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Thermo-Mechanical &Vibration Analysis of I.C Engine Piston

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Abstract: *In the internal combustion engine, large number of parts are reciprocating parts which are responsible for giving the motion to the engine The main objective of this work is to investigate and analyze the stress distribution of piston at actual working condition. We tried to validate the piston by applying the estimated pressure load on the piston head and tried to validate the stress developed in it. We also applied different material at same loading conditions. In this present work an attempt has been made to compare vonmisses stresses, strain, heat flux and natural frequencies of three different materials. The variation of results between these materials is shown with the help of graphs.*
Keywords: *IC engine , material properties, troubles of piston, types of piston, vonmises stress,*

I. Introduction

There are significant research works proposing for engine piston designs, new geometries, materials and manufacturing techniques, and this evolution has undergone with a continuous improvement over the last decades and required thorough examination of the smallest details. Engine pistons are one of the complex components and its damage mechanisms have different origins and are mainly wearing, temperature, and fatigue related. Among the fatigue damages, thermal fatigue and mechanical fatigue, either at room or at high temperature, play a prominent role. For mechanical fatigue analysis we have considered vibration analysis of the piston and used finite element method ANSYS 15.0.

An internal combustion engine (ICE) is a heat engine where the combustion of a fuel occurs with an oxidizer (usually air) in a combustion that is an integral part of the working fluid flow circuit. In an internal combustion engine the expansion of the high-temperature and high-pressure gases produced by combustion apply direct force to some component of the engine. The force is applied typically to pistons, turbine blades, or a nozzle. This force moves the component over a distance, transforming chemical energy into useful mechanical energy. The Piston is a ‘heart’ of IC engine. It’s one of the key components of the engine. The function of the piston is bearing the gas pressure and making the crankshaft rotation through the piston pin. Piston works in high temperature, high pressure, high speed at poor lubrication conditions. Piston contact with high temperature gas directly, the instantaneous temperature can be up to 2500K. Because of the high temperature and the poor cooling condition, the temperature of the top of the piston can be reach 600~700K when the piston working in the engine and the temperature distribution is uneven. The top of the piston bears the gas pressure, in particular the work pressure.

Engine pistons are one of the most complex components among all automotive and other industry field components. The engine can be called the heart of a vehicle and the piston may be considered the most important part of an engine. There are lots of research works proposing, for engine pistons, new geometries, materials and manufacturing techniques, and this evolution has undergone with a continuous improvement over the last decades and required thorough examination of the smallest details.

Kawasaki Z650 specifications:
Engine type: 4-stroke,air cooled ,DOHC
Bore ✕ Stroke: 62✕54 mm
Compression Ratio: 9.5:1
Maximum horse power = 64 bhp@8500 rpm
Maximum torque = 5.8 N-m@7000rpm
Density of petrol C_8H_{18} = 732.22kg/m^3 at 60F

T = 60F = 288.855k = 15.5 ^{0}C
Cylinder Numbering: Left to Right 1-2-3-4.
Mass = density$\times$Volume = 0.00000073722$\times$162500 = 0.12 kg.
Molecular wt. for petrol = 144.2285 g/mole
R = Gas constant
PV = mRT
Where m = mass/molecular wt. = 0.12/144.2285 = 8.3061x10^{-4}x10^3 = 0.8306 mole.

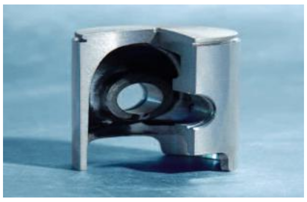
$$P = \frac{mRT}{V} = \frac{0.12\times8.3143\times288.555}{0.1442285\times0.0001625} = 12{,}283{,}753.39 \text{ j/m3} = 12.28 \text{ N/mm}^2.$$

Vivek Zolekar and Dr. L.N. Wankhade[1] proposes by using the simple concepts of FEA we were able to find critical areas of failure of model. The piston experiences maximum stress in the region where the combustion of the fuel takes place, i.e. at the piston head. Topology optimization using Altair's optimization software OptiStruct found to be very useful for generating new concept designs in less time.

Ch.Venkata Rajam, P.V.K.Murthy, M.V.S.Murali Krishna, G.M.Prasada Rao[2] had done design, analysis and optimization of piston which is stronger, lighter with minimum cost and with less time. Since the design and weight of the piston influence the engine performance. Analysis of the stress distribution in the various parts of the piston to know the stresses due to the gas pressure and thermal variations using with Ansys.

II. Types Of Piston

2.1 Two-Stroke Pistons:

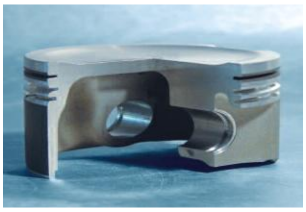


It is subject to strong mechanical and thermal loads due to the design principle of two-stroke engines. Special aluminum alloys are used so as to meet these requirements in the best possible way.

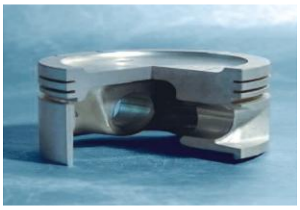
2.2 Cast Solid Skirt Pistons:

Distinguish themselves with a long operating life and economic viability for gasoline and diesel engines. In these pistons, the piston crown, ring zone and skirt make a robust unit. Therefore the possibilities for use range from a model engine to a large engine.

2.3 Forged Solid Skirt Pistons:

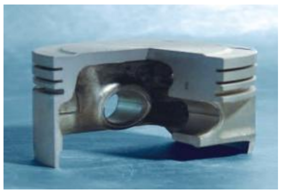


It has increased strength due to the manufacturing process. This means that smaller wall cross sections and lower piston weights are possible. These pistons are installed, above all, in mass produced engines that are subject to heavy loads, and in engines for racing sports.



2.4 Autothermik Hydrothermik Pistons:

These have cast steel strips and are slotted at the transition from the ring area to the skirt area. These pistons run very smoothly and are preferred for installation in car engines.



2.5 Autothermatik Hydrothermatik Pistons:

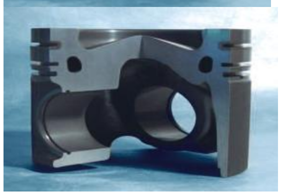
It has cast steel strips, but they are not slotted and so they make a uniform body with greater strength. They are preferred for installation in gasoline and diesel engines for cars that are subject to heavy loads.

2.6 ECOFORM Pistons With Pivoted Side Core:

It is weight optimized pistons for passenger car petrol engines. As a result of a special casting technology these pistons offer low weight and high structural rigidity.

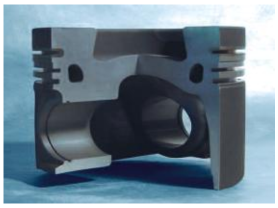
2.7 Ring Carrier Pistons-Pin Boss Bushes:

It has a ring carrier made of special cast iron which is cast into the piston. This provides protection to the top ring groove from the wear and tear which diesel engines in particular are subject to. In order to make it possible to increase the loads to which the pin boss can be subjected, this piston has pin boss bushes that are made of a special material.



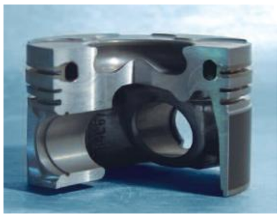
2.8 Ring Carrier Pistons With Cooling Gallery:

It is used in situations in which particularly high operating temperatures occur. In order to reduce the high temperatures – which are caused by the increased performance – in the piston crown and in the ring area, intensive cooling is done by circulating oil in the cooling gallery.



2.9 Ring Carrier Pistons With Cooling Gallery And Crown Reinforcement:

It is used for highly loaded diesel engines. For additional protection and in order to avoid cracking in the combustion chamber and the crown, these pistons have a special hard anodized layer (HA layer) on the piston crown.



2.10 Pistons With Cooled Ring Carrier:

It has significantly improved heat dissipation at the first ring slot. This is achieved with a combination of ring carrier and cooling gallery, in which the two components are combined into one system in a special production process.

2.11 FERROTHERM Pistons:

It Consist of a steel piston head and aluminum Piston skirt which have a moveable connection to each other via the piston pin. Due to great strength and low wear and tear, it is possible to achieve low exhaust emission values for diesel engines that are subjected to particularly high loads.

III. Troubles Of Piston

3.1 No Start/Hard Starting:

There are three requirements to get an engine to start — fuel (in the right proportion), oxygen (air), and fire (timed spark). If the engine won't run, one of these things is missing.

Air is almost a given. Even with a significant intake obstruction there will be at least enough air getting into the engine to get it to fire at an idle speed. One exception here is a totally sealed off induction. This would most likely occur after the engine has been removed from storage and someone forgot to remove the intake plug. This source of the no start problem is, however, rarely encountered. Fuel is a much more common culprit. Over priming an engine will prevent it from firing even once. The presence of a strong fuel smell in the exhaust pipe indicates a flooded engine. Moving the mixture to idle cutoff and throttle to wide open while cranking will solve this one whether you have a carbureted or injected engine. Letting the engine sit for awhile also helps get rid of excessive fuel. Use wide open throttle and mixture idle cutoff while cranking

3.2 Miss/Rough Running:

The two most common sources of this symptom are ignition misfire and clogged fuel injector. The misfire most usually shows up on the preflight mag check. To find the offending plug, run the engine on the magneto with the bad drop. If a four or six point EGT/CHT system is installed, note the cold cylinder. Trace the ignition lead back to the magneto with the miss. The plug circuit (plug, high tension lead, or tower in the distributor block) has a short or open. The most common cause here is a dirty/bad spark plug or a chaffed ignition lead.

3.3 High Cylinder Head Temperature:

You may have run into this with a partially logged injector. If not, try these other sources. Baffling: Bad inter-cylinder or cylinder head baffling can cause localized cooling air loss. Check for stiff or loose baffle seals. The classic birds' nest is often a common culprit here too. A healthy starling can build a very effective air block in 15 to 30 minutes. If a cylinder has recently been changed, expect higher head temps on that cylinder for the next 30 to 50 hours of operation. If all the head temps are high look for a more generalized problem. Check for numerous gaps and holes in the baffling. A small air leak goes a long way in dropping the cooling air pressure and causing temperatures to rise. Also, check the cowl flaps for proper rigging. Some models of aircraft have different cowl flap rigging for different years and engines in the same model.

3.4 High Oil Temp:

High cylinder head temperatures and high oil temps often go together. In this case look for the common causes of both: bad or damaged baffling or its seals, cowl flap rigging, mag timing, or cooling air blockage. If just the oil temp is high and cylinder head temps are normal, look for these common sources: Dirty or excessive paint on the fins will slow heat conductivity and allow the temperature to rise more than normal also. This one will be seen mostly on hot summer days where the cooler needs all the help it can get. A quick visual inspection will cue you to this culprit.

Another common source here is what's called the "Vernatherm" or temperature bypass valve. This unit is a thermostatic valve that works much the same as the coolant thermostat in your car or truck. As the oil gets hotter, the valve closes harder, forcing more oil through the cooler.

3.5 Low Oil Pressure:

The three most important factors that determine oil pressure in any given engine are: oil pump volume, engine internal clearances/leakage, and oil viscosity. The two most common causes of this symptom are oil viscosity and internal clearances/leakage. Oil viscosity is affected by oil grade, temperature and oil damage. The wrong oil grade for ambient temperatures or high oil temperatures will often cause low oil pressure. Oil can be damaged by excessive heat and/or excessive operating time before oil change. All these factors will tend to thin the oil and cause a pressure drop. Any excessive internal leakage in the engine will also cause a drop in pressure even at normal operating temperatures. The most common culprit here is debris under the oil pressure relief valve. This acts to hold the valve off its seat and bleed off oil, dropping the pressure. Remove the valve and clean the face and seat. Note the type of debris that was caught in the valve. This may be an indication of larger problems as noted in the next section.

3.6 Low Cylinder Compression:

This problem is usually found during a scheduled engine inspection. However, excessively low compression on one cylinder is usually noticeable when running the engine as well. The three most common leakage points are intake valve, exhaust valve, and rings. If an intake or exhaust valve is leaking it will be plainly audible in the intake (intake valve) or exhaust (exhaust valve) system. If the leakage is not bad the valve may be recapped without pulling the cylinder. The valve may also be sticky and just require some cleaning of the guide to devolve deposits. This can be found by checking the looseness of the valve in the guide when the valve rocker cover is removed.

IV. Objective And Methodology

The current thesis aims to analyze and optimize study of piston for its structural, thermal and vibration under static conditions with three different materials properties.

Methodology followed:

The methodology followed in this thesis is as follows:

1. The design of piston and its working conditions is studied.
2. Obtaining the dimensions of piston.
3. Obtaining loads and thermal conditions from the field.

4. Obtaining boundary conditions required for analysis.
5. Preparing a 3D model using CATIA.
6. Meshing the model using ANSYS i.e., small elements with nodes.
7. The following cases were considered for analysis in ANSYS to assess the structural, vibration, thermal characteristics of piston

- ✓ Applying loads for different material properties on piston model in analysis
- ✓ Thermal analysis with applying different temperatures modules at different portions in ANSYS
- ✓

Material Properties

S.No.	Piston Material	Structural Steel	Cast Iron	A2618 Aluminum Alloy
1.	Young's modulus of elasticity	200 KN/mm^2	100 KN/mm^2	73.7 KN/mm^2
2.	Poisson's Ratio	0.266	0.27	0.33
3.	Density	7860 kg/m^3	7200kg/m^3	2768 kg/m^3
4.	Coefficient of thermal expansion	1.17×10^{-5} m/^{0}C	1.0×10^{-5} m/^{0}C	2.59×10^{-5} m/^{0}C
5.	Shear modulus	80 KN/mm^2	45 KN/mm^2	25 KN/mm^2

V. Results And Discussions

5.1 Static Structural Analysis Results

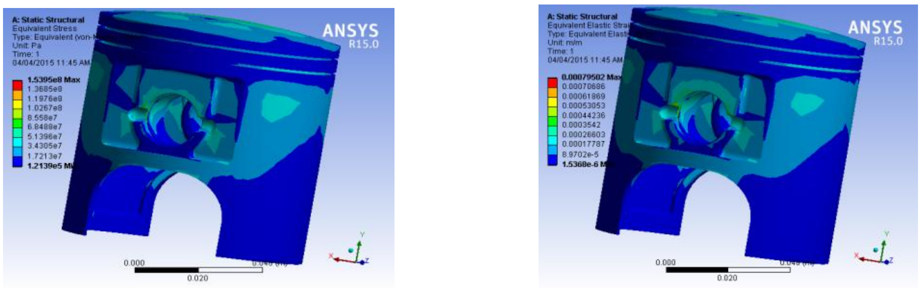


Fig.5.1.1 Vonmises stresses and Vonmises strain for structural steel

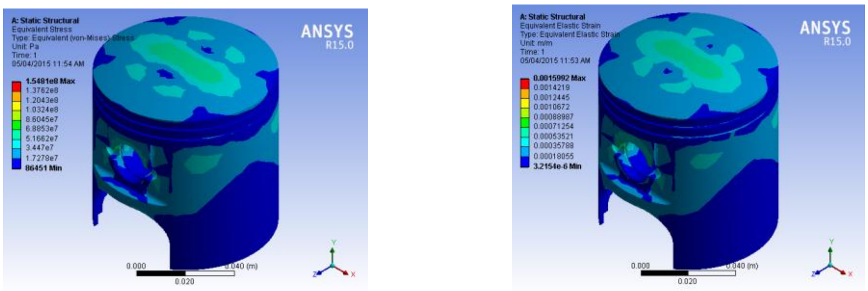


Fig.5.1.2 Vonmises stresses and Vonmises strain for Cast Iron

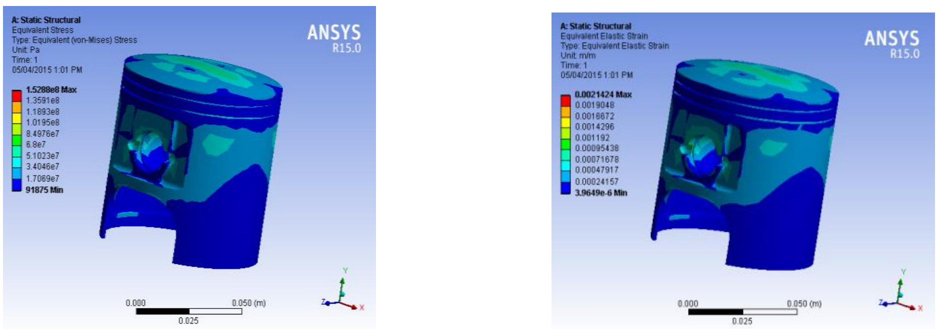


Fig.5.1.3 Vonmises stresses and Vonmises strain for A2618 Aluminium alloy

Table 5.1.1: Vonmises stresses and Vonmises Strains for Structural Steel

Material	Load (MPa)	Vonmises Stress (MPa)	Vonmises Strain	Total Deformation (m)
Structural Steel (density: 7860 Kg/m³) (young's modulus: 200KN/mm²) (Poisons Ratio 0.266)	10	1.5395E+2	0.00079502	0.060001
	12	2.0012E+2	0.0010335	0.060001
	15	2.3092E+2	0.0011925	0.060001
	16	2.465E+2	0.0012783	0.060002
	18	2.7691E+2	0.00143	0.060002

Table 5.1.2: Vonmises stresses and Vonmises Strains for Cast Iron

Material	Load (MPa)	Vonmises Stress (MPa)	Vonmises Strain	Total Deformation (m)
Cast Iron (density: 7200 Kg/m³) (young's modulus: 100KN/mm²) (Poisions Ratio 0.27)	10	1.5481E+2	0.0015992	0.060002
	12	1.8562E+2	0.0019174	0.060002
	15	2.3808E+2	0.0023974	0.060003
	16	2.4752E+2	0.0025565	0.060003
	18	2.7866E+2	0.0028786	0.060004

Table 5.1.3: Vonmises stresses and Vonmises Strains for A2618 Aluminum alloy

Material	Load (MPa)	Von misses Stress (MPa)	Von misses Strain	Total Deformation (m)
A2618 Aluminium alloy (density: 2768 Kg/m³) (young's modulus: 73.7KN/mm²)	10	1.5288E+2	0.0021424	0.060003
	12	1.8343E+2	0.0025705	0.060003
	15	2.2931E+2	0.0032134	0.060004
	16	2.446E+2	0.0034277	0.060004
	18	2.7518E+2	0.0038562	0.060005

Structural steel (low carbon steel) is a low cost material that is easy to shape, while not as hard as higher carbon steels, its surface hardness can be increased by carburizing. structural steel contains approximately 0.05-0.25% carbon making it malleable and ductile. Structural steel has a relatively low tensile strength, but it is cheap and malleable.

When using Cast Iron which contains approximately 0.7-1.5% carbon making it brittle. The value of Vonmises stress for Cast Iron is higher than structural steel and Aluminum alloy.

Using Lighter materials like Aluminum alloys, gives the advantage of low weight structures. For example, A2618 has the density of 2768 Kg/m³ compared with structural steel which has 7860 Kg/m³. Due to this effect A2618 achieves both strength and stiffness.

From the below Fig.6.4 it was observed that the A2618 Aluminum alloy possess low vonmises stress values compared to Structural Steel, Cast Iron respectively. Hence A2618 Aluminum alloy has been chosen to be best suitable material for stress application due to its low stress and high strength.

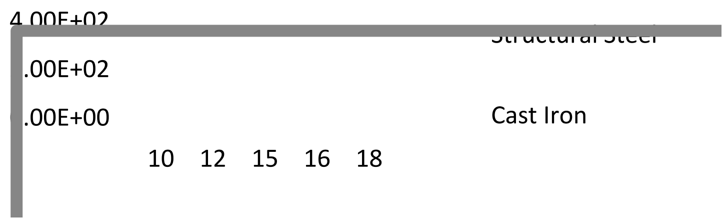


Fig 5.1.4 Graph for Vonmises stress comparison

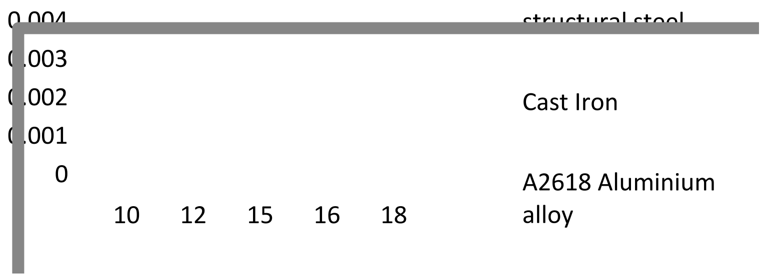


Fig.5.1.5 Graph for Vonmises strain comparison

5.2 Thermal Analysis Results:

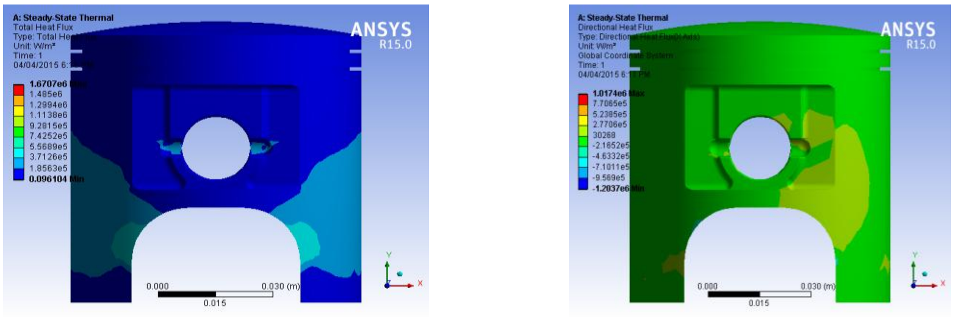


Fig.5.2.1 Max and Min Heat Flux for Structural Steel

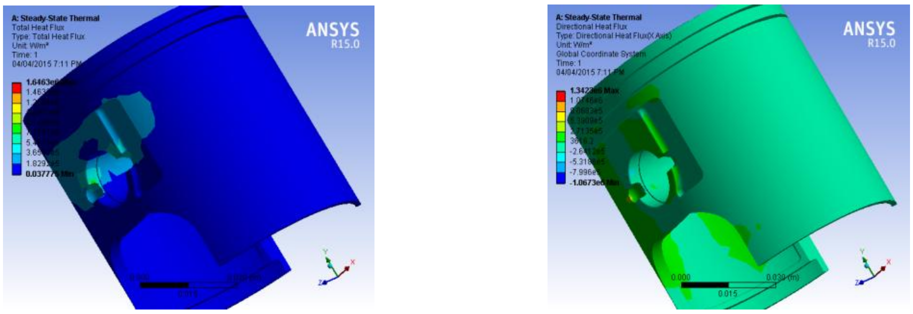


Fig.5.2.2 Max and Min Heat Flux of Cast Iron

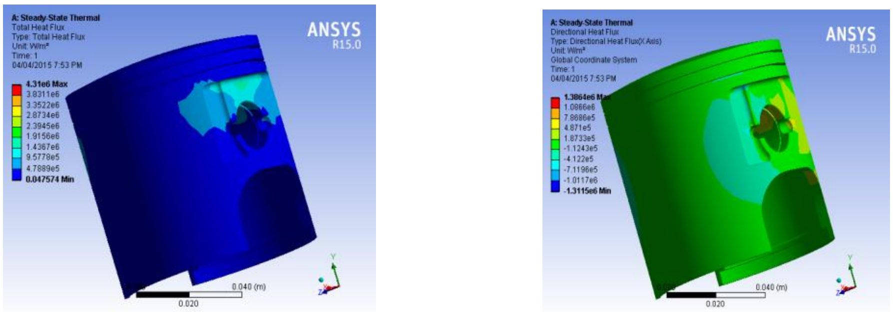


Fig.5.2.3 Max and Min Heat Flux for A2618 Aluminum alloy

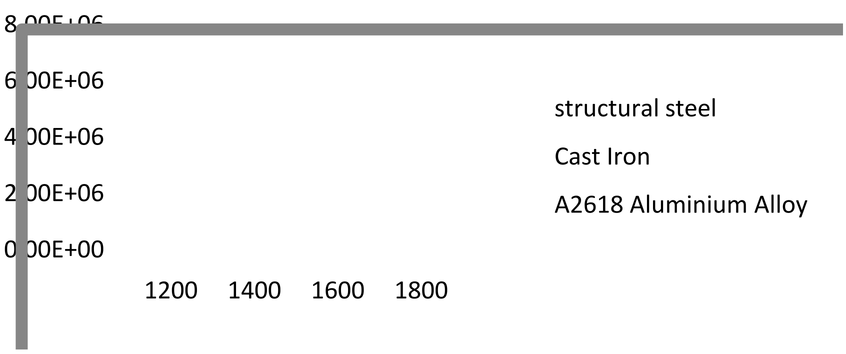


Fig.5.2.4 Graph for Max Heat Flux comparison

From the above Fig.5.2.4 it was observed that the heat flux in both structural steel and Cast Iron is approximately same and lower when compared to A2618 Aluminum alloy.

5.3 Modal Analysis Results:

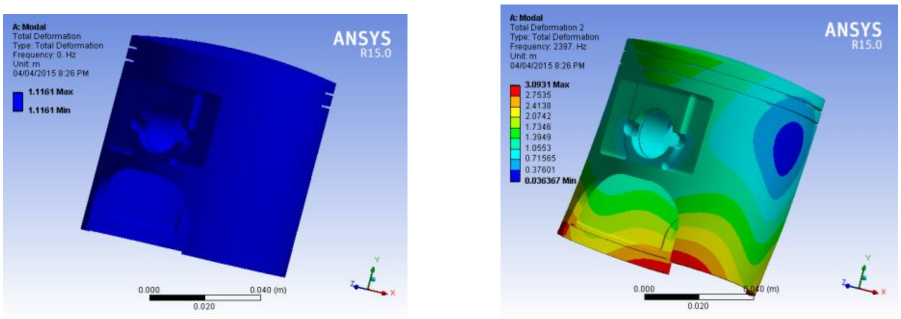


Fig.5.3.1Deformations at different modes for Structural Steel

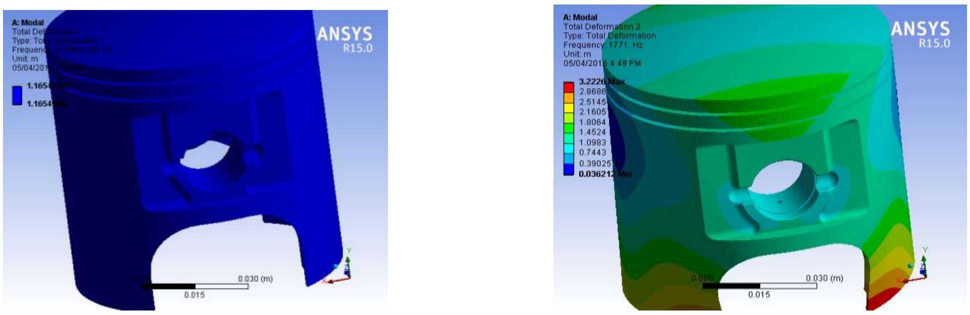


Fig.5.3.2 Deformations at different modes of Cast Iron

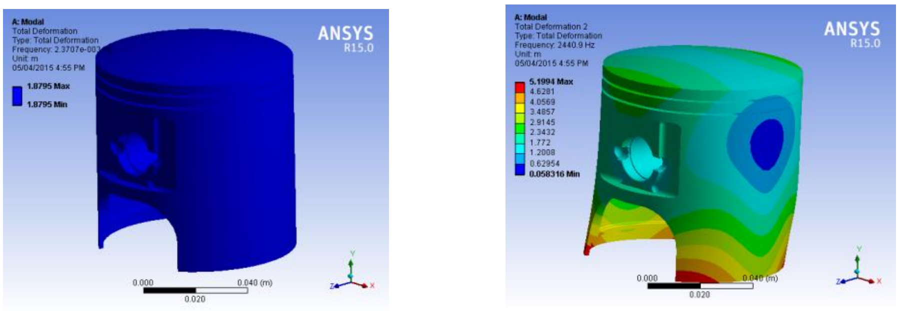


Fig.5.3.3 Deformations at different modes for Structural Steel

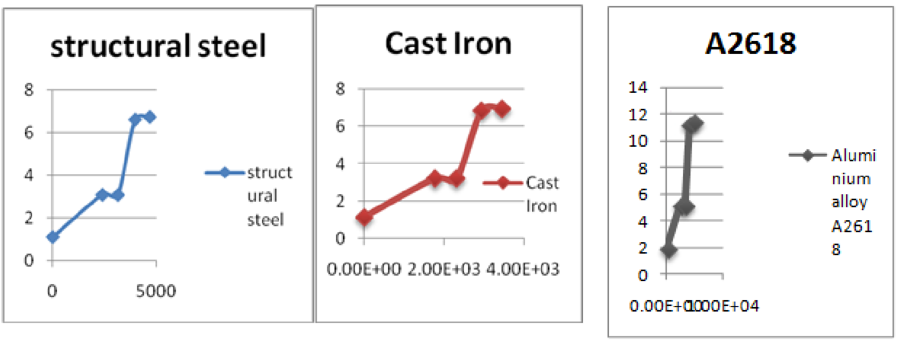


Fig 5.3.4 Graph for deformation at different frequencies for three materials

From the above Fig. 6.13 it was observed that the deformation due to frequency is high in A2618 Aluminum alloy rather than Structural Steel and Cast Iron.

VI. Conclusion

The Piston of four stroke I.C engine was designed in CATIA V5 and analyzed in ANSYS. The design of Piston was made with different materials like Structural Steel, Cast Iron and A2618 Aluminum alloy.

All the three materials were analyzed in terms of Vonmises stresses, Vonmises Strains, Heat Flux and Deformation at different frequency levels.

- It was found that Structural Steel and Cast Iron are experiencing more vonmises stress value than A2618 Aluminum alloy when 18MPa pressure is applied on Piston.
- Since the aluminum alloys used for pistons have high heat conductivity, therefore, these pistons ensure high rate of heat transfer and thus keeps down the maximum temperature difference between the centre and edges of the piston head or crown
- So, it is convenient to use aluminum alloy as piston material rather than cast iron or structural steel. Other advantage is aluminum alloys are about three times lighter than cast iron, therefore, its mechanical strength is good at low temperatures, Sometimes, the pistons of aluminum alloys are coated with aluminum oxide also.

Future scope:

- This work can be extended by using some more type of aluminum alloys as piston material such as cast aluminum, forged aluminum, cast steel and forged steel.
- Aluminum alloys may be coated with aluminum oxides for pistons working at elevated temperatures.

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