IOP Conference Series: Materials Science and Engineering

PAPER • OPEN ACCESS

Analysis and experimental investigation of ceramic powder coating on aluminium piston

To cite this article: S Pal *et al* 2017 *IOP Conf. Ser.: Mater. Sci. Eng.* **263** 062071

IOP Conf. Series: Materials Science and Engineering **263** (2017) 062071 doi:10.1088/1757-899X/263/6/062071

Analysis and experimental investigation of ceramic powder coating on aluminium piston

S Pal, A Deore, A Choudhary, V Madhwani and D Vijapuri
Department of Manufacturing Engineering, School of Mechanical Engineering, VIT University, Vellore - 632014, Tamilnadu, India

Email: soumenpal@vit.ac.in

Abstract: Energy conservation and efficiency have always been the quest of engineers concerned with internal combustion engines. The diesel engine generally offers better fuel economy than its counterpart petrol engine. Even the diesel engine rejects about two thirds of the heat energy of the fuel, one-third to the coolant, and one third to the exhaust, leaving only about one-third as useful power output. Theoretically if the heat rejected could be reduced, then the thermal efficiency would be improved, at least up to the limit set by the second law of thermodynamics. Low Heat Rejection engines aim to do this by reducing the heat lost to the coolant. Thermal Barrier Coatings (TBCs) in diesel engines lead to advantages including higher power density, fuel efficiency, and multifuel capacity due to higher combustion chamber temperature. Using TBC can increase engine power by 8%, decrease the specific fuel consumption by 15-20% and increase the exhaust gas temperature by 200K. Although several systems have been used as TBC for different purposes, yttria stabilized zirconia with 7-8 wt.% yttria has received the most attention. Several factors playing important role in TBC life include thermal conductivity, thermo chemical stability at the service temperature, high thermo mechanical stability to the maximum service temperature and thermal expansion coefficient (TEC). This work mainly concentrates on the behaviour of three TBC powders under the same diesel engine conditions. This work finds out the best powder among yttria, alumina and zirconia to be used as a piston coating material i.e., the one resulting in lowest heat flux and low side skirt and bottom temperature has been chosen for the coating purpose. This work then analyses the coated sample for its surface properties such as hardness, roughness, corrosion resistance and microstructural study. This work aims at making it easier for the manufacturers choose the coating material for engine coating purposes and surface properties for operating them in their service period.

1. Introduction

Diesel engines play a major role in the automotive industry. It has assumed a dominating role in both transport and agricultural industry due to its higher fuel economy and low running cost. However, the heat carried away by the coolant and exhaust gases carry considerable amount of fuel energy from the combustion chamber in diesel engines leaving only 30-40% of the total energy for conversion into useful work. The engine cooling system absorbs combustion and friction generated heat and dissipates it to the surroundings to ensure engine temperature always remains in the safe level. The lubrication system and exhaust gases are the other sources which carry away the heat from the combustion chamber.

According to second law of thermodynamics, insulating the combustion chamber of an internal combustion engine will theoretically result in improved thermal efficiency. So, if the working

IOP Conf. Series: Materials Science and Engineering **263** (2017) 062071 doi:10.1088/1757-899X/263/6/062071

temperature inside the combustion chamber can be increased, the heat loss through coolant fluid will be less and hence the thermal efficiency of the internal combustion engine can be improved.

In engine, there is heat transfer to the gases during intake stroke and the first part of the compression stroke, however during combustion and expansion processes heat transfer take place from the gases to the walls. So, the piston crown/head, piston ring and the piston skirt should have enough stiffness which can endure the pressure and the friction between contacting surfaces. Bhagat and Jibhakate [1] concluded that the stiffness and hardness of the material play a major role under thermal effects of regular operation and under extreme conditions on the crown of the piston. They observed that deformation in the piston skirt usually causes crack on the upper end of the piston head which eventually can lead to piston failure. Another group [2] performed thermal analysis in ANSYS on diesel engine piston ad observed that the highest stressed area in the piston is the crown of the piston and reported results about temperature distribution and its effect on compression rings. Thermal analysis on engine pistons were also evaluated by many researchers [3-7].

Studies on corrosion in gasoline engines was done by Jardine F [8] and it is reported that corrosion is primarily because of sulphuric acid formed in the engine. This problem is more common in winters. Behaviour of aluminium engine block in 3.5% NaCl solution atmosphere was investigated by Kaiser and Dutta [9]. Valente and Galliano [10] found that corrosion resistance properties of composite coatings is influenced by porosity which can be adjusted using plasma spraying parameters.

Thermal barrier coatings (TBC) have the capacity to give higher thermal efficiency to the engine. Further TBC improves combustion and reduces emissions. Ceramics used as TBC have more thermal durability than metals, and display improved wear characteristics than conventional materials. Thermal analysis of a ceramic coating diesel engine piston by 3-D finite element method was carried out by Buyukkaya and Cerit [11]. They used MgO-ZrO_2 as the coating material and compared the results of four different pistons. It was observed that surface temperature (maximum) in the coated piston having material with less thermal conductivity improved by 48% for AlSi alloy and 35% in case of steel. Further work on ceramic TBC was reported by the same author [12,13].

In the present study, various tests have been performed on Al 6061 substrate, coated with yttria stabilized zirconia powder. Zirconia was finalized by performing ANSYS analysis on titania, alumina and zirconia coatings. The main emphasis of this work is to assess and compare thermal properties of the coated and uncoated pistons on ANSYS Workbench platform. Kirloskar make diesel engine piston was considered. To simulate the real-world conditions, piston is designed in CATIA V5.

2. Methodology

2.1. Design

In order to perform thermal analysis study, piston was designed in CATIA V5 software. Details of the engine and piston dimensions is given in Table 1 and the model is shown in Figure 1 and Figure 2.

Table 1. Engine and piston dimensions.

Item	Specification
Make	Kirloskar engine
Type of engine	Four stroke, Single cylinder, Naturally aspirated, Water cooled, constant speed engine
Bore, mm	80
Stroke, mm	110
Compression ratio	16.5 : 1
Rated power	3.7 kW @ 1500 rpm
Type of fuel	Diesel

Type of injection	Direct injection
Fuel injection pressure, bar	200
No. of nozzle holes	3
Nozzle hole diameter	0.26 mm
Inlet valve opens (IVO)	15 Btdc
Inlet valve closes (IVC)	45 Abdc
Exhaust valve opens (EVO)	45 Bbdc
Exhaust valve closes (EVC)	10 Atdc

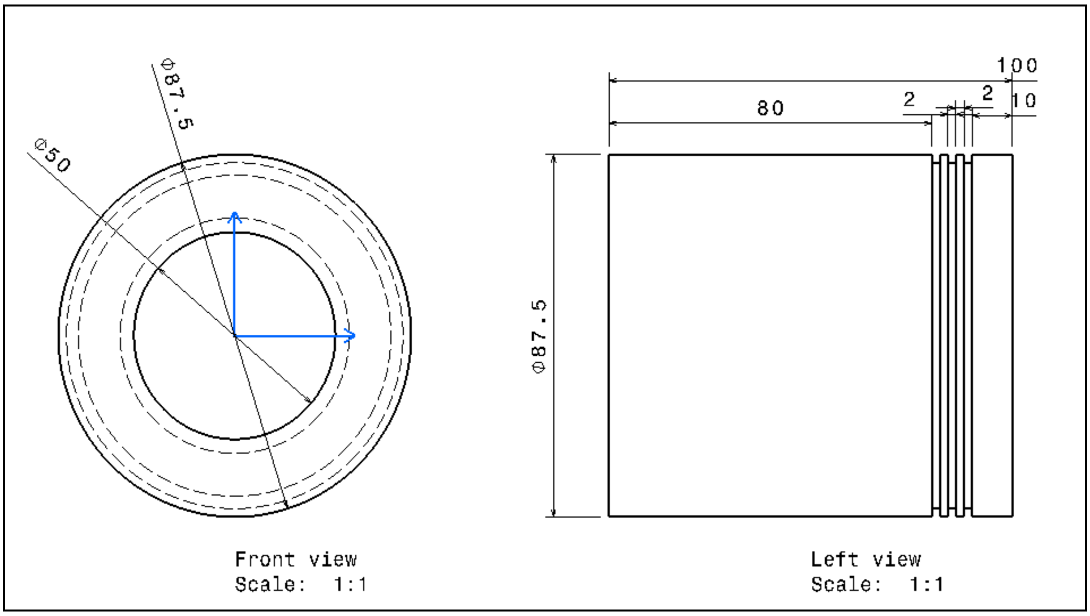


Figure 1. 2-D Model of Piston Design.

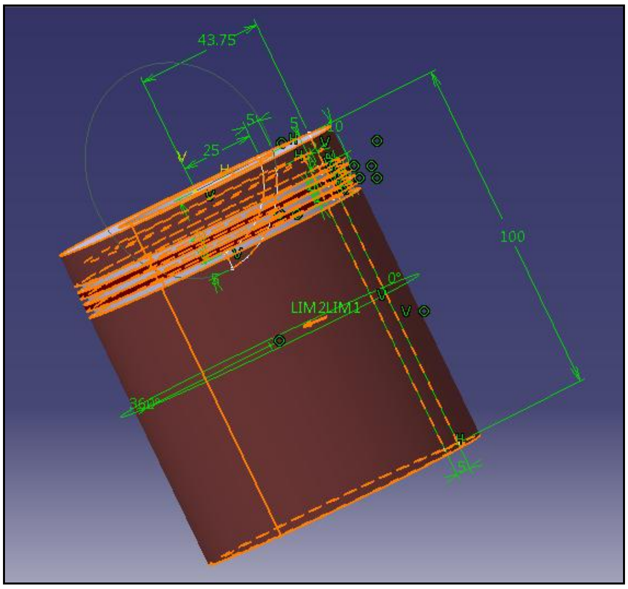


Figure 2. 3D model of piston design.

2.2. Analysis

The piston is one of the most stressed components of an entire vehicle. Pressures at the combustion chamber may reach about 180–200 bar. Speeds reach about 25 m/s and temperatures at the piston crown may reach about 600°C. As one of the major moving parts in the power-transmitting assembly, the piston must be designed so that it can withstand the extreme heat and pressure of combustion.

For this purpose, to simulate actual engine combustion chamber conditions steady state thermal analysis is done in ANSYS workbench software. Boundary conditions applied for the simulation are: piston head temperature 600^0C, side skirt temperature 22^0C, and material Aluminium alloy 6061. The coating on samples was to be done with APS process but there is no way to simulate that condition in ANSYS hence to achieve coating like properties 3 mm thick plate with same dimensions as piston head was created and material was assigned for respective simulation. Once simulation was done the results were analysed for properties like temperature distribution, directional heat flux, overall deformation and deformation in z-direction.

2.3. Sample preparation

2.3.1. Surface preparation for coating. Three methods of surface roughening for thermal spray are widely used: rough threading, grit blasting, and a combination of rough threading followed by grit blasting. In case of our sample, grit blasting was done to make surface rough enough to improve the adhesion of substrate and coating. The parameters are given in Table 2.

Table 2. Grit Blasting Parameters.

Parameter	Specification
Substrate	Aluminium 6061 Alloy
Blast Powder	Al_2O_3
Particle Size (mean diameter)	0.5 mm
Blasting Distance	60 mm
Pressure	0.2 MPa / 29 psi
Angle of nozzle	45°
Time of blasting	6 s
Equipment	Econoline RA 36-1

2.3.2. Preparation of NiCrAlY Bond coat. The chromium and aluminium in these coatings provide Protection through the formation of an oxide scale. The addition of yttria acts to improve the adhesion of this oxide layer. This dense, well-adherent scale is critical for the prolonged life of high temperature ceramic coating systems such as thermal barrier coatings and ceramic abrasive systems. The alumina acts as an oxygen diffusion barrier that helps to minimize bond coat oxidation. NiCrAlY alloys also decrease the inter-laminar stress between ceramic top coat and substrate. The bond coat specifications are given in Table 3.

Table 3. Bond coat powder specification.

Commercial code	Amdry 962
Weight composition	Ni-62-65 % Cr 21-23 % Al 9-11% Y 0.8-1.2%
Service temperature	980ºC
Manufacture	Gas Atomization

2.3.3. Plasma Spray coating. Plasma spraying is expected to influence the NiCrAlY bond coat by improving the contact to Al base substrate, reduce cracks resulting from the relaxation of residual stresses in the planar direction and lower deformation of partially melted particle resulting in less voids. Plasma spray process will result in sharp NiCrAlY bond – zirconia coating interface, and smaller zirconia crystals.

Zirconia coating on the piston heads was done using plasma spray process. The process parameters and powder specifications are given in Table 4 and Table 5 respectively.

Table 4. Plasma spraying parameters.

Parameter	Specification
Torch input power	10-18 KW
Plasma gas (Ar) flow Rate	150± 5% (l/min)
Secondary gas (N_2) flow rate	100 ± 5% (l/min)
Powder feed rate	40 g/min
Powder carrier gas flow rate	Up to 450 (m/s)
Torch to base Distance	76.2 ± 10 % mm
Anode nozzle Diameter	8 mm
Arc current	450 amperes
Powder injection and angle	Radial injection through nozzle (near the exit) 90º
Plasma gas injection	Vortex injection
Equipment	Metco 9 MB

Table 5. Coating powder specifications.

Parameter	Value
Code	Metco 201B-NS
Manufacture	Fused and crushed or agglomerated
Morphology	Angular and blocky or spheroidal
Service temperature	≤ 900 ^{0}C (1650 ^{0}F)
Melting point	2565 ^{0}C (4650 ^{0}F)
Density	2.4 ± 0.25 (g/cm^3)

IOP Conf. Series: Materials Science and Engineering **263** (2017) 062071 doi:10.1088/1757-899X/263/6/062071

2.4. Experimentation

2.4.1. Coating thickness measurement test. Engine piston is a very sensitive component. The dimensions of the components are very critical as the injection timing, fuel consumption, spark timing mapping, and overall Engine Control Unit (ECU) mapping is done for those particular dimensions. From literature review the decided coating thickness was 300 microns and hence the plasma spray parameters were decided to get the coating of 0.3 mm. To verify it coating thickness test was performed according to ASTM B499 standards.

2.4.2. Vickers hardness test. Low hardness of the top groove of the piston is the reason for various kinds of damages which leads to the failure of the component. ASTM E384-2011 standards were followed for the test. Test was performed on 3 coated and 3 uncoated samples for the varying loading conditions.

2.4.3. Salt Spray test for corrosion resistance. Engine cylinders operate under increased pressures and reduced operating temperatures to comply with Tier II NO_x regulations and Energy Efficiency Design Index (EEDI) guidelines. This leads to increase in cold corrosion. Conditions below the dew point are created in engines leading to water condensation on the cylinder liner walls. Condensate combines with sulphur, forming sulphuric acid, corrodes the liner surface, piston head and causes excessive wear to liner material.

This test was performed as per the ASTM B117-11 standard. The duration of the sample observation was 72 hours. White rust formation was to be observed. The standard test parameters are given in Table 6.

Table 6. Salt spray test parameters.

Chamber Temperature	34.5 – 35.5 ^{0}C
pH Value	6.65 – 6.85
Volume of salt solution collected	1.0 – 1.5 ml/hr
Concentration of solution	4.80 – 5.30% of NaCl
Air pressure	14 – 18 psi
Components loading in the chamber position	30^0 angle

2.4.4. Surface Profilometer study for roughness measurement. Since piston is very sensitive component of the engine the dimensions need to be very accurate in order to perform properly. Plasma spray coating of zirconia may change the surface properties due to increased surface roughness. To evaluate the roughness amount, 3 coated and 3 uncoated samples were studied.

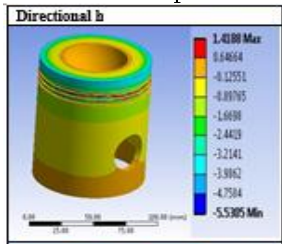
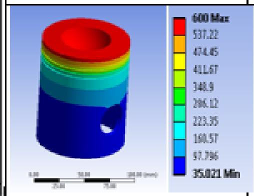
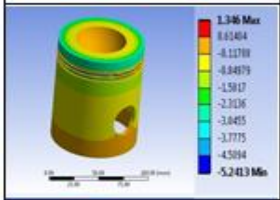
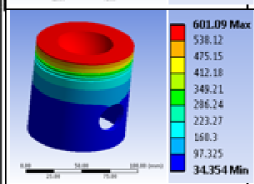
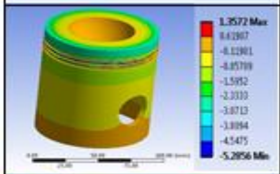
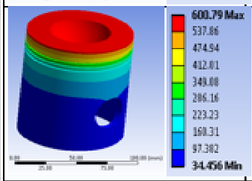
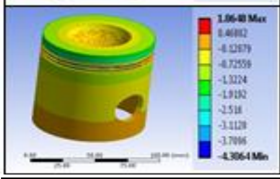
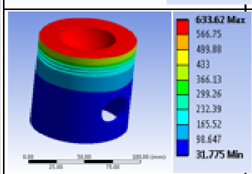
2.4.5. Optical microscope study. The main purpose of microscopic study is to observe the substrate-bonding-coating. The top surface was studied at 100x, 200x and 400x to get the zirconia microstructure. The cross section of the sample was studied under microscope to get bonding area characteristics.

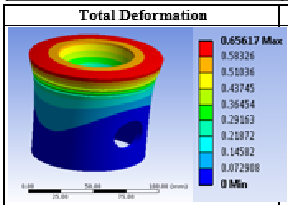
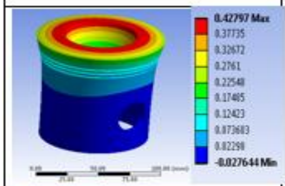
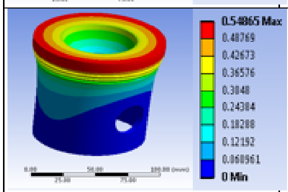
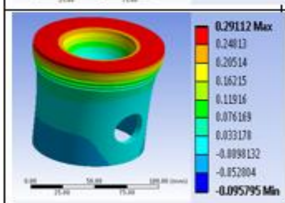
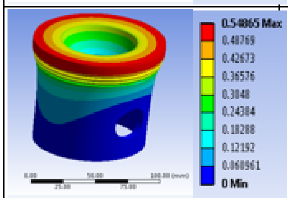
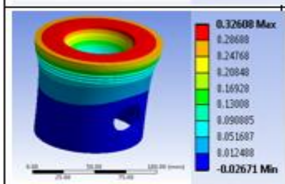
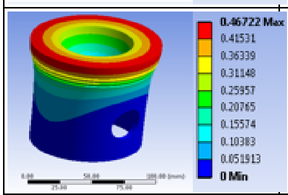
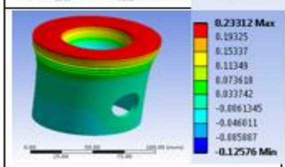
3. Results and Discussion

3.1. Results of ANSYS simulation

The results of the simulations are summarised in Table 7.

Table 7. Simulation results for uncoated and coated pistons showing (a) directional heat flux (b) temperature distribution (c) total deformation (d) directional deformation.

Directional h	Maximum values(W/mm²)	Temperature distribution	Top surface Temperature in ° C	Bottom surface Temperature in ° C
	**Uncoated – 4.7584**		Uncoated- 600	Uncoated- 35.021
	**Alumina – 4.5094**		Alumina- 601.09	Alumina- 34.354
	**Titania – 4.5475**		Titania- 600.79	Titania- 34.456
	**Zirconia – 3.7096**		Zirconia- 633.32	Zirconia- 31.775

Total Deformation	Maximum Deformation(mm)	Directional deformation Z direction	Directional deformation Z direction(mm)
	**Uncoated- 0.65**		**Uncoated- 0.42**
	**Alumina- 0.54**		**Alumina- 0.29**
	**Titania- 0.588**		**Titania- 0.32**
	**Zirconia- 0.467**		**Zirconia- 0.23**

In case of temperature distribution, the zirconia coating resulted in highest piston head temperature which in turn suggests that the temperature in the combustion chamber will be highest in case of zirconia coating. This helps to reduce the heat lost by cooling gases (according to 2^{nd} law of thermodynamics), which results into the engine working more efficiently i.e. consuming less fuel.

Directional heat flux in z-direction are lowest in the case of zirconia coating. One of the major reasons of failure and deterioration of piston is high heat flux through it. So, in this case it will be highest in uncoated piston and lowest in zirconia coated piston. Further, total maximum deformation caused by the thermal stress is least in case of zirconia and highest for uncoated piston.

3.2. Results of coating thickness measurement test

The results of the coating thickness measurement in microns are shown in Table 8. The thickness is approximately achieved against the targeted 300 microns.

Table 8. Results of coating thickness measurement.

Sample No	1	2	3
Thickness (microns)	267	287	280

3.3. Results of Vickers hardness test

The observations recorded have been tabulated in the table 9.

Table 9. Result of Vickers hardness test.

S. No.	Un-coated	Coated
1	48.8	55.2
2	48.3	53.6
3	47.7	54.6
4	48.3	54.8
5	48.5	55.8
6	47.6	54.4

The average Vickers hardness for uncoated samples is 48.2 HV 5kg and for coated samples is 54.73 HV 5kg. So, hardness is improved using zirconia as TBC. This effect on hardness can be attributed to nanostructured stabilised zirconia powder which was plasma sprayed on to the aluminium substrate which increased the hardness. The bonding material NiCrAlY used also contributes to increased hardness.

The real-world effect of these results translates into better hardness properties of the piston crown. This will in turn result in longer life of the component and extended service period.

3.4. Result of salt spray test

Uncoated sample was affected by the white rust at the end of 12 hours. There was no formation of rust at the surface of the coated sample at the end of 72 hours. The main reason for the formation of rust was exposed surface of aluminium alloy to the alkaline environment.

The plasma coating was less porous, and the composition of the coating and bonding material prevents the aluminium substrate from being susceptible to corrosion. So, coating the sample with stabilised zirconia makes it less prone to corrosion that happens in the engine at cold start (acidic and moisture) conditions which results in the higher service duration of the component.

Since this is an accelerated test for corrosion, we can compare the probable behaviour of sample in actual working conditions and from this it can be concluded that coated sample will be less affected by corrosion that uncoated sample.

IOP Conf. Series: Materials Science and Engineering **263** (2017) 062071 doi:10.1088/1757-899X/263/6/062071

3.5. Result of surface profilometry for roughness measurement

Results of the surface profilometer study for uncoated and coated samples are shown in Figure 3 and Figure 4 respectively.

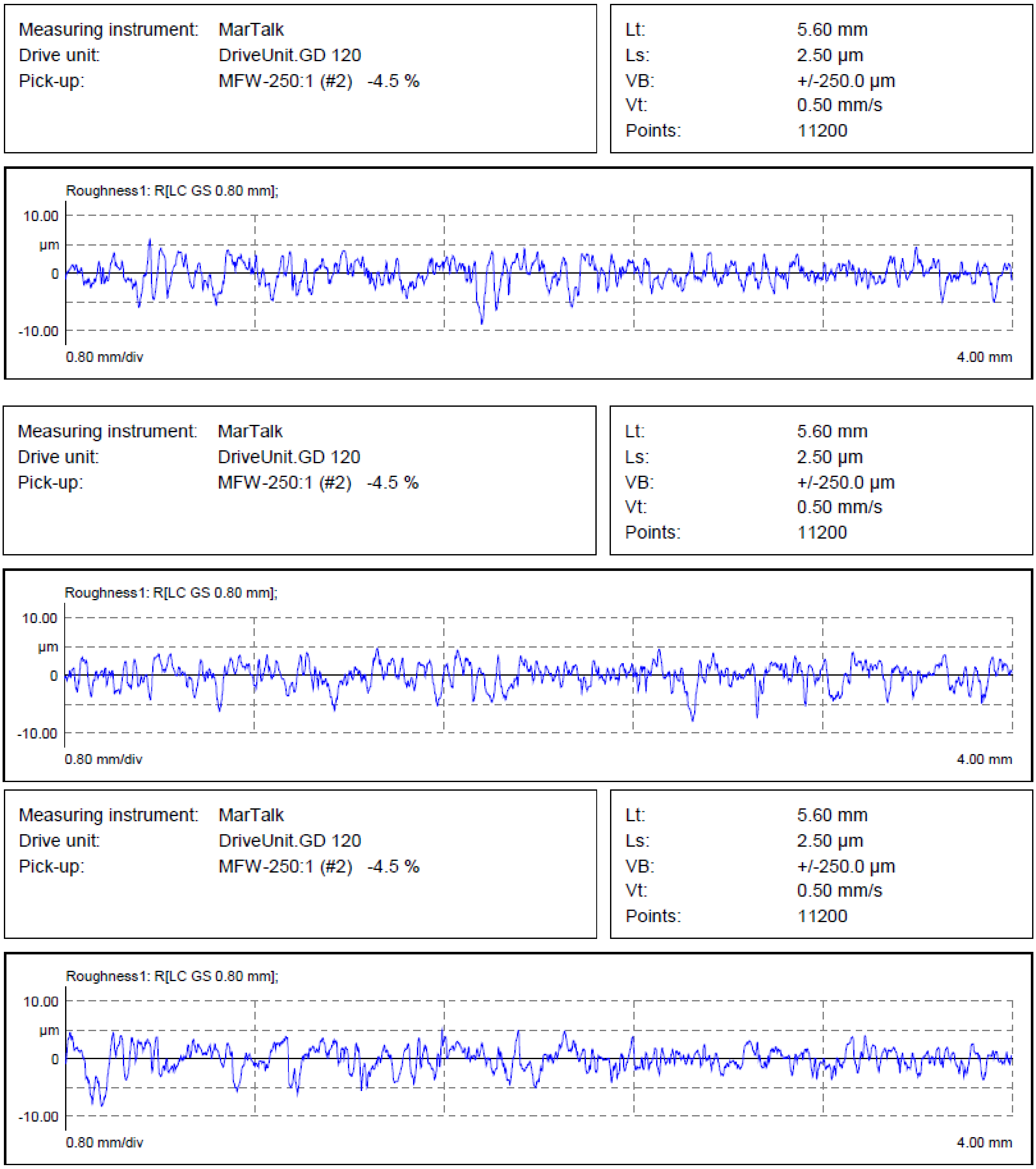


Figure 3. Surface profilometer study on the uncoated samples.

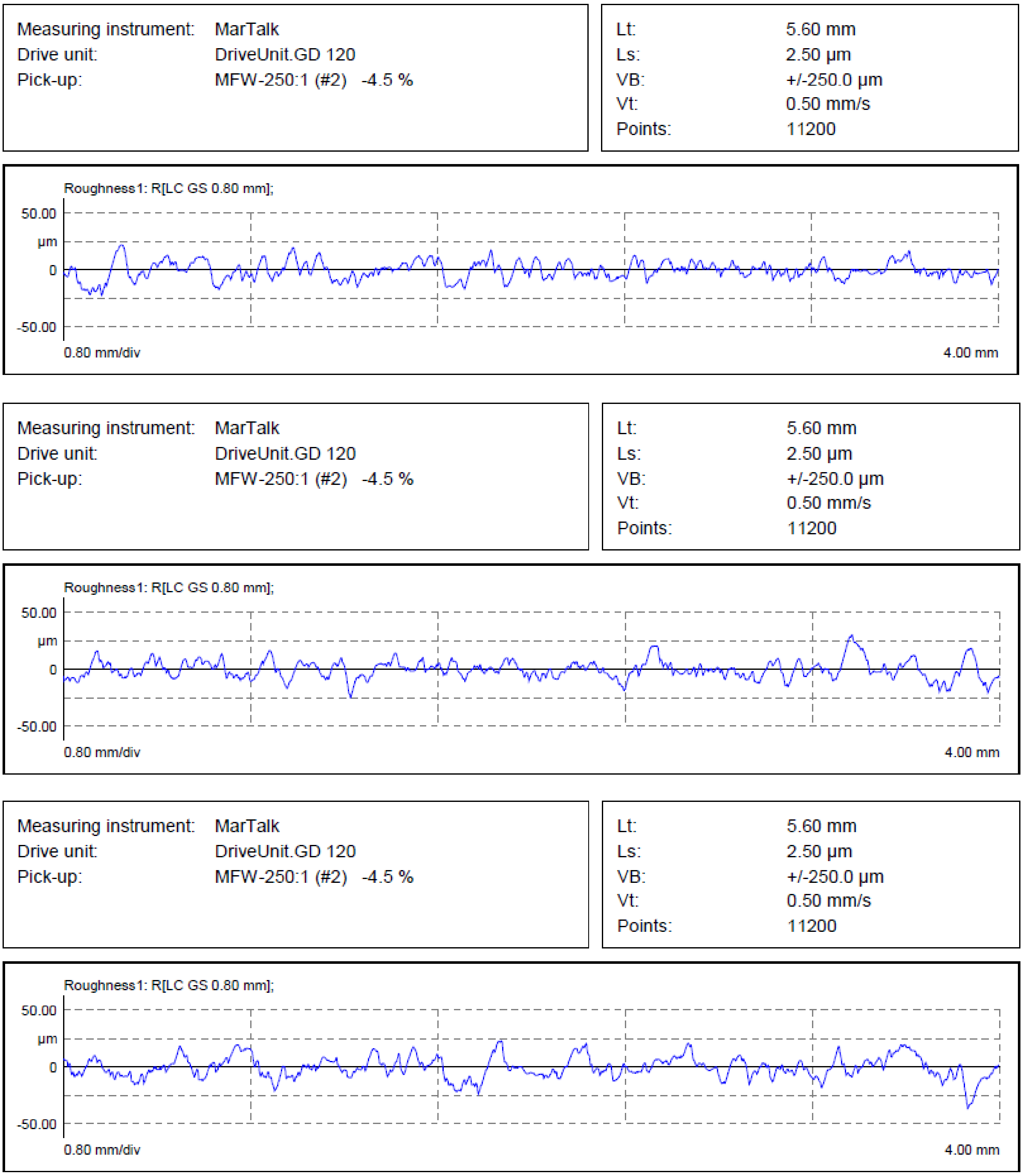


Figure 4. Surface profilometer study on the coated samples.

Average roughness value for uncoated sample (in microns): 1.6102
Average roughness value for coated sample (in microns): 6.5028

Since piston head is a very sensitive part in terms of dimensioning and profile, it is very important for the surface to have proper finish to keep the operations of piston going regularly. In the surface roughness test, the head of piston isn't in sliding or friction contact with any other moving or stationary surface, hence variation of +/- 10 microns of roughness is acceptable. So, it can be observed that the roughness values are well within the acceptable limits.

3.6. Results of optical microscope study:
Top surface of the coating is shown in Figure 5.

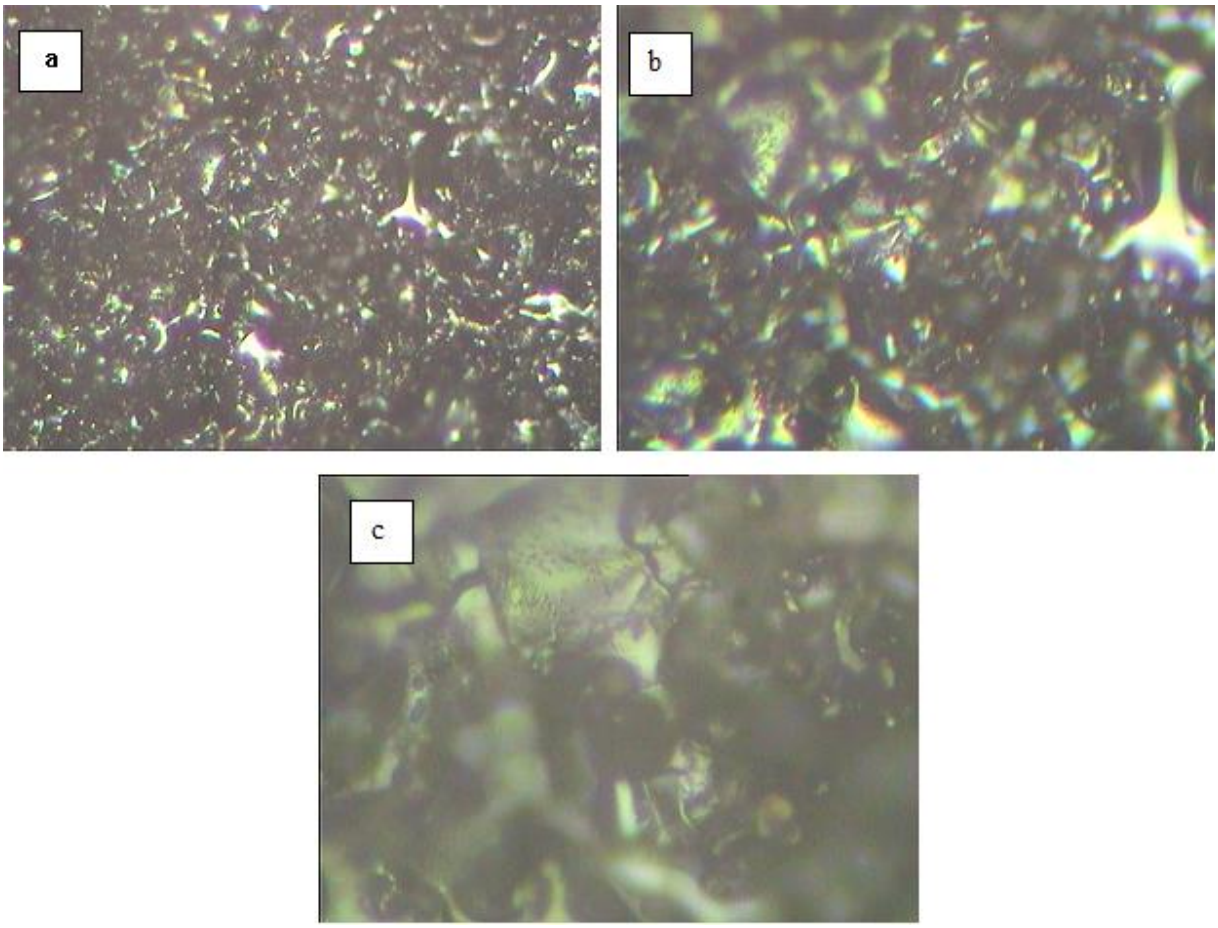


Figure 5. Top surface of the coating under (a) 100x (b) 200x (c) 400x.

Cross-section optical microstructure images are shown in Figure 6.

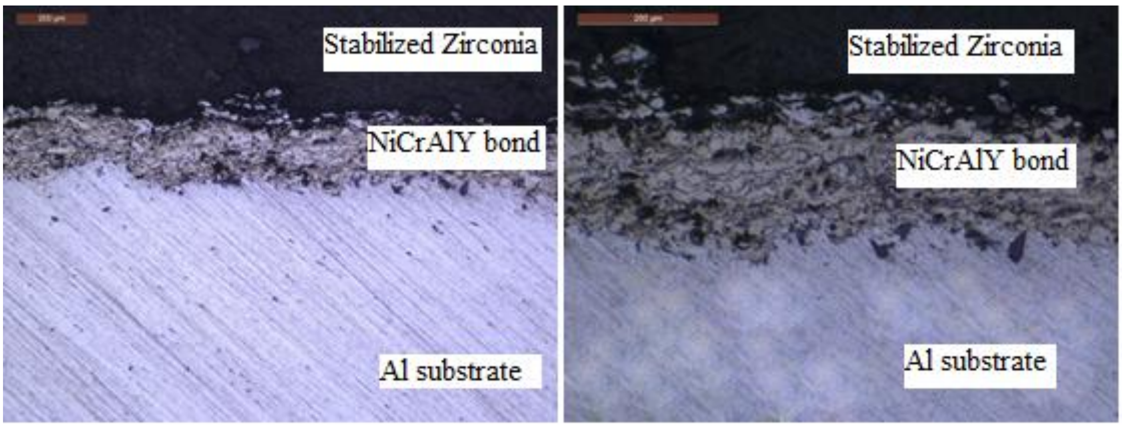


Figure 6. Optical microscope image of cross-section interface at 2 different magnifications.

The 3 layers viz. substrate – NiCrAlY bonding – stabilised zirconia coating are clearly visible. Due to surface preparation by grit blasting the substrate looks roughened improving the adhesion of coating to the substrate. Magnified view of coating reveals specific traits of the plasma spray coating i.e., insertion of bonding material in the aluminium surface because of the high pressure and high temperature environments. We can also observe few black colour particulate in the bonding layer which are the stabilised zirconia particulates that penetrated due to high pressure and temperature environment. Overall, we can observe very definite and well bonded layers of substrate and coatings.

4. Conclusion

There has been lot of research done in the sector of Thermal Barrier Coatings (TBC) especially at the microscopic level. The main focus of this work was to study the application of TBCs as the top layer on the head of the piston. To scientifically and analytically select the correct and most suitable powder for the application, steady state thermal analysis was performed. And then the Aluminium samples were coated with the best suitable powder which was found to be partially stabilised zirconia by the means of plasma spray coating.

The authors conclude the following:

- From thermal analysis, it can be concluded that zirconia comes out as a superior option compared to alumina and titania ceramic powders as TBCs. Zirconia can be selected as a coating material for piston head or any other similar application where substrate is subjected to similar temperature and stress conditions. Use of yttria stabilized zirconia in Al piston leads to reduced heat flux, increased top surface temperature, reduced temperature at piston skirt and bottom area. This reduces the damage to the piston, increasing its service period and efficiency.
- Various piston damages that occur at the piston head are mostly due low hardness of the top surface. Application of stabilised zirconia as TBC by the means of plasma spray coating with specific parameters increases the hardness of the sample that reduces piston damages.
- Salt spray study was performed to measure corrosion resistance of the engine piston due to acidic and humid conditions which are observed during early morning start, cold start etc. Uncoated sample was affected by the white rust at the end of 12 hours. Sample coated with zirconia showed no signs of rust at the end of 72 hours. Hence, coated pistons have better corrosion resistance.
- Surface roughness test show that the application of TBC increases the roughness in very small amounts and does not affect the engine operations. Further, post processing finishing operations can be used to improve the surface finish.

Acknowledgements

We thank Spraymet surface technologies, Bangalore for plasma spray coating facility and Microlab, Chennai for salt spray test facility.

References

[1] Bhagat A R and Jibhakate Y M 2012 Thermal Analysis and Optimization of IC Engine Piston using finite element method *International Journal of Modern Engineering Research* **2** 2919-21
[2] Al-Beiruti A, Al-Quraishi M and Ezzulddinyousif I 2009 Thermal Effects on Diesel Engine Piston and Piston Compression Rings *Engineering and Technology Journal* **27** 1444-54
[3] Wang Y X, Liu Y Q and Shi H Y 2010 Finite Element Static and Dynamic Analysis for a Piston *Advanced Materials Research* **97-101** 3323-3326
[4] Esfahanian V, Javaheri A and Ghaffarpour M 2006 Thermal analysis of an SI engine piston using different combustion boundary condition treatments *Applied Thermal Engineering* **26** 277-287
[5] Srinadh M and Rajasekhara Babu K 2015 Static and Thermal Analysis of Piston and Piston Rings *International Journal of Engineering Technology, Management and Applied Sciences* **3(8)** 51-58
[6] Singh P and Pramanik D 2015 Structural and thermal analysis of a C. I. engine piston of different materials using FEM technique *MR International Journal of Engineering and Technology* **7(1)** 41-48
[7] Szmytka F, Salem M, Aria FR and Oudin A 2015 Thermal fatigue analysis of automotive diesel piston: Experimental procedure and numerical protocol *International Journal of Fatigue* **73** 48–57

[8] Jardine F 1925 Engine corrosion-its causes and avoidance *SAE technical paper*
[9] Kaiser M S and Dutta S 2014 Corrosion Behaviour of Aluminium Engine Block in 3.5% NaCl Solution *Journal of Materials Science and Chemical Engineering* **2** 52-58
[10] T. Valente, F. P. Galliano 2000 Corrosion resistance properties of reactive plasma-sprayed titanium composite coatings *Surface and Coatings Technology* **127** 86-92
[11] Buyukkaya E and Cerit M 2007 Thermal analysis of a ceramic coating diesel engine piston using 3-D finite element method *Surface and Coatings Technology* **202(2)** 398-402
[12] Cerit M and Coban M 2014 Temperature and thermal stress analyses of a ceramic-coated aluminum alloy piston used in a diesel engine *International Journal of Thermal Sciences* **77** 11-18
[13] Cerit M 2011 Thermo mechanical analysis of a partially ceramic coated piston used in an SI engine *Surface and Coatings Technology* **205(11)** 3499-3505