Thermal Analysis of Ceramic Coated (Mullite Ysz) Piston using Finite Element Analysis

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Abstract— Recent researches reveal that the thermal barrier coating (TBC) on engine surfaces plays a vital role on analyzing the emission and performance characteristics of IC engines. In this research, an effort is made to investigate the thermal analysis and heat transfer analysis of thermal barrier coated piston of IC Engines using Finite Element Analysis. Yttria Stabilized Zirconia and Mullite chosen as a thermal barrier coating material because of higher thermal expansion coefficient, low thermal conductivity, high melting point and having good mechanical properties and also maintains stable phase structure at higher temperatures. Literature review shows that piston crown surface is one of the primary components in diesel engine which highly influences in the efficiency and performance calculation of IC Engines. In this work, piston crown surface selected as a coating surface and ceramic material coated by plasma spraying technique with optimizing pressure and velocity. Thermal and heat transfer analysis of piston crown surface will help to identify the temperature variations within IC engines. Result of this analysis shows the temperature distribution of piston surface at which the maximum temperatures and minimum temperatures are occurs. So, this methodology will help to evaluate the temperature distribution and thermal stress analysis numerically. The results of diesel engines are also validated with determined experimental values, it shows good agreements with considerable deviation.

Key words: Yttria Stabilized Zirconia, Mullite, Piston Crown, Thermal Barrier Coating (TBC)

I. Introduction

Thermal barrier coatings (TBCs) consisting of stabilized zirconia are now employed in most turbine engines, permitting gas temperatures to be raised substantially above those of uncoated systems. The TBC coating usually comprises four different layers: ceramic top coat layer (TC), bond coat layer (BC), thermally grown oxide layer (TGO), and thick substrate layer (SUB). Large thermal expansion mismatch between the metal and the ceramic layers as well as volume growth of the TGO layer at high temperature have been reported as the main sources of large cyclic residual stresses within the different layers of the TBC. A significant number of finite element (FE) simulations have been carried out in order to understand the mechanisms of the residual stress development in different layers as well as the failure process of the TBC. Some FE models have been developed to investigate the cracking scenarios in the TC layer, in which the constitutive behavior of the ceramic TC layer is of primary importance. A few FE models are concerned with rumpling in which a progressive geometry change of the BC and TGO layers occur. For these cases, the constitutive behavior of the TC layer is of secondary importance. In these studies, the mechanical behavior of the TC layer has been assumed to be linear elastic or linear elastic with creep at high temperature. Some cracking and failure scenarios have been proposed based on the stress fields in the TC layer which have been obtained from the simulation results by assuming linear elastic behavior for the TC layer. Xie et al. calculated the stress fields in the TC layer using a viscoplastic constitutive model and showed that these stress fields differed significantly from those obtained by simpler models and thus altered the cracking scenarios extracted from simpler models.

Nonlinear behavior of plasma sprayed yttria stabilized zirconia (YSZ) coating under compressive stress has been experimentally observed during different tests like: uniaxial loading, bending of bi-material beam, indentation, and thermal cycling of bi-material beam. During service, TBCs are exposed to high temperatures for extended times, leading to YSZ sintering. Sintering may heal microcracks, eliminate some porosity, improve inters plat bonding and create a denser structure which indeed leads to increased stiffness. Since the residual stress within the TC layer after thermal cycling is a function of its stiffness, the stress fields obtained by the models considering sintering for the TC layer may differ significantly from those obtained by simpler models not considering the effect of sintering on stiffness evolution. Sintering may result in higher values of residual stresses within the TC layer. In this paper, finite element analysis of the TBC provided to the piston coated with Mullite YSZ is to be studied.

Mullite (3Al2O3.2SiO2) is a low cost refractory oxide that currently constitutes the building block of an efficient TBC architecture. Mullite has a low thermal expansion coefficient (4.5-5.6 X 10-6/0C) that represents, for instance, a close match with SiC (4.02 X10-6/0C) and excellent high temperature properties (e.g., high thermal shock and thermal stress resistance) offered mainly by its interlocking grain structure.

The CTEs of the Mullite-YSZ composites vary according to their respective volume fractions. For instance, using data taken from the existing literature for the thermal expansion coefficients, bulk modulus of both mullite and YSZ and applying the models mentioned above values of 6-7 X 10-6/0C for a mullite/ YSZ 75/25 vol. % and of 7.5-8.3X10-6/0C for a mullite/ YSZ 50/50 vol.%, respectively, are obtained. This gradual transition toward the CTE value of YSZ (10.6X10-6/0C) is pictured as a potential solution to ease the stress induced by the bond and top coats CTE mismatch. A proper understanding of the mechanical properties such as the elastic modulus, hardness or plastic/elastic recovery work serves for an efficient design of such refractory oxide multilayers.

II. Materials

During the early years, cast iron was used as piston material because of its good wear properties, but it has high specific weight, causing increased inertia effects. Later on Aluminum alloy containing silicon came into existence. It helps in the higher strength and reduced expansion. Generally two configurations of Silicon is used in Aluminum alloy. They are eutectic and hyper- eutectic, containing 12% and 22% respectively. If silicon content is more than 12%, the material becomes brittle. Performance of an engine can be increased by insulating the components of combustion chamber. Due to insulation, the components cannot with stand the higher temperatures resulting in failure.

In order to prevent this risk, ceramic coatings are employed which can resist high temperatures to work efficiently as Aluminum alone cannot withstand high temperatures.

Ceramic Coatings are used as a protective coating on or in between the engine parts, which result in reduction of friction, increase wear resistance and improve heat shielding. All these factors have noticeable influence on the performance parameters and the component life in a vehicle. These coatings help the components to interact in more uniform and compatible fashion. Zirconium based ceramic coatings are widely used. Zirconium along with Mullite and Yttria has very good mechanical properties, impact and thermal shock resistance. Zirconium-based ceramic coatings are used as thermal barrier coatings owing to their low thermal conductivity and their relatively high coefficients of thermal expansion compared to other ceramics which reduce the detrimental interfacial stresses.

The problem in the combustion chamber with conventional materials is that most of the heat generated in an engine will be lost through heat transfer. Hence, the solution is to make the components insulate and withstand high temperatures in the combustion chamber. By TBCs, burning of gases in an engine can be done more efficiently by raising the temperature of the air-fuel mixture.

Thermal barrier coatings (TBC) aids in increasing the thermal efficiency of the engine as the heat rejections to surroundings are low with ceramics. The excess heat can be used for improved burning of the air-fuel mixture and reduction in emissions. These coatings have high thermal durability so it is not necessary to cool them immediately like it has to be done for conventional materials. Wear and corrosive properties are very much better than regularly used component materials. Lower heat transfer from the combustion chamber due to coatings helps in using the in-cylinder heat more efficiently. More heat can be transferred to exhaust system. This heat can be used for heat recovery systems for generation of power etc.

Most recent development in the zirconia ceramics are the partially stabilized zirconia (PSZ) and transformation-toughened zirconia. PSZ is reliable, tough and has higher strength than zirconia. Its applications include aerospace coatings, automotive primers and topcoats. PSZ has got thermal expansion coefficient only about 20% lower than cast iron, so the piston slap problem can be avoided. Its thermal conductivity is about one-third of other ceramics. So due to these factors it can be used for heat engine components. The Transformed - toughened zirconia is much improved form of PSZ, it has higher toughness than that of PSZ. Yttria stabilized zirconia (YSZ) has good value compare to other PSZ. Combination of YSZ and Mullite ($3Al_2O_3.2SiO_2$) is coated over the piston crown, Mullite forms stable phase structure over the high temperature.

III. METHODOLOGY

- After defining the materials properties finite element modeling of piston was done in the geometry section of the system by giving the bore diameter, bond coat and top coat thickness.
- Then, model analysis of ceramic coated piston has been carried out. In this step, materials are assigned to particular solid i.e. piston, coating, rings. Contact between ring and ring groove, bond coat-substrate and top coat substrate are defined default which is bonded contact. Meshing also created by taking default settings.

A. Modelling of Piston

The ceramic coating (TBC) were made by removing few millimeter (mm) of the piston material on the crown at the edges.

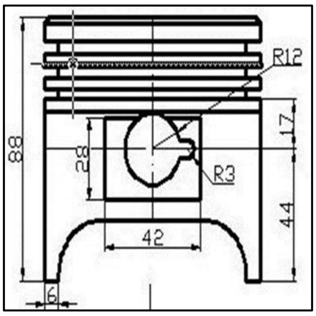

Fig. 1: Front view of piston

Piston is drawn with standard specification as shown in the figure 2 in pro-E wildfire v5.0 and save as in the format STEP file.

IV. ANALYSIS OF PISTON

1) In ANSYS workbench Engineering data is set according to the requirement of the piston material
2) Geometry is imported to ansys system as already saved STEP file of piston
3) Model section has meshing of piston, details of meshing of piston; details of statistics are needed to change according to the requirement of the modal.
4) In detailing part, values are needed to be given for modal, magnitude of temperature, film coefficient temperature.
5) In the solution part, temperature and total heat flux are selected.

The coating provides an appreciable change in the distribution of thermal heat flux value in the piston, which can be considered as a desirable one to choose coating of piston as a process of controlling thermal stress.

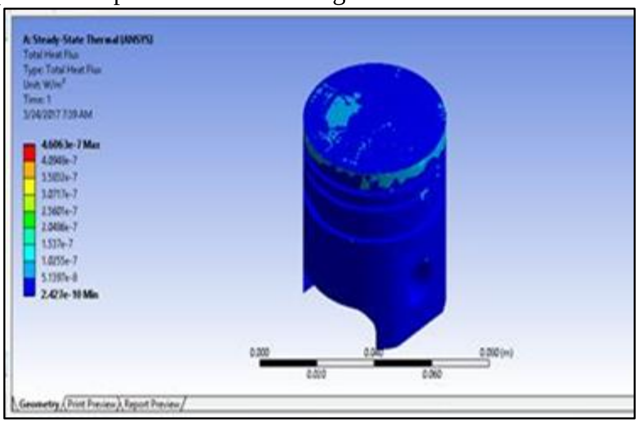

Fig. 2: Total heat flux for coated piston

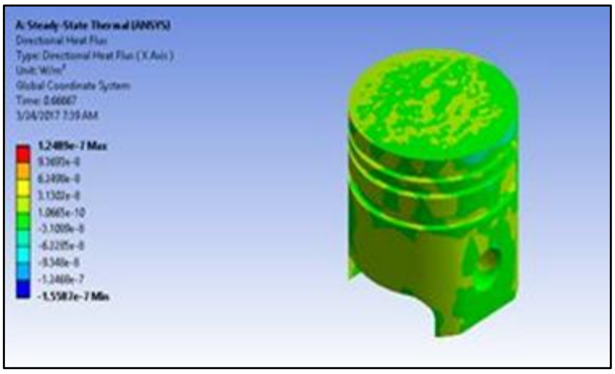

Fig. 3: Directional heat flux for coated piston

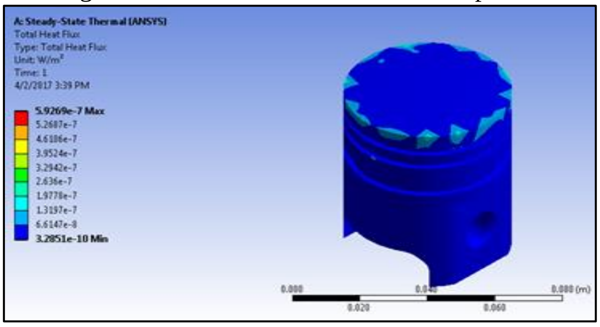

Fig. 4: Total heat flux for uncoated piston

V. Conclusion

From the analysis made it's proven that the coating made to the piston provides an appreciable change in the property variation of thermal heat flux value. Usage of ceramic material Mullite ($3Al_2O_3.2SiO_2$) YSZ as coating material, it allows very few amount of heat can pass through it. The process employed, will help us in controlling engine damage, decreasing ignition delay and improving engine component life by allowing less amount of heat to be transferred through it and constraining it in the cylinder of the piston.

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