Thermodynamic Stability Analysis of Y-PSZ Coated Diesel Engine Piston over the Bond Coat of Alumina

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Abstract – This paper deals with the investigation of plasma sprayed Yttria partially stabilized zirconia (Y-PSZ) as thermal barrier coating (TBC). The thermal barrier coating, as the name suggests, is a coating of material of low thermal conductivity value, low enough to make it capable to reduce heat from the hot working fluid to penetrate into the substrate in high temperature applications like internal combustion engines, gas turbines etc. The investigation has been made in terms of thermal behavior of plasma sprayed Y-PSZ coating over aluminum (12 % by wt. Si) substrate using intermediate bond coat of Al_2O_3. The results indicate that Y-PSZ/Al_2O_3 TBC set up is highly effective in lowering the temperatures within the substrate, thereby increasing thermal efficiency of the system. A particular TBC thickness performs more effectively at elevated operated temperatures and for a particular convection conditions system, thicker layer of TBC gives better results than a thinner one.

Index Terms - Diesel engine piston, Y-PSZ, TBC, Bond coat.

Abbreviations: Y-PSZ (Yttria partially stabilized zirconia), TBC (Thermal Barrier Coating).

1. INTRODUCTION

The ceramics as thermal barrier coating in high temperature engineering application is in use for more than two decades now. Ceramic coating on diesel engine components increases the thermal efficiency of the engine and reduces the associated emissions. In an internal combustion engine heat is transferred from combustion chamber to piston head, cylinder walls and then to the cooling water circulated through water jackets around the cylinder. Generally, in case of diesel engines about 18-22 percent of heat energy from fuel combustion is rejected to coolant fluid. To reduce heat loss to the cooling water thermal barrier ceramic (TBC) coating is used. Initially thermal barrier coating was applied on gas turbine blades, but after 1979 the ceramic coating was introduced to adiabatic engines. Piston crown surface, cylinder liner, valves were used for ceramic coatings. For the aim of the thermal barrier ceramic coatings, thermal expansion, thermal conductivity, wear properties, creep and corrosion resistance are some of the important properties of coatings.

Some researchers have given the experimental bonding strength values of ceramic coatings [1-4].

Flame spray and plasma spray techniques are frequently used as thermal spray techniques. The literature work on the bonding strength of ceramic coatings shows the plasma-sprayed ceramic coatings have higher bonding strength than flame sprayed coatings [5]. According to many researchers, the adhesion strength between the substrate and the ceramic coating can be increased by using a bond coat. The bonding strength of ceramic coating without bond coat is less than that with bond coat. Microstructure and mechanical properties, such as grain size [6-9], porosity [10], fracture toughness [11] and hardness [12] have strong effect on abrasive and sliding wear resistance of ceramics and coatings under different operating conditions. Among many coating materials, zirconia as wear resistant material is extensively used for high temperature engineering applications.

The performance of internal combustion engines should be improved depending on some technological requirements and rapid increase in the fuel expenses. On the other hand, the improvements in engine materials are forced by using alternative fuels and environmental requirements. Therefore, the performances of engine materials become increasingly important.

1.1 TBC DESIGN

The basic TBC system consists of a top layer of thermally insulating material and an intermediate bond coat as shown in Fig 1. The interlayer, usually known as bond coat, basically provides sufficient adhesive strength between ceramic layer and the substrate and to aid to that, it also acts as a protection barrier for oxidation and corrosion. Basically, the material of top coat must possess certain properties to make it suitable for thermal barrier coating. The very basic requirement amongst them is low thermal conductivity value. Ceramics with their high thermal resistance offers an excellent coating surface by absorbing the thermal shocks and protecting the substrate. However, there is sufficient difference in the thermal expansion coefficient values of the top coat material and the substrate.

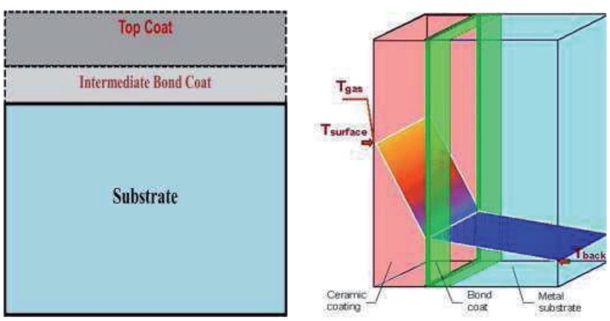

Fig. 1 Basic TBC design

In case of bonding of two different materials, thermal stresses are generated in high thermal loading conditions due to the mismatch in the values of coefficient of thermal expansion. The intermediate bond coat basically serves as filler for this gap and the whole TBC system can therefore be considered to form a graded structure termed as Functionally Graded Material (FGM) structure.

1.2 GEOMETRY SELECTED

The simulation testing was performed to carry out thermal analysis on both uncoated as well as coated substrates. The part geometry considered for this analysis was a quarter part of a 74 mm diameter diesel engine piston, as shown in Fig. 1.2. This model was taken as uncoated substrate. The reason for this particular geometry selection of the model is to investigate the effect of insulated piston crown on the ic engine piston and thermal stability of the ceramic has been investigated with the aluminium substrate. To analyze the effect of thermal barrier coating, four other similar models were generated but with the top surface coated with TBC layer of thickness 150, 250, 350 and 450 microns respectively, through intermediate layer alumina of thickness 100 microns for all four models.

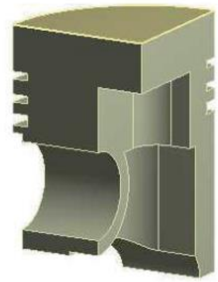

Fig. 2 Model chosen for Simulation

2. FINITE ELEMENT MODELING

The finite element modeling was carried out using commercial ANSYS code. The top layer, intermediate layer and the base in each coated model were assigned the thermal properties (isotropic thermal conductivity, density and specific heat) of respectively Y-PSZ, Al_2O_3 and AlSi (12 wt. %) as stated in Table 1.

Table 1 Thermal properties of materials used

Material	Thermal Conductivity (w/m°c)	Thermal Expansion (1/K)	Density (kg/m^3)	Specific Heat (J/Kg°c)
AlSi	155	21	2700	960
Al_2O_3	30	7.4	3960	850
Y-PSZ	1.4	10.9	5650	620

The uncoated model was assigned the material properties of AlSi (12 wt. %) as the substrate material. Fig. 2. shows typical tetrahedral meshing of a model with 218252 nodes and 130130 elements.

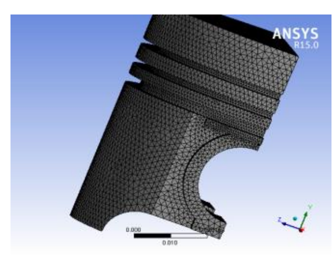

Fig. 3 Meshed Model

2.1 BOUNDARY CONDITIONS

The coated free surface was considered to be exposed to convection conditions of high temperature environment (temperature of 650 K and convection coefficient of 900 (W/m^2K) while free surface opposite to it was applied convection condition of 383.15 K temperature and convection coefficient of 150W/m^2K. Same convection conditions were applied on free surfaces of the uncoated model. Further, initial uniform temperature of 300 K was assigned for each model under investigation. These thermal conditions were chosen from the suitable thermal conditions of a diesel engine conditions used in the analyses.

3 RESULT OF FINITE ELEMENT SIMULATION

The temperature profiles of the uncoated and ceramic coated piston (150, 250, 350 and 450 micron coated) have been shown in fig. 4(a), 4(b), 4(c), 4(d), 4(e) respectively.

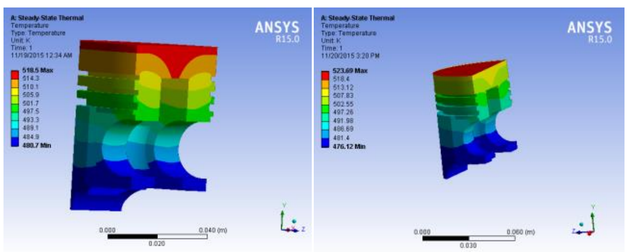

Fig.4 (a) Temperature distribution for uncoated piston Fig. 4(b) Temperature distribution for 150 micron coated piston.

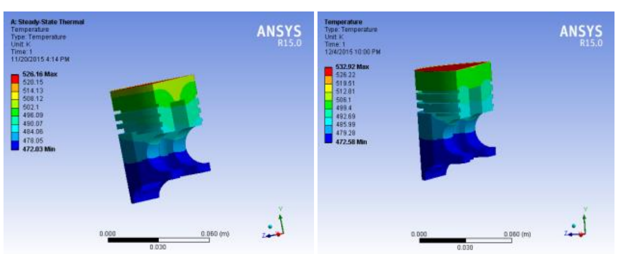

Fig 4(c) Temperature distribution for 250 micron coated piston. Fig.4 (d) Temperature distribution for 350 micron coated piston.

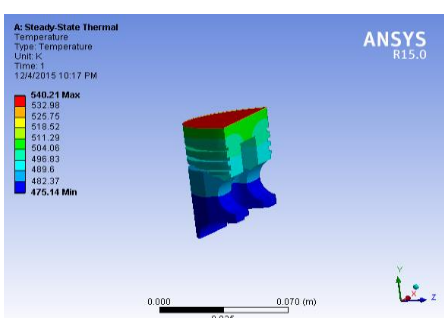

Fig. 4(e) Temperature distribution for 450 micron coated piston.

Table 2: Difference in the top surface temperature for different cases

Type of Piston	Temperature of the Top surface (K)	Increased temperature with respect to uncoated piston (K)	Percentage increase in temperature (%)
Uncoated Piston	518.5	-	-
150 microns coated piston	523.69	5.19	1
250 microns coated piston	526.16	7.66	1.48
350 microns coated piston	532.92	14.42	2.78
450 microns coated piston	540.21	21.71	4.18

Variation on the temperature at the top surface of diesel engine piston can be explained graphically as shown in Fig. 5

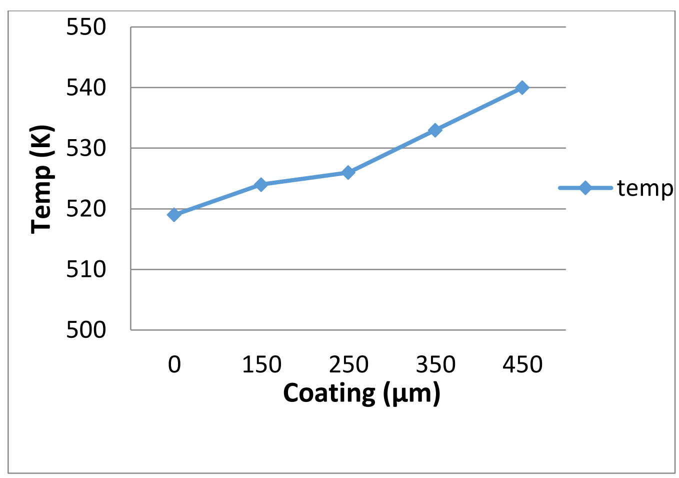

Fig. 5. Graph representing change in the variation of temperature at the top surface of piston with increasing thickness of coating

4 CONCLUSIONS

Following results are concluded based on the simulation results performed in ANSYS 15:

- Finite element methods based ANSYS simulation were used to study the effects of Y-PSZ/ Al_2O_3 thermal barrier coating over substrate (Al alloy- 12

- wt % Si). Effect of changing top coat thickness at constant bond coat thickness was observed by the methodology.
- Application of Y-PSZ /Al_2O_3 TBC is highly effective in reducing heat loss content from the hot working media into the substrate, which in turn, is responsible for increase in thermal efficiency of the system or decrease in cooling load of the system and lowering the substrate temperatures.
- As the top coat thickness increases with same bond coat thickness, TBC becomes more effective in terms of decreasing substrate temperatures and increasing the top coating surface temperatures. The results show that after steady state of thermal loading and as compared to an uncoated model, coating top surface temperature increases by 1% (simulation) for 150 coated model to 4.18% (simulation) for 450 coated model.

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