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# Simulation and Analysis of Thermo Mechanical Coupling Load and Mechanical Dynamic Load for a Piston

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## ABSTRACT:

Engine pistons are one of the most complex components among all automotive. In this paper, a Full 3-D solid model piston of a new designed piston was established by CATIA V5 software, and the finite element analysis model was also established by using ANSYS software. During working process, the piston is subject to heat, and pressures developed in the combustion as well as variations in pressures during various strokes of the engine. Hence, there is a need to study the behaviour of the piston to the loads acting on it. In this work, the distributions of stress and temperatures in the piston and rings are found using finite element analysis package, ANSYS UNDER two loading conditions i.e. only gas pressure, and combination of thermal load and gas pressure. CAD model is imported into ANSYS and static couple field analysis (Non-linear structural and thermal) is performed by applying various loads (thermal and combustion pressure) on the piston in the ANSYS. By varying materials ( Al Alloy 2024 , Al Alloy 8090 & Ti Alloy ) The stress and temperature distributions on the piston are studied and the conclusions are drawn.

## INTRODUCTION:

Along the development of automobile technology, the reliability, efficiency, durability, low exhaust gas and noise and operating performance of automobile engines is wished to be carried to a higher level.

It is well known that almost all these properties of an internal combustion engine are closely associated with its mechanical behaviors etc. Thus it is necessary to reveal these mechanical characteristics of an engine in order to improve its general property and quality, and it is far more important in piston system. To meet these requirements, lots of research works have been made for engine pistons, and many great developments have been achieved. Notwithstanding all these improvements, there are a huge number of damaged pistons. Although damage mechanisms have different origins, thermal fatigue and mechanical fatigue play a prominent role. Heat load is the major factor to cause ablation and heat crack of piston head, and mechanical load is easy to bring crack at piston pin seat. For a better understanding of the damaging mechanism, and to enhance the service life and the reliability of pistons, a great deal of complex mechanical fatigue tests and the hot fatigue tests are carried out by some piston manufacturers during the developing of new pistons. But they are high cost and time-consuming. Consequently, finite element analysis is usually used for stress and temperature determination. In this work, finite element thermo mechanical coupling analysis and mechanical dynamic analysis will be performed for a new designed piston to exam the design details. Based on the results from the analysis, practical guidelines would be provided for engine design in order to reduce engine block vibration, suppress noise, improve efficiency etc.

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In an automobile Industry piston is found to be most important part of the engine which is subjected to high mechanical and thermal stresses. Due to very large temperature difference between the piston crown and cooling galleries induces much thermal stresses in the piston. Besides the gas pressure, piston acceleration and piston skirt side force can develop cycle of mechanical stresses which are superimposed on the thermal stresses. Due to this reason thermo-mechanical stresses are one of the main causes of the failure of the piston.

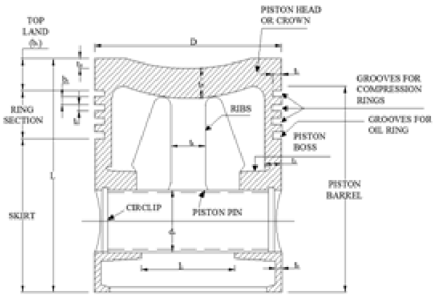
## LITERATURE REVIEW:

Ji Wu1,a, Shulin Duan1,b, Zhanhua Wu1,c, Hui Xing,d and Qin'an Liu did a paper on The Coupled Thermal and Mechanical Load Analysis in the 6S50MC-C Type Marine Diesel' Piston. MAN Diesel's 6S50MC-C two-stroke marine diesel engine is researched in this paper. The intensity under the effect of thermal load, mechanical load and coupled loads are analyzed. As the boundary conditions of the temperature field distribution, the mean temperature and the mean heat transfer coefficient are calculated firstly. Based on the temperature field, the thermal intensity is obtained in ANSYS. Then the study analyzes the stress and the strain distribution when the mechanical load and the coupled loads are applied. Through the analysis of different loads, the maximum stress is 696MPa in thermal load, 191MPa in mechanical load and 659MPa in coupled loads. The maximum deformation is 1.011mm in thermal load, 0.147mm in mechanical and 1.022mm in coupled loads. The intensity meets the design requirement. The stress concentration and the deformation of the piston crown mainly are generated by the thermal load. To reduce the destructive effect of thermal, it requests enhancing cooling and warming up the main engine.

Lokesh Singh, Suneer Singh Rawat, Taufeeque Hasan, Upendra Kumar's study is FINITE ELEMENT ANALYSIS OF PISTON IN ANSYS. A piston is a component of reciprocating engines. Its purpose is to transfer force form expanding gas in the cylinder to the crank shaft via piston rod and a connecting rod. It is one of the most complex components of an automobile. In some engines the piston also acts as a valve by covering and uncovering ports in the cylinder wall. In present, work a three dimensional solid model of piston including piston pin is designed with the help of CATIA and SOLIDWORKS software. The thermal stresses, mechanical stresses and couples thermo-mechanical stresses distribution and deformations are calculated. After that fatigue analysis was performed to investigate factor of safety and life of the piston assembly using ANSYS workbench software. Aluminium-silicon composite is used as piston material. The stress analysis results also help to improve component design at the early stage and also help in reducing time required to manufacture the piston component and its cost.

## Designing of the Piston

The design procedure adopted in this work is presented below and the results are tabulated:




## Design Considerations of a Piston

In designing a piston for I.C. engine, the following points should be taken into consideration

1. It should have enormous strength to withstand the high gas pressure and inertia forces.
2. It should have minimum mass to minimize the inertia forces.
3. It should form an effective gas and oil sealing of the cylinder.
4. It should provide sufficient bearing area to prevent undue wear.

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5. It should disperse the heat of combustion quickly to the cylinder walls.
6. It should have high speed reciprocation without noise.
7. It should be of sufficient rigid construction to withstand thermal and mechanical distortion.
8. It should have sufficient support for the piston pin.

### Piston Function Design Requirement

1. Easily move to the reciprocating motion inside of cylinder
2. Reducing friction between the connecting rod and piston pin
3. There is no strain occurring the piston pin
4. Piston move even at minimum pressure

### Piston Structural Design Requirement

1. Piston designed in cylindrical shape because easily Move to the up & down direction
2. Piston should be a compact size
3. Piston head geometry (curve, flat) should be in correct shape so that in gives maximum efficiency

### Material for Pistons

The most commonly used materials for pistons of I.C. engines are cast iron, cast aluminum, forged aluminum, cast steel and forged steel. The cast iron pistons are used for moderately rated engines with piston speeds below 6 m / s and aluminum alloy pistons are used for highly rated engines running at higher piston speeds. It may be noted

1. Since the coefficient of thermal expansion for aluminum is about 2.5 times that of cast iron, therefore, a greater clearance must be provided between the piston and the cylinder wall in order to prevent seizing of the piston when engine runs continuously under heavy loads. But if excessive clearance is allowed, then the piston will develop ‘piston slap’ while it is cold and this tendency increases with wear. The less clearance between the piston and the cylinder wall will lead to seizing of piston.

2. Since the aluminum alloys used for pistons have high **heat conductivity (nearly four times that of cast iron), therefore, these pistons ensure high rate of heat transfer and thus keeps down the maximum temperature difference between the center and edges of the piston head or crown.

3. Since the aluminum alloys are about three times lighter than cast iron, therefore, its mechanical strength is good at low temperatures, but they lose their strength (about 50%) at temperatures above 325°C. Sometimes, the pistons of aluminum alloys are coated with aluminum oxide by an electrical method.

| MATERIAL | CAST ALUMINIUM ALLOY |
|---|---|
| Young's Modulus | 71GPa |
| Poison Ratio | 0.33 |
| Coefficient of conduction | 174.15 W/mK |
| Tensile strength | 485MPa |
| Yield strength | 435MPa |
| Density | 2.77E-6 Kg/mm |

## CALCULATIONS

$$t_H = D\sqrt{\frac{3P}{16\sigma_t}}$$

$$\text{Indicated Power, I.P} = \frac{PLAN}{60}$$

$$\text{Cross-sectional Area, A} = \frac{\Pi}{4}D^2$$

P = $P_m$ = indicated mean effective pressure.

Brake Power, $B.P = I.P * \eta_{mech}$

Heat flow through piston head, $H = C * H.C_v * m * B.P$

### Radial Ribs:

Radial ribs may be four in number the thickness of the ribs varies from

$$\frac{t_h}{3} \text{ to } \frac{t_h}{2}$$

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### Piston Rings:

Out of four rings, three are compression rings and one is

Radial thickness of the piston rings oil ring

Axial thickness of piston rings, $t_1 = D\sqrt{\frac{(3P)}{\sigma_t}}$

Distance from the top of piston to first ring groove i.e., $t_2 = 0.7t_1$ to $t_1$

Width of the top land., b1 = 1.2tH

Width of other ring land, b2 = 0.75t2 to t2

### Piston Barrel:

Radial depth of piston ring grooves (b) is 0.4mm more than radial thickness of piston (t1).,

b = t1 + 0.4

Maximum thickness of barrel, t3 = 0.03D + b + 4.5mm

Piston wall thickness towards the open end, t4 = 0.25t3 to t3

### Piston Skirt:

Maximum gas load = $\frac{\pi}{4} D^2 p_{max}$

Length of the piston, L = Length of skirt + Length of ring section + Top land

L= l + (4t2 + 3b2) + b1

### Piston Pin:

Load on the pin due to bearing pressure = Bearing pressure * Bearing ratio * Bearing area = pb1 * d0 * L1 (L1 = 0.45D)

Maximum load on the piston due to Gas pressure $\frac{\pi}{4} D^2 p$

Dimensions of the piston are calculated using the above equations and are presented in table:

| S.no | Parameter | Value |
|---|---|---|
| 1 | Thickness of piston head ($t_H$) | 8.82 |
| 2 | Radial thickness of piston | 2.33 |
| 3 | Axial thickness of piston | 1.76 |
| 4 | Width of top land ($b_1$) | 8.82 |
| 5 | Width of other land ($b_2$) | 1.32 |
| 6 | Radial depth of piston | 2.74 |
| 7 | Piston wall thickness towards | 2.57 |
| 8 | Length of piston (L) | 65.68 |
| 9 | Diameter of piston (D) | 70.56 |
| 10 | Diameter of piston pin ($d_{0=}$) | 31.75 |

### FINITE ELEMENT ANALYSIS USING ANSYS:

| Parameters | Al Alloy 2024 | Al Alloy 8090 | Ti Alloy |
|---|---|---|---|
| Young's Modulus (GPa) | 71 | 77 | 96 |
| Ultimate Tensile Strength (MPa) | 310 | 340 | 1070 |
| Yield Strength (MPa) | 280 | 210 | 930 |
| Poisson's Ratio | 0.33 | 0.33 | 0.36 |
| Thermal Conductivity (w/mk) | 121 | 95.3 | 640 |
| Coefficient of Thermal Expansion (1/k) | 2.30E-05 | 2.14E-05 | 9.40E-06 |
| Density (kg/m3) | 2770 | 2540 | 4620 |

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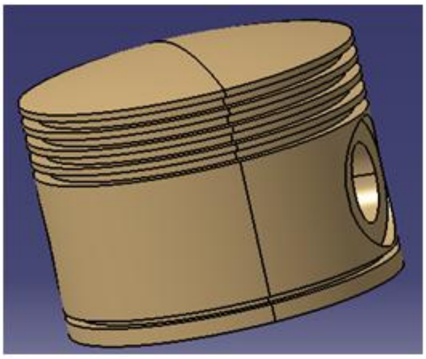
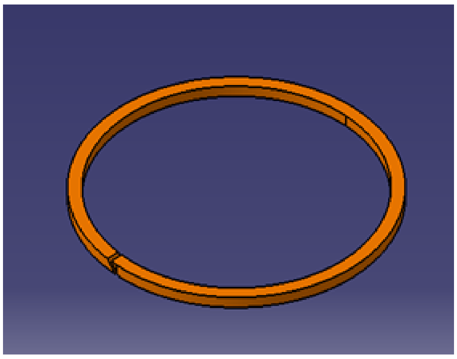
| Parameters | Ductile Nodular Spheroidal cast iron | ASTM grade 50 ( ISO grade 350 ,EN – JL 1060 ) Grey cast iron |
|---|---|---|
| Poisson ratio | 0.275 | 0.26 |
| Modulus of elasticity (GPa) | 176 | 157 |
| Thermal conductivity (w/m k) | 33 | 46 |
| Ultimate tensile strength (MPa) | 414-827 | 362 |
| Yield tensile strength ( MPa) | 240-621 | 228 |
| Density g/c.c | 7.2 | 7.1 |

## MODEL IN CATIA V5:



| S.no | Boundry Field | Temperature (ºC) | Hot transfer coefficient (W/(m.K) |
|---|---|---|---|
| 1 | Piston crown | 750 | 450 |
| 2 | Piston skirt | 140 | 300 |
| 3 | Piston pin hole | 140 | 210 |
| 4 | Bottom of combustion chamber | 180 | 90 |
| 5 | Other ring | 180 | 250 |



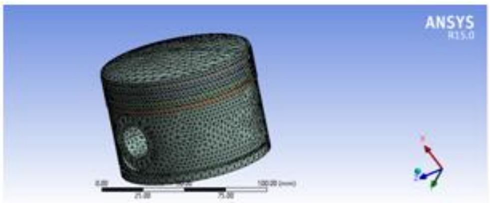
**ASSEMBLE OF PISTON WITH RING**

## TEMPERATURE DISTRIBUTION ON PISTON SURFACE:

## STATIC LOAD ON PISTON SURFACE:

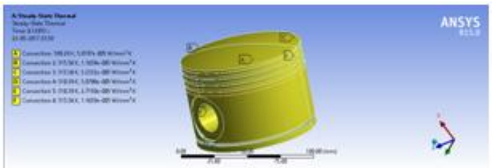
| S.no | Boundary field | Load | Value(mpa) |
|---|---|---|---|
| 1 | Piston round bank, piston head | PZ | 6.5 |
| 2 | Bottom of the first groove | PZ×76% | 4.96 |
| 3 | first and the second groove | PZ×25% | 1.625 |
| 4 | Bottom of the second groove | PZ×20% | 1.3 |
| 5 | second and the third | PZ×15% | 0.975 |
| 6 | Bottom of the third groove | PZ×10% | 0.65 |

## Mesh model in ansys

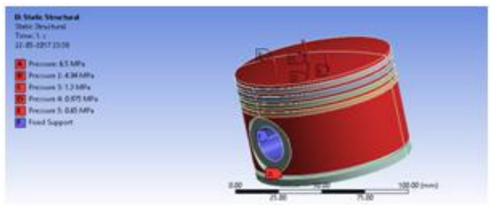



**Mesh model with nodes : 60837 and elements: 32744**

## Temperature input for thermal analysis




## Pressure load and boundary condtion for static structural analysis



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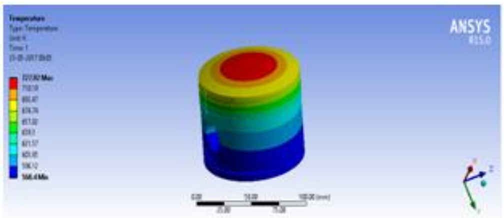
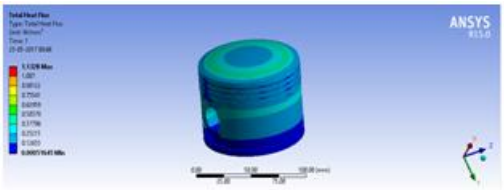
**CASE1: MATERIAL USED FOR PISTON : Al Alloy 2024 AND PISTON RING : cast iron**

**Thermal analysis:**

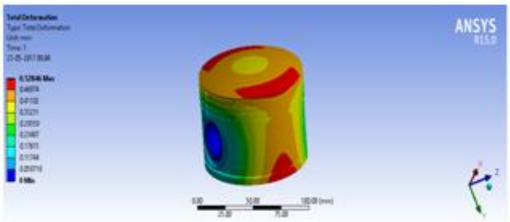



**Heat flow in piston assemble**

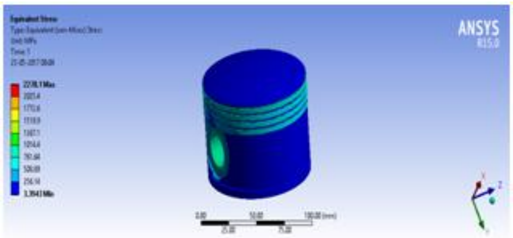



**Heat flux in piston assemble**

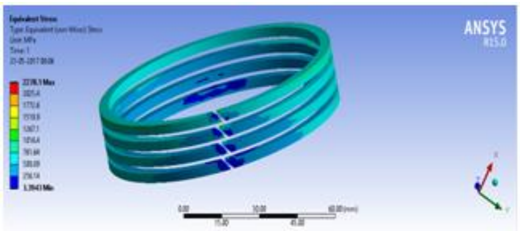
**Static analysis:**



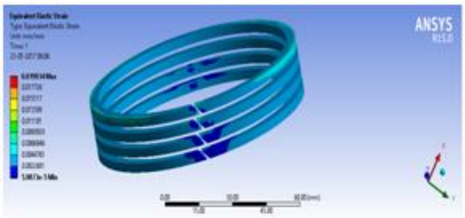

**Deformation of piston**




**Von mises stress for piston assembly**



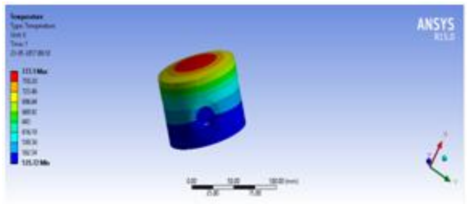

**Piston ring stress**



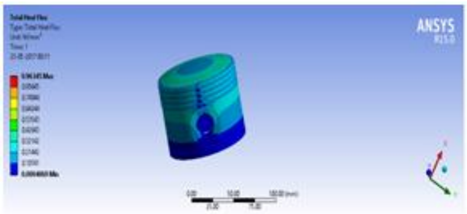

**Piston ring strain**

**CASE2: MATERIAL USED FOR PISTION : Al Alloy 8090 AND PISTION RING : cast iron**

**Thermal analysis:**

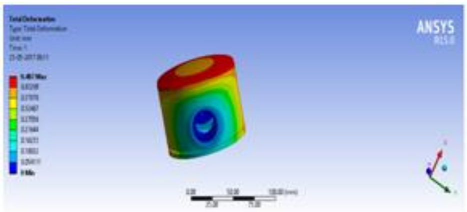



**Heat flow in piston assemble**

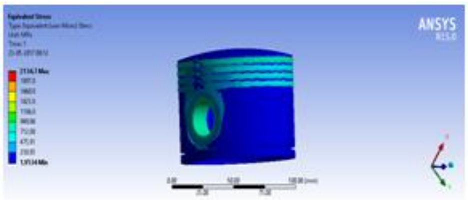



**Heat flux in piston assemble**

**Static analysis:**




**Deformation of piston**




**Von mises stress for piston assembly**

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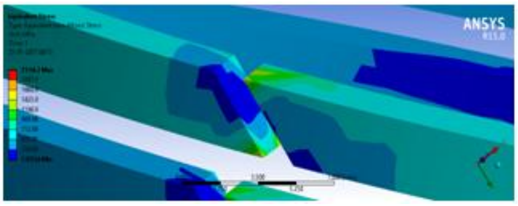
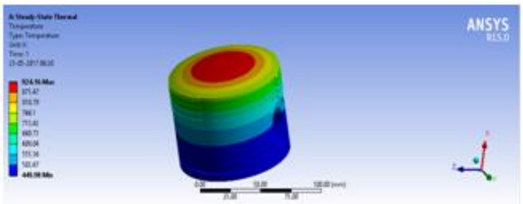


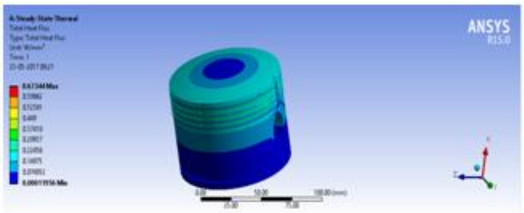

Piston ring stress

**CASE3: MATERIAL USED FOR PISTION : Ti Alloy AND PISTION RING : cast iron**

**Thermal analysis:**

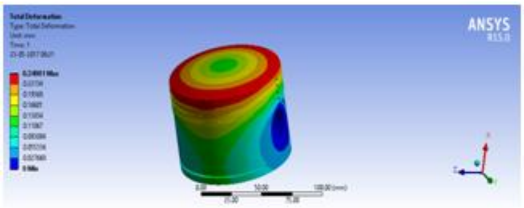



Heat flow in piston assemble

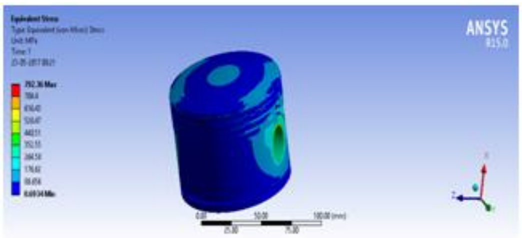



Heat flux in piston assemble

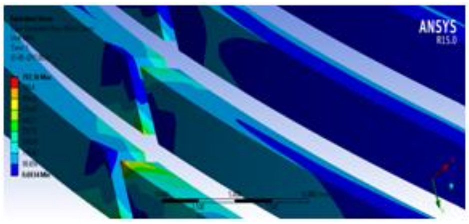
**Static analysis:**




Deformation of piston

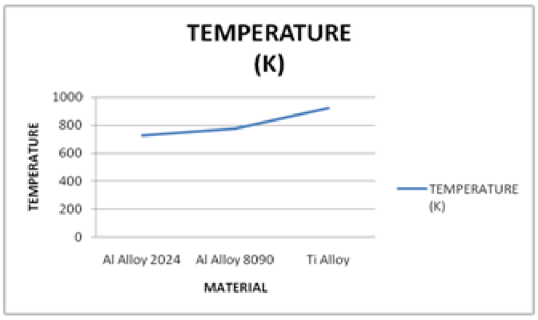


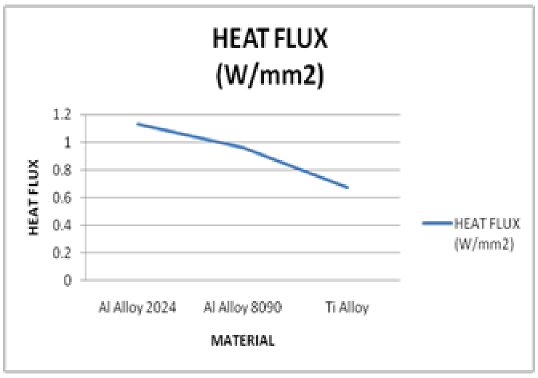

Von mises stress for piston assembly

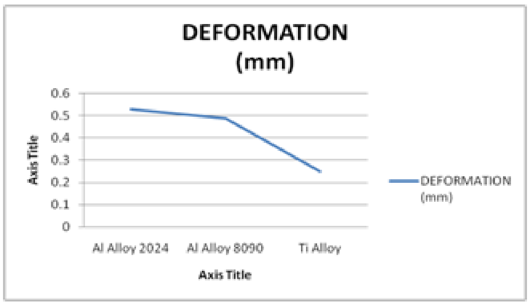



Piston ring stress

**RESULTS:**



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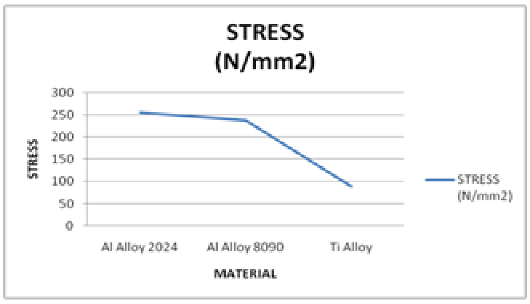


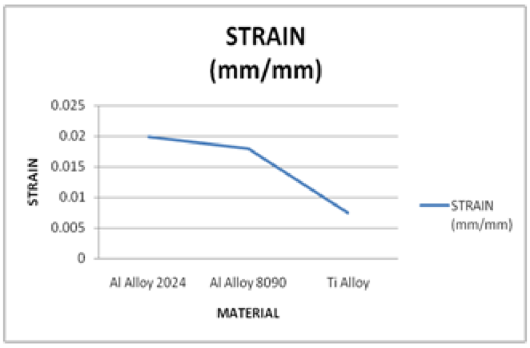


## ANALYTICAL CALCULATION FOR PISTON

Analytical calculations are done for Al Alloy 2024 piston. For doing analytical calculation material properties and dimensional information should be known and so all the parameters consider for design of piston are calculated by using one analytical problem.

Design Considerations for a Piston In designing a piston for an engine, the following points should be taken into consideration:

It should have enormous strength to withstand the high pressure.

It should have minimum weight to withstand the inertia forces.

It should form effective oil sealing in the cylinder.

It should provide sufficient bearing area to prevent undue wear.

It should have high speed reciprocation without noise.

It should be of sufficient rigid construction to withstand thermal and mechanical distortions.

It should have sufficient support for the piston pin.

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,

$$t_H = 0.433 * D * \sqrt{\left(\frac{Pmax}{Ft}\right)}$$

Where, P= maximum pressure in N/mm²

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

ft = permissible tensile stress for the material of the piston.

For Al Alloy 2024 may be taken as 310 N/mm2

Here the material is a particular grade of Al Alloy 2024 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 65.68×70.56.

Heat Flow through the Piston Head (H):

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

$$H = 12.56 * tH * K * (Tc - Te) \text{ KJ/sec}$$

Where, K=thermal conductivity of material which is W/m0 k

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

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

Radial Thickness of Ring (t1)

$$t1 = D * \sqrt{\frac{3p_w}{F_t}}$$

Where, D = cylinder bore in mm

Pw= pressure of fuel on cylinder wall in N/mm².

Its value is limited from 0.0245N/mm² to 0.042N/mm².

For present material, σt is 90Mpa

Axial Thickness of Ring (t2)
The thickness of the rings may be taken as
t2= 0.7t1 to t1
Minimum axial thickness (t2) t2 =D/10*z
Where z = 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=0.75 *t2 to t2
Maximum Thickness of Barrel (t3)
t3 =0.03*D+b+4.5 mm

Where ,
b = Radial depth of piston ring groove b= t1+0.4

## DEFORMATION:

$$E = \frac{\sigma}{\varepsilon}$$

$$\frac{\delta d}{d} = \frac{\sigma}{E}$$

$$\delta d = \frac{\sigma d}{E}$$

## HEAT FLUX:

q = -k × gradT
Where, q - heat flux, which is the vector in w/m2; k - the heat conduction coefficient of the material trated as the constant, in w/(m.k); gradT - the temperature gradient, also a vector,
◦C/m.

## STRESS CALCULATION:

Stress on Piston Crown $\sigma b = 3pD^2/16tH^2$
Thermal Stress,
σt= E* Coefficient of thermal Expansion*Temp. Difference
Thermo-mechanical Stress:
σtm = σb + σt

## TABLE FOR ANALYTICAL RESULTS:

| S.no | Case study | Temperature (K) | Heat flux (W/mm²) | Deformation(mm) | Stress (N/mm²) | Strain (mm/mm) |
|---|---|---|---|---|---|---|
| 1 | Al Alloy 2024 | 710.27 | 1.079 | 0.493 | 210.34 | 0.0176 |
| 2 | Al Alloy 8090 | 757.57 | 0.9475 | 0.37 | 215.45 | 0.0154 |
| 3 | Ti Alloy | 904.56 | 0.6635 | 0.15 | 90.56 | 0.0068 |

## TABLE FOR FEM RESULTS:

| S.no | Case study | Temperature (K) | Heat flux (W/m m²) | Deformation (mm) | Stress (N/ mm²) | Strain (mm/ mm) |
|---|---|---|---|---|---|---|
| 1 | Al Alloy 2024 | 727.92 | 1.132 | 0.528 | 256.14 | 0.0199 |
| 2 | Al Alloy 8090 | 777.1 | 0.9634 | 0.487 | 238.93 | 0.01794 |
| 3 | Ti Alloy | 924.16 | 0.6734 | 0.249 | 88.65 | 0.0075 |

## COMPARISON FEM VS THOERITICAL

| Case study | Temperature (K)fem | Temperature (K)analytical | Heat flux (w/mm2) fem | Heat flux (w/mm2) (analytical) | Deformation (mm) fem | Deformation (mm) analytical |
|---|---|---|---|---|---|---|
| Al Alloy 2024 | 727.92 | 710.27 | 1.132 | 1.079 | 0.528 | 0.493 |
| Al Alloy 8090 | 777.1 | 757.57 | 0.9634 | 0.9475 | 0.487 | 0.37 |
| Ti Alloy | 924.16 | 904.56 | 0.6734 | 0.6635 | 0.249 | 0.15 |

| Case study | Stress fem | Stress Analytical | Strain fem | Strain analytical |
|---|---|---|---|---|
| Al Alloy 2024 | 256.14 | 210.34 | 0.0199 | 0.0176 |
| Al Alloy 8090 | 238.93 | 215.45 | 0.1794 | 0.0154 |
| Ti Alloy | 88.65 | 90.56 | 0.0075 | 0.0068 |

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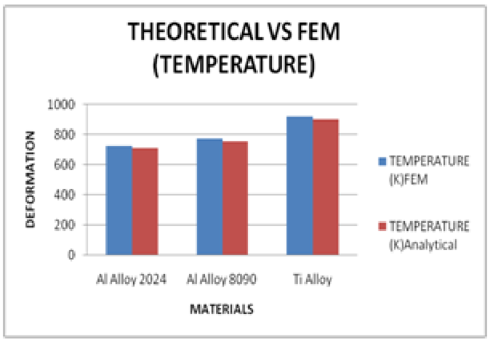


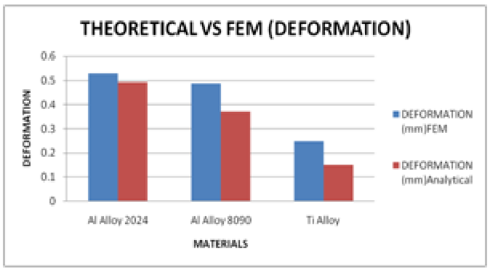


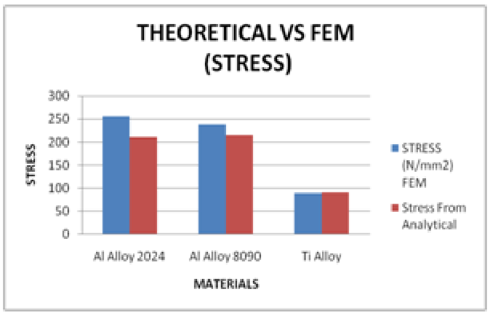


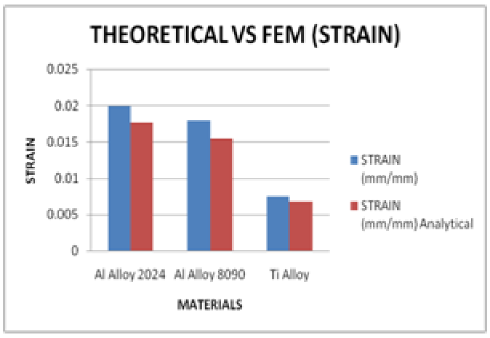


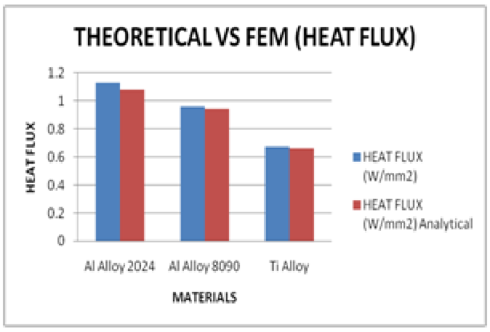


## DISCUSSION:

It is clear from figure and graphs that the maximum displacement is observed in the piston with rings made of Al alloy 2024 and Ti alloy. As it is expected maximum displacement is observed at the top of the centre of the piston. It is shown in the figure, that the maximum stress intensity is observed in Al alloy 2024 with 256.14 MPa and minimum in with Ti alloy 88.65 MPa. It is observed that the maximum stress intensity is on the bottom surface of the all piston crown and along the edges. Again in piston made of titanium alloy moderate stress intensity is found. Whereas the yield strength of the piston is very high in Titanium alloy piston followed Al alloy 2024 and Al alloy 8090.

Piston ring observe high stress region at the open end. Thermal analysis of piston shows that the value of maximum temperature is slightly varies for all the materials at the top surface of the piston crown, but maximum value of temperature in the piston made of titanium alloy. This is due to thermal conductivity of the materials. Minimum temperature is in the skirt of the piston is observed as shown in figure. Figure shows that max total heat flux is observed in piston and rings of Al alloy and piston of titanium alloy shows the lowest value of max total heat flux along the edges. Piston rings are made of Nodular Spheroidal Cast Iron. GCI Piston Rings show more deformation than in piston. Stress intensity is equal in both. Maximum temperature is equal in both materials, where minimum temperature is higher in piston,

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## CONCLUSION:

- It is concluded from the above study that using CATIAV5R20 software design and modelling become easier. Only few steps are needed to make drawing in three dimensions. Same can be imported to ANSYS for analysis.
- Piston made of three different materials Al alloy 2024, Al alloy 8090 and Titanium Ti-6Al-4V (Grade 5) are analyzed.
- Structural analysis shows that the maximum stress intensity is on the bottom surface of the piston crown in all the materials, but stress intensity is close to the yield strength of Al alloy piston.
- Maximum temperature is found at the centre of the top surface of the piston crown. Depending on the thermal conductivity of the materials, heat transfer rate is found maximum in Ti alloy piston and minimum in Al alloy 2024.
- For the given loading conditions, Ti Alloy of piston is found most suitable. But when the loading pattern changes, other materials may be considered.
- With the advancement in material science, very light weight materials with good thermal and mechanical properties can be used for fail safe design of the I.C.engine. This will reduce the fuel consumption and protect the environment.

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