ISSN(online): 2321-0613

Temperature and Thermal Stress Analyses of a Ceramic-Coated Aluminum Alloy Piston in a Diesel Engine

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Abstract— The aim of this work is to determine both temperature and thermal stress distributions in a plasma sprayed magnesia-stabilized zirconia coating on an aluminum piston crown to improve the performance of a diesel engine. The coating is done on the piston crown to the extent of 0.2 to 1.6 mm coating thickness with magnesia zirconia excluding the bond coat layer. Effects of the coating thickness on temperature and thermal stress distributions are investigated, including comparisons with results from an uncoated piston by means of the finite element analysis. Temperature and thermal stress analyses are performed for various coating thicknesses from 0.2 to 1.6 mm excluding the bond coat layer. In the analysis a quarter of the piston model is used for various conditions an uncoated piston crown and a ceramic-coated piston crown and the boundary conditions are applied to solve the field equations using ANSYS WORKBENCH15 FEA software. Temperature at the coated surface is significantly higher than that of the uncoated piston. It is observed that the coating surface temperature increases with coating thickness by decreasing rate. The higher combustion chamber temperature provided by means of coating results in the better thermal efficiency of the engine. It also provides for a reduction in the substrate surface temperature. The normal stress on the coated surface decreases with increasing coating thickness. Maximum normal stress occurs on the bond coat surface.

Key words: Temperature, Coating Thickness, Thermal Barrier, Vonmises Stress, Piston Crown Temperature

I. INTRODUCTION

Piston is the most important part of an I.C. engine which helps to convert the heat energy into mechanical energy. It is a cylindrical part that moves up and down in the cylinder. The space between the piston and cylinder wall is known as piston clearance, which provides space for a thin film of lubricant between piston and cylinder wall. Piston is subjected to greater thrust and higher temperature during the power stroke. Therefore, piston must be strong and light to reduce the inertia loads on the bearings. Its purpose is to transfer force from expanding gas in the cylinder to the crankshaft via a connecting rod. Since the piston is the main reciprocating part of an engine, its movement creates an imbalance. This imbalance generally manifests itself as a vibration, which causes the engine to be perceivably harsh. The friction between the walls of the cylinder and the piston rings eventually results in wear, reducing the effective life of the mechanism. The sound generated by a reciprocating engine can be intolerable and as a result, many reciprocating engines rely on heavy noise suppression equipment to diminish droning and loudness. To transmit the energy of the piston to the crank, the piston is connected to a connecting rod which is in turn connected to the crank. Because the linear movement of the piston must be converted to a rotational movement of the crank, mechanical loss is experienced as a consequence. Overall, this leads to a decrease in the overall efficiency of the combustion process.

Fig. 1: Photograph of a diesel engine piston

II. RELATED WORK MODELLING AND ANALYSIS OF THE PISTON

Thermal barrier coatings (TBCs) are commonly applied to substrates to insulate them thermally so as to allow for higher operating temperature. The desire to increase thermal efficiency or reduce fuel consumption of engines makes it tempting to adopt higher compression ratios, in particular for diesel engines, and reduced in cylinder heat rejection. Coating of the diesel engine pistons is one engineering application of TBCs among others. TBCs are applied to insulate combustion chamber components or selected surfaces like the piston crown. Heat rejection is then reduced in the cylinder and the metallic surfaces are protected from thermal fatigue, especially from power and exhaust strokes of the diesel engine cycles. The coating is a ceramic-based material that has low thermal conductivity and good strength is capable of enduring higher temperatures than metals. One of the widely used materials is zirconia, which is applied by a plasma-spraying technique. The main purpose of this is to raise the temperature of the piston crown's surface during the expansion stroke, thereby decreasing the temperature difference between the wall and the gas to reduce heat transfer. Some of the additional heat energy in the cylinder can be converted and used to increase power and efficiency. Additional benefits include protection of metallic combustion chamber components from thermal stresses and reduction of cooling requirements. A simpler cooling system will reduce the weight and cost of the engine while improving reliability. There are many potential advantages of low heat rejection (LHR) for engine concepts such as reducing fuel consumption and emissions as well as more durable pistons and exhaust valves.

The bond coat layer is used between the TBC and the metal substrate. The bond coat material is an intermetallic alloy that provides oxidation resistance at high temperatures and aids in the adhesion of the TBC layer to the substrate. The bond coat plays an important role in reducing the internal stresses which may arise between the substrate and the ceramic coating because of thermal shock. The coefficient of thermal expansion (CTE) of the bond coat should be between that of the TBC and the metal substrate

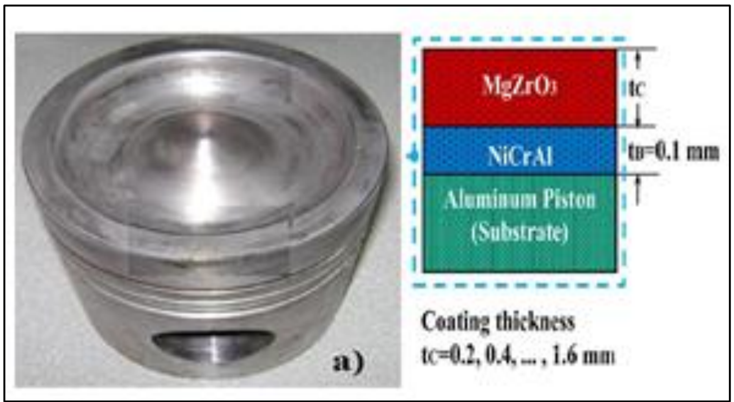

Fig. 2: The piston used in the FE analyses: a) photograph of the piston used diesel engine, b) the coating parameters

S No.	Material Properties	Materials for the piston			
		Piston (Aluminum Alloy)	Bond Coat (NiCrAl)	Ceramic Coating ($MgZrO_3$)	Rings (Cast Iron)
1	Modulus of elasticity (GPa)	90	90	46	200
2	Poisson's ratio (m/m)	0.33	0.27	0.20	0.30
3	Thermal conductivity(W/m °C)	155	16.1	0.8	16
4	Thermal Expansion 10^{-6} (1/°C)	21	12	8	12
5	Density (kg/m^3)	2700	7870	5600	7200
6	Specific heat (J/kg °C)	910	764	650	460

Table 1: Material properties of piston and coatings

III. TEMPERATURE AND THERMAL STRESS ANALYSES

Steady-state thermal stress analyses are performed to study the effect of thermal barrier coating of various thicknesses of the stabilized magnesia-zirconia on diesel engine pistons. The variations of temperature and thermal stress on the piston are investigated for both coated and uncoated piston crowns. Thermal stress analyses are performed by using the general purpose package software ANSYS, produced by ANSYS Inc. The piston model used in the simulation is manufactured for the diesel engine. The engine chosen for this analysis is adirect injection diesel engine with a 130 mm bore and 160 mm stroke. The engine is rated at 300 kW at 1500 rev/min for turbocharged configuration and water-cooled. The geometric compression ratio is 19:1. In the simulation, an axi symmetric finite element model is used to reduce the total number of elements and computational time because of geometrical symmetry, thermal boundary conditions and loading. Uniform shapes and forms of elements play a significant role in providing accurate results. Therefore, the meshing of the piston, bond coat and coating is achieved with a axisymmetric 2D plane (thermal-stress) element with eight nodes in such a way that it can support irregular shapes without losing too much accuracy. The system is modeled in multi-layers with a defined interface between them such as a top coat, bond coat and substrate. Pistons body is aluminum and piston crown is are made of SiC. These materials are assumed to be linearly elastic and isotropic.

It is well known that heat transfer phenomena are complex in the diesel engine piston. So, it is assumed that the major mechanism of heat transfer between the combustion chamber and the piston surface is the convection in the thermal stress analyses. A convection heat load is applied to the piston crown surface. That is, the convection heat load is enhanced to take into account the radiation effect. The engine in wide open throttle (WOT) condition is considered.

$$h_{gas}(t) = \alpha\, V_C(t)^{-0.06} P(t)^{0.8} T(t)^{-0.4} (S_P + b)^{0.8} \qquad (1)$$

Where $h_{gas}(t)$ is the instantaneous convective heat transfer coefficient (W/m^2 ^{0}K), VC(t), P(t) and T(t) are the instantaneous cylinder volume (m^3), pressure (10^5 Pa) and temperature (K), and SP the mean piston speed (m/s), respectively. The calibration constants a and b are calculated as 130 and 1.4. Averaged cycle values of heat transfer coefficient and temperature are used for the piston top. Boundary conditions for the oil-cooled part of the piston are obtained from the literature as 95 ^{0}C and 1500 W/m^2 ^{0}C, respectively. The other boundary conditions (temperature and heat transfer coefficient) are taken from the literature. Temperatures of the rings are 200, 180, 160 and 140 ^{0}C for first and second compression, cooling and oil rings, respectively. The average heat transfer coefficient and temperatures predicted as the boundary conditions are given in Fig.3. This model process is successfully applied by piston manufacturers to evaluate design alterations.

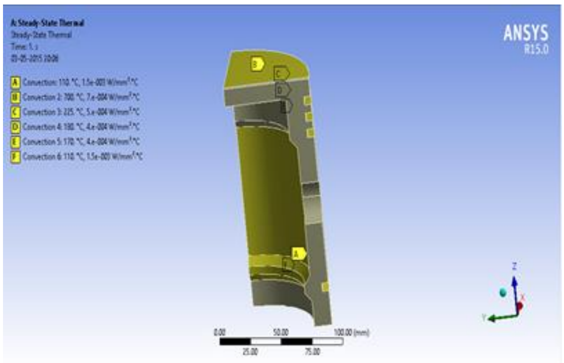

Fig. 3: Piston model with various thermal boundary conditions

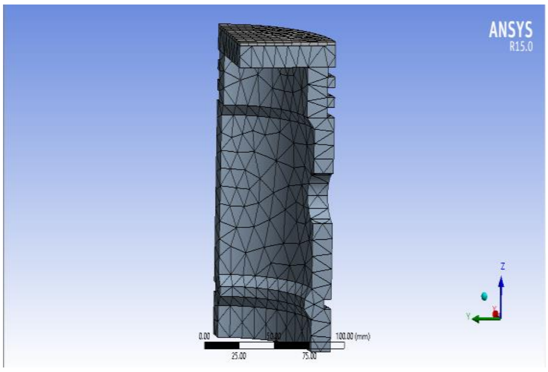

Fig. 4: Meshed quarter part of the piston with coating

A. Heat Transfer Analysis:

For the uncoated piston, a counter-plot of the temperature is shown in Fig. 5. As expected, the high temperatures are observed at the crown center area, since it is subjected to the heat flux circumferentially. The maximum temperature is at the center and the minimum is at the bottom of the crown head on the piston top surface. To be more precise, the extreme values are 426.72 ^{0}C and 327.02 ^{0}C respectively.

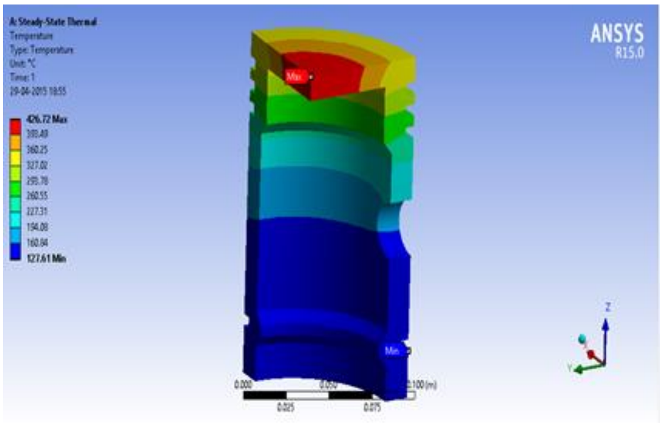

Fig. 5: Variation of temperature in the piston without coating

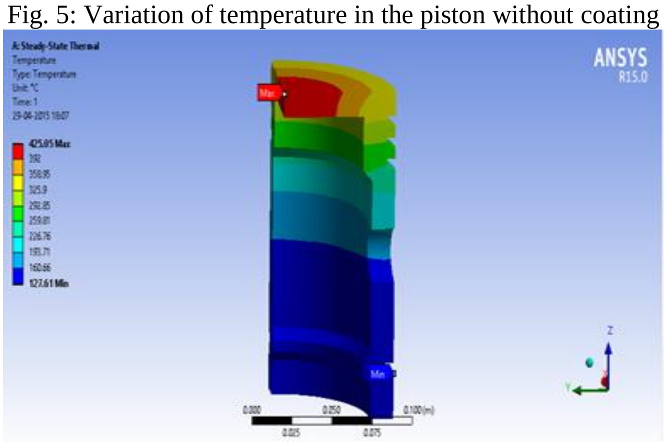

Fig. 6: With 0.4mm coating thickness

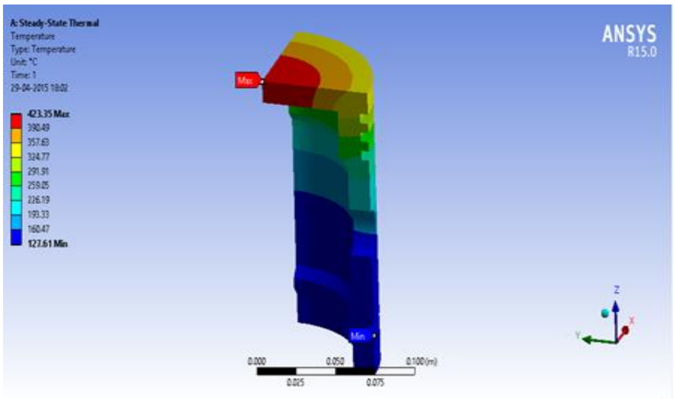

Fig. 7: With 0.8mm Coating Thickness

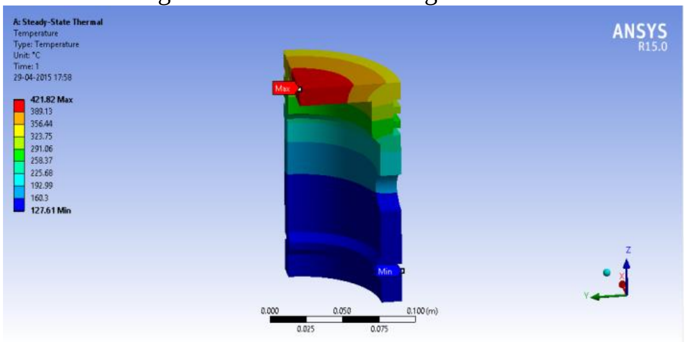

Fig 8.With 0.4 mm Coating Thickness

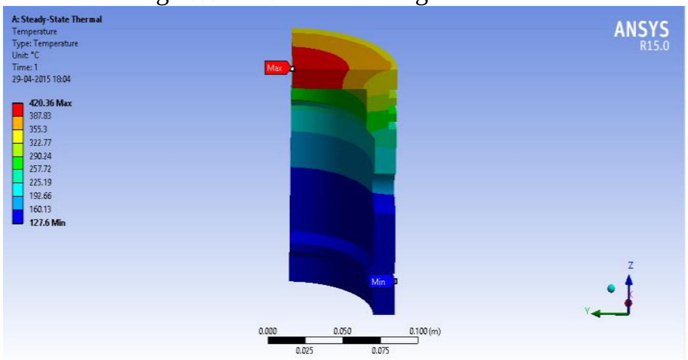

Fig. 8.1: With 1.2 mm Coating Thickness

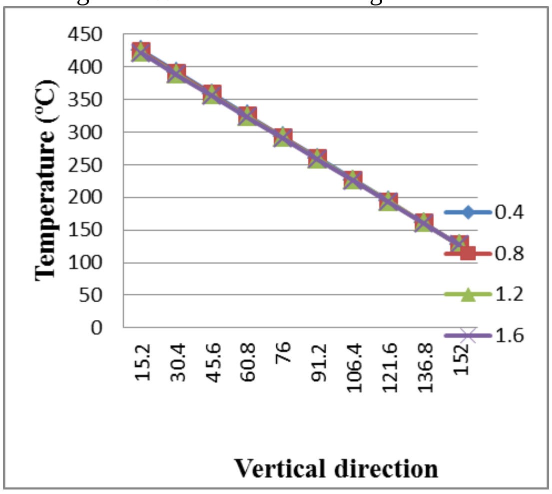

Fig. 8.2: Variation of temperature in the piston (substrate) in vertical direction for different coating thickness

Fig 8.2 shows the variation of temperature in vertical direction in the piston. It is observed that the temperature is gradually decreasing for the various coating thickness in vertical direction. The temperature is less for the 1.6 mm coating thickness and more for 0.4 coating thickness.

Vonmises Stresses: Vonmises stress of the piston (substrate) for varying coating thickness 0.4 mm to 1.6 mm is shown

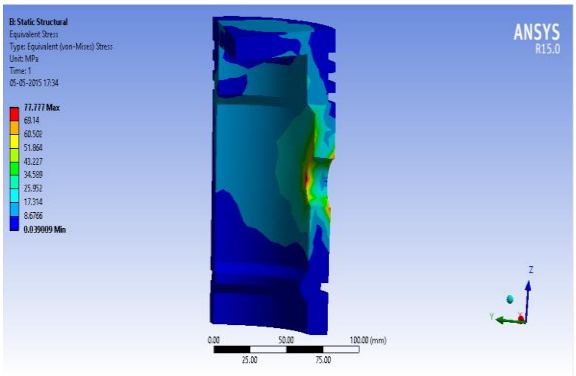

Fig. 9: With 0.8 mm coating thickness

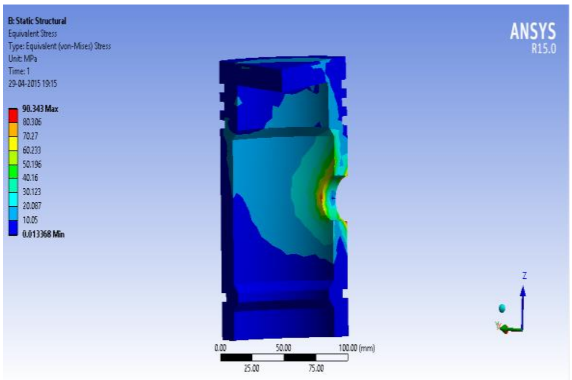

Fig. 10: With 0.6 mm coating thickness

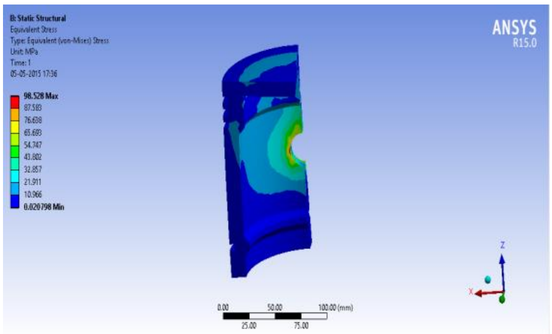

Fig. 11: With 1.2 mm coating thickness

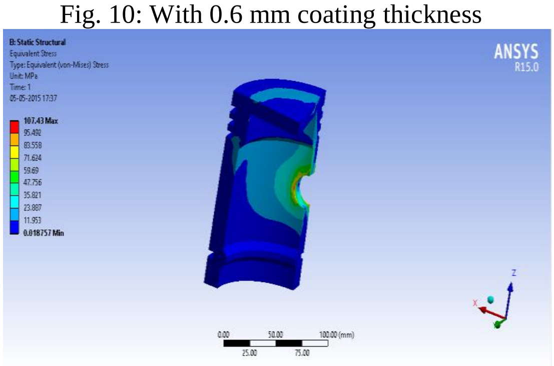

Fig. 12: With 1.6 mm coating thickness

The stresses are plotted for the piston(substrate) due to the temperature loading. Fig.12 shows the variation of vonmises stresses in the uncoated piston and it is observed that the maximum stress on the crown is 20.23 to 3.69 MPa, where the remaining stresses upto 107.43 MPa in the piston body.

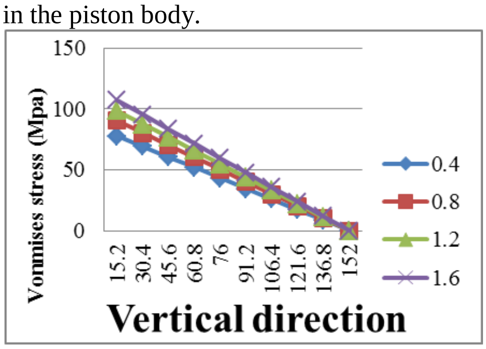

Fig. 12.1: Variation of maximum temperature and maximum thermal stresses in the piston (substrate) with coating thickness

Coating thickness, mm	Temperature, ^{0}C	Vonmises stress, MPa
0.4	425.05	77.77
0.8	423.35	90.34
1.2	421.82	98.52
1.6	420.36	107.43

Table 2: Variation of maximum temperature and maximum thermal stresses in the piston (substrate) with coating thickness

B. Heat Transfer Analysis:

Temperature distribution of the ceramic coated piston (MgZrO_3 & NiCrAl) for varying coating thickness 0.4 mm to 1.6 mm is shown

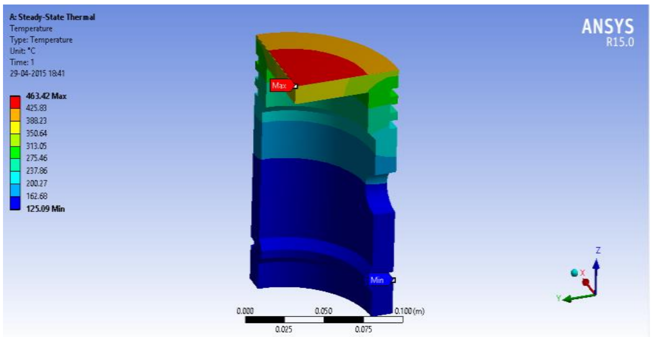

Fig. 13: With 0.4 mm coating thickness

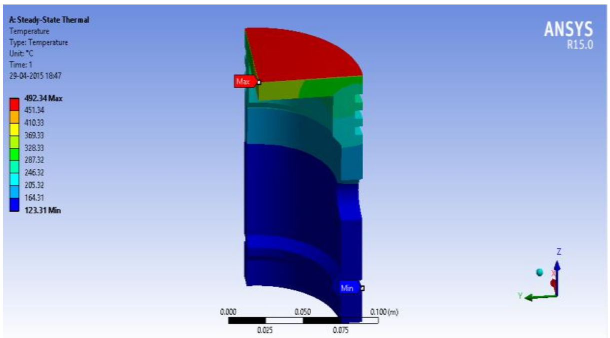

Fig. 14: with 0.8 mm coating thickness

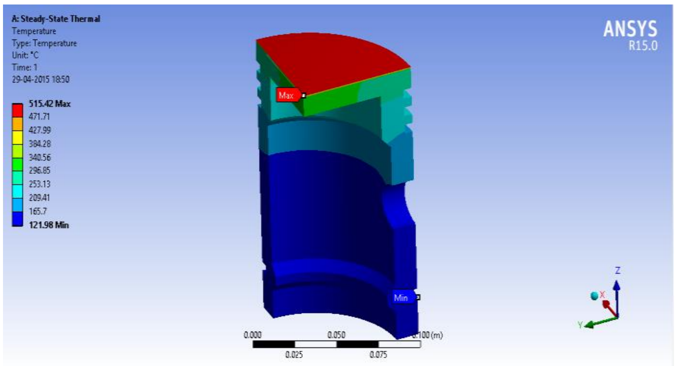

Fig. 15: With 1.2 mm coating thickness

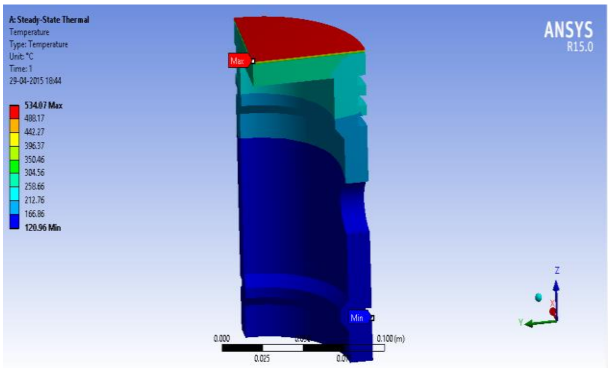

Fig. 16: with 1.6 mm coating thickness

The variation of the temperature in the ceramic coated piston with coating thickness of 1.6 mm and it is observed that the highest temperature is 534.07 ^{0}C and in the crown around 422.5 to 534.07 ^{0}C, where as in the piston body 120.96 to 295.45 ^{0}C

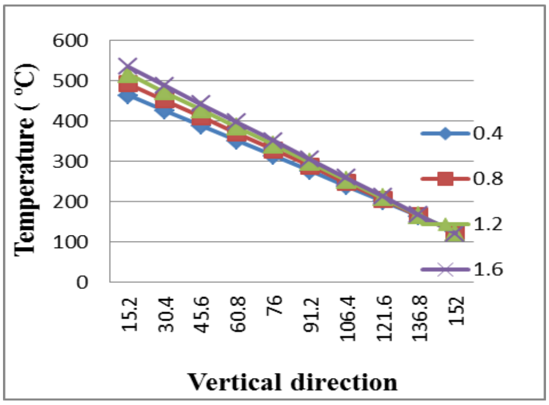

Fig. 16.1: Variation of temperature in the ceramic coated piston ($MgZrO_3$ & NiCrAl) in vertical direction for different coating thickness

Vonmises stress of the ceramic coated piston ($MgZrO_3$ & NiCrAl) for varying coating thickness 0.4 mm to 1.6 mm is shown

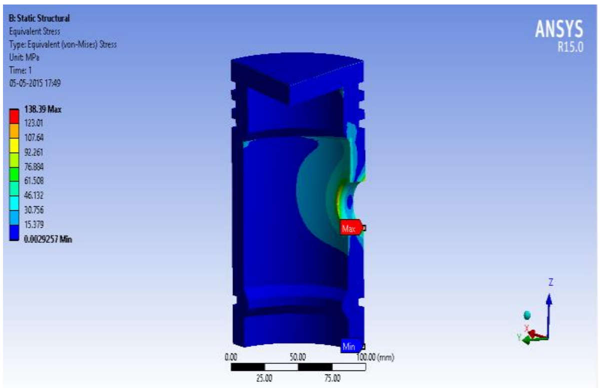

Fig. 16: With 0.4 mm coating thickness

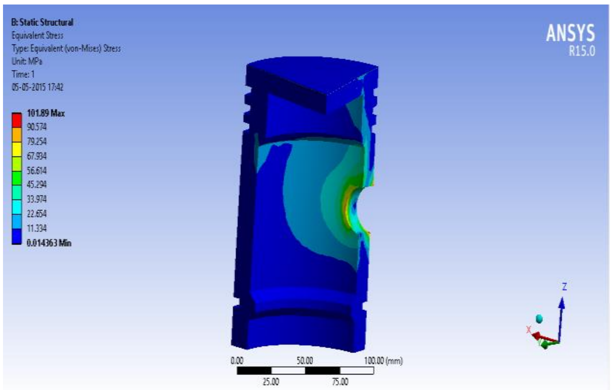

Fig. 17: with 0.8 mm coating thickness

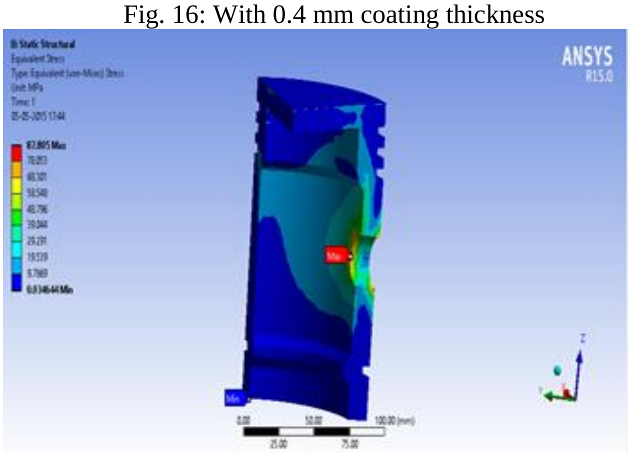

Fig. 18: With 1.2 mm coating thickness

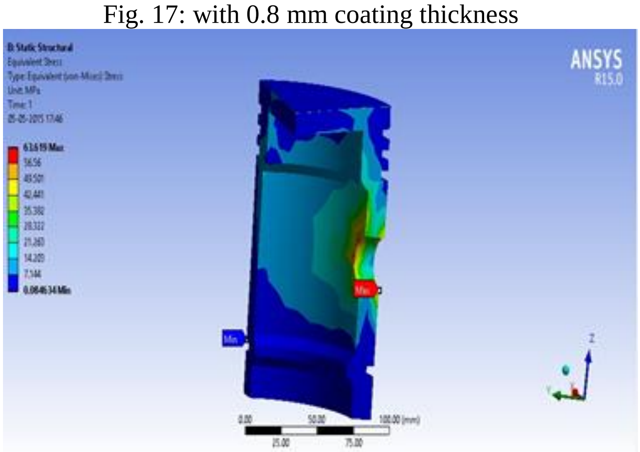

Fig. 19: with 1.4 mm coating thickness

Variation of vonmises stress in the ceramic coated piston ($Mgzro_3$ & NiCrAl) with 1.6 mm coating thickness

The stresses are plotted for the piston due to the temperature loading. Fig.19 shows the variation of vonmises stresses in the ceramic coated piston and it is observed that the maximum stress on the crown is 5.96 to 4.38 MPa, where the remaining stresses upto 63.619MPa in the piston body

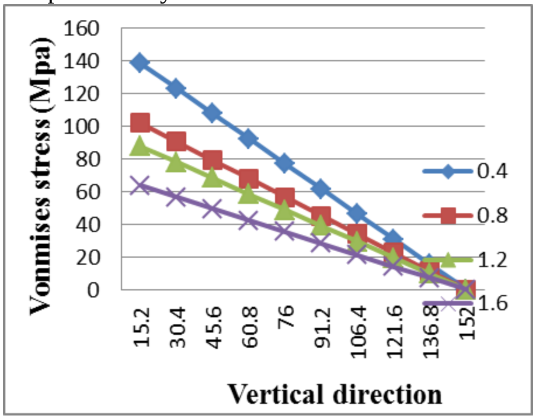

Fig. 20: Variation of vomises stress in the ceramic coated piston (Mgzro3 & NiCrAl) in vertical direction for different coating thickness

Coating thickness, mm	Temperature, ^{0}C	Vonmises stress, MPa
0.4	463.42	138.39
0.8	492.34	101.89
1.2	515.42	87.80
1.6	534.07	63.61

Table 3: Variation of maximum temperature and maximum thermal stresses in the ceramic coated piston ($Mgzro_3$ & NiCrAl) with coating thickness

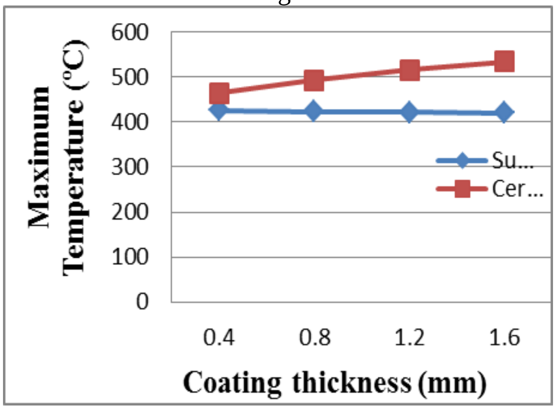

Fig. 21: Variation of maximum temperature in the substrate and ceramic coated piston with different coating thickness

Shows the variation of maximum temperature in the piston. It is observed that the maximum temperature for piston(substrate) is gradually decreasing from 0.4 mm to 1.6 mm coating thickness, whereas ceramic coated piston the maximum temperature is increasing from 0.4 mm to 1.6 mm coating thickness.

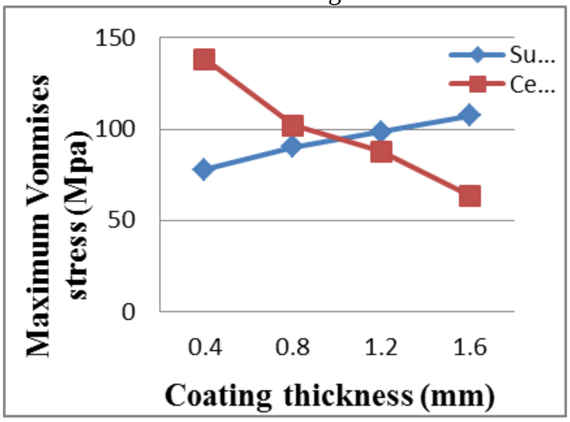

Fig. 22: Variation of maximum vonmises stress in the substrate and ceramic coated piston with different coating thickness

Shows the variation of maximum vonmises stress in the piston. It is observed that the maximum vonmises stress for the piston(substrate) is increased from 0.4 mm to 1.6 mm coating thickness and for ceramic coated piston is gradually decreased from 0.4 mm to 1.6 mm coating thickness.

IV. CONCLUSIONS AND FUTURE SCOPE OF WORK

A. Conclusions

The following conclusions are drawn from the present work

1) The numerical simulations clearly show that temperature and thermal stress distribution are a function of coating thickness. For all the coating thicknesses, the highest temperature appeared at the crown center and on the edges of the crown head on the top surface of the coating and on the piston surface. The temperature at the surface of the coated region is significantly higher than that of the uncoated piston surface.
2) Increase in the maximum temperature at the crown center, compared with the uncoated piston, is 8.6%, 15.37%, 20.7% and 25.1% for 0.4 mm, 0.8 mm, 1.2 mm and 1.6 mm thick coating, respectively. It is clear that a higher combustion chamber temperature is provided by means of TBC. As a result, thermal efficiency of the engine increases.
3) Moreover, reduction of the piston (substrate) surface temperature has a positive effect on engine performance. It is quite obvious that the maximum thermal stress is a function of coating thickness.
4) The maximum vonmises stress in the piston crown is reduced with increase in bond coating thickness.
5) Thermal performance of the piston increases with increased coating thickness. When stress values obtained from FEA are compared with the mechanical properties of the aluminum alloy and zirconia material, it can be seen that calculated stress values are lower than the allowable stress values of the materials.

B. Future Scope of Work

An experimental set up may be used to validate the boundary conditions and a suitable correlation may be made on the engine combustion.

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