Material and Cost Optimization of Piston and Piston Ring of Heavy Duty Vehicles Using Finite Element Analysis

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ABSTRACT

In this Research paper J.P. Diesel Company manufacturing Piston facing problem of ceasing of piston due low heat dissipation and failure due to High combustion pressure. Hence as a first step design modification is done by providing four ribs and two ribs for a multi cylinder four stroke diesel engine using CREO parametric 3.0 software. After modification in design Static Structural and Steady state thermal analysis is done using ANSYS software, as per analysis results we can successfully reduced the stress and improve heat flux and factor of safety. In next step three different materials have been selected for structural and thermal analysis of piston and piston ring, structural and thermal analysis is performed using ANSYS software for existing material and modified design-1 and modified design-2 for three different aluminium materials. Result of structural and thermal analysis for different designs and materials is compared with existing design & material of piston and piston ring. Most suitable material for piston and piston ring will be selected to optimize the existing design of piston. For material cost optimization the masses of different material are noted and calculated and compared of existing material and for optimized material.

Keyword: - *Ceasing, heat dissipation.*

1. INTRODUCTION

Internal combustion engines are those engines in which the combustion of fuel takes place inside the engine cylinder. the Internal combustion engines use either petrol or diesel as their fuel in petrol engines also known as spark ignition engines or SI engine the correct proportion of air and fuel (petrol) is mixed in the carburetor and fed in to the engine cylinder where it is ignited by means of a spark produced at the spark plug. In the diesel engine also known as Compression ignition engine or CI engine only air is supplied to the engine cylinder during suction stroke and it is compressed to a very high pressure, thereby raising its temperature from 600° C to 1000° C. The two stroke petrol engines are generally used in very light duty vehicles such as Scooters, bike, moped and three wheelers, the two stroke diesel engine generally used for marine propulsion. The four stroke petrol engines are generally used in light vehicles like cars, jeep and airplane also, the four stroke diesel engine are generally used in Heavy Duty Vehicles such as bus, trucks, Tractors, locomotive and earth moving machinery.

1.1 Problem Definition :

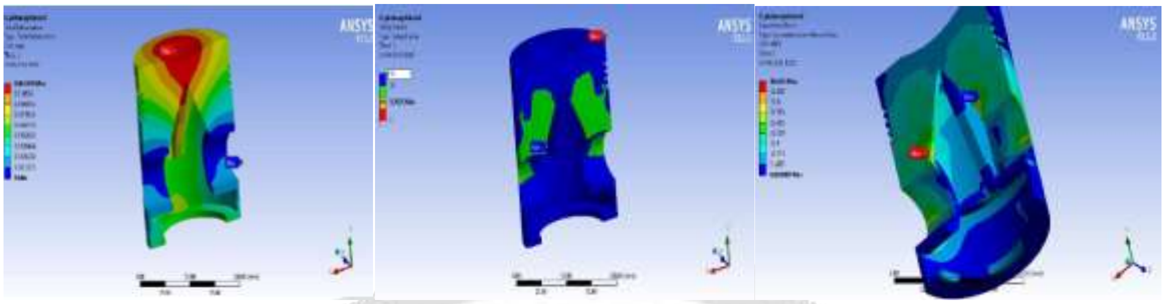
The piston is one of the most critical components of an engine, Company manufacturing Piston facing problem of ceasing of piston due low heat dissipation and failure due to High combustion pressure. Therefore it must be designed to withstand from damage that is caused due to extreme heat and pressure of combustion process. So, reason can be find out Stress analysis and thermal analysis of existing design of piston and piston rings

1.2 Objectives :

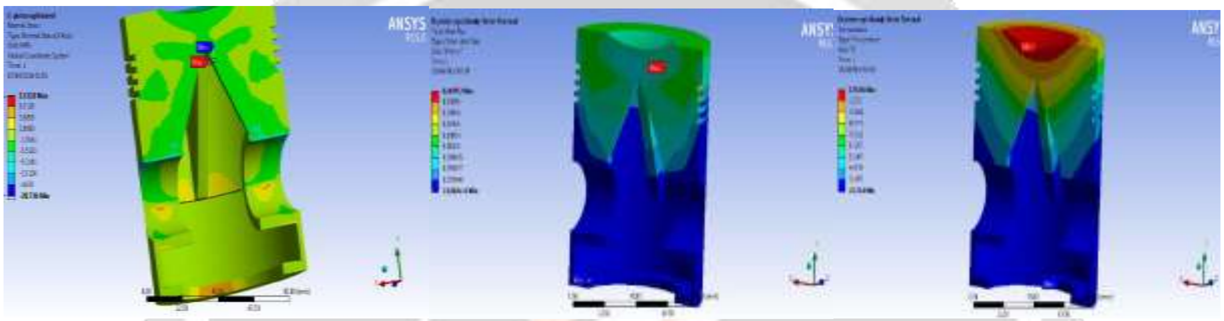
To calculate the stresses and deformation by considering the gas load, Using FEA and analytical approach to validate it. For studying thermal parameter playing role in piston failure will be done by heat flow Analysis using

ANSYS workbench 15.0 and validate it analytically. As material selection plays important role in design a component, Suitable material will be selected considering static, thermal and weight optimization Parameter..

2. Static Structural & Steady State Thermal Analysis of Modified Design-1:



(A)Total Deformation **(B)Factor of safety** **(C) Equivalent von-mises stress**

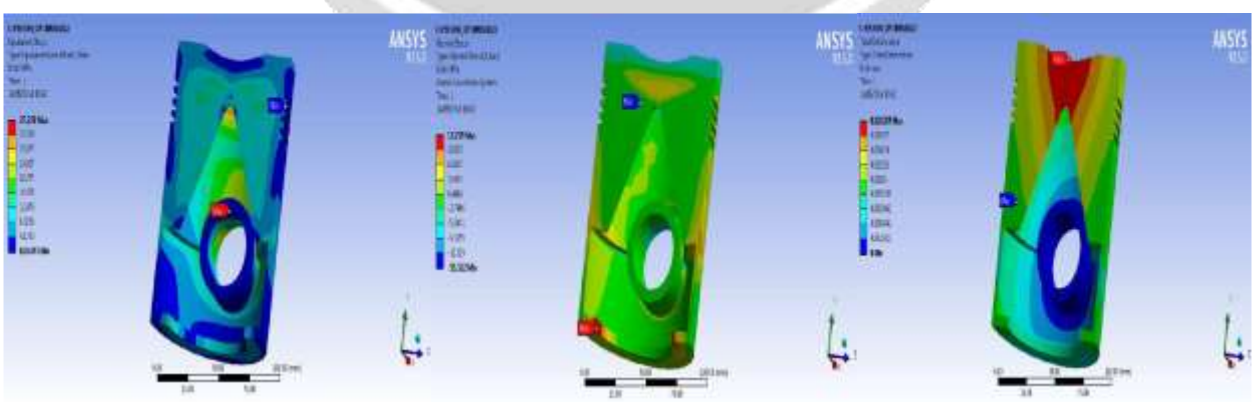


(D) Normal Stress **(E) Total heat flux** **(F) Temprature**

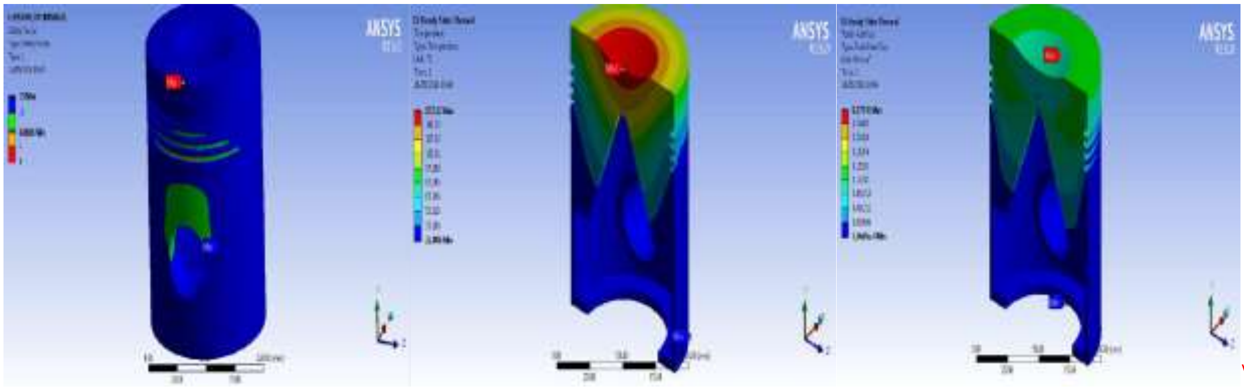
Fig No -1: Static Structural & Steady State Thermal Analysis of modified Design-1 using ANSYS R15.0

In Fig no. 1(A) in Modified design-1 on the top of piston crown maximum deformation 0.011839 mm occurs, in Fig no. 1(B) in Modified design-1 of the piston minimum factor of safety 3.29 occurs, in Fig no. 1(C) in Modified design-1 on the rib end in piston maximum Equivalent von-mises stress of 46.16 N/mm^2 occurs, In Fig no. 1(D) in Modified design-1 at the ribs joints in piston maximum normal stress of 13.51 N/mm^2 occurs, in Fig no. Fig no. 1(E) in Modified design-1 at the bottom of piston crown maximum total heat flux of 0.26953 W/mm^2 occurs, in Fig no. 1(F) in Modified design-1 at the top of piston crown maximum temperature of 123.56°C occurs.

2.1 Static Structural Analysis of Existing material for Modified Design-2



(A) Equivalent von-mises stress **(B) Normal Stress** **(C) Total Deformation**

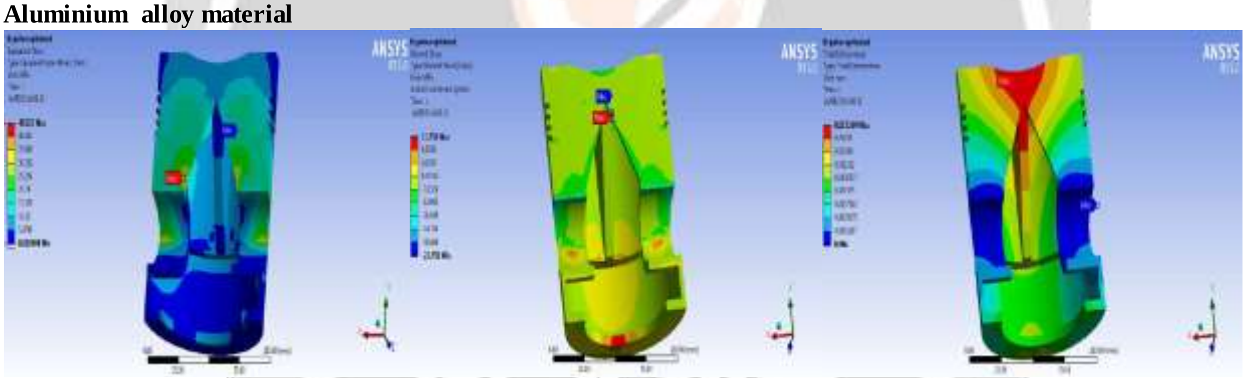


(D) Factor of safety **(E) Temprature** **(F) Total heat flux**

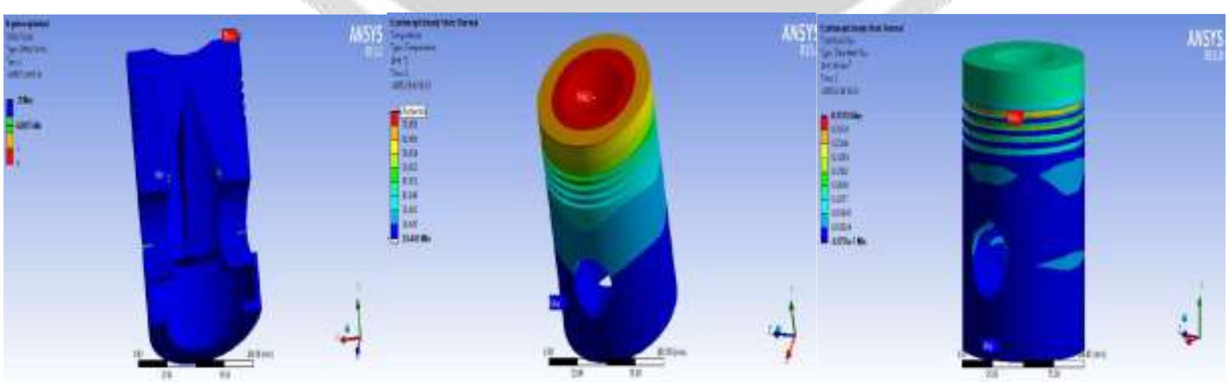
Fig No -2: Static Structural & Steady State Thermal Analysis of modified Design-2 using ANSYS R15.0

As shown in figure no. 2 (A) maximum equivalent (von Mises) stress is 37.37 N/mm² at a point of fixed support for piston pin, and in figure no. 2 (B) shows max normal stress is 13.21 N/mm² at bottom surface of piston. As shown in figure no. 2 (C) maximum deformation 0.01828 mm at top of the piston, and As shown in figure no. 2 (D) minimum factor of safety 4.066 in modified design-2 which consists two ribs at a angle of 180° As shown in figure no. 2 (E) Maximum temperature is 157.27°C at the top of the piston head, and in figure no. 2 (F) total heat flux is 0.27545 W/mm²

2.2 Static Structural and Steady state thermal Analysis of Modified Design-1(Four Ribs at 90°angle) for Aluminium alloy material



(A) Equivalent von-mises stress **(B) Normal Stress** **(C) Total Deformation**

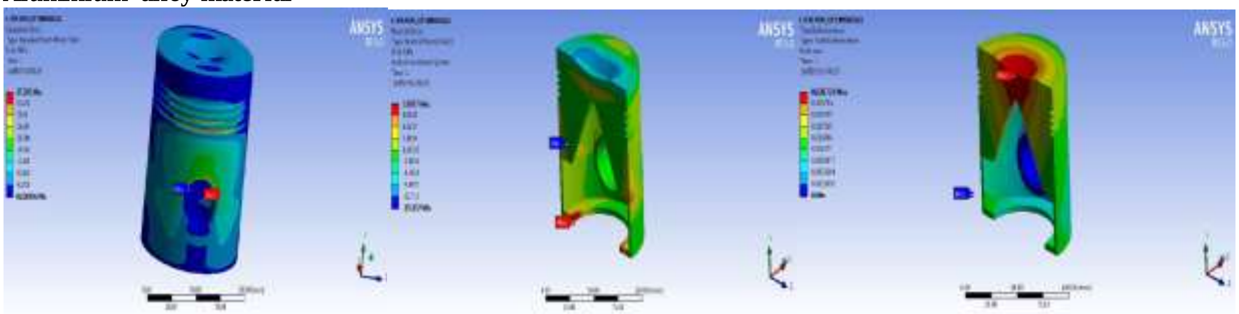


D) Factor of safety **(E) Temprature** **(F) Total heat flux**

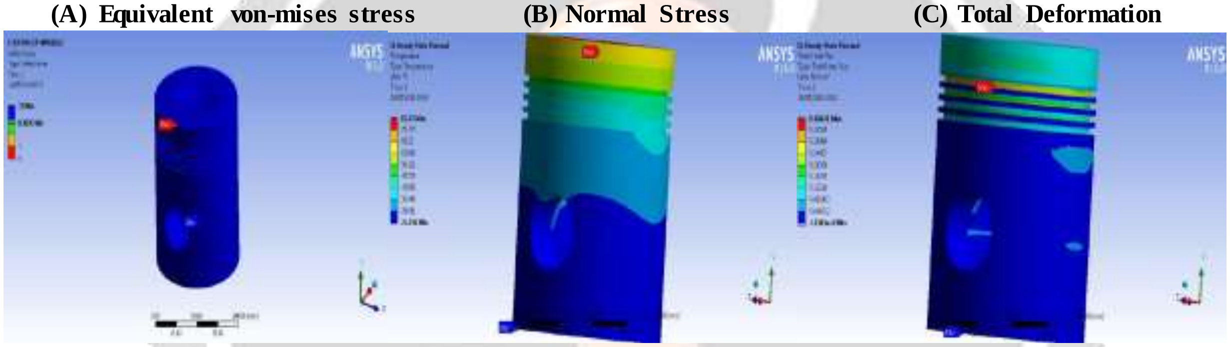
Fig No -3: Static Structural & Steady State Thermal Analysis of modified Design-1 for Aluminium alloy material using ANSYS R15.0

As shown in fig no 3 (A) maximum equivalent (Von Mises) stress for Modified Design-1 (Four ribs at angle of 90°) is 45.51 N/mm², in fig no 3 (B) maximum normal stress for Modified Design-1 (Four ribs at angle of 90°) is 11.75 N/mm², in fig no fig no 3 (C) total deformations for Modified Design-1 (Four ribs at angle of 90°) is 0.01726 mm, in fig no 3 (D) minimum Factor of safety for Modified Design-1 (Four ribs at angle of 90°) is 6.81, in fig no 3 (E) maximum Temperature for Modified Design-1 (Four ribs at angle of 90°) is 77.83°C, in fig no fig no 3 (F) maximum principle stress for Modified Design-1 (Four ribs at angle of 90°) is 0.3233 W/mm².

2.3 Static Structural and Steady state thermal Analysis of Modified Design-2 (Two Ribs at 180° angle) for Aluminium alloy material



(A) Equivalent von-mises stress **(B) Normal Stress** **(C) Total Deformation**

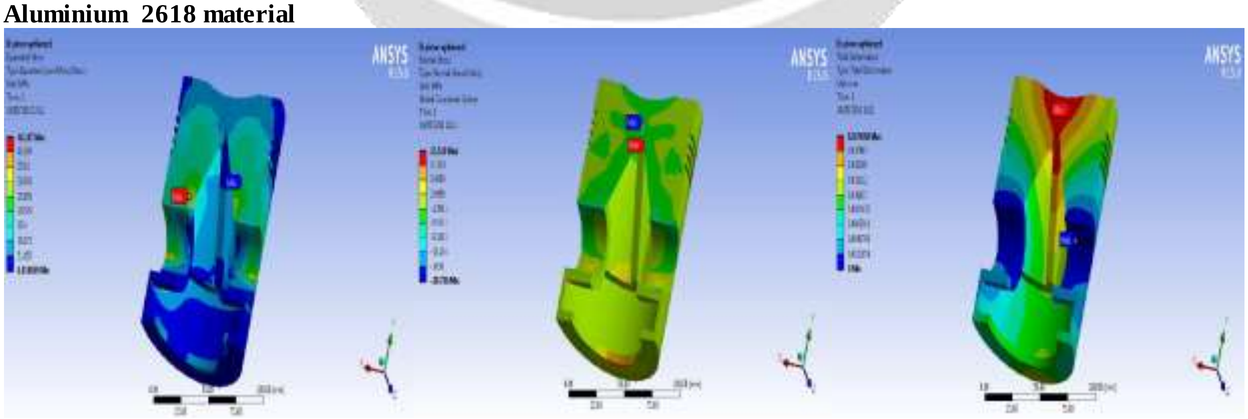


D) Factor of safety **(E) Temprature** **(F) Total heat flux**

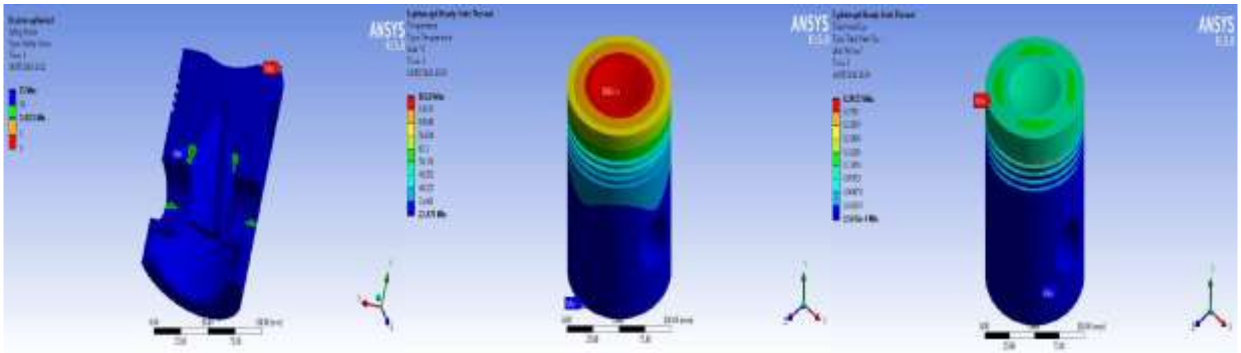
Fig No -4: Static Structural & Steady State Thermal Analysis of modified Design-2 for Aluminium alloy material using ANSYS R15.0

As Shown in fig no 4 (A) for modified design-2 (Two Ribs at angle of 180°) is 37.315 N/mm², in fig no 4 (B) for modified design-2 (Two Ribs at angle of 180°) is 13.07 N/mm, in fig no 4 (C) for modified design-2 (Two Ribs at angle of 180°) is 0.02672 mm, in fig no 4 (D) for modified design-2 (Two Ribs at angle of 180°) is 8.307, in fig no 4 (E) for modified design-2 (Two Ribs at angle of 180°) is 82.33°C, in fig no 4 (F) for modified design-2 (Two Ribs at angle of 180°) is 0.3664 W/mm².

2.3 Static Structural and steady state thermal Analysis of Modified Design-1(Four Ribs at 90° angle) for Aluminium 2618 material



(A) Equivalent von-mises stress **(B) Normal Stress** **(C) Total Deformation**

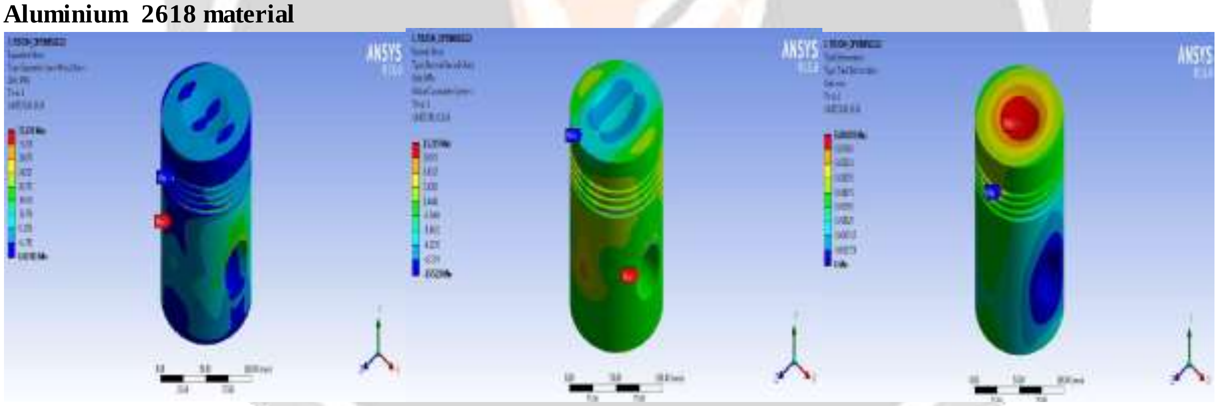


D) Factor of safety **(E) Temprature** **(F) Total heat flux**

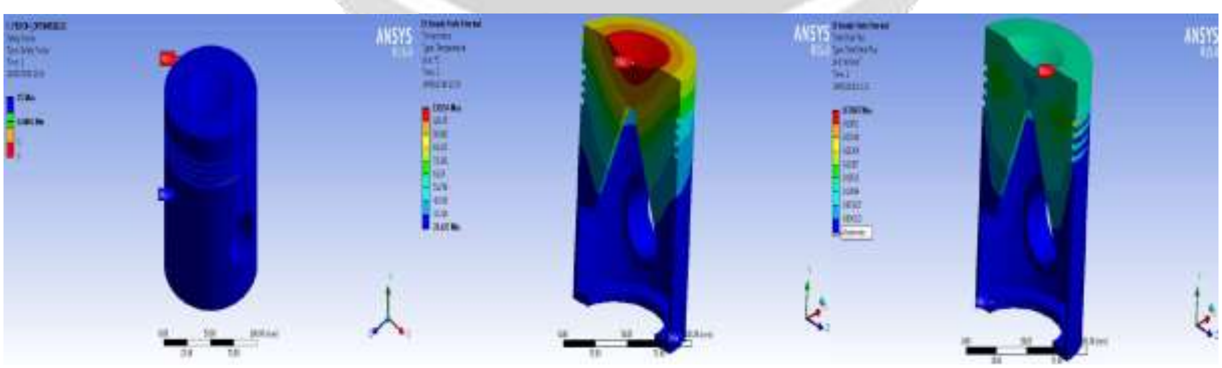
Fig No -5: Static Structural & Steady State Thermal Analysis of modified Design-1 for Aluminium 2618 material using ANSYS R15.0

As shown in fig no 5 (A) maximum equivalent (Von Mises) stress for Modified Design-1 (Four ribs at angle of 90°) is 46.16 N/mm², in fig no 5 (B) maximum normal stress for Modified Design-1 (Four ribs at angle of 90°) is 13.51 N/mm², in fig no 5 (C) total deformations for Modified Design-1 (Four ribs at angle of 90°) is 0.01966 mm, in fig no 5 (D) minimum Factor of safety for Modified Design-1 (Four ribs at angle of 90°) is 5.41, in fig no 5 (E) maximum Temperature for Modified Design-1 (Four ribs at angle of 90°) is 102.8°C, in fig no 5 (F) maximum principle stress for Modified Design-1 (Four ribs at angle of 90°) is 0.2915 W/mm².

2.4 Static Structural and steady state thermal Analysis of Modified Design-2(Four Ribs at 180° angle) for Aluminium 2618 material



(A) Equivalent von-mises stress **(B) Normal Stress** **(C) Total Deformation**

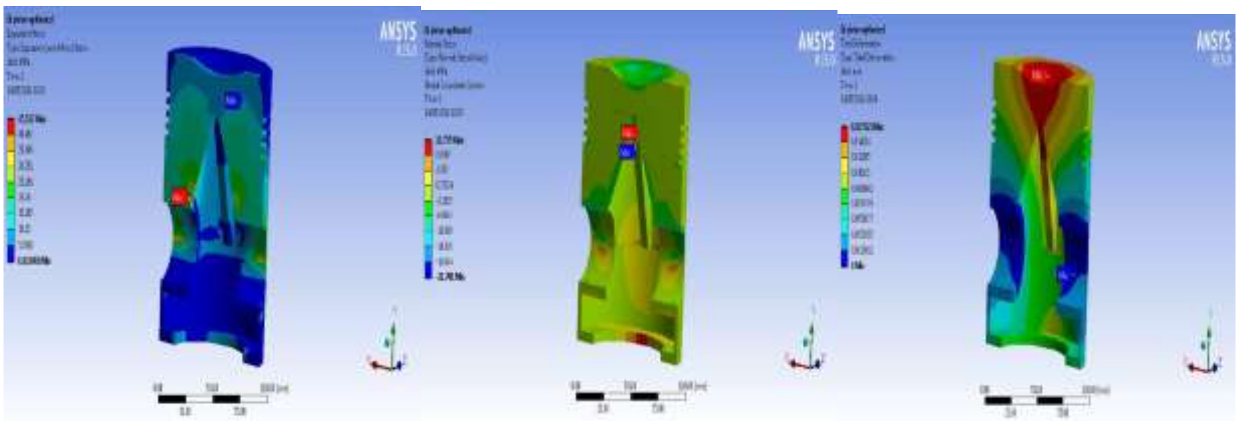


D) Factor of safety **(E) Temprature** **(F) Total heat flux**

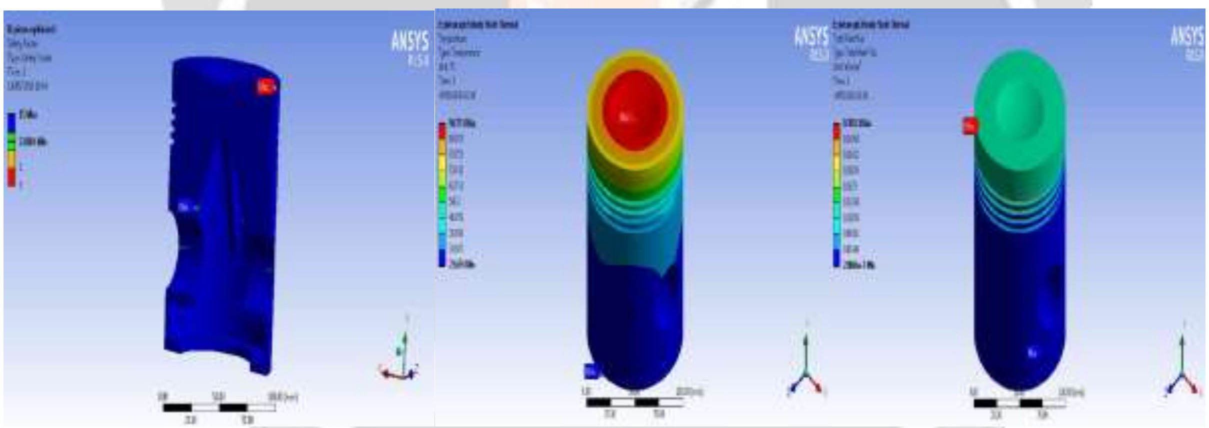
Fig No -6: Static Structural & Steady State Thermal Analysis of modified Design-2 for Aluminium 2618 material using ANSYS R15.0

As shown in fig no 6 (A) for modified design-2 (Two Ribs at angle of 180°) is 37.37 N/mm², in fig no 6 (B) for modified design-2 (Two Ribs at angle of 180°) is 13.21 N/mm², in fig no (C) for modified design-2 (Two Ribs at angle of 180°) is 0.03038 mm, in fig no (D) for modified design-2 (Two Ribs at angle of 180°) is 6.68, in fig no 6 (E) for modified design-2 (Two Ribs at angle of 180°) is 110°C, in fig no 6 (F) for modified design-2 (Two Ribs at angle of 180°) is 0.3268 W/mm².

2.5 Static Structural and steady state thermal Analysis of Modified Design-1(Four Ribs at 90° angle) for Aluminium 4032 material



(A) Equivalent von-mises stress **(B) Normal Stress** **(C) Total Deformation**

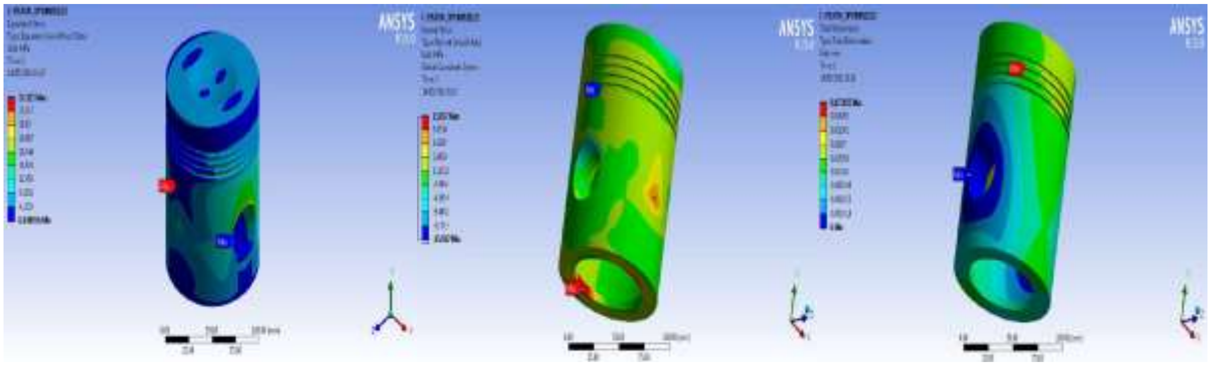


D) Factor of safety **(E) Temprature** **(F) Total heat flux**

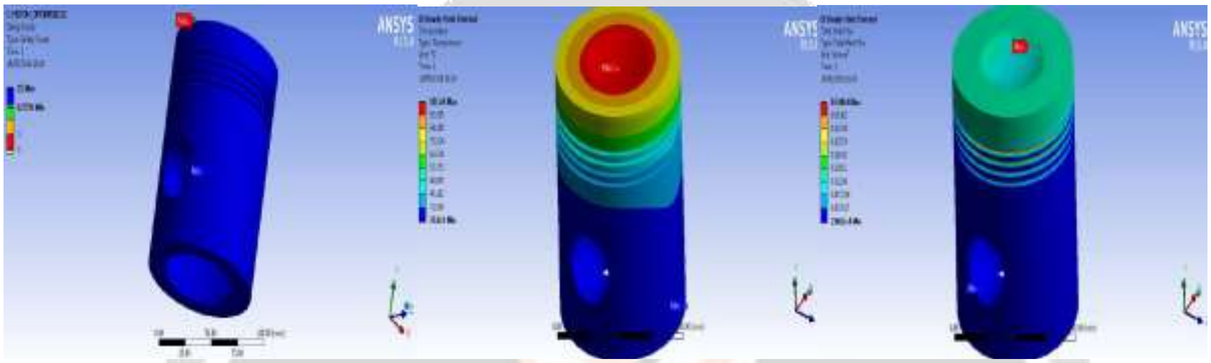
Fig No -7: Static Structural & Steady State Thermal Analysis of modified Design-1 for Aluminium 4032 material using ANSYS R15.0

As shown in fig no 7 (A) maximum equivalent (Von Mises) stress for Modified Design-1 (Four ribs at angle of 90°) is 45.51 N/mm², in fig no 7 (B) maximum normal stress for Modified Design-1 (Four ribs at angle of 90°) is 11.75 N/mm², in fig no 7 (C) total deformations for Modified Design-1 (Four ribs at angle of 90°) is 0.01592 mm, in fig no 7 (D) minimum Factor of safety for Modified Design-1 (Four ribs at angle of 90°) is 7.03, in fig no 7 (E) maximum Temperature for Modified Design-1 (Four ribs at angle of 90°) is 94.77°C, in fig no 7 (F) maximum principle stress for Modified Design-1 (Four ribs at angle of 90°) is 0.3011 W/mm².

2.6 Static Structural and steady state thermal Analysis of Modified Design-2(Four Ribs at 180° angle) for Aluminium 4032 material



(A) Equivalent von-mises stress **(B) Normal Stress** **(C) Total Deformation**

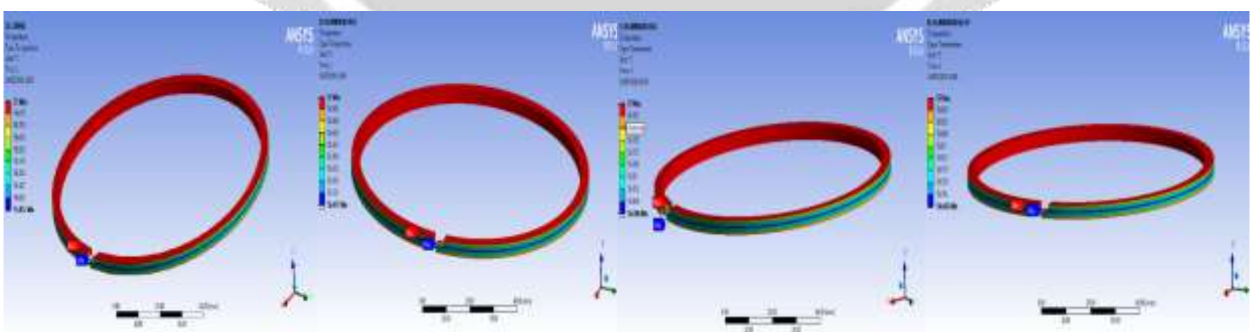


D) Factor of safety **(E) Temprature** **(F) Total heat flux**

Fig No -8: Static Structural & Steady State Thermal Analysis of modified Design-2 for Aluminium 4032 material using ANSYS R15.0

As shown in fig no 8 (A) for modified design-2 (Two Ribs at angle of 180°) is 37.31 N/mm², in fig no 8 (B) for modified design-2 (Two Ribs at angle of 180°) is 13.07 N/mm², in fig no 8 (C) for modified design-2 (Two Ribs at angle of 180°) is 0.02711 mm, in fig no 8 (D) for modified design-2 (Two Ribs at angle of 180°) is 8.57, in fig no 8 (E) for modified design-2 (Two Ribs at angle of 180°) is 101.68°C, in fig no 8 (F) for modified design-2 (Two Ribs at angle of 180°) is 0.3386 W/mm².

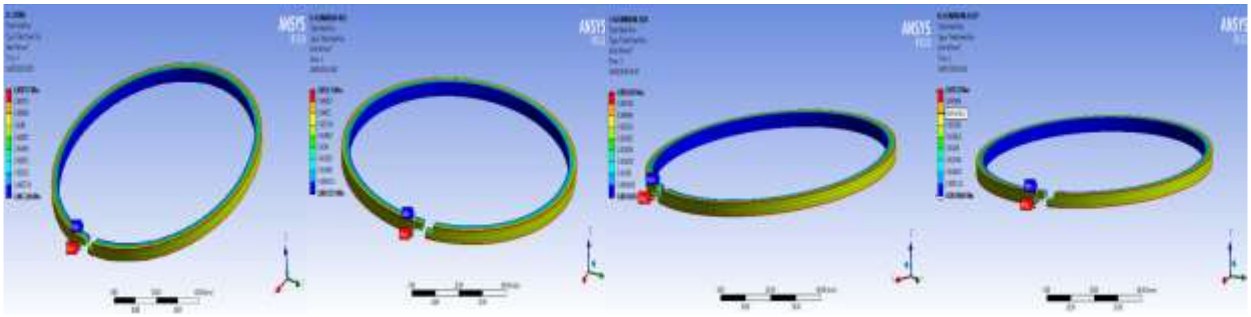
2.7 Steady State Thermal Analysis of Piston Ring of Existing Material (Gray CI), Aluminium alloy, Aluminium 2618 & Aluminium 4032



(A) Gray Cast Iron **(B) Aluminium 4032** **(C) Aluminium 2618** **(D) Aluminium Alloy**

Fig no. 9 Steady State thermal Analysis Temperature for Piston ring using Different material

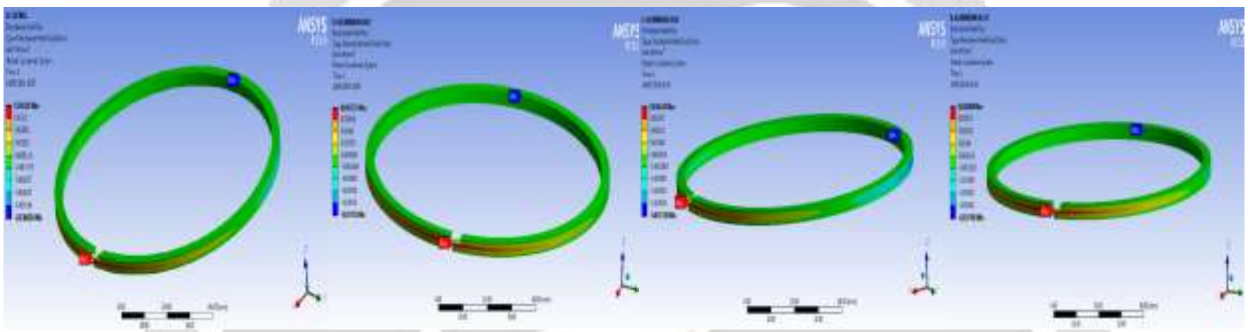
As shown in 9 (A) temperature for gray cast iron is 55.87°C minimum in fig no 9 (B) temperature for Aluminium 4032 is 56.47°C minimum in fig no 9 (C) temperature for Aluminium 2618 is 56.38°C is minimum in fig no 9 (D) temperature for Aluminium Alloy is 56.66°C minimum



(A) Gray Cast Iron **(B) Aluminium 4032** **(C) Aluminium 2618** **(D) Aluminium Alloy**

Fig no. 10 Steady State thermal Analysis Total Heat Flux for Piston ring using Different material

As shown in fig no 10 (A) Total heat flux for gray cast iron is 0.05053 W/mm² is maximum, in fig no 10 (B) Total heat flux for Aluminium 4032 is 0.05115 W/mm² is maximum, in fig no 10 (C) Total heat flux for Aluminium 2618 is 0.05104 W/mm² is maximum, in fig no 10 (D) Total heat flux for Aluminium Alloy is 0.05132 W/mm² is maximum.



(A) Gray Cast Iron **(B) Aluminium 4032** **(C) Aluminium 2618** **(D) Aluminium Alloy**

Fig no. 11 Steady State thermal Analysis Directional Heat Flux for Piston ring using Different material

As shown in fig no 11 (A) Directional heat flux for gray cast iron is 0.04119 W/mm² is maximum, in fig no 11 (B) Directional heat flux for Aluminium 4032 is 0.04172 W/mm² is maximum, in fig no 11 (C) Directional heat flux for Aluminium 2618 is 0.04164 W/mm² is maximum, in fig no 11 (D) Directional heat flux for Aluminium Alloy is 0.04188 W/mm² is maximum.

3. Material Cost Optimization:

For cost optimization of piston material should be change, without affecting its structural and thermal parameters, density of aluminium is 2700 gram/mm³ and density of cast iron is 7200 gram/mm³, because of Aluminium has less density than grey cast iron, weight in aluminium piston will be lesser than gray cast iron piston material.
Mass for the Gray cast iron, Aluminium alloy, Aluminium 4032, Aluminum 2618 for two ribs in modified design-2 and two ribs in modified design-1four ribs for piston are shown in table no 6.1.

Material and design	Mass in Kg
Grey cast iron Existing Design	3.0884
Aluminium alloy with 2 ribs	1.1768
Aluminium alloy with 4 ribs	1.2236
Aluminium 4032 with 2 ribs	1.1406
Aluminium 4032 with 4 ribs	1.1861
Aluminium 2618 with 2 ribs	1.1768
Aluminium 2618 with 4 ribs	1.2236

Table no. 6.1 Piston mass for different material and design

As shown in table no 6.1, mass of aluminium alloy piston is 1.1768 kg (for two ribs) and mass of Grey cast iron piston is 3.0884 kg

Aluminium alloy (two ribs) is selected as suitable material for as optimized material, hence we can calculate cost of piston on basis of it.

- **Material cost of existing design and material for piston:**
  Material cost = mass (kg) * price of material (Rs/kg)
  Material cost = 3.0884 * 83.75[10]
  = 258.65 InR
- **Material cost of optimized design and material for piston:**
  Material cost = mass (kg) * price of material (Rs/kg)
  Material cost = 1.1768 * 102[11]
  = 120.03 InR

Prize difference for material cost between optimized design and material to existing material and design is 138.62 InR, hence we can say that price is cut down approximately 54 % then current design..

4. RESULTS AND CONCLUSIONS

4.1 Results:

Material	Existing design	Gray cast iron	Aluminium alloy	Aluminium 2618	Aluminium 4032
Factor of safety	2.78	3.29	6.81	5.41	7.03
Maximum Equivalent stress (N/mm^2)	54.61	46.16	45.51	46.16	45.51
Maximum normal stress (N/mm^2)	19.39	13.51	11.75	13.51	11.75
Maximum Deformation (mm)	0.02781	0.01839	0.01726	0.01966	0.01592

Table no. 2 Static structural analysis for piston with FOUR ribs using different materials

Material	Existing design	Gray cast iron	Aluminium alloy	Aluminium 2618	Aluminium 4032
Factor of safety	2.78	4.066	8.3	6.68	8.57
Maximum Equivalent stress (N/mm^2)	54.61	37.37	37.31	37.37	45.51
Maximum normal stress (N/mm^2)	19.39	13.21	13.07	13.21	13.07
Maximum Deformation (mm)	0.02781	0.01828	0.02672	0.03038	0.02710

Table no. 3 Static structural analysis for piston with TWO ribs using different materials

Material	Existing design	Gray cast iron	Aluminium alloy	Aluminium 2618	Aluminium 4032
Temperature (°C)	173.06	145.3	77.46	102.8	94.77
Total heat flux (W/mm^2)	0.2954	0.2524	0.3233	0.2915	0.3011

Table no. 4 Steady state thermal analysis for piston with FOUR ribs using different materials

Material	Existing design	Gray cast iron	Aluminium alloy	Aluminium 2618	Aluminium 4032
Temperature (°C)	173.06	157.27	82.33	110.54	101.68
Total heat flux (W/mm^2)	0.2954	0.2754	0.3664	0.3268	0.3386

Table no. 5 Steady state thermal analysis for piston with FOUR ribs using different materials

Material	Gray cast iron	Aluminium alloy	Aluminium 2618	Aluminium 4032
Directional heat flux (W/mm^2)	0.04119	0.04188	0.04164	0.04172
Total heat flux (W/mm^2)	0.05053	0.05132	0.05104	0.05113

Table no. 6 Steady state thermal analysis for piston ring using different materials

4.2 Conclusions:

At the end of study and analysis of piston with different design modification and material application, I achieved above table of results.

There are two aspect involve in piston design 1. Strength to bear pressure of gas produces during power stroke.2.Ability of material to dissipate heat to cooling media. For strength of piston the parameter responsible are Equivalent von mises Stress, Normal stress, Total deformation and Factor of safety. For Heat dissipation Temperature and Total heat flux are governing parameter.

Comparing from above table by adding four& two ribs to piston its strength increases compare to existing design. By applying Aluminium alloy , Aluminium 2618, Aluminium 4032 to modified design, comparing all of above Two ribs Design is best suitable from strength and heat dissipation Point of view. From strength point, two rib designs with Aluminium alloy is best suited as comparatively Equivalent on misses stress, normal stress max principal stress decreases so it will increase strength. Total deformation slightly increases but it's within limit and factor of safety increases by two times .so, strength wise material and design selection are optimum.

From heat dissipation point of view also aluminium alloy material is best suited as temperature decreases and total heat fluxes increases so it sign more heat dissipation. Problem of seizure can be avoided.

Compare to existing design of grey cast iron two rib modified design with aluminium alloy weights 1/3 rd. so, cost wise also design is optimum. As, weight decreases manufacturing cost per kg also decreases. Hence, material optimization along with cost optimization is done.

Aluminium alloy material provides less weight and higher strength, so as to reduce the inertia forces, which will reduce the running cost of engine.

Parameters	**Existing Design Value**	**Optimized Material and Design Value**	**% Difference**
Factor of Safety	2.78	6.81	244% Increases
Maximum Equivalent stress	54.61 N/mm^2	45.51 N/mm^2	16.67% Reduces
Maximum Normal stress	19.39 N/mm^2	11.75 N/mm^2	60.59% Reduces
Maximum Deformation	0.02781 mm	0.01726 mm	62.06% Reduces

Table no. 7 Result of Static structural analysis

.Parameters	Existing Design Value	Optimized Material and Design Value	% Difference
Maximum Temperature	173.06°C	77.46°C	55.24% Reduces
Total heat flux	0.2954 W/mm^2	0.3233 W/mm^2	8.62% increases

Table no. 8 Result of Steady state Thermal analysis

- **FUTURE SCOPE**

Further research can be done with the modification in design to increase more strength and thermal properties. Different Aluminum alloy material could be analyze or applied for enhancing structural and thermal properties, dynamic analysis can also done for moving piston to improve performance. This work shows the improvement in piston same process can also apply for other IC engine parts for improve performance.

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