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# Analysis of Piston of Internal Combustion Engine under Thermo-mechanical Load

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## Abstract

*The main objective of this article is to study the thermal and structural performance of piston using finite element based commercial software ANSYS. Piston is modelled using SOLIDWORKS and analysis would be performed through ANSYS workbench. Optimization analysis has been performed considering three different materials such as Grey Cast iron, structural steel and aluminium alloy because these three material have good compression strength and their thermal conductivity and density will different for each one. For the same amount of pressure Aluminium alloy has shown maximum deformation and equivalent strain, where von misses stress value is minimum for it. Whereas, Structural steel and Grey cast iron shows deformation and strain values less than that of Aluminium alloy for same pressure load. Aluminium alloy has highest heat flux and lowest temperature on piston head under thermal load. Piston receives thermal energy generated via combustion and higher heat flux ensures quick cooling of component by quick drainage of thermal energy. Grey cast iron and Structural steel has half of the value of heat flux to that of Aluminium alloy. Therefore, Aluminium alloy is the preferable material for the design of automobile piston among the given three materials.*

***Keywords: Internal Combustion Engine, Piston, ANSYS, FEA, Load Analysis***

## 1. Introduction

Single-slider crank mechanism is a four linkage single slider mechanism that is used in internal combustion engines. An internal combustion engine consists of cylinder, piston, crankshaft, piston rings, inlet & exhaust valves, and connecting rod. The component of IC engine which is exposed to combustion is piston. The main aim of automobile manufacturers and researchers has been to modify engine’s performance and maximize its power output for limited fuel consumption. Piston is the main component of whole engine assembly. Various researches and modifications have been done throughout the decades to reduce wear and tears, to resist high pressure, maintain temperature generated during combustion and to increase overall lifecycle of piston and its components. In the engine cylinder, during power stroke piston experiences extreme temperatures. Piston also undergoes cyclic gas pressure and inertial forces due to reciprocation. Under these thermal and mechanical stresses piston may fail. Since, this thermal and mechanical stress depends upon the properties of piston materials. So, the material preferred for the piston, cylinder, piston rings, and other related parts of an internal engine must have high thermal conductivity, high wear and tear strength. Due to the versatile nature, castability and mechanical properties of magnesium and aluminium alloys have several applications for example automotive and aerospace industries [1].

**Fig.1. Automobile Piston as given by Sachit and Nandish [6]**

It was noticed by them that heat loss would relatively high for high performance engines these engines piston might be made of magnesium alloy. Whereas, aluminium-based alloy was ideal to design the piston for torque-based engine where peak pressure was high and acts for longer duration. Aluminium alloys have different thermal conductivities and densities, which may be used as a piston material [2]. Authors compared the change in gas pressure with different materials of piston and identified the effect of pressure and temperature on various piston materials. Anugu *et al*. [3] conducted the static analysis on a 1300 cc diesel motor piston. The materials selected in this analysis, were Aluminium, Grey Cast iron and Structural steel. The values of stress, deformation and the strain were found low for steel material as compared to Grey Cast Iron and Aluminium alloy. Carvalheira and Gonçalves [4] did FEA on piston made of Aluminium alloy and Ductile Iron. For material properties, thermal expansion coefficient should be low, so that heat energy generated via combustion can be utilized properly, sent it to camshaft. It should have low density so that inertial forces generated should be of lower extent and it should not affect the movement of piston.

To improve lifespan of piston coating on the bowl in the crown was done, piston coating would also increase the structural strength of the piston significantly for the same engine operating conditions compared to the uncoated one. Roychoudhury *et al.* [5] found that due to thin layer of TiSiCN coating on the piston deformation reduced nine times and the stresses reduced by 33.97%. Sachit and Nandish [6] showed that coating of $Cr_2O_3$ on the piston, which was also known as Thermal Barrier Coating (TBC), increases the engine performance and also maintains an appropriate temperature, which results in efficient combustion. Schematic representation of automobile piston is shown in **Fig. 1** as suggested by [6]. That helps in spreading the temperature, which causes low thermal stresses hence low thermal fatigue and expansion. $Cr_2O_3$ on the piston also works as an oxidant and corrosion resistant barrier. Piston crown aluminium coating with plasma sprayed magnesia-stabilized zirconia was done by Cerit and Coban [7]. Authors observed that the highest temperature would be at crown centre of piston surface. Thermal barrier coating provides higher combustion chamber temperature. Cerit [8] studied the effect of partially coating of a SI engine piston on thickness and width of coating. Temperature distributions were dependent on coating thickness and were found to be higher in case of coated ones to that of uncoated ones. On coated surface temperature increases as the thickness increases. Normal stress were also dependent upon thickness of coating, and decreases with increase in thickness. Junju *et al* [9] compared the results of hermos- mechanical analysis with aluminium alloy crown and ceramic crown piston. It was found that stress and temperature distribution was low in ceramic material than the aluminium alloy. Therefore, ceramic crown structural stresses will be less and thermal efficiency will enhance. [10] In a reciprocating engine, temperature difference was generated during different strokes, so heat transfer takes place, from higher temperature to lower temperature. During the intake stroke and the initial part of compression stroke, heat flow was observed to the gases. At the combustion stroke and the expansion strokes, temperature of the gas increases, so heat flow takes place from gas to the cylinder walls. Therefore, the stiffness of the piston head and piston skirt should be good, so that piston head and skirt tolerate the pressure and friction between the contact surfaces of the piston and the cylinder walls. The piston crown should have optimum stiffness, so that stress concentration could be reduced throughout the head and that would reduce deformations. Reddy and Kumar [11] did thermal analysis and optimization of piston and found that the upper end of piston may generates a crack due to deformation caused during working, by piston skirt. An increase in width of crack can be observed if the stiffness of the material was low.

So, in order to reduce deformations, stiffness should be enough.Dong and Jun [12] analysed piston skirt which was formed by the Isothermal Forming Process, the manufacturing the piston with this process results in homogeneity of metal flow, also enhances the plastic flow and decreases the deformation pressure. These factors were important to give piston an ideal shape.Piston rings are located between the cylinder and the piston, these are necessary components that allow the engine to operate efficiently. Piston rings provide necessary lubrication to preventing scuffing and also prevents knocking of piston against cylinder walls and maintain gas compression between the piston and the walls of cylinder by sealing the cylinder**.** Srinadh and Rajasekhara [13] performed static analysis on piston under thermal and mechanical load. Piston rings were made of cast iron, aluminium (A360) and Zamak. Piston rings have three different profiles such as rectangular, semi-circular and tapered. It was found by them that semi-circular ring gives the best results out of three cross-sections of piston rings in the term of deformations, strain and heat flux properties. Various piston geometries for example Deep Cylindrical Piston (DCP), Shallow Re-Entrant Piston (SRP), and Hemispherical Existing Piston (HEP) at different compression ratios , 15:1, 17:1, 16:1; respectively has been considered by Premkumar *et al.* [14]. It was found by them that SRP would be the optimum geometry for piston making, because SRP geometry piston showed minimum stress, due to geometry bowl. Factor of safety was highest for SRP and it also showed enough stiffness. [15] For different shape of combustion chambers, generally three shapes were used, which are Hemispherical Combustion Chamber (HCC), Torodial Combustion Chamber (TCC) and Shallow depth Combustion Chamber (SCC), in which HCC have a good thermal efficiency and low brake specific fuel consumption. Hence, through detailed literature review it is noticed that further research is required on piston considering various material properties with different cross-section of piston rings and geometry of piston to improve the thermal and mechanical efficiency of engine. Thus in this article authors has been performed the static analysis on piston under combination of thermal and internal radial pressure using finite element based software ANSYS. Here, considered the three different materials such as Grey Cast iron, structural steel and aluminium each material has dissimilar thermal conductivity and density with good compression strength.

### 1.1 Methodology

The static analysis of piston of internal combustion engine under thermal and mechanical load are performed by using finite element method based commercial software ANSYS. To discretize the piston of engine considered the four-node 181 shell element. To solve the multi-dimensional problem using Green-Gauss theorem that will expressed as:

$$\underbrace{\int_V \sigma^T \varepsilon(\delta) dV}_{\text{Strain energy}} - \underbrace{\int_V \delta^T f dV}_{\text{Body force}} - \int_S \underbrace{\begin{bmatrix} (n_x\sigma_x + n_y\tau_{xy} + n_z\tau_{xz})\delta_x \\ +(n_x\tau_{xy} + n_y\sigma_y + n_z\tau_{yz})\delta_y \\ +(n_x\tau_{xz} + n_y\tau_{yz} + n_z\sigma_z)\delta_z \end{bmatrix}}_{\text{Surface force or traction force}} dS = 0 \quad (1)$$

Here, $\sigma$ represents six independent component of stress $\sigma = \left[\sigma_x, \sigma_y, \sigma_z, \tau_{yz}, \tau_{xz}, \tau_{xy}\right]^T$ normal stresses and shear stresses; $\varepsilon$ represents six strains corresponding to strains $\varepsilon = \left[\varepsilon_x, \varepsilon_y, \varepsilon_z, \gamma_{yz}, \gamma_{xz}, \gamma_{xy}\right]^T$; *dV* is volume integration *dV = dx dy dz;* distributed force per unit volume $f = \left[f_x, f_y, f_z\right]^T$; displacement vector is $\delta = \left[u_x, u_y, u_z, \theta_x, \theta_y, \theta_y\right]^T$; the unit normal to surface *dA* is $n = \left[n_x, n_y, n_z\right]^T$.

The total potential energy of the general elastic body is written as:

$$\Pi = \frac{1}{2}\int_V \sigma^T \varepsilon dV - \int_V \delta^T f dV - \int_S \delta^T T dS - \sum_i \delta_i^T P_i \quad (2)$$

Here, $\sigma$ = [D][B]{δ} and ε = [B]{δ}; [D] is the flexural rigidity matrix and [B] is the strain-displacement matrix. Flexural rigidity may be written as $D = \frac{Eh^3}{12(1-\mu^2)}$ for the flat and curved panel.

The stress-strain relations according to generalised Hook's law will be written as:

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{yz} \\ \tau_{xz} \\ \tau_{xy} \end{Bmatrix} = \begin{bmatrix} \bar{Q}_{11} & \bar{Q}_{12} & 0 & 0 & 0 & \bar{Q}_{16} \\ \bar{Q}_{12} & \bar{Q}_{22} & 0 & 0 & 0 & \bar{Q}_{26} \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \bar{Q}_{44} & \bar{Q}_{45} & 0 \\ 0 & 0 & 0 & \bar{Q}_{45} & \bar{Q}_{55} & 0 \\ \bar{Q}_{16} & \bar{Q}_{26} & 0 & 0 & 0 & \bar{Q}_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_x - \alpha_x \Delta T \\ \varepsilon_y - \alpha_y \Delta T \\ \varepsilon_z \\ \varepsilon_{yz} \\ \varepsilon_{xz} \\ \varepsilon_{xy} - \alpha_{xy} \Delta T \end{Bmatrix} \quad (3)$$

Here, $\alpha_x$, $\alpha_y$, $\alpha_{xy}$ are the linear coefficient of thermal expansion along x-axis, y-axis, $\Delta T$ denotes the change in temperature inside the cylinder due to combustion.

Firstly, for the static analysis of piston of internal combustion engine are performed by solving this governing equation that may be expressed as:

$$[K_L]\{\delta\} = \{F_P\} + \{F_T\} \quad (4)$$

Here, $[K_L]$ is stiffness matrix that may be expressed as:

$[K_L] = \int_{K=1}^{n} [B]^T [D][B] dxdydz$; $\{\delta\}$ is displacement vector represents six degree of freedom three displacements $u_x$, $u_y$, $u_z$ and three rotations $\theta_x$, $\theta_y$, $\theta_z$ along $x$-axis, $y$-axis and $z$-axis, respectively; $F_p\}$ and $\{F_T\}$ are uniformly distributed load or internal radial pressure and thermal load vector.

### 1.2 Model description

Firstly, developed three-dimensional model of piston through SOLID WORKS as shown in **Fig. 2** considering the following geometric properties.

- Outer radius of piston metal = 46.50mm
- Inner radius of piston metal = 41 mm
- Thickness of piston =5.50 mm
- Internal radius of piston pin hole = 11 mm
- Outer radius of piston pin hole = 13.7 mm

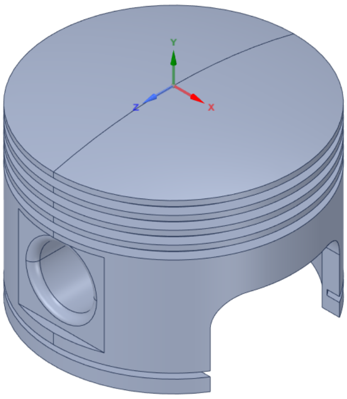


**Fig. 2. 3D model of piston**

Thereafter, developed SOLID WORK model is imported to ANSYS workbench, and after assigning suitable material properties as given in **Table 1**. Meshing is done. The materials selected for analysis is Aluminium Alloy, Structural Steel, and Grey Cast Iron.

**Table.1. Material properties of considered materials**

| Material | Young's Modulus ($E$) GPa | Density ($\rho$) kg/m$^3$ | Poisson's Ratio ($\mu$) | Thermal conductivity ($\alpha$) C$^{-1}$ |
|---|---|---|---|---|
| Aluminium Alloy | 73.7 | 2768 | 0.33 | 0.0000259 |
| Structural Steel | 200 | 7860 | 0.266 | 0.0000117 |
| Grey Cast Iron | 110 | 7200 | 0.28 | 0.000011 |

In order to analyse the model by FEM, 2323 elements of Quad4 shape and 16318 elements of Quad8 shape are generated in the meshing of the model as shown in **Fig. 3**.

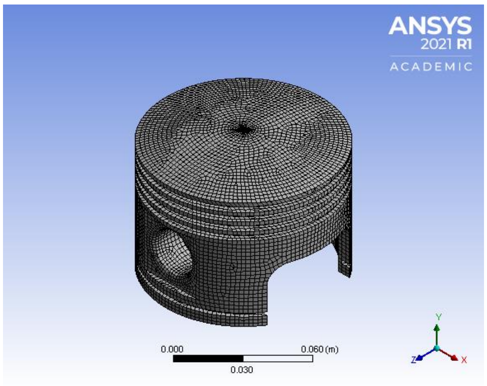


**Fig. 3. Meshing of piston**

### 2. Results and Discussion

Boundary conditions are defined as load and support for static structural analysis is shown in **Fig. 4** for thermal analysis convection coefficient and heat flow. Study of static load conditions on piston applied the radial pressure 5 MPa which acts on head of the piston and second one is the frictionless support, which is provided by the piston pin hole to the geometry. Pattern of deformation, von-misses stress and strain are identified for all three materials. Equivalent stress is often used in piston design because it can characterize any random 3D stress state to a single positive stress value. Finally, total deformation, equivalent stress and strain with different materials are presented in **Fig. 5-7** for clear understanding.

### 2.1. Static Structural Analysis

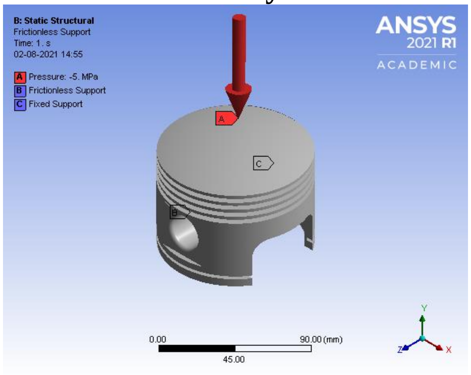
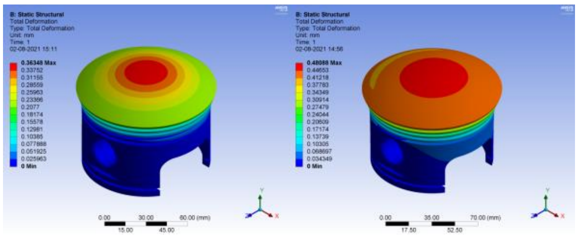
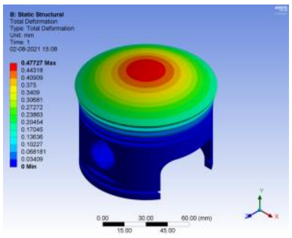


**Fig. 4. Boundary condition to for structural analysis.**



(a) Structural Steel (b) Aluminium Alloy



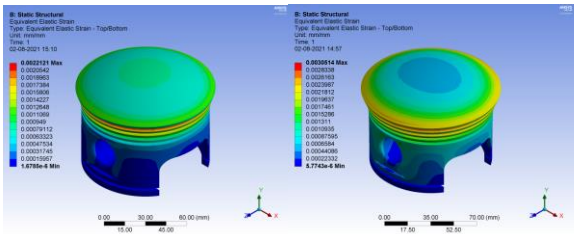
c) Cast Iron

**Fig. 5. Total Deformation of piston structure under 5 MPa for different materials used.**

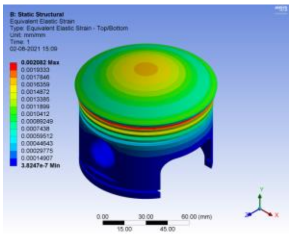
**Table 2. Maximum and minimum deformation due to mechanical loads**

| **Material** | **Deformation (mm)** | | |
|---|---|---|---|
| | **Max.** | **Min.** | **Average** |
| **Structural steel** | 0.36348 | 0 | 0.058823 |
| **Aluminium alloy** | 0.48088 | 0 | 0.11622 |
| **Grey cast iron** | 0.47727 | 0 | 0.059615 |

It is noticed from **Fig. 5** that maximum deformation occurs around centre of piston head, irrespective of material type used. Maximum, minimum and average deformations for three different materials are given in **Table 2**. However, the magnitude of deformation is different for different material. Aluminium alloy shows maximum deformation trend of about 0.48088 mm, while Structural steel shows minimum deformation of 0.36348 mm under the action of 5 MPa pressure.



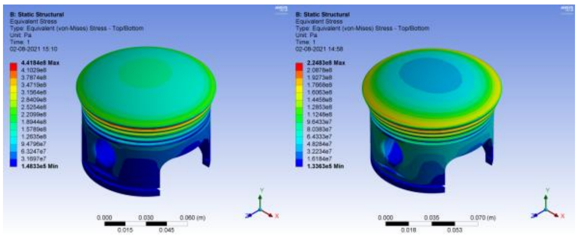
(a)Structural Steel (b) Aluminium Alloy



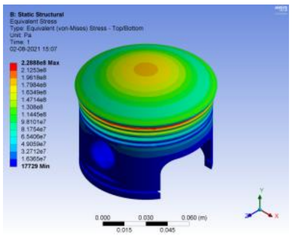
(c) Cast Iron

**Fig. 6. Schematic representation of equivalent strains for three different Materials.**

It is shown in **Fig. 6** that generated equivalent strains may be maximum for Aluminium alloy, while structural steel and Grey cast iron has minimum with a slight difference between them.



(a) Structural Steel (b) Aluminium Alloy



(c) Cast Iron

**Fig. 7. Structural Analysis Strain of Materials**

It can be observed from **Fig. 7** that Structural steel is experiencing more von mises stresses than Aluminium alloy and Grey cast iron. The maximum and minimum Von mises strain and stresses of piston under mechanical load or radial pressure are also tabulated in **Table 3 & 4**, respectively.

**Table. 3. Maximum and minimum Von Mises strain due to mechanical loads**

| **Material** | **Von Miss strain** | | |
|---|---|---|---|
| | **Maximum** | **Minimum** | **Average** |
| **Structural steel** | 0.0022121 | $1.678\times10^{-6}$ | $4.795\times10^{-4}$ |
| **Aluminium alloy** | 0.0030514 | $5.774\times10^{-6}$ | $8.690\times10^{-4}$ |
| **Grey cast iron** | 0.002082 | $3.825\times10^{-7}$ | $4.546\times10^{-4}$ |

**Table.4. Maximum and minimum Von Miss stresses due to mechanical loads**

| **Material** | **Equivalent stress (pascal)** | | |
|---|---|---|---|
| | **Maximum** | **Minimum** | **Average** |
| **Structural steel** | $4.4184\times10^{8}$ | $1.4833\times10^{5}$ | $8.1855\times10^{7}$ |
| **Aluminium alloy** | $2.2483\times10^{8}$ | $1.3363\times10^{5}$ | $5.4844\times10^{7}$ |
| **Grey cast iron** | $2.2888\times10^{8}$ | 17729 | $4.2248\times10^{7}$ |

## 2.2. Steady State Thermal Analysis

Next, thermal analysis has been performed on piston considering the following boundary conditions in shown in **Fig. 8** such as primary boundary condition is 2330 $W/m^2$ convection coefficient on outer surface and 750 $W/m^2$ on inner surface, and secondary boundary condition is 9923 W heat flow on the piston head. Temperature profile for different material is observed as well as maximum heat flux and directional heat flux values are identified. Finally, Temperature, heat flux and directional heat flux values with different materials are presented in **Fig. 9-11** for clear understanding. The temperature profile is shown in **Fig. 9** and maximum and minimum temperature is tabulated in **Table 5.** It is observed that the distribution of temperature is maximum at the surface of the piston head and minimum at skirt and pin irrespective of the material used in the analysis. Grey cast iron have maximum temperature of 619.2$^o$c, while Aluminium alloy has the minimum of 533.54$^o$c of the materials used fig 8.

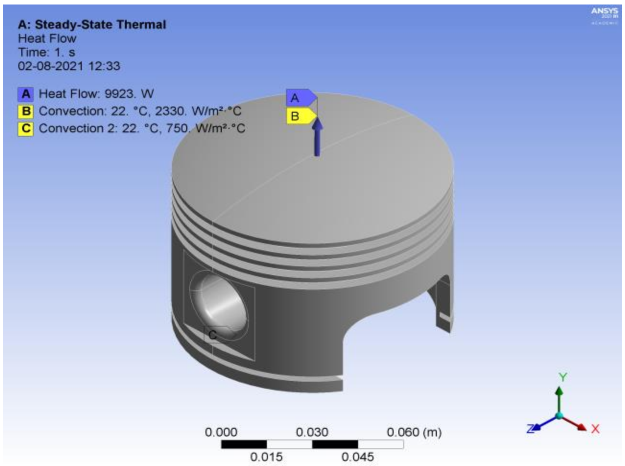
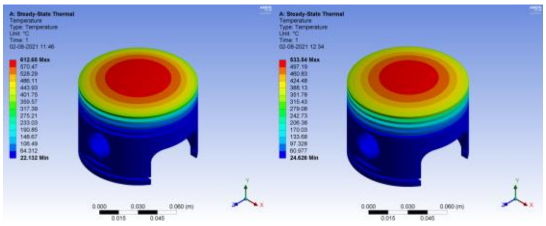
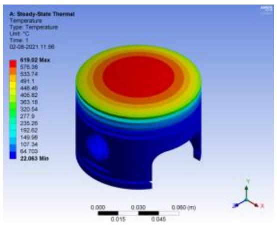


**Fig. 8. Boundary conditions for thermal analysis**

Heat transferred per unit area or heat flux is maximum for all three material around the perimeter of piston head as shown in **Fig. 10** and given in **Table 6**. Aluminium alloy has highest heat flux of 2.0324 x $10^6$ $w/m^2$, while Grey cast iron has the lowest heat flux around 1.001 x $10^6$ $w/m^2$.

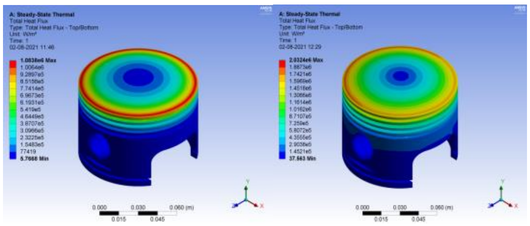


(a) Structural Steel (b) Aluminium Alloy

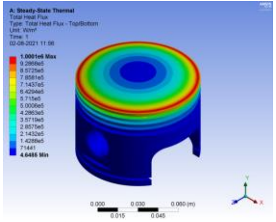


(c) Cast Iron

**Fig. 9. Temperature distribution plot for three different materials.**



(a) Structural Steel (b) Aluminium alloy



(c) Cast Iron

**Fig. 10. Total heat flux under steady state thermal condition for three different materials of Automobile Piston.**

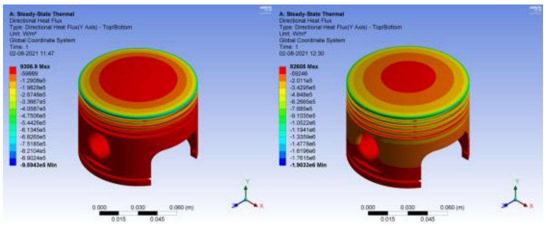
**Table.5. Comparison piston temperature for various materials under thermal load**

| Material | Temperature | | |
|---|---|---|---|
| | **Maximum** | **Minimum** | **Average** |
| **Structural Steel** | 612.5 | 22.132 | 117.29 |
| **Aluminium alloy** | 533.24 | 24.626 | 119.27 |
| **Grey cast iron** | 619.02 | 22.063 | 116.41 |

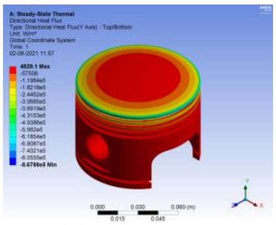
Moreover, directional heat flux along *y*-axis is presented in **Fig.11** and tabulated in **Table 7**. It is noticed that the directional heat flow along *y*-axis is maximum for structural steel around 9306.9 w/m$^2$ while, minimum for Grey cast iron only 4829.1 w/m$^2$.

**Table.6. Comparison of heat flux of piston under thermal load**

| Material | Heat flux (w/m$^2$) | | |
|---|---|---|---|
| | **Maximum** | **Minimum** | **Average** |
| **Structural Steel** | $1.0838\times10^6$ | 5.7668 | $1.3916\times10^5$ |
| **Aluminium alloy** | $2.0324\times10^6$ | 3.563 | $3.3833\times10^5$ |
| **Grey cast iron** | $1.0001\times10^6$ | 4.6485 | $1.2117\times10^5$ |



(a)Structural Steel (b)Aluminium alloy



(c) Cast Iron

**Fig. 11. Directional Heat flux generated along *Y*- axis of different materials used.**

**Table.7. Minimum and maximum directional heat flux along Y-axis**

| Material | Heat flux (w/m$^2$) | | |
|---|---|---|---|
| | **Maximum** | **Minimum** | **Average** |
| **Structural steel** | 9306.9 | $-9.594\times10^5$ | - 55635 |
| **Aluminium alloy** | 82605 | $-1.903\times10^6$ | $-1.378\times10^5$ |
| **Grey cast iron** | 4829.1 | $-8.679\times10^5$ | - 48359 |

## Conclusions

Effect of thermal and structural load on automobile piston for three different materials has been studied. For the same amount of pressure Aluminium alloy has shown maximum deformation and equivalent strain, however von misses stress has minimum values for it. Structural steel and Grey cast iron shows deformation and strain values less than that of Aluminium alloy. However, under thermal load Aluminium alloy has highest heat flux and lowest temperature on piston head. Piston receives thermal energy generated via combustion and higher heat flux ensures quick cooling of component by quick drainage of thermal energy. Higher value of heat flux also marks dimensional stability which also signals creep resistance. Grey cast iron and Structural steel has half of the value of heat flux to that of Aluminium alloy.

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