Modeling and analysis of Piston and Piston rings of SI engine for different materials using FEM

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Abstract
This research paper deals with the modeling and analysis of piston rings using SOLIDWORKS and ANSYS. In the work presented, both Structural and Thermal analysis of rings is deliberated in order to quantify the stress that the rings can bear. The various parameters studied under structural analysis are displacement and ultimate stress limit and parameters in thermal analysis are thermal gradients, heat flow rates, and heat fluxes calculated using six distinct materials of the piston rings. A cumulative analysis is performed which considers the combined effect of mechanical and load for determination of the dimensions of the rings.

Keywords: Engine, Piston ring, Modeling, Spark Ignition, Finite Element methods

1. INTRODUCTION
Sakharkar and Wankhade have suggested a method for performing thermal analysis of the internal combustion engine using computer aided techniques. The thermal and structural analysis of the piston is performed using finite element analysis which includes tools like finite element analysis (FEA), Computer Aided Three-dimensional Interactive Application (CATIA) and ANSYS workbench. Thereafter, the stiffness of the piston is determined using different Aluminium alloy materials.

Review on piston ring tribology surveying around 150 journals has been published by Andersson et al. The major issues dealt in the paper are the functions of piston and rings, the design parameters influencing the leakage, gas emissions, lubrication, friction losses, wear and tear of sliding surfaces, and effect of temperature on performance of the engine. A discussion on the materials to be used for piston skirt and cylinder liner is also presented. An extensive study is performed and summary is presented which gives the functions of the different parts of the engine in nutshell.

Parthiban et al., have projected a study of the wear characteristics of the piston ring pack inside the piston assembly of an engine in their paper. Different coatings on the piston ring have been used for analysis purpose. The coating is useful in reducing temperatures of parts and thereby increasing the life of the part. Piston rings have been designed and analysis performed. A comparison of the structural analysis for various coatings has been plotted.

Jaber and Rai have designed piston and piston rings for a 1-cylinder four stroke IC engine. Analysis – both structural and thermal; is accomplished through ANSYS software, using two different materials of piston ring and three materials for piston. Complete analysis is dealt with and results presented. Results show that the piston made of Titanium alloy has highest yield strength; AISI4340 steel and Al alloy 4032 follow it. Also the displacement is maximum for AISI 4032 and minimum for AISI-4340 steel alloy. The Piston Rings made of Nodular...
Spheroidal Cast Iron exhibit lower deformation as compared to that of Grey Cast Iron, although maximum heat flux is deliberated by the grey cast iron piston rings. Satyanarayana and Renuka have deliberated the analysis, design of piston and piston rings using materials of three types, viz. Cast iron, Aluminium alloy and Cast steel materials. Similar analysis was performed and reduction in thermal stress was obtained. A substantially better safety factor and thermal heat flux were also realized. Devan and Reddy have conducted the thermal analysis of piston using several Aluminium alloys as materials. The alloys are - AlSi, Al-Mg-Si, AlSiC-10 and AlSiC-12. The authors concluded that with the increase in the concentration of carbide in the AlSiC alloy, the maximum heat flux gets reduced.

In this present work, an analysis of thermal and stress distribution of piston and piston rings is performed using various materials. An attempt has been made to increase the heat flow rate and decrease the thermal stress of the piston and its rings using alloys of zinc, aluminium and iron. A single cylinder 110cc Honda petrol engine has been utilized for the purpose of design. Procedure for analytical design of different materials has been depicted. Design is then analysed using ANSYS 16.0 software for thermal and structural analysis of all the materials.

2. MATERIALS AND METHODS:

2.1 Piston and Piston Ring Design:

Piston is an important unit of reciprocating IC engines. It moves up and down inside the cylinder and is made leakage proof by piston rings. It is pushed downwards by the expansion forces caused due to combustion process, thereby transferring the forces produced due to combustion to the crank shaft. Piston sustains cyclic gas pressures and inertial forces during operation of the engine. During its operation, the life of the piston may get reduced due to piston side wear, piston head cracks etc. These are rings that are positioned in the slots cut in the piston that pushes out against the cylinder walls. They form a gas tight seal with the cylinder. With an appropriate space in the area connecting the piston surface to cylinder liner wall, the design of piston is such that it can withstand thermal expansion. The rings along with the ring grooves form a labyrinth seal, thus isolating the combustion chamber and the crankcase.

2.2 Selection of Materials:

Recently, emphasis is being given to development of IC Engines of improved power capacity by improvising on the design of engines. For this purpose, use of lightweight materials is a preferred choice. Zabala et al., researched and found that advanced ultra-high tensile strength steels, alloys of Aluminium, magnesium and Silicon, polymers, and carbon-fibre reinforced composite materials are some of the light weight materials. Manufacturers acknowledge that for a vehicle weight reduction of 10%, a 6% to 8% improvement in fuel consumption is observed.
1. Grey Cast Iron (GCI)
2. Ductile Nodular Spheroidal cast iron
3. Al Mg Si
4. AISI 4032
5. Silicon carbide fibre reinforced Zirconium diBoride
6. Zamac 7.

The mechanical properties of the various materials used for design of piston and piston rings are in table 1.

Table 1. Mechanical Properties of the Materials used for Piston and Piston Ring

| Material / Properties | DNS Cast Iron | GCI | Al-Mg-Si | AISI 4032 | ZrB2-Sic | Zamac |
|----------------------|---------------|-----|----------|-----------|----------|-------|
| Young's modulus      | 17.6* x 10^3 | 157* x 10^3 | 70* x 10^3 | 79* x 10^3 | 474* x 10^3 | 96* x 10^3 |
| Ultimate tensile     | 827           | 362 | 310      | 380       | 1070     | 240   |
| strength (MPa)       |               |     |          |           |          |       |
| Yield strength       | 621           | 228 | 276      | 315       | 380      | 269   |
| (MPa)                |               |     |          |           |          |       |
| Poisson's ratio      | 0.27          | 0.26 | 0.33     | 0.33      | 0.11     | 0.29  |
| Thermal conductivity | 33            | 46  | 210      | 155       | 93.7     | 113   |
| (W/m-K)              |               |     |          |           |          |       |
| Density (g/Cm^3)     | 7.2           | 7.1 | 2.7      | 2.68      | 2.06     | 6.6   |
| Tensile strength     | 137.83        | 40  | 215      | 380       | -        | -     |
| (MPa)                |               |     |          |           |          |       |

2.3 Analytical Calculation for Piston and Rings:

The terminology used is
- Piston - head thickness ($t_H$)
- Heat flows through the piston head ($H$)
- Ring - Radial thickness ($t_I$)
- Ring - Axial thickness ($t_2$)
- Width of the top land ($b_1$)
- Width of other ring lands ($b_2$)
2.4 Pressure of gas acting on the Piston (N/mm²)

This is the ideal gas equation

\[ p = \frac{mRT}{V_d} \quad (1) \]

where,

\[ R = 8.3143 \frac{J}{mol \cdot K} \text{ - Gas constant; } \]
\[ m = \frac{dV_d}{1000} = 0.080473 \text{ kg} \]
\[ T = 288 \text{ K} \text{ - room temperature in Kelvin; } \]
\[ V_d = \text{displacement volume; } V_d = 109.19 \text{ cc} \]

1. Mean gas pressure (N/m²)

\[ P_{mean} = \frac{(2 \cdot \pi \cdot T_{max})}{V_d} \quad (2) \]

where, \( T_{max} = 8.7 \text{ N-m} \) is maximum torque

2. Indicated power (W)

\[ IP = n \cdot P_{mean} \cdot l \cdot A \cdot N \cdot k / 60 \cdot 1000 \quad (3) \]

where,

\[ l = 55.6 \text{ mm; length of stroke; } \]
\[ A = 1963.5 \text{ mm}^2 \text{; cross-section area of cylinder; } \]
\[ D = 50 \text{ mm; cylinder bore; } \]
\[ N \text{ is engine speed (rpm)} \]
\[ k \text{ is a constant; } k = 2 \text{ (four stroke engine)} \]
\[ n \text{ is number of cylinders; } n=1 \]

3. Brake Power (W)

\[ P = 2 \cdot \pi \cdot N \cdot T_{max} / 60 \quad (4) \]

4. Piston head thickness (mm)

The thickness of piston head as calculated using the Grashoff’s formula

\[ t_1 = D \left( \frac{3P_{max}}{16\gamma} \right) \quad (5) \]
where \( \sigma_t \) is allowable tensile strength (MPa). The thickness of piston head as calculated using the based on heat dissipation \((H)\)

\[
i_t h_2 = \frac{H}{12.56*K^*|T_1-T_2|} \tag{6}
\]

where,

\( HCV \) is Higher Calorific Value of fuel (KJ/Kg); \( HCV = 47000 \) KJ/Kg
\( M \) is mass of fuel used per brake power per second (Kg/KW s)
\( C \) is ratio of heat absorbed by the piston to the total heat developed in the cylinder; \( C = 0.05 \)
\( K \) is thermal conductivity (W/m K)
\( T_1 \) is the temperature at the centre of the piston head (deg C)
\( T_2 \) is the temperature at the edge of the piston head (deg C)
\( T_1 - T_2 = 75 \) °C for Alloys and 220 °C for Cast iron

Out of the two values \( t_{h1} \) and \( t_{h2} \) calculated using equations (5) and (6), the larger value is chosen as the thickness of the piston head.

5. **Ring radial thickness (mm)**

\[
t_1 = D \sqrt{\frac{3*P_w}{\sigma_t}} \tag{7}
\]

where,

\( P_w \) is allowable radial pressure on cylinder wall; \( P_w = 0.042 \) N/mm²

6. **Ring axial thickness (mm)**

\[
t_2 = \frac{D}{10*N_r} \tag{8}
\]

where,

\( N_r \) is number of rings; \( N_r = 3 \)

7. **Width of the top land (mm)**

\[
l_1 = 1.2 \times \text{max}(t_{h1}, t_{h2}) \tag{9}
\]

8. **Width of the other lands (mm)**

\[
b_2 = t_2 \quad \ldots \tag{10}
\]
9. **Maximum thickness of the barrel (mm)**

\[ t_3 = 0.03 \times D - t_4 + 4.9 \] (11)

10. **Piston wall thickness towards the open end (mm)**

\[ t_4 = 0.35 \times t_3 \] (12)

Using the above mentioned formulae, values are calculated of design parameters of piston and rings for the different materials.

3. **3D - MODELING**

The art of representation of an object or system is termed modeling. It is the process of producing a design which can be analysed through soft computing tools. The primary aim of preparing a model of any object or system is to be able to anticipate the effect of standard inputs on the changes in the system. Therefore, the model should be a close approximation of the real system keeping into consideration that the salient features of the system are retained. A 3D piston and piston ring model has been shown in figure 1 and figure 2 respectively.

![Figure 1. 3D Model of a Piston](image1.png)

![Figure 2. 3D Model of a Piston Ring](image2.png)
4. **STRUCTURAL ANALYSIS**:

Structural analysis is the determination of the effects of loads on physical structures and their components. Structures subject to this type of analysis include all that must withstand loads, such as buildings, bridges, vehicles, machinery, furniture, attire, soil strata, prostheses and biological tissue.

Structural analysis incorporates the fields of applied mechanics, materials science and applied mathematics to compute a structure’s deformations, internal forces, stresses, support reactions, accelerations, and stability. The results of the analysis are used to verify a structure’s fitness for use, often saving physical tests. Structural analysis is thus a key part of the engineering design of structures.

5. **THERMAL ANALYSIS**

Thermal analysis is a group of techniques in which the variation of a physical property of a substance is measured as a function of temperature. The most commonly used techniques are those which measure changes of mass or changes in energy of a sample of a substance.

6. **MESH GENERATION**:

The finite element method (FEM) is used to simplify a complex problem, by dividing the larger element into smaller elements, such that they can be solved relatively to each other. The practical application of FEM is generally termed finite element analysis (FEA). Figures 3 and 4 shows the generated mesh of piston and piston ring for Grey cast iron.

![Figure 3. Mesh for Piston](image-url)
7. BOUNDARY CONDITIONS FOR PISTON AND PISTON RINGS:

7.1 Thermal load:

a. Piston:

(i) On the crown is $0.03 \text{ W/mm}^2 \cdot ^\circ \text{C}$;
(ii) At the edges and ring grooves is $0.24 \text{ W/mm}^2 \cdot ^\circ \text{C}$;
(iii) At the skirt is $0.16 \text{ W/mm}^2 \cdot ^\circ \text{C}$; and
(iv) Inside the piston $0.01 \text{ W/mm}^2 \cdot ^\circ \text{C}$.

b. Piston Ring:

The bulk temperature applied at the top of the rings is $300 \ ^\circ \text{C}$ and the convection coefficient is $0.03 \text{ W/mm}^2 \cdot ^\circ \text{C}$. Figures 5.14 to 5.19 show the boundary conditions for thermal analysis for the various materials of piston ring.

7.2 Structural load:

a. Piston:

The pressure acting on the piston and ring is calculated as $15.44 \text{ MPa}$. This force acts in downward direction.

b. Piston Ring:

The outer side of the piston ring is taken as the fixed support.
Figure 5. Thermal Analysis of Piston of DNS Cast Iron

Figure 6. Thermal Analysis of Piston Ring of DNS Cast Iron

Figure 7. Structural Analysis of Piston of DNS Cast Iron
8. RESULTS AND DISCUSSION:

8.1 Temperature Distribution:

The maximum temperature is observed at the topmost surface of the piston and the ring, as it is in direct contact with the expanding gases. As the heat flows to the piston and the rings to the liner, the temperature distribution varies. This distribution should be uniform throughout that is there should be a gradual drop in temperature from the top to the bottom of the piston. If this is not the case, the piston will experience excessively high stress. This will affect the working of the piston and ring.
From figure 9 and figure 10, it is clear that the maximum dispersion of temperature occurs for DNS Cast iron followed by Grey Cast Iron in the case of piston and for Grey Cast iron in the case of piston ring.

**8.2 Heat Flux Distribution:**
Heat flows from the piston to the liner via the rings. The more the heat is dissipated, better will be the performance of the engine.

**Figure 10.** Temperature Distribution of Piston Rings

**Figure 11.** Piston Maximum Heat Flux Distribution
During analysis, it was observed that the maximum heating occurs at the top periphery of the piston. In order to maintain the geometry of the piston, it is essential that the temperature of the piston should not exceed the material design limit. Therefore, proper flow of heat is a must. With an appropriate heat flow, the cylinder wall temperatures will increase, thus reducing the piston and ring friction. This results in lower consumption of fuel and decreased heat flux. The heat flux distribution depends upon the thermal conductivity of the material. It is observed that the piston designed using Al-Mg-Si shows best conductivity and the piston ring made of grey cast iron material shows best performance.

8.3 Total Deformation:

Deformation in the piston arises due to the pressure generated by the expansion of gases in the combustion chamber. The maximum deformation is mainly in the centre of the piston crown. In terms of deformation, the piston and piston ring of DNS Cast iron is good. However piston ring of ZrB$_2$-SiC also shows comparable results.
Figure 14. Piston Ring Deformation

8.4 Distribution of Strain:

Figure 15. Piston Strain Distribution
Figure 15 and figure 16 depict that in the piston made of AISI 4032 and ring made of DNS cast iron show least change in dimensions under loading conditions. Hence, maintaining their shape during the operating cycles.

8.5 Von-Mises Stress Distribution:

It is observed that in each case, the piston experiences maximum stress due to mechanical load around the piston pin area. This is because the forces acting on the piston are transferred to the connecting rod via the piston pin, which is taken as the fixed support for the analysis.

Figure 17. Piston Stress Distribution

On application of loads, the lowest stresses are experienced by piston of AISI 4032 and ring of ZrB2-SiC.

Figure 18. Piston Ring Stress Distribution
8.6 Factor of Safety:

Factor of Safety can be described as the amount of times the material is capable of carrying the actual load. For the different materials, the plots of the FOS values are shown in bar graphs in figures.

![Figure 19. Factor of Safety of Piston](image1)

![Figure 20. Factor of Safety of Piston Ring](image2)

It is observed that the Grey cast iron piston and Zamac piston ring are capable of working in excessive load conditions.
9. CONCLUSION AND FUTURE SCOPE:

On comparison of the results of analysis of piston for the six different materials, it was observed that the piston material of AISI 4032 is the best in terms of lowest stress on the piston crown, has the highest heat dissipation and comparably lower deformation. For the piston ring, the best material is Zirconium di Boride with 20% SiC, with least deformation, lowest stress intensity, good heat flux and a high factor of safety.

Further studies can be conducted with other components of the engine made using these materials, thereby improving their strength and reducing their weight. In this way, the consumption of fuel will be decreased significantly and overall efficiency of the engine will increase.

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