Design and Coupled Field Analysis of Ceramic Coated Petrol Engine Piston

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ABSTRACT – *Piston is the a crucial part of an ic engine as its responsible for converting the chemical energy in to a mechanical energy. The mechanical efficiency of the piston is dependent on how conveniently and effortlessly does the piston transfer the energy. As piston bares both high level of thermal as well as mechanical stresses, it is important to learn about the allowable limits of the material used to make the piston. This work is an attempt to determine whether it is possible to reduce the thermal stresses on the piston and thus improving its life expectancy. The ultimate success of an ceramic engine would be eliminating the cooling systems and hence decreasing the cost of the engine. The objective is to create a coating of appropriate thickness and subject it to thermal and structural loads and the study the variations obtained on a coated pistons compared to an uncoated piston. SOLIDWORKS software is used to model the components and the analysis is done using ANSYS software. The results obtained and used to determine whether the ceramic material under investigation is fit for the purpose or not.*

Index Terms: Piston, Coating, Ceramic, Analysis, thermal stress, structural loads

I. INTRODUCTION

The innovative studies and research will continue as long as there is a scope to improve the performance and cost of an ic engine. Ceramic engine is one among such ambitious studies. These innovative studies have been continuing and now a days there is a rapid increase in the study of ceramic engines for converting the fuel energy into the mechanical energy at the most possible rate by coating the internal combustion chambers with the low heat conducting materials, there is a rapid increase in the temperature and pressure in the internal combustion chamber, so the efficiency of the engine should be increased.

By using the ceramics there is a possibility of removing the cooling systems. This happens when the ceramic coating applied to the internal chamber are aimed to reduce heat which passes from the in-cylinder to the engine cooling system, so that the cooling system can be removed. If the deletion of the cooling system takes place, then there will be increase in the engine efficiency, the cost of engine is also being reduced.

If the engines are coated with the heat resistant materials then it would increase the temperature and pressure inside the combustion chamber and thus it would become easy to ignite the charge during a power stroke of the engine. This would eliminate the problems caused by thermal stresses on the components of the materials as they all are shielded by ceramic coating like a cap over head on a scorching afternoon.

A. Ceramic Engines

Ceramic are known for its high temperature resisting properties. A ceramic engine is an ambitious project to use these materials to reduce damages caused by thermal stresses on the engine components. This should increase performance, decrease fuel consumption and reduce pollution. This should also enable various fuels to be used (i.e. multi-fuel capability).

B. Ceramic Coating of Automotive Components

With the evolution of technology and our knowledge of materials a wide varieties of materials have been used to improve the output of automotive components. Using ceramic coating we expect to regulate the temperature variations in and out of the components. Regulating these temperature fluctuations among both internal and external engine parts can improve horsepower and performance characteristics, leading to more efficient vehicle operation. Ceramic coatings are increasingly used to provide protection between different engine parts, helping to increase wear resistance, reduce friction, and improve heat shielding. These factors have a significant influence on horsepower ratings, and augmenting them through ceramic coating can often enhance an automobile's performance.

C. Applying a Ceramic Coating

Before a ceramic coating is applied to an automotive component, the component's surface is typically treated with a smoothing agent or sandblasting in order to remove the uneven outer surface and any contaminants that may have accumulated. After the clean bottom layer is revealed, the part is often heated in an oven to reduce its molecular porosity. Without this treatment, any contaminants remaining after the initial stage may be brought to the surface, forcing the coating layer to detach from the substrate.

D. Characterization of Material

The material chosen for this work is Al 2618 as base material for a combustion engine piston. The relevant mechanical and thermal properties of Al 2618 aluminum alloys are listed in the below table.

Table I: Material properties of Aluminium (Al 2618) alloy

S.No	Parameter	Al	Units
1	Elastic Modulus	74	GPa
2	Ultimate Tensile Strength	420	MPa
3	Yield strength	310	MPa
4	Poison's ratio	0.33	-
5	Thermal conductivity	160	W/mK
6	Coefficient of thermal	22	1) µm/mk
7	Density	3	g/cc

E. Cordierite $(Mg,Fe)_2Al_3(Si_5AlO_{18})$ Properties

Cordierite is magnesium iron aluminium cyclosilicates. This is mainly a structural ceramic, often used for kiln furniture due to its extremely good thermal shock resistance. Like other structural ceramic materials, it also has good thermal and electrical insulating capabilities.

Table II: Material properties of cordierite

S.No	Parameter	cordierite	Units
1	Thermal	3.0	W/m-K
2	Thermal expansion	1.7	1/ ⁰C
3	Density	2.6	g/cc
4	Poison's ratio	0.21	_
5	Young's modulus	70	GPa

II. PROBLEM FORMULATION

The main objective is to investigate and analyze the structural and thermal stress distribution of the piston at a combustion process. The analysis is carried out to reduce the stress concentration on the upper end of the piston i.e. Piston head/crown and piston skirt and sleeve using ANSYS software. In this paper the material Al 2618 (uncoated piston) is replaced with coated piston. Analytical calculation is done to finalize the dimension and check the strength of piston. Piston model is created in SOLIDWORKS using the calculated analytical dimension. Analysis of both the uncoated and coated piston is performed using the software namely ANSYS 16. After analysis comparisons is made between the uncoated piston and coated piston in terms of total deformation, equivalent stress, and total strain.

III. ANALYTICAL DESIGN

IP = indicated power produced inside the cylinder (W)
η = mechanical efficiency = 0.8
n = number of working stroke per minute = N/2 (for four stroke engine)
N = engine speed (rpm)
L = length of stroke (mm)
A = crosssection area of cylinder (mm2)
r = crank radius (mm)
l_c = length of connecting rod (mm)
a = acceleration of the reciprocating part (m/s2)
m_p = mass of the piston (Kg)
V = volume of the piston (mm3)
th = thickness of piston head (mm)
D = cylinder bore (mm)
p_{max} = maximum gas pressure or explosion pressure (MPa)
σ_t = allowable tensile strength (MPa)
σ_{ut} = ultimate tensile strength (MPa)
F.O.S = Factor of Safety = 3
K = thermal conductivity (W/m K)
T_c = Temperature at the centre of the piston head (K)
T_e = Temperature at the edge of the piston head (K)
HCV = Higher Calorific Value of fuel (KJ/Kg) = 47000 KJ/Kg
BP = brake power of the engine per cylinder (KW)
m = mass of fuel used per brake power per second (Kg/KWs)
C = ratio of heat absorbed by the piston to the total heat developed in the cylinder = 5% or 0.05
b = radial width of ring (mm)
P_w = Allowable radial pressure on cylinder wall, (N/mm2) = 0.025 MPa,
σ_p = permissible tensile strength for ring material (N/mm2) = 1110 N/mm2
h = axial thickness of piston ring (mm)
h_1 = width of top lands (mm)
h_2 = width of ring lands (mm)
t_1 = thickness of piston barrel at the top end (mm)

t_2 = thickness of piston barrel at the open end (mm)
L_s = length of skirt (mm)
μ = coefficient of friction (0.01)
L_1 = length of piston pin in the bush of the small end of the connecting rod (mm)
d_o= outer diameter of piston pin (mm).

A. DETERMINATION OF DIMENSIONS OF PISTON

Number of cylinder = Single cylinder
Bore = 51mm
Stoke = 48.8mm
Piston displacement = 99.27cc
Length of connecting rod = 97.6mm
Compression Ratio = 8.4
Fuel consumption = 87Kmpl

Performance:
Maximum power = 6.03kw @ 7500 rpm
Maximum Torque = 8.05Nm @ 5500 rpm
Mechanical efficiency of the engine (η) = 80 %
η = Brake power (BP) /Indicating power (IP)
I.P = B.P/ η = 6.02/0.8= 7.52 kW
Indicative power, IP = P×A×L×N/2= P× (π×D²/4) ×L× (N/2)
7.52 × 1000 = P × (π × (0.051)2/4) × 0.0488 × (7500/(2x60))
7520 = P × 0.006227
P = 7520/0.006227
P = 12.08 × 105 N/m² = 1.208 MPa
Maximum pressure, p_{max}= 10 × P = 10 × 1.208= 12.08 MPa

Properties:
Density=2.68g/cc
Ultimate Tensile Strength=317MPa
Yield Strength=165MPa
Young's Modulus = 71.0 GPa
Thermal Conductivity=113w/mk
Coefficient of Thermal Expansion=25.9×10^{-6}/°C
Let FOS=3
Thickness of the Piston head:
$t_H= \sqrt{}\ (3\times P\times D^2)\ /16\times\sigma_t$ or $t_H= \sqrt{}\ (3\times P\times D^2)\ /16\times (\sigma_{ut}/FOS)$ = 7.47 mm
Radial thickness of rings:
$t_1 = D \sqrt{}\ 3\times p_w/\ \sigma_p= 51\times\sqrt{3} \times 0.025/105.66 = 1.36$mm
Axial thickness of the piston:
$t_2 = 0.7t_1= 0.7\times1.36 = 0.95$ mm
Width of the top land (b_1):
$b_1 = t_H$ to $1.2\times t_H$= 7.47 mm (consider $b_1 = t_H$)
Width of other lands (b_2):
$b_2 = 0.75\ t_2$ to t_2=0.75 × 0.95= 0.7125 mm (consider b_2=0.75t_2)
Thick of piston barrel at the top end:
$t_3 = 0.03D+t_1+4.9= 0.03 \times 51+1.36+4.9 = 7.73$ mm
Thick of piston barrel at the open end:
t_4= 0.25 t_3 to 0.35 t_3= 0.25 × 7.73= 1.93 mm
Length of skirt:
L_s = 0.6 D to 0.8D= 0.6 × 51= 30.6 mm
Length of piston pin in the connecting rod bushing:
L_1= 45% of the piston diameter = 0.45 × 51= 22.95 mm
Piston pin diameter:
d_0 = 0.28 D to 0.38 D= 0.28 × 51= 14.28 mm

Table III: Final Dimension of piston

S.No	Description	Nomenclatu	Value in mm
1	Thickness of piston head	T_H	7.47
2	Radial width of the ring	t_1	1.36
3	Axial thickness of the piston	t_2	0.95
4	Width of top land	b_1	7.47
5	Width of ring land	b_2	0.7125
6	Thickness of piston barrel at the top end	t_3	7.73
7	Thickness of piston barrel at the open end	t_4	1.93
8	Length of skirt	L_s	30.6
9	Length of piston pin in the connecting rod bushing	L_1	22.95
10	Piston pin diameter	d_o	14.28

IV. GEOMETRICAL MODELING AND FINITE ELEMENT ANALYSIS

A. MODELING:

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 SOLIDWORKS software.

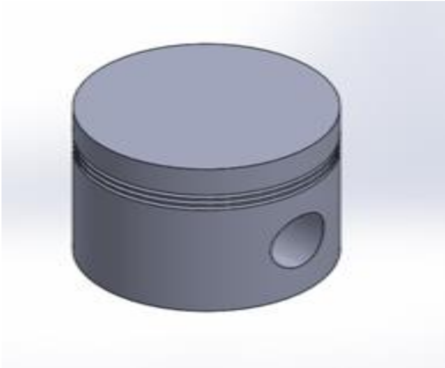

Fig 4.1: Isometric view of piston

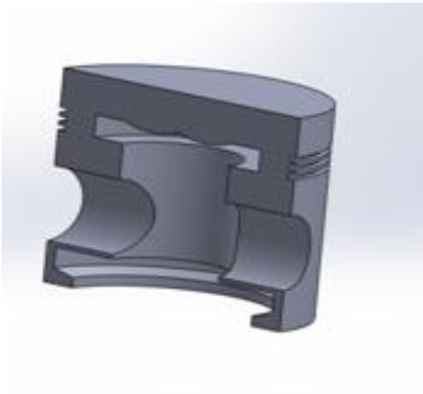

Fig 4.2: Sectional view of piston

B. MESHING OF 3D MODEL OF PISTON

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

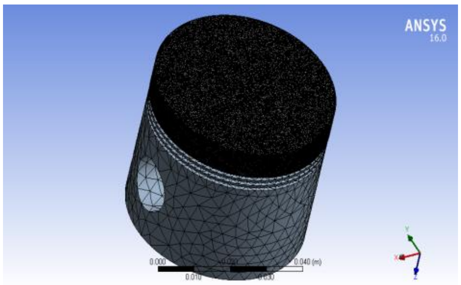

Fig 4.3: meshed image from ANSYS

C. BOUNDARY CONDITION FOR STRUCTURE ANALYSIS (UNCOATED AND COATED PISTON)

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 work bench. Fixed support has given at surface of the pin hole because the piston will move from Top dead center (TDC) to Bottom dead center (BDC) with the help of fixed support at pin hole. So whatever the load is applying on the pistons due to gas explosion causes the failure of piston pin including bending stresses. As per analytical calculation pressure acting on the piston due to combustion is 12.08 MPa.

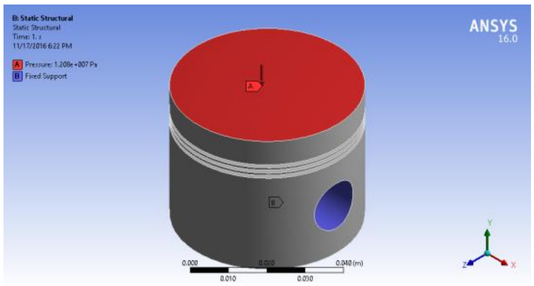

Fig 4.4: Boundary conditions for structural analysis

D. BOUNDARY CONDITION FOR STRUCTURAL ANALYSIS UNDER COUPLED FIELD (UNCOATED AND COATED PISTON)

Temperature distribution, loading and Boundary condition for uncoated and coated piston. Figure 4.5 shows the temperature distribution, loading and the boundary condition considered for the analysis. The temperature distribution at piston head, top land, piston ring area and piston skirt according to table 4.1 is applied for thermal analysis and the uniform pressure is applied on crown of piston which is indicated by red color and the model is constrained on upper half of piston pin hole as shown by violet color. The cordierite coating is 0.00175mm thick.

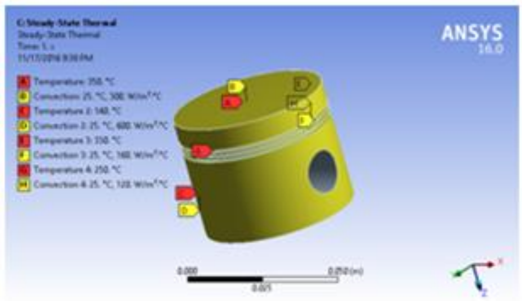

Fig 4.5: Temperature and convection coefficient distribution

Table IV: Temperature and heat transfer coefficient applied to the piston

S.No	Piston Region	Temperature in ^{0}C	Heat Transfer Coefficient(W/ m^{2}K)
1	Piston Head	350	300
2	Width of Top Land	330	160
3	Piston Ring Area	250	120
4	Piston Skirt Land	140	600

E. STRESS, STRAIN DISTRIBUTION &TOTAL DEFORMATION OF UNCOATED PISTON UNDER COUPLED FIELD ANALYSIS

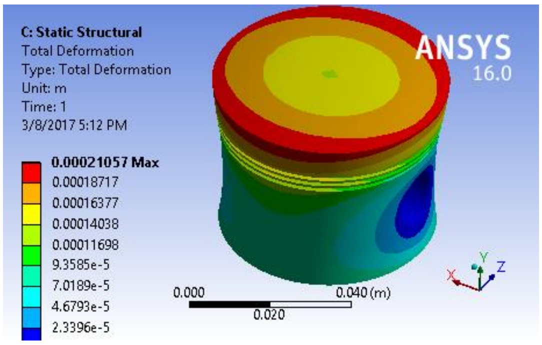

Fig 4.6: Total deformation of uncoated piston

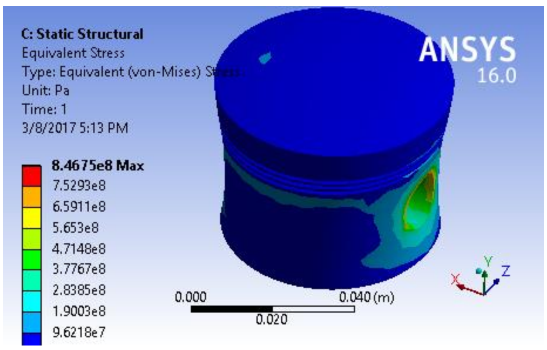

Fig 4.7: Von-Mises stress of uncoated piston

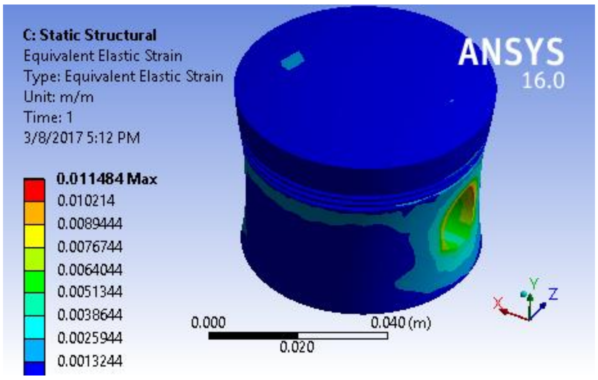

Fig 4.8: Elastic strain of uncoated piston

F. STRESS, STRAIN DISTRIBUTION &TOTAL DEFORMATION OF COATED PISTON UNDER COUPLED FIELD ANALYSIS

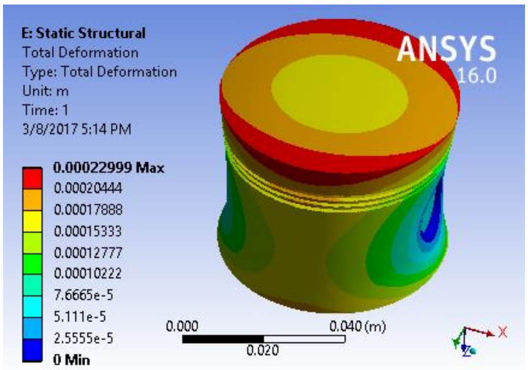

Fig 4.9: Total deformation of coated piston

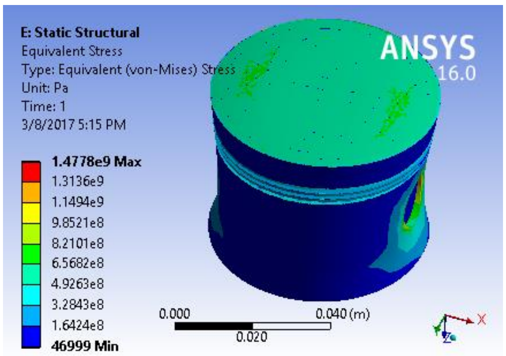

Fig 4.10: Von-Mises Stress of coated piston

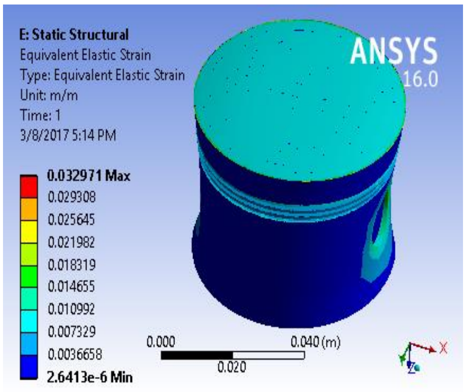

Fig 4.11: Elastic Strain of coated piston

G. TEMPERATURE VARIATION BETWEEN COATED AND UNCOATED PISTON

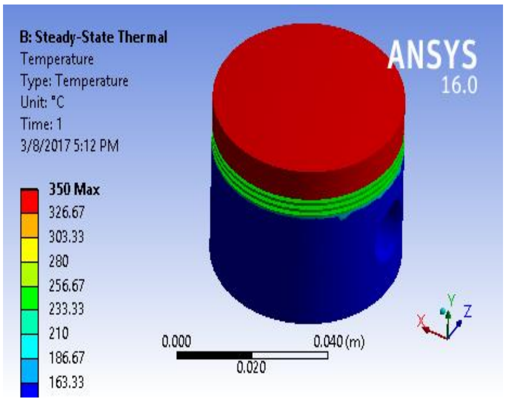

Fig 4.12: Temperature in uncoated piston

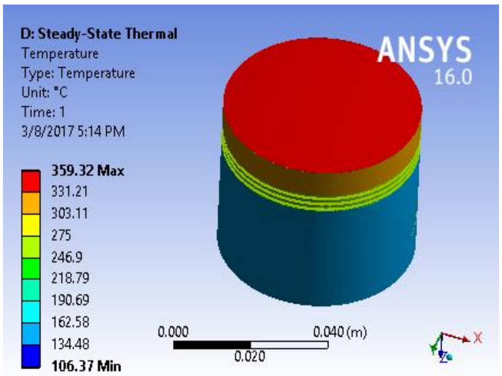

Fig 4.13: Temperature in coated piston

V. RESULTS

Table V: Comparison of results for Coated and Uncoated Pistons

Results	Coated Piston	UnCoated Piston
Von-mises stress (pa)	1.47 e9	8.46 e8
Elastic strain	0.0329	0.01148
Deformation(mm	0.00023	0.00021
Temperature (^{0}c)	359.32	350

VI. CONCLUSIONS

The results cleary show that cordierite is not fit for the purpose of ceramic coating. It causing more harm to the piston the difference between the stress and strain values are unacceptable there only slight difference between deformation Combined CAD and ANSYS, get the results of stress and deformation and temperature when the piston under the mechanical loads, thermal loads and assembly the mechanical and thermal load. And get the discussion as below:

1. The temperature is higher at the combustion chamber side of the deviation from the center of the piston. Highest temperature appears in the throat of the exhaust port of the combustion chamber adjacent side, the temperature reached 350°C. The temperature of the piston ring area is extremely important for the reliability of the engine, if the temperature of the ring zone is too high, it will make the lubrication oil to be deterioration even carbonization. It causes the piston ring bonded, loss of activity to make the piston rapid wear, deformation.
2. The stress under the mechanical action, the maximum stress value is more than that of the coasted piston but the min stress value is drastically decreased and the colored indication of the results shows that maximum stress on the uncoated piston is near the gudgeon pin whereas in coated piston, it distributed over the crown.
3. When under the assembly of mechanical and thermal loads, the value of the largest displacement is 0.2mm, causing at the edges of the piston top. The stress of the top of the piston is mainly

caused by the temperature load and the deformation of the piston is caused by the thermal expansion

VII. FUTURE SCOPE OF WORK

Further more research is required to select the base material and coating material which has less weight and higher strength with high thermal coefficient of thermal expansion.

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BIOGRAPHIES

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