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Research article

Numerical simulation of piston with different materials for justification of its strength

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Abstract

This project deals with the determination of best material among the three selected ones. Initially, based on systematic literature review, three materials, i.e. aluminum 4032, grey cast iron and titanium 6Al-6V, were selected, and their properties were determined. Then, design specifications form YAMAHA FZV3 was taken, and required design parameters and necessary dimensions of the piston were calculated. After this, the piston's Design was performed using SOLIDWORKS 2016, followed by structural and thermal analysis using ANSYS 16.0. Finally, the results were compared and it was noticed that among three materials the highest deformation was seen for aluminum which was 31.77% more than titanium alloy while the maximum difference in stress was for grey cast iron with 39.7% more than titanium alloy. Also, the heat flux for titanium alloy was least. This indicated that titanium 6Ai-4V gave better for durability and structural and theoretical performance. Hence, it was concluded to be the best material among the selected ones for the piston used.

Keywords: Piston, SOLIDWORKS, ANSYS, Structural and thermal analysis

1. Introduction

The piston is an integral component of an internal combustion engine that can transfer the combustion cycle's energy into the crankshaft [1]. It also seals the combustion chamber and prevents from any possible leakage with the help of piston ring. It also maintains a suitable quality of oil within the combustion chamber's cylindrical wall and regulates the oil consumption. The component like piston head, compression ring, fluid ring, piston pin and connecting rod as a whole make a complete piston assembly [2]. Piston operates under extreme working environment. They have to face continuous periodic load, huge pressure and excess stress and uneven deformation due to continuous reciprocating motion. Moreover, the chemical reactions and burning of the air-fuel mixture create high thermal stress [3]. So, under different mechanical and thermal loading condition, the piston's stress, deformation, and thermal behaviour should be investigated to better its performance. In the meantime, exploring multiple materials should also be carried out to find out their possibility [4].

The authors in [5] analyzed the theretical performance of thermo-mechanical conditions of piston utiling FEA. The parameter calculation was performed like fatigue life and stress loading on piston followed by their comparison with accelerated life testing. The result demonstrated highest stress on the inner chamber at the top most surface of the piston. In the same the maximum stress acted at the pin set portion of piston in the upper segment. Similarly, in [6] the demonstration of proper view of the thermal behaviour of piston along with its failure modes. They concluded that the there are two major reasons for mechanical loading ie. improper control of air temperature in post intercooler and utilization of injector codes that are neutral. In [7] the study on the impact on piston due to the effect of emissions in diesel engine containing geometry of the cone and inlet tube, shape of exit cone and monolithis's location. They improved the flow distribution and enhanced the performance of catalytic converters with larger service life Jaichandar and Annamalia in [8] investigated TDI i.e. turbocharged direct injection system under different torque and speed consideration for a diesel engine to determine the impact of injection of pilot. For the knowledge of direc impact on engine performance, variation of duration and timing plot were done. They obtained that pilot injection greatly affected the NO_x emission levels and at low engine speed effect due to injection timing was noticed.

This paper presents the numerical assessment and piston analysis using the finite element method for the YAMAHAFZV3 engine model utilizing multiple materials. The thermal and structural performance of the piston is analyzed using the selected materials to predict better material for piston manufacturing. In this study, titanium alloy is purposed to be more durable and better to handle load than currently used piston material i.e. aluminum alloy. Here, dimensions of pistons are calculated based on the properties of material used. This study will help in manufacturing piston with larger life based on structural and thermal property.

2. Numerical assessment of piston

2.1 Material Selection

To resist extreme load and thermal variation, the performance of the material plays a vital role. The properties of materials determine the size and capacity of components' performance be made using that particular material. Based on the strength, resistance and workability, three different materials were selected for piston materials. The materials include aluminium 4032, grey cast iron and titanium (6Al-4v). The mechanical, as well as thermal properties of these materials, are tabulated in Table 1.

Table1: Properties of materials used for numerical calculation and analysis [9-11]

Properties	Grey Cast Iron	Aluminum alloy (Al-4032)	Titanium alloy (6Al-4v)
Young's Modulus (GPa)	80	79	104
Shear Modulus (GPa)	31	26	40
Poisson's Ratio	0.255	0.33	0.31
Ultimate tensile strength (MPa)	100	380	900
Thermal Conductivity (W/m-k) at room temperature	40	155	6.7

2.2 Numerical calculation

Here, the theoretical calculations of stress and the piston's dimensions are made. The stress and load involved are calculated using the specifications of the YAHAMA FZV3 engine. The dimensions of the piston's are obtained by following the guidelines of the machine design handbook [12, 13]. To calculate the external parameters involved in the piston, the specifications of the engine was used, which is shown in Table 2 [14]:

Table 2: Design specifications

Parameter	Details
Engine type	Air-cooled, 4-stroke, SOHC, 2-valve
Displacement	149 cc
Maximum power	12.4 PS @ 7250 rpm
Maximum torque	13.6 Nm @ 5500 rpm
Bore	57.3 mm
Compression ratio	9.5:1
stroke	57.9 mm
Supply of fuel	F.I.

I. Torque

Whenever the engine exerts, twisting force is created, and the measure to determine this force is said to be Torque.

From Table 2, maximum power is given as P= 12.4 PS= 9.12 kW

So, Torque = $\frac{p*60}{2\pi N}$= 6.83 Nm (1)

where, N= speed in rpm.

II. Diameter of piston

Under the principle that volume is equal to displacement, the piston's diameter can be determined.

$$\pi r^2 h = cubic\ centimeter \quad (2)$$

where, cubic centimeter= 149cc (Table 2)

$3.14*r^2*0.0057=149*10^{-5}$

r= 29mm and D= 58mm

III. The pressure inside the cylinder

The ratio of force pre-unit area can be considered as pressure. For pressure inside the cylinder, we know the formula:

$$P=\frac{F}{A} \quad (3)$$

We know that, velocity $V = 2LN/60$ = 13.77 m/s (4)

So, force= $\frac{9.12*10^3}{13.77}$ = 662.3 N

Area= πr^2 = $2.64*10^{-3}$ (5)

Hence, pressure = 0.2508MPa

Maximum pressure=15*P_{min}=3.76 MPa (6)

2.2.2 Piston dimension calculation

The dimensions of piston parameters are determined by using specific procedures. The parameters and principle used for obtaining the values of each component are shown below.

i. Piston head thickness

If p is the maximum pressure (N/mm²), D is piston's outer diameter(mm), and σt is permissible tensile stress for the material of the piston respectively, then Using Ghracffs law, the formula determines the diameter of the piston head

$$t_H= D\sqrt{\frac{3}{16}\frac{P}{\sigma t}} \quad (7)$$

ii. Piston ring's radial thickness

If D is bore diameter, $P_{.W.}$ is gas pressure inside cylinder and σt is allowable tensile strength, then the thickness of piston (Radial) is given by the formula

$$t_1= D\sqrt{3*\frac{pw}{\sigma t}} \quad (8)$$

iii. Ring thickness (Axial)

Considering t2 as the axial thickness of ring their variation can range from,

t2 = 70%t1 to 100%t1 (9)

iv. Thickness (top land)

Considering b1 as top land thickness, their variation can be obtained within the range of

b1 = 100% tH to 120% tH (10)

v. Width (Other lands)

If b2 is the width of other lands, then its value ranges from,

Width of other ring lands varies from

b2 = 75%t2to 3 (11)

vi. Ultimate width of Barrel

Let t3 be the Barrel highest thickness of Barrel,

$t_3 = 0.03D + b + 4.5$ (12)

where,

b = ring groove depth of piston in the radial direction.

vii. Thickness (Open End Barrel)

Suppose t4 is the gap of the open-end Barrel than its range include

$t_4 = 25\%t_3$ to $35\%t_3$ (13)

viii. The gap between the first piston ring (T_l)

$T_L = 0.055D$ (14)

Second ring = 0.004*D (15)

ix. Depth of the groove Dr

$D_r = t_1 + 0.4$ (16)

x. Length of piston

$L_p = l_{ps} + 3*t_1 + 3*D_r$ (17)

L_ps= laps of piston =50%D (18)

xi. Piston pin diameter

P_{do}= 30% D to 45% D (19)

xii. The internal diameter of the piston

$P_{DI} = 0.6 * P_{DO}$ (20)

Based on the above expressions, the dimensions of piston with different materials are tabulated below:

Dimensions	With Aluminium (4032)	With grey cast iron	With titanium (6Al-4V)
Length of piston	43 mm	43.6	42.4
Diameter of piston	58	58.7	56.8
The diameter of the external hole of the piston	19	20	17.6
The diameter of the internal hole of the piston	14	14.4	14.3
Axial thickness of the piston	1.9	2.3	1.7
The radial thickness of the piston	2.1	2.6	1.9
Ring groove depth	2.5	2.9	2
Gaps between rings	3.19	3.8	2.6
The thickness of top land	5	5.3	4.5
End thickness of piston top	6	6.7	5.2
End thickness of piston open	2.11	2.5	1.7

3. Modeling and analysis

3.1 Piston model

Based on the piston's calculated dimensions for three different materials, i.e. aluminium alloy, grey cast iron and titanium alloy, three-dimensional model of the piston was prepared using SOLIDWORKS 2016 software for further analysis. The diagrammatic representation of the piston model is shown in Fig. 1.

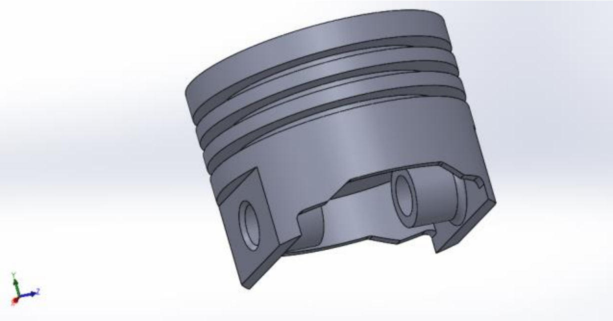

Fig. 1 SOLIDWORKS design of piston

3.2 Analysis

To perform simulation of the piston material, ANSYS 16.0 software was used.

Structural and thermal analysis are used simultaneously to select the material by evaluating structural and thermal performance.

3.2.1 Structural analysis

It is used to determine the deformation and stress induced by a model whenever any load is applied to a structure or its components. To perform structural analysis in ANSYS 16.0 for piston, 3D Design is first imported to ANSYS 16.0 workbench and is meshed to break down the components into a number of nodes and elements. In this Design, fine mesh is performed using tetrahedral element. It should be mentioned that due to the specific geometry of the investigated piston, which was relatively complex, the "fine" automatic mesh was used for the solution. The investigated parameters were von-Mises stress and deformation. By changing the mesh from "fine" to "very fine", the solution time increased by more than 3 times, but the answers changed by less than 2%. Therefore, to reduce the calculation time, the same "fine" mesh was used.

As a boundary condition, the pressure of 3.76 MPa we applied on the piston head and the support is frictionless. Then, the parameters like Von-Mises stress and deformation are determined by completing the post-processing.

3.2.2 Thermal analysis

It is used to predict the thermal behaviour of the system. The piston's imported 3D drawing is meshed under fine mesh type and uses the tetrahedral element to perform this ANSYS 16.0 analysis. After breaking down the piston into smaller nodes and elements, boundary conditions are applied. For this, constant temperarure of 400-degree Celcius is applied on the piston head, and convective heat transfer medium is employed with the temperature of 22^0C. Then, Film coefficient= 59 W/m^2-K (for Aluminium), 55 W/m^2-K (for grey cast iron), 40 W/m^2-K (for titanium alloy) is assigned, and simulation is performed to find the value of temperature distribution and heat flux.

For the thermal analysis in steady-state, matrix equation is utilized to solved for the temperature which is given as [15]:

$$[K(T)]\{T\}= \{Q(T)\} \qquad (21)$$

where, K and Q are functions of temperature and are condidered constant and no transient effect are considered during this analysis.

The heat flux q is defined as the heat flow across the contact interface, and is governed by the following equation:

$$q= - (T_{contact} - T_{target})* TCC \qquad (22)$$

here, T_{targe}t designated the targated node while $T_{contact}$ signifies the node of contact where as by default set TCC is defined to be very high as per the conductivity of the material in model KXX concerned with ASMDIAG geometry bounding box.

i.e.

$$TCC=KXX*10000/ASMDIAG \qquad (23)$$

Finally, the contour for heat flux is obtained in terms of vector mode as:

$$Q= -KXX \bigtriangledown \mathbf{T} \qquad (24)$$

where, vector mode is activated for calculation of magniture and direction.

Similarly, the governing equation for transient thermal analysis is given by the formula,

$$K\ (\partial^2 T/\partial x^2 + \partial^2 T/\partial y^2 + \partial^2 T/\partial z^2)+q = \rho c(\partial T/\partial \mathrm{t}) \qquad (25)$$

where, T, t K and c represents temperature in K, time, thermal conductivity in W/Km and Specific heat of the material in J/kg.K.

The equation represents the sum of rate of heat conduction and rate of heat flux which is equivalent ot rate of energy stored inside the volume. In every cycle of engine, there is change in instantaneous temperature inside the cylinder causing temperature variation [16].

With the fluctuation fo gas temperature the thermal boundary condition of the piston will also change. The formula to represent such change is obtaind by the relation [17]:

$$\alpha = 130 d^{-0.2} p^{0.8} T^{-0.53} \{c\ C\ [1 + 2(V_{roc}/V)^2 P_{IMPE}^{-0.2}]\}^{0.8} \quad (26)$$

Here, PIMPE is mean indicated pressure, and T, P,V, are the instantaneous value of temperature, pressure, and volume.

4. Results

4.1 Results for structural analysis

Based on structural analysis, all three materials' maximum equivalent stress and deformation values are shown below. From Table 3, it is clear that the value of equivalent stress for grey cast iron is maximum, and titanium alloy is the least which is shown in below.

Table 3: Result for structural analysis

Parameter	Aluminum alloy	Grey Cast Iron	Titanium alloy
Equivalent stress (Mpa)	5.2148e6	6.2315e6	4.4582e6
Total deformation (mm)	9.5439e-7	6.7694e-7	6.5116e-7

Similarly, the value of deformation of titanium alloy is lowest while Aluminium is the highest. The result shows that for piston working under similar environments and the same application of load, titanium alloy will provide piston better ability to handle load compared with aluminium 4032 and grey cast iron. The design contours for structural analysis using all the materials shown in Figs. 2 to 7.

Using aluminium alloy 4032 as material (Figs. 2 and 3):

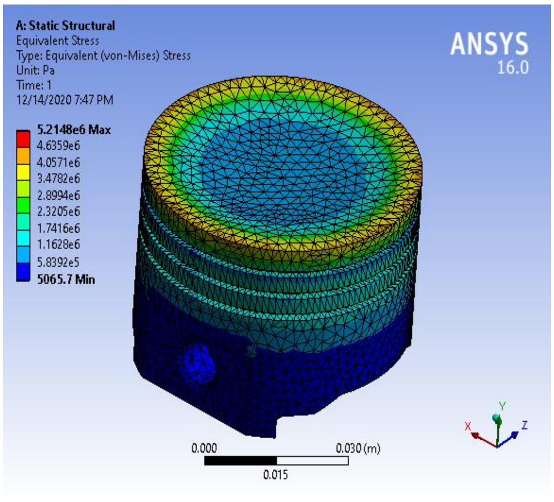

Fig. 2 Equivalent stress

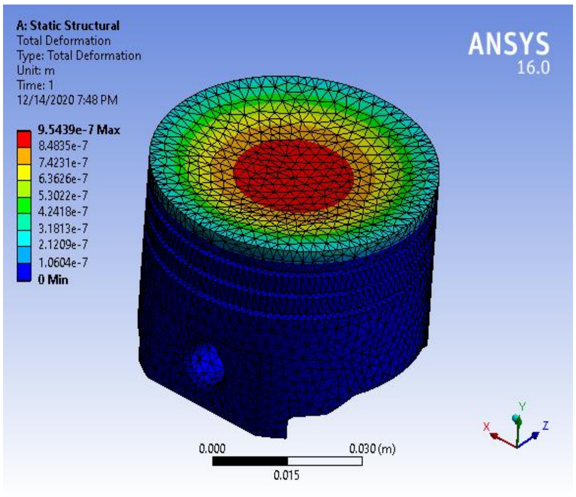

Fig. 3 Total deformation

Using grey cast iron as the material (Figs. 4 and 5):

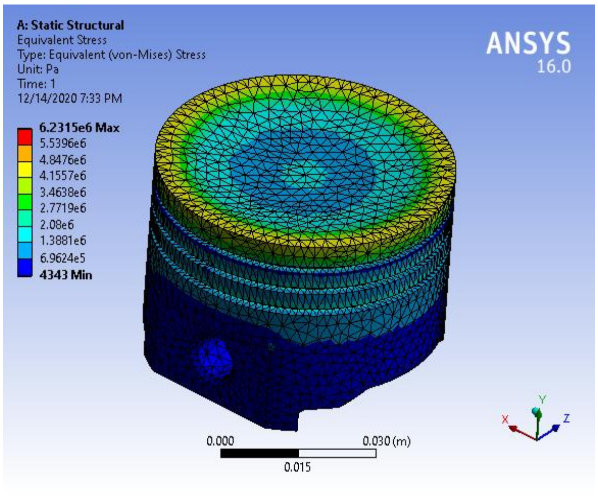

Fig. 4 Equivalent stress

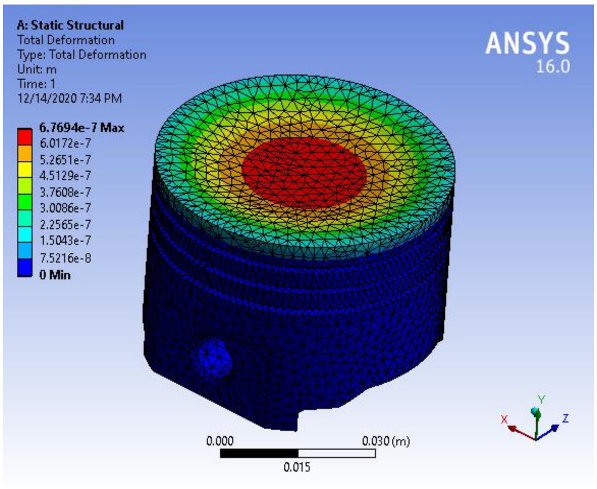

Fig. 5 Total deformation

Using Titanium alloy as material (Figs. 6 and 7):

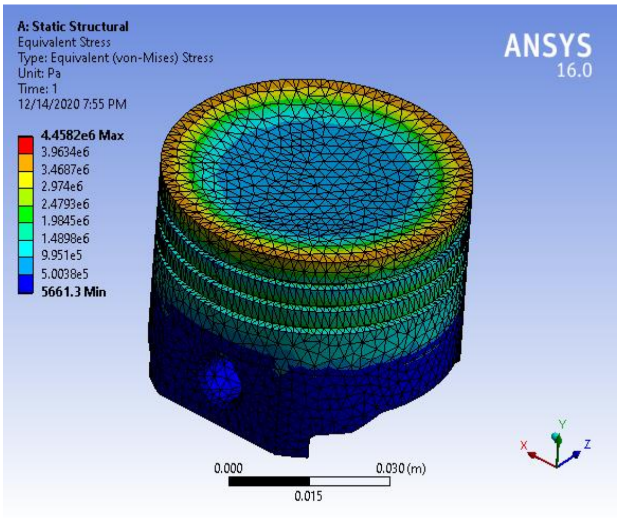

Fig. 6 Equivalent stress

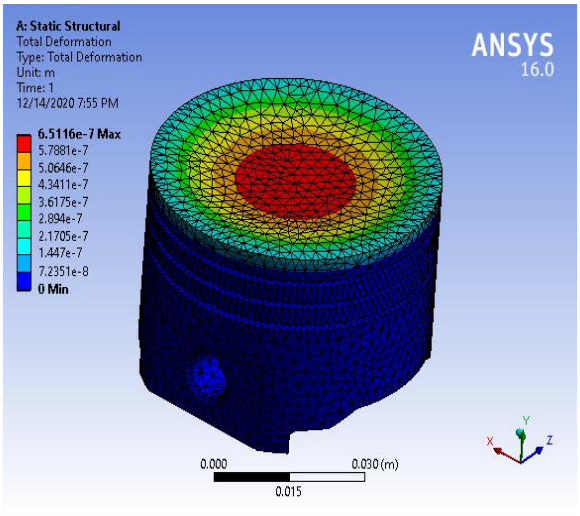

Fig. 7 Total deformation

4.2 Results for Thermal Analysis

Based on thermal analysis, the minimum temperature and maximum heat flux values are shown in Table 4.

Table 4: Thermal analysis result

Parameter	**Aluminium alloy**	**Grey Cast Iron**	**Titanium alloy**
Min. temperature (ºC)	22.069	22	22
Heat flux (W/m^2-K)	7.3851e6	2.9204e6	1.6772e6

Form Table 4; it is clear that minimum temperature is similar for piston design using all three materials. However, for aluminium alloy, the heat flux is maximum, and for titanium alloy, it is minimum. Hence, it can be concluded that titanium alloy could have better thermal resistance than aluminium alloy and grey cast iron. The design contour for heat flux and temperature distribution is shown in Figs. 8 to 13.

Using Aluminium as a material (Figs. 8 and 9):

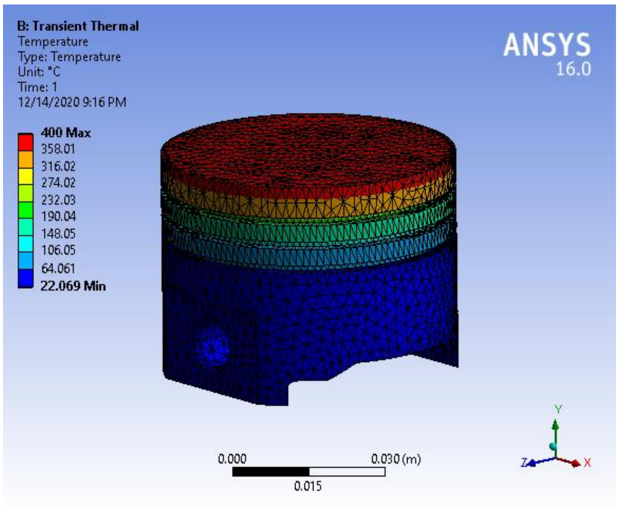

Fig. 8 Temperature distribution

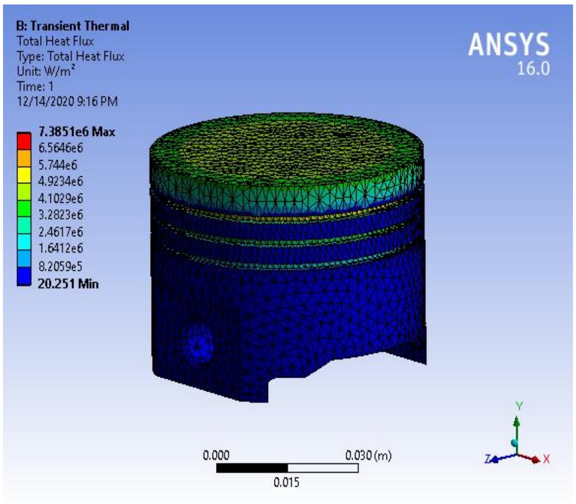

Fig. 9 Heat flux

Using Cast Iron as material (Figs. 10 and 11):

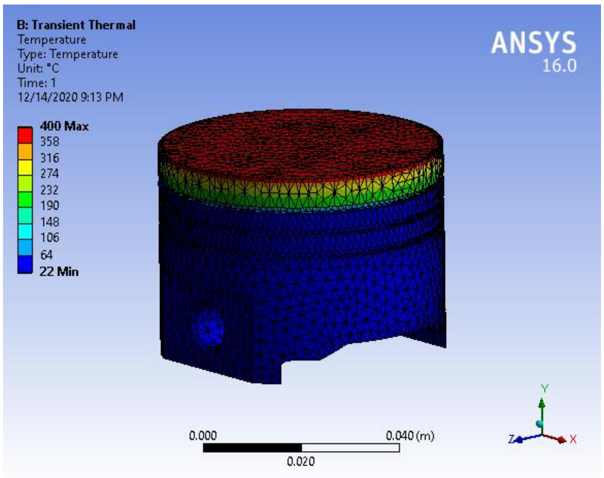

Fig. 10 Temperature distribution

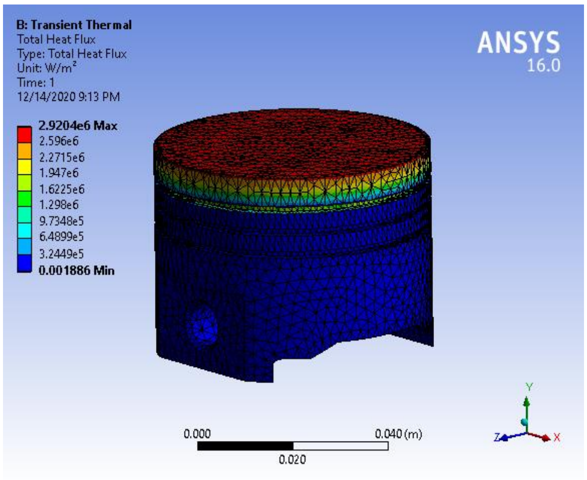

Fig. 11 Heat flux

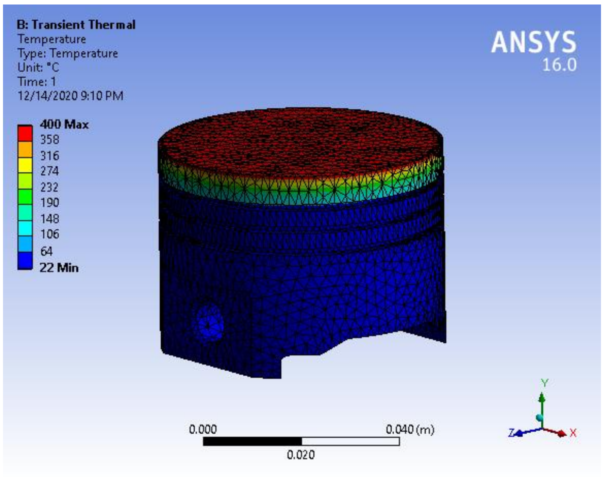

Fig. 12 Temperature distribution

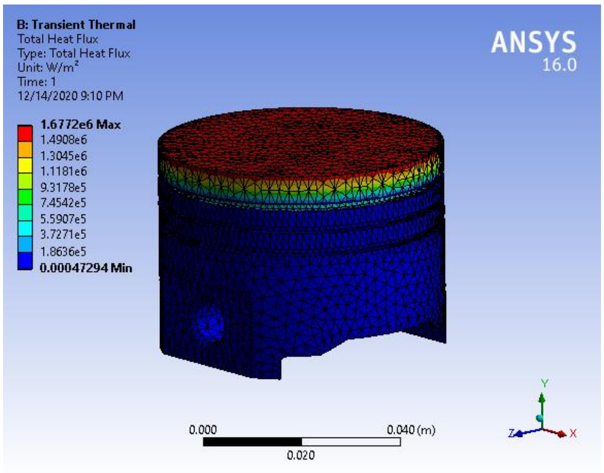

Fig. 13 Heat flux

5. Conclusion

As per the structural analysis, the equivalent stress and deformation for titanium 6Al-4V were minimal compared with Aluminium and grey cast iron. i.e. the deformation of aluminum and grey cast iron was 31.7% and 3.8% greater than titanium allow while the stress induced were 16.9 % and 39.7 % greater respectively This showed that titanium had better load-bearing capacity than the other two materials. Similarly, as per the thermal analysis, the heat flux for titanium alloy was less, indicating that it can resist more heat flow under a similar working condition than cast iron and Aluminium. Hence, the analysis showed that titanium 6Al-4V has better structural and thermal performance than the other two material. In conclusion, titanium 6Ai-4V was the best material and can be considered for further piston manufacturing advancement.

Nomenclature

Cc : Cubic centimeter (-)
N : Speed (rpm)
P : Power (KW)
σ_t : Permissible tensile stress (N/mm^2)
h : Height of piston cylinder (mm)
D : Diameter of piston (mm)
F : Force acting in cylinder (N)
t_2 : Ring thickness (mm)
b_1 : Thickness of top land (mm)
b_2 : Width of other lands (mm)
t_3 : Ultimate width of barrel (mm)
b : Depth of ring groove (mm)
t_4 : Thickness of open end barrel (mm)
T_l : Gap between the rings (mm)
D_r : Depth of groove (mm)
L_p : Length of piston (mm)
L_{ps} : Laps of piston (mm)
P_{do} : Piston pin diameter (mm)
P_{di} : Internal diameter of piston pin (mm)
K : Thermal conductivity (W/m-k)
t : Time (s)
V : Volume (mm^3)
c : Specific heat (Jkg/K)
q : Heat flux (W/m^2-k)
$T_{contact}$: Temperature at node of contact (^{0}C)
T_{target} : Temperature of targeted node (^{0}C)
Q_1 : Heat flux in vector mode (W/m^2-k)
$\bigtriangledown$T : Temperature variation in vector mode (K)
P_{IMPE} : Mean indicated pressure (MPa)
KXX: Conductivity of material in model (W/m-k)
ASMDIAG*:* Geometry boundary box in ANSYS (-)
TDI : Turbo charged direc injection (-)
NOX : Oxides of Nitrogen (-)

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