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Design and thermal analysis of ceramic coated Mercedes Benz piston

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ABSTRACT

Piston is considered to be one of the important parts of an internal combustion engine. It is a part which bears the pressure of the combustion of the gas inside the cylinder. Normally they are made up of cast iron which bears the gas pressure. It is used to deliver the power via connecting the rod to the main shaft of the engine. Nowadays they are made of aluminum alloy to keep it lightweight. As the top surface of the piston has to bear the load, it is advisable to cover it with some coating material so that it could bear the thermal load. Piston made up of gray cast iron coated with a ceramic material (MgZrO3) which is bonded by special material (NiCrAl) is designed for Mercedes Benz/1985 by machine design approach to determine the dimensions of the piston and then it is modeled in ANSYS Workbench 17.1. The pressure of the 5 N/mm2 is applied on the piston. The equivalent stresses are found to be same for both coated and non-coated piston. Thermal analysis of both coated and the non-coated piston is done. The properties like equivalent stresses, temperature variation, and total deformation under pressure and thermal load are determined with the change in the thickness of the ceramic coating material. It is concluded that ceramic coated piston is able to handle the thermal load and is indifferent towards the structural load.

Keywords*: IC engine, Piston, ANSYS, & ceramic coated piston*

1. INTRODUCTION

Normally, piston made of cast iron material, having high specific weight and good resistance to wear. Piston, made of cast iron, possess high inertia forces because of high specific weight. They are replaced by the piston made up of Aluminum and its alloys. They are very light in weight and possess high strength when mixed with silicon. As the research progresses, several new material coatings are available. Ceramic coating is also becoming popular in the manufacturing industry. This coating enhances the performance of the engine parameters. TBC prevents the piston parts from the high temperature generating from the combustion. The high temperature is responsible for the failure of the engine parts. Thus, there is are a requirement to find how effective this TBC is in term of temperature. Thermal analysis on the piston is done for uncoating and ceramic coating.

The combustion chamber of Internal Combustion (IC) engine should be insulated for the effective utilization of heat in order to maintain a low rate of heat transfer. Temperatures rise to very high values because of insulation in the cylinder. Commonly used conventional materials are unable to bear very high temperatures in IC engines. Hence, there is a requirement to use ceramic coatings, which acts as a thermal barrier, which helps to reduce heat transfer and withstand high temperatures on the surface of the piston. The life of components, especially connecting rod, piston and other internal parts of the cylinder are affected due to high temperatures in the internal combustion engine

1.1. Introduction to piston

The piston is cylindrical in shape and is capable of taking pressure energy produced by the gases burnt inside the cylinder to power the crankshaft through connecting rod in a continuous manner. The piston also performs compression of gasses inside the cylinder along with the exhaust of gasses after the complete combustion process.

All the activities, mentioned above happen simultaneously one after the other. It is a reciprocating member which runs the shaft of the engine by transferring energy.

1.2. Parts of piston

The above-mentioned pistons are open at mouth end and consist of the following parts:

1.2.1 Piston Head: The piston head or crown0may be of three types. Depending upon the design of combustion chamber, they are of a flat type, convex type or concave type. It is used to bear the pressure generated by gases in the cylinder.

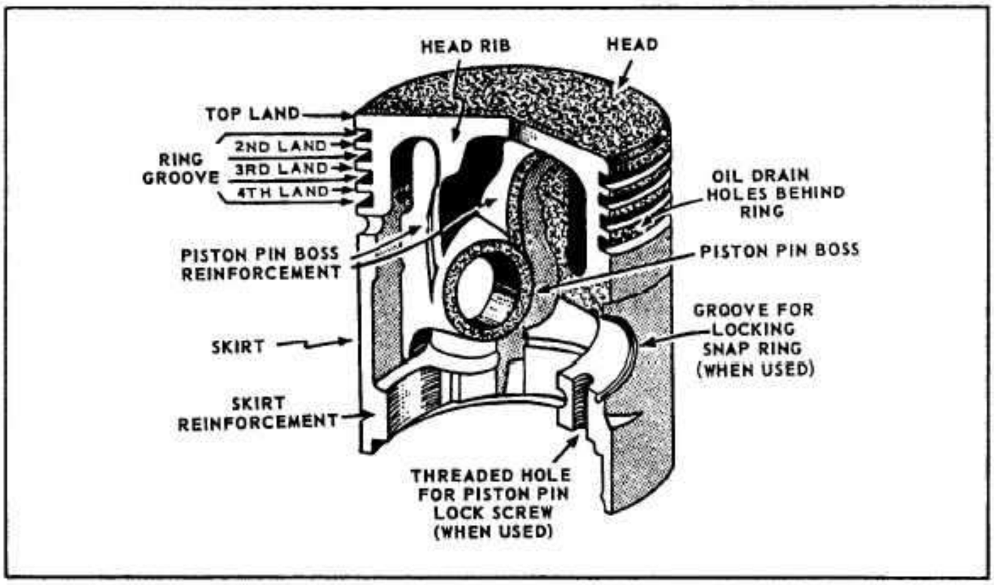

Fig. 1.1: Different parts of the piston

1.2.2 Piston rings: They are used to lock the cylinder and prevents charge leakage past the piston.

1.2.3 Skirt: The function of the skirt is to acts as a bearing for the side thrust, developed by the connecting rod on the walls of the engine cylinder.

1.2.4 Gudgeon pin: Piston pin or wrist pin is the common names of gudgeon pin**.** It is used to join the piston to the connecting rod in an IC engine.

1.2.5 Piston head: It is designed by considering the following two facts. It should have enough strength to overcome the straining effect produced by gas pressure. It is developed by Combustion blast inside the engine cylinder, and the heat obtained from the combustion should be dissipated to the cylinder walls and fins as quickly as possible.

1.2.6 Piston rings: Usually, three compression ring and an oil ring are attached as a set of a piston ring that performs reciprocating motion. The compression ring prevents blow-by phenomenon. Combustion gas at high pressure flows into the crankcase from the combustion chamber. The main work of oil ring is to prevent the excess of movement of lubricant to the inner wall of the cylinder liner. The division of the combustion chamber from the rest of the engine is the main function of the piston rings. Some assumption must be made before designing the piston rings. The first piston ring should not be too far back the piston head. This increases the clearance gap between the piston and the cylinder walls, thus, increases the leakage of hydrocarbon compounds found in the fuel, into the exhaust gases. A number of rings mainly depends on the height of piston and depends on the pressure obtained during the combustion. At medium speeds, the first ring takes over the 75% of the entire pressure. The choice of the number of rings should be the result of careful analysis, with one hand, depends on to the gas that passes into the crankcase should be the minimum, on the other, the number of rings determines the mass of the piston, engine height, and friction losses. The next figure shows some examples of some designs in piston rings and also the flowing of the oil while working. Examples and designs of piston ring a), b) pumping oil through the rings, c) scraping d) oil flow to the piston, e) gap between the piston ring and the piston itself. At the time piston movement, towards the BDC, the friction rings are in position as shown in. with the scraped oil filling the clearance gap that exists between the rings and grooves of the piston. At the time of piston movement to the TDC position the oil moves over the rings as shown in Oil, which thus moves along the side of the TDC, is finally burned in the combustion chamber of IC engine. The emissions of toxic components in the exhaust gases increase with use of Burnt oil and are not economical, the emission occurs as hydrocarbons. Burning oil also creates a sludge, carbon deposits in the interior walls of the chamber, which easily lead to SI engines to self-igniting.

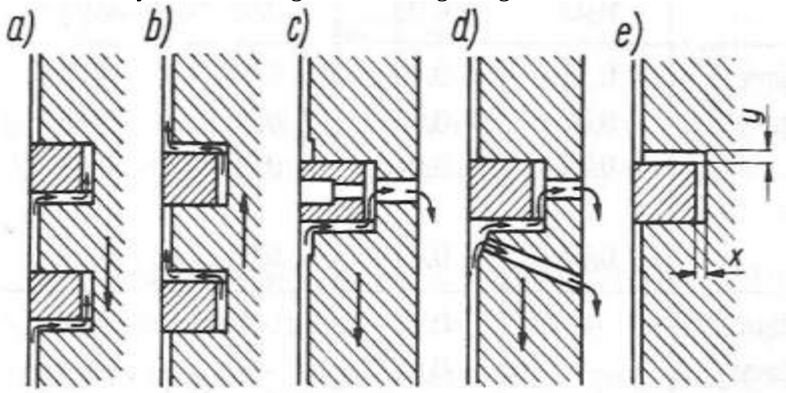

Fig. 1.2: Examples and design of piston rings

1.2.7 Piston barrel: A piston is a main part of reciprocating engines & pumps, gas compressors and pneumatic cylinders and other similar mechanisms based machines. It is the moving component that is contained in a cylinder and is made tight by piston rings so that gas does not leak out.

1.2.8 Piston pin: Gudgeon pin is used to connect the piston and the connecting rod and is also called Piston Pin. The piston pin is made hollow and may be tapered from inside. The inner diameter is at the center of the pin which is depicted in Fig. 1.3. This pin passes through the bosses which are provided inside the skirt of the piston and the bush which is fitted at the small end of the connecting rod.

For design purpose, The center of piston pin is lie in the range of 0.02 *D* to 0.04 *D* above the center of the piston skirt, in order to suppress the turning effect due to friction and to find pressure distribution between the piston and the cylinder liner of IC engine.

Piston pin material is hardened steel alloy which contains nickel, chromium, vanadium or molybdenum having a tensile strength ranging from 700 MPa to 900 MPa**.**

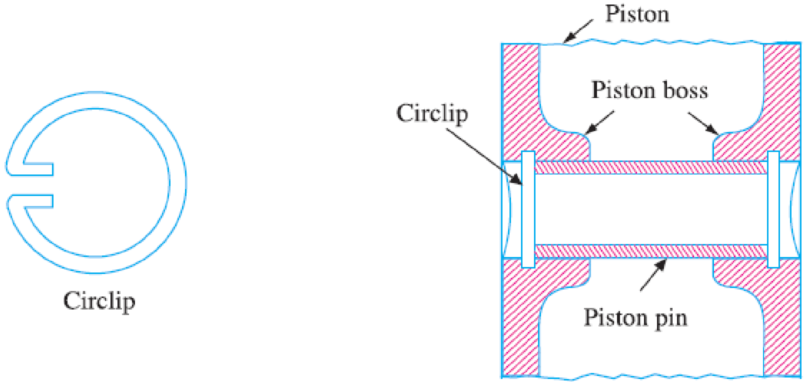

Fig. 1.3: Piston Pin of Full floating Type. [Book R. S. Khurmi]

1.3. Factors responsible for design

The following steps should be taken into consideration to design a piston for I.C. engine

- It should have adequate strength to withstand the maximum gas pressure and inertia forces of reciprocating parts of the engine.
- It should possess minimum mass to minimize the inertia forces of reciprocating parts.
- It should form an effective oil seal of the cylinder.
- It should provide sufficient bearing area to reduce undesired wear and tear.
- It should transfer the heat of combustion quickly to the cylinder walls.
- It should reciprocate at high speed with less noise.
- It should be made sufficiently rigid to withstand thermal and mechanical distortion.
- It should have sufficient support for the gudgeon pin.

1.4. Materials

Pistons have to work in extreme conditions inside the cylinder, where the temperature reaches around 600 °C. Thus, there is need of material which can withstand the extremities of pressure, temperature, and friction. Many types of piston material are available. Most common amongst them are cast iron, aluminum, and structural steel. Several alloys are also used while making the piston besides, for uniform pistons with larger speeds light alloys of aluminum are used. Advantages in aluminum alloys: low density (about one-third of the cast iron), good thermal conductivity, ease in casting and good machinability. Disadvantages are: mean (2.5 times greater than cast iron), lower hardness, decrease in strength in high temperatures and finally slightly higher price.

The small density of aluminum allows the production of lightweight pistons, which influences positively in fuel consumption and also reduce the stress and pressure from inertia forces of the reciprocating parts. Concerning the relative, great coefficient of heat conduction of aluminum alloys which results in decreasing the temperature of the piston head. It is essential in spark-ignition engines. To reduce the drawback in the alloy, it is preferable to choose the lowest rate of coefficient of expansion, with the addition of Si (up to 20%). This effect is lowered considerably.

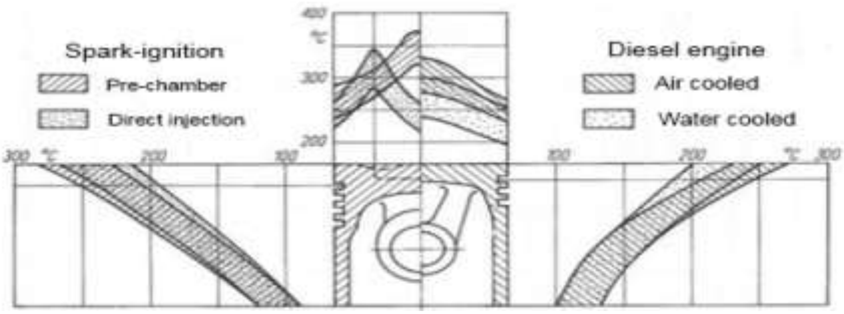

Fig. 1.4: Types of temperature on SI and CI pistons

In order to increase resistance to abrasion, heat treatment of piston alloy is done and it is artificially aged so that hardness of 120 - 140 HB can be achieved.

Aluminum alloys are be classified into the following types:

i. Copper aluminum alloys Al-Cu
ii. Eutectic aluminum alloys Al-Si
iii. Hypereutectic aluminum alloys Al-Si

1.5. Material Properties

Gray cast iron is used in the manufacturing of piston. This material is used for the designing of the piston. Gray cast iron material properties are given in Table 1.1 below:

Table 1.1: Material properties of Gray cast iron material

S. No.	Property	Gray cast iron
1	Young's Modulus (GPa)	110
2	Poisson's ratio	0.3
3	Thermal Conductivity (W/mm ^{0}C)	52
4	Thermal expansion coefficient(1/^{0}C)	1.1x10^{-5}
5	Density (Ton/mm3)	7.2 x10^{-09}
6	Specific heat(J/kg^{0}C)	460

After modeling of the piston is opened in the model mode and meshing of the piston is started.

2. ANALYSIS OF PISTON

The analysis, include designing of the piston, which is done using a machine design approach and all the parameters are determined according to steps given below. This is followed by modeling of the piston by using the dimensions determined from the step 1. This is followed by structural and thermal analysis of piston.

2.1 Design of piston

The dimensions of the piston are found by using the machine design approach and is as follows:

2.1.1 Diameter of cylinder: From design data handbook by Mahadevan (page 358, equation 18.10 a)

We know,

$$D = \left[\frac{1000 \times 4P}{(\pi/4)P_m v}\right]^{\frac{1}{2}}$$

Where,

P = Maximum Engine power =66kW (from Table no. 3.1)

P_m =Mean effective pressure =9 Pa

v = Mean speed of the piston (m/s) = 4m/s (from design data book Table 18.1 page no. 364)

Substituting the values in the above equation, we have

$$D = 96.653\ mm$$
$$D \approx 97mm\ (approx)$$

2.1.2Length of stroke

Normally length of stroke is given by $L = 1.5\ D$ but in case of Mercedes Benz i,t is taken as $L = 1.4\ D$

Thus length of stroke = 1.4 x 97mm=135.8 mm

$$L \approx 136\ mm$$

2.1.3Diameter of Piston

Now, diameter of Piston (D) = Bore diameter of cylinder = 97mm

2.2Designing of Head of Piston

For finding the thickness of piston head, the following two methods are employed

1. Strength basis
2. Heat dissipation

To find the thickness of piston head on the basis of strength, we require tensile stress for cast iron which may be taken as (σ_t= 40 MPa) and p = maximum gas pressure inside the cylinder = 5MPa

$$t_h = \sqrt{\frac{3pD^2}{16\sigma_t}} = 19.78 \approx 20mm$$

The number of working strokes in a Merced Benz (4 Stroke engine) per minute is (N=2800 rpm)

$$n = N / 2$$
$$n = 1400$$

Area of cylinder (Cross-sectional) is denoted by A and is found as follows:

$$A = \frac{\pi}{4}D^2 = 7386\ mm^2$$

The cylinder Indicated Power (IP)

$$IP = \frac{LAnp_m}{60} = 21.1kW$$

Brake power,

$$BP = IP \times \eta_m = 8.44\ kW$$

The heat generated in the cylinder falls on the piston head (Assuming $C_1 = 0.051$)

$$H = C_1 \times HCV \times m \times BP$$

$$H = 2711W$$

For the second method mentioned above and taking the following Assumption

a) Thermal conductivity values for gray cast iron $k = 46.6$ W/m/°C

b) Difference of temperature ($T_C - T_E$) = 222°C),

The piston head thickness may be computed as

$$t_h = \frac{H}{12.56\ k(T_c - T_E)} = 20.8\ mm$$

Adopting the higher value for it,

t_h of piston head= 21 mm

Taking the ratio of $L / D = 1.25$

The radius of a cup of the piston equal to 0.7 D = 68 mm.

2.2.1 Radial ribs

Radial ribs are provided to give structural support to the piston head. It four in number.

The thickness ranges from t_h / 3 to t_h / 2, where t_h is the piston's head thickness

The range of Thickness = 7 to 10 mm

Assuming it as t_R = 8 mm

2.2.2 Piston rings

Normally, each piston possesses four rings. First one in oil ring and the other are compression rings

Taking $P_w = 0.042$ N/mm^2, and σ_t (Tensile strength of ring material)= 110 MPa

Piston ring radial thickness

$$t_1 = D\sqrt{\frac{3p_w}{\sigma_t}} = 3.28mm$$

and thickness (axial) of the piston rings

$t_2 = 0.7$x t_1 to t_1 = 2.296 to 3.28 mm

Take t_2 = 3 mm

The axial thickness (Minimum) of the ring of the piston is found as,

$$t_2 = \frac{D}{10n_r} = 2.425mm$$

Thus the axial thickness of the piston ring as already calculated (*i.e.* t_2 = 3 mm) is satisfactory.

The distance from the top of the piston to the first ring groove,

The width of the top land of the piston,

$z_1 = t_h$ to 1.2 t_h = 21 to 1.2 × 21 mm = 21 to 25 mm=23mm

The width of lands of other ring,

$z_2 = 0.75\ t_2$ to t_2 = 0.75 × 3 to 3 mm = 2.25 to 3 mm

From above, y_1 = 23 mm; and y_2 = 2.5 mm**.**

The gap (separation) between the ends of the ring is

$Gap_1 = 3.5\ t_1$ to $4\ t_1$ = 3.5 × 3.28 to 4 × 3.28 mm = 11.48 to 13.12 mm

The gap (separation) when the ring is in the cylinder is determined as,

Gap_2 = 0.002 xD to 0.004 xD = 0.002 × 97 to 0.004 × 97 mm

= 0.194 to 0.388 mm

Adopting Gap_1 = 12.3 mm and Gap_2 = 0.29 mm.

2.2.3 Piston barrel

As we know, the radial depth of the grooves (y) of the piston is 0.4 mm more than t_1 (the radial thickness of the piston rings).

Thus, y is calculated as:

$y = t_1 + 0.4 = 3.28 + 0.4 = 3.68$ mm

The thickness (maximum) of barrel = 0.03 times diameter +4.5 mm

$$t_3 = 0.03 \times D + y + 4.5 = 11.1 \text{ mm}$$

Wall thickness of piston,

$$t_4 = 0.25x\ t3 \text{ to } 0.35x\ t3 = 2.775 \text{ to } 3.885 \text{ mm}$$

Adopting, $t_4 = 3.32$ mm

2.2.4 Piston skirt

Let L = Skirt length of the piston (mm).

The gas inside the cylinder gets compressed and apply the pressure known as side thrust. This side thrust is μ times the maximum pressure developed.

Assuming μ = 0.1

$$T = \mu \frac{\pi D^2}{4} p = 3.694kN$$

Given $P_b = 0.45$ N/mm^2,

The side thrust is,

$$T = P_b \times D \times L = 0.45 \times 97 \times L = 43.65xL \text{ N}$$

Finding length, we have

$$43.65L = 3694 \text{ or } L = 3694 / 43.65 = 84.62 \text{ mm.}$$

The total length of the piston,

L = Length of the skirt + Length of the ring section + Top land

$= L + (4\ t_2 + 3z_2) + z_1$

$= 85 + (4 \times 3 + 3 \times 2.5) + 23 = 127.5$ mm.

2.2.5 Piston pin

Let

d_0 = Outside diameter of the pin in mm,

l_1 = Length of pin in the bush of the small end of the connecting rod in mm (Taking $l_1 = 0.45 \times D$),

pb_1 = Pressure in the bearing bush or the bearing pressure at the small end of the connecting (N/mm^2).

$pb_{1\ (\text{bronze bushing})} = 25$ N/mm^2.

Bearing pressure load on the pin = Bearing pressure (pb_1) × Bearing area = $pb_1 \times d_0 \times l_1$

$= 25 \times d_0 \times 0.45 \times 97 = 1.091\ d_0$ kN

The gas pressure (p) acting on the piston produces maximum load, give as

$$= \frac{\pi D^2}{4} p = 36.930kN$$

From above, we find that

$1.091\ d_0 = 36.930$ or $d_0 = 36.930 / 1.091 = 34$ mm.

The inside diameter of the pin (d_i) is usually taken as $0.6\ d_0$.

∴ $d_i = 0.6 \times 34 = 20.5$ mm

3. MODELING OF PISTON

The piston is modeled in ANSYS design modeler with the help of dimensions which are determined above using machine design approach. The modeling requires dimension used to create sketches which are extruded or revolved to convert it into the desired three-dimensional model.

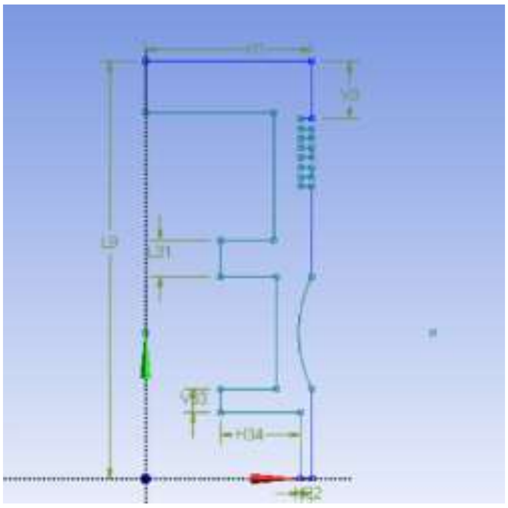

Fig. 3.1: Sketch of the piston

After preparing the sketch it is revolved about the y-axis. The desired 3D model piston is achieved as depicted in figure 3.2 given below.

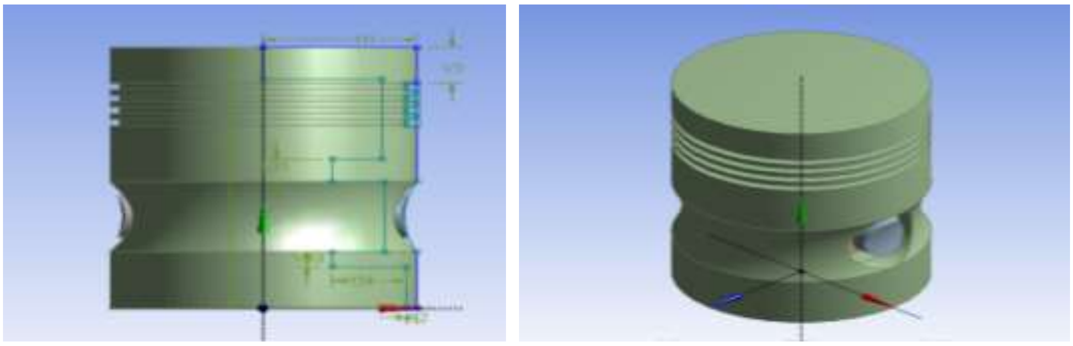

Fig. 3.2: Piston sketch (Front view) & (Isometric view)

3.1. Modeling of ceramic coated piston

The following figure depicts the layer of MgZrO3 coating on piston head joined by the NiCrAl material which binds it.

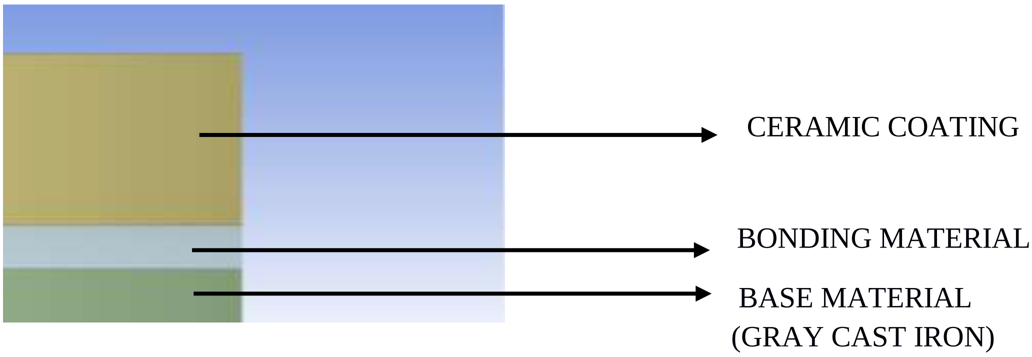

Fig. 3.3: Schematic of layering of ceramic coating with bonding mate

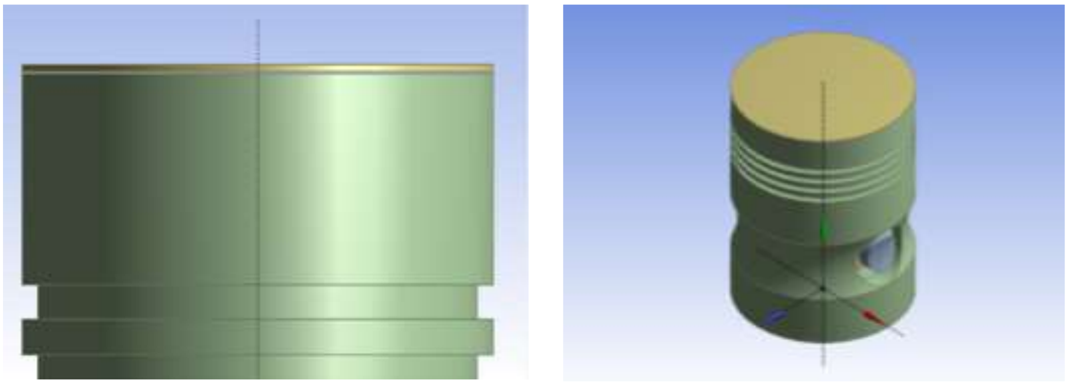

Fig. 3.4: Front view of the piston (ceramic coated) & Isometric (3D)

3.2. Meshing of piston

Meshing is a technique in which a solid model is divided into several small parts. These parts are termed as 'elements' and the vertices are termed as nodes. With the combination of these nodes and elements, the mesh is formed. Here our object is divided automatically to form a mesh of SOLID 186 and SOLID 187 type. The number of elements is 4661 and the number of nodes is 10698 for the uncoated piston. The mesh formed should be checked properly for any defects arising from the solid modeling or quality aspect. General defects in the solid modeling are free edges, opening in a sketch which leads to the poor mesh. The mesh quality is checked by the several parameters like aspect ratio and connectivity, types of mesh elements.

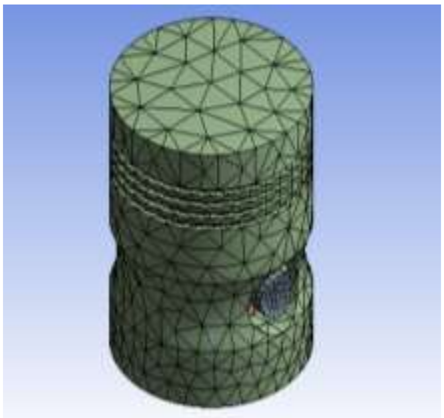

Fig. 3.5: Meshing of the piston

4. DESIGN OF EXPERIMENT

To understand the variation in the equivalent stresses, Total deformation and the maximum temperature of the ceramic coated piston with the application of different layers of coat thickness. The design of the experiment is used. This enables us to determine the values of the unknown without actually doing any change in the dimensions of the geometrical design. So, remodeling is not done again and again.

4.1 Table of design points

Table 4.1: Table of a Design experiment

Table of Design Points

	A	B	C	D	E	F
1	Name	Update Order	P1 - Extrude8.FD1	P2 - Temperature Maximum	P3 - Equivalent Stress Maximum	P4 - Total Deformation Maximum
2	Units		mm	C	MPa	mm
3	DP 0 (Current)	1	0.6	697.05	46.156	0.028246
4	DP 2	3	0.9	694.01	46.114	0.028011
5	DP 3	4	1.2	685.2	46.174	0.027784
6	DP 5	6	1.5	686.17	46.256	0.027511
7	DP 6	7	1.8	681	46.264	0.027309
8	DP 7	8	2.1	686.05	46.216	0.027054
9	DP 8	9	2.4	681.16	46.223	0.026789
10	DP 10	11	0.8	694.08	46.116	0.028106
11	DP 11	12	1	694.54	46.087	0.027948
12	DP 12	13	1.1	690.35	46.107	0.027866

4.2 Variation of temperature with respect to coat thickness

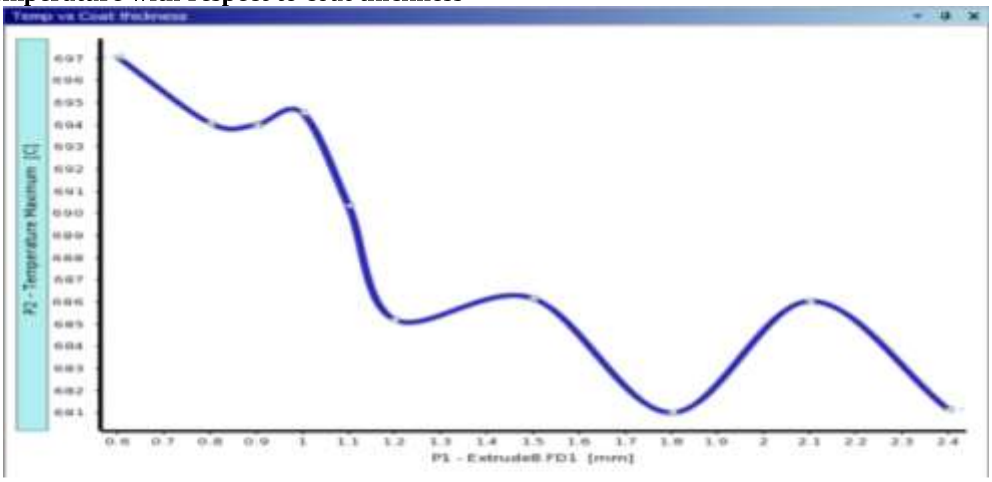

Fig. 4.1: Figure showing the changing temperature with the change in a coating thickness of $MgZrO_3$

4.3 Variation of Equivalent stress with respect to coat thickness

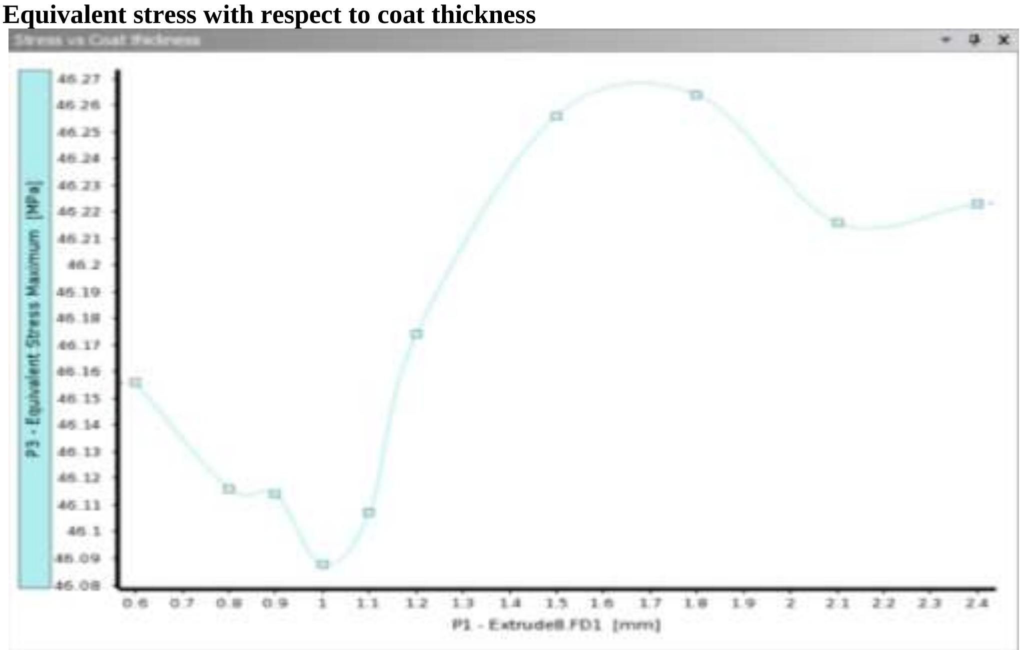

Fig. 4.2: Figure showing the change in Equivalent (Von Mises) stresses to the coating thickness of $MgZrO_3$

4.4 Change in Total Deformation to coat thickness

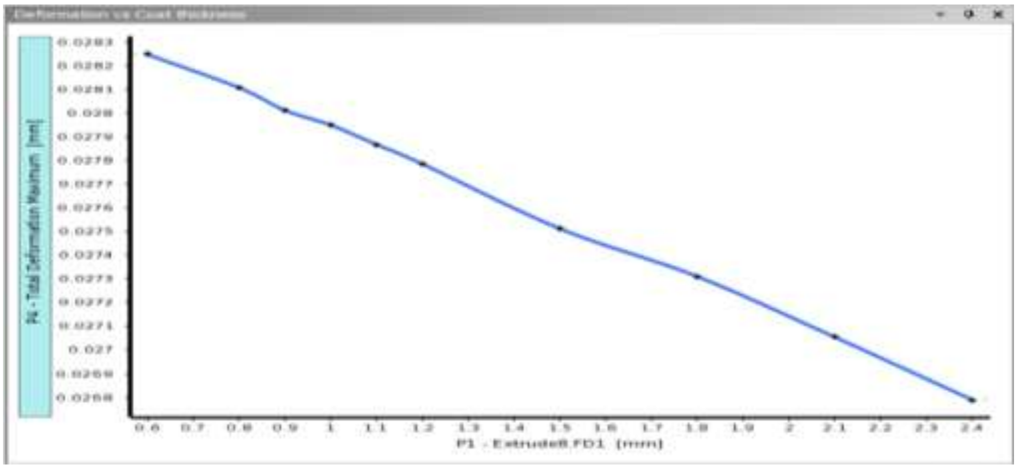

Fig. 4.3: Figure showing the change in deformation to the coating thickness of $MgZrO_3$

5. CONCLUSION

The Static structural and the thermal analysis of the piston of Mercedes Benz , made up of the gray cast iron and is coated with the ceramic material ($MgZrO_3$) is glued by (NiCrAl) material is performed. The following conclusion could be drawn from it:

1. Equivalent stresses are found to be around 46 MPa. The change in Equivalent Stresses with the change in the thickness of coats are found to be very little and it's almost constant while comparing with the equivalent stresses of the uncoated piston (Figure 4.11). We may say coat thickness does not affect Equivalent stresses.
2. With the increase in the thickness of the coating of ceramic material, the piston's maximum temperature decreases
3. The temperature of the piston crown was found to be in the range of 600 ºC to 700 ºC but with the application of the ceramic coating, the temperature of piston top land just below the coating was found to 150 ºC less than the top surface. This proves that the ceramic coating is helpful as a thermal barrier.
4. With the increase in coating thickness, there are decreases in total deformation.

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