Comparative Analysis of Piston with Metal Matrix Composites

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***Abstract*—The use of composite materials has been increased in strengthening of mechanical components in recent past. Composite materials have properties such as high strength to weight ratio, ease of fabrication, good electrical and thermal properties compared to metals. Analysis of such composite materials starts with estimation of resultant properties. The pistons are made of Aluminum and its alloy LM-6 for lightweight, thermal conductivity. But it is subjected to deformation and stress under high pressure and temperature. As an alternative, an Aluminium metal matrix composite is applied as a material for piston by reinforcing Silicon Carbide, Alumina, Boron Carbide to Aluminum in percentages such as 10%, 20%, 30%, 40% etc. and the resultant properties such as stress, deformation, heat flux is computed using Ansys and the material with minimum stress, minimum deformation and maximum heat flux is put into automobile use. From the analysis, Silicon Carbide Reinforced Aluminium with 40% SiC reinforcement with stress 57.6 MPa, deformation 0.0296 mm, heat flux 10.5 MW/m^2 can be suggested for automobile use with further real time analysis.**

Index Terms- Composite materials, Aluminium Metal matrix composite, LM-6.

I. INTRODUCTION

Every automotive company are developing their own automotive parts to compete in the global market and one among them is the engine In internal combustion engine, piston is the important part which act as the heart of engine. It is a cylindrical component which reciprocates in the cylindrical bore of the engine by means of various forces that act on it during combustion process. There are different types of piston and its shape depends on the engine size and crown design. The piston is one of the most stressed components of an entire vehicle because it is placed in the cylinder below combustion chamber. Therefore, it is must be designed to withstand from damage that caused of the extreme heat and pressure of combustion process. There are many damages or failures for piston due to high pressure and heat such as piston skirt seizing, piston head seizing, piston ring damage and cylinder damage. The value of stress that is obtained during damages can be determined by using finite element analysis.

Finite Element Analysis is a simulation technique which evaluates the behavior of components, equipment and structures for various loading conditions including applied forces, pressures and temperatures. Thus, a complex engineering problem with non-standard shape and geometry can be solved using finite element analysis where a closed form solution is not available. The finite element analysis methods result in the stress distribution, displacements and reaction loads at supports for the model. Finite element analysis techniques can be used for a number of scenarios such as mesh optimization, design optimization, material weight minimization, shape optimization and code compliance.

Fig.1 Piston

With finite element analysis, the stresses value that act to the piston is determined by simulation. Thus, it can reduce the cost and time due to manufacturing the components and the same time it can increased the quality of the product. To ensure the stresses value are accurate value, there is a process which is called mesh optimization. Mesh optimization process is a process of numerical method and approximation solution are required to solve most of partial differential equation for a component.

II. LITERATURE REVIEW

The research paper “Advanced Design Optimization for Composite Structure: Stress Reduction, Weight Decrease and Manufacturing Cost Savings” by Shayan Ahmadian (2012) states that the existing piston was redesigned with fibre-composite material in order to enhance weight reduction. The author gives us the result of maximum principal stress, minimum principal stress, Von-misers stresses and total deflection. This research work explains about the use of different aluminium alloys for piston.

The research work on “Design and Analysis of Piston by SiC Composite Material” in International Journal for Innovative Research in Science & Technology by Abino John, Jenson T Mathew, Vasdev Malhotra, Nitin Dixit (May 2015) states the structural and thermal analysis of piston by reinforcing silicon carbide on aluminium. This also states the use of composite materials for the manufacture of piston.

The research paper “Design Analysis and Optimization of Piston using CATIA and ANSYS” in International Journal of Innovative Research in Engineering & Science by Ch.Venkata Raja, P.V.K.Murthy, M.V.S.Murali Krishna, G.M.Prasada Rao (January 2013) states that Design, Optimization, Analysis of the stress distribution in the various parts of the piston to know the stresses due to the gas pressure and thermal variations using with Ansys and helps to understand about the design calculations and optimization techniques.

In this research paper “Comparative Study of Different Materials with Al-Sic for Engine Valve Guide by using FEM” in World Journal of Engineering and Technology (2016) by Hemendra Kumar, Srivastva, Arurendra Singh Chauhan, Manmohan Kushwaha, Amaan Raza, Prashantkr Bhardwaj, Vaibhav Raj an effort has been designed to raise the reliability of engine using Al-SiC composites with other alternatively materials for the engine valve guides. The stresses were observed to be well below the permitted stress for all the materials but the Al-SiC composites found the most suitable one. The deformations and stresses induced due to structural and thermal loading is illustrated and discussed. Christo Ananth et al.[7] discussed about E-plane and H-plane patterns which forms the basis of Microwave Engineering principles.

The research paper “Composite Materials in Aerospace Applications” by Nikhil V Nayak in International Journal of Scientific and Research Publications gives a brief review of composites usage in aerospace sector and the nature of composite materials behaviour and special problems in designing and working with them are then illustrated.

In this paper “Finite Element Analysis of Composite Material Using ANSYS” by Kunal Songra technique for upgrading reinforced concrete column have been analysed with the application of composite material like FRP and Linear analysis of column specimen was accomplished using ANSYS. This gives the idea about the analysis techniques by application of composites.

III. METAL MATRIX COMPOSITES

A metal matrix composite is composite material with at least two constituent parts, one being a metal and the other material may be a different metal or another material, such as a ceramic or organic compound. When at least three materials are present, it is hybrid composite. A metal matrix composite is complementary to a cement. A metal matrix composite are made by dispersing a reinforcing material into a metal matrix. The reinforcement surface can be coated to prevent a chemical reaction with the matrix. For example, carbon fibers are commonly used in aluminium matrix to synthesize composites showing low density and high strength. However, carbon reacts with aluminium to generate a brittle and water-soluble compound Al_4C_3 on the surface of the fibre. To prevent this reaction, the carbon fibres are coated with nickel or titanium boride.

The matrix is the monolithic material into which the reinforcement is done, and is completely continuous. This means that there is a path through the matrix to any point in the material, unlike two materials joined together. In structural applications, the matrix is usually a lighter metal such as aluminum, magnesium, or titanium, and provides a rigid support for the reinforcement. In high-temperature applications, cobalt and cobalt–nickel alloy matrices are common. The reinforcement material is embedded into a matrix. The reinforcement does not always serve a structural task but is also used to change physical properties such as wear resistance, friction coefficient, or thermal conductivity. The reinforcement can be either continuous, or discontinuous. Discontinuous metal matrix composite can be isotropic, and can be worked with standard metalworking techniques, such as extrusion, forging and rolling.

Continuous reinforcement uses monofilament wires or fibers such as carbon fiber or silicon carbide. Because the fibers are embedded into the matrix in a certain direction, the result is an orthotropic structure in which the alignment of the material affects its strength. One of the first MMCs used boron filament as reinforcement. Discontinuous reinforcement uses whiskers, short fibers, or particles. The most common reinforcing materials in this category are alumina and silicon carbide.

IV. MODELLING

Bajaj Pulsar Classic Piston (56.4mm * 57mm) is to be designed as per calculations and analysed.

A. Design Considerations

In designing a piston for an engine, the following points should be taken into consideration:

1. It should have enormous strength to withstand the high pressure.
2. It should have minimum weight to withstand the inertia forces.
3. It should form effective oil sealing in the cylinder.
4. It should provide sufficient bearing area to prevent undue wear.
5. It should have high speed reciprocation without noise.
6. It should have sufficient support for the piston pin.
7. It should be of sufficient rigid construction to withstand thermal and mechanical distortions
8. It should withstand high compression temperature.

B. Design Procedure

The procedure for piston designs consists of the following steps:

- Thickness of piston head (t_H)
- Heat flows through the piston head (H)
- Radial thickness of the ring (t_1)
- Axial thickness of the ring (t2)
- Width of the top land (b_1)
- Width of other ring lands (b_2)

The above steps are explained as below:

1. Thickness of Piston Head (t_H):

The thickness of piston head calculated using the following Grashoff's formula,

$$t_H = ((3pD^2)/(16\sigma_t))^{0.5} \text{ in mm}$$

where

P= maximum pressure in N/mm²

D= cylinder bore/outside diameter of the piston in mm.

σ_t =permissible tensile stress for the material of the piston.

Here the material is a particular grade of AL-Si alloy whose permissible stress is 50 MPa- 90MPa. Before calculating thickness of piston head, the diameter of the piston has to be specified. The piston size that has been considered here has L*D specified as 56.4*57.

2. Heat Flow through the Piston Head (H):

The heat flow through the piston head is calculated using the formula

$$H = 12.56 * t_H * K * (T_c - T_e) \text{ Kj/sec}$$

Where

K=thermal conductivity of material

T_c = temperature at center of piston head in °C.

T_e = temperature at edges of piston head in °C.

3. Radial Thickness of Ring (t_1):

The radial thickness of the piston head is calculated using the formula

$$t_1 = D\,(3p_w/\sigma_t)^{0.5}$$

Where

D = cylinder bore in mm

Its value is limited from 0.025N/mm² to 0.042N/mm².

σ_t is 90Mpa.

4. Axial Thickness of Ring (t2)

The axial thickness of the rings may be taken as

$$t_2 = 0.7t_1 \text{ to } t_1$$

Minimum axial thickness (t2) = D/ (10*n_r)

Where

n_r = number of rings

5. Width of the top land (b_1)

The width of the top land varies from

$$b_1 = t_H \text{ to } 1.2\, t_H$$

6. Width of other lands (b_2)

The width of other ring lands varies from

$$b_2 = 0.75t_2 \text{ to } t_2$$

7. Maximum Thickness of Barrel (t_3)

The maximum thickness of Barrel varies from

$$t_3 = 0.03*D + b + 4.5 \text{ mm}$$

b = Radial depth of piston ring groove

Thus, the dimensions for the piston are calculated and these are used for modelling the piston in CATIA V5R16. In the above procedure the ribs in the piston are not taken into consideration, so as make the piston model simple in its design.

C. Calculated Values

1. Length of piston = 56.4 mm
2. Diameter of piston = 57 mm
3. Thickness of piston head = 8.5 mm
4. Radial Thickness of ring = 1.5 mm
5. Axial Thickness of ring = 1.5 mm
6. Width of top land = 10 mm
7. Thickness of Barrel = 9.6 mm

D. Modelling using CATIA V5 R20

Modelling of piston is done using CATIA V5 R 20 software .The dimensions calculated is design calculation used for modelling the piston.

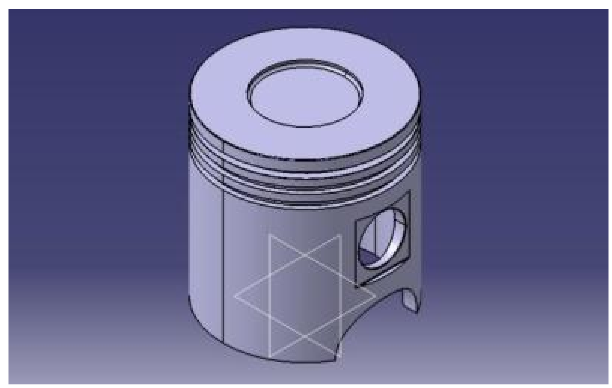

Fig.2 Modelling piston in CATIA V5.

V. ANALYSIS

Aluminium, LM-6, Aluminium metal matrix composite is applied as a material for piston by reinforcing Silicon Carbide, Alumina, Boron Carbide to Aluminum in percentages such as 10%, 20%, 30%, 40% etc. and the resultant properties such as stress, deformation, heat flux is computed using Ansys. The properties of above materials are given in the table 1 given below

Property / Material	Density (kg/m^3)	Young's modulus (GPa)	Poisson ratio	Thermal Conductiv -ity ($Wm^{-1}C^{-1}$)	Specific Heat ($J\ kg^{-1}C^{-1}$)
Pure Al	2700	70	0.33	234	951
LM-6	2770	71	0.33	170	875
Al/SiC (10%)	2770	95	0.29	135	908
Al/SiC (20%)	2840	100	0.28	145	874
Al/SiC (30%)	2860	125	0.27	150	840
Al/SiC (40%)	2900	150	0.26	155	804
Al/Al_2O_3 (10%)	2850	87	0.29	140	897
Al/Al_2O_3 (20%)	3050	114	0.28	129	918
Al/Al_2O_3 (30%)	3120	127	0.27	119	947
Al/Al_2O_3 (40%)	3270	147	0.26	108	978
Al/B_4C (10%)	2780	102	0.285	152	808
Al/B_4C (20%)	2850	120	0.275	139	898
Al/B_4C (30%)	2880	132	0.265	128	920
Al/B_4C (40%)	2920	148	0.26	118	945

Table 1 Properties

A. *Structural Analysis*

1. Considerations

The piston is analysed at the pressure of 8MPa applied at piston head because the pressure above the SI Engine Piston is limited upto 8Mpa and provided with frictionless supports is provided for piston in hole provided for piston pin and piston skirt. Meshing provided is tetrahedral mesh to get accurate results.

2. Meshing

The meshing provided here is tetrahedral Mesh.

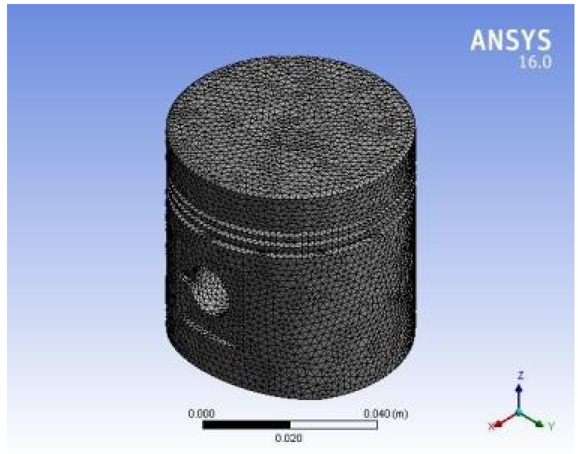

Fig.3 Tetrahedral Meshing

B. *Thermal Analysis*

The piston is analysed at the temperature of 1773K applied at piston head because the temperature above the SI Engine Piston head is limited upto 1773K and provided with convection is provided for piston in hole provided for entire faces. Meshing provided is tetrahedral mesh to get accurate results.

C. *Numerical Analysis*

The Numerical Analysis is done to validate the analysis in Ansys. The results of numerical analysis is shown in Table 3

1. Maximum Normal Stress in Piston:

The maximum normal stress in piston is given by Grashof's formula:

$\boldsymbol{\sigma_t = (3pD^2)/ (16\ t_H^2)}$ **in MPa**

P = maximum pressure in N/mm²

D = cylinder bore/outside diameter of the piston in mm.

σ_t = Tensile stress for the material of the piston.

$\sigma_t = (3*8*57^2)/ (16*8.5^2)$ in MPa

$\boldsymbol{\sigma_t = 67.44}$ **MPa < 110 MPa .**Thus **t**he design is safe.

2. Maximum Heat Flux Through the Material:

The maximum heat flux in piston is given by

$\boldsymbol{q = (12.56*t_H * k * (T_c-T_e))/A}$ **in W/m²**

k=thermal conductivity of material (234 $Wm^{-1}K^{-1}$)

T_c = temperature at center of piston head in °C.

T_e = temperature at edges of piston head in °C.

$q = (12.56*0.0085 * 234 * (1500-30))/0.026\ W/m^2$

$\boldsymbol{q = 14.12\ MW/m^2}$

D. *Solution*

The solution for LM-6, Al-SiC till 30% reinforcement is given below and Al-Al2O3 and Al-B4C are performed by changing material properties and results are given in Table 2

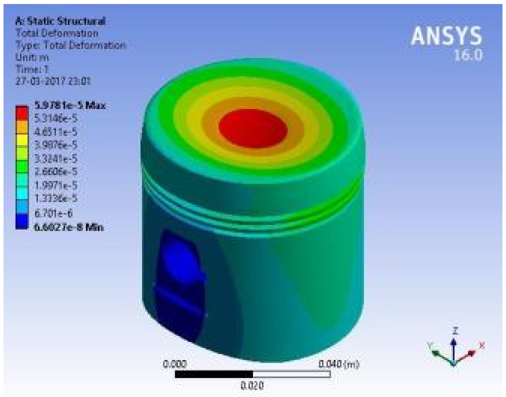

Fig.4 Deformation LM-6

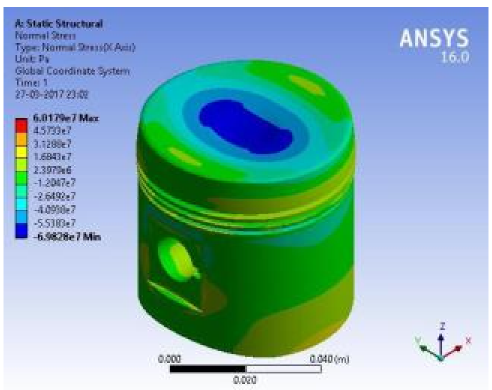

FIG.5 STRESS LM-6

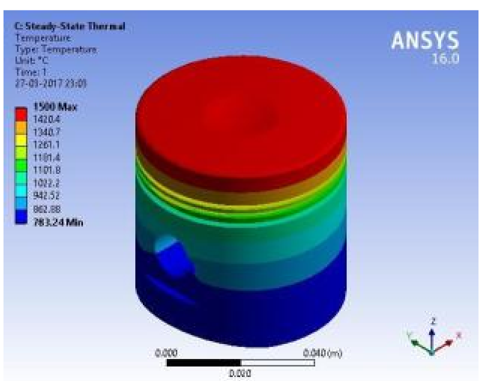

Fig.6 Temperature LM-6

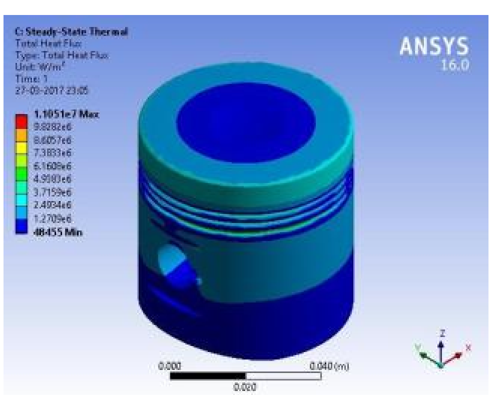

Fig.7 Heat Flux LM-6

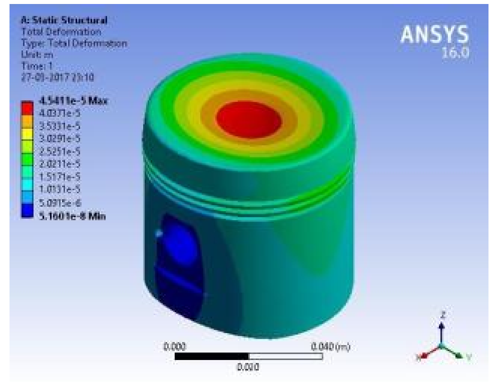

Fig.8 Deformation Al-SiC(10%)

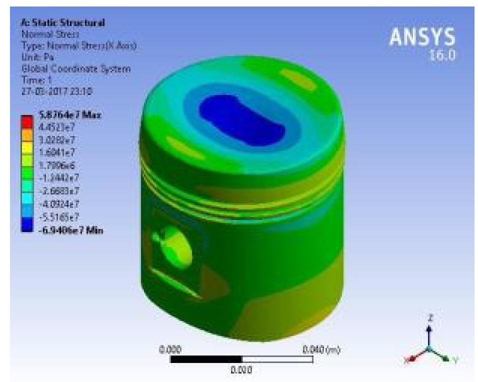

FIG.9 STRESS AL-SIC(10%)

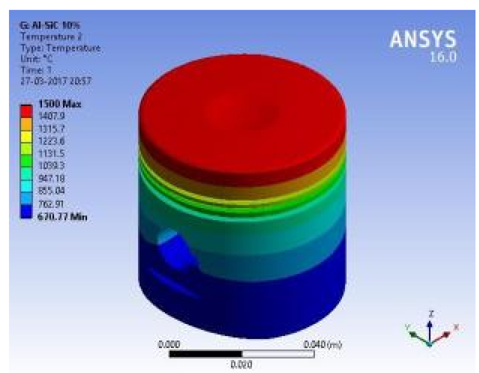

Fig.10 Temperature Al-SiC(10%)

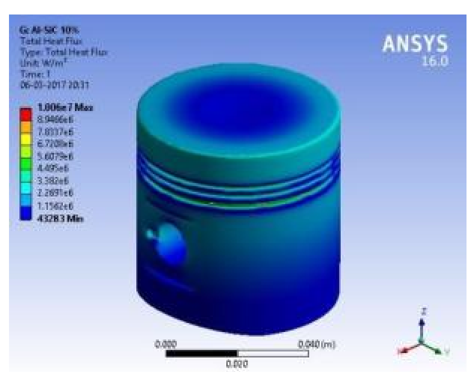

Fig.11 Heat Flux Al-SiC(10%)

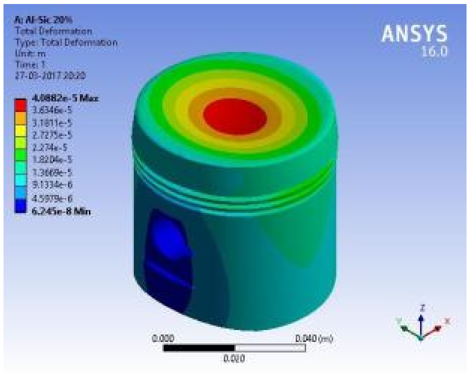

FIG.12 DEFORMATION AL-SIC(20%)

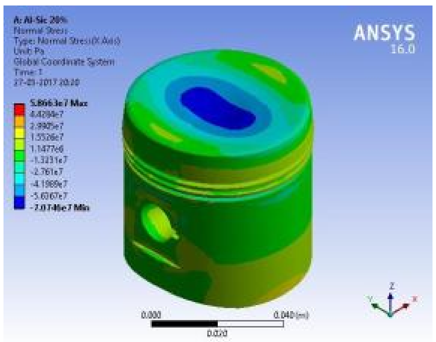

FIG.13 STRESS AL-SIC(20%)

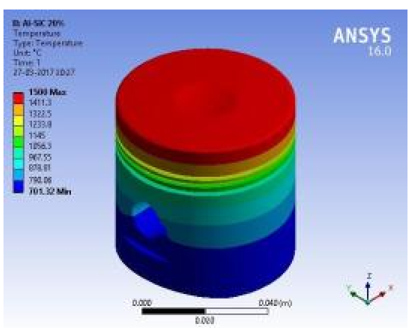

FIG. 14 TEMPERATURE AL-SIC(20%)

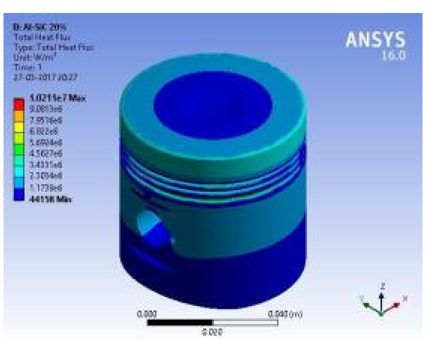

FIG 15 HEAT FLUX AL-SIC(20%)

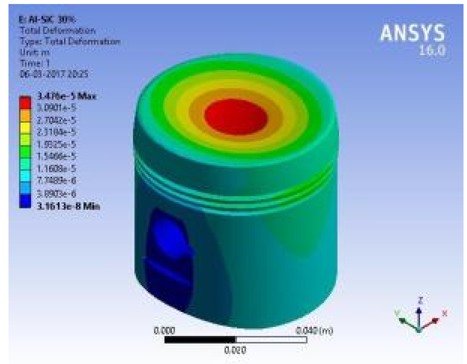

FIG.16 DEFORMATION AL-SIC(30%)

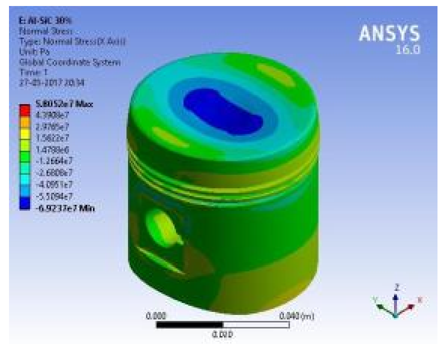

FIG.17 STRESS AL-SIC(30%)

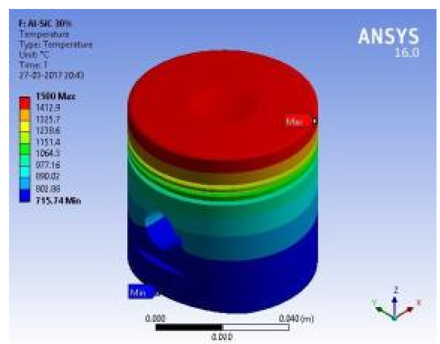

FIG. 18 TEMPERATURE AL-SIC(30%)

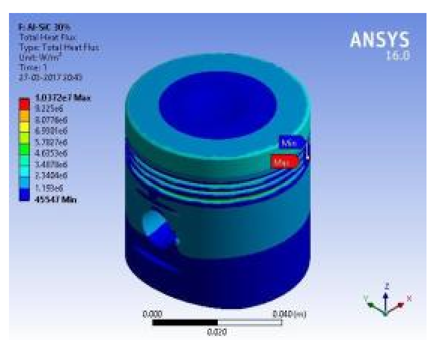

FIG 19 HEAT FLUX AL-SIC(30%)

VI. RESULTS

Material	Alloy %	Normal Stress (Max) MPa	Deformation (Max) (mm)	Heat Flux (Max) (MW/m^2) Steady State	Heat Flux (Max) (MW/m^2) Transient
Aluminium and alloy	Pure Al	68.49	0.076	12.34	748
	LM-6	60.2	0.0599	10.51	602
Silicon carbide Reinforced Aluminium	10 % SiC	58.7	0.045	10.066	496
	20 % SiC	58.86	0.04088	10.2	521
	30 % SiC	58.05	0.0346	10.37	529
	40 % SiC	57.6	0.02906	10.5	538
Alumina Reinforced Aluminium	10% Al_2O_3	58.76	0.0495	10.31	512
	20% Al_2O_3	58.40	0.0398	9.84	493
	30% Al_2O_3	58.05	0.0342	9.48	470
	40% Al_2O_3	57.69	0.0296	8.96	445
Boron carbide Reinforced Aluminium	10% B_4C	58.58	0.036	10.38	525
	20% B_4C	58.23	0.034	10.2	509
	30% B_4C	57.87	0.032	9.84	483
	40% B_4C	57.69	0.0295	9.4	455

TABLE 2 RESULTS

Material	Alloy %	Normal Stress (Max) (MPa) Numerical	Normal Stress (Max) (MPa) Ansys	Heat Flux (Max) (MW/m^2) Numerical	Heat Flux (Max) (MW/m^2) Ansys
Aluminium	Pure Al	68.49	67.44	12.34	14.24
	LM-6	60.2	63.44	10.51	10.258
Silicon carbide Reinforced Aluminium	10 % SiC	58.7	61.20	10.066	8.146
	20 % SiC	58.86	59.80	10.2	8.749
	30 % SiC	58.05	59.06	10.37	9.052
	40 % SiC	57.6	58.50	10.5	9.351
Alumina Reinforced Aluminium	10% Al_2O_3	58.76	59.80	10.31	8.442
	20% Al_2O_3	58.40	59.66	9.84	7.784
	30% Al_2O_3	58.05	59.47	9.48	7.180
	40% Al_2O_3	57.69	58.92	8.96	6.516
Boron carbide Reinforced Aluminium	10% B_4C	58.58	59.63	10.38	8.762
	20% B_4C	58.23	59.58	10.2	8.432
	30% B_4C	57.87	59.23	9.84	7.782
	40% B_4C	57.69	58.67	9.4	7.210

TABLE 3 NUMERICAL RESULTS AND ANSYS RESULTS COMPARISON

1. GRAPHS

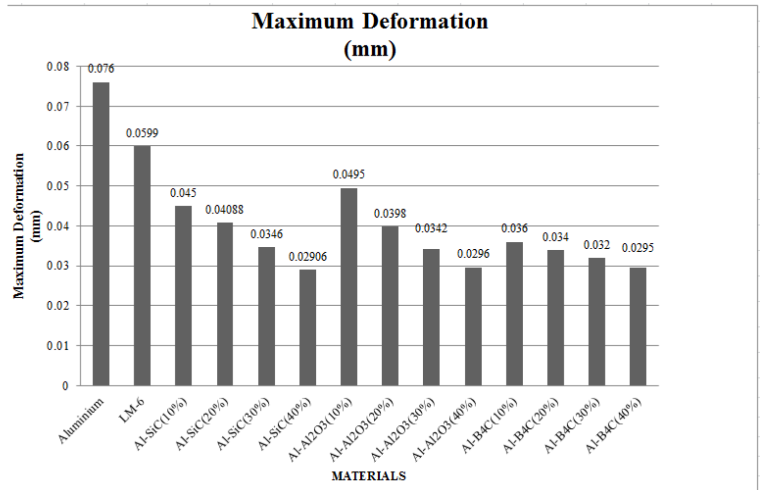

FIG. 20 DEFORMATION

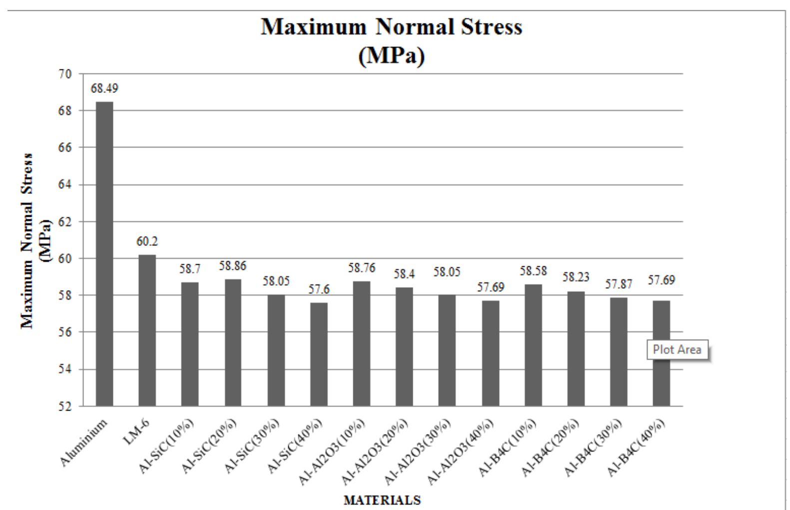

FIG. 21 STRESS

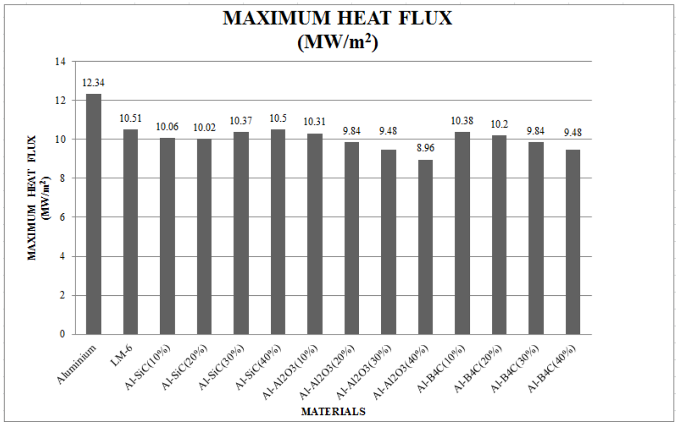

FIG.22 HEAT FLUX STEADY STATE

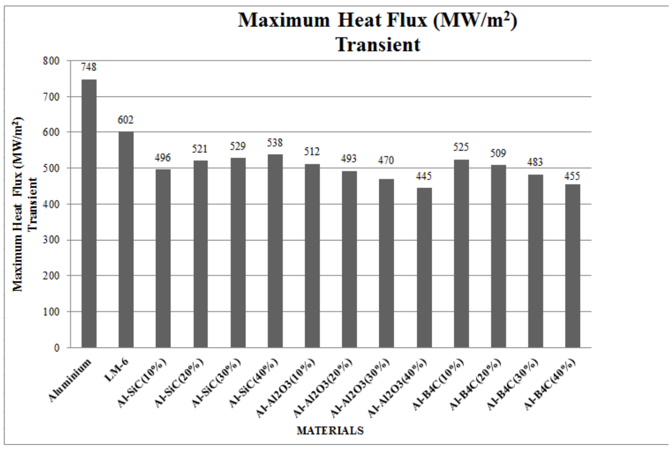

FIG.23 HEAT FLUX TRANSIENT ANALYSIS

VII. DISCUSSION

A. Normal Stress

From the analysis, the maximum normal stress occurs at the centre of the piston head. The maximum normal stress is higher for aluminium (68.69 MPa). By adding alloying elements LM-6, the maximum stress value decreases to 61 MPa. This is due to increase in compressive strength, tensile strength, corrosion resistance by adding manganese, magnesium, silicon etc. Also, by reinforcement of silicon carbide in percentages 10%, 20%, 30%, 40% the compressive strength, tensile strength, fatigue resistance of the material increases and elongation is decreases, the ability of the molecules with in the material to resist stress increases, and by addition of reinforcement material by 10%, 20%, 30%, 40% will increase the ability to resist load and the maximum normal stress values are obtained as 58.6 MPa, 58.85 MPa, 58.05 MPa, 57.6 MPa. Hence the normal stress for 40% reinforcement of Silicon carbide on Aluminium will minimum. It is also noted that the maximum normal stress for reinforcement of Al_2O_3 in percentages 10%, 20%, 30%, 40%, the normal stress will be 58.76 MPa, 58.4 MPa, 58.05 MPa, 57.69 MPa and the maximum normal stress for B_4C will be 58.58 MPa, 58.23 MPa, 57.87 MPa, 57.69 MPa. By comparison the maximum normal stress for 40% reinforced silicon carbide on Aluminium Metal Matrix Composite is lesser (57.60 MPa) as compared to other reinforcements. The material with lesser value of maximum normal stress will reduce the piston wear, fatigue and increase the life of the piston.

B. Deformation

From the analysis, the maximum deformation occurs at the centre of the piston head. The maximum deformation is higher for aluminium (0.076 mm). By adding alloying elements LM-6, the maximum deformation value decreases to 0.0599 mm. This is due to increase in compressive strength, tensile strength, corrosion resistance by adding manganese, magnesium, silicon etc. Also, by reinforcement of silicon carbide in percentages 10%, 20%, 30%, 40% the compressive strength, tensile strength, fatigue resistance of the material increases and elongation is decreases, the ability of the molecules with in the material to resist load increases, and by addition of reinforcement material by 10%, 20%, 30%, 40% will increase the ability to resist load and the maximum deformation values are obtained as 0.045 mm, 0.04088 mm, 0.0346 mm, 0.02906 mm. Hence the deformation for 40% reinforcement of Silicon carbide on Aluminium will minimum. It is also noted that the maximum deformation for reinforcement of Al_2O_3 in percentages 10%, 20%, 30%, 40%, the deformation will be 0.0495 mm, 0.0398 mm, 0.0342 mm, 0.0296 mm and the maximum deformation for B_4C will be 0.036 mm, 0.034 mm, 0.032 mm, 0.0295 mm. By comparison the maximum deformation for 40% reinforced silicon carbide on Aluminium Metal Matrix Composite is lesser (0.02906 mm) as compared to other reinforcements. Hence the lesser amount of deformation ensure the proper combustion of fuel, stroke length and travel of piston.

C. Heat flux:

The maximum temperature in the engine occurs after the constant volume heat addition. Hence at that temperature the steady state thermal analysis is carried out. The temperature is limited upto 1773K.

By Fourier law,

$$\mathbf{q = k.t.\,(dT/dx)}$$

Hence heat flow is proportional to thermal conductivity. From this equation, the heat flux increases with thermal conductivity. The maximum heat flux is higher for aluminium (12.34 MW/m^2). By adding alloying elements LM-6, the maximum heat flux increases to 10.51 MW/m^2. This is due to increase in thermal conductivity and specific enthalpy of the material. Also, by reinforcement of silicon carbide in percentages 10%, 20%, 30%, 40% the thermal conductivity and specific enthalpy of the material increases consecutively, the ability of the molecules with in the material to conduct heat increases, and by addition of reinforcement material by 10%, 20%, 30%, 40% will increase the ability to conduct heat and the maximum heat flux values are obtained as 10.06 MW/m^2, 10.02 MW/m^2, 10.37 MW/m^2, 10.5 MW/m^2. Hence the heat flux for 40%

reinforcement of Silicon carbide on Aluminium will maximum. It is also noted that the maximum heat flux for reinforcement of Al_2O_3 in percentages 10%, 20%, 30%, 40%, the heat flux will be 10.31 MW/m^2, 9.84 MW/m^2, 9.48 MW/m^2, 8.96 MW/m^2 and the maximum heat flux for B_4C will be 10.38 MW/m^2, 10.2 MW/m^2, 9.84 MW/m^2, 9.48 MW/m^2. By comparison the maximum heat flux for 40% reinforced silicon carbide on Aluminium Metal Matrix Composite is greater (10.5 MW/m^2) as compared to other reinforcements. Hence the greater the heat flux will ensure the proper heat transfer and heat dissipation characteristics.

VIII. CONCLUSION

The 40% Silicon Carbide reinforced Aluminium Metal Matrix Composite with comparatively minimum normal stress (59.6 MPa), minimum deformation (0.0296mm), maximum heat flux (10.5 MW/m^2), is suggested to automobile use with further real time analysis.

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