

# Temperature and Stress Analysis of Ceramic Coated SiC-Al Alloy Piston Used in a Diesel Engine Using FEA

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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 Silicon Carbide (SiC) piston crown to improve the performance of a diesel engine. The coating is done on the piston crown to the extent 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 an axisymmetric model of the piston with axisymmetric elements are used in both thermal and coupled field analysis. The boundary conditions are applied to solve the field equations using ANSYS 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.

**KEYWORDS:** Temperature, Coating thickness, Thermal barrier, Vonmises stress, Piston crown temperature.

## I. INTRODUCTION

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 [1-4]. 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 [5-6]. 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 [7-10].

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

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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. The coating thickness has a significant effect on the combustion temperature, the temperature gradient and the stress distribution in both coating and interfacial stresses.

The thermal shock resistance of a ceramic coating depends on its elastic modulus, thermal expansion coefficient and thermal conductivity [11-15]. It is known that thicker coating can provide better insulation, but residual thermal stress leads to spallation of thicker coatings. Therefore, determining the proper thickness of the TBC plays an important role not only in the accurate assessment of the temperature drop, but also in the resulting performance of the coated system. Although many factors affect the overall performance of the coatings, two of them are more important: oxidation of the bond coat and thermal mismatch between the substrate (SUBS) and the top coating (TC), which affect the lifetime of the coating system. Thermal mismatch causes high stress value at the interface. On the other hand, the lifetime of the TBCs can be limited by stresses owed to changing thermal loads during the operation which lead to crack nucleation and propagation in a parallel direction to the ceramic-bond coat interface, leading in turn to delamination of coating. Arising from normal stress, the other typical TBC failure occurs through spalling of the ceramic top coat from the bond coat (BC) [16].

Modeling of the piston temperature distribution is very important for keeping the thermal stresses within acceptable levels at the interfaces (BC/TC and SUBS/BC). Computer simulations of thermal stress analyses are very useful and economically viable for reducing the time and cost at the design stage of a piston in diesel engines before the first prototype is constructed [17-21]. There are many research papers on the calculation of the temperature distribution [3,4,10,19,20], but thermal stress analyses are limited. The aim of this work is to investigate the SiC piston crown temperature and stress distribution by using various thicknesses of the coating materials to achieve higher diesel engine performance.

## II. RELATED WORK MODELING AND ANALYSIS OF THE PISTON

As shown in Fig. 1a, the SiC piston model used in the simulation is a diesel engine piston. Thermal stress analyses have been carried out by means of the finite element technique, which is a powerful numerical tool. A quarter of the piston model and thickness of the coatings are shown in Fig.1b. Analyses have been performed for various conditions: an uncoated piston crown and a ceramic-coated piston crown with a ceramic top coat ranging in thickness from 0.2 to 1.6 mm [2]. The coating is composed of a 0.1 mm bond coat (NiCrAl) and the ceramic (MgZrO<sub>3</sub>) deposited onto the piston crown or substrate (SUBS) by air plasma spraying (see Fig. 1b). The variation of the temperature on the piston is examined as well as the interfacial stresses at the BC/TC and SUBS/ BC interfaces. They are compared with the results of the uncoated piston. Thermal barrier coatings are used to increase the operating temperature of the material. The coating has a ceramic-metal configuration and may not be isotropic. Usually, non-homogeneous ceramic coatings are applied to metal substrates. Thermally-sprayed ceramic material has layered structures with a defect density resulting from successive impact of a multitude of fully or semi molten particles. Plasma sprayed coatings have exhibited transversely isotropic symmetry. Although properties of coating materials are different in through thickness and in-plane directions, the material behaves linearly in each direction. The most important problem with the coated[22] system is the thermal stresses which occur during operation because of the considerable mismatch between the thermal expansions coefficients of the metal substrate and the ceramic coating. TBCs are preferred because of their low conductivity and their relatively high coefficients of thermal expansion. In this study, magnesia-stabilized zirconia (MgZrO<sub>3</sub>) used in TBCs as a deposit material is preferred because of its good thermal insulating properties and thermal stability at cryogenic and high temperature applications [6] compared with other coating materials such as alumina. The coating material is stabilized magnesia-zirconia which has flexural strength of 520 MPa and compressive strength of 1450 MPa. The thickness of the ceramic top coating has been changed from 0.2 mm to 1.6 mm with a 0.2 mm increment. Some of the thermo-mechanical properties of the zirconia, interlayer metallic bond coat, rings and piston are listed in Table1. The piston material is aluminum and SiC including silica, copper, chromium, magnesium, etc. Mechanical properties of the aluminum alloy piston are 485 MPa, 450 MPa and 295 MPa for ultimate, yield and shear strength respectively.

# International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 8, August 2015

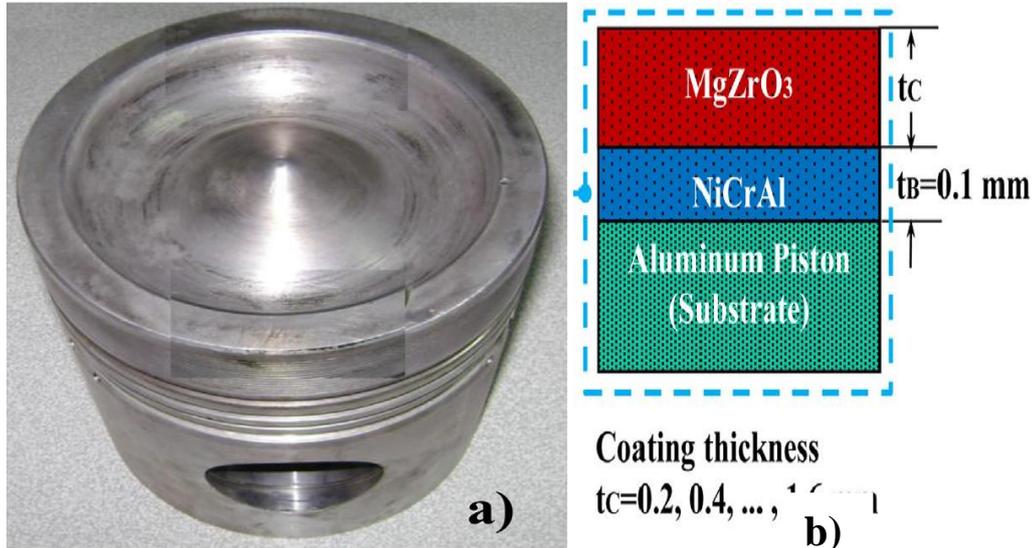


Fig1. The piston used in the FE analyses: a) photograph of the piston used diesel engine, b) the coating parameters

Table1: Material properties of piston and coating

Component	Material	Youngs modulus, GPa	Poisson's ratio	Thermal expansion coefficient $\times 10^{-6} / ^\circ\text{C}$	Thermal conductivity, $\text{W/m}^\circ\text{C}$
Ceramic coating	$\text{MgZrO}_3$	46	0.20	8	0.8
Bond coat	NiCrAl	90	0.27	12	16.1
Piston crown	SiC	410	0.3	4	120
Body of piston	Aluminium	79	0.34	25	174

### 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 a direct 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 axisymmetric 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 an 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. Piston body is aluminum and piston crown is 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. The

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Vol. 4, Issue 8, August 2015

thermal circuit method is used to model the heat transfer in the ring land and skirt region with the following assumptions: the effect of piston motion on the heat transfer is neglected, the rings do not twist, the rings and skirt are fully engulfed in oil and there is no cavitation, and also the conductive heat transfer in the oil film is neglected. Symmetric constraints are imposed in axi symmetric axis. That is, all of the displacements on the axi symmetrical axis are set to zero in the radial direction. The symmetric thermal boundary condition is also applied to the radial direction on the symmetry axis. Local average heat transfer coefficient and gas temperature boundary conditions are applied for the piston top. The piston surface is heated at the outlet of the swirl chamber and cooled through contact with cooler components of the combustion chamber. In the analyses, the Hohenberg equation is used to predict instantaneous heat transfer coefficients,

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

where  $h_{gas}(t)$  is the instantaneous convective heat transfer coefficient ( $W/m^2 \text{ } ^\circ K$ ),  $V_C(t)$ ,  $P(t)$  and  $T(t)$  are the instantaneous cylinder volume ( $m^3$ ), pressure ( $10^5 \text{ Pa}$ ) and temperature ( $K$ ), and  $S_P$  the mean piston speed ( $m/s$ ), respectively. The calibration constants  $\alpha$  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  $95 \text{ } ^\circ C$  and  $1500 \text{ W/m}^2 \text{ } ^\circ C$ , respectively. The other boundary conditions (temperature and heat transfer coefficient) are taken from the literature. Temperatures of the rings are 200, 180, 160 and  $140 \text{ } ^\circ C$  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.2. This model process is successfully applied by piston manufacturers to evaluate design alterations.

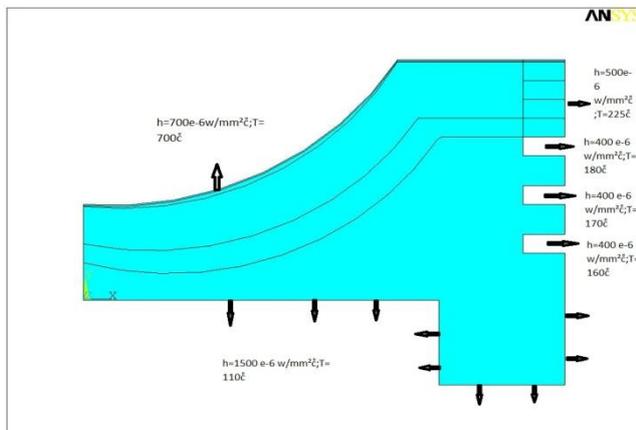


Fig.2 The piston model with thermal boundary conditions

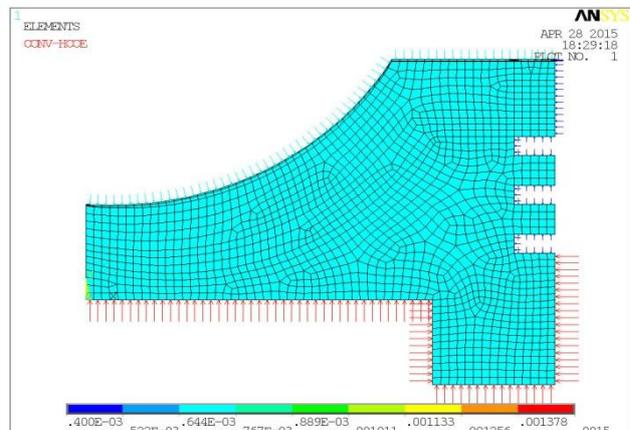


Fig.3 Finite element model with boundary conditions

The axis symmetric geometric model of the piston is shown in Fig.2. The element plane 183 an 8-noded axisymmetric element from ANSYS library is used for the meshing of piston with coating and refined finite element model is shown in Fig.3 after convergence check. The number of nodes and elements in the mesh are 4446 and 1407 respectively.

## IV. RESULTS AND DISCUSSIONS

**Heat Transfer Analysis:** The temperature variation after the steady state heat transfer analysis is shown in Fig.4a to Fig.4d by varying coating thickness 0.4 mm to 1.6 mm. Fig.4a shows the variation of the temperature in the piston with coating thickness of 0.4 mm and it is observed that the highest temperature is in coating thickness,  $623.691 \text{ } ^\circ C$  and in the crown around 567 to  $624 \text{ } ^\circ C$ , where as in the piston body 110 to  $452 \text{ } ^\circ C$ . Fig.4b shows the variation of the temperature in the piston with coating thickness of 0.8 mm and it is observed that the highest temperature is in coating thickness,  $628.078 \text{ } ^\circ C$  and in the crown around 512 to  $628 \text{ } ^\circ C$ , where as in the piston body 110 to  $455 \text{ } ^\circ C$ .

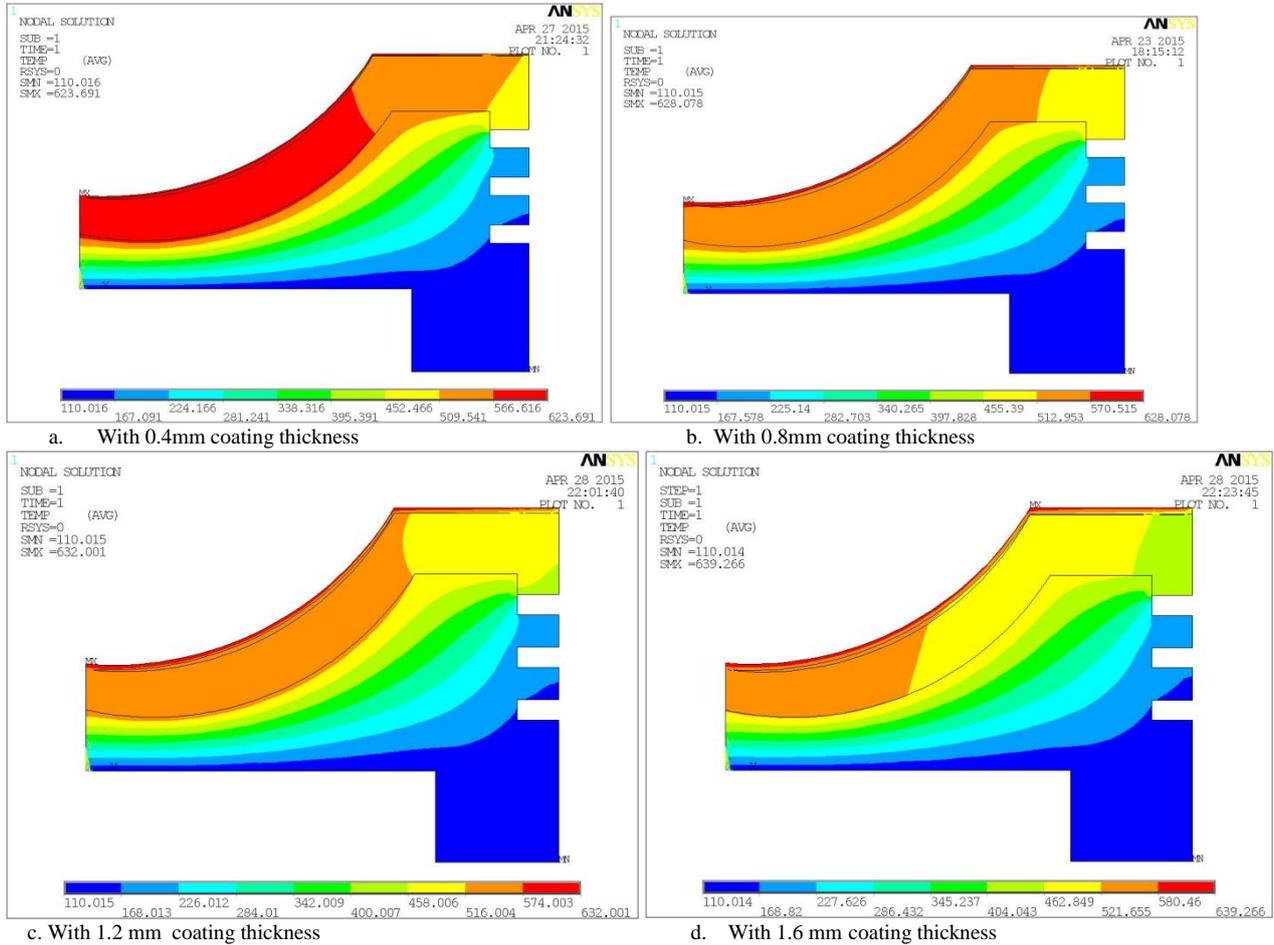


Fig.4 Variation of temperature in piston in centigrade with varying coating thickness

Fig.4c shows the variation of the temperature in the piston with coating thickness of 1.2 mm and it is observed that the highest temperature is in coating thickness, 632.001 °C and in the crown around 516 to 632 °C, where as in the piston body 110 to 458 °C. Fig.4d shows the variation of the temperature in the piston with coating thickness of 1.6 mm and it is observed that the highest temperature is in coating thickness, 639.266 °C and in the crown around 521 to 639 °C, where as in the piston body 110 to 462 °C. 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 and bowl lip areas, 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 bowl on the piston top surface. To be more precise, the extreme values are 346.292 °C and 307 °C respectively. Results obtained from the thermal analyses by the finite element technique, the temperature variations for the uncoated piston and coated pistons with various coating thicknesses of the ceramic material are discussed systematically. In the radial direction, the temperature decreases from the crown center to the bottom of the bowl, then it increases towards the bowl lips and finally decreases again at the edge of the crown surface. Under the same conditions, counter-plots of the temperature distributions are shown in Fig.4a to 4d for the ceramic coating thicknesses of 0.4 mm, 0.8 mm, 1.2 mm and 1.6 mm. It is observed that the values of maximum temperature at the crown center of the pistons on the coating surface are 623.69 °C, 628.07 °C, 632 °C and 639.26 °C respectively. As expected, the maximum amount of increase in the temperature of the piston's crown top surface is observed for 1.6 mm thick coating, because of the low ceramic thermal conductivity with respect to the aluminum alloy. It is obvious that the temperature of the piston top surface increases with coating thickness.

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(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 8, August 2015

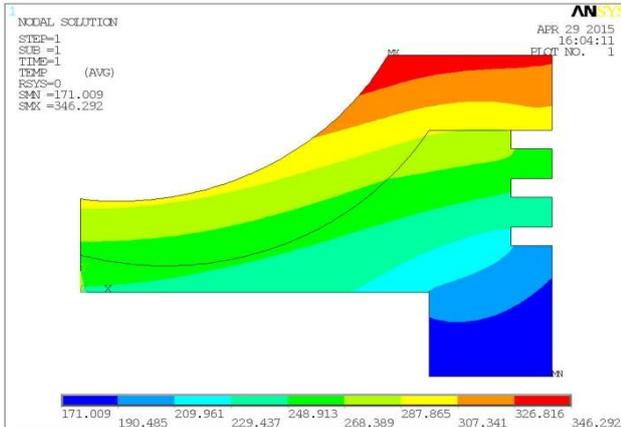


Fig. 5 Variation of temperature in piston in centigrade for without coating

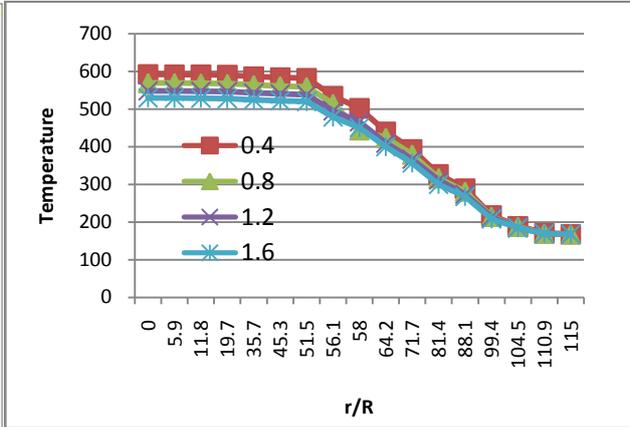


Fig. 6 Variation of temperature in the piston in radial direction

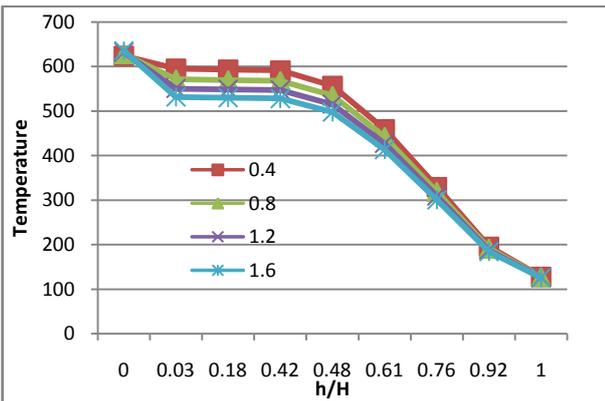


Fig.7 Temperature in the piston in tangential direction on the left end

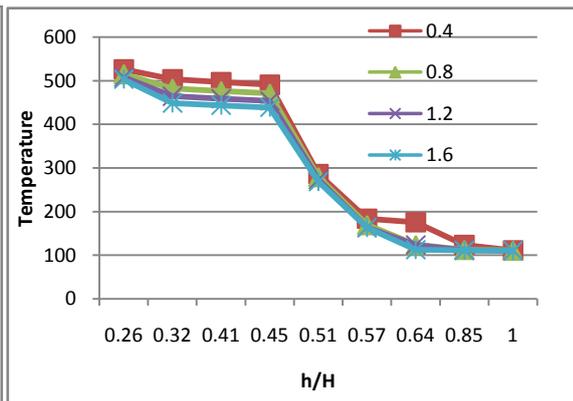


Fig. 8 Temperature in the piston in tangential direction on the right end

Fig.6 to 8 shows the variation of temperature in radial and tangential direction in the piston. It is observed that the temperature is gradually decreasing the radially and tangentially also for the various coating thickness. The temperature is more for the higher coating thickness and less for lower coating

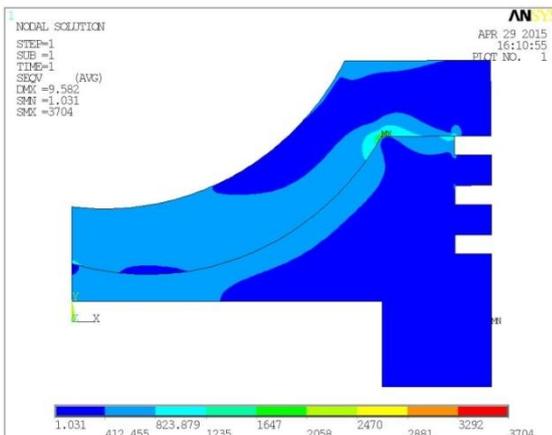


Fig.9 Vonmises stress in piston without coating, MPa

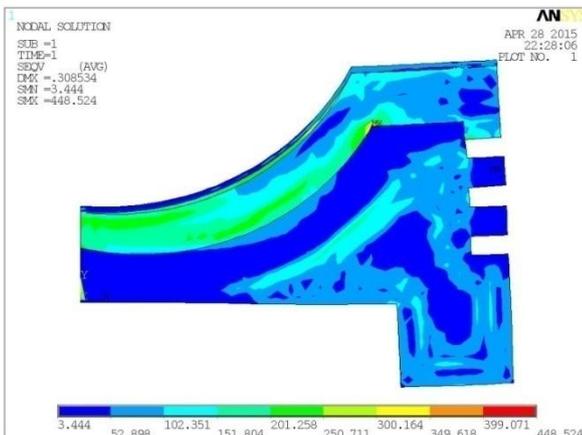


Fig.10 Variation of vonmises stress in piston with coating thickness 0.4mm, MPa

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Vol. 4, Issue 8, August 2015

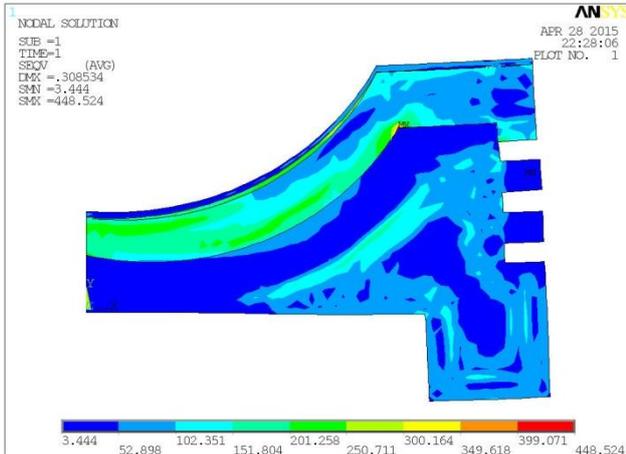


Fig.11 Vonmises stress in piston with coating thickness 0.8mm, MPa

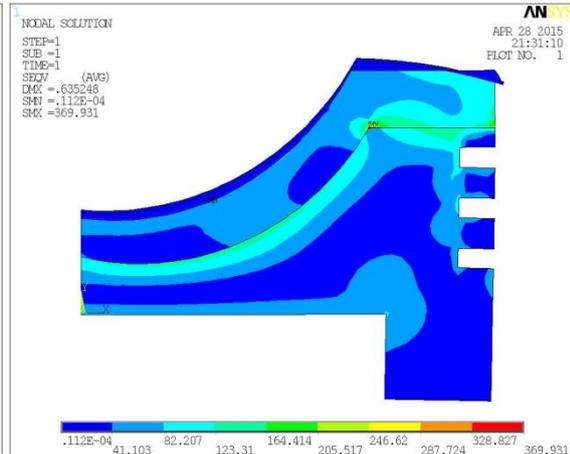


Fig.12 Vonmises stress in piston with coating thickness 1.2 mm, MPa

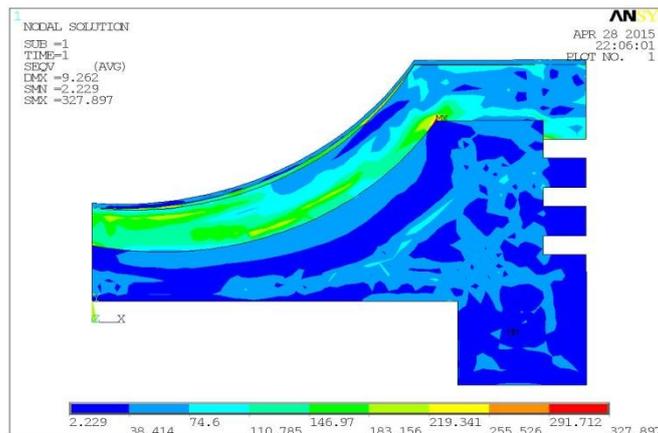


Fig. 13 Vonmises stress in piston with coating thickness 1.2 mm, MPa

**Thermal Stresses:** The stresses are plotted for the uncoated and coated piston due to the temperature loading. Fig.9 shows the variation of vonmises stresses in the uncoated piston and it is observed that the maximum stress on the crown is 1232 MPa, the interface stress is 3704 MPa which is due to sharp corner and concentrated at the point. The stresses are plotted for the coated piston due to the temperature loading. Fig.10 shows the variation of vonmises stresses in the 0.4mm coating thickness on piston and it is observed that the maximum stress on the crown is 645.426 MPa, where as in the body of the piston the stress is 72 MPa . The stresses are plotted for the coated piston due to the temperature loading. Fig.11 shows the variation of vonmises stresses in the 0.8 mm coating thickness on piston and it is observed that the maximum stress on the crown is 448.5 MPa, where as in the body of the piston the stress is 76 MPa. The stresses are plotted for the coated piston due to the temperature loading. Fig.12 shows the variation of vonmises stresses in the 1.2 mm coating thickness on piston and it is observed that the maximum stress on the crown is 369.9 MPa, where as in the body of the piston the stress is 67 MPa. The stresses are plotted for the coated piston due to the temperature loading. Fig.13 shows the variation of vonmises stresses in the 1.6 mm coating thickness on piston and it is observed that the maximum stress on the crown is 327.9 MPa, where as in the body of the piston the stress is 56 MPa.

## International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 8, August 2015

Table2: Variation of temperature and thermal stresses in the piston crown with coating thickness

Coating thickness, mm	Temperature on the crown, °C	Thermal stress, MPa
0.0(no coating)	346.292	1232
0.4	623.69	645.42
0.6	628.07	448.52
1.2	632	369.93
1.6	639.26	327.9

### V. CONCLUSION

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 bowl rim 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. Increase in the maximum temperature at the crown center, compared with the uncoated piston, is 32.7%, 55.8%, 72.5% and 84.8% 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. 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. The maximum normal and shear stress components occur in the bond coat. The results indicate that thermal stress is related to coating thickness. It increases with the coating thickness on the SUBS. The greatest value of the normal stress which produces spalling of the ceramic is produced on the bond coat. It is nearly twice the value of the maximum normal stress on the substrate. As seen here, 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.

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