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Design and Analysis of Multicylinder Four Stroke Spark Ignition Axial Engine (Duke Engine)

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ABSTRACT
Engine is a very important component in automobiles and it is act as a prime mover. The engine transmits power to the road wheels trough linkages (Clutch, gearbox, propeller shaft and differential) against to the self-weight of the vehicle and external load, which results the engine components undergo stressed. The engine components also exposed to the heat so that the thermal stress are induced. Based on the above said points the stress and strain analysis is very important for engine components. The main aim of this paper is to design and simulate the thermal and structural stress analysis of a multicylinder four stroke spark ignition axial engine applications of 2318.84cc. The engine was designed by using solid works software and the three-dimensional thermal and structural analysis was done in the ANSYS software. This work investigated the amount of heat flow in the engine components (Cylinder and piston) and failure analysis of engine components (connecting rod and Crank shaft) of a multicylinder four stroke spark ignition axial engine. In this analysis three different materials were used for each components of an axial engine and based on the results suggested the best material for each engine components.

Keywords: FEA, multicylinder four strokes spark ignition axial engine, solidworks

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INTRODUCTION

An engine is a device which converts one form of energy into another form of energy. Axial engine is an internal combustion engine which converts chemical energy into mechanical energy.

Fig. 1. *Conventional engine piston, connecting rod and crank shaft arrangement Inline motion.*

The construction, working and performance are little bit difference as compared to the conventional engines. Axial engine is four stroke spark ignition internal combustion engine which has five cylinders. The engine capacity is three litters. The duke engine cylinders arranged from linear arrangement into circular orientation (sinusoidal wave) (Figure 1, 2).

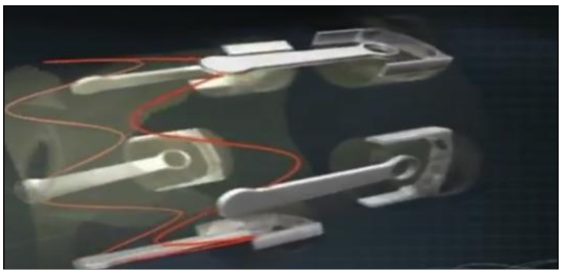

Fig. 2. *Sinusoidal wave motion (axial engine).*

The engine works on the principle of wobble plate. The wobble does not rotate round and it is connected to Z shaped crank. The wobble plate translates the motion from the piston to crank. The pistons are mounted in mono block which rotates around the shaft. These pistons drive a star shaped component is called reciprocator.

The reciprocator allows all parts to move in sinusoidal motion. A stationary cylinder head mounted up on the mono-block (Cylinder block) with the help of bearings. The cylinder head consists of spark plugs and specially designed ports. The air and exhaust gases entering and leaving trough these ports. In suction stroke the charge enters in to cylinder trough inlet port and compressed in the cylinder further exposed to the spark plug for ignition of power stroke.

Due to power stroke, the piston moves towards downwards so that the wobble plate rotates accordingly with cylinder head movements causing the piston reaches the exhaust port. There the exhaust gases leave the cylinder through exhaust port.

LITERATURE SURVEY

Siddhartha Joshi (2016) described that the Overall economy of Duke Engine is less as compared with modern conventional engines he concerns in terms part or full load fuel performance, design aspects and manufacturing aspects. Frictional losses that faced in internal combustion engines are reduced due to reduction in parts [1].

Ardiyansyah Syahrom, et al. (2006) Designed, fabricated and tested multistage symmetrical wobble plate compressor. Improved the design of piston side forces and shaft deflections. The concluded the compressor design is useful for natural gas vehicle refueling. Found that wobble-plate compressors are mainly used in automotive air-conditioning systems, which require low pressures that can be achieved using single-stage compression.

The advantages and applications of wobble plate compressors are further enhanced with the introduction of the symmetrical wobble-plate configuration of duke engine [2]. New Zealand company Duke Engines started in 1993 has created several different engines and installed one in a car in 1999. The engine runs a 5-cylinder, 3 liters, 4-stroke internal combustion engine platform with its unique axial arrangement. This engine is compared to the conventional engine weight is reduced 30%.

During development, the Duke has been tested at MAHLE Powertrain in the United Kingdom and in the United States; test results are available with it also having multi-fuel capabilities [3]. List out the components of the axial engine components and the components of axial engine was described [4–6].

Importance of swash plate and wobble plate in axial engine was described and applications also described [8]. The axial engine components like piston cylinder and cylinder head were designed [7], crank design was assumed (Figures 3–21).

METHODOLOGY

Geometric Model Representations

The geometric models of multicylinder spark ignition axial engine components were designed in the solid works. The models are imported in the ansys in IGES format. The meshing and boundary conditions were applied for engine components.

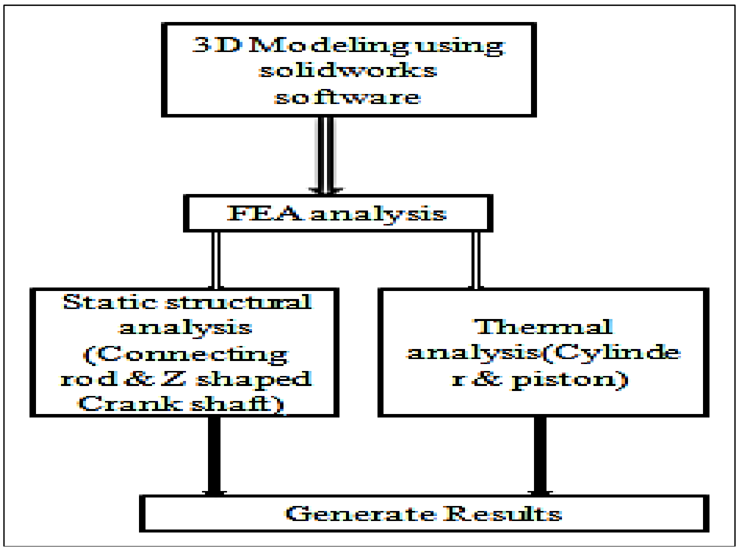

Fig. 3. *Design and analysis flow chart of multicylinder spark ignition axial engine.*

2D

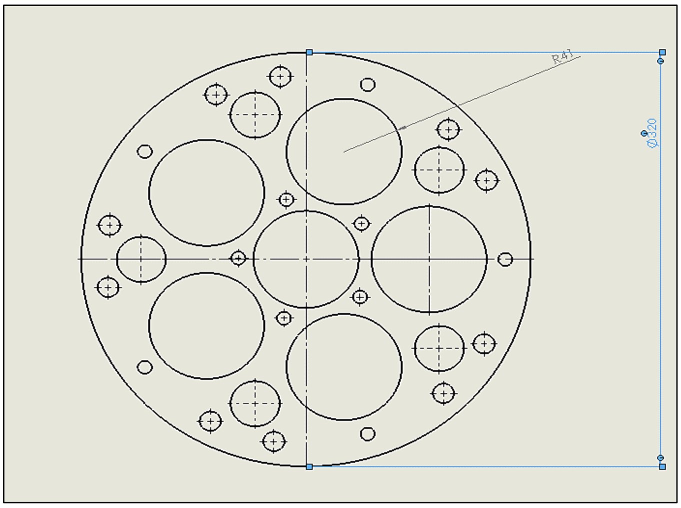

Fig. 4. *Cylinder head.*

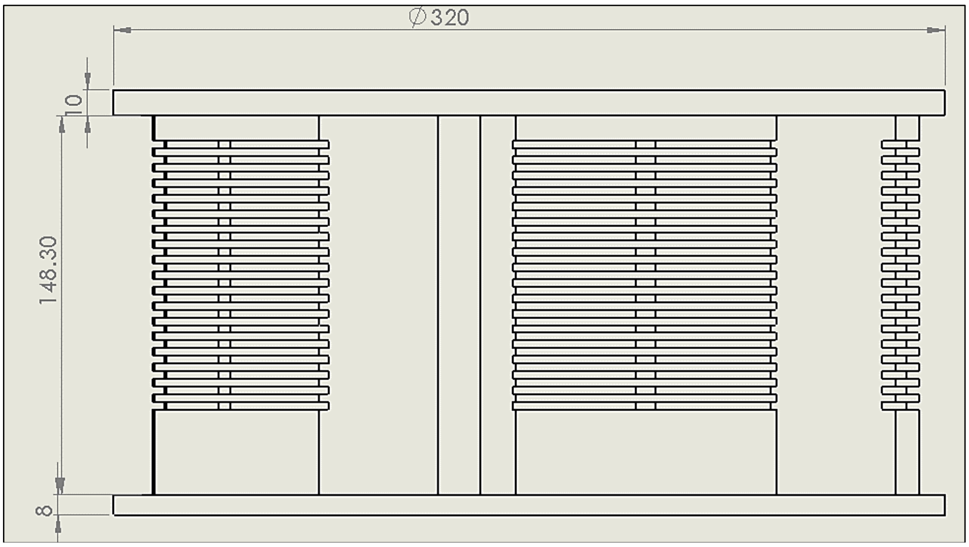

Fig. 5. *Cylinder block.*

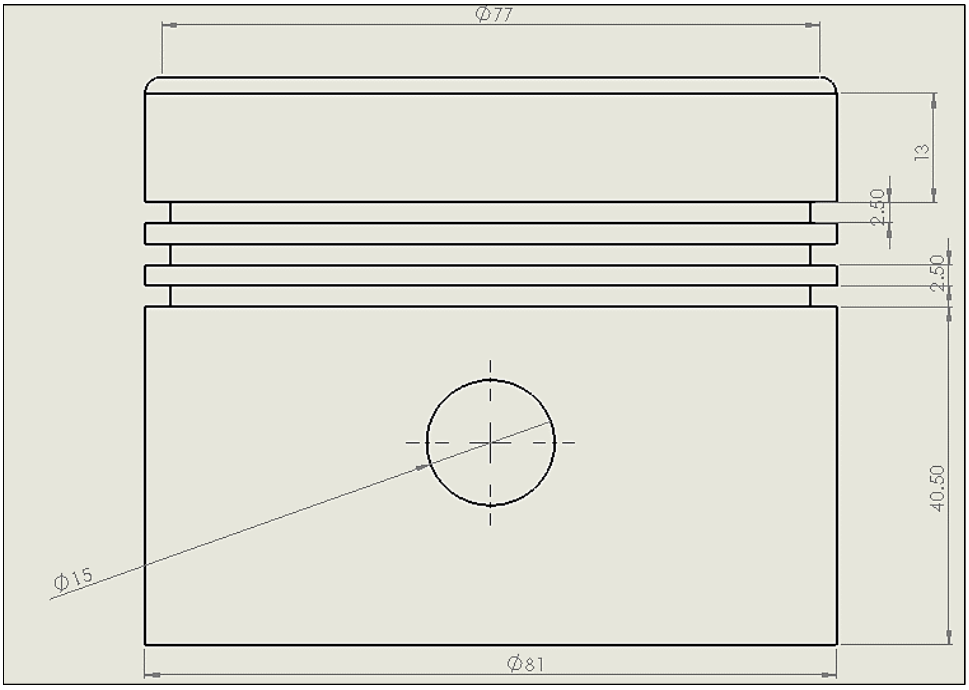

Fig. 6. *Piston.*

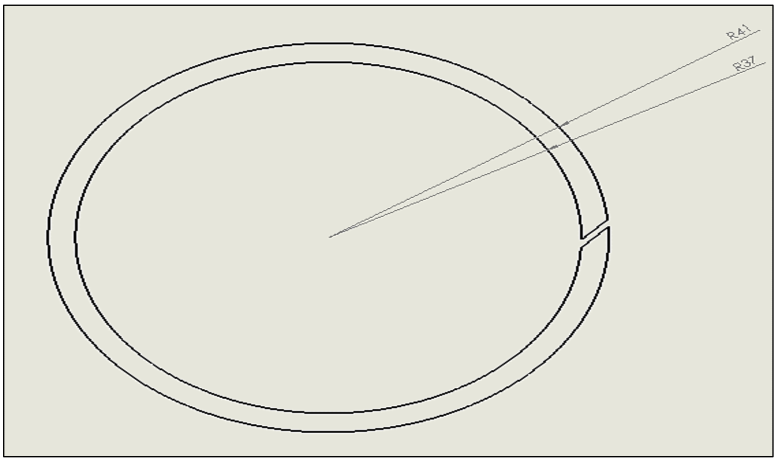

Fig. 7. *Piston ring.*

Fig. 8. *Connecting rod.*

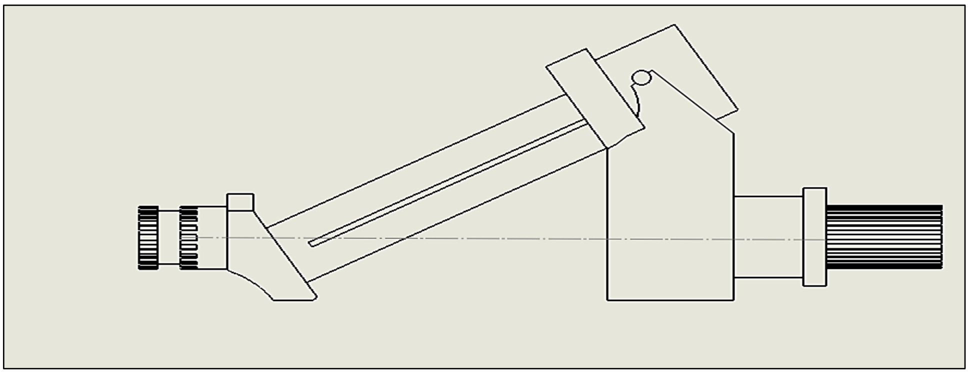

Fig. 9. *Z-shaped crank.*

3D

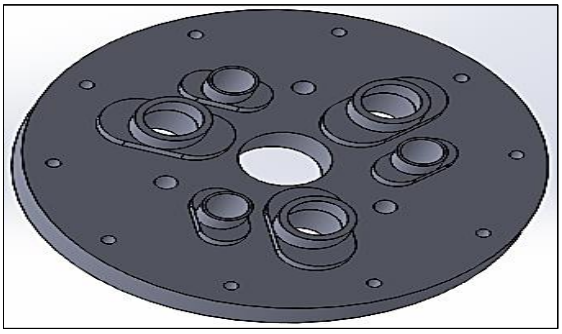

Fig. 10. *Cylinder head.*

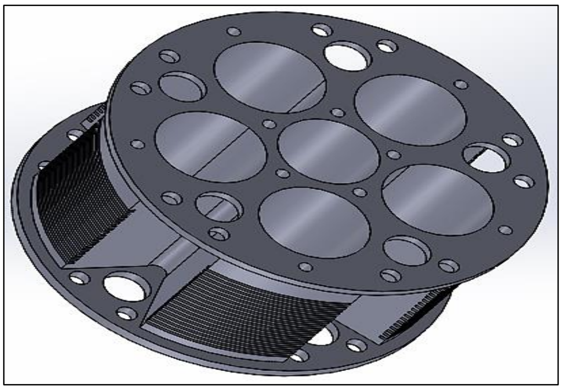

Fig. 11. *Cylinder.*

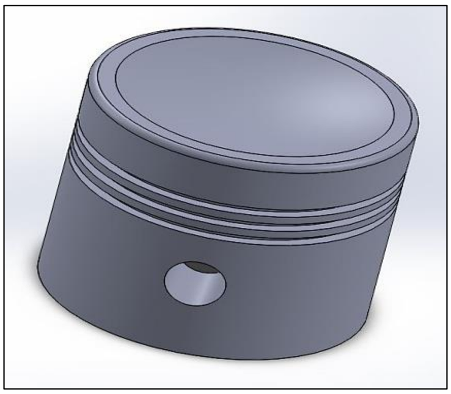

Fig. 12. *Piston.*

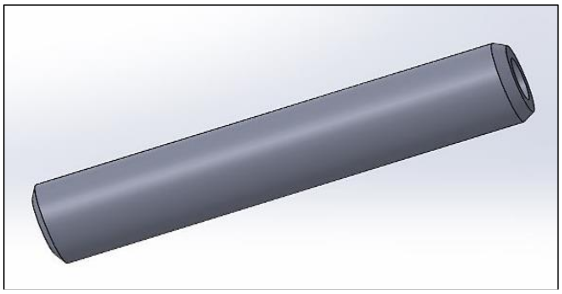

Fig. 13. *Piston pin.*

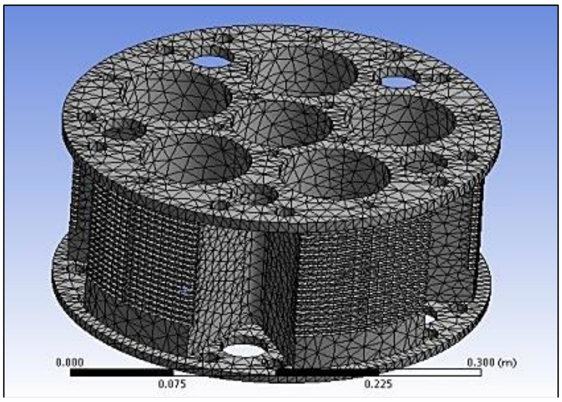

Fig. 14. *Piston rings.*

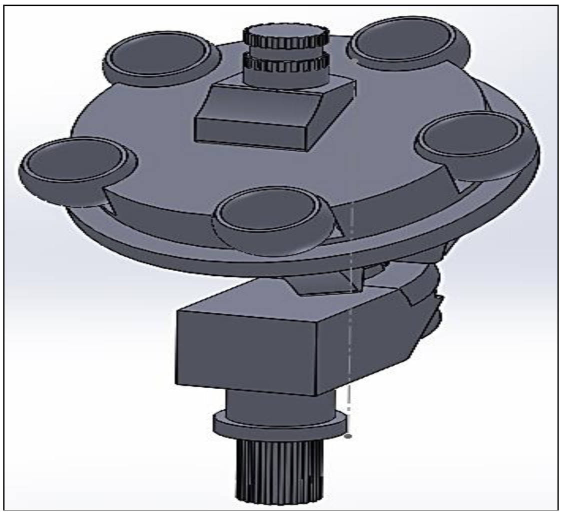

Fig. 15. *Z Shaped crank.*

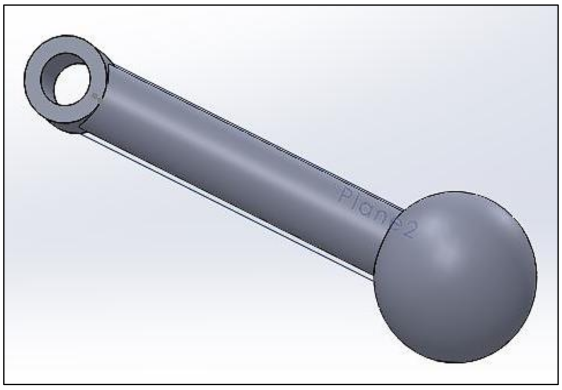

Fig. 16. *Connecting rod.*

Assembly

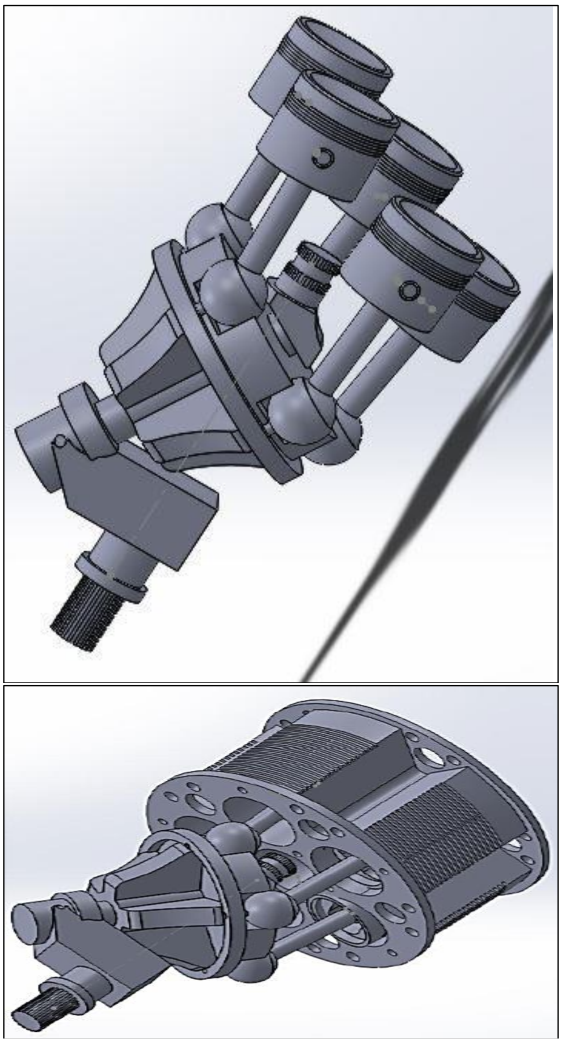

Fig. 17. *Assembly of an axial engine.*

Meshing of the Engine Components

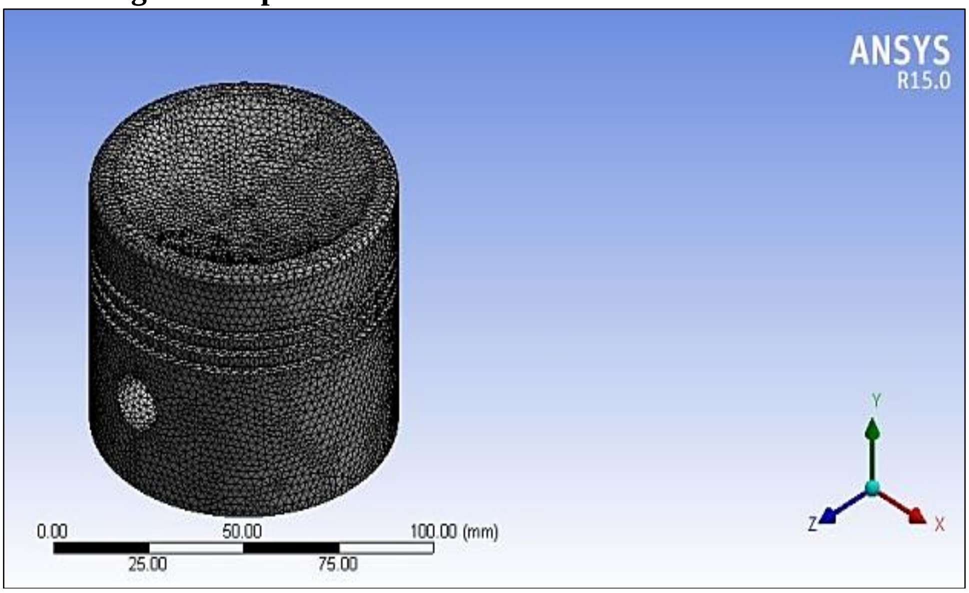

Fig. 18. *Meshing of axial engine piston.*

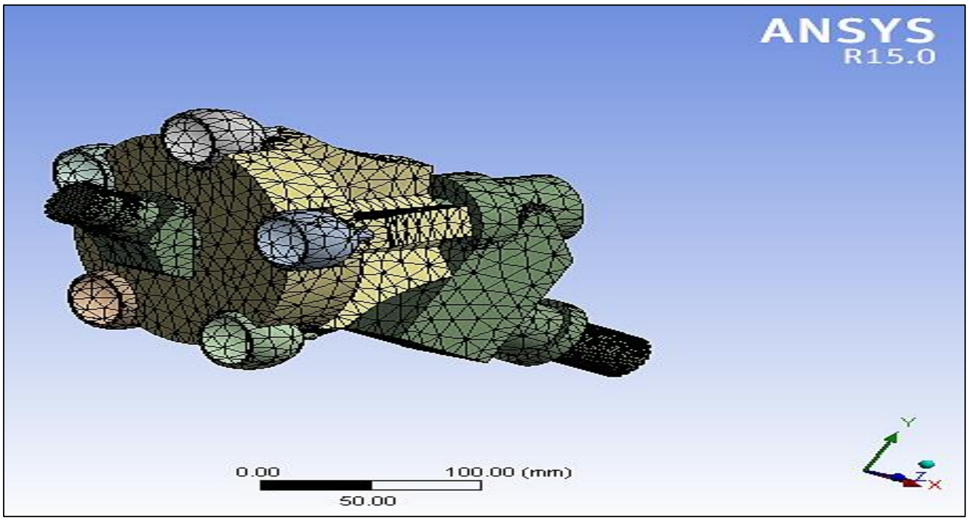

Fig. 19. *Meshing of axial engine z shaped crank.*

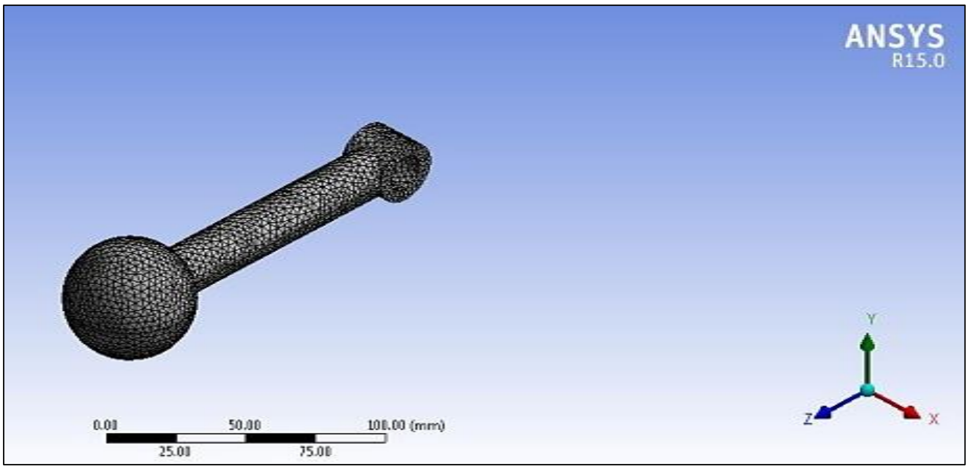

Fig. 20. *Meshing of axial engine connecting rod.*

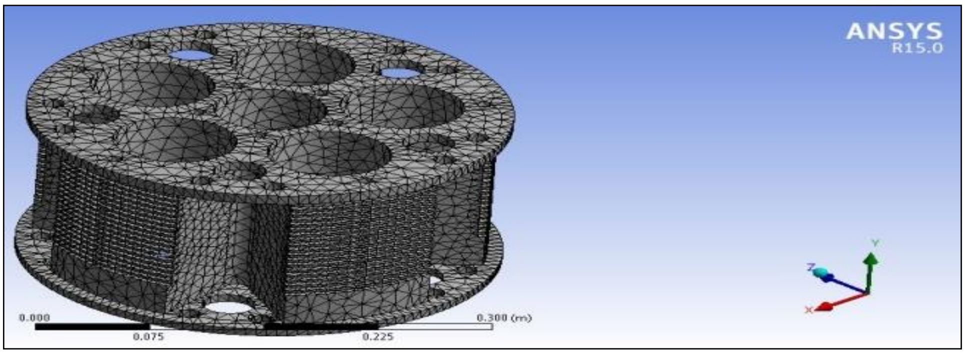

Fig. 21. *Meshing of axial engine multicylinder.*

Boundary Conditions

Piston

Boundary conditions were applied on models (Piston and Cylinder) at a two fixed surfaces namely BC1 and BC2 are shown in the Figures 22–26. BC1 were applied on top surface of the piston and BC2 was applied on skirt surface on the piston (Convection process). Figure 24 indicates the actual boundary conditions on piston surfaces.

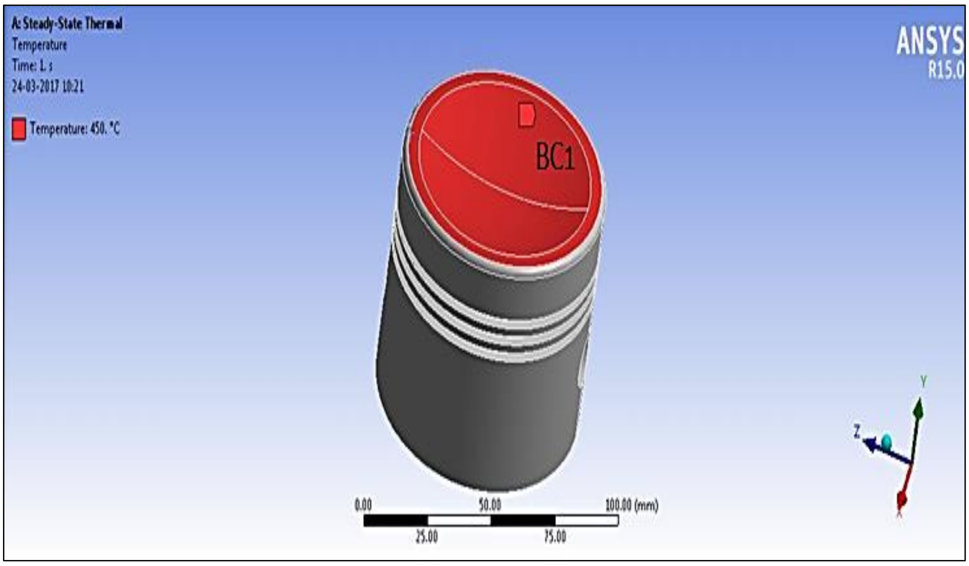

Fig. 22. *Temperature on the piston head.*

Fig. 23. *Actual boundary conditions on piston surfaces.*

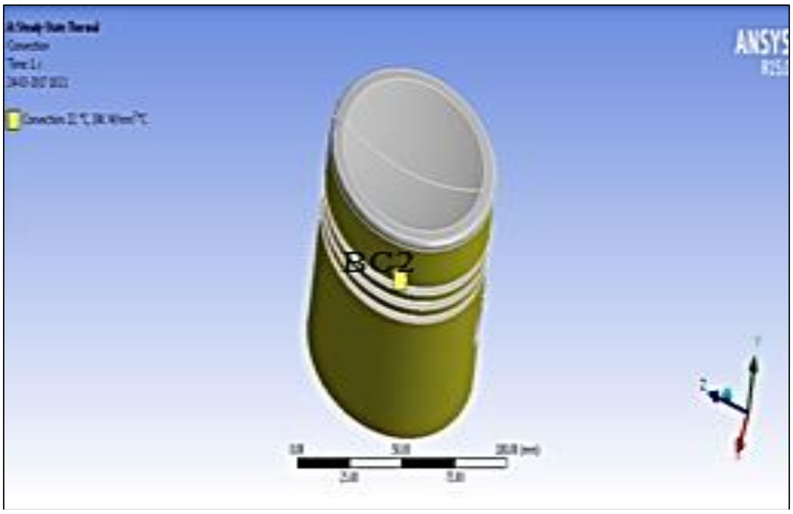

Fig. 24. *Convection in the piston.*

Multicylinder

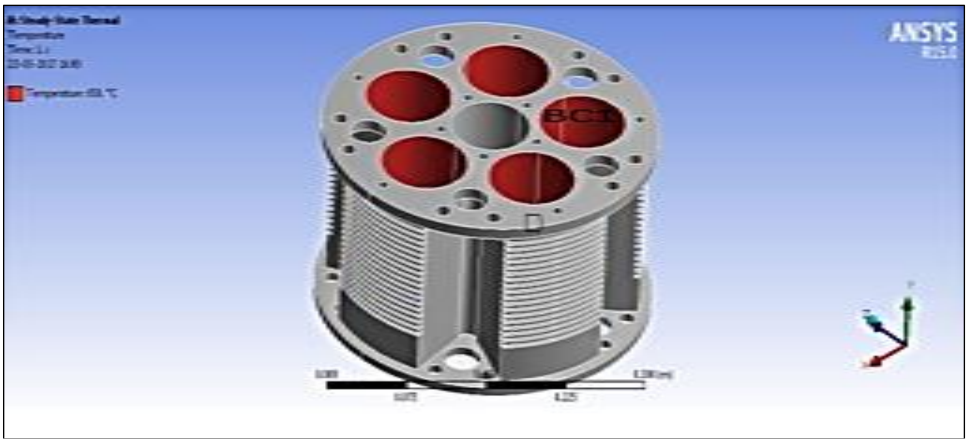

Fig. 25. *Temperature on cylinders.*

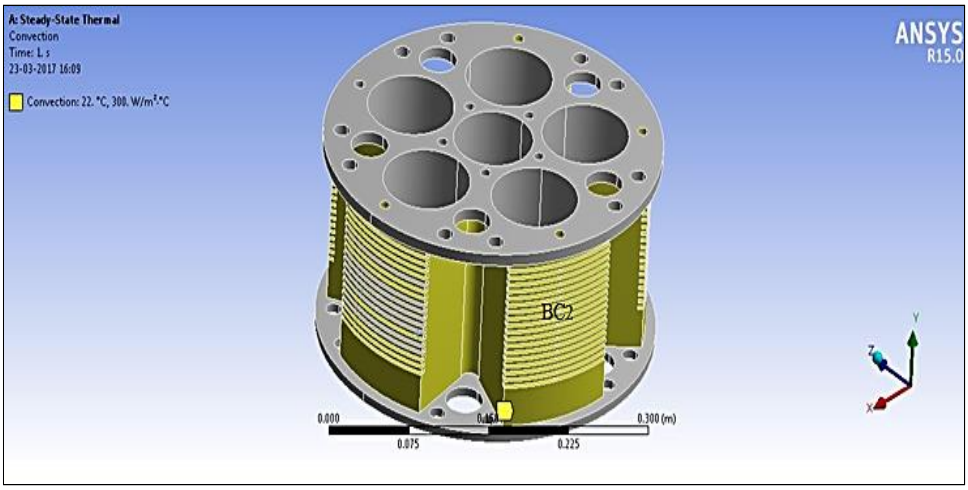

Fig. 26. *Convection in the cylinder block.*

Z Shaped Crank With Wobble Plate

Boundary conditions were applied on a model at two fixed surfaces namely BC1 and BC2 are shown in the Figures 27 and 28. BC1 were applied on top surface of the wobble plate and BC2 was applied on z shaped crank main journal.

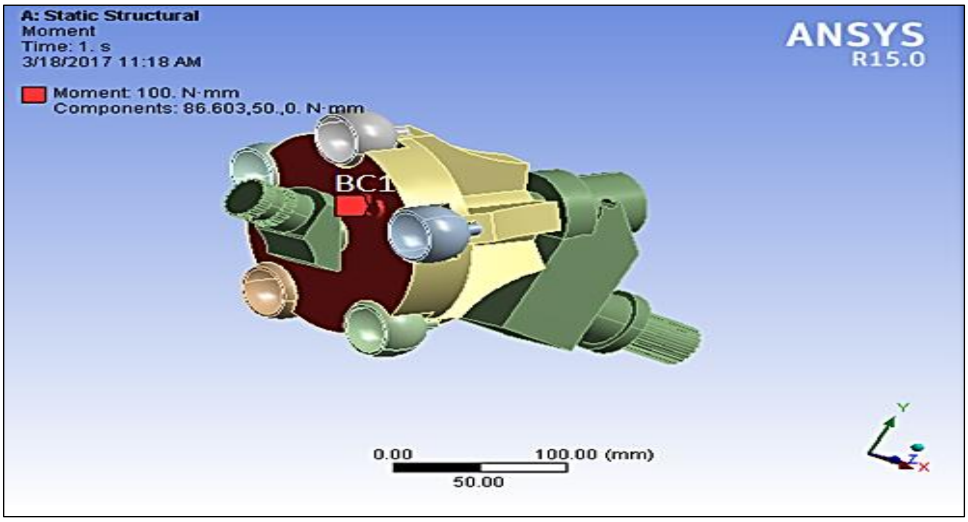

Fig. 27. *Moment in the crank (clock wise direction).*

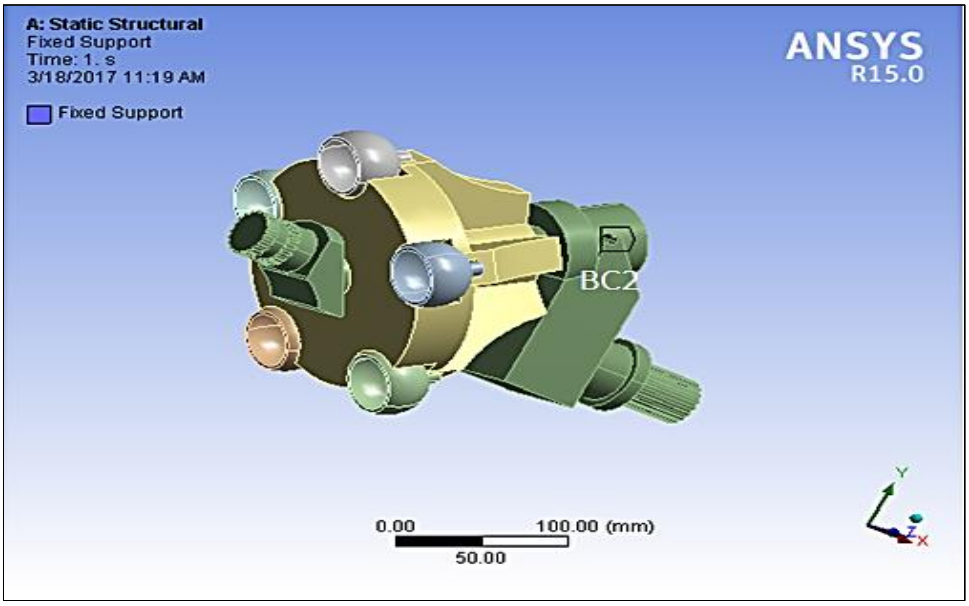

Fig. 28. *Fixed support in crank.*

Engine Specifications

S. no.	Description	Specifications
1	Number of cylinders	5
2	Bore	81.0 mm
3	Stroke	90.3 mm
4	Compression ratio	10.3:1
5	Number of strokes	4
6	Fuel	Petrol
7	Speed	8000 rpm
8	Engine displacement	2318.84cc
9	Crankshaft stroke	89 mm
10	Efficiency	60.80%

Theoretical Design Considerations

Piston and Piston Rings

The combustion occurs on the surface of piston so that the piston is exposed to the peak pressures. The work done is transferred to the crank shaft trough connecting rod. The piston rings are located in the piston groves. Two types of piston rings are used: compression ring and oil ring. The main purpose of the compression and oil rings are to avoid leakage of combustible gases from the combustion chamber into the crankcase and to avoid entering of engine oil from the crankcase into the combustion chamber.

1.$t_H = \sqrt{(3PD^2)}/16\,\sigma_t =$

$\sqrt{(3*4*75^2)}/16*60 = 9.05$mm

2.$t_1 = D\sqrt{(3P_w)} / \sigma_t) = 81\sqrt{(3*0.404)/90}$ = 2.95mm

3. $t_2 = D/(10*n_R = 81.0/(10*3) = 2.7$mm

4. $b_1 = 1.2t_H = 1.2*9 = 10.8$mm

5. $b_2 = t_2 = 2.7$mm

6.t_3=0.03D+b+4.5=0.03*81+3.4*4.5= 8.23mm

b = t_1+0.4=2.95+0.4 = 3.35mm

7. L = Length of ring section +Length of skirt +Top land Barrel = 73.15mm

Cylinder and Cylinder Head

Cylinder is a rigid body. This cylinder is exposed to the high static & dynamic loads. The role of the cylinder head is to with stand the high pressures and temperatures in the I.C. engines. The cylinder head is located on the top of the cylinder block and in between cylinder head and block gasket is located. The cylinder head had a provision for locating valve mechanism and passage of water.

1. $t_{w} = (P*D)/\sigma_c + C = (4*81)/60+1.5 = 6.9 \approx 7.0$mm
2. $t_{h} = \sqrt{(C * P / \sigma_c)} = 81\sqrt{(1.5 * 4}/60 = 25.61$mm
3. Lc = 1.5*length of stroke =1.15*2*81.0= 186.3mm

Piston Pin

Piston pin is also called as gudgeon pin. It links the piston and small end of the connecting rod. Maximum gas force is equal to the load on the piston at the small end

Load on the piston = projected area* bearing pressure $d_p\ L_p\ P_{bp} = d_p * 2d_p * 10 = 20d_p^2$
Therefore, $F_c = 20d_p^2 = 986 = 20d_p^2 = 8.03$mm

Connecting Rod

It is one of the motion transmitted member between piston and crankshaft. The big end of the connecting rod is a ball joint which is connected to the crank and the small end of the connecting rod is connected to the piston trough gudgeon pin (Figures 29–31).

1.B=4d= 40mm 2. H=5d =50mm
3. A= $\frac{\pi}{4}d^2$= 62.8
4. I= 3.2 mm^3
5. F_l = Force on the connecting rod F_c
$F_c = F_l = \frac{\pi}{4}d^2 * 3.15$=314*3.15= 986 N
L= 2*length of stroke = 2*90.3= 180.6mm

RESULTS AND DISCUSSIONS

Figures 32–42 show the maximum von misses stress was concentrated on the connecting rod and wobble plate with z shaped crank under loading. The maximum von misses stress value was 194.74 and 5.47 MPa. Figures 43–67. Shows the minimum total het flux in the piston and cylinder. The minimum value of the total heat flux was 4.04 and 3.08 W/m^2 for structural steel and gray cast iron. Tables 1 and 2 represent the FEA static analysis of connecting rod and wobble plate with z shaped crank. Tables 3 and 4 represent the FEA thermal analysis of piston and cylinder.

Structural Static Analysis of Connecting Rod

Structural Steel

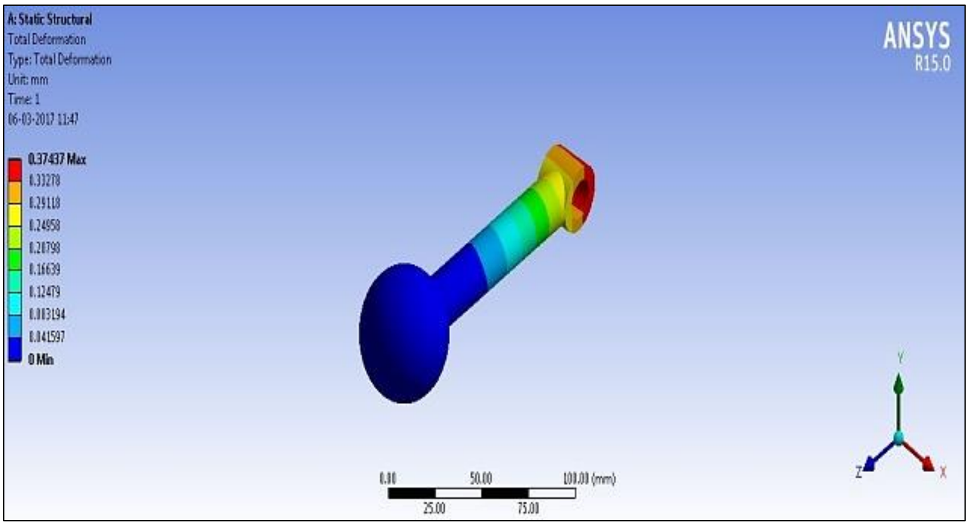

Fig. 29. *Total deformation in connecting rod.*

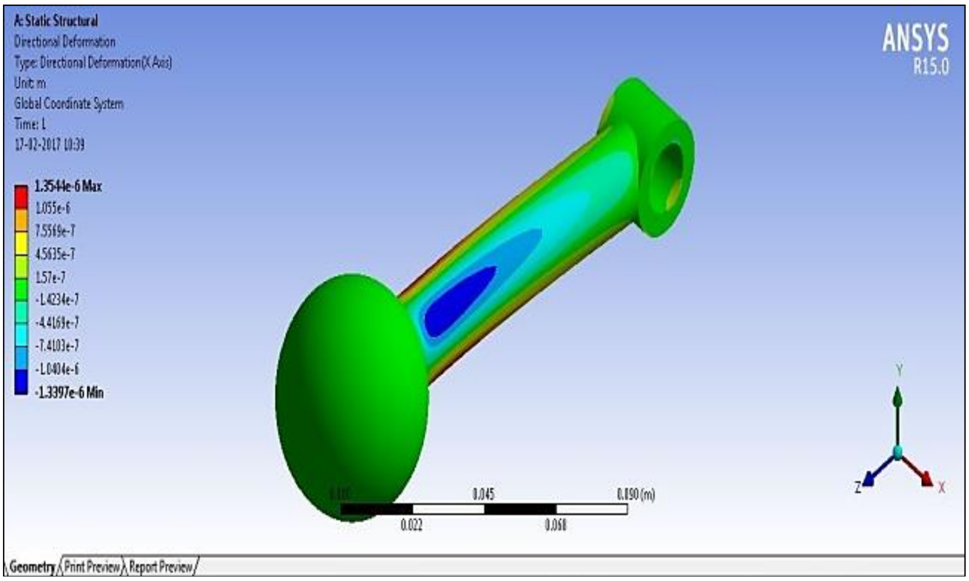

Fig. 30. *Directional deformation in connecting rod.*

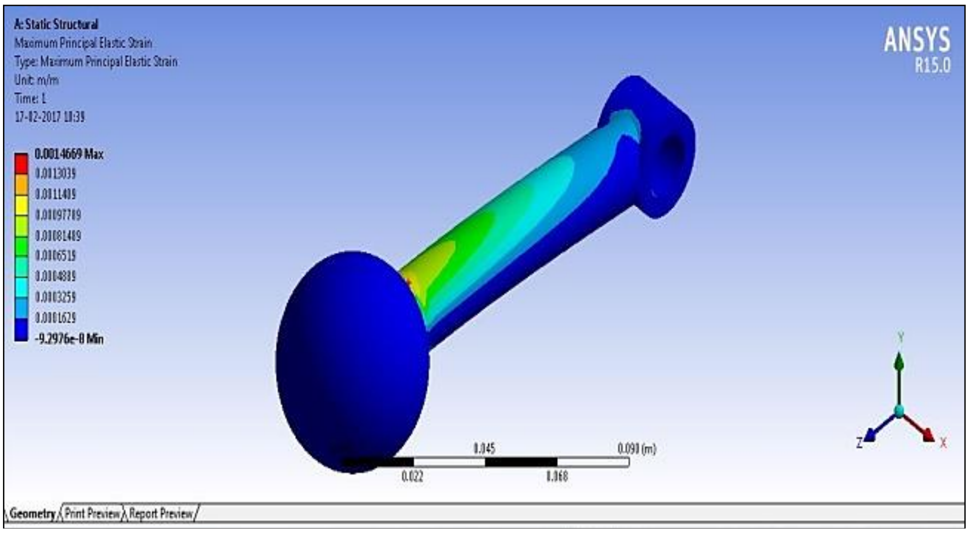

Fig. 31. *Equivalent strain in connecting rod.*

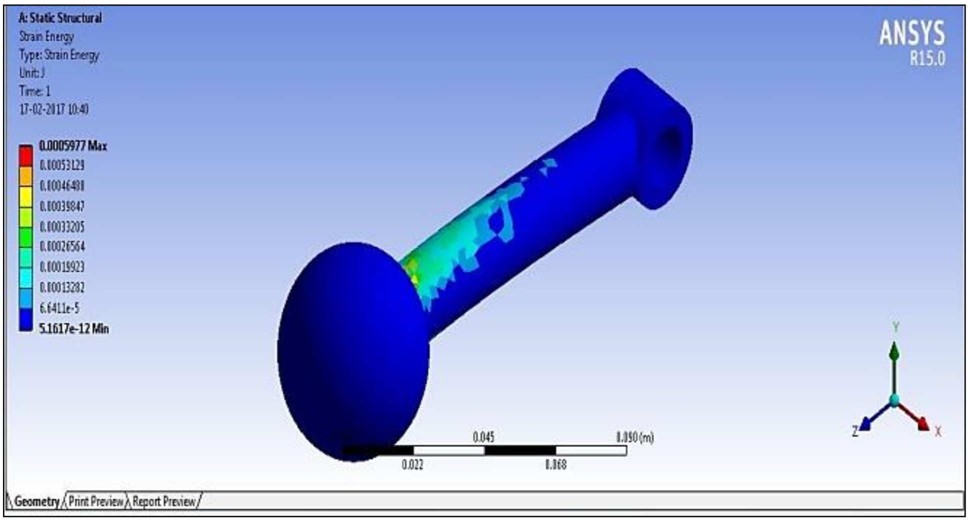

Fig. 32. *Equivalent stress in connecting rod.*

Steel 4340

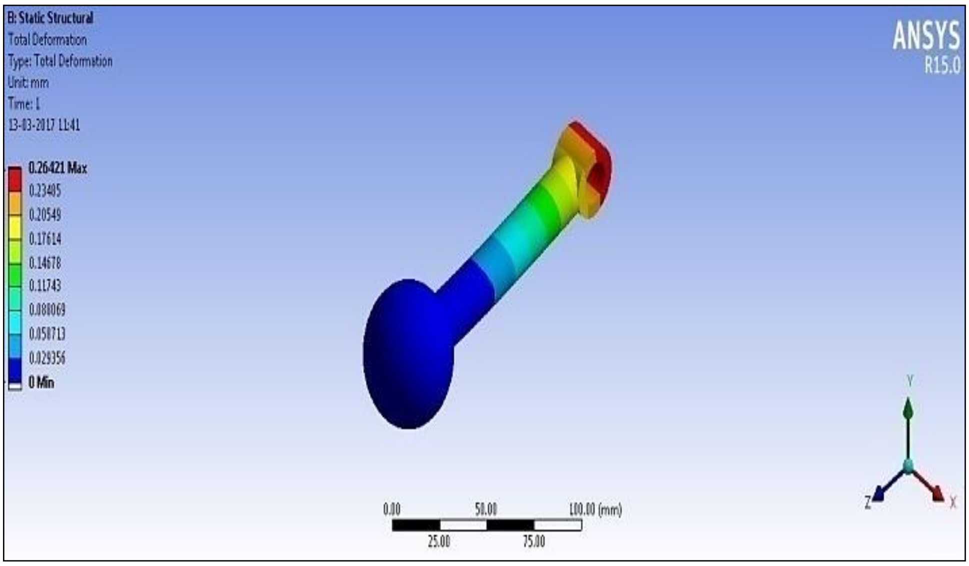

Fig. 33. *Total deformation in connecting rod.*

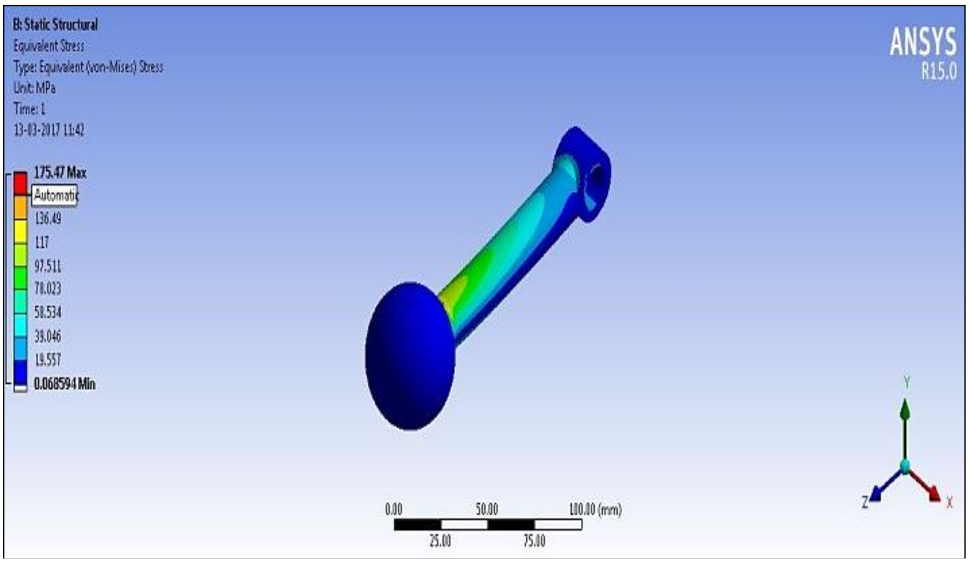

Fig. 34. *Equivalent stress in connecting rod.*

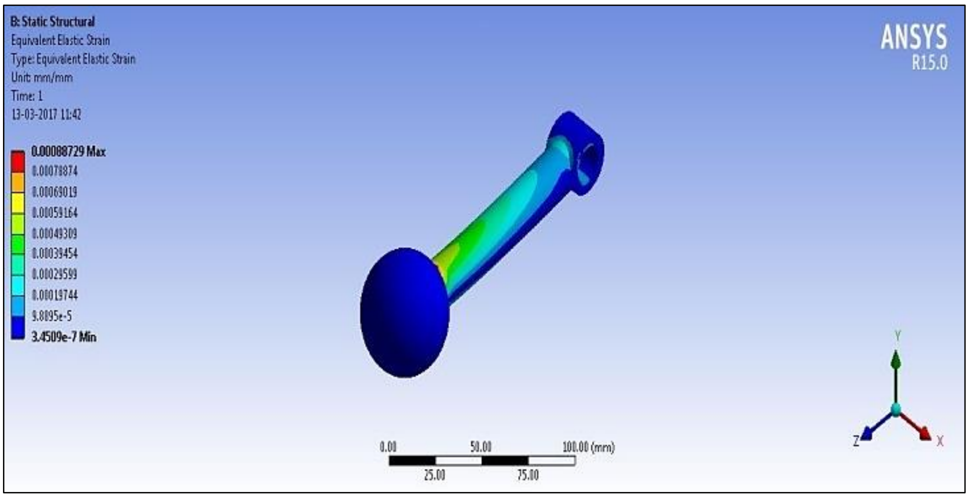

Fig. 35. *Equivalent strain in connecting rod.*

Steel V350

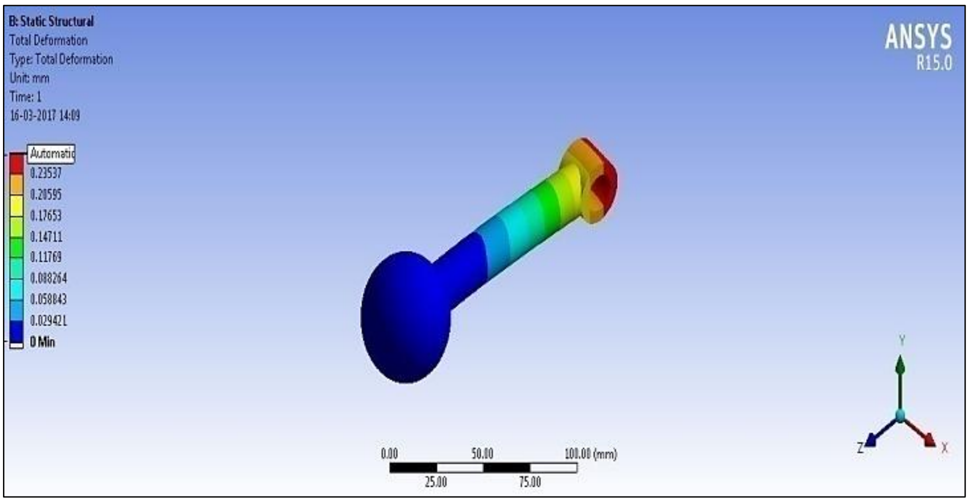

Fig. 36. *Total deformation in connecting rod.*

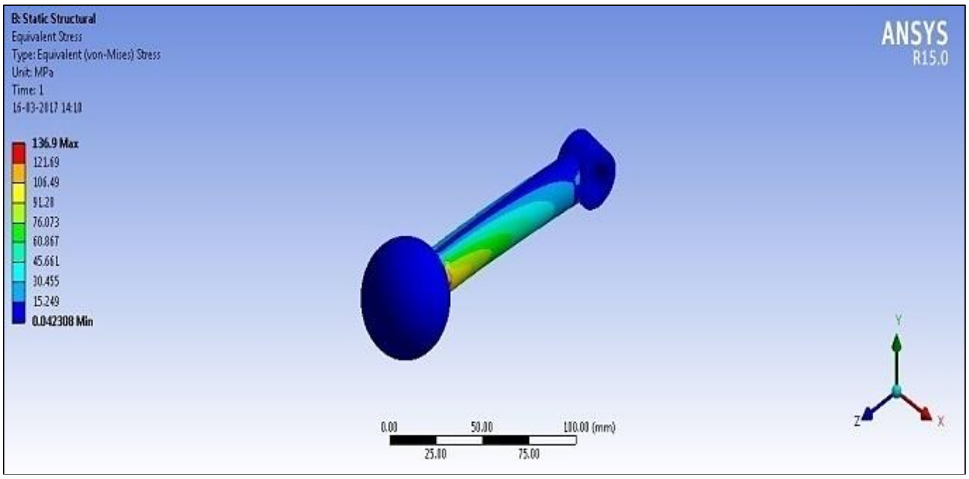

Fig. 37. *Equivalent stress in connecting rod.*

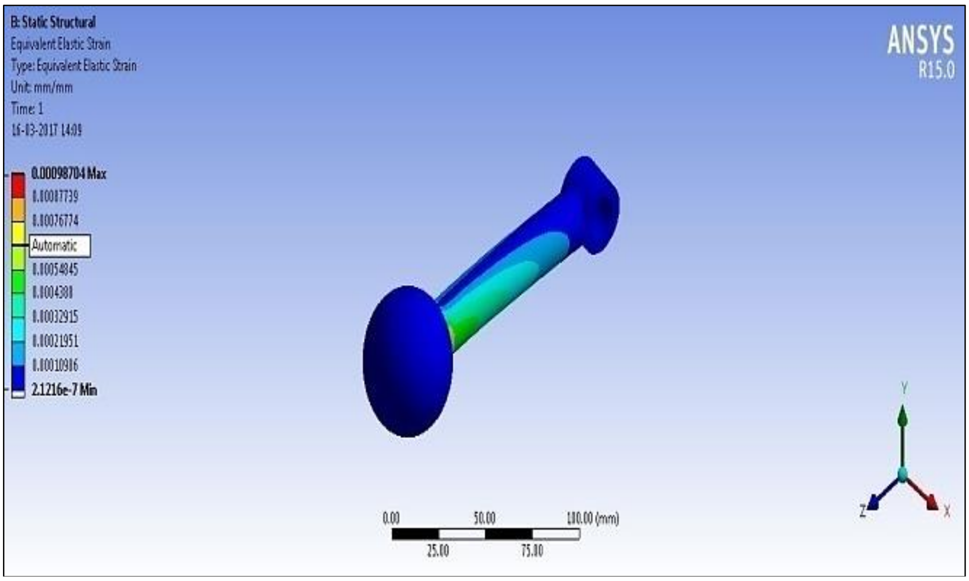

Fig. 38. *Equivalent strain in connecting rod.*

Structural Static Analysis of Wobble Plate With Z Shaped Crank

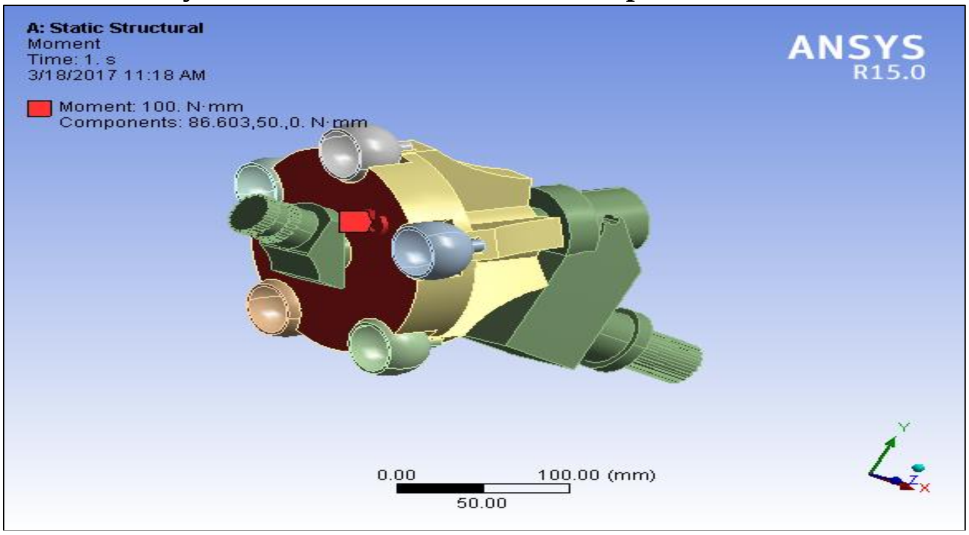

Fig. 39. *Moment in the crank (clock wise direction).*

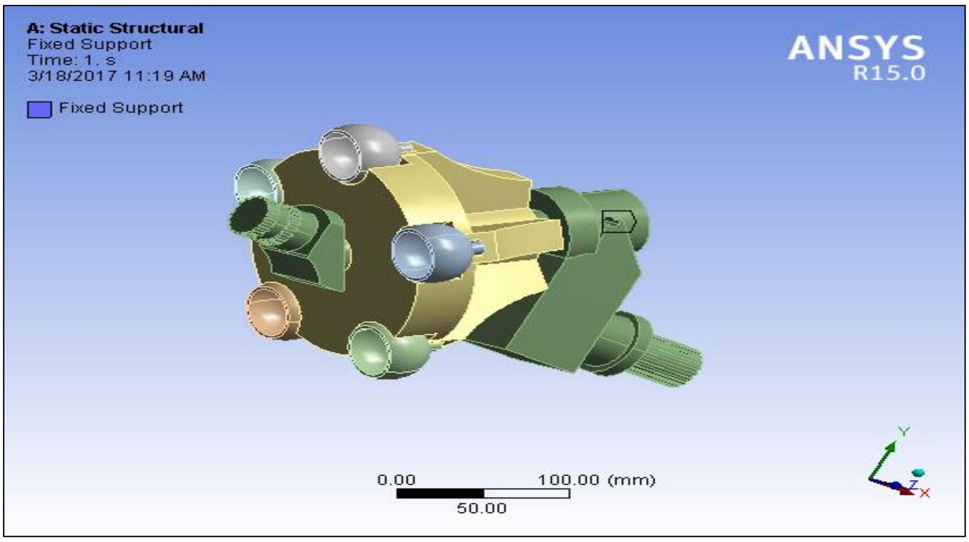

Fig. 40. *Fixed support in crank.*

Structural Steel

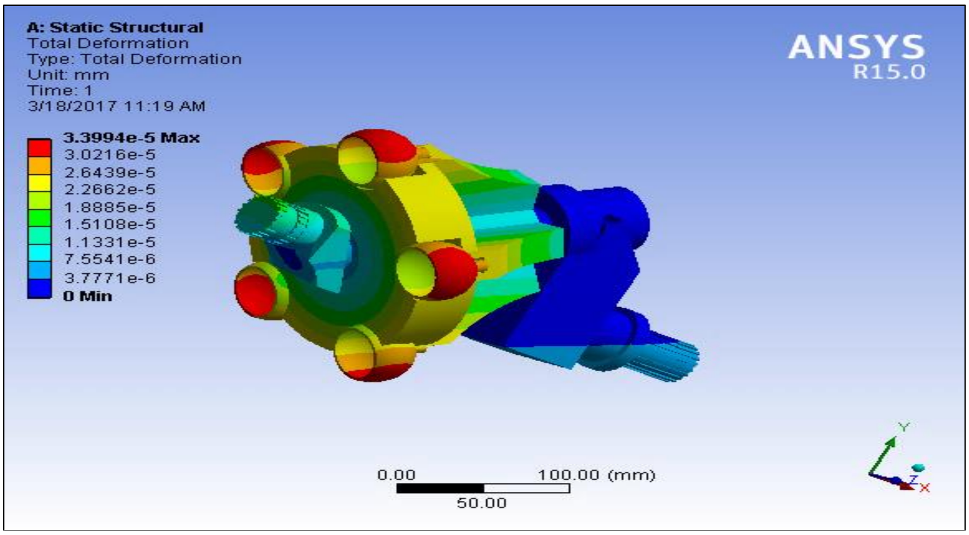

Fig. 41. *Total deformation in crank.*

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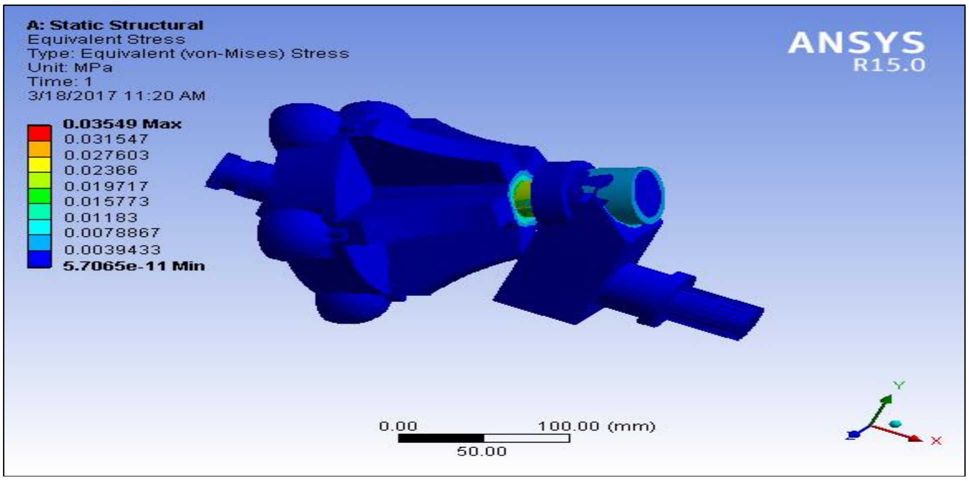

Fig. 42. Equivalent stress in crank.

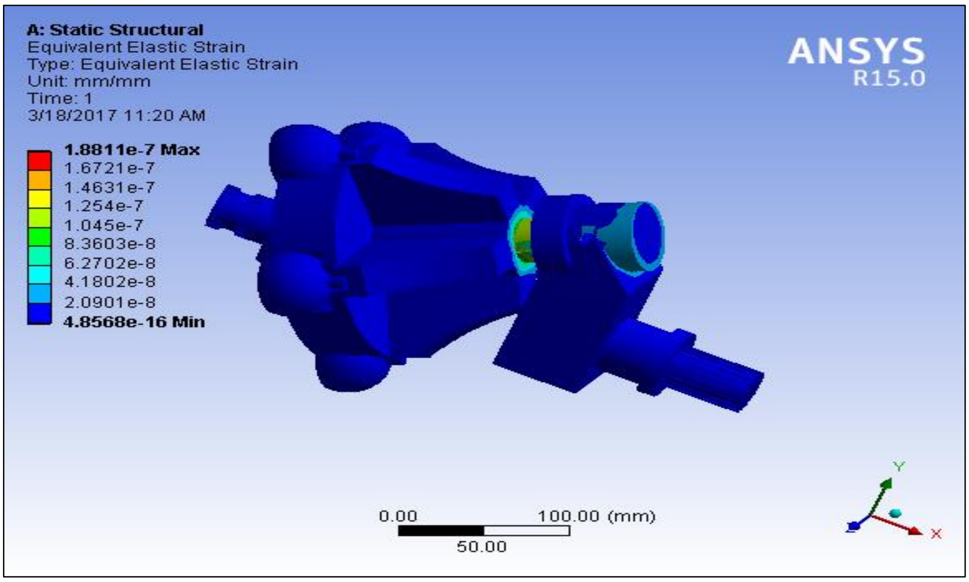

Fig. 43. Equivalent strain in crank.

Stainless Steel

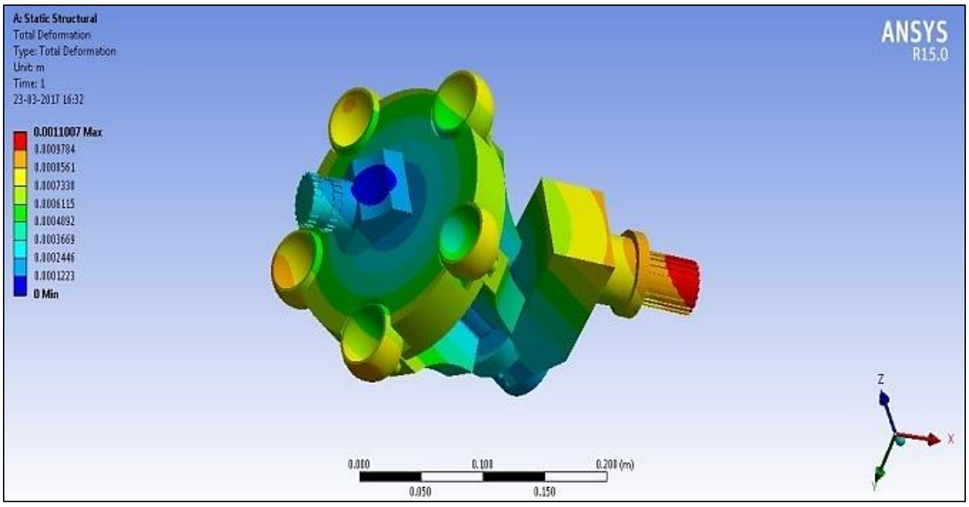

Fig. 44. Total deformation in crank.

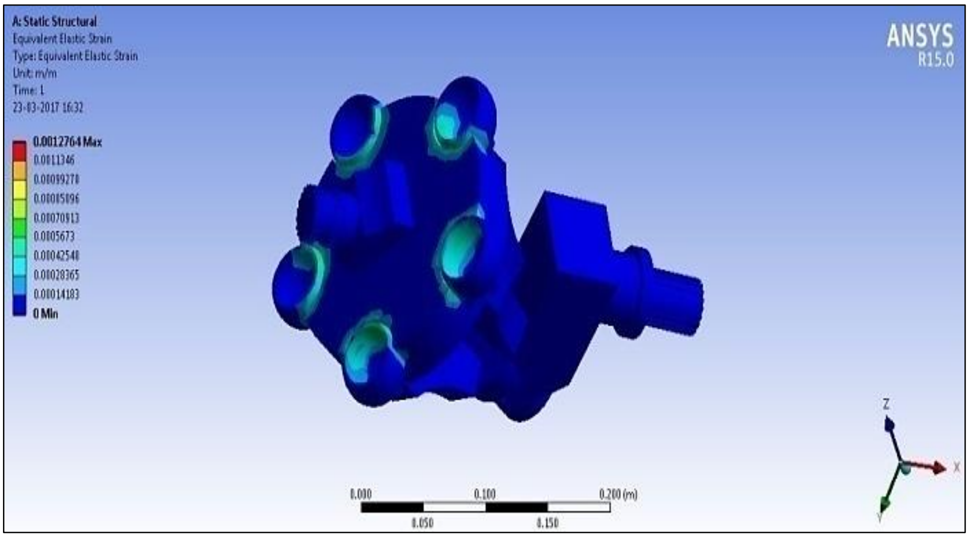

Fig. 45. *Equivalent stress in crank.*

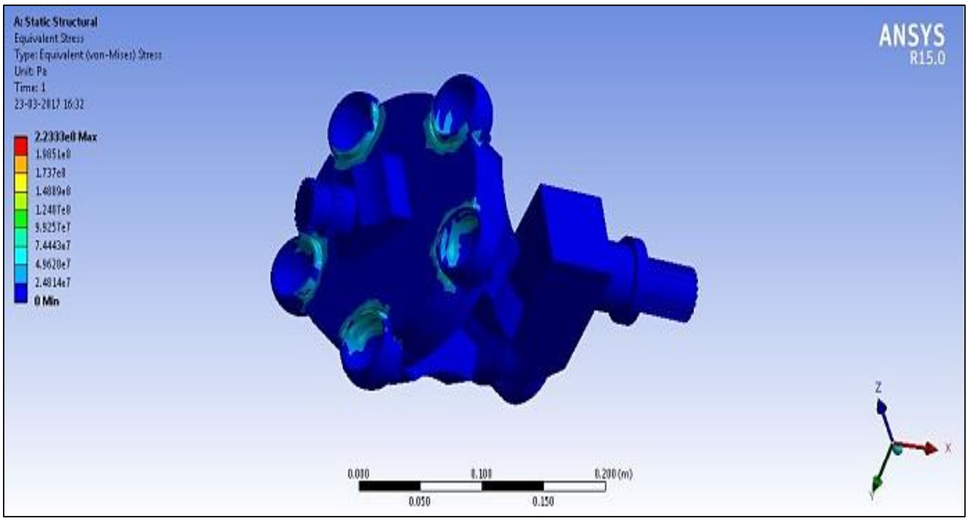

Fig. 46. *Equivalent strain in crank.*

Aluminum Alloy

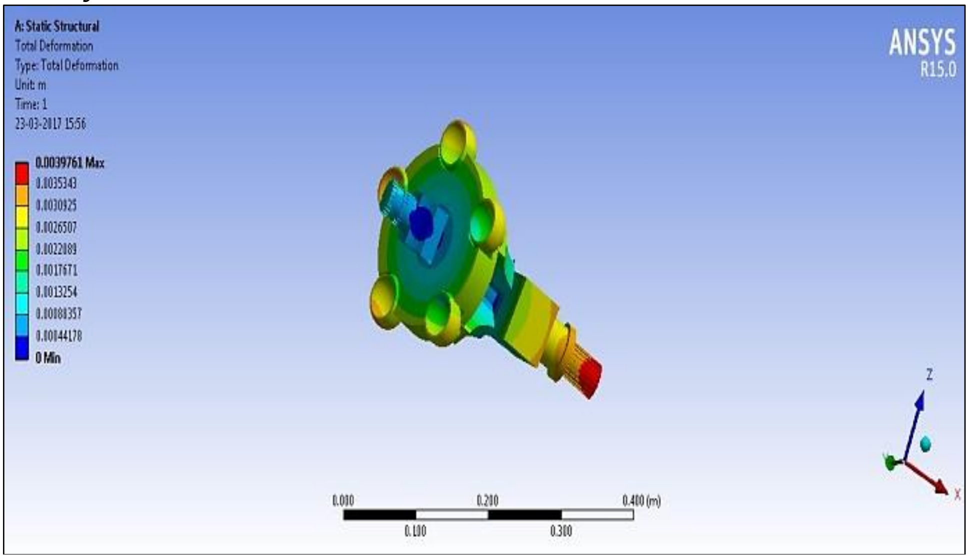

Fig. 47. *Total deformation in crank.*

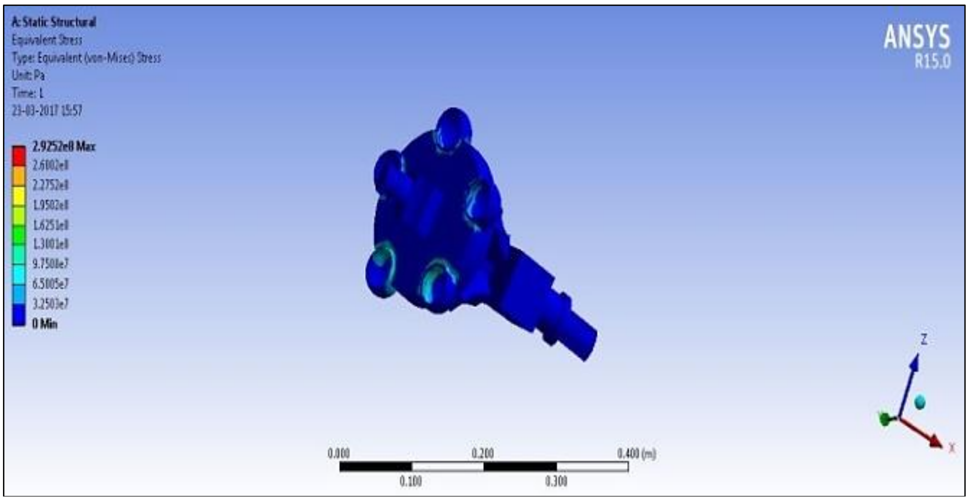

Fig. 48. *Equivalent stress in crank.*

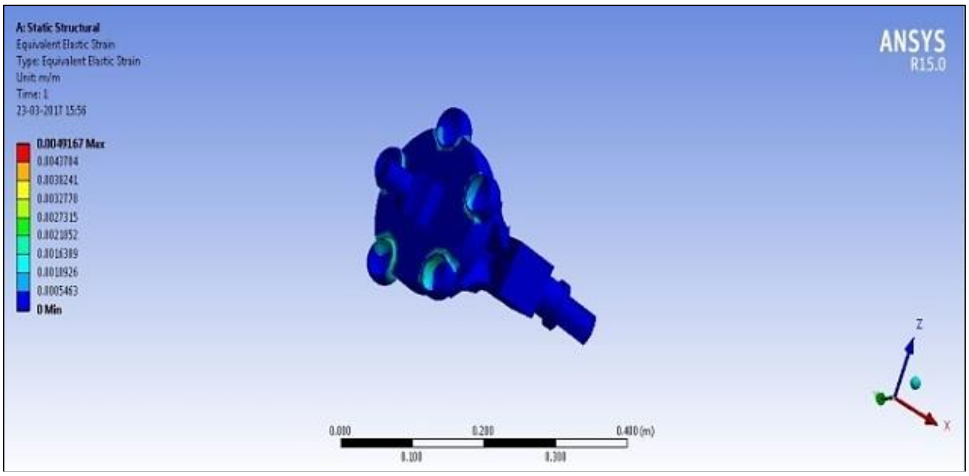

Fig. 49. *Equivalent strain in crank.*

Thermal Analysis of Piston

Aluminum

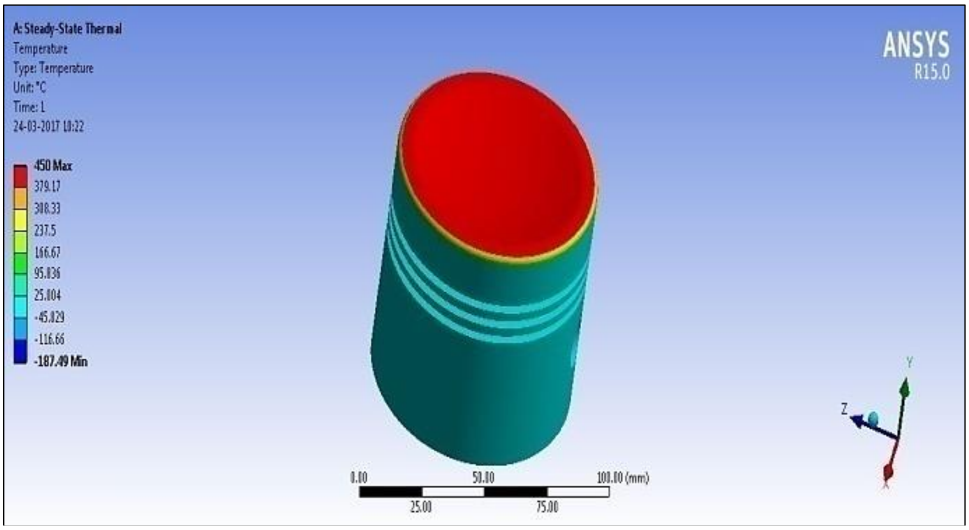

Fig. 50. *Temperature distribution in piston.*

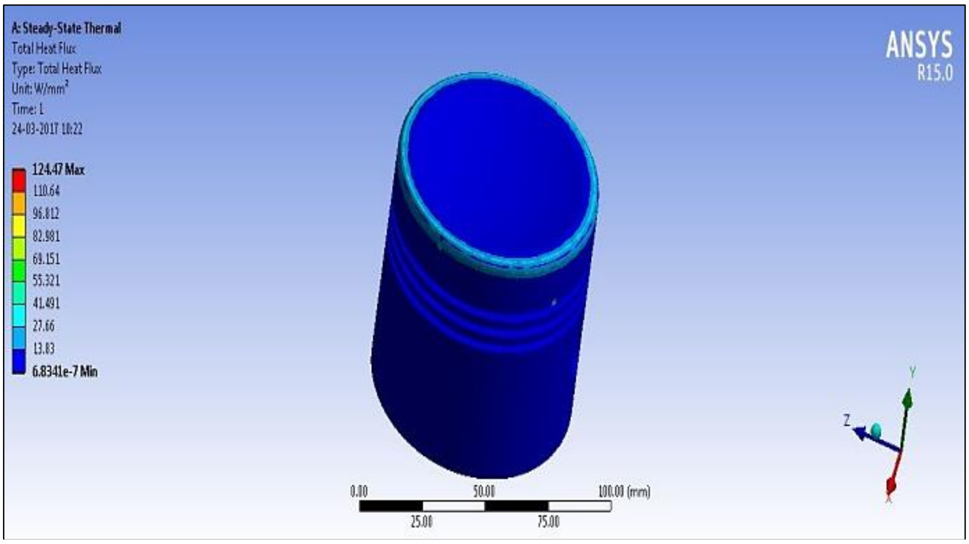

Fig. 51. *Total heat flux in piston.*

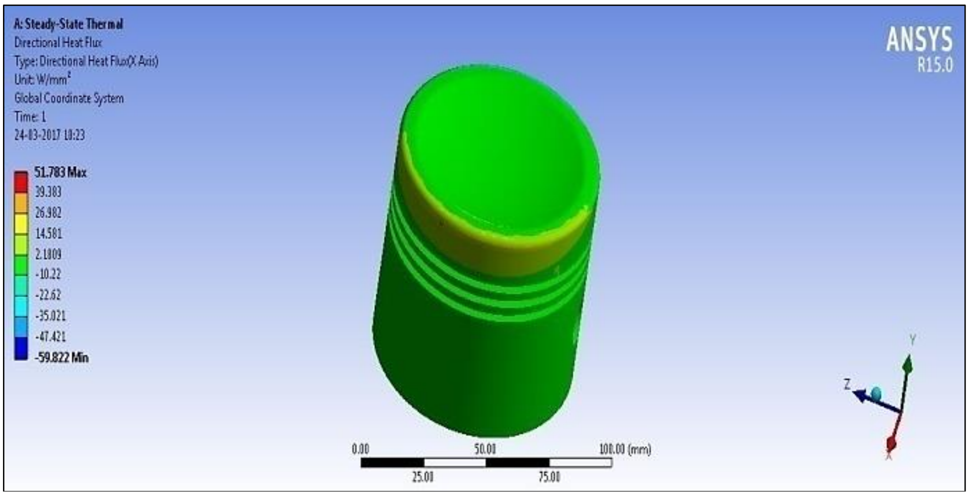

Fig. 52. *Directional heat flux in piston.*

Structural Steel

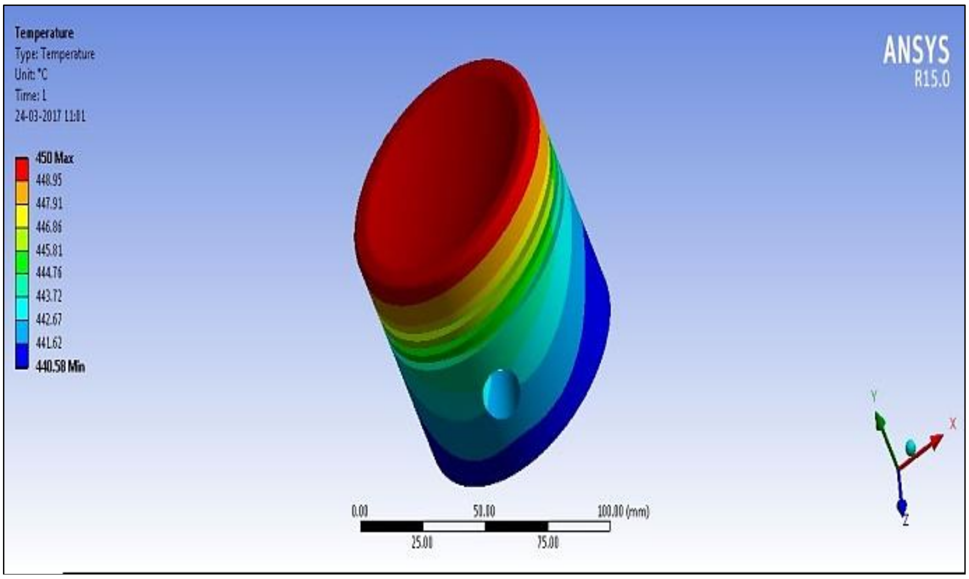

Fig. 53. *Temperature distribution in piston.*

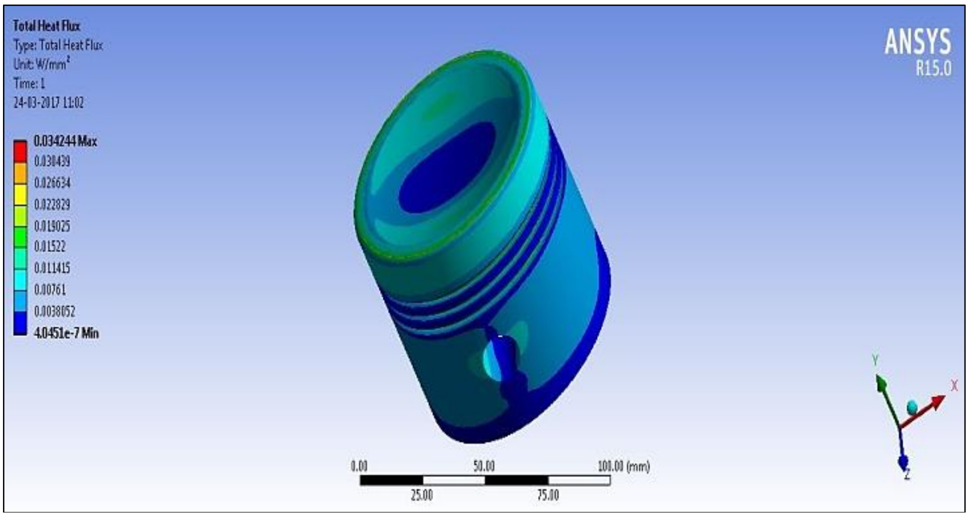

Fig. 54. *Total heat flux in piston.*

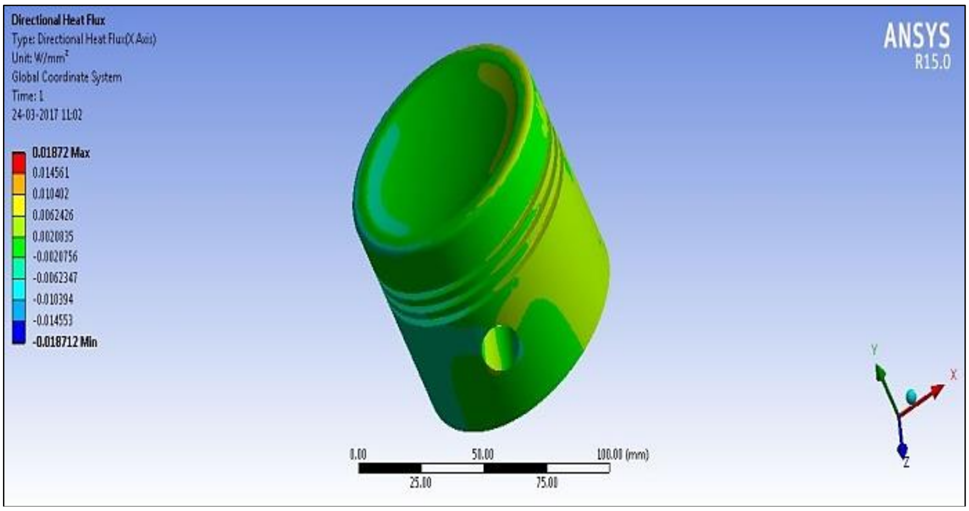

Fig. 55. *Total heat flux in piston.*

Cast Iron

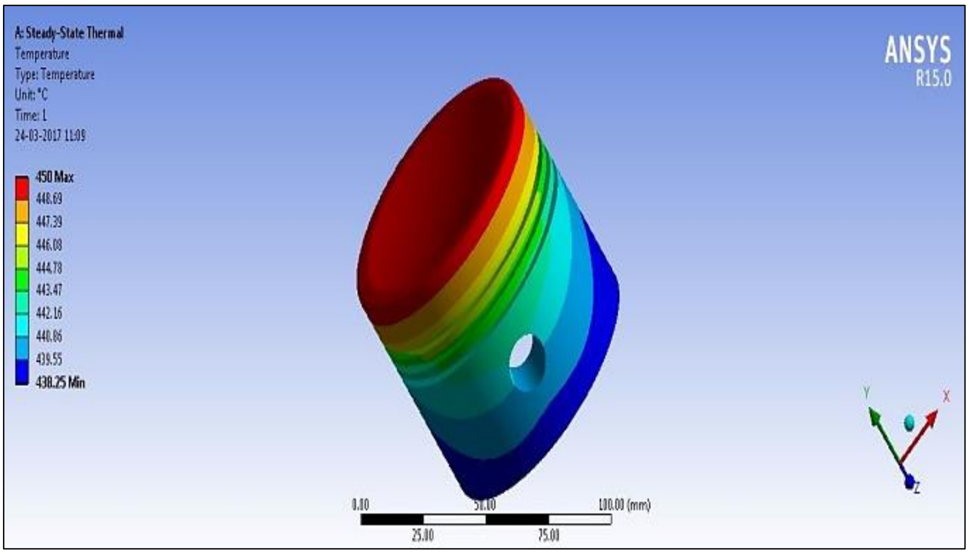

Fig. 56. *Temperature distribution in piston.*

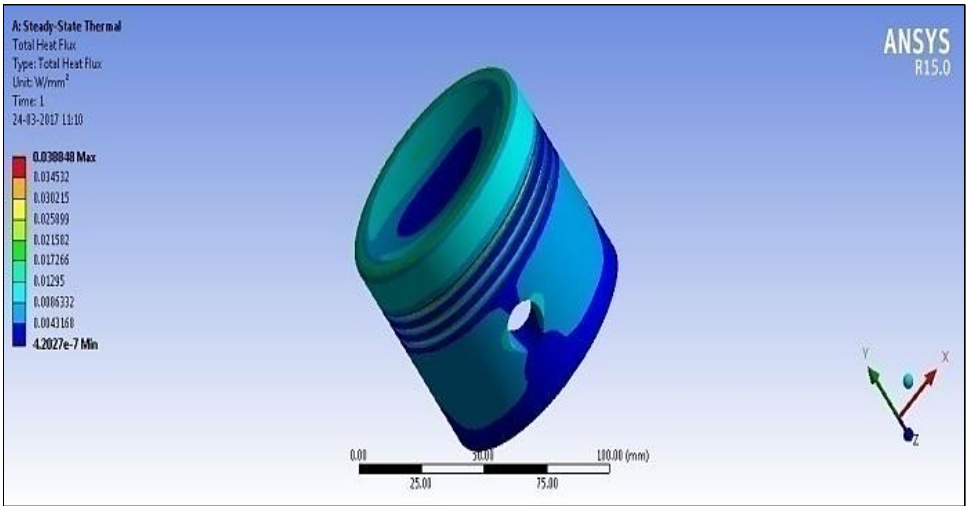

Fig. 57. *Total heat flux in piston.*

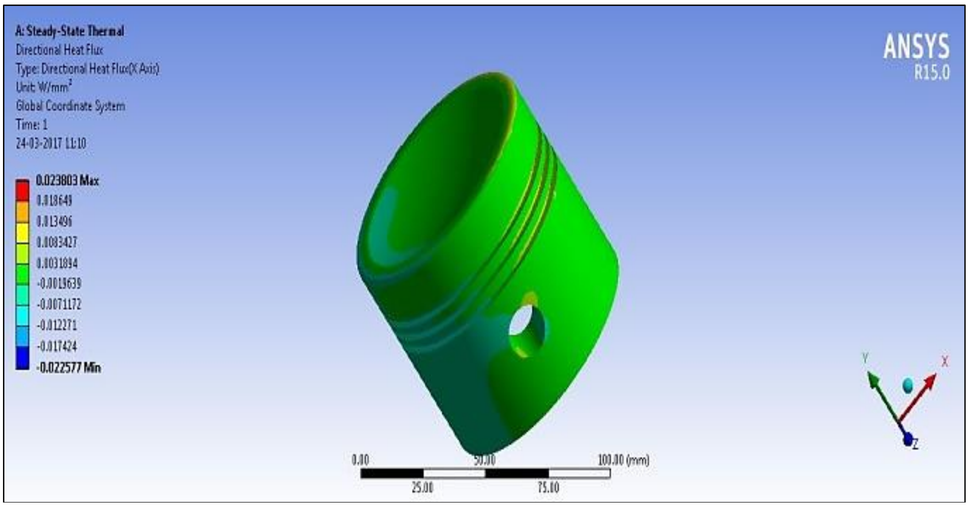

Fig. 58. *Total heat flux in piston.*

Thermal Analysis of Multicylinder Aluminum Alloy

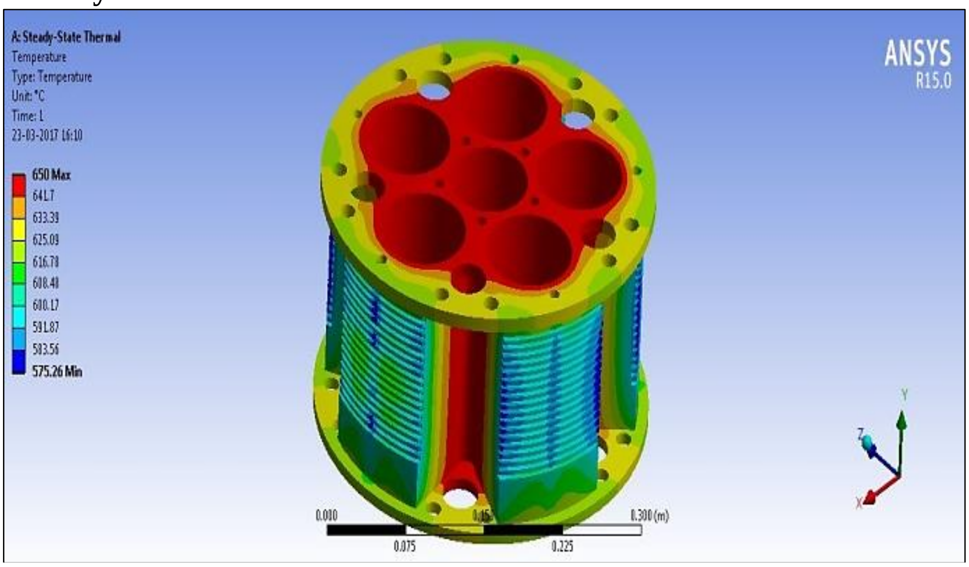

Fig. 59. *Temperature distribution in cylinder.*

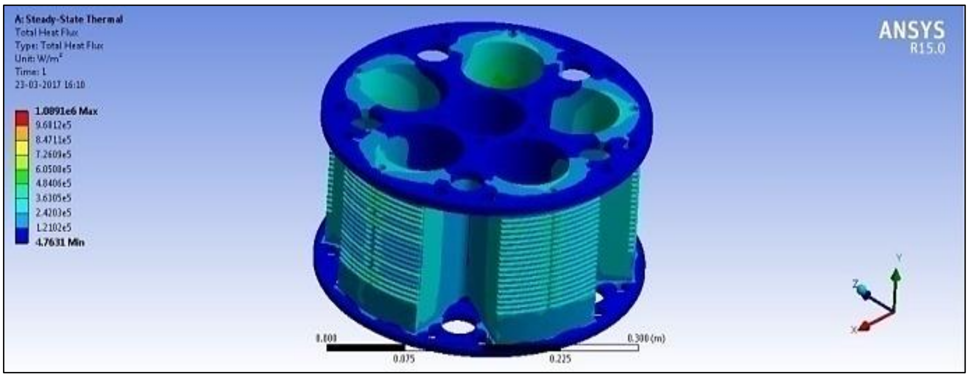

Fig. 60. Total heat flux in cylinder.

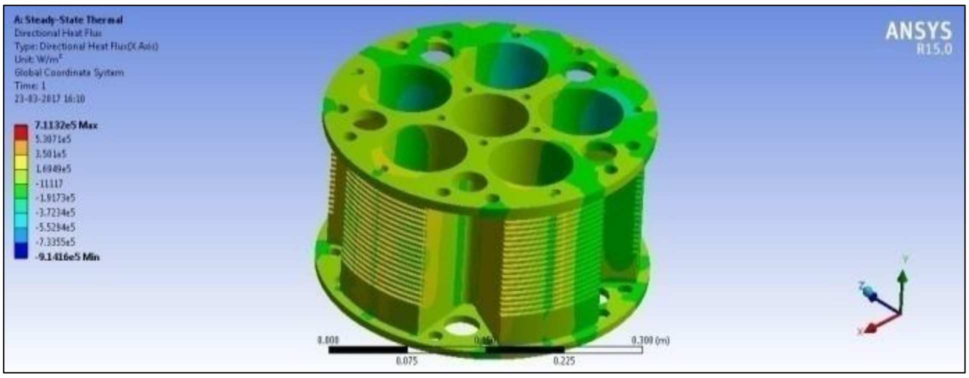

Fig. 61. Directional heat flux in cylinder.

Structural Steel

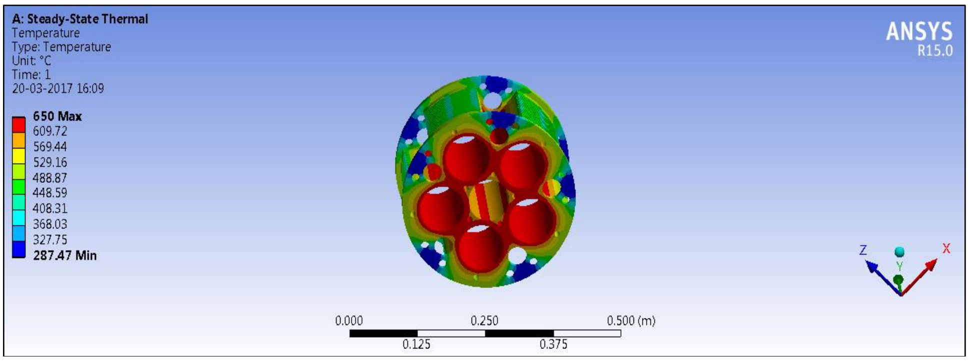

Fig. 62. Temperature distribution in cylinder.

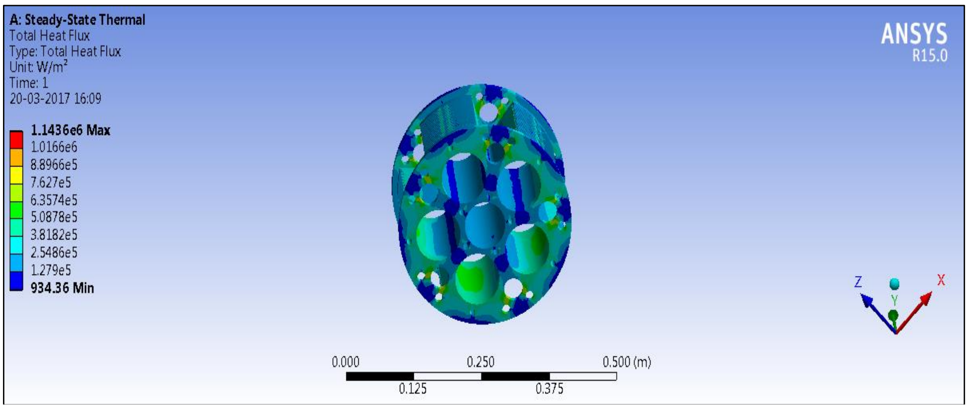

Fig. 63. Total heat flux in cylinder.

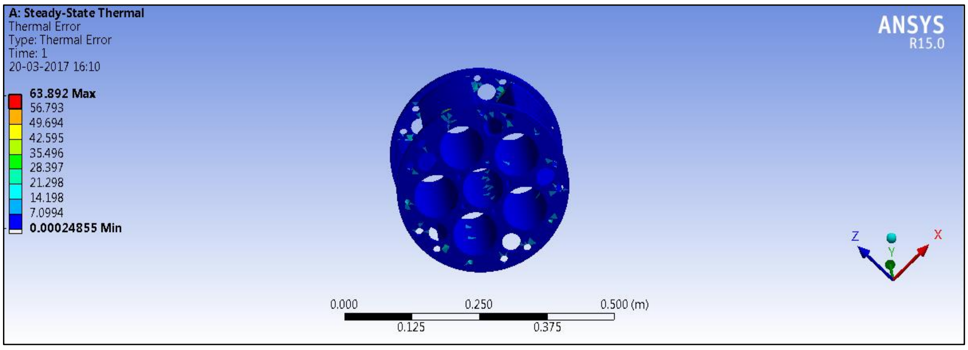

Fig. 64. *Thermal error in cylinder.*

Gray Cast Iron

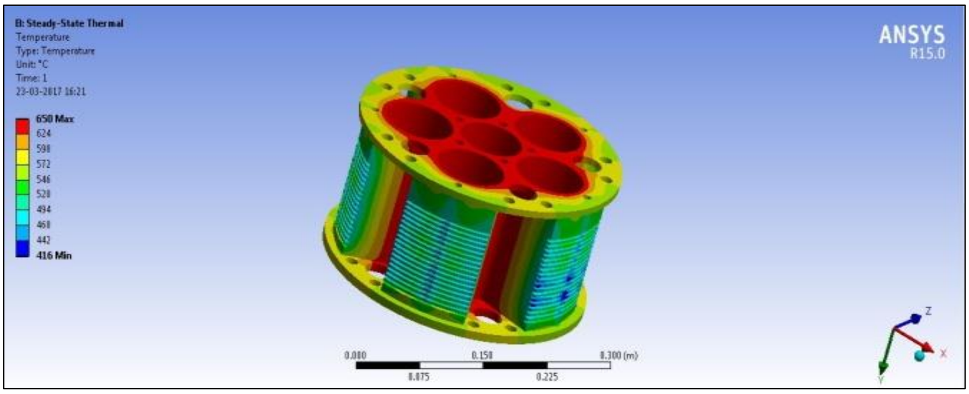

Fig. 65. *Temperature distribution in cylinder.*

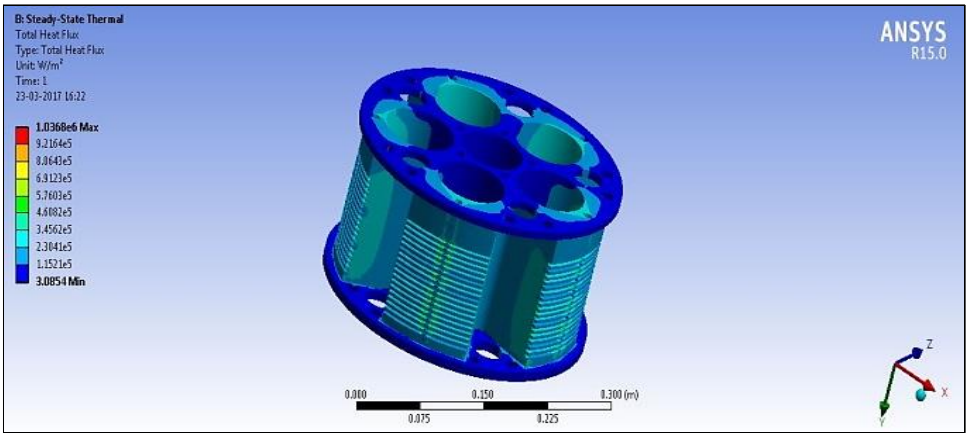

Fig. 66. *Total heat flux in cylinder.*

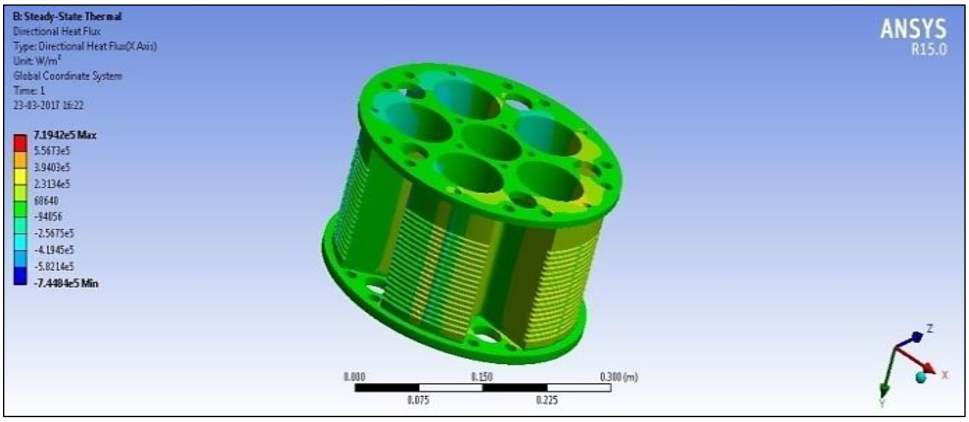

Fig. 67. *Directional heat flux in cylinder.*

Table 1. *FEA static analysis on the connecting rod with different materials.*

Variables		Structural steel	Steel 4340	Steel V350
Total deformation (mm)	Min	0	0	0
	Max	0.37437	0.26421	2.6479
Equivalent stress (von-misses stress) (MPa)	Min	–6.419e-002	0	4.2308e-002
	Max	194.74	175.47	136.9
Equivalent strain (mm/mm)	Min	–3.2256e-007	3.4509e-007	2.126e-007
	Max	1.0997e-003	0.88729e-003	9.8704e-004

Table 2. *FEA static analysis on the wobble plate with z shaped crank with different materials.*

Variables		Structural steel	Aluminum alloy	Stainless steel
Total deformation (mm)	Min	0	0	0
	Max	3.39994e-005	1.9221e-003	1.1007e-003
Equivalent stress (von-misses stress) (MPa)	Min	3.549e-002	0	0
	Max	5.47065e-016	2.2662e+008	2.2333e+008
Equivalent strain (mm/mm)	Min	4.8568e-016	0	0
	Max	1.8811e-007	2.277e-003	1.2764e-003

Table 3. *FEA thermal analysis on the Piston with different materials.*

Variables		Aluminum	Cast iron	Structural steel
Temperature (°C)	Min	–187.49	438.25	440.58
	Max	450	450	450
Total heat flux (W/m^2)	Min	6.8341e-007	4.2.27e-007	4.0451e-007
	Max	124.47	3.8848e-002	3.4244e-002
Directional heat flux (W/m^2)	Min	–59.822	-2.2577e-002	-1.8712e-002
	Max	51.783	2.3803e-002	1.872e-002

Table 4. *FEA thermal analysis on the cylinder with different materials.*

Variables		Aluminum	Structural steel	Gray Cast iron
Temperature (°C)	Min	575.26	287.47	416
	Max	650	650	650
Total heat flux (W/m^2)	Min	4.7631	934.36	3.0854
	Max	1.0891e+006	1.1436e+006	1.0368e+006
Directional heat flux (W/m^2)	Min	–9.1416e+005	–9.8591e+005	–7.4484
	Max	7.1132e+005	8.4134e+005	7.1942e+005

CONCLUSION

Modeling of an axial engine was done in Solid works software. Thermal and static analysis was done in Ansys 15.0 software. Analysis carried out on Piston, connecting rod, cylinder block and wobble plate with Z-shaped crank with different materials. The temperature distribution, total heat flux, directional heat flux values of structural steel, aluminum and cast iron of different components were compared. Total deformation, equivalent stresses (Von misses' stresses) and Equivalent strain values of structural steel, cast iron and stainless steel were compared.

- The best suitable material used for piston and multicylinder is structural steel and cast iron. The total heat flux values of stainless steel and cast iron are 4.045 & 3.08 W/m^2. This total heat fluxes are very less when compared to other materials. In this material, thermal stress is will reduce compared to other materials.

- The best suitable material for connecting rod is structural steel because the maximum von misses stress is very high as compared to other materials. The maximum von misses stress value is 194.74 MPa. This value is within the yield stress of structural steel value. The yield stress of structural steel value is 250 MPa.
- The best suitable material for wobble plate with Z shaped crank is structural steel because the maximum von misses stress is very high as compared to other materials. The maximum von misses stress value is 5.47 MPa. This value is within the yield stress of structural steel value.

NOMENCLATURE

t_H Thickness of piston head
t_1 Radial thickness of ring
t_2 Axial thickness
b_1 Width of top land
b_2 Width of the other ring lands
t_3 Piston barrel
L Length of the piston
t_w Thickness of cylinder wall
t_h Thickness of cylinder head
Lc Length of cylinder
I Moment of inertia of the connecting rod
H Height of the section
Q Heat flux or Total heat flux(W/m^2)
T Temperature
σ_V Equivalent stress (von-misses stress) (MPa) of engine components (Connecting rod and crank with wobble plate)
ε Equivalent strain (mm/mm)

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