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Coupled Field Analysis of an SI Engine Piston

N Meena Priyanka¹, A Swarna Kumari²

P.G. Student, Department of Mechanical Engineering, JNTU Kakinada, Andhra Pradesh, India¹

Professor, Department of Mechanical Engineering, JNTU Kakinada, Andhra Pradesh, India²

ABSTRACT: The piston in an Internal combustion engine is usually made up of Aluminium alloy because of its low weight, low density and high thermal conductivity. During the combustion process, high temperature will get generated inside the cylinder. Because of this high thermal stress and structural stress will be produced. Due to these the failure of the piston takes place. To avoid the failure of the piston, an attempt is made to reduce the in thermal and structural stress intensities using a layer of Thermal barrier coating materials, like Zirconia and Yttria stabilized zirconia (YSZ) which has low thermal conductivity, high thermal resistance, chemical inertness, high resistance to erosion, corrosion and high strength was selected as a coating material for engine component. The geometric modelling of piston of uncoated and coated are made using CATIA and later imported into ANSYS for analysis. The thermal analysis and structural analysis of various thicknesses of bond, ceramic coated pistons and uncoated piston are analysed and compared. The stresses and total deformations of Uncoated and Coated pistons also compared. From the analysis it was found that stress, deformation and heat flux for the coated piston has better performance than uncoated piston.

KEYWORDS: Combustion, Thermal barrier coatings, Yttria stabilized zirconia, Thermal analysis, Structural analysis, CATIA, ANSYS.

I. INTRODUCTION

The efficiency and energy conservation have always been the quest of engineers concerned with Internal combustion engines. The petrol engine rejects about two thirds of the total heat energy of the fuel, one third to the coolant and one third to the exhaust, leaving only about one third as useful power output[1]. If the heat rejected will be less then the Thermal efficiency would be improved[2]. Ceramics have a higher thermal durability than metals, low thermal conductivity materials can be used to control temperature distribution and heat flow[3]. To reduce the heat rejection to the coolant, Thermal barrier coating materials are used as a coating materials for piston crown. Thermal barrier coatings have been successfully applied to the Internal combustion engine, in particular the engine piston[4].

The objectives are not only to reduce the in-cylinder heat rejection and thermal fatigue protection of underlying metallic surfaces and also to reduce the engine emissions. The application of Thermal barrier coatings reduces heat loss to the engine cooling jacket through the surfaces exposed to the heat transfer areas such as piston rings, cylinder liner. The insulation of piston crown with the ceramic coating affects the combustion process and hence the performance and exhaust emission characteristics of the engine. The normal stress on the coated surface decreases with the coating thickness up to a thickness of 1mm for which the values of stress is the minimum. If the coating thickness exceeds 1mm, the normal stress decreases steadily and the maximum shear stress rises in a decreasing rate. The maximum coating thickness was found to be 1mm[5]. The Thermal barrier coating system consists of a top coat and bond coat. The top coat is a ceramic layer which acts as an insulator and the bond coat as an oxidation resistant metallic layer between the substrate and the top coat[6]. The top coat provides thermal insulation for the underlying substrate. The properties for this coating require a material that combines low thermal conductivity and a coefficient of thermal expansion[7].

The preferred material for this purpose is Zirconia. Zirconia may exists as three phases, which are stable at different temperatures. The temperature up to 1200⁰C it is the monoclinic phase and it is stable. It will transform from monoclinic phase to tetragonal phase above 1200 at which the volume decrease of 4% will takes place. Above 2370⁰ it will transform into cubic phase. By adding 20% yttria to the cubic phase zirconia it can be fully stabilized but fully

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stabilized zirconia coating perform very poorly in thermal cycling tests. By adding 7 to 9% of yttria, zirconia will be partially stabilized. This is known as Yttria partially stabilized zirconia[8]. The application of Thermal barrier coatings on the diesel engine piston head reduces the heat loss to the engine cooling-jacket through the surfaces exposed to the heat transfer such as cylinder head, liner, piston crown and piston rings. It is important to calculate the piston temperature distribution in order to control the thermal stresses and deformations within acceptable levels. As much as 60% of the total engine mechanical power lost is generated by piston ring assembly The thermal analysis of piston is important from different point of views. First, the highest temperature of any point on piston should not exceed 66% of the melting point temperature of the alloy. This limiting temperature for the current engine piston alloy is about 370°C. This temperature level can be increased in ceramic coating diesel engines[9-10].

The temperature distribution over the volume of the piston at steady state after the application of thermal loads are like the maximum temperature occurs at the top of the piston and the minimum temperature occurs at the bottom of the piston[11]. In Internal combustion engines, most of the heat generated during combustion process is absorbed by the piston. This is direct heat loss to the piston and it causes reduction in Indicated power and in turns the performance of Internal combustion engine. Piston coated with a ceramic thermal barrier can be applied to improve reliability and durability of engine performance and efficiency in diesel engines[12]. Ceramic coatings provide potential for higher engine thermal efficiencies, longer life and higher reliability of engine components. Thermal barrier coatings offer the possibility of reducing particulate emissions Thermal barrier coatings decrease the amount of condensable hydrocarbons. Under low load and speed conditions the base engines produces plate like particles, the TBC engine produces smaller spherule particles. ZrO₂ stabilized with Y₂O₃ over NiCrAlY binding layer as a coating material gives good results for aluminium alloyed pistons. As ceramic coating material, ZrO₂ stabilized with Y₂O₃ is expensive for practical usage. Cylinder walls also can be coated to reduce heat rejection[13]. The usage of thin ceramic coatings to improve the Spark ignition engine performance and emission characteristics. Thus a thin ceramic coating applied on the spark ignition engines can be a useful means for improving performance, fuel economy and exhaust emissions. In this research, the coating thickness of 0.15mm was selected as the interface material and the rest of 0.35mm for ceramic material. The experiment was carried out by Plasma spraying technique. The bond coat present in the TBC system protects the underlying substrate from oxidation and improves adhesion between the ceramic and the metal. The oxidation occurs because of oxygen reaching the bond coat by diffusion through the lattice of the top coat and permeation through the pores. In this NiCrAl is used as a bond coat because it is having high oxidation resistance, high corrosion resistance and Yttria stabilized zirconia as top coat which acts as an insulator[14].

II. COMPONENT SPECIFICATION AND MATERIAL PROPERTIES

The piston is modelled in CATIA V5, which is one of the most effective modelling packages. The both uncoated and coated pistons were modelled in CATIA V5. The specifications used for designing the piston are

Diameter	81mm
Stroke	87mm
Height	75mm
Pin diameter	23mm
No.of piston rings	4
Thickness of sealing part	3mm
No.of oil holes	8
Wall thickness of leading part	3mm

Table I Piston specifications

The materials generally used for piston are Cast iron and Aluminium alloy. Cast iron posses high strength and high weight where as Aluminium alloy posses low strength and low weight. Cast iron piston can be used where load is

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the major consideration. The piston having Al alloy is better because of its low weight. But the piston of Al alloy transfers more heat to the components which are near th the piston i.e., piston rings, cylinder etc. In this work, an attempt is made to reduce the heat transfer by using Thermal barrier coating materials which acts as insulator. Initially the piston is modelled with a material of Aluminium alloy and an analysis is done for it using ANSYS. Later the piston is designed with thickness of 0.5mm less in all directions than previous modelled piston. This 0.5mm can be coated with interface material and TBC materials.

Properties of materials:

Material	Thermal conductivity (W/mm ²)	Thermal expansion 10 ⁻⁶ (/°C)	Density (Kg/m ³)	Specific heat (J/Kg ⁰ C)	Poisson's ratio	Young's modulus (GPa)
Al alloy	147	25.9	2770	875	0.33	90
AlSi	155	21	2700	960	0.28	80
NiCrAl	16.1	12	7870	764	0.27	90
YPSZ	1.4	10.9	5650	620	0.25	11.25

Table II Material properties

III. GEOMETRIC MODELLING AND FINITE ELEMENT ANALYSIS

The dimension calculated for the piston according to the procedure and the specification given in the design data book are used for preparing the model using CATIA modelling software. Piston was modelled in CATIA which is shown below.

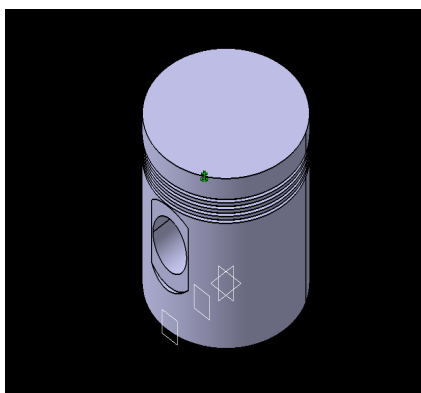


Fig:1 3D model of piston

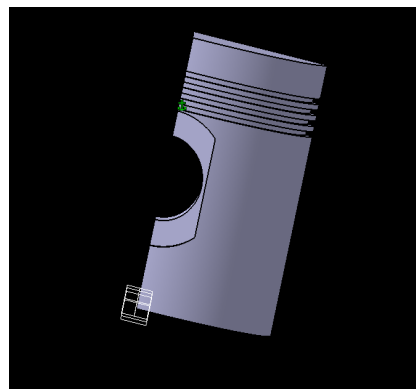


Fig:2 Quarter section of piston

The pistons of uncoated and coated which are designed in CATIA are imported into ANSYS for analysis. The coated piston is modelled with different coating thicknesses of bond coat and ceramic coat as 0.15mm, 0.25mm,

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0.35mm etc. Later bond coat is fixed as 0.15mm and ceramic coat values are taken as 0.15mm, 0.25mm and 0.35mm.

The model imported into ANSYS is meshed using Hex-dominant method. The uncoated piston contains number of nodes as 60285, elements as 15839 and coated piston contains nodes as 168202 and elements as 52811.

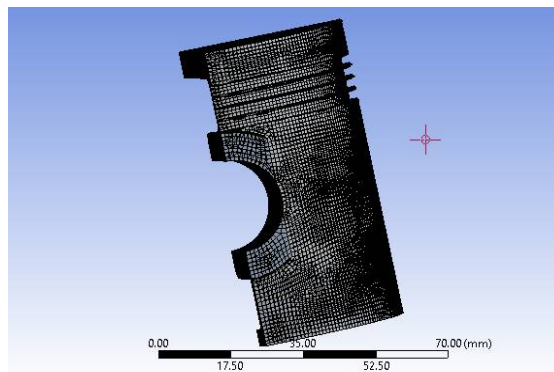


Fig:3 Meshed model of piston

Combustion of gases in the combustion chamber generates high temperatures and it exerts on the head of the piston crown. The convection values are taken as boundary conditions in thermal analysis using ANSYS workbench. Piston thermal boundary conditions consists of the combustion side thermal boundary condition, upper ring land, lower ring land, skirt and underside thermal boundary conditions.

The inner temperature was estimated to be 650⁰C with a convection coefficient of 800W/m²K. The upper ring land temperature of the piston was specified as 300⁰C with a convection coefficient of 230W/m²K. The lower ring land temperature of the piston is defined as 110⁰C with a convection coefficient of 200W/m²K. The piston skirt, inside surface and piston pin temperatures are defined as 85⁰C with convection coefficient of 60W/m²K.

After giving the thermal boundary conditions, solve the analysis. Here the results are Temperature, Total heat flux and Directional heat flux. Later this thermal solution setup is transferred to static-structural.

Combustion of gases in the combustion chamber exerts pressure on the head of the piston during power stroke. The pressure force will be taken as boundary condition in structural analysis using ANSYS workbench. Cylindrical support has given at surface of pin hole because the piston will move from Top dead centre to bottom dead centre with the help of fixed support at pin hole. So whatever the load is applying on the piston due to gas explosion causes the failure of piston pin including bending stresses.

To get the Maximum gas pressure P,

$$t_H = \sqrt{\frac{3PD^2}{16\sigma_t}}$$

Where P - Maximum gas pressure

D - outside diameter of the piston

σ_t - Permissible bending stress for piston material

For Al alloy $\sigma_t = 50$ to 90 MPa

t_H . thickness of piston head = 7mm

From this the Maximum gas pressure = 3.5N/mm²

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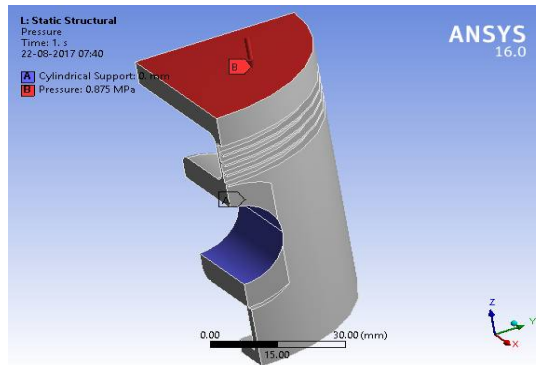


Fig:4 Boundary conditions

IV. RESULTS AND DISCUSSION

Thermal and structural analysis is being performed on these pistons i.e. the piston of Aluminium alloy, piston coated with different thicknesses of bond coat as NiCrAl and ceramic coat as Ytria stabilized zirconia. The structural and thermal analysis of both uncoated and coated pistons are done in ANSYS. From the Coupled field analysis of uncoated and coated piston, temperature, total heat flux, stress, total deformation, directional deformation and maximum principal stress values are determined.

Results obtained using different thicknesses of bond coat and ceramic coat.

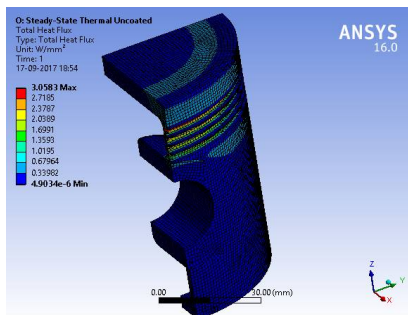


Fig:5 Heat distribution with uncoated piston

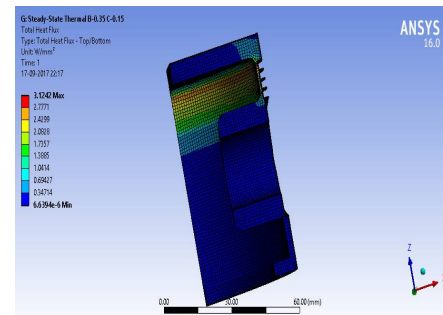


Fig:6 Heat distribution with coated piston

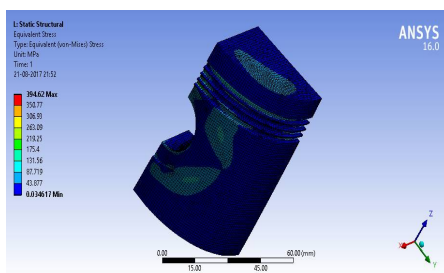


Fig:7 Stress distribution of uncoated piston

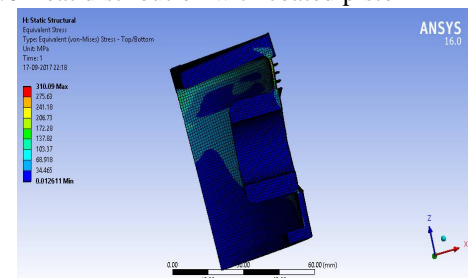


Fig:8 Stress distribution of coated piston

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Fig 5 shows the Heat distribution with uncoated piston. It was shown that the total heat flux value decreases from top to the bottom of the piston. The total heat flux found at the top of the piston is 3.0583W/mm^2 and at the minimum value is $4.9034\text{e}^{-6}\text{W/mm}^2$. Fig 6 shows the heat distribution with coated piston. In this the maximum heat flux value is 3.2398W/mm^2 and the minimum value is $6.639\text{e}^{-6}\text{W/mm}^2$.

Fig 7 shows the stress distribution of uncoated piston. The maximum stress occurs at first piston ring and it was found as 394.62MPa . The minimum stress value was found as 0.03416MPa . Fig 8 shows the stress distribution of coated piston. The maximum stress occurs at first piston ring and it was found as 310.09MPa . The minimum stress value was found as 0.0126MPa .

The Directional deformation for uncoated piston was found as 1.4264mm and for coated piston as 1.0297mm . The result indicates that the coated piston will have lesser deformations. Maximum principal stress for uncoated piston was found as 158.52MPa and for the piston coated with thermal barrier coating was found as 111.31MPa . The piston with ceramic coating has less amount of maximum principal stress than uncoated piston.

Type of coat (mm)	Temperature (°C)	Total heat flux (W/mm ²)	Directional deformation (mm)	Equivalent stress (MPa)	Total deformation (mm)	Max principal stress (MPa)
B-0.15 C-0.35	340.3	3.2398	1.0974	321.33.	0.50443	120.3
B-0.25 C-0.25	340.04	3.154	1.0604	314.4	0.48982	112.36
B-0.3 C-0.2	339.91	3.139	1.0448	312.15	0.4848	111.72
B-0.35 C-0.15	339.78	3.1242	1.0297	310.09	0.48075	111.31
Uncoated	340.71	3.0583	1.4264	394.62	0.67292	158.52

Table III Results obtained using different thicknesses of bond coat and ceramic coat.

Now fix the bond coat as 0.15mm and change the ceramic coat as 0.15mm , 0.25mm and 0.35mm . Analysis is done to the coated pistons of same bond coat thickness and different coating thicknesses. The results obtained are

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Type of coat (mm)	Temperature (°C)	Total heat flux (W/mm ²)	Directional deformation (mm)	Equivalent stress (MPa)	Total deformation (mm)	Max principal stress (MPa)
B-0.15 C-0.15	340.33	3.2445	0.36159	328.69	0.51974	117.14
B-0.15 C-0.25	340.31	3.2425	0.3614	323.85	0.5112	117.98
B-0.15 C-0.35	340.3	3.2398	0.36088	321.33	0.50443	120.3
Uncoated	340.71	3.0583	1.4264	394.62	0.67292	158.52

Table IV Results obtained using fixed bond coat and different ceramic coat thicknesses

The total heat flux found at the top of uncoated piston is 3.0583W/mm² and for coated piston the maximum heat flux value is 3.2445W/mm². The maximum stress occurs at first piston ring and it was found as 394.62MPa for uncoated piston. The maximum stress occurs at first piston ring and it was found as 328.69MPa.

The Directional deformation for uncoated piston was found as 1.4264mm and for coated piston as 0.36159mm. The result indicates that the coated piston will have lesser deformations. Maximum principal stress for uncoated piston was found as 158.52MPa and for the piston coated with thermal barrier coating was found as 117.14MPa. The piston with ceramic coating has less amount of maximum principal stress than uncoated piston.

V. CONCLUSIONS

In thermal analysis, Total heat flux gradient is maximum near the piston crown and piston ring areas for all the types of pistons. Highest Heat flux of 3.2398W/mm² is found on the piston of AlSi piston coated with bond coat of 0.15mm and ceramic coat of 0.35mm. Highest temperature of around 340.3°C is found on the top of the piston. Temperature distribution is uniform throughout the piston. AlSi piston coated with bond coat of 0.15mm and ceramic coat of 0.35mm gave better temperature distribution compared to other types of pistons. In structural analysis pressure of 0.875MPa is applied on the piston head (quarter portion of the piston) and fixed supports are attached at the piston pin areas. Total deformation, Equivalent stress, Maximum principal stress and Elastic strain are determined. Coated piston with bond coat of 0.35mm and ceramic coat of 0.15mm recorded the lowest deformation of 0.48075mm. Lowest stress values are recorded for Ceramic coated piston of bond coat of 0.35mm and ceramic coat of 0.15mm. Maximum principal stress values also less for Ceramic coated piston of bond coat of 0.35mm and ceramic coat of 0.15mm. By analyzing the above results, piston of AlSi coated with bond coat of 0.35mm and ceramic coat of 0.15mm showed better results compared to piston made up of Aluminium alloy.

By verifying the above results piston coated with thermal barrier coating material i.e coated with yttria stabilized zirconia attained high amount of Total heat flux, less Equivalent stress, less amount of Maximum principal stress and less deformations compared to the uncoated piston.

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REFERENCES

- [1] J.Rajasekharan, B.M.Gnanasekharan, "Effect of thermal barrier coating for the improvement of SI engine performance & emission characteristics" (2013)
- [2] C Ramesh kumar and G Nagarajan, "performance and emission characteristics of a low heat rejection spark ignited engine fuelled with E20" (2011)
- [3] Durga raghu ram Pendyala, Karthik V M, Puviyarasan M, "Analysis of effect of thermal barrier coating materials on efficiency of IC engines using 3D Finite element method" (2014)
- [4] Mesut Durat and Murat kapsiz, "the effects of coating materials in spark ignition engine design" (2011)
- [5] Muhammet cerit, "Thermo mechanical analysis of a partially ceramic coated piston used in an SI engine" (2010)
- [6] M Cerit, V Ayhan, A Parlak and H Yasar, "Thermal analysis of a partially ceramic coated piston: effect on cold start HC emission in a spark ignition engine" (2010)
- [7] Vinod kumar yadav and yogesh mishra, "Design and Structural Analysis of Ceramic Coated Petrol Engine Piston Using Finite Element Method" (2015)
- [8] Siew hwa chan, "Performance and emissions characteristics of a partially insulated gasoline engine" (2000)
- [9] K. Sridhar, R. Reji Kumar, M. Narasimha " Thermal barrier analysis in diesel" (2013)
- [10] Ekrem buyukkaya, Muhammet cerit, " Effects of ceramic coating over diesel engine piston using 3D finite element method" (2007)
- [11] R.Silambarasan and S.Balakrishnan, "Design and thermal analysis of partial ceramic coated piston of spark ignition engine" (2015)
- [12] S.Satya murthi and M.Prabhakaran, "Numerical investigation of ceramic coating on piston crown using Finite element analysis" (2016)
- [13] K. Thiruselvam, "Thermal barrier coatings in internal combustion engine" (2002)
- [14] Mesut durat, Murat kapsiz, Ergul mart, Ferit fecici and Adnan parlak, "The effects of coating materials in spark ignition engine design" (2011)