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DESIGN AND ANALYSIS OF IC ENGINE COMBUSTION CHAMBER AND PISTON BY COMPOSITE MATERIALS (AL & MG) USING FINITE ELEMENT ANALYSIS

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Abstract: Among all automotive and other industrial area components, engine pistons and combustion chambers are the most complicated. The development of an IC Engine with greater power capacity has been discovered to be appealing by the present trend. The goal of lightening the structure's weight and, by extension, reducing fuel consumption, is one of the design criteria. A better engine design has made this possible. The "Heart" of the engine is the piston and combustion chamber, and their operating conditions are the worst of all the major engine components. Therefore, it is crucial for the combustion chamber and piston's design and structural analysis.

Thermal analysis and structural analysis are performed in this research. Operating gas pressure, temperature, and the material characteristics of the piston and combustion chamber are the parameters considered for the analysis. Boundary conditions employed in the analysis of pistons include pressure on the piston head under operating conditions, unequal temperature distribution from the piston head to the skirt, and heat flux and pressure for combustion chambers.

In the current work, a single-cylinder, air-cooled combustion chamber and piston are created using Catia V5 software and saved in.igs format. The design is then loaded into the software Ansys (18.1 version), where analysis is then carried out. On various alloys of aluminium and magnesium, static structural analysis is first carried out, followed by thermal analysis, and the results are compared with those from FEA analysis. At the conclusion, the static structural analysis yielded three separate values: simulated outcomes, theoretical results, and percent error. The results have demonstrated that while an alloy containing a higher percentage of magnesium can tolerate high pressure and stress, the degree of deformation that results is also quite significant.

Key words: - *Hoop stress, Longitudinal stress, Deformation, Heat flux, Temperature etc.*

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NOMENCLATURE:

1.	I.P = Indicated Power.
2.	B.P = Brake Power.
3.	P_{imep} = Indicated Mean Effective Pressure.
4.	d = Cylinder bore diameter.
5.	Pa = Atmospheric Pressure.
6.	r = Compression ratio.
7.	e = Cutoff ratio.
8.	l = length of stroke.
9.	L = Actual length of cylinder.
10.	t = Thickness of Cylinder
11.	ή = Mechanical efficiency.
12.	¥ = Heat capacity ratio.
13.	N = Engine speed in RPM.
14.	A= Area of cylinder bore.
15.	$ή_v$ = Volumetric effciency
16.	$ɗ_{air}$ = Density of air.
17.	m_{air} = Mass of air.
18.	m_{fuel} = Mass of fuel.
19.	C.V = Calorific value of fuel.
20.	v_a = Actual volume sucked.
21.	v_t = Total volume of cylinder.

22.	Thickness of piston head(th).
23.	Piston ring width (b).
24.	Piston ring height (h).
25.	Top land height (h_1).
26.	Distance b/w two rings (h_2).
27.	Length of piston (l).

1. INTRODUCTION: The combustion chamber is the place within an engine where the fuel-air mixture is compressed with the help of piston and then ignited. The better the combustion chamber is designed the better the engine breathes i,e higher the volumetric efficiency, higher the efficiency of the engine, which is somewhat also depends on design of combustion chamber. Because of importance of its design, considerable number of research and development has been done, due to which the compression ratio has been increased from 4:1 before the 1st world war period to 8:1 to 11:1 in current scenario. One of the major problems in case of I.C engine is the loss of useful energy produce during the combustion due to which thermal efficiency decreases. This loss in exergy decreases the overall pressure over the piston which in turn decreases the net torque on crank. To reduce this loss of exergy to some extent Magnesium with Aluminum has been used as composite. ***Dayadi Nageswararao et al. (2016)*** have designed a cylinder fin in ANSYS workbench 15.0 modeling software. Authors attempted to use mild steel, grey cast iron, magnesium alloy, and aluminium alloy in place of aluminium alloy 204 in this project. The fin has a circular cross section with a rectangular form. Author changes the distance between 2 fins and the thickness of the fins from 3mm to 2-2.5mm, both by lowering the thickness and altering the distance between the next fins. Increasing efficiency as a result. When magnesium alloy is employed, the weight of the fin body is decreased. The fin body has undergone thermal examination by the author using several materials, geometries, and thicknesses. According to the analysis' findings, utilising circular fins made of aluminium alloy with a thickness of 2.5 mm is preferable since it increases heat transfer rate. However, employing round fins makes the fin body heavier. In light of this, the author has determined that employing aluminium alloy is preferable. ***Alexey Alexandrovich Gorshkalev et al. (2014)*** has done thermal analysis of combustion chamber and gas dynamics analysis for combustion chamber which shows Thermal condition calculation for crank mechanism and strength analysis method for crank mechanism of that chamber at the end of combustion chamber. For gas dynamics analysis, author used k-epsilon method for turbulence. for strength analysis static structural analysis are done in ANSYS software. After above analysis pressure reaches to 6.18 MPa and max temperature of combustion is 2514 K.

2. DESIGN OF COMBUSTION CHAMBER AND PISTON: The design of the combustion chamber follows the steps and guidelines outlined in the book Machine Design (Bhandari V. B., 2010) and Thermodynamics (Incropera F. P,1996).

2.1 Design Consideration for Combustion chamber and piston:

a) It should have enough strength to sustain fluctuating high temperature and pressure.
b) It should have high fatigue life.
c) Materials of Combustion chamber and piston should be corrosion resistant.
d) Deformation should be minimum.
e) Wear and Tear should be minimum due to continuous reciprocating motion of piston.
f) The piston should weight a minimum amount to withstand the forces of inertia.
g) The cylinder should effectively create an oil seal.
h) It needs to be sufficiently rigidly built to withstand mechanical and thermal distortions.

2.2 Procedure for Combustion chamber Design parameters (For structural analysis): Different combustion chamber parameters have been evaluated in this procedure. Firstly, the Indicated power and Indicated mean effective pressure are evaluated by assuming certain parameters like speed and mechanical efficiency, after that diameter and length are evaluated (Bhandari V. B. 2010).

(1) Indicated Power (I.P):

I.P = B.P/ή (J/s)

taking ή = 80% = 0.8

At 3000 RPM, B. P = 36 $*10^3$ (approx)

I.P = $36*10^3/0.8$

I.P = $45*10^3$ (J/s).

(2) Indicated Mean Effective pressure:

$$P_{imep} = \mathbf{Pa} * \mathbf{r}^{¥} \frac{[\,¥(\mathbf{e}-\mathbf{1}) - \mathbf{r}^{\mathbf{1}-¥}\,(\mathbf{e}^{¥}\ -\mathbf{1})]}{[(¥-\mathbf{1})(\mathbf{r}-\mathbf{1})]}$$

following data are assumed.

¥ = 1.4

r = 13.

e = 5 - 8% of 1.15* Average length of stroke (131.8 mm).

P_{imep} = 1264.18KPa.

(3) Bore of Combustion chamber:

$$\boldsymbol{I.P} = (\boldsymbol{P_{imep}} * \boldsymbol{A} * \boldsymbol{L} * \boldsymbol{N}/2)/60\ \boldsymbol{kW}$$

I.P=45.

N = 3000 RPM

$$A = \frac{\prod d^2}{4}$$

l=1.3 *d.

d=106.588 mm.

(4) Length of stroke:

l/d = 1.3.

l = 1.3*d.

l = 137.8 mm

(5) Total Length of Cylinder:

L = l *1.15

L=159 mm (approx)

(6) Thickness criteria for Combustion chamber (thin cylinder):

Taking limiting condition for thin cylinder.

d ≥ 20*t.

t = 5.4 mm (approx)

(7) Apparent Hoop stress and Longitudinal stress:

$$σ_h = \frac{P_{max} * d}{2 * t}$$

$$σ_l = \frac{P_{max} * d}{4 * t}$$

Where,

$σ_h$ = Theoretical Hoop stress.

$σ_l$ = Theoretical Longitudinal stress.

P_{max} = 8*P_{imep}. (Assumed).

(8) Actual Hoop stress and Longitudinal stress:

$$σ'_h = σ_h - μ * σ_l$$

$$σ'_l = σ_l - μ * σ_h$$

Where,

$σ'_h$ = Actual hoop stress.

$σ'_l$ = Actual longitudinal stress.

μ = Poisson ratio of cylinder material.

(9) Rectangular annular fin:

Thickness of fins = 2 mm.

Characteristic length = 54.44 mm.

From the above expression the below tabulated parameters are calculated in Table I:

Table I: Design Parameters

S.No	Design Parameters	Value J/s
1	Indicated Power	45*10^3 J/s
2	Indicated Mean effective pressure	1264.18 KPa
3	Bore of Combustion chamber	106.588 mm
4	Length of stroke	137.8 mm
5	Total length of cylinder	159 mm
6	Thickness of cylinder	5.4 mm

Combustion chamber was modeled using CATIA V5 which is shown in the given Figures:

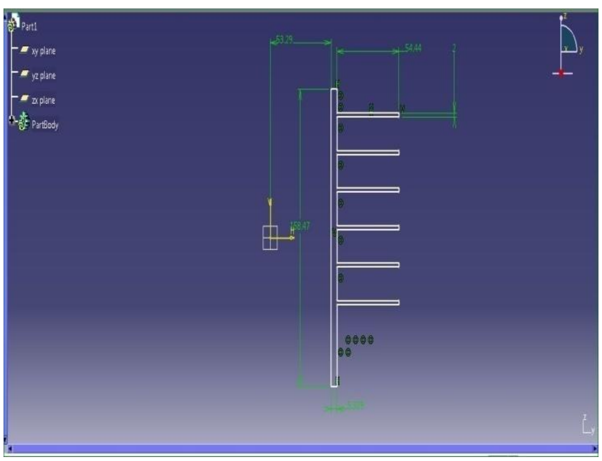


Figure 1. 2D Sketch of Combustion Chamber

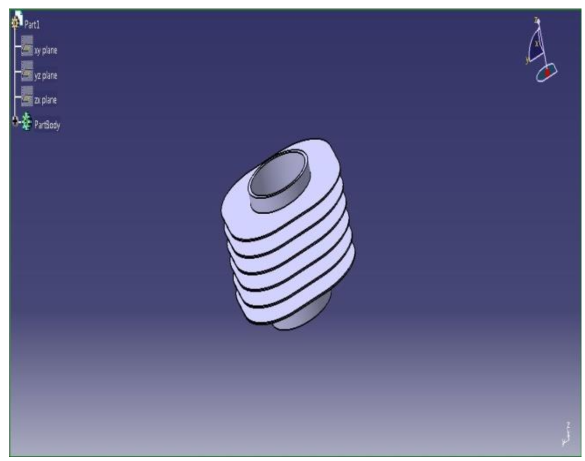


Figure 2. Combustion Chamber with Fins

Combustion chamber created in CatiaV5 software is now ready to import in Ansys software for further analysis.
3. MESHING OF COMBUSTION CHAMBER: After the combustion chamber are modeled in CATIA V5 software, it is imported in Ansys 18.1 version software where FEA analysis will be done (Dayadi N et al., 2016). In

S. No	Meshing Parameters	Parameter Values
1	Number of nodes	430055
2	Number of elements	232189
3	Inflation (Maximum layers)	5
4	Relevance	100
5	Elements size	0.003m

FEA analysis, large and complex shape domains are broken down into smaller domain called elements. This process is called Meshing. Each elements have certain nodes over which Ansys software calculate unknown variables using governing differential equation (GDE) and shown in **Table II**

Table II: Meshing Parameters of Combustion Chamber

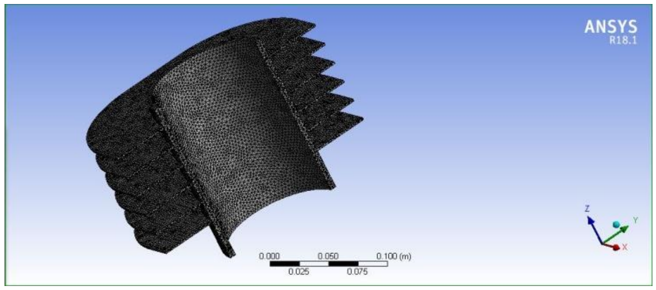


Figure III Meshing of Combustion Chamber

3.1 Boundary Condition: For Hoop stress or circumferential stress, pressure of 10.113 MPa (taken from above calculation) are applied on normal to inner face of cylinder. Displacement have been kept free in circumferential direction and restricted in other two direction, i.e in radial and longitudinal direction as analysis are done in cylinder coordinate. For Longitudinal stress, Pressure of 10.113 MPa are applied perpendicular to the plane of top surface of cylinder and kept the bottom surface fixed. This boundary condition has been kept same for all static structural analysis of different w/w alloy material (Venkatareddy et al. 2016, Saigakov E.A et al. 2014).

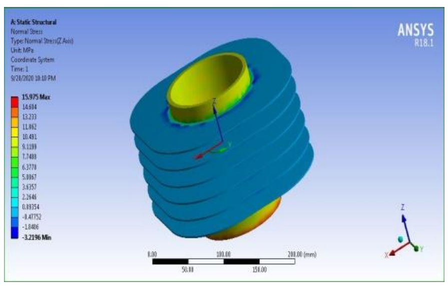


Figure IV: Longitudinal stress of 50%Al - 50%Mg

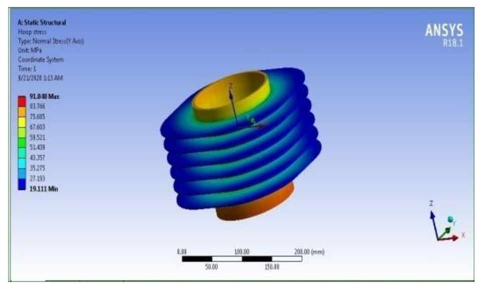


Figure V: Hoop stress of 50%Al - 50%Mg

Table III Comparison b/w simulated and theoretical result of 50% Al & 50%Mg

S. No	Result	Longitudinal stress (MPa)	Hoop stress (MPa)
1	Simulated result	15.975 MPa	91.848 MPa
2	Theoretical result	16.93 MPa	84.46 MPa
3	Error Percent	5.64%	8.49%

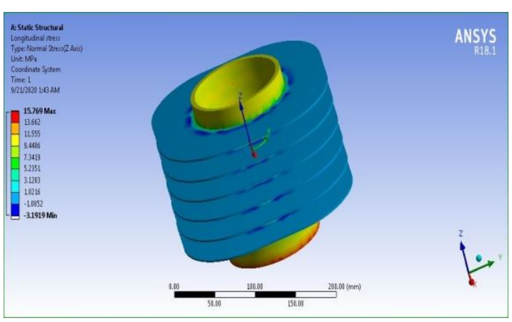


Figure VI: Longitudinal stress of 40%Al - 60%Mg

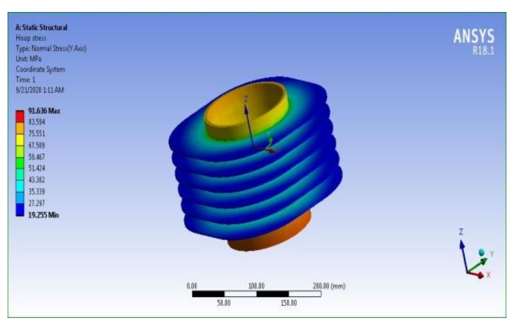


Figure VII: Hoop stress of 40%Al - 60%Mg

Table IV: Comparison b/w simulated and theoretical result of 40% Al & 60%Mg

S.No	Result	Longitudinal stress (MPa)	Hoop stress (MPa)
1	Simulated result	15.769 MPa	91.636 MPa

2	Theoretical result	16.89 MPa	84.32 MPa
3	Error Percent	6.63%	8.62%

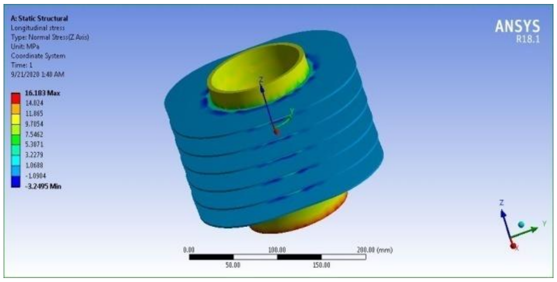


Figure VIII: Longitudinal stress of 60%Al-40%Mg

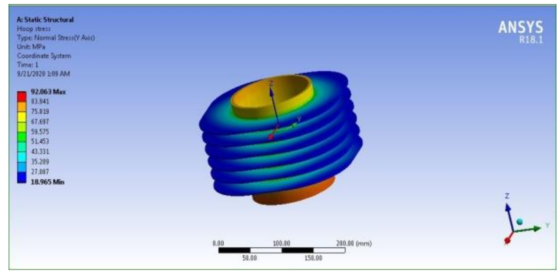


Figure IX: Hoop stress of 60%Al-40%Mg

Table V: Comparison b/w simulated and theoretical result of 60% Al & 40%Mg

S. No	Result	Longitudinal stress (MPa)	Hoop stress (MPa)
1	Simulated result	16.183 MPa	92.063 MPa
2	Theoretical result	15.94 MPa	84.25 MPa
3	Error Percent	5.38%	9.19%

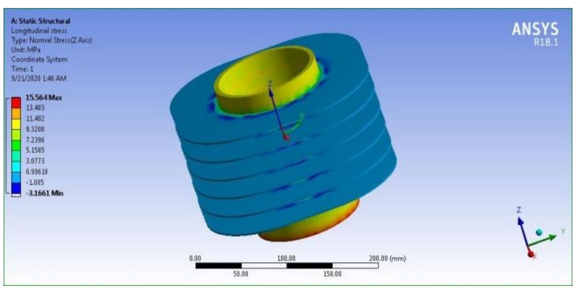


Figure X: Longitudinal stress of 30%Al-70%Mg

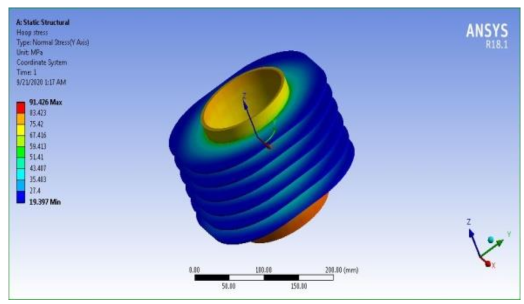


Figure XI: Hoop stress of 30%Al - 70%Mg

Table VI: Comparison b/w simulated and theoretical result of 30% Al & 70% Mg

S.No	Result	Longitudinal stress (MPa)	Hoop stress (MPa)
1	Simulated result	15.564 MPa	91.426 MPa
2	Theoretical result	16.85 MPa	84.187 MPa
3	Error Percent	7.63%	8.59%

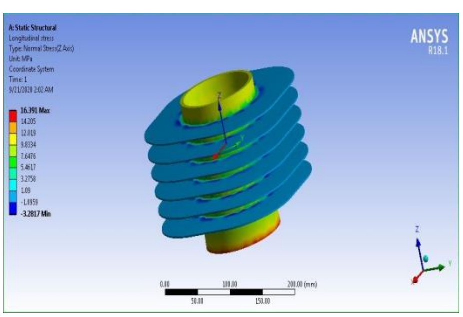


Figure XII: Longitudinal stress of 70%Al-30%Mg

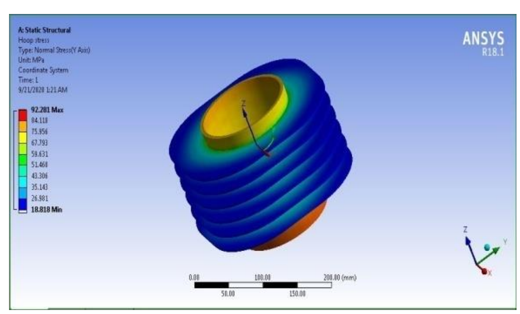


Figure XIII: Hoop stress of 70%Al - 30%Mg

Table VII: Comparison b/w simulated and theoretical result of 70% Al & 30%Mg

S. No	Result	Longitudinal stress (MPa)	Hoop stress (MPa)
1	Simulated result	16.391 MPa	92.281 MPa
2	Theoretical result	15.28 MPa	84.6 MPa
3	Error Percent	7.27%	9.07%

4. STATIC THERMAL ANALYSIS OF COMBUSTION CHAMBER: The combustion chamber is a turbo-engine component where fuel, supplied by fuel feeding nozzles, is mixed with air which comes from the compressor. Structural static analysis shall be performed on combustion outer case for operating internal pressure and thermal loads (Dayadi N et al. 2016).

(1) Volumetric efficiency.

$\acute{\eta}_v = V_a/V_t$

$0.8 = V_a / (\prod/4 * d^2 * l)$

$0.8 = V_a / (\prod/4 * 0.106^2 * 0.158)$

$V_a = 0.0011148\ m^3$.

(2) Mass of sucked air/cycle(kg).

$m_a = V_a * d_{air}$

$m_a = 0.0011148 * 1.225$.

$m_a = 0.00135975$ kg.

(3) Air - Fuel ratio.

$m_a / m_f = 12{:}1$ **(assumed)**

$m_a/12 = m_f$

$0.00135975/12 = m_f$

$m_f = 0.00011381$ kg/cycle.

(4) Energy released/sec (MJ).

Energy released/cycle, $E = m_f * C.V$

$E = 0.00011381 * 45.5*10^6$

E = 5155.15 J.

N = 3000RPM

No. of power stroke/min = 3000/2 = 1500

No. of power stroke/sec = 1500/60 = 25

Energy released/sec = E * 25 = 5155.15 * 25 = 128878.75 J.

(5) Heat Flux & Volumetric heat generation.

Heat Flux = Energy released / cylinder area.

Heat Flux = 128878.75/(∏*d*l)

Heat Flux = 128878.75/ (∏*0.106*0.158) = 2.45MJ/m²

Heat generation/volume = 128878.5 / $(\prod/4 * d^2 * l)$

Heat generation/volume = 92.478MJ/m³

(5) Heat Transfer Coefficient (HTC)

Different parts of combustion chamber face different environment, so the heat transfer coefficient will be different in different parts of combustion chamber.

(6) Turbulent Convective Heat Transfer correlation

$Nu = a(Re)^{0.85}$

hl/k = a((V*l)/√)0.85

$(h*0.106)/0.15 = 0.8\ ((16.642*0.106)/100*10^{-6})^{0.85}$

h=4606.91 W/m²K.

4.1 Boundary Condition: Inner wall of combustion chamber comes in direct contact with hot gas, so heat transfer coefficient as calculated above is 4606.91 W/m²K and temperature of hot gases (Surrounding temperature of inner wall) = 1500° C. Heat flux on the inner wall as evaluated above is 2.45MJ/m²

4.2 Analysis and Result for Temperature Distribution

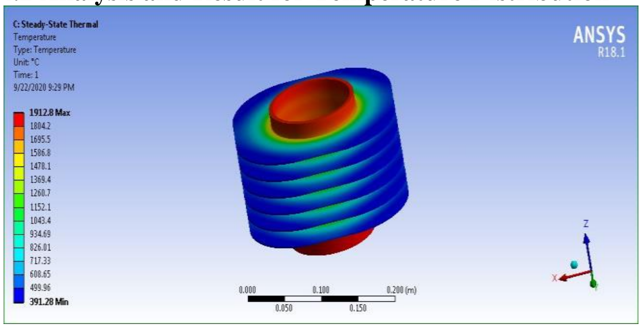


Figure XIV: 50%Al & 50%Mg

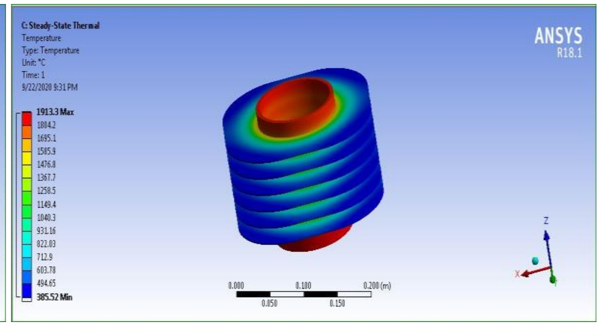


Figure XV: 40%Al & 60%Mg

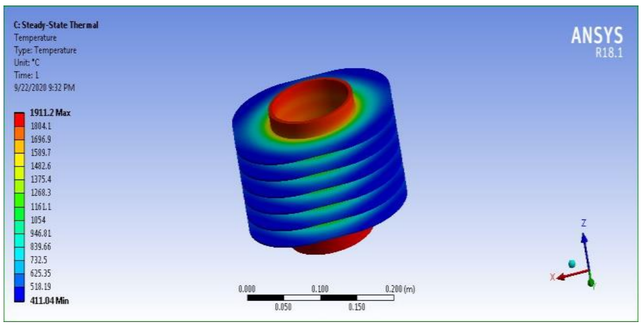


Figure XVI: 60%Al & 40%Mg

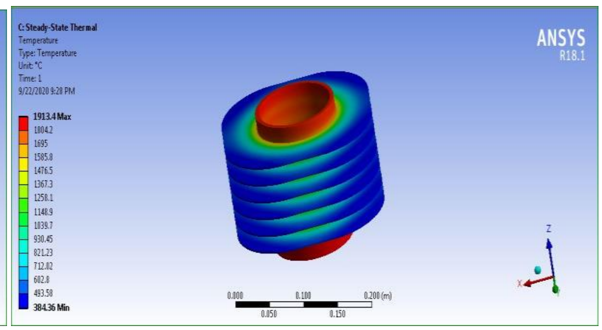


Figure XVII: 30%Al & 70%Mg

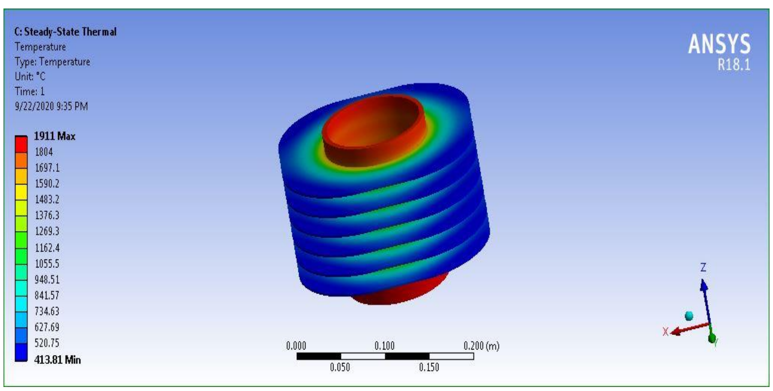


Figure XVIII: 70%Al & 30%Mg

Table VIII: Temperature distribution in combustion chamber in different alloys

Composition	**Maximum Temperature (in Celsius)**	**Minimum Temperature (in Celsius)**
50%Al - 50%Mg	1912.8	391.28
40%Al - 60%Mg	1913.3	385.52
60%Al - 40%Mg	1911.2	411.04
30%Al - 70%Mg	1913.4	384.36
70%Al - 30%Mg	1911	413.81

5. PROCEDURE FOR PISTON DESIGN: Pistons are made with characteristics that serve distinct purposes when an engine is running. The majority of the initial pressure and thrust generated by combustion is applied to the piston head or crown. Rapid directional shifts expose the piston pin area to a substantial amount of force. Additionally, it experiences thermal expansion as a result of heat being transferred from the piston's head to its body. More thermal expansion can occur in the piston pin area than in other places (Sroka Z. J. et al. 2012). The following is an illustration of the appropriate piston design procedures:

5.1 Thickness of piston head:

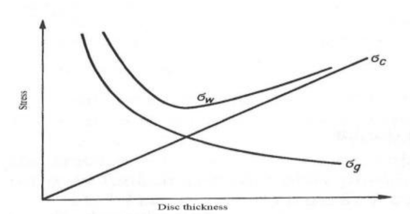


Figure-XIX: Two criteria relations

Where, **σ_g = Load stress and σ_c = Thermal stress.**

As we can see from above graph that there are two criteria for calculating piston head thickness and there is an optimal thickness where the least stress in the crown is given, which is as follows:

1) On the basis of strength.

2) On the basis of heat dissipation.

I) On the basis of strength:

$$t_b = \frac{D\sqrt{3 * P_{max}}}{16 * \sigma_t}$$

Where, D = Diameter of bore.

P_{max} = Maximum pressure on piston crown.

σ_t = Tensile stress of piston material.

Taking maximum pressure =10MPa and tensile stress = 150 MPa.

Diameter of bore as calculated above = 107mm (approx).

t_h = 12mm(approx).

II) On the basis of heat dissipation:

(1) $t_b = \left[\frac{H}{12.56 * k * (T_c - T_e)}\right] * 10^3$

Where,

H= Heat flow through piston head = (0.05 * heat flux)

k= Thermal conductivity of piston material.

T_c & T_e = Difference in temperature b/w center and edge of piston crown, taking thermal conductivity = 125W/m-K and temperature difference b/w center and edge is taken as 160°C.

t_h = 25mm (approx).

As we can see that two different values of thickness are obtained, so thickness of higher value should be chosen for safety.

(2) Piston ring width:

$$b = \frac{D\sqrt{3 * P_w}}{\sigma_t}$$

Where,

B = Piston ring width.

Taking D = 107mm and P_w = 0.042MPa.

b = 3.62mm (approx).

Height of piston ring, h = 0.7b to b = 2.53 mm.

(3) Top land

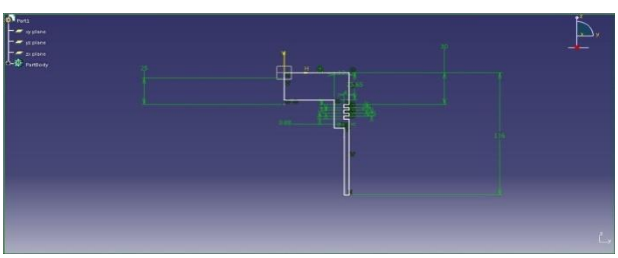
$h_1 = 1.2 * t_h = 30.78mm$

Distance b/w two rings, $h_2 = 0.75 * h \text{ to } h = 2.53mm.$

(4) Piston barrel
Top land thickness,
$t_3 = (0.03*d) + b + 4.9 = 11.11$mm.
Piston bottom thickness, $t_4 = 0.25*t_3$ to $0.35*t_3 = 3.88$mm.
(5) Length of piston
Length of piston, $L = 1.1*D = 117.7$mm.
(6) Piston pin length within bush
$l_1 = 0.45*D$.
$l_1 = 16$mm.
(7) Outer and inner diameter of piston pin.
$D_o = 38$mm (taken from reference)
$D_i = 0.6*Do = 22.8$mm.

Table IX: Design Specification for Piston

S No	Parameters	Dimensions in mm
1	Thickness of piston head (t_h)	25
2	Piston ring width (b)	3.62
3	Top land length (h_1)	30.78
4	Distance b/w two rings (h_2)	2.53
5	Top land thickness (t_3)	11.11
6	Piston skirt thickness (t_4)	3.88
7	Length of piston (L)	117.7
8	Piston pin length within bush(l_1)	16
9	Outer diameter of piston pin (D_o)	38
10	Inner diameter of piston pin (D_i)	22.8
11	Diameter of bore (D)	107



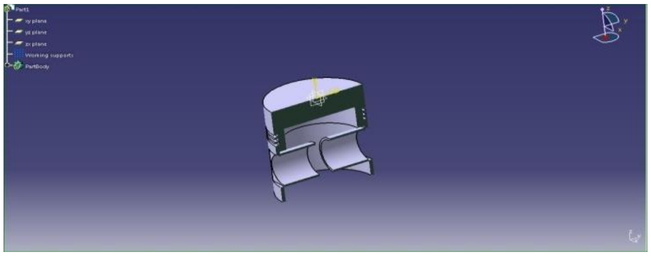


Figure XX: Piston 2D view **Figure XXI: Piston cross-section view**

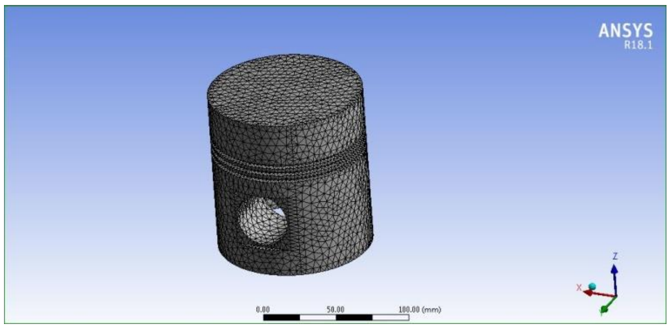


Figure XXII: Meshed model of piston

Table X: Meshing Parameters for Piston

S. No	Meshing Parameters	Parameter Values
1	Number of nodes	48035
2	Number of elements	26245
3	Inflation (Maximum layers)	5
4	Relevance	100
5	Elements size	0.00365m

5.2 Boundary condition for structural analysis of piston: Fixed support is given to the piston pin hole as the piston will move up and down with the help of piston pin fixed at pin hole. Pressure of 1.246 MPa as calculated above is applied on piston crown (Prabou R et al., 2018, Sonar D.K et al.,2015, Vaishali R.N et al., 2015, Szmytka F. et al, 2015, Saigakov E.A, 2014).

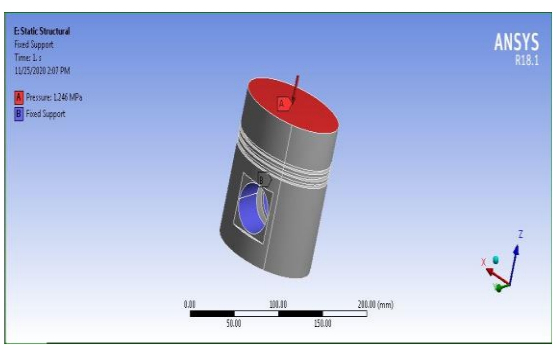


Figure XXIII: Applied pressure with fixed support

6. RESULT AND ANALYSIS FOR DEFORMATION AND STRESS:

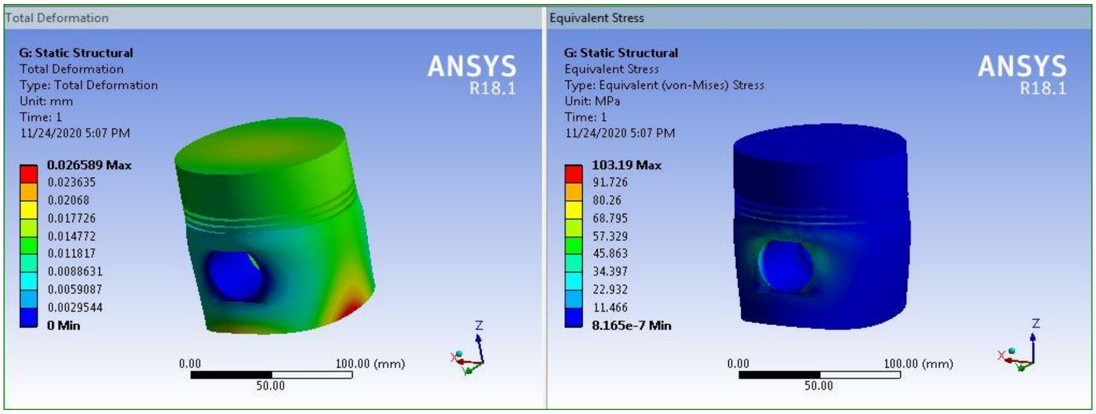


Figure XXIV: Total deformation and Equivalent (Von-mises) stress for 50%Al -50%Mg

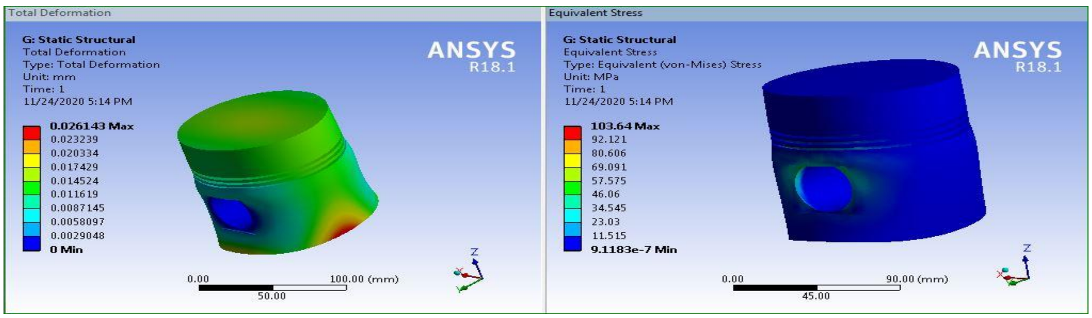


Figure XXV: Total deformation and Equivalent (Von-mises) stress for 60%Al-40%Mg

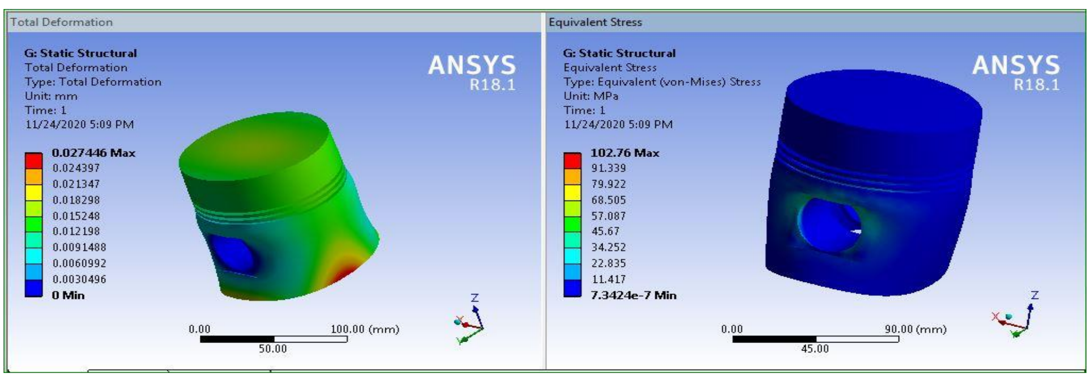


Figure XXVI: Total deformation and Equivalent (Von-mises) stress for 40%Al-60%Mg

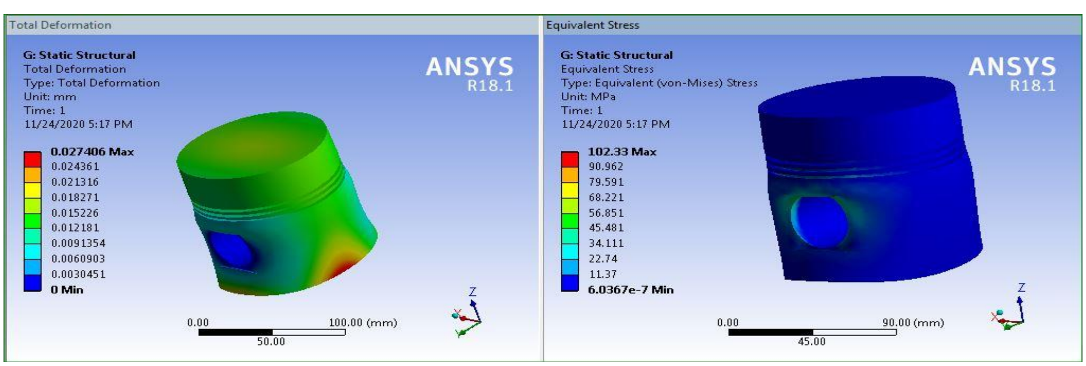


Figure XXVII: Total deformation and Equivalent (Von-mises) stress for 30%Al-70%Mg

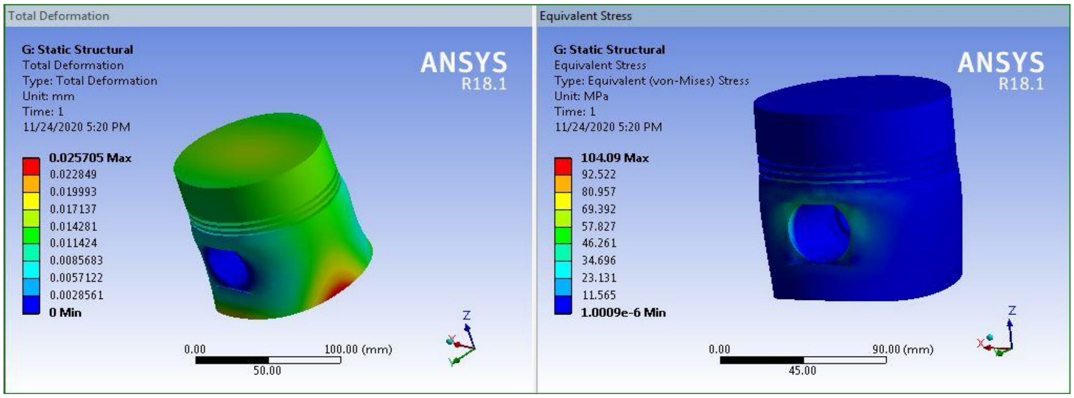


Figure XXVIII: Total deformation and Equivalent (Von-mises) stress for 70%Al-30%Mg

7. BOUNDARY CONDITION FOR THERMAL ANALYSIS: Heat Flux is given to the piston crown as calculated above = 2.45W/mm^2 (Lu Y. et al., 2017, Bhagat A. R et al., 2012).

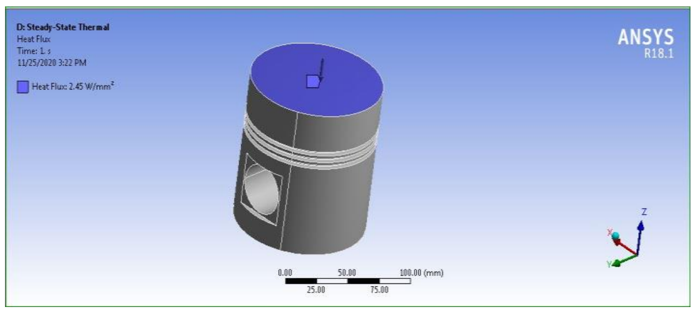


Figure XXIX: Applied Heat flux on crown.

7.1 Thermal Analysis Results:

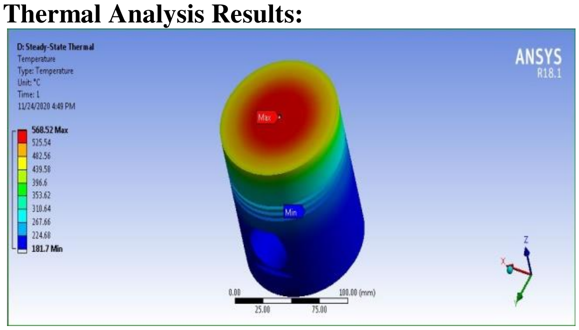


Figure XXX: 50%Al - 50%Mg

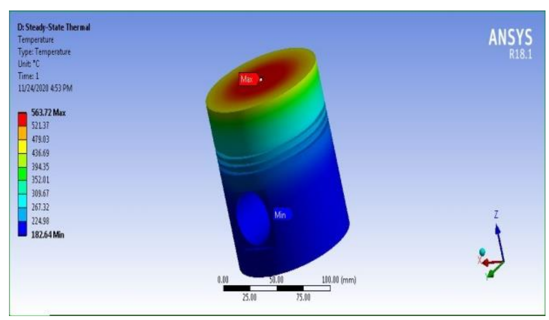


Fig XXXI: 60%Al - 40%Mg

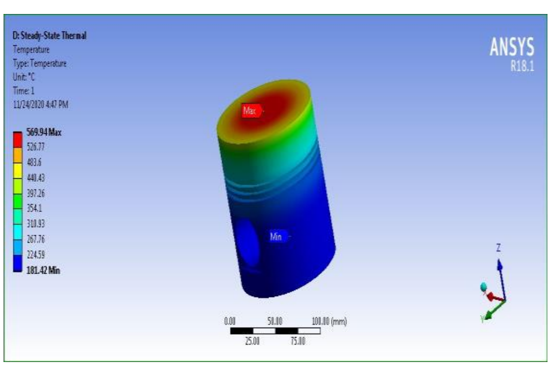
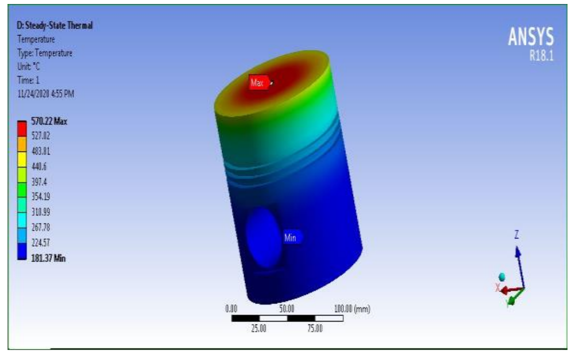


Figure XXXII: 40%Al - 60%Mg
Figure XXXIII: 30%Al - 70%Mg



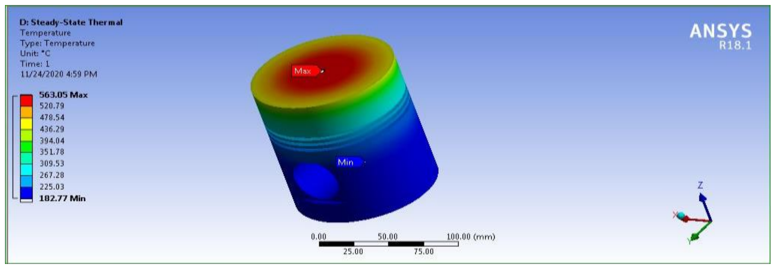


Figure XXXIV: 70%Al - 30%Mg

Table XI: Temperature distribution in Piston head in different alloys

Composition	Maximum Temperature (in Celsius)	Minimum Temperature (in Celsius)
50%Al - 50%Mg	568.2	181.7
40%Al - 60%Mg	569.94	181.42
60%Al - 40%Mg	563.72	182.64
30%Al - 70%Mg	570.22	181.37
70%Al - 30%Mg	563.05	182.77

8. CONCLUSIONS: Based on observation of the study the following conclusions are made very carefully which are depicted below:

1) It is concluded from the above study that temperature and stress produced by applying different boundary condition is within appreciable limit so the design is safe.
2) From the above results it has been concluded that with higher percentage of Magnesium in the alloy decreases the overall stress produced in the piston and combustion chamber, but at the same time deformation is also increases significantly.
3) This signify that adding a lower percentage of Magnesium in Aluminum can be considered good for optimizing stress, deformation, and temperature.

8. 1 Future Scope:

1) This work can be extended by using some more various proportional type of aluminium- Magnesium alloys as piston and combustion chamber materials
2) Aluminium- Magnesium alloys may be coated with aluminium oxides for pistons and combustion chamber working at elevated temperatures.
3) The analysis can be further carried out for thermal analysis from which we can compute the thermal stress induced in various portions of piston head and combustion chamber fins.

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