

Design and Structural Analysis of Ceramic Coated Petrol Engine Piston Using Finite Element Method

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ABSTRACT: Piston is made of aluminium alloys is a crucial part in internal combustion engine. When the combustion of fuel take place insides the engine cylinder, high pressure and high temperature will be developed as the engine will operate at high load and at high speed. As a result of this high thermal and high structural stresses in the piston is produced inside the engine cylinder and if these stresses exceeds the designed values, the failure of piston take place. To avoid the failure of the piston thermal and structural intensity should be reduced to safe allowable limits. In this work an attempt is made to reduce the thermal and structural stress intensity by coated the piston with ceramic material. The zirconia-based ceramic coatings are used as thermal barrier coatings owing their low conductivity and their relatively high coefficient of thermal expansion. Firstly the structural and thermal stresses analyses are investigated on a conventional (uncoated) piston made of aluminium alloy namely A2618. Secondly the structural and thermal analyses are performed on the piston coated with zirconium material using the ANSYS software. The effects of coating on the thermal behaviours of the piston are investigated. The main objective is to investigate and analyse the structural and thermal stress distribution of the piston at the real engine condition during combustion process. The analysis is carried out to reduce the stress concentration on the upper end of the piston .i.e. piston head/crown and piston skirt and sleeve using ANSYS software. The result obtained is compared to select the better material for piston manufacturing.

KEYWORDS: Engine piston, thermal analysis, structural analysis, FE analysis.

I.INTRODUCTION

Automobile components are in great demand these days because of increased use of automobiles. The increased demand is due to improved performance and reduced cost of these components. Research & development and testing engineers should develop critical component in shortest possible time to minimize launch time for new products. This necessitates understanding of new technologies and quick absorption in the development of new product. A piston is a component of reciprocating IC engines. It is moving component that is contained by a cylinder and is made gas-tight by piston rings. The piston of an internal combustion engine receives the impulse from expanding gas and transmits it to the connecting rod. The combustion of gas on the top of piston generates considerable amount of heat and the piston must also transmit heat to the cylinder walls from where it is absorbed by cooling water or air. The modern IC engines run around 5000 rpm and hence will generate considerable inertia force which can be controlled if piston is light weight. In an engine its purpose is to transfer force from expanding gas in the cylinder to the crank shaft via a piston rod or connecting rod. It is the important part in an engine, piston endures the cyclic gas pressure and the inertial force at work and this working condition may cause the fatigue damage of piston, such as piston side wear, piston head/crown cracks and so on. The investigation indicates that the greatest stress appears on the upper end of the piston and stress concentration is one of the main reasons for fatigue failure. On the other hand piston overheating –seizure can only occurs when something burns or scrapes away the oil film that exists between the piston and the cylinder wall. A piston is a component of reciprocating engines, reciprocating pump and gas compressors a moving component that is contained by a cylinder and is made gas-tight by piston rings. In an engine, its purpose is to transfer force from

International Journal of Innovative Research in Science, Engineering and Technology

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Vol. 4, Issue 6, June 2015

expanding gas in the cylinder to the crankshaft via a piston rod and connecting rod. In a pump, the function is reversed and force is transferred from the crankshaft to piston for the purpose of compressing or ejecting the fluid in the cylinder.

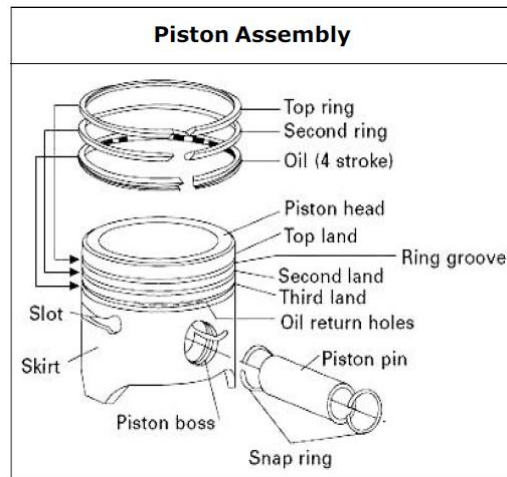


Fig.1 showing assembly of Piston

1.1 RESEARCH OBJECT- PISTON

Engine piston is most complex part compared to other components in an automobile sector. Still lots of research work have been conducting on piston regarding material composition, geometry and manufacturing technique. The function of the internal combustion engine piston is to receive the energy from expanding gasses after during combustion and transmit it to the crankshaft by means of connecting rod. Piston expands appreciably when it gets heated during the operation so actual clearances need to be given otherwise it will lead to engine seize. And hence to avoid this case pistons are made up of cast aluminium alloy matrix with the combination of reinforcement in different weight percentage. For the better result here replace the conventional piston material (uncoated) with coated material. The zirconia-based ceramic coatings are used as thermal barrier coatings owing their low conductivity and their relatively high coefficient of thermal expansion. The addition of coating material to the aluminium matrix improves the tensile strength, compressive strength, hardness and thermal behaviours. The coated material is having more factor of safety compare to uncoated alloy material because of more yield strength at elevated temperature due to presence of the coating in the alloys.

Thermal Barrier Coatings in petrol engines lead to advantages including higher power density, fuel efficiency, and multi fuel capacity due to higher combustion chamber temperature. Using thermal Barrier Coatings can increase engine power and decrease the specific fuel consumption and increase the exhaust gas temperature. Although several systems have been used as thermal barrier coatings for different purposes, zirconium has received the most attention. Several important factors playing an important roles in thermal barrier coatings lifetimes including thermal conductivity, thermal, chemical stability at the service temperature, high thermo- mechanical stability to the maximum service temperature and the thermal expansion coefficient.

Piston of the engine piston must possess the following characteristics:

- Strength to resist gas pressure.
- Strength to resist inertia forces.
- Must have minimum weight.
- Must be able to reciprocate with minimum noise.
- Must have sufficient bearing area to prevent wear.
- Must seal the gas from top and oil from the bottom.
- Must disperse the heat generated during combustion.

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 6, June 2015

- Must have good resistance to distortion under heavy forces and high temperature.

The paper describes the materialistic optimization with using finite element analysis technique to predict the higher stress and critical region on the component. The optimization is carried out to reduce the stress concentration on the upper end of the piston i.e. (piston head/crown and piston skirt and sleeve). With using computer aided design (CAD), Unigraphics (UG NX-8) software the structural model of a piston will be developed. Furthermore, the finite element analysis performed with using ANSYS software.

1.2 CHARACTERIZATION OF MATERIAL

The material chosen for this work are A2618 as base material for a combustion engine piston. The relevant mechanical and thermal properties of A2618 aluminum alloys are listed in the below table 1. The zirconia-based ceramic coatings are used as thermal barrier coatings owing to their low conductivity and their relatively high coefficients of thermal expansion, which reduce the detrimental interfacial stresses. Material properties of the MgZrO₃, NiCrAl and piston material made of A2618 alloy. Piston is coated with a 350 μm thickness of MgZrO₃ over a 150 μm thickness of NiCrAl bond coat as shown below table 2

Table 1 Material properties of aluminium alloy

S/no.	Parameter	A2618	Unit
1	Elastic Modulus	73.7	Gpa
2	Ultimate Tensile strength	480	Mpa
3	0.2% yield strength	420	Mpa
4	Poisson's ratio	0.33	
5	Thermal conductivity	147	W/m°C
6	Coefficient of thermal expansion	25.9x10 ⁻⁶	1/ °C
7	Density	2767.99	Kg/m ³

Table 2 Material properties of coating material

S/no	Parameter	NiCrAl	MgZrO ₈	Unit
1	Thermal conductivity	161	8	W/m°C
2	Thermal expansion	0.000012	0.000008	1/ °C
3	Density	7870	5600	kg/m ³
4	Poisson's ratio	0.27	0.2	
5	Youngs modulus	90000	46000	Mpa

1.3ENGINE SPECIFICATION

The Engine selected for this work is a single cylinder four stroke air cooled 100cc type Bajaj Kawasaki petrol engine. The main parameter shows in the table below table 3

Table 3Engine specification

Engine	Type	4-Stroke, air cooled, single cylinder
	Number of cylinder	Single cylinder
	Bore	51mm
	Stroke	48.8 mm
	Piston displacement	99.27 cc
	Length of Connecting rod	97.6mm

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 6, June 2015

	Compression ratio	8.4
	Fuel consumption	87kmpl (under standard condition)
Performance	Maximum power	6.03kw@ 7500 rpm
	Maximum torque	8.05 N-m@5500 rpm
Transmission	Clutch	Wet multi disc type
	Transmission	4-speed, constant mesh type
	Gear shift pattern	All down foot shift
Dimensions	Overall length	1925mm
	Overall width	785mm
	Overall height	1030mm
	Wheel base	1215mm
	Ground clearance	150mm
	Kerb weight with full tank	109kg
Capacity	Fuel tank	9.3 liters including 2.2 liter reserve

II.PROBLEM FORMULATION

The main objective is to investigate and analyse the structural and thermal stress distribution of the piston at the real engine condition during combustion process. The analysis is carried out to reduce the stress concentration on the upper end of the piston.i.e. piston head/crown and piston skirt and sleeve using ANSYS software. In this paper the material A2618 (uncoated piston) is replaced with coated piston. Analytical calculation is done to finalized the dimension and check the strength of piston. Piston model is created in UG-Nx8 using the calculated analytical dimension. Analysis of both the uncoated and coated piston is performed using the software namely ANSYS 13. After analysis comparisons is made between the uncoated piston and coated piston in terms of total deformation, equivalent stress, and total strain.

III.METHODOLOGY

- Analytical design of piston using specification of Bajaj Kawasaki petrol engine.
- Creation of 3D models of piston using UG-Nx8.
- Meshing of 3D models using ANSYS 13.0.
- Analysis of pistons using static stress analysis method.
- Comparative performance of aluminium alloy pistons under static stress analysis method.
- Analysis of pistons under thermal and mechanical loads i.e. the pistons are subjected to a uniform gas pressure and non-uniform temperature distribution.
- Comparative performance of the aluminium alloy pistons (uncoated and coated) under thermal and mechanical loads i.e. the pistons are subjected to a uniform gas pressure and non-uniform temperature distribution.

3.1 ANALYTICAL DESIGN

IP = indicated power produced inside the cylinder (W), η = mechanical efficiency = 0.8 , n = number of working stroke per minute = $N/2$ (for four stroke engine), N = engine speed (rpm), L = length of stroke (mm), A = cross-section area of cylinder (mm²), r = crank radius (mm), l_c = length of connecting rod (mm) , a = acceleration of the reciprocating part (m/s²) , mp = mass of the piston (Kg), V = volume of the piston (mm³), th = thickness of piston head (mm), D = cylinder bore (mm) , pmax = maximum gas pressure or explosion pressure (MPa), σ_t = allowable tensile strength (MPa), σ_{ut} = ultimate tensile strength (MPa), F.O.S = Factor of Safety = 2.25, K = thermal conductivity (W/m K), Tc = temperature at the centre of the piston head (K), Te = temperature at the edge of the piston head (K), HCV = Higher Calorific Value of fuel(KJ/Kg) = 47000 KJ/Kg, BP = brake power of the engine per cylinder (KW), m = mass of fuel used per brake power per second (Kg/KWs), C = ratio of heat absorbed by the piston to the total heat developed in the cylinder = 5% or 0.05, b = radial width of ring (mm), Pw = allowable radial pressure on cylinder wall, (N/mm²) = 0.025 MPa, σ_p = permissible tensile strength for ring material (N/mm²) = 1110 N/mm² , h = axial thickness of piston

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 6, June 2015

ring (mm), h_1 = width of top lands (mm) , h_2 = width of ring lands (mm), t_1 = thickness of piston barrel at the top end (mm), t_2 = thickness of piston barrel at the open end (mm), l_s = length of skirt (mm), μ = coefficient of friction (0.01), l_1 = length of piston pin in the bush of the small end of the connecting rod (mm), d_o = outer dia. of piston pin (mm).

3.2 DETERMINATION OF DIMENSION OF PISTON

The piston is designed according to the procedure and specification which are given in machine design and data hand books. The dimensions are calculated in terms of SI Units. The pressure applied on piston head, temperatures of various areas of the piston, heat flow, stresses, strains, length, diameter of piston and hole, thicknesses, etc., parameters are taken into considerations

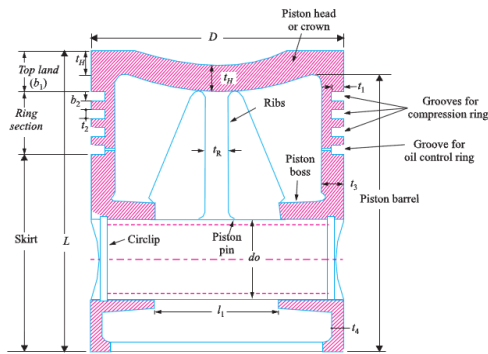


Fig 2 Main Dimension of piston

Mechanical efficiency of the engine (η) = 80 %.

$$\eta = \frac{\text{Brake power (BP)}}{\text{Indicating power (IP)}}$$

Therefore, I.P = B.P/ η , = 6.02/0.8= 7.52 kW

Also, Indicative power, IP = $P \cdot A \cdot L \cdot N / 2 = P \cdot (\pi \cdot D^2 / 4) \cdot L \cdot (N / 2)$

Substituting the values from table 1.3, we have

$$7.52 \times 1000 = P \times (\pi \times (0.051)^2 / 4) \times 0.0488 \times (7500 / (2 \times 60))$$

$$7520 = P \times 0.006227$$

$$P = 7520 / 0.006227$$

$$P = 12.08 \times 10^5 \text{ N/m}^2 \text{ or } 1.208 \text{ MPa}$$

Maximum pressure, $p_{max} = 10 \times P$, = 10 x 1.208= 12.08 MPa

Thickness of the Piston head: According to Grashoff's formula the thickness of the piston head is given by

$$t_H = \sqrt{(3 \cdot P \cdot D^2) / 16 \cdot \sigma_t} \text{ or } t_H = \sqrt{(3 \cdot P \cdot D^2) / 16 \cdot (\sigma_{ut} / \text{FOS})} \quad (\text{since } \sigma_t = \sigma_{ut} / \text{FOS})$$

$$= \sqrt{(3 \cdot 12.08 \cdot 51^2) / (16 \cdot 480 / 2.25)} = \sqrt{94260.24 / 3413.3} = \sqrt{27.6} = 5.25 \text{ mm}$$

Radial thickness of rings: $t_1 = D \sqrt{3 \cdot p_w / \sigma_p} = 51 \times \sqrt{3 \times 0.025 / 110} = 51 \times 0.02611 = 1.33 \text{ mm}$

Axial thickness of the piston: $t_2 = 0.7 t_1 = 0.7 \times 1.33 = 0.932 \text{ mm} \approx 1 \text{ mm}$

Width of the top land (b_1): $b_1 = t_H$ to $1.2 t_H = 6.53 \text{ mm}$ (consider $b_1 = t_H$)

Width of other lands (b_2): $b_2 = 0.75 t_2$ to $t_2 = 0.75 \times 1 = 0.75 \text{ mm}$ (consider $b_2 = 0.75 t_2$)

Thk of piston barrel at the top end: $t_3 = 0.03 D + t_1 + 4.9 = 0.03 \times 51 + 1.33 + 4.9 = 7.76 \text{ mm}$

Thk of piston barrel at the open end: $t_4 = 0.25 t_3$ to $0.35 t_3 = 0.25 \times 7.76 = 1.94 \text{ mm} \approx 2 \text{ mm}$

Length of skirt: $L_s = 0.6 D$ to $0.8 D = 0.6 \times 51 = 30.6 \text{ mm}$

Length of piston pin in the conn. rod bushing: $l_1 = 45\%$ of the piston dia = $0.45 \times 51 = 22.95 \text{ mm}$

Piston pin diameter: $d_0 = 0.28 D$ to $0.38 D = 0.28 \times 51 = 14.28 \text{ mm}$

Note: Center of the piston pin should be 0.02D to 0.04D above the center of the skirt

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 6, June 2015

Table 4- Final Dimension of piston

S/no.	Description	Nomenclature	Value in mm
1	Thickness of piston head	t_H	5.25
2	Radial width of the ring	t_1	1.33
3	Axial thickness of the piston	t_2	1
4	Width of top land	b_1	6.53
5	Width of ring land	b_2	0.75
6	Thickness of piston barrel at the top end	t_3	7.76
7	Thickness of piston barrel at the open end	t_4	2.7
8	Length of skirt	l_s	30.6
9	Length of piston pin in the connecting rod bushing	l_1	22.95
10	Piston pin diameter	d_0	14.28

IV. GEOMETRICAL MODELING AND FINITE ELEMENT ANALYSIS

4.1 GEOMETRICAL MODELING

The dimension calculated for the piston according to the procedure and the specification given in the design data book are used for preparing the model using UG Nx-8 3D modelling software. Piston was modelled using UG Nx-8 software which is shown in below figure 3 and 4

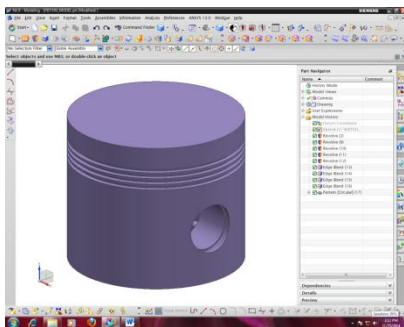


Fig 3- 3D- model of piston

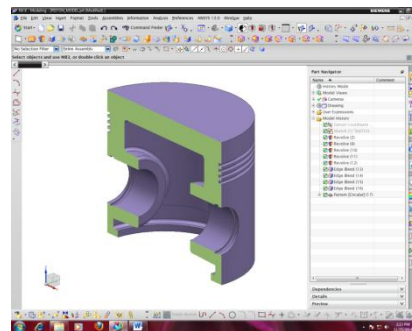


Fig 4- 3D- half section of piston

4.2 MESHING OF 3D MODEL OF PISTON

The element selected for meshing the piston model is solid187 tetrahedron type of element which is higher order tetrahedral element. The mesh count contains 33743 numbers of nodes and 19541 numbers of elements. Below figure shows the meshed model of piston.

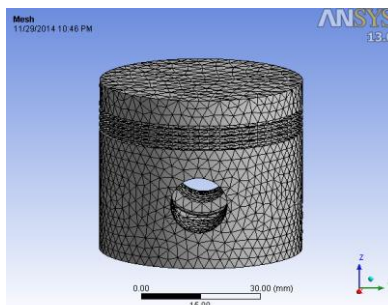


Fig 5- Meshing of 3D model

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 6, June 2015

4.3 BOUNDARY CONDITION FOR STRUCTURE ANALYSIS (UNCOATED AND COATED PISTON)

Combustion of gases in the combustion chamber exerts pressure on the head of the piston during power stroke. The pressure force will be taken as boundary condition in structural analysis using ANSYS work bench. Fixed support has given at surface of the pin hole because the piston will move from Top dead center (TDC) to Bottom dead center (BDC) with the help of fixed support at pin hole. So whatever the load is applying on the pistons due to gas explosion causes the failure of piston pin including bending stresses. As per analytical calculation pressure acting on the piston due to combustion is 12.08 MPa. The load variation analysis is performed on piston at 100%, 125%, 150%, 175%, 200%, 225% and 250% of the calculated pressure as the load varies from 100% to 250% in Bajaj Kawasaki four stroke petrol engines.

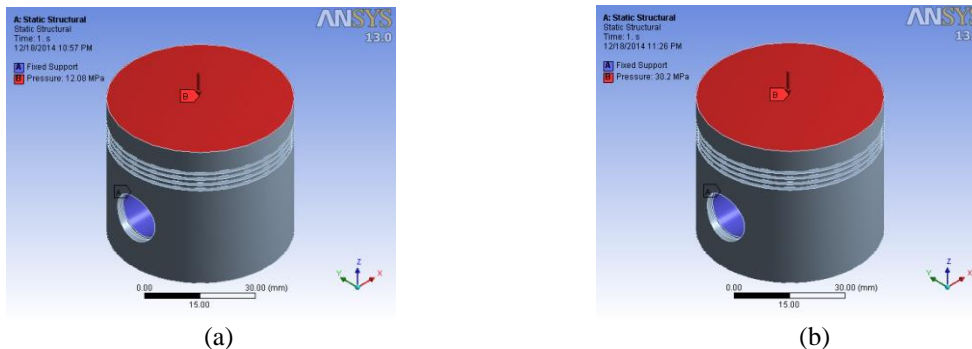


Fig 6- Boundary condition for structural analysis (a) at 100% of load (b) at 250% of load

4.4 STRESS DISTRIBUTION AND TOTAL DEFORMATION BEFORE COATING

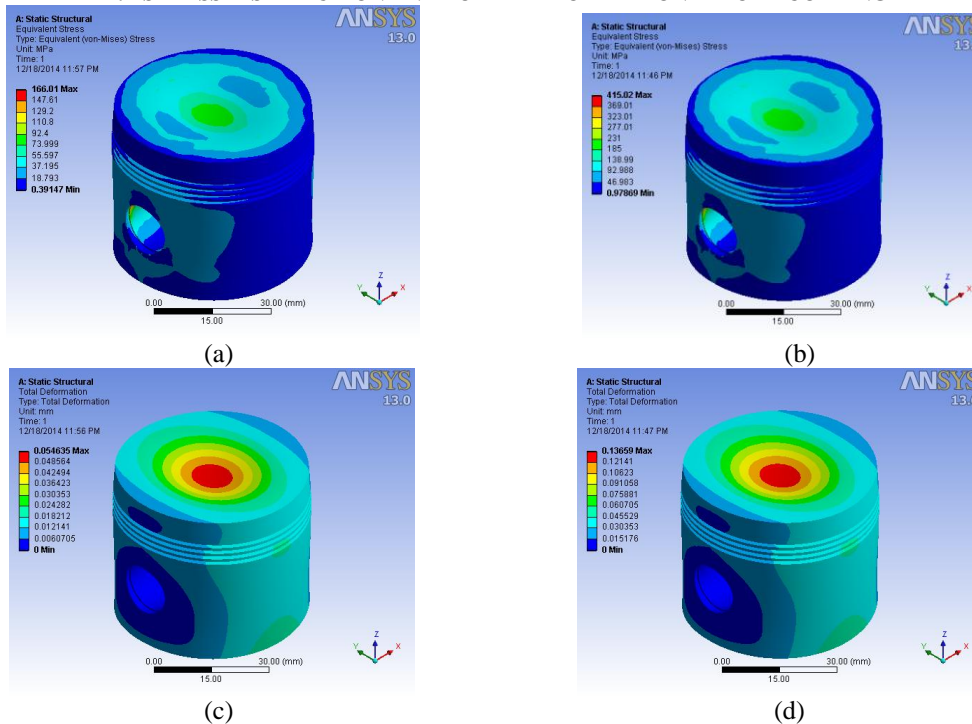


Fig 7- stress distribution and total deformation of uncoated piston (a) Equivalent stress at 100% load (b) Equivalent stress at 250% load (c) Total deformation at 100% load (d) Total deformation at 250% load

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 6, June 2015

4.5 BOUNDARY CONDITION FOR STRUCTURE ANALYSIS UNDER COUPLED FIELD (UNCOATED AND COATED PISTON)
Temperature distribution, loading and Boundary condition for uncoated and coated piston. Figure shows the temperature distribution, loading and the boundary condition considered for the analysis. The temperature distribution at piston head, top land, piston ring area and piston skirt according to table 4.1 is applied for thermal analysis and the uniform pressure from 100% to 250% of calculated pressure is applied on crown of piston which is indicated by red color and the model is constrained on upper half of piston pin hole as shown by violet color.

Table 5 – Temperature and heat transfer coefficient applied to the piston

S/No	Piston region	Temperature in °C	Heat transfer coefficient (W/m ² K)
01	Piston Head	350	300
02	Width of top land	330	160
03	Piston ring area	250	120
04	Piston skirt land	140	600

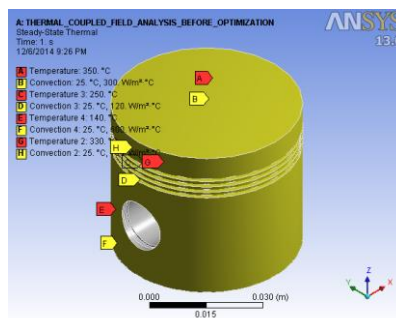


Fig8 - Temperature and convection coefficient distribution

4.6 STRESS DISTRIBUTION & TOTAL DEFORMATION OF UNCOATED PISTON UNDER COUPLED FIELD

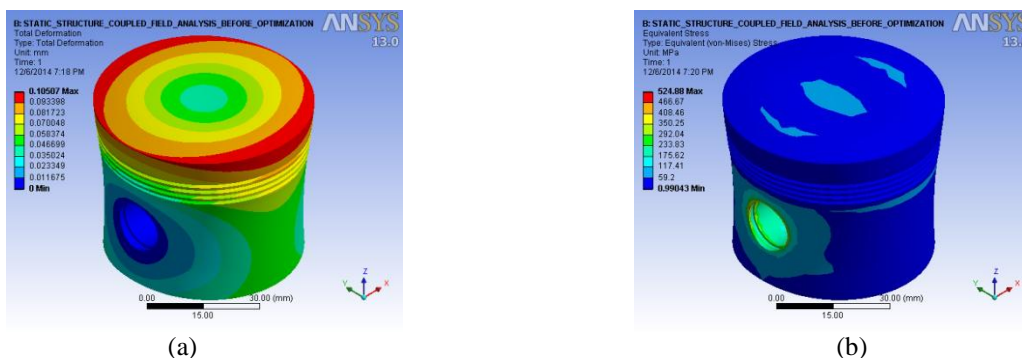


Fig 9- stress distribution and total deformation of uncoated piston under coupled field (a) Equivalent stress at 100% load (d) Total deformation at 1000% load

4.7 STRESS DISTRIBUTION & TOTAL DEFORMATION OF COATED PISTON UNDER COUPLED FIELD

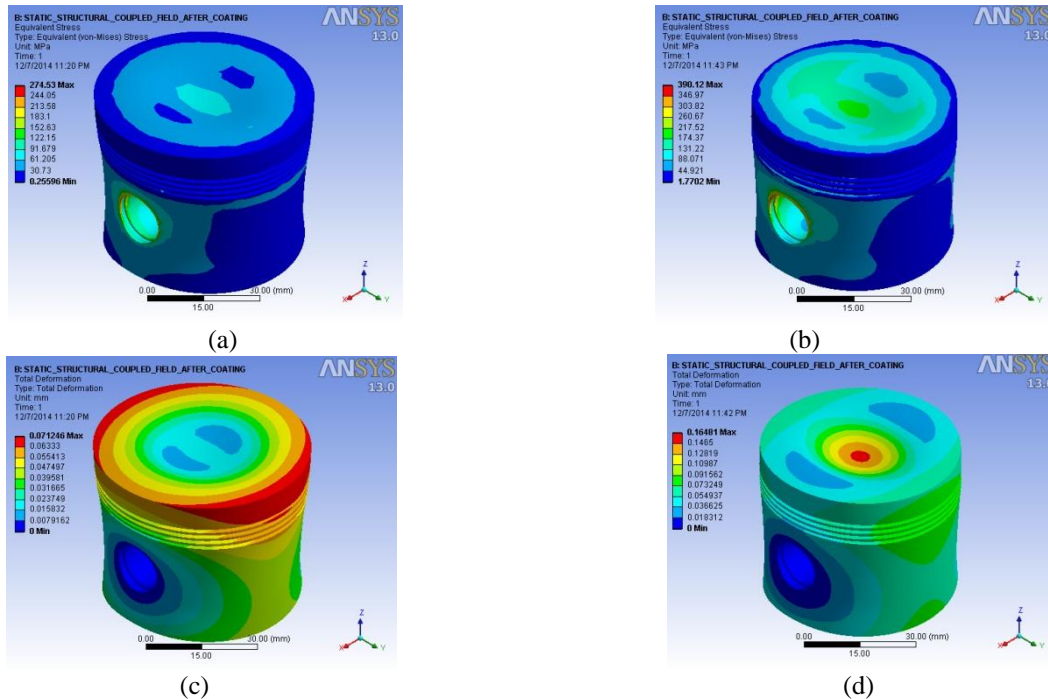


Fig 10- stress distribution and total deformation of coated piston under coupled field (a) Equivalent stress at 100% load (b)Equivalent stress at 250% load(c) Total deformation at 100% load (d)Total deformation at 250% load

V.RESULT

The values of equivalent stress and total deformation at different loading condition are recorded

Table 6 Static structural analysis result of uncoated piston under thermal and mechanical loads

S/no	Pressure/ load (Mpa)	Equivalent stress (Mpa)	Total deformation (mm)
01	12.08 (100%)	524.88	0.10507

Table 7 Static structural analysis result of coated piston under thermal and mechanical loads

S/no	Pressure/ load (Mpa)	Equivalent stress (Mpa)	Total deformation (mm)
01	12.08 (100%)	274.453	0.071246
02	15.10 (125%)	290.73	0.0701
03	18.12 (150%)	307.48	0.07525
04	21.14 (175%)	324.68	0.099344
05	24.16 (200%)	342.26	0.12117
06	27.18 (225%)	363.05	0.14299
07	30.70 (250%)	390.12	0.16481

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 6, June 2015

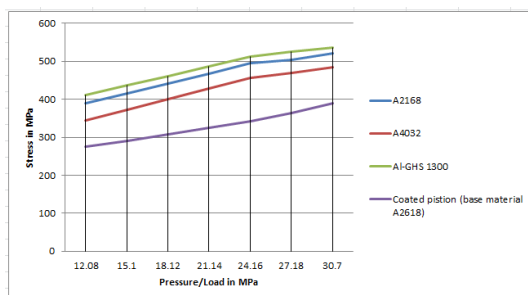
V. CONCLUSION

The result showed that coated piston with ceramic material has better performance in stress and deformation in comparison with the aluminium alloy named A2618 under the joint action of the thermal and mechanical loads.

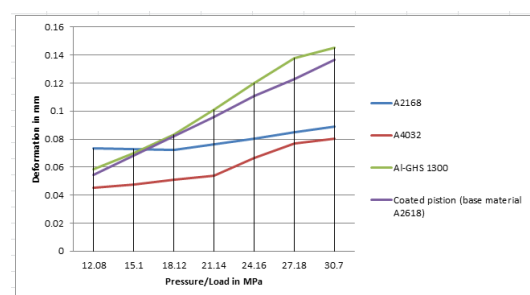
The preliminary thermo-mechanical FE analysis was presented in the thesis. Its main purpose was to compare behaviour of the piston made of different type of materials under thermal load. The new composite material was primarily considered due to low hysteresis of the coefficient of thermal expansion for heating and cooling. The obtained results shows that the new composite piston has around 2.5 times lower radial displacements than the actual one. Therefore, a dimensional stability of the piston is strongly improved. The radial component of the stress is also much lower for the new composite piston as well.

Combined CAD and ANSYS, get the results of stress and deformation and temperature when the piston under the mechanical loads, thermal loads and assembly the mechanical and thermal load. And get the discussion as below:

- 1) The temperature is higher at the combustion chamber side of the deviation from the center of the piston. Highest temperature appears in the throat of the exhaust port of the combustion chamber adjacent side, the temperature reached 350°C . The temperature of the piston ring area is extremely important for the reliability of the engine, if the temperature of the ring zone is too high, it will make the lubrication oil to be deterioration even carbonization. It causes the piston ring bonded, loss of activity to make the piston rapid wear, deformation.
- 2)
- 3) The stress under the mechanical action, the maximum stress value of the piston is 390 Mpa, and the most stress of other parts below 100Mpa. For the tensile strength of the piston, it's having an enough strength margin.
- 4) When under the assembly of mechanical and thermal loads, the value of the largest displacement is 0.16 mm, causing at the center of the piston top. The stress of the top of the piston is mainly caused by the temperature load and the deformation of the piston is caused by the thermal expansion.
- 5)



Graph 1- showing Stress vs. Pressure/load



Graph 2 - showing Deformation vs. Pressure/load

VII.FUTURE SCOPE OF WORK

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

REFERENCES

- [1] Cuddy, M. R. &Wipke, K. B. (1997), Analysis of Fuel Economy Benefit of Drive train. Hybridization <http://www.nrel.gov/vehicle/fuels/vsa/pdfs/22309.pdf> (National Renewable energy laboratory).
- [2] F.S. Silva (2006) Fatigue on engine pistons – A compendium of case studies.EngineeringFailure Analysis, 13 pp(480–492).
- [3] EkremBuyukkaya, MuhammetCerit(2007) Thermal analysis of a ceramic coating diesel engine piston using 3-D finite element method. Surface and Coatings Technology 202, 2 pp(398–402).
- [4] Dr.NajimA.Saad, Dr.Haitham R. Abed Ali, Dr.HayderShakirAbudalla, (2008), numerical analysis of the thermal –stresses of a petrol engine

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 6, June 2015

- piston with different materials, The Iraqi Journal for Mechanical and Material Engineering, 8, 3 pp (249-256).
- [5] Gudimetal P, Gopinath C.V, (2009) Finite Element Analysis of Reverse Engineered Internal Combustion Engine Piston, AIJSTPME, 2, 4 pp(85-92).
- [6] Yanxia Wang, YongqiLiu,Haiyan (2010), Simulation and Analysis of Thermo-Mechanical Coupling Load and Mechanical Dynamic Load for a Piston; IEEE, pp (106-110).
- [7] Wu, Yi Zeng, DongjianFeng, Zhiyuan, (2010) Finite Element Analysis for the Thermal Load of Piston in a Dimethyl Ether Fueled Diesel Engine, IEEE
- [8] PiotrSzurgott and TadeaszNiezgoda, “ Thermo-mechanical FE analysis of the piston made of composite material with low hysteresis”. Journal of kones power train and transport, Vol 18 Nov 2011
- [9] MesutDurat, Murat Kapsiz, Ergun Nart, FeritFicici& Adnan Parlak, (2012), The effects of coating materials in spark ignition engine design; Materials & Design, 36 PP (540-545).
- [10] Ajay singhRai (2014), “Design, analysis and optimization of three aluminum piston alloys using FEA; Journal of engineering research and application. ISSN: 2248-7622 Vol.4 Issue (Version 3, January 201 pp94-102)
- [11] R. S. Khurmi, J. K. Gupta (2005); Machine Design; 14th ed.; Eurasia Publishing House (Pvt.)Ltd., Ramnagar, New Delhi