THERMAL ANALYSIS OF YZTP COATED PISTON CROWN

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ABSTRACT

Conventionally, the small portion of the total energy produced in internal combustion engine is converted to useful work. More than half of this energy is expelled from the system through frictional losses, cooling the engine components, exhaust, etc. The most effective way of increasing the percentage of useful work is to reduce the energy loss. One way of reducing the energy loss or increasing the efficiency of the engine is by using thermal barrier coatings (TBC) on the various elements of the combustion chamber like valves, piston, cylinder surfaces, and rings. For this design we add varying thickness ranging up to 1000 micrometers of metallic material to grey cast iron alloy pistons. The ceramic material used is yttria stabilized zirconia. The thermal and static analysis is performed on aluminium alloy pistons coated with the thickness 300,500,700 micrometers for all the different materials. After performing the complete analysis we compare heat flux of the coated pistons to that of non coated pistons.

Keywords: yttria stabilized zirconia coating, heat flux, coating thickness, stress and strain, temperature.

1. INTRODUCTION

In recent years the world is coming across many various devastation but the major concern is about global warming. The main cause of global warming is air pollution, which is caused due to release of harmful pollutants such as nitrogen oxides, carbon oxides, hydrocarbon etc. NO_x is the main pollutant which is released due to incomplete combustion of fossil fuels. Automobiles constitutes of around one-third of the air pollution.

Air pollution caused by these automobiles is mostly due incomplete combustion of the fuels which tends to release carbon monoxide and nitrogen oxides, which is undesirable for mankind. One of the ways to control the pollution is complete burning of the fuel. This feat can be executed by having a metallic coating the piston head with high thermal conductivity so that the heat of the previous combustion is conducted around surface quickly. With this fuel injected is burnt completely.

Internal Combustion(IC) engine is a main part of Automobile design, whose efficiency and performance depends on the amount of heat produced due to combustion of the fuel in the engine. An IC Engine is that kind of prime mover that converts chemical energy to mechanical energy. The fuel on burning changes into gas which impinges on the piston and pushes it to cause reciprocating motion. The reciprocating motion of the piston is then converted into rotary motion of the crankshaft with the help of connecting rod. The purpose of IC engine is to transfer force from expanding gas in the cylinder to the crankshaft via a piston rod. Piston is subjected to the cyclic gas pressure and the inertial forces, causing fatigue damage, side wear, head cracks etc. Thus, it must possess good strength to resist gas pressure, minimum weight to reduce inertia, reciprocate with minimum noise, sufficient bearing area to prevent wear, disperse the heat generated during combustion and good resistance to distortion under heavy forces and heavy temperature. In most of existing piston some amount of heat is transferred through piston surface, which results in decrease in engine efficiency. This can be reduced to some extent by coating the piston with proper material. Thermal Barrier Coatings, as the name suggests are coatings which provide a barrier to the flow of heat. Thermal Barrier Coatings (TBC) performs the important function of insulating components such as gas turbine and aero engine parts operating at elevated temperatures.TBC are layer systems deposited on thermally highly loaded metallic components.

Piston coating is the process of coating a layer of desired material on piston head which will affect the performance of the engine. There are different kinds of surface coating processes such as cathodic arc deposition, ion plating, electroplating, spray coating, etc., but the mainly used technique is plasma transferred wire arc thermal spraying. It is process of spraying the hot metal powder on the surface.

Coated pistons have many advantages compared to the uncoated pistons, some of them are :

- Thermal Barrier protection of piston.
- Increasing in overall operating temperatures.
- Increases in performance.
- Increase in volumetric efficiency and thermal efficiency.
- Reduction of fuel consumption.

2. LITTERARY SURVEY

The work on performance of TBC on various piston materials, as seen in the literature, is shown in table 1. They have shown simulated results using finite elements method based software as ANSYS, in majority. It can be seen that almost all studies are done on diesel engine and many of them done on piston material as aluminium alloys. The main material in composition of TBC are seen to be NiCrAl [1,2,3,5,9,11] and YSZ(Yttria stabilized zirconia) [1,5,7,8,10] followed by others which are mullite, alumina, zirconium etc. The major performance measures studied by various authors are temperature distribution, deformation, thermal stresses, fuel and brake thermal efficiency. The temperature distribution in piston is crucial parameter influencing the thermal stresses and deformation. The thermal insulation thus obtained is supposed to lead, to an improvement in the engine's heat efficiency and a reduction in fuel consumption. The thickness of coating applied ranges from 0.1to 0.8 mm.

3. MATERIALS

3.1 YTTRIA STABILIZED ZIRCONIA

Yttria Stabilized Zirconia is the strongest ceramic material. This material offers the highest flexural strength of all Zirconia based materials, they exhibits a trait called transformation toughening which allows it to resist crack propagation. Applied stress, magnified by the stress, magnified by stress concentration at crack tip, can cause the tetragonal phase to convert to monoclinic, with the associated volume expansion. Materials related to YTZP include calcia-, magnesia-, ceria- or alumina-stabilized zirconias.

3.2 STEEL

Steel is an alloy of iron and carbon and other elements. Because of its high tensile strength and low cost, it is a major component used in buildings, infrastructure, tools, ships, automobiles, machines and weapons. Iron is the base metal of steel. Iron is able to take on two crystalline forms. The density of steel varies based on the alloying constituents but usually ranges between 7,750 and 8,050 kg/m^3.

4. MODELING AND ANALYSIS

Table 1: ENGINE SPECIFICATIONS:

BORE	70mm
STROKE	66.7mm
INDICATED POWER	5Hp
SPARK IGNITION TIMING	25 BTDC
SPEED	3000rpm
COMPRESSION RATIO	3:1 to 9:1
SPECIFIC FUEL CONSUMPTION	475 gm/kWh
LUBRICATING OIL	SAE-40

MAKE	Greaves Limited

Experiment was conducted on the engine of four- stroke, single cylinder, variable compression ratio (3:1–9:1) and variable spark timing (250 to 280 BTDC), water-cooled, SI engine with a maximum power of 2.2 kW coupled with eddy current dynamometer.
Maximum pressure of an S.I engine = $5N/mm^2$
Mechanical efficiency = 80%

4.1 DESIGNING OF PISTON

Indicated Power,
I.P = 5 Hp = 5*745.6KW = 3.728 KW

Thickness of piston head on basis of strength,

$t_H = D\sqrt{\frac{3 \times P_{max}}{16 \times \sigma_t}}$ = 70*√(3*5)/(16*100) = 7.14mm

Number of working strokes for minute = n

N = N/2 = 3000/2 =1500 r.p.m

Area of cross-section,

$A = \pi r^2 = \pi * (35)^2 = 3848.45\ mm^2$

Brake Horse Power,

B.P = I.P * η = 3.728 * 0.8 = 2982.8 KW

Thickness of ribs = $t_h/3$ or $t_h/2$

t_r = 3 mm

Radial thickness of piston rings,

$t_1 = D\sqrt{3p_w/\sigma}$ = 2.23 mm

Axial thickness of piston rings,

$t_2 = 0.7t_1$ to t_1 = 1.78 mm

Width of the top land,

$b_1 = t_h$ to $1.2\ t_h$ = 7.85 mm

Width of ring land,

$b_2 = 0.75t_2$ to t_2 = 1.42 mm

Thickness of Barrel at the top end,

$b = 0.4 + t_1$ = 2.63 mm

t_3 = 0.03*D + b + 4.5 mm = 9.23 mm

Thickness of piston barrel at the open end,

t_4= 0.25 t_1 to 0.35 t_1 = 2.15 mm

Piston pin diameter,

do=0.03D=2.1mm

Length of piston skirt,

R = p_b*D*l

l = 61.1 mm

TABLE 2: PISTON PARAMETERS

Thickness of piston head	7.14mm
Radial thickness of piston ring	2.23 mm
Axial thickness of piston ring	1.78 mm
No of piston rings	4
Width of top land	7.85 mm
Width of ring land	1.42 mm
Thickness of piston barrel at top end	9.23 mm
Thickness of piston barrel at open end	2.15 mm
Piston pin dia.	2.1mm
Length of Skirt	61.1 mm
Total length of piston	80.33mm

5. MODELLING AND ANALYSIS

5.1 CATIA

CATIA is defined as computer-aided three-dimensional interactive application. It is multi-program software. It provides tools to complete product definition, including functional tolerances as well as kinematics definition. It provides a wide range of applications for tooling design, for both generic tooling and mould & die.

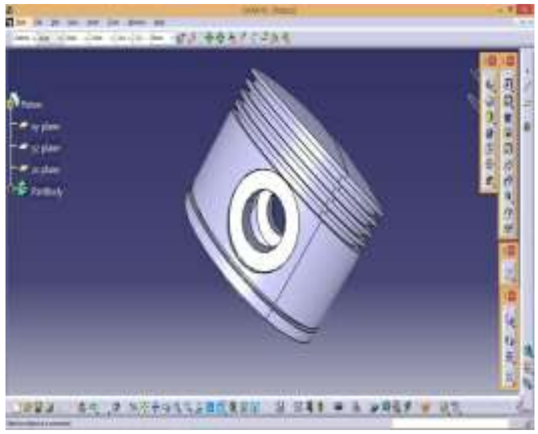


Fig 1: Design of the piston in CATIA

5.2 ANSYS

ANSYS is general-purpose finite element analysis (FEA) software package. Finite Element Analysis is a numerical method of deconstructing a complex system into very small pieces (of user-designated size) called elements. The software implements equations that govern the behaviour of these elements and solves them. all creating a comprehensive explanation of how the system acts as a whole. These results then can be presented in tabular or graphical forms. This type of analysis is typically used for the design and optimization of a system far too complex to analyze by hand. Systems that may fit into this category are too complex due to their geometry, scale, or governing equations.

6. ANALYSIS RESULTS:

The main aim of the project is to determine the static and thermal analysis of the piston coated with yttria stabilized zirconia(YTZP) of three different thicknesses and comparing them with conventional (i.e. uncoated) piston. With these results we can investigate heat flux, temperature, deformation, stress and strain of the coated and uncoated pistons. Here analysis of the piston model has been performed to obtain the value and parameters at which the piston would be damaged. Damages may have different origins: mechanical stresses; thermal stresses; wear mechanisms; temperature degradation, oxidation mechanisms; etc. For this analysis parameters like Pressure, Temperature, Thermal Stress .have been used and to discuss the effects of these parameters on the model are as follows

6.1 STATIC ANALYSIS

6.1.1 STRESS ANALYSIS

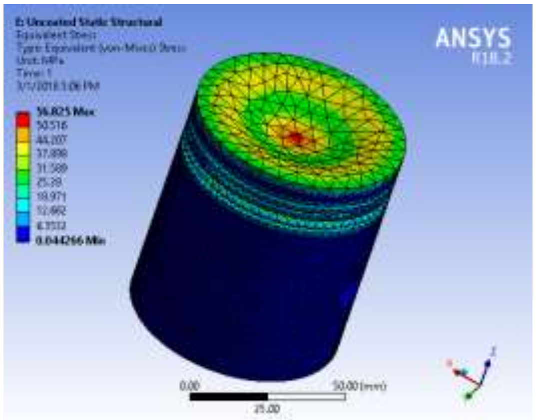


Fig.2 Stress analysis of uncoated structural steel piston

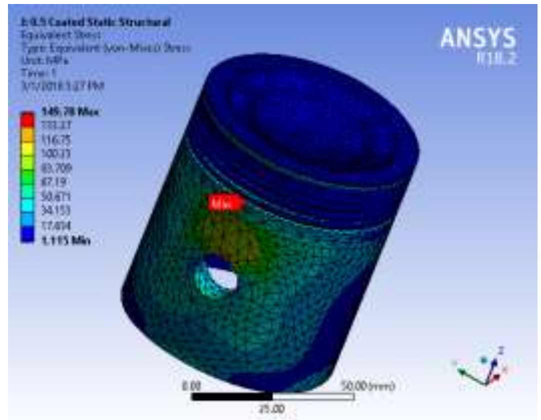


Fig.4 Stress analysis of piston coated with ytzp of 500µm thickness

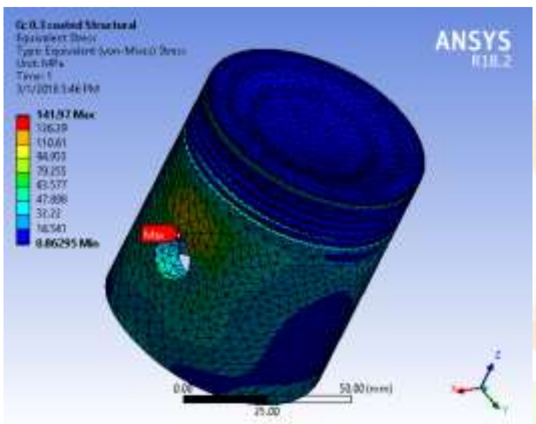


Fig.3 Stress analysis of piston coated with ytzp of 300µm thickness

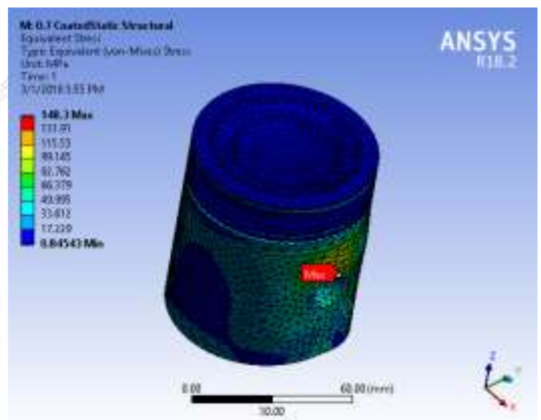


Fig.5 Stress analysis of piston coated with ytzp of 700µm thickness

6.1.2. STRAIN ANALYSIS

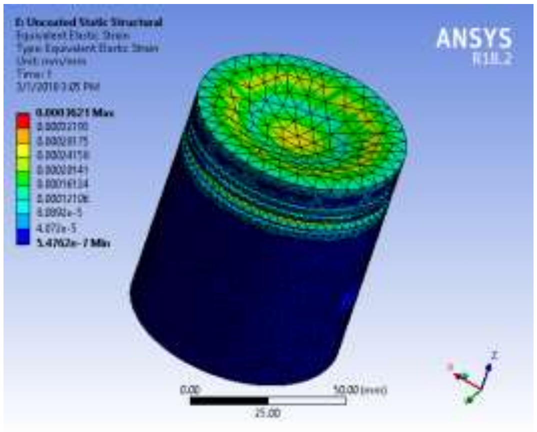


Fig.6 Strain analysis of uncoated structural steel piston

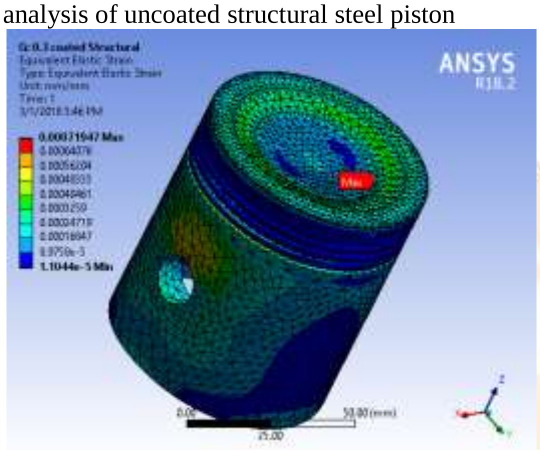


Fig.7 Strain analysis of piston coated with ytzp of 300µm thickness

6.1.3 DEFORMATION ANALYSIS

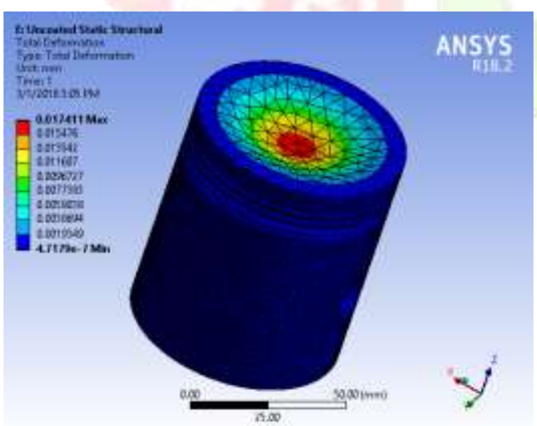


Fig.10 Deformation analysis of uncoated structural steel piston

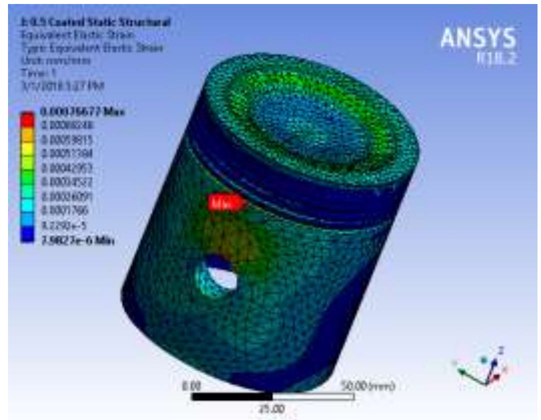


Fig.8 Strain analysis of piston coated with ytzp of 500µm thickness

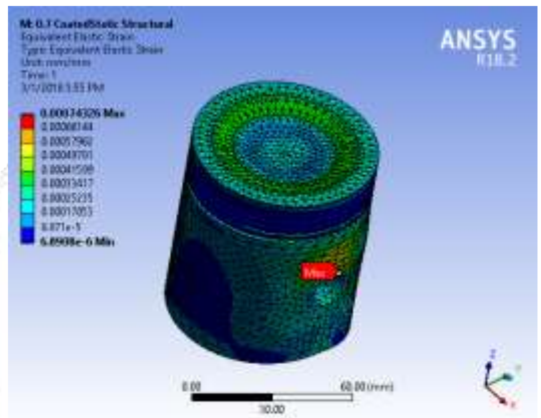


Fig.9 Strain analysis of piston coated with ytzp of 700µm thickness

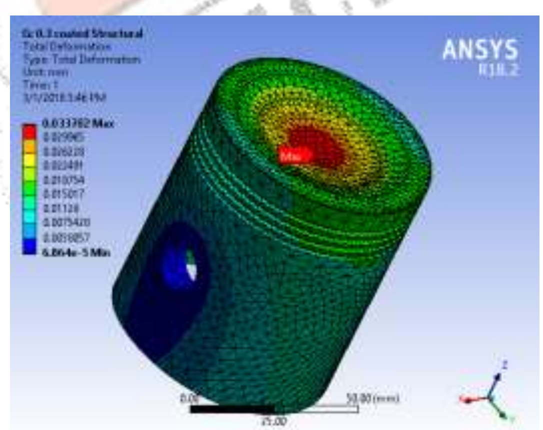


Fig.11 Deformation analysis of piston coated with ytzp of 300µm thickness

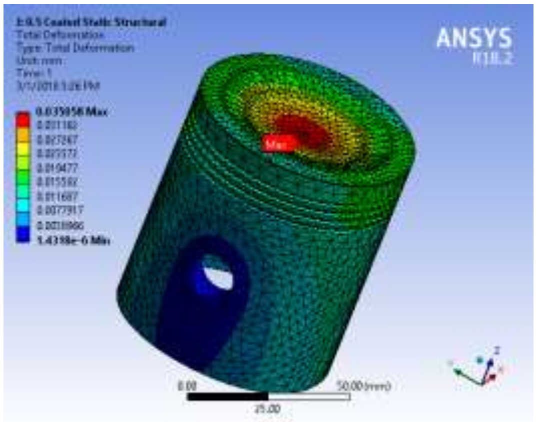


Fig.12 Deformation analysis of piston coated with ytzp of 500µm thickness

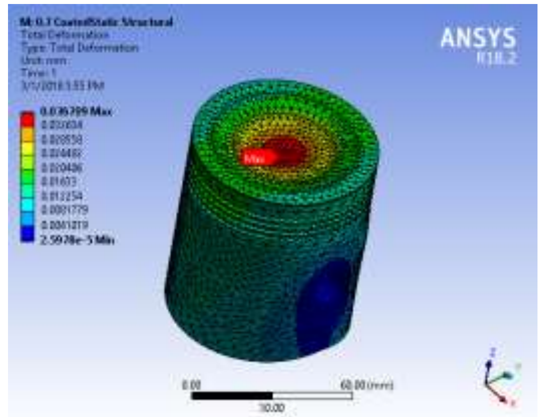


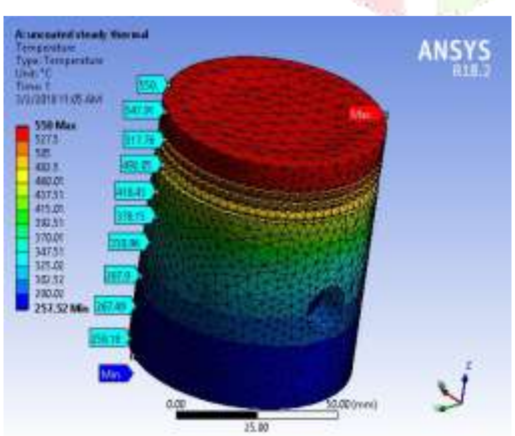
Fig.13 Deformation analysis of piston coated with ytzp of 700µm thickness

TABLE 3: COMPARISON OF STATIC ANALYSIS

Piston with coating of yttria stabilised zirconia	Maximum stress on the piston top land (MPa)	Maximum strain on the piston top land (mm/mm)	Maximum deformation on the piston top land (mm)
Uncoated	57	0.00028	0.017411
Thickness t=300µm	48	0.00072	0.033702
Thickness t=500µm	50	0.00043	0.035058
Thickness t=700µm	50	0.00042	0.036709

6.2 STEADY THERMAL ANALYSIS

6.2.1 TEMPERATURE ANALYSIS



Temperature analysis of uncoated structural steel

Fig.14

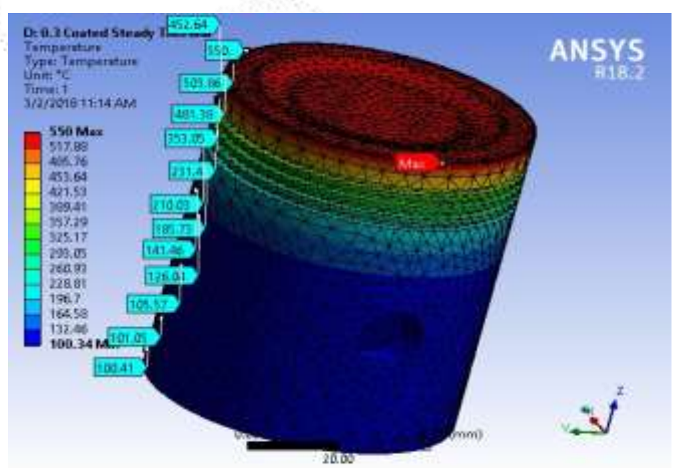


Fig.15 Temperature analysis of piston coated with ytzp of 300µm thickness

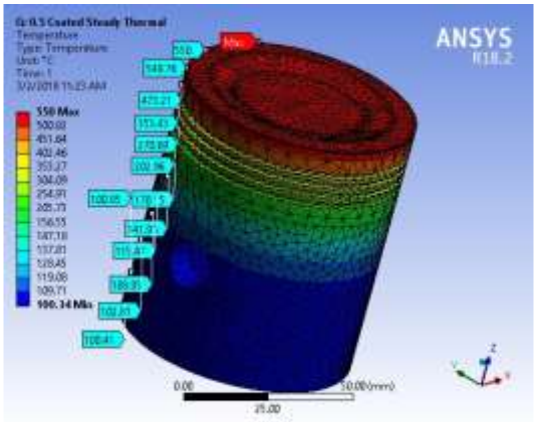


Fig 16: Temperature analysis of piston coated with ytzp of 500µm thickness

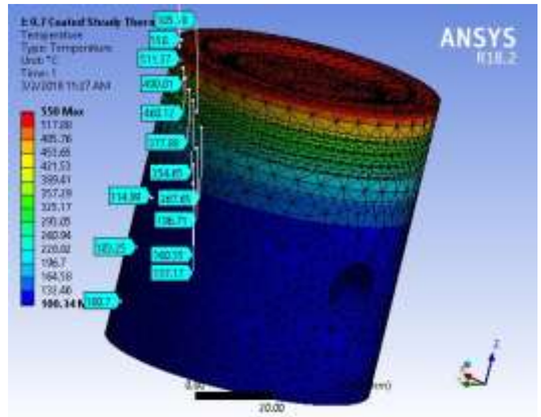


Fig.17 Temperature analysis of piston coated with ytzp of 700µm thickness

6.2.2 HEAT FLUX ANALYSIS

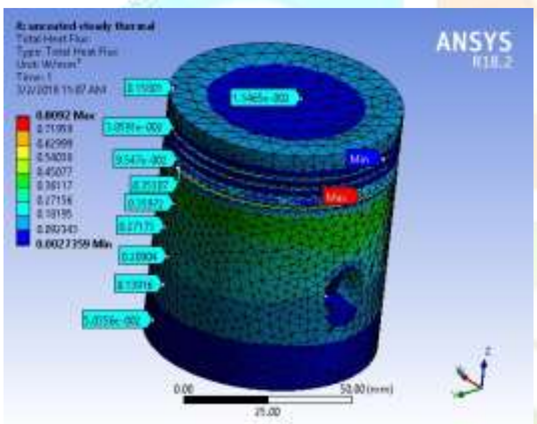


Fig.18 Heat Flux analysis of uncoated structural steel

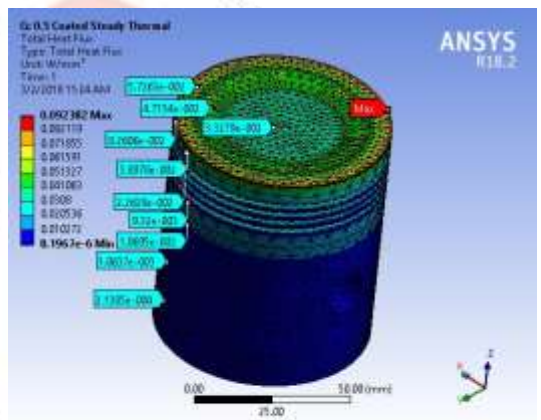


Fig.20 Heat Flux analysis of piston coated with ytzp of 500µm thickness

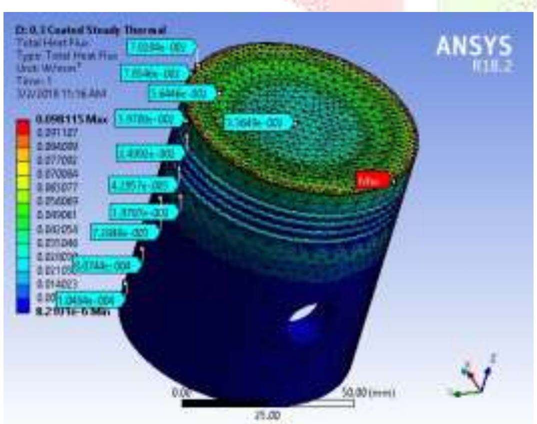


Fig.20 Heat Flux analysis of piston coated with ytzp of 300µm thickness

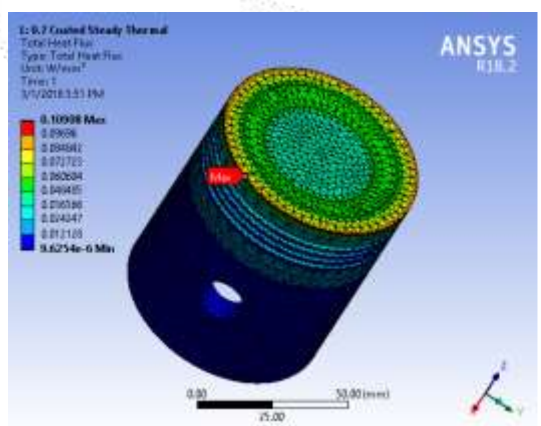


Fig.21Heat Flux analysis of piston coated with ytzp of 700µm thickness

TABLE 4: COMPARISON OF STEADY THERMAL ANALYSIS

Piston with coating of yttria stabilised zirconia	Temperature at end piston top land (·C)	Heat Flux at end piston top land (W/mm^2)
Uncoated	518	0.1580
Thickness t=300µm	452	0.0981
Thickness t=500µm	402	0.0924
Thickness t=700µm	378	0.0855

6.3 TRANSIENT THERMAL ANALYSIS

6.3.1 TEMPERATURE ANALYSIS

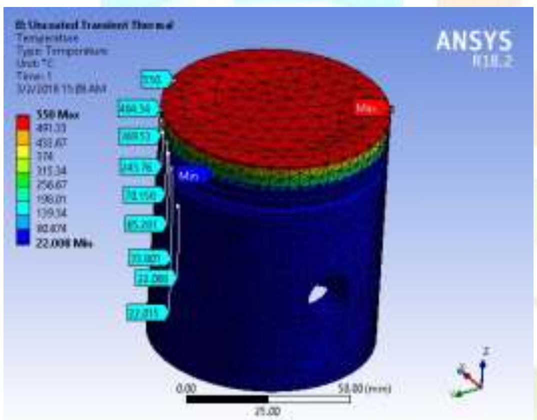


Fig.22 Temperature analysis of uncoated structural steel piston

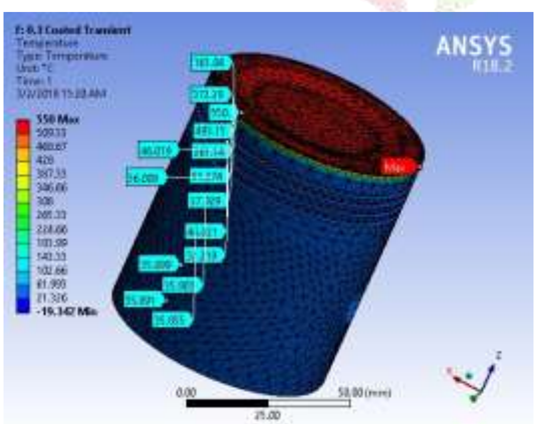


Fig.23 Temperature analysis of piston coated with ytzp of 300µm thickness

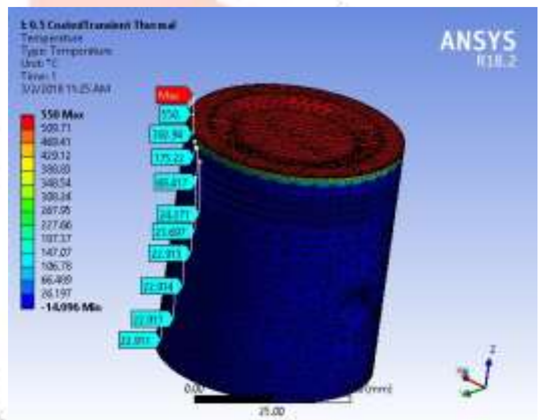


Fig.24 Temperature analysis of piston coated with ytzp of 500µm thickness

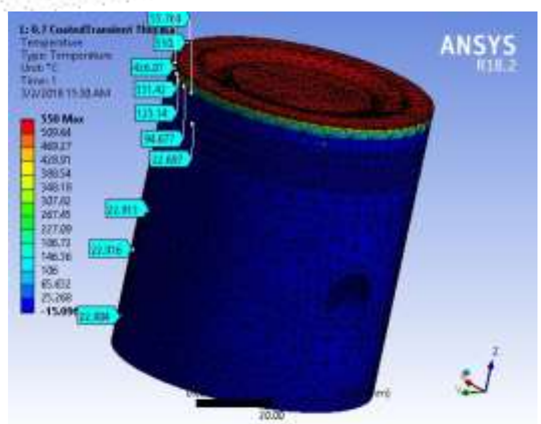


Fig.25 Temperature analysis of piston coated with ytzp of 700µm thickness

6.3.2 HEAT FLUX ANALYSIS

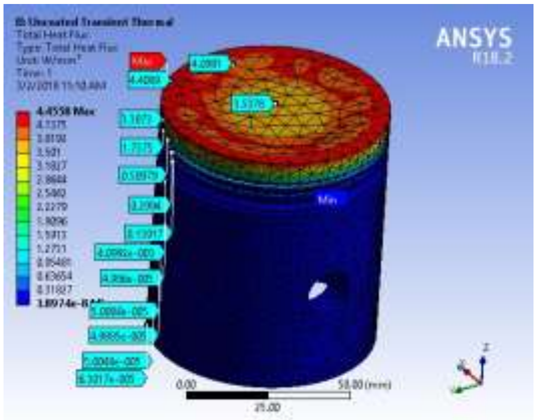


Fig.26 Heat Flux analysis of uncoated structural steel piston

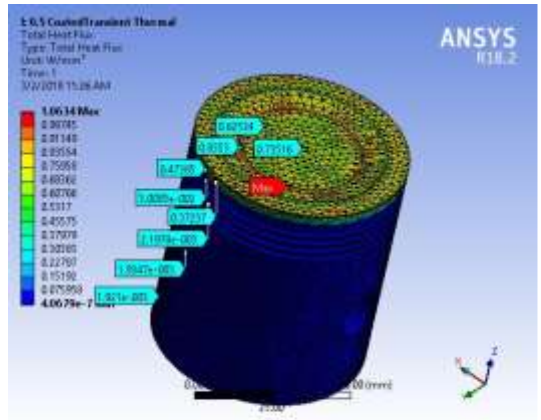


Fig.28 Heat Flux analysis of piston coated with ytzp of 500µm thickness

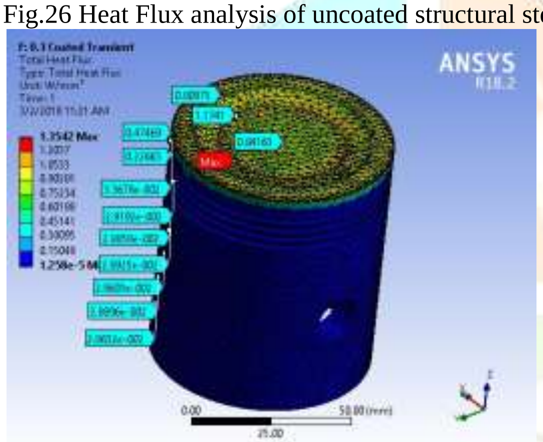


Fig.27 Heat Flux analysis of piston coated with ytzp of 300µm thickness

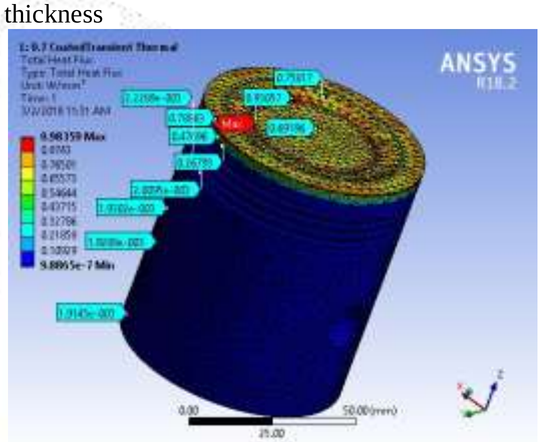


Fig.29 Heat Flux analysis of piston coated with ytzp of 700µm thickness

TABLE 5: COMPARISON OF TRANSIENT THERMAL ANALYSIS

Piston with coating of yttria stabilised zirconia	Temperature at end piston top land (·C)	Heat Flux at end piston top land (W/mm^2)
Uncoated	433	4.4089
Thickness t=300µm	372	1.1741
Thickness t=500µm	350	0.9875
Thickness t=700µm	332	0.9834

7. RESULTS DISSCUSION

7.1 STATIC ANALYSIS

- The maximum stress acting on uncoated piston top land is 56.825 MPa.
- The maximum stress acting on piston coated with ytzp of thickness 300µm is 47.848 MPa. The stress has reduced by 15.8%.
- The maximum stress acting on piston coated with ytzp of thickness 500µm is 50.67 MPa. The stress has reduced by 10.8%.
- The maximum stress acting on piston coated with ytzp of thickness 700µm is 49.95 MPa. The stress has reduced by 12.1%
- The maximum strain acting on uncoated piston top land is 0.00028 mm/mm.
- The maximum strain acting on piston coated with ytzp of thickness 300µm is 0.00072 mm/mm. The strain has increased by 157%.
- The maximum stress acting on piston coated with ytzp of thickness 500µm is 0.00043 mm/mm. The stress has increased by 53.6%.
- The maximum stress acting on piston coated with ytzp of thickness 700µm is 0.00042 mm/mm. The stress is reduced by 50%.
- The maximum deformation acting on uncoated piston top land is 0.017411mm.
- The maximum deformation acting on piston coated with ytzp of thickness 300µm is 0.033702mm. The deformation has increased by 93%.
- The maximum deformation acting on piston coated with ytzp of thickness 500µm is 0.035058 mm/mm. The deformation has increased by 101%.
- The maximum deformation acting on piston coated with ytzp of thickness 700µm is 0.036709 mm/mm. The deformation has increased by 111%.

7.2 STEADY STATE THERMAL ANALYSIS

- The temperature attained at the end of the uncoated piston top land is 518°C.
- The temperature attained on the piston top land coated with ytzp of thickness 300µm is 452°C. The temperature has reduced by 12.7%.
- The temperature attained on the piston top land coated with ytzp of thickness 500µm is 402°C. The temperature has reduced by 28.3%.
- The temperature attained on the piston top land coated with ytzp of thickness 700µm is 378°C. The temperature has reduced by 27%.
- The maximum heat flux attained on uncoated piston is 0.1580 W/mm^2.
- The maximum heat flux attained on the piston top land coated with ytzp of thickness 300µm is 0.0981 W/mm^2. The heat flux has reduced by 38%.
- The maximum heat flux attained on the piston top land coated with ytzp of thickness 500µm is 0.0924 W/mm^2. The heat flux has reduced by 41.5%.
- The maximum heat flux attained on the piston top land coated with ytzp of thickness 700µm is 0.0855 W/mm^2. The heat flux has reduced by 46%.

7.3 TRANSIENT THERMAL ANALYSIS

- The temperature attained at the end of the uncoated piston top land is 433°C.

- The temperature attained on the piston top land coated with ytzp of thickness 300µm is 372°C. The temperature has reduced by 14.1%.
- The temperature attained on the piston top land coated with ytzp of thickness 500µm is 350°C. The temperature has reduced by 19.2%.
- The temperature attained on the piston top land coated with ytzp of thickness 700µm is 332°C. The temperature has reduced by 23.3%.
- The maximum heat flux attained on uncoated piston is 4.4089 W/mm^2.
- The maximum heat flux attained on the piston top land coated with ytzp of thickness 300µm is 1.1741 W/mm^2. The heat flux has reduced by 73%.
- The maximum heat flux attained on the piston top land coated with ytzp of thickness 500µm is 0.9875 W/mm^2. The heat flux has reduced by 77.6%.
- The maximum heat flux attained on the piston top land coated with ytzp of thickness 700µm is 0.9834 W/mm^2. The heat flux has reduced by 77.7%.

8. CONCLUSSION

Yttria stabilised zicronia coated piston showed 24.86% increased heat flux over conventional. A uniform temperature distribution was observed in coated piston over conventional piston. More heat of 2.458% is converter into work using YTZP coating on piston crown which leads to overall increased performance of engine. From the analysis it was observed oil used for lubrication was not evaporated due to YTZP coating, resulted temperature (273°C to 311°C) was within the limit which indicates the safe guard to liner.

9. FUTURE SCOPE

This project focuses mainly on the individual performance of piston crown; a coupled analysis can be done with cylinder to obtain the performance of the engine as a whole. Different piston materials and coating materials can be tested. Coating surface is also an important factor which affects the work done and heat rejection in engine, but from the thermal barrier coating literature it was found that rough coating surface was best suited for better performance.

10. REFERENCE

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