Design and Analysis of Piston using Aluminium Alloys

Anup Kumar Shetty¹, Abijeet TK², James William Machado³, Shrivathsa TV⁴

¹,²,³UG students, ⁴Assistant Professor,
Department of Mechanical Engineering,
Srinivas Institute of Technology, Mangalore, Karnataka, India

Abstract: This paper describes the structural analysis of four different aluminium alloy pistons, by using finite element method (FEM). The specifications used for designing the piston belong to four stroke single cylinder engine of Bajaj Pulsar 220cc and the parameters used for the simulation are operating gas pressure, temperature and material properties of piston. The results predict the maximum stress and strain on different aluminium alloy pistons using FEA. Modeling of various aluminium alloy piston are done using CATIA V5R20. Static structural analysis is performed by using ANSYS WORKBENCH 14.5. The best aluminium alloy material is selected based on stress analysis. The analysis results are used to optimize piston geometry of best aluminium alloy.

Keywords: A2618, A4032, Al-GHS 1300, Ti-6Al-4V, CATIA V5R20, ANSYS WORKBENCH 14.5, Piston, Strain, Stress.

I. INTRODUCTION

Piston is an important component of reciprocating engine. It is the moving component that is contained by a cylinder and is made gas-tight by piston rings. In an engine, the purpose of piston is to transfer force from expanding gases in the cylinder to the crankshaft via a piston rod and/or connecting rod. In some engines, the piston also acts as a valve by covering and uncovering ports in the cylinder wall. Piston endures the cyclic gas pressure and the inertial forces at work, and this working condition may cause the fatigue damage of piston, such as piston side wear, piston head cracks and so on. Piston in an IC engine should possess characteristics such as strength to resist gas pressure, minimum weight, reciprocate with minimum noise, seal the gas from top and oil from the bottom, disperse the heat generated during combustion, and have good resistance to distortion under heavy forces and high temperatures.

The analytical design of pistons of different aluminum alloys based on the specifications of four stroke single cylinder engine of Bajaj Pulsar 220cc is carried out and based on the values obtained[1], piston modeling is done on CATIA V5R20. The material properties of various aluminum alloys are collected and are used for the static structural analysis of piston. Pistons are further imported to ANSYS WORKBENCH 14.5[1, 2]. The parameters required for analysis are collected and the effects of various parameters such as mass, volume, FOS on the pistons are studied. All the necessary boundary condition required for static structural analysis is obtained [2] and are considered for analysis. [3] The fundamental concepts and design methods concerned with single cylinder petrol engine have been studied. Hence it provides a fast procedure to design a piston which can be further improved by the use of various software and methods [4]. The analysis is carried out to reduce the stress concentration on the upper end of the piston.[5] With using computer aided design software the structural model of a piston is developed. Furthermore, the finite element analysis is done using Computer Aided Simulation software ANSYS.

II. METHODOLOGY

For the analytical design, torque \( T = 19.12 \text{ Nm} \) at 7000rpm is considered as specified by the manufacturer of Bajaj Pulsar 220cc. It includes the following calculations and dimensions.

[1] Considering the design constraints,
Brake power, \( BP = 14.015 \text{Kw} \)
Indicated power, \( IP = 17.518 \text{Kw} \)
Maximum pressure, \( P_{\text{max}} = 13.65 \text{MPa} \)
A. ANALYTICAL DESIGN OF A2618 ALUMINUM ALLOY PISTON
A2618 aluminium alloy has an elastic modulus of 73.7GPa and Poisson’s ratio of 0.33. The ultimate tensile strength is 480MPa and tensile yield strength is 420MPa. It has a density of 2767.99kg/m³.
Thickness of the Piston Head (t₁) = 7.338 mm
Radial width of the piston ring (b) = 1.749mm
Axial thickness of the piston ring (h) = 1.224 mm
Width of ring land (h₂) = 0.918 mm
Thickness of piston barrel at the top end (t₁) = 8.659mm
Thickness of piston barrel at the open end (t₂) = 2.164 mm
Length of the skirt (l₁) = 40.2 mm
Piston pin diameter (d₀) = 18.76 mm
The center of the piston pin is 21.44 mm from the bottom edge of piston.

B. ANALYTICAL DESIGN OF A4032 ALUMINUM ALLOY PISTON
A4032 aluminium alloy has an elastic modulus of 79GPa and Poisson’s ratio of 0.33. It has an ultimate tensile strength of 380MPa and tensile yield strength of 315Mpa. It has a density of 2684.95 kg/m³.
Thickness of the Piston Head (t₁) = 8.247 mm
Radial width of the ring (b) = 1.749 mm
Axial thickness of the piston ring (h) = 1.224 mm
Width of ring land (h₂) = 0.918 mm
Thickness of piston barrel at the top end (t₁) = 8.659 mm
Thickness of piston barrel at the open end (t₂) = 2.164 mm
Length of the skirt (l₁) = 40.2 mm
Piston pin diameter (d₀) = 18.76 mm
The center of the piston pin is 21.44 mm from the bottom edge of piston.

C. ANALYTICAL DESIGN OF AL-GHS 1300 ALLOY PISTON
Al-GHS 1300 aluminium alloy has an elastic modulus of 98GPa and Poisson’s ratio of 0.30. It has an ultimate tensile strength of 1300MPa and tensile yield strength of 1220Mpa. It has a density of 2780 kg/m³.
Thickness of the Piston Head (t₁) = 4.459 mm
Radial width of the ring (b) = 1.749 mm
Axial thickness of the piston ring (h) = 1.224 mm
Width of ring land (h₂) = 0.918 mm
Thickness of piston barrel at the top end (t₁) = 8.659 mm
Thickness of piston barrel at the open end (t₂) = 2.164 mm
Length of the skirt (l₁) = 40.2 mm
Piston pin diameter (d₀) = 18.76 mm
The center of the piston pin is 21.44 mm from the bottom edge of piston.

D. ANALYTICAL DESIGN OF Ti-6Al-4V ALLOY PISTON
Ti-6Al-4V aluminium alloy has an elastic modulus of 113.8GPa and Poisson’s ratio of 0.33. It has an ultimate tensile strength of 950MPa and tensile yield strength of 880Mpa. It has a density of 4430 kg/m³.
Thickness of the Piston Head (t₁) = 5.216 mm
Radial width of the ring (b) = 1.749 mm
Axial thickness of the piston ring (h) = 1.224 mm
Width of ring land (h₂) = 0.918 mm
Thickness of piston barrel at the top end (t₁) = 8.659 mm
Thickness of piston barrel at the open end (t₂) = 2.164 mm
Length of the skirt (l₁) = 40.2 mm
Piston pin diameter (d₀) = 18.76 mm
The center of the piston pin is 21.44 mm from the bottom edge of piston.

III. CASE STUDY
The 3D model of all four pistons is imported into ANSYS WORKBENCH 14.5 for static-structural analysis. Meshing of the model is done with an element size of 10 mm and the relevance for the model was set to 100 which give a fine mesh. Tetrahedral mesh was applied. The model has a total of 19180 nodes and 11867 elements. In static-structural analysis, pressure of 13.65MPa is applied on the top of piston and frictionless support is applied on the piston pin holes as well as on the piston surface.
A. ANALYSIS OF A2618 ALUMINIUM ALLOY PISTON

1) STATIC-STRUCTURAL ANALYSIS

Figure 1. Meshed Model

2) OBSERVATIONS

Static-structural analysis for A2618 alloy piston

a) Equivalent (Von-Mises) stress:
   - Maximum equivalent stress was found to be 226.22Mpa.
   - Minimum equivalent stress was found to be 1.5524Mpa.

b) EQUIVALENT ELASTIC STRAIN:
   - Maximum equivalent elastic strain was found to be 0.0031032.
   - Minimum equivalent elastic strain was found to be 3.7334×10⁻⁵

B. ANALYSIS OF A4032 ALUMINIUM ALLOY PISTON

1) Static-Structural Analysis

Figure 2. Equivalent stress (Von-Mises) of A2618 alloy piston

Figure 3. Equivalent elastic strain of A2618 alloy piston

Figure 4. Equivalent stress (Von-Mises) of A4032 alloy piston
2) OBSERVATIONS
Static-structural analysis for A4032 alloy piston
a) Equivalent (Von-Mises) stress:
   • Maximum equivalent stress was found to be 187.23 Mpa.
   • Minimum equivalent stress was found to be 1.3937 Mpa.
b) Equivalent elastic strain:
   • Maximum equivalent elastic strain was found to be 0.0024104.
   • Minimum equivalent elastic strain was found to be $2.6176 \times 10^{-5}$

C. ANALYSIS OF AL-GHS 1300 ALUMINIUM ALLOY PISTON
1) STATIC-STRUCTURAL ANALYSIS
2) OBSERVATIONS
Static-structural analysis for Al-GHS 1300 alloy piston
a) Equivalent (Von-Mises) stress:
   • Maximum equivalent stress was found to be 342.32 Mpa.
   • Minimum equivalent stress was found to be 1.745 Mpa.
b) Equivalent elastic strain:
   • Maximum equivalent elastic strain was found to be 0.0035315.
   • Minimum equivalent elastic strain was found to be $3.0259 \times 10^{-5}$
D. ANALYSIS OF Ti-6Al-4V ALUMINIUM ALLOY PISTON

1) STATIC-STRUCTURAL ANALYSIS

![Figure 8. Equivalent stress (Von-Mises) of Ti-6Al-4V alloy piston](image)

**Figure 8. Equivalent stress (Von-Mises) of Ti-6Al-4V alloy piston**

![Figure 9. Equivalent elastic strain of Ti-6Al-4V alloy piston](image)

**Figure 9. Equivalent elastic strain of Ti-6Al-4V alloy piston**

2) OBSERVATIONS

Static-structural analysis for Ti-6Al-4V alloy piston

a) Equivalent (Von-Mises) stress:
   - Maximum equivalent stress was found to be 311.25Mpa.
   - Minimum equivalent stress was found to be 1.85Mpa.

b) Equivalent elastic strain:
   - Maximum equivalent elastic strain was found to be 0.0027464.
   - Minimum equivalent elastic strain was found to be $2.4618 \times 10^{-5}$

IV. RESULTS AND DISCUSSIONS

3D models of piston are created based on the dimensions obtained. CATIA V5R20 is used for creating the 3D model. These models are then imported into ANSYS WORKBENCH 14.5 for analysis. Static structural analysis of pistons is carried out. Meshing is done with an element size of 10mm and a relevance of 100 is given which gives a fine mesh. For static structural analysis, gas pressure is applied on the top of the piston and frictionless support is applied across the surface of piston and also on the piston pin holes. Then results are obtained for von-Mises stress and maximum elastic strain. A comparison is made between these results and the best suited aluminium alloy is selected based on the parameters.

A. STATIC-STRUCTURAL ANALYSIS RESULTS

The static structural analysis of A2618, A4032, Al-GHS1300, and Ti-6Al-4V are done and results are obtained for Equivalent (Von-Mises) stress, equivalent elastic strain. These results are plotted graphically and a comparison is made between these results.
From figure 10, we can observe that in case of equivalent (von-mises) stress, piston made of A4032 is found to have least stress of 187.23MPa in comparison with remaining materials including the present material. Highest stress of 342.32MPa is observed in piston made of Al-GHS 1300. Maximum equivalent stress on A2618 was found to be 226.22Mpa and that of Ti-6Al-4V was found to be 311.25Mpa.

![Equivalent elastic strain](image)

*Figure 11. Equivalent elastic strain*

From figure 11, we can observe that in case of equivalent elastic strain, the least equivalent elastic strain was found to be 0.0024104 in A4032 piston in comparison with remaining materials including the present material and maximum equivalent elastic strain was found to be 0.0035315 in Al-GHS 1300. In case of A2618 alloy piston, maximum equivalent elastic strain was found to be 0.0031032 and in Ti-6Al-4V alloy piston it was found to be 0.002746.

V. CONCLUSION

Pistons made of different aluminum alloys like A2618, A4032, AL-GHS 1300, Ti-6Al-4V were designed and analyzed successfully. In static-structural analysis, the pistons were analyzed to find out the equivalent (von-mises) stress, equivalent elastic strain. The results show that in case of equivalent (von-mises) stress, piston made of A4032 is found to have least stress of 187.23MPa in comparison with remaining materials. Highest stress of 342.32MPa is observed in piston made of Al-GHS 1300. This is because the yield strength of the piston is very high in Al-GHS 1300 followed by Ti-6Al-4V, A2618 and A4032. From the stress analysis figures, it can be observed that maximum stress intensity is on the bottom surface of the piston crown in all the materials. In case of equivalent elastic strain, the least equivalent elastic strain and maximum equivalent elastic strain were found in alloy A4032 and alloy Al-GHS 1300 respectively corresponding to the stress induced.

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