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Analysis of Magnesium-Lithium Alloy Piston

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Abstract: ***In modern automobile world, vehicle parts are created using materials that are strong and which are having minimum weight. One of the most important parts in a vehicle engine is its piston. A piston should be strong enough to withstand structural and thermal loads along with good conductivity, corrosion resistance, and it should have minimum weight to reduce inertia force due to reciprocating motion. Commonly used piston material is Aluminium alloys. Magnesium lithium alloys are ultra lightweight material having only half density than that of Aluminium alloys. Magnesium lithium alloys are less strong when compared to Aluminium alloys and they react more to thermal loads and corrosion. This project's aim is to find out whether Magnesium lithium alloys can be used as piston material. For that, piston is modeled based on basic dimensions and properties of a Maruti Omni engine. Different pistons were modeled based on properties of Aluminium alloy (B390) and Magnesium-lithium alloy (LA141), to withstand same pressure and thermal load. The pistons were then analyzed in ANSYS 16.0 software for comparison. Thermal and structural loads were applied and the combined results were studied.***

Keywords: piston, magnesium-lithium alloy, aluminium alloy, structural analysis, thermal analysis.

1. Introduction

In an IC engine, as rpm increases there is also an increase in the amount of force/hp required to change the direction of the piston and rod. The heavier the piston and connecting rod, more force is required to change its direction. At the top and bottom of each stroke, the piston comes to a stop. A force is required to get the piston moving again. The greater the weight, more force is required to move the piston. To improve the mechanical efficiency and reduce the inertia force in high speed machines, the weight of the piston must be reduced. In engine, transfer of heat takes place due to difference in temperature. During combustion and expansion process, the heat transfer takes place from the gases to the walls. So the piston ring, piston crown and the piston skirt should have enough stiffness which can endure the pressure and the friction between contacting surfaces. As an important part in engine, the working condition of piston is directly related to the durability and reliability of engine. The most commonly used materials for pistons of I.C. engines are cast iron, aluminium alloy, cast steel and forged steel. Many researchers have done projects to find out best material for pistons which have minimum weight with good thermal properties. In earlier days, magnesium was used as piston material. Magnesium is the lightest structural material. But due to its igniting character, use of the material was limited to low temperature applications. Later aluminium alloys were introduced which have good thermal properties and corrosion resistance with good strength. Recently, researchers found that alloying magnesium with earth metal creates less dense material with better properties. Advantages of magnesium alloys are

- Low density, lesser than that of magnesium.
- High specific strength.
- Good radiation absorption of electromagnetic waves.
- Good castability,
- Good machining property.
- Improved corrosion resistance.

Some disadvantages of magnesium alloys are:

- Cold forming capability is low.
- Limited corrosion resistance.
- Reduction of strength at elevated temperature.
- High chemical reactivity

Alloying Magnesium and Lithium results in creating ultra light weight material with good properties. Researches show that adding 5-10% of lithium in magnesium gives light weight material with good thermal and corrosion properties. Magnesium–lithium alloys have density from 1.35 to 1.65 g/cm^3 because of the addition of the lightest metal, Lithium (Li), which is only nearly half the density of Aluminium-based alloys. Alloying magnesium with lithium can also change the crystal structure of magnesium. The Mg–Li base alloys can also be strengthened by introducing strengthening agents, like rare earth elements or other alloying elements.

Even though Mg–Li base alloys possess advantages over other alloy systems, there still exist some drawbacks limiting their wide applications. Both Mg and Li are highly active elements. Adding Lithium in Mg alloys cause difficulties for the preparation and processing of Mg–Li alloys as Li oxidizes even at room temperature. The low corrosion resistance is a main concern of the Mg and Mg–Li base alloys. Also Mg–Li base alloys have low strength. This project aims on feasibility of magnesium alloys used for making piston.

2. Engine Properties

The engine selected for the project is Maruti Omni engine. Piston is modeled based on the dimensions and specifications of this engine.

Table 1: Specification of engine

Specification	Description
Bore (D)	68.5mm
Stroke (l)	72.0 mm
No. of cylinders	3
Displacement	796 cc

Compresiion ratio	8.7
Maximum engine output	24.5 kW @ 5000 rpm
Maximum torque	59 Nm @ 2500 rpm

3. Experiment

3.1 Material and properties

A commonly used piston material is Aluminium alloy. Here, Aluminium alloy B390 is used to compare the results. Magnesium lithium alloy LA141 was selected for the current study.

Table 2: Materials and properties

Parameter	Aluminium alloy (B390)	Magnesium alloy (LA141)
	Value	Value
Density	2.71 g/cm3	1.35 g/cm3
Tensile strength	317 Mpa	145 Mpa
Elongation at break	1%(in 50mm)	23%(in 50mm)
Thermal expansion co-efficient	18 µm/m @100 ℃	21.7 µm/m @100℃
Thermal conductivity	134 W/mK	80 W/mK
Specific heat	0.9 kJ/kgK	1.449 kJ/kgK
Poisson's ratio	0.33	0.35
Elastic modulus	76 Gpa	42 pa

3.2 Load calculations

The maximum pressure inside the cylinder was calculated from efficiency and otto cycle equation as 6.5 MPa. The results from Morse test conducted on engine were used to find heat flux.

The amount of heat conducted through piston head (H) is given by.

$H = [C * HCV * m * BP] * 10^3$ (1)

Where,
C is the ratio of heat absorbed by the piston to the total heat developed in the cylinder (C=5% or 0.05)
HCV= higher calorific value of fuel (43890 kJ/kg)
m = mass of fuel used per brake power per second (0.00045 kg/kW/s)
BP = brake power of the engine per cylinder (1.4 kW)
Heat flux= H/piston area=$375150\ W/m^2$

3.3 Design of piston

According to Grashoff's formula, the thickness of the piston head is given by, $t_h = D\sqrt{\frac{3*p_{max}}{16*\sigma_b}}$ (2)

Where,
t_h= thickness of piston head (mm)
D = cylinder bore (mm)
p_{max}= maximum gas pressure or explosion pressure (MPa)
σ_b = permissible bending stress (MPa)
The thickness of piston ribs is given by, $t_R = \frac{t_h}{3}$ to $\frac{t_h}{2}$ (3)

The radial width of the ring is given by, $b = D\sqrt{\frac{3p_w}{\sigma_t}}$ (4)

Where,
b = radial width of ring (mm)
p_w = allowable radial pressure on cylinder wall (MPa)
σ_t = permissible tensile strength for ring material (MPa)
The axial thickness of piston ring , h=0.7b to b (5)
Width of top land, $h_1 = t_h$ to $1.2t_h$ (6)
Width of ring lands, $h_2 = 0.75h$ to h (7)

The thickness of the piston barrel at the top end and lower end is given by,
$t_3 = 0.03D + b + 4.9$ and $t_4 = 0.25t_3$ to $0.35t_3$ (8)
Length of skirt is given by, $l_s = 0.65D$ to $0.8D$ (9)
Length of piston pin , $l_1 = 0.45\ D$ (10)
The value of permissible temperature difference between centre and edge of piston, $(T_c - T_e) = \left[\frac{H}{12.56*k*t_h}\right] * 10^3$ (11)

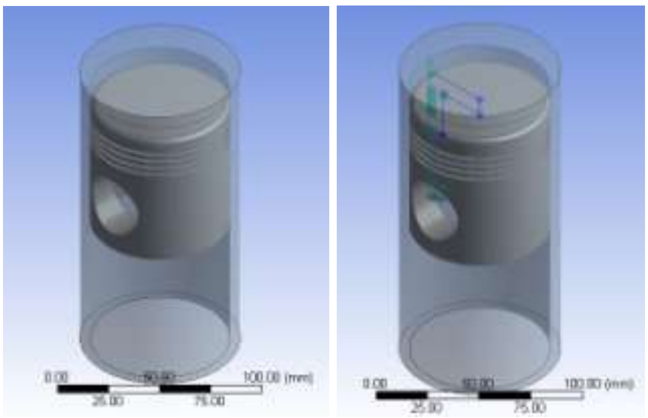
Table 3: Dimensions and properties of piston

Parameter	*B390 piston*	*LA141 piston*
Thickness of piston head	6 mm	9 mm
Number of piston ribs	0	4
Thickness of ribs	-	4 mm
Radial width of pison rings	2 mm	2 mm
Axial thickness of piston rings	2 mm	2 mm
Width of top land	7 mm	10 mm
Ring land	2 mm	2 mm
Thickness of barrel at top end	9 mm	9 mm
Thickness of barrel at lower end	3 mm	3 mm
Length of skirt	50 mm	50 mm
Length of piston pin in bush	31 mm	31 mm
Inner diameter of piston pin	19 mm	19 mm
Diameter of piston boss	46 mm	46 mm
Length of cylinder	150 mm	155 mm
Permissible temperature difference	136.8°C	152.8°C

Piston ribs are required if the piston head thickness is more than 6 mm.

3.4 Modelling and analysis

Pistons were modeled in Design modeler in Ansys16.0. The models were meshed. A grid independence study was done and mesh with 2 lakh elements was selected. All available data of both alloys were fed to engineering data section.



(a) (b)
Figure 1: Model of piston using (a) B390 and (b) LA141

The model was analyzed in steady state thermal. Heat flux of $375150\ W/m^2$ was applied on piston head surface. Convection coefficients were applied in inner piston surface as 100 $W/m^2{}^\circ C$ and on outer cylinder surface as 2000 $W/m^2{}^\circ C$. Ambient temperature was selected as 30°C. The model was then analyzed in static structural. Maximum load of 6.5 MPa was applied on the piston head surface. Cylindrical support was applied on the surface for piston pin. The results from thermal analysis were imported to the static structural analyses. Also the piston cylinder clearance for Aluminium was selected as 0.75 mm and clearance for Magnesium lithium alloy was selected as 1 mm to compensate for higher expansion coefficient. The cylinder is assumed to be made of gray cast iron.

4. Results and Discussion

The result of thermal analysis for Aluminium alloy is given below.

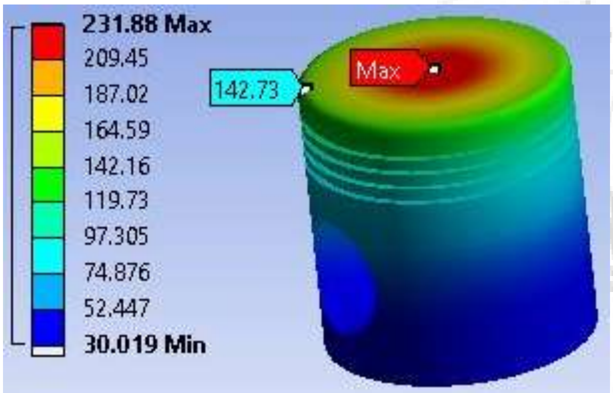
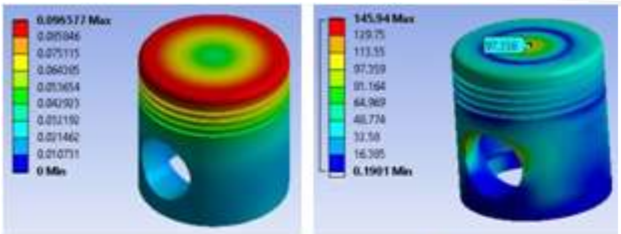


Figure 2: Resultant temperature on B390 piston.

Maximum temperature was found out to be 231.88°C. Temperature at edge of piston head was obtained as 142.73°C. Difference between temperature at center and edge of piston head is 89.15°C. The permissible temperature variation was calculated to be 136.8°C. So the design is safe. The results were exported to structural analysis. Maximum pressure 6.5 MPa was applied to piston surface. Deformation and stresses were found out using analysis.



(a) (b)

Figure 3: (a) Deformation and (b) Stress on B390 piston.

Maximum deformation was found out to be 0.0965 mm. Maximum stress on piston obtained is 145.94 MPa. Maximum stress on piston head is 97.338 MPa. Ultimate tensile strength of material is 317 MPa and working stress is 158.5 MPa. So the design of piston was found to be safe. Same loads and conditions were applied on Magnesium-lithium alloy. The result of thermal analysis are.

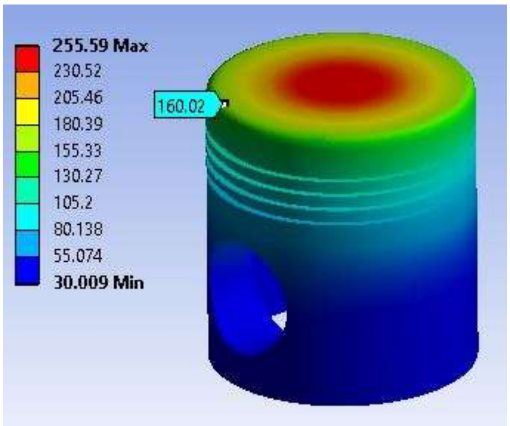
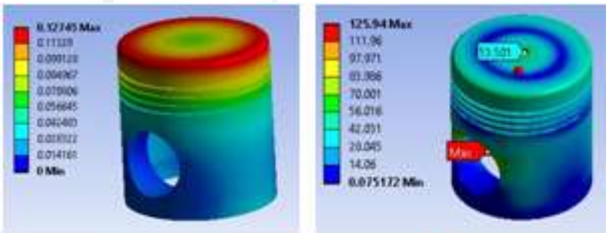


Figure 4: Resultant temperature on LA141 piston**.**

Maximum temperature was found out to be 255.59°C. Temperature at edge of piston head was obtained as 160.02°C. Difference between temperature at centre and edge of piston head is 95.57°C. The permissible temperature variation was calculated to be 152.8°C. So the design is safe. The results were exported to structural analysis. Maximum pressure 6.5 MPa was applied to piston surface. Deformation and stresses were found out using analysis.



(a) (b)

Figure 3: (a) Deformation and (b) Stress on B390 piston

Maximum deformation was found to be 0.127 mm. Maximum stresses on piston obtained is 125.94 MPa, located at piston pin area. Maximum stress on piston head is 53.501 MPa. Ultimate tensile strength of material is 145 MPa and working stress is 72.5 MPa. The stress concentration at piston pin area is exceeding the limits, whereas the maximum stress on piston head is in desired limits. The comparison of results of Aluminium alloy piston and Magnesium-lithium alloy piston is given below.

Table 3: Comparison of results

Properties	Aluminium alloy	Magnesium alloy
Maximum temperature	231.88°C.	255.59°C.
Temperature variation between piston centre and edge	89.15°C.	95.57°C.
Permissible limit of temperature variation	136.8°C.	152.8°C.
Maximum deformation	0.0965 mm	0.165mm
Maximum stress	145.94 MPa	125.94 MPa
Maximum stress on piston head	97.4 MPa	53.50 MPa
Working stress	158.5MPa	72.5 MPa

5. Conclusion

From obtained results, Magnesium-lithium LA141 alloy is not safe to be used as a piston material, as the piston exceeds working stress values at piston pin area. This might be due to the increased temperature on the piston. Normal temperature on piston head of an SI engine ranges from 200°C to 260°C. For Aluminium alloy, the heat transfer assumed gives a maximum temperature of 232°C. Above 350°C the properties like tensile strength of Aluminium alloys tends to reduce. For Magnesium-lithium alloy, the same heat transfer assumed gives a maximum temperature of 255.6°C .But tensile strength of Magnesium lithium alloy tends to decrease when temperature increases above 250°C. With current heat transfer rates, Magnesium lithium alloy may fail. If the heat transfer to coolant is increased, the maximum temperature on piston can be reduced and the alloy could be used as a piston material.

If the Alloy is used as piston material, weight of the piston can be reduced. Proposed Magnesium-lithium alloy is lighter by 50%. But due to reduced strength of Magnesium alloy when compared to strength of aluminium alloy, the piston head thickness of the piston is increased and piston ribs were added. Comparison of volume and weight of both alloys are given below.

Properties	Aluminium alloy piston	Magnesium alloy piston
Volume (m^3)	1.0355E-04	1.1735-04
Weight (g)	280.63	158.43

The Magnesium alloy piston is 43.5 % lighter than the Aluminium alloy. Lighter piston results in low inertia force and lesser load on connecting rod. As thermal conductivity is less for Magnesium alloy, better cooling is required. Also Magnesium alloy have more thermal expansion, resulting in requirement of higher piston cylinder wall clearance. According to (11), Magnesium –lithium alloys (LAM830) were designed and prepared in a vacuum induction furnace under controlled argon atmosphere. The alloys were then processed by hot extrusion, and their mechanical properties and microstructural evolution were analysed. Sr addition results in the precipitation of Al−Sr. Microstructure of the alloys is further refined as a result of the hot extrusion treatment. The resulting LAM830−0.5Sr alloy shows an optimal tensile strength of 265.46 MPa. These alloys might be able to replace conventional piston as well as other engine parts in future. More analysis and experiments are required to check behavior of different Magnesium –lithium alloys.

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