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DESIGN AND THERMAL ANALYSIS OF CERAMIC COATED ALUMINIUM ALLOY PISTON

T. G. Thiyagarajan[1], A. Velladurai[2]

[1]Dept. of Manufacturing Engineering, Central Institute of Plastics Engineering and Technology, Chennai, India.
[2]Assistant Professor, Dept. of Manufacturing Engineering, Central Institute of Plastics Engineering and Technology, Chennai, India.

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Abstract – *The purpose of this paper is to determine the temperature distribution in a ceramic coated direct injection (DI) engine piston. Temperature distribution on the piston's top surface and substrate surface is investigated by using finite element based software called Ansys. Mullite, Yttrium stabilized Zirconia (Y-PSZ) and Magnesia-stabilized Zirconia (Mg-PSZ) are used as ceramic coating applied on aluminium alloy piston crown. The 2 thickness of ceramic top coating is about 200μm and for NiCrAl bond coat is taken to be100μm. It is observed that the maximum surface temperature occurs on Magnesia-stabilized Zirconia coated piston and substrate temperature considerably reduced compared to the uncoated piston. Through the experimental test results like hardness, Microstructure, corrosion test and thermal torch experiment it is confirmed that the coated specimen having improved properties. All the results are compared with coated and uncoated specimens.*

Key Words: **Direct Injection Engine, Ansys, Surface Temperature, Mullite, Magnesia-stabilized Zirconia, Yttrium-stabilized Zirconia, NiCrAl.**

1. INTRODUCTION

The input energy of an internal combustion engine has three parts: energy used by coolant, energy which is utilized for useful work and energy lost through exhaust and only one third of the total energy converted to work. Thus the efficiency and overall performance of internal combustion engine can be increased by utilizing these heats loss into the useful work. To minimize heat transfer and improve the performance of an internal combustion engine a technology of insulating the piston, cylinder head, combustion chamber and valve's surfaces with thermal barrier coating materials has been introduced[1]. TBC applied to high temperature areas or transfer surfaces of gas turbine and IC engine to improve its performance [2]. TBC's were also applied in adiabatic engines not only for reduced in cylinder heat rejection and thermal fatigue protection of underlying metallic surfaces, but also for possible reduction of engine emission. The TBC often consists of monolithic ceramic such as zirconia, which thermally insulates the system while sustaining high temperature gradients and in some cases, large temperature differences. The bond coat is an intermetallic alloy that provides oxidation resistance at high temperatures and aids in the adhesion of the TBC to the substrate [3]. A one another reason of using TBC it the increase in fuel prices and reduction supply of high quality fuel. Analysis of temperature distribution helps the designer to estimate the project cost before actual designing begins. Thus, thermal analysis of piston is very important.

2. THERMAL BARRIER COATING

TBC's are used to increase the operating temperature of the material. The coating always has a ceramic-metal configuration and must be isotropic. Mostly, non-homogeneous ceramic coatings are applied to the metal substrates. Thermally-sprayed ceramic material has a layered structure, with a defect density resulting from successive impacts from a number of fully or semi-molten particles. Plasma-sprayed coatings exhibit transverse isotropic symmetry. Although properties of coating materials are different in thickness and in plane directions, the materials behave linearly in each direction. In this study Mullite, Yttrium-stabilized Zriconia and Magnesia-stabilized Zirconia are compared. Yttrium-stabilized ziroconia is suggested to use is limited to a maximum of 500C due to lack of toughening above these temperatures. The toughening mechanism is due to the transformation of tetragonal to monoclinic crystal structure. Another undesirable property of this material is the low temperature (250C range) degradation in humid environments. T.M. Youshonis et.al [3] studied Mullite has survived severe cyclic fatigue tests in high-output diesel engines. Magnesia-stabilized zirconia is beneficial at higher temperatures (above 500C) due to higher transformation toughening mechanism. Properties of piston alloy and coating materials are shown in table 1.

Table -1: Thermal Properties of Material [3, 6]

Material	**Thermal Conductivity [W/m^{0}C]**	**Thermal Expansion10^{-06} [1/^{0}C]**	**Specific Heat [J/kg^{0}C]**
Piston (aluminium alloy)	155	21	910
Bond coat (NiCrAl)	16	12	460
Mullite	3.3	5.3	1260
Y-PSZ	1.4	10.9	620
Mg-PSZ	0.8	8	650

3. STEADY STATE THERMAL ANALYSIS

In the present work numerical analysis of Kirloskar DM10 single cylinder water-cooled four stroke direct injection engine piston made up of aluminium alloy has done in ansys workbench. The engine is rated 7.4KW at 1500 rev/min. The geometric compression ratio is 17.5:1. Finite element analysis carried out on conventional, Mullite, Yttrium-stabilized zirconia and Mangnesia-stabilized zirconia coated piston. The piston is coated with 200 µm top coat and 100 µm NiCrAl bond coat.

The materials to the geometry are assigned at modal section of the section. The geometry has default bonded contact between top coat-bond coats, bond coat-substrate and piston rings-rings groove. After modeling of piston fine meshing has been created by taking default element type and settings in workbench. The model contains approximately 40,637 nodes and 20,531 elements.

The heat transfer phenomena in internal combustion engine always have been a topic research due to some complexity. For the analysis convection is selected as a major mechanism of heat transfer. The heat transfer problem for internal combustion engine is very complicated because of following reasons [4]:

- Inside the cylinder the temperature of gases changes continuously.
- To determine the exact value of temperature and heat transfer coefficient is not much easy.
- Piston is the main component responsible for combustion thus it subjected to high temperature and heat transfer coefficient.

The equation devised by Hohenbergis used to predict instantaneous heat transfer coefficients [3].

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

where,

$h_{gas}(t)$ is the instantaneous convective heat transfer coefficient($W/m^2\,K$),

$V_c(t)$, $P(t)$, $T(t)$ and S_P are the instantaneous cylinder volume (m3), pressure (105 Pa), temperature (K) and mean piston speed (m/s), respectively.

Before applying the boundary conditions, some assumptions are made []:

- 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 are no cavitations.
- The conductive heat transfer in oil film is neglected.

The heat transfer coefficients and temperatures obtained from literature [3] taken as the boundary conditions for the analysis shown in Fig. 1. The combustion chamber temperature is 650^0C with convection coefficient of $800e^{-06}$. The region between piston crown and liner temperature is 300^0C with convective coefficient of $230e^{-06}$. The temperature at the rings is 85^0C with convective coefficient of $625e^{-06}$. The region between rings temperature is 110^0C with convective coefficient of $191e^{-06}$. The temperature at the piston crown under is 110^0C with $717e^{-06}$ convective coefficient. The temperature at the skirt inside is 110^0C with convective coefficient of $191e^{-06}$. The temperature at the piston skirt inside is 85^0C and convective coefficient is $60e^{-06}$.

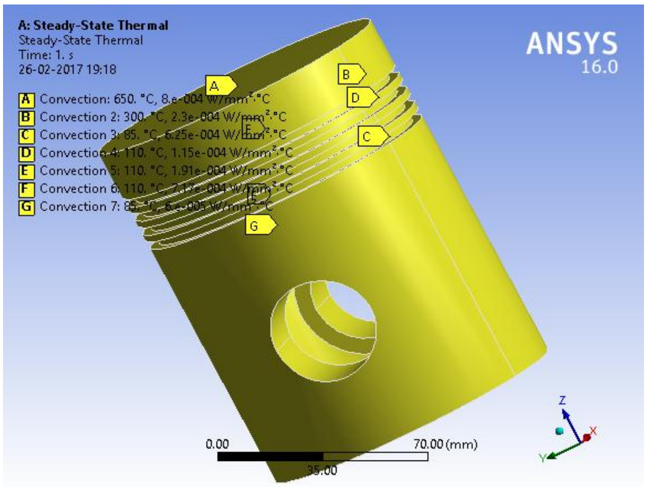

Fig-1: Boundry conditions

4. RESULTS AND DISCUSSION

4.1 Temperature Distribution

a) Uncoated Piston (Standard)

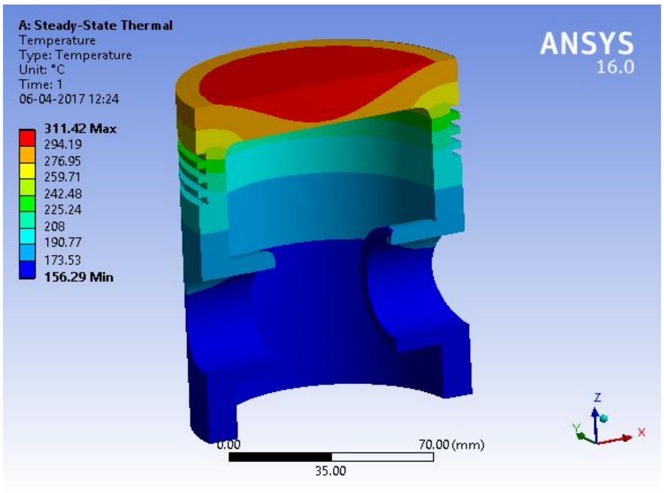

Fig-2: Temperature distribution in Uncoated Piston

b) 100µm NiCrAl bond coat and 200µm Mullite top coat

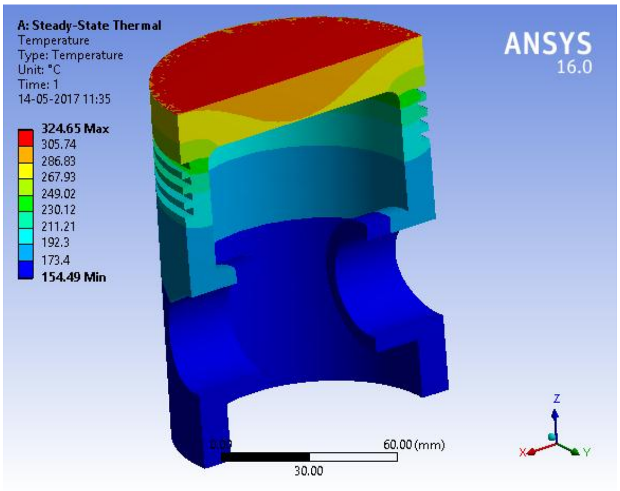

Fig-3: Temperature distribution for Mullite coated Piston

c) 100µm NiCrAl bond coat and 200µm Y-PSZ top coat

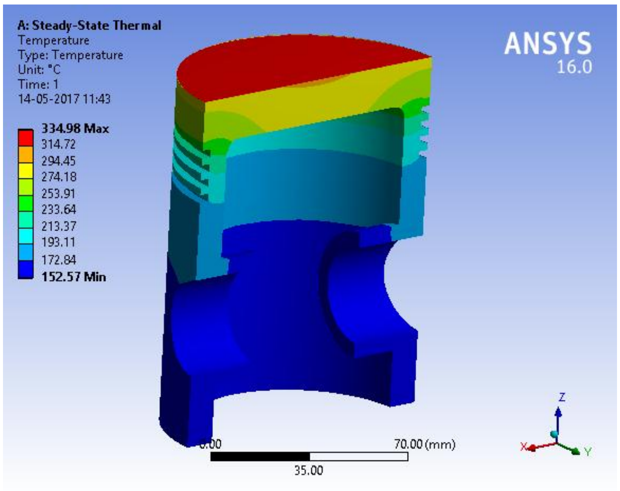

Fig-4: Temperature distribution for Y-PSZ coated Piston

d) 100µm NiCrAl bond coat and 200µm Mg-PSZ top coat

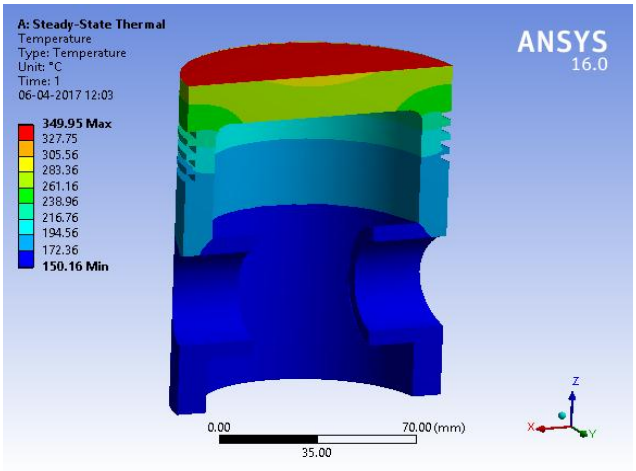

Fig-5: Temperature distribution for Mg-PSZ coated Piston

The finite element method is used to determine the temperature distribution for uncoated, mullite, Y-PSZ and Mg-PSZ coated piston. For this purpose steady state thermal analysis has carried out using commercial code Ansys. The maximum and minimum temperatures for uncoated piston are obtained about 311.42 and 156.29^{0}C. The maximum temperature at the top surface of mullite coated piston is 324.65^{0}C and maximum substrate temperature is 305.74^{0}C and minimum temperature is 154.49^{0}C. The maximum temperature at the top surface of Y-PSZ coated piston is 334.98^{0}C and maximum substrate temperature is 294.45^{0}C and minimum temperature is 152.57^{0}C. The maximum temperature at the top surface of Mg-PSZ coated piston is 349.95^{0}C and maximum substrate temperature is 283.36^{0}C and minimum temperature is 150.16^{0}C. With same boundary conditions the temperature distributions for uncoated, mullite, Y-PSZ and Mg-PSZ are calculated. From the above results Mg-PSZ having highest surface temperature and minimum substrate temperature. Mg-PSZ can be the alternate thermal barrier coating for Mullite and Y-PSZ.

4.2 Sample Preparation

Several of uncoated and coated aluminium alloy sample with a thickness of approximately 10 mm thickness and a breadth about 25 mm were prepared. The surfaces of sample were grit blasted and followed by ultrasonic cleaning using ethanol. Samples that were sprayed based on reference [8] which is sample surface coated with thickness between 100µm of bond coat and 200µm of Magnesia-stabilized Zirconia top coat.

Fig-6: Microscopic view of coated sample

4.3 Vicker's Hardness Test

Observed value for ceramic coated sample in HV5kg is 47.0,47.7,48.1. Observed value for uncoated sample in HV5kg is 44.0,43.8,44.8.

4.4 Salt Spray Test (Coated):

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 degree angle.

Observation:
No white formation found.

4.5 Flame Torch Test

Table 2 represents the temperature difference of uncoated aluminium alloy sample. Table 3 represents the temperature difference of 100µm NiCrAl bond coat and 200µm Magnesia stabilized Zirconia top coated sample.

Table-2: Temperature on uncoated sample

Front	Back
226.4^{0}C	135.0^{0}C
393.2^{0}C	297.0^{0}C
466.1^{0}C	374.2^{0}C

Table-3: Temperature on ceramic coated sample

Coated Side	Uncoated Side
365.3^{0}C	145.5^{0}C
446.9^{0}C	287.8^{0}C
530.3^{0}C	397.5^{0}C

5. CONCLUSION

From the above analysis, it is clear that TBC help to increase the temperature of the piston. The maximum temperature for top coating surface occurs throughout the piston crown for Magnesia-stabilized zirconia. Coated piston has a significantly higher temperature the uncoated piston. The corresponding top surface maximum temperature for the uncoated, Mullite coated piston, Yttrium-stabilized zirconia and Magnesia-stabilized zirconia is 311.42^{0}C, 324.65^{0}C, 334.98^{0}C and 349.95^{0}C respectively. The maximum temperature on the top surface is observed for Magnesia-stabilized zirconia which is about 349.5^{0}C. Magnesia-stabilized zirconia coated sample has improved hardness compared to the uncoated sample. From the flame torch test it is observed that magnesia-stabilized zirconia coated sample has elevated temperature compared to uncoated one. Magnesia-stabilized zirconia has similar properties of Yttrium-stabilized zirconia which is a better candidate material for thermal barrier coating.

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