THERMAL ANALYSIS OF IC ENGINE PISTON AND COMPARISON BETWEEN ALUMINIUM, ZIRCONIUM WITH TITANIUM COATINGS BY USING FEM

S USHA KIRAN
THERMAL ENGINEERING,
MECHANICAL DEPT
QIS COLLEGE OF ENGINEERING AND TECHNOLOGY
Email:sandipaguushakiran@gmail.com

Dr M.V. MALLIKARJUNA
AMIE(I), MTech, Ph.D
PROFESSOR and HOD
MECHANICAL DEPT
Email:qiscetac@gmail.com

ABSTRACT

Piston is the 'heart' of the automobile engine. It's one of the key components of the engine and it's working the hard condition which accelerated the piston wear and broken. A good design of the piston in this project is compared with existing piston to extend the Mean Time between Maintenance. In order to achieve the deformation, thermal and stress distribution of the piston, ANASYS software is used to analyze the piston under the thermal loads and mechanical loads. The results are shown that the temperature distribution occurs on the top of the piston when the piston under the thermal load and the greatest stress occurs on the piston pin when the piston under the thermal-structure coupling. The temperature distribution is conformed to the facts, but the greatest stress is a bit large when coupling.
keywords: piston design, coating materials, High strength alloys, FEA.

INTRODUCTION

Functionally graded materials are of widespread interest because of their superior properties such as corrosion, erosion and oxidation resistance, high hardness, chemical and thermal stability at cryogenic and high temperatures. These properties make them useful for many applications, including Thermal Barrier Coating (TBC) on metallic substrates used at high temperatures in the fields of aircraft and aerospace, especially for thermal protection of components in gas turbines and diesel engines.

Thermal barrier coatings have been successfully applied to the internal combustion engine, in particular the combustion chamber in order to simulate adiabatic changes. The objectives are not only for reduced in-cylinder heat rejection and thermal fatigue protection of underlying metallic surfaces, but also for possible reduction of engine emissions and brake specific fuel consumption. The application of TBC reduces the heat loss to the engine cooling-jacket through the surface exposed to the heat transfer such as the cylinder head, liner, piston crown and piston rings. The insulation of the combustion chamber with ceramic coating affects the combustion process and, hence, the performance and exhaust emissions characteristics of the engines improve. On the other hand, the desire of increasing the thermal efficiency or reduce fuel consumption of engines leads to the adoption of higher compression ratios, in particular for diesel engines, and reduced in-cylinder heat rejection. Both of these factors cause increased mechanical and thermal stresses of materials used in combustion chamberThe application of TBC to the surfaces of these components enhances high temperature durability by reducing the heat transfer and lowering temperature of the underlying metal. Typical TBCs failure is by spalling of the ceramic top coat from the bond coat. There are many factors that influence the overall performance of coatings and cause spalling of the coating. However oxidation and thermal mismatch are identified as two major factors influencing the life of the coating system. The coatings are permeable to the atmospheric gases and liquids resulting in the oxidation of the bond coat and spalling of the coating.

In this paper, the main emphasis is placed on the study of thermal behavior of functionally graded coatings obtained by means of using a commercial code, ANSYS on aluminum and steel piston surfaces and the results are verified with numerical and experimental works.

COATINGS

Coating is a covering that is applied to an object. The aim of applying coatings is to improve surface properties of a bulk material usually referred to as a substrate. One can improve amongst others appearance, adhesion, wet ability, corrosion resistance, wear resistance, scratch resistance, etc. They may be applied as liquids, gases or solids. Coatings can be measured and tested for proper opacity and film thickness by using a Drawdown card.

NANO COATING:

Nano-coating is a recently developed technology used for coating any kind of material in hard coating and low friction coating both in which coating is done at nano scale that is of the order of 10-9 . The two major types of nano coating are

1. Physical vapour deposition (PVD)

2. Chemical vapour deposition (CVD)

PHYSICAL VAPOUR DEPOSITION (PVD)

Thin film deposition is a process applied in the semiconductor industry to grow electronic materials and in the aerospace industry to form thermal and chemical barrier coatings to protect surfaces against corrosive environments and to modify surfaces to have the desired properties. The deposition process can be broadly classified into physical vapour deposition (PVD) and chemical vapour deposition (CVD). In CVD, the film growth takes place at high temperatures,
leading to the formation of corrosive gaseous products, and it may leave impurities in the film. The PVD process can be carried out at lower deposition temperatures and without corrosive products, but deposition rates are lower and
it leaves residual compressive stress in the film. Electron beam physical vapour deposition, however, yields a high deposition rate from 0.1 μm / min to 100 μm /
min at relatively low substrate temperatures, with very high material utilization
efficiency.

Parameters of PVD

Deposition chamber vacuum pressure: 10-3 tor No of electron guns: 6
Accelerating voltage: 20kv-25kv
Evaporation rate: 10-2 g/cm2sec

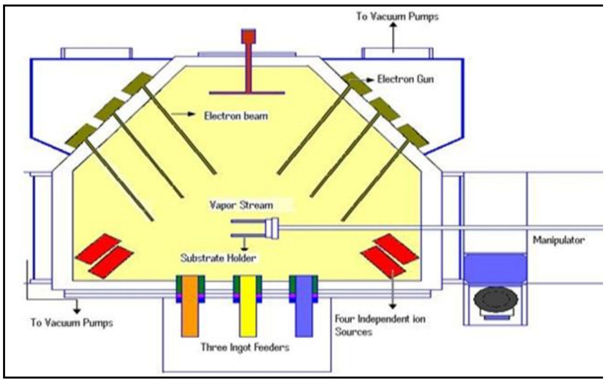


Fig 1 Electron beam deposition physical vapour method

LITERATURE SURVEY

Thermal behavior of functionally graded coatings on AlSi and steel piston materials were investigated by means of commercial code, namely ANSYS. Thermal analysis were employed to deposit metallic, cermets and ceramic powders such as NiCrAl, NiCrAl+MgZrO3 and MgZrO3 on the substrate. The numerical results of AlSi and steel pistons were compared with each other. The maximum surface temperature of coated AlSi and coated steel piston were compared with their corresponding uncoated piston. The heat resistance of each piston was compared.

The resistance of the coated piston was found more than the uncoated aluminium piston by 14.5%. The resistance of the piston was found more than uncoated steel piston by 11.3%. The coated piston yields comparatively less wear wit uncoated piston. This is one of the first few papers that deal with studies for nanostructure coatings. In this paper three different applications were discussed. Conventional air plasma spray of nano crystalline alumina-titania ware coatings for turbine applications was studied. Finally a brief mention of recent progress in spraying dense materials for use a standalone ceramics is been studied. Also the various coating thickness on the component were discussed.

Finite Element Method

Definition of FEM is hidden in its words itself. Basic theme is to make calculations at only limited (Finite) number of points and then interpolate the results for entire domain (surface or volume). It is a numerical method which uses mathematical representation of actual problem and gives approximate results.

Finite: Any continuous object has infinite degrees of freedom & it's just not possible to solve the problem in this format. Finite Element Method reduces degrees of freedom from Infinite to Finite with the help of discretization i.e. meshing (node & elements).

Element: All the calculations are made at limited number of points known as nodes. Entity joining nodes and forming a specific shape such as quadrilateral or triangle etc. is known as Element. To get value of variable (say displacement) anywhere in between the calculations points, interpolation function (as per the shape of element) is used.

INTRODUCTION TO ANSYS

ANSYS is commercial 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 behavior 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 tabulated or graphical forms. This type of analysis is typically used for the design and optimization of a system far too complex to solve analytically. Systems that may fit into this category are too complex due to their geometry, scale, or governing equations.

Structural

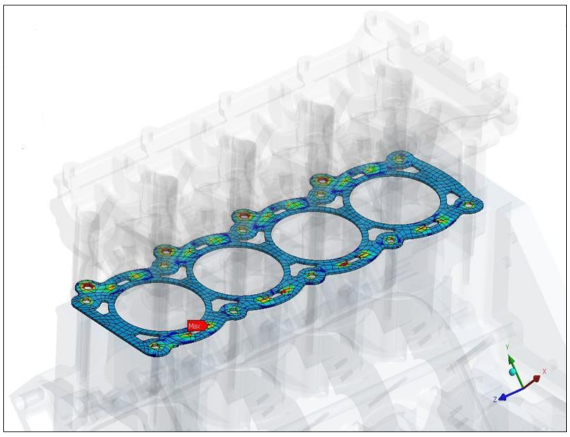


Figure 2: Structural Analysis

Thermal

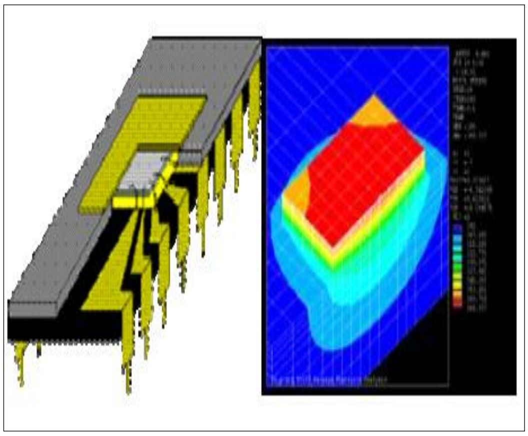


Figure 3: Thermal Analysis

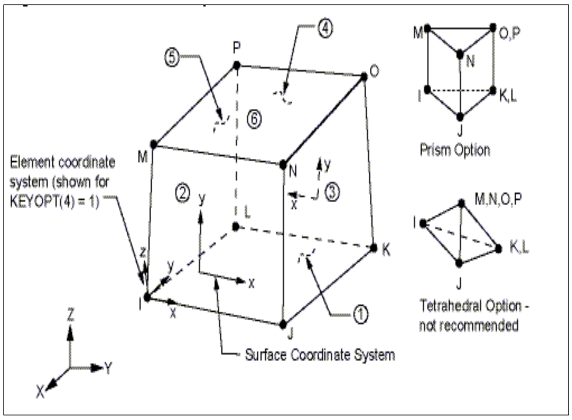


Figure 4:SOLID45 Geometry

MODELING AND MESHING

The geometric modelling can be done with the help of computer aided software's like Ideas, Pro-E, and Catia etc. In this analysis the model is created with the help of Catia V5 and the model is saved as step file or iges file. Iges file is having less data loss when compared to other file formats. Once model is generated in Catia, the file is exported from Catia in the required format for further analysis.

Procedure for Piston Design

The procedure for piston designs consists of the following steps:

- Thickness of piston head (tH)
- Heat flows through the piston head (H)
- Radial thickness of the ring (t1)
- Axial thickness of the ring (t2)
- Width of the top land (b1)
- Width of other ring lands (b2)

The above steps are explained as below:

Thickness of Piston Head (th)

The piston thickness of piston head calculated using the following Grashoff's formula,

$$t_H = \sqrt{(3pD^2)/(16\sigma_t)} \text{ in mm}$$

Where

P= maximum pressure in N/mm²

D= cylinder bore/outside diameter of the piston in mm.

□t=permissible tensile stress for the material of the piston.

Here the material is a particular grade of AL-Si alloy whose permissible stress is 50 Mpa-

90Mpa.

Before calculating thickness of piston head, the diameter of the piston has to be specified.

The piston size that has been considered here has an L*D specified as 152*140.

Heat Flow through the Piston Head (H)

The heat flow through the piston head is calculated using the formula

H = 12.56*tH * K * (Tc-Te) Kj/sec

Where,

K=thermal conductivity of material which is 174.15W/mk

Tc = temperature at center of piston head in °C.

Te = temperature at edges of piston head in °C.

Radial Thickness of Ring (t1)

t1 = D□3pw/□t

Where D = cylinder bore in mm Pw= pressure of fuel on cylinder wall in N/mm^2. Its value is limited from $0.025N/mm^2$

to $0.042N/mm^2$. For present material, □t is 90Mpa

Axial Thickness of Ring (t2)

The thickness of the rings may be taken as

t2 = 0.7t1 to t1

Let assume t2 =5mm

Minimum axial thickness (t2)

= D/(10*nr)

Where nr = number of rings

Width of the top land (b1)

The width of the top land varies from

b1 = tH to 1.2 tH

Width of other lands (b2)

Width of other ring lands varies from

b2 = 0.75t2 to t2

Maximum Thickness of Barrel (t3)

t3 = 0.03*D + b + 4.5 mm

Where

b = Radial depth of piston ring groove

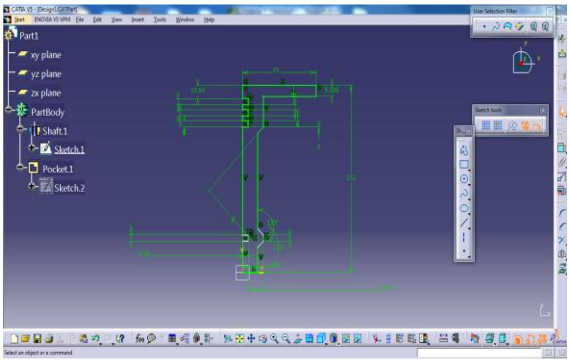
Thus, the dimensions for the piston are calculated and these are used for modelling the piston in CATIA. In the above procedure the ribs in the piston are not taken into consideration, so as make the piston model simple in its design. In modelling a piston considering all factors will become tedious process. Thus, a symmetric model is developed using the above dimensions.

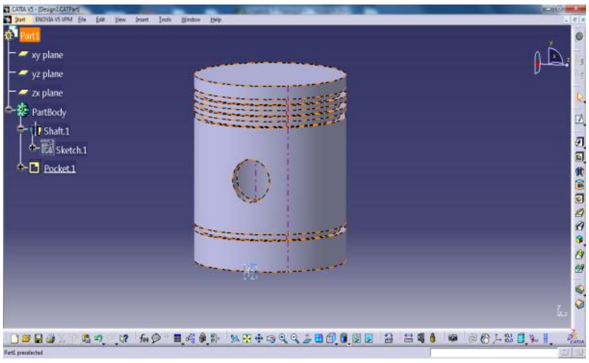
DESIGN1 – PARAMETERS:

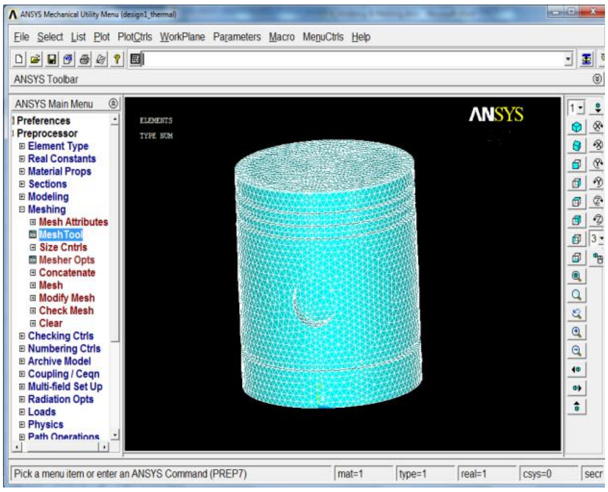
S No	Design1 - Dimensions	Size in mm
1	Length of the Piston(L)	152
2	Cylinder bore/outside diameter of the piston(D)	140
3	Thickness of piston head (tH)	9.036
4	Radial thickness of the ring (t1)	5.24
5	Axial thickness of the ring (t2)	5
6	Width of the top land (b1)	10.84
7	Width of other ring lands (b2)	4

DESIGN2 – PARAMETERS:

S No	Design 2 -Dimensions	Size in mm
1	Length of the Piston(L)	152
2	Cylinder bore/outside diameter of the piston(D)	140
3	Thickness of piston head (tH)	9.036
4	Radial thickness of the ring (t1)	4
5	Axial thickness of the ring (t2)	4
6	Width of the top land (b1)	9.36
7	Width of other ring lands (b2)	3







ANALYSIS RESULTS & DISCUSSIONS

Analysis is the process of breaking a complex topic or substance into smaller parts to gain a better understanding of it. The current model is undergone Thermal Analysis and followed by Static Analysis, together called as Coupled Filed Analysis. The Steps involved in the thermal analysis is explained as below.

THERMAL ANALYSIS

The basis for thermal analysis in **ANSYS** is a heat balance equation obtained from the
principle of conservation of energy. The finite element solution performed is via ANSYS which calculates nodal temperatures, and then uses the nodal temperatures to obtain the other thermal quantities. Only the ANSYS Multi physics, ANSYS Mechanical, ANSYS Professional, and ANSYS FLOTRAN programs support thermal analyses. The ANSYS program handles all three primary modes of heat transfer: conduction, convection, and radiation.

CONVECTION MODE OF HEAT TRANSFER

The convection is specified as a surface load on conducting solid elements or shell elements. The convection film coefficient and the bulk fluid temperature at a surface; **ANSYS** then calculates the appropriate heat transfer across that surface. If the film coefficient depends upon temperature, a table of temperatures is specified along with the corresponding values of film coefficient at each temperature.

For use in finite element models with conducting bar elements (which do not allow a convection surface load), or in cases where the bulk fluid temperature is not known in advance, ANSYS offers a convection element named LINK34. In addition, you can use the FLOTRAN CFD elements to simulate details of the convection process, such as fluid velocities, local values of film coefficient and heat flux, and temperature distributions in both fluid and solid regions.

RADIATION MODE OF HEAT TRANSFER

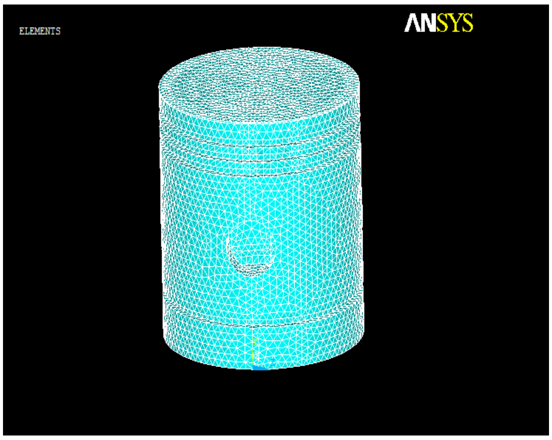
ANSYS can solve radiation problems, which are nonlinear, in four ways:

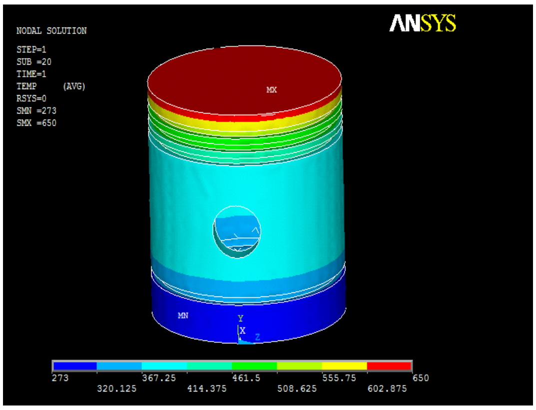
By using the radiation link element, LINK31 By using surface effect elements with the radiation option (SURF151 in 2-D modelling or SURF152 in 3-D modelling) by generating a radiation matrix in AUX12 and using it as a super element in a thermal analysis.

Typical applications can solve with ANSYS by using coupled field analysis:

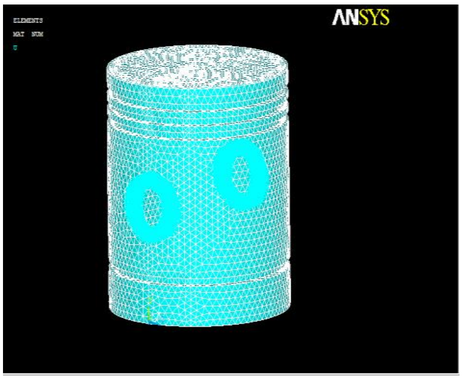
- Thermal stress
- Induction heating
- Induction stirring
- Steady-state fluid-structure interaction
- Magneto-structural interaction
- Electrostatic-structural interaction
- Current conduction-magneto statics

Optimization-design

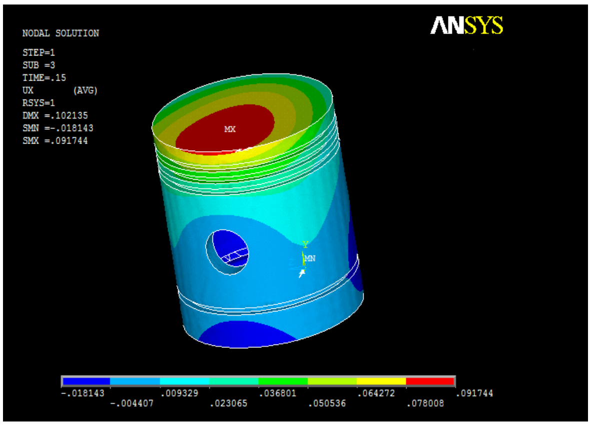


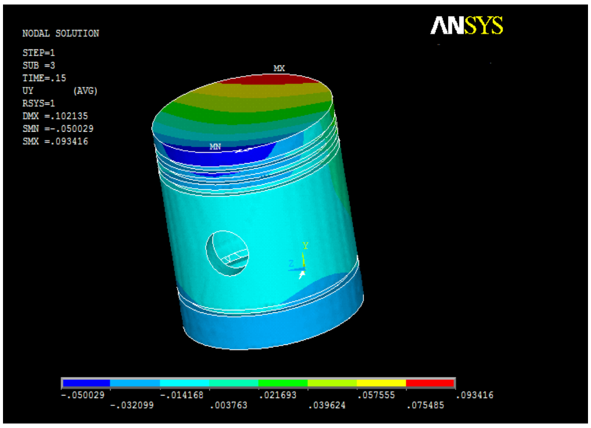


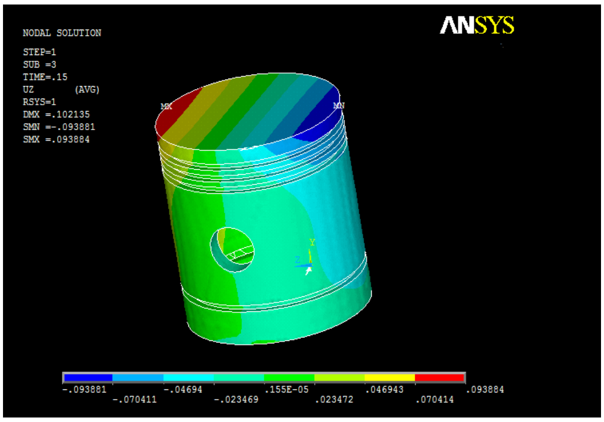
Static Analysis

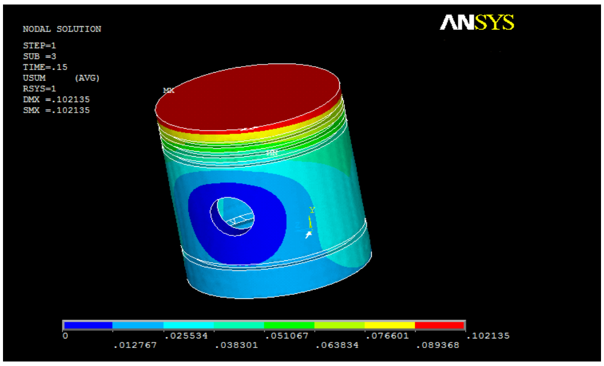


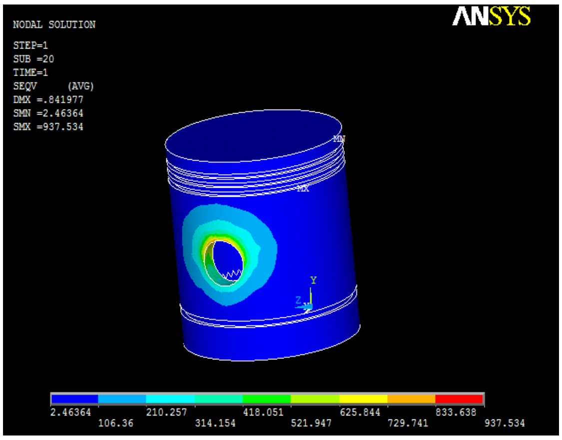
Deformation Plots for Uncoated Aluminium Piston for Design1:



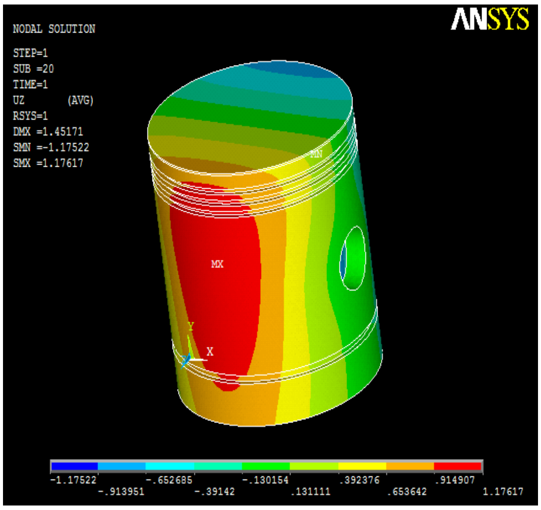


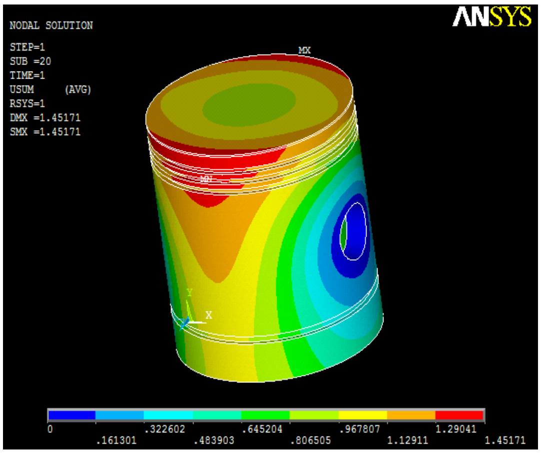


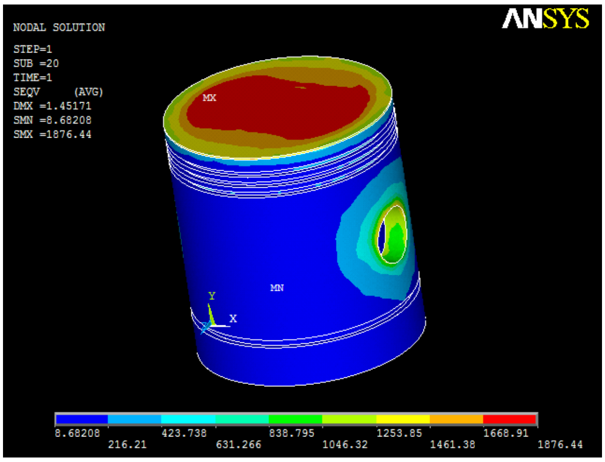


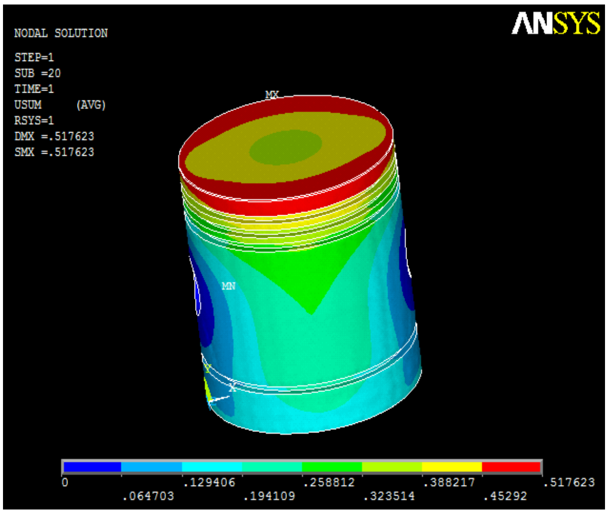


Deformation Plots for Coated Zirconium Piston for Design1:



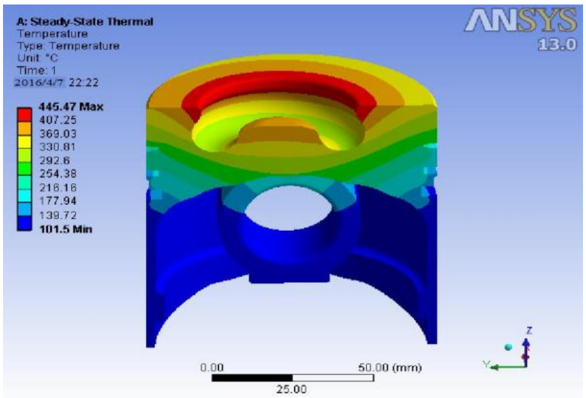




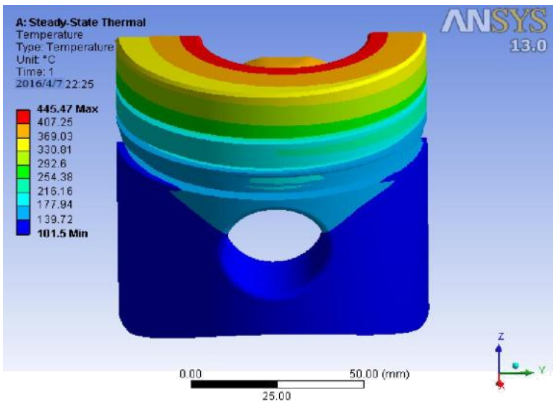


Results of temperature distribution

Figures show the temperature distribution of piston



The temperature field of piston in the thermal load acts (Internal)

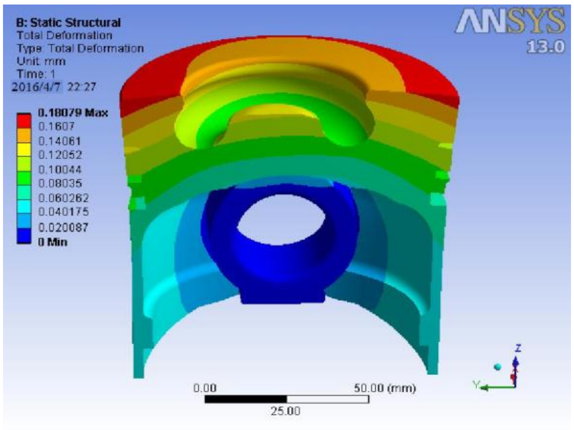


temperature field of piston in the thermal load acts (External)

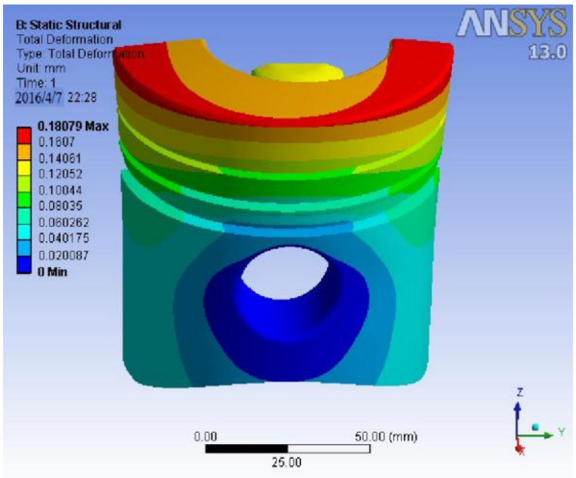
The temperature distribution of the piston is uneven, with the maximum value of 445.5 °C and the minimum value of 101.5 °C. There is a big range of temperature distribution on the top surface of the piston area. The temperature is higher at the combustion chamber side of the deviation from the center of the piston. Highest temperature appears in the throat of the exhaust port of the combustion chamber adjacent side, the temperature reached 445.5 °C. The lowest temperature of the top surface of the piston edge is on the inlet side with 292 °C. The temperature was gradually reduced with the increase of the piston radius. The D-value between maximum temperature and minimum temperature on the top surface is 38 °C. The maximum temperature of the first piston ring groove zone appears in the exhaust side of the annular groove end surface reaches 300 °C. The maximum temperature on skirt portion is 177 °C, while a minimum of 101.5 °C, and the temperature difference is 70 °C. The maximum temperature on the inner cavity of piston is 254.5 °C which at the back of the combustion chamber.

Deformation Plots for Coated Titanium alloy Piston for Design1

Results of deformation distribution



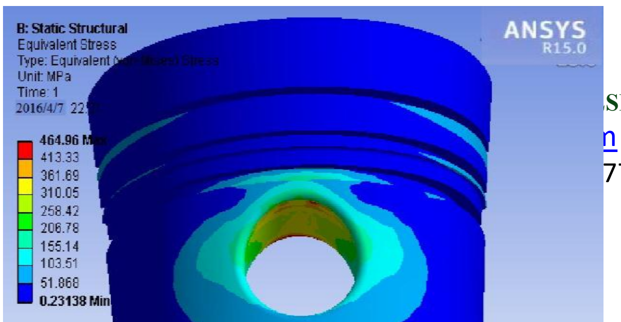
Temperature distribution in the thermal and force coupling

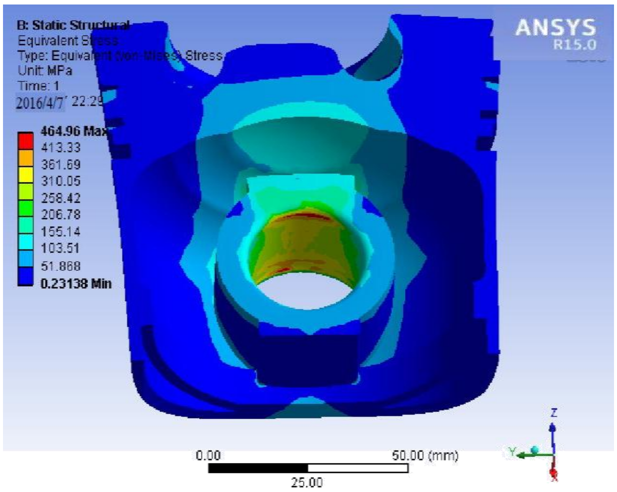


Temperature distribution in the thermal and force coupling

The figures are the deformation contours of the piston under the mechanical and thermal loads. From the figure, it's obvious to see that the edge of the top of the piston and fire shore have the biggest deformation. The value is between 0.16~0.18mm. For overall analysis of the piston, from top to bottom of the piston cylindrical, deformation decreases gradually and then gradually increase.

Results of stress distribution





Stress distribution in the thermal and force coupling

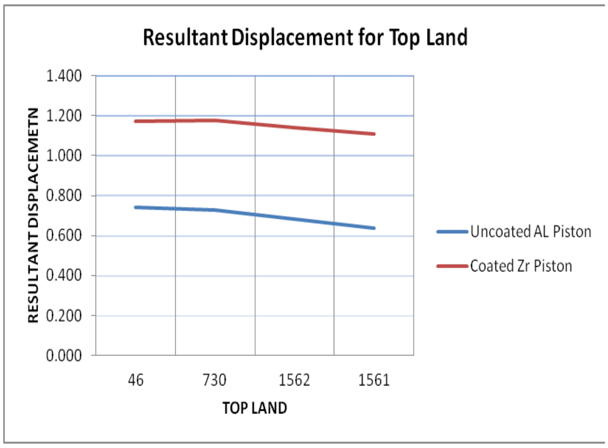
Stress distribution in the thermal and force coupling (Internal)

Figures show the stress map when the piston under the joint action of the temperature and the side thrust. The largest stress produces on the top of the piston pin boss, the value is 465Mpa. The result shows that the temperature contributed a great deal on the piston stress. The values of the most sections of the piston are under 100Mpa.

CONCLUSIONS

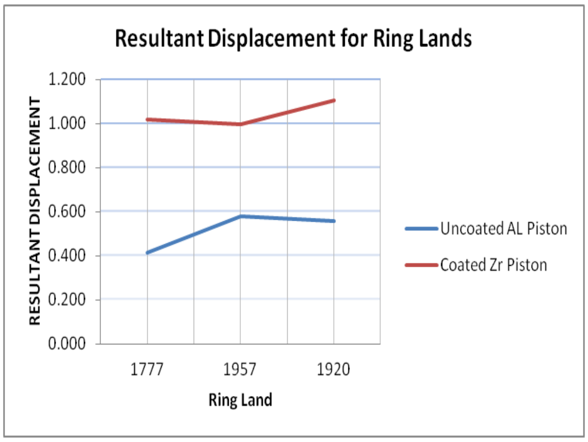
A finite element model of the piston without and with coating layer is created in **ANSYS** and analyzed in the influence of thermal load on the top surface of the piston. The results are analyzed and concluded as follows

Resultant Displacement comparison for Top Land for Uncoated and Coated Piston for Design1:



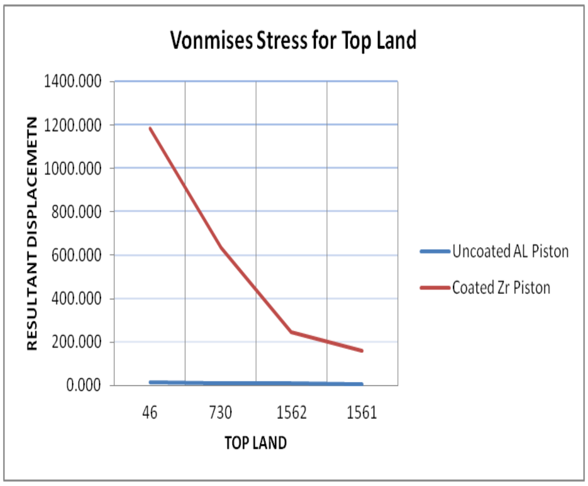
From the above graph it can be concluded that coated zirconium piston has more resultant displacement when compared to the Uncoated AL Piston.

Resultant Displacement comparison for Ring Land for Uncoated and Coated Piston for Design1:



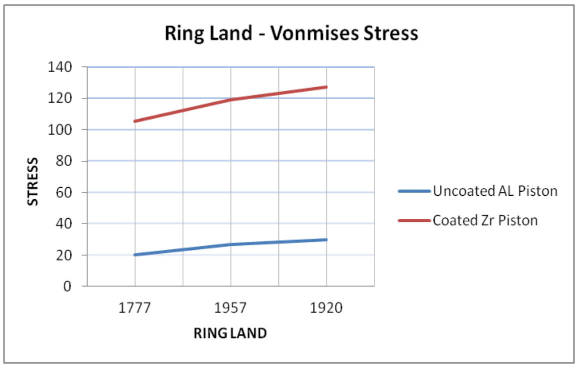
From the above graph it can be concluded that coated zirconium piston has more resultant displacement when compared to the Uncoated AL Piston.

Vonmises Stress comparison for Top Land for Uncoated and Coated Piston for Design1:



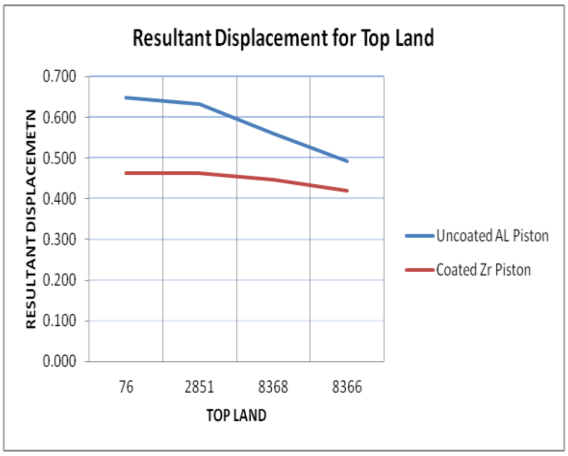
From the above graph it can be concluded that coated zirconium piston has more resultant Vonmises Stress when compared to the Uncoated AL Piston.

Vonmises Stress comparison for Ring Land for Uncoated and Coated Piston for Design1:



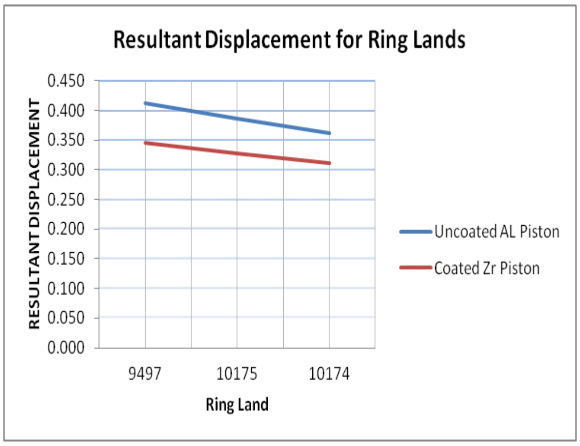
From the above graph it can be concluded that coated zirconium piston has more resultant Vonmises Stress when compared to the Uncoated AL Piston.

Resultant Displacement comparison for Top Land for Uncoated and Coated Piston for Design2:



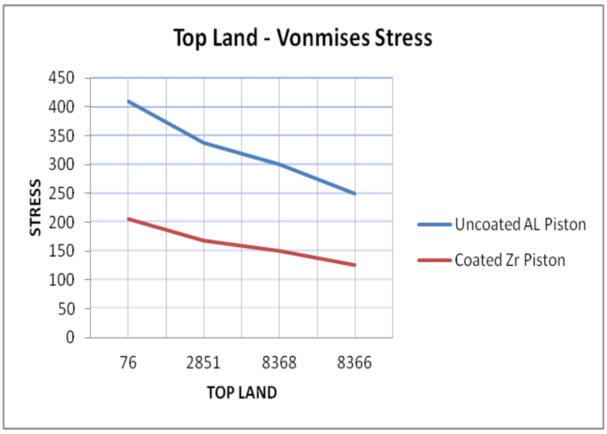
When compared to Design1, optimized design 2 has better resultant displacement for the coated Zr piston, when compared with the uncoated with the Aluminium Piston.

Resultant Displacement comparison for Ring Land for Uncoated and Coated Piston for Design2:

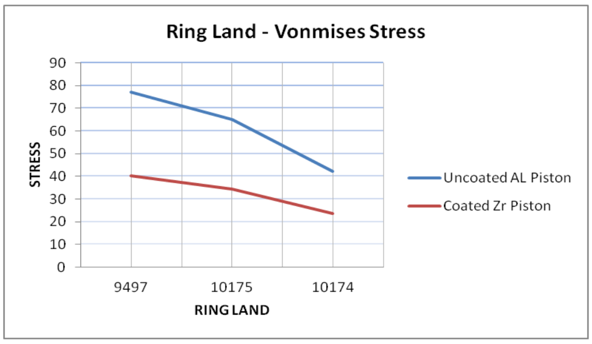


When compared to Design1, optimized design 2 has better resultant displacement for the coated Zr piston, when compared with the uncoated with the Aluminium Piston.

Vonmises Stress comparison for Top Land for Uncoated and Coated Piston for Design2:



Vonmises Stress comparison for Ring Land for Uncoated and Coated Piston for Design2:



The thermal stresses of both coated and uncoated pistons are obtained and compared. The maximum thermal stress of Zirconium is low as compared to the maximum thermal stress obtained by the uncoated aluminium piston. The Contour plots for the deformations and as well as for stresses already shown in the earlier chapter. As the thermal stresses are reduced, the heat transfer in the piston is also reduced resulting in increased combustion which should result with the increase in engine power.

Comparison between aluminium and titanium coating alloys

The aluminum alloy of coating piston was chosen to compare with titanium coating piston, the results of stress distribution, temperature distribution and coupling stress distribution of these two pistons are shown as table below.

Resuts comparison

Type	Aluminum alloy	Titanium alloy
Stress		
	The maximum stress occurs on	The maximum stress occurs on
	the up edge of the piston pin, the	the up edge of the piston pin,
	value is 860Mpa.	the value is 465Mpa.
Temperature		
	The maximum temperature	The maximum temperature
	occurs on the junction of the top	occurs on the junction of the top
	surface of the piston and	surface of the piston and
	combustion chamber, the value is	combustion chamber, the value
	267 °C.	is 445 °C.

The table shows that the titanium alloy piston has better performance in stress field and deformation field. And the temperature of titanium alloy is more than aluminum alloy in working area. Considering that the melting point of aluminum is 500 °C and for titanium is 1700 °C, regarding to its melting point, we improved it by 25%. A conclusion can be drawn that titanium has better thermal property than aluminum.

When under the assembly of mechanical and thermal loads, the value of the largest displacement is 0.16~0.18mm, causing at the edge of the piston top and the fire shore. 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.

The result showed that titanium alloy piston has a better performance in stress and deformation in comparison with aluminum alloy. Considering that the melting point of aluminum is 500 °C and for titanium is 1700 °C, regarding to its melting point, we improved it by 25%. A conclusion can be drawn that titanium has better thermal property than aluminum.

REFERENCES

1. Ekrem Buyukkaya, "Thermal Analysis of functionally graded coating AlSi alloy and steel pistons", Surface and coatings technology (2007)

2. Reinhold H. Dauskardt, "THERMAL BARRIER COATINGS" (1999).

3. M. Foy, M. Marchese, G. Jacucci, Engineering plasma spray films by knowledge based simulations proceedings of IFIP conference on, in: Arthur B. Baskin, et al., (Eds.), Cooperative Knowledge Processing for Engineering Design, Kluwer Academic Publishers, The Netherlands, 1999, p. 289.

4. J.S. Lee, T. Matsubara, T. Sei, T. Tsuchiya, J. Mater, Preparation and properties of Y2O3-doped ZrO2 thin films by the sol-gelprocess, Surface Coating Technology (1997).

5. J.N.Reddy, "An introduction to finite element analysis".

6. Zhang T, Xu L, Xiong W, et al. Experimental research on the thermal contact resistance between Cu-Cu in vacuum and low temperature. Cryogenics, 1999.

7. ANSYS manual guide.

8. www.sciencedirect.com

9. www.azom.com - "Functionally Graded Materials (FM) and Their Production Methods".