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Design, Analysis and Optimization of Three Aluminium Piston Alloys Using FEA

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ABSTRACT
This paper describes the stress distribution and thermal stresses of three different aluminum alloys piston by using finite element method (FEM). The parameters used for the simulation are operating gas pressure, temperature and material properties of piston. The specifications used for the study of these pistons belong to four stroke single cylinder engine of Bajaj Kawasaki motorcycle. This paper illustrates the procedure for analytical design of three aluminum alloy pistons using specifications of four stroke single cylinder engine of Bajaj Kawasaki motorcycle. The results predict the maximum stress and critical region on the different aluminum alloy pistons using FEA. It is important to locate the critical area of concentrated stress for appropriate modifications. Static and thermal stress analysis is performed by using ANSYS 12.1. The best aluminum alloy material is selected based on stress analysis results. The analysis results are used to optimize piston geometry of best aluminum alloy.
Keywords- A2618, A4032, Al-GHS 1300, ANSYS 12.1, Deformation, Piston, Strain, stress.

I. INTRODUCTION

An Internal Combustion Engine is that kind of prime mover that converts chemical energy to mechanical energy. The fuel on burning changes into gas which impinges on the piston and pushes it to cause reciprocating motion. The reciprocating motion of the piston is then converted into rotary motion of the crankshaft with the help of connecting rod.

IC engines are used in marine, locomotives, aircrafts, automobiles and other industrial applications.

1.1 Research Object - Piston

A piston is a component of reciprocating IC-engines. It is the moving component that is contained by a cylinder and is made gas-tight by piston rings. In an engine, its purpose is to transfer force from expanding gas in the cylinder to the crankshaft via a piston rod.

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.

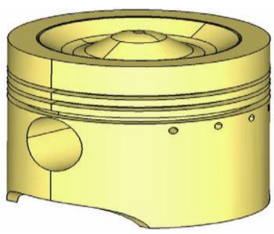


Figure 1.1- Model of a Piston

Piston in an IC engine must possess the following characteristics:

- Strength to resist gas pressure.
- Must have minimum weight.
- Must be able to reciprocate with minimum noise.
- Must have sufficient bearing area to prevent wear.
- Must seal the gas from top and oil from the bottom.
- Must disperse the heat generated during combustion.
- Must have good resistance to distortion under heavy forces and heavy temperature.

In engine, transfer of heat takes place due to difference in temperature and from higher temperature to lower temperature. Thus, there is heat transfer to the gases during intakes stroke and the first part of the compression stroke, but the during combustion and expansion processes the heat transfer take place from the gases to the walls. So the piston crown, piston ring and the piston skirt should have enough stiffness which can endure the pressure and the friction between contacting surfaces. In addition, as an important part in engine, the working condition of piston is directly related to the reliability and durability of engine

1.2 Characterisation of Materials

The materials chosen for this work are A2618, A4032 and Al-GHS1300 for an internal combustion engine piston. The relevant mechanical and thermal properties of A2618, A4032 and Al-GHS1300 aluminium alloys are listed in the following table [2], [6].

S N	PARAMETERS	A2618	A4032	Al-GHS 1300
1	Elastic Modulus (GPa)	73.7	79	98
2	Ultimate Tensile Strength (MPa)	480	380	1300
3	0.2% Yield Strength (MPa)	420	315	1220
4	Poisson's Ratio	0.33	0.33	0.3
5	Thermal Conductivity (W/m/^{o}C)	147	154	120
6	Coefficient of Thermal Expansion (1/K)	25.9 x 10^{-6}	79.2 x 10^{-6}	18 x 10^{-6}
7	Density (Kg/m^3)	2767.9 9	2684.9 5	2780

Table 1.1 Thermal and Mechanical Properties of three Aluminum Alloys

1.3 Engine Specifications

The engine used for this work is a single cylinder four stroke air cooled type Bajaj Kawasaki petrol engine. The engine specifications are given in Table 1.2. [1]

PARAMETERS	VALUES
Engine Type	Four stroke, Petrol engine
Induction	Air cooled type
Number of cylinders	Single cylinder
Bore	51 mm
Stroke	48.8 mm
Length of connecting rod	97.6 mm
Displacement volume	99.27 cm^3
Compression ratio	8.4
Maximum power	6.03 KW at 7500 rpm
Maximum Torque	8.05 Nm at 5500 rpm
Number of revolutions/cycle	2

Table 1.2 Engine Specifications

II. PROBLEM FORMULATION

The objective of the present work is to design and analysis of pistons made of A2618, A4032 and Al-GHS1300. In this paper the materials (A2618 and A4032) of piston are replaced with Al-GHS1300. Piston models are created in ANSYS 12.1. After analysis a comparison is made between existing A2618 and A4032 pistons viz Al-GHS1300 in terms of volume, weight, inertia force, factor of safety, deformation, strain and stresses.

III. METHODOLOGY

- Analytical design of pistons using specifications of Bajaj Kawasaki petrol engine.
- Creation of 3D models of piston using ANSYS.
- Meshing of 3D models using ANSYS.
- Analysis of pistons using static stress analysis method.
- Comparative performance of three aluminum alloy pistons under static stress analysis method.
- Analysis of pistons under thermal and mechanical loads i.e. the pistons are subjected to a uniform gas pressure and non-uniform temperature distribution.
- Comparative performance of the three aluminum alloy pistons under thermal and mechanical loads i.e. the pistons are subjected to a uniform gas pressure and non-uniform temperature distribution.
- Select the best suited aluminum alloy.
- Optimize the model for mass reduction.
- Analyze the optimized model under static stress.
- Analyze the optimized model under thermal and mechanical loads.

3.1 Analytical Design

Let

IP = indicated power produced inside the cylinder (W)
η = mechanical efficiency = 0.8
n = number of working stroke per minute
= N/2 (for four stroke engine)
N = engine speed (rpm)
L = length of stroke (mm)
A = cross-section area of cylinder (mm^2)
r = crank radius (mm)
l_c = length of connecting rod (mm)
a = acceleration of the reciprocating part (m/s^2)
m_p = mass of the piston (Kg)
V = volume of the piston (mm^3)
t_h = thickness of piston head (mm)
D = cylinder bore (mm)
p_{max} = maximum gas pressure or explosion pressure (MPa)
σ_t = allowable tensile strength (MPa)
σ_{ut} = ultimate tensile strength (MPa)
F.O.S = Factor of Safety = 2.25
K = thermal conductivity (W/m K)
T_c = temperature at the centre of the piston head (K)
T_e = temperature at the edge of the piston head (K)
HCV = Higher Calorific Value of fuel

(KJ/Kg) = 47000 KJ/Kg

BP = brake power of the engine per cylinder (KW)

m = mass of fuel used per brake power per second (Kg/KW s)

C = ratio of heat absorbed by the piston to the total heat developed in the cylinder = 5% or 0.05

b = radial width of ring (mm)

P_w = allowable radial pressure on cylinder wall (N/mm^2) = 0.025 MPa

σ_p = permissible tensile strength for ring material (N/mm^2) = 1110 N/mm^2

h = axial thickness of piston ring (mm)

h_1 = width of top lands (mm)

h_2 = width of ring lands (mm)

t_1 = thickness of piston barrel at the top end (mm)

t_2 = thickness of piston barrel at the open end (mm)

ls = length of skirt (mm)

μ = coefficient of friction (0.01)

l_1 = length of piston pin in the bush of the small end of the connecting rod (mm)

d_o = outer diameter of piston pin (mm)

Mechanical efficiency of the engine (η) = 80 %.

$$\eta = \frac{\text{Brake power (B.P)}}{\text{Indicating power (I.P)}}$$

$$\text{Therefore, I.P} = \frac{B.P}{\eta} = \frac{6.2}{0.8} = 7.75 \text{ KW}$$

$$\text{Also, I.P} = P \times A \times L \times \frac{N}{2}$$

$$I.P = P \times \frac{\pi D^2}{4} \times L \times \frac{N}{2}$$

Substituting the values from Table 1.2, we have

$$7.75 \times 1000 = P \times \frac{\pi (0.051)^2}{4} \times (0.0488) \times \frac{(5000)}{2 \times 60}$$

So, $P = 18.66 \times 10^5 \text{ N/m}^2$ or $P = 1.866$ MPa

Maximum Pressure $p_{max} = 10 \times P$
$= 10 \times 1.866 = 18.66$ MPa

3.1.1 Analytical design for A2618 alloy piston

Analytical design for A2618 alloy piston is as follows:

Thickness of the Piston Head

According to Grashoff's formula the thickness of the piston head is given by

$$t_h = D\sqrt{(3p_{max}/16\sigma_t)}$$

where $\sigma_t = \sigma_{ut}/2.25 = 213.33$ MPa

Therefore $t_h = 51 \times \sqrt{(3 \times 18.66)/(16 \times 213.33)}$
$= 6.53$ mm

Empirical formula:

$$t_h = 0.032\,D + 1.5 = 3.2 \text{ mm}$$

On the basis of the heat dissipation, the thickness of the piston head is given by:

$$t_h = \frac{[\,C \times HCV \times m \times BP] \times 10^6}{12.56 \times K\,(T_c - T_e)}$$

$$= \frac{[0.05 \times 47000 \times 34.45 \times 10^{-3} \times 6.2] \times 10^6}{12.56 \times 147 \times 20 \times 3600}$$

$$= 3.775 \text{ mm}$$

The maximum thickness from the above formula is t_h is 6.53 mm.

Piston Rings

The radial width of the ring is given by:

$$b = D\sqrt{(3\,p_w/\sigma_p)} = 51\sqrt{(3 \times 0.025/110)}$$
$$= 1.33 \text{ mm}$$

Axial thickness of the piston ring is given by:

$$h = (0.7b \text{ to } b) = 0.7 \times 1.33 = 0.932 \text{ mm}$$
$$\approx 1 \text{ mm}$$

Width of Top Land and Ring Lands

Width of top land:

$$h_1 = (t_h \text{ to } 1.2\,t_h) = 6.53 \text{ mm}$$

Width of ring land:

$$h_2 = (0.75h \text{ to } h) = 0.75 \text{ mm}$$

Piston Barrel

Thickness of piston barrel at the top end:

$$t_1 = 0.03\,D + b + 4.9$$
$$= 0.03 \times 51 + 1.33 + 4.9 = 7.76 \text{ mm}$$

Thickness of piston barrel at the open end:

$$t_2 = (0.25\,t_1 \text{ to } 0.35\,t_1)$$
$$= o.25 \times 7.76 = 1.94 \text{ mm} \approx 2 \text{ mm}$$

Length of the skirt

$$ls = (0.6\,D \text{ to } 0.8\,D)$$
$$= 0.6 \times 51 = 30.6 \text{ mm}$$

Length of piston pin in the connecting rod bushing

l_1 = 45% of the piston diameter
$= 0.45 \times 51 = 22.95$ mm

Piston pin diameter

$$d_o = (0.28\,D \text{ to } 0.38\,D)$$
$$= 0.28 \times 51 = 14.28 \text{ mm}$$

The centre of the piston pin should be 0.02 D to 0.04D above the centre of the skirt.

Similarly, analytical design of A4032 and Al-GHS1300 is carried out and the results are summarized as follows:

3.1.2 Analytical design for A4032 alloy piston

Thickness of the Piston Head: t_h = 7.3 mm.
Piston Rings: b = 1.33 mm and h = 1 mm.
Width of Top Land: h_1 = 7.3 mm
Ring Lands: h_2 = 0.75 mm
Thickness of piston barrel at the
Top end: t_1 = 7.76 mm
Open end: t_2 = 2 mm.
Length of the skirt: ls = 30.6 mm
Length of piston pin in the connecting rod bushing:
l_1 = 22.95 mm
Piston pin diameter: d_o = 14.28

3.1.3 Analytical design for Al-GHS1300alloy piston

Thickness of the Piston Head: t_h = 4 mm.
Piston Rings: b = 1.33 mm and h = 1 mm.
Width of Top Land: h_1 = 4 mm
Ring Lands: h_2 = 0.75 mm
Thickness of piston barrel at the
Top end: t_1 = 7.76 mm
Open end: t_2 = 2 mm.
Length of the skirt: ls = 30.6 mm
Length of piston pin the connecting rod bushing:
l_1 = 22.95 mm
Piston pin diameter: d_o = 14.28

3.2 Creation of 3D models of piston using ANSYS

Following is the sequence of steps in which the piston is modeled:

- Firstly Keypoints are generated.
- A straight line is drawn through Keypoints to form a half portion of the piston.
- Fillets are applied at corners.
- Area command is applied to generate half area of the piston.
- Extrude command is applied to generate volume of the piston.
- Finally, the hole is created.

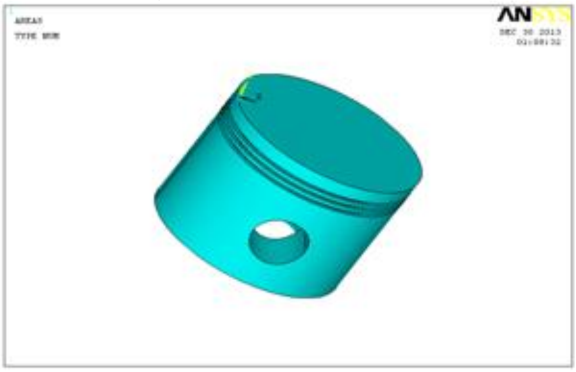


Figure 3.1 Model of Piston

3.3 Meshing of 3D model of Piston

For static stress analysis the element used is 10 node tetrahedron named SOLID187. The element size is taken as 8 and number of element divisions is 5.

For coupled field analysis the element used is 10 node tetrahedron named SOLID227. The element size is taken as 5 and number of element divisions is 2.

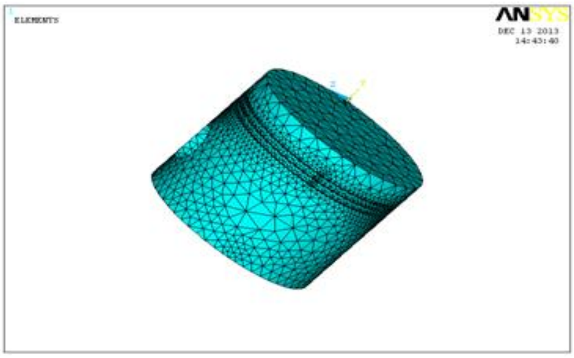
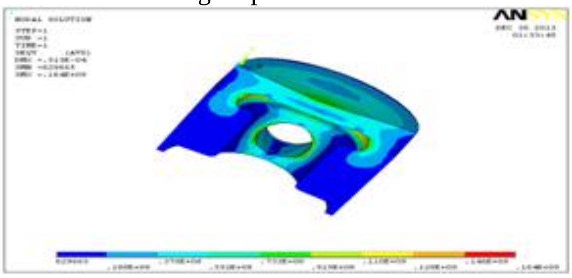


Figure 3.2 Meshing of Piston

3.4 Analysis of piston using static stress analysis method

- Frictionless support at pin bore areas and fixed all degree of freedom.
- Downward pressure (18.66 MPa) due to gas load acting on piston head.



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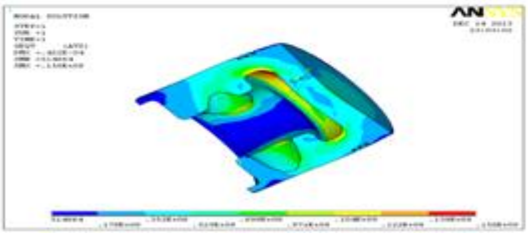

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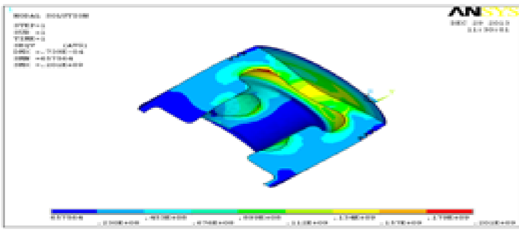

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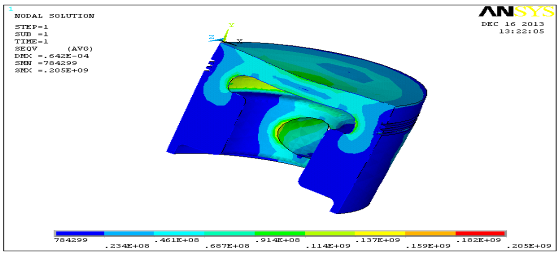
Figure 3.3 Stress analysis of (a) A2168 (b) A4032 (c) Al-GHS1300 alloy pistons

3.5 Comparative Analysis of three Aluminum alloys under static stress analysis method.

The load variation analysis is performed for the three different piston alloys. The load is varied from 125% to 250% of the calculated pressure of the Bajaj Kawasaki four stroke petrol engine.



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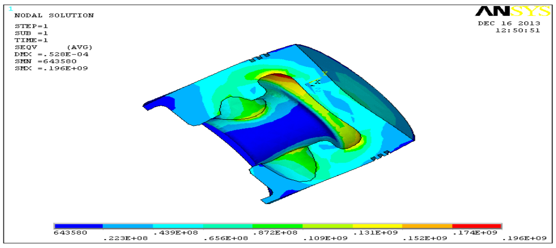

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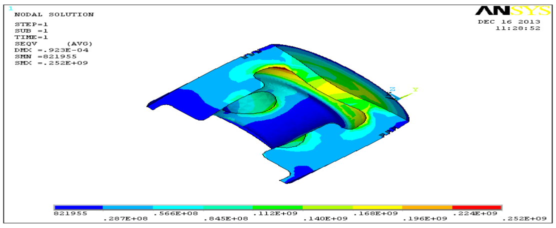

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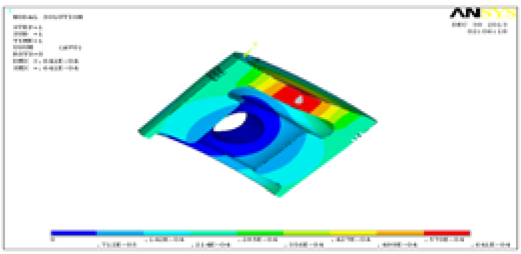
Figure 3.4 Stress at 125% pressure on (a) A2168 (b) A4032 (c) Al-GHS1300 alloy pistons



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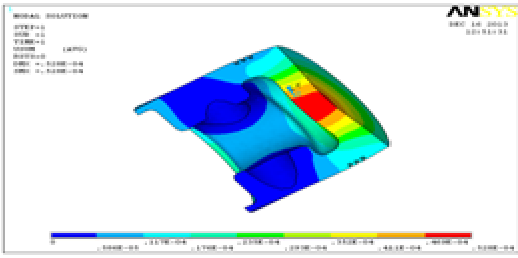

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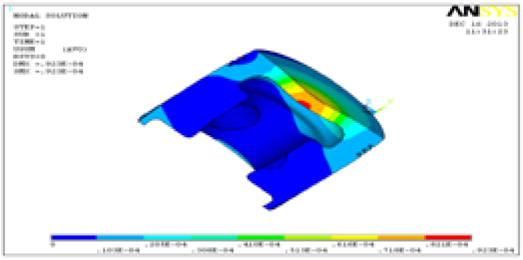

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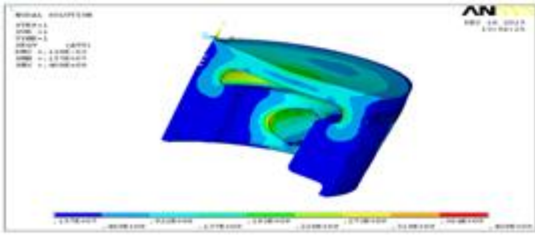
Figure 3.5 Deformation at 125% pressure on (a) A2168 (b) A4032 (c) Al-GHS1300 alloy pistons

The values of stress and deformation at 150% to 225% load are recorded in Table 4.1, all the figures are not been included, in order to avoid confusion. The stress and deformation at 250% load are as following:



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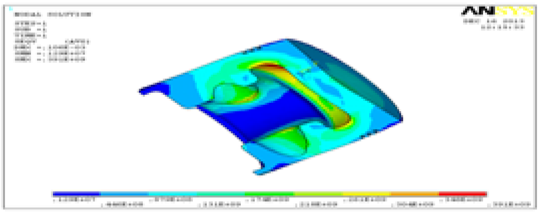

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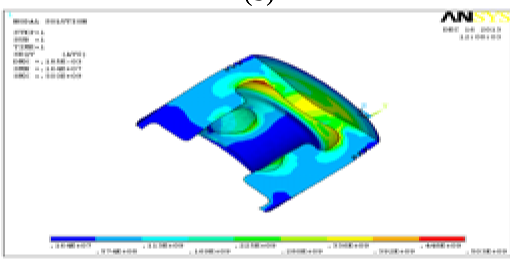

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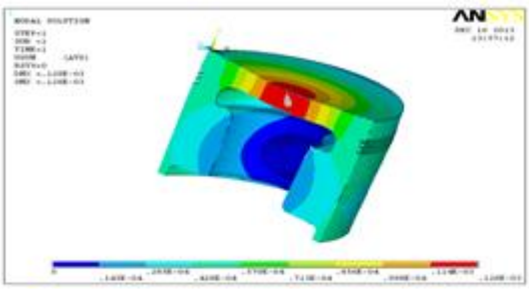
Figure 3.6 Stress at 250% pressure on (a) A2168 (b) A4032 (c) Al-GHS1300 alloy pistons



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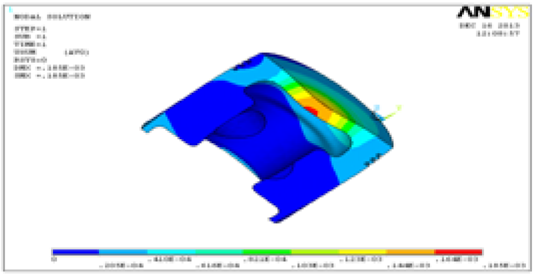

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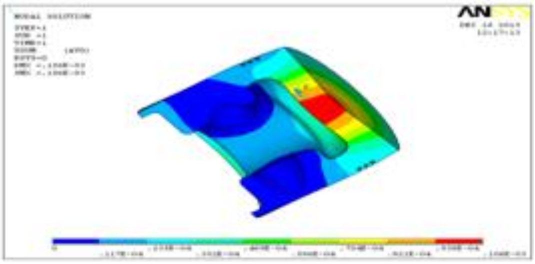

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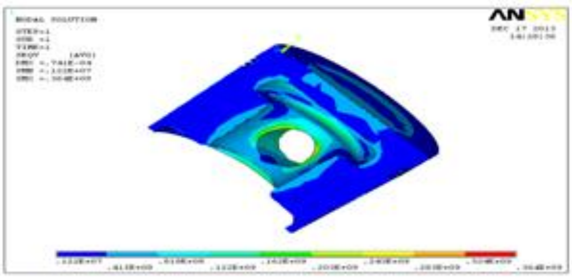
Figure 3.7 Deformation at 250% pressure on (a) A2168 (b) A4032 (c) Al-GHS1300 alloy pistons

3.6 Analysis of piston under thermal and mechanical loads (coupled field)

- Frictionless support at pin bore areas.
- Downward pressure (18.66 MPa) to gas load acting on piston head.
- Temperature and heat transfer coefficient applied to the piston.

SN	PISTON REGION	TEMP (K)	HEAT TRANSFER COEFFICIENT (W/m^2K)
1.	Piston Head	623	300
2.	Width of top land	603	160
3.	Piston Ring Area	523	120
4.	Piston skirt land	413	600

Table 3.1 Temperature and heat transfer coefficient applied to the piston.



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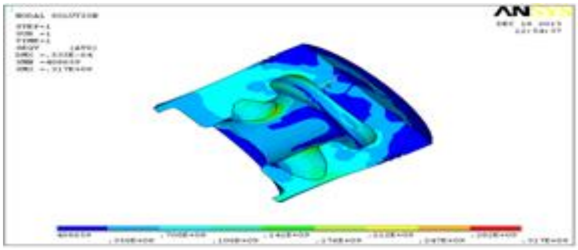

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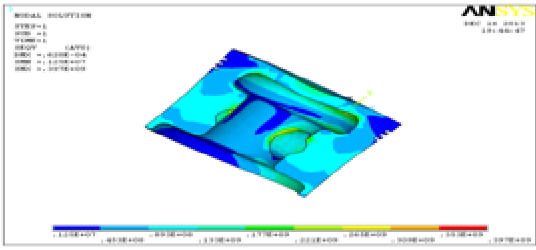

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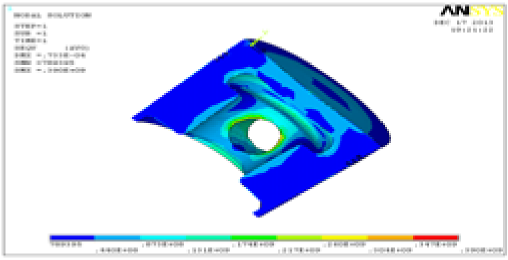
Figure 3.8 Stress at coupled field on (a) A2168 (b) A4032 (c) Al-GHS1300 alloy pistons

3.7 Comparative Analysis of three Aluminum alloys under coupled field analysis.

The coupled field variation analysis is performed for the three different piston alloys. The load is varied from 125% to 250% of the calculated pressure of the Bajaj Kawasaki four stroke petrol engine.



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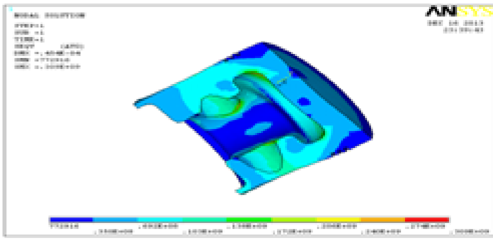

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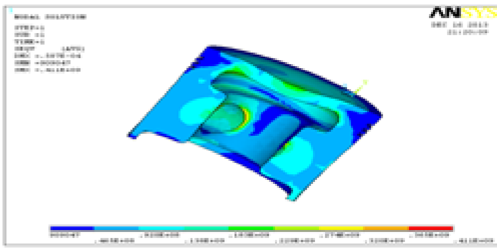

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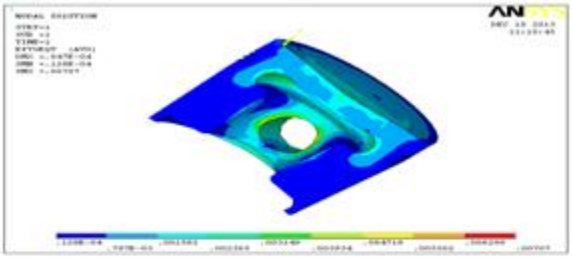
Figure 3.9 Stress at coupled field with 125% load (a) A2168 (b) A4032 (c) Al-GHS1300 alloy pistons

The values of stress under coupled field at 150% to 225% load are recorded in Table 4.2 , all the figures are not been included, in order to avoid confusion. The stress at 250% load are as following:



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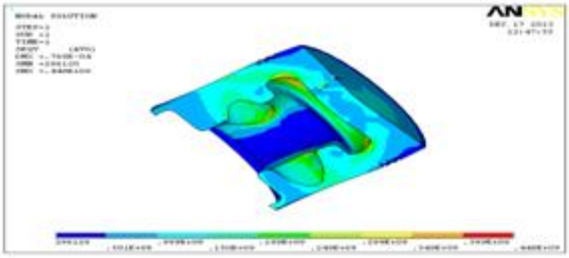

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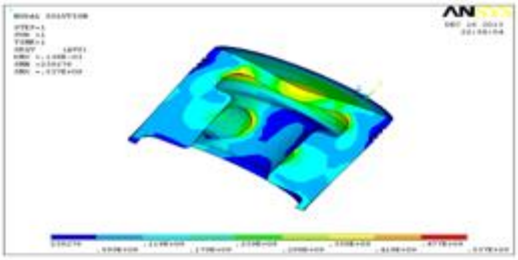

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Figure 3.10 Stress at coupled field with 250% load (a) A2168 (b) A4032 (c) Al-GHS1300 alloy pistons

3.8 Selection of Best suited Aluminium alloy piston

Depending on the parameters listed in Table 4.3, the best suited Aluminium alloy is selected for the design of piston of Bajaj Kawasaki four stroke petrol engine.

3.9 Optimization of model for mass reduction

After selecting the best suited material, we found that the FOS for Al-GHS1300 is 6, so further reduction of mass is possible with this material. While in the other materials, the FOS is 2.56 (A2618) and 2.02(A4038), so mass reduction is impossible with these materials.

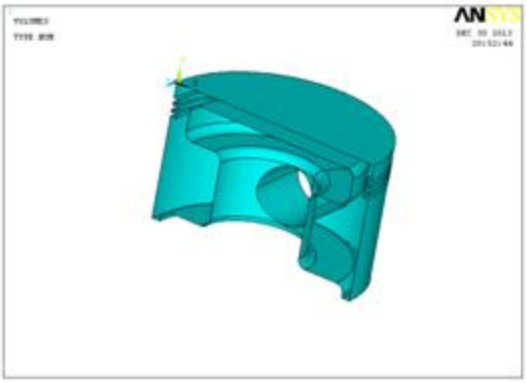
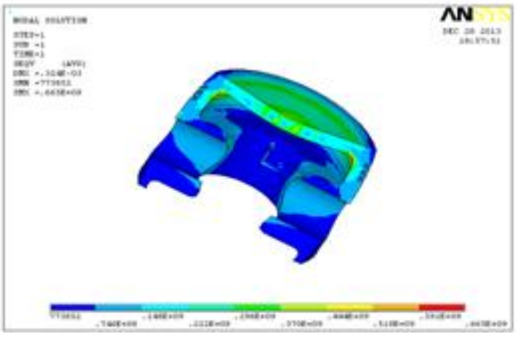


Figure 3.11 Optimized model of piston

3.10 Analysis of the optimized model under static stress



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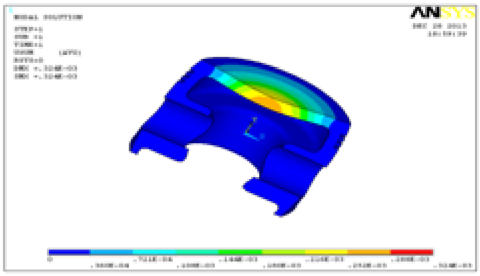

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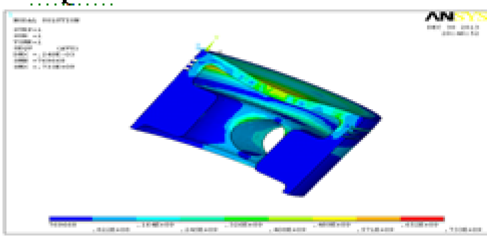
Figure 3.12 (a) Stress and (b) Deformation under static stress analysis for optimized piston

3.11 Analysis of the optimized model under coupled field



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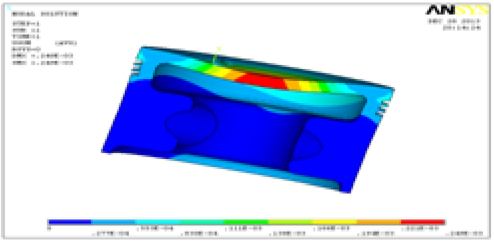

(b)

Figure 3.13 (a) Stress and (b) Deformation under coupled field for optimized piston

IV. RESULTS

The values of deformation, stress and strain at different load conditions are recorded in Table 4.1

SN	PRESSURE/ LOAD (MPa)	MATERIAL	ANSYS RESULTS		
			DEFORMATION (mm)	STRESS (MPa)	STRAIN
1	125% (23.32)	A2168	0.0642	205	0.002791
		A4032	0.0528	196	0.00248
		Al-GHS 1300	0.0923	252	0.002577
2	150% (28)	A2168	0.077	246	0.00335
		A4032	0.634	235	0.002977
		Al-GHS 1300	0.111	302	0.003094
3	175% (32.66)	A2168	0.0898	286	0.003908
		A4032	0.0739	274	0.003473
		Al-GHS 1300	0.129	352	0.003609
4	200% (37.32)	A2168	0.103	327	0.004465
		A4032	0.0844	313	0.003969
		Al-GHS 1300	0.148	403	0.004124
5	225% (41.985)	A2168	0.115	368	0.005
		A4032	0.095	352	0.004465
		Al-GHS 1300	0.166	453	0.004639
6	250% (46.65)	A2168	0.128	409	0.005582
		A4032	0.106	391	0.00496
		Al-GHS 1300	0.185	503	0.005155

Table 4.1 Deformation, stress and strain under different loading conditions

The values of deformation, stress and strain under coupled field are recorded in Table 4.2

SN	PRESSURE/ LOAD (MPa)	MATERIAL	ANSYS RESULTS		
			DEFORMATION (mm)	STRESS (MPa)	STRAIN
1	125% (23.32)	A2168	0.0733	390	0.005305
		A4032	0.0454	345	0.00401
		Al-GHS 1300	0.0587	411	0.4299
2	150% (28)	A2168	0.0727	416	0.005658
		A4032	0.0475	373	0.004373
		Al-GHS 1300	0.0649	436	0.004502
3	175% (32.66)	A2168	0.0725	442	0.00601
		A4032	0.0509	401	0.004736
		Al-GHS 1300	0.0831	461	0.004824
4	200% (37.32)	A2168	0..0761	468	0.006363
		A4032	0.0537	429	0.005099
		Al-GHS 1300	0.101	486	0.005087
5	225% (41.985)	A2168	0.0804	495	0.006716
		A4032	0.0663	457	0.005462
		Al-GHS 1300	0.120	512	0.00535
6	250% (46.65)	A2168	0.0847	521	0.00707
		A4032	0.0768	485	0.005826
		Al-GHS 1300	0.138	537	0.005613

Table 4.2 Deformation, stress and strain under coupled field

The best suited material is selected on the basis of the parameters mentioned in Table 4.3 below.

SN	PARAMETER	A2618	A4032	Al-GHS 1300
1.	Volume (mm^3)	55320	57482	54009
2.	Weight (gm)	153.13	154.34	141.06
3.	Inertia Force (N)	1229.217	1238.93	1132.328
4.	FOS	2.56	2.02	6.07
5.	Strain	0.004953	0.001984	0.002062
6.	Stress (MPa)	164	156	201
7.	Deformation (mm)	0.0714	0.422	0.739

Table 4.3 Parameters for selection of material

The results before and after optimization of Al-GHS 1300 are recorded in Table 4.4

SN	PARAMETER	BEFORE	AFTER
1.	Thickness of Piston head (mm)	4	3.2
2.	Width of top land (mm)	4	3.2
3.	Piston Barrel (mm)	7.76	4.4
4.	Skirt length (mm)	30.6	25
5.	Thickness of Piston pin boss (mm)	6	2.14
6.	Volume (mm^3)	54009	42582
7.	Weight (gm)	141.06	118.38

Table 4.4 Parameters of Al-GHS 1300 before and after optimization

V. CONCLUSION

It is concluded from the results that the weight and volume of Al-GHS 1300 is least among the three materials. Hence the inertia forces are less, which enhances the performance of the engine. The FOS of Al-GHS 1300 is 6, much higher than the other materials, so further development of high power engine using this material is possible. Further research may be done to select a material with less weight and higher strength, so as to reduce the inertia forces.

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