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Finite Element Analysis of Piston Using Thermal Barrier Coating

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ABSTRACT

The piston is responsible for transmitting gas pressure exerted by combustion gases into reciprocating motion and is responsible for kinetic energy. During this process, the piston crown is continuously subjected to various thermal and structural loads such as gas pressure load, side thrust, and connecting rod load, inertia load. This will result in piston seizing by overheating, and cracks on top land ultimately affecting engine efficiency. To reduce heat absorption and increase insulating property Thermal barrier coating is applied on top land. The modeling of the piston is made on Solid works. In this project, the Analysis is performed on a piston made of aluminum alloy with and without thermal barrier coating materials (Magnesium zirconate, Lanthanum doped zirconate, Yttria stabilized zirconia). Structural analysis, Steady-state thermal analysis is carried out on the piston in ANSYS and aims to study its behavior by comparing it with the conventional piston.

Keywords: Thermal Barrier Coating, Structural Analysis, Steady State Thermal Analysis

1. INTRODUCTION

In an internal combustion engine piston is the reciprocating part that transmits force generated by combustion of air fuel mixture. It occurs by pushing the piston through great amount force which is produced by expansion of combustion gases. In a conventional IC engine air -fuel mixture of proportioned quantity enters in the cylinder when piston moving towards bottom dead center and intake takes place. At the time of compression stage air-fuel mixture is compressed to high limits of temperature and pressure, at the end of stroke charge ignites and combustion of charge results in expansion of combustion gases which pushes the piston down at great speed and piston transmits this energy to piston pin, connecting rod, crank shaft. Due to this impact various thermal forces, Inertia force, combustion gas pressure, connecting rod load and side thrust, acts on piston, and most of them acts on top land or crown of piston.

Throughout this process most of the heat produced is absorbed by the piston. To prevent piston from failing, cracks on crown, piston seizure due to overheating, a thermal barrier coating on piston surface is utilized. Thermal barrier coating acts as insulator which acts as barrier for heat to transmit into piston. The materials used for coating have low thermal conducting property and high coefficient of thermal expansion, Retain its structure and phase at elevated temperature. The study indicates that 30% of heat is carried away by engine cooling system and good solution may be engine thermal barrier coating. Thermal barrier coating owing their insulating properties which helps in increasing the fuel economy as fuel burns more due increased temperature in the region, which in turn increase engine efficiency. Thermal barrier coating reduces hydrocarbon, reduces emission by producing less smoke and carbon monoxides. Another study indicates that significant increase in temperature results in increase in the thermal efficiency of engine. This will reduce the heat loss from piston as a result of burning un-burnt gases.

Thermal barrier coating reportedly modifies prior condition for combustion of fuel will result in lessen ignition delay time and shortening fuel consumption.

2. REALATED WORK

OBJECTIVE: The objective of this project is to increase the insulating property of piston by coating various types of TBC material on piston crown namely La1.7Dy0.3Zr2O7, MgZrO3 and Yttria stabilized zirconia (YSZ) and perform comparative study by varying thickness of coating. By performing static structural analysis and Steady state thermal analysis in ANSYS most effective thermal barrier coating material is identified.

PROBLEM IDENTIFICATION:

· In the internal combustion engine, piston subjected to fatigue load, gas pressure load and side thrust.

· Engine cooling system carries away 30 percentage of heat which is direct loss.

·Overheating of piston result ultimately piston seizure

·Un-burnt fuel mixture cause reduction in engine efficiency

LITERATURE REVIEW:

[1] Thermal barrier coating on IC Engine Piston to enhance better utilization of heat produced inside the combustion chamber ultimately improving engine's efficiency

Year of publication: 2017

Author: Mohsin Attar, Prof.Mr. Ajay Bhongade

Observation: This research is aimed to improve efficiency of engine with utilizing Yttria stabilized zirconia as thermal barrier coating material. This research considered 150 cc engine piston and compared with yttria stabilized zirconia coating with various thickness on top land of piston. This research suggested that using YSZ coating of 0.6mm reduces heat flux and temperature on crown of piston.

[2] Analysis on a thermal barrier coated (TBC) piston in a single cylinder diesel engine powered by Jatropha biodiesel–diesel blends

Author: Harish Venu, Prabhu Appavu

Year of publication: 2019

Observation: This research work aimed to improve diesel efficiency operated with Jatropha bio diesel blends using Yttria stabilized zirconia coating (YSZ). Yttria stabilized zirconia of 200 micro meter thick layer is coated by plasma spray technique at temperature 8300℃ on piston operated on JB20(20% jatropha biodiesel and 80% diesel fuel). This research indicates in improving combustion characteristics and lowering Hydro carbon, carbon dioxide emissions.

[3] Design and static thermal analysis of piston using thermal barrier coating materials using fem

Author: Mr. Vatti Sairam Krishna, Mr.K. Muralidhar

Year of publication: 2021

Observation:

In this research thermal analysis is conducted on piston of 150cc engine of materials Al402, Ti64AlV coated with Thermal barrier coating materials, Mgzro3 ,Ni-Cr-Al of 0.4mm and suggested that Al-Sic piston coated Ni-Cr-Al Is efficient and suited for high temperature application.

[4]Design and Thermal Analysis of Ceramic Coated Diesel Engine Piston (Mgzro3 & Nicral)

Author:M.Mathanbabu,P.Mohanraj,S.Navaneetha,Krishnan ,T.Naveen Kumar ,S.Vijay

Year of publication: 2019

Observation: In this research Mahindra Scorpio Group M11B15-Piston is considered and piston material as Alsic and steel is assumed. Thermal analysis is conducted for uncoated piston and piston coated with thermal barrier coating materials MgZrO3 and NiCrAl as bond coat. This research compared results of analysis and suggested that piston coated with MgZrO3 has better insulating property.

[5] Static and Thermal Analysis of Aluminium Alloy Piston with Ceramic Coating

Author: G.Venkata Srinivasa Rao, CH.Venkateswara Rao, T.N.Charyulu, Sk.Nakki Jani, N.Ch.Sai Prathap

Year of publication:2019

Observation: In this research paper piston is designed in catia v5 and the model is then imported to ansys and in ansys geometric model is converted into FEA model and apply boundary conditions to find the stress, temperature distribution and heat flux and piston is coated with two thermal barrier coatings those are ALSIC(aluminium silicon) and NICRAL(nickel chromium aluminium).They concluded that based on their analysis aluminium silicon carbide has more temperature resistance and less amount of heat flux as compared with aluminium alloys.

[6] Design and thermal analysis of ceramic coated aluminium alloy piston

Author: T. G. Thiyagarajan, A. Velladurai

Year of publication: 2017

Observation: In this paper they mainly focus on determining the temperature distribution of a ceramic coated piston. In this research they used various materials to coat piston like mullite, yttrium stabilized zirconia(Y-PSZ), and Magnesium Stabilized Zirconia (Mg-PSZ) are used as ceramic coatings. Based on the analysis the uncoated piston has less performance has compared with the coated one. And they found that magnesium stabilized zirconia has similar properties of Yttrium stabilized zirconia which is best suitable for TBC material.

[7] Investigation on effect of Yttria Stabilized Zirconia coated piston crown on performance and emission characteristics of a diesel engine

Author: G. Sivakumar, S. Senthil Kumar

Year of publication: 2014

Observation: In this paper experimental investigation made on three-cylinder diesel engine with piston coated with Yittria stabilized zirconia and performance and emissive characteristics are studied. Based on study TBC material coated engine has improved Brake specific fuel consumption and hydrocarbon emission reduced up to 35.27% and carbon monoxide reduction up to 2.7%.

[8]Thermo-Mechanical Analysis of a Piston with Thermal Barrier Coatings (Tbc)

Author: Abhinav Lal, Mr. Morrish kumar

Year of publication: 2017

Observation: In this paper FEA analysis and thermal analysis is conducted on piston of Al-sic and Titanium material and coated with MgZrO3 and Yittria partially stabilized zirconia. This research suggest that Al-sic coated with MgZrO3 of 0.5 mm thickness retained its Temperature near to titanium piston.

[9]Thermal Behaviorand Optimization of Piston Coating Material (Al-Si) Used in Petrol Engine

Author: M. Sivanesan and C. Vinothkumar

Year of publication:2016

Observation: In this paper piston is with various amount of thickness from 0.2 to 1.6mm without considering bond carbidecoating layers. In this research paper they are mainly focusing on thermal stress distribution of piston at real engine during combustion. They conduct thermal and structural analysis by coating with different materials like aluminium oxide, zirconium oxide and mullite. Finally, they concluded that aluminium oxide has higher efficiency as compared with other materials

3. PROPOSED WORK

DESIGN:

Thickness of piston head	10.378 mm
Radial thickness of piston ring	2.59 mm
Axial thickness of piston ring	2.08 mm
No of piston rings	4
Width of top land	11.415 mm
Width of ring land	1.664 mm
Radial depth of piston ring groove	2.99 mm
Thickness of piston barrel at top end	10.01 mm
Piston pin diameter	25.2 mm
Diameter of piston boss	43.434 mm
Length of Skirt	50.4 mm
Total length of piston	75.126 mm
Thickness of piston barrel at open end	2.505 mm

In this work we have considered royal Enfield 500cc engine which dimensions as bore B=84mm and stroke l=90mm, maximum power=27.184 bhp at 5250 rpm,maximum torque=41.3 Nm at 4000 rpm

DIMENSIONS OF ROYAL ENFIELD 500cc Engine Piston

Table : 1

MODELLING IN SOLID WORKS: In this project we have considered Royal Enfield 500cc engine piston of material Aluminium alloy and designed using Solid Works. Ceramic material of 0.3mm and 0.5mm thick layers are modeled.

Piston without Thermal barrier coating:

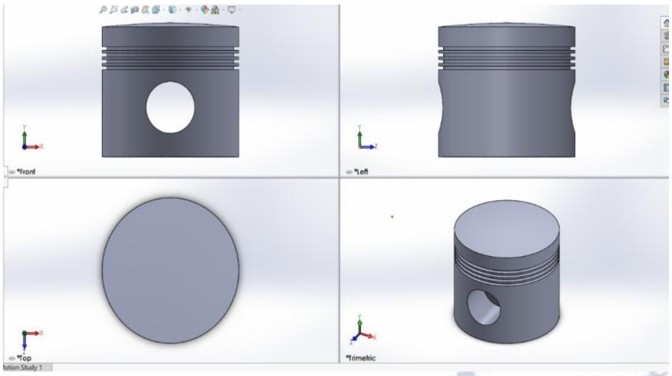
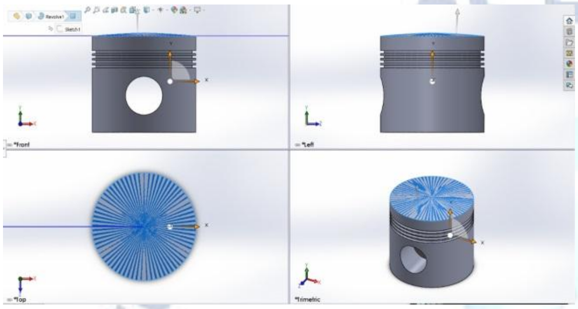


Figure: 1



Piston with Thermal barrier coating:

Figure:2

MATERIAL INFORMATION

Based on the properties and studying the literature review we are choosing three materials those are Magnesium zirconate (MgZrO3),lanthanum doped zirconate($La_{1.7}Dy_{0.3}Zr_2O_7$, Yttria Stabilized Zirconia(YSZ) and their compositions are tabulated below.

1.Aluminium alloy(Al6061)

Derived from	Young's modulus and Poisson's ratio
Young's modulus	70000MPa
Poisson's ratio	0.33
Bulk modulus	68627MPa
Shear modulus	26316MPa
Isotropic secant coefficient of thermal expansion	23.6 1/°C
Tensile ultimate strength	310MPa
Tensile yield strength	276MPa
Thermal	
Isotropic thermal conductivity	0.167 W/mm°C
Specific heat constant pressure	896mJ/kg°C
Density	2.7×10^{-6}kg/mm^3

Table: 2

2. Magnesium zirconate (MgZrO3)

structural	
Derived from	Young's modulus and Poisson's ratio
Young's modulus	46000MPa
Poisson's ratio	0.2
Bulk modulus	25556MPa
Shear modulus	19167MPa
Isotropic secant coefficient of thermal expansion	2.7×10^{-05} 1 /°C
Tensile ultimate strength	180MPa
Tensile yield strength	51MPa
Thermal	
Isotropic thermal conductivity	0.0008 W/mm°C
Specific heat constant pressure	1.04×10^{6}mJ/kg°C
Density	5.6×10^{-6}kg/mm^3

Table: 3

3.Lanthanum doped zirconate ($La_{1.7}Dy_{0.3}Zr_2O_7$)

structural	
Derived from	Young's modulus and Poisson's ratio
Young's modulus	1.75×10^{5}MPa
Poisson's ratio	0.28
Bulk modulus	1.3258×10^{5}MPa
Shear modulus	68359MPa
Isotropic secant coefficient of thermal expansion	1.035×10^{-05} 1 /°C
Thermal	
Isotropic thermal conductivity	0.000468 W/mm°C
Specific heat constant pressure	1.356×10^{6}mJ/kg°C
Density	5.6×10^{-6}kg/mm^3

Table: 4

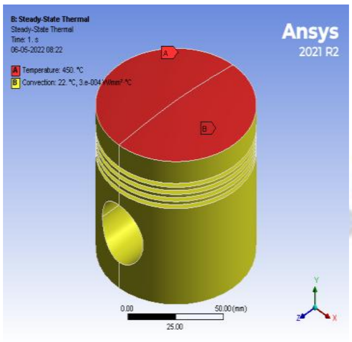
4.Yttria Stabilized Zirconia(YSZ)

structural	
Derived from	Young's modulus and Poisson's ratio
Young's modulus	2.1×10^{5}MPa
Poisson's ratio	0.3
Bulk modulus	1.75×10^{5}MPa
Shear modulus	80769MPa
Isotropic secant coefficient of thermal expansion	6.69×10^{-05} 1 /°C
Tensile ultimate strength	690MPa
Tensile yield strength	550MPa
Thermal	
Isotropic thermal conductivity	0.0022 W/mm°C
Density	6.02×-06 kg/mm^3

Table: 5

ANALYSIS: The designed piston model from Solid works is imported to ANSYS work bench and steady state thermal analysis, static structural analysis carried out as,designed piston is imported in ansys and the materials are assigned for the piston and also for the coating on the piston crown. Meshing is done for the piston and tetrahedron elements are formed in meshing. Loads applied on the piston crown such as temperature and co efficient of convection film. Then the solver is made to run so that the solution can be obtained. Total heat flux and temperature is obtained. Static structural analysis carried out as,Upto meshing same procedure is followed. At static condition the loads were applied.Pressure at piston crown and the surfaces are considered to be non frictional contact. Analysis is carried to observe total deformation, stress and strain.

BOUNDARY CONDITIONS FOR PISTON:



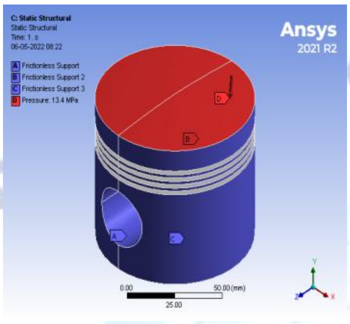
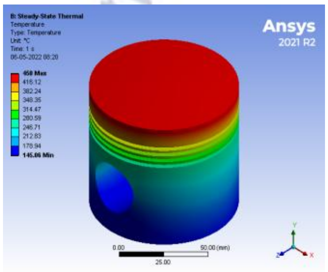
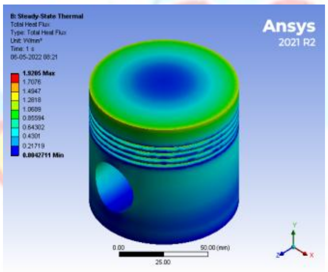


Fig: 3(a) Fig: 3(b)

STEADY STATE THERMAL ANALYSIS:

Material: Al6061 + without coating

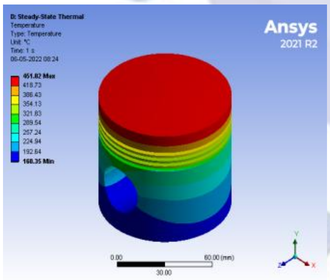


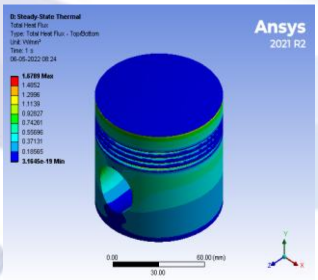


(a) (b)

Fig: 4(a) Temperature Distribution, (b) Total Heat Flux

Material: Al6061 + with MgZrO3 of 0.5 mm thickness coating

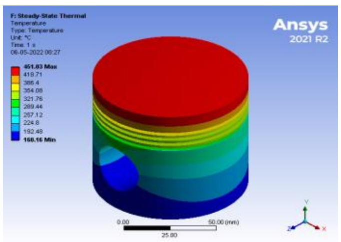


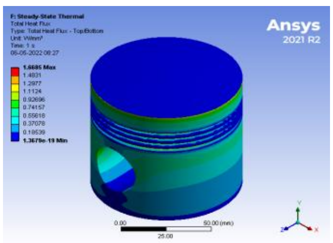


(a) (b)

Fig: 5 (a) Temperature Distribution, (b) Total Heat Flux

Material: Al6061 + with MgZrO3 of 0.3 mm thickness coating

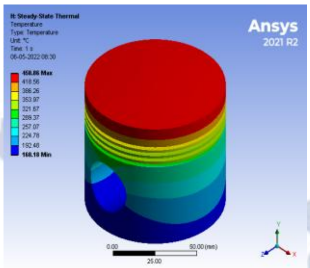




(a) (b)

Fig: 6 (a) Temperature Distribution, (b) Total Heat Flux

Material: Al6061 + with La1.7Dy0.3Zr2O7 coating of 0.5 mm thickness



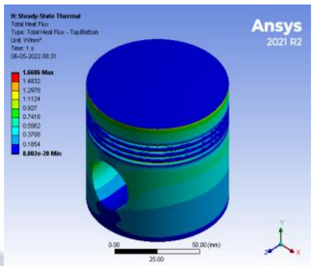
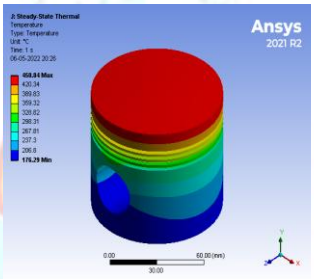
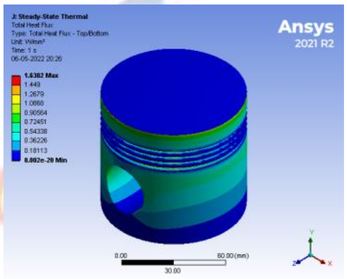


Fig. 7(a) Fig. 7(b)

Fig: (a) Temperature Distribution, (b) Total Heat Flux

Material: Al6061 + with La1.7Dy0.3Zr2O7 coating of 0.3mm thickness

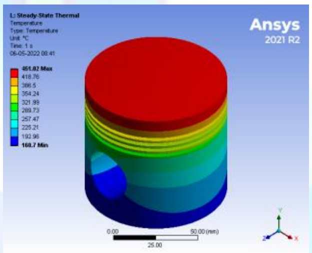


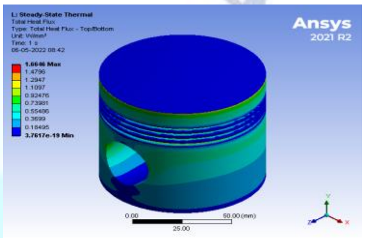


(a) (b)

Fig: 8 (a)Temperature Distribution, (b) Total Heat Flux

Material: Al6061 + with YSZcoating of 0.5 mm thickness

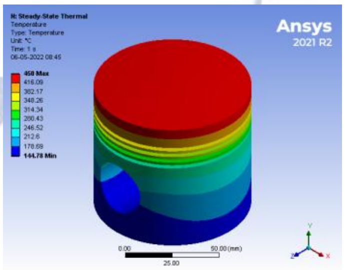


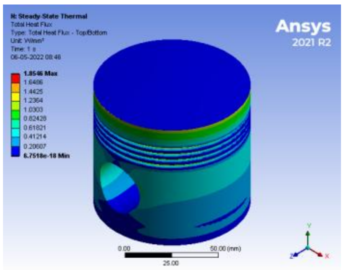


(a) (b)

Fig: 9(a) Temperature Distribution, (b) Total Heat Flux

Material: Al6061 + with YSZcoating of 0.3 mm thickness



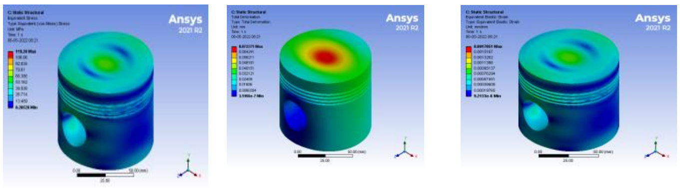


(c) (d)

Fig: 10(c) Temperature Distribution, (d) Total Heat Flux

STATIC STRUCTURAL ANALYSIS:

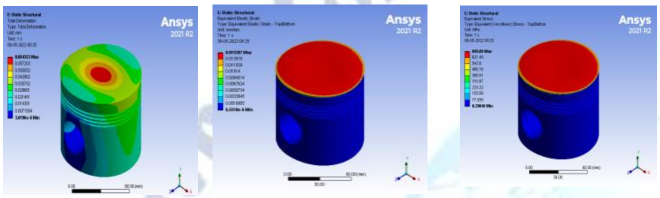
Material:Al6061 + without coating



(a) (b) (c)

Fig: 11 (A) Equivalent Stress (B) Total Deformation (C) Equivalent Elastic Strain

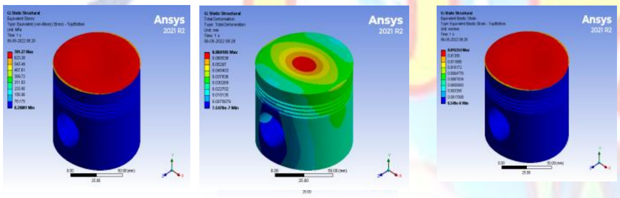
Material: Al6061 + with MgZrO3 of 0.5 mm thickness coating



(a) (b) (c)

Fig: 12(a) Total Deformation (b) Equivalent Elastic Strain (c) Equivalent Stress

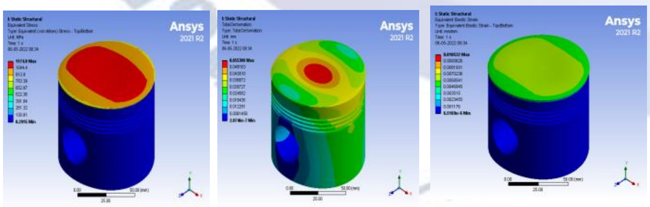
Material: Al6061 + with MgZrO3 of 0.3 mm thickness coating



(a) (b) (c)

Fig: 13 (a) Equivalent Stress (b) Total Deformation (c) Equivalent Elastic Strain

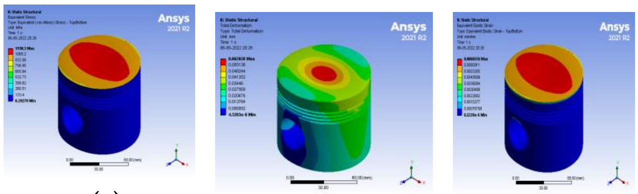
Material: Al6061 + with La1.7Dy0.3Zr2O7 coating of 0.5 mm thickness:



(a) (b) (c)

Fig: 14 (a) Equivalent Stress (b) Total Deformation (c) Equivalent Elastic Strain

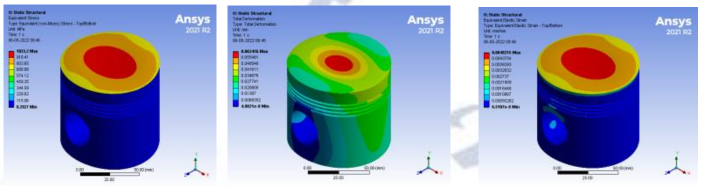
Material: Al6061 + with La1.7Dy0.3Zr2O7 coating of 0.3 mm thickness:



(a) (b) (c)

Fig: 15 (a) Equivalent Stress (b) Total Deformation (c) Equivalent Elastic Strain

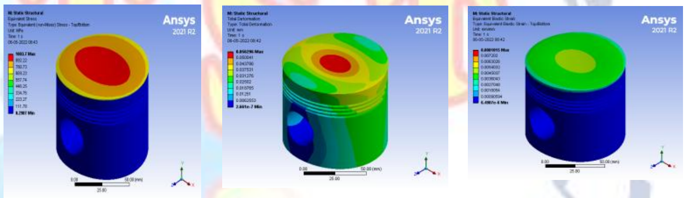
Material: Al6061 + with YSZcoating of 0.3 mm thickness



(a) (b) (c)

Fig: 16(a) Equivalent Stress (b) Total Deformation (c) Equivalent Elastic Strain

Material: Al6061 + with YSZcoating of 0.5 mm thickness



(a) (b) (c)

Fig: 17(a) Equivalent Stress (b) Total Deformation (c) Equivalent Elastic Strain

4. RESULTS

From the analysis of 0.3 mm and 0.5 mm thickness of Thermal barrier coating, results of Total heat flux, Temperature distribution and von-Misses stress and equivalent strain are obtained and values are listed below

Piston with 0.5 mm coating thickness

Material	Temperature℃		Heat flux W/mm²	
Al6061+TBC	Max	Min	Max	Min
Uncoated	450	145	1.920	0.00427
Mgzro3	450	160.5	1.6709	3.1645e-19
Ldz	450	160.18	1.6686	8.002e-20
Ysz	450	160.7	1.6646	3.1677e-19

Table: 6

Material	Total deformation mm		Equivalent elastic strain		Von-Mises stress MPa	
Al6061 +TBC	max	min	max	min	max	min
Uncoated	0.072	3.195e-7	0.001705	9.2133e-6	119.28	0.26528
MgZrO3	0.064353	3.0196e-8	0.015207	6.551e-6	699	0.2909
LDZ	0.055378	2.87e-7	0.010532	6.519e-6	1174.9	0.2195
YSZ	0.056296	2.661e-7	0.0081015	6.498e-19	1003.6	0.2907

Table: 7

Piston with 0.3 mm coating thickness:

Material	Temperature°C		Heat flux W/mm²	
Al6061+TBC	Max	Min	Max	Min
Mgzro3	450	160.15	1.6685	1.367e-19
Ldz	450	176.29	1.6302	8.002e-20
Ysz	450	144.78	1.8546	6.571e-18

Table: 8

Material	Total deformation mm		Equivalent elastic strain		Von-Mises stress MPa	
Al6061+TBC	Max	Min	Max	Min	Max	Min
Mgzro3	0.068105	7.547e-7	0.015254	6.594e-6	701.27	0.29989
LDZ	0.06202	4.320e-8	0.0068516	6.522e-6	1198.2	0.29279
YSZ	0.062416	4.9281e-8	0.0049215	6.510e-6	1033.2	0.2927

Table: 9

5. CONCLUSION

Hence the results from analysis of Aluminum alloy piston coated with 0.5mm thickness of Yttria stabilized zirconia and Lanthanum doped zirconate has less heat flux compared with magnesium zirconate and heat flux decreases with increase in thickness of Thermal barrier coating. With decrease in heat flux results better utilization of heat therefore engine efficiency increases.From observing the Analysis results piston coated with TBC material is more efficient than uncoated piston.

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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