Modelling and Anaylsis of I.C. Engine Piston Crown Using FEM Package Ansys

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Abstract
A piston is a component of reciprocating engines, pumps and gas compressors. It is located in a cylinder and is made gas-tight by piston rings. In an engine, its purpose is to transfer force from expanding gas in the cylinder to the crankshaft via a piston rod and/or connecting rod. The alloy from which a piston is made not only determines its strength and wears characteristics, but also its thermal expansion characteristics. Hotter engines require more stable alloys to maintain close tolerances without scuffing. The normal temperature of gasoline engine exhaust is approximately 650ºC (923ºK). This is also approximately the melting point of most aluminum alloys and it is only the constant influx of ambient air that prevents the piston from deforming and failing. For this purpose testing different types of materials such as aluminum alloys and cast iron piston. In this project we design the three models of pistons flat head, concave head & convex heads by using Pro-Engineer 5.0 software, and imported them to make analysis in ANSYS 11.0 soft ware. And find out the vonmiss stresses, total deformation, heat distribution, and heat flux. By comparing the results we can say among these which one of the piston had better results.

Keywords
Ansys, FEA, Piston Crown, Piston Skirt, CAD, Stress Concentration

I. 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 component of reciprocating IC-engines. It is the moving component that is contained by a cylinder and is made gas-tight by piston rings. In an engine, its purpose is to transfer force from expanding gas in the cylinder to the crankshaft via a piston rod and/or connecting rod. As an important part in an engine, piston endures the cyclic gas pressure and the inertial forces at work, and this working condition may cause the fatigue damage of piston, such as piston side wear, piston head/crown cracks and so on. The investigations indicate that the greatest stress appears on the upper end of the piston and stress concentration is one of the mainly reason for fatigue failure. On the other hand piston overheating-seizure can only occur when something burns or scrapes away the oil film that exists between the piston and the cylinder wall.

Understanding this, it's not hard to see why oils with exceptionally high film strengths are very desirable. Good quality oils can provide a film that stands up to the most intense heat and the pressure loads of a modern high output engine. Thermal analysis is a branch of materials science where the properties of materials are studied as they change with temperature. FEM method is commonly used for thermal Analysis [2]. Kamo et. al. [3]considered a problem of optimum coating thickness. Compared to thick coatings, thin coatings offer the advantage of longer durability and the moderate increase in surface temperature. Thermally sprayed TBCs are usually two-layer, the layer adjoining the substrate provides adequate adherence of the coating, protects base metal from corrosion and facilitates stress relaxation, the outermost layer is sprayed with ceramic material coat and a 0.25 mm thick layer of partially stabilized zirconia [4].

II-Related Work

A. Heat Engines

Any type of engine or machine which derives heat energy from the combustion of fuel or any other source and coverts this energy into mechanical work is termed as a heat engine.

Heat engines may be classified as:

1. External Combustion Engines
2. Internal Combustion Engines

1. External Combustion Engines (E.C. Engines)

In this case, combustion of fuel takes place outside of the cylinder as in case of steam engines where the heat of combustion is employed to generate steam which is used to move a piston in a cylinder.

2. Internal Combustion Engines (I.C. Engines)

In this case, combustion of the fuel with oxygen of the air occurs within the cylinder of the engine. The internal combustion engines group includes engines employing mixtures of combustible gases and air, known as gas engines, those using lighter liquid fuel or spirit known as petrol engines and those using heavier liquid fuels, known as oil compression or diesel engines.

Even though internal combustion engines look quite simple, they are highly complex machines. There are hundreds of components which have to perform their functions satisfactorily to produce output power. There are two types of engines

1. Spark ignition engine (S.I engine)
2. Compression ignition engine (C.I engine)

According to the cycle of operations again these engines are classified as

- Two-stroke engines
- Four-stroke engines

A Two-stroke S.I engine:-

Dugald Clark invented the two stroke engine in the year 1878. The two strokes are literally "suction" and "exhaust". In two stroke engine the cycle is completed in one revolution of the crank shaft.

The main difference between two stroke and four stroke engines is in the method of filling the fresh charge and removing the burnt gases from the cylinder. In the four stroke engines these operations are performed by the engine piston during the suction and exhaust strokes respectively. In a two stroke engine, the filling process is accomplished by the charge compressed in the crankcase or by a blower. The induction of the compressed charge moves out the product of combustion through exhaust ports. Therefore no piston strokes are required for these two operations. Two strokes

ISSN : 2249-5762 (Online) | ISSN : 2249-5770 (Print)

are sufficient to complete the cycle, one for compressing the fresh charge and the other for expansion or power stroke.

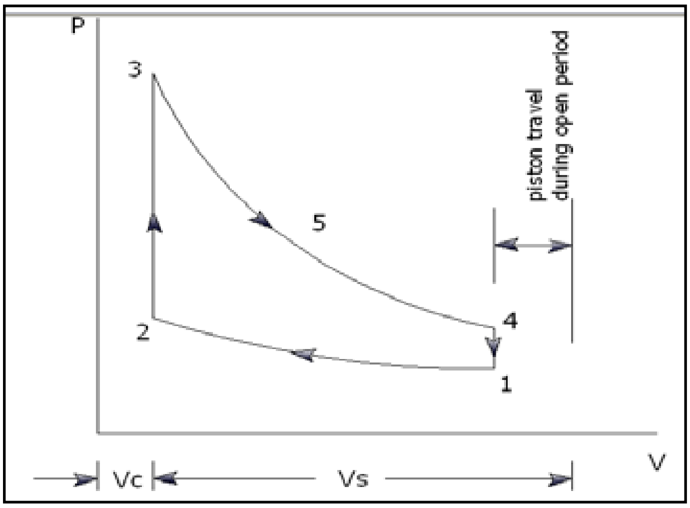


Fig. 1: Ideal Indicator Diagram of Two-Stroke SI Engine


Fig. 2: Piston Samples

The cylinder/piston fit is one of the most important factors governing the success of a home-built model engine. Material selection wise, the home constructor has a number of choices but each has their own characteristics, advantages, and disadvantages. The most common choices, in ascending order of experience required, are:

1. Steel liner, Cast Iron piston
2. Cast Iron liner, Cast Iron piston
3. Steel liner, Steel piston
4. Steel liner, Aluminium piston, Cast Iron ring(s)

The normal temperature of gasoline engine exhaust is approximately 650ºC (923ºK). This is also approximately the melting point of most aluminium alloys and it is only the constant influx of ambient air that prevents the piston from deforming and failing.

Forced induction increases the operating temperatures while “under boost” and if the excess heat is added faster than engine can shed it, the elevated cylinder temperatures will cause the air and fuel mix to auto-ignite on the compression stroke before the spark event. This is one type of engine knocking that causes a sudden shockwave and pressure spike, which can result in an immediate and catastrophic failure of the piston and connecting rod.

Although internal combustion engine pistons commonly contain trace amounts (less than 2% each) of copper, manganese, and nickel, the major element in automotive pistons is aluminum due to its light weight, low cost, and acceptable strength. The alloying element of concern in automotive pistons is silicon. However, when silicon is added to aluminum they only blend together evenly on a molecular level up to approximately a 12% silicon content. Silicon in this context can be thought of as “powdered sand”. Any silicon that is added to aluminum above a 12% content will retain a distinct granular form instead of melting. Special moulds, casting, and cooling techniques are required to obtain uniformly dispersed silicon particles throughout the piston material.

The alloy from which a piston is made not only determines its strength and wears characteristics, but also its thermal expansion characteristics. Hotter engines require more stable alloys to maintain close tolerances without scuffing. Silicon improves high heat strength and reduces the coefficient of expansion so tighter tolerances can be held as temperatures change.

Hypereutectic alloys are also slightly lighter than standard alloys. But the castings are often made thinner because the alloy is stronger, resulting in a net reduction of up to 10 percent in the pistons total weight. Hypereutectic alloys are more difficult to cast because the silicon must be kept evenly dispersed throughout the aluminum as the metal cools. Particle size must also be carefully controlled so the piston does not become brittle or develop hard spots making it difficult to machine. Some pistons also receive a special heat treatment to further modify and improve the grain structure for added strength and durability.

III. Piston Design

Parts of a piston
Piston head or Crown
Piston rings
Piston barrel
Ribs
Piston skirt
Gudgeon pin

Technical Terms Related to Piston

1.Bore

The diameter of an engine cylinder.

2. Stroke

The distance the piston moves from bottom dead center to top dead center.

3. Displacement

The measurement of an engine’ size It is equal to the number of cubic inches the piston displaces as it moves from bottom dead center to top dead center, multiplied by the total number of cylinders.

Displacement = A x S x N

Where A = area of the piston (in square inches)

S = stroke (in inches)
N = number of cylinders

Compression ratio: the extent to which the combustible gasses are compressed within the cylinder. It equals the volume existing within the cylinder with the piston at bottom dead center divided by the volume within the cylinder when the piston is at top dead center.

Compression Ratio = X/Y

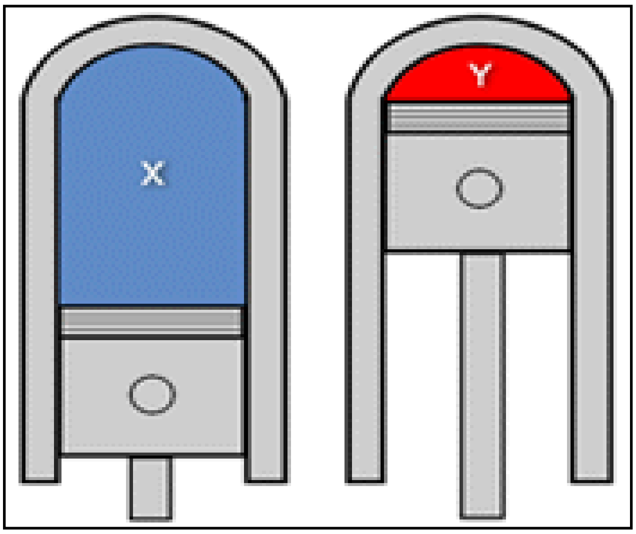


Fig. 3: Compression Ratio

Mean piston speed

The mean piston speed is the average speed of the piston in a reciprocating engine. It is obtained by multiplying the stroke length two times for each revolution of the crankshaft by the rotational speed of the engine, since the piston moves up and down the stroke per revolution.

For example, a piston in an automobile engine which has a stroke of 90 mm will have a mean speed at 3000 rpm of

(90 / 1000) * 2 * (3000 / 60) = 9 m/s.

It is a good indicator of the class and performance of an engine relative to its competitors.

There are some features of close tolerance piston mentioned below:

1. Piston can swell and stick.
2. Fits tightly in the cylinder.
3. Tight Tolerance fit.
4. Properties alter due to atmospheric change.
5. Backlash may such, some of the bin material into the valve which also can cause the piston to stick.

Piston Ring

Piston ring is an open-ended ring that fits into a groove on the outer diameter of a piston in a reciprocating engine such as an internal combustion engine or steam engine. The three main functions of piston rings in reciprocating engines are:

1. Sealing the combustion/expansion chamber.
2. Supporting heat transfer from the piston to the cylinder wall.
3. Regulating engine oil consumption.

The gap in the piston ring compresses to a few thousandths of an inch when inside the cylinder bore.

Fig. 4: Piston Rings

Wear Due to Piston Side-Load

Top ring and oil control rings will be coated with Chromium or Nitride-possibly plasma sprayed or has a PVD (physical vapour deposit) ceramic coating. For enhanced scuff resistance and further improved wear, most modern diesel engines have top rings coated with a modified chromium coating known as CKS. The lower oil control ring is designed to leave a lubricating oil film, a few micrometers thick on the bore, as the piston descends. Three piece oil rings, i.e. with two rails and one spacer, are used for four-stroke gasoline engines

Drawbacks of a Piston

Since it's a main reciprocating part of an engine and hence it creates the problems of unbalancing due to its inertia. Due to friction between wall of the cylinder and piston rings its life becomes short and it generates the unpleasant sound due reciprocating mechanism. To transmit the energy of reciprocating piston, it is connected to a connecting rod and crank mechanism and due to these parts there occurs mechanical loss. The motion of the crank shaft is not smooth, since energy supplied by the piston is not continuous and it is impulsive in nature.

Detonation causes three types of failure:

1. Mechanical damage (broken ring lands)
2. Abrasion (pitting of the piston crown)
3. Overheating (scuffed piston skirts due to excess heat input or high coolant temperatures)

The high impact nature of the spike can cause fractures; it can break the spark plug electrodes, the porcelain around the plug, cause a clean fracture of the ring land and can actually cause fracture of valves-intake or exhaust. The piston ring land, either top or second depending on the piston design, is susceptible to fracture type failures.

When the piston crown temperature rises rapidly it never has time to get to the skirt and expand and cause it to scuff. It just melts the center right out of the piston. That's the biggest difference between detonation and pre-ignition when looking at piston failures. Without a high pressure spike to resonate the chamber and block, we could never hear pre-ignition. The only sign of pre-ignition is white smoke pouring out the tailpipe and the engine quits running.

There are no engines that will live for any period of time when pre-ignition occurs. When people see broken ring lands they mistakenly blame it on pre-ignition and overlook the hammering from detonation that caused the problem. A hole in the middle of the piston, particularly a melted hole in the middle of a piston, is due to the extreme heat and pressure of pre-ignition.

Another thing detonation can cause is a sandblasted appearance to the top of the piston. The piston near the perimeter will typically have that kind of look if detonation occurs. The detonation, the

ISSN : 2249-5762 (Online) | ISSN : 2249-5770 (Print)

mechanical pounding, actually mechanically erodes or fatigues material out of the piston. We can typically expect to see that sanded look in the part of the chamber most distant from the spark plug, The typical pre-ignition indicator, of course, would be the hole in the piston. This occurs because in trying to compress the already burned mixture the parts soak up a tremendous amount of heat very quickly.
The only ones that survive are the ones that have a high thermal inertia, like the cylinder head or cylinder wall. The piston, being aluminum, has a low thermal inertia (aluminum soaks up the heat very rapidly). The crown of the piston is relatively thin, it gets very hot, it can't reject the heat, it has tremendous pressure loads against it and the result is a hole in the middle of the piston where it is weakest.
Remove carbon deposits, an accumulation of carbon deposits in the combustion chamber and on the top of the pistons can increase compression to the point where detonation becomes a problem. Carbon deposits are a common cause of detonation in high-mileage engines, and can be especially thick if the engine consumes oil because of worn valve guides and seals, worn or broken piston rings and/or cylinder wear.

1.7.10 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 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

1.7.10.1 Thermal Barrier Coatings

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.
By retaining minimal heat on the surface of the piston, less heat is transferred to the incoming fuel mixture, leading to a reduction in pre-ignition which leads to detonation. 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. This allows more of the fuel molecules to be oxidized, which in turn, means less fuel is needed for optimum power. The result is an engine that makes more power, can be run with a leaner air/fuel mix and less initial timing and has less thermal expansion due to a reduction in the heat absorbed.
By applying a Dry Film Lubricant, friction, galling and wear is reduced. The lubricants are capable of carrying loads beyond the crush point of the piston. In addition, the lubricants are "fluid retaining" materials that actually hold oil to the surface beyond the pressure where the oil would normally be squeezed off. The ability to carry greater loads, up to 350,000 PSI, while increasing lubricity (reduced friction) allows tighter piston to wall clearances to be run. This leads to better sealing with no increase in friction.
By applying Tech Line's TLTD to the underside of the piston, oil that is splashed onto the piston to cool it will shed rapidly. Heat transfers most rapidly when there is a large difference in temperature. The longer oil clings to a hot surface the hotter the oil becomes. By shedding the cooling oil more rapidly, cooler oil is splashed over the surface more frequently. If the oil "hangs" longer, it absorbs less heat and blocks cooler oil from contacting the hot surface. A cooler piston grows less, allowing tighter piston to wall clearances.
The thermal barrier crown coating is applied to the top of the piston and is designed to reflect heat into the combustion chamber, thereby increasing exhaust gas velocity and greatly improving scavenging potential. The 0.0015" thick coating can also assist in extending piston life by decreasing the rate of thermal transfer.

1. 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. No manufacturing allowance is required as this application is made to wear in to the cylinder wall.

2. Thermal Barrier Crown (CC)

The thermal barrier crown coating is applied to the top of the piston and is designed to reflect heat into the combustion chamber, thereby increasing exhaust gas velocity and greatly improving scavenging potential. The 0.0015" thick coating can also assist in extending piston life by decreasing the rate of thermal transfer.

3. KoolKote (KK)

KoolKote is an aerospace quality hard anodize applied to all surfaces of the piston with a buildup of 0.001". It will withstand greater temperatures and will not flake, chip or peel. This coating does alter the heat transfer and expansion characteristics of the piston.

4. 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 buildup.

5. Oil Shed 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.
Results:

Structural Anaylsis

Material Date:

Table 11: cast iron > Constants

Structural Analysis	
Young's Modulus	1.1e+005 MPa
Poisson's Ratio	0.28
Density	7.2e-006 kg/mm³

Table 12: Static Structural > Loads

Object Name	Pressure	Fixed Support
Scope		
Scoping Method	Geometry Selection	
Geometry	2 Faces	4 Faces
Definition		
Define By	Normal To	
Type	Pressure	Fixed Support
Magnitude	20 MPa	

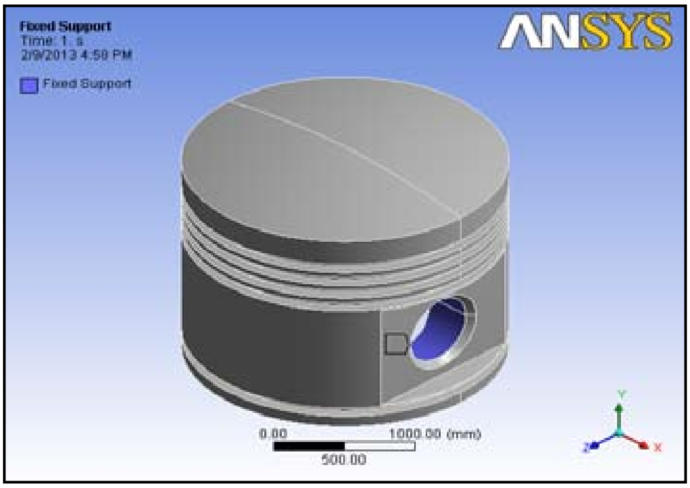


Fig. 5: Figure Shows the Boundary Conditions Applied For Piston

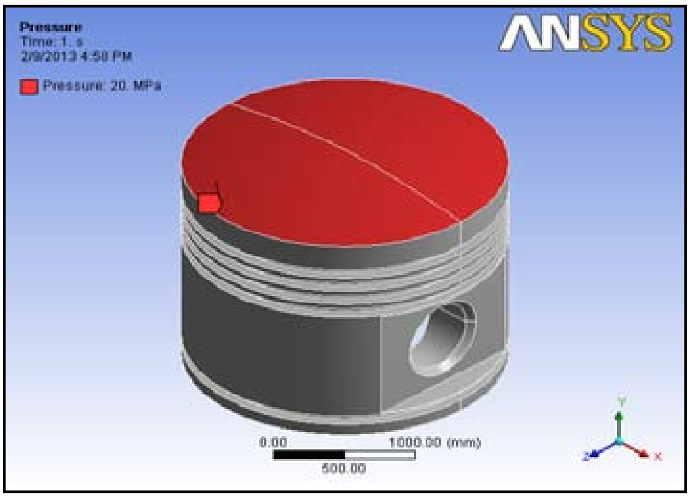


Fig. 6: Figure Shows Structural Load Acting on the Piston Head

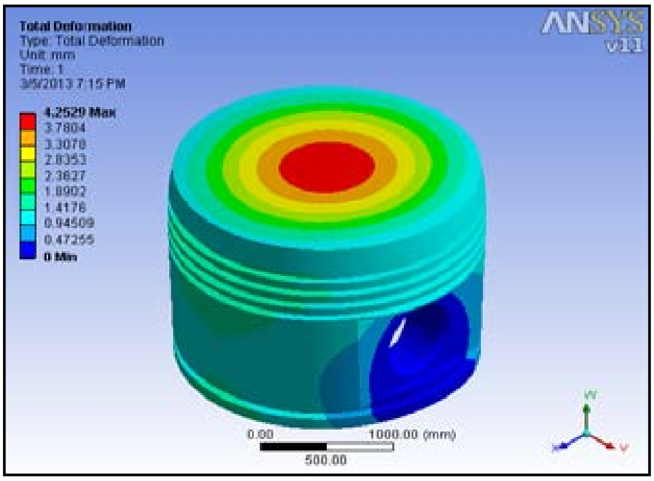


Fig. 7: Total Deformation for Concave Shaped Crown Piston

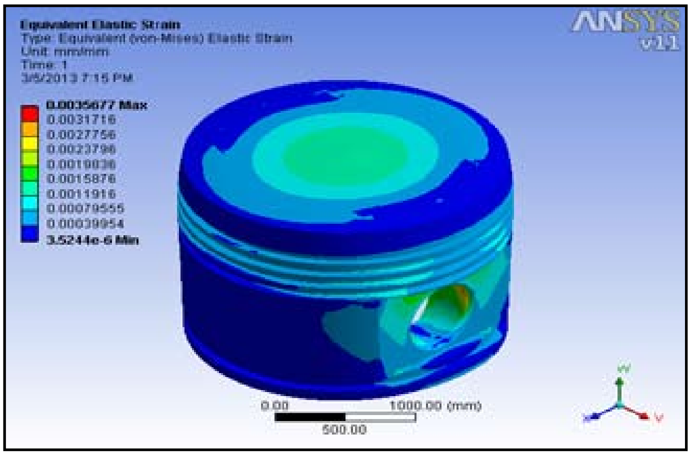


Fig. 8: Equivalent Strain Generated in the Concave Shaped Crown Piston

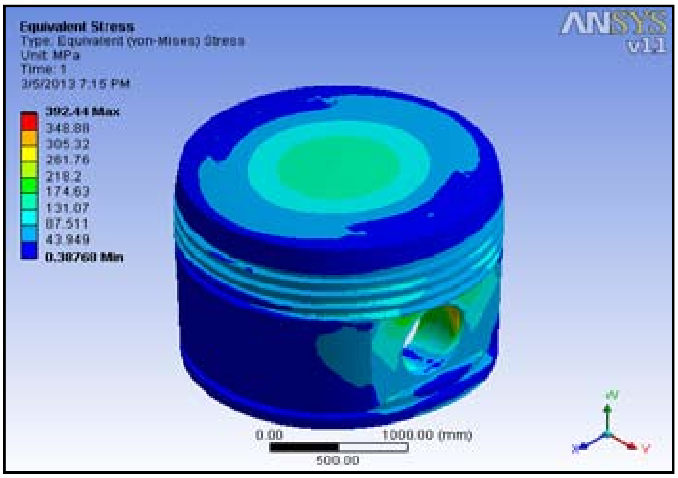
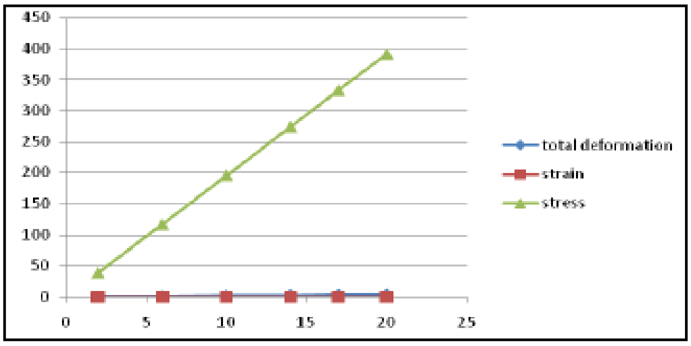


Fig. 9: Equivalent Stress Generated in the Concave Shaped Crown Piston



Graph 7: Graph of Concave Shaped Piston Crown Having Total Deformations, Stresses, Strains Versus Loads

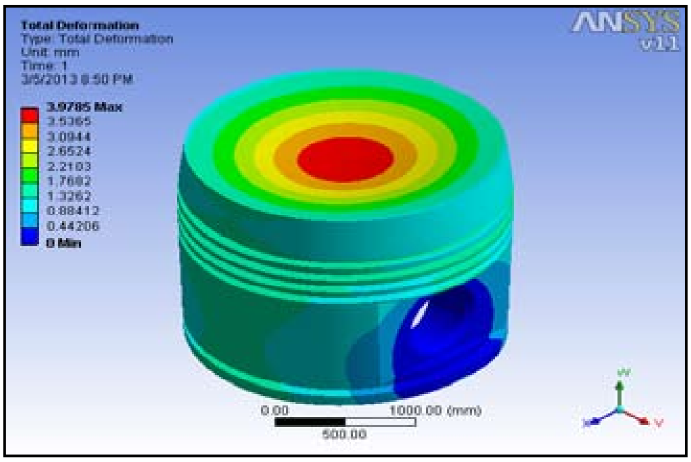


Fig. 10: Total Deformation for Convex Shaped Crown Piston

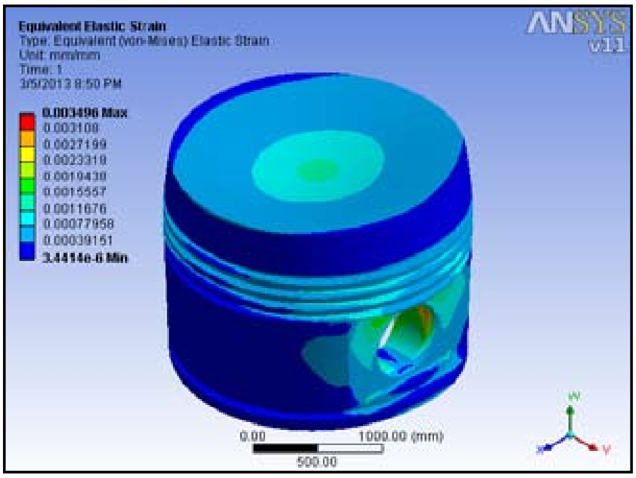


Fig. 11: Equivalent Strain Generated in the Convex Shaped Crown Piston

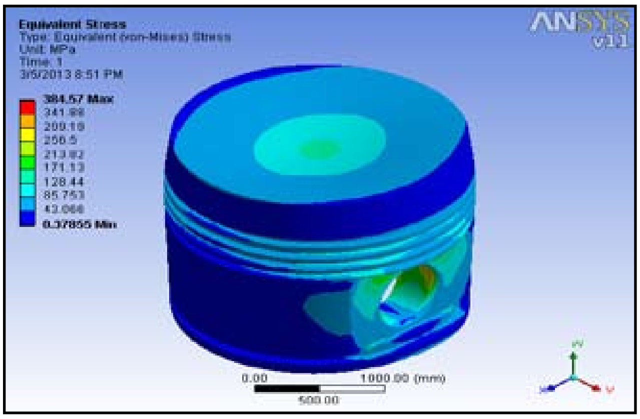
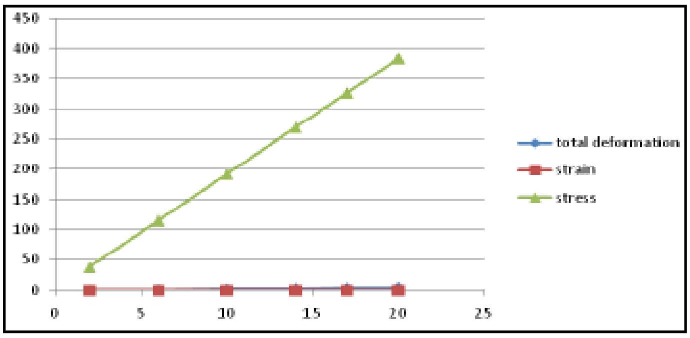


Fig. 12: Equivalent Stress Generated in the Convex Shaped Crown Piston



Graph 8: Graph Of Convex Shaped Piston Crown Having Total Deformations, Stresses, Strains Versus Loads

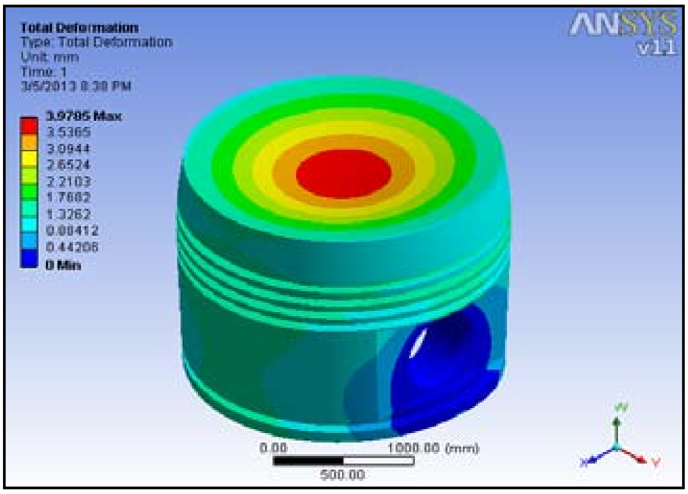


Fig. 13: Total Deformation for Flat Shaped Crown Piston

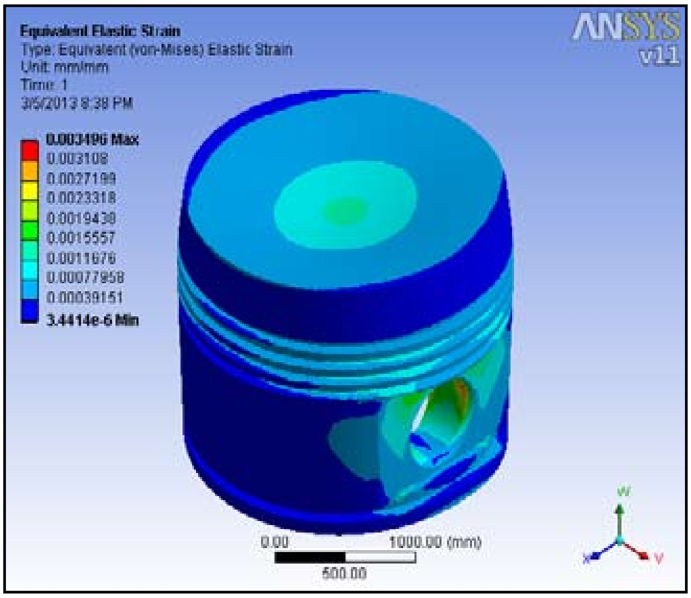


Fig. 14: Equivalent Strain Generated in the Flat Shaped Crown Piston

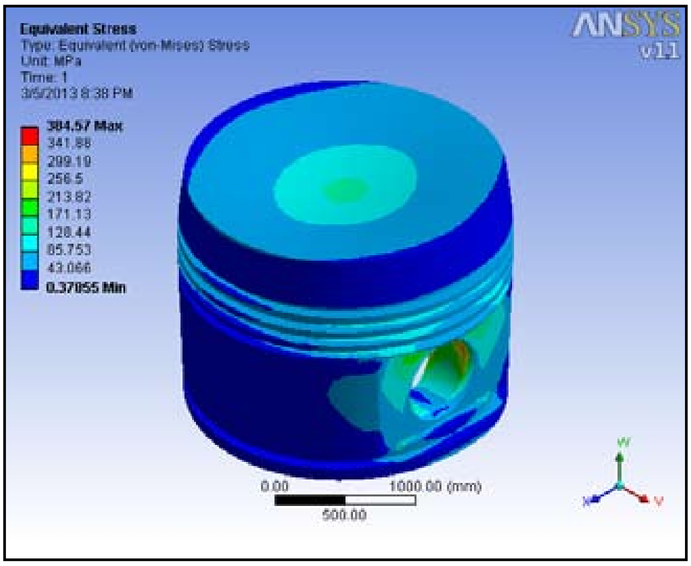
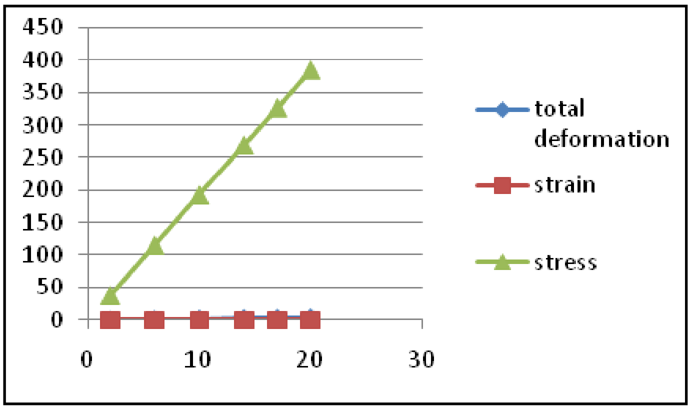


Fig. 15: Equivalent Stress Generated in the Flat Shaped Crown Piston



Graph 9: Graph of flat Shaped Piston Crown

Having Total Deformations, Stresses, Strains Versus Loads

Thermal Analysis

Material Data

Table 13: cast iron > Constants

Structural	
Young's Modulus	1.1e+005 MPa
Poisson's Ratio	0.28
Density	7.2e-006 kg/mm³
Thermal Expansion	1.1e-005 1/°C
Thermal	
Specific Heat	447. J/kg·°C

Table 14: Steady-State Thermal > Loads

Object Name	Convection	Convection 2
Scope		
Scoping Method	Geometry Selection	
Geometry	2 Faces	1 Face
Definition		
Type	Convection	
Film Coefficient	4.649e-005 W/ mm²·°C	3.5e-005 W/ mm²·°C
Ambient Temperature	300. °C	50. °C

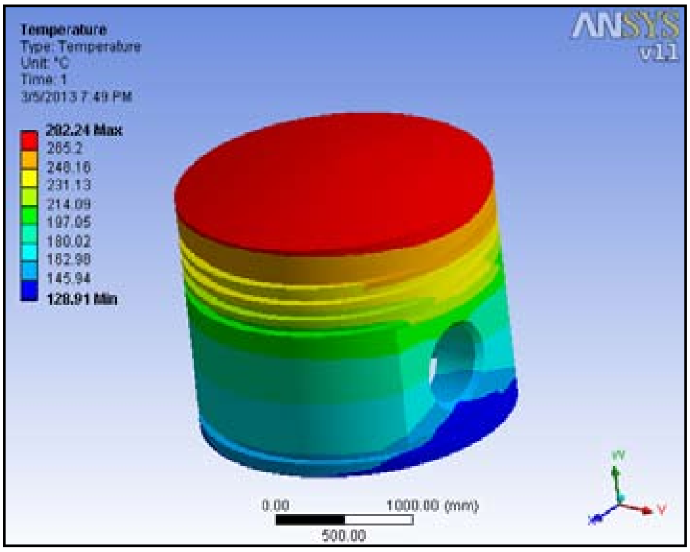


Fig. 16: Temperature Distribution for Concave Shaped Crown Piston

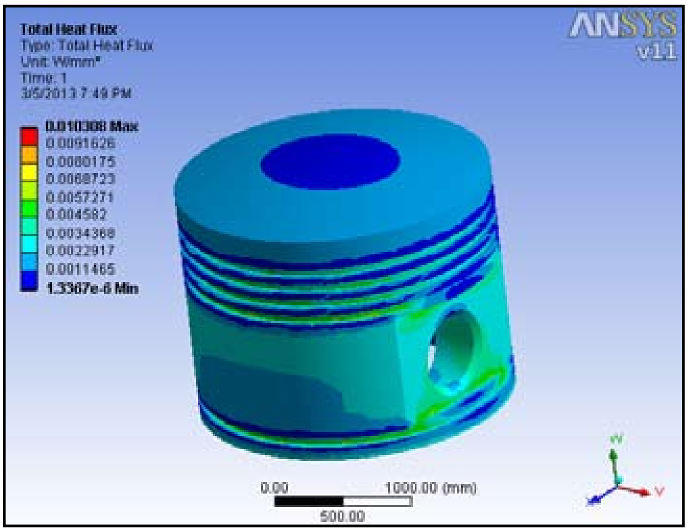
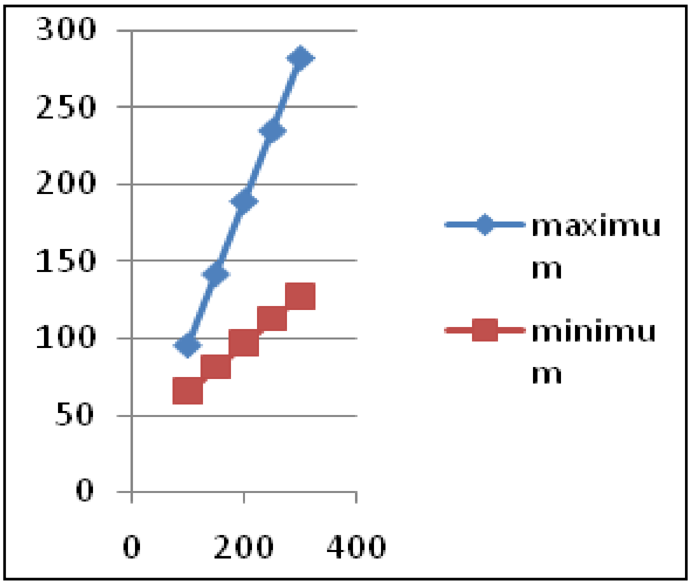


Fig. 17: Total Heat Flux for Concave Shaped Crown Piston



Graph 10: Graph of Concave Shaped Piston Crown Having Maximum Temperature, Minimum Temperature Versus Applied Load.

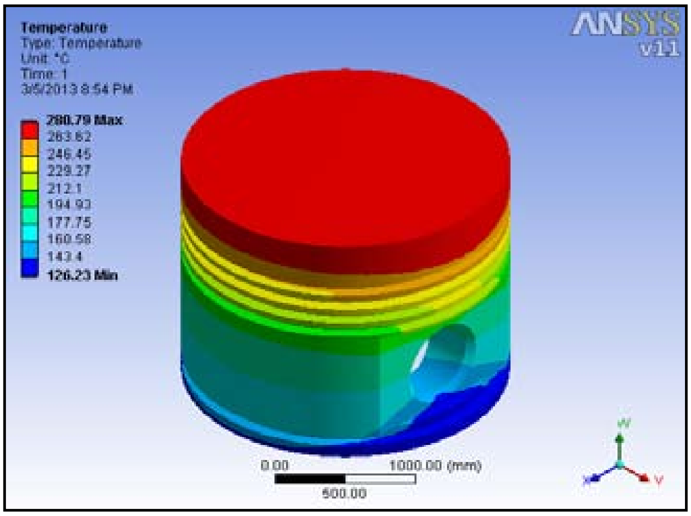


Fig. 18: Temperature Distribution for Convex Shaped Crown Piston

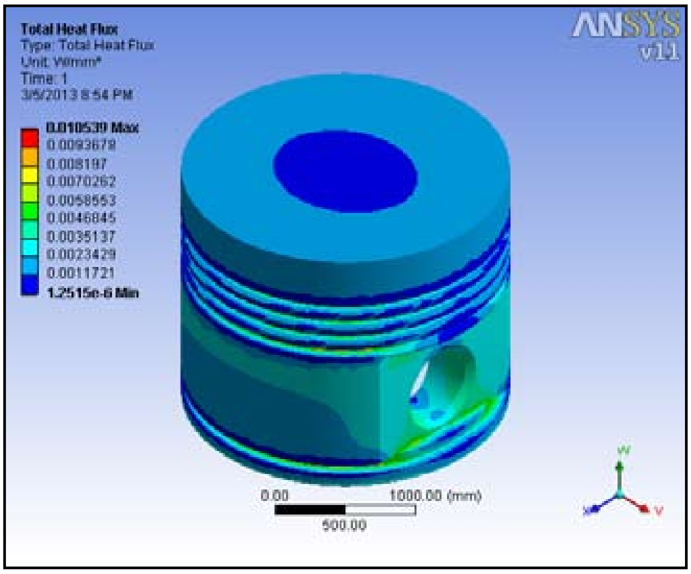
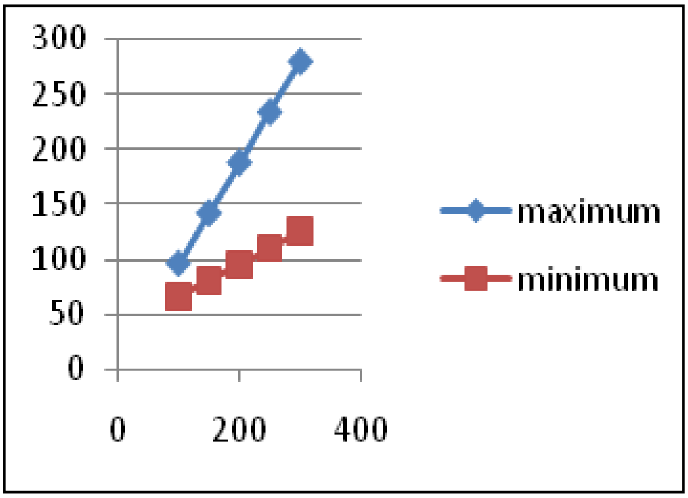


Fig. 19: Total Heat Flux for Convex Shaped Crown Piston



Graph 11: Graph of Convex Shaped Piston Crown Having Maximum Temperature, Minimum Temperature Versus Applied Load.

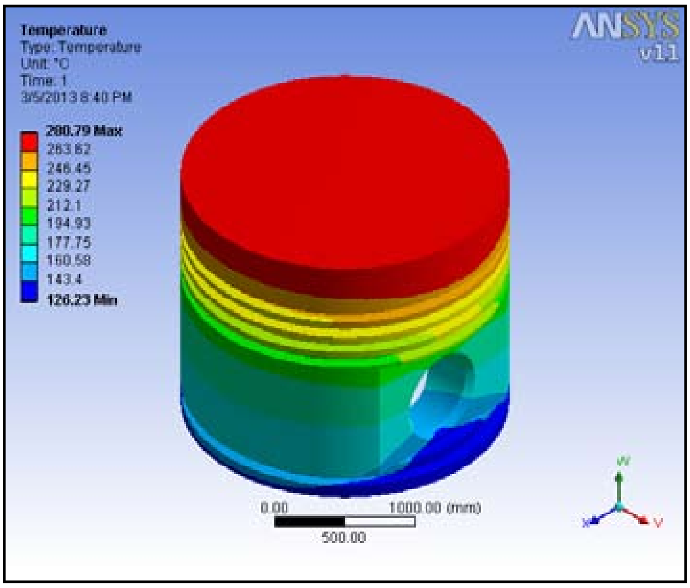


Fig. 20: Temperature Distribution for flat Shaped Crown Piston

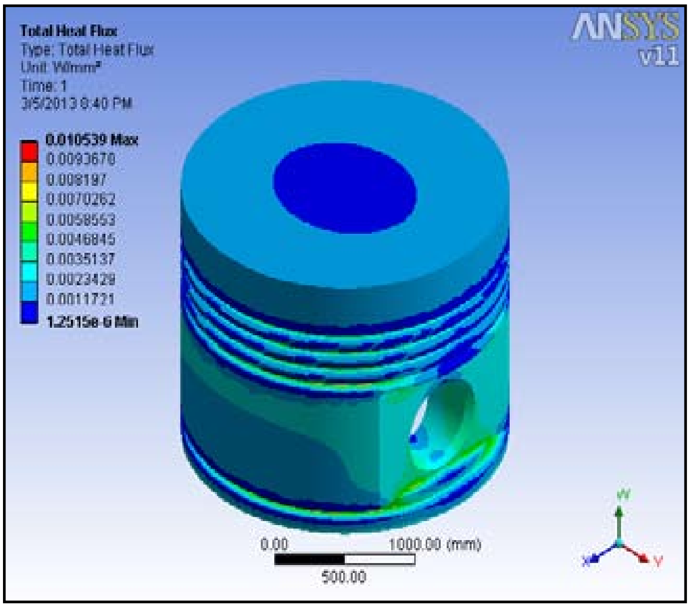
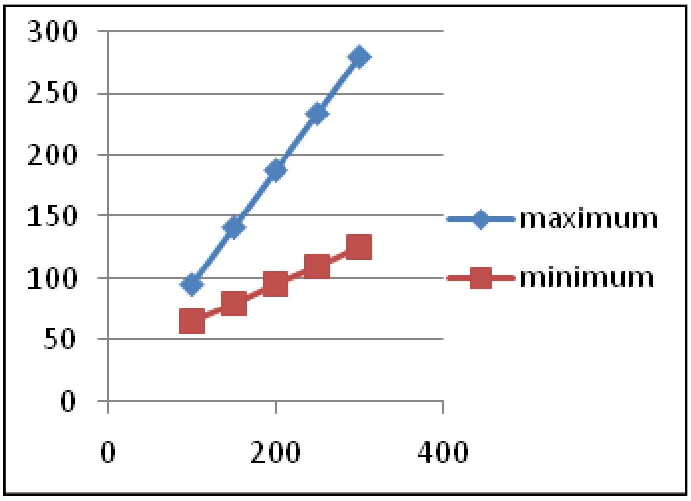


Fig. 21: Total Heat Flux for Flat Shaped Crown Piston



Graph 12: Graph of Flat Shaped Piston Crown Having Maximum Temperature, Minimum Temperature Versus Applied Load.

The above analysis results of the piston with different crown shapes were tabulated bellow.

Table 15: Final Results of Different Crowns for Aluminum Alloy

Shape of crown	Convex crown	Concave crown	Flat crown
Equivalent Stress Mpa	384	392	384
Deformation (mm)	3.9	4.28	3.9
Temperature °C Maximum Minimum	 280 126	 282 128	 280 128°
Total Heat Flux(w/mm²) Maximum Minimum	 0.010539 1.25e-6	 0.010308 1.3367e-6	 0.10539 1.25e-6

Conclusion

By comparing and analyzing the theoretical and practical results, the obtained theoretical and practical results such as von miss stresses, total deformation, and thermal heat transfer are within the safe zone of standard for three shapes of crown.

So, far the taken bore sizes the obtained results, are within the standard and design is safe. Finally the convex shape crown piston is having better design.

By changing piston materials with different compositions we can design the piston according to their strength and heat fluxes are can also be done by using FEM.

References

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