Design And Finite Element Analysis of An IC Engine Piston Using Aluminum Alloys

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***Abstract*—The piston is a key component in internal combustion engines, responsible for transmitting combustion forces to the crankshaft. This study focuses on the design and structural analysis of a piston used in a Bajaj Pulsar 150 engine through Finite Element Analysis (FEA). Different aluminum alloy materials are evaluated to determine their suitability under thermal and mechanical loading conditions.**

A three-dimensional model of the piston is created using CATIA software and analyzed in ANSYS Workbench. Parameters such as stress distribution, deformation, and strain are examined for each material. The results are compared to identify the most efficient material based on strength, weight, and durability. The findings contribute to improving piston performance while minimizing the risk of failure in real operating conditions.

***Index Terms*—Modeling, Analyze, crown, piston rings, hubs, skirt, thermal stresses, and force stresses.**

I. INTRODUCTION

A piston is a fundamental component of reciprocating internal combustion engines, responsible for converting the energy generated during fuel combustion into mechanical motion. It operates within the cylinder and maintains a gas-tight seal with the help of piston rings. The force produced by expanding gases is transmitted through the piston to the crankshaft via the connecting rod, enabling the engine to perform useful work. During operation, the piston is subjected to repeated cycles of high pressure and temperature. These cyclic loads can lead to various forms of damage, including wear along the piston surface and cracks near the crown region.

Studies have shown that the upper portion of the piston, particularly the crown, experiences the highest stress concentration, making it more susceptible to fatigue failure. Additionally, insufficient lubrication or excessive heat can cause piston seizure, which occurs when the protective oil film between the piston and cylinder wall breaks down. Thermal and mechanical loads play a crucial role in determining the performance and durability of a piston. Elevated temperatures reduce material strength and can significantly affect the lifespan of the component. Therefore, understanding the thermal behavior of piston materials is essential. Thermal analysis, often performed using numerical techniques such as the Finite Element Method (FEM), allows engineers to evaluate how material properties change with temperature and how heat is distributed within the piston. An internal combustion engine functions by burning fuel within a confined space, producing high-pressure gases that exert force on engine components. This force acts directly on the piston, causing it to move linearly within the cylinder. The linear motion is then converted into rotational motion at the crankshaft. This energy transformation process is central to engine operation and efficiency. Historically, the development of internal combustion engines dates back to early innovations such as the engine designed by Étienne Lenoir, which marked a significant milestone in mechanical engineering. In modern engineering practice, computational tools such as finite element analysis are widely used to simulate piston behavior under various operating conditions. These methods enable accurate prediction of stress distribution, deformation, and potential failure regions, thereby reducing the need for extensive experimental testing. As a result, engineers can optimize piston design for improved performance, reliability, and cost-effectiveness.

II. PROBLEM STATEMENT:

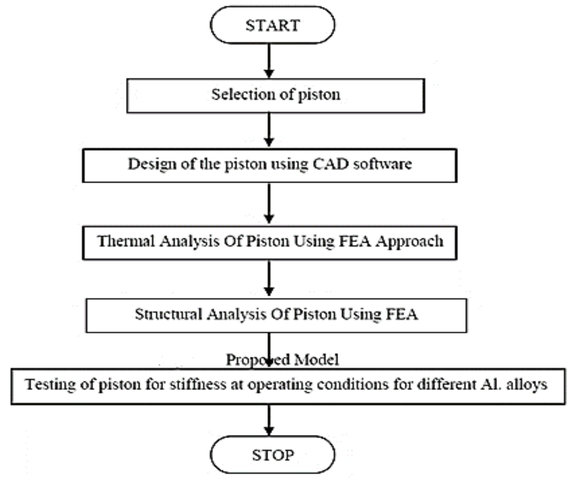
The design of an engine piston must ensure minimum weight while maintaining sufficient strength to withstand thermal and mechanical loads. Excess weight increases engine vibration and reduces efficiency, whereas insufficient strength may lead to failure during operation. The piston is subjected to varying forces caused by combustion pressure, inertia, and side thrust from the connecting rod. Additionally, thermal loads arise due to heat transfer from combustion gases. These factors continuously change with engine speed and load conditions, making the design process complex. The objective of this study is to analyze piston performance using different aluminum alloys and determine an optimal material and design configuration that minimizes deformation, reduces stress concentration, and improves overall durability.

III. EXISTING SYSTEM:

The pistons are generally made up of Cast iron, Aluminum alloy because of its high heat transfer rate. This expands appreciably on heating so right amount of clearance needs to be provided or else the engine will lead to seize. The pistons are also manufactured using steel. Steel pistons have become attractive for high-stress and motorsport diesel applications because the material is physically so much stronger than aluminum. Because the whole piston is steel, ring-land wear is no concern. And steel pistons can be fit with enormous oil galleys to provide tremendous piston cooling.

IV. PROPOSED SYSTEM:

The piston materials that have been used is the namely aluminum alloy. Lightweight materials have high specific strength, high hardness and wear resistance, low friction coefficient and thermal expansion, high thermal conductivity, high heat-absorbing ability and good ability in abatement. The different materials are analyzed for the manufacturing of piston i.e., aluminum alloy Al-GHy-1250, A-390 T-5, A-2618 because it has high shear modulus, less deformation under application of same load and it can withstand heat shocks.

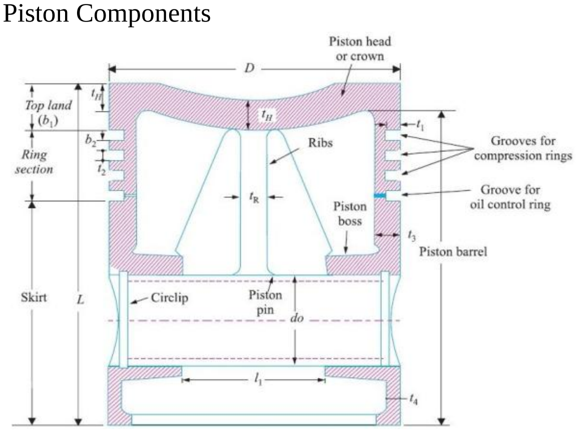


V. METHODOLOGY

The methodology adopted in this work involves both design and simulation processes:

- A 3D model of the piston is developed using CATIA based on engine specifications.
- The model is exported in IGES format for compatibility with analysis software.
- The geometry is imported into ANSYS Workbench for simulation.
- Material properties for selected aluminum alloys are assigned.
- Boundary conditions, including applied pressure and fixed supports, are defined.
- Meshing is performed to discretize the model into finite elements.
- Structural and thermal analyses are conducted to evaluate stress, deformation, and temperature distribution.
- Results obtained for different materials are compared to determine the most suitable option.

Piston Components



A piston consists of several important parts, each performing a specific function:

- Crown: The top surface exposed to combustion pressure and heat.
- Skirt: Guides piston movement within the cylinder and absorbs side thrust.
- Piston Pin: Connects the piston to the connecting rod and allows rotational motion.
- Piston Rings: Provide sealing, control oil consumption, and transfer heat to the cylinder wall.

These components collectively ensure efficient engine operation by maintaining sealing, reducing friction, and transferring loads effectively.

Forces Acting-

During operation, the piston is subjected to multiple forces, including:

- Combustion gas pressure
- Inertial forces due to reciprocating motion
- Frictional forces between piston and cylinder wall
- Thermal stresses caused by temperature variations

The piston must be designed to withstand these forces while maintaining structural integrity and performance.

Functions

1. To reciprocate in the cylinder as a gas tight plug causing suction, compression, expansion and exhaust strokes.
2. To receive the thrust generated by the explosion of the gas in the cylinder and transmit it to the connecting rod.
3. To form a guide and bearing to the small end of the connecting rod and to take the side thrust due to obliquity of the rod.

Piston is considered to be one of the most important parts in a reciprocating engine in which it helps to convert the chemical energy obtained by the combustion of fuel into useful (work) mechanical power. The purpose of the piston is to provide a means of conveying the expansion of gases to the crankshaft via connecting rod, without loss of gas from above or oil from below. Piston is essentially a cylindrical plug that moves up & down in the cylinder. It is equipped with piston rings to provide a good seal between the cylinder wall & piston.

Piston Design

By knowing the basic engine specifications like bhp, bore, stroke, compression ratio, maximum power and maximum torque we find the various dimensions of the piston which are sated below

1) Thickness of the piston head
2) Radial thickness of the ring
3) Axial thickness of the ring
4) Height of the first land
5) Thickness of the piston barrel
6) Radial thickness of ring grove
7) Length of piston skirt
8) Length of piston
9) Diameter of piston pin hole
10) Thickness of piston at open end

VI. FEA & ANSYS

Finite Element Analysis is a computational method used to predict how components behave under various physical conditions. It involves dividing a complex structure into smaller elements, allowing detailed analysis of stress, strain, and deformation. In this study, ANSYS Workbench is used to perform structural analysis of the piston. The software enables simulation of real-world loading conditions and provides accurate results for evaluating material performance. This approach reduces the need for experimental testing and helps optimize design efficiently.

Why is FEA needed?

- To reduce the amount of prototype testing

1 Computer simulation allows multiple “what-if” Scenarios to be tested quickly and effectively.

- To simulate designs that are not suitable for prototype testing

1 Example surgical implants, such as an artificial knee.

- The bottom line:

1. Cost saving
2. Time saving. reduce time to market
3. Create more reliable, better-quality and competitive design.

VII. CAD/CAM/CAE

The Modern world of design, development, manufacturing so on, in which we have stepped can't be imagined without interference of computer. The usage of computer is such that, they have become an integral part of these fields. In the world market now the competition in not only cost factor but also quality, consistency, availability, packing, stocking, delivery etc. So are the requirements forcing industries to adopt modern technique rather than local forcing the industries to adapt better techniques like CAD / CAM / CAE etc.

The possible basic way to industries is to have high quality products at low costs is by using
1) CAD
2) CAE
3) CAM
Further many tools are been introduced to simplify & serve the requirement CATIA, PRO-E, UG are some among many.

This penetration of technique concern has helped the manufacturers to
1) Increase productivity
2) Shortening the lead-time
3) Minimizing the prototyping expenses
4) Improving Quality
5) Designing better products

Engineering Design:
CATIA and Pro-E offer a range of tools to enable the generation of a complete digital representation of the product being designed. In addition to the general geometry tools there is also the ability to generate geometry of other integrated design disciplines such as industrial and standard pipe work and complete wiring definitions. Tools are also available to support collaborative development. A number of concept design tools that provide up-front Industrial Design concepts can then be used in the downstream process of engineering the product. These range from conceptual Industrial design sketches, reverse engineering with point cloud data and comprehensive free-form surface tools.

VIII. DESIGN SOFTWARE

1. CATIA V5
2. ANSYS

PISTON MATERIALS
The selection of piston material is crucial for achieving optimal performance. The material must possess:
- High strength-to-weight ratio
- Good thermal conductivity
- Resistance to wear and corrosion
- Ability to withstand high temperatures

Aluminum alloys are widely used due to their lightweight nature and excellent heat transfer properties. In this study, materials such as A2618, ALGHY1250, and A390 T-5 are analyzed and compared.

Experimental validation (design and analysis by FEA)
It is not always possible to obtain the exact analytical solution at any location in the body, especially for those elements having complex shapes or geometries. Always what matters are the boundary conditions and material properties. In such cases, the analytical solution that satisfies the governing equation or gives extreme values for the governing functional is difficult to obtain. Hence for most of the practical problems, the engineers resort to numerical methods like the finite element method to obtain approximate but most probable solutions. Finite element procedures are at present very widely used in engineering analysis. The procedures are employed extensively in the analysis of solids and structures and of heat transfer and fluids, and indeed, finite element methods are useful in virtually every field of engineering analysis.

Description of the method
In any analysis we always select a mathematical model of a physical problem, and then we solve that model. Although the finite element method is employed to solve very complex mathematical models, but it is important to realize that the finite element solution can never give more information than that contained in the mathematical model.

Important features of finite element method:
The finite element method is a technique in which a given domain is represented as a collection of simple

domains, called finite elements. The following are the three basic features of the finite element method.

1) Division of whole into parts; which allows representation of geometrically complex domains as collection of simple domains that enable a systematic derivation of the approximation functions.
2) Derivation of approximations functions over each element; the approximation functions are often algebraic polynomials that are derived using interpolation theory.
3) Assembly of elements, which is based on continuity of the solution and balance of internal fluxes.

The basic equation used to solve the static analysis problem is:

$\{Q\} = [K] \{ \delta \}$

Where, {Q} = the equivalent vector which is obtained by lumping the element and edge loads at the nodes,

[K] = the global stiffness matrix of the system, and

$\{\delta\}$ = the unknown nodal displacement vector.

Finite element modeling and analysis

Three Phases of Analysis:

For determining stresses and deflections the following steps of the analysis are essential:

1) Preparation of Input Data: The requisite data for the given problem is geometry (i.e., Model), material properties and boundary conditions (i.e., loads and constraints).
2) Solution: This involves solving the necessary equations to calculate the unknown parameters.
3) Arrangements of Results: The results obtained for stress analysis may be presented in the form of tables or graphical images like stress patterns, displacement patterns.

Steps Followed in ANSYS programme.

The three important steps in ANSYS programming are:

1) Preprocessing
2) Solution
3) Post Processing

1) Preprocessing:

This phase consists of making available the input data such as geometry, material properties, meshing of the model, boundary conditions and has the following steps:

a) Set up: Here we enter the analysis type, the material properties, and the geometry (i.e., prepare the model). The model may be built parametrically or a model from other software package can be imported.
b) Create FE model: In this step we divide the total volume into small simple regular volumes, which can be easily meshed. Then we define the mesh size for each small volume by virtually dividing all the edges of the small volume into same divisions.
c) Loading: In this step the boundary conditions are imposed, i.e., forces and constraints, on the model are defined.

2) Solution:

In this phase a solver is used to solve the basic equation for the analysis type and to compute the results.

This phase is taken care by the software programme. In the solution process, the solver goes through following steps to compute the solution for a steady state analysis,

a) Formulate element matrices,
b) Assembly and triangular the overall stiffness matrix,
c) calculate the solution by back substitution,
d) Compute the stresses, displacements, etc.

3) Post processing:

This is the phase where the results are reviewed for the analysis done, by obtaining graphic displays, vector-plots and tabular reports of stress and displacement, etc.

Designing piston with using CATIA:

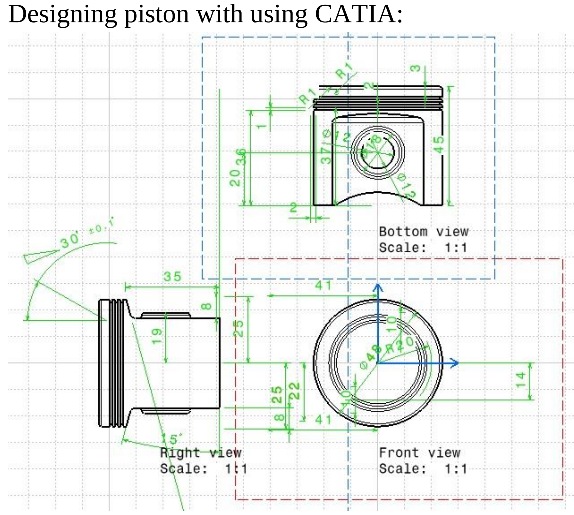


Fig. Drafting of Piston

OBSERVATIONS

The analysis is done in ANSYS Workbench for different types of aluminum alloy materials which is suggested best material with different material properties. Following different type of results like Equivalent Stress, Total Deformation is obtained as shown in figure. Applying the following boundary condition on BAJAJ PULSAR 150 piston and execute the structural and thermal analysis using ANSYS workbench.

1) Boundary condition: -

Maximum Pressure is 12.9 MPa, apply on Piston top head and fixed support has given at surface of pin holes.

2) Material: -

- A2618
- ALGHY1250
- Aluminum A390 T-5

These above materials are applied simultaneously to BAJAJ PULSAR 150 two-wheeler Piston and analysis of Structural in ANSYS Workbench, these results are shown in following pictures: -

BAJAJ PULSAR 150 Two-Wheeler Piston structural analysis Result with A2618 Material:

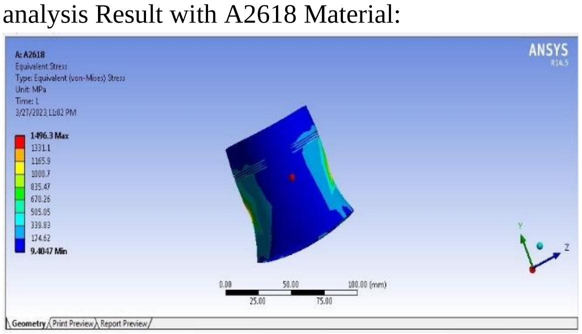


Figure 4.5 A2618 Equivalent Stress

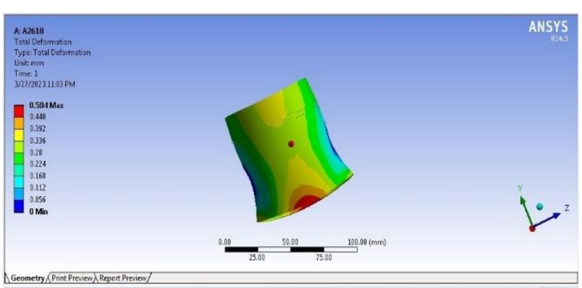


Figure 4.6 A2618 Total Deformation

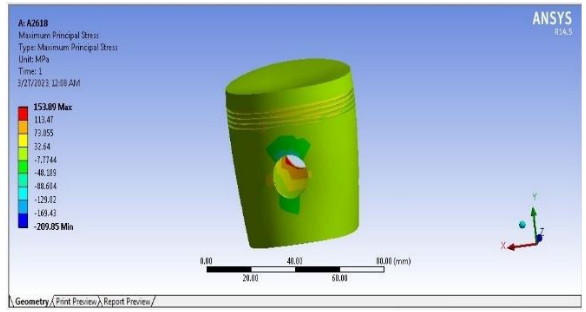


Figure 4.7 A2618 Maximum Principal Stress

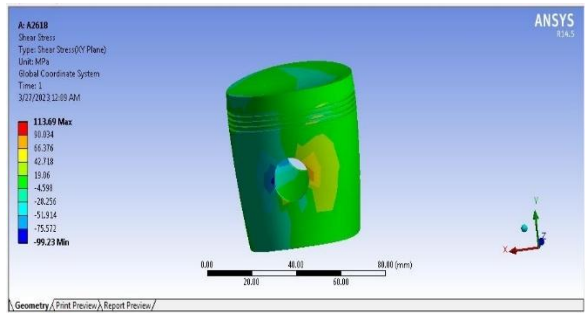


Figure 4.8 A2618 Shear Stress

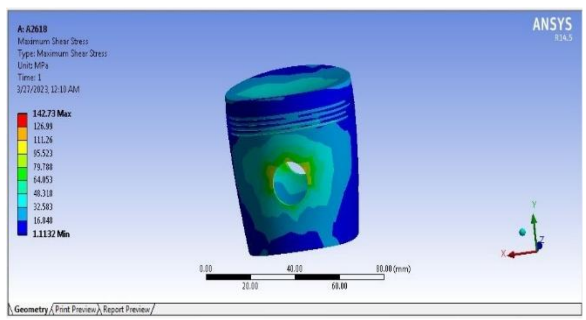


Figure 4.9 A2618 Maximum Shear Stress

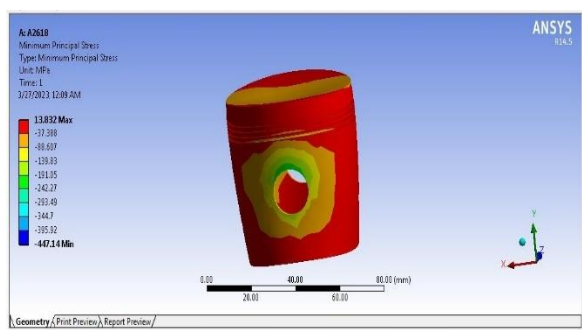


Figure 4.10

BAJAJ PULSAR 150 Two-Wheeler Piston structural analysis Result with ALGHY1250 Material: -

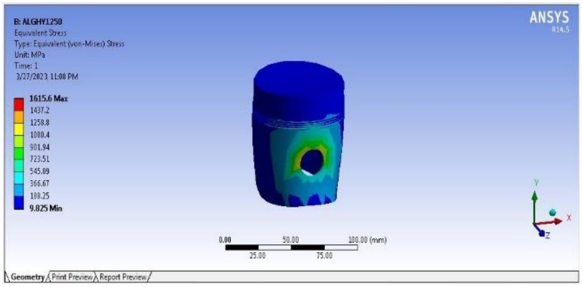


Figure 4.11 ALGHY1250 Equivalent Stress

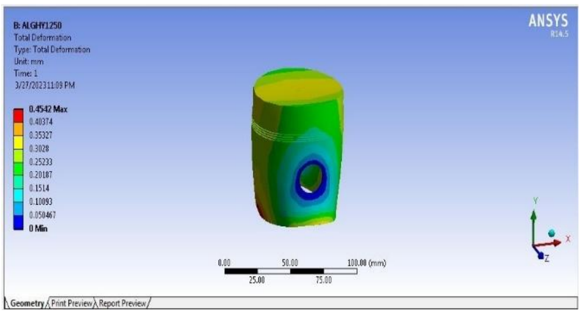


Figure 4.12 ALGHY1250 Total Deformation

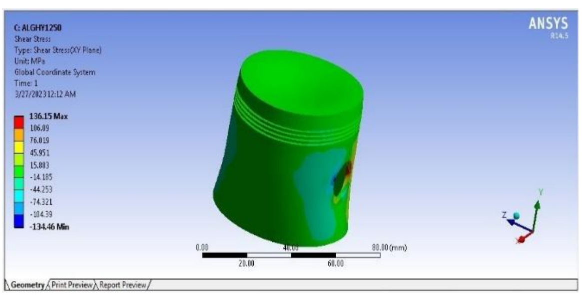


Figure 4.13 ALGHY1250 Shear Stress

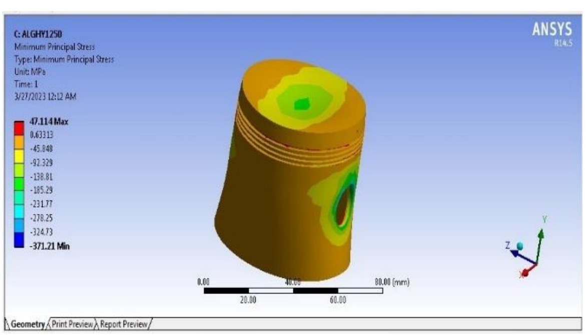


Figure 4.14 ALGHY1250 Minimum Principal Stress

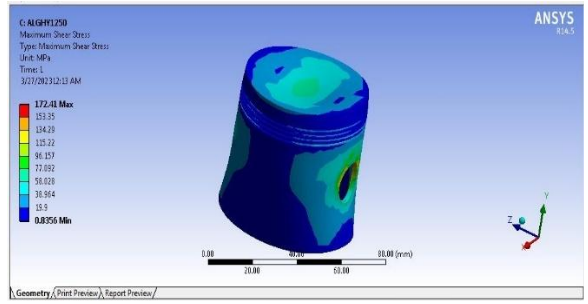


Figure 4.15 ALGHY1250 Minimum Shear Stress

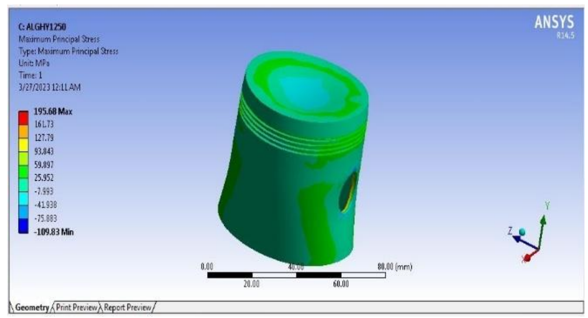


Figure 16 ALGHY1250 Maximum Shear Stress

BAJAJ PULSAR 150 Two-Wheeler Piston structural analysis Result with ALGHY1250 Material with Changed Dimension: -

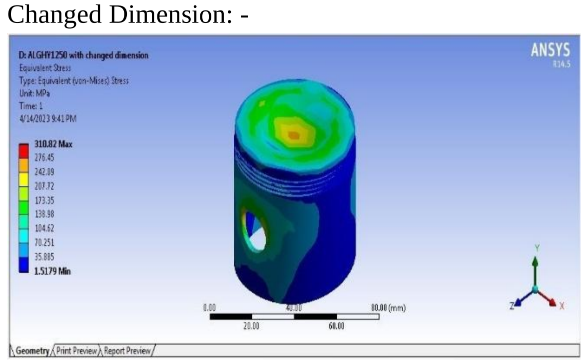


Figure 4.17 ALGHY1250 with changed dimension Material Equivalent Stress

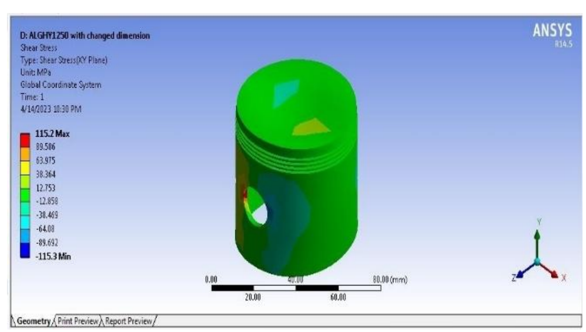


Figure 18 ALGHY1250 with hanged dimension Material Total Deformation

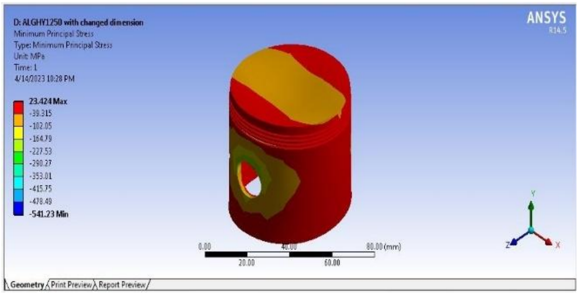


Figure 4.19 ALGHY1250 With Changed dimension Shear Stress

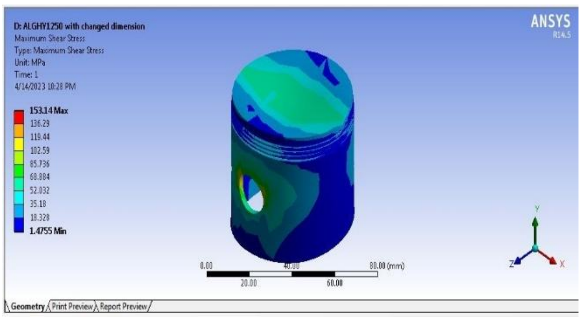


Figure 4.20 ALGHY1250 With Changed dimension Minimum Shear Stress

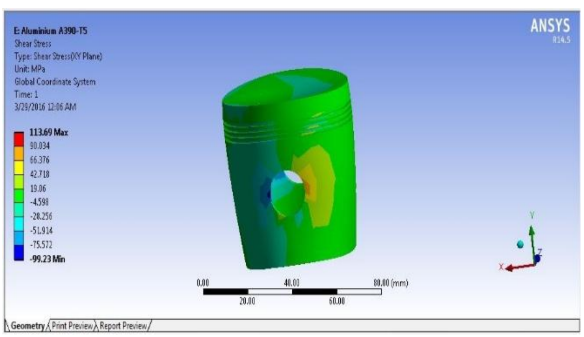


Figure 4.21 ALGHY1250 with Changed dimension Maximum Principal Stress

BAJAJ PULSAR 150 Two-Wheeler Piston structural analysis Result with Aluminum A390 T-5:

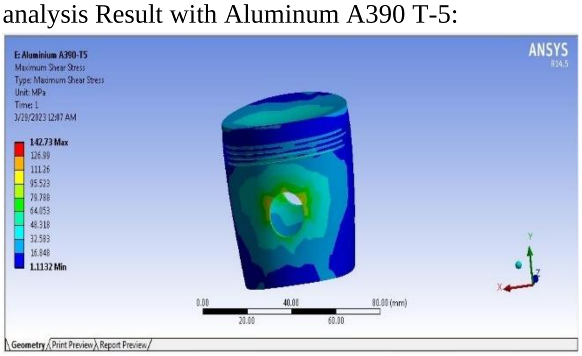


Figure 4.22 Alumnium A390 T-5 Shear Stress

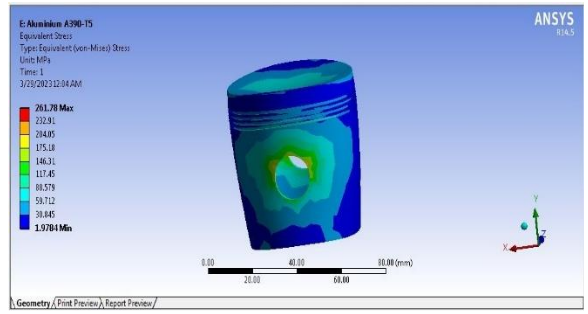
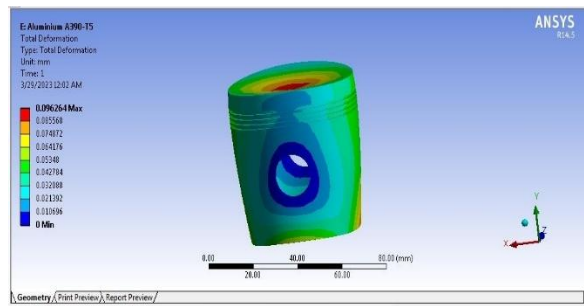


Figure 4.23 Alumnium A390 T-5 Minimum Shear Stress



4.24 Aluminium A390 –T5 Von Mises

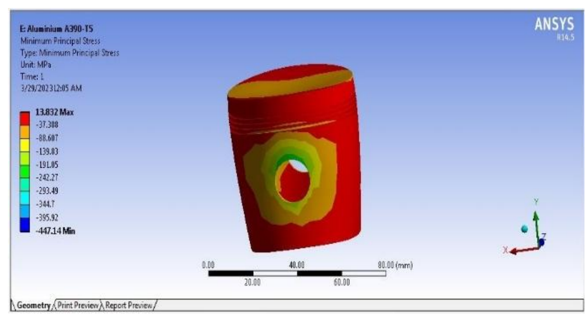


Figure 4.25 Aluminium A390 –T5 Total Deformation

IX. RESULT:

Structural: -From the table we found that the value of Total Deformation for Aluminum A390 T-5 varies from 0.0 mm to 0.0962mm, Values of Equivalent Stress or Von Misses varies from 1.9784 Mpa to 261.78Mpa, Shear Stress 113.69 Mpa, Maximum Principal Stress 153.89 Mpa, and Minimum Principal Stress 13.832 Mpa.

The value of Total Deformation for A2618 varies from 0.0 mm to 0.10606 mm, Values of Equivalent Stress or Von Misses varies from 1.9784 Mpa to 261.78Mpa, Shear Stress 113.69 Mpa, Maximum Principal Stress 153.89 Mpa, Minimum Principal Stress 13.832 Mpa.

The value of Total Deformation for ALGHY1250 varies from 0.0mm to 0.10839mm, Values of Equivalent Stress or Von Misses varies from 1.4845 Mpa to 308.12Mpa, Shear Stress 136.15 Mpa, Maximum Principal Stress 195.68 Mpa, Minimum Principal Stress 47.114 Mpa.

The value of Total Deformation for ALGHY1250 with changed dimension varies from 0.0 mm to 0.14066 mm, Values of Equivalent Stress or Von Misses varies from 1.5179 Mpa to 310.82Mpa, Shear Stress 115.2 Mpa, Maximum Principal Stress 153.14 Mpa, Minimum Principal Stress 23.424 Mpa.
When we compare ALGHY1250 with changed dimension with Aluminum A390 T-5, A2618, ALGHY1250 it is found that Total Deformation is slightly increases but it is under allowable limit. Similarly Shear Stress, Maximum Principal Stress and Minimum Principal Stress are almost like the same but in comparison with Aluminum A390 T-5 mass is reduced by 3.16%, in comparison with A2618 mass is reduced by 4.48% and in comparison, with ALGHY1250 mass is reduced by 8.2%. The equivalent stress values obtained are well below the permissible value as well as ALGHY1250 with changed dimension improves so the design of piston is safe.

X. CONCLUSIONS

The structural analysis of piston of ALGHY1250 with changed dimension, Aluminum A390 T-5, A2618, ALGHY1250 Materials the following conclusions are made, on application of 12.9 MPa gas pressure on piston. Values of Shear Stress, Maximum Principal Stress and Minimum Principal Stress are almost like the same but in comparison with Aluminum A390 T-5 mass is reduced by 3.16%, in comparison with A2618 mass is reduced by 4.48% and in comparison, with ALGHY1250 mass is reduced by 8.2%. The equivalent stress values obtained are well below the permissible value as well as ALGHY1250 with changed dimension improves so the design of piston is safe. Thus, we can conclude that piston ALGHY1250 with changed dimension is suitable to use and can withstand in real working conditions and can bear mechanical stresses generated

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