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RESEARCH ARTICLE

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THERMAL AND MECHANICAL ANALYSIS OF PISTON BY USING COMPOSITE MATERIALS

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ABSTRACT

In this Paper the stress distribution is evaluated on the four stroke engine piston by using FEA. The finite element analysis is performed by using FEA software. The couple field analysis is carried out to calculate stresses and deflection due to thermal loads and gas pressure. These stresses will be calculated for three different materials. The results are compared for all the three materials and the best one is proposed. The materials used in this project are aluminium alloy, grey cast iron and SiC reinforced ZrB2 composite material. In this project the natural frequency and Vibration mode of the piston were also obtained and its vibration characteristics are analyzed. With using computer aided design (CAD), UNI-GRAPHICS software the structural model of a piston will be developed. Furthermore, the finite element analysis performed with using software ANSYS. SiC reinforced ZrB2 : Silicon carbide reinforced Zirconium diboride is a ceramic matrix composite (CMC) material.

Keywords: Stress distribution, Four stroke engine piston, Finite element analysis, Aluminium alloy, Grey cast iron and SiC, Natural frequency, Vibration mode, Computer aided design (CAD), Ceramic matrix composite (CMC) material ,Ansys.

1. INTRODUCTION

Automobile components are in great demand these days because of increased use of automobiles. The increased demand is due to improved performance and reduced cost of these components. R&D and testing engineers should develop critical components in shortest possible time to minimize launch time for new products. This necessitates understanding of new technologies and quick absorption in the development of new products. A piston is a moving component that is contained by a cylinder and is made gas-tight by piston rings. In an engine its purpose is to transfer from expanding gas in the cylinder to the crank shaft via piston rod and or connecting rod. As an important part in an engine piston endures the cyclic gas pressure and inertia forces at work and this working condition may cause the fatigue damage of the piston. The investigations indicate that greatest stress appears on the piston and stress concentration is one of the main reason for fatigue failure.

2.PROBLEM DEFINITION AND METHODOLOGY

In this paper the stress distribution is evaluated on the four stroke engine piston by using FEA. The finite element analysis is performed by using FEA software. The couple field analysis is carried out to calculate stresses and deflection due to thermal loads and gas pressure. These stresses will be calculated for three different materials. The results are compared for all the three materials and the best one is proposed. The materials used in this project are aluminium alloy,grey cast iron and SiC reinforced ZrB2 composite material. In this project the natural frequency and Vibration mode of the piston were also obtained and its vibration characteristics are analyzed. With using computer aided design (CAD), UNI-GRAPHICS software the structural model of a piston will be developed. Furthermore, the finite element analysis performed with using software ANSYS.

The methodology used for doing the analysis is as follows:

- Develop a 3D model from the available 2D drawings of the Piston.
- The 3D model is created using UNIGRAPHICS-NX software
- The 3D model is converted into parasolid and imported into ANSYS to do couple field analysis.
- The thermal analysis is performed on the piston model with the heat of (160°C-200°C) for Aluminum alloy material.
- Temperature distribution is plotted from the thermal analysis for Aluminum alloy material.
- Structural analysis is performed by applying temperature distribution from the thermal analysis as body loads and working pressure of 2Mpa to find the stress distribution due to thermal and structural loads for Aluminum alloy material.
- Plot deflections and stresses for the piston from the above analysis.
- The above analysis is repeated for grey cast iron and SiC reinforced ZrB2 composite material.
- Perform modal analysis for all the 3 materials.
- Compare the results for all the 3 materials.

3. MODELING AND ANALYSIS

Piston Design

The piston is designed according to the procedure and specification which are given in machine design and data hand books. The dimensions are calculated in terms of SI Units. The pressure applied on piston head, temperatures of various areas of the piston, heat flow, stresses, strains, length, diameter of piston and hole, thicknesses, etc., parameters are taken into consideration

3.1.Design Considerations for a Piston:

- In designing a piston for an engine, the following points should be taken into consideration:
- It should have enormous strength to withstand the high pressure.
- It should have minimum weight to withstand the inertia forces.
- It should form effective oil sealing in the cylinder.
- It should provide sufficient bearing area to prevent undue wear.
- It should have high speed reciprocation without noise.
- It should be of sufficient rigid construction to withstand thermal and mechanical distortions.
- It should have sufficient support for the piston pin.

3.2.Procedure for Piston Design

- The procedure for piston designs consists of the following steps:

1. Thickness of piston head (tH)
2. Heat flows through the piston head (H)
3. Radial thickness of the ring (t1)
4. Axial thickness of the ring (t2)
5. Width of the top land (b1)
6. Width of other ring lands (b2)

The above steps are explained as below:

Thickness of Piston Head (th)

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

tH = √ (3pD2)/ (16t) in mm

Where

P= maximum pressure in N/mm²

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

σt=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 a L*D specified as 152*140.

Heat Flow through the Piston Head (H)

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

H = 12.56*tH * K * (Tc-Te) Kj/sec

Where

K=thermal conductivity of material which is 174.15W/mk

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

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

Radial Thickness of Ring (t1)

$t1 = D\sqrt{3pw/\sigma t}$

Where D = cylinder bore in mm

Pw= pressure of fuel on cylinder wall in N/mm^2. Its value is limited from $0.025N/mm^2$ to $0.042N/mm^2$. For present material, σt is 90Mpa

Axial Thickness of Ring (t2)

The thickness of the rings may be taken as

t2 = 0.7t1 to t1

Let assume t2 =5mm

Minimum axial thickness (t2)

= D/(10*nr)

Where nr = number of rings

Width of the top land (b1)

The width of the top land varies from

b1 = tH to 1.2 tH

Width of other lands (b2)

Width of other ring lands varies from

b2 = 0.75t2 to t2

Maximum Thickness of Barrel (t3)

t3 = 0.03*D + b + 4.5 mm

Where

b = Radial depth of piston ring groove

Thus, the dimensions for the piston are calculated and these are used for modeling the piston in unigraphics. In the above procedure the ribs in the piston are not taken into consideration, so as make the piston model simple in its design. In modeling a piston considering all factors will become tedious process. Thus, a symmetric model is developed using the above dimensions.

3.3. Assumptions made

It is very difficult to exactly model the piston, in which there are still researches are going on to find out transient thermo elastic behavior of piston during combustion process. There is always a need of some assumptions to model any complex geometry. These assumptions are made, keeping in mind the difficulties involved in the theoretical calculation and the importance of the parameters that are taken and those which are ignored. In modeling we always ignore the things that are of less importance and have little impact on the analysis. The assumptions are always made depending upon the details and accuracy required in modeling.

1. The assumptions which are made while modeling the process are given below:-
2. The piston material is considered as homogeneous and isotropic.
3. Inertia and body force effects are negligible during the analysis.
4. The piston is stress free before the application of analysis.
5. The analysis is based on pure thermal loading and thus only stress level due to the above said is done the analysis does not determine the life of the piston.
6. Only ambient air-cooling is taken into account and no forced Convection is taken.
7. The thermal conductivity of the material used for the analysis is uniform throughout.
8. The specific heat of the material used is constant throughout and does not change with temperature.

3.4. The Piston Model

The following are the sequence of steps in which the piston is modeled.

- Drawing a half portion of piston
- Exiting the sketcher
- Developing the model
- Creating a hole

3.5. Applying the boundary conditions

In thermal and structural analysis of piston, we have to apply thermal and boundary conditions on 3D model of piston.

.Design Specification before optimization

S.No.	Dimensions	Size in mm
1	Length of the Piston(L)	152
2	Cylinder bore/outside diameter of the piston(D)	140
3	Thickness of piston head (t_H)	9.036
4	Radial thickness of the ring (t_1)	5.24
5	Axial thickness of the ring (t_2)	5
6	Width of the top land (b_1)	10
7	Width of other ring lands (b_2)	4

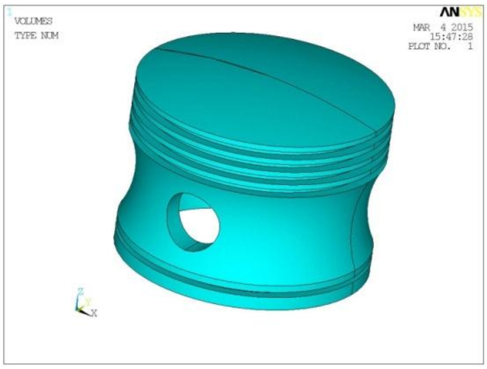


Fig. Piston 3D model isometric view

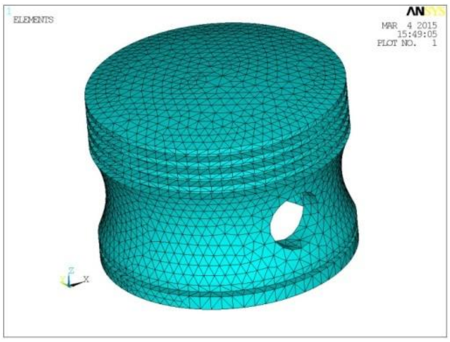


Fig. Piston mesh model

3.6. Thermal boundary conditions

It is important to calculate the piston temperature distribution in order to control the thermal stresses and deformations within acceptable levels. The temperature distribution enables us to optimize the thermal aspects of the piston design at lower cost, before the first prototype is constructed. Most of the Internal Combustion(IC) engine pistons are made of an aluminum alloy which has a thermal expansion coefficient,80% higher than the cylinder bore material made of cast iron. This leads to some differences between running and the design clearances. Therefore, analysis of the piston thermal behavior is extremely crucial in designing more efficient engine. In this project the analysis is carried out for 3 different materials. The thermal and material properties are given in the below table.

Table.1 Material properties

S.no	Name of the property	Al-Alloy	Grey cast Iron	SiC reinforced ZrB2 Composite
1	Thermal conductivity	174 W/mK	53.3 W/mK	93.7 W/mK
2	Specific heat	0.13 J/KgK	490 J/KgK	500 J/KgK
3	Young's Modulus	71e3 Mpa	1.24e5 Mpa	4.86e5 Mpa
4	Poisson's Ratio	0.33	0.3	0.11
5	Density	2770 Kg/m3	7060 Kg/m3	2060 Kg/m3
6	Thermal Expansion Coefficient	1e-6 /K	9e-6 /C	5.9e-6 /K

Applying Temperatures, Convections and Loads

The piston is divided into the areas defined by a series of grooves for sealing rings. The boundary conditions for mechanical simulation were defined as the pressure acting on the entire piston head surface (maximum pressure in the engine cylinder). It is necessary to load certain data on material that refer to both its mechanical and thermal properties to do the coupled Thermo-mechanical calculations .The temperature load is applied on different areas and pressure applied on piston head. The regions like piston head and piston ring regions are applied with large amount of heat (160°C-200°C). The convection values on the piston wall ranges from 232W/mK to 1570W/mK. The working pressure is 2Mpa.

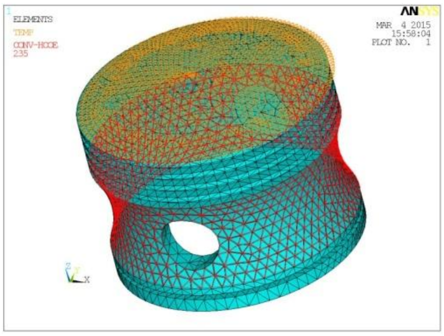


Fig. Temperature boundary condition of 200 degrees C applied on Piston

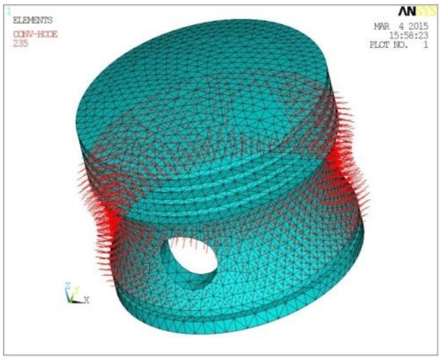


Fig. Convection boundary condition applied on Piston

Results of temperature distribution for Aluminium alloy material

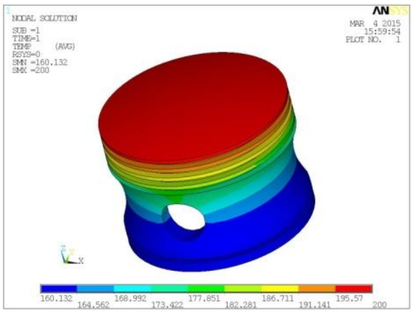


Fig. Temperature distribution on the Piston on the front side for Al-Alloy material

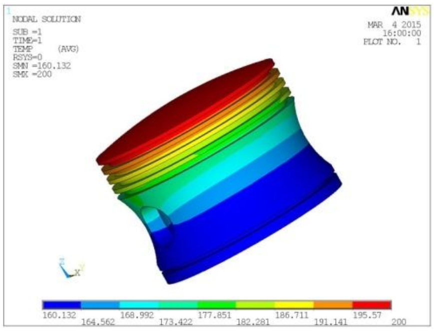


Fig. Temperature distribution on Piston on the rear side for Al-Alloy material

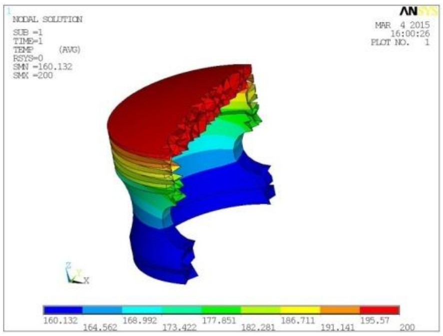


Fig. Temperature distribution on the Piston along the thickness for Al-Alloy material

4.STRUCTURAL ANALYSIS

Structural boundary conditions

Structural analysis is performed on the piston by applying temperature distribution from the thermal analysis as body loads using Ansys. Also a pressure of 2Mpa on the piston head. As we are coupling thermal analysis with structural analysis, this analysis is called couple field analysis.

For doing structural analysis the element type used is solid 95.

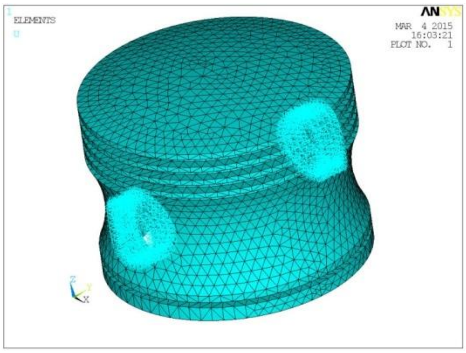


Fig. Structural boundary condition applied on the Piston

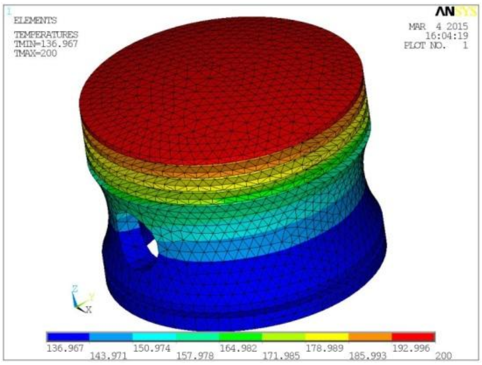


Fig. Temperature distribution is applied as Thermal loads on Piston from the thermal analysis

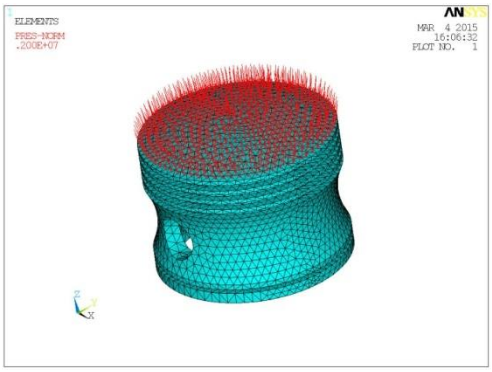


Fig. Pressure load of 2Mpa is applied on Piston

Results of deflections and stresses for Aluminium alloy material

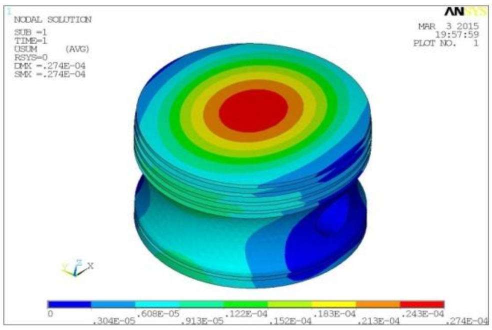


Fig. Total deflection of Piston for aluminium material

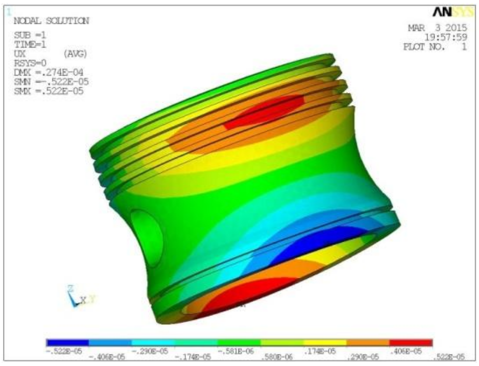


Fig. Deflection in X-dir of Piston for aluminium material

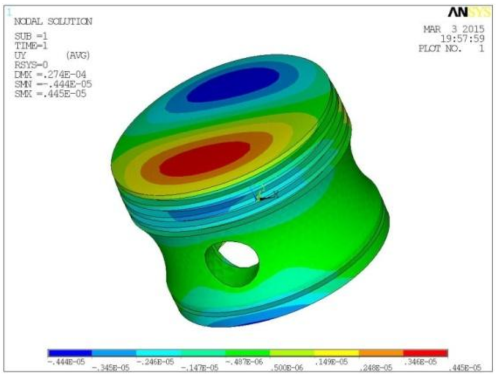


Fig. Deflection in Y-dir of Piston for aluminium material

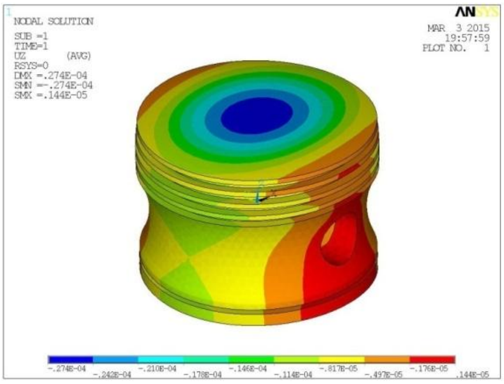


Fig. Deflection in Z-dir of Piston for aluminium material

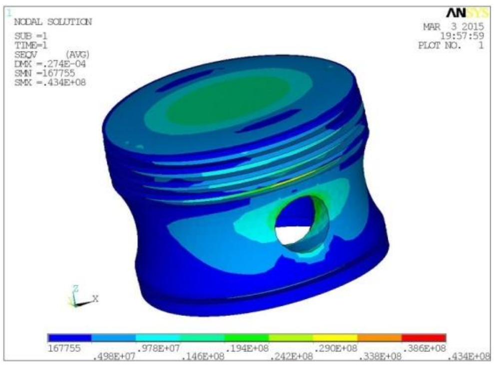


Fig. Von-Mises stress on Piston for aluminium material

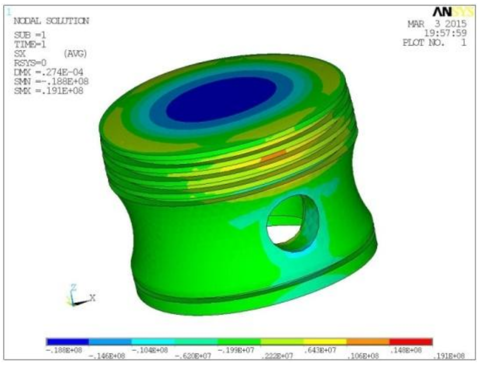


Fig. X-dir stress on Piston for aluminium material

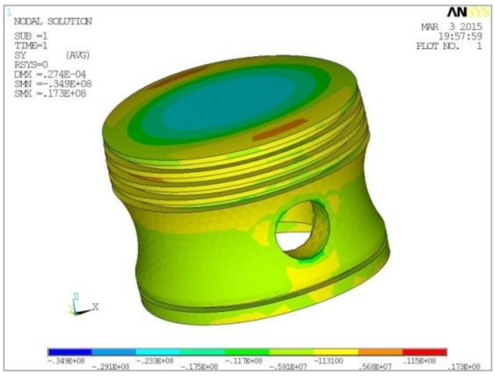


Fig. Y-dir stress on Piston for aluminium material

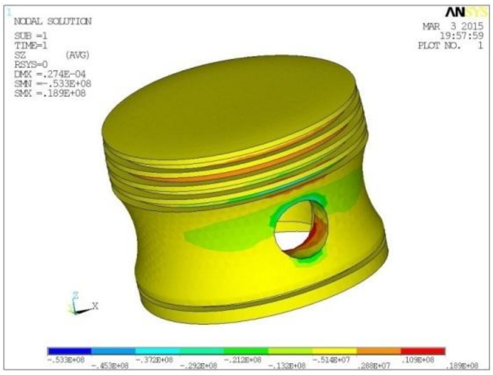


Fig. Z-dir stress on Piston for aluminium material

From the above analysis the total deflection on the piston observed is 0.02mm and the maximum Von-Mises stress observed is 43.4Mpa.The permissible strength of the material is 90Mpa.From the results the stresses on the piston is very well less than the permissible strength of the material. The couple field analysis is carried out for **grey cast iron** material and **SiC reinforced ZrB2 Composite material** by applying the respective material properties as mentioned in table.1 and by keeping the boundary conditions and loading constant. The results obtained for both the materials are shown below.

Results of temperature distribution for Grey cast iron material

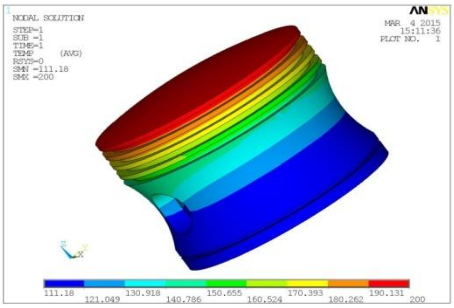


Fig. Temperature distribution on the Piston on the front side for Grey cast iron material

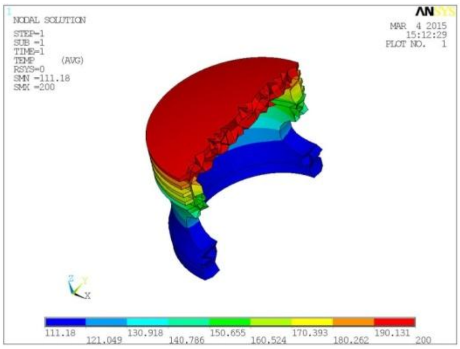


Fig. Temperature distribution on Piston on the rear side for Grey cast iron material

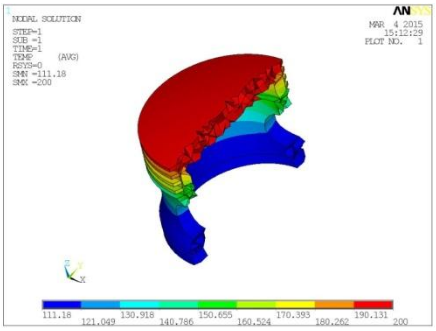


Fig. Temperature distribution on the Piston along the thickness for Grey cast iron material

Structural Results of deflections and stresses for Grey cast iron material

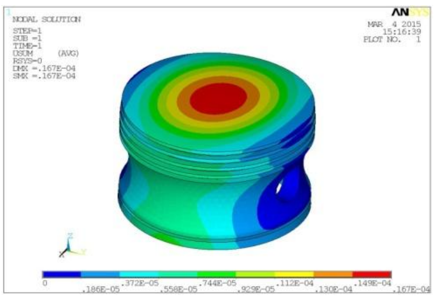


Fig. Total deflection of Piston for Grey cast iron material

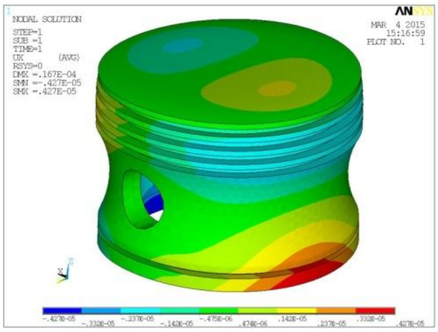


Fig. Deflection in X-dir of Piston for Grey cast iron material

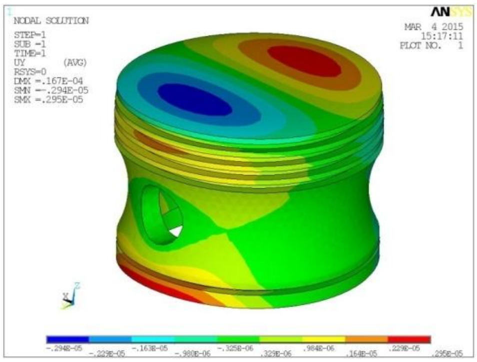


Fig. Deflection in Y-dir of Piston for Grey cast iron material

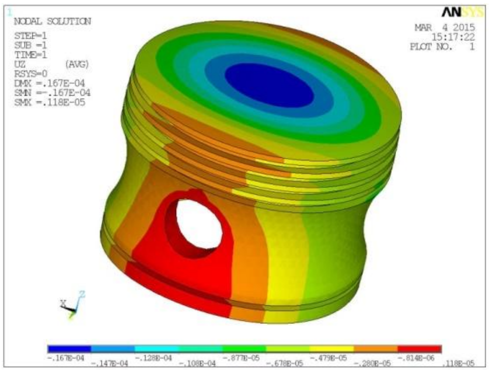


Fig. Deflection in Z-dir of Piston for Grey cast iron material

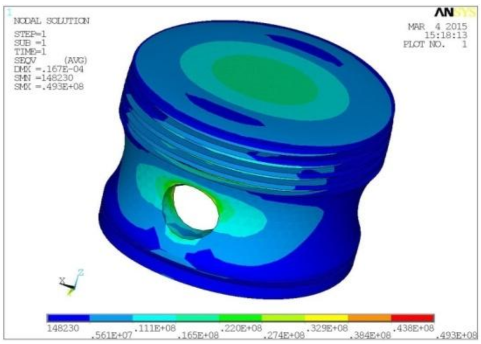


Fig. VonMises stress on Piston for Grey cast iron material

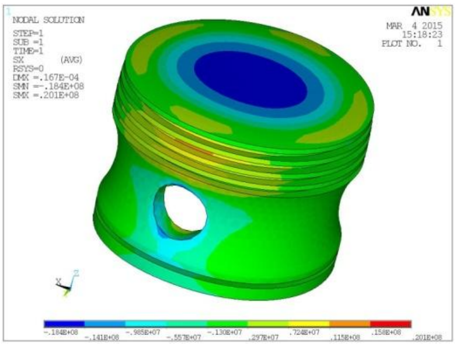


Fig. X-dir stress on Piston for Grey cast iron material

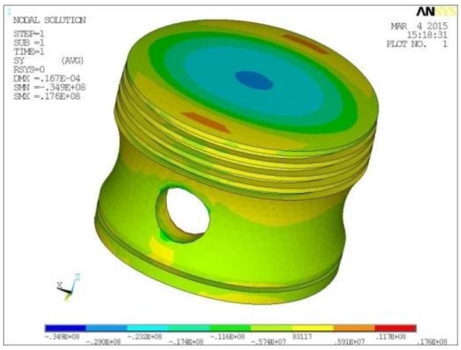


Fig. Y-dir stress on Piston for Grey cast iron material

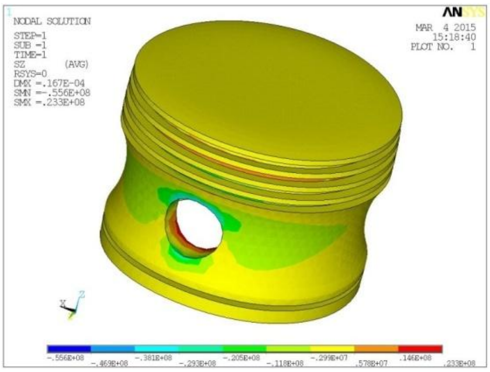


Fig. Z-dir stress on Piston for Grey cast iron material

From the above analysis the total deflection on the piston observed is 0.016mm and the maximum Von-Mises stress observed is 49.3Mpa.The permissible strength of the material is 90Mpa.From the results the stresses on the piston is very well less than the permissible strength of the material. The couple field analysis is carried out for **SiC reinforced ZrB2 Composite material** by applying the respective material properties as mentioned in table.1 and by keeping the boundary conditions and loading constant. The results obtained for are shown below.

Results of temperature distribution for SiC reinforced ZrB2 Composite material

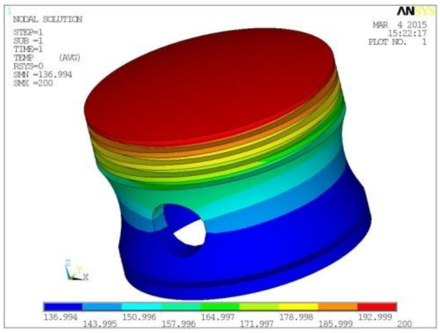


Fig. Temperature distribution on the Piston for SiC reinforced ZrB2 Composite material

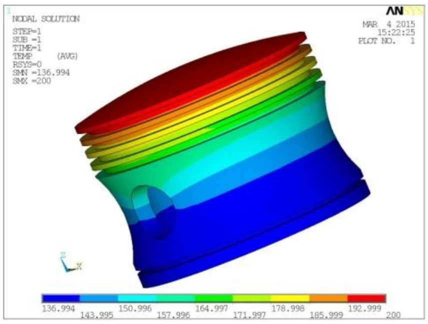


Fig. Temperature distribution on Piston on the rear side for SiC reinforced ZrB2 Composite material

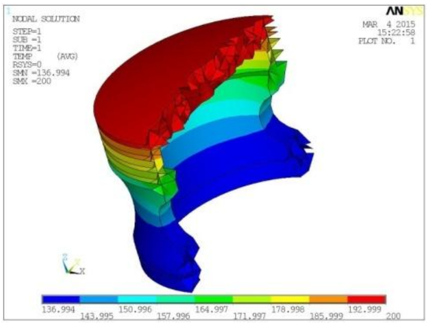


Fig. Temperature distribution along the thickness for SiC reinforced ZrB2 Composite material

Structural Results of deflections and stresses for SiC reinforced ZrB2 Composite material

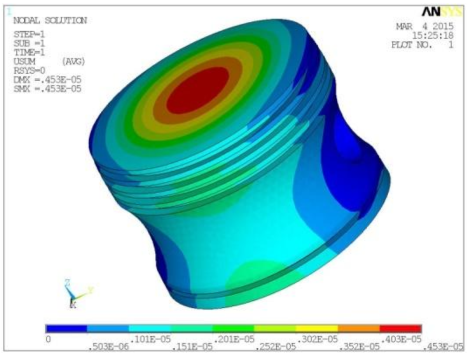


Fig. Total deflection of Piston for SiC reinforced ZrB2 Composite material

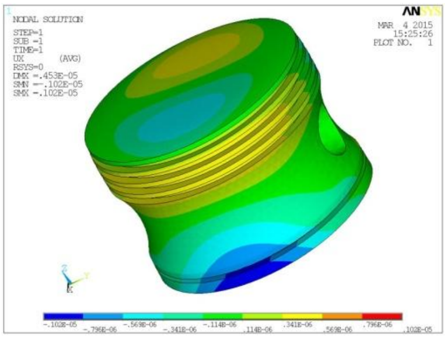


Fig. Deflection in X-dir of Piston for SiC reinforced ZrB2 Composite material

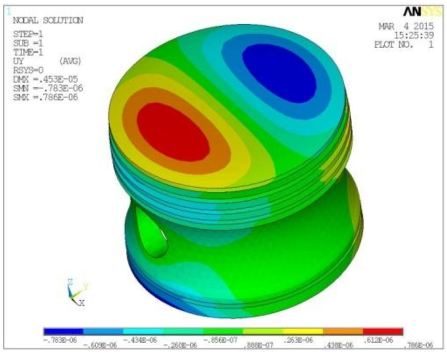


Fig. Deflection in Y-dir of Piston for SiC reinforced ZrB2 Composite material

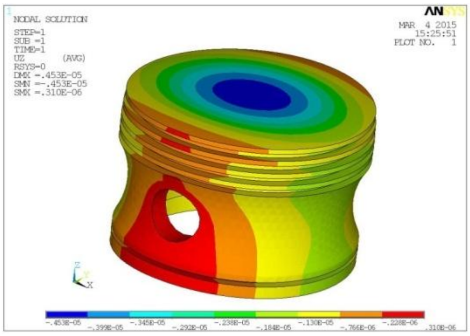


Fig. Deflection in Z-dir of Piston for SiC reinforced ZrB2 Composite material

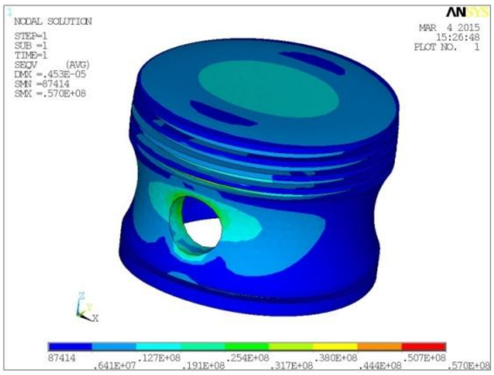


Fig. VonMises stress on Piston for SiC reinforced ZrB2 Composite material

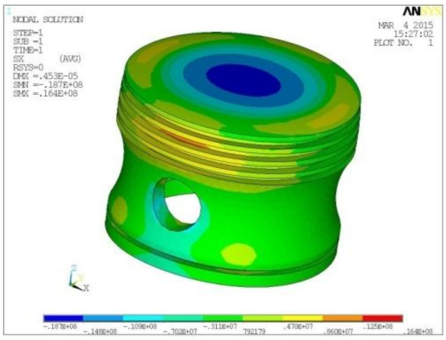


Fig. X-dir stress on Piston for SiC reinforced ZrB2 Composite material

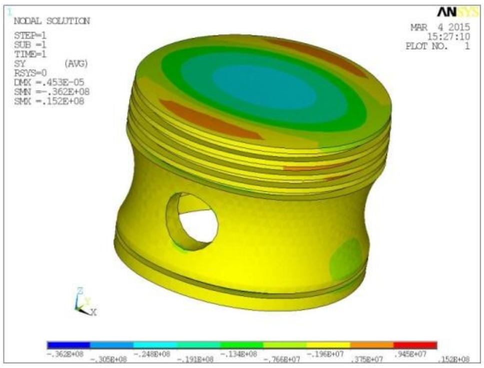


Fig. Y-dir stress on Piston for SiC reinforced ZrB2 Composite material

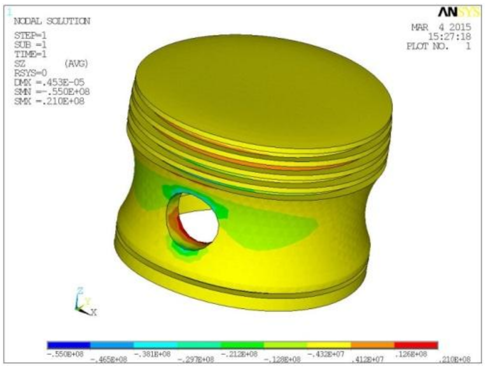


Fig. Z-dir stress on Piston for SiC reinforced ZrB2 Composite material

From the above analysis the total deflection on the piston observed is 0.0045mm and the maximum VonMises stress observed is 57 Mpa. The permissible strength of the material is 90Mpa.The results of all the analysis with different materials are compared and tabulated in the below table. From the results it is observed that stresses are within permissible limits for all the materials and it is observed that the deflections are very less for **SiC reinforced ZrB2 Composite material** compared to **Al-Alloy and Grey cast iron.**

Table.2 Comparison of results for 3 materials

S.No	Item	Al-Alloy	Grey cast Iron	SiC reinforced ZrB2 Composite
1	Usum (mm)	0.027	0.016	0.0045
2	Ux (mm)	0.0052	0.0042	0.001
3	Uy (mm)	0.0044	0.0029	0.00078
4	Uz (mm)	0.0014	0.0011	0.00031
5	VonMises stress (Mpa)	43.4	49.3	57
6	Stress in X-Dir (Mpa)	19.1	20.1	16.4
7	Stress in Y-Dir (Mpa)	17.3	17.6	15.2
8	Stress in Z-Dir (Mpa)	18.9	23.3	21

5. MODAL ANALYSIS:

Modal analysis was carried out on piston with 3 different materials (Al-alloy, Grey cast iron and SiC reinforced ZrB2 Composite material) to determine the first 10 natural frequencies and fundamental mode shape of the structure. This would enable us to understand the dynamic behavior of the structure. The more is the fundamental natural frequency the more will be the stiffness of the structure. The boundary conditions used for modal analysis is as below

- Piston pin locations constrained in all DOF as shown in the figure.

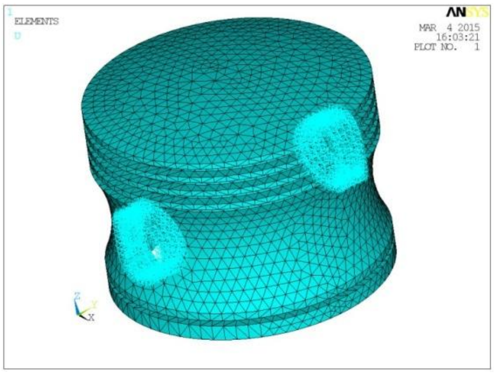


Fig: Piston pin locations constrained in all DOF

Results of Modal analysis of piston for Al-alloy material: The first 10 natural frequencies of piston with Al-alloy material and the corresponding mode numbers are tabulated in the below table and mode shape of the fundamental natural frequency is plotted in the below figure.

Mode No.	Frequency (Hz)
1	4759.2
2	6164.9
3	7422.2
4	7763
5	9890.6
6	10479
7	11186
8	13574
9	14360
10	14691

Table 3: First 10 natural frequencies of piston with Al-alloy material

Mode shape @ 4759 Hz

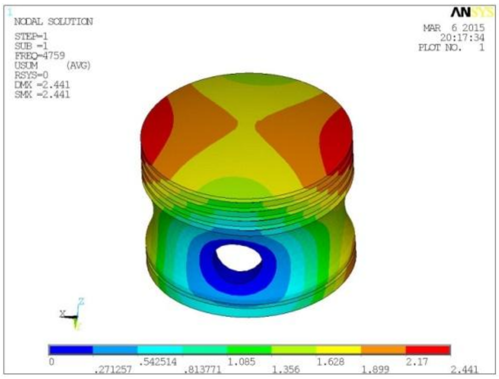


Fig: 1st Mode shape @ 4759 Hz of piston with Al-alloy material

From thee modal analysis the fundamental natural frequency observed on the piston with Al-alloy material is 4759 Hz.

Results of Modal analysis of piston with Grey cast iron material: The first 10 natural frequencies of piston with grey cast iron material and the corresponding mode numbers are tabulated in the below table and mode shape of the fundamental natural frequency is plotted in the below figure.

Mode No.	Frequency (Hz)
1	4006
2	5124.1
3	6181.8
4	6481.5
5	8281.3
6	8776.5
7	9294.6
8	11396
9	12003
10	12245

Table 4: First 10 natural frequencies of piston with grey cast iron material

Mode shape @ 4006 Hz

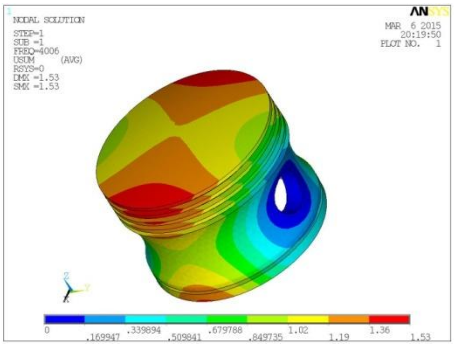


Fig: 1st Mode shape @ 4006 Hz of piston with grey cast iron material

From the modal analysis the fundamental natural frequency observed on the piston with grey cast iron material is 4006 Hz.

Results of Modal analysis of piston with SiC reinforced ZrB2 Composite material: The first 10 natural frequencies of piston with SiC reinforced ZrB2 Composite material and the corresponding mode numbers are tabulated in the below table and mode shape of the fundamental natural frequency is plotted in the below figure.

Mode No.	Frequency (Hz)
1	15717
2	18708
3	22853
4	24119
5	31508
6	33331
7	33854
8	43991
9	45055
10	45343

Table 5: First 10 natural frequencies of piston with SiC reinforced ZrB2 Composite material

Mode shape @ 15717 Hz

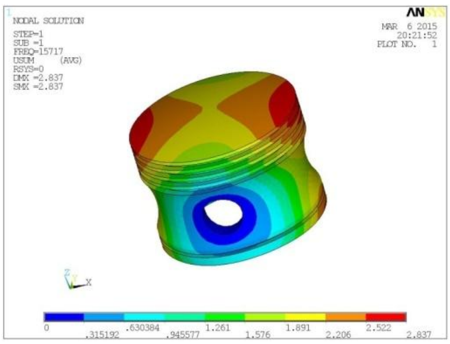


Fig: 1st Mode shape @ 15717 Hz of piston with SiC reinforced ZrB2 Composite material

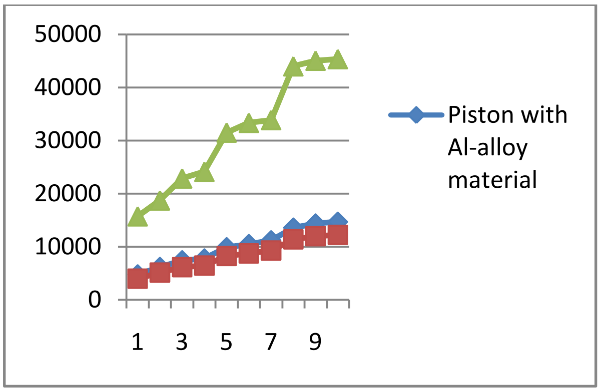
From the modal analysis the fundamental natural frequency observed on the piston with SiC reinforced ZrB2 Composite material is 15717 Hz.

The first 10 natural frequencies obtained for the piston with 3 different materials (Al-alloy, Grey cast iron and SiC reinforced ZrB2 Composite material) are tabulated and compared as shown below.

Mode No.	Frequency (Hz)		
	Piston with Al-alloy material	Piston with grey cast iron material	Piston with SiC reinforced ZrB2 Composite material
1	4759.2	4006	15717
2	6164.9	5124.1	18708
3	7422.2	6181.8	22853
4	7763	6481.5	24119
5	9890.6	8281.3	31508
6	10479	8776.5	33331
7	11186	9294.6	33854
8	13574	11396	43991
9	14360	12003	45055
10	14691	12245	45343

Table 6: Comparisons of first 10 natural frequencies of piston for different material

Comparison of natural frequencies for different materials of piston in the graphical format



Graph1:Comparison of natural frequencies of piston for different materials

From the above modal analysis results it is observed that the first 10 natural frequencies are more for the piston with SiC reinforced ZrB2 Composite material. This indicates that the piston with SiC reinforced ZrB2 Composite material has more stiffness and dynamic response.

6.CONCLUSION

In this paper finite element analysis for static and dynamic conditions of the engine piston with different materials was performed. The main objective of this project was to study the response of aluminium alloy,grey cast iron and SiC reinforced ZrB2 composite material for the applied temperatures and pressure. From the results it is concluded that the piston with SiC reinforced ZrB2 composite material is having less defections, while the piston with aluminium alloy and grey cast iron is having more deflections for the applied temperatures and pressures. It is also observed that the stresses for all the materials is within the allowable limits of the respective material. From the modal analysis, it is observed that piston with aluminium alloy and grey cast iron is having less geometric stiffness, while the piston with SiC reinforced ZrB2 composite material is having more geometric stiffness.So,it is concluded that the fuselage piston with SiC reinforced ZrB2 composite material is the best choice for the manufacturing of the piston. In this project for complex designs it is recommended the use of the stress analyses software because complex geometries may cause larger errors in the analytical procedure.

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