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Development of AI-Alloy piston coating material for high specific power engine application

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ABSTRACT

The depletion of conventional fuel source at tremendous rate and increasing environment pollution has motivated extensive research and development in combustion chamber of engine. In the present study, multilayer ceramic coating on the piston crown was developed to improve thermal efficiency, combustion and exhaust emission, fuel consumption. Also ceramic coating on crown withstands the elevated temperature and pressure and provides maximum working efficiency. The property advantages of Alumina and Yttria Stabilized Zirconia in combination were utilized to fabricate the Thermal Barrier Coating (TBC) in this study. The multilayer coating of alumina and zirconia was fabricated using air plasma spray method. For effective bonding, Ni-based bond coat was applied on the substrate before TBC top coat. Research piston similar to the actual piston was used use to fabricate TBC coating. Microstructural characterization was carried out to check the coating uniformity using Optical and Scanning Electron Microscope. Defect free uniform coating was formed with average thickness of bond coat, alumina and YSZ was about 90 µm, 70 µm and 180 µm respectively. The performance of TBC coating on crown of research piston was assessed by subjecting to thermal barrier and thermal shock tests. In thermal barrier test, a maximum temperature drop of 265°C was observed at 590 °C. Delamination of bond coat was observed after 90 cycles. Microstructural analysis was also carried out to study the damage occurred during thermal exposure. All the observation and the test results of this investigation are reported here.

Keywords— *Thermal barrier coating, TBC coating material, Yttria stabilized zirconia, Air plasma spray coating, Observation*

1. INTRODUCTION

In automobile sector, performance and the fuel consumption have become a major factor. The desire to reach higher efficiencies, lower specific fuel consumptions and reduce emissions in modern internal combustion (IC) engines has become the focus of engine researchers and manufacturers for the past three decades. High temperature produced in an I.C engine may contribute to high thermal stresses. Without appropriate heat transfer mechanism, the piston crown would operate ineffectively which reduce life cycle of piston and hence mechanical efficiency of engine. Heat concentration or hotspots on any area of piston crown create thermal stresses that may affect the durability of piston material [1]. Hence, a piston needs adequate surface coating which should give protection at high temperature. Thermal barrier coatings (TBCs), which protect metallic components from high-temperature environments, have been widely applied to the fields of high-temperature and corrosion- resistant structural parts.

The motive to increase thermal efficiency or reduce fuel consumption of engine makes it tempting to adopt higher compression ratio particularly for diesel engine and reduced in cylinder heat rejection. Both this factor leads to an increase in mechanical and thermal stresses. The durability concerns for the material and component in the engine cylinder limit allowable in cylinder temperature. Applications of TBC's to the surface of these components enhance high temperature durability by reducing heat transfer and lowering temperature of the underlying metal. The diesel engine with its combustion chamber wall insulated by ceramics is referred as Low Heat Rejection (LHR) engine [2]. The LHR engine has been conceived basically to improve fuel economy by eliminating the conventional cooling system and converting part of the increased exhaust energy into shaft work using the turbocharged system.

TBCs are required not only to limit the heat transfer through the coating but also to protect the engine components from oxidation and corrosion. No single coating composition appears to satisfy these multifunctional requirements. As a result, a "coating system" needs to be evolved [3]. Hence, coating system consists of multi layers to achieve long term effectiveness in the high temperature, oxidative and corrosive environment in which they are to function.

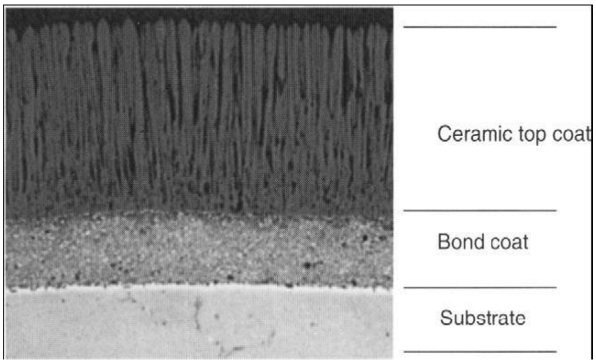


Fig. 1: Thermal barrier coating consists of bond coat and ceramic top coat on substrate [1]

Thermal mismatch which mainly occurs due to improper adhesion and difference in thermal expansion coefficients between TBC coating and piston material. The bond materials are specially designed to provide optimal properties for both adherence of the top coating and integrity of the interfacing substrate [4]. TBC system from the bond coat to top ceramic coat by incorporating one or more intermediate layers into the coating system can minimize ceramic metal thermal expansion coefficient.

Thermal barrier coating is mainly done on combustion chamber component like piston, cylinder head, linear, valves, combustion chamber etc. The piston is one of the most critical component of the engine therefore it must be designed to withstand from damage that is caused due to extreme heat and pressure of combustion process. Hence, in present study, it was decided to coat TBC on the piston crown and study the efficiency of LHR engine. However, due to unavailability of LHR engine, research piston which is replicating LHR piston crown of same material were used in this present study [5].

Fig. 2: Research Piston

2. METHODOLOGY AND EXPERIMENTAL WORK

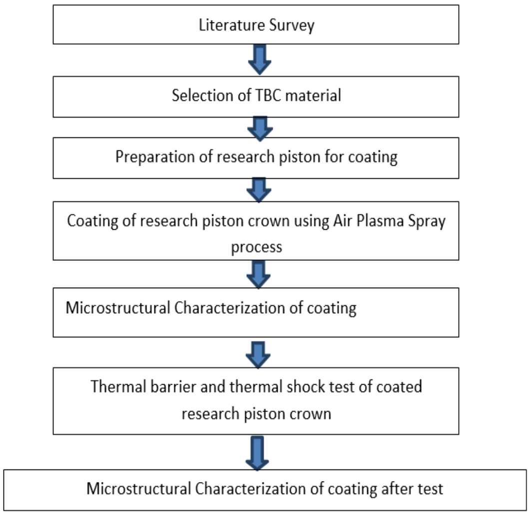


Fig. 3: Flowchart showing the methodology adopted

TBC Coating Materials
In this present study, multilayer coating was fabricated on the research piston. First layer was bond coat, second layer and third layers were Alumina and Yitria Stabilized Zirconia respectively. Piston material and coating materials used in this study are given below.

Bond Coat
Bond coat is intermediate layer in between substrate material and top coat. Thermal mismatch which mainly occurs due to improper adhesion and difference in thermal expansion coefficients between TBC coating and piston material. The bond materials are specially designed to provide optimal properties for both adherence of the top coating and integrity of the interfacing substrate. Ni-Co-Al alloy was used as a bond coat material and the chemical composition

Table 1: Chemical Composition of Ni-Cr Alloy Bound Coat

Elements	**Ni**	**Co**	**Al**
Weight %	24.5	6	0.4

Alumina

It has very high hardness and chemical inertness. Alumina has relatively high thermal conductivity and low thermal expansion coefficient compared with Yittria stabilized zirconia. Even though alumina alone is not having good thermal barrier coating candidate, addition of alumina in combination with Yttria stabilized zirconia can increase the hardness of the coating and improve the oxidation resistance of the substrate.

Yttria Stabilized Zirconia (YSZ)

This is most commonly used TBC material for variety of high temperature applications due to its attractive high temperature properties. The main advantages of zirconia their activity low thermal conductivity high thermal expansion coefficient used good thermal cycling resistance. Zirconia is often more useful in its phase 'stabilized' state. Upon heating, zirconia undergoes disruptive phase changes. By adding small percentages of yttria, these phase changes are eliminated, and the resulting material has superior thermal, mechanical, and electrical properties.

Table 2: Chemical Composition of 8% YSZ

Phase	**Y_2O_3**	**SiO_2**	**TiO_2**	**Al_2O_3**	**Fe_2O_3**	**Monoclinic phase**	**ZrO_2**
Weight %	7.5	0.05	0.05	0.05	0.05	10	Balance

Air plasma spray coating

APS is spraying of molten or heat softened material onto a surface to provide a coating. Spraying is controlled by control unit which is connected to the plasma gun by means of rubber pipes. Plasma gases such as argon, nitrogen and hydrogen gas flows around the cathode and through anode, which shapes as a constructing nozzle. The temperature around the cathode and anode jackets is maintained by means of water flow. Control unit is connected by gas cylinder and rectifier. This unit controls the gas flow from cylinder and DC current in rectifier generate the spark for millisecond by means of spark generator and supply to plasma gun. Temperature up to 15000 k is maintained when the gas flows through the tube and spark generates higher spark plasma.

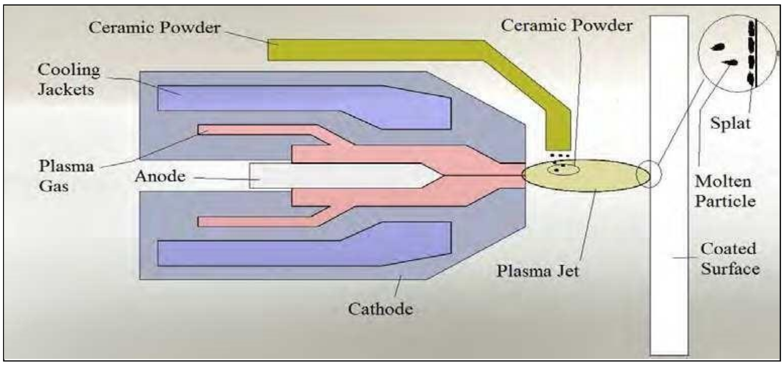


Fig. 4: Schematic Diagram of Air Plasma Spray

The coating thickness on substrate is measured by Digital Film Thickness machine (DFT) as shown in. Dry Film Thickness was measured on either magnetic steel surfaces or non-magnetic metal surfaces. Firstly, the machine is set on zero at substrate surface. Check the thickness of bound coat after application of bound coat material. Further, coat the bond coat layer by top coat layer and check the total thickness.

Fig. 5: Digital Film Thickness machine (DFT)

3. PROCESS SEQUENCE

Based on the literature survey, multilayer coating with 80-100 µm thickness bond coat, 60-80 µm alumina top coat and 150-200 µm, were planned using APS technique. The process of coating involves the following steps:

(a) Surface Preparation: The surface of the research piston was cleaned by dipping it in methanol and dried in oven. This was done to remove dirt, oil, grease, etc., from the surface. Then, the surface of the research piston was made rough using grit blasting. This will ensure effective bonding with the bond coat. This is followed by ultrasonic cleaning.

(b) Bond Coating: The prepared surface is then coated with an adhesive bond coat by Air Plasma Spray. Ni-5%-1%Co Al was used for bond coating which is commonly used as a bond coat material. The particle size was about 4-6 µm. The coating was carried out by three passes in order to control the coating thickness in the range of 80 to 100 µm since it is a manual process. After bond coating, the surface is grit blasted for a shorter time to prepare the bond coat surface for effective adhesion with top coat.

(c) Thermal barrier coating: Top coat was prepared after the bond coat as two layers of ceramic coating with different ceramic powders (Alumina + YSZ). The first layer was prepared with Alumina particle. Double pass coating was carried out to maintain coating thickness between 60-80 µm. Third layers were prepared with 8%YSZ. Four pass coating was carried for YSZ coating to maintain coating thickness between 150-200 µm.

4. MICROSTRUCTURAL OBSERVATION

Initially, visual inspection was carried out on the coating surface to check the uniformity of coating and also macro level defects such as cracks, porosity, etc. Along with research piston, a test coupon was also coated to examine the coating uniformity, thickness and bonding between substrate and coating layers. The cross section of the research piston was analyzed after thermal shock and thermal barrier tests to check whether coating is intact with substrate or any delamination. Microstructural examination of metallographic samples was carried out using optical microscope (Carl Ziess AXIOTECH100).

Fig. 6: Optical Microscope

Coating uniformity, bonding between substrate and coating layers, thickness and chemical composition of coating were analyzed using Scanning Electron Microscope (JSM-IT300) equipped with Energy Dispersive Spectrometer (EDAX - Octane plus).

Fig. 7: Scanning Electron Microscope with EDS Attachment

4.1 Thermal Barrier and Thermal Shock Tests

These tests were performed at Surface Engineering Laboratory (Burner Rig Facility under MRP 1302), Christ University, Bangalore to assess the performance of TBC coating at working temperature similar to IC engines. Both the test facilities involve the following primary steps:

- Placement of the test sample in the test sample holder, ceramic coating facing on oxy-acetylene flame maintained at about 1200-1400 deg. Celsius.
- Infra-red light gun for measurement of the temperature
- Air cooling system to cool the back of the substrate

4.2 Thermal shock and thermal barrier tests

The research piston was subjected to thermal shock cycle which involves expose the research piston crown to 550 ºC temperature for 5 minutes followed by cooling for 1 minute in ambient condition and repeated this cycle number of times. In the thermal shock test rig facility, the test sample was moved in and out of the flame so that the ceramic coating on the research piston crown is subjected to thermal shock. The coated research pistons were subjected to 100 thermal shock cycles and the TBC coating was inspected to check coating degradation if any.

Fig. 8: Thermal Shock Test Set-Up

The thermal barrier test involves exposing the TBC coating surface to different temperatures and measure the temperature drop across the ceramic coating to determine the efficiency of the TBC coating. In this test, surface of research piston crown having TBC coating was exposed to different temperatures (from 200 to 550 ºC) using an oxy-acetylene flame and recorded the temperature underneath TBC coating after steady state condition achieved. The temperature drop across the coating of research piston at various temperatures was measured using infra-red thermometer to check the thermal efficiency of TBC coating. The test duration was about 2 hours.

Fig. 9: Infra-Red thermometer used for temperature measurement

4.3 Results and Discussions Microstructural Observations

Shows the top coat surface of the multi-layer coated research piston and test coupon. The top coat was observed with rough surface. The surface hardness of the TBC surface was measured with surface roughness meter and the average surface roughness value (R_a) was about 9.2µm shows the high magnification SEM Micrograph of the top coat surface. It could be observed that that there was no micro level defects such as cracks, porosity, etc.

Fig. 10: TBC coating on Test Coupon

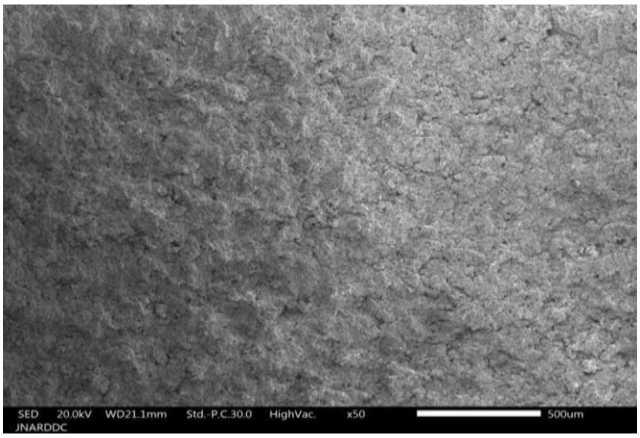
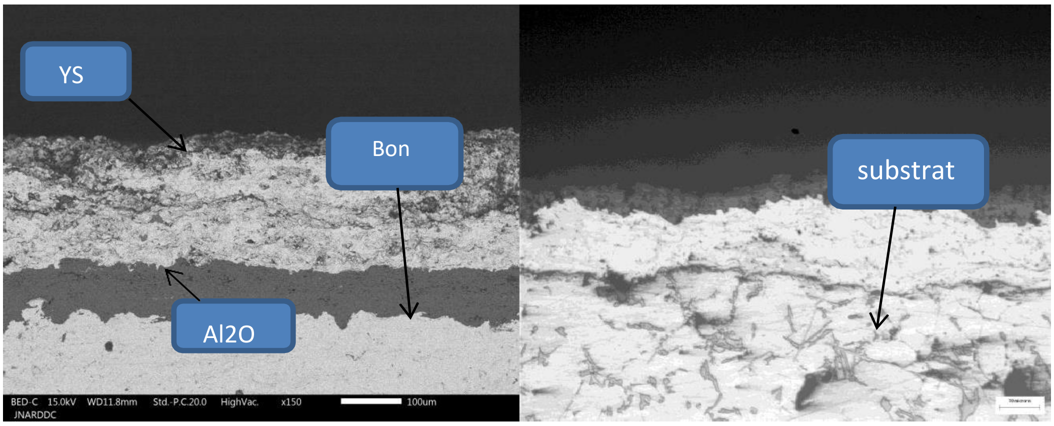


Fig. 11: SEM high magnification image of the top coat surface

Optical and SEM micrographs of the cross section of bond coat and multi-layer TBC coating deposited on the test coupon.



(a) (b)

Fig. 12: (a) SEM and (b) Optical micrographs of the cross section of test coupon

In the test coupon, the bond coat, Alumina and YSZ coat were observed to be uniform throughout the cross section analyzed in microscope. Thickness of top coat (Alumina + YSZ) was ranging between 200 - 280 µm. Top coat was observed with voids and porosity as well as micro cracks throughout the layer. It indicates that the preparation of TBCs for microscopic examinations is a challenging process that should be conducted. Pull-out particles also easily occur because of the brittle and porous nature of the top coat, which results not only in a damaged surface but also in a false impression of the porosity. NiCoAl bond coat with a thickness about 60-80 µm showed a dense structure. These layers remained partially melted to form a strong mechanically bond or interlocking adhesion to the aluminum alloy substrate.

4.4 Thermal barrier and thermal shock tests

The test results of thermal barrier test. It can be observed from the graph that maximum temperature drop of 265 °C was observed when the temperature of TBC surface was maintain at 590°C. In thermal shock test, after 90 cycle's degradation / delamination of coating was observed and hence the test was stopped after 100 cycles.

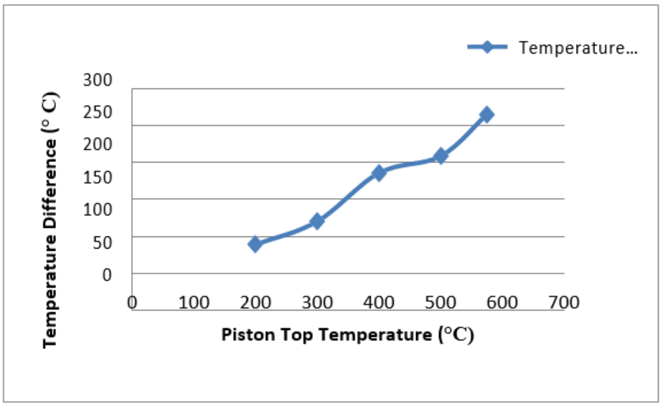


Fig. 13: Temperature Difference on Various Piston Top Temperatures

4.5 Microstructural observations of Research Piston after thermal Exposure

Microstructural observation on the surface after thermal exposure was carried out using SEM and compared with as fabricated surface. It is evident from the micrograph that micro cracks and deterioration of the TBC coating were observed on the surface of research piston after the thermal exposure.

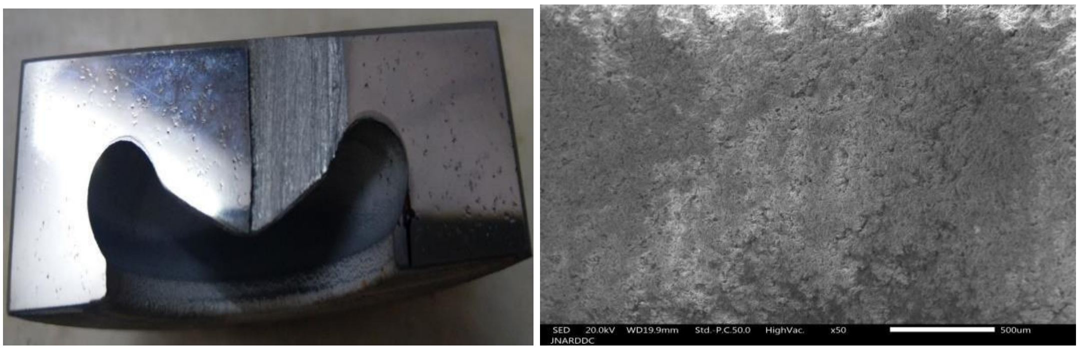


Fig. 14: Coated surface after thermal barrier test

In research piston also, the regions which are in-line with the plasma revealed defect free bond coat and ceramic top coats as observed in test coupons and shown in the figure. The average coating thickness (Bond coat + Alumina + YSZ) varied between 280 and 350 µm. Average thickness of bond coat, alumina and YSZ was about 90 µm, 70 µm and 180 µm respectively. As observed in test coupon, the defect seen in ceramic top coat could be attributed to ceramic particles pull out during the cutting, grinding and polishing steps.

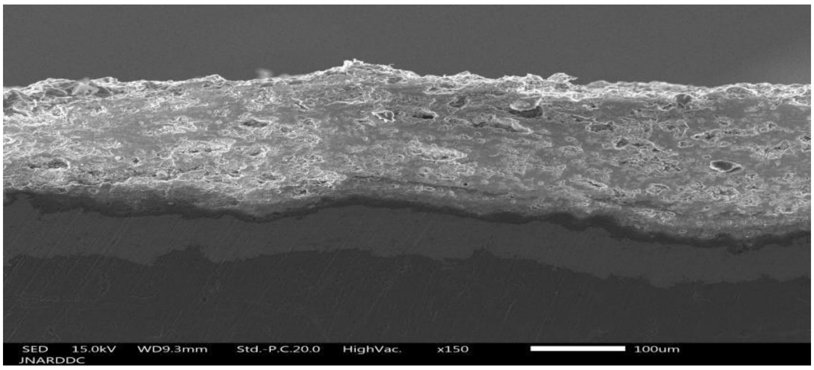


Fig. 15: SEM micrograph showing uniform coating on research piston

It is evident from the above micrograph (Figure), there is no delamination of bond coat or top coat. It is obvious that thermal barrier tests have shown a maximum temperature drop of about 290 °C across the TBC which is well below the melting temperature of substrate material (577 °C for Al-11.7 Si alloy). It was observed that though there was better inter-locking of bond coat and substrate in the bowl region, coating has peeled-off after the thermal barrier and thermal shock tests.

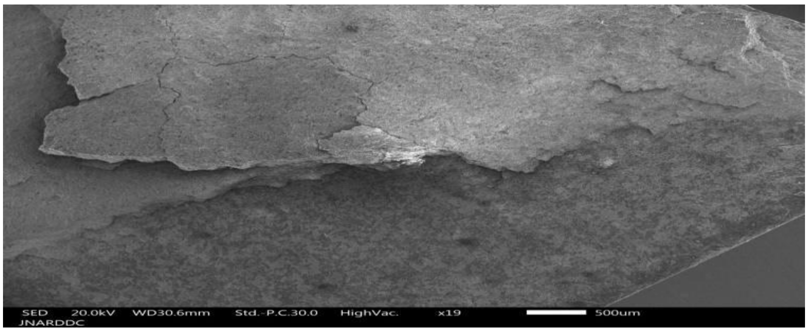


Fig. 16: Coating peels off after thermal shock test

SEM analysis of the cross section of the bowl region revealed delamination of bond coat from the substrate. It might be due to the reason that during the initial stabilization of flame in the burner, temperature might have crossed more than 700 °C in the bowl region. Hence, there might have been melting of substrate at interface and lead to delamination.

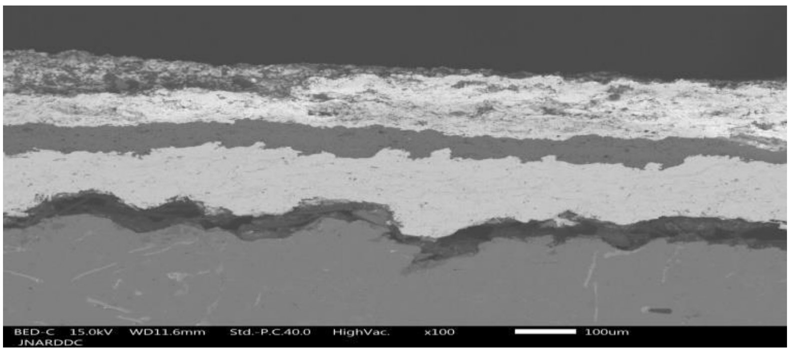


Fig. 17: Delamination between substrate and bound coat

4.6 Electro Discharge Spectrometer (EDS) analysis

EDS spot / selected area analysis on the substrate, bond coat, top coats (Alumina + YSZ) was carried out to check composition as shown in the figure and the results are reported below.

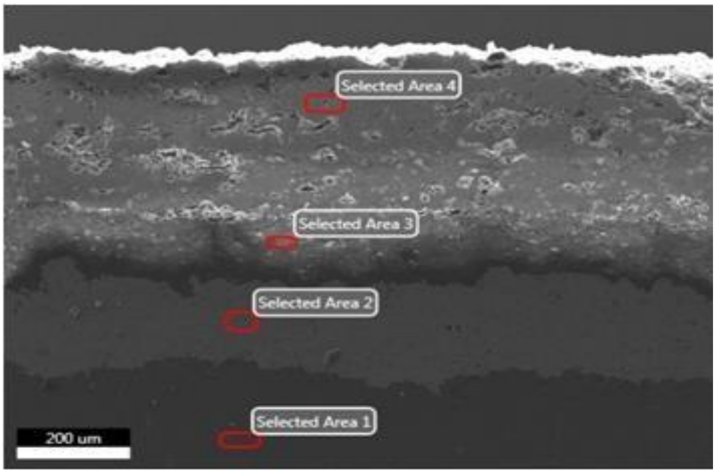


Fig. 18: SEM Micrograph Showing EDS analysis on various regions

In micrograph, selected areas 1, 2, 3 and 4 represents substrate, bond coat, Alumina layer and YSZ layer respectively. The elemental composition of substrate (Selected Area 1) is tabulated in Table. And corresponding X-Ray spectrum is shown in fig. Substrate material was basically Al-Si alloy having approximately 14 wt. % Si and very close to the piston used in automobiles.

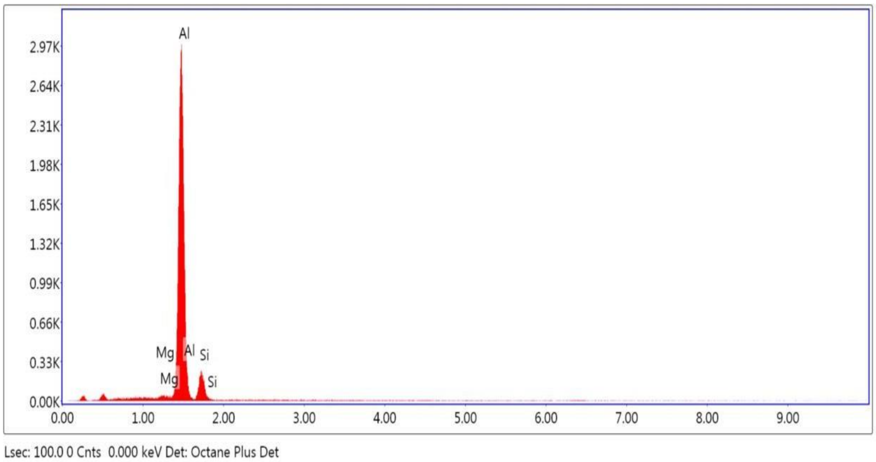


Fig. 19: EDS Spectrum on Substrate (Selected Area 1)

Table 3: Chemical Composition of Substrate (Selected Area 1)

Elements	Mg k	Al k	Si k
Weight %	0.93	85.08	13.99
Atomic %	1.04	85.47	13.50

The elemental composition of bond coat (Selected Area 2) is tabulated and corresponding X-Ray spectrum is shown in the figure. EDS elemental analysis show the presence of Nickel and confirms the presence of bond coat.

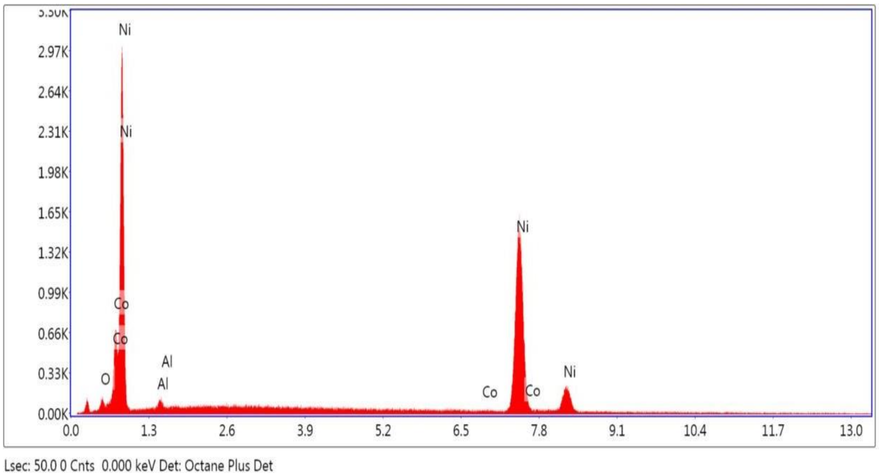


Fig. 20: EDS Spectrum on Bond Coat (Selected Area 2)

Table 4: Chemical composition of bond coat (Selected Area 2)

Elements	O k	Co L	Al k	Ni k
Weight %	2.46	4.79	4.04	91.74
Atomic %	8.39	4.46	2.03	15.13

The elemental composition of Alumina layer (Selected Area 3) is tabulated in Table and corresponding X-Ray spectrum is shown in the figure EDS elemental analysis show the presence of Aluminium and Oxygen and confirms the presence of Alumina layer.

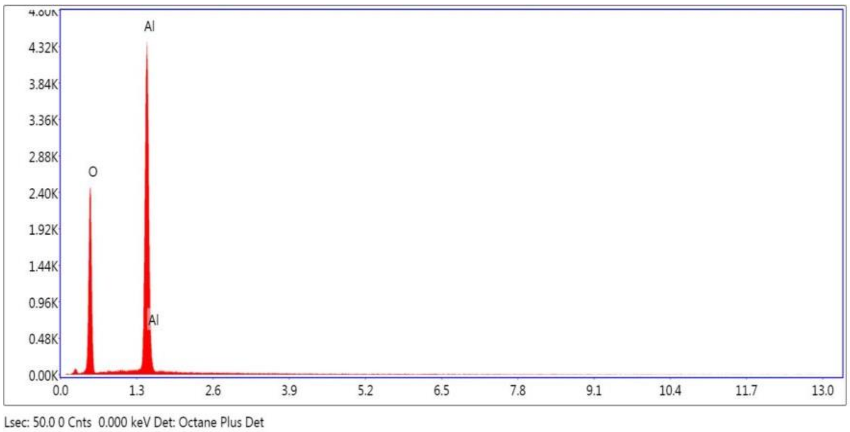


Fig. 21: EDS Spectrum on Alumina Layer (Selected Area 3)

Table 5: Chemical Composition of Alumina Layer (Selected Area 3)

Element	O k	Al k
Weight %	54.49	45.51
Atomic %	66.88	33.12

The elemental composition of YSZ layer (Selected Area 4) and corresponding X-Ray spectrum is shown in figure EDS elemental analysis show the presence of Zirconia and Ytria and confirms the presence of YSZ layer.

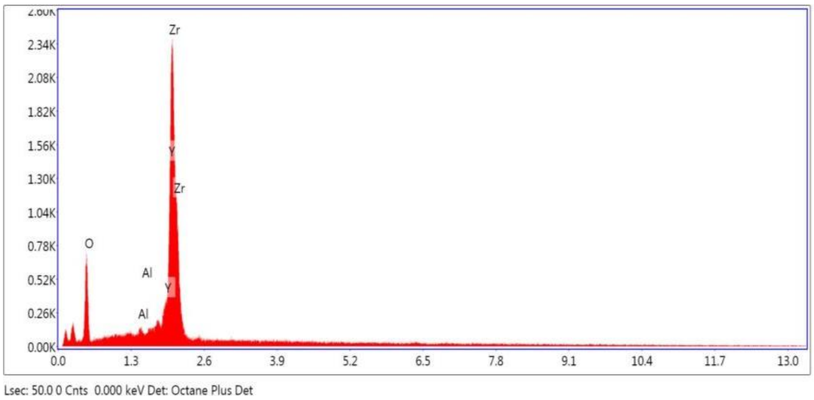


Fig. 22: EDS Spectrum on YSZ layer (Selected Area 4)

Table 6: Chemical Composition of YSZ layer (Selected Area 4)

Element	O k	Al k	Y k	Zr l
Weight %	41.09	0.54	5.83	52.74
Atomic %	79.51	0.62	1.96	17.90

Figure shows the line scan profile across the coating with elements such as Ni, Zr, Y, Al, Si, O, Etc.

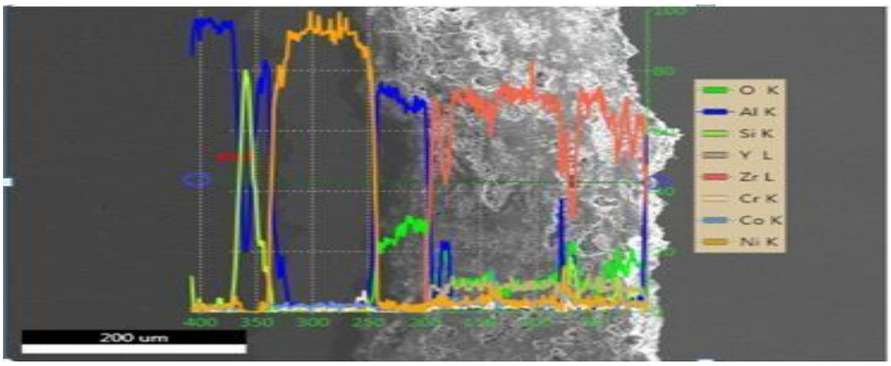


Fig. 23: EDS Line Scan Profile across Coating

Different layers (Bond coat + Top coats) and the interfaces were identified clearly using EDS elemental analysis and line scan profile. This helped in making distinction between coating layers and measuring the coating thickness precisely at various locations.

5. CONCLUSION

In this present study, the following conclusions were derived from the experimental observations.

- It could be possible to successfully fabricate multi-layer TBC coating (Alumina + YSZ with Ni- Co-Al bond) using Air Plasma Spray technique.
- In test coupon as well as in research piston, the bond coat, Alumina and YSZ coat were observed to be uniform throughout the cross section where the plasma and ceramic powder feed was in line with substrate.
- There were no defects such as cracks, porosity, etc. observed in the TBC coating. The coating surface was slightly rough and the surface roughness value (Ra) was about 9.2 µm
- The average coating thickness (Bond coat + Alumina + YSZ) varied between 280 and 350 µm. Average thickness of bond coat, alumina and YSZ was about 90 µm, 70 µm and 180 µm respectively.
- NiCoAl bond coat showed a dense structure and this layer remained partially melted to form a strong mechanically bond or interlocking adhesion to the aluminum alloy substrate.
- Non-uniform coating was observed in the shadow regions of research piston. In this region, uniform deposition of coating was a tedious job due to the equipment configuration, i.e., shadow regions are not in-line with plasma and the powder feed.
- In thermal barrier test, a maximum temperature drop of 265 °C was observed at 590 °C. Delamination of bond coat was observed after 90 cycles.
- Different layers (Bond coat + Top coats) and the interfaces were identified clearly using EDS elemental analysis and line scan profile. This helped in making distinction between coating layers and measuring the coating thickness precisely at various locations.

It was envisaged from this investigation that with proper design modification of equipment and also with number of experimental trial, the coating uniformity can be ensured in all the regions of piston. It will further help in improving the piston performance in actual working conditions. Also, reducing the ceramic particle size to nanometer level will help in obtaining smooth surface with very low surface roughness.

6. ACKNOWLEDGEMENT

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7. REERENCES

[1] Gataowski et. al. “studied on ceramic coatings applied to diesel engine combustion chambers”, 1990.
[2] Shankar.v. et.al. ” Thermal And Metrological Studies on Yttria Stabilized Zirconia Thermal Barrier Coatings and a Simulated Model to Co-Relate the Findings”, Christ university, Bangalore.2016.
[3] S.Satheesh,G. Kumarsan, “Design And Analysis Of Thermal Barrier Coating For Piston”, department of mechanical engineering, C.M.S. collage of engineering,2016 in International conference on engineering innovation and solution.
[4] Murat ciniviz et.al. ” Ceramic Coating Applications and Research Fields for Internal Combustion Engines” selcuk university technical education faculty, turkey, 2012.
[5] Vishnu Sankar, “Thermal Barrier coating Material Selection, Method of Preparation and Application” vol. 3, no.2, 2014, international journal of mechanical engineering an robotic research.
[6] T.Tamilselvan, “Experimental Investigation on Multilayer Coated Piston Running with Diesel Engine” department of automobile engineering, surya group of institution Vikkaravandi, 2017, international journal of science research.
[7] David R. Clarke, “Material Selection Guideline for Thermal Conductivity Thermal Barrier Coating” material department, collage of engineering, university of California. (17)
[8] W. Ma et.al.,”New Generation Perovskit Thermal Barrier Coating Material” 2008, ASM International.
[9] X.Q.Cao et.al. “Ceramic Material for Thermal Barrier Coating”, Changchun institute of applied chemistry, China, 2003.
[10] Emine Bakan et.al. “Ceramic top coats of plasma- sprayed thermal barrier coating: material process and properties” 2017, ASM international.
[11] Lavanya S. et. al. [15] “FEA and Experimental Investigation on The Thermal Properties of the Ceramic Coating on Aluminium Piston” department of mechanical engineering, Chennai, Tamil Nadu.2015.
[12] Shankar.v. et.al. [19] “Lab Scale Preparation And Evaluation Of Yttria Stabilized Zirconia Thermal Barrier Coatings And Its Influence On The Diesel Engine Performance”, Christ university, Bangalore.(2016).
[13] Dipak kumar and K.N.Pandey. [21] “Study on Thermal Fatigue Behaviour of Plasma sprayed Yttria-Zirconia Thermal Barrier Coatings (Tbcs) Systems on Aluminium Alloy” mechanical engineering department, MNNIT, Allahabad. (2014).

