Thermal Analysis of IC Engine Piston With Thermal Barrier Coating

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Abstract- *The main purpose of this research is to analyze the effect of ceramic coating on piston to improve the thermal efficiency of the engine. The engine life and performance is mainly depends on the design and the materials used for their manufacturing. Piston plays a vital role in improving the performance of an engine. The piston crown is the top surface closest to the cylinder head of the piston which is subjected to tremendous pressure forces and heat during normal engine operation.*

The main objective of this paper is to analyse numerically a heat transfer in the zirconium coated piston and uncoated piston of four stroke IC engine which is determined mainly as a function of temperature from crown to skirt. Piston as design using CATIA V5 works, boundary conditions were calculated analytically from experiment and a study state thermal analysis was performed using ANSYS Workbench.

Thermal analysis of piston has been done by selecting Aluminium alloy (uncoated piston) as piston material by coating with 100 micron such as . An analysis of thermal stress and damages due to application of pressure is presented and analysed in this work. The maximum and minimum temperature distribution and heat flux distribution with uncoated piston and its coating material was observed. The result of project increased surface temperature of the coated piston with material which has low thermal conductivity has improve considerable. Because of reduced heat losses, efficiency will improve. The effect of ceramic coating on piston to improve the thermal efficiency due to the complete combustion along with reduction of engine emission.

Keywords- Thermal barrier coating ; Zirconium oxide; CATIA V5; ANSYS workbench; IC Engine.

I. INTRODUCTION

Automobile components are in great demand these days because of increased use of automobiles. The increased demand is due to improved performance and reduced cost of these components. R&D and testing engineers should develop critical components in shortest possible time to minimize launch time for new products. This necessitates understanding of new technologies and quick absorption in the development of new products. A piston is a component to reciprocating IC-engine. It is the moving component that is contained by a cylinder and is made gas-tight by piston rings. In an engine, its purpose is to transfer force from expanding gas in the cylinder to the crankshaft via a piston rod and/or connecting rod. As an important part in an engine, piston endures the cyclic gas pressure and the inertial forces at work, and this working condition may cause the fatigue damage of piston, such as piston side wear, piston head/crown cracks and so on.

The investigations indicate that the greatest stress appears on the upper end of the piston and stress concentration is one of the mainly reason for fatigue failure. On the other hand piston over heating-seizure can only occur when something burns or scrapes away the oil film that exists between the piston and the cylinder wall. In Internal Combustion Engines, most of the heat generated during combustion process is absorbed by piston. This is direct heat loss to the piston. This reduces Indicated Power and in turns the performance of Internal Combustion Engine. Engine coating with a ceramic thermal barrier can be applied to improve reliability and durability of engine performance and efficiency in Petrol engines. In a conventional diesel engine, about 30% of the total energy is rejected to the coolant and it was reported that the engine coating may be a good solution.

Thermal barrier coatings are generally applied on the cylinder head, piston and valves by plasma spray method. Coating these parts with ceramic also limits the negative effects of wear, friction, heating, corrosion and oxidation. It was also reported in a theoretical diesel cycle analysis that more the heat transfer decreases, the less energy will be lost, thus increasing the work output and the thermal efficiency. In another study, with engine coating an increase in engine power and decrease in specific fuel consumption, as well as significant reduction in exhaust gas emissions and smoke density have been addressed in comparison to the uncoated engine. Using the coated piston, the required temperature in the combustion chamber will be maintained. This will reduce the heat loss to the piston. This reduction in the heat loss will be used to burn the un-burnt gases there by reducing the polluted exhaust gases

A one another reason of using TBC is the continuous increase in fuel prices and reduction in supply of high quality fuel. On the other hand combustion of these fuels leaves HC particles, CO emissions and smoke behind them due to improper combustion at low temperature. TBC allows using low quality fuels by making the piston temperature much higher than uncoated one due to which proper combustion of fuel occurs. Due to proper combustion of fuel the thermal barrier coating reduces HC, CO emissions in the environment. TBC mainly consists three layers of substrate, bond coat and top coat. The substrate is a metal surface which takes maximum load on it. High temperature aluminum alloys are generally used for substrate material. Bond coat is used to provide bonding between substrate and top coat surface. It also helps to reduces stresses occurring during thermal shock. The top coat is material of lower thermal conductivity to withstand at higher temperature. To determine and control the temperature and stress in internal combustion engine temperature distribution for piston have to investigate. Analysis of temperature distribution helps the designer to estimate the project cost before actual designing begins. Thus, thermal analysis of piston is very important.

Thermal barrier coating in order to reduce emissions of engine. An effective way for reducing vehicle emission and increase engine performance is accomplished by coating piston head with low thermal conductivity materials such as tungsten carbide, zirconium and titanium dioxide etc. Ceramic coatings protect the piston from thermal shocks. The primary purpose of this ceramic coating is to enhance the engine performance by the reduction of heat loss as well to enable high temperature components to function at even higher temperatures with increased durability of engines.

OVERVIEW OF THERMAL BARRIER COATING

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.

The main purpose of this is to raise the temperature of the piston head 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.

performance. Similar to structural parameters, there are several studies conducted on the analysis of numerical parameters; but the very problem-specific nature of GA hinders making general conclusions about the suitable levels of them. Moreover, these studies analyze these parameters one at a time, ignoring the interaction between the parameter types. The literature on this class of parameters is more ambiguous than the previous class. In this study, all of the numerical parameters of GA are examined with a priori known level of structural parameter setting. General insights about the best combination of these parameters are presented on particular problem domains. More detailed explanation about numerical parameters is provided in the following sections. Testing Scheme A test problem is taken from the literature for GA based simulation-optimization application, and significance of different values of the parameters on GA performance is analyzed on this test problem by factorial designs and ANOVA (Analysis of Variance). Two types of performance measure are considered throughout the analysis.

Fig: Sample of thermal barrier coated piston head

SELECTED TBC PROPERTIES

1. High melting temperature
2. Low thermal conductivity
3. Affinity with the substrate material with respect to the thermal expansion coefficient, to grant adhesion
4. High mechanical strength at high temperature
5. Good resistance to erosion and corrosion
6. No phase changes from ambient to operating condition temperatures
7. Chemical stability to avoid reactions with fuel mixture or exhausts
8. Low sintering rate of the porous microstructure
9. Fatigue resistance at both low and high cycles
10. Toughness

The coating porosity affects both its thermal conductivity and elastic modulus. For a TBC with lower thermal expansion coefficient, it is better to have a lower elastic modulus for a durable coating

II. LITRATURE SURVEY

X.Q. Cao (1) In the paper done on ceramic materials for thermal barrier coatings is carried out different materials. In the periodical table of elements, the elements whose oxides find applications in TBCs are mainly distributed in IIIB (rare earth elements), IVB (Ti, Zr and Hf), IIIA (Al) and IVA (Si). The IIA elements (Mg and Ca) can only be used as stabilizers of zirconia. Rare earth oxides are promising materials for TBCs because of their low thermal conductivity, high thermal expansion coefficients chemical inertness.

S.Sathyamoorthi (2) In this paper related to piston crown coating used to finite element analysis method. An experimental work is conducted to detect the change in engine characteristics with the influence of functionally graded coating material. The experimental setup was constructed and results were obtained for thermal efficiency, Performance and emissions. The obtained results were compared between uncoated and Zirconia coated piston. The maximum surface temperature of the coated piston with material which has low thermal conductivity has improved approximately by 14%. Because of reduced heat losses, efficiency will improve.

Ravindra Geholt (3) In this paper deals with the steady state thermal analysis of diesel engine piston coated with ceramic coating having holes on its surface. Temperature distribution on the piston's top surface and substrate surface is investigated by using finite element based software called Ansys. Yttria-stabilized Zirconia is used as ceramic coating applied on Al–Si piston crown. The 2 thickness of ceramic top coating is about 0.4 mm and for NiCrAl bond coat it is taken to be 0.1 mm. Temperature distribution is investigated by choosing various radiuses of holes created on the ceramic coating surface about 1.5 mm, 2 mm and 2.5 mm. From the results it is observed that the top surface (coated surface) temperature is increasing with increase the radius of the holes.

GEOMETRY GENERATION

The geometry of IC engine piston has been made in CATIA V5. The geometry has been imported to ANSYS for the analysis. The geometric dimension of piston using the value of diameter and height of the piston. Parameter refer to constraints whose value determine the shape or geometry of the model or assemble. The Maxwell-stefan diffusion model is implemented to study mass transport properties using the transport of concentrated species module of ANSYS. The energy equation is used to describe and analyse the heat transfer as well as temperature profile of the present model using the heat transfer module. The energy equation, coupled with electrochemical heat generation, assuming the local temperature equilibrium, is solved using the heat transfer module.

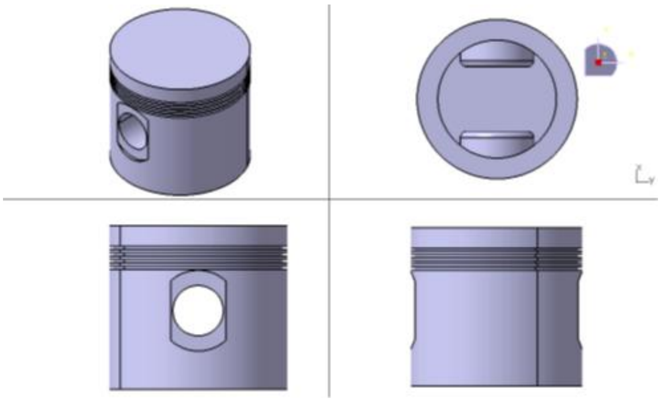

Fig: Various Views of the Designed Piston

GEOMETRIC MODELLING

Sl.no	Dimensional parameters	Dimensions
1	Internal Diameter	60mm
2	External Diameter (Bore)	81mm
3	Length of The Piston	75mm
4	Clearance	7mm

TABLE: Dimensions of the Piston

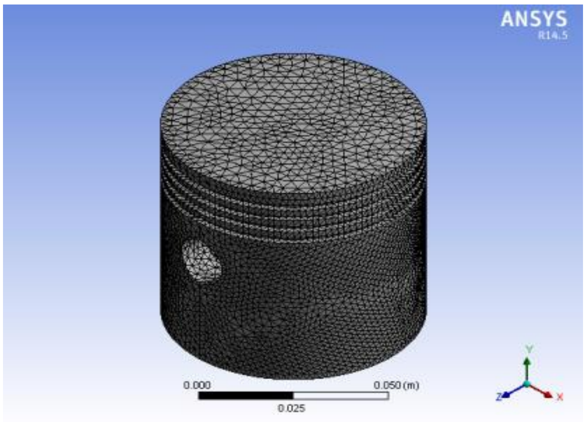

Figure : Meshing of Piston

For meshing ,
Minimum edge length= 4.509e-002 m
Number of Nodes = 285935
Number of Elements = 144834

BOUNDARY CONDITION

The boundary conditions are define as convection coefficient and heat flux flow in case of thermal analysis. From the study of a realistic problem, it is found that there will be frictionless support, which is provided by the piston pin hole. For thermal analysis, first boundary conditions are 1330 W/m^2 convection coefficient on outer surface and $450W/m^2$on inner surface, and second boundary condition is 5923 W heat flow on the piston head. The materials used for the piston are uncoated in aluminium alloy and over the coating of zirconium dioxide to 100 micron. A heat flux of 2.1Mpa has been applied on top of the piston.

III. RESULTS AND DISCUSSION

The model of IC engine piston has been developed using CATIA V5 and analysis has been done using ANSYS fluent. The analysis has been performed for temperature distribution and heat flux.

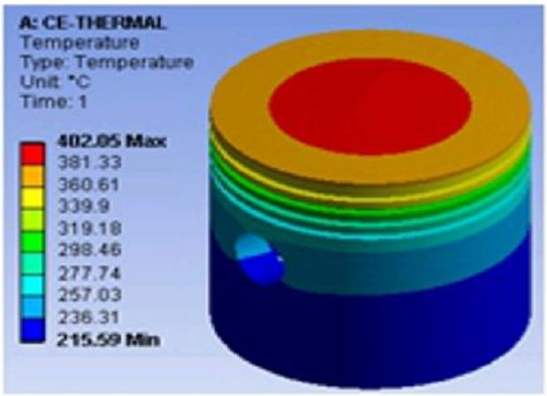

Figure 6.1 Temperature distribution in uncoated piston

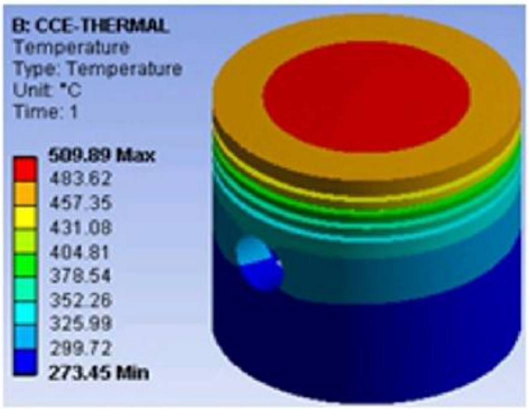

Figure 6.2 Temperature distribution in coated piston

Comparison of temperature flow in uncoated and zirconium dioxide coated piston

The temperature distribution in piston with ZrO_2 coat on top of the piston. It is observed that a lower heat rejection from the combustion chamber through thermally insulated components causes an increase in available energy which in turn would increase in cylinder work and the amount of energy carried by the exhaust gases, which could also be utilized in later stages. It is relatively a thermal barrier coating material zirconium which has approximately 26.8% more thermal stability than uncoated piston. It can resist phase transition up to 1300K with thermal conductivity of 2.17 W/mK which is an added advantage in terms of reliability of engine operation in the event of sudden surge in temperature during combustion.

It is observed that the temperature variation in uncoated was 402°C to 215°C against 509.89°C to 273.45°C which indicates the heat enhancement in ZrO_2 coated engine due to low heat rejection to neighboring components like piston liner and head. Temperature along the radius of the piston was determined 401.91°C to 359.8°C and 508°C to 464°C in uncoated and ZrO_2 coated respectively indicates that the nodal temperature was uniform in ZrO_2 coated when compared to uncoated piston.

The vertical temperature was observed from top of the piston to bottom of the piston which is to be 361.89°C to 215.81°C for uncoated piston and 461.24°C to 273.61°C for ZrO_2 coated piston.

A temperature of 280°C and 298°C for uncoated piston and ZrO_2 piston was noted at the place of lubricating oil which is under safe limit of SAE40 lubricant oil melting temperature according to data available.

Distribution of heat flux also uniform in ZrO_2 coated piston than uncoated piston resulted in better heat transfer per unit area for ZrO_2.

IV. CONCLUSION

From the FEA result, the maximum temperature value of the coated piston was shown at the piston combustion chamber. Therefore, this area must be coated intensively. The maximum surface temperature of the coated piston with material which has low thermal conductivity has improve considerable. Because of reduced heat losses, efficiency will improve. The effect of ceramic coating on piston to improve the thermal efficiency due to the complete combustion along with reduction of engine emission.

In the present study the review of the thermal barrier coating materials which can be used in IC engine application is presented with their corresponding properties. Every TBC materials have their own properties. For any application proper selection of the TBC material is require to be done. Various researchers have used different TBC materials to enhance the performance of the IC engine. It has a positive effect on the power and exhaust emission of the engine.

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