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Thermal Analysis of Ceramic Coated Aluminum Alloy Piston using Finite Element Method

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Abstract

The objective of this paper is to establish the temperature distributions in plasma sprayed Yttria Stabilized Zirconia (YSZ) and magnesia stabilized zirconia ($MgZrO_3$) thermal barrier coating on an aluminum alloy piston crown to raise the potential of a diesel engine. The influence of ceramic coating thickness on temperature variations are studied by finite element method using ANSYS. The temperature distribution analyses were conducted for the ceramic coating thickness of 0.3mm over the piston crown surface. The results of the piston coated with two different coatings were analyzed. It is observed that, the peak exterior surface temperature of the ceramic piston with the material $MgZrO_3$ is increased by 32% and 20% for the piston coated with yttria stabilized zirconia compared with conventional aluminum alloy piston. It is concluded that the substrate temperature of the piston coated with $MgZrO_3$ and yttria stabilized zirconia is reduced by 25% and 17% compared with uncoated aluminum alloy piston. The lower substrate surface temperature by coating results in improved heat to work conversion efficiency of the engine.

Keywords: ANSYS, Finite Element Method, $MgZrO_3$, Thermal Analysis, Yttria Stabilized Zirconia (YSZ)

1. Introduction

The compression ignition engine is undergoing a technological progress in the field of ceramic engine technology. The adiabatic principle could be achieved by providing ceramic thermal barrier coating to the internal combustion engine components such as piston crown, cylinder liner, cylinder head etc[1]. The Thermal barrier coatings are applied to insulate combustion chamber results in reduction of heat rejection in the cylinder and the metallic surfaces are protected from thermal fatigue, especially from power and exhaust stroke of diesel engine cycles. There are many advantages of low heat rejection for engine concepts such as reduced consumption of fuel and exhaust emissions as well as durable engine components[2]. It is observed that the combustion temperature of 200^0C – 250^0C higher in low heat rejection engine compared to conventional diesel engine leads to higher level of NO_x emission[3]. Therefore, the fuel injection timing was changed to 34^0crank angle in low heat rejection engine and found that the NO_x emission was reduced to about 39% and specific fuel consumption was reduced to about 5% compared with the diesel engine.

The LHR engine Al_2O_3-TiO_3 coated cylinder head, inlet and exhaust valves, piston operated with diesel and corn-oil methyl ester provides lower smoke emission[4]. It is observed that, a drop in engine brake power and fuel economy associated with improvements in the engine exhaust emissions except nitric oxide emission were found in the thermal barrier laminated engine compared with that of the conventional diesel engine. With higher quantity of corn methyl ester in solutions for both coated engine and conventional engine, the smoke emission was reduced by 8.1% for corn methyl ester mixture compared with that of uncoated diesel engine. But NO_X emission was increased by 8.8% for blended fuel solutions in low heat rejection engine compared with uncoated diesel engine.

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The conventional diesel engine is converted to low heat rejection engine by encrusting the engine components like cylinder head, piston and valves (inlet and exhaust) by partially stabilized zirconia using plasma spray process operated with cashew nut shell methyl ester (CNSME) provides a gain in brake thermal efficiency of CNSME in LHR engine compared with conventional engine[5]. In the emission characteristics front, smoke, CO and HC were considerably decreased by 14.3%, 27.7% and 7.2 % respectively for low heat rejection engine at full load condition, while NO_X noticed to be increased.

In this study, the comparative thermal analysis were performed between YSZ coated piston, $MgZrO_3$ coated piston and uncoated piston using FEA.

2. Thermal Analysis of Piston

In the present numerical simulation workPro-E, a modeling tool has been employed for modeling the piston. The developed model of the piston is saved in IGES format and imported in ANSYS for conducting the finite element analysis. The aim of the paper is to investigate the Al Si alloy piston temperature distribution by using different coating materials to achieve higher engine performance. A quarter part of piston model is shown in Figure 1. Analyses have been performed for uncoated piston crown and ceramic-coated piston crown with a coat thickness of 0.3mm. The coating consists of 0.1mm bond coat (Ni Cr Al) and the ceramics YSZ and $MgZrO_3$ deposited onto the piston crown. Some of the properties of the ceramic coat, interlayer metallic bond coat, rings and piston are listed in the Table 1 are obtained from the literatures[6,7]. The bond coat layer is an inter-metallic alloy used between the thermal barrier coating and the metal substrate provides oxidation resistance and the internal stress resistance at higher temperatures helps in the bonding of the TBC layer to the substrate material[8].

2.1 Thermal Boundary Conditions

The heat transfer phenomena are complex in the heat engine piston. It is assumed that, the heat diffusion between gas and the piston surface is the convection in the temperature analyses[8,9]. A convection heat load includes the radiation effects on the surface of the piston. The heat conduction model is performed in the zone of piston ring land and piston skirt with the following presumptions: (a) the influence of piston displacement on

Table 1. Material properties of piston, piston rings and ceramics

Material	Density (kg/m^3)	Thermal Conductivity (W/m K)	Thermal coefficient of Expansion (10^{-6} K^{-1})	Young's Modulus (G pa)
Piston (aaluminum alloy)	2700	155	21	70
Bond coat (Ni Cr Al)	7870	16.1	12	90
Ceramic coating ($MgZrO_3$)	5600	0.8	8	46
Ceramic coating (YSZ)	5650	1.40	10.9	11.25
Oil rings	7200	25	10	135
Compression rings	7300	46	10	110

the heat transmission is neglected. (b) There is no ring deformation (ring twist) has been permitted during piston motion. (c) Heat transfer due to convection in oil film is neglected. Symmetrical constraints are provided in the axially symmetrical axis and there is no radial displacement[6]. Based on the literature, the average convective heat transfer coefficient and temperature used for the top of the piston crown are 700 $W/m^{2\,0}C$ and 700^0C. It is pretended that the inner temperature of the gas was taken as the mean temperature results on suction, compression, and combustion and gas explusion temperature in the course of engine operation. Hence, the inside temperature was 110^0C with heat transfer coefficient of 1500 $W/m^{2\,0}C$ and other boundary conditions are also taken from literature[8]. Piston lateral surface temperature was 225^0C with a convective heat transfer coefficient of 500 W/m^2 C. The piston ring temperatures are 200^0C, 180^0C, 160^0C for compression rings and 140^0C for oil rings. Piston skirt temperature was 110^0C and heat transfer coefficient of $1500W/m^{2\,0}C$.

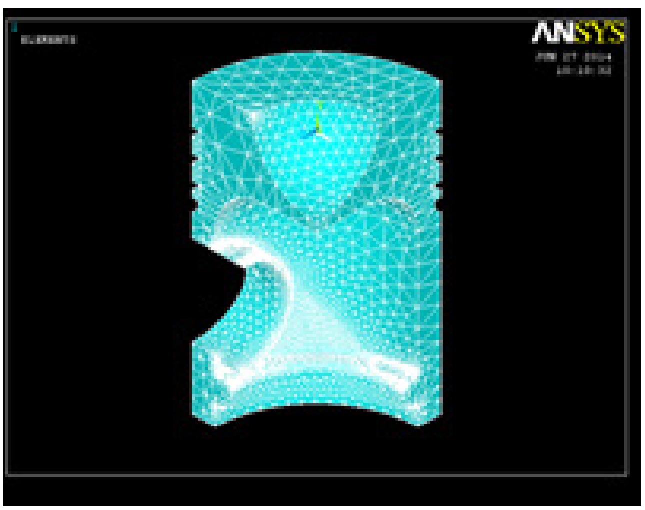

Figure 1. Piston Model.

To study the effect of thermal barrier coating (TBC) of 0.3mm thickness on diesel engine piston, steady state thermal analyses were performed by ANSYS. The engine selected for this analysis is COMET, single cylinder diesel engine with a bore of 76mm and 55mm stroke. The engine rated at 3H.P at 1500revolutions/minute. The geometric compression ratio is 17.5:1.

3. Results and Discussions

The thermal investigations were done to determine the temperature difference of the uncoated aluminum alloy piston and thermal barrier ceramic piston. The thermal variations on uncoated conventional aluminum alloy piston and ceramic coated pistons are shown in Figs. (2, 3& 4).The maximum surface temperature is found as 408.60^0 C at the rim of the uncoated piston bowl. Similarly, the

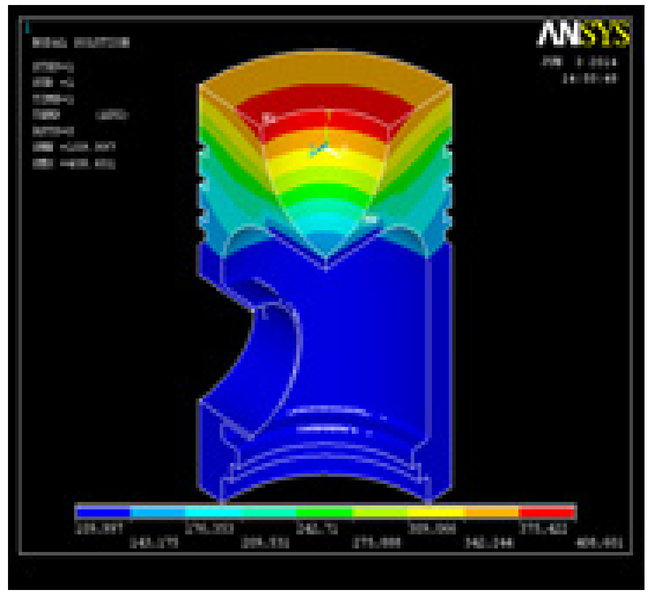

Figure 2. Temperature distribution of conventional aluminum alloy piston.

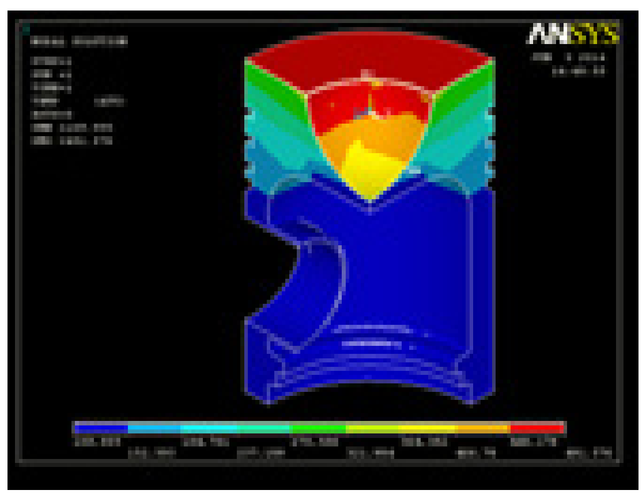

Figure 3. Temperature distribution of YSZ coated piston.

higher temperature of 491.57^0 C and 542.56^0 C were observed at the bowl lip of YSZ coated piston and $MgZrO_3$ coated piston. The temperature varies from the piston fringe to the crown edge due to the fact that the verge of the piston bowl has more heat diffusion area compared to the piston crown edge. The crown surface was laminated with ceramic material; the heat conduction was dropped due to lower thermal conductivity of the ceramic material. The higher surface temperature has been observed with

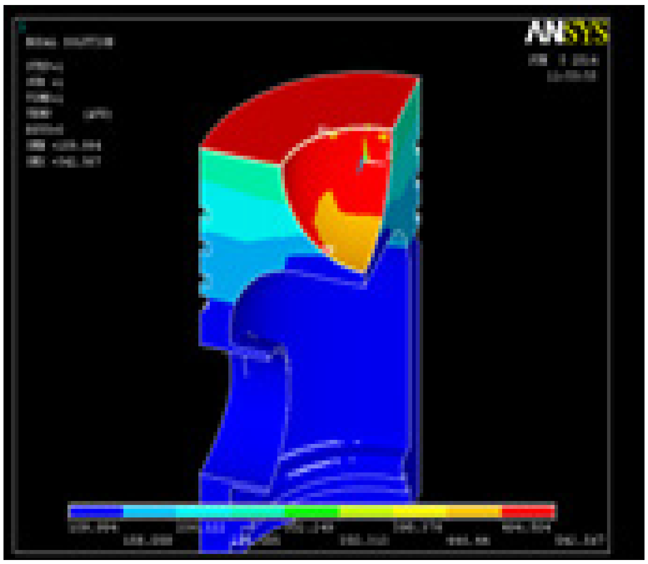

Figure 4. Temperature distribution of MgZrO3 coated piston.

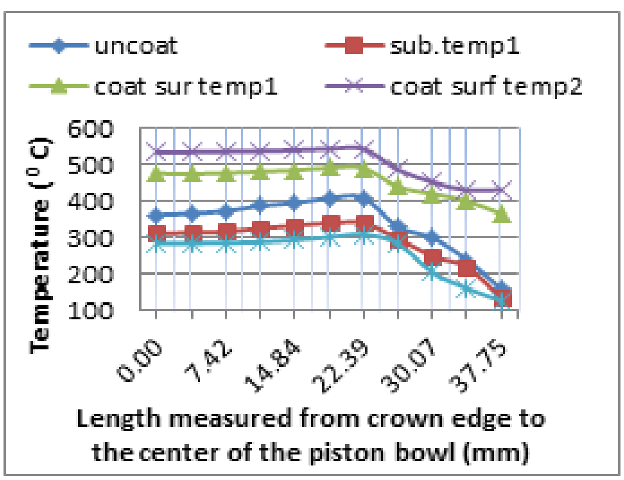

Figure 5. Temperature distributions are plotted against the length along the substrate and coating surface for both coated and uncoated piston.

$MgZrO_3$ coated piston due to lower thermal conductivity and lower thermal expansion coefficient. The temperatures were noticed to be higher at the coated surface of the piston than the metallic surface because the coated surface does not seem to allow any heat transfer into the piston. The variation of surface temperature of coated piston and uncoated piston to the distance measured from crown edge to the piston bowl center were shown in figure (5).The higher exterior temperature of the piston base metal (substrate) of the $MgZrO_3$ coated piston and YSZ coated piston are 310^{0}C and 340^{0}C respectively. The higher temperature of the conventional piston is found to be 410^{0}C at the piston bowl lip. It can be observed that the substrate of the coated piston subjects to less thermal load compared to base metal of the uncoated piston. Similar results were observed in the earlier findings[6].

4. Conclusions

The present investigation indicates that the maximum temperature was reached at the piston combustion bowl fringe and piston crown surface temperature is higher for the material has low thermal conductivity. The superficial temperature of the piston crown coated with $MgZrO_3$ is higher than the piston crown surface temperature of YSZ coated piston and uncoated piston by 32% and 20%. It is clear that as a result of higher combustion temperature by TBC, the decrease of cooling load of the engine system could be achieved and thermal efficiency could also expected to be increased. As an effect of thermal barrier coating, the strength of the base substrate material could be increased. Thus the thermal analyses were performed in coated and uncoated diesel engine piston.

6. References

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Nomenclature

YSZ	Yttria stabilized zirconia
LHR engine.	Low heat rejection engine.
FEA	Finite element Analysis.
TBC	Thermal barrier Coating.
H.P	Horse power
Uncoat	Surface temperature of uncoated piston.
Sub.temp1	Substrate surface temperature of YSZ coated piston.
Sub.temp 2	Substrate surface temperature of $MgZrO_3$ coated piston.
Coat surf temp 1	Surface temperature of YSZ coated piston.
Coat surf temp 2	Surface temperature of $MgZrO_3$ coated piston.
CNSME	Cashew Nut Shell Methyl Ester.