering,
PES University, Electronic City Campus, Bengaluru-560100, INDIA

[2]Department of Mechanical Engineering, Vijay Vittal Institute of Technology, Bengaluru-560077, INDIA

[3] Department of Industrial and Production Engineering, The National Institute of Engineering, Mysuru, INDIA

*Corresponding Author

DOI: https://doi.org/10.30880/ijie.2021.13.01.006
Received 13 February 2020; Accepted 14 April 2020; Available online 30 January 2021

Abstract: In the present scenario, the atmospheric plasma spray is used as a very important and effective weapon to produce the thermal barrier coating (TBC) on the substrate which will impart required surface characteristics to the components which are demanded by the industry. The TBC is used to impart the required characteristics such as wear, corrosion and thermal resistance to the hot section component where these will undergo severe service condition at elevated temperature. Research is carried out to replace the conventional liners in the I.C Engine by the thermal barrier coated ceramic liner. To achieve this, in this work cast iron substrate is used and it has been coated with a thermal barrier coating with the help of atmospheric plasma spraying. Coating consists of equalproportion yttria stabilized zirconia (YSZ) and pure alumina as topcoat ceramic material and in-between these topcoat and substrate there are two bond coat first bond coat is nickel-iron-aluminium composite powder (Metco 452) between the substrate and second bond coat. Second is alumina-nickel-aluminide powder blend (Metco 410 NS) between the topcoat and first bond coat. Coatings were subjected to microstructure analysis, porosity and adhesion strength. In this work, top coating thickness ie. 300µm exhibits more percentage of porosity ie.4.2% than other two coating thickness 200 and 100 µm 3.9% and 3.5% respectively. The bond coat will possess porosity percentage of 4.0 %, 3.5 % and 3 % for C3, C2 and C1 respectively. The adhesion strength test of the coatings was conducted and determined by the help of varying the topcoat thickness from 100µm to 300 µm with a step of 100 µm. In this work, it was established that the topcoat with the 100 µm exhibits the very good bond strength 70.81 MPa when compared with other two coating thickness 200µm and 300 µm have the adhesion strength 69.1 MPa and 65.52 MPa respectively. ASTM C 633 standard is used to prepare and conduct the test.

Keywords: Plasma spray, microstructure, porosity, adhesion strength, coating thickness

1. Introduction

It is very much necessary to apply the thermal barrier coating (TBC) to the gas turbine and the diesel engine to improve the engine performance and protecting the hot section component trying to make them long-lasting. TBC plays a significant role in keeping components of Internal Combustion Engine (i.c engine) namely liner of the cylinder, crown

*Corresponding author:haridasanayak@gmail.com

and piston rings in proper surface texture. The friction between the cylinder and piston will lead into the tear and wear of the liner. In this context, the conventional liner is replaced by the plasma sprayed ceramic coated liner to impart wear-resistant and strong bonding of the liner with the engine cylinder. Application of this thermal barrier coating will extend and improve the lives of the liner and make the liner will available for the greater time of operation. In this work atmospheric plasma spraying technique is adopted because of its high efficiency, good feasibility and cost-effective. The coatings were produced in nature of high dense, less porous and possess very good lamellar structures.

The thermal barrier coating is subjected to the various testing environment such as hot corrosion, wear, adhesion test [1]. The chemical composition and the microstructure plays an important role in the life prediction of TBC. Microstructural uniformity of the thermal barrier coating is very much necessary to improve the following properties of the coating such as the thermal and mechanical property of the system [2]. The degradation of the coating is not only by oxidation and hot corrosion, apart from this development of stress and strain during the operation of the component at high pressure and temperature. The reason behind the generation of stress and strain may be due to centrifugal and aerodynamic forces, vibrations and thermomechanical cycling [3]. Increase in the porosity of the coating will decrease the thermal conductivity and will harm the mechanical strength of the coating due to a decrease in cohesion between lamellas [4].

It is also of prime importance on the selection of the substrate and the coating material to use as a liner in engines. M. Gupta [5] studied the Failure Analysis of a single layer and Multi-layered thermal barrier coating prepared by the Suspension Plasma-Sprayed coating technique on the substrate Hastelloy-X for the gas turbine application. They have conducted a thermal cyclic fatigue test (TCF) and thermal shock test. The failure mode in TCF testing was cracking close to the topcoat– bond coat interface. In single-layer topcoats, splitting happened close to the topcoat– bond coat interface while in bilayer topcoats, the failure happened in the upper topcoat layer close to the interface between the two topcoat layers because of lower fracture toughness of the second topcoat layer. Isrihetty Senain [6] developed the thin film of TiO2 by Sol-gel method using Titanium butoxide for different coating thickness. Different thickness films are subjected to Annealing. From the above, they found that the annealing process and the number of layer influence the crystallinity and morphology of TiO2 thin film. Xiaotao Luo [7] studied the thermal barrier coating prepared by the high-velocity thermal spray technique on the substrate mild steel and evaluated adhesion strength and tensile properties of coatings. These studies pointed to a robust new strategy to interpret adhesion and cohesion of sprayed coatings subjected to deliberate variations in chemistry, roughness and processing. Markus Mutter [8] used the Inconel 718 as the substrate for their research and deposited 8YSZ on it. They studied the effect of spray Parameters on the Mechanical Properties of coatings. From their exploration they found that the coating microstructure is characterized by the molecule condition; low molecule liquefying prompts high porosity and the other way around. Depositing the coating with the chose spray parameters with an all-around characterized substrate condition permits designing the thermal stress that is superimposed on the quenching stress. Woo Y Lee [9] studied the various failure methods of thermal barrier coatings and its reason to fail. He has used the different types of Functionally Graded Materials (FGM) such as YSZ, Al_2O_3, $3Al_2O_3.2\ SiO2$ (Mullite) and TiO_2.

The main purpose of the thermal barrier coating is to provide the insulation for the components of Gas Turbine and diesel engines. These coatings are made up of ceramic materials and which will increase the capacity of the liner to withstand for the high-temperature operation. Generally, the thermal barrier coating is consists of one ceramic topcoat and one bond coat, this bond coat is in between the ceramic topcoat and the substrate. In this work, the typical coating is made up of two bond coat layer and one topcoat layer. The bond coat thickness is maintained at 75 µm each and the top ceramic coat is varied from 100 µm to 300 µm in steps of 100 µm. The bond coat between the topcoat and the substrate will provide the proper sticking of the topcoat to the substrate and also acts as a reservoir for Alumina in the thermally grown oxide (TGO) during the coating is exposed to elevated temperature. At an elevated temperature of operation these thermal barrier coating may peel off, this will leads to failure of the thermal barrier coating. This can be avoided if sufficient adhesion is exhibited by the coating between the substrate and topcoat. Generally, the Yttria stabilized zirconia is used as a ceramic material is to build a thermal barrier coating due to its good characteristics such as low thermal conductivity, high hardness and low density. Apart from above it also has the following characteristics such as high thermal expansion coefficient, phase stability at elevated temperature and inertness to the chemical reactions when compared with other ceramics.

Ultimately the life of the thermal barrier coating purely depends on how the bond coat clings to the substrate and how the bonding (adhesive or cohesive) in the interface of bond coat and topcoat. Delaminating of the coating either in the region of bond coat and substrate or in the region of topcoat and bond coat will lead to the tear and wear of the coating and further, it leads to the failure of the coating. Finally, the coating should possess the characteristic of longlasting, in this context adhesion of the coating to the substrate will play an important role in the question of the durability of the coating. In this work, the adhesion strength of the coating is studied and discussed in details.

2. Experimental Details

2.1 Coating Architecture

In this work, we have selected properly blended equal-proportion (50:50) Yttria Stabilized Zirconia (YSZ) and Pure Alumina (Al_2O_3) as a ceramic topcoat and two bond coat. The first bond coat (BC1) which is very next to the substrate is made up of the Nickel-Iron Aluminium Composite Powder (Metco 452). The bond coat (BC2) in between the ceramic topcoat and the first bond coat is Alumina Nickel Aluminide powder blend (Metco 410 NS). The coating architecture is as shown in figure 1. In all the specimens, each bond coat is having the thickness is equal to 75µm and topcoat thickness varies from 100 µm, 200 µm and 300 µm (Termed as C1, C2 and C3).

Table 1 gives the information about the various bond coat and topcoat materials, their particle size, chemical composition, the morphology of coating, what process is followed to melt the powder and spray on to the substrate and their critical characteristics. Table 2 is put light on the plasma spray parameter such as pressure maintained for the primary gas, secondary gas and the carrier gas. It also gives information about the current, voltage spray distance and the feed rate for the different coating powder and different coating thickness.

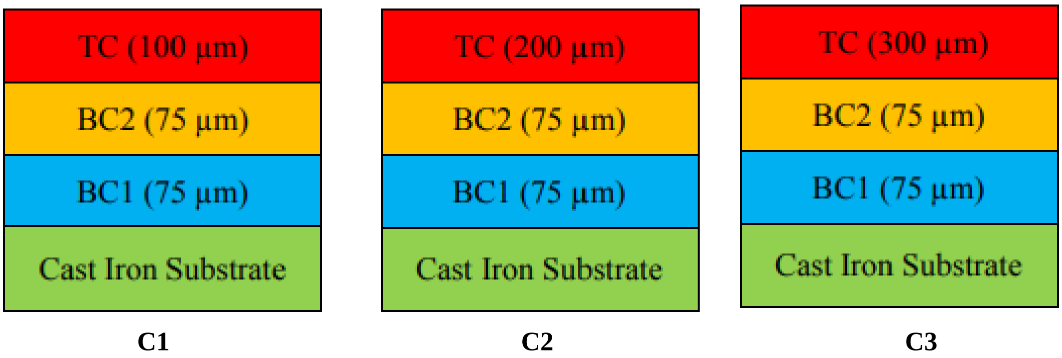

Fig. 1 - The architecture of thermal barrier coating on cast iron substrate

Table 1 - Composition of coating materials

Parameters	**Metco 452 (BC1)**	**Metco 410NS (BC2)**	**Equal Proportions blended Mixture**	
			Metco105SFP Top Coat(TC)	**Metco 204NS** Top Coat (TC)
Application	**Cast Iron substrate**	**Cast Iron substrates**	**Cast Iron substrate**	**Cast Iron substrate**
Chemical Composition	Fe 38Ni10Al	Al_2O_3 30(Ni20Al)	99.5 Al_2O_3	ZrO_2 8Y_2O_3
Particle Size	125+45□m	90+15□m	31+3.9□m	125+11□m
Morphology	Clad	Blend	Angular/Blocky, Fused and Crushed	Agglomerated & Plasma densified (HOSP)
Process	Air Plasma Combustion Powder	Air Plasma, Combustion Powder	Air Plasma, combustion Powder	Air Plasma
Properties	The material experiences an Exothermic Reaction amid Spraying and Forms a Strong Metallurgical Bond with the Base Metal Oxidation Resistant up to 810°C.	Coatings are Denser, Stronger, More Abrasive and Shock Resistant than Pure Ceramics and Very Hard and Smooth.	Excellent Dielectric Strength and refractoriness.	Well known for excellent flow, chemical homogeneity and structural integrity For the thermal protection of hot section components 250 °C.

2.2 Specimen Preparation for Microstructure, Adhesion Strength

The specimens are prepared from the cast iron is of dimensions 30mmx30mmx5mm (length, width and thickness) for microstructure as per ASTM standard E 1920-03 [10]. To conduct the adhesion strength the specimens are made by the cylindrical solid rod of diameter 25 mm and length is 70mm each. One of the diametrical sides of the specimen is coated with above-said coating materials with variation in topcoat thickness. At the same time for adhesion test specimens without coating also prepared of diameter 25mm and length 70mm. Figure 2. Shows the as-sprayed specimens for various coating thickness (C1, C2, C3). These specimens are prepared for the morphology of the coatings.

Table 2 - Plasma spray parameters

Material	Primary gas Pressure (Argon) kPa	Secondary gas Pressure (Hydrogen) kPa	Carrier gas (Argon) flow lpm	Current A	Voltage V	Spray distance mm	Feed rate kg/h
50% Al_2O_3+50%ZrO_2 8Y_2O_3 (TC)	700	520	60	600	65	64-125	2.7
Metco 452 (BC1)	700	340	37	500	65	100-175	4.1
Metco 410NS (BC2)	700	350	37	500	65	75-125	1.6

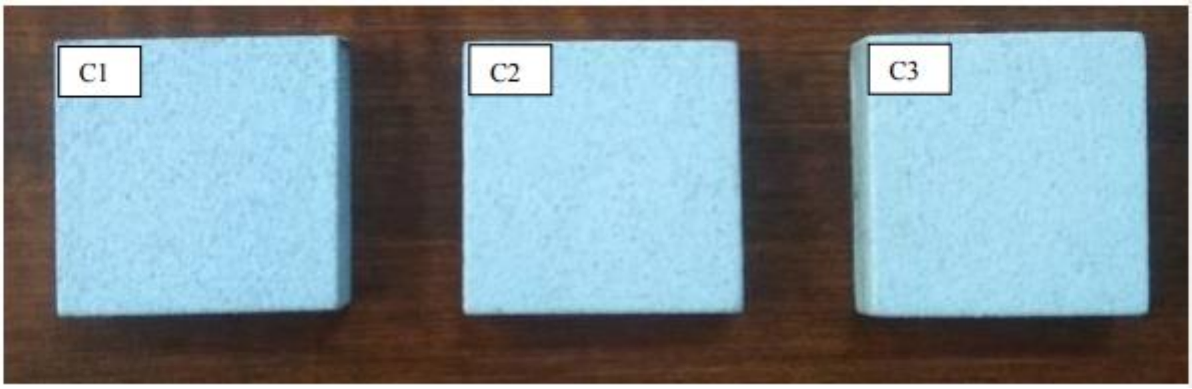

Fig. 2 - Specimens as-sprayed coating for microstructure

2.3 Microstructure and Coating Thickness

Specimens were prepared for the microstructure as per the ASTM standard E 1920-03. The top surface of the coatings was viewed under Carl Zeiss, Neon 40 Crossbeam Scanning Electron Microscope (SEM). Coating thickness is measured as per the ASTM standard E 1182-93 (Reapproved 1988) [11].

2.3 Porosity Test

The formation of pores is the common phenomenon observed in all types of thermal barrier coating irrespective of the methodology and technique used for the coating. Porosity is having its advantages and disadvantages in the function of the thermal barrier coating. The porous can be categorised like mesopores, microporous and nanoporous. It is also categorised depending on their size that A type and B type [12-13], a porous which is having the size 1-10µm are belonged to A-type and from 11-25µm belongs to B type. In the present work, the different layers of coating systems were subjected to porosity measurement. In the procedure, the cross-sectional SEM images of coating systems were fed to the IMAGE J software. This software scans the SEM images and records the percentage of porosity. The average of 5 trials at different spots was recorded. The porosity test is conducted as per the ASTM standard E 2109-01 [14].

2.4 Adhesion Strength

The coated diametrical side is joined with the uncoated diametrical side of the uncoated specimen with the help of epoxy adhesive and ultimate length of the specimen is increased to 140mm, this length is very much necessary to hold the specimen in the UTM (Universal Testing Machine). The particulars of the machine are, make; Venus instruments, model 40PC-M, load range 0-40kN, least count 0.1kN with adjustable jaws 10-25mm. While joining the coated and uncoated specimens with the help of adhesive glue at a contact pressure of 3-4 bar was applied on the specimen axially by holding it in a C-clamp as shown in figure 3 (d). The adhesive used in this work is Epoxy polymer-3M ScotchWeld-DP460 off-white (as shown in Fig.3. c) and curing temperature at 70°C for 2 hours. Figure 3(a-g) illustrate the coated specimen, uncoated specimen, adhesive glue used, specimen kept in C clamp after adhesive glue is applied, joined specimen and these joined specimens or ready specimen kept inside the furnace for curing. As per the ASTM standard C-633 [15] adhesion test was conducted.

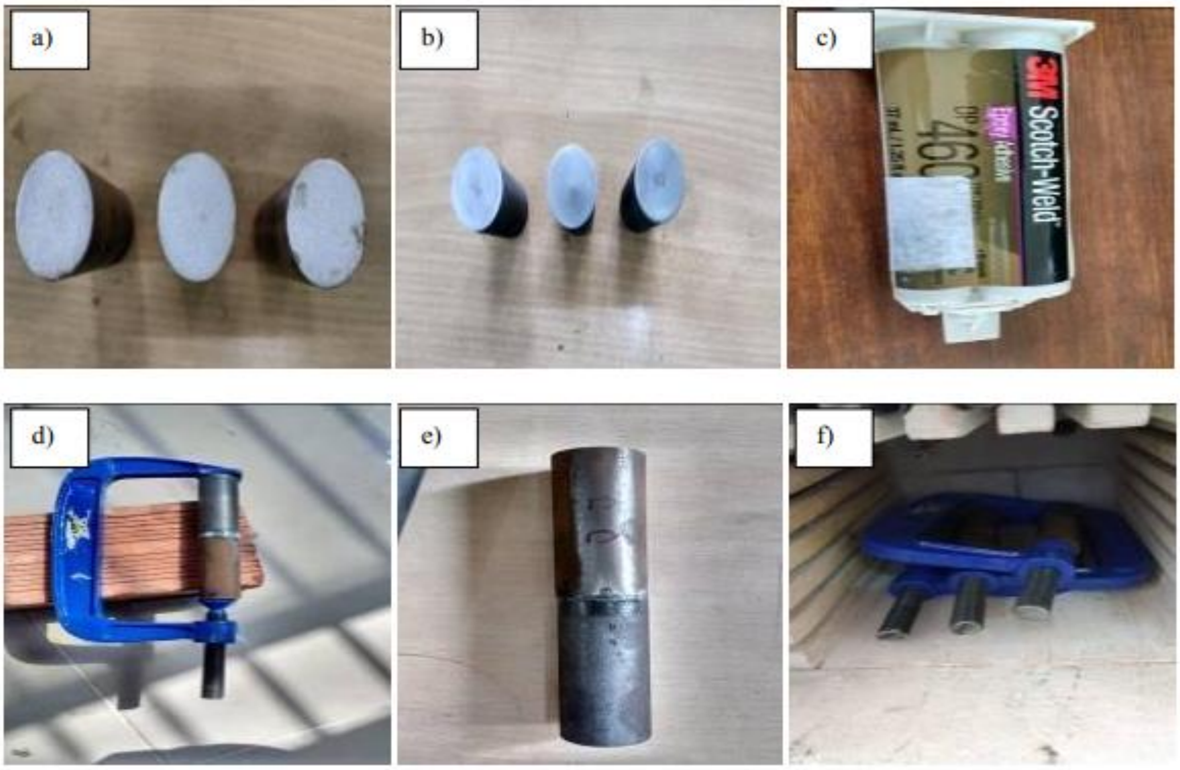

Fig.3. Specimen prepared for adhesion strength a) with coating b) without coating c) adhesive glue d) holding the specimen in C-clamp e) specimen joined for test f) specimen kept at the furnace for curing.

Table 3 - Properties of Epoxy polymer (3M Scotch-Weld-DP460 off white)

Solids Content	100%
Viscosity at room temperature	95-100 N Sm^{-2}
Cure Schedule at 23-70□C	30-120 Minutes
Tensile Strength at room temperature	>90 MPa
Tensile Shear Strength (Al-Al at 25□C)	>21 MPa
Volume Receptivity at room temperature	>21 MPa

3. Results and Discussion

3.1 The microstructure of as-sprayed Coatings

Plasma sprayed thermal barrier coating process is complex and involve many interrelated variables [16]. This process takes place at high temperature and high pressure, a small change in the controllable or uncontrollable parameters will have a huge influence on the microstructure of the coatings.

The proper observation microstructure of as-sprayed coating under the Scanning Electron Microscope (SEM) reveals that as-sprayed coating contains the molten particles, semi-melted particles and rarely observed small porous. Majority of the coating surface contained with molten particles and very few un-molten particles are observed. The porosity will play an important role and influence the adhesive strength of the coating. Porosity will have an adverse effect on the bonding of the coating to the substrate and will play important role in the degradation of the coating and will form a channel for the influencer to the rate of oxidation. Figure 4 and Figure 5 illustrate the microstructure of the various coating thickness of as-sprayed coatings.

The bond coat between the ceramic topcoat and the substrate will reduce the ceramic-metallic thermal expansion mismatch, minimize the cracking in the coating and prolong the delamination of the coating. This bond coat layer will help to accommodate the space for thermally grown oxide (TGO), which will become a further barrier for oxidation. Minor cavities and lamellar structure were observed in the cross-sectional microstructure of the coatings and which will help to offer resistance to the spallation of the coating. It is also observed that there will be micropores and microcracks, which will help to reduce the residual stress induced in coating and reduction in thermal conductivity of the coating.

It is a well-established relationship between mechanical strength and microstructure. It is observed that there will be less number of micropore and cavities in C1 when compared with C2 and C3, these will little be increased in the coating thickness from 200µm to 300µm (C2 and C3). This may be due to impinges of plasma spray at high force and temperature to the substrate may create mechanical locking between the substrate and the coating layer which will minimize the microporous and the microcracks.

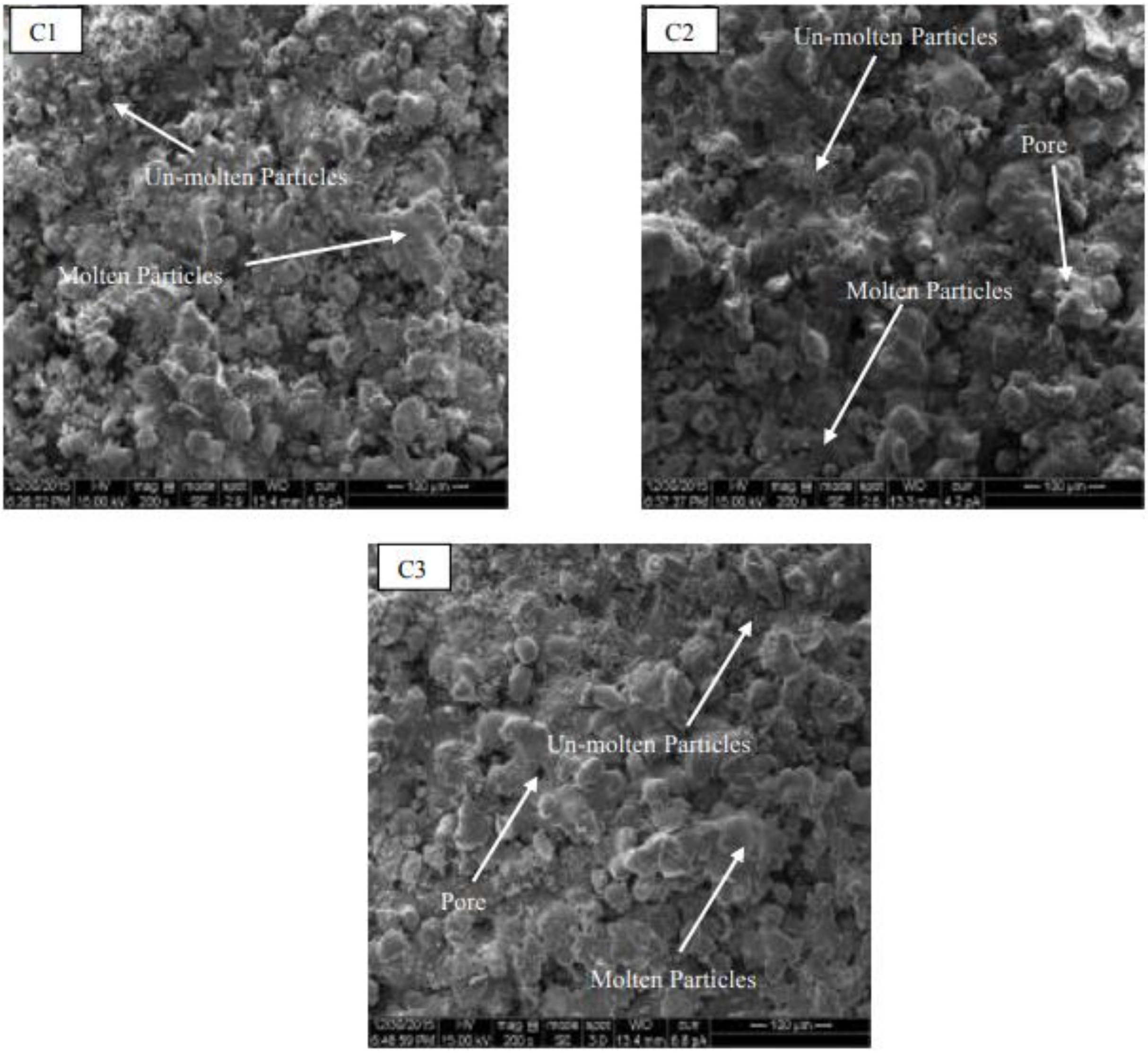

Fig. 4 - The microstructure of as-sprayed specimen of different coating thickness at lower magnification 200x

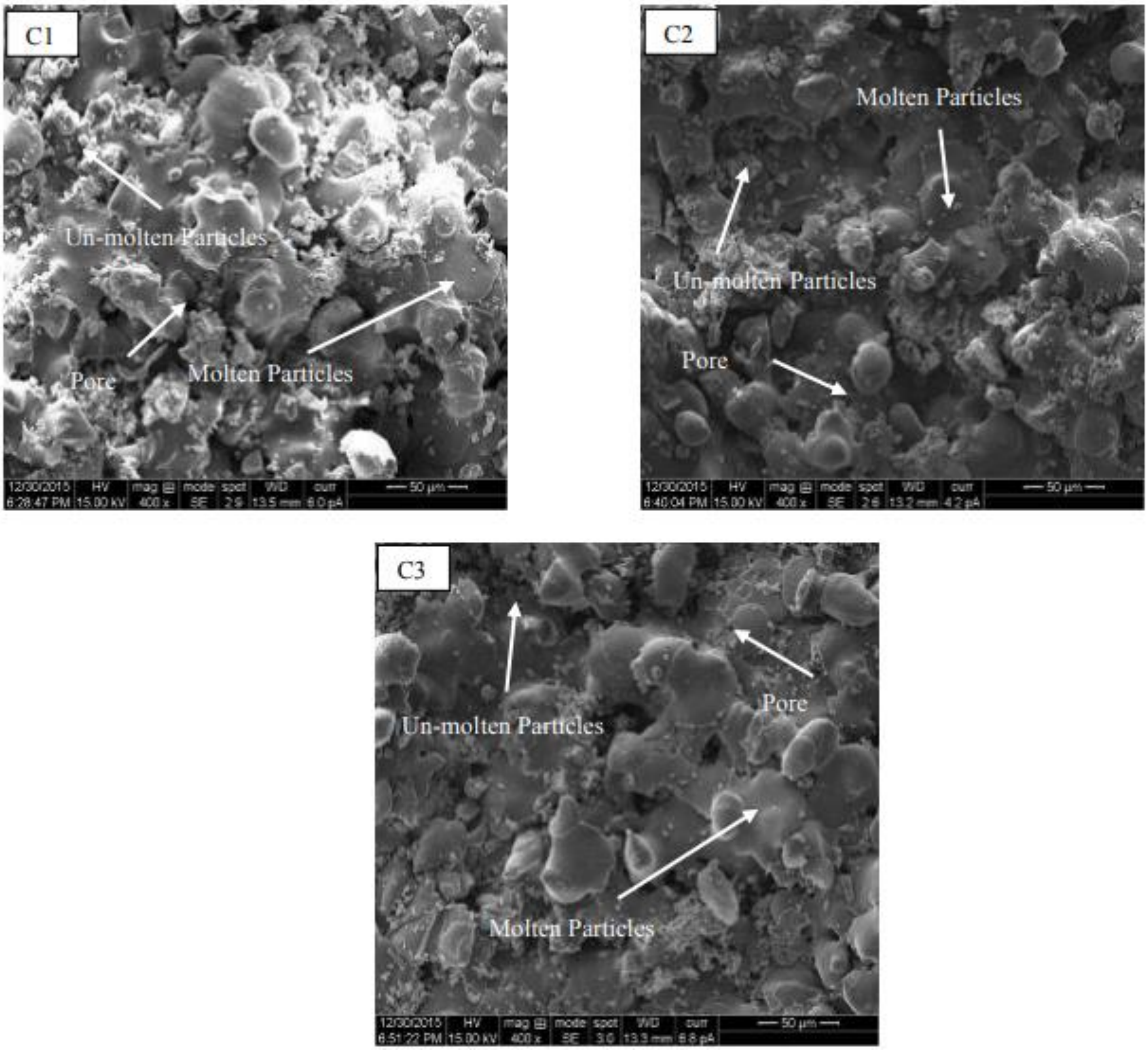

Fig. 5 - The microstructure of as-sprayed specimen of different coating thickness at higher magnification 400x

Figure 6 represents the cross-section portion of the coating, in these cross-sections, all the three coatings (C1, C2, C3) are possessing the lamellar structure of the coating. This lamellar structure is the main significant characteristics of atmospheric plasma spraying. It is also observed that these coatings with a many-layered composite made out of ceramic material splats surrounded by oxides which were the consequences of interpass oxidation during the atmospheric plasma spraying (APS) process. It is also observed that the irregular particles in coating materials of the spraying will adhere loosely on the surface, which caused undulating outer surface with local protrusion and high surface roughness [17]. In this cross-section of coating thickness, there are two distinct regions are observed one is a refined modified layer free from pores and oxides and another one is a lamellar layer which is the lower region of the coating. Apart from the above, It is also observed that there will be a coarse top surface in the coating.

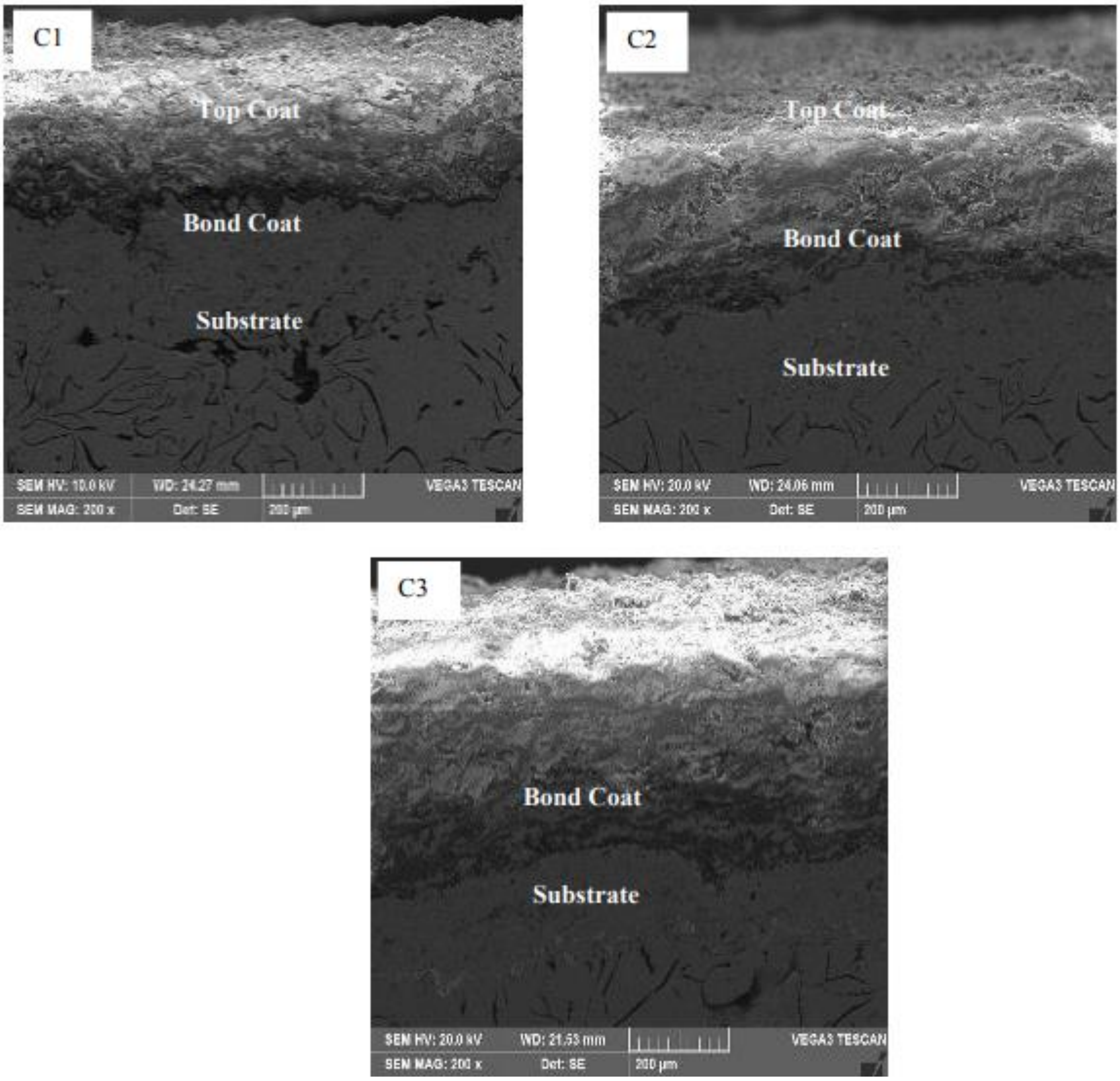

Fig. 6 - The cross-sectional view of the coating for all the three different coating thickness C1, C2, C3

3.2 Porosity of as sprayed coating

Many researchers are working in the direction of reducing the porosity in the coating for many years. Ekberg et al. [18] tried to reduce the porosity by post coating heat treatment to the specimens, in that they observed the fine porous were reduced and the coarse pores will be increased. Many other researchers are used plasma suspension spraying to reduce the coating porosity. The preliminary requirements to avoid or reduce the porosity is by achieving dense coating with the regular packing of splats in coating and the minimum number of voids in the coating. It is not so easy to obtained less porosity in the coating, this is a very complex task and depends on many parameters [19]. To achieve this, it is very much needed to optimize the various parameter which influences the porosity percentages. In this direction, many researchers are trying to minimize the porosity by adopting a multi-layer coating technique, doping elements, nanocomposite etc.

Cross-section image taken from the Scanning Electron Microscope (SEM) is subjected to the porosity test using the Image-J software. Here the porosity obtained for the thick coating sample, C3 is around 3-4%, for the samples C2 and C1 are around 2-3% and around 2% respectively. The highest percentage of porosity is observed in the coating C3 may be due to the process of laying of the coating in many passes. It is observed that in each pass the plasma spray gun will lay down the thickness approximately equal to 20 µm. The C1 coating will possess less number of percentage of porous may be due to less number of passes were required to get the necessary coating thickness. In C1 coating structure posses less percentage of porosity, it may be due to the proper mechanical interlocking between the substrate and the topcoat, it is also due to diffusion of the coating material into the bond coat because of the high temperature of plasma spraying operation. Porosity is also reduced may be due to inducing of less residual stress between the inner layers of the coating. The overall percentage of porosity is reduced in this work when compared with the other researcher [2021] and it may be due to optimization of spray parameter such as gas pressure, current, voltage, standoff distance, the powder feed rate and reduce the number of passes to obtained the required coating thickness. Figure 7 illustrates the percentage porosity of bond coat and topcoat.

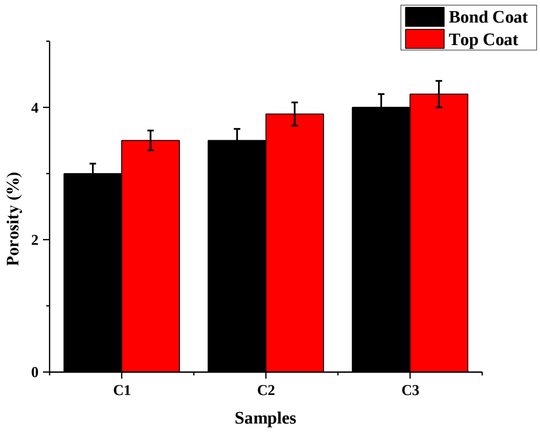

Fig. 7 - Porosity percentage for three different coating thickness C1, C2, C3

3.3 Adhesion or Bond strength of coatings

The strength of the coating system mainly depends on the type of failure during the tension test. Here the adhesion or bond strength is calculated by the formula Maximum Load/Initial cross-sectional area. The average adhesion and cohesion strength is recorded. The adhesion test results are shown in Table 4. From the data, it is observed that the average bond strength of C1, C2 and C3 samples, it is about 70.81, 69.1 and 65.52MPa. The variation of bond strength with topcoat thickness is shown in Figure 8. From the graphs, it is noticed that bond strength decreases with increase in topcoat thickness. Figure 9. Illustrate the fractured surface of coating frameworks. From the fractured surfaces, it is seen that crack happened at the interface of substrate and bond coat, a bond coat and topcoat. In a portion of the examples (Figure 9), the incomplete crack has happened. It implies that these coatings exhibit greater adhesion strength when compared with the other samples of the same test.

From the chemical analysis of the bond coat of cast iron substrate samples, it is seen that the bond layer consists of as high as 52% of Fe. There may be a possibility of a fusion of this Fe into the cast iron substrate which in turn increases the bond strength. The bond strength of coating frameworks is diminishing with the increase of topcoat thickness. As the topcoat thickness increases, the exposition of the substrate to the high-temperature plasma fire gets prolonged. Because of this, the thermal mismatch between the substrate and the bond layer increases. Exposure of substrate to high-temperature flame also increases residual stresses. These are the main reasons for the reduction in bond strength of the sample with the increase in topcoat thickness. The bond strength of coating samples investigated in this research is found to be more than that of earlier researchers [22].

Figure 10 demonstrates the stress-strain relations, in which we can observe two distinct regions. The first region is due to slipping of the specimen from the jaws of the Universal Testing Machine (UTM). And second, the distinct region is due to elongation of the specimen at the region of where bond coat and substrate meet each other or interface. However, the strain rate is found in the second region which, shifts between the 5% to 6% and it is the clear indication of the specimens which are tested under tensile tests are ductile.

3.3.1 Factors Influencing the Adhesion Strength of Coatings

The amount of adhesion of the coatings is evaluated by observing the remaining particles that are attached to the substrate. The real adhesion is evaluated based on the detachment of the coating over the substrate. Primarily, the main reason for the poor adhesion is due to the problem that is associated with the spraying process. The poor spraying technique will result in the formation of the residual stresses between the coating layers. The inter splats defect or the procedure followed by the researcher to experiment such as traction speed as well as specimen alignment inside the chuck of UTM may also be the reasons for poor bonding. It is also found that the capacity of interlocking of the molecules will increase with an increase in the density of the coating. The adhesion strength is also influenced by the re-joining of partially melted particles in the coating and how the relaxation of stress which was developed during the coating process from the local plastic deformation. In multilayer thermal barrier coatings the bond strength also depends on the appropriate bonding between topcoat, a bond coat and substrate materials.

Researchers have found that if the roughness value R_a of substrate increases, the bond strength also increases [23]. Limarga et al. [24] conducted an adhesion test on multilayered plasma-sprayed Al_2O_3 and ZrO_2 coatings from which they obtain adhesion strength of 5MPa to 23MPa. In their examinations, the adhesion test samples have failed at the interface of bond and ceramic layers. As per their results, some of the samples gave low adhesion strength which is mainly due to the poor surface roughness of ceramic surface even though the unimportance of mechanical interlocking. Further, investigations show that the poor roughness of the ceramic surface is directly related to finer grain sizes of powder used.

These finer grains indirectly affects the adhesion strength. Based on the above concept, it has been noticed that the roughness values of sample C1 are higher than the roughness of C2 and C3 samples. Hence these samples have higher adhesion strength and it indicates that surface roughness greatly influences the adhesion strength of coating systems. That is as the grain size increases, surface roughness increases which in turn increases the bond strength of coating systems. Lima and Trevisan [25] have worked on the failure of functionally graded coatings under tensile strength test. They observed that increasing the topcoat thickness with more number of passes will reduce the adhesion strength of coatings. They attributed this to the greater interruption time available for spraying the next layer. Similar trends of observations are observed in our investigation. In the case of C2, C3 samples the topcoat thickness is 200 and 300µm. These samples require several passes which are 40 to 50% higher compared to C1 samples, to achieve the required thickness. The higher number of passes increases the number of ceramic interfaces and homogeneity of coatings. When these samples are subjected to tensile test, they fail at ceramic interfaces which give a higher magnitude of cohesion.

Table 4 - Location of Failure and Bond Strength of Cast Iron substrate coating systems

Samples →	C1		C2		C3	
↓ Trials	Strength MPa	Failure Location	Strength MPa	Failure Location	Strength MPa	Failure Location
1	72.76 68.92	BC1/S	71.65 68.91 66.74	BC1/S	63.28 64.71 68.57	BC1/S
2	70.75	BC1/S		BC/S		BC1/S
3		BC1/TC2		BC1/S		BC1/S
Mean Strength MPa	70.81		69.1		65.52	

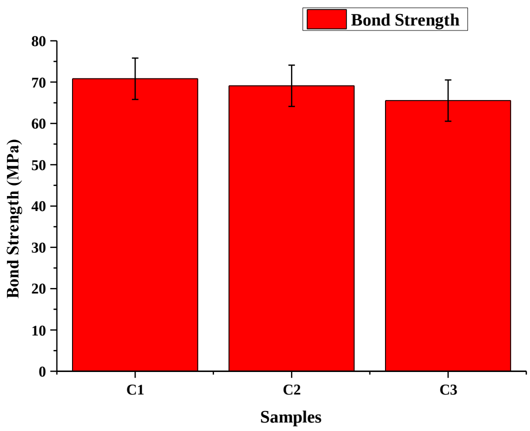

Fig. 8 - Bond Strength for three different coating thickness C1, C2, C3

In this work, all the thermal barrier coating systems before adhesion test have similar spraying coat material and the spray parameters, except the topcoat thickness which is 100µm, 200µm and 300µm. In the Atmospheric plasma spraying process, powders were melted in a plasma jet and then propagated towards the substrate surface. In this process, the particles of different category such as melted, semi-melted state were quickly flattened and solidified then a splat-like structure formed. Thus, the structure of the top surface was extremely nonuniform.

The coatings can be categorised as two regions, one is surface where the coatings are of coarse, the second one is the region where the splats of the coatings are relatively smoother. Apart from the above the thermal barrier coatings are manufactured from Atmospheric plasma spraying (APS) also posses the cracks, micropores and oxidation of interlace between the splats are considered as defects of the coatings. All these defects will influence both the brittle ceramic topcoat and ductile metallic bond coat to provide the favourable location to produce the stress concentration and, thereby, weaken the adhesive linkage inside the coating system. Under the influence of all these will leads to the generation of flaws or porosity. These porous or flaws will be the major reason for the weaker bonding especially at the region of the nonuniform and porous interface. As for as coating is concerned, irregular defects at the bond coat/ceramic coat interface have initiated the failure process. The fracture surfaces of the tested coatings, shown in Fig. 9, could be representative of such failure behaviour. Lima et al. studied the adhesion properties of TBCs with a thermally sprayed bond coat and found that a singular defect in the bond coat/zirconia interface can initiate the whole failure process [26]. Also, according to the research by Sobolev et al, rebonding of partially melted particles and stress relaxation from local plastic deformation can influence such adhesion properties during the spraying process [27].

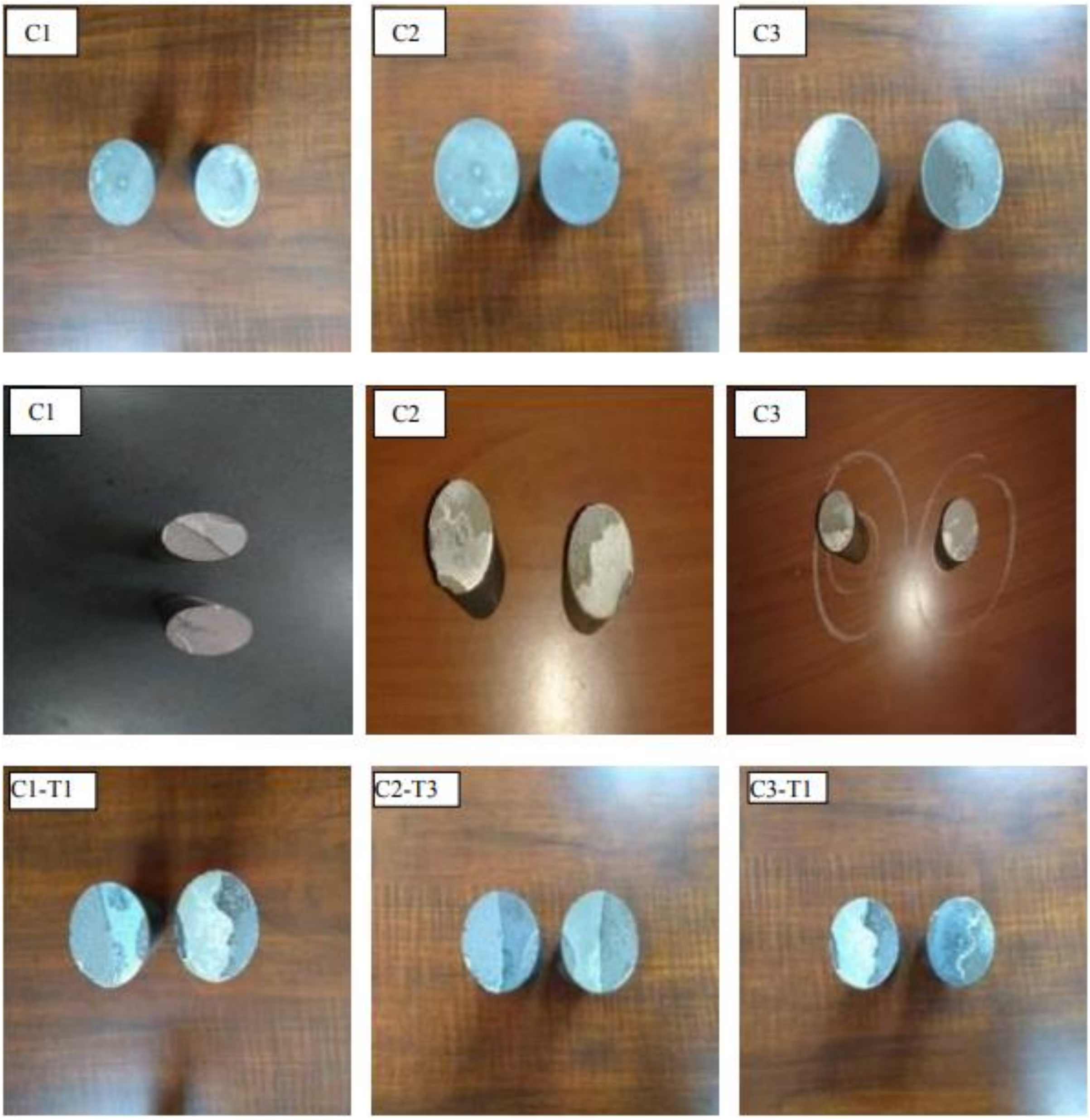

Fig. 9 - Fractured surface of coating systems after adhesion test-defects

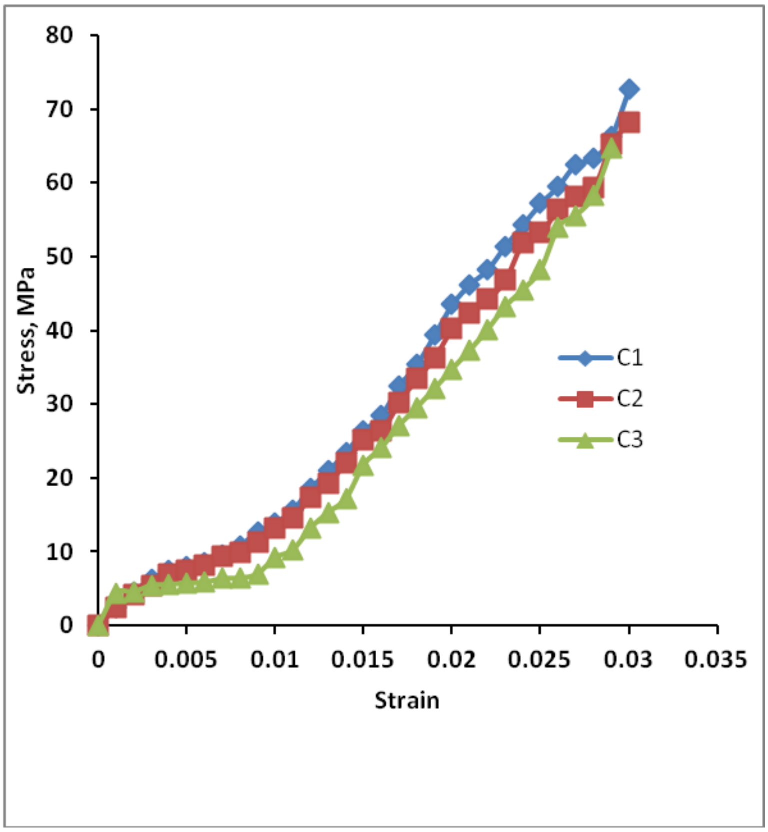

Fig. 10 - Stress-strain diagram of cast iron substrate coating systems

3.4 Overall Discussion

After the adhesion strength test was conducted, the thorough observation of the coating, 3 types of failures has been observed. First one is failure took place between the coating layers it has been termed as a cohesive failure, the second one is the coating failed in between substrate and bond coat layer, it has termed as adhesive failure. The third one is partly adhesive and partly cohesive which is termed as the mixed mode of failure. It is also observed that if the tensile stress or load increases and when it crosses the limit of adhesion strength of the coating, the failure took place between the bond coat and topcoat layers in the most of the specimen.

The bond strength of the coating depends on many parameters, in that following are the few parameters which will have more influences on the bond strength of the coating such as porosity of the coating, melted and unmelted particles and the thickness of the coating. In this work, we are trying to correlate how the porosity and the thickness of the coating influence the bond strength of the coating.

The porosity of the coating will generally decrease the tensile value of the coating, the small size of the pore will lead to microscopic failure of the coating when a tensile load is applied. Generally these porous are have less influence while the compressive load is applied. These porous are influences the bond strength when the coating is of thicker, one strange phenomenon when the these porous will increase the bond strength for thin coating it may be due to penetration of glue into the coating. Apart from the pores the micro-cracks also influence the bond strength of the coating, these micro-cracks are influences the macroscopic failure of the coatings.

The thinner coating that is C1 posses high bond strength may be due to following reason, porosity in the coating may allow the penetration of the adhesive glue into the coating and which may increase the bond strength of the coating. This will increase the bond strength of the thinner coating, in case of thicker coating possibility of penetration is limited [28]. It is also observed that in bond strength test there is a direct pull, which produces the failure at the zone of ceramic topcoat and the metallic bond coat, this is an adhesive failure mode. It indicates that the bonding strength between the cognate splats is termed as cohesive strength is more than the non-cognate splats termed as adhesion strength. A similar observation is also observed by the other earlier researcher also [29].

It is also observed that the adherence property is also directly proportioned with the volume fraction of porosity and the un-melted particles, the only way is to increase the bond strength is the preparing the dense coating which will reduce the unmelted particles and the reduce the volume fraction of coating porosity. It is also believed that the residual stress also plays an important role in the strength of the coating. This is agreed upon by the other researcher also [30]. The cohesive strength of a material is closely linked to its resistance to contact deformation and its ability to deform without fracture [31-32]. Bonding Strength is also depended on the what type adhesive we are using, working temperature, curing temperature, surface cleanliness, the surface roughness, surface chemical property, surface texture of the substrate.

3.5 Conclusions

In this work, Thermal barrier coating is prepared by properly blended equal-proportion (50:50) Yttria Stabilized Zirconia (YSZ) and Pure Alumina (Al_2O_3) as a ceramic topcoat and two bond coat. Both bond coat and topcoat layers were produced by the APS technique. From the research, we are trying to fix the optimal coating thickness for the topcoat by considering all the parameter such as microstructure, porosity and mechanical strength etc. We aim to develop the thermal barrier coating and this coating should possess good characteristics towards the above-said properties. In this context, in our work, we have come to the following conclusions.

1) Three different topcoat thickness thermal barrier coatings were investigated for their adhesion strength using ASTM standard C-633. The thickness ranged from 100µm-300µm in the step of 100µm. 100 µm topcoat exhibits very good adhesion strength of 70.81 MPa, the other two topcoat thickness 200µm and 300 µm have the adhesion strength 69.1 MPa and 65.52 MPa respectively. Finally, it is concluded that the moderate topcoat thickness ie. 100 µm and 200 µm posses very good adhesion strength, from this it is concluded that the optimal thickness of the coating will not be too thicker or too thinner topcoat it is in between the thinner and thicker.

2) In this work, top coating thickness ie. 300µm exhibits more percentage of porosity ie.4.2% than other two coating thickness 200 and 100 µm 3.9% and 3.5% respectively. The bond coat will possess porosity percentage of 4.0 %, 3.5 % and 3 % for C3, C2 and C1 respectively.

3) In this work, it is observed that most of the coatings are failed at the region of interface between the topcoat and bond coat. It is termed as a cohesive type of failure. It is also seen adhesive and Mixed mode of failure also took place while conducting adhesion test.

References

[1] Ahmad, N. A., Kamdi, Z., & Mohd Tobi, A. L. (2018). Wear and corrosion behavior of tungsten carbide-based coating on carbon steel. International Journal of Integrated Engineering, 10(4), 119-125

[2] R.A. Mahesh, R. Jayaganthan, & S. Prakash. (2009). Microstructural characteristics and mechanical properties of HVOF sprayed NiCrAl coating on superalloys. Journal of Alloys and Compounds, 468, 392-405

[3] Jie Cai, Qingfeng Guan, Peng Lv, Xiuli Hou, & Zhiping Wang, Zhiyong Han. (2015). Adhesion Strength of Thermal Barrier Coatings with Thermal-Sprayed Bondcoat Treated by Compound Method of High-Current Pulsed Electron Beam and Grit Blasting, Journal of Thermal Spray Technology, 24, 798-806

[4] A. Portinha, V. Teixeira, J. Carneiro, J. Martins, M.F. Costa, R. Vassen, & D. Stoever. (2005). Characterization of thermal barrier coatings with a gradient in porosity. Surface Coatings Technology, 195, 245-251

[5] M. Gupta, N. Markocsan, R. Rocchio-Heller, J. Liu, X.-H. Li, & L. O. Ostergren. (2018). Failure Analysis of Multi-layered Suspension Plasma-Sprayed Thermal Barrier Coatings for Gas Turbine Applications. Journal of Thermal Spray Technol., 27,402-411

[6] Senain, I., Nayan, N., & Saim, H. (1). (2010). Structural and Electrical Properties of TiO2 Thin Film Derived from Sol-gel Method using Titanium (IV) Butoxide. International Journal of Integrated Engineering, *2*(3), 29-36

[7] Xiaotao Luo, Gregory M. Smith, & Sanjay Sampath. (2018). On the Interplay between Adhesion Strength and Tensile Properties of Thermal Spray Coated Laminates-part I: High-Velocity Thermal Spray Coatings. Journal of Thermal Spray Technol., 1-12

[8] Markus Mutter, Georg Mauer, Robert Mu¨cke, Olivier Guillon, & Robert Vaßen. (2018). Systematic Investigation on the Influence of Spray Parameters on the Mechanical Properties of Atmospheric Plasma-Sprayed YSZ Coatings. Journal of Thermal Spray Technol., 1-15

[9] Woo Y Lee, David P Stinton, Christopher C Berndt, Fazil Erdogan, Y Der Lee, & Zaher Mutasim. (1996). Concept of Functionally Graded Materials for Advanced Thermal Barrier Coating App.lications. Journal of American Ceramic Society, 79, 3003-3012

[10] ASTM Standard E 1920-03 Standard Guide for Metallographic Preparation of Thermal Sprayed Coatings

[11] ASTM Standard E 1182-93 Standard Test Method for Measurement of Surface Layer Thickness by radial Sectioning

[12] Thirumalaikumarasamy D, Shanmugam K, & Balasubramanian V. (2014). Establishing empirical relationships to predict porosity level and corrosion rate of atmospheric plasma-sprayed alumina coatings on AZ31B magnesium alloy. J. Magnes. Alloy, 2, 140-153

[13] Yong Suk Heo, DongHeon Lee, Yeon-Gil Jung, & Kee Sung Lee. (2015). Indentations on Air Plasma Sprayed Thermal Barrier Coatings Prepared by Different Starting Granules. Hindawi Publishing Corporation Journal of Nanomaterials,1-9

[14] ASTM Standard E 2109-01 Test Method for Determining Area Percentage Porosity in Thermal Sprayed Coatings

[15] ASTM standard C 633-79 (reapproved 1999) Test Method for Adhesion or Cohesion Strength of Thermal Spray Coatings

[16] O.Sarikaya. (2005). Effect of some parameters on microstructure and hardness of alumina coatings prepared by the air plasma spraying process. Surface Coating and Technology, 190, 388-393

[17] Emine Bakan, & Robert Vaßen. (2017). Ceramic Top Coats of Plasma-Sprayed Thermal Barrier Coatings: Materials, Processes, and Properties. J. of Thermal Spray Technol., 26, 992-1010

[18] John Gerald Odhiambo, WenGe Li, YuanTao Zhao, & ChengLong Li. (2019). Porosity and its Significance in Plasma-Sprayed Coatings. Coatings, 9, 1-19

[19] N. Krishnamurthy, S. C. Sharma, M. S. Murali, & P. G. Mukunda. (2009). Adhesion behaviour of plasma-sprayed thermal barrier coatings on Al-6061 and cast iron substrates. Frontiers of Material Science China, 1-6

[20] N.Krishnamurthy, M. S. Murali, P. G. Mukunda, & M. R. Ramesh. (2010). Wear Behavior of Plasma-Sprayed Al_2O_3 Coatings on Cast Iron Substrate. International Journal of Materials Science, 5, 157-165

[21] A. Limpichaipanit, A. Watcharapasorn, S. Wirojanupatump, P. Niranatlumpong, & S. Jiansirisomboon. (2013). Fabrication and Properties of Thermal Sprayed AlSi-Based Coatings from Nanocomposite Powders. Journal of Thermal Spray Technol., 2, 18-27

[22] Ekberg J, Ganvir A, Klement U, Cresci S, & Nordstierna L. (2018). The influence of heat treatments on the porosity of suspension plasma-sprayed yttria-stabilized zirconia coatings. J. Therm. Spray Technol., 27,391-401

[23] Robert Eriksson, S¨orenSj¨ostr¨om, H˚akanBrodin, Sten Johansson, Lars Ostergren, & Xin-Hai Li. (2014). TBC bond coat-top coat interface roughness: influence on fatigue life and modelling aspects. Surface and Coatings Technology, 236, 230-238

[24] Limarga A.M, & Clarke D.R. (2009). Characterization of Electron Beam Physical Vapor Deposited Thermal Barrier Coatings Using Diffuse Optical Reflectance. International Journal of Applied Ceramic Technology, 6, 400-409

[25] C. R. C. Lima, & R. E. Trevisan. (1997). Graded plasma spraying premixed metal-ceramic powders on a metallic substrate. J. Therm. Spray Technol., 6, 199-204

[26] C.R.C. Lima & J.M. Guilemany. (2007). Adhesion Improvements of Thermal Barrier Coatings with HVOF Thermally Sprayed Bond Coats. Surf. Coat. Technol., 201, 4694-4701

[27] V.V. Sobolev, J.M. Guilemany, J. Nutting, & J.R. Miquel. (1997). Development of Substrate-Coating Adhesion in Thermal Spraying. Int. Mater. Rev., 42, 117-136

[28] M. Hadad, G. Marot, P. De´ mare´ Caux, D. Chicot, J. Lesage, L. Rohr, & S. Siegmann. (2007). Adhesion tests for thermal spray coatings: correlation of bond strength and interfacial Toughness. Surface Engineering, 23, 279283

[29] Jinshuang Wang, Junbin Sun, Hao Zhang, Shujuan Dong, Jianing Jiang, Longhui Deng, Xin Zhou, & Xueqiang Cao. (2018). Effect of spraying power on microstructure and property of nanostructured YSZ thermal barrier coatings. Journal of Alloys and Compounds, 730, 471-482

[30] Ekrem ALTUNCU, & Fatih USTEL. (2012). Adhesion Properties of the Plasma Spray Coatings. Metals, 23-28.

[31] Hawthorne HM, & Xie Y, (2001). An attempt to evaluate cohesion in WC/Co/Cr coatings by controlled scratching. Meccanica, 36,675-682

[32] Aleksandar Vencl, Saioa Arostegui, GregoryFavaro, FatimaZivic, Mihailo Mrdak, Slobodan Mitrovic, & Vladimir Popovic. (2011). Valuation of adhesion/cohesion bond strength of the thick plasma spray coatings by scratch testing on coatings cross-sections. Tribology International, 44, 1281-1288