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Comparative study of different shapes and sizes of heat expansion slots in a ceramic-coated piston

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Abstract - Piston skirt is provided with expansion slots in order to facilitate effective heat transfer from crown to the skirt so that excessive thermal expansion can be controlled. The slots are designed in different shapes (viz. T, horizontal, vertical, H, etc.) depending on the type of application and process can be increased. The project deals with the analysis and simulation of these different slots and thermal barrier coatings in similar environment and boundary conditions. Out of various types of piston slots and different thickness and types of coating, the combination which maximizes the engine performance is likely to be chosen. Different types of results are plotted for increasing thickness of the coatings, various types of slots and the values of deformations and maximum temperature obtained by analysing the models. The plots and results thus obtained are optimized and the comparison between the effectiveness of the above mentioned shapes and the thickness of coatings are discussed in the project.

Keywords: Thermal barrier coatings, Piston slots, Thermal Analysis, ANSYS.

1. Introduction

A piston is an engine component that transfer force from expanding gas in the cylinder to the crankshaft via a piston rod and/or connecting rod. It is a moving component that is made airtight using piston rings inside the cylinder. When combustion of fuel inside the cylinder takes place, a lot of heat and pressure is generated inside the combustion chamber. The temperature could reach up to 500°C in SI Engines and 900°C in CI Engines. This heat travels to the piston crown and cylinder walls mainly by conduction and convection processes. The heat reaching to cylinder walls due to combustion process and also due to the friction between piston rings and cylinder walls is compensated by the coolant flowing however the heat reaching to the piston crown also travels to the piston rings by conduction and also to the piston skirt, which is provided to dissipate this heat slowly. On the piston skirt, the temperature falls as the depth of the skirt increases. Temperature distribution inside the piston must be calculated in order to control the thermal stresses and deformations. By calculating these parameters, the stresses and deformations can be optimized without making the first prototype. This saves a lot of time and money in real time environment. The most common material used for manufacturing pistons of SI Engine is aluminum alloy which has a thermal expansion coefficient 80% higher than the cylinder bore material made of cast iron. The highest magnitude of heat transferred in the piston sub-assembly. Thermal barrier coatings are also applied on the top of piston crown so that the temperature inside the combustion chamber during combustion

temperature of any point in piston must not exceed more than 66% of the melting point temperature of the alloy. This limits the temperature for the aluminum alloy in the range of 600 to 700K. The temperature within the piston is not constant at all the surfaces. Therefore, thermal deformations and thermal stresses are produced inside the material.

1.1 Piston Slots

For controlling excessive thermal expansion in the piston during combustion, different types of methods are used like winding the wire around piston and making the shape of the piston as oval. The most common way of controlling expansion is making slots on the piston skirt. The basic purpose of making slots is to minimize the heat transfer to the skirt and also controlling the thermal expansion by expanding the piston material within the slot gap, thus avoiding any chances of seizure also between skirt and cylinder. The common slot shapes used are vertical, horizontal, T slots etc.

1.2 Thermal Barrier Coatings

To increase the performance of the engine, Thermal Barrier Coating (TBCs) is also used. This is applied on the top surface of the piston i.e. piston crown to insulate them thermally, it allows higher operating temperature inside combustion chamber. This coating acts as a barrier for the heat which is produced during combustion and thus, the heat is retained inside the combustion chamber. In addition, the metallic surface of the piston is also protected from thermal fatigue which is generated during power and exhaust strokes. The coating generally used is a ceramic-based material that has low thermal conductivity and good strength which is capable of enduring higher temperatures than metals. One of the widely used materials for coating is Zirconia which is applied by plasma-spraying technique. The main purpose of this is to raise the temperature of the piston crown's surface during the expansion stroke, thereby decreasing the temperature difference between the wall and the gas to reduce heat transfer. Thus, the cooling load and requirements are also reduced. A simpler cooling system will reduce the weight and cost of an engine while improving reliability. Some of the additional heat energy in the cylinder can be converted and used to increase the power and efficiency of the engine.

The bond coat layer is used between piston material crown and coating material. The bond coat material is an inter-metallic alloy that acts as the adhesion between TBC layer and piston material and also provides oxidation resistance at very high temperatures. It plays an important role in reducing the internal stresses produced between the substrate and the ceramic coating because of thermal shock mainly during power stroke. The coefficient of thermal expansion of the bond coat lies between the coefficient of thermal expansion values of the TBC and the metal substrate. The coating thickness has a significant effect on the combustion temperature, temperature gradient and the stress distribution inside the material. Therefore, determining the proper thickness of the TBC plays an important role accurate measurement of the temperature drop and resulting performance of the coated system.

1.3 Objectives

Considering the above, it is evident that both piston slots and TBCs are used for increasing the performance of engine. Therefore, it is clear that, if both the things are on the piston and optimized results for piston slots and coating thickness is used, performance of engine can be increased. The primary objectives of this project are reducing the overall weight of the piston, heat transfer rate from crown to the skirt, thereby optimizing the minimum temperature reaching to the piston skirt by taking different shapes and sizes of slots. An effort has also been made by using different types and thickness of coatings on the piston crown surface to optimize the results for better effectiveness. Simulation of the results with both piston slots and the coating simultaneously was also performed in the study.

2. Literature Review

The basic need of piston slots is to control the expansion of the piston skirt and to reduce the overall material consumption which in turn reduces the weight of the piston. Chitthaarth and Manivannan [2] made piston slots by taking different alphabets of English i.e. and Z. The CAD package and analysis software used for design and analysis are CATIA and ANSYS respectively. The piston material was taken as aluminium alloy and the dimensions were taken from Hero Hunk 150cc. Initially the thermal analysis was done using ANSYS and then the structural analysis was performed. The temperature and the heat flux of the piston were obtained for both slots. Z slot has the least heat flux and is more efficient and effective than Y slot. Thus Z slot was implemented on the piston. Buyukkaya and Cerit [1] made thermal analyses on a conventional uncoated diesel piston made of aluminium silicon alloy and steel to calculate the temperature distribution of the piston surface at different locations using $MgO–ZrO_3$ material as TBC for higher thermal efficiency, improved combustion and reduced emissions. The highest temperature on piston should not exceed 66% of the melting point temperature of the alloy thus limiting the maximum temperature. Zirconia-based ceramic coatings have low conductivity and their relatively high coefficients of thermal expansion which reduce the detrimental interfacial stresses. The Piston was coated with a 350 μm thickness of $MgZrO_3$ over a 150 μm thickness of NiCrAl bond coat. Different boundary conditions were used including ring land, skirt, underside, piston pin and combustion side thermal boundary condition. The inside temperature was estimated to be 650°C with a convection coefficient of 800 W/m^2 K. Similarly, the surface temperatures and convection coefficient for lateral surface, ring temperatures, piston skirt and pin were found. The maximum temperature values for lip of conventional piston bowl, ceramic at the top verge of the piston bowl and base metal were also determined. The surface temperature with AlSi alloy is found to improve approximately 48% via ceramic coating and 35% for the steel piston.

Study of temperature and thermal stress distributions in a plasma sprayed magnesia-stabilized zirconia coating on an aluminium piston crown was done by Cerit and Coban [3] to improve the performance of a diesel engine by determining both temperature and thermal stress distributions on an aluminium piston crown. Since TBCs are applied to substrates to insulate them thermally so as to allow for higher operating temperature, heat transfer between the wall and the gas is also reduced due to reduction in temperature difference between them. NiCrAl is taken as the bond coat which serves as an intermetallic alloy between TBC and metal substrate which reduces the internal stresses which may arise between the substrate and the ceramic coating because of thermal shock and also provides oxidation resistance at high temperatures and aids in the adhesion of the TBC layer to the substrate. The materials and their properties for piston, bond coat and coating materials were suitably taken and different boundary conditions were applied for finite element analysis by ANSYS. The analysis values led to different graphs which show that the temperature and the thermal stress are function of coating thickness. The temperature at the crown face of the piston increases with the increasing thickness of the thermal barrier coating.

The methodology and the coating parameters were obtained using the work of Cerit [4]in the thermal and mechanical analysis of partially coated piston in order to determine the temperature and thermal stress distribution in ceramic coated pistons. Author says that the degree of insulation is an important factor that needs to be investigated for knock free performance. Here TBC was used only near the crevice (not completely coated on the top surface) by removing a layer having a certain thickness and width from the standard piston top surface circumferentially to reduce the cold start HC emission at idle and to improve the performance characteristics at the wide open throttle conditions. A 0.15 mm of NiCrAl bond coat and various thicknesses from 0.05 mm to 1.35 mm of ceramic MgZrO3 layers was coated on the annulus section by using plasma spray coating technique. Steady state thermal and structural analyses were carried out to investigate the effect of thermal barrier coating on temperature gradients and stress distributions by using ANSYS. Effects of different coating thicknesses on the aluminium piston of a single cylinder and water cooled SI engine were investigated to determine the optimum coating thickness that could minimize the surface stress and interfacial stress and the likelihood of coating separation. Piston and rings are made of AlSi alloy and cast iron respectively. These materials were assumed to be linear elastic and isotropic.

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Coating materials selected was stabilized zirconium commonly used in TBCs due to its superior thermal insulating properties, chemical and thermal stability at cryogenic and high thermal applications. Different graphs both the coated and uncoated piston was obtained comparing properties like normal stress, temperature distribution etc with coating thickness and the radial distance. The maximum normal stress, which may cause surface crack, takes place at the middle of the bottom surface of the ceramic coating width in radial direction. When the coating thickness increases gradually, it moves towards the inner edge of the coating. The other maximum normal stress which causes spalling of the ceramic top coat from the bond coat occurs on the bond coat interface. The von Misses stress decreases with increasing coating thickness. The shear stress which causes lateral cracks increases with the coating thickness increase and reaches its maximum level at the inner edge of the coated region at the interface of the substrate. Finally, it was found that the optimum coating thickness for the ceramic coating was slightly below 1 mm.

Hejwowski and Weronski [6] conducted an experimental study on effect of thin thermal barrier coatings on diesel engine performance. Different materials with different coating thickness were taken in order to obtain the variation between engine characteristics (brake power, brake torque, etc.) and engine speed. They concluded that the coating thickness should be kept less than 0.5 mm in order to obtain maximum output and least emissions. The brake torque, brake power and specific fuel consumption was plotted versus the engine speed for different combination of the materials and significant increase in engine performance was found at high engine speeds. Power increased by approximately 8%, brake moment by 6% and exhaust gas temperature was found to be 200K higher than in the engine with metal pistons. Esfahanian*et al*[5] discussed the boundary conditions used for the thermal analysis of SI engine piston thoroughly. Heat transfer to an engine piston crown is calculated using the boundary conditions for ring land, skirt, underside, piston pin thermal and the combustion side. Thermal circuit method is used to model the heat transfer in the ring land and skirt region with the required assumptions. Various equations were used in the determination of the heat transfer coefficients of the piston boundary conditions analytically and through literature survey. Wu-Shung*et al* [8] did an investigation of heat transfer of a reciprocating piston to investigate effects of frequency, amplitude and Reynolds number on heat transfer rate of the piston using simulation of a reciprocating piston cooled by fluid. The larger the frequency, amplitude and Reynolds number are, the apparent enhancements of the heat transfer rate are obtained.

Xiqun Lu *et al* [9] performed the thermal analyses on the marine diesel engine using inverse heat transfer method is employed to conduct thermal numerical analysis on a 4- ring articulated piston of marine diesel engine. Experiment was conducted on a fired engine test rig, consisted of a single-cylinder diesel engine and a hydraulic dynamometer. The instant gas temperature values were calculated according to measured gas pressure in combustion chamber and Woschni formula as followed was employed in this paper to obtain the instant Coefficient of heat Transfer (CoHT). The results obtained using the formulas were almost same as those coming from the experiment. The final CoHT determined according to designed iterative method was applied for thermal analysis.

3. Design and Model of Piston Head Assembly

The dimensions of the piston in consideration was taken that of the Hero Hunk (150 cc) bike [2]. A separate layer of bond coat as well as coating was modelled in SolidWorks itself and assembled with the piston crown. The piston used was of Aluminium Alloy (2618) because of its light weight and acceptable strength. The other materials used for coating and bond coat are tabulated below:

Piston Material	1) Aluminium Alloy (2618)
Types of Slots	1) Horizontal 2) Slanted 3) T- slot
Coating Material	1) $MgZrO_3$ 2) Al_2O_3-TiO_2
Bond Coat	1) NiCrAl
Depth of Coating	1) Bond coat: 0.15 mm 2) Depth of Coating: 0.15 to 1.4 mm

Table 3.1: Materials used for coating and bond coat

The types of slots were carefully chosen from large number of options in order to obtain productive results. Three types of slots were finalized, viz., horizontal, vertical and T-slot. The bond coat used is NiCrAl because of its intermetallic nature between metal substrate and the coating material. The thickness of coating in increased gradually and the assembly is simulated with the same boundary conditions.

3.1 Material Properties

The material properties used for the project was obtained from various literature sources and from the commercial FE analysis package ANSYS. The thermal and mechanical properties of the materials are listed below.[1][4][6]

Material	**E (GPa)**	**1/m (m/m)**	**k (W/m ^{0}C)**	**α*10^{-6} (1/^{0}C)**	**ρ (kg/m^3)**	**C (J/m^{0}C)**
Al Alloy - 2618	74.49	0.33	146	22	2760	875
NiCrAl	90	0.27	16.1	12	7870	764
Al_2O_3-TiO_2	13	0.24	1.4	1.3	3000	800
$MgZrO_3$	46	0.2	0.8	8	5600	650

Table 3.2: Material properties of piston and coating materials [1][4][6]

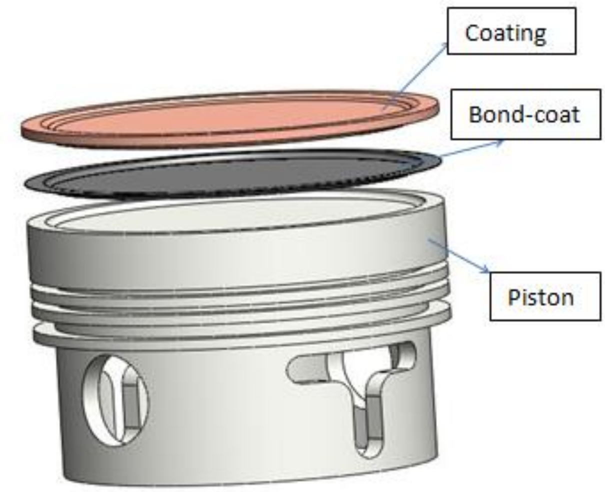

Fig. 3.1 Solid Model of the Piston head Assembly (T-slot)

The separate layers of the bond coat and the thermal coating is clearly visible in the exploded view of the assembly. This is to enable the user to apply different material properties for each individual component.

3.2 Solid Models

Horizontal Slanted T-slot

Fig. 3.2 Solid Model of Different Slots

4. Methodology

The solid model of the piston with thermal barrier coating on the crown surface and the slot on the piston skirt was developed using SOLIDWORKS and the thermal and mechanical stress analysis was carried out on the piston using commercially available CAD package; ANSYS. The dimensions of the piston in consideration was taken that of the Hero Hunk (150 cc) bike. A separate layer of bond coat as well as coating was modelled in SOLIDWORKS itself and assembled with the piston crown. This was to assign different material properties to the piston material, bond coat & coating material separately in ANSYS.
The assembly was imported in ANSYS and the mechanical properties (Poisson's ratio, Young's Modulus, Tensile Strength, etc.) was assigned to each of the material specifically. These properties were obtained through the literature review conducted for this project.
The boundary conditions were applied to the piston crown and the maximum temperature and pressure was applied on it. Proper constraints on the piston skirt were applied and the results were simulated. The result obtained for the specific bond coat and surface coating thickness was observed. Similar studies were conducted on the pistons with different dimensions of coating as well as bond coat. Also, different types of coating materials were also used (with same bond coat NiCrAl) and the results were simulated.
Same experiment was conducted with the piston with different kind of slot and the results obtained for types of coating materials and coating thickness were noted. These results were compared to the simulation results of the uncoated and stock piston (without slot).
Two types of analysis have been done on the model viz., **Thermal Stress Analysis** and **Steady-State Thermal Analysis**. Boundary conditions for various parts of the piston are taken from literature. Using convection coefficient and temperature as parameters for boundary conditions, the temperature and thermal stress distribution on the piston has been obtained. The graphs for various kinds of slots are then plotted between thickness of coating and temperature on the surface of piston crown with and without coating. Analysis has been performed using Al Alloy (2618) as piston material, $MgZrO_3$ as the coating material and NiCrAl as the bond coat all the type of piston slots. The same analysis for other combination of materials for both piston and coating (Al Alloy (2618), Al_2O_3-TiO_2,) is performed. The maximum temperature observed in the coated as well as uncoated assembly is plotted against the coating thickness on the same graph in order to compare the difference due to coating. These graphs were drawn for the combinations pistons with different slots the coatings applied on the crown surface. The results were compared to the observations of the stock (uncoated) piston.

4.1 Boundary Conditions used for ANSYS analysis of the Assembly

After thorough literature review of numerous research papers, the convection coefficients and ambient temperature were determined will be used in the analyses. The piston is heated at the top surface combustion chamber and cooled using oil cooled circuit around the piston rings.
However, the values are calculated using selective formulas obtained from different research papers because of the complexity of the geometry and the conditions. The final results are depicted below [3].

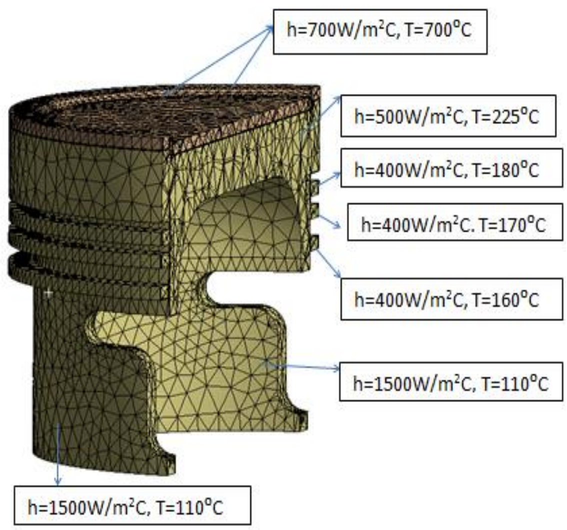

Fig 4.1 Boundary Conditions for ANSYS [3]

4.2 Steady-state Thermal and Thermal Stress Analysis

Thermal Analysis was carried out in ANSYS on the above described assembly using the boundary conditions as explained below. Thermal stress analysis was carried out on the uncoated piston with different types of slots (viz., T-slot, horizontal, vertical) and total deformation, directional deformation was obtained using the software. Maximum values of the outputs were tabulated and compared. In steady-state thermal analysis, the temperature of the piston top surface with coating was calculated for each individual coating thickness. The temperature of the substrate was also calculated for the same. This procedure was repeated for each type of slots. The analysis showed considerable difference between the maximum temperature of the top coating surface and the substrate temperature. This variation is thoroughly discussed in the results. The temperature distribution of the piston with T-slot is shown below. Also, the directional deformation of the different types of piston slots is also described further.

The thermal stress analysis of various types of piston head assemblies was performed using ANSYS and the maximum total deformation was compared. The deformation observed was least for the piston head assembly with slanted slot. Therefore, the thermal stress analysis was carried out with both the coatings ($MgZrO_3$and Al_2O_3-TiO_2) with gradually increasing coating thickness in order to obtain the variation of total deformation in the piston. The following diagram shows the thermal stress analysis of the piston head assembly with slanted slot and TBC on the crown.

5. Results and Discussions

The following graphs were obtained for the piston with different types of slots with increasing coating thickness with $MgZrO_3$ top coat. The result obtained in the following graph show resemblance with the previous works [3][4].

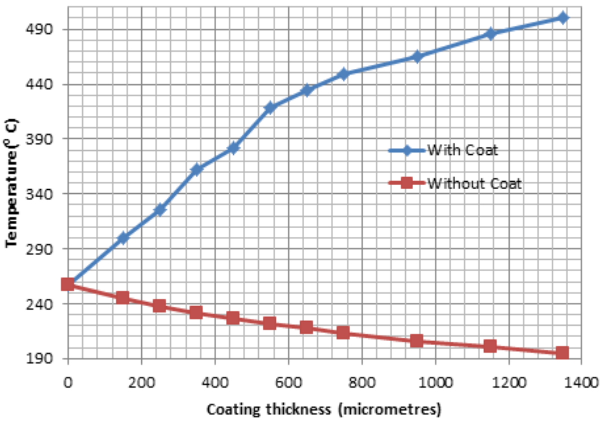

Fig. 5.1 Temperature v/s Coating thickness in Stock piston

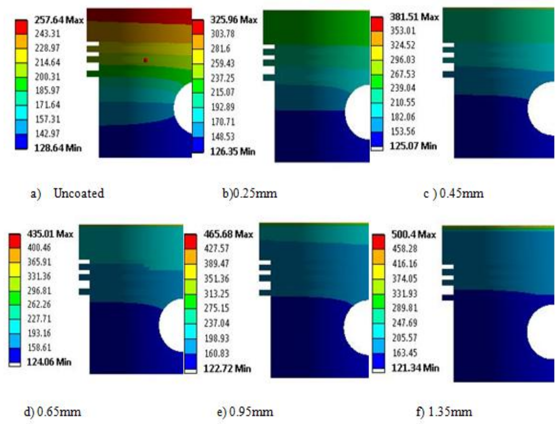

Fig. 5.5 Temperature Distribution of the assembly with top coating surface in Stock Piston with various coating thickness

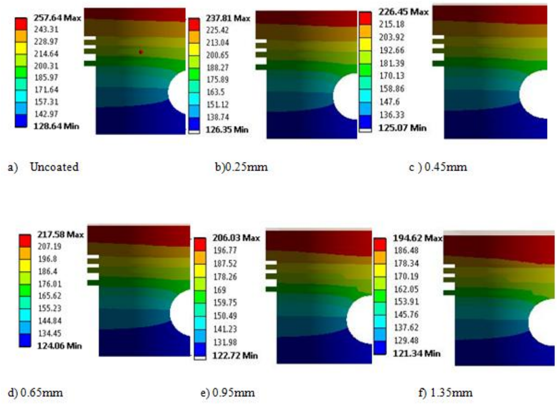

Fig. 5.6 Temperature Distribution of the substrate (without top coat) in Stock Piston with various coating thickness

The temperature contours of piston head assembly with as the stock piston are displayed in further discussion. The temperature difference between the top coat and the metal substrate increases considerably with increase in coating thickness. Similar analysis was performed with the piston head with different types of slots (horizontal, slanted, T-slot) and the above graphs were obtained. The maximum temperature was substantially increased in the piston head assembly with different slots. The gradual variation in the increase of the top surface temperature of the stock piston can be observed in the figures (**Fig 5.5 & Fig 5.6)**.

6. Observations

- According to the analysis performed in ANSYS, as the coating thickness increases, the temperature obtained at the top surface of the piston increases.
- As the coating thickness increases, the temperature obtained at the surface below the bond coat decreases.
- The difference in temperature between the top surface of the coating and the surface below the bond coat (i.e. top surface of the piston without coating) increases as the thickness of coating increases.
- The temperature at the bottom surface of the piston skirt decreases when different kinds of piston slots are used.
- The deformation of the pistons with different slots decreases as compared to the stock piston.

- The thermal stress of the pistons with different slots increases compared to the stock piston.

From the above graphs and contours, it can be concluded that the temperature of the top surface increases substantially when coating ($MgZrO_3$) is applied. The maximum temperature in stock piston without coating was found to be **257.64 °C** whereas the maximum temperature in coated piston with T-slot was observed to be **501.68°C.** Also, the metal substrate temperature decreased from **257.64 °C** to **194.62 °C** in stock piston. However, not much of a difference in maximum temperature was observed in the top coat in piston with different types of slots. The maximum temperature was about **500 °C** in every configuration.

Therefore, the ANSYS analysis in piston head assembly with **T-slot** coated with Al_2O_3-TiO_2 was simulated in order to find the difference in performance of both the coatings in terms of maximum top coat temperature. The temperature contour and the graphs of the above described configuration are plotted further.

6.1 Maximum temperature of the two types of coating materials in Piston head with T-slot ($MgZrO_3$, Al_2O_3-TiO_2)

The following graph **(Fig 6.1)** compares the maximum temperature obtained on the piston top coat with both the materials ($MgZrO_3$, Al2O3-TiO_2) with the temperature obtained on the metal substrate. The maximum value of temperature for **Al_2O_3-TiO_2** was found to be 437.33 ^{0}C for 1.35 mm. Therefore, it is comparatively less efficient than the former one as the maximum temperature reaches about 501 ^{0}C in $MgZrO_3$ coating.

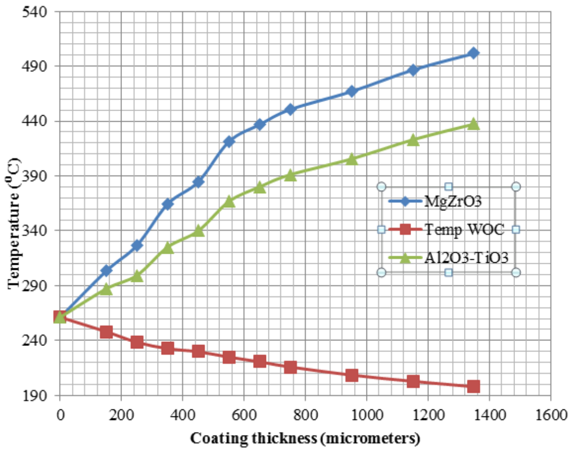

Fig. 6.1 Temperature v/s Coating thickness in T-Slot (both materials)

6.2 Thermal Stress Analysis of piston head assembly

From the **Table 6.1**, it can be concluded that the total deformation decreases in piston head with different slots. It was observed that the total deformation for pistons was found to be least in piston head with slanted slot (about 9 %). Therefore, the further analysis with different coatings was carried out on the piston head with slanted slot.

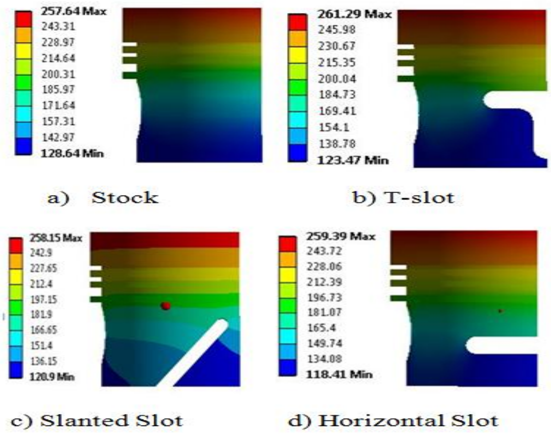

Fig. 6.2 Temperature Distribution in the piston with different types of slots

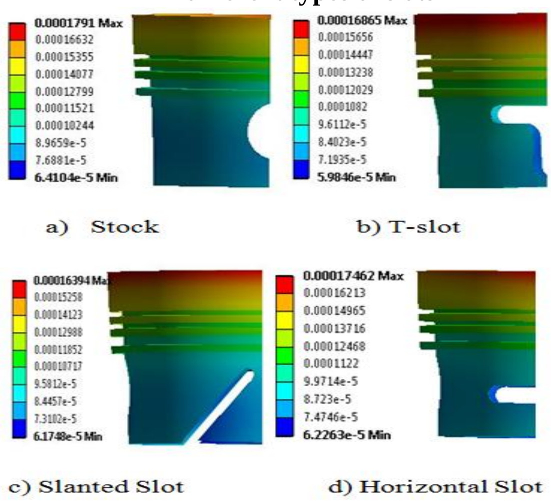

Fig. 6.3 Total deformation in the piston with different types of slots

Type of Piston Slot	Total deformation (in mm)	Directional deformation (in mm)	Equivalent stress $*10^7$ (N/m^2)
Stock	0.1791	0.15765	3.845
T-slot	0.16865	0.15447	4.2505
Horizontal	0.17461	0.16882	4.3524
Slanted	0.16394	0.14022	3.8064

Table-6.1: Maximum Deformation and Von-Mises Stress in Piston with Different Slots

6.3 Maximum total deformation of the two types of coating materials in Piston head with slanted slot ($MgZrO_3$, Al_2O_3-TiO_2)

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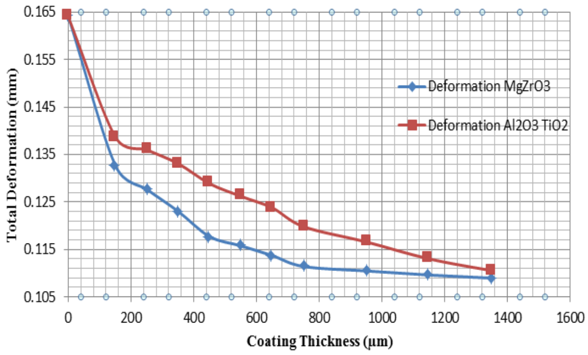

Fig. 6.4 Total deformation v/s coating thickness in two coatings

From the above graph, it can be seen that the deformation in $MgZrO_3$ is comparatively less than that of Al_2O_3-TiO_2 coating. Also, the value of total deformation approaches near constant after a certain coating thickness. In the above graph, the total deformation decreases along with the coating thickness with decreasing rate. For $MgZrO_3$, the total deformation decreases from 0.16394 mm (uncoated) to 0.11142 mm (0.75 mm coating thickness) and further to 0.10897 mm (1.35 mm coating thickness). Therefore, about 33 % decrease in deformation occurs till halfway in the graph and it changes 1 % on application of thicker coatings. Therefore, it is economical to restrict the coating thickness to about 0.75 mm since it shows negligible reduction in total deformation beyond that value.

Conclusions

The temperature of the top surface increases substantially when $MgZrO_3$ coating is applied. The maximum temperature in stock piston without coating was found to be **257.64 ^{0}C** whereas the maximum temperature in coated piston with T-slot was observed to be **501.68^{0}C.** The maximum value of temperature for **Al_2O_3-TiO_2** was found to be **437.33 ^{0}C** for 1.35 mm. Therefore, it is comparatively less efficient than **$MgZrO_3$** coating.The metal substrate temperature decreased from **257.64 ^{0}C** to **194.62 ^{0}C (25%)** in stock piston due to application of thermal barrier coatings.The total deformation decreases in piston head with different slots. It was observed that the **total deformation for pistons was found to be least in piston head with slanted slot (about 9 %).** The deformation in $MgZrO_3$ is comparatively less than that of Al_2O_3-TiO_2 coating. Also, the value of total deformation approaches near constant after a certain coating thickness. Almost 33 % decrease in deformation occurs till 0.75 mm coating thickness and it changes 1 % on further application of coating. Therefore, the efficiency of $MgZrO_3$ top coat piston head was found to be more efficient than Al_2O_3-TiO_2. However, further economic and cost effective analysis must be performed in order to arrive at a final conclusion.As the coating on the piston upper surface is used, the coating absorbs most of heat produced during combustion and thus heat lost decreases.Thus the temperature on the surface of base metal also decreases due to which less heat flow to the bottom part of the piston i.e. piston skirt.The temperature at the surface of the coated region is significantly higher than that of the uncoated piston surface and this higher combustion chamber temperature is provided by means of coating.As a result, thermal efficiency of the engine increases. Use of coating for pistons increases the temperature of the combustion chamber of the engine and the thermal strength of the base metal. Cooling load of the engine would decrease accordingly.

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