Modeling and Numerical Simulation of Material Science, 2024, 14, 1-38
https://www.scirp.org/journal/mnsms
ISSN Online: 2164-5353
ISSN Print: 2164-5345

# Static and Thermal Analysis of Aluminium (413,390,384 and 332) Piston Using Finite Element Method

**Offei David Inusah[1], Jacob Kwaku Nkrumah[2], Vincent Akolbire Atindana[2]**

[1]Automotive Engineering Department, Tamale Technical University, Tamale, Ghana
[2]Automotive Engineering Research Institute, Jiangsu University, Zhenjiang, China
Email: doinusah@tatu.edu.gh, jnkrumah@tatu.edu.gh, vaatindana@tatu.edu.gh

**How to cite this paper:** Inusah, O.D., Nkrumah, J.K. and Atindana, V.A. (2024) Static and Thermal Analysis of Aluminium (413,390,384 and 332) Piston Using Finite Element Method. *Modeling and Numerical Simulation of Material Science*, **14**, 1-38.
https://doi.org/10.4236/mnsms.2024.141001

**Received:** July 4, 2023
**Accepted:** November 25, 2023
**Published:** November 28, 2023



## Abstract

The main objective of this research was to examine the suitability of aluminium alloy to design a piston of an internal combustion engine for improvement in weight and cost reduction. The piston was modelled using Autodesk Inventor 2017 software. The modelled piston was then imported into Ansys for further analysis. Static structural and thermal analysis were carried out on the pistons of the four different materials namely: Al 413 alloy, Al 384 alloy, Al 390 alloy and Al 332 alloy to determine the total deformation, equivalent Von Mises stress, maximum shear stress, and the safety factor. The results of the study revealed that, aluminium 332 alloy piston deformed less compared to the deformations of aluminium 390 alloy piston, aluminium 384 alloy piston and aluminium 413 alloy piston. The induced Von Mises stresses in the pistons of the four different materials were found to be far lower than the yield strengths of all the materials. Hence, all the selected materials including the implementing material have equal properties to withstand the maximum gas load. All the selected materials were observed to have high thermal conductivity enough to be able to withstand the operating temperature in the engine cylinders.

## Keywords

Total Deformation, Von Mise Stress, Heat Fux, Piston Groove, Static Structural

## 1. Introduction

Piston is one of the most important moving components of reciprocating Internal Combustion engines. It is a moving component within a cylinder, and it is made gas-tight by piston rings. In an internal combustion engine, piston is used to transfer force from the expanding gas in the cylinder to the crankshaft through a connecting rod. Piston endures the cyclic gas pressure and the inertial forces at work, and this working condition may cause the fatigue damage of the piston, such as piston side wear, piston head cracks and so on [1]. Based on the important role played by pistons in an internal combustion engine, there is the need to optimize the design of the piston by considering various parameters. The functions of the piston and the loads that act on it present a very special set of requirements for the piston material. If low piston weight is the goal, then a low-density material is preferred. Besides its design shape, the strength of the material is the deciding factor for the load capacity of the piston. The change in loads over time requires a good static, dynamic strength, and temperature resistance due to the thermal loads. The thermal conductivity of the piston material is of significance for the temperature level in the combustion chamber. A piston material with a high thermal conductivity is mostly preferred because it promotes uniform temperature distribution throughout the piston. Low temperatures not only allow greater loading of the material, but also have a beneficial effect on the process parameters at the piston crown, such as the volumetric efficiency and knock limit. When an internal combustion engine is running, pistons are exposed to severe changes in temperature. The transient heat stresses that arise place cyclical loads on the piston that can sometimes exceed the elastic limit of the piston material. The piston material must be able to withstand the cyclical loads the piston is exposed to. Due to the piston motion and forces that act on the sliding and sealing surfaces, piston materials must also meet high requirements for seizure resistance, low friction, and wear resistance. The material pairing of the piston and its sliding counterparts is particularly critical, as a lubrication conditions. They must be considered as a tribological system. Special surface treatments or coatings will improve the properties of the base material. A material with good machining properties supports cost-effective production in large quantities. Combustion engines can be classified into two categories as External combustion (EC) engines and internal combustion (IC) engines. In internal combustion engine, piston is subjected to loads such as thermal and structural stress [2]. The piston of an internal combustion engines has the following parts: Piston Crown—which carries gas pressure, Skirt—which acts as a bearing against the side thrust of the connecting rod, Piston Pin is used to connect the piston to the connecting rod. These pins are made from hard steel alloy and have a finely polished surface. Most piston pins are hollow, to reduce weight and Piston Rings—which seal the annular space between cylinder wall and the piston which also scrap off the surplus oil on the cylinder walls as shown in **Figure 1**.

The working condition of a piston in an internal combustion engine is the nastiest. During the combustion stroke the fuel get ignited with the help of a spark plug in a spark ignition engine. Due to this combustion of gases in the cylinder the thermal deformation and mechanical deformation causes piston cracks. Piston converts the chemical energy after the burning of fuel into

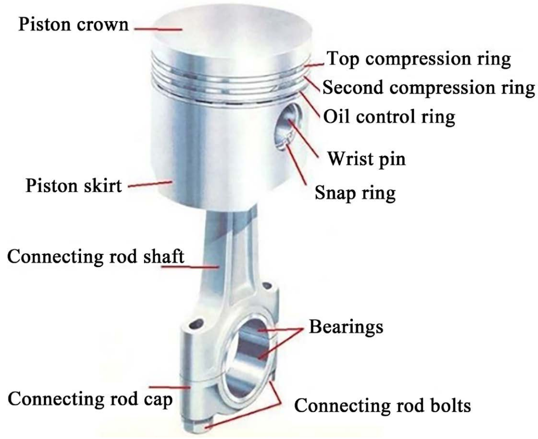


**Figure 1.** Parts of a piston with a connecting rod [3].

mechanical energy. The piston ring is used to provide seal between the cylinder wall and the piston. The piston must be able to work with low friction, high explosive forces, and high temperatures around 2000˚C to 2800˚C [4]. The piston is normally designed to be strong, but its weight should be less to prevent inertia forces due to the reciprocating motion. To increase the efficiency of its operation and better functionality, the piston material should satisfy the following requirements: light weight, good wear resistance, good thermal conductivity, high strength to weight ratio, free from rust, easy to cast and easy to machine. Piston should be designed and fabricated with such features to satisfy the above requirements. The recessed area located around the circumference of the piston is used to retain the piston rings. These rings are expandable and are categorised into three types. These types are Compression ring, wipper or second compression ring and oil ring. Compression ring is used to prevent the leakage from combustion chamber during combustion process. It is located closest to the piston head. The wiper ring is placed between compression ring and oil ring. It further seals the combustion chamber and keeps the cylinder wall clean by wiping out the excess oil. Combustion gases passed through the compression ring are stopped by the wiper ring. Oil ring is located near the crank case which is used to wipe excess oil from the cylinder wall during piston movement. Automobile components are in great demand these days because of increased in technological advancement and population which places a higher demand for the automobiles. The internal combustion engine piston can be made from different kinds of materials including Alumimum alloy, [5].

Piston is one of the components of the engine that is directly exposes to the burning flames of the fuel in the cylinders of an internal combustion engines. Because of its proximity to the flame, its material should not only be strong, but it should be able to endure the heat in the cylinders. There are high chances of failure of piston due to wear and tear. There are different kinds of materials that are used to manufacture pistons. Some of these materials are Cast steel, Cast iron and some aluminium alloys. This study intends to determine the suitability of aluminium alloy 413 for piston which is neither part of the special eutectic, hypereutectic or eutectic aluminium alloy families which are aluminium alloy materials known for piston design and manufacture. The common materials that are used to produce piston which are Cast Steel and Cast iron have very high densities compared to aluminium alloys. These high densities of these materials implied that; they have high weight. Materials that have high weight can retain heat for long time, meaning they have slow heat dissipation rate. Internal combustion engines which use pistons made with such materials are susceptible to overheating. Aluminium alloys have low densities meaning, they have less weight and have high heat dissipation rate making them the preferred materials for modern automotive components. Hence, the decision to design and a piston of an internal combustion engine made with aluminium alloy.

## 2. Related Work

Automobile engines are referred to as internal combustion engines because of the burning of the gases in the cylinders of the engine. This chemical process needed to be converted to mechanical movement of other parts of the engine. Pistons play a very critical role in the conversion process. This makes the piston as one of the most important moving components in the internal combustion engines. Automotive piston design for weight and cost optimisation is a tropical research interest area for many authors. Aluminium alloys are mostly the target materials for weight optimisation. For instance, Manisha *et al.* [6] indicated that, generally pistons are made of aluminium alloy and cast iron. They believed Aluminium alloy is preferable in comparison with cast iron because of its light weight which makes it suitable for reciprocating part. They concluded by saying that aluminium alloys have some drawbacks in comparison with cast iron, which they indicated as, Aluminium alloys are less in strength and in wearing qualities. The heat conductivity of Aluminium is about thrice that of cast iron. They found that aluminium alloy pistons are normally made thicker which is necessary for strength to give proper cooling. In the same vein, Vinary [7] established that the most used materials for pistons of internal combustion engines are cast iron, cast aluminium, forged aluminium, cast steel and forged steel. He opined that cast iron pistons are used for moderately rated engines with piston speeds below six minute per seconds and aluminium alloy pistons are used for highly rated engines running at higher piston speeds. He indicated that since the coefficient of thermal expansion for aluminium is about two and a half times that of cast iron, therefore, a greater clearance must be provided between the piston and the cylinder wall (than with cast iron piston) to prevent seizing of the piston when engine runs continuously under heavy loads. He went further to state that, if excessive clearance is allowed, then the piston will develop “piston slap” while it is cold, and this tendency increases the wear. He then concluded that since aluminium alloys used for pistons have high heat conductivity (nearly four times that of cast iron), 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. Sheasby *et al.* [8] in their study, they observed that aluminium alloy has its own advantages. They opined that aluminium alloy is not as stronger as cast iron and hence its piston would have to be designed to have a thicker section. As a result of which the weight of the aluminium piston will increased. They found that an aluminium alloy piston in actual practice is only about 50 percent in weight as compared to its cast iron counterpart. They went further to indicate that aluminium alloy is relatively soft because that fine particles in the lubricating oil become embedded in it. They concluded by saying that aluminium alloy piston with fine particles embedded in it causes a sort of grinding or abrasion of the cylinder walls thus shortening cylinder life and, important drawback of using aluminium alloy pistons for cast iron cylinders is their unequal coefficient of expansion which causes engine slaps.According to Amit *et al.* [2] in their research into design and optimization of hybrid piston for 4 stroke single cylinder 10 HP diesel engine, the materials which are used for internal combustion engines pistons are: Cast iron, Cast Aluminium, cast steel and forged aluminium. In their view the material used for piston is mainly aluminium alloy. They went further to state that, Aluminium pistons can be either cast or forged. But due to reduction of weight in reciprocating parts, the use of aluminium for piston was essential. To obtain equal strength a greater thickness of metal is necessary. Aluminium is inferior to cast iron in strength and wearing qualities, and its greater coefficient of expansion necessities greater clearance in the cylinder to avoid the risk of seizure. The heat conductivity of aluminium is about thrice that of cast iron this combined with the greater thickness necessary for strength. Similarly, Ajay *et al.* [9] considered three aluminium alloy materials for their piston design and these materials are namely: A2618, A4032 and Al-GHS 1300. It was revealed from their results that the weight and volume of Al-GHS 1300 is least among the three materials. Hence the inertia forces are less, which enhances the performance of the engine. The factor of safety (FOS) of Al-GHS 1300 is 6, which was much higher than the other materials, so further development of high-power engine using this material is possible. According to Mohd Nawajish *et al.* [10] in their study into structural and thermal analysis of the internal combustion engine piston using different materials indicated that the value of maximum temperature is same for all the materials at the top surface of the piston crown, but minimum value of temperature in the piston made of Gray Cast iron. The highest value of minimum temperature is found in the piston of Al alloy. This is due to high thermal conductivity of the Aluminium alloys. Minimum temperature was observed at the skirt of the piston and that max total heat flux was observed in piston of Al 7050 T7451 and piston of gray cast iron shows the lowest value of max total heat flux and concluded that, Maximum von mises stress, Maximum von mises strain and Maximum deformation are less in Piston of Al 7050 T7451 alloy in comparison of Al 6061 and gray cast iron. Minimum Factor of safety for all the materials is more than one but among all the materials factor of safety of Al 7050 T7451 is highest which is two pointsforty-five. Hence it can be said that Al 7050 T7451 piston is safe. After performing analysis on four different alloys namely 42CrMo, Al-Mg-Si, Al-Si, Al-Si-C-12 and under three different load conditions (Mechanical loads, Thermal loads, both Mechanical and Thermal loads), they conclude that 42CrMo, Al-Si-C-12 undergo least deformation under thermal loads and under mechanical loads Al-Si, Al-Si-C12 undergo least deformation. In the case of both Mechanical and Thermal loads Al-Si-C-12 undergoes the least deformation. This was mainly because while 42CrMo can withstand high temperatures but cannot withstand high mechanical loads and in the case of Al-Si, it can withstand mechanical loads but cannot withstand high temperatures like 42CrMo. In the case of Al-Si-C-12, it can withstand both mechanical and thermal loads. Hence Al-SI-C-12 undergoes least deformation when both mechanical and thermal loads are applied. In conclusion while designing a piston, 42CrMo must be used to make the piston top land because it is the surface of piston that directly encounters combustion of fuel and high temperatures, and Al-Si-C-12 must be used for piston skirt and rest of the piston [11]. According to Shuoguo Z. [12] opined that when Pistons are operating, they directly touch the high temperature gas, and their transient temperature can reach more than 2500 K and generates 18KW power. Piston is heated seriously, and its heat transfer coefficient is about 167 w/m·˚C and when its heat dissipation condition is poor, the piston temperature can reach 600 - 700 K approximately and the temperature distributes unevenly. Based on these conditions, they set out to conduct thermal analysis on the piston. Through the analysis of the operation of the piston, it was found that, the piston temperature distribution was uneven. The maximum steady state temperature of the piston was 2500 K under the temperature effect of the repeated changes in the high temperature gas. The highest temperature appears at the top surface of the piston crown. The temperature of the piston pin changes between 700 K and 800 K. The temperature of the first ring groove was the most important evaluation index of thermal load of the piston and its temperature was between 1300 K and 1500 K. The highest temperature differs by 1800 K from the minimum temperature, which made the piston to develop larger thermal stress and thermal damage. The value of the piston's hysteresis can be limited, primarily by proper selection of the piston's chemical composition and by selection of the appropriate piston manufacturing processes, including the piston heat treatment processes. The long experience in the pistons manufacturing and testing led to the selection of different Aluminium alloys, which is used in pistons mass production. Specific designs and the usage of the engines, however, require the introduction of the additional requirements that result, that it is necessary to correct the chemical composition of the piston alloys. The most used piston aluminium alloys are Al-Si alloys, containing about 12% Si. They are near eutectic alloys, further comprising several alloying additives [13]. For the same purpose it is important to determine the von Mises equivalent stresses of the piston. Also, it was noticed in the piston head, the von Mises equivalent stresses do not exceed the allowable stress of the material. In the analysis, they observed that the values of the equivalent stresses calculated using the finite element method are very similar to the ones calculated using the analytical method. Also, they stated that both types of equivalent stresses can be used for the designing of the piston, their values being sensibly equal, and the distribution is identical. The maximum total deformation of the piston due to mechanical-thermal load is lower than the maximum total deformation due to thermal load was found at the edge of the top surface of the piston head and has the same sense as the deformation due to thermal load. They then concluded that the deformation due to mechanical load cancels in part the deformation due to thermal load [14]. According to Adil *et al.* [15] indicated that the thermal load from the combustion of the air-fuel is also a cyclic load on the piston. It acts mainly during the expansion stroke on the combustion side of the piston. The thermal load has a very high peak at the point of combustion, but the duration of this peak is very short (only a few milliseconds depending on the engine speed). This peak generates a cyclic loading on the piston crown, but this temperature fluctuation only occurs close to the surface of the material within the piston, which is exposed to the combustion gases. Most of the piston mass reaches a quasi-static temperature during engine operation with limited cycle variation. Although there is no cycle variation there is still significant variation of the quasi-static temperature within the piston. The heat transfer from the combustion gas to the piston takes place predominantly by forced convection, and only a small portion by radiation. In the thermal Finite Element analysis of the piston; the quasi-static temperature was modelled using steady state conditions. The heat transfer calculations require the determination of the combustion gas temperature. The gas temperature in the cylinder varies considerably depending on the state of the combustion. The convective heat transfer phenomena depend on three factors which are: the heat transfer coefficient of the medium in which heat transfer is taking place, surface area for the heat transfer to take place and temperature difference between the surrounding and surface temperature of the part of the piston. The requirement condition was to maximize the heat transfer for the safety of the material otherwise high temperature material will get melt. They concluded by indicating that their thermal analysis shows that, the thermal load on different areas of the piston helps in predicting the critical areas of the piston so that a suitable material for the piston and structure of the crown of the piston can be chosen. They demonstrated in their results that the reduced skirt length piston temperature reduced by 10 - 20˚ as compared to simple piston while boundary conditions are same. Similarly total heat flux variation also reduced in the case of the reduced skirt length piston as compared to simple piston. Piston failure occurs because of thermo-mechanical overload by insufficient intercooling thermo-mechanical overload by over fuelling, [16]. Bhagat *et al.* [17] observed that, Piston skirt may appear deformed at work, which usually causes crack on the upper end of piston head. Due to the deformation, the greatest stress concentration is caused on the upper end of piston, the situation becomes more serious when the stiffness of the piston is not enough, and the crack generally appeared at the point which may gradually extend and even cause splitting along the piston vertical. The stress distribution on the piston mainly depends on the deformation of piston. Therefore, to reduce the stress concentration, the piston crown should have enough stiffness to reduce the deformation. The Finite Element Analysis is carried out for standard piston model used in diesel engine and the result of analysis indicate that the maximum stress has changed from 228 MPa. to 89 MPa. And biggest deformation has been reduced from 0.419 mm to 0.434 mm.

## 3. Method and Materials

The cast aluminium alloy (Al 413) has been selected asthe implementing material for design of the piston of an internal combustion engine. The implementing material (Al 413) has the following nominal composition: 82.5% Al, 11% Si, 0.35% Mn, 0.15% Tin, 0.5% Zn, 2.0% Mg, 2.0% Fe, and 1.0% Cu. The alloy has a density of 2.66 g/cm$^3$, which is relatively light compared to most of the metals known for piston manufacture such as steel and its alloys for the purpose of weight and cost reduction. Cast aluminium alloy 413 is one of the strongest aluminium alloys suitable for components that requires high strength and can withstand high temperature such as pistons. The copper content in the cast aluminium alloy 413 increases its susceptibility to corrosion, but this sacrifice is necessary to make such a strong-yet-workable material. Table 1 shows the mechanical and physical properties of the selected material (Al 413).

The commonly known aluminium alloy materials for pistons design and manufacturing currently in operation are: Eutectic aluminium alloy with the properties summarized in Table 2, Hypereutectic aluminium alloy with the properties indicated in Table 3 and Special Eutectic aluminium alloy having the properties shown in Table 4. In this study, analysis of the piston would be based on comparing piston made of Eutectic aluminium alloy, Hypereutectic aluminium alloy and Special Eutectic aluminium alloy to a piston made with aluminium alloy 413. Tables 2-4 show the mechanical and physical properties of the three Aluminium alloys for piston.

### 3.1. Design Calculations of the Piston

The piston is a disc which reciprocates within a cylinder. The piston of an internal combustion engine receives the impulse from the expanding gas and transmits the energy to the crankshaft through the connecting rod. The piston must also dissipate a large amount of heat from the combustion chamber to the cylinder walls. The design calculations of the various parts of the piston are as outlined these subsequent sections.

#### 3.1.1. Engine Specification

**Vehicle Model**: Toyota HiAce (5L-E Engine)

**Fuel type**: Diesel

**Compression ratio**: 18.5:1

**Number of cylinders**: 4 cylinder in-line, 4 stroke cycle engines

Table 1. Properties of Al 413.

| Parameters | Value | SI Unit |
|---|---|---|
| Density | 2.66 | g/cm$^3$ |
| Ultimate Tensile Strength | 290 | MPa |
| Tensile Yield Strength | 131 | MPa |
| Compressive yield Strength | 131 | Mpa |
| Poisson's Ratio | 0.33 | |
| Young's Modulus | 71 | Gpa |
| Shear Modulus | 26.7 | Gpa |
| Shear strength | 170 | Mpa |
| Thermal Conductivity | 121 | W/m·K |
| Fatigue Strength | 130 | Mpa |
| Coefficient of thermal expansion | 204 | μm/m·K |
| Elongation at break | 3.5% | |
| Heat of fusion | 389 | J/g |
| Specific Heat Capacity | 0.963 | J/g·˚C |
| Melting Point | 574-582 | ˚C |
| Melting temperature | 649-760 | ˚C |
| Casting temperature | 635-704 | ˚C |

Table 2. Properties of the eutectic alloy (Al 384.0).

| Parameters | Value | SI Unit |
|---|---|---|
| Density | 2.82 | g/cm$^3$ |
| Ultimate Tensile Strength | 331 | MPa |
| Tensile Yield Strength | 165 | MPa |
| Compressive yield Strength | | MPa |
| Poisson's Ratio | 0.33 | |
| Young's Modulus | 11 | GPa |
| Shear Modulus | | GPa |
| Shear strength | 200 | MPa |
| Thermal Conductivity | 96.2 | W/m·K |
| Fatigue Strength | 138 | MPa |
| coefficient of thermal expansion | 21 | μm/m·K |

Table 3. Properties of the hypereutectic alloy (Al 390.0).

| Parameters | Value | SI Unit |
|---|---|---|
| Density | 2.71 | g/cm$^3$ |
| Ultimate Tensile Strength | 317 | MPa |

Continued

| | | |
|---|---|---|
| Tensile Yield Strength | 248 | MPa |
| Compressive yield Strength | | MPa |
| Poisson's Ratio | 0.33 | |
| Young's Modulus | 11.8 | GPa |
| Shear Modulus | | GPa |
| Shear strength | 200 | MPa |
| Thermal Conductivity | 134 | W/m·K |
| Fatigue Strength | 138 | MPa |
| coefficient of thermal expansion | 18 | µm/m·K |

**Table 4.** Properties of the special eutectic alloy (Al 332).

| Parameters | Value | SI Unit |
|---|---|---|
| Density | 2.71 | g/cm$^3$ |
| Ultimate Tensile Strength | 250 | MPa |
| Tensile Yield Strength | 190 | MPa |
| Compressive yield Strength | | MPa |
| Poisson's Ratio | 0.33 | |
| Young's Modulus | 73 | GPa |
| Shear Modulus | 27 | GPa |
| Shear strength | 190 | MPa |
| Thermal Conductivity | 100 | W/m·K |
| Fatigue Strength | 90 | MPa |
| coefficient of thermal expansion | 21 | µm/m·K |

**Cylinder bore and stroke**: 99.5 mm × 96.0 mm
**Engine displacemen**t: 2986 cm$^3$
**Maximum power**: 111 Kw at 145 Km/h
**Maximum Torque**: 260 Nm at 1600 - 2400 rpm

#### 3.1.2. Pressure and Force Acting on the Piston

Engine: 2986 cc Diesel 4 in line cylinder (water cooled)

Volume per cylinder $= \frac{2986}{4} = 746.5\ \text{cm}^3 = 746.5 \times 10^3\ \text{mm}^3$

Density of diesel: $832 \times 10^{-9}$ kg/mm$^3$

Operating temperature ($T$) = 240˚C

Molecular weight of diesel = 230 g/mole = $230 \times 10^{-3}$ kg/mole

$$\text{Gas constant}(R)\text{ of diesel} = \frac{\text{Universal gas constant}}{\text{Molecular weight of diesel}}$$

$$\frac{8314.3}{230 \times 10^{-3}} = 36.15 \times 10^3\ \text{J/kgmol} \tag{1.1}$$

From the ideal gas equation, pressure can be calculated as:

$$PV = mRT$$

$$P = \frac{mRT}{V} \tag{1.2}$$

But

$$\text{Density}(\rho) = \frac{\text{mass}(m)}{\text{Volume}(v)}$$

$$\begin{aligned} \text{Mass}(m) &= \text{density of diesel} \times \text{volume per cylinder} \\ &= 832 \times 10^{-9} \times 746.5 \times 103 = 0.621088\ \text{kg} = 62.1088 \times 10^{-2}\ \text{kg} \end{aligned} \tag{1.3}$$

Pressure developed in a cylinder $(P)$

$$= \frac{62.1088 \times 10^{-2} \times 36.15 \times 10^{3} \times 240}{746.5 \times 10^{3}} = \frac{5388559.488}{746.5 \times 10^{3}} = 7.218\ \text{N/mm}^2 \tag{1.4}$$

The piston of an internal combustion engine is designed for the maximum force acting on the piston ($F_P$) due to the gas pressure.

Let

$F_P$ = Gas Force acting on the Piston;

$D$ = Cylinder bore diameter and;

$P$ = Pressure developed in a cylinder.

$$F_P = \frac{\pi D^2}{4} \times P = \frac{\pi (99.5)^2}{4} \times 7.218 = 56124.6\ \text{N} = 54.124\ \text{kN} \tag{1.5}$$

### 3.1.3. Piston Design Procedure

The thickness of the piston head or crown is determined based on strength as well as based on heat dissipation and the larger of the two values is adopted.

The thickness of the piston head based on strength is given as.

$$t_H = \sqrt{\frac{3P \cdot D^2}{16\sigma_t}} \tag{1.6}$$

where:

$P$ = the pressure developed in the engine cylinders;

$D$ = cylinder bore diameter and;

$\sigma_t$ = allowable tensile stress of the Aluminium alloy which is taken between 50 to 90 MPa.

The design considered the tensile stress of piston Aluminium alloy to be 80 MPa.

$$t_H = \sqrt{\frac{3 \times 7.218 \times 99.5^2}{16 \times 80}} = \sqrt{\frac{214380.0135}{1280}} = \sqrt{167.484} = 12.9\ \text{mm} \approx 13\ \text{mm} \tag{1.7}$$

Therefore, the piston head or crown is 13 mm.

### 3.1.4. Radial Ribs

The radial ribs may be four in number. The thickness of the ribs varies from $t_H/3$ to $t_H/2$.

Therefore:

Thickness of the ribs, $t_R = \frac{13}{3}$ to $\frac{13}{2} = 4.33$ to $6.5\ \text{mm}$ .

The design adopted, $t_R = 6\ \text{mm}$ .

### 3.1.5. Piston Rings

Let us assume that there are a total of four rings ( $n_r = 4$ ) out of which three are compression rings and one is an oil ring.

Taking $t_1$ as the radial thickness of the piston rings and it is given as:

$$t_1 = D\sqrt{\frac{3P_w}{\sigma_t}} \tag{1.8}$$

where,

$P_w$ = pressure of the gas on the clinder wall in N/mm$^2$. Its value is limited from 0.025 N/mm$^2$ to 0.042 N/mm$^2$ and;

$\sigma_t$ = allowable tensile stress of aluminium alloy materials is taken from 50 N/mm$^2$ to 90 N/mm$^2$.

$$t_1 = 99.5\sqrt{\frac{3\times 0.039}{80}} = 3.8\ \text{mm} \tag{1.9}$$

Therefore, the radial thickness is taken as 3.8 mm. The axial thickness of the piston rings is given as:

$$t_2 = 0.7t_1 \text{ to } t_1 = 0.7\times 3.8\ \text{mm} = 2.66 \text{ to } 3.8\ \text{mm}$$

The design adopted,

$$t_2 = 3\ \text{mm}$$

The minimum axial thickness of the position of the piston ring,

$$t_2 = \frac{D}{10n_r} = \frac{99.5}{10\times 4} = 2.5\ \text{mm} \tag{1.10}$$

Thus, the axial thickness of the piston ring as already calculated ( $t_2 = 3\ \text{mm}$ ) is satisfactory.

The distance from the top of the piston to the first ring groove, that is, the width of the top land,

$$b_1 = t_H \text{ to } 1.2t_H = 13 \text{ to } 1.2\times 13\ \text{mm} = 13 \text{ to } 15.6\ \text{mm}$$

The design adopted,

$$b_1 = 14\ \text{mm} \tag{1.11}$$

and width of other ring lands,

$$b_2 = 0.75t_2 \text{ to } t_2 = 0.75\times 3 \text{ to } 3\text{mm} = 2.25 \text{ to } 3\text{mm} \tag{1.12}$$

The design adopted $b_1 = 14\ \text{mm}$ and $b_2 = 2.5\ \text{mm}$ .

The gap between the free ends of the ring is given as:

$$G_1 = 3.5t_1 \text{ to } 4t_1 = 3.5\times 3.8 \text{ to } 4\times 3.8\ \text{mm} = 13.3 \text{ to } 15.2\ \text{mm} \tag{1.13}$$

and the gap when the ring is in the cylinder,

$$G_2 = 0.002D \text{ to } 0.004D = 0.002 \times 99.5 \text{ to } 0.004 \times 99.5 \text{ mm} = 0.199 \text{ to } 0.398 \quad (1.14)$$

The design adopted $G_1 = 13.8 \text{ mm}$ and $G_2 = 0.3 \text{ mm}$.

### 3.1.6. Piston Barrel Design

Since the radial depth of the piston ring grooves ($b$) is about 0.4 mm more than the radial thickness of the piston rings ($t_1$), therefore,

$$b = t_1 + 0.4 = 3.8 + 0.4 = 4.2 \text{ mm} \quad (1.15)$$

The maximum thickness of barrel,

$$t_3 = 0.03D + b + 4.5 \text{ mm} = 0.03 \times 99.5 + 4.2 + 4.5 = 11.7 \text{ mm}$$

The piston wall thickness towards the open end is given as.

$$t_4 = 0.25t_3 \text{ to } 0.35t_3 = 0.25 \times 11.7 \text{ to } 0.35 \times 11.7 = 2.9 \text{ to } 4.0 \text{ mm} \quad (1.16)$$

The design adopted, $t_4 = 3.8 \text{ mm}$.

### 3.1.7. Piston Skirt Designs

Let

$l$ = Length of the skirt in mm.

The maximum side thrust ($R$) on the cylinder due to gas pressure ($p$),

$$R = \mu \times \frac{\pi D^2}{4} \times p \quad (1.17)$$

Taking $\mu = 0.1$ gives.

$$= 0.1 \times \frac{\pi (99.5)^2}{4} \times 7.218 = 5612.46 \text{ N} \quad (1.18)$$

Also, the side thrust due to bearing pressure on the piston barrel ($p_b$) is given as.

$$R = P_b \times D \times 1$$

Taking

$$P_b = 0.45 \text{ N/mm}^2$$

$$R = 0.45 \times 99.5 \times 1 = 44.7751 \text{ N} \quad (1.19)$$

Equating 1 and 2 gives

$$5612.46 = 44.775l$$

$$l = \frac{5612.46}{44.775} = 125.34 \text{ mm}$$

Therefore, the length of the piston skirt ($l$) is 125.34 mm.

Total length of the prison,

$$\begin{aligned} L &= \text{Length of the skirt} + \text{Length of the ring section} + \text{Top land} \\ &= 1 + (4t_2 + 3b_2) + b_1 \\ &= 125.34 + (4 \times 3 + 3 \times 3) + 14 = 160.34 \text{ say } 160 \text{ mm} \end{aligned} \quad (1.20)$$

Therefore, the total length of the piston is 160 mm as shown in **Table 5**.

Table 5. Piston design parameters.

| S/N | Parameters | Size (mm) |
|---|---|---|
| 1 | Cylinder Bore or Piston diameter | 99.5 |
| 2 | Thickness of the piston head ($t_H$) | 13 |
| 3 | Radial thickness of the piston rings ($t_1$) | 3.8 |
| 4 | Axial thickness of the Piston rings ($t_2$) | 3.0 |
| 5 | Width of the top land ($b_1$) | 14 |
| 6 | Width of the other lands ($b_2$) | 3 |
| 7 | Maximum thickness of the barrel ($t_3$) | 11.7 |
| 8 | length of the piston skirt ($l_1$) | 125 |
| 9 | Total length of the piston ($L$) | 160 |
| 10 | Outer diameter of the piston pin ($d_o$) | 50 |
| 11 | Inner diameter of piston pin ($d_i$) | 30 |
| 12 | Piston wall thickness towards the open end ($t_4$) | 3.8 |

## 3.2. Procedure for the Numerical Methods

This section of the study presented the procedure for the numerical methods which included: the geometry of the piston, meshing of the piston in Ansys and the boundary conditions set for the study.

### 3.2.1. The Geometry of the Piston

The piston was modelled in Autodesk inventor software 2017. The piston was modelled based on the design dimensions generated in the design process. The modelled component is as shown in Figure 2.

### 3.2.2. Meshing of Component

Meshing is very important step in static structural and thermal analysis process. Meshing is an integral part of the engineering simulation process where complex geometries are divided into simple elements that can be used as discrete local approximations of the larger domain. The mesh size influences the accuracy, convergence, and speed of the simulation. The meshing details of the model pistonare: number of nodes 19,860 and element size 10,548. The meshing of the internal combustion piston is as shown in Figure 3.

### 3.2.3. The Boundary Conditions Set for the Analysis

The static structural Analysis of the IC piston made with the four different cast Aluminium alloy materials was done in Ansys software version 2020 R2. The gudgeon pin hole in the piston was constraint (fixed) and a compressive load 56124.6 N was applied at the piston head portion of the piston as shown in Figure 4. Compressive load was considered, because internal combustion pistons are designed for the maximum gas load acting on the piston. This load subject the piston to compression and the piston only comes under tension due to the inertial of the reciprocating and rotating parts of the engine. The calculated

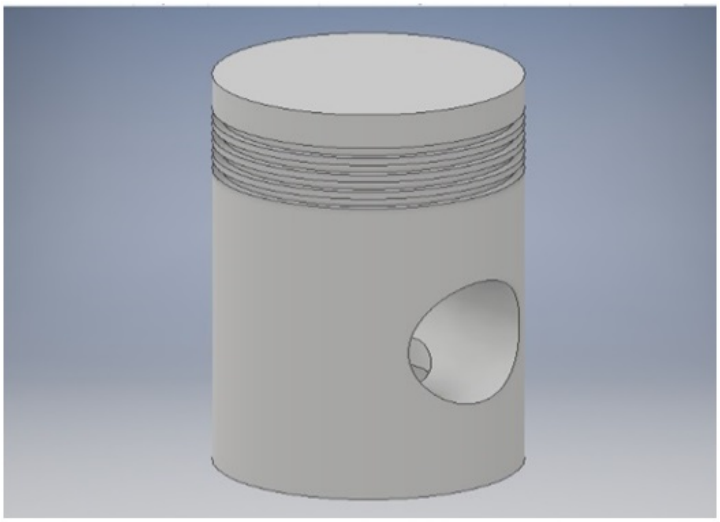

Figure 2. Geometry of the piston.

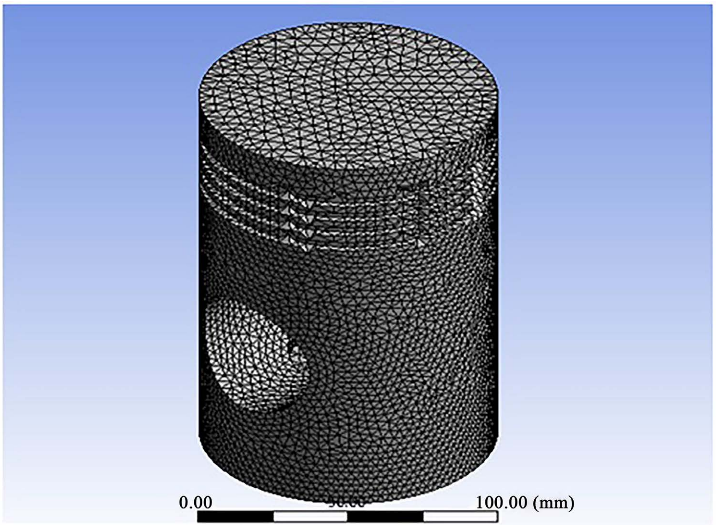


Figure 3. Piston meshed in Ansys.

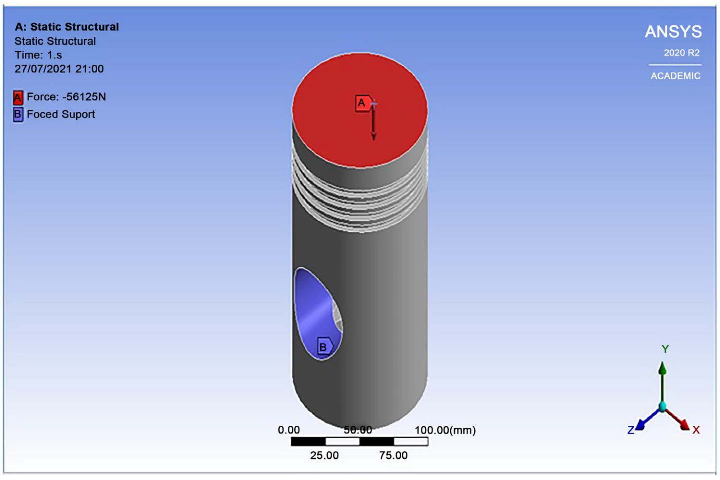


Figure 4. Boundary condition for the static analysis.

maximum gas load acting on the piston of the engine under consideration is 56124.6 N. The parameters that were considered for the static structural analysis were: total deformation, equivalent (Von Mises) stress, maximum shear stress and the safety factor of the four materials assigned to the model.

## 4. Experimental Results and Discussion

This section presents the simulated results on the static structural analysis for the implementing material (Aluminium 413 alloy) and all the three piston materials, namely: Aluminium 384 alloy, Aluminium 390 alloy and aluminium 332 alloy used in this work. The section also discusses and compared the results obtained from the simulation.

### 4.1. Static Structural Analysis Results

**a) Aluminium 413 alloy**

**Figure 5** shows the total deformation of the implementing material which is aluminium 413 alloy. It was observed that, the maximum deformation of 0.040552 mm occurred at the centre of the aluminium 413 alloy piston crown. From the centre, it was realised that averagely a deformation of 0.018023 mm spread out evenly throughout the piston crown, the first land up to the piston bosses. It was again observed that, below the piston bosses, there was minimum deformation of 0.0045058 mm. Based on the above data, it was reasonable to inferred that the implementing material has strength enough to resist the deformation that will be induced in the piston due to the maximum gas load.

The maximum equivalent (Von Mises) stress induced in the Al 413 piston has a maximum magnitude of 41.17 MPa and a minimum value of 0.028513 MPa for the given loading condition. The compressive yield strength of Al 413 is 131 MPa. The stress distribution in the Al 413 piston was lower at the first piston land and below the piston boss. It was observed from **Figure 6** that a maximum stress of 22.885 MPa occurred at the centre of the piston crown and below the second piston groove to the piston boss. The induced Von Mises stresses are far lower compared to the compressive and tensile yield strengths of 131MPa and 131 MPa respectively for the Al 413 material. The above results suggest that the model can therefore withstand the given loading condition.

**Figure 7** shows the induced shear stress in the Al 413 alloy material piston. It is observed that the maximum shear stress of 11.633 MPa occurred at the centre of the piston crown. The characteristics of the induced shear stress in **Figure 7** are consistent with the normal direct stress shown in **Figure 6**. It is again observed that, the maximum induced shear stress of 20.927 MPa is far lower than the yield shear stress of 170 MPa of the Al 413 alloy material. It is therefore predicted that the piston made with Al 413 alloy can withstand the shear load that the burnt gases will impose on the piston.

The Ansys generated factor of safety for Al 413 alloy piston model has a maximum and minimun factor of safety range magnitudes of 15 and 3.1819 respectively as shown in **Figure 8**. The factor of safety was generally observed to

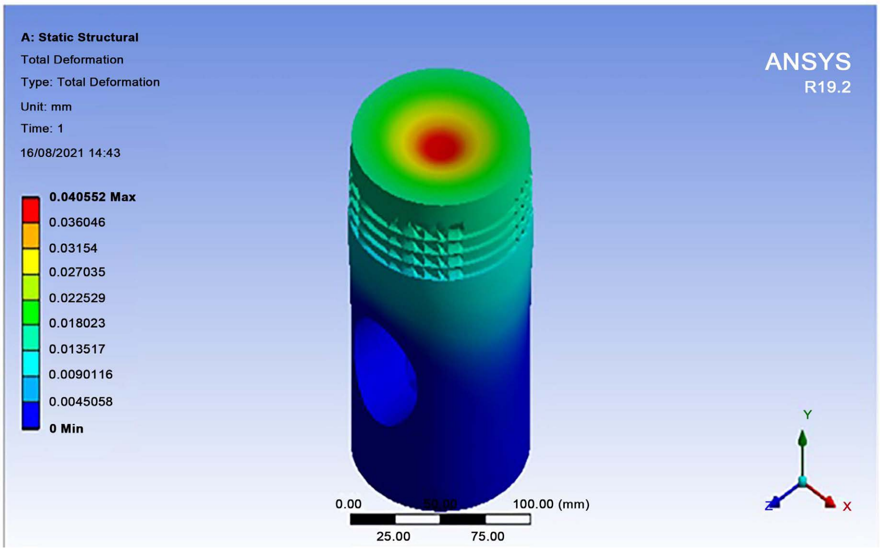


Figure 5. Total deformation for Al 413 piston.

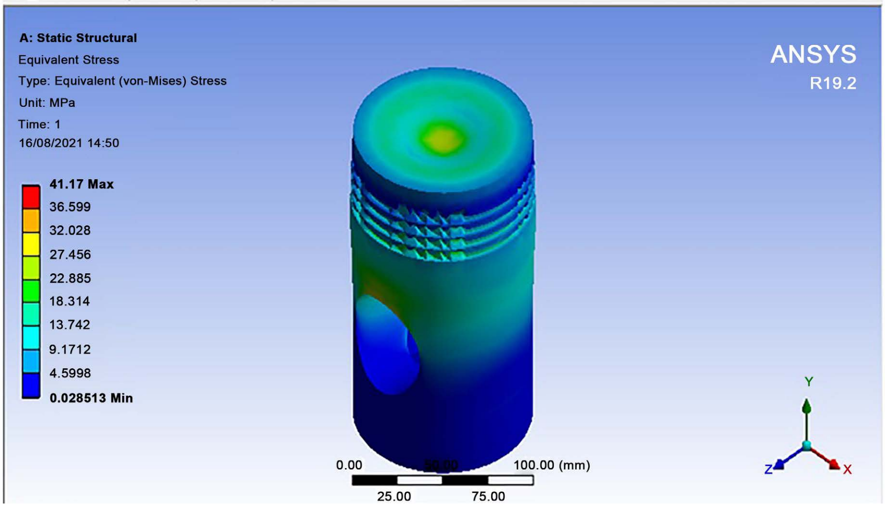


Figure 6. Equivalent von mises stress Al 413 piston.

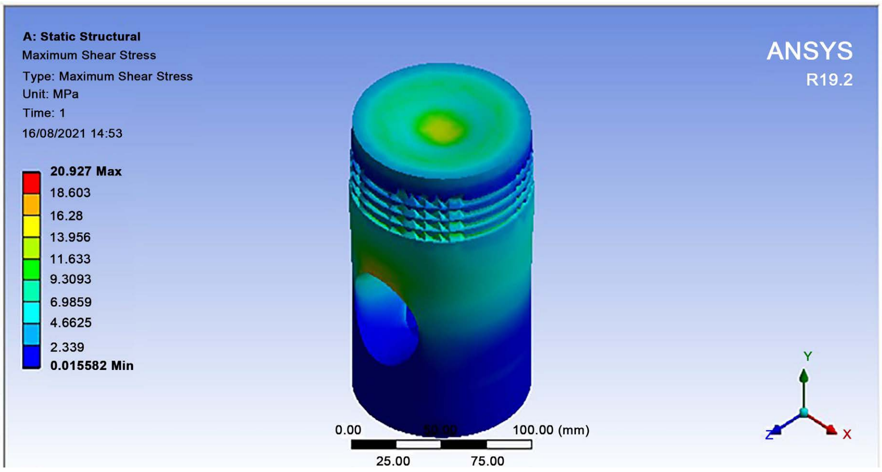


Figure 7. Equivalent shear stress for Al 413 piston.

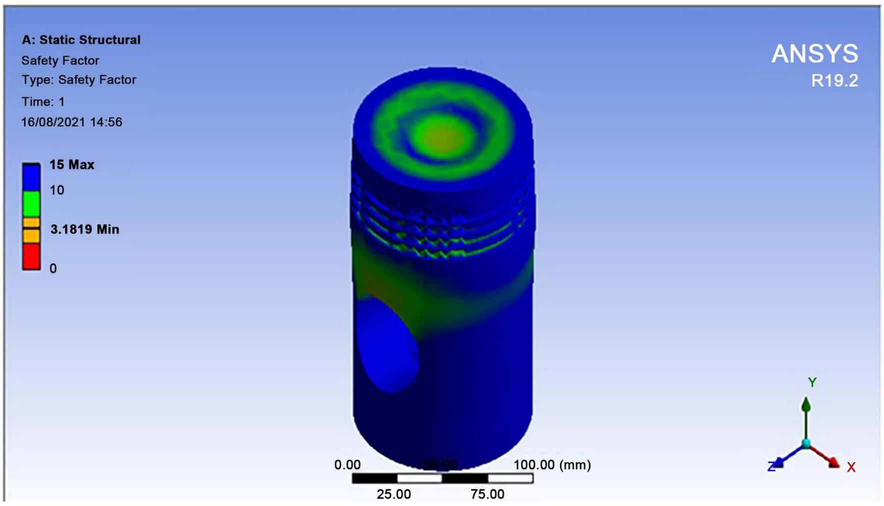


Figure 8. Factor of Safety of Al 413 piston.

be maximum at most parts of Al 413 alloy piston. The centre of the piston crown was observed to have a low factor of safety than the other parts. The model is therefore very safe.

Table 6 shows the summarised results for the implementing material which is Al 413 alloy when the static structural analysis was conducted in Ansys software.

**b) Aluminium 384 Alloy**

Figure 9 shows the total deformation of aluminium 384 alloy piston. It is observed that, the maximum total deformation of 0.26114 mm occurred at the centre of the aluminium 384 alloy piston crown. From the centre, it was realised that averagely a total deformation of 0.11633 mm spread out evenly throughout the piston crown, the first land up to the piston bosses. It was again observed that, below the piston bosses, there was minimum deformation of 0.029083 mm. The above data also shows that, the aluminium 384 alloy have the required properties to withstand the induced deformation.

The equivalent Von Mises stress is one of the most important parameters that was used to determine the suitability of the material to be able to withstand an applied load. The maximum equivalent (Von Mises) stress induced in the Al 384 alloy piston has a maximum magnitude of 41.17 MPa for the given loading condition. The compressive and tensile yield strengths of Al 384 alloy are 165 MPa and 165 MPa respectively as shown in Figure 10. The stress distribution in the Al 384 alloy piston was lower at the first piston land and below the piston boss. It was observed that the maximum stress of 27.456 MPa occurred at the centre of the piston crown and below the second piston groove to the piston boss. The induced Von Mises stress was observed to be far lower compared to the compressive yield strength of the Al 384 alloy material. The model piston can therefore withstand the given loading condition.

Figure 11 shows the induced maximum shear stress of the Al 384 alloy piston. It is observed that the maximum shear stress of 16.28 MPa occurred at the centre of the piston crown. The characteristics of the induced shear stress are consistent

**Table 6.** Summarised results for Al 413 alloy piston.

| Parameters | Maximum | Minimum |
|---|---|---|
| Total deformation | 0.040552 mm | 0.0045058 mm |
| Equivalent Elastic Strain | 0.0062772 | $6.981 \times 10^{-7}$ |
| Equivalent Von Mises Stresss | 41.17 MPa | 0.028513 MPa |
| Maximum Shear Stress | 20.927 MPa | 0.015582 MPa |
| Factor of Safety | 15 | 3.1819 |

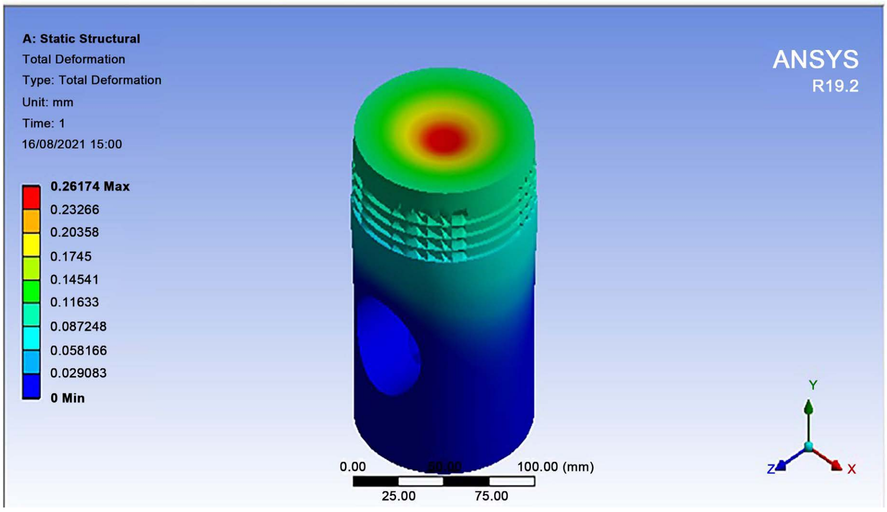


**Figure 9.** Total deformation for Al 384 alloy piston.

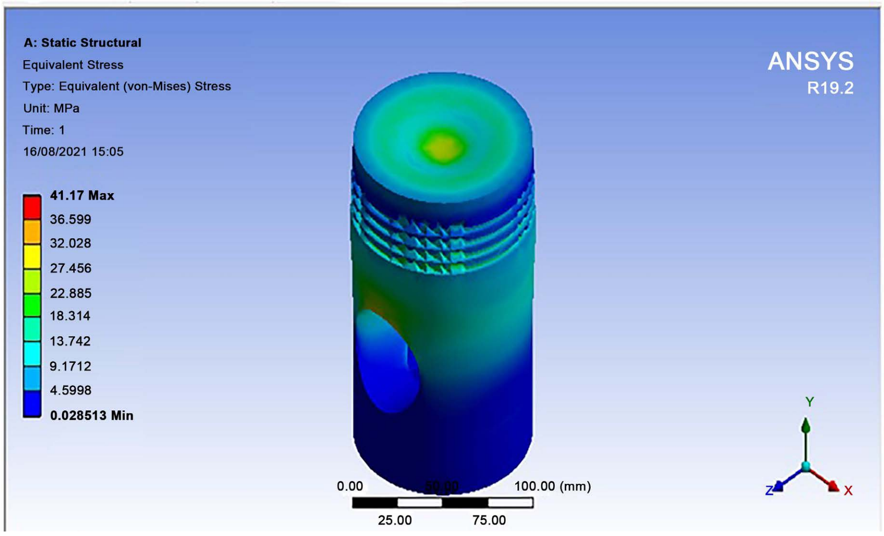


**Figure 10.** Von Mises Stress for Al 384 piston.

with the normal direct stress. It was again observed that, the maximum induced shear stress of 20.927 MPa was far lower than the yield shear strength of Al 384 alloy with the magnitude of 200 MPa. It is therefore projected that the piston made with Al 384 can withstand the shear load that the burnt gases will impose on the piston.

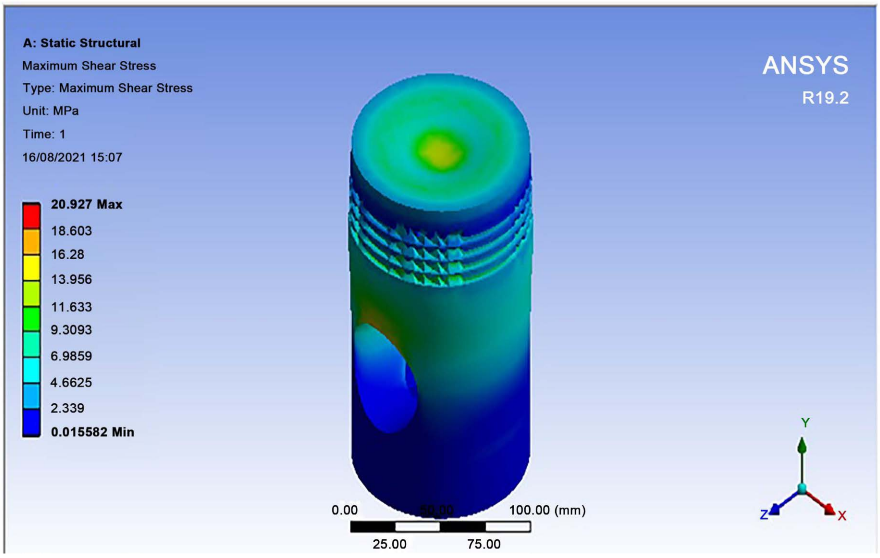


Figure 11. Maximum shear stress for Al 384 piston.

The Ansys generated factor of safety of Al 384 alloy piston madel has a maximum and minimun factor of safety range magnitudes of 15 and 1 respectively as shown in Figure 12. The factor of safety was generally observed to be maximum at most parts of Al 384 alloy piston. The centre of the piston crown was observed to have a lower factor of safety than the other parts. The model piston is therefore very safe.

Table 7 shows the summarised results for Al 384 alloy piston when the static structural analysis was conducted in Ansys software.

**c) Aluminium 390 Alloy Piston Results**

Figure 13 shows the total deformation of aluminium 390 alloy piston alloy. It is observed that, the maximum deformation of 0.244 mm occurred at the centre of the aluminium 390 alloy piston crown. From the centre, averagely a deformation of 0.1084 mm was observed to spread evenly throughout the piston crown, the first land up to the piston bosses. It was again observed that, below the piston bosses, there was a minimum deformation of 0.027111 mm towards the end of the piston. The deformation was observed not to be significant enough to affect the aluminium 390 alloy piston in operation. Hence, the aluminium 390 alloy will be able to withstand the maximum gas load.

The maximum equivalent (Von Mises) stress induced in the Al 390 piston has a maximum magnitude of 41.17 MPa for the given loading condition as shown in Figure 14. The yield strength of Al 390 is 248 MPa. The stress distribution in the Al 390 alloy piston was lower at the first piston land and below the piston bosses. It is observed that a maximum stress of 27.456 MPa occurred at the centre of the piston crown and below the second piston groove to the piston bosses. The maximum induced Von Mises stress is far lower compared to the yield strength of the Al 390 alloy. The model can therefore withstand the given loading condition.

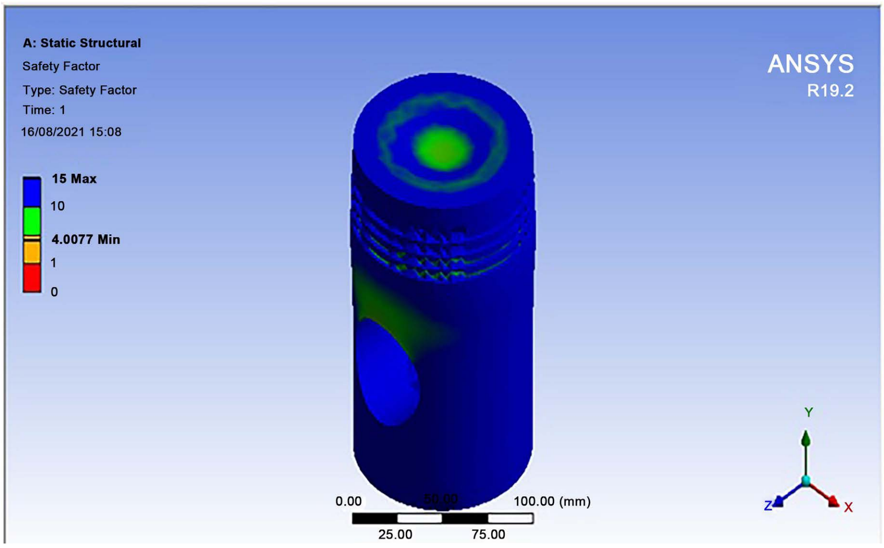


Figure 12. Factor of safety for Al 384 piston.

Table 7. Summarised results for Al 384 alloy piston.

| Parameters | Maximum | Minimum |
|---|---|---|
| Total deformation | 0.26174 mm | 0.029088 mm |
| Equivalent Elastic Strain | 0.0040517 | $4.5059 \times 10^{-6}$ |
| Equivalent Von Mises Stresss | 41.17 MPa | 0.028513 MPa |
| Maximum Shear Stress | 20.927 MPa | 0.015582 MPa |
| Factor of Safety | 15 | 1 |

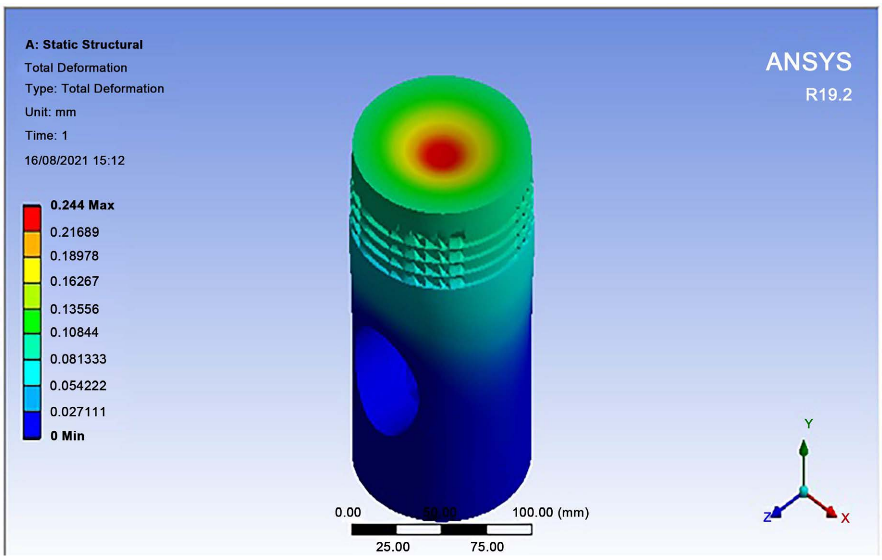


Figure 13. Total deformation of Al390 piston.

Figure 15 shows the induced shear stress of the Al 390 alloy piston. It is observed that the maximum shear stress of 13.956 MPa occurred at the centre of the piston crown. The characteristics of the induced shear stress are consistent

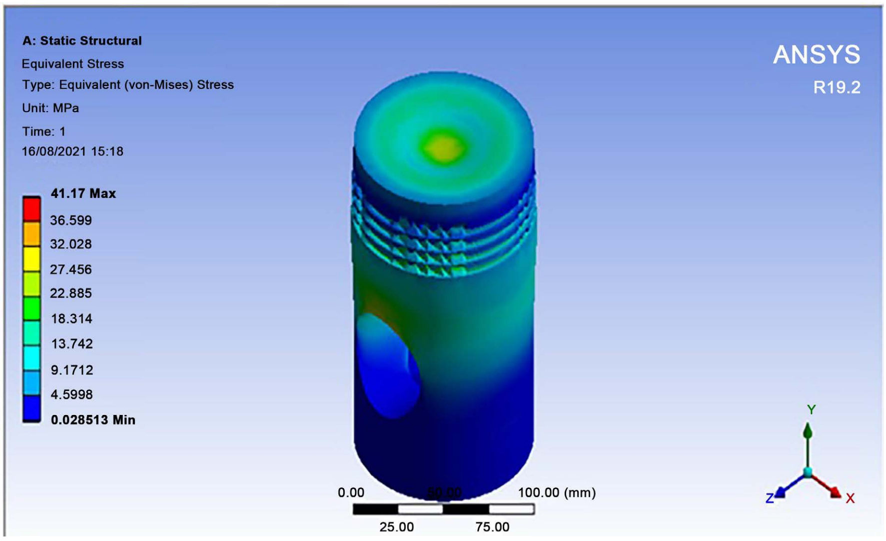


**Figure 14.** Von mises stress for Al 390 piston.

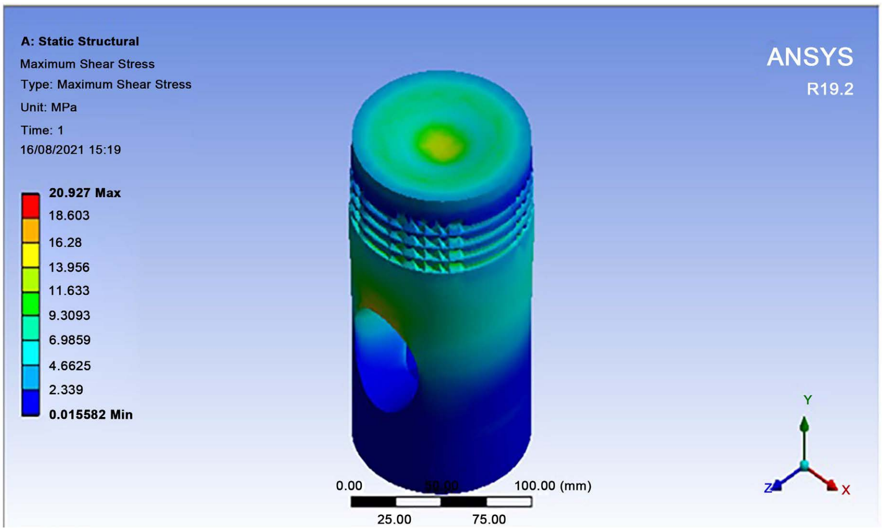


**Figure 15.** Maximum shear stress for Al 390 piston.

with the normal direct stress. It is also observed that, the maximum induced shear stress of 20.927 MPa is far lower than the yield shear stress of Al 390 alloy material which has a magnitude of 190 MPa. It is therefore predicted that the piston made with Al 390 can withstand the shear load produced by the burnt gases in the engine cylinders.

Figure 16 shows the Ansys generated factor of safety for Al 390 alloy piston model which has a maximum and minimun factor of safety range magnitudes of 15 and 1 respectively. The factor of safety was generally observed to be maximum at most parts of Al 390 alloy piston. The centre of the piston crown was observed to have a low factor of safety value of 6.0237 than the other parts. The model is therefore considered to be very safe.

Table 8 shows the summarised results for Al 390 alloy piston when the static structural analysis was conducted in Ansys software.

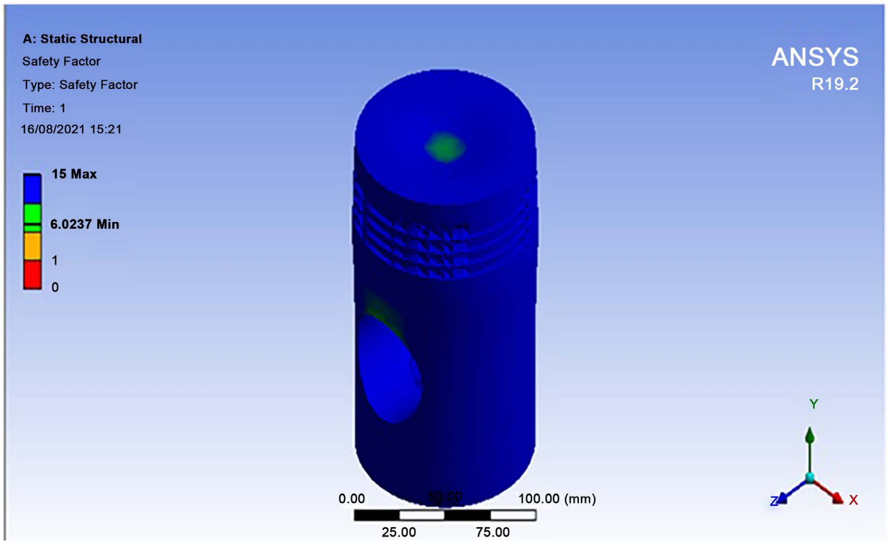


Figure 16. Factor of safety of Al 390 alloy piston.

Table 8. Summarised results for Al 384 alloy piston.

| Parameters | Maximum | Minimum |
|---|---|---|
| Total deformation | 0.244 mm | 0.027111 mm |
| Equivalent Elastic Strain | 0.003777 | $4.200 \times 10^{-6}$ |
| Equivalent Von Mises Stresss | 41.17 MPa | 0.028513 MPa |
| Maximum Shear Stress | 20.927 MPa | 0.0155 MPa |
| Factor of Safety | 15 | 1 |

**d) Aluminium alloy 332 material results**

Figure 17 shows the total deformation of aluminium 332 piston alloy. It is observed that, the maximum deformation of 0.039441 mm occurred at the centre of the aluminium 332 alloy piston crown. From the centre, averagely a deformation of 0.017529 mm was observed to spread evenly throughout the piston crown, the first land up to the piston bosses. It was again observed that, below the piston bosses, there was minimum deformation of 0.0043823 mm towards the end of the piston.

The maximum equivalent (Von Mises) stress induced in the Al 332 piston has a maximum magnitude of 41.17 MPa for the given loading condition as shown in Figure 18. The yield strength of Al 332 is 190 MPa. The stress distribution in the Al 332 piston was lower at the first piston land and below the piston bosses. It was observed that the maximum stress of 22.885 MPa occurred at the centre of the piston crown and below the second piston groove to the piston bosses. The induced Von Mises stress is far lower compared to the compressive yield strength of the Al 332. The model therefore can withstand the given loading condition.

Figure 19 shows the induced shear stress of the Al 332 piston. It was observed that the maximum shear stress of 13.956 MPa occurred at the centre of the

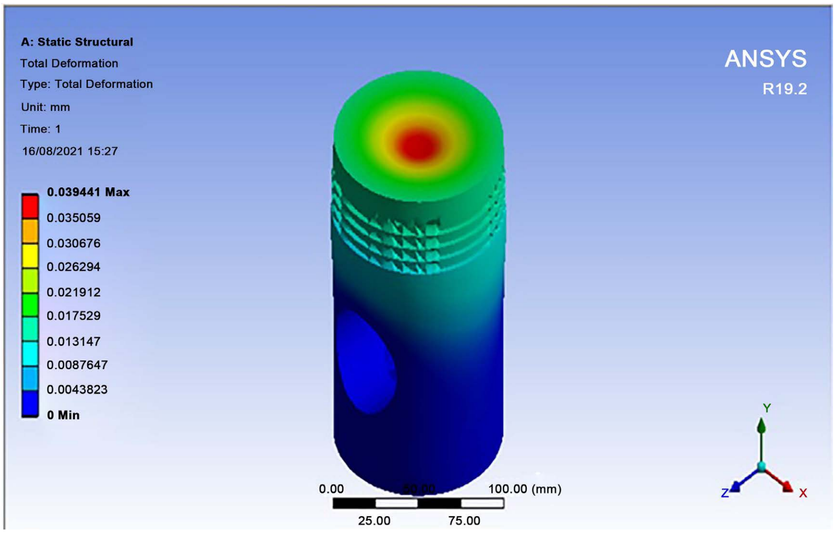


**Figure 17.** Total deformation for Al 332 piston.

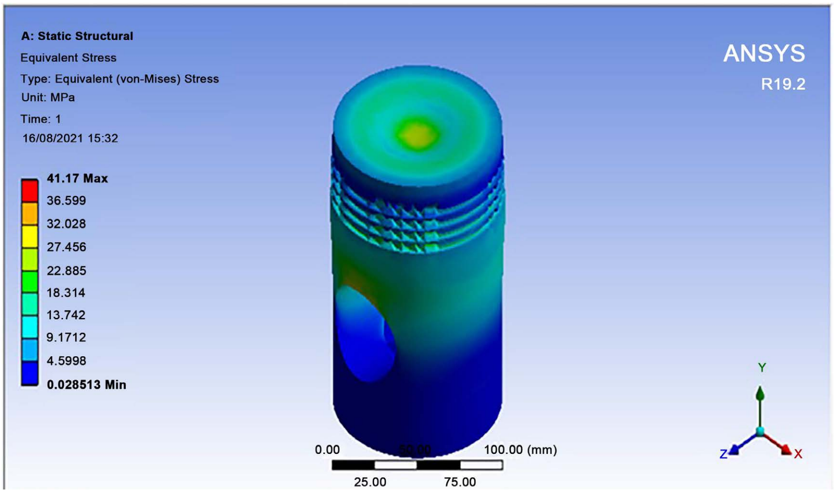


**Figure 18.** Von Mises Stress for Al 332 piston.

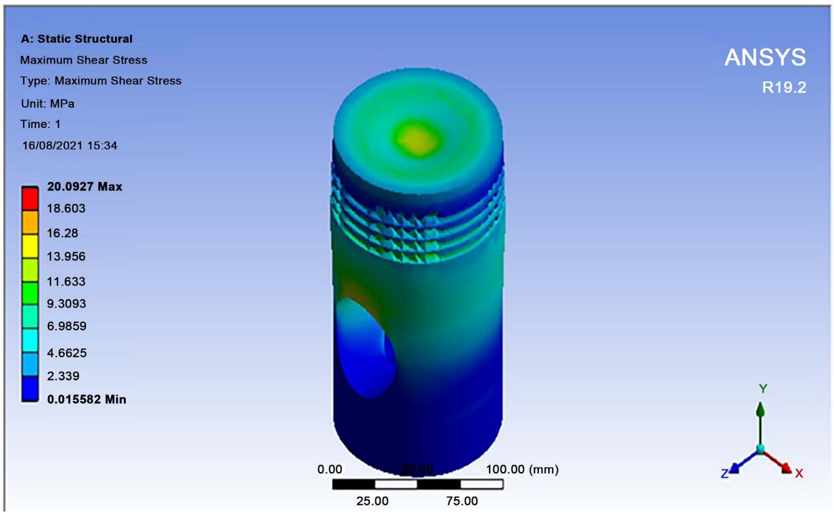


**Figure 19.** Maximum shear stress for Al 332 piston.

piston crown. The characteristics of the induced shear stress are consistent with the normal direct stress. It was observed that, the maximum induced shear stress of 20.927 MPa is far lower than the yield shear stress of Al 332,190 MPa which is of magnitude 190 MPa. It is therefore predicted that the piston made with Al 332 can withstand the shear load that the burnt gases produced in the engine cylinders.

The Ansys generated factor of safety for Al 332 alloy piston madel has a maximum and minimun factor of safety range magnitudes of 15 and 1 respectively as shown in **Figure 20**. The factor of safety was generally observed to be maximum at most parts of Al 332 alloy piston. The centre of the piston crown was observed to have a low factor of safety than the other parts. The model is therefore very safe.

**Table 9** shows the summarised results for Al 332 alloy piston when the static structural analysis was conducted in Ansys software.

## 4.2. Comparison of Static Structural Results

**Figure 21** shows the comparison of the total deformation results of the static structural analysis of the piston of the four different materials, namely: aluminium 332 alloy, aluminium 390 alloy, aluminium 413 alloy and aluminium 384 alloy. When the static structural results of the total deformation was compared as presented in **Figure 21** shows that, the total deformation of aluminium 332 alloy piston was 0.039441 mm representing 4.15%, aluminium 390 alloy piston yielded a total deformation of 0.244 mm representing 25.67%, aluminium 413 alloy piston yielded a total deformation of 0.40552 mm representing 42.65%, and aluminium 384 alloy piston yielded a total deformation of 0.26174 mm also representing 27.53%. It was observed that, aluminium 332 alloy piston deformed less compared to the deformations of aluminium 390 alloy piston, aluminium 384 alloy piston and aluminium 413 alloy piston. In terms of deformation, the implementing material which is aluminium 413 alloy deformed more than all the materials. The material with superior properties to resist deformation among the four selected materials is aluminium 332 alloy. The deformations suffered by all the four materials for the piston were observed not to be significant enough to affect the smooth operation of the piston in practice, hence the pistons made of aluminium 332 alloy, aluminium alloy 390, aluminium alloy 413 and aluminium alloy 384 can be described to be fit for purpose.

**Figure 22** was used to compare the results of the equivalent Von Mises stresses of the piston of the four different materials, namely: aluminium 390 alloy, aluminium 332 alloy, aluminium 413 alloy and aluminium 384 alloy. One of the most important parameters for this study is the Von Mises stress. This is one of the parameters that was used to determine whether the piston will either fail or not when compared with the yield strengths of the materials. When the induced equivalent (Von Mises) stress is equal or more than the yield strength of the material, then the component made of that material cannot withstand the loading condition, hence the design will fail. But when the Von Mises stresses

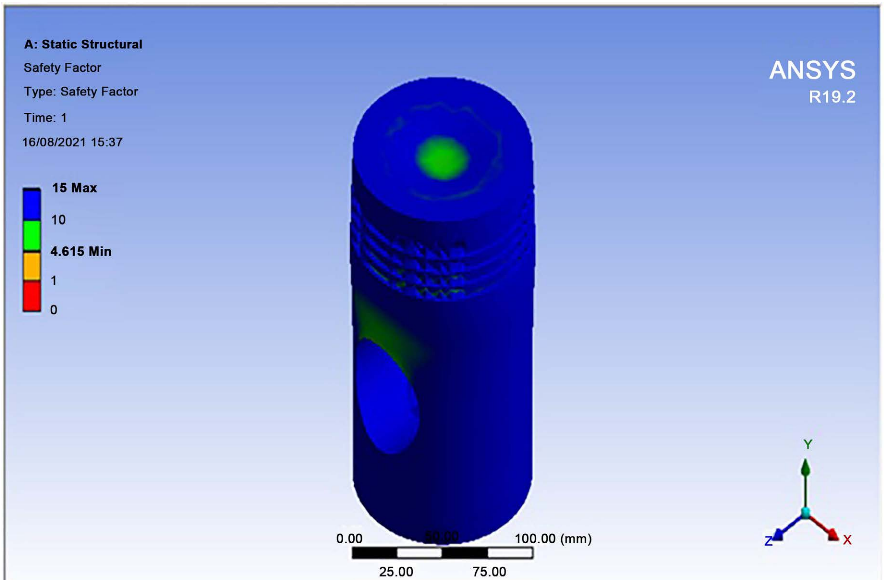


Figure 20. Factor of safety for Al 332 piston.

Table 9. Summarised results for Al 332 alloy piston.

| Parameters | Maximum | Minimum |
|---|---|---|
| Total deformation | 0.039441mm | 0.0043823 mm |
| Equivalent Elastic Strain | 0.0061052 | $6.789 \times 10^{-7}$ |
| Equivalent Von Mises Stresss | 41.17 MPa | 0.028513 MPa |
| Maximum Shear Stress | 20.927 MPa | 0.015582 MPa |
| Factor of Safety | 15 | 1 |

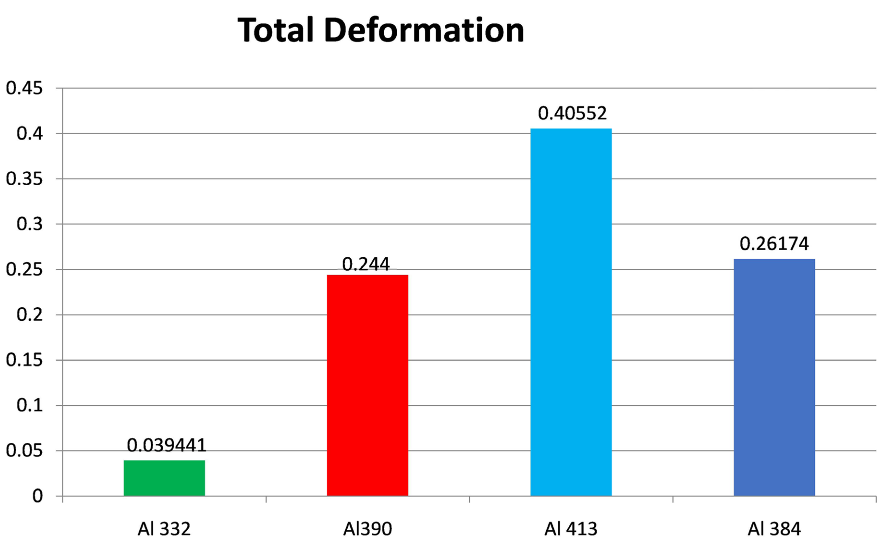


Figure 21. Comparison of total deformation of the four different materials.

induced in the piston made of the four different materials were compared as shown in Figure 22, the results shows that the induced stress yielded in the aluminium 390 alloy piston was 41.17 MPa representing 25%. It was very interesting

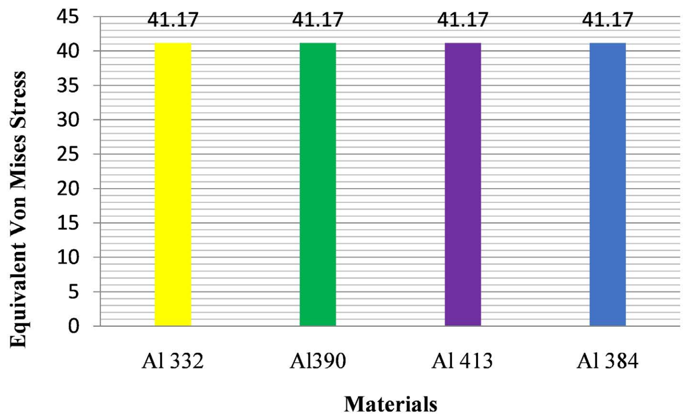


**Figure 22.** Comparison of equivalent von misese stress.

to note that, the Von Mises stresses induced in the pistons of all the four selected materials were the same. The induced Von Mises stresses in the pistons of the four different materials were observed to be far lower than the yield strengths of all the materials. Hence, all the selected materials including the implementing material have equal properties to withstand the maximum gas load.

When the maximum shear stresses induced in the pistons made of the four different materials, namely, aluminium 390 alloy, aluminium 332 alloy, aluminium 413 alloy and aluminium 384 alloy were compared using pie chart **Figure 23** shows that, the induced maximum shear stress in all the four different materials yielded the same value of 20.927 MPa. The induced maximum shear stresses were observed to be far lower than the shear strengths of aluminium390 alloy, aluminium 332 alloy, aluminium 413 alloy and aluminium 384 alloy which have shear strengths of 200 MPa, 190 MPa, 170 MPa and 200 MPa respectively. The comparison shows that, all the materials have equal qualities and properties to withstand maximum shear stress.

**Table 10** shows the comparison of the factor of safety values of all the four materials, namely: aluminium 332 alloys, aluminium 390 alloy, aluminium 413 alloy and aluminium 384 alloy. **Table 10** revealed that, all the pistons made of the four different materials have the same maximum factor of safety values of 15. Hence, the pistons made of the four different materials have good factor of safety ranges to be able to carry the intended load.

## 4.3. Thermal Analyses Results

The thermal analysis of the piston made with the four different materials was done in Ansys software version R19.2. The piston boss was constraint (fixed) and a given operating temperature of 90˚C was applied at the piston crown of the piston. Thermal conductivities of the materials were considered by way of measuring the heat flux induced in the pistons made with the four different materials. This is because pistons are designed for the maximum heat conductivity acting on the piston head. The parameters that were considered during the thermal analyses were: temperature, total heat flux, and directional heat flux, of the four (4) different materials assigned to the model piston.

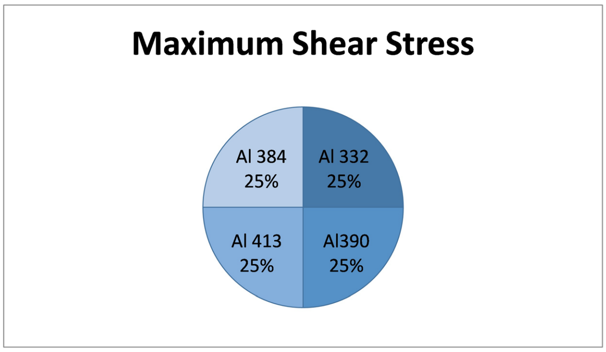


**Figure 23.** Comparison of maximum shear stress.

**Table 10.** Comparison of factor of safety of all four materials.

| Materials | Safety Factor | |
|---|---|---|
| | Maximum | Minimum |
| Aluminium 332 Alloy | 15.0000 | 1.0000 |
| Aluminium 390 Alloy | 15.0000 | 2.1819 |
| Aluminium 413 Alloy | 15.0000 | 1.0000 |
| Aluminium 384 Alloy | 15.0000 | 1.0000 |

**a) Aluminium 413**

**Figure 24** shows the effects of the operating temperature on the aluminium 413 alloy piston. It was observed that, the temperature distribution throughout the piston has been impressive. The piston made of aluminium 413 alloy was able to withstand the imposed temperature of 90˚C in the combustion chamber without any effect on the piston. Hence, the aluminium 413 alloy which is the implementing material will be able to withstand the temperature imposed. This shows that Al 413 material is suitable for the purpose.

Heat flux is the rate of thermal energy flow per unit surface area of heat transfer surface such as heat in an internal combustion engine. Heat flux is the main parameter used in calculating heat transfer. **Figure 25** shows the total heat flux of aluminium 413 alloy piston when subjected under a temperature of 90˚C. It was observed that, the maximum total heat flux of about $4.705 \times 10^{-13}$ W/mm$^2$ occurred at where the piston rings are located. Some small patches of the maximum heat flux were observed to have occurred at the first piston land and the crown. The maximum total heat flux of $8.4684 \times 10^{-13}$ W/mm$^2$ was induced in the aluminium 413 alloy piston. The thermal conductivity of Al 413 alloy material is 121 W/m.K. The induced heat flux is lower compared to the thermal conductivity of the aluminium 413 alloy material. Hence, the implementing material which is aluminium 413 alloy will be able to withstand the heat generated in engine.

Heat flux has both directionand magnitude, and so it is a vector quantity. **Figure 26** shows the directional heat flux of aluminium 413 alloy material. It was observed that, the induced maximum directional heat flux in the aluminium 413

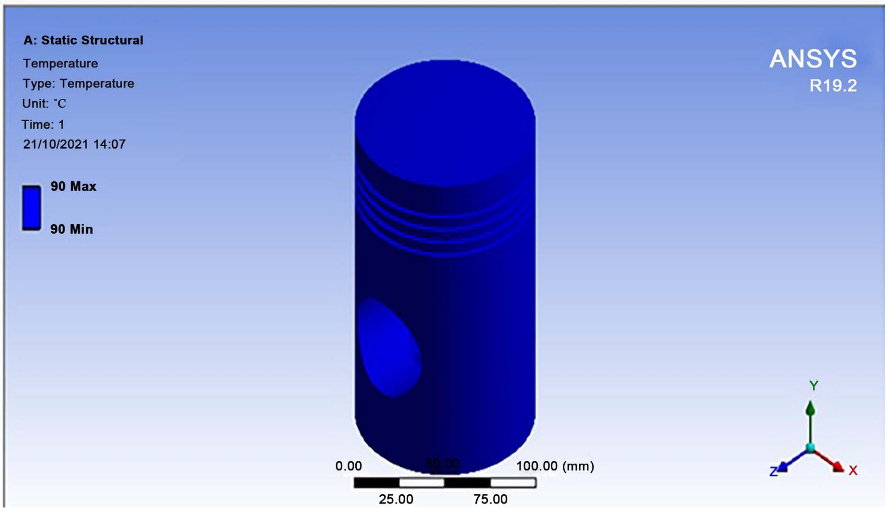


**Figure 24.** Temperature distribution in Al 413.

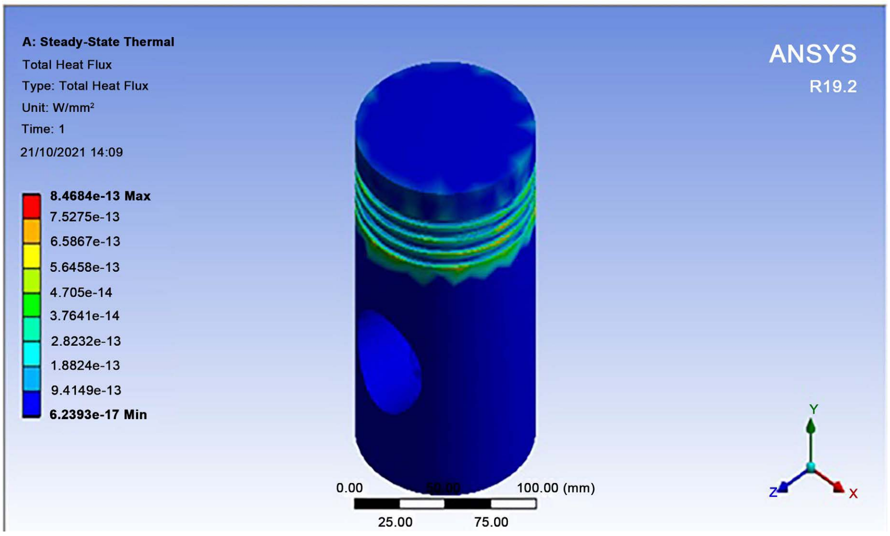


**Figure 25.** Total heat flux in Al 413 piston.

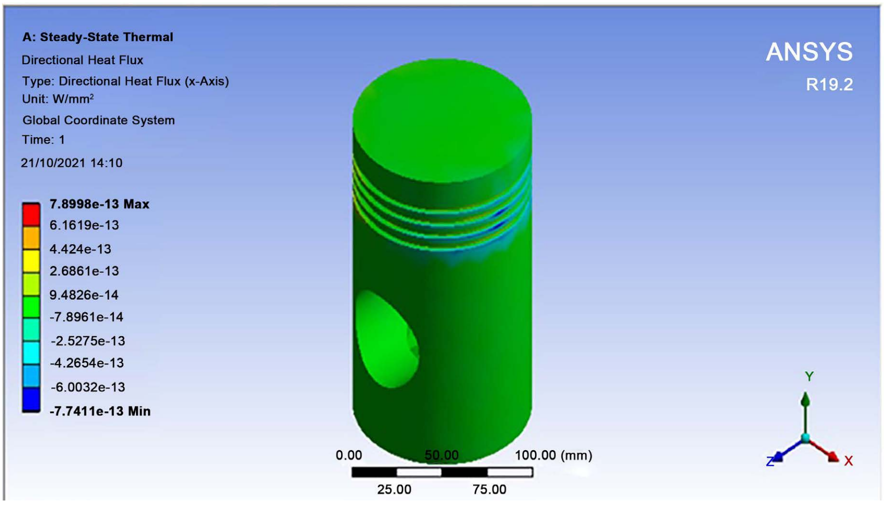


**Figure 26.** Directional heat flux of Al 413.

piston was $7.8998 \times 10^{-13}$ W/mm$^2$. The minimum induced directional heat flux was observed to have occurred at the piston grooves. Generally, it was observed that the maximum directional heat flux of about $-7.7411 \times 10^{-13}$ W/mm$^2$ occurred at the top of piston head uniformly to the bottom of the piston skirt. The maximum induced directional heat flux was observed to be far lower compared to the thermal conductivity of 121 W/m·K of the Al 413 material. The model is therefore considered tobe fit for purpose since it can withstand the given heat condition.

**b) Aluminium 384**

The thermal analysis was conducted by subjecting the pistons made of the four different materials under a temperature of 90˚C. Figure 27 shows the effects of the operating temperature on the aluminium 384 alloy piston. It was observed that, the temperature distribution throughout the piston has been impressive. The piston made of aluminium 384 alloy was able to withstand the imposed temperature of 90˚C in the combustion chamber without any effect on the piston. Hence, the aluminium 384 alloy will be able to withstand the temperature imposed on the piston. This shows that Al 384 material will be suitable for the intended purpose.

Figure 28 shows the total heat flux of aluminium 384 alloy piston when subjected under a temperature of 90˚C. It was observed that, the maximum total heat flux of $6.6937 \times 10^{-13}$ W/mm$^2$ occurred at where the piston rings are located. Some small patches of maximum heat flux were observed to have occurred at the first piston land and the crown. The thermal conductivity of Al 384 alloy material is 96.2 W/m·K. The induced heat flux is far lower compared to the thermal conductivity of the aluminium 384 alloy material. Hence, the piston made of aluminium 384 alloy will be able to withstand the heat generated in the engine.

Figure 29 shows the directional heat flux in aluminium 384 alloy piston material. It was observed that, the induced maximum directional heat flux in the aluminium 384 piston was $7.5602 \times 10^{-14}$ W/mm$^2$. The minimum induced directional heat flux of $-4.7743 \times 10^{-13}$ W/mm$^2$ was observed to have occurred around the piston grooves. Generally, it was observed that the maximum directional heat flux of about $7.5602 \times 10^{-14}$ W/mm$^2$ occurred at the top of piston head and distributed uniformly to the bottom of the piston skirt. The maximum induced directional heat flux was observed to be far lower compared to the thermal conductivity of 96.2 W/m·K of the Al 384 material. The model can therefore befit for purpose since it can withstand the given heat condition.

**c) Aluminium 390**

The thermal analysis was conducted by subjecting the pistons made of the four different materials under a temperature of 90˚C. Figure 30 shows the effects of the operating temperature on the aluminium 390 alloy piston. It was observed that, the temperature distribution throughout the piston has been impressive. The piston made of aluminium 390 alloy was able to withstand the imposed temperature of 90˚C in the combustion chamber without any effect on the piston. Hence, the aluminium 390 alloy material will be able to withstand the

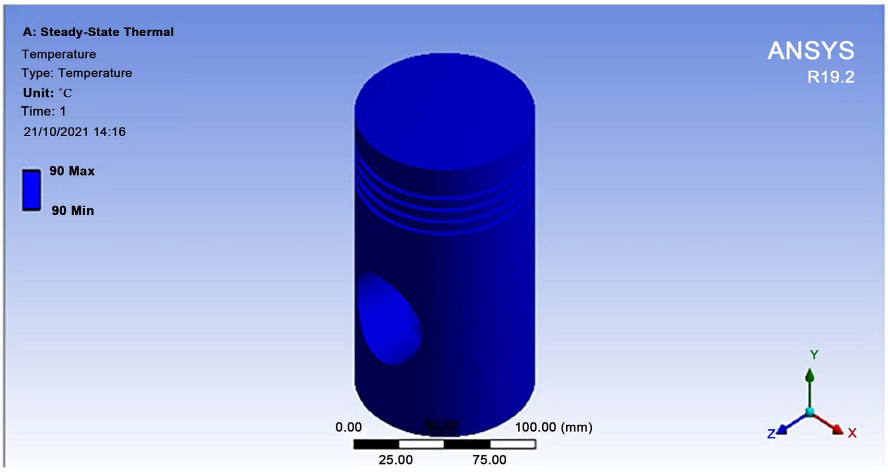


Figure 27. Temperature induced in Al 384 piston.

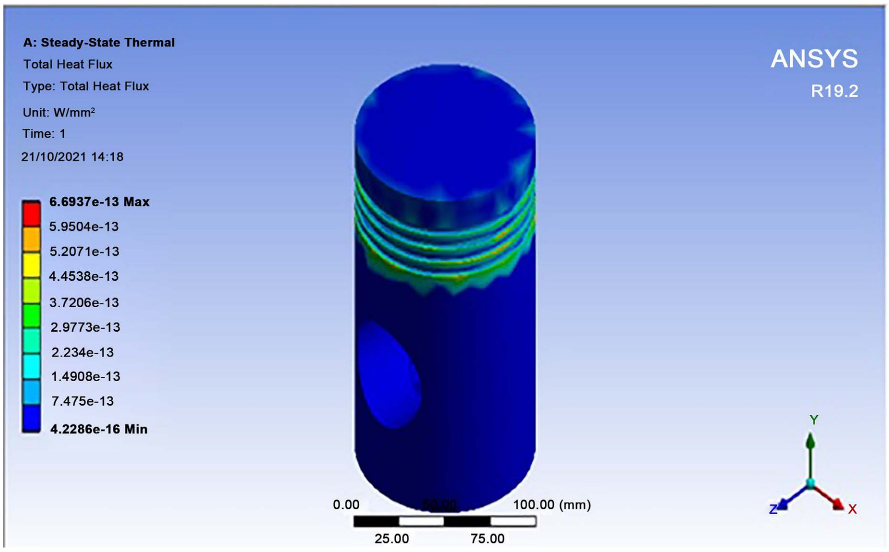


Figure 28. Total heat flux in Al 384 piston.

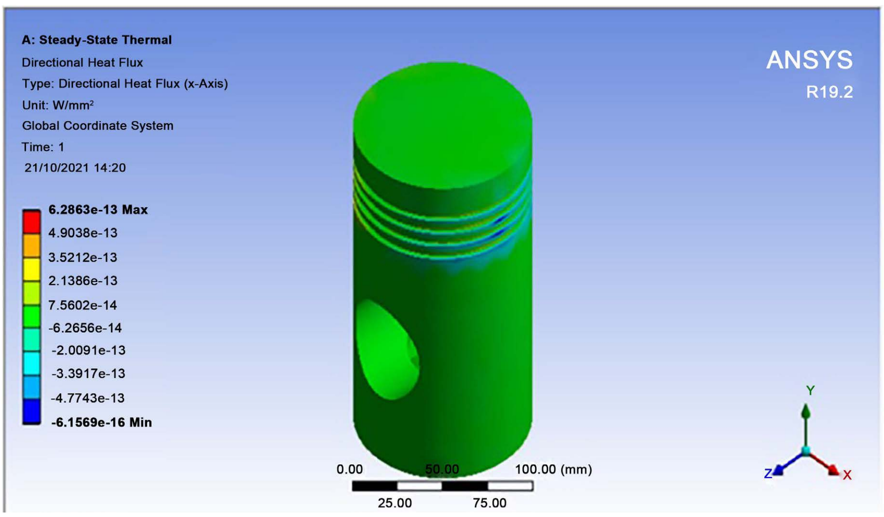


Figure 29. Directional heat flux in Al 384 piston.

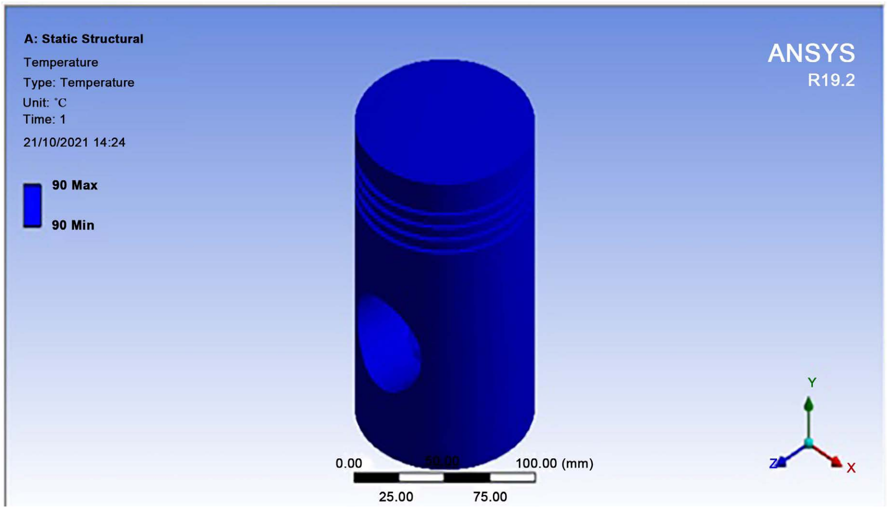


**Figure 30.** Temperature in Al 390 piston.

temperature imposed. This shows that Al 390 material will be suitable for the intended purpose.

**Figure 31** shows the total heat flux in aluminium 390 alloy piston when subjected under a temperature of 90˚C. It was observed that, the maximum total heat flux of about $9.4602 \times 10^{-13}$ W/mm$^2$ occurred at where the piston rings are located. Some small patches of the maximum heat flux were observed to have occurred at the first piston land and the crown. The thermal conductivity of Al 390 alloy material is 134 W/m·K. The induced heat flux is far lower compared to the thermal conductivity of the aluminium 390 alloy material. Hence, the piston made with aluminium 390 alloy will be able to withstand the heat generated in the engine.

**Figure 32** shows the directional heat flux of aluminium 390 alloy material. It was observed that, the induced maximum directional heat flux in the aluminium 390 piston was $8.7528 \times 10^{-13}$ W/mm$^2$. The minimum induced directional heat flux was observed to have occurred at the piston grooves. Generally, it was observed that the maximum directional heat flux of about $-8.7397 \times 10^{-13}$ W/mm$^2$ occurred from the top of the piston head and uniformly distributed to the bottom of the piston skirt. The maximum induced directional heat flux was observed to be far lower compared to the thermal conductivity of 134 W/m·K of the Al 390 material. The model can therefore be fit for purpose since it can withstand the given heat condition.

**d) Aluminium 332**

The thermal analysis was conducted by subjecting the pistons made of the four different materials under a temperature of 90˚C. **Figure 33** shows the effects of the operating temperature on the aluminium 332 alloy piston. It was observed that, the temperature distribution throughout the piston has been remarkable. The piston made of aluminium 413 alloy was able to withstand the imposed temperature of 90˚C in the combustion chamber without any effect on the piston. Hence, the aluminium 332 alloy piston will be able to withstand the

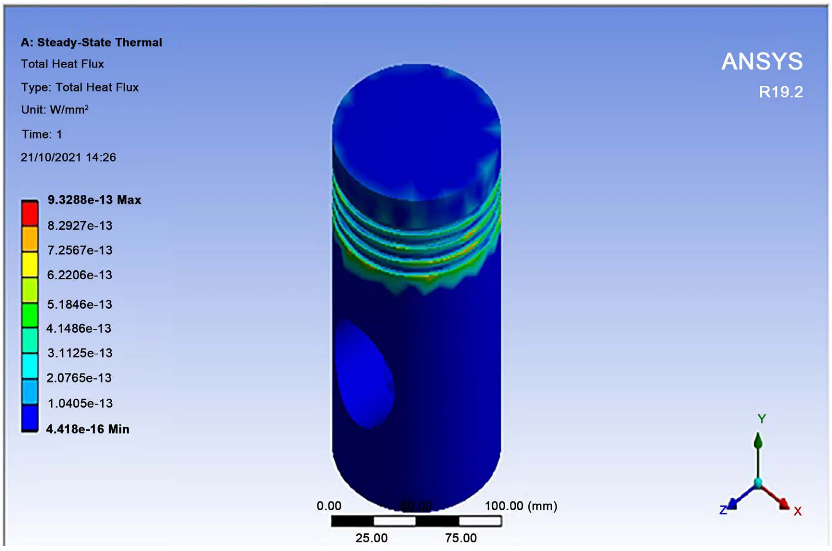


**Figure 31.** Total heat flux in Al 390 piston.

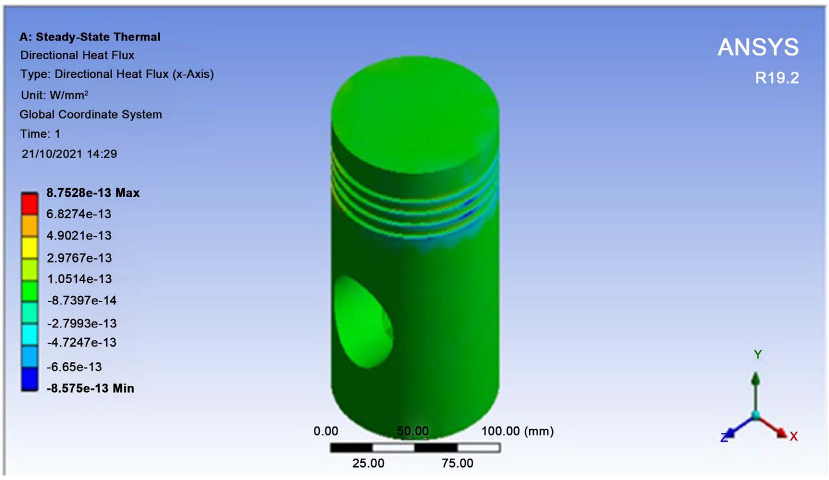


**Figure 32.** Directional heat flux in Al 390.

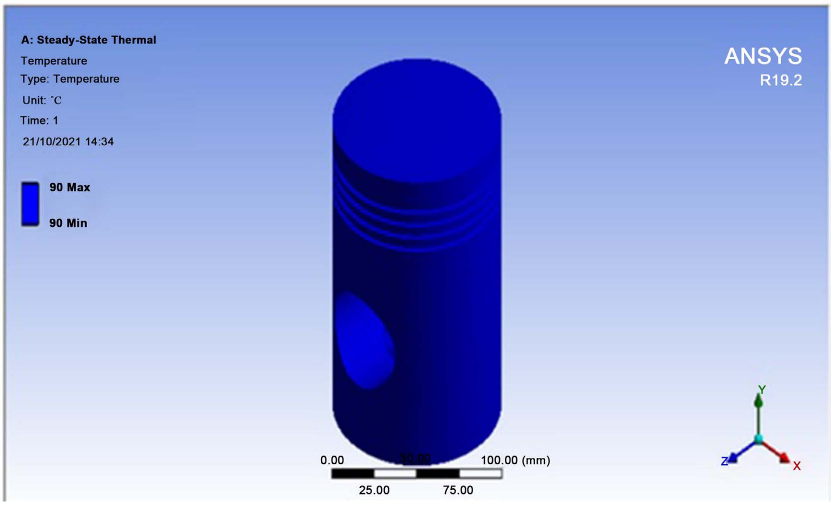


**Figure 33.** Temperature in Al 332 piston.

temperature imposed. This shows that Al 332 material will be suitable for the intended purpose.

Figure 34 shows the total heat flux of aluminium 332 alloy piston when subjected under a temperature of 90˚C. It was observed that, the maximum total heat flux of $6.9816 \times 10^{-13}$ W/mm$^2$ was induced in the aluminium 332 alloy piston and it occurred at where the piston rings are located. Some small patches of the maximum heat flux were observed to have occurred at the first piston land and the crown. The thermal conductivity of Al 332 alloy material is 100 W/m·K. it was observed that, the induced heat flux is far lower compared to the thermal conductivity of the aluminium 332 alloy material. Hence, the piston made of aluminium 332 alloy will be able to withstand the heat generated in engine.

Figure 35 shows the directional heat flux of aluminium 332 alloy material. It was observed that, the induced maximum directional heat flux in the aluminium 332 piston was $6.538 \times 10^{-13}$ W/mm$^2$. The minimum induced directional heat flux was observed to have occurred at the piston grooves. Generally, it was observed that averagely, a directional heat flux of $7.8962 \times 10^{-14}$ W/mm$^2$ was induced in the aluminium 332 alloy piston and it occurred from the top of piston head and distributed uniformly to the bottom of the piston skirt. The maximum induced directional heat flux was observed to be far lower compared to the thermal conductivity of 100 W/m·K of the Al 332 material. The model piston can therefore be fit for purpose since it can withstand the given heat condition.

### Comparison of Thermal Analysis Results

Figure 36 shows the comparison of the temperature that was imposed on the pistons made with aluminium 390 alloy, aluminium 332 alloy, aluminium 384 alloys and aluminium 413 alloy. It was evident from Figure 36 that, the same operating temperature of 90˚C was applied to all the pistons made with the four different materials. The results obtained shows that, the piston made of all the selected aluminium alloys was able to withstand the imposed temperature of 90˚C in the combustion chamber without any effect on the pistons

Figure 37 shows the comparison of total heat flux induced in the pistons made with the four different materials. It was observed that, aluminium 390 alloy piston yielded $9.33 \times 10^{-13}$ W/mm$^2$, aluminium 332 alloy piston yielded total heat flux of $6.98 \times 10^{-13}$ W/mm$^2$, aluminium 384 alloy piston yielded to a total heat flux of $6.69 \times 10^{-13}$ W/mm$^2$ and aluminium 413 alloy piston yielded to a total heat flux of $8.47 \times 10^{-13}$ W/mm$^2$. When compared it was found from the above data that, aluminium 390 alloy piston yielded the highest total heat flux. Meaning the aluminium 390 alloy piston material has the tendancy to dissipate heat more faster than the remaining three materials. The implementing material which is aluminium 413 alloy was also observed to have yielded the second highest heat flux. Impliedly, the implementing material also have superior properties to dissipate heat more faster than aluminium 332 alloy piston and aluminium 384 alloy pistons. When the total heat flux induced into the pistons made with the four different materials were compared, it was observed that the

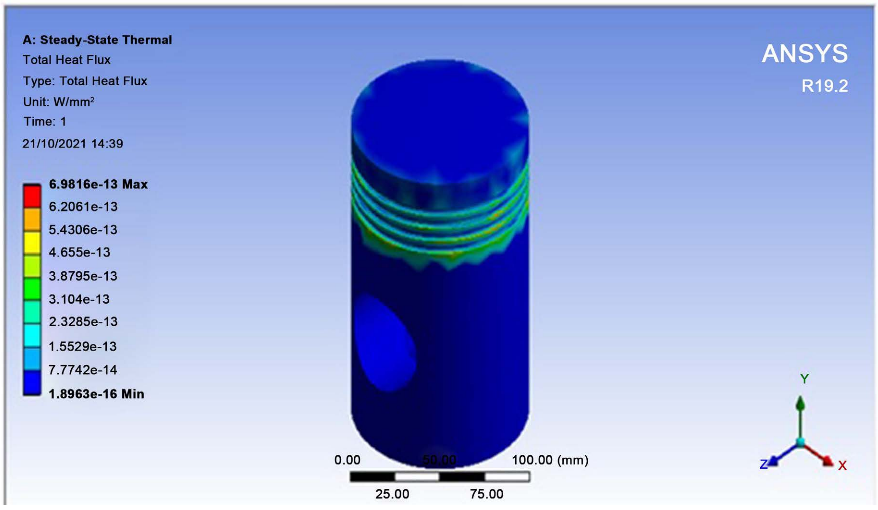


**Figure 34.** Total heat flux in Al 332 piston.

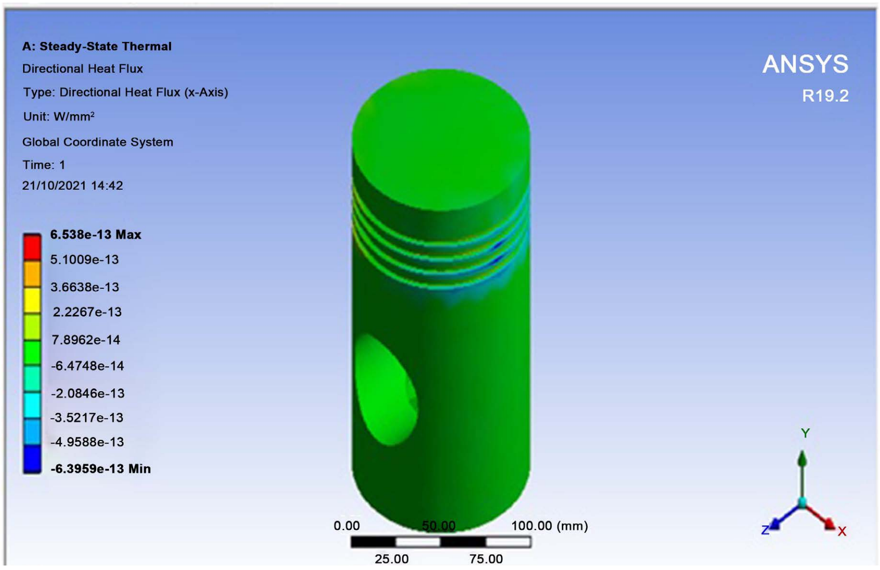


**Figure 35.** Directional heat flux in Al 332.

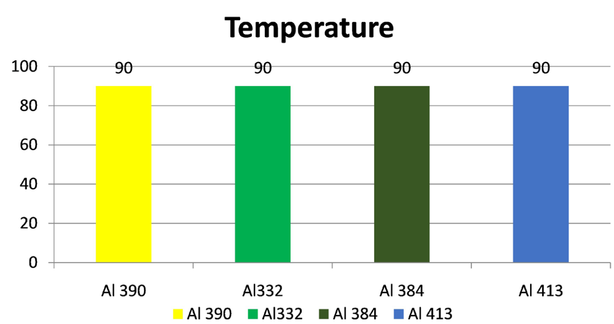


**Figure 36.** Comparison of temperature.

thermal conductivities of the materials were far higher than the induced total heat flux. Hence, all the pistons made with the four different materials will be able to withstand the operating temperature in engine cylinders.

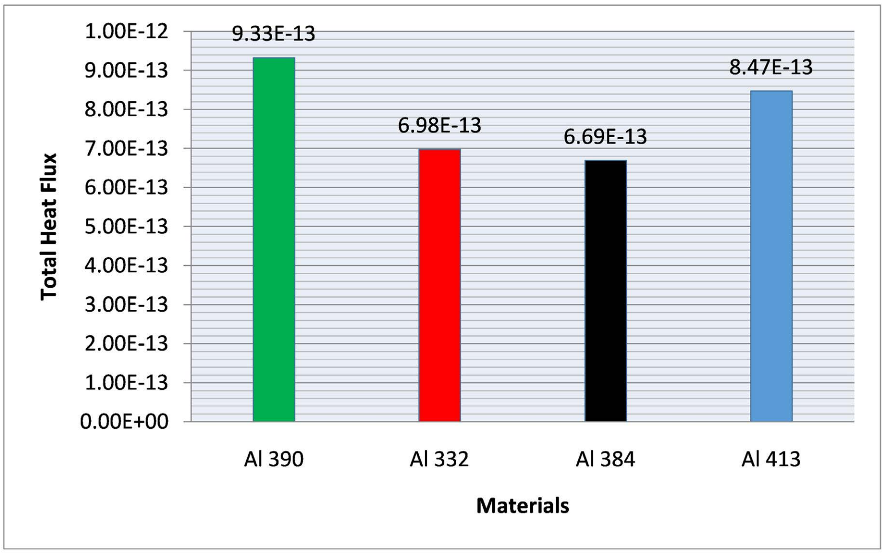


**Figure 37.** Comparison of total heat flux.

**Figure 38** shows the comparison of directional heat flux of all the four different piston materials, namely: aluminium 332 alloy, aluminium 390 alloy, aluminium 384 alloy and aluminium 413 alloy. It was observed that, aluminium 332 alloy piston yielded a directional heat flux of $6.538 \times 10^{-13}$ W/mm$^2$ representing 22%, aluminium 390 alloy piston yielded a directional heat flux of $8.7528 \times 10^{-13}$ W/mm$^2$ representing 30%, aluminium 384 alloy piston yielded a directional heat flux of $6.2863 \times 10^{-13}$ W/mm$^2$ representing 21% and aluminium 413 alloy piston yielded a directional heat flux of $7.8998 \times 10^{-13}$ W/mm$^2$ representing 27%. The results show that, aluminium 390 alloy piston yielded the highest directional heat flux. The result of the directional heat flux is consistent with the results of the total heat flux.

## 5. Conclusion

This study considered two methods of analysis which were static structural, ang thermal analysis. The parameters that were considered under the static structural analysis were: total deformation, equivalent Von Mises stress, maximum shear stress, and the factor of safety of the four pistons made with aluminium 332 alloy, aluminium 390 alloy, aluminium 384 alloy and aluminium 413 alloy. The piston of an internal combustion engines comes under both compressive and tensile loads, but the compressive loads are much greater than the tensile loads, therefore the piston was designed for the maximum compressive gas load. The main objective of this project was to determine the possibility of using aluminium 413 alloy material to design and manufacture piston for Toyota HiAceminibus. The piston was modelled using Autodesk inventor 2017 software using the dimension obtained from actual design calculations. The dimensioning of the pistons was obtained through systematic and rigorous calculations based on theoretically empirical formulas for pistons design. The pistons in the Ansys were subjected to a compressive load of 56124.6 N. Then Finite Element Analysis technique was

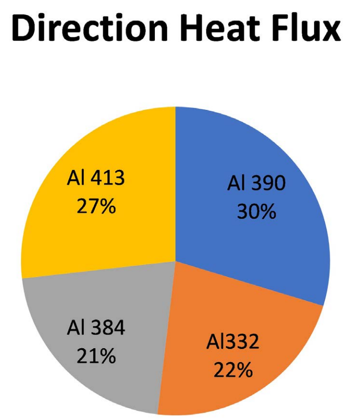


**Figure 38.** Comparison of directional heat flux.

used to determine the total deformation, equivalent Von Mises stress, maximum shear stress and factor of safety of the pistons of the four different materials and compared. The results of the analysis showed that, the stresses induced in the pistons made of the four different materials were far below the yield strengths of the selected aluminium alloy materials. Hence, it can be concluded that all the pistons of the four different materials can withstand the compressive gas loads that were imposed on them. The study can also conclude that, aluminium 332 alloy material has superior ability to resist deformation better than aluminium 390 alloy, aluminium 384 alloy and aluminium 413 alloy materials. The study can further conclude by stating that, all the four aluminium alloy materials has shown evidence enough to suggest that they have equal ability to withstand shear stress. The materials can also withstand the operating temperature in the engine cylinders since all the selected piston aluminium alloy materials have high thermal conductivity enough beyond the induced heat flux. Future studies into piston design and simulation should consider the following areas: finding out the best method of manufacturing that is suitable for aluminium alloy pistons production and also consider conducting further test by fixing the prototype pistons in a real engine to identify any issues with the design.

## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

## References

[1] Aikawa, T., Ishikawa, A. and Hara, S. (1999) Aluminum Alloy for Internal Combustion Piston and Alumium Alloy Piston Toyota All of Japan. U.S. Patent No. 5996471.

[2] Solanki, A.B., Patel, C.H. and Makawana, A.Y. (2014) Design Analysis and Optimisation of Hybrial Piton for 4 Strokes Single Cylinder 10HP (7.35kw) Diesel Engine. *International Journey of engineering Trends and Technology*, **16**, 258-262. https://doi.org/10.14445/22315381/IJETT-V16P251

[3] Attar, V.K. and Arora, H. (2016) Transient Thermal Analysis of Internal Combustion Engine Piston in Ansys Workbench by Finite Element Method. *International*

*Journal of Engineering Sciences and Research Technology*, **5**, 805-810.

[4] Santos, J.R., Voorwald, H.J., Gomes, J.F.S. and Meguid, S.A. (2017) Effect of Cadmium Coating on the Fatigue Strength of AISI 4140 Steel Used in Oil and Gas Company. *Proceedings of the 7th International Conference on Mechanics and Materials in Design*, 511-516.

[5] Ashkenazi, D. (2019) How Aluminum Changed the World: A Metallurgical Revolution through Technological and Cultural Perspectives. *Technological Forecasting and Social Change*, **143**, 101-113.

[6] Shinde, M.B., Sakore, T.V. and Katkam, V.D. (2016) Design Analysis of Piston for Four Stroke Single Cylinder Engine Using Ansys. *International Journal of Current Engineering and Technology*, 94-99.

[7] Kuppast, V.V., Kurbert, S.N., Umeshkumar, H.D. and Adarsh, B.C. (2013) International Thermal Analysis of Piston for the Influence on Secondary Motion. *International Journal of Engineers Research and Applications*, **3**, 1402-1407.

[8] Sheasby, P.G. and Pinner, R. (2001) The Surface Treatment and Finishing of Aluminium and Its Alloys. 6th Edition. https://www.asminternational.org/

[9] Singh, A.R. and Kumar, P. (2014) Design Analysis and Optimisation of These Aluminium Piston Alloys Using FEA. *International Journal of Engineering Research and Applications*, **4**, 94-102.

[10] Nawajish, M., Rizvi, I.A. and Kumar, A. (2018) Structural and Thermal Analysis of IC Engine Piston Using Different Materials. *International Journal of Advance Research in Science and Engineering*, **10**, 369-373.

[11] Kaushik, G.V.N. (2019) Thermal and Static Structural Analysis. *International Journal of Innovation Technology and Exploring Engineering*, **8**, 873-881.

[12] Zhao, S.G. (2012) Design the Piston of Internal Combustion Engine by Pro/Engineer. *Proceedings of the 2nd International Conference on Electronic & Mechanical Engineering and Information Technology* (*EMEIT* 2012). https://doi.org/10.2991/emeit.2012.479

[13] Jankowski, A. and Kowalski, M. (2017) Design of a New Alloy for Internal Combustion Engines Pistons. *Processing of 7th International Conference on Mechanics and Materials in Design Albunferia*, Portugal, June 2017, 607-618.

[14] Cioata, V.G., Nexa, K.I.V. and Ratiu, S.A. (2017) Mechanical and Thermal Analysis of the Internal Combustion Engine Piston Using Ansys. *IOP Conference Series: Materials Science and Engineering*, **163**, Article 012043. https://doi.org/10.1088/1757-899X/163/1/012043

[15] Adil, H., Gerguri, S., Durodola, J., Fellows, N., Bonatesta, F. and Audebert, F. (2019) Comparative Study and Evaluation of Two Different Finite Element Models for Piston Design. *Journal of Engineering Research and Application*, **9**, 23-37.

[16] Anamika, P.K. and Thakur, H.C. (2016) Thermal Analysis of Piston of IC Engine. *International Journal of Scientific and Engineering Research*, **7**, 374-381.

[17] Bhagat, A.R., Jibhakate, Y.M. and Kedar, C. (2012). Thermal Analysis Optimisation IC Engine Piston Using Finite Elements Method Research Gate. https://www.researchgate.net/