Weight optimization of Piston using CREO parametric and ANSYS

MSSR Ravikiran¹, Saidge Akhil Prasad², Vaddepally Srujana³, Korlepara Shanmukh Sai Abhimanyu⁴

¹,²,³,⁴Mechanical Engineering, SreeNidhi Institute of Science and Technology, Hyderabad, Telangana 500072, India

E-Mail: ravikiranmssr@sreenidhi.edu.in, akhilprasadadsige007@gmail.com, srujanavaddepally99@gmail.com, shanmukhsai1234@gmail.com

Abstract. The Piston is a crucial element of an IC engine. The Piston is a reciprocating component of the IC engine that converts thermal energy and pressure energy liberated by the ignition of the air-fuel into mechanical work. The design of the Piston and selection of material is a challenging assignment for the designer. This paper describes the design procedure for a piston of a four-stroke petrol engine. The optimization of Piston with different materials was carried out in the present work. The analysis is done by considering two designs, one is primary, and the other is an optimized one. The modelling is achieved by utilizing the Creo parametric and further investigation in ANSYS workbench. The design process involves the evaluation of varied piston measurements using the analytical technique at the maximum power condition. While computing various aspects, the cumulative impact of mechanical stress and thermal distribution are considered. Three different materials are considered for designing the Piston, and their performances are scrutinized. The Aluminium cast alloy is the most used in manufacturing the pistons. However, the analysis done in this project has given better results for Aluminium Silicon Carbide. All the results for it have turned out to be better than the Aluminum Cast alloy.

1. Introduction

The automotive sector is one of the world's largest monetary areas as far as revenue and demand is concerned. The engine is one of the pivotal parts of a motor vehicle. An engine can be defined as a machine used to convert chemical energy into mechanical energy. Heat engines such as IC engines burn fuel to generate heat, which is used to do work. A piston is a non-stationary component present inside the cylinder, and it is made airtight with the help of piston rings. According to many researchers, stress concentration is more at the Piston's top-end and is considered one of the critical reasons for fatigue failure. Overheating seizure of Piston can also occur when something scratches or burns away the oil film that arises between the Piston and cylindrical wall of the engine. The majority of forces acting on the Piston are due to the explosion of fuel, the compression force of fuel gases, the friction force between contact surfaces, and thermal load.
1.1. **Functions of a Piston:**
- To perform strokes within the cylinder.
- To transfer the thrust produced by the combustion of the air-fuel mixture in the cylinder to the connecting rod.
- To seal the combustion chamber with the help of piston rings.
- To act as a guide for connecting rod and to support fuel gas mixture with the help of a unique design which is known as a piston crown.

![Figure 1. Piston](image)

1.2. **Design consideration for the Piston:**
- The Piston ought to have high strength and thermal resistance properties to withstand high pressures caused due to gases and inertia forces.
- The material should dissipate heat efficiently from the crown to the piston rings and from the bearing zone to the combustion chamber walls.
- The Piston needs to be designed in such a way that the weight should be kept minimum to reduce the inertia forces.
- The material of the Piston should possess excellent wearing qualities.
- The material must be a corrosion resistive material.
- The Piston construction should be made rigid to withstand thermal, mechanical distortion.

2. **LITERATURE REVIEW**

This topic is a review of Piston's design and analysis based on improving strength as per material properties.

Vibhandik (2014) studied the design and optimization of Piston and deformation due to thermal stresses utilizing CAE tools. He chose a Diesel engine piston (TATA motors). Based on thermal analysis results, he optimized the Piston design made of titanium alloy and aluminium alloy. Pistons are usually made of structural steel. This analysis's fundamental objective is to lessen stress concentration on the top end of the Piston and increase the durability of Piston. Titanium has demonstrated better thermal properties; it also improves piston qualities. However, for an extensive application, titanium is expensive this reason. It can be utilized distinctly in some exceptional cases.

Ch. Venkata Rajam (2013), the research is mostly centered around the design and optimization of Piston using CATIA and ANSYS. The objective of mass optimization of the Piston was achieved by ceramic coating on the crown of the Piston. The heat flow was not much influenced by length, the Piston diameter, so both the parameters were kept constant. After the application of pressure loads and thermal loads over the Piston, volume was varied. Volume was dependent on the length, diameter, and thickness of the Piston. The results obtained through this investigation proved that, by a decrease in
the Piston volume, the thickness of barrel and width of other rings lands, von mises stress are increased, and deflection increased after optimization. However, all the design parameters were within design considerations.

Manjunatha T. R. (2013) examined both low pressure and high-pressure cases and analysis that were carried out during compression, suction stroke and to identify areas that are probably to fail under maximum stress case. The metal utilized for the Piston is aluminium alloy, and the cylinder is cast-iron for both high and low-pressure cases. He inferred that stress developed in compression and suction stroke is lesser than the allowable stress. Hence, the design is considered to be safe.

Swati S. Chougule (2013), the goal of this paper is to analyze and research the strain distribution of Piston at actual condition during the ignition process. The parameters used for simulation are material properties of Piston and gas pressure. She stated that there was a chance for reducing—the thickness of the Piston. The mass was reduced by 24.319%, the stress during dynamic and static analysis, which are under the permissible stress value.

R. C. Singh (2014), the study discusses the failure of I.C. engines piston. It was found that the function coefficient is dependent on surface roughness of liner surface and thermal performance of the Piston. The stress values got through FEA during analysis are contrasted with the Piston's metal properties like aluminium alloy zirconium material and so on were within limits.

Current research is about exploring ways of improving the design of the Piston. Grey cast iron (FG 260), Cast aluminium alloy, Aluminum silicon carbide can be used as replacements for present piston materials. However, due to their ductility and strength, Improved foundry procedures are required for light metal castings. A significant challenge for lightweight materials is the ability to supply a quality component at a lower cost. This research paper will conclude with a cost-benefit perspective for typical light-metal applications and optimized Piston design with less weight.

3. CALCULATIONS OF PISTON:

| PARTICULAR          | TYPE/DIMENSION                      |
|---------------------|-------------------------------------|
| cooling system      | air-cooled cooling system           |
| valve system        | overhead camshaft                   |
| displacement (cc)   | 97.2 cc                             |
| maximum power       | 5.66 [K] 5000 [K] [K]              |
| strokes, cylinders  | 4-stroke, single-cylinder           |
| maximum torque      | 7.130 [K] 2500 [K] [K]             |
| compression ratio   | 9.9: 1                              |
| starting mode       | kick start / self start             |
| ignition type       | capacitor discharge ignition (d.c)  |
| bore diameter       | 50 mm.                              |
| stroke length       | 49 mm.                              |
1) Piston diameter:

\[ \Pi r^2 h = c. \text{cyl} \]

Cylinder area = displacement

\[ 3.14 \times r^2 \times 0.049 = 97 \times 10^{-5} \]

\[ r = 0.025 \ m \]

\[ D = 2 \times 0.025 \ m = 0.05 \ m = 50 \text{mm} \]

2) Cylinder inside pressure = \( \frac{F}{A} \)

\[ \text{Force} = \frac{\text{power}}{\text{velocity}} = \frac{5.6 \times 10^3}{0.16} = 686.274 \text{ N} \]

\[ \text{area} = 3.14 \times r^2 = 3.14(0.025)^2 = 0.34953 \text{ mm}^2 \]

Maximum pressure = \( 15(0.34953) = 5.24 \text{ MPa} \)

Calculations of dimensions of the Piston’s head for analysis:

3) The thickness of the Piston’s head by strength consideration

\[ t_h = D \sqrt[3]{\frac{3P}{16\sigma_t}} \text{ mm} \]

\[ P = \text{max pressure (N/mm}^2) = 8 \text{ N/mm} \]

\( \sigma_t = \text{permissible tensile stress for piston material} \)

\( D = \text{outer diameter of the Piston (mm)}. \)

\[ t_h = 4.01 \text{ mm} \]

4) The radial thickness of rings

\[ (t_i) = D \sqrt[3]{\frac{3P_w}{\sigma_t}} \]

Where the diameter of the cylinder bore \( (D) = 50 \text{mm}. \) pressure on cylinder walls \( (P_w) \) value ranges from 0.042 N/mm² to 0.0667 N/mm² for present material, \( \sigma_t = 152.2 \text{ Mpa}. \)

5) Axial thickness of piston ring \( (t_2) \):

\[ t_2 = (0.7 \times t_1) \text{ to } (t_1) \]

\[ t_2 = 0.7 \times t_1. \]

\[ t_2 = 1.26 \text{ mm}. \]

6) The breadth of top land \( (b_1) \):

\[ b_1 = (t_h) \text{ to } (1.2(t_h)) \]

\[ b_1 = (1.2 \times 4.01) = 4.81 \text{mm} \]

7) The thickness of another land \( (b_2) \):

\[ b_2 = (0.75 \times t_2) \text{ to } (t_2) \]

\[ b_2 = (0.75 \times 1.66) = 1.242 \text{mm} \]
8) The maximum thickness of the barrel ($t_3$):

$$t_3 = 0.03D + b + 4.5 \text{ mm}.$$ $$b = (0.4 + t_1) = 0.812 + 0.4 = 2.212 \text{ mm}$$ $$t_3 = 0.03D + 2.212 + 4.5 \text{ mm}$$ $$t_3 = 8.212 \text{ mm}.$$  

9) The thickness of the open-end of the barrel

$$T_{open} = (0.20 \times T_p)$$ $$T_{open} = (0.20 \times 8.212)$$ $$T_{open} = 2.053 \text{ mm}.$$  

11) The gap between the two rings ($T_1$):

$$T_1 = 0.055 \times D = 2.75 \text{ mm}$$ Second piston ring = 0.04 $D = 2.00 \text{ mm}.$

10) Depth of Piston rings groove ($D_r$):

$$D_r = (0.4 + t_1) = 0.4 + 1.812$$ $$D_r = 2.212 \text{ mm}$$

11) Piston length ($L_P$):

$$L_P = h_1 + 2h_2 + 3t_2 + 0.65D$$ $$= 4.81 + 3(1.66) + 2(1.242) + 0.65 (50)$$ $$L_P = 44.77 \text{ mm}.$$  

12) Piston pindiameter:

$$Pin_{do} = 0.3D \text{ to } 0.45D,$$ $$Pin_{do} = 0.32 (50)$$ $$Pin_{do} = 16 \text{ mm}$$ $$Pin_{di} = 12 \text{ mm}.$$  

**Table 2. Summary of dimensions of the Piston**

| Parameters                          | Calculated values (in mm) |
|-------------------------------------|---------------------------|
| Piston length                       | 44.77                     |
| Piston diameter                     | 50                        |
| Piston pin outer diameter           | 16                        |
| Piston pin internal diameter        | 12                        |
| Piston thickness (axial)            | 1.63                      |
| Piston thickness (radial)           | 1.812                     |
| The gap between the two piston rings| 2.75                      |
| Depth of piston ring groove         | 2.212                     |
| Piston open-end thickness           | 2.053                     |
| Piston top-end thickness            | 4.81                      |
| Top land thickness                  | 4.01                      |
The Piston is designed using the dimensions obtained through calculations. Figure 2 shows the basic flat-headed piston design with a diameter of 50mm and volume 48652 mm$^3$ and Figure 3 is the developed design where the Piston is of 50mm diameter, and the volume is 31175 mm$^3$. The Piston is modeled utilizing Creo parametric software and is then subjected to FEA analysis on ANSYS workbench. Model is converted into IGES format and imported in Ansys workbench, and fine meshing is done.

4. Results and discussions
Results obtained from static structural analysis and transient thermal analysis are shown below. For better understanding, standard Piston and optimized design are denoted by $P_1$ and $P_2$, respectively.

4.1. FOR GREY CAST IRON (FG260):

Figure 4. Deformation of $P_1$ for grey cast iron (FG 260)

Figure 5. Equivalent strain of P1 for grey cast iron (FG 260)
Figure 6. Equivalent stress of $P_1$ for grey cast iron (FG 260)

Figure 7. The factor of safety of $P_1$ for grey cast iron (FG 260)

Figure 8. Temperature distribution of $P_1$ for grey cast iron (FG260)

Figure 9. Heat flux of $P_1$ for grey cast iron (FG260)

Optimized design

Figure 10. Deformation of $P_2$ for grey cast iron (FG 260)

Figure 11. The equivalent strain of $P_2$ for grey cast iron (FG 260)

Figure 12. Equivalent stress of $P_1$ for grey cast iron (FG260)

Figure 13. The factor of safety of $P_2$ for grey cast iron (FG 260)
Result analysis (Grey cast iron FG260)

Though the equivalent stresses in piston 2 are more than that in piston 1, piston 2 is the ideal design because stress values are under the material's permissible limit. Also, the temperature difference in piston 2 is slightly bigger than the piston 1. The design of pistons is such that the piston 2 deformation is under the limit. Observing all the cases opting for piston 2 is better as its weight is much lesser than the first one.

4.2. For Cast Iron Alloy:

**Figure 14.** Temperature distribution of P₁ for grey cast iron (FG260)

**Figure 15.** Heat flux of P₁ for grey cast iron (FG260)

**Figure 16.** Deformation of P₁ for cast aluminium alloy

**Figure 17.** Equivalent strain of P₁ for cast aluminium alloy

**Figure 18.** Equivalent stress of P₁ for cast aluminium alloy

**Figure 19.** Factor of safety of P₁ for cast aluminium alloy
Figure 20. Temperature distribution of $P_1$ for cast aluminium alloy

Optimized design

Figure 21. Heat flux of $P_1$ for cast aluminium alloy

Figure 22. Deformation of $P_1$ for cast aluminium alloy

Figure 23. The equivalent strain of $P_2$ for cast aluminium alloy

Figure 24. Equivalent stress of $P_2$ for cast aluminium alloy

Figure 25. The factor of safety of $P_2$ for cast aluminium alloy

Figure 26. Temperature distribution of $P_2$ for cast aluminium alloy

Figure 27. Heat flux of $P_2$ for cast aluminium alloy

Result analysis (cast aluminium alloy):
Both the equivalent stresses obtained in the analysis are lesser than the allowable stress. So, considering the piston 2 would not be any disadvantage in functioning. Also, the temperature difference in the piston 2 is slightly better than the piston 1. The Piston with the given dimensions can
accommodate more deformation than the obtained two. Observing all the cases opting for piston 2 is better as its weight is much lesser than the first one and all the resultant values are way under the permissible-limit.

### 4.3. For Aluminium Silicon Carbide:

**Figure 28.** Deformation of P$_1$ for aluminium silicon carbide

**Figure 29.** Equivalent strain of P$_1$ for aluminium silicon carbide

**Figure 30.** Equivalent stress of P$_1$ for aluminium silicon carbide

**Figure 31.** Factor of safety of P$_1$ for aluminium silicon carbide

**Figure 32.** Temperature distribution of P$_1$ for aluminium silicon carbide

**Figure 33.** Heat flux of P$_2$ for aluminium silicon carbide

**Figure 34.** Factor of safety of P$_1$ for aluminium silicon carbide

**Figure 35.** Equivalent strain of P$_2$ for aluminium silicon carbide
Both the equivalent stresses obtained in the study are lesser than the limit they are supposed to be. Also, the temperature difference in piston 2 is slightly better than the piston 1. The Piston with the given dimensions can accommodate more deformation than the obtained two. Observing all the cases opting for piston 2 is better as its weight is much lesser than the first one, and all the resultant values are way under the permissible limit.

5. Conclusions

- Compared to piston 1, piston 2 has less mass, volume. The change in volume percentage is nearly 35.9%. It is better to use piston 2. The criteria for its design are to keep its functionality the same and reduce the material.
- All the deformation, equivalent stress, temperature distribution, and heat flux values obtained for both the pistons are below the permissible level, and a slight rise of those in piston 2 can be neglected.
- Aluminium cast alloy is generally the most used material in manufacturing pistons, among all the three materials considered in this paper. However, the analysis done in this project has given better results for Aluminium Silicon Carbide. All the results for it have turned out to be better than the Aluminium Cast alloy.
- Another material considered is Grey Cast iron, which gives results with a small deviation from the Aluminium silicon carbide. However, Grey Cast iron is a brittle material, and its reliability is lesser than a ductile material. The results tabulated earlier for piston 2 are listed in the below table.
Table 3. Results of thermal and static analysis of Piston 2

| Results                        | Aluminium cast alloy | Aluminium silicon carbide | Grey cast iron |
|--------------------------------|----------------------|---------------------------|----------------|
| Equivalent stress (MPa)        | 190.27               | 193.838                   | 198.6          |
| Total deformation (mm)         | 0.0507               | 0.0094                    | 0.029          |
| Heat flux (W/mm²)              | 2.2749               | 4.1813                    | 1.8862         |
| Temperature distribution(°C)   | 300-40.3             | 300-78.29                 | 300-22.01      |

- When any of the two materials is compared to Aluminium silicon carbide, it can be observed that all the values are better for Aluminium silicon carbide.
- The heat flux of Aluminium silicon carbide is high among the three materials, and it implies higher heat exchange, which in turn avoids detonation, knocking of I.C engine, and faster heat transfer.
- Similarly, the low deformation and low equivalent stress values also work in favor of the material. Hence, it can be inferred that aluminium-silicon carbide is the best of the three considered materials that can be used in manufacturing.
- From this investigation, it can be concluded that the properties of Aluminium silicon carbide are better compared to Grey Cast iron and Cast Aluminum alloy, and it is a more preferable material for making the Piston more effective.

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