International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 08 Issue: 08 | Aug 2021 www.irjet.net p-ISSN: 2395-0072

Design Modification of Piston by Crowning and its Analysis

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Abstract - *Piston is the heart and one of the crucial and most complex part of the engine. This paper tries to differentiate the original flat head piston of one of the award winning bike of India i.e. TVS Sport BS-VI model with different crowning shapes like dome head and concave head using finite element analysis method. The piston performance depends on the fatigue life (stress, strain and total deformation). So, an effort has also been made to increase the fatigue life of the piston by crowning and getting better results than the flat head piston in steady state structural and thermal analysis under the similar conditions of load, pressure and temperature. Exploring a new material is always interesting so Aluminium A356 T6 is used as the material to compare all the three crowning shapes. CATIA P3 V5-6R2017 is used for designing and optimization (crowning) and ANSYS 14.0 workbench is used for the analysis.*

***Key Words*: Piston, TVS Sport BS-VI, Crowning, Fatigue Life, Aluminium A356 T6.**

1. INTRODUCTION

Piston is a moving component of an engine enclosed in a cylinder. The cylinder is made gas tight by piston rings. Piston converts heat energy to mechanical work and vice-versa. A piston goes through suction (mixture intake), compression (mixture is compressed), expansion (fuel power) and exhaust (fuel removal). Piston transfer the force output of an expanding gas in the cylinder to a crankshaft, which in turn provides rotational momentum to the flywheel. This type of system is called as a reciprocating engine. Hydraulic cylinder or actuator controls the movement of the piston back and/or forth.

Nowadays, the piston life is a matter of concern for the automobile industries to avoid piston failures due to the major forces acting over the piston. These major forces occur due to explosion and compression of fuel gases, thermal load, inertia force due to high frequency of reciprocating piston, friction and forces. The piston failure occurs due to running unmixed fuel, over-speeding the engine, detonation, heat seizure, debris getting through the air filter and bearing failure.

In an Internal combustion engine pistons are classified as trunk pistons (long relative to their diameter), crosshead pistons (large slow-speed diesel engine piston), slipper pistons (piston for petrol engine which is reduced in size and weight), deflector pistons (used in two-stroke engines) and racing pistons (piston strength is much higher than passenger car engine and the weight is much less).

2. LITERATURE REVIEW

The piston head is affected by the gas pressure due to high pressure inside the cylinder. Here the piston of TVS Sport BS-VI is designed according to the standard dimensions using software like CATIA V5. The correct method of designing a piston would be to consider the thermal stresses and normal stresses acting on the face of the piston. For simplified analysis, we use the steady state process by applying constraints and force on the piston head. But at the same time, we cannot ignore the effect that combustion power stroke produces i.e. impact load of piston. In real environment, the piston is subjected to gaseous forces and stresses acting on it. So we have to study the stress distribution, total deformation and strains using software like ANSYS.

2.1 Existing System

Piston is generally made of cast iron, aluminium because of its high heat transfer rate. Piston of TVS Sport BS-VI is specifically made flat head because of readily availability and ease of productivity. Pistons from the earlier times have been made flat head. Flat head piston distributes the load evenly on the entire piston.

2.2 Proposed System

The material used for designing and analysis of the piston is Aluminium A356 T6 because it has high shear modulus, less deformation than steel under application of same load and it can withstand heat shocks. Also crowning of the piston is done to increase the fatigue life based on the different piston heads. The piston head can be classified into flat top, dome shape, dish (concave) shape. Here the flat head piston is compared with dome head and concave head. The piston head or crown receives the majority of the initial pressure and force caused by the combustion. Piston is also subjected to thermal expansion caused by the transfer of heat from the head to the body of the piston. Piston is heated in such a way that its temperature reaches around 512°C and is distributed unevenly on the piston surface. On the basis of these conditions thermal analysis of the piston will be done. Mean pressure of 1.403 Mpa is used for static structural analysis. The properties of the material used for the analysis are given in the table below.

Table -1: Property of Aluminium A356 T6

Density	2671.1 kg/m^3
Tensile Yield Strength	165 MPa
Ultimate Tensile Strength	234 MPa
Poisson's Ratio	0.33
Young's Modulus	72.4 GPa
Specific Heat	875 J/kg°C

3. METHODOLOGY

- Theoretical calculations for piston design using given engine specification of TVS Sport BS-VI.
- Making 3D design of flat head piston using CATIA P3 V5-6R2017.
- Static structural and thermal analysis of the flat head piston using ANSYS 14.0 workbench.
- Making 3D design of dome head and concave head piston.
- Static structural and thermal analysis of dome head and concave head piston.
- Comparing the results of dome head and concave head with flat head piston.

4. THEORETICAL CALCULATION FOR PISTON

4.1 Engine Specification

Table -2: TVS Sport BS-VI

Engine Type	Single Cylinder, 4 Stroke, fuel injection, air cooled spark ignition
Displacement	109.7 cc
Max. Power	6.1 KW @ 7350
Max. Torque	8.7 N-m @ 4500
Compression Ratio	10.0: 1
Starting	Kick Start / Self Start
Ignition	Electronic Control Unit
Bore	53.5 mm
Stroke	48.8 mm

4.2 Calculations

(a) Torque
P = (2πNT)/60
We know that
P = 6.1KW = (2×3.14×7350×T)/60
T = 7.92 N-m

(b) Diameter of piston
$\pi r^2 h = cc$
Cylinder area = displacement
We know the displacement,
So to find diameter of piston
$3.14 \times r^2 \times 0.0488 = 109.7 \times e^{-5}\ m^3$
r = radius
Diameter, D = 2×r
D = 2×0.0267 m = 0.0535 m = 53.51 mm

(c) Pressure inside cylinder
Pressure = force/area
Force = power/velocity
We know that power
Velocity = (2LN)/60 = (2×0.0488×7350)/60
Velocity = 11.95 m/s
Force = $6.1e^3/11.95$ = 510.46N
P = F/A
Area = $\pi r^2 = 3.14\ (0.0267)^2 = 2.2396\ e^{-3} m^2$
P = $510.46/2.239e^{-3}$ = 0.2279Mpa (min)
Maximum pressure = $15 \times P_{min}$
$P_{max} = 15 \times 0.2279 = 3.418$Mpa
Max pressure = 3.418 Mpa

(d) Thickness of piston head calculated using the following Grasshoff's formula

$$t_H = \sqrt{\frac{3}{16} \times \frac{P}{\sigma t}}$$

Where,
P = maximum pressure in N/mm^2
D = cylinder bore/outside diameter of the piston in mm.
σ_t = permissible tensile stress for the piston material.
t_H = 3.47 mm

(e) Radial thickness of ring (t_1)

$$t_1 = D \times \sqrt{\frac{3 \times p_w}{\sigma t}}$$

Where,
D = cylinder bore in mm
Pw = pressure of fuel on wall in N/mm^2.
Its value is from 0.042 to 0.0667 N/mm^2
For present material, σ_t is 152.2 Mpa
t_1 = 1.94 mm

(f) Axial thickness of ring (t_2)
It may be taken as t_2 = 0.7t1 to t1
$t_2 = 0.92 \times 1.94$
t_2 = 1.78 mm

(g) Top land thickness (b_1)
The width of the top land varies from
$b_1 = t_H$ to $1.2\ t_H$
$b_1 = 1.2 \times 3.47$
b_1 = 4.164mm

(h) Thickness of other land (b_2)
$b_2 = 0.75\ t_2 = 0.75 \times 1.78$
b_2 = 1.335mm

(i) Maximum thickness of barrel (t_3)
t_3 = 0.03 D+b+4.5 mm
b = t1+0.4
b = 1.94+0.4

$b = 2.34$ mm

(j) Open end of the barrel thickness (T_{open})

At the open end the thickness is taken as

$T_{open} = (0.20 \text{ to } 0.30T_p)$

$T_{open} = 0.25 \times 8.4453 = 2.111$

$T_{open} = 2.111$ mm

(k) Gap between the rings (T_L)

$T_L = 0.055 \times D$

$T_L = 2.94$ mm

Second ring = 0.04 D = 0.04×53.51

Second ring = 2.14 mm

(l) Depth of ring groove (D_r)

$D_r = t1+0.4$

$D_r = 1.94+0.4$

$D_r = 2.34$ mm

(m) Length of piston

$L_p = L_{ps}+3\times t_1+3\times D_r$

$L_{Ps} = 0.5D = 0.5\times53.51 = 26.755$

$L_{Ps} = 26.755$

$L_P = 26.755+3\times1.94+3\times2.34$

$L_P = 39.595$ mm

(n) Piston pin diameter

$P_{do}=0.3D$ to 0.45

$P_{do} = 0.32\times53.51$

$P_{do}=17$ mm

$P_{di}=12$ mm

Table -3: Calculated Values for Piston Design

Parameters	Calculated Values
Piston length	39.595 mm
Piston diameter	53.51 mm
Piston hole external diameter	17 mm
Piston hole internal diameter	12 mm
Piston axial thickness	1.78 mm
Piston radial thickness	1.94 mm
Depth of ring groove	2.34 mm
Gap between the rings	2.94 mm
Top land thickness	4.164 mm
Piston top end thickness	4.164 mm
Piston open end thickness	2.111 mm

5. 3D DESIGN OF FLAT HEAD PISTON

To the calculated values and standard dimensions the piston is designed in CATIA by drawing sketch profile first and then revolving it 360 degrees about an axis by shaft tool and the solid piston is generated. Then pocket holes are made on the solid design of piston and dressing features may be used to dress up the sharp corners and edges to reduce stresses.

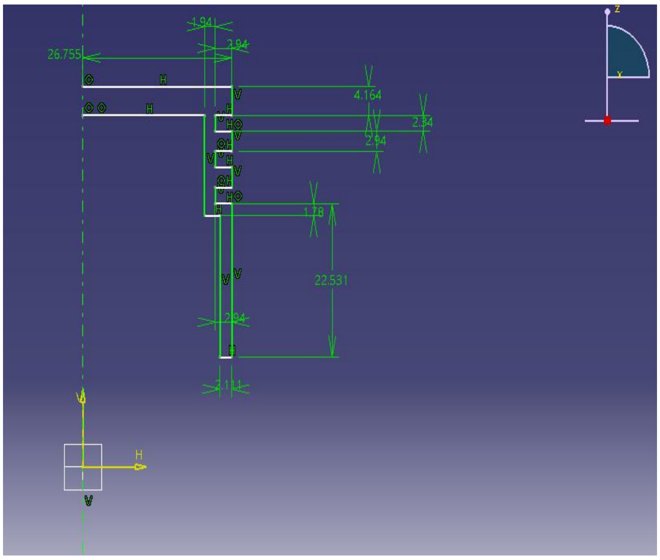

Fig -1: Sketcher Profile of Flat Head

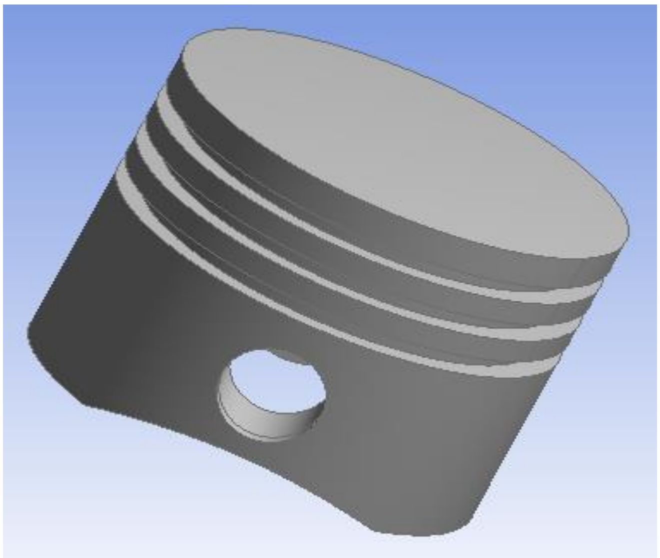

Fig -2: Finished Flat Head Piston

6. STATIC ANALYSIS OF FLAT HEAD PISTON

6.1 Meshing

The .igs file of piston is imported to ANSYS from CATIA and meshing is done by triangle surface mesher with 41539 nodes and 22703 elements.

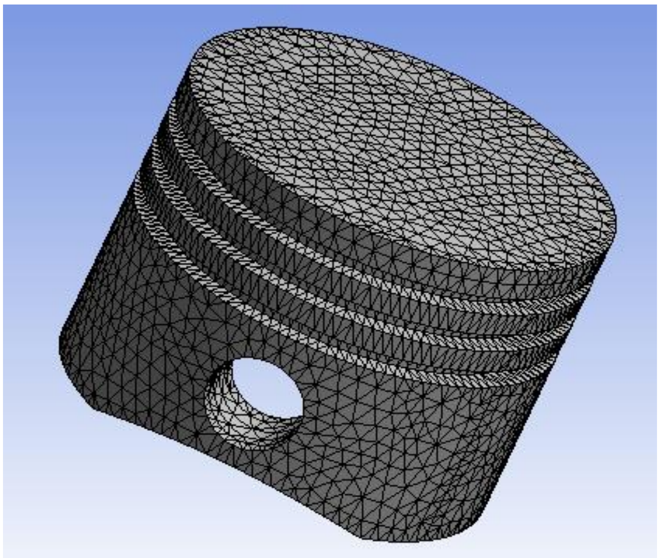

Fig -3: Meshed Image of Flat Head Piston

6.2 Static Structural and Thermal Analysis

The static structural analysis is done by applying boundary conditions like combustion of gases in the combustion chamber exerts pressure on the piston head during power stroke and fixing the support on piston skirt. The pressure acting on piston head is taken as 1.04 MPa. After that we insert the analytical properties to be determined such as von-mises stress, equivalent elastic strain, total deformation and fatigue life. For steady state thermal analysis boundary conditions consists of applying a convection heat transfer coefficient of 500 W/m^2°C, ambient temperature of 22°C and maximum temperature constraint of 512°C. All analysis of flat head is shown below.

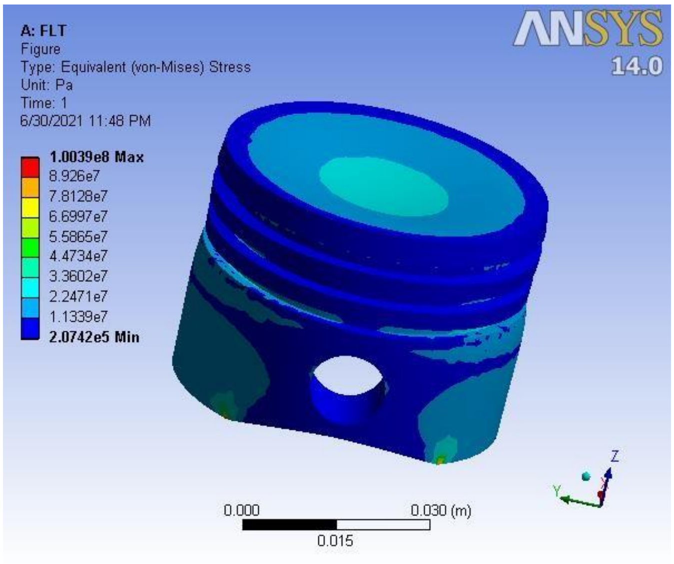

Fig -4: Equivalent Von-Mises Stress

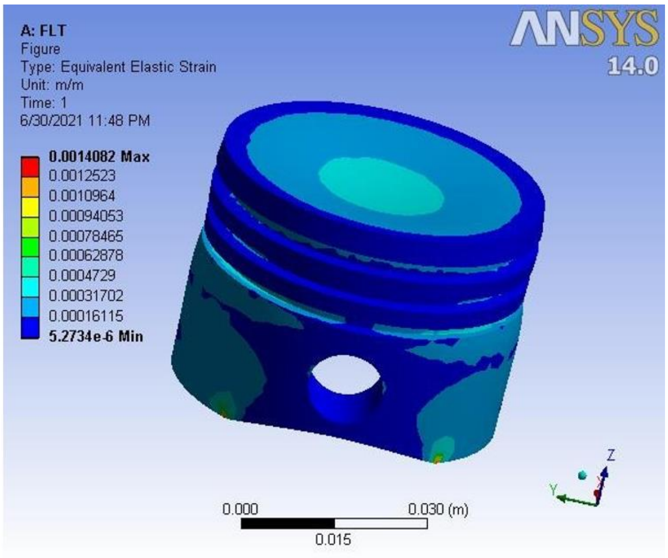

Fig -5: Equivalent Elastic Strain

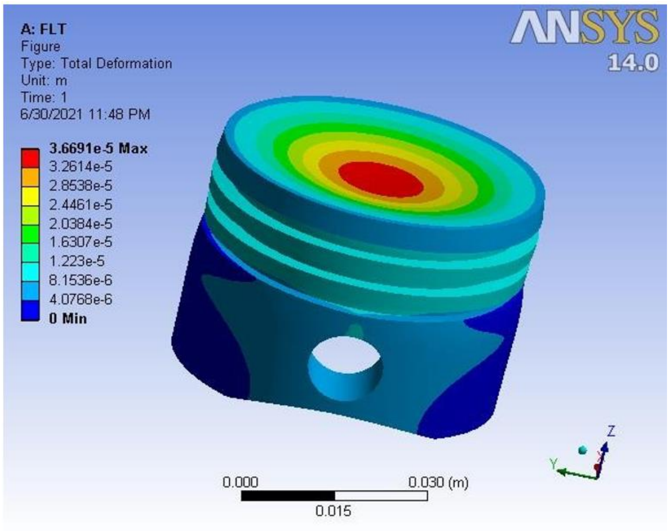

Fig -6: Total Deformation

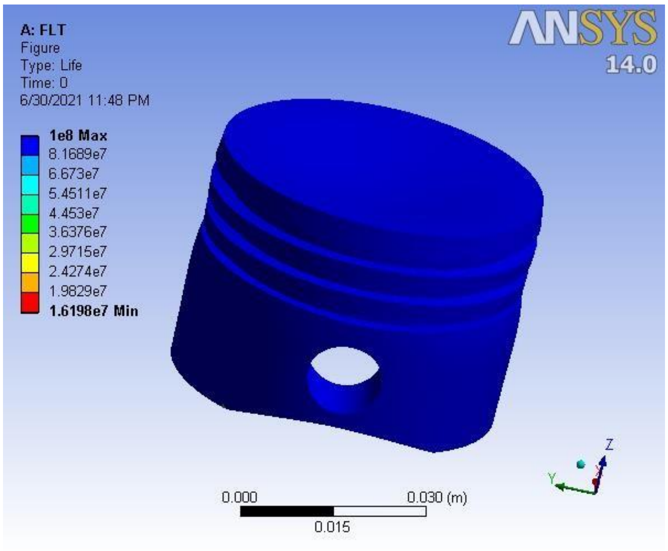

Fig -7: Fatigue Life

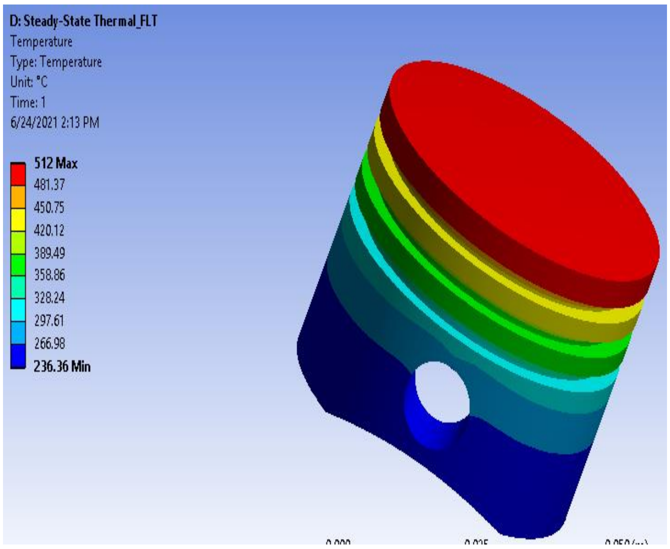

Fig -8: Temperature Distribution

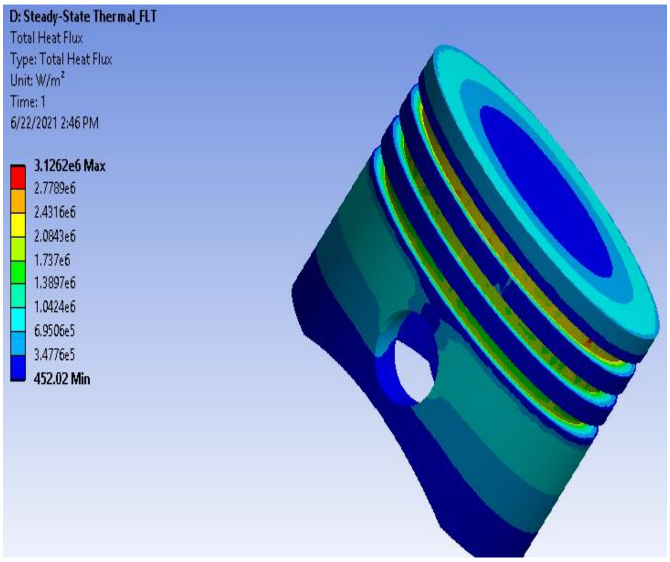

Fig -9: Total Heat Flux

7. 3D DESIGN OF DOME HEAD AND CONCAVE HEAD

The designing of Dome Head and Concave Head piston is done respectively in the similar way it was done for Flat Head piston. First the sketcher profile is made then it is revolved 360 degrees to obtain the solid 3D shape.

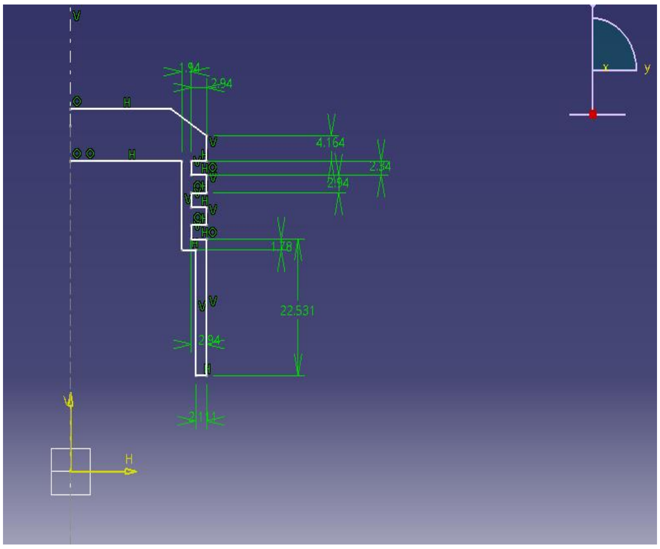

Fig -10: Sketcher Profile of Dome Head

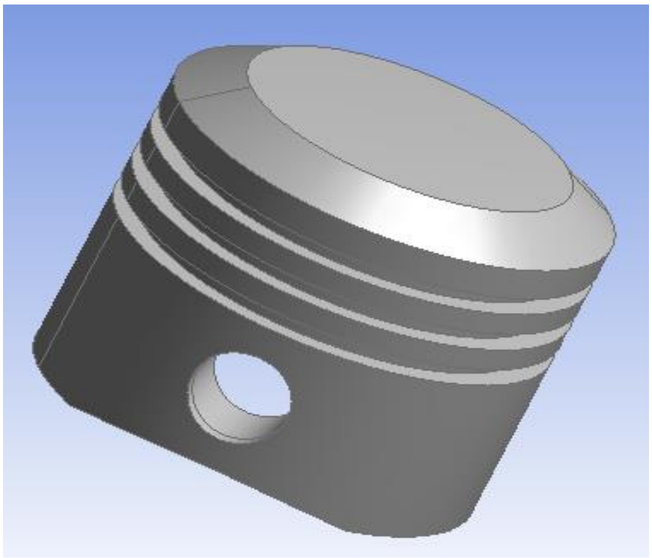

Fig -11: Finished Dome Head Piston

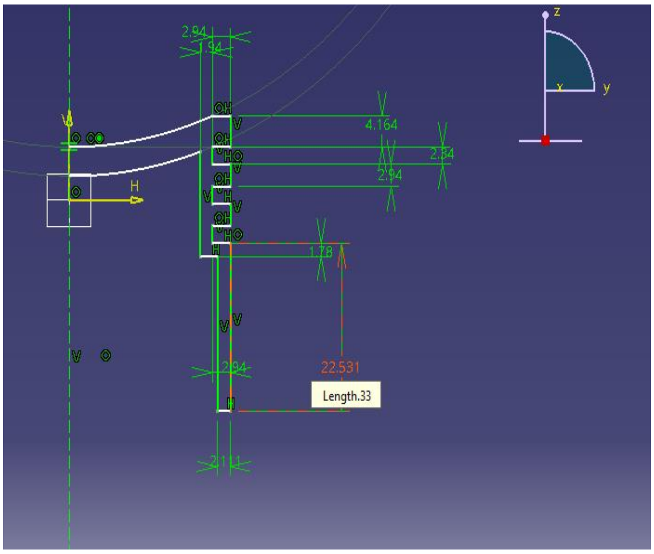

Fig -12: Sketcher Profile of Concave Head

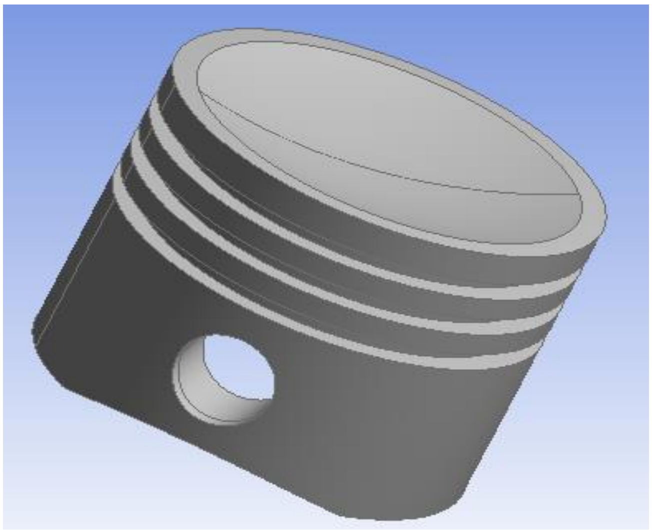

Fig -13: Finished Concave Head Piston

8. STATIC ANALYSIS OF DOME HEAD AND CONCAVE HEAD PISTON

The meshing and analysis of both dome head and concave head piston is done respectively by applying similar conditions of load, pressure and temperature as was done in the flat head static structural and thermal analysis.

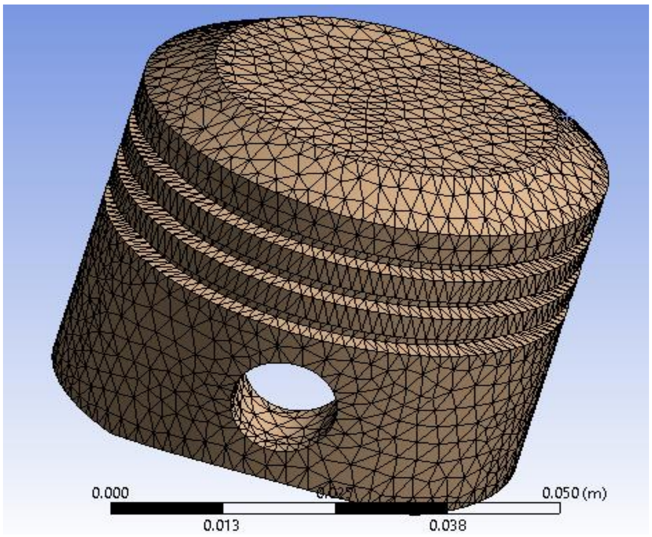

Fig -14: Meshed Image of Dome Head Piston

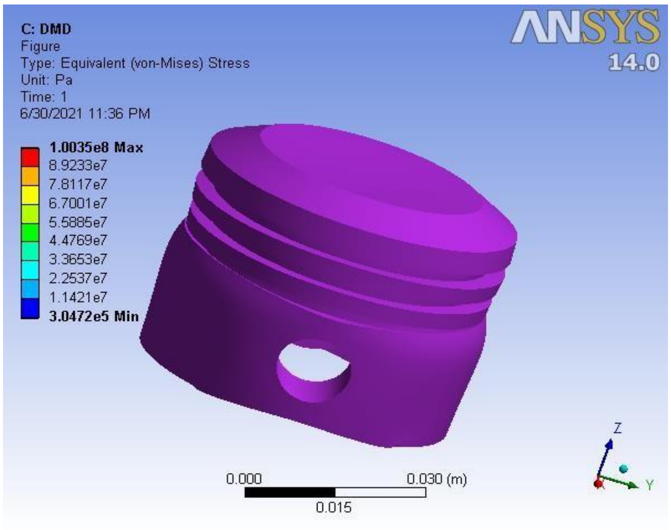

Fig -15: Equivalent Von-Mises Stress

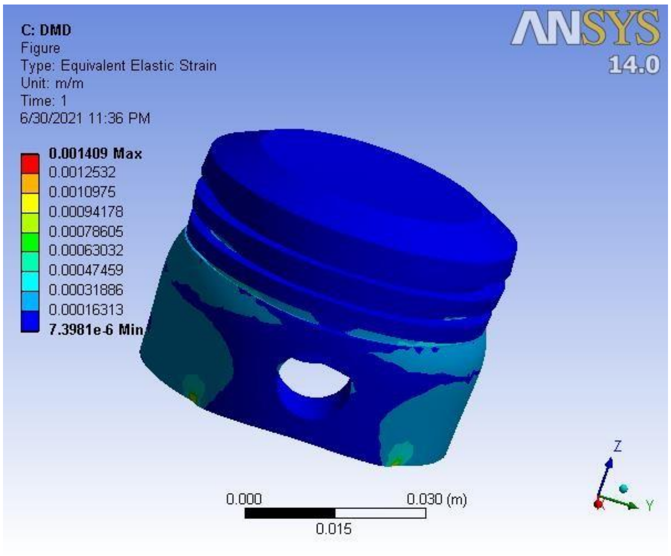

Fig -16: Equivalent Elastic Strain

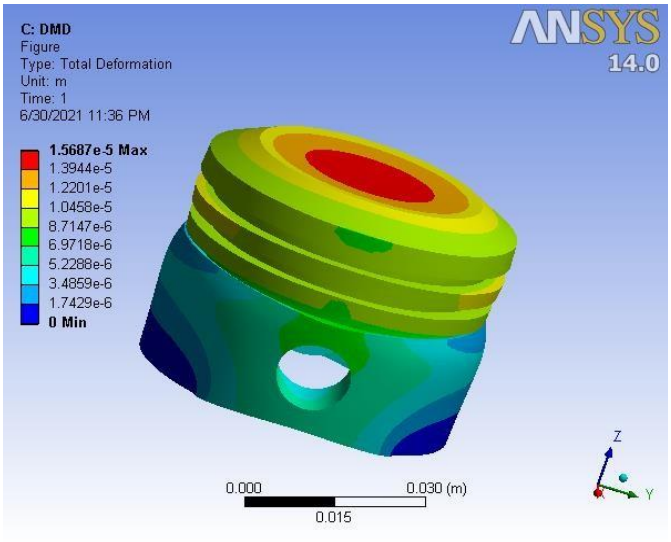

Fig -17: Total Deformation

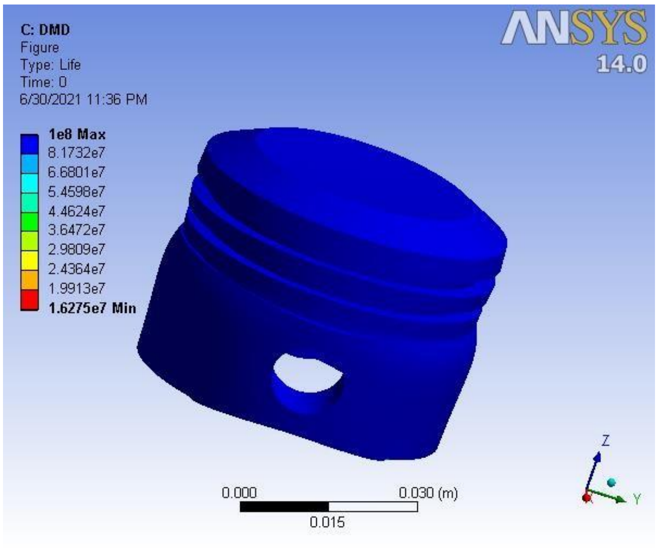

Fig -18: Fatigue Life

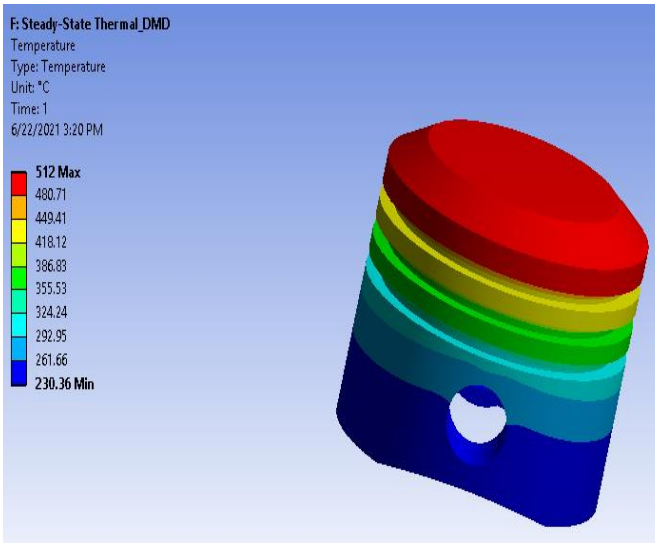

Fig -19: Temperature Distribution

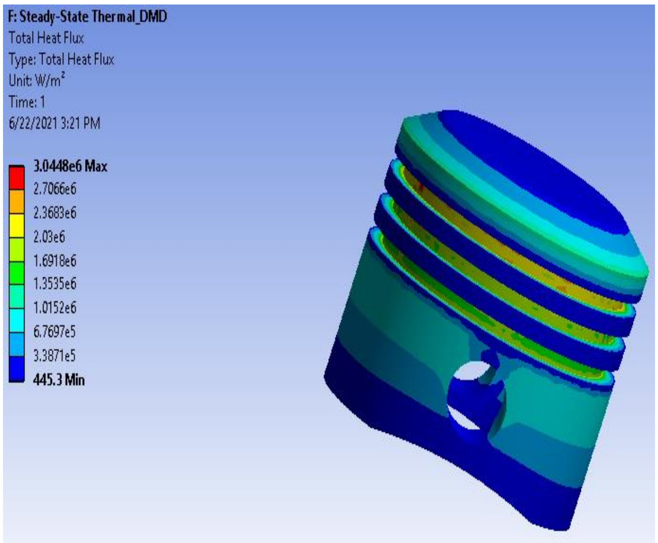

Fig -20: Total Heat Flux

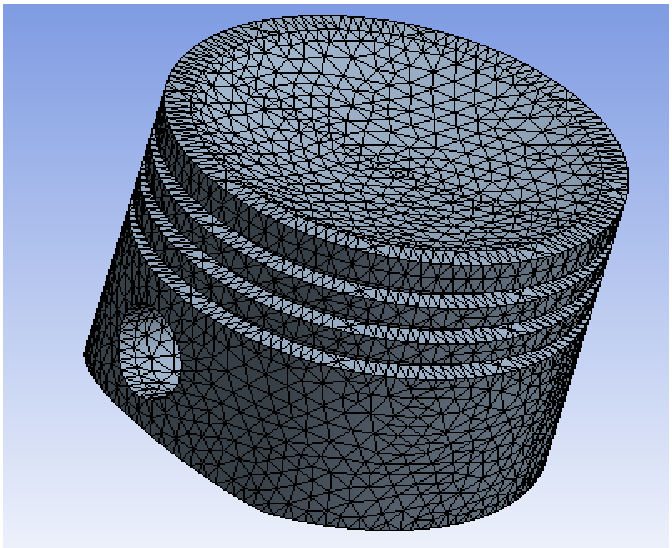

Fig -21: Meshing of Concave Head Piston

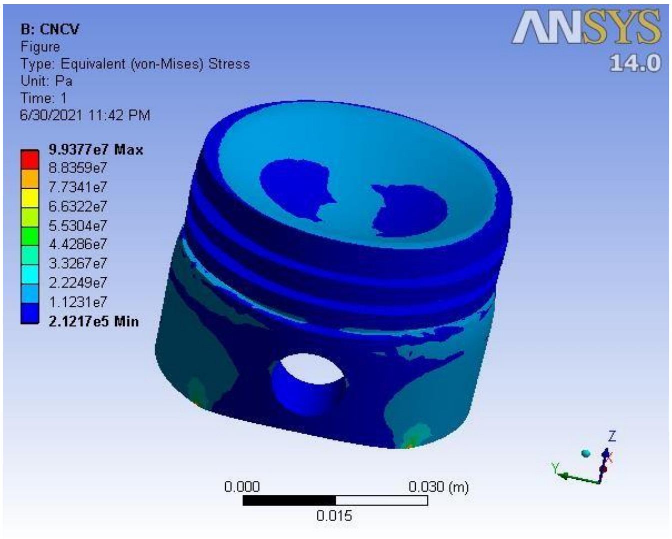

Fig -22: Equivalent Von-Mises Stress

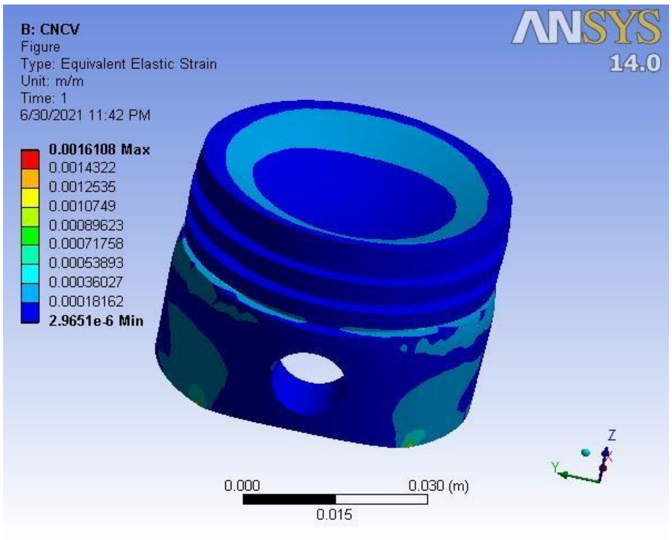

Fig -23: Equivalent Elastic Strain

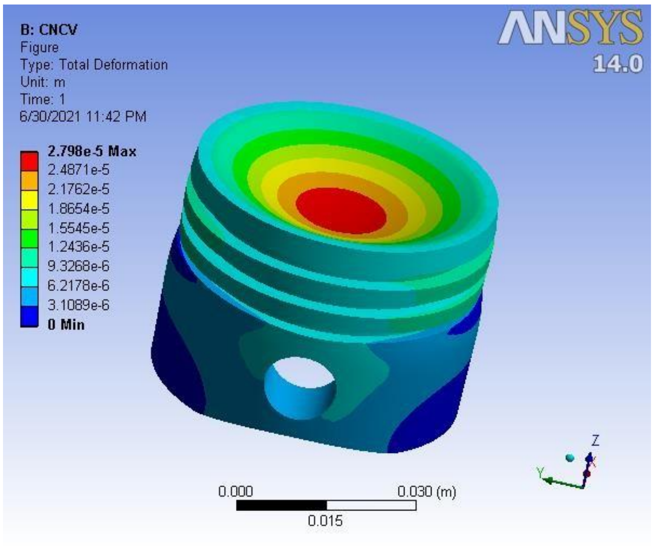

Fig -24: Total Deformation

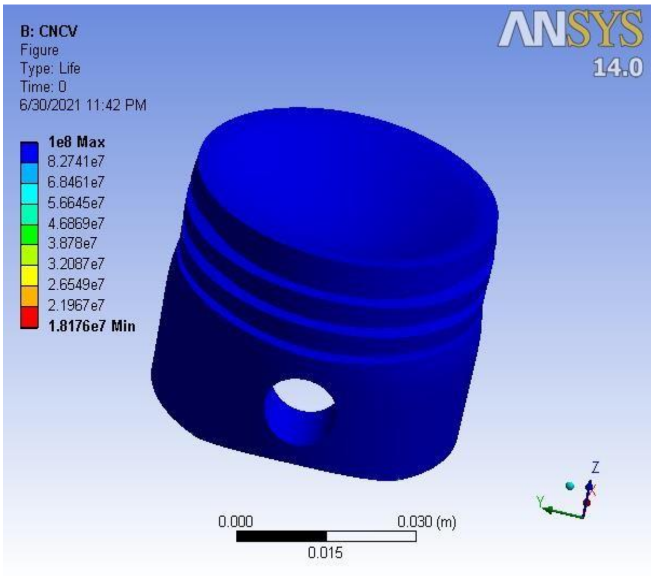

Fig -25: Fatigue Life

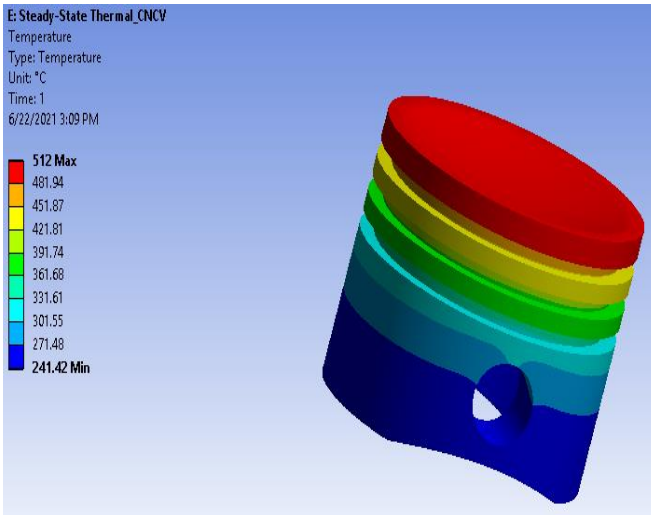

Fig -26: Temperature Distribution

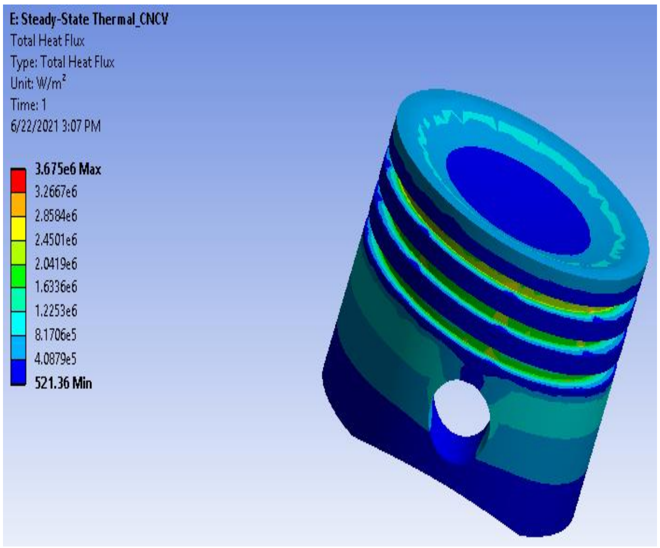

Fig -27: Total Heat Flux

9. RESULTS

Flat Head:

A maximum stress of 1.0039e+008 Pa and minimum of 2.0472e+005 Pa are observed. Total deformation of 3.6691e-005m is obtained for the applied pressure which is considerable after many numbers of cycles of operation. Maximum value of strain i.e., 1.4082e-003 m/m is observed. The heat fluxes observed are 3.1262e+006 W/m^2 and 452.02 W/m^2 as maximum and minimum respectively. Minimum Fatigue Life is 1.6198e+007 cycles.

Dome Shaped:

A maximum stress of 1.0035e+008Pa and minimum of 3.8472e+005Pa are observed. Total deformation of 1.5687e-005m is obtained for the applied pressure which is considerable after many numbers of cycles of operation. Maximum value of strain i.e., 1.409e-003 m/m is observed. The maximum and minimum heat fluxes observed are 3.0448e+006 W/m^2 and 445.3 W/m^2 respectively. Fatigue life is 1.6275e+007 cycles.

Concave Shaped:

A maximum stress of 9.9377e+007 Pa and minimum of 2.1217e+007 Pa are observed. Total deformation of 2.798e-005m is obtained for the applied pressure which is considerable after many numbers of cycles of operation. Maximum value of strain i.e., 2.965e-006m/m is observed. The heat fluxes observed are 3.675e+006 W/m^2 and 521.36 W/m^2 as maximum and minimum respectively. Minimum Fatigue Life is 1.8176e+007 cycles.

CONCLUSION

The stresses and total deformations observed in Flat head shaped piston are larger than the Concave and Dome shaped piston. The total deformation is minimum in Dome Shape. This Project only focuses on the theoretical implementation of the idea but practical working of the piston may have different affects. The heat flux distribution over the Dome Head shaped piston shows a least value which implies that not much of heat being transferred to skirt side of piston. This will result in increased life of piston rings and piston pin as they won't get subjected to thermal fatigue. Minimum life cycle was found maximum in Concave Head piston this implies that Concave head has more life that any other piston. If piston has to fail at the minimum number of cycles for all pistons Concave Head piston would prevail. Hence, Concave Head and Dome Head are showing better results than Flat Head shaped piston but Concave Head is more preferable for design modification.

FUTURE SCOPE

The ANSYS analysis of the model designed on the basis of the dimensions found in this paper can be done. This Project only focuses on the theoretical implementation of the idea but practical working of the piston may have different affects. As the Concave Head and Dome Head shaped piston are giving better results than the Flat Head shaped piston thus TVS can use the modified design to increase the life of piston and by using the different material or the material used in the research for better strength and light weight and work towards the weight minimization and inertia force.

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