NON-LINEAR STATIC STRUCTURAL ANALYSIS OF OPTIMIZED PISTON FOR BIO-FUEL USING ANSYS

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ABSTRACT

An optimized piston which is lighter and stronger is coated with zirconium for bio-fuel. The low grade LHR engines are using ceramic coatings on piston, liner and cylinder head, while medium grade LHR engines provide air gap in the piston and other components. It is necessary to test the coated piston for withstanding the stresses and strains. In this paper, the coated piston undergone a vonmisses test by using ANSYS for load applied on the top. Analysis of the stress distribution was done on various parts of the coated piston for finding the stresses due to the gas pressure and thermal variations. Vonmisses stress is increased by 16% and deflection is increased after optimization. But all the parameters are well with in design consideration.

Key Words: ANSYS, Vonmisses Stress, Non-linear Analysis, Zirconium coating.

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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 [1].

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 upper end of the piston and stress concentration is one of the mainly reason for fatigue failure [2].

The piston is designed for LHR engines for bio-fuel. The vegetable oils are promising substitutes for diesel fuel as they are renewable in nature. The vegetable oils have the problems of high viscosity, low volatility and their polyunsaturated character. Hence crude vegetable oil was converted into biodiesel by treating crude vegetable oil was stirred with methanol at around 60-70^{o}C with 0.5% of NaOH based on weight of the oil, for about 3 hours. At the end of the reaction, excess methanol is removed by distillation and glycerol, which separates out was removed. The methyl esters were treated with dilute acid to neutralize the alkali and then washed to get free of acid, dried and distilled to get pure vegetable oil esters or biodiesel. The drawbacks associated with vegetable oils and biodiesels for use in diesel engines call for LHR engines. The concept of LHR engine is to reduce heat loss to coolant by providing thermal insulation in the path of heat flow to the coolant. LHR engines are classified depending on degree of insulation such as low grade, medium grade and high grade insulated engines. Several methods adopted for achieving low grade LHR engines are using ceramic coatings on piston, liner and cylinder head, while medium grade LHR engines provide air gap in the piston and other components with low-thermal conductivity materials like Superni, cast iron and mild steel etc and high grade LHR engine is the combination of low grade and medium grade engines. To create hot combustion chamber ceramic coating of 500 microns given on the crown of the aluminum piston by plasma spray technique [3]. A linear FEA analysis is undertaken when a structure is expected to behave linearly, i.e. obeys Hook's Law. The stress is proportional to the strain, and the structure will return to its original configuration once the load has been removed. A structure is a load bearing member and can normally be classified as a bar, beam, column, or shaft [4].

2. Modeling

2.1 Optimized 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.

2.1.1. 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.

2.2 Thermal and Geometric Properties

Aluminum Alloy:

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. As much as 60% of the total engine mechanical power lost is generated by piston ring assembly. The piston skirt surface slides on the cylinder bore. A lubricant film fills the clearance between the surfaces. The small values of the clearance increase the frictional losses and the high values increase the secondary motion of the piston. 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 [5]. The thermal and geometric properties are as shown in below table 1

Table 1: Thermal and Geometric Properties

S.No.	Name of the Property	Value
1	Thermal conductivity	174.15 W/mK
2	Specific Heat	0.13 J/kgK
3	Young's Modulus	71e3 Mpa
4	Poisson's Ratio	0.33
5	Density, Dens	2.77e-6 kg/mm³

3. Optimization

After generating an accurate finite element model a strategy for the optimization workflow was defined. Target of the optimization was to reach a mass reduction of the piston [6].

Objective Function: Minimize mass

Subject to constraints:

(i) Maximum Vonmises stress<Allowable or design stress

(ii) Factor of safety>1.2

(iii) Manufacturing constraints

(iv) After carrying out static structural analysis the stresses in each loading conditions were studied and then area where excess material can be removed were decided so that maximum vonmises stress does not exceed allowable and factor of safety is kept above 1.5 .

(v) Following reasons where scope for material removal

a. Radial Thickness of the ring
b. Axial Thickness of the ring
c. Maximum Thickness of the Barrel
d. Width of the Top Land
e. Width of other ring lands

3.1. The Piston Model before optimization

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
- Applying fillets

Piston was modeled using CATIA V5 software which is shown in Fig.1

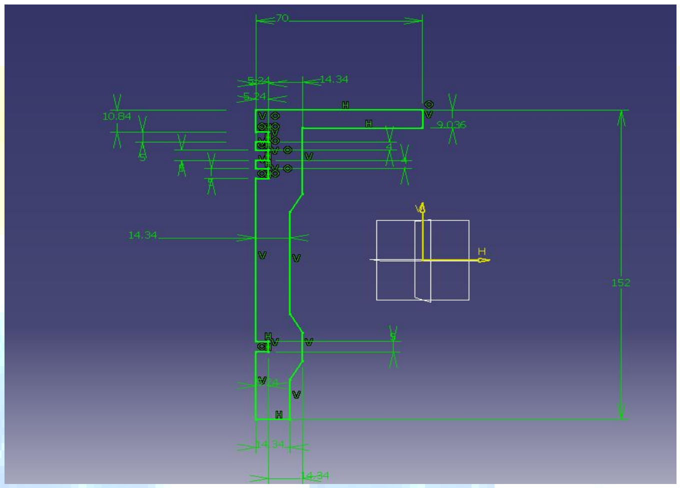

Figure 1 Piston before optimization

It was then imported to ANSYS 11.0. for analysis and optimization. Specifications of piston before optimization are shown in Table 2.

Table 2:.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

3.2 The Piston Model after optimization

The optimized model of the piston is as shown in below Figure. 2.

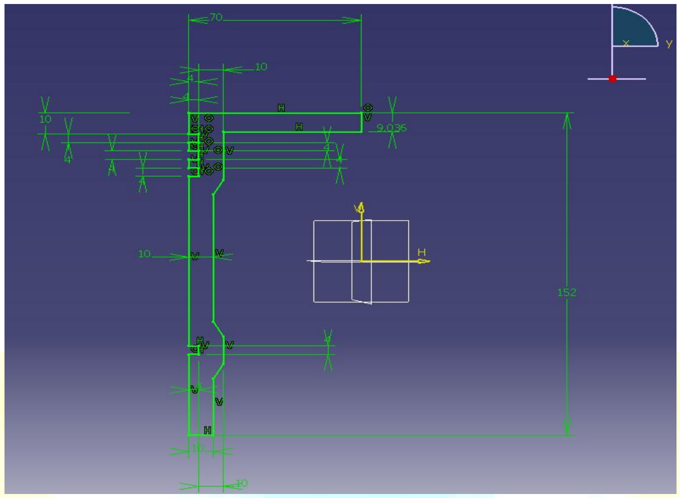

Figure 2 Piston after optimization

The model of the piston as shown in Figue 3

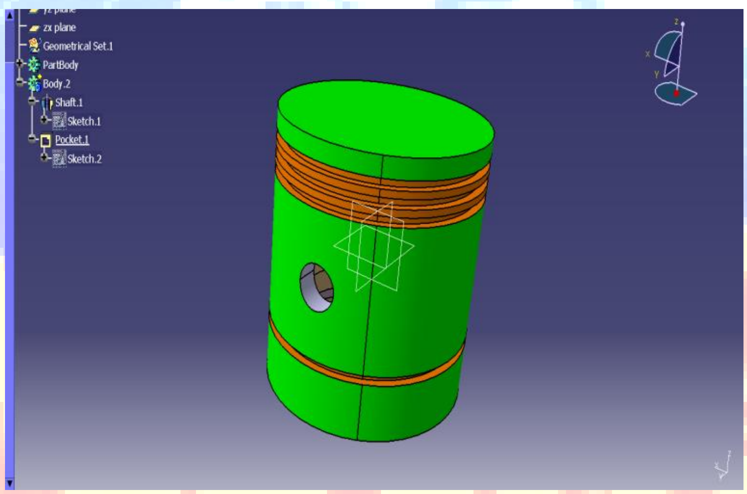

Figure 3 Model of the piston

The optimized values after optimization using ANSYS are given in the following Table 3

Table 3: Design values after optimization

S.No.	Parameter	BEFORE OPTIMIZATION	AFTER OPTIMIZATION	DESIGN CONSIDERATION
1	Volume	997021 mm^3	752994mm^3	752994mm^3
2	Radial thickness of the ring (t_1)	5.24 mm	3.46 mm	4 mm
3	Axial thickness of	5 mm	3.52 mm	4 mm

	the ring (t_2)			
4	Maximum Thickness of Barrel (t_3)	14.34 mm	9.08 mm	10 mm
5	Width of the top land (b_1)	10.84 mm	9.36 mm	10 mm
6	Width of other ring lands (b_2)	4 mm	3.24 mm	3 mm
7	Von mises stress	63.019Mpa	75.95Mpa	63-76Mpa
8	Deflection	0.0198 mm	0.120mm	0.120mm

After obtaining the optimized piston [7], it had undergone the linear static structural analysis.

3.3 Coated Piston Materials

The piston is coated with zirconium and the details of material are as follows:

Conventional metals and lubricants fail to perform at elevated temperatures, advanced ceramic materials such as nitrides and carbides of silicon(Si_2N_4 and SiC); oxides of chromium, aluminum, and iron(Cr_2O_3, Al_2O_3 and FeO_2); and partially stabilized oxide of zirconium (ZrO_2 or PSZ)] provide an alternative, Low ductility, low tensile strength, and low bending strength have impeded the direct replacement of metals with ceramics in conventional engine designs. A high temperature resistant coating has recently been developed with main objective to provide thermal insulation to metallic components at elevated temperature especially for diesel, gas turbine and aero-engine applications [8].The zirconium coating is applied on head of the optimized piston with 140mm diameter and 0.005mm thickness. This coating process and analysis is performed in ANSYS Workbench. The properties of material as follows

Table 4: Thermal and geometric properties of zirconium

S.No.	Name of the Property	Value
1	Thermal conductivity	7.32 W/mm·°C
2	Specific Heat	2.19 J/kg·°C
3	Young's Modulus	2.2e5 Mpa
4	Poisson's Ratio	0.31
5	Density, Dens	5.5e-7kg/mm³

The following Figure 4 shows coated piston and Figure 5 shows fixing of Body-to-Ground at gudgeon pin hole.

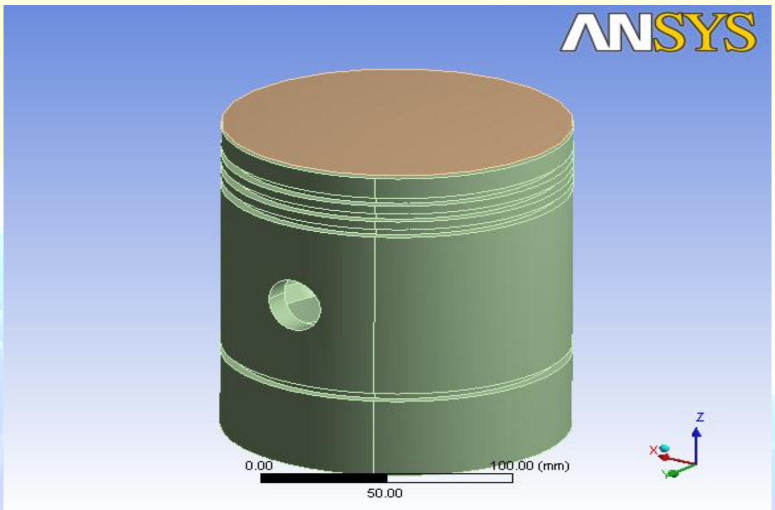

Figure 4 Coated Piston

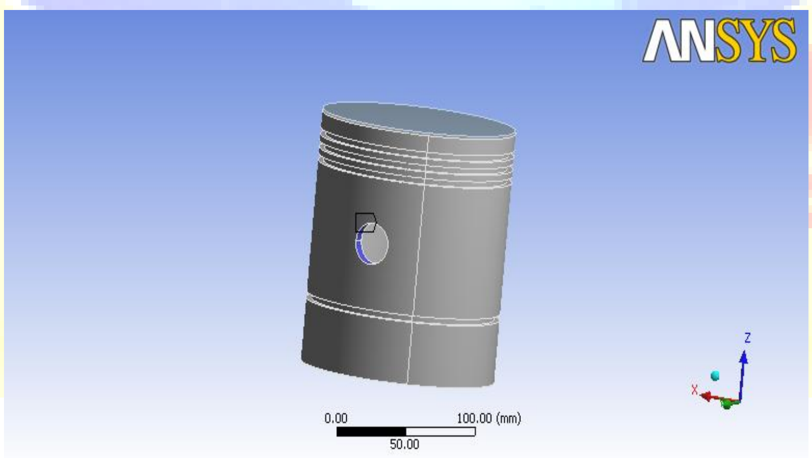

Figure 5 Fixing of Body-to-Ground at gudgeon pin hole.

3.4. Nonlinear Static Structural Analysis

After obtaining the above results and the nonlinear static structural analysis is performed by applying the pressure 2MPa on the head and varies with respect to time. The pressure and time given in the table located at right and bottom side of the workbench. Select the magnitude as Pressure Vs Time in details view. The large deflection is on in solver control

i). Static Structural shape of coated piston

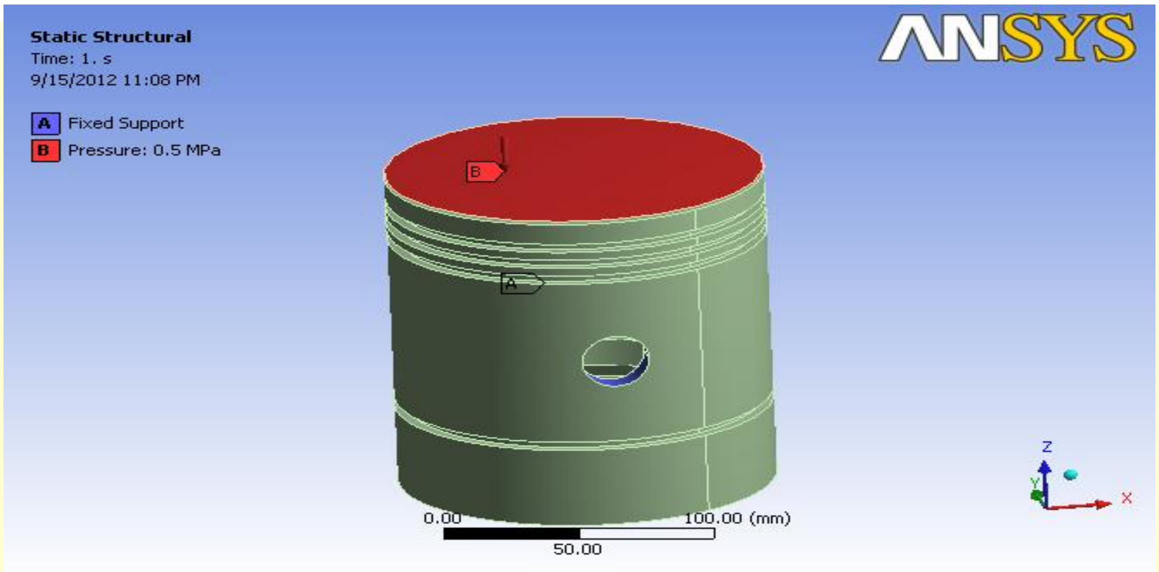

Figure 6 Static Structural

ii). Nonlinear Static Structural Analysis - Total deformation of Coated Piston

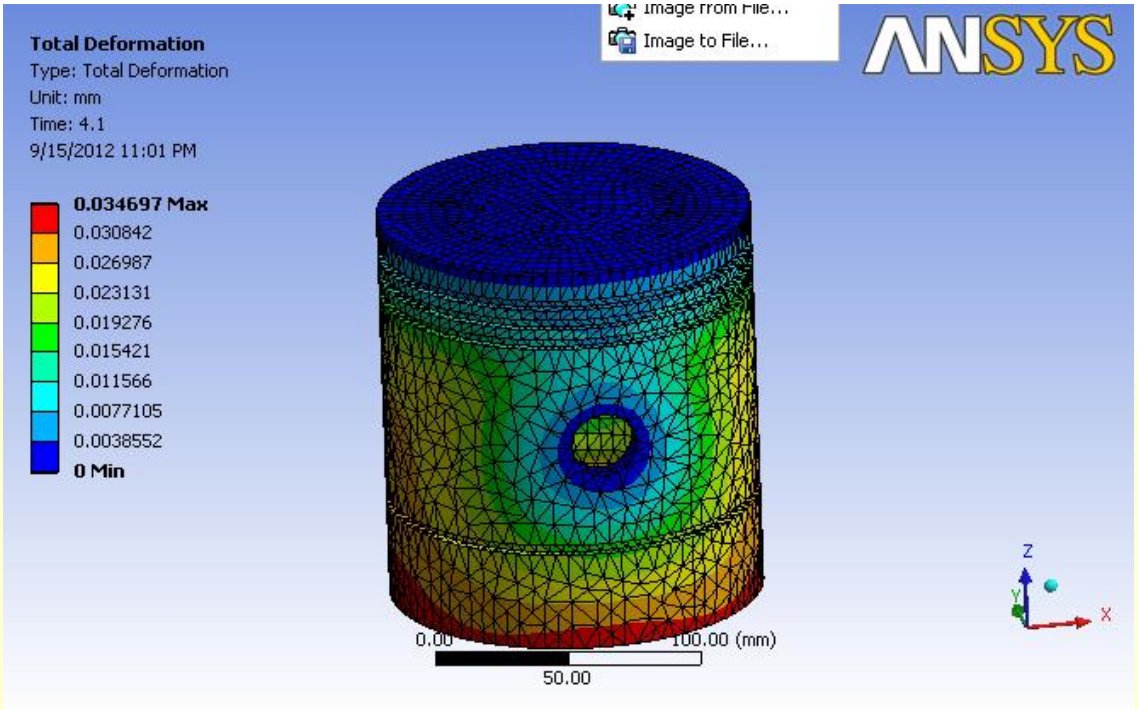

Figure 7 Nonlinear Static Structural Analysis - Total Deformation of Coated Piston

iii).von-Mises or Equivalent Stresses of Coated Piston

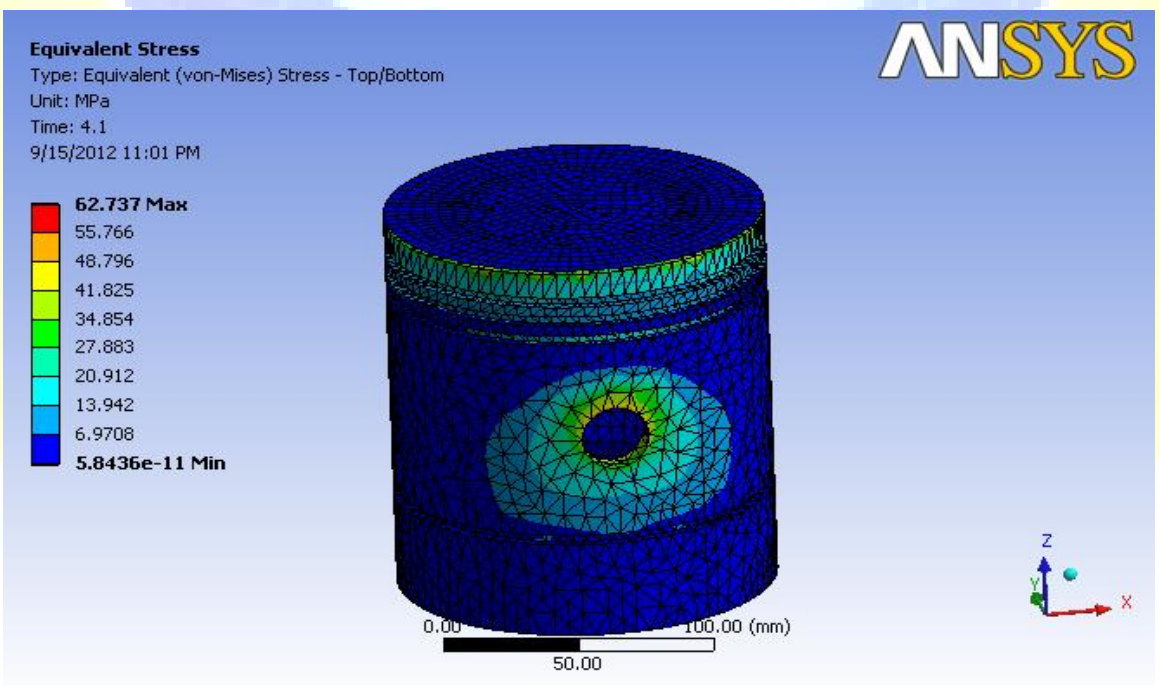

Figure 8 Nonlinear Static Structural Analysis - von-Mises Stresses

iv).Equivalent Elastic Strain

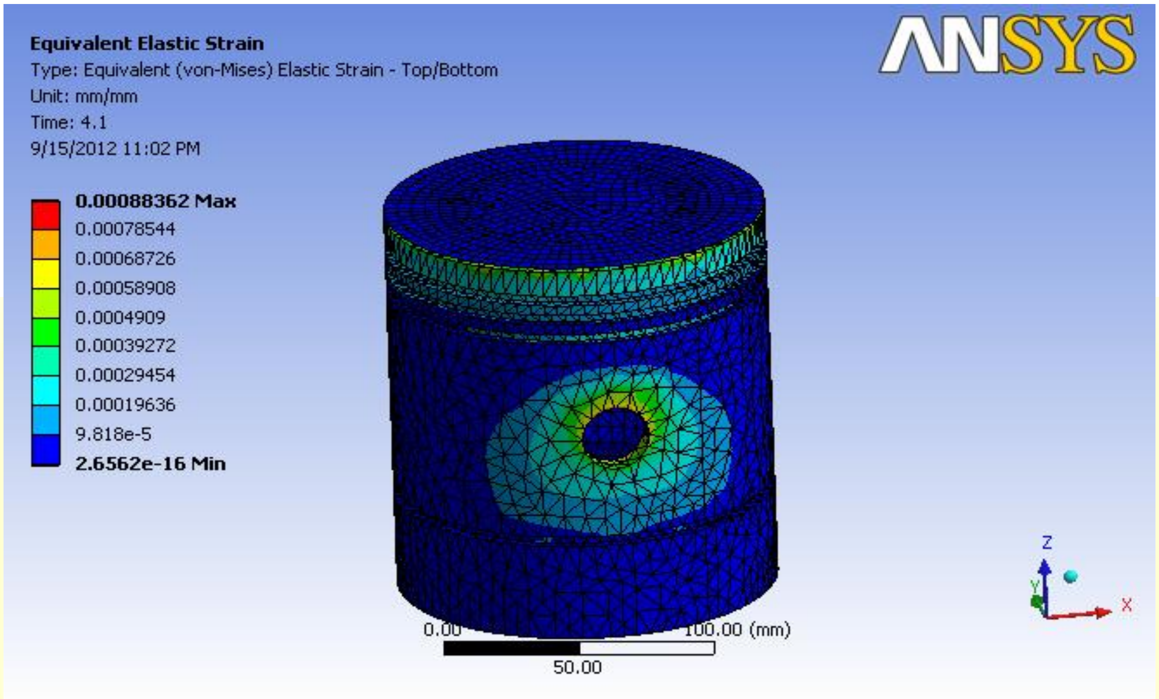

Figure 9 Equivalent Elastic Strain of Coated Piston

4. Results and Discussions

The following images are shown for resulted vonmisses stresses before and after optimization

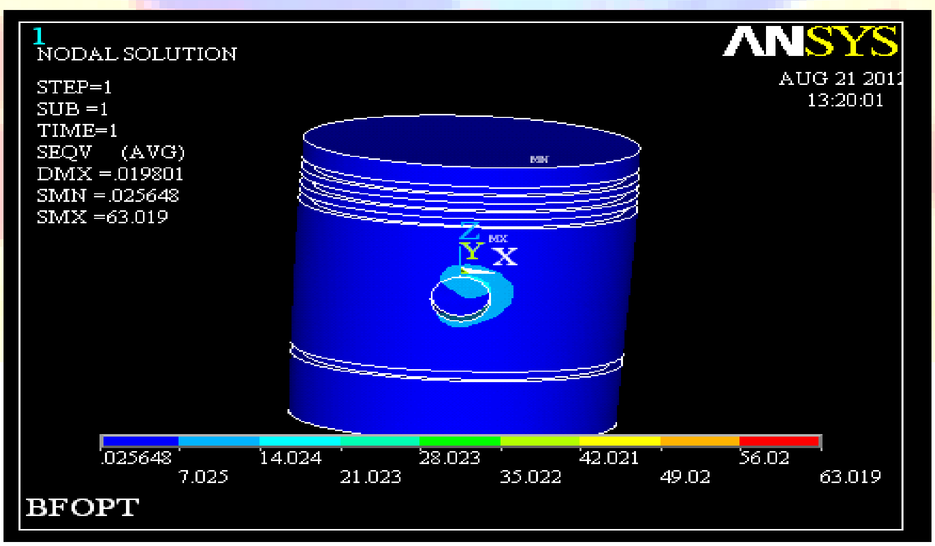

Figure 10 Vonmisses stress before optimization

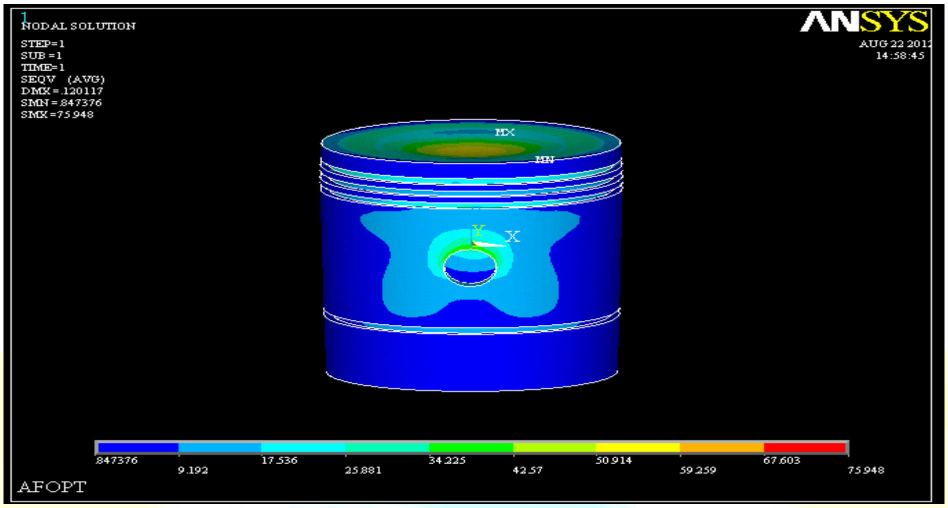

Figure 11 Vonmisses stress after optimization

The optimized values after optimization using ANSYS are given in the following Table 5

Table 5: Design values after optimization

S.No.	Parameter	BEFORE OPTIMIZATION	AFTER OPTIMIZATION	DESIGN CONSIDERATION
1	Volume	997021 mm³	752994mm³	752994mm³
2	Radial thickness of the ring (t_1)	5.24 mm	3.46 mm	4 mm
3	Axial thickness of the ring (t_2)	5 mm	3.52 mm	4 mm
4	Maximum Thickness of Barrel (t_3)	14.34 mm	9.08 mm	10 mm
5	Width of the top land (b_1)	10.84 mm	9.36 mm	10 mm
6	Width of other ring lands (b_2)	4 mm	3.24 mm	3 mm
7	Von mises stress	63.019Mpa	75.95Mpa	63-76Mpa
8	Deflection	0.0198 mm	0.120mm	0.120mm

The length 152mm of the piston obtained is same as before and after optimization process. The value after optimization is taken into consideration. It is not considerable that the variations in piston length. Applying the temperature and pressure loads on different areas of the piston and heat flow has not affected the length.

The diameter also same even after optimization process i.e., 140mm and is taken into consideration for design purposes. The heat flow in the piston material and pressure on the head has not affected in length and diameter as these are larger than other parameters. So the piston can withstand easily on sizes of these parameters.

The volume has varied after applying temperature and pressure loads over the piston as volume is depends on not only on length and diameter and also on thicknesses. The volumetric size after optimization is taken into consideration. The volume of piston before optimization is 997021 mm^3 and for the same after optimization is 752994mm^3

The radial thickness of the piston has affected more as it is very small in size and the temperature and heat flow are very high to this size of thickness. Before optimization value is given as 5.24mm and obtained after optimization is 3.46mm. This is rounded to next highest value i.e., 4mm and is taken into consideration for design. The axial thickness of the piston ring before optimization is 5mm, it is changed to 3.52mm after optimization, since the more and more heat and stress applied through groves as it is very near to the head of the piston. This is rounded to next highest value i.e., 4mm is taken into consideration for design.

The maximum thickness of the barrel before optimization is 14.34mm has much affected in variation of size after applying pressure and temperature loads and is changed to 9.08mm and rounded to next highest value i.e., 10mm taken into consideration.

The width of the top land has not much affected while comparing with the maximum thickness of the barrel. The initial value i.e., before optimization is 10.84mm and is changed after applying pressure which is directly applied on the head i.e., top of the piston as a result the shape of the piston on top will become just like a bowl. The value after optimization is obtained as 9.36mm and it is rounded to 10mm. This value is considerable for design.

The width of the other lands i.e., near piston rings are 4mm in size and is changed due to pressure and heat applied on rings through groves. The value after optimization is 3.24mm and is rounded to 3mm.

The von misses stress initially was 63.019Mpa, after optimization it is obtained as 75.95Mpa and it is permissible up to 90Mpa. So the piston with these considerations can withstand easily.

The deflection due to pressure applied is more than that of temperature applied. In this analysis the pressure as well as temperature loads are taken into consideration for applying on the piston.

The deflection before optimization is given as 0.0198mm and after optimization it is obtained that 0.120mm, this value is taken into consideration for design purpose.

The values obtained after applying the loads are depend on the area chosen by the user. The factor of safety is as follows:

A. The mass of the piston before optimization is 2.72. and factor of safety of is 1.42
B. The mass of the piston after optimization is 2.08. and factor of safety of is 1.2

4.1 Nonlinear Static Structural Analysis of coated piston

i). Parameter: Von mises stress

Table 6: . Nonlinear Static Structural Analysis of Coated Piston – Von mises stress

AFTER OPTIMIZATION	COATED PISTON	DESIGN CONSIDERATION
74.95Mpa	62.737Mpa	62-75 Mpa

The von mises stress initially was i.e., for optimized conventional piston is 74.95Mpa after coating the von-Mises Stress is obtained as 62.737Mpa and it is permissible up to 90Mpa. So the piston with these considerations can withstand easily and is under Non-Linear control. The values of the von misses stresses of coated piston are also within the permissible one. Therefore coating of zirconium with 0.005mm thickness on head of piston can be considered for the use of bio-fuel.

4.2 Related graphs: The graphs are obtained for the above results shown in the images

4.2.1 Graphs of Material Properties: The piston is made up of Aluminum Alloy, and its properties values are shown in the following graphs.

i). Thermal Conductivity Vs Temperature: The following graph shows about the aluminum properties of Thermal Conductivity and Temperature.

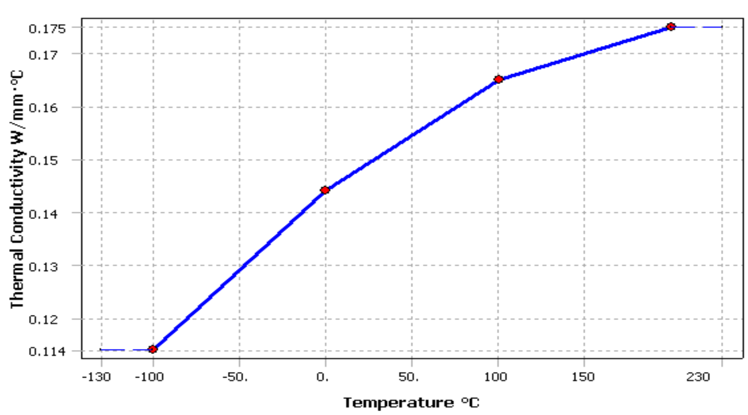

Figure 12 Thermal Conductivity Vs Temperature

It is observed that thermal conductivity increasing on increase of temperature.

ii).Alternating Stress Vs Cycle: The following graph shows alternating stress for aluminum per cycle.

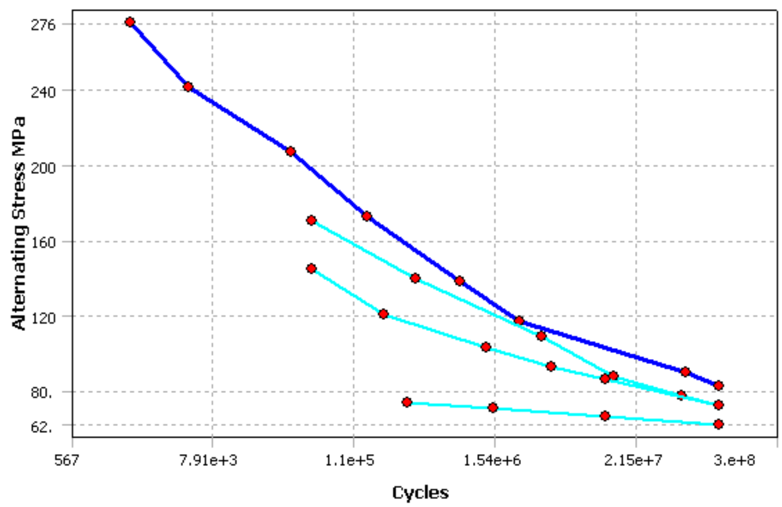

Figure 13 Alternating Vs Cycles

It is observed that the alternating stress is declining on cycles

iii).Pressure Vs Time Graph**:** The following graph shows that there is an increase in pressure with respect to time.

The graph is obtained according the user given input.

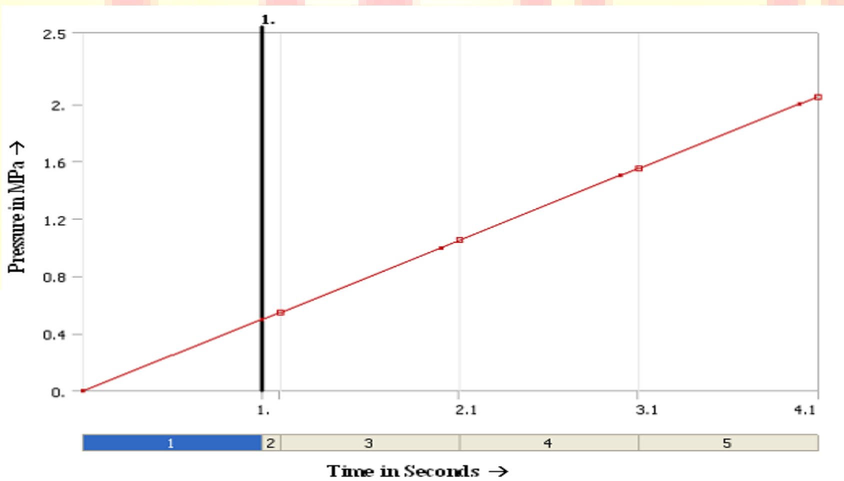

Figure 14: Pressure Vs Time

iii).Equivalent Stress or von-Mises Stress Table, Chart and Graph:

Table 7. Nonlinear Static Structural Analysis - Equivalent Stress or von-Mises Stress

Steps	Time [s]	[A] Equivalent Stress (Min) [MPa]	[B] Equivalent Stress (Max) [MPa]
1	1.	3.3286e-011	55.819
2	1.1	1.3679e-011	55.956
3	2.1	2.2867e-011	57.339
4	3.1	1.4671e-011	58.745
5	4.1	5.8436e-011	62.737

The above table shows the details of Min. and Max. Equivalent Stresses in MPa.

According the above values given in table the following chart is obtained

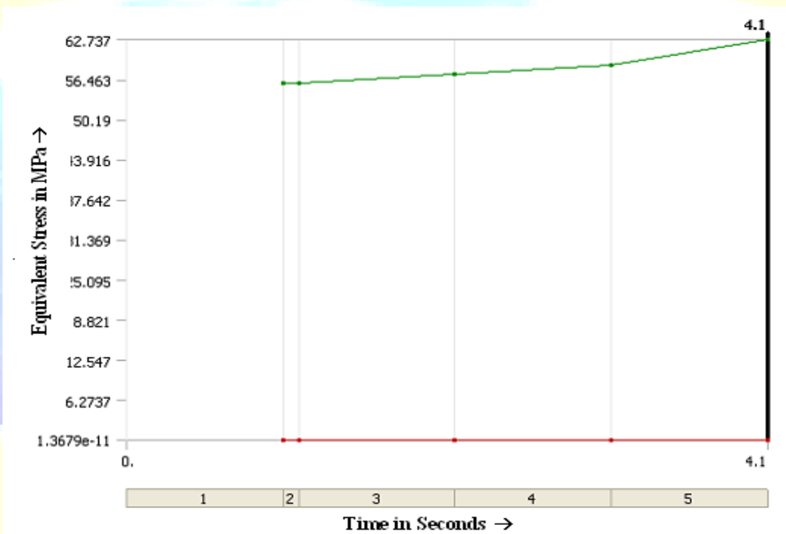

Figure 15 Chart for Equivalent Stress Vs Time

The following graph of equivalent stress with respect to times obtained according to above table and chart.

Figure 16 Graph for Equivalent Stress Vs Time

It is observed that the von-Mises stress in increasing with respect to time.

iv).Equivalent Elastic Strain Table, Chart and Graph:

The Min. and Max. Equivalent Elastic Strain values with respect to Time is as shown in below table.

Table 8: Nonlinear Static Structural Analysis - Equivalent Elastic Strain

Steps	Time [s]	[A] Equivalent Elastic Strain (Min) [mm/mm]	[B] Equivalent Elastic Strain (Max) [mm/mm]
1	1.	1.513e-016	7.8619e-004
2	1.1	6.2178e-017	7.8811e-004
3	2.1	1.0394e-016	8.0759e-004
4	3.1	6.6685e-017	8.2739e-004
5	4.1	2.6562e-016	8.8362e-004

The above table shows the details of Min. and Max. Equivalent Elastic Strain in MPa.

According these values the following chart is obtained.

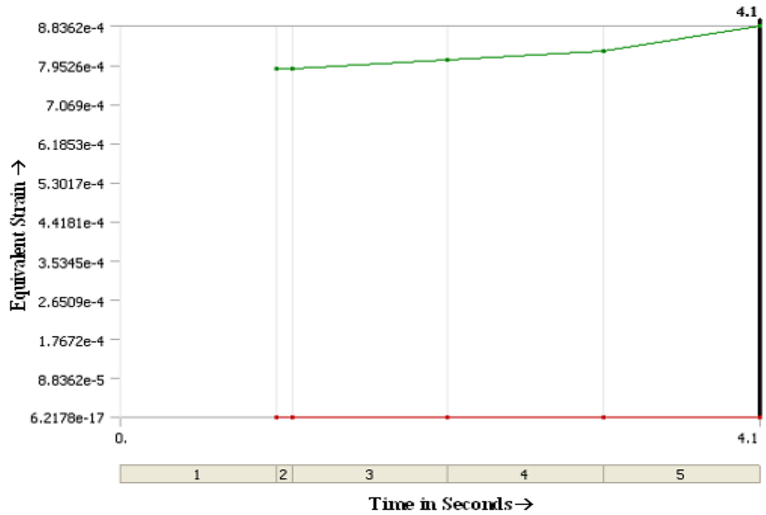

Figure 17 Chart for Equivalent Strain Vs Time

The following graph of equivalent elastic strain with respect to times obtained according to above table and chart.

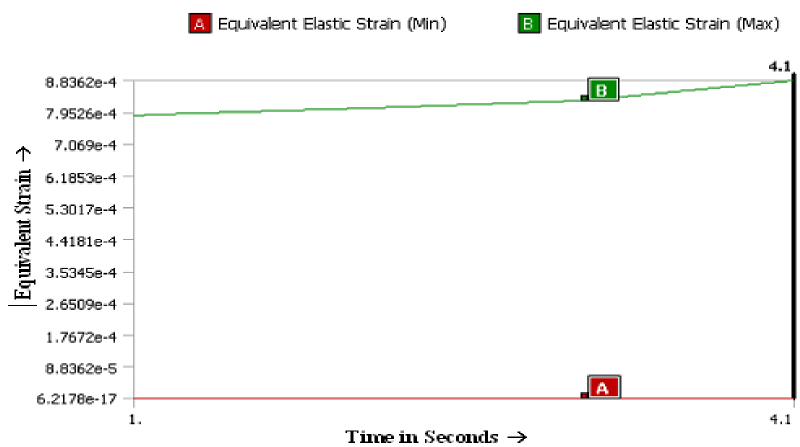

Figure 18: Graph for Equivalent Strain Vs Time.

It is observed that the Equivalent Strain is increasing with respect to time.

v). Total Deformation Table, Chart and Graph:

The Min.. and Max. Total Deformation values with respect to Time are as shown in below table.

Table 9: Nonlinear Static Structural Analysis - Total Deformation

Steps	Time [s]	[A] Total Deformation (Min) [mm]	[B] Total Deformation (Max) [mm]
1	1.	0.	3.1018e-002

2	1.1		3.0899e-002
3	2.1		3.0553e-002
4	3.1		3.1745e-002
5	4.1		3.4697e-002

The above table shows the details of Min. and Max. Deformation values in mm.

According the values given above table the following chart is obtained.

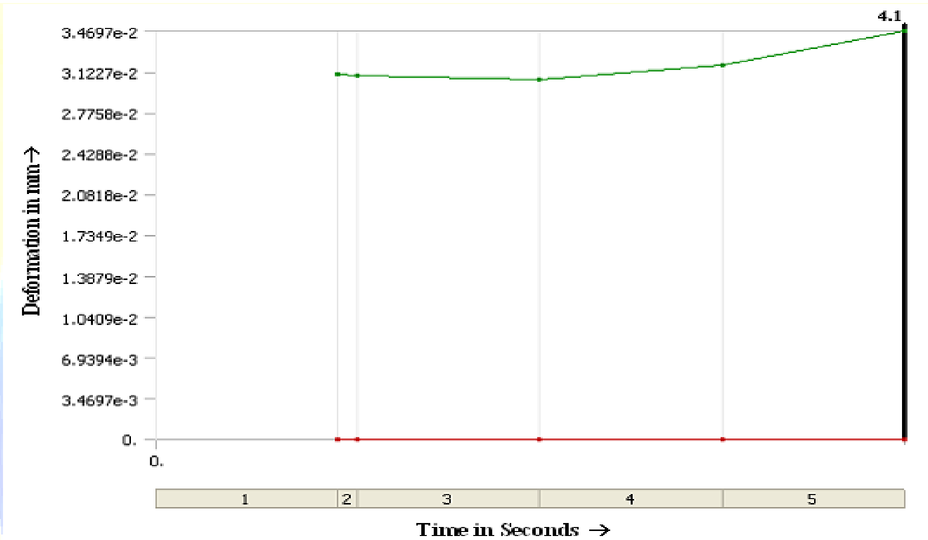

Figure 19 Chart for Deformation Vs Time.

The following graph of Total Deformation with respect to times obtained according to above table and chart.

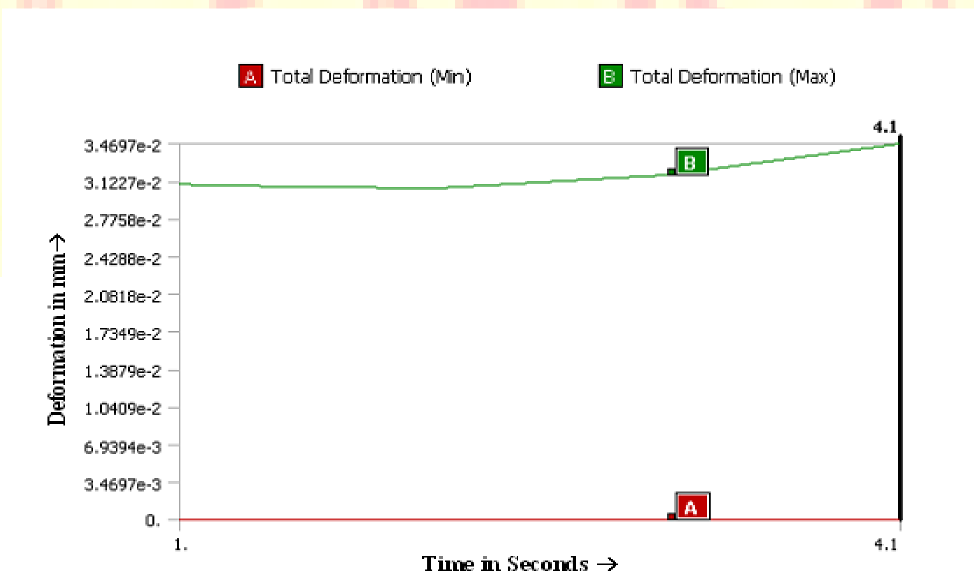

Figure 20 Graph for Deformation Vs Time

It is observed that a deformation occurred towards inner side for some time and increased gradually towards outer side of the piston with respect to time.

5. Conclusion

The deflection due to pressure applied after optimization is more than before optimization and this value is taken into consideration for design purpose. The stress distribution on the piston mainly depends on the deformation of piston. Therefore, in order to reduce the stress concentration, the piston crown should have enough stiffness to reduce the deformation.

All the phases in this project given can be extended to the piston design with reduction of material at bottom. The material is removed to reduce the weight of the piston so as to improve the efficiency. It is essential to obtain the optimized results for new piston with reduced material.

In brief:

1 The optimal mathematical model which includes formation of piston crown and quality of piston ad piston skirt.

2. The FEA is carried out for standard piston model used in diesel engine ceramic coating on crown and the result of analysis indicate that the maximum stress has changed from 63.019Mpa to 74.95Mpa.

The zirconium coated piston also obtained with the parameters, stress for given pressure and are within the permissible values. The coated piston is useful for bio-fuel. The same design, analysis can be extended to connecting rod, other parts of the engine and different coated pistons. The variational properties, which are applied on piston, can also be analyzed with the same approach for optimistic design. The different material can be used for piston for which the same analysis can extended.

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