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Thermal Behaviour And Optimization of Piston Coating Material (Al-Si) Used In Petrol Engine

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Abstract: Thermal analyses are investigated on a petrol piston coating with many alloys. Thermal analyses are performed on piston coated with Aluminium Silicon alloy material by using a commercial coating, various coating thickness from 0.2 to 1.6mm excluding the bond coat layers. The effects of coating on the thermal behaviours of the pistons are investigated. The finite element analysis is performed by using computer aided design software. The main objective is to investigate and analyze the thermal stress distribution of piston at the real engine condition during combustion process. The mesh optimization by using finite element analysis technique to predict the higher stress and critical region on the component. The main emphasis is placed on the study of the analysis is carried out to reduce the stress concentration on the upper end of the piston (i.e. piston head/crown and piston skirt and sleeve). With using Solid works software the structural model of a piston will be developed. Furthermore, the finite element analysis is done using simulation software ANSYS.

Key word: Petrol Engine · Aluminium silicon alloy material · Zirconium material · Mullite material

INTRODUCTION

A reciprocating engine is also known as a piston engine. It is a heat engine that uses one or more reciprocating pistons to convert pressure into a rotating motion. The main types are the internal combustion engine, used further classified in two ways as a spark-ignition (SI) engine, where the spark plug initiates the combustion or a compression-ignition (CI) engine, where the air within the cylinder is compressed, thus heating it, so that the heated air ignites fuel that is injected then or earlier [1-3].

Types of Piston Engine: A petrol engine is an internal combustion engine with spark-ignition, designed to run on petrol gasoline and similar volatile fuels. In most petrol engines, the fuel and air are usually pre-mixed before compression although some modern petrol engines now use cylinder-direct petrol injection. The pre-mixing was formerly done in a carburetor, but now it is done by electronically controlled fuel injection. The process differs from a diesel engine in the method of mixing the fuel and air and in using spark plugs to initiate the combustion process. The diesel engine is an internal combustion engine in which ignition of the fuel that has been injected into the combustion chamber is initiated by the high temperature which a gas achieves when greatly compressed adiabatic compression. This contrasts with spark-ignition engines such as a petrol engine gasoline engine or gas engine using a gaseous fuel as opposed to gasoline, which use a spark plug to ignite an air-fuel mixture. The diesel engine has the highest thermal efficiency of any practical internal or external combustion engine due to its very high compression ratio.

Petrol Engine: Gasoline or petrol engines are also known as spark-ignition (S.I.) engines. Petrol engines take in a flammable mixture of air and petrol which is ignited by a timed spark when the charge is compressed. [2] Four stroke Spark-ignition (S.I) engines require four piston strokes to complete one cycle, an air-and-fuel intake stroke moving outward from the cylinder head, an inward movement towards the cylinder head compressing the charge, an outward power stroke and an inward exhaust stroke.

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Suction Stroke: The inlet valve is opened and the exhaust valve is closed. The piston descends, moving away from the cylinder head. The speed of the piston moving along the cylinder creates a pressure reduction or depression which reaches a maximum below atmospheric pressure at one-third from the beginning of the stroke.

Compression Stroke: Both the inlet and the exhaust valves are closed. The piston begins to ascend towards the cylinder head. The induced air-and-petrol charge is progressively compressed to something of the order of one-eighth to one-tenth of the cylinder's original volume at the piston's innermost position.

Power Stroke: Both the inlet and the exhaust valves are closed and just before the piston approaches the top of its stroke during compression, a spark-plug ignites the dense combustible charge. By the time the piston reaches the innermost point of its stroke, the charge mixture begins to burn, generates heat and rapidly raises the pressure in the cylinder until the gas forces exceed the resisting load.

The burning gases then expand and so change the piston's direction of motion and push it to its outermost position. The cylinder pressure then drops from a peak value.

Exhaust Stroke: At the end of the power stroke the inlet valve remains closed but the exhaust valve is opened. The piston changes its direction of motion and now moves from the outermost to the innermost position. Most of the burnt gases will be expelled by the existing pressure energy of the gas, but the returning piston will push the last of the spent gases out of the cylinder through the exhaust-valve port and to the atmosphere.

M. L. S. Dev Kumar Sir *et al* [4] have discussed a conventional internal combustion engine. The small portion of the total energy produced is converted to useful work. More than half of this energy is expelled from the system through frictional losses, cooling the engine components, exhaust, etc. The sum of these losses is termed as energy loss for the engine. According to the simulation results conducted in this study, it has been concluded that steel is having maximum temperature distribution than AlSi alloy piston.

Ramesh N. Movado *et al* [5] have discussed the desire to reach higher efficiencies, lower specific fuel consumptions and reduce emissions in modern internal combustion (IC) engines. It has become the focus of engine researchers and manufacturers for the past three decades. The recent trend in Four Stroke Diesel Engine performance of engine depend on their heat losses in inside engine but from review of following paper were given different methodologies and formulation for try to reduced losses and more efficient vehicle.

K Ramesh Babu *et al*. [6] have discussed the engine head and its thermal analysis. It is also attempted in this paper. Copper coated engine showed higher temperature at salient points when compared with conventional engine at salient points like, on the top of the piston and liner. The peak surface temperature of copper coated engine was predicted be increased to 772 K from 745 K of the conventional engine amounting to an increase of 3.5%.

Problem Definition: The piston is one of the most critical components of an engine. Therefore, it must be designed to withstand from damage that is caused due to extreme heat and pressure of combustion process. the value of stress that cause the damages can be determine by using FEA.the objective of this study is to improve the live strength and thermal conductivity and reduce the co-efficient of expansion and withstand the thermal stress during combustion process.

1. To calculate the equivalent (von misses) stress and total deformation by considering the thermal conductivity of the aluminum composite.
2. To optimize the piston model for mass reduction by using different composition of aluminum material under same design of piston. The material are pure aluminum, al-si (slumming)86.5%Al,1%cu,then the materials are investigated.

Objective: Thermal barrier coatings are highly advanced material systems applied to metallic surfaces, such as Petrol or diesel engine parts, operating at elevated temperatures.

In fact, in conjunction with active film cooling, Thermal barrier coatings permit flame temperatures higher than the melting point of the metal airfoil in some turbine applications.

The application of Thermal barrier coatings on the petrol engine piston head reduces the heat loss to the engine cooling-jacket through the surfaces exposed to the heat transfer such as cylinder head, liner, piston crown and piston rings.

Scope:
High speed engine with low heat
Long life of engine
Less maintenance cost
Life of engine will increase

Piston Design: The piston is designed according to the procedure and specification (Tab:1) shown that given below in design 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.

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.

Functions of the Piston:

- To receive the impulse from the expanding gas & transmit the energy to the crank shaft through the connecting rod.
- It transmits the force of combustion gases to the crank shaft.
- It controls the opening & closing of the parts in a 2-stroke engine.
- It acts as a seal to escape of high pressure gases in to the crank case.

Characterstics of Piston:May 17, 2016

- Hammering effect of a combustion gas pressure.
- High temperature of the gases.
- Light in weight.
- Silent in a operation.
- Mechanically strong

Thickness of Piston Head (t_H):

$t_H = D\surd 3/16xp/\sigma t$ (in mm)

$= 4.57$ mm

where

P = 1.05N/mm² = maximum pressure

D = 96 mm = cylinder bore

σ_t = 90 N/mm² = tensile stress for the material of the piston.

Radial Thickness of Ring (t_1)

$t_1 = Dv3xp_w/\sigma_t$ (in mm)

$= 3.25$ mm

where

P_w = 0.034N/mm²= Pressure of fuel on cylinder wall

D = 96 mm = cylinder bore.

σ_t = 90 N/mm²= permissible stress for the material of the piston.

Axial Thickness of Ring (t_2)

$t_2 = 0.7t_1$ so $t_2 = 2.4$mm

Width of the top land (b_1)

$b_1 = 1.2xt_H = 5$ mm

Width of other lands (b_2)

$b_2 = 0.75xt_2 = 1.7$ mm

Maximum Thickness of Barrel (t_3)

$t_3 = 0.03xD + b + 4.5 = 8.68 (b = 0.4 + t_1)$

Table 1: Design Specification

S.No	Dimensions	Size in mm.
1	Length of the Piston(L)	127
2	Cylinder bore/outside diameter of the piston (D)	96
3	Thickness of piston head (tH)	4.57
4	Radial thickness of the ring (t1)	3.25
5	Axial thickness of the ring (t2)	2.4
6	Width of the top land (b1)	5
7	Width of other ring lands (b2)	1.7

Aluminum-Silicon Alloy: Aluminum-Silicon alloys are of greater importance to engineering industries as they exhibit high strength to weight ratio, high wear resistance, low density, low coefficient of thermal expansion etc.[6] Silicon imparts high fluidity and low shrinkage, which result in good cast ability and weld ability. The most important cast aluminum alloy system is Al–Si, where the high levels of silicon (4.0–13%) contribute to give good casting characteristics. Aluminum alloys are widely used in engineering structures and components where light weight or corrosion resistance is required. Aluminumilicon alloys form a eutectic at 11.7 wt% silicon, the eutectic temperature being 577 ºC. This represents a typical composition for a casting alloy because it has the lowest possible melting temperature. Al-12Si wt% alloys are therefore common. Al-Si alloys are designated 4xxx alloys according to the Aluminum Association Wrought Alloy Designation System. The major features of the 4xxx series are:

a. Heat treatable
b. Good flow characteristics,
c. Easily joined, especially by brazing

There are two major uses of the 4xxx series – for forging and weld filler alloy. These both applications are due to the excellent flow characteristics provided by relatively high silicon content. Effects of silicon in the Al-Si alloys are as follows:

- Thermal expansion is reduced substantially by silicon
- Magnetic susceptibility is only slightly decreased by silicon
- The lattice parameter is decreased slightly by silicon
- Machinability is poor because of the hardness of the silicon.

Piston Coatings: The piston is one of the very first parts that should be considered for coating. Coating the piston reduces friction and wear, reduces part operating temperature, can increase horse power and torque, reduce [2-5] or eliminate detonation, allow higher compression ratios to be utilized and allow tighter piston to wall clear lances for a better ring seal.

Pistons can be coated with three different systems. They are:

- Dry Film Lubricants,
- Thermal Barriers and
- Oil Shedding Coatings.

These systems can be beneficial on all pistons whether 4 stroke, 2 stroke, gas, alcohol, diesel, reciprocal or rotary. Either CBC2 or CBX may be applied. CBX is recommended for all High Compression 13:1 and higher, Turbo Charged, Super Charged or engines running Nitrous Oxide. CBC2 should be run on all other engines.

Both CBC2 and CBX insulate the piston against damaging heat transfer, keeping more of the heat generated by combustion, pushing down on the piston for greater power.

The coatings can also allow heat at the surface to move more evenly over the surface reducing hot spots and the coatings reflect heat into the chamber for more even distribution of heat, allowing more efficient combustion of the fuel. By applying a Dry Film Lubricant, friction, galling and wear is reduced.

Skirt Coating (SC): This is coating applied to the skirt of the piston only, designed to show wear. This coating is a 0.0003” to 0.0005” thick spray-on dry film that will help reduce friction.

Thermal Barrier Crown (CC): The thermal barrier crown coating is 0.0015” thick coating can also assist in extending piston life by decreasing the rate of thermal transfer.

Kolkata (KK): Kolkata is an aerospace quality hard anodize applied to all surfaces of the piston with a build-up of 0.001”.

Tuff Skirt (TS): Tuff Skirt is a lubricating, anti-friction / anti-wear coating applied to the piston skirt only. Unlike standard Skirt Coating, Tuff Skirt will not wear and is designed to withstand many different types of endurance applications, is 0.0005” per surface and finished diameter of skirt should include the coating build up.

Oil Shield Coating (OS): This coating is applied to the underside of the piston. It is intended to reduce the reciprocating weight by repelling oil quicker than an untreated part. No additional manufacturing is required Result.

Numerical Analysis

FEA: Finite Element Analysis (FEA) is one of the branches of solid mechanics that uses numerical methods and algorithms to solve and analyze problems that involve analysis of structures or objects. Even with high-speed supercomputers only approximate solutions can be achieved in many cases.

- Meshing and Pre-Processing
- Numerical Solver
- Post Processor

Material Selection: The coating material generally use in below in material selection (Table 2), which that preferred is NiCrAl. The last layer is known to be ceramic layer which is coated over the piston for 350 µm thickness. This layer can be coated with Zirconium oxide or Mullite or Aluminium oxide.

Table 2: Material Selection

Material: Aluminium Alloy (Al-4032)		Material: Mullite	
Property	Maximum	Property	Maximum
Density	2680 Kg/m^3	Density	2700 Kg/m^3
Coefficient of Thermal Expansion	1.94 x 10^{-5} 1/°C	Coefficient of Thermal Expansion	3.5 x 10^{-6} 1/°C
Thermal Conductivity	138 W/ m °C	Thermal Conductivity	1.9 W/ m °C
Reference Temperature	22 °C	Reference Temperature	22 °C
Young's Modulus	78600 MPa	Young's Modulus	91000 MPa
Poisson's Ratio	0.34	Poisson's Ratio	0.23
Bulk Modulus	81875 MPa	Bulk Modulus	56173 MPa
Shear Modulus	29328 MPa	Shear Modulus	36992 MPa
Tensile Yield Strength	315 MPa	Tensile Yield Strength	55 MPa
Tensile Ultimate Strength	380 MPa	Tensile Ultimate Strength	550 MPa
Material: Inconel Alloy (NiCrAl)		Material: Zirconium oxide	
Property	Maximum	Property	Maximum
Density	8220 Kg/m^3	Density	5000 Kg/m^3
Coefficient of Thermal Expansion	1.17 x 10^{-5} 1/°C	Coefficient of Thermal Expansion	2.3 x 10^{-6} 1/°C
Thermal Conductivity	11.1 W/ m °C	Thermal Conductivity	1.7 W/ m °C
Reference Temperature	22 °C	Reference Temperature	22 °C
Young's Modulus	199 MPa	Young's Modulus	100000 MPa
Poisson's Ratio	0.29	Poisson's Ratio	0.22
Bulk Modulus	157.94 MPa	Bulk Modulus	59524 MPa
Shear Modulus	77.132 MPa	Shear Modulus	40984 MPa
Tensile Yield Strength	1034 MPa	Tensile Yield Strength	115 MPa
Tensile Ultimate Strength	1241 MPa	Tensile Ultimate Strength	1200 MPa
Material: Aluminium Oxide (Al_2O_3)		Material: Grey cast iron	
Property	Maximum	Property	Maximum
Density	3000 Kg/m^3	Density	7200 Kg/m^3
Coefficient of Thermal Expansion	4.5 x 10^{-6} 1/°C	Coefficient of Thermal Expansion	1.05 x 10^{-5} 1/°C
Thermal Conductivity	1200 W/ m °C	Thermal Conductivity	0.467 W/ m °C
Reference Temperature	22 °C	Reference Temperature	22 °C
Young's Modulus	2.15 x 10^5 MPa	Young's Modulus	140000 MPa
Poisson's Ratio	0.21	Poisson's Ratio	0.22
Bulk Modulus	1.23 x 10^5 MPa	Bulk Modulus	111110 MPa
Shear Modulus	88843 MPa	Shear Modulus	54264 MPa
Tensile Yield Strength	69 MPa	Tensile Yield Strength	228 MPa
Tensile Ultimate Strength	690 MPa	Tensile Ultimate Strength	1130 MPa

Different meshing characteristics were used for the domain. Although the methods were different, the same mixed configuration of triangular and quad core cells were used for the domain. The mesh model of the piston is shown in Figure 1.

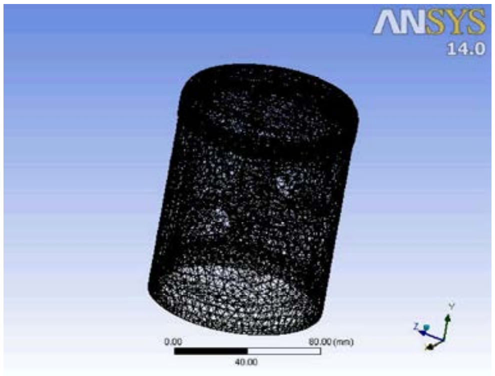


Fig. 1: Mesh over the Piston Assembly

The thermal effects are taken initial valve taken form 623.15k while the engine is in operation. The convection a position in the piston convection initial valve 295.5k red(a) valve, again The temperature and convection over doing the result valve 6×10^{-}4 w/mm^{2}k and 143k the model are as given in Figure 2.

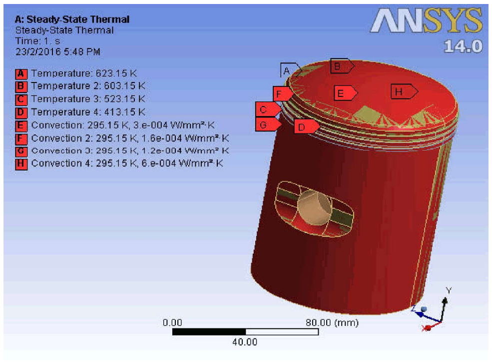


Fig. 2: Thermal boundary condition

In general the pressure force over the piston will be of 1.5 MPa for the petrol engines. The structural boundary condition is are given shown in Figure. 3.

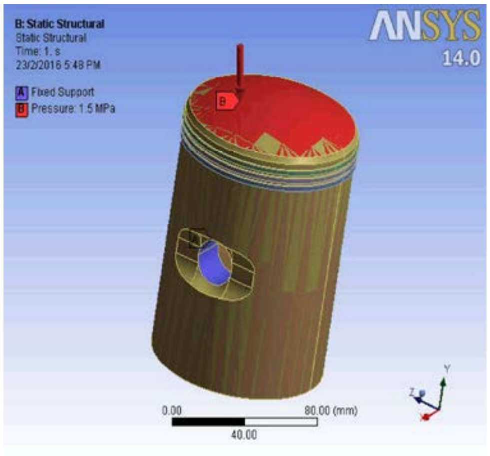


Fig. 3: Structural boundary condition

By defining these boundary conditions the thermal and structural performance for the piston are calculated from the (Table 3) given below.

Table 3: Boundary condition

Thermal Boundary Condition			
Sl. No	Component	Temperature	Convection film coefficient
1.	Piston head	350 °C	300 W/m^2 K
2.	Width of top land	330 °C	160 W/m^2 K
3.	Piston ring	250 °C	120 W/m^2 K
4.	Piston skirt land	140 °C	600 W/m^2 K
Structural Boundary condition			
Piston head		Pressure – 1.5 MPa	

The zirconium oxide coating holds a high temperature than other materials. So in thermal behaviour it's clear that we are opted to choose aluminium oxide for coating the piston from the Table 4.

Table 4: Thermal behaviours

	Total Temperature		Heat flux	
Parameter	Minimum	Maximum	Minimum	Maximum
Aluminium Oxide	295.15 °C	623.15 °C	6.824 x 10^{-13} W/mm^2	7.6014 W/mm^2
Mullite	295.15 °C	623.15 °C	4.14 x 10^{-18} W/mm^2	7.5755 W/mm^2
Zirconium Oxide	295.15 °C	623.15 °C	4.844 x 10^{-18} W/mm^2	7.575 W/mm^2

The aluminium oxide holds a high stress so the material has the capability to hold high strength than other materials. The contours of stress, strain and deformation are shown in Table 5.

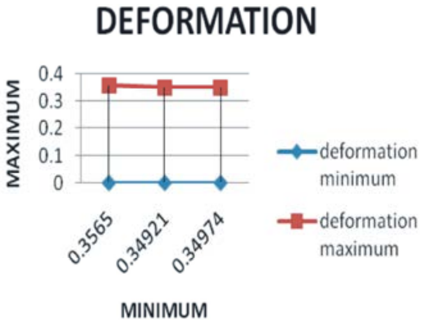
Table 5: Structural behaviors

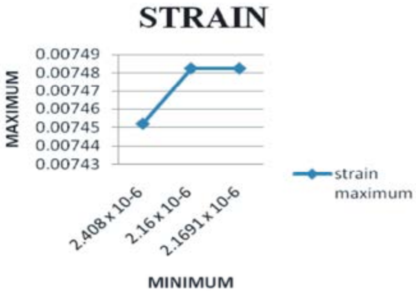
	Deformation		Stress		Strain	
Parameter	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
Aluminium Oxide	0	0.3565 mm	0.0001545 MPa	1210.9 MPa	2.408 x 10^{-6}	0.0074519
Mullite	0	0.34921 mm	0.00018 MPa	797.99 MPa	2.16 x 10^{-6}	0.0074823
Zirconium Oxide	0	0.34974 mm	0.000174 MPa	796.74 MPa	2.1691 x 10^{-6}	0.00748

While we consider the weight mullite coated material has a less weight than all other materials. But aluminium oxide coated piston has better performance in terms of other structural and thermal parameters. So it's recommended to use the aluminium oxide coating for petrol engine to get higher thermal and structural characteristics are shown in Table 6.

Table 6: Weight of the piston and its components

	Total	Body	Layer – 1	Layer - 2	Piston Ring
Aluminium Oxide	1.338 Kg	1.1733 Kg	6.1857 x 10^{-2} Kg	5.267 x 10^{-2} Kg	1.6712 x 10^{-2} Kg
Mullite	1.3327 Kg	1.1733 Kg	6.1857 x 10^{-2} Kg	4.7408 x 10^{-2} Kg	1.6712 x 10^{-2} Kg
Zirconium Oxide	1.3731 Kg	1.1733 Kg	6.1857 x 10^{-2} Kg	8.7793 x 10^{-2} Kg	1.6712 x 10^{-2} Kg





CONCLUSION

The piston has been modeled in solid works by performing theoretical calculations. The piston thermal behavior has been studied in detail before preceding this project. Different types of coatings have been carried out by the developers to increase the performance of the engine. Even though they have changed we are still moving further to improve some more performance. So we have studied in detail about different material and came to conclusion as the aluminum oxide holds a good thermal as well as structural behavior. The thermal and structural analysis over the piston has been carried out with different types of coating like aluminum oxide, zirconium oxide and mullite. From the numerical analysis it's clear that the aluminum oxide holds a better performance than any other materials for a petrol engine.

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