UNIVERSITY OF EDUCATION, WINNEBA

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DESIGN AND THERMAL ANALYSIS OF ALUMINIUM ALLOY PISTON USING FINITE ELEMENT METHOD

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DECLARATION

Student's Declaration

I, **David Offei Inusah** declare that this thesis, with exception of quotations and references contained in the published works which have all been identified and duly acknowledged, is entirely my original work, and it has not been submitted, either in part or whole, for another degree elsewhere.

SIGNATURE: ....

DATE: ....

Supervisor's Declaration

I hereby declare that the preparation and presentation of this work was supervised in accordance with guidelines for supervision of thesis as laid down by the University of Education, Winneba.

NAME OF SUPERVISOR: MR. CHIBUDO KENNETH NWORU

SIGNATURE:..

DATE: ....

DEDICATION

This thesis is dedicated to my heavenly father the mighty God and my spiritual father Alhaji Seidu Hardi for strengthening and guiding me through my tribulations. The work is also dedicated to my dearest mother the late Mary Takoro, my wife Afriyie Esther Offei, my children: Offei Patience Ayisha, Offei Jemimah Rukaya, Offei Justine Sumaila, Offei Eunice Amina and Offei Gloria Rahama.

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ABSTRACT

Piston is one of the most important moving components in an internal combustion engine. Because of its proximity to the burning flames in the engine, its material must be able to withstand the high temperature in the engine. There are some known materials which are used for piston design of which aluminium alloy is part. The known aluminium alloys for piston design have been classified into three main categories, namely: eutectic, hypereutectic and special eutectic aluminium alloys. The main objective of this research was to examine the suitability of an aluminium alloy which is not part of the three classifications to design a piston for an internal combustion engine. 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 piston of four different materials namely: Al 413 alloy, Al 384 alloy, Al 390 alloy and Al332 alloy to determine the total deformation, equivalent elastic strain, equivalent Von Mises stress, maximum principal stress and the safety factor. It was found 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. It was found that the thermal conductivitie 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. It was therefore concluded that, all the pistons made with the four different materials have equal qualities to withstand the fatigue stress induced in the pistons.

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background of the Study

According to Jadhav et al (2016), a piston is a component of reciprocating Internal Combustion engines. It is a moving component within a cylinder and it is made gas-tight by piston rings. In an engine, piston is used to transfer force from 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.

Based on the important role play by piston in an internal combustion engine, there is a need to optimize the design of 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 both good static and dynamic strength. Temperature resistance is likewise important, 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 advantageous, 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.

Pistons are exposed to severe changes in temperature at times. The transient heat stresses that arise place cyclical loads on the material that can sometimes exceed the elastic limit.

Materials must also be resistant to these stresses. Due to the motions and forces that occur at 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 are the lubrication conditions. They must be considered as a tribological system. Special surface treatments or coatings 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 in two groups 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 Solank et al (2014).

The main functions of a piston are: to receive the gas load and transmit it to the crankshaft through the connecting road, to disperse the heat of combustion from combustion chamber to the cylinder walls and to reciprocate in the cylinders as a gas tight plug causing suction, compression, expansion and exhaust strokes. The piston of an internal combustion engines have the following parts: Piston Crown which carries gas pressure, Skirt which acts as a bearing against the side thrust of the connecting rod, Piston pins are 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 piston and scrap off the surplus oil on the cylinder as shown in Figure 1.1

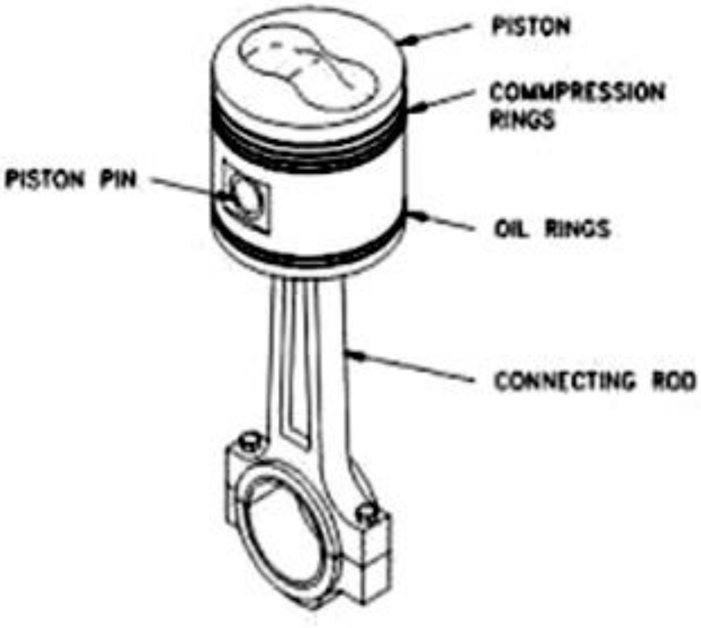


Figure 1.1 Parts of a Piston with a Connecting Rod
Source: K. Sathish Kumar (2016)

Siva Prasad (2016) opined that, piston reciproc0ates in the cylinder to complete the cyclic events and transmit gas pores to the crankshaft through the connecting rod. Piston is the most important component in an internal combustion engine. The working condition of a piston in an internal combustion engine is 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 mechanical energy. The piston ring is used to provide seal between the cylinder wall and the piston. It must be able to work with low friction, high explosive forces and high temperatures around 2000°C to 2800°C. The piston is to be strong but its weight should be less to prevent inertia forces due to reciprocating motion. In order to increase the efficiency of 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.

A recessed area located around the circumference of the piston is used to retain piston ring. These rings are expandable and split in type. Three such rings employed in a diesel engine are:

Compression ring, wiper 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 use of automobiles. The increased demand is due to improved performance and reduced cost of these components. This necessitates understanding of new technologies and quick absorption in the development of new products. As an important part in an engine, piston endures the cyclic gas pressure and inertia forces at work and this working condition may cause the fatigue damage of the piston (Vengatesvaran and Prithiviraj, 2018).

The internal combustion engine piston can be made from different kinds of materials including Alumimum alloy. In this study the piston was first modelled in Autodesk Inventor software and finally the piston is analysed in ANSYS software. The two steps involved in this study are:

1.2 Statement of Problem

Piston in an internal combustion engine is one of the most important components in the engine. It is one of the components of the engine that is directly expose to burning flame of the fuel. 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 aluminium alloys. This study intends to fish out the very type of aluminium alloy which is best suitable for manufacturing piston for improve weight reduction and cost. 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 are able to retain heat for long time, meaning they have slow heat dissipation rate. Internal combustion engines which uses pistons made with such materials are susceptible to overheating. Aluminium alloys have low densities meaning, they have less weight and also have high heat dissipation rate making them the preferred materials for modern automotive components. Hence, the decision to design and actualised a piston of internal combustion engine made with aluminium alloy. This research analysed areas of maximum stress concentration on the piston made with aluminium alloy for improve life.

1.3 Objectives of the Study

The objectives of the research are to:

1. model an internal combustion engine piston by using Autodesk Inventor software;
2. perform structural and thermal analysis of piston by using ANSYS software;

3. identify a suitable Aluminium alloy material for manufacturing of the piston under specified conditions;
4. Compare the performance of three Aluminium alloys and Al 413 alloy pistons under structural and thermal analysis process;

1.4 Significance of the Study

Aluminium alloys are preferred materials that can be used to design and manufacture automotive components to reduce weight and cost. Generally speaking, the Automotive industry if Africa has not begun well in the last decades. This is because, there was low skilled labour and lack of interest by African governments to develop the automotive sector to the benefit of their people. Every component of the automobile is imported depriving the economy from the needed taxes. The government of Ghana in recent past has initiated the drive to industrialised the automotive sector. The country has so far seen a significant growth in the automotive industry of late. The sector is now experiencing vehicle manufacturing giants coming into the country to set up assembling plants. This will not only boost the local economy but also create jobs for the teaming youth of the country. Government through the ministry of trade and industry has an objective in the Ghana Automotive policy which seeks to encourage local manufactures to go into automotive component manufacturing to supply the local Automotive assembly.

This study is significant because it seeks to contribute towards governments' effort to developing the automotive industry in Ghana. This work explores the possibility of using local materials such as aluminium alloys to design and manufacture a piston for an internal combustion engine for the local automotive industry in Ghana.

1.5 Limitations of the Study

The common materials that are used to manufacture pistons are steel and its alloys and cast irons. The acceptability of aluminium alloy in the automotive industry as an alternative material to design and manufacture a piston of an internal combustion engine is not in doubt but the challenge is the very aluminium alloy that is most suitable for this assignment is still blur.

Furthermore, the best method that can be used to design and manufacture a piston made with aluminium alloy is not yet clear. Traditionally, Casting is the best manufacturing method for manufacturing pistons.

Finally, the manufacturing processes involve in piston manufacturing is laborious and also the appropriate technology to use to ensure good and accurate finishing is a challenge to this research.

1.6 Delimitations of the Study

In designing and manufacturing internal combustion engine piston one is expected to have the following components such as compression and scraper rings, piston pin and piston clips. But considering the condition and inadequate equipment the researcher could not be able to add those components mention from the above.

1.7 Organisation of the Study

Chapter 1 gives a brief description of the thesis. The chapter has the following sub-headings, background of the study, problem statement of the study, objectives of the study, significance of the study and limitations of the study.

Chapter 2 covers the literature review related to the study. Chapter 3 presents the method for computation of overall piston manufacturing processes.

Chapter 4 presents the modelling data and analysis. Chapter 5 covers the discussion of data, findings from the study, and recommendations of the study and conclusions of the study.

CHAPTER TWO

LITERATURE REVIEW

2.0 Introduction

The piston is subjected to a complex state of loading and it is essential to check out or analyse the stress distribution, temperature distribution, heat transfer, thermal load, mechanical load in order to minimize the stress, minimize the thermal stress and different loads on working condition of the piston. Piston is the most important component in an internal combustion engine. The working condition of piston in an internal combustion engine is so worst. During the combustion stroke the fuel get ignited with the help of spark plug. Due to this, combustion of gases in the cylinder the thermal deformation and mechanical deformation causes piston cracks and tortuosity. Due to these factors, the piston has been the topic of research on various aspects such as production technology, materials, thermal and fatigue analysis.

2.1 Piston Materials

In their study into design and analysis of piston of internal combustion engine on different materials Prasad, et al (2016) opined that, generally pistons are made of aluminium alloy and cast iron. They were of the opinion that Aluminium alloy is more 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 in order to give proper cooling.

In his research in the design and analysis of internal combustion engine piston, by Raja (2016) established that the most commonly 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) in order 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 with 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.

Vigneswaran, et al (2018) in their study, they observed that aluminium alloy have its own advantages. They opined that aluminium alloy is not as stronger as cast iron and hence its piston would have to be design to have a thicker section. As a result of which the weight of the piston is 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 as a result of which 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 also, important drawback of using aluminium alloy pistons for cast iron cylinders is their unequal coefficient of expansion which causes engine slaps Vigneswaran et al (2018).

According to Amit et al (2014) in their research into design analysis 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 ron 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. The research conducted into design, analysis and optimisation of three aluminium piston alloys using FEA, Ajay et al (2014) considered three aluminium alloy materials for their design and the materials are namely: A2618, A4032 and Al-GHS 1300. It was concluded 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 (2018) in their study into structural and thermal analysis of internal combustion engine piston using different materials very important in piston design and manufacture. Their results indicates 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 point forty five. Hence it can be said that Al 7050 T7451 piston is safe. They finally concluded that Al 7050 T7451 is the suitable material for using in production of Piston.

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 comes in contact with combustion of fuel and high temperatures and Al-Si-C-12 must be used for piston skirt and rest of the piston Kaushik (2019).

2.2 Thermal Analysis on Internal Combustion Piston

The analysis of temperature effects on the internal combustion piston is crucial since the piston is directly expose to the combusting fuel in the cylinders.

In their study into transient thermal analysis of internal combustion engine piston in Ansys workbench by finite element method, Kumar and Himanshu (2016) concluded in their study that, the thermal stress reduction in the piston is very important factor which is responsible for the designing of piston crown or piston head. In their study, their main consideration was to optimize the piston with a reduction in piston weight. The material of the piston would be reduced, then the optimized result of the piston obtained. 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 vertically. The stress distribution on the piston mainly depends on the deformation of piston. Therefore, in order to reduce the stress concentration, the piston crown should have enough stiffness to reduce the deformation.

According to Shuoguo (2012), in his research into design of piston of an internal combustion engine, when Pistons are operating, they directly touch the high temperature gas and their transient temperature can reach more than 2500K 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. On the basis of these conditions, they set out to conduct thermal analysis on the piston. Through the analysis of the operation of the piston, it results indicates that, the piston temperature distribution was uneven. The maximum steady state temperature of the piston was 2500K 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 piston pin changes between 700K and 800K. 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 1500K. The highest temperature differs by 1800 K from the minimum temperature, which made the piston to develop larger thermal stress and thermal damage.

Pistons in internal combustion engines operate under permanent changes in their temperature and structural stresses distribution, due to changes in engine external loads and engine speed. The materials of the pistons must therefore have appropriate properties not only at the room temperature but also at the operating temperature of the pistons. The maximum temperature of the pistons, which are present on the piston crown, can reach 320-350 ºC. In the lower part of the piston, at the piston skirt, the temperature reaches a value of 100-140 ºC. Very important is the temperature in the region of the piston ring grooves, which is determined and limited by the properties of the lubricating oil, it should be a maximum of 230-240 ºC. If the temperature in this area exceeds this value, the piston must be internally cooled. Large temperature differences in the piston cause the occurrence of high thermal stresses, which superimpose to the mechanical stresses. Large differences in the piston stresses and temperature gradients cause deformation of the pistons, which should disappear after the withdrawal of stresses and temperature. The presence of pistons permanent dimensional changes, because of pistons permanent heating and cooling, known as hysteresis, is a serious problem that needs to be taken into account in the pistons design process. The value of these distortions, determine in fact the dimension of the clearance in a piston-cylinder liner assembly, which effect on piston seizure, lubricating oil consumption, exhaust gases blow by into the crankcase and harmful emissions, mainly unburned hydrocarbons.

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 Alumimum alloys, which is used in the 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 commonly used piston aluminium alloys are Al-Si alloys, containing about 12% Si. They are near eutectic alloys, further more comprising a number of alloying additives Jankowski & Miroslaw (2017).

The field of temperature in the piston was noticed that the maximum value of the temperature was in the centre of the piston head and it decreases towards the edge of the piston head, the difference between the centre and the edge of the piston head being of 4-500 ^{o}C, and the difference between the top surface of the piston and the bottom surface being around 8-100 ^{o}C, which confirms both the analytical calculation and data from the literature. They also noticed that both radial and tangential stresses have, on the top and bottom surfaces, values and signs corresponding to the results obtained through the analytical calculation. The total deformations caused by thermal loads were maximum on the top surface of the piston head (0.164 mm), on the edge, and have the opposite deformations sense due to mechanical load. Regarding the mechanical-thermal load, the radial and tangential stresses correspond in terms of values and signs with those determined analytically. They went further to state that, in the case of the complex load, the equivalent stresses were of interest, because in the design stage these stresses were compared to the allowable stress of the material the piston is made of. It was noted that the values of the equivalent stresses calculated with the theory of the maximum shear stresses in the piston head, do not exceed 55 MPa, a value much lower than the allowable stress of the material which is between (80-120 MPa).

For the same purpose it is important to determine the von Mises equivalent stresses. Also, it was noticed in the piston head, the von Mises equivalent stresses do not exceed the allowable stress of the material. In their 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 Cioata et al (2017).

According to Adil et al (2019), they opined 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.

According to Vinay et al (2016) in their study into thermal analysis of piston for the influence on secondary motion they observed that, the piston crown is exposed to very high combustion temperatures. Figure 2.1 shows the typical values of temperature at different parts of a cast iron piston. It may be noted that the maximum temperature occurs at the centre of the crown and decreases with increasing distance from the centre. The temperature is the lowest at the bottom of the skirt. Poor design may result in the thermal overloading of the piston at the centre of the crown. The temperature difference between piston outer edge and the centre of the crown is responsible for the flow of heat to the ring belt throughout the path offered by metal section of the crown. It is therefore necessary to increase the thickness of the crown from the centre to the outer edge in order to make a path of greater cross-section available for the increasing heat quantity. The length of the path should not be too long or the thickness of the crown cross-section too small for the heat to flow. This will cause the temperature at the centre of crown to build up and thereby excessive temperature difference between the crown and the outer edge of the piston will result. This may even lead to cracking or piston during overload operation.

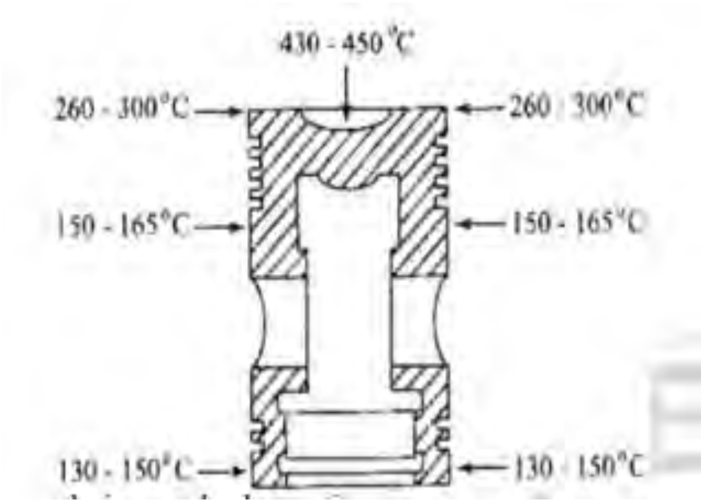


Figure 2.1: Piston Temperature distributions
Source: Vinary V. Kuppast et al (2013)

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 also 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 compare to simple piston. Piston failure occurs because of thermo-mechanical overload by insufficient intercooling thermo-mechanical overload by over fuelling Preeti, et al (2016).

In their thermal analysis and optimisation of I. C Engine piston using finite element method, Bhagat et al (2012) they 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, in order 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.

2.3 Aluminium Classification and Applications

According to Sheasby and Pinner (2001) in their study they observed that the chief alloying constituents added to aluminium are copper, magnesium, silicon, manganese, nickel and zinc. All of these are used to increase the strength of pure aluminium. Two classes of alloys may be considered. The first are the 'cast alloys' which are cast directly into their desired forms by one of the three methods (i.e., sand-casting, gravity die casting or pressure die casting), while the second class, the 'wrought alloys', are cast into ingots or billets and hot and cold worked mechanically into extrusions, forgings, sheet, foil, tube and wire. The main classes of alloys are the 2000 series (Al-Cu alloys), which are high-strength materials used mainly in the aircraft industry, the 3000 series (Al-Mn alloys) used mainly in the canning industry, the 5000 series (Al-Mg alloys) which are used unprotected for structural and architectural applications, the 6000 series (Al-Mg-Si alloys) which are the most common extrusion alloys and are used particularly in the building industry, and the 7000 series (Al-Zn-Mg alloys) which are again high strength alloys for aircraft and military vehicle applications. The alloy used in any particular application will depend on factors such as the mechanical and physical properties required, the material cost and the service environment involved. If a finishing treatment is to be applied, then the suitability of the alloy for producing the particular finish desired will be an additional factor to be taken into account. The great benefit of aluminium is that such a wide variety of alloys with differing mechanical and protection properties is available, and these, together with the exceptional range of finishes which can be used, make aluminium a very versatile material.

The Aluminium Association Alloy and Temper Designation System is recognized by the American National Standards Institute (ANSI) as the United States national standard, and as such is incorporated into ANSI Standards H35.1.and H35.2. The maintenance of the system is managed by the Aluminium Association, Inc., under ANSI's charter. In addition, there is an International Accord recognizing the Aluminium Association Wrought Alloy Designation System as the de facto international standard; this Accord has been ratified by almost all of the world's aluminium producing countries. The alloy designation system is briefly described below, first for wrought alloys and then for cast alloys, and these are followed by a brief description of the temper designation system."

2.3 Aluminium Alloys for Internal Combustion Engine Pistons

According to Aluminium Taschenbush, the association opined that, in an internal combustion engine, pistons convert thermal into mechanical energy. The functions of the pistons are: to transmit the gas forces through the connecting rod to the crank shaft, to seal in conjunction with the piston rings the combustion chamber against gas leakage to the crankcase and to prevent the infiltration of oil from the crankcase into the combustion chamber, to dissipate the absorbed combustion heat to the cylinder liner and the cooling oil. Aluminium alloys are the preferred material for pistons both in gasoline and diesel engines due to their specific characteristics: low density, high thermal conductivity, simple net-shape fabrication techniques (casting and forging), easy machinability, high reliability and very good recycling characteristics. Proper control of the chemical composition, the processing conditions and the final heat treatment results in a microstructure which ensures the required mechanical and thermal performance, in particular the high thermal fatigue resistance. The continuing development of modern gasoline and diesel engines leads to specific objectives for further piston development: reduction of piston weight, increase of mechanical and thermal load capacity, lower friction and thus improved scuffing resistance, etc. In addition, the basic requirements for durability, low noise level and minimum oil consumption have to be taken into account. These goals are achieved by a targeted combination of high-performance aluminium piston materials, novel piston designs and the application of innovative coating technologies. For future development, new aluminium materials using e.g. powder metallurgical production methods or aluminium-based metal matrix composites produced by various methods as well as other lightweight materials such as magnesium alloys, carbon, etc., are being investigated. However, the on-going improvements achieved with cast and forged aluminium alloys reveal that aluminium piston materials still offer great optimization potential and will continue to play a dominant role as piston material in the future.

Pistons are subjected to high mechanical and thermal loads. The mechanical loads on the piston result from extreme pressure cycles with peak pressures up to 200 bar in the combustion chamber and huge forces of inertia caused by the extremely high acceleration during the reciprocating motion of pistons. These mechanical loads are superimposed by thermal stresses which are primarily generated by the high temperature gradients prevalent on the piston top. Ever rising demands regarding power density as well as the need for reduced emissions, low noise and more efficient fuel and oil consumption are the main engineering challenges for engines. For the pistons, these challenges translate into maximum strength requirements in the relevant temperature range combined with minimum weight. In gasoline engines, the thermal loads have risen significantly during the last years as a result of higher power demands. Also, the stresses at average ignition pressure have increased as a consequence of the introduction of knock control, direct fuel injection and turbocharging. Moreover, high speed concepts have led to an increase in inertia load. The requirements for pistons for diesel engines are even more demanding. Modern diesel engines for passenger cars (equipped either with direct injection or super-charging with charge cooling) operate with injection pressures up to 2,000 bar, mean effective pressures over 20 bar, peak pressures of 170 to 200 bar, and achieve specific powers of up to 80 kW per litre. But also, the demand for ever lower exhaust gas emissions asks for significantly improved piston material characteristics.

Pistons are produced from cast or forged, high-temperature resistant aluminium silicon alloys. There are three basic types of aluminium piston alloys. The standard piston alloy is a eutectic Al-12%Si alloy containing in addition approximately 1% each of Cu, Ni and Mg. Special eutectic alloys have been developed for improved strength at high temperatures. Hypereutectic alloys with 18 and 24% Si provide lower thermal expansion and wear, but have lower strength. In practice, the supplier of aluminium pistons uses a wide range of further optimized alloy compositions, but generally based on these basic alloy types. The majority of pistons are produced by gravity die casting. Optimized alloy compositions and a properly controlled solidification conditions allow the production of pistons with low weight and high structural strength. Forged pistons from eutectic and hypereutectic alloys exhibit higher strength and are used in high performance engines where the pistons are subject to even high stresses. Forged pistons have a finer microstructure than cast pistons with the same alloy composition. The production process results in greater strength in the lower temperature range. A further advantage is the possibility to produce lower wall thicknesses and hence reducing the piston weight. Also, aluminium metal matrix composite materials are used in special cases. Pistons with Al2O3 fibre reinforced bottoms are produced by squeeze casting and used mainly in direct injection diesel engines. The main advantage, apart from a general improvement of the mechanical properties, is an improvement of the thermal fatigue behaviour.

According to Aikawa et al, in their united states patent of Aluminium Alloy for Internal Combustion Engine piston and Aluminium Alloy piston opined that, their present invention relates to an aluminium alloy with good high-temperature Strength and good abrasion resistance for internal-combustion pistons, which is Suitable for pistons to be used in internal-combustion engines Such as diesel engines and gasoline engines, and also to pistons comprising the aluminium alloy. 2. Description of the Related Art Hyper-eutectic Al-Si alloys that contain Si in an amount of not smaller than 12.6% by weight have a small thermal expansion coefficient and good abrasion resistance. While Solidifying, the melt of Such an Al-Si alloy produces primary crystals of pro-eutectic Si having high hardness. Therefore, the alloys are used for internal-combustion engine pistons that require high abrasion resistance. However, the machine workability of the alloys is poor since the growth of pro-eutectic Sit herein is too great. For effective utilization of energy resources, recently, it is desired to increase the combustion efficiency of internal combustion engines.

The increase in the combustion efficiency involves an increase in combustion temperatures, for which various parts that constitute the internal-combustion engines, especially pistons, require good high-temperature Strength. For conventional internal-combustion engine pistons, often used are eight types of aluminium alloys of JIS H5202 (AC8A, AC8B, AC8C).

These are all Al-Si-Cu-Mg alloys, of which AC8A and AC8B additionally contain Ni. However, these conventional aluminium alloys have poor high-temperature Strength. Japanese Patent Publication (JP-B) Sho-60-47898 dis closes an improved aluminium alloy which is prepared by adding V and/or Mo to an Al-Si-Cu-Mg alloy and which has good high-temperature Strength while Still having good castability intrinsic to the Al-Si-Cu-Mg alloy base. Japanese Patent Application Laid-Open (JP-A) Hei-8- 104937 discloses a method for improving both the high temperature Strength and the abrasion resistance of an Al-Si-Cu-Mg alloy by adding P, Ca, Fe and Ti to the alloy, in which the ratio of P and Ca to the other additives is controlled to fall between 0.5 and 50 by weight so that the action of P to produce fine pro-eutectic Si grains is protected from being attenuated by Ca and So that the action of Ca to improve the eutectic texture of the alloy is protected from being attenuated by P. However, the techniques disclosed in these publications are still problematic in that the alloys proposed therein are not resistant to thermal loads to be applied to the proposed internal-combustion pistons, as their Strength at high temperatures (especially, at 250 to 300° C.) is poor, and that the thermal expansion coefficient of the alloys is large and the abrasion resistance thereof is poor, as the uppermost Si content of the alloys is limited to 13%. Also known are nine types of aluminium alloys of JIS H5202 (AC9A, AC9B) having a low thermal expansion coefficient and improved abrasion resistance which, however, are still problematic in that their high-temperature strength is low and their castability and workability is extremely poor.

CHAPTER THREE

METHODS AND MATERIALS

3.0 Introduction

This chapter outlines and describes the design considerations necessary for piston design and manufacturing, material selection and the mechanical properties of some selected piston materials. The determination of dimensions, modelling of the piston and the procedure for numerical methods are also outlined in this chapter.

3.1 Significance

The main objective of the study is to find out and suggest optimum material for piston based on quality and economy considering material weight and dimensional issues at the same time. After generating an accurate finite element model, it was observed that, the temperature distribution throughout the piston has been impressive. The temperature was far below the thermal conductivity of the aluminium 413 alloy. Hence, the aluminium 413 alloy which is the implementing material will be able to withstand the temperature imposed. Hence it important to know that Al 413 material will be suitable for the purpose. Target of the optimization was to reach at minimum thermal stresses in the piston.

3.3 Material Selection

The cast Aluminium alloy (Al 413) has been selected for the manufacturing of the piston for an internal combustion engine. The cast Aluminium alloy (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 some 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 3.1 shows the mechanical and physical properties of the selected material (Al 413).

Table 3. 1: Properties of Al 413

Parameters	Value	SI Unit
Density	2.66	$\mathrm{g/cm^3}$
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	$\mathrm{W/m.K}$
Fatigue Strength	130	Mpa
Coefficient of thermal expansion	204	$\mu m/m.k$
Elongation at break	3.5%	
Heat of fusion	389	J/g
Specific Heat Capacity	0.963	J/g ℃
Melting Point	574-582	℃
Melting temperature	649-760	℃
Casting temperature	635-704	℃

3.1.1 Common Aluminium Alloys for Piston Design and Manufacture

The commonly known Aluminium alloy materials for pistons design and manufacturing currently in operation are: Eutectic Aluminium alloy with the properties summarized in Table 3.2, Hypereutectic Aluminium alloy with the properties indicated in Table 3.3 and Special Eutectic Aluminium alloy having the properties shown in Table 3.4. 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 7068. Tables 3.2, 3.3 and 3.4 show the mechanical properties of the three Aluminium alloy piston materials.

Table 3. 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	$\mu m/m.k$

Table 3. 3 Properties of the Hypereutectic Alloy (Al 390.0)

Parameters	**Value**	**SI Unit**
Density	2.71	g/cm^3
Ultimate Tensile Strength	317	MPa
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	$\mathrm{W/m.K}$
Fatigue Strength	138	MPa
coefficient of thermal expansion	18	$\mu m/m.k$

Table 3. 4 Properties of the Special Eutectic Alloy (Al 332)

Parameters	Value	SI Unit
Density	2.71	$\mathrm{g/cm^3}$
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	$\mathrm{W/m.K}$
Fatigue Strength	90	MPa
coefficient of thermal expansion	21	$\mu m/m.k$

3.4 Theoretical Design Calculation of Piston

The piston is a disc which reciprocates within a cylinder. It is either moved by the fluid or it moved the fluid which enters the cylinder. The main function of the piston of an inter combustion engine is to receive the whim from the expanding gas and to transmit the energy to the crankshaft through the connecting rod. The piston must also disperse a large amount of heat from the combustion chamber to the cylinder walls.

The piston of internal combustion engines are usually of trunk types as show. Such pistons are open at one end and consist of the following parts:

Head or crown.

The piston head or crown may be flat, convex or concave depending upon the design of combustion chamber. It withstands the pressure of gas in the cylinder bore.

Piston rings:

The piston rings are used to seal the cylinder in order to prevent leakage of the gas past the piston.

Skirt:

The skirt acts as a bearing for the side thrust of the connecting rod on the walls of cylinder.

Piston pin:

It is also called gudgeon pin or wrist pin. It is used to connect the piston to the connecting rod.

3.5.1 Design considerations of a piston

In designing a piston for internal combustion (IC) engine, the following factors should be taken into consideration:

1. It should have a minimum mass to minimise the inertia force
2. It should have enormous strength to withstand the high gas pressure and inertia forces
3. It should form an effective gas and oil sealing of the cylinder
4. It should provide sufficient bearing area to prevent undue wear.
5. It should disperse the heat of combustion quickly to the cylinder walls.
6. It should have high speed reciprocation without noise

7. It should be sufficient rigid construction to withstand thermal and mechanical distortion
8. It should have sufficient support for the piston pin

3.5.2 Common materials for internal combustion pistons

The most commonly used material for pistons in internal combustion engines are:

1. Cast iron
2. Cast aluminium
3. Forge aluminium
4. Cast steel
5. Forge steel

The cast iron material pistons are used for moderated rated engines with speed below 6 m/s and aluminium alloy pistons are used for high rated engines running at higher piston speeds. It may be noted that:

1. Since the coefficient of thermal expansion for aluminium is about 2.5 times that of the cast iron, therefore a greater clearance must be provided between the piston and the cylinder walls (than that of cast iron piston) in order to prevent seizing of the piston when engine runs continuously under heavy loads. But if excessive clearance is allowed, then the piston will develop a piston slap while it is cold and this tendency will increase with wear. The less clearance between the piston and the cylinder wall leads to seizing of piston.
2. Since the aluminium alloys used for pistons have high, heat conductivity (nearly four times that of the cast iron), therefore, these pistons ensure high-rate heat transfer and thus keep down the maximum temperature difference between the centre and edges of the piston head or crown.

3. (a). For a cast iron piston, the temperature at the centre of the piston head or crown (T_C) is about 425^0C to 450^0C under full load conditions and the temperature at the edges of the piston head (T_E) is about 200^0C to 225^0C.

   (b) For Aluminium alloy pistons, T_C is about 260^0C to 290^0C and T_E is about 185^0C to 215^0C.

4. Since aluminium alloys are about three times lighter than cast iron, therefore, its mechanical strength is good at low temperatures, but they lose their strength (about 50%) at temperatures above 325^0C. Sometimes the pistons of aluminium alloys are coated with aluminium oxide by an electrical method.

3.5.3 Piston head or crown

The head or crown is designed keeping in view of the following two main considerations,

1. It should have adequate strength to withstand the straining action due to pressure of explosion inside the engine cylinder, and
2. It should dissipate the heat of combustion to the cylinder walls as quickly as possible. On the basis of the of the first, consideration of straining action, the thickness of the piston head or crown is determined by treating it flat circular plate of uniform thickness fixed at the outer edges and subjected to a uniformly distributed load due to the gas pressure over the entire cross section.

   The thickness of the piston head (t_H) according to Grashoff's formula is given by,

$$t_H = \sqrt{\frac{3p.D^2}{16\sigma_t}}\ (in\ mm)$$

where P = Maximum gas pressure or explosion pressure in N/mm^2,

D = Cylinder bore or outside diameter of the piston in mm, and

σ = Permissible bending (tensile) stress for the material of the piston in MPa or N/mm^2. It may be taken as 35 to 40 MPa for grey cast iron, 50 to 90 MPa for nickel cast iron and Aluminium alloy and 60 to 100 MPa for forged steel.

On the basis of second consideration of heat transfer, the thickness of the piston head should be such that the heat absorbed by the piston due combustion of fuel is quickly transferred to the cylinder walls. Treating the piston head as a flat circular plate, its thickness is given by

$$T_H = \frac{H}{12.56k(Tc - Te)} \text{ in min}$$

The temperature difference (T_C-T_E) may be taken 220˚C for cast iron and 75˚C for Aluminium.

The heat flowing through the position head (H) may be determined by the following expression,

$$H = C \times HCV \times m \times B.P. \quad \text{(in kW)}$$

Where

C= Constant representing that portion of the heat supplied to the engine which is absorbed by the piston. Its value is usually taken as 0.05.

HCV= Higher calorific value of the fuel in kJ/kg. It may be taken as 45×10^3 kJ/kg for diesel and $47 \text{x } 10^3$ kJ/kg for petrol,

M = Mass of the fuel used in kg per brake power per second, and

B.P = Brake power of the engine per cylinder

2. When t_H is 6mm or less, then no ribs are required to strengthen the piston head against gas loads. But when t_H is greater than 6mm, then a suitable number of ribs at the center line of the boss extending around the skirt should be provided to distribute the side thrust from the connecting rod and thus to prevent distortion of the skirt. The thickness of the ribs may be takes as $t_H/3$ to $t_H/2$.

3. F = For engines having length of stroke to cylinder bore (L/D) ratio up to 1.5, a cup is provided in the top of the piston head with a radius to 0.7 D. This is done to provide a space for combustion chamber.

3.5.4 Piston rings design

The piston rings are used to impart the necessary radial pressure to maintain the seal between the piston and the cylinder bore. These are usually made grey cast iron or alloy cast iron because of their good wearing properties and also, they retain spring characteristics even at high temperatures.

The piston rings are of the following two types:

1. Compression rings or pressure rings and
2. Oil control rings or oil scraper

The compression rings or pressure rings are inserted in the grooves at the top portion of the piston and may be three to seven in number. These rings also transfer heat from the piston to the cylinder liner and absorb some part of the piston fluctuation due to the side thrust.

The oil control rings or oil scrapers are provided below the compression rings. These rings provide proper lubrication to the liner by allowing sufficient oil to move up during upward stroke and at the same time scrap the lubricating oil from the surface of the liner in order to minimize the flow of the oil to the combustion chamber.

The radial thickness (t_1) of the ring may be obtained by considering the radial pressure between the cylinder wall and the ring. From bending stress consideration in the ring, the radial thickness is given by

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

Where D = Cylinder bore in mm

P_w= Pressure of gas on the cylinder wall in N/mm^2. Its value is limited from 0.025 N/mm^2 to 0.042 N/mm^2 and

$\sigma =$ Allowable bending (tensile) stress in MPa. Its value may be taken from 85 MPa to 110 MPa for cast iron rings.

The axial thickness (t_2) of the rings may be taken as 0.7 t_1 to t_1.

The minimum axial thickness (t_2) may also be obtained from the following empirical relation:

$$t_1 = \frac{D}{10n_R}$$

Where;

$nR = Number\ of\ rings$

The width of the top land (i.e.) the distance from the top of the piston to the first ring groove) is made larger than other ring lands to protect the top ring from high temperature conditions existing at the top of the piston,

Therefore,

Width of top land**,**

$$\boldsymbol{b_1 = t_H\ to\ 1.2t_H}$$

The width of other ring lands (the distance between the ring grooves) in the piston may be made equal to or slightly less than the axial thickness of the ring (t_2).

Therefore;

Width of other ring lands,

$$\boldsymbol{b_2 = 0.75\, t_2\ to\ t_2}$$

The depth of the ring grooves should be more than the depth of the ring so that the ring does not take any piston side thrust.

The gap between the free ends of the ring is given by 3.5 t_1 to 4 t_1. The gap, when the ring is in the cylinder, should be 0.002 d to 0.004 D.

3.5.5 Piston barrel design

It is a cylinder portion of the piston. The maximum thickness (t_3) of the piston barrel may be obtained from the following empirical relation:

$$t_3 = 0.03\,D + b + 4.5\,mm$$

Where:

b = Radial depth of piston ring groove which is taken as 0.4mm larger than the radial thickness of the piston ring:

$$(t_1) = t_1 + 0.4\text{mm}$$

The piston wall thickness (t_4) towards the open end is decreased and should be taken as

$$0.025\,t_3\ to\ 0.35\,t_3.$$

3.5.6 Piston Skirt design

The portion of the piston below the ring section is known as piston skirt. It acts as a bearing for the side thrust of the connecting rod. The length of the piston skirt should be such that the bearing pressure on the piston barrel due to the side thrust does not exceed 0.25 N/mm^2 of the projected area for low-speed engines and 0.5 N/mm^2 for high-speed engines. It may be noted that the maximum thrust will be during the expansion stroke. The side thrust (R) on the cylinder liner is usually taken as 1/10 of the maximum gas load on the piston.

The maximum gas load on the piston is,

$$F_P = P \times \frac{\pi D^2}{4}$$

Therefore; Maximum side thrust on the cylinder,

$$R = \frac{F_P}{10} = 0.1 \times P\,x\,\frac{\pi D^2}{4}$$

Where :

P = Maximum gas pressure in N/mm^2, and

D = Cylinder bore in mm

The side thrust (R) is also given by

R = Bearing pressure x Projected bearing area of the piston skirt

$$= P_b \ x \ D \ x \ l$$

Where :

l = Length of the piston skirt in mm.

From the two equations of the side thrust (R), the length of the piston skirt (l) is determined. In actual practice, the length of the piston skirt is taken as 0.65 to 0.8 times the cylinder bore. Now the total length of the (L) is given by

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

The length of the piston usually varies between D and 1.5 D. It may be noted that a longer piston provides better bearing surface for quiet running of the engine, but it should not be made unnecessarily forces.

3.5.7 Piston pin design

The piston pin (also called gudgeon pin or wrist pin) is used to connect the piston and the connecting rod. It is usually made hollow and tapered on the inside, the smallest inside diameter being at the center of the pin. The piston pin passes through the bosses provided on the inside of the piston skirt and the bush of the small end of the connecting rod. The center of piston pin should be 0.02 D to 0.04 D above the center of the skirt, in order to off-set the turning effect of the friction and to obtain uniform distribution of pressure between the piston and the cylinder liner.

The material used for the piston pin is usually case-hardened steel alloy containing nickel, chromium, molybdenum or vanadium having tensile strength from 710 MPa to 910 MPa.

The piston pin should be designed for the maximum gas load or the inertia force of the piston, whichever is larger. The bearing area of the piston pin should be about equally divided between the piston pin bosses and the connecting rod bushing. Thus, the length of the pin in the connecting rod bushing will be about 0.45 of the cylinder bore or piston diameter (D), allowing for the end clearance of the pin etc. The outside diameter of the piston pin (d_0) is determined by equating the load on the piston due to gas pressure (p) and the load on the piston pin due to bearing pressure (P_{b1}) at the small end of the connecting rod bushing.

The mean diameter of the piston bosses is made 1.4 d_0 for cast iron pistons and 1.5 d_0 for Aluminium pistons, where d_0 is the outside diameter of the piston pin. The piston bosses are usually tapered, increasing the diameter towards the piston wall.

Let :

d_o = Outside diameter of the piston pin in mm

l_1 = Length of the piston pin in the bush of the small end of the connecting rod in mm. Its value is usually taken as 0.45 D.

P_b =Bearing pressure at the small end of the connecting rod bushing in N/mm^2. Its value for the bronze bushing may be taken as 25 N/mm^2.

The load on the piston due to gas pressure or gas load is given as;

$$F_P = \frac{\pi D^2}{4} \times P$$

and load on the piston pin due to bearing pressure or bearing load

$$= \text{Bearing pressure x Bearing area} = P_b \times d_o \times l_1$$

From the two equations the outside diameter of the piston pin (d_0) may be obtained.

3.3 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

Cylinder bore and stroke: $99.5\ mm \times 96.0mm$

Engine displacement: $2986\ cm^3$

Maximum power: $111\ Kw\ at\ \ 145\ Km/h$

Maximum Torque: $260\ Nm\ at\ 1600 - 2400\ rpm$

3.4 Pressure and Force Acting on the Piston

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

$$\text{Volume per cylinder}$$

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

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

$\text{Operating temperature(T)} = 240°\text{C}$

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

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

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

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

$$\text{PV} = \text{mRT}$$

$$\text{P} = \frac{\text{mRT}}{\text{V}}$$

But

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

Mass $(\mathrm{m}) = \text{density of diesel} \times \text{volume per cylinder}$

$= 832 \times 10^{-9} \times 746.5 \times 10^{3} = 0.621088\mathrm{kg} = \mathbf{62.1088 \times 10^{-2}kg}$

Pressure developed in a cylinder $(\mathrm{P}) = \frac{62.1088 \times 10^{-2} \times 36.15 \times 10^{3} \times 240}{746.5 \times 10^{3}}$

$$= \frac{5388559.488}{746.5 \times 10^{3}} = \boldsymbol{7.218\ N/mm^{2}}$$

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

Let

$\mathrm{F_P}$ = Gas Force acting on the Piston

D = Cylinder bore diameter and

P = Pressure developed in a cylinder

$$\mathrm{F_P} = \frac{\pi D^2}{4} \times p = \frac{\pi (99.5)^2}{4} \times 7.218 = 56124.6\ \mathrm{N} = 56.1246\ \mathrm{KN}$$

3.5 Piston Design Procedure

3.5.1 Piston head or crown design

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

The thickness of the piston head on the basis of strength is given as;

$$\mathrm{t_H} = \sqrt{\frac{3p.D2}{16\sigma t}}$$

Where:

P = the pressure developed in the engine cylinders

D = cylinder bore diameter and

σ_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.

$$t_H = \sqrt{\frac{3 \times 7.218(99.5)2}{16 \times 80}} = \sqrt{\frac{214380.0135}{1280}} = \sqrt{167.484} = 12.9\ mm\ \approx \mathbf{13\ mm}$$

Therefore, the piston head or crown is **13mm**

3.5.2 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 $\frac{13}{2} = 4.33\ to\ 6.5\ mm$

The design adopted t_R = **6 mm**

3.5.3 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;

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

Where;

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

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

$$\mathrm{t_1} = 99.5\sqrt{\frac{3\ \times 0.039}{80}} = \mathbf{3.8\ mm}$$

Therefore, the radial thickness is taken as $\mathbf{3.8\ mm.}$ The axial thickness of the piston rings is given as;

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

The design adopted

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

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

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

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

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

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

The design adopted

$$b_1 = 14\ mm$$

and width of other ring lands,

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

The design adopted $\mathbf{b_1 = 14\ mm; and\ b_2 = 2.5mm}$

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

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

and the gap when the ring is in the cylinder,

$$\mathrm{G_2} = 0.002 \text{ D to } 0.004 \text{ D} = 0.002 \times 99.5 \text{ to } 0.004 \times 99.5 \text{ mm} = 0.199 \text{ to } 0.398$$

The design adopted $\mathrm{G_1} = 13.8$ mm; and $\mathrm{G_2} = 0.3$mm

3.5.4 Piston barrel design

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

$$b = t_1 + 0.4 = 3.8 + 0.4 = \mathbf{4.2\ mm}$$

The maximum thickness of barrel,

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

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

$$t_4 = 0.25t_3\ to\ 0.35t_3 = 0.25 \times 11.7\ to\ 0.35 \times 11.7 = 2.9\ to\ 4.0\ mm$$

The design adopted $t_4 = \mathbf{3.8\ mm}$

3.5.5 Piston skirt designs

Let

l = Length of the skirt in mm.

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

$$R = \mu \times \frac{\pi D^2}{4} \times p$$

Taking $\mu = 0.1$ gives;

$$= 0.1 \times \frac{\pi(99.5)^2}{4} \times 7.218 = 5612.46\,N \qquad \mathbf{1}$$

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

$$\mathrm{R = p_b \times D \times l}$$

Taking

$$P_b = 0.45\ N/mm^2$$

$$\mathrm{R = 0.45 \times 99.5 \times l = 44.775l\ N} \qquad \mathbf{2}$$

Equating 1 and 2 gives

$$5612.46 = 44.775l$$

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

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

Total length of the prison,

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

$$= l + (4\,t_2 + 3b_2) + b_1$$

= 125.34 + (4$\times 3 + 3 \times 3$) + 14 = 160.34 say **160 mm**

Therefore, the total length of the piston (L) is **160 mm**

3.5.6 Piston pin

Let

d_0 = Outside diameter of the pin in mm,

l_1 = Length of pin in the bush of the small end of the connecting rod in mm, and

P_{b1}= Bearing pressure at the small end of the connecting rod bushing in N/mm^2. Its value for bronze bushing is taken as 25 N/mm^2.

Load on the pin due to bearing pressure is given as;

= Bearing pressure × Bearing area = $p_{b1} \times d_0 \times l_1$

$Taking\ \ l_1 = 0.45D = 0.45 \times 99.5 = 44.775$

$$= 25\times\ d_0 \times 44.775 = 1119.375\, d_0\, N \qquad \mathbf{3}$$

Also, the maximum load on the piston due to gas pressure or maximum gas load (F_P)

$$= \frac{\pi\, D^2}{4} \times p = \frac{\pi(99.5)^2}{4} \times 7.218$$

$$F_P = 56124.56\, N \qquad 4$$

Equating 3 and 4 gives

$$1119.375\ \mathrm{d_0} = 56124.56$$

$$\mathrm{d_o} = \frac{56124.56}{1119.375} = 50.14\mathrm{mm} \approx 50\ \mathrm{mm}$$

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

$$\mathrm{d_i} = 0.6 \times 50 = 30\ \mathrm{mm}$$

Assuming the piston pin is made of heat-treated alloy steel for which the bending stress (σ_b) may be taken as 140 MPa. To check if the induced bending stress in the pin is satisfactory or not.

The maximum bending moment at the center of the pin is given as;

$$\mathrm{M} = \frac{\mathrm{F_P.D}}{8} = \frac{56124.56 \times 99.5}{8} = 698049.215\ \ \mathrm{Nmm}$$

It is also known that maximum bending moment (M),

$$\mathrm{M} = \frac{\pi}{32}\left[\frac{(\mathrm{d_0})^4 - (\mathrm{d_i})^4}{\mathrm{d_0}}\right]\sigma_\mathrm{b}$$

Therefore,

$$698049.215 = \frac{\pi}{32}\left[\frac{(35)^4 - (21)^4}{35}\right]\sigma_\mathrm{b}$$

$$10681.42\sigma_\mathrm{b} = 698049.215$$

$$\sigma_\mathrm{b} = \frac{698049.215}{10681.42} = 65.4\ \ \mathrm{N/mm^2} = 65.4\ \mathrm{MPa}$$

Therefore, the induced bending stress is **65.4 MPa**

Since the induced bending stress in the piston pin is less than the permissible value of 140 MPa therefore, the dimensions for the pin as calculated above ($d_o = 50\ mm\ and\ d_i = 30\ mm$) are satisfactory.

Table 3. 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

3.7 Procedure for the numerical methods

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

3.7.1 The geometry of the piston

The piston was modeled in Autodesk inventor software 2017. The piston was modeled base on the design dimensions generated in the design process. The modeled component is as shown in Figure 3.3, internal design of the piston is shown in Figure 3.4 and the detailed drawing of the piston shown in Figure 3.5.

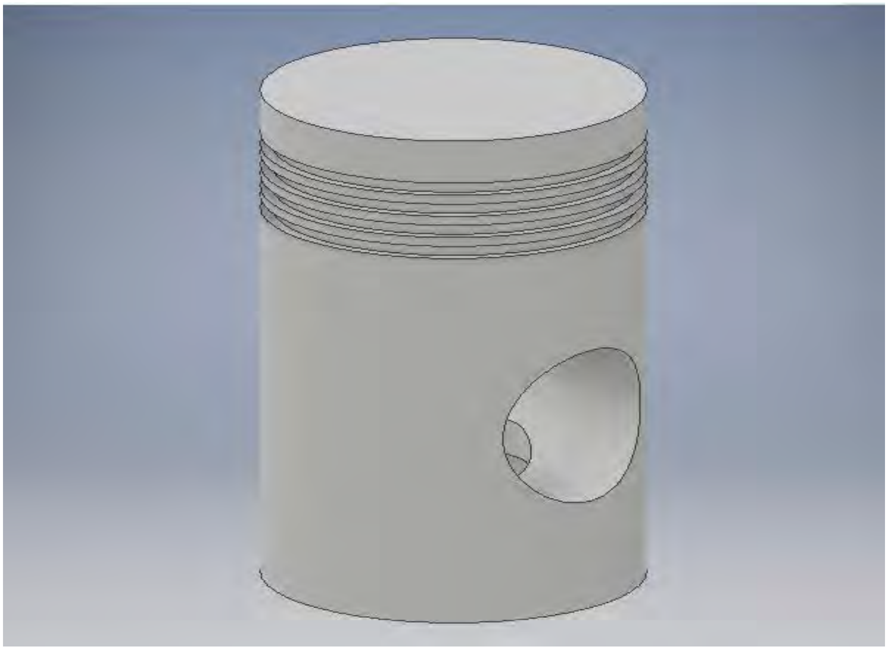


Figure 3.1 Geometry of the Piston

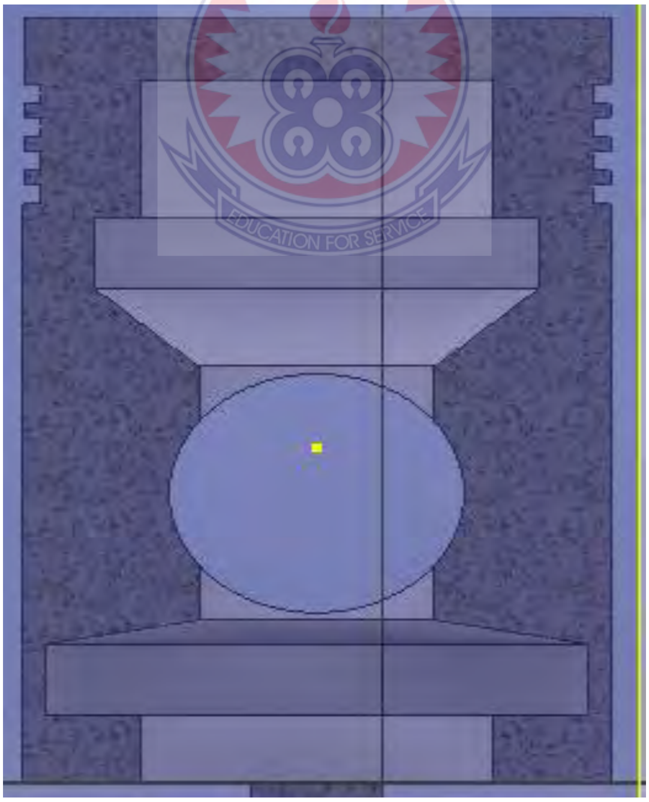


Figure 3. 2 Internal designs of the piston

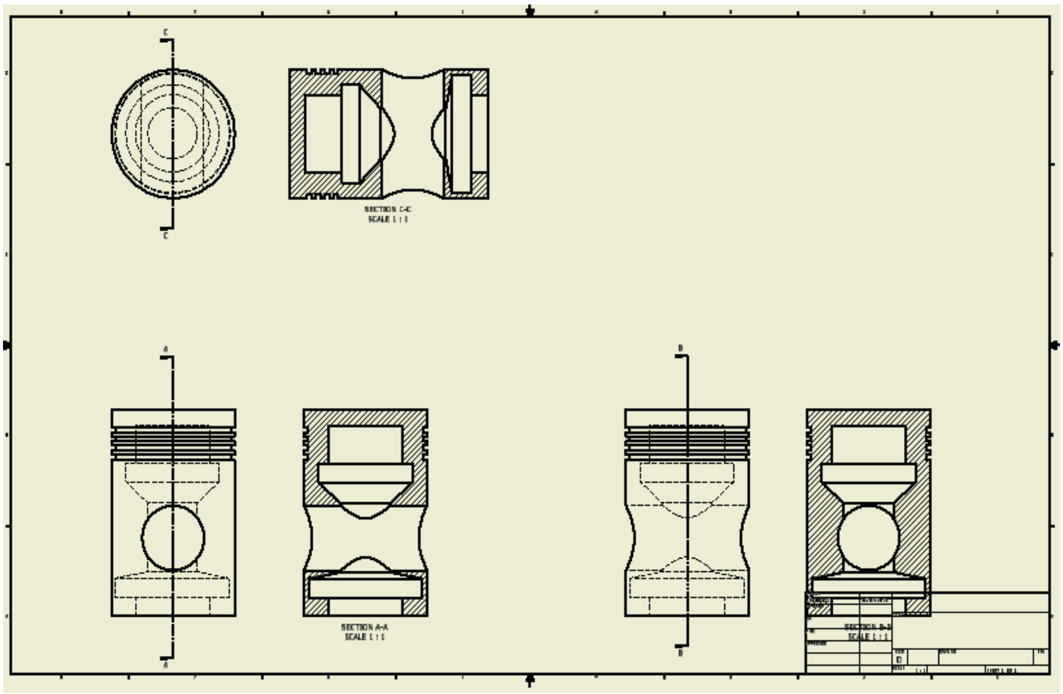


Figure 3. 3 Detailed drawing of the design

3.7.2 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 connecting rods are: number of nodes 19860 and element size 10548. The meshing of the internal combustion piston is as shown in Figure 3.4.

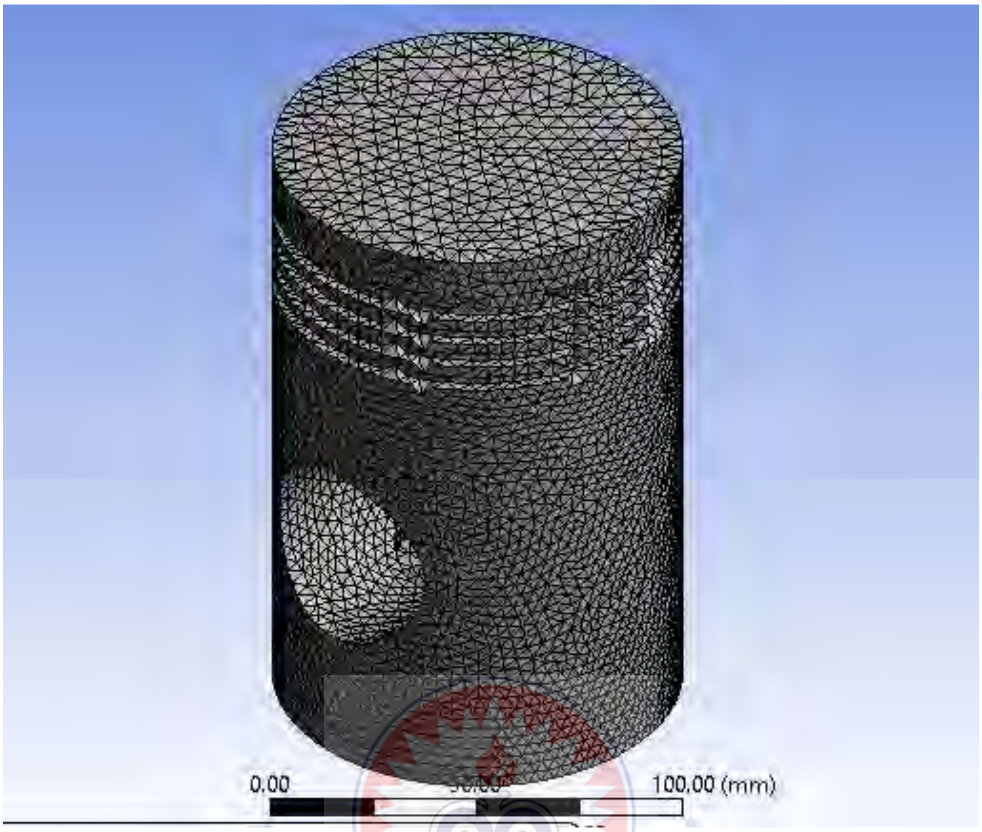


Figure3. 4 Piston Meshed in Ansys

3.5.3 The Boundary Conditions Set for the Analysis

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

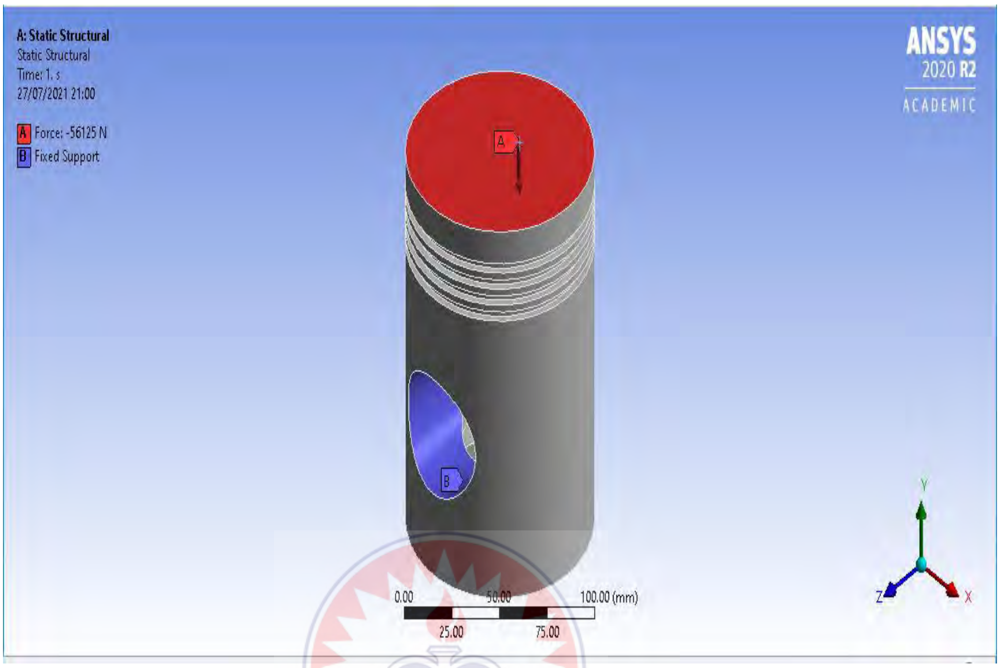


Figure 3. 5 The boundary condition for the analysis

CHAPTER FOUR

PRESENTATION AND ANALYSIS OF RESULTS

4.0 Introduction

This chapter presents the simulated results on the static structural and thermal 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 chapter also discusses and compared the results obtained from the simulation and the piston test results.

4.1 Static Structural Analysis results of the Piston made of the four different materials

a. Aluminium 413 alloy

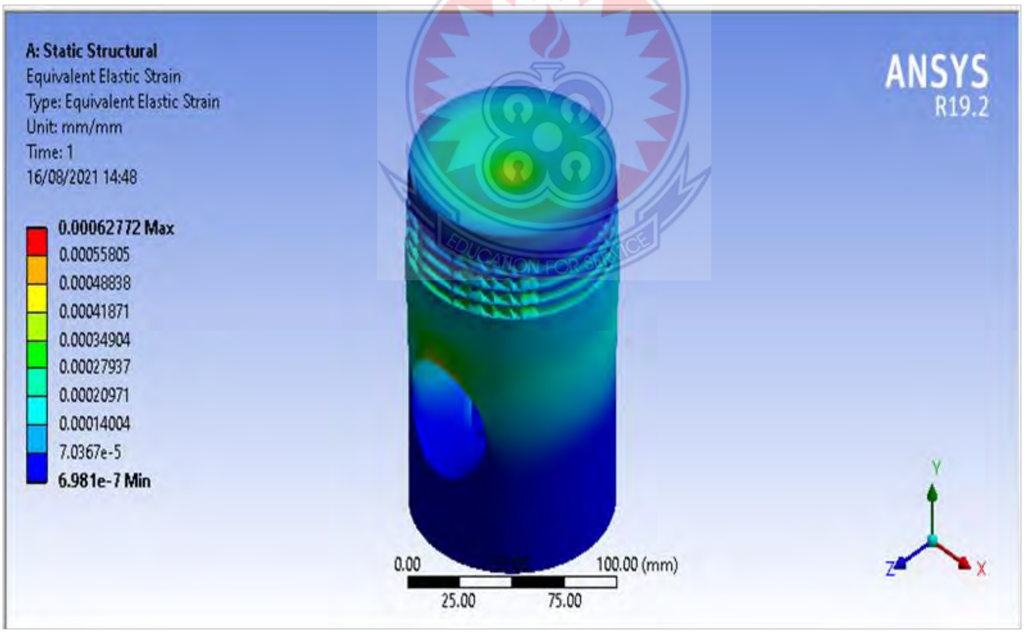


Figure 4. 1: Total deformation for Al 413 piston

Figure 4.1 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 conclude that the implementing material has strength enough to resist the deformation that will be induced in the piston due to the gas load.

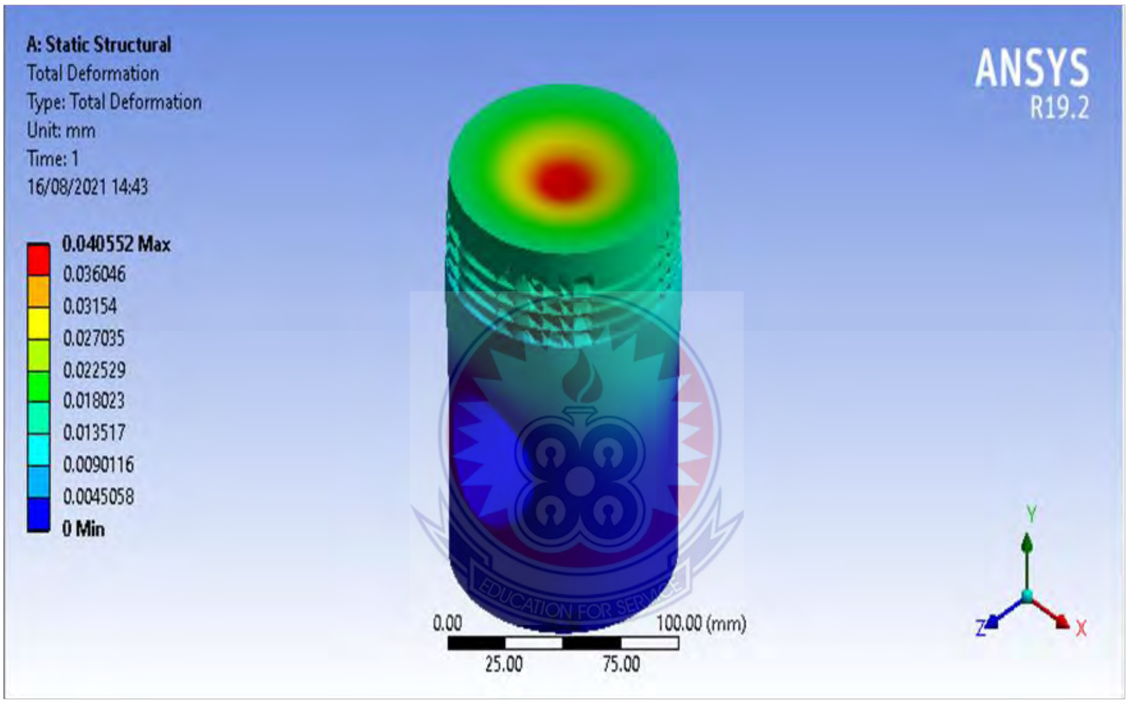


Figure 4. 2: Equivalent Elastic strain for Al 413 piston

Figure 4.2 shows the equivalent elastic strain induced in the piston made of Al 413. It was observed that maximum equivalent strain occurred at the centre of the piston crown where the maximum deformation also occurred. The maximum equivalent strain that occurred at the centre of the piston crown was of a magnitude of 0.00034904 mm. It was evident that, the first land of the piston suffered minimum equivalent elastic strain as compared to the induced strain that occurred at the centre of the piston crown. From the third piston ring groove up to the upper part of the piston boss also suffered averagely severe equivalent elastic strain of about 0.00020971 mm. It was again observed that below the piston boss up to the end of the piston did not suffer any visible form of equivalent elastic strain.

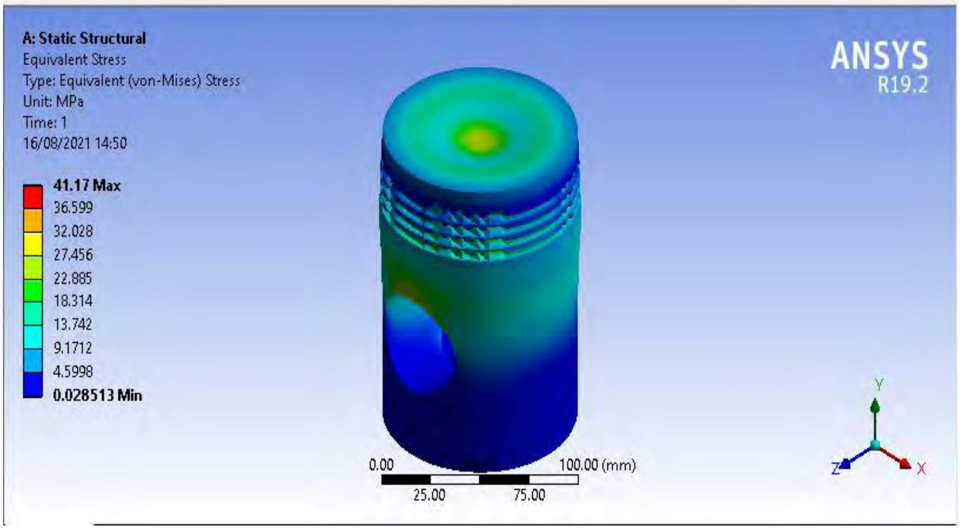


Figure 4.3: Equivalent Von Mises Stress Al 413 piston

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 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 boss. The induced Von Mises stresses are far lower compared to the compressive and tensile yield strengths of 131MPa and 131MPa respectively for the Al 413 material. The above results suggest that the model can therefore withstand the given loading condition.

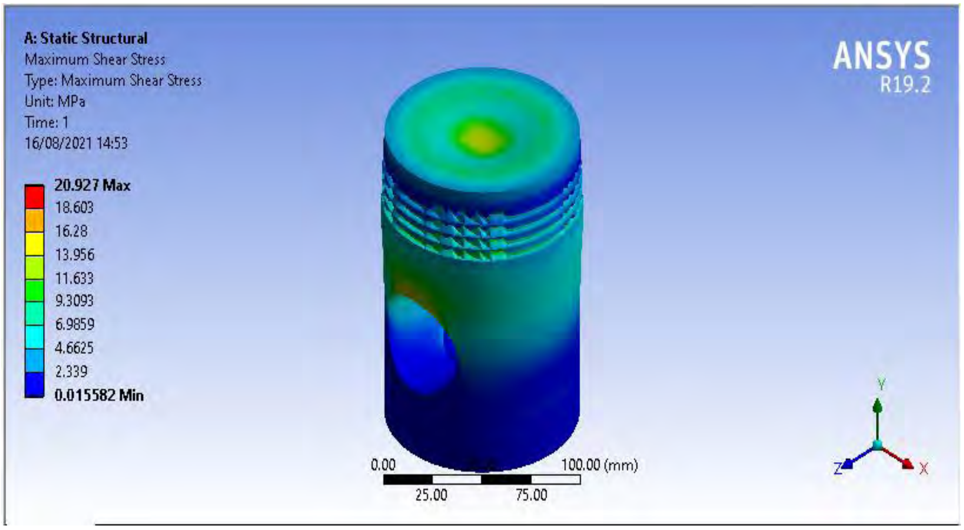


Figure 4.4: Equivalent Shear Stress for Al 413 piston

Figure 4.4 shows the induced shear stress of the Al 413 alloy material piston. It was 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 are consistent with the normal direct stress shown in Figure 4.3. It was 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.

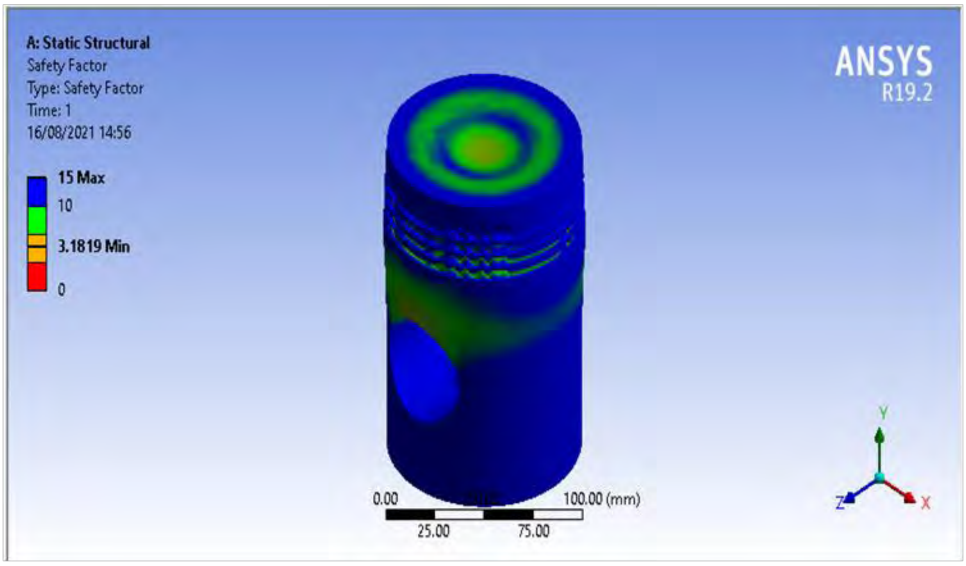


Figure 4.5: Factor of Safety of Al 413 piston

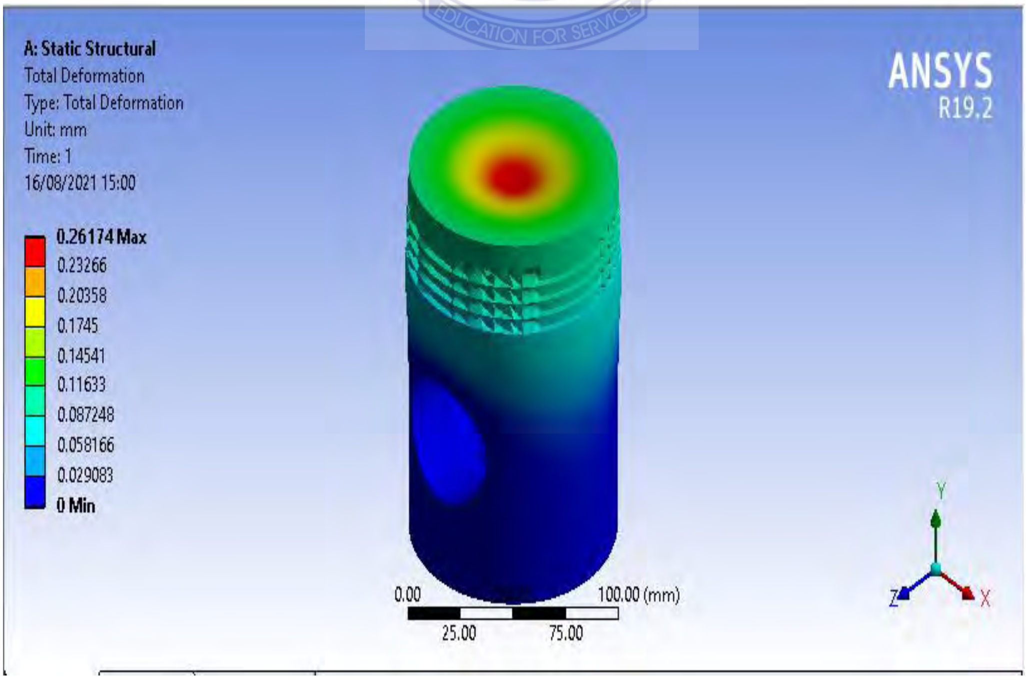
The Ansys generated factor of safety for Al 413 alloy piston model has a maximum and minimun factor of safety range magnitudes of 15 and 3.1819 respectively. The factor of safety was generally observed to be maximum at most parts of Al 413 alloy piston. The centre of the piston crown was observed to have a low factor of safety than the other parts. The model is therefore very safe.

Table 4. 1 Summarised Results for Al 413 Alloy Piston

Parameters	**Maximum**	**Minimum**
Total deformation	$0.040552\ mm$	$0.0045058\ mm$
Equivalent Elastic Strain	0.0062772	6.981×10^{-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

Table 4.1 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



A: Static Structural
Total Deformation
Type: Total Deformation
Unit: mm
Time: 1
16/08/2021 15:00

Figure 4.6: Total deformation for Al 384 alloy piston

Figure 4.6 shows the total deformation of aluminium 384 alloy piston. It was 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 0.1745 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.

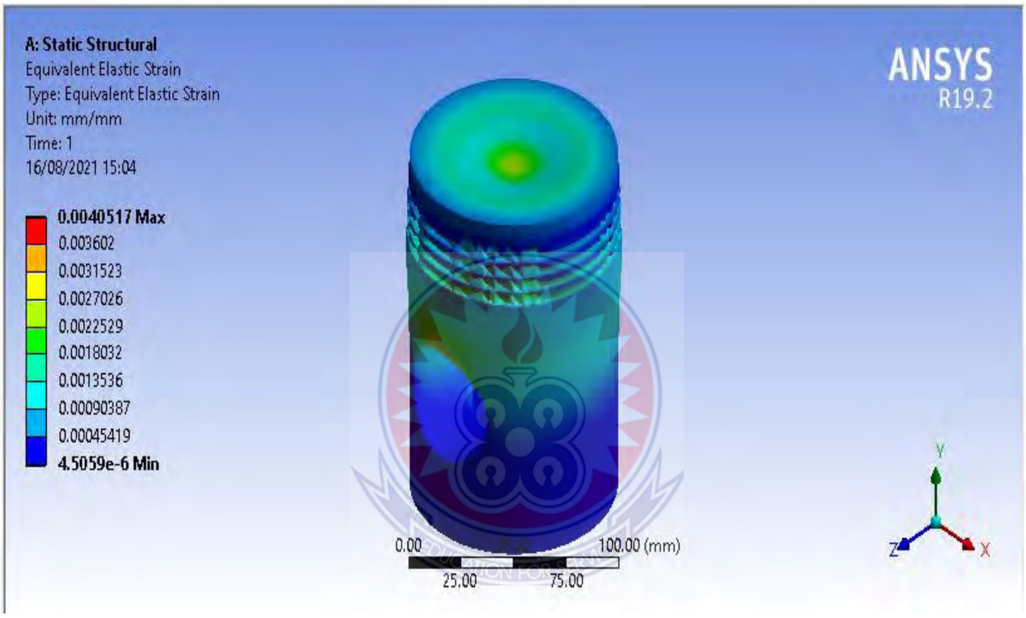


Figure 4. 7: Equivalent elastic strain for Al 384 piston

Figure 4.7 shows the simulated results on equivalent elastic strain for aluminium 384 alloy piston. It was observed that maximum equivalent elastic strain occurred at the centre of the piston crown where the maximum deformation also occurred. The maximum equivalent elastic strain that occurred at the centre of the piston crown has a magnitude of 0.022529 mm. It was evident that, the first land of the piston did not suffer much strain as compared to the centre of the piston crown. From the third piston ring groove up to the upper part of the piston boss also suffered averagely severe equivalent elastic strain of about 0.0013536 mm. It was again observed that below the piston boss up to the end of the piston did not suffer any visible form equivalent elastic strain. Hence, the model piston made of aluminium 384 alloy will be able to withstand the imposed gas load.

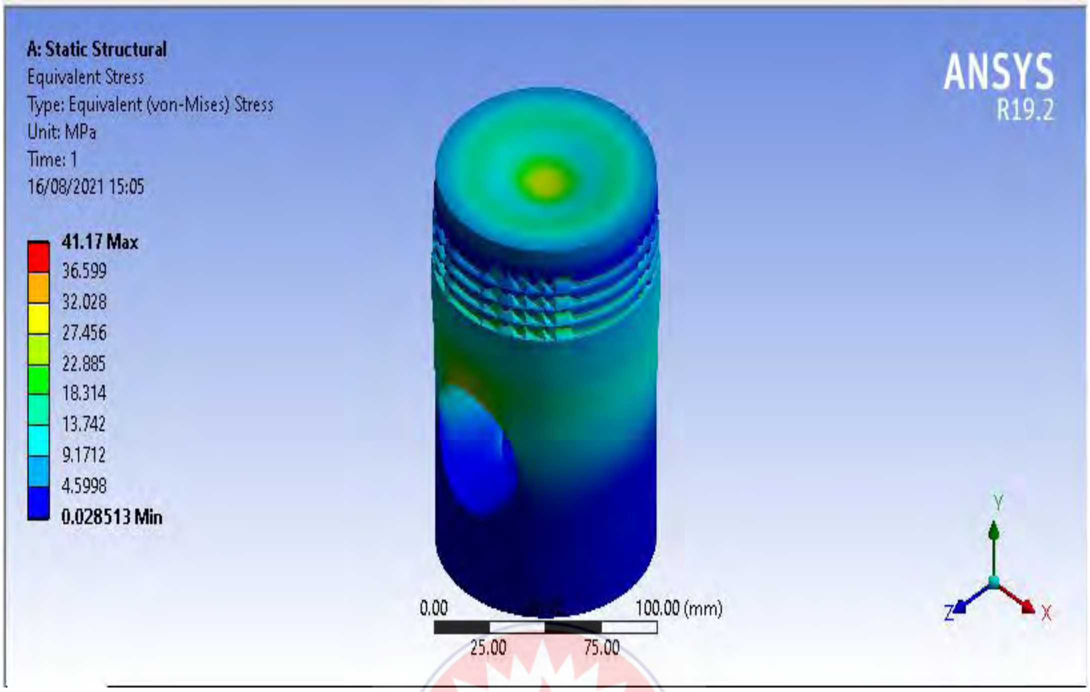


Figure 4. 8: Equivalent Von Mises Stress for Al 384 piston

The equivalent Von Mises stress is one of the most important parameters that were used to determine the suitability of a 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. 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.

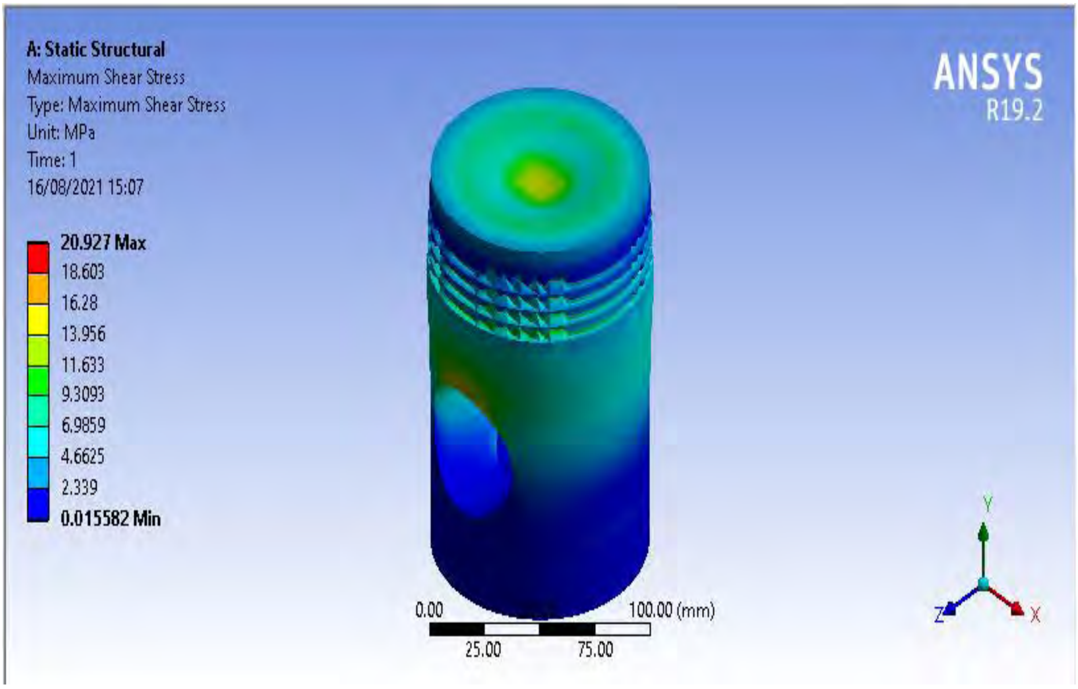


Figure 4. 9: Maximum shear stress for Al 384 piston

Figure 4.9 shows the induced maximum shear stress of the Al 384 alloy piston. It was 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 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 predicted that the piston made with Al 384 can withstand the shear load that the burnt gases will impose on the piston.

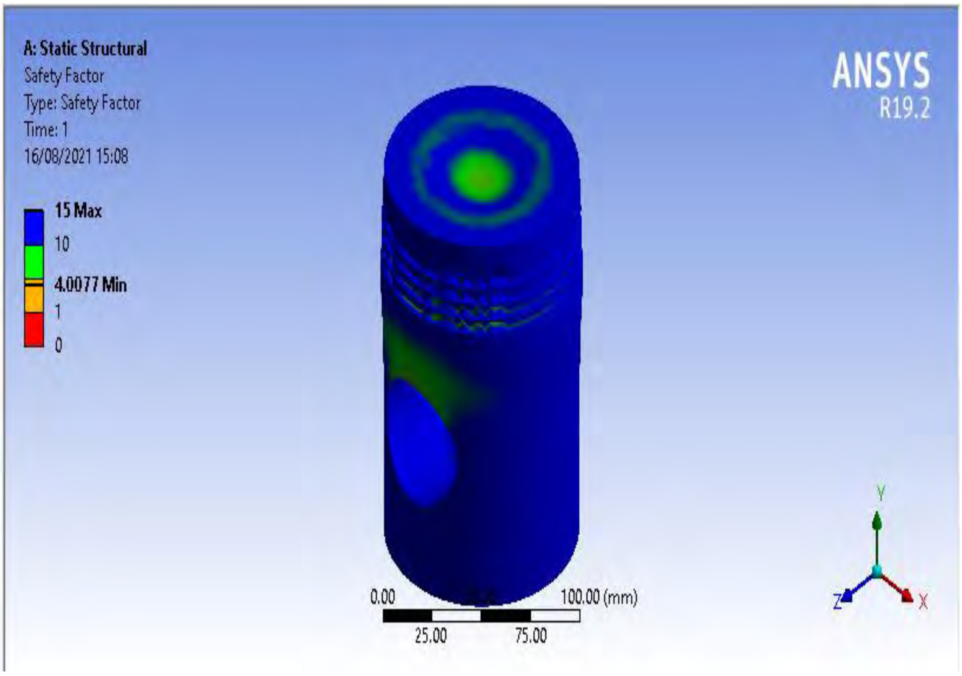


Figure 4. 10: Factor of safety for Al 384 piston

The Ansys generated factor of safety for Al 384 alloy piston madel 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 384 alloy piston. The centre of the piston crown was observed to have a low factor of safety than the other parts. The model piston is therefore very safe.

Table 4. 2 Summarised Results for Al 384 Alloy Piston

Parameters	**Maximum**	**Minimum**
Total deformation	$0.26174\ mm$	$0.029088\ mm$
Equivalent Elastic Strain	0.0040517	4.5059×10^{-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

Table 4.2 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

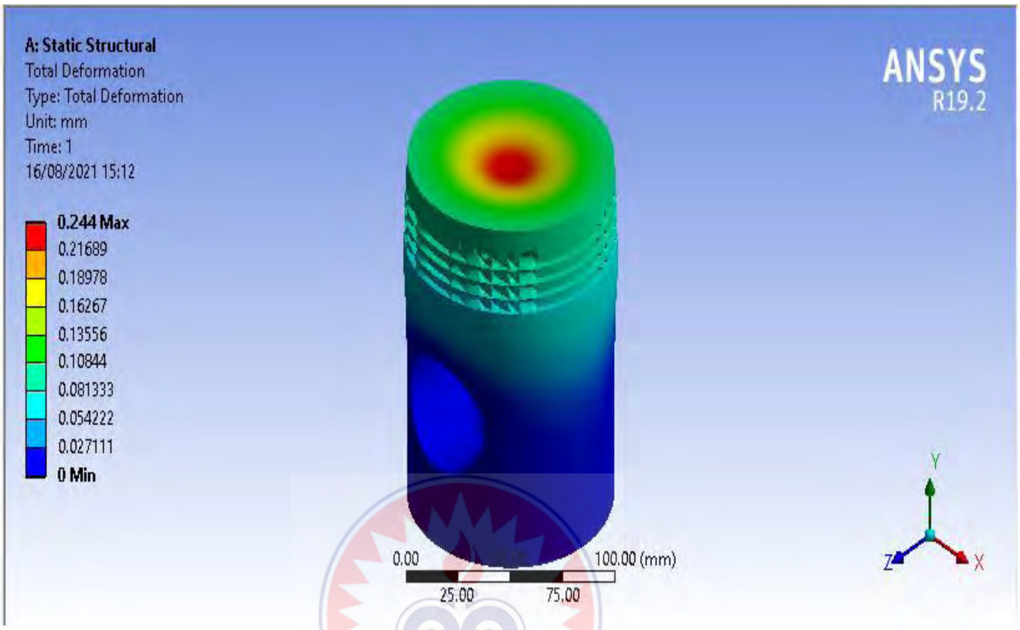


Figure 4. 11: Total deformation for Al 390 alloy piston

Figure 4.11 shows the total deformation of aluminium 390 alloy piston alloy. It was 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.

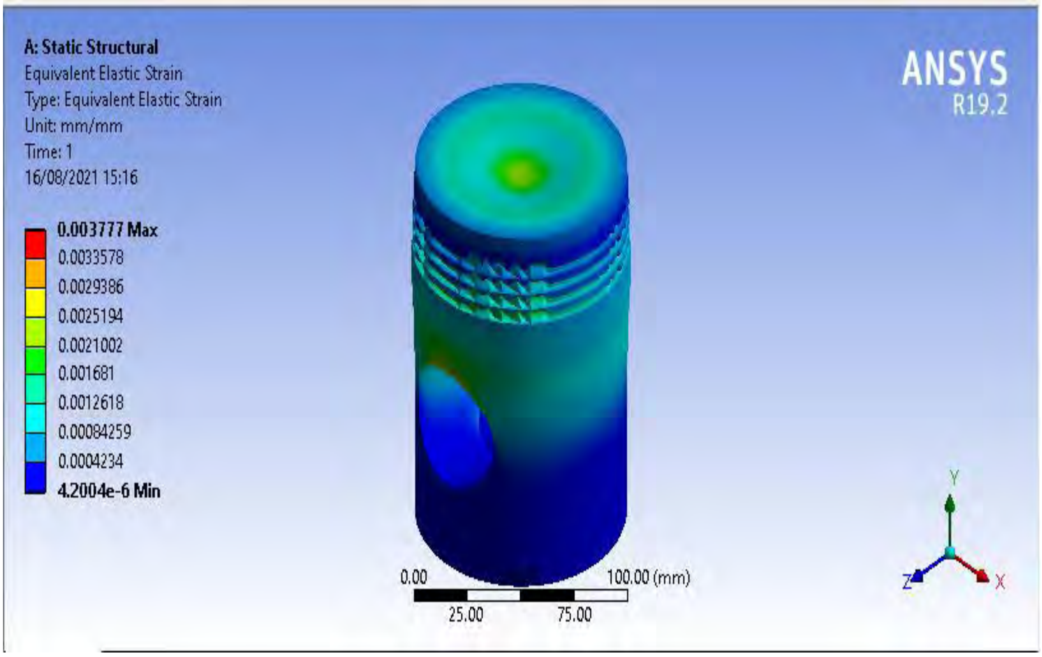


Figure 4. 12: Equivalent elastic strain for Al 390 alloy piston

Figure 4.12 shows the maximum equivalent elastic strain of the aluminium 390 alloy piston when the maximum gas load was imposed. It was observed that, the maximum equivalent elastic strain occurred at the centre of the piston crown where the maximum deformation also occurred. The maximum equivalent elastic strain that occurred at the centre of the piston crown was of a magnitude of 0.003777 mm. It was evident that, the first land of the piston suffered minimum equivalent elastic strain as compared to the centre of the piston crown. From the third piston ring groove up to the upper part of the piston bosses also suffered averagely severe equivalent elastic strain of about 0.00084259 mm. It was again observed that below the piston boss up to the end of the piston did not suffer any visible form of equivalent elastic strain. Hence, the piston made with aluminium 390 alloy will be able to endure the induced equivalent elastic strain.

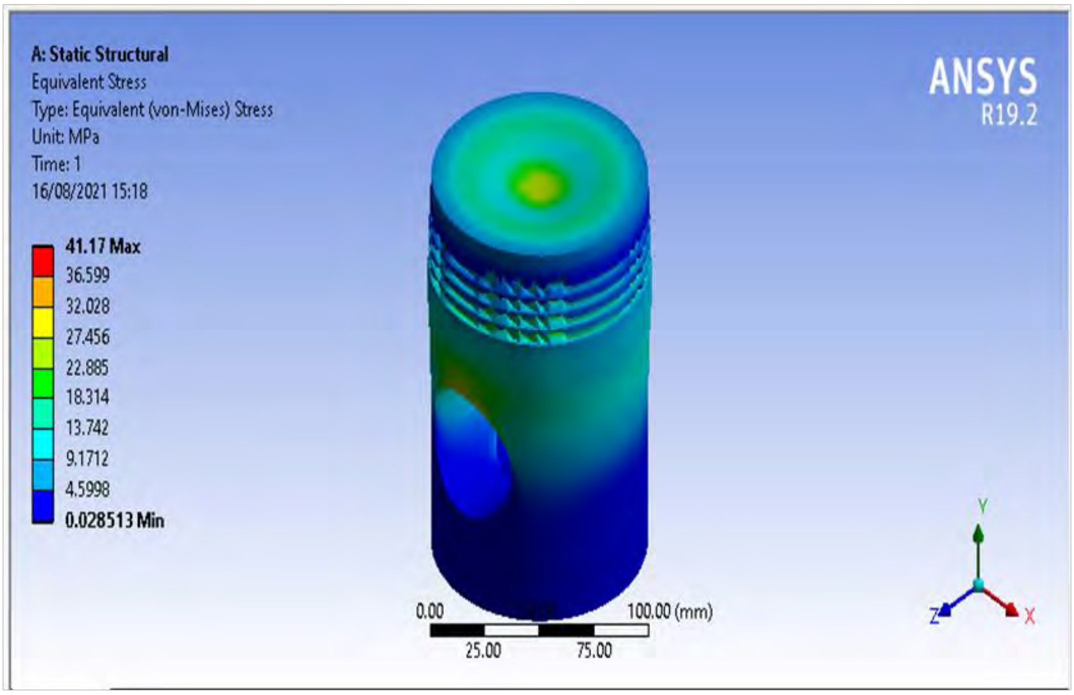


Figure 4. 13: Equivalent Von Mises Stress for Al 390 alloy piston

Figure 4.13 shows one of the most important parameters for this study which is equivalent Von Mises stress. 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. 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 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 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.

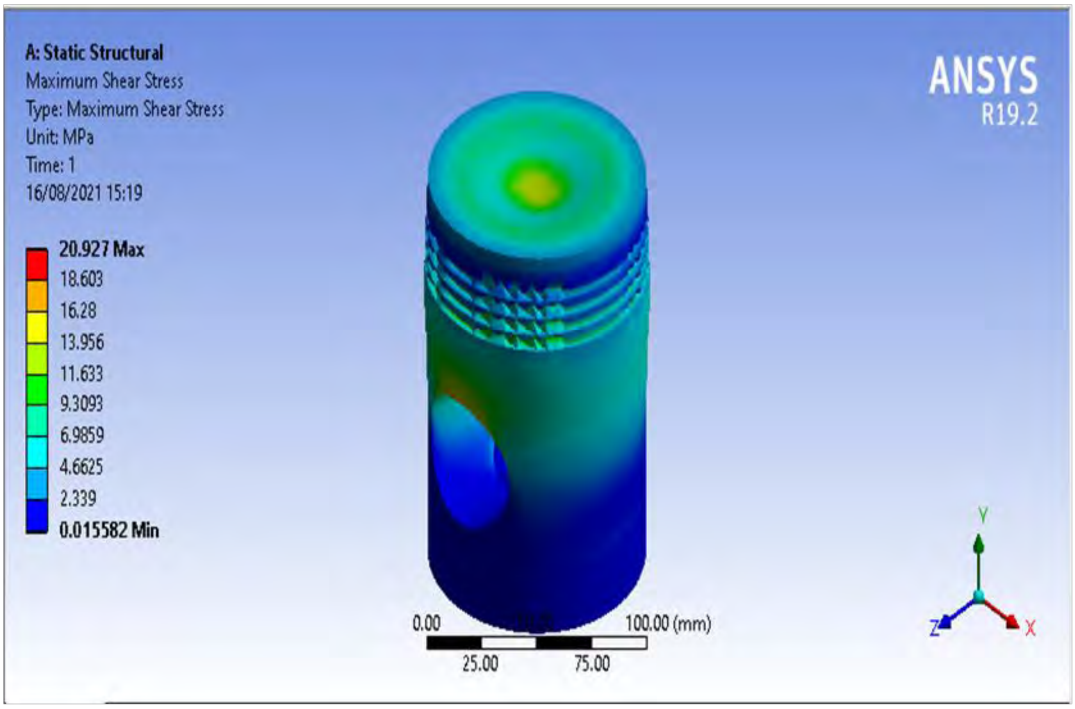


Figure 4. 14: Maximum shear stress for Al 390 alloy piston

Figure 4.14 shows the induced shear stress of the Al 390 alloy piston. It was 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 with the normal direct stress. It was also observed that, the 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.

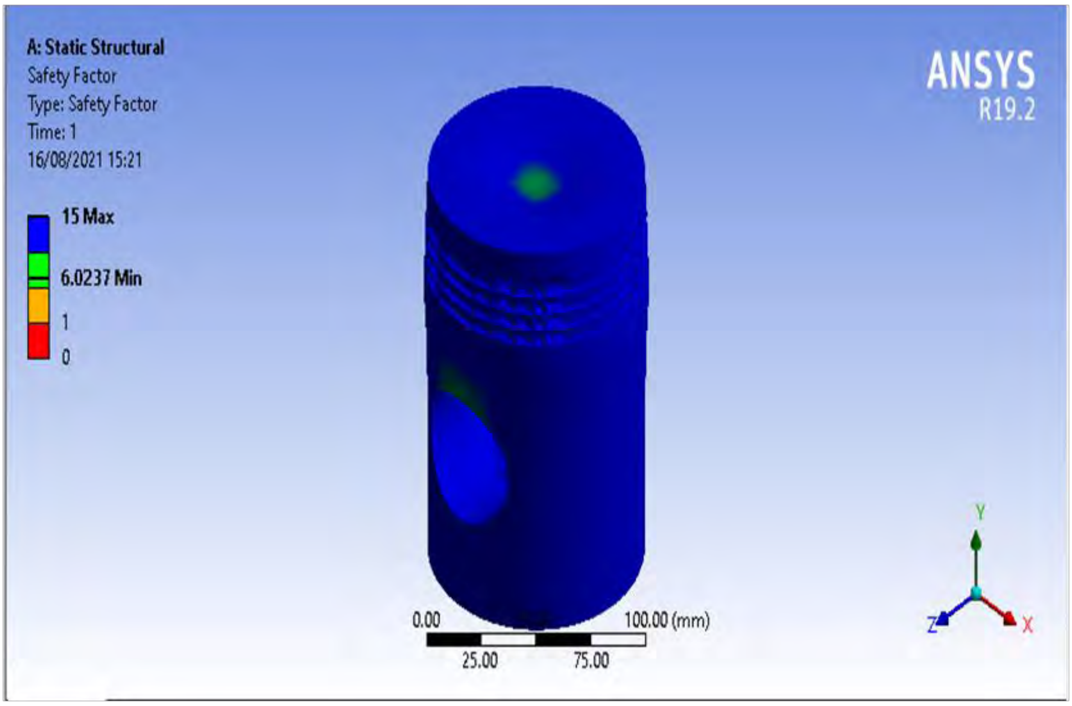


Figure 4. 15: Factor of safety of Al 390 alloy piston

The Ansys generated factor of safety for Al 390 alloy piston madel 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 4. 3 Summarised Results for Al 384 Alloy Piston

Parameters	**Maximum**	**Minimum**
Total deformation	$0.244\,mm$	$0.027111\,mm$
Equivalent Elastic Strain	0.003777	4.200×10^{-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

Table 4.3 shows the summarised results for Al 390 alloy piston when the static structural analysis was conducted in Ansys software.

d. Aluminium alloy 332 material results

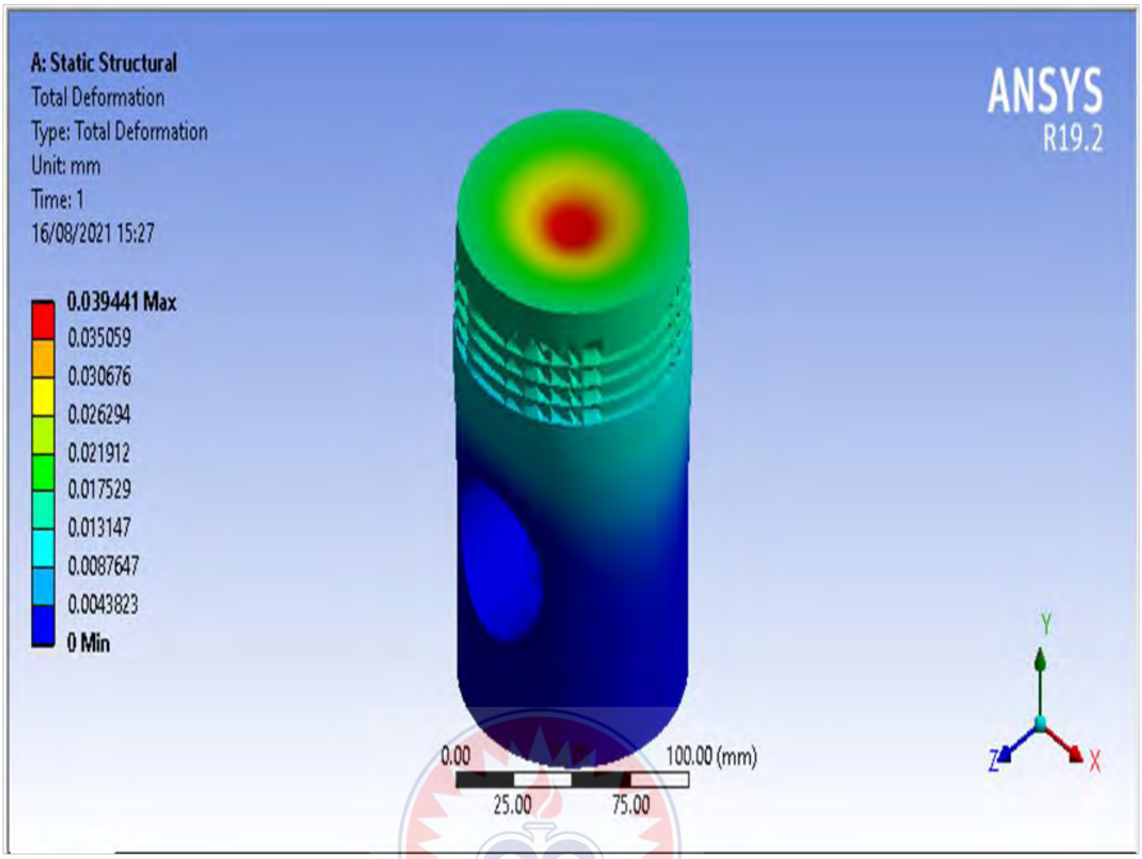


Figure 4. 16: Total deformation for Al 332 alloy piston

Figure 4.16 shows the total deformation of aluminium 332 piston alloy. It was 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.

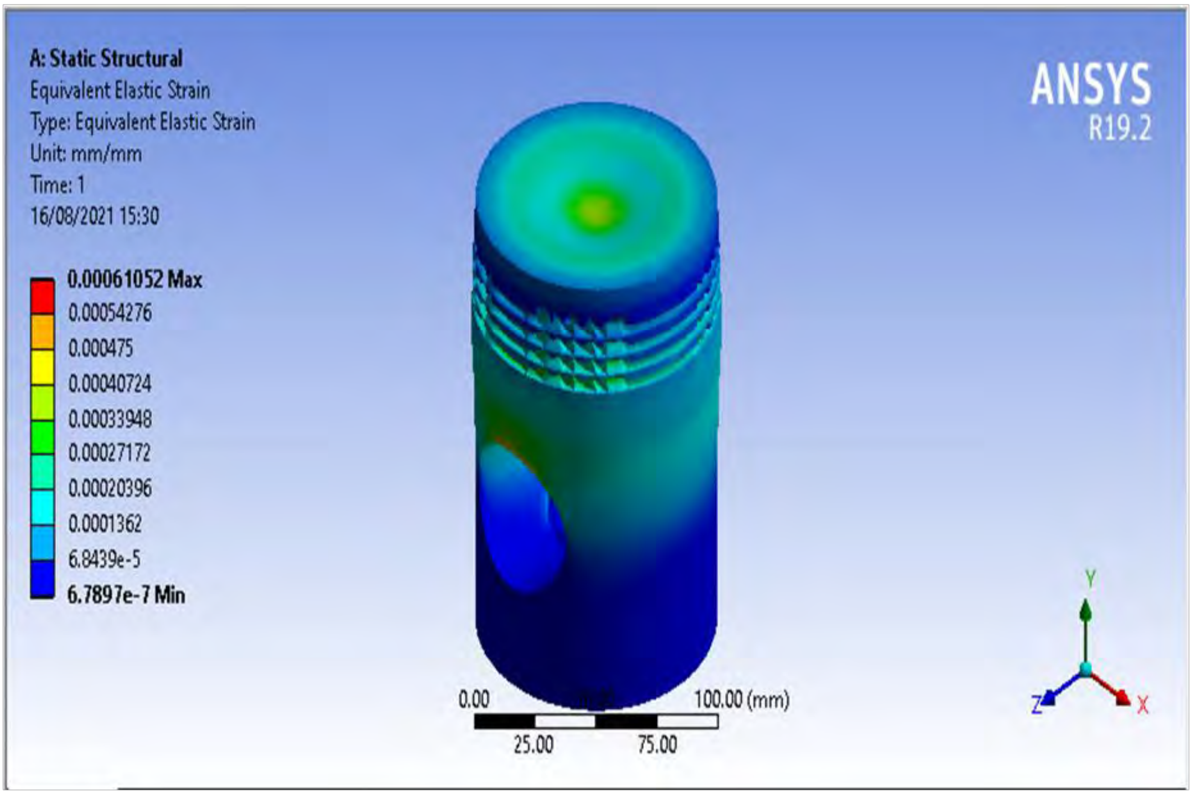


Figure 4. 17: Equivalent elastic strain for Al 332 alloy piston

From Figure 4.17, it was observed that maximum equivalent elastic strain occurred at the centre of the piston crown where the maximum deformation also occurred. The maximum equivalent elastic strain that occurred at the centre of the piston crown was of a magnitude of 0.00061052 mm. It was evident that, the first land of the piston did not suffer much strain as compared to the centre of the piston crown. From the third piston ring groove up to the upper part of the piston bosses also suffered averagely mild equivalent elastic strain of about 0.00020396 mm. It was again observed that below the piston bosses up to the end of the piston did not suffer any visible form of equivalent elastic strain.

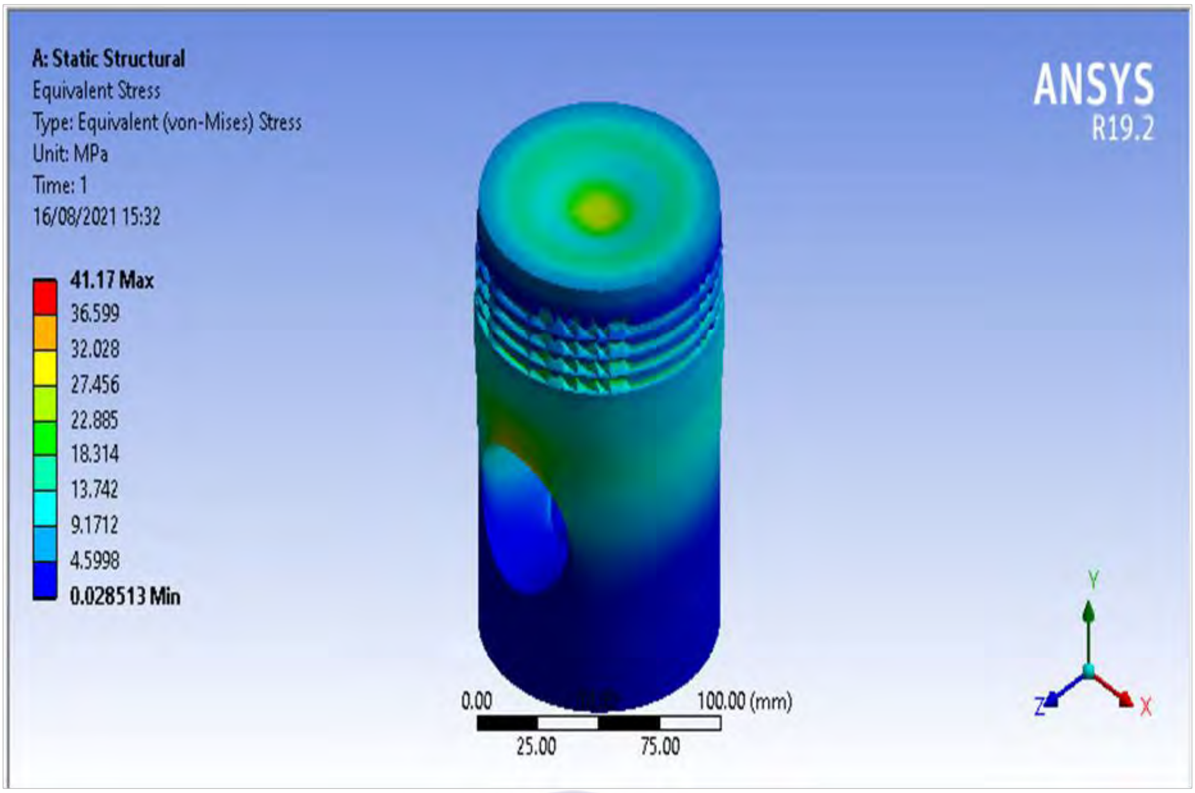


Figure 4. 18: Equivalent Von Mises Stress for Al 332 alloy piston

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. 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 can therefore withstand the given loading condition.

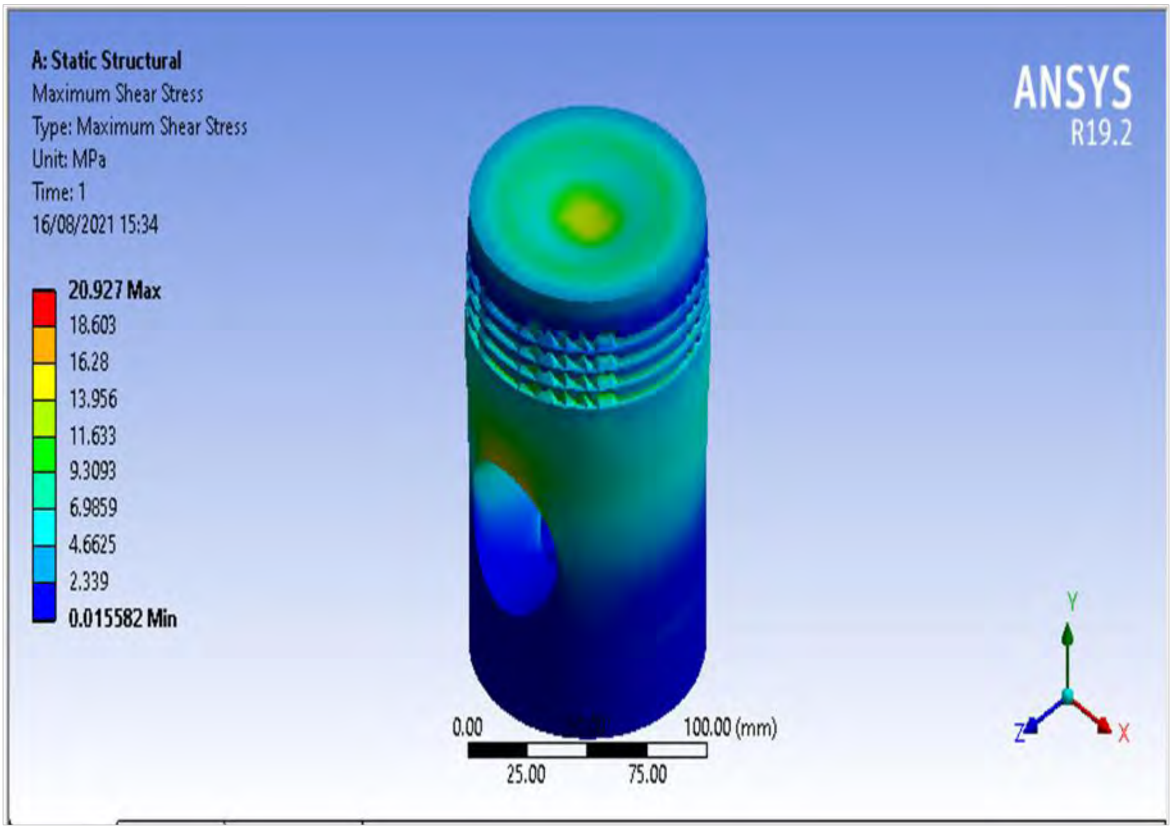


Figure 4. 19: Maximum shear stress for Al 332 alloy piston

Figure 4.19 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 piston crown. The characteristics of the induced shear stress are consistent with the normal direct stress. It was observed that, the 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.

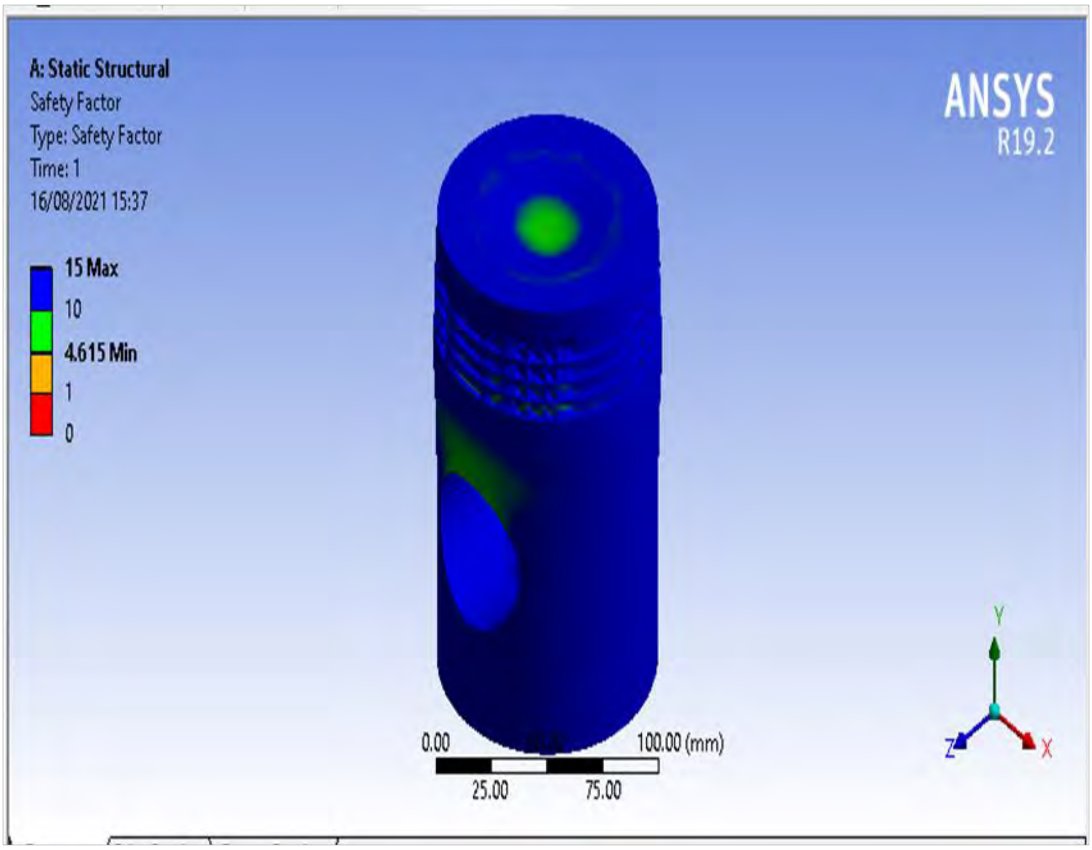


Figure 4. 20: Factor of safety for Al 332 alloy piston

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. 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 4. 4 Summarised Results for Al 332 Alloy Piston

Parameters	**Maximum**	**Minimum**
Total deformation	$0.039441 mm$	$0.0043823\ mm$
Equivalent Elastic Strain	0.0061052	6.789×10^{-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

Table 4.4 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

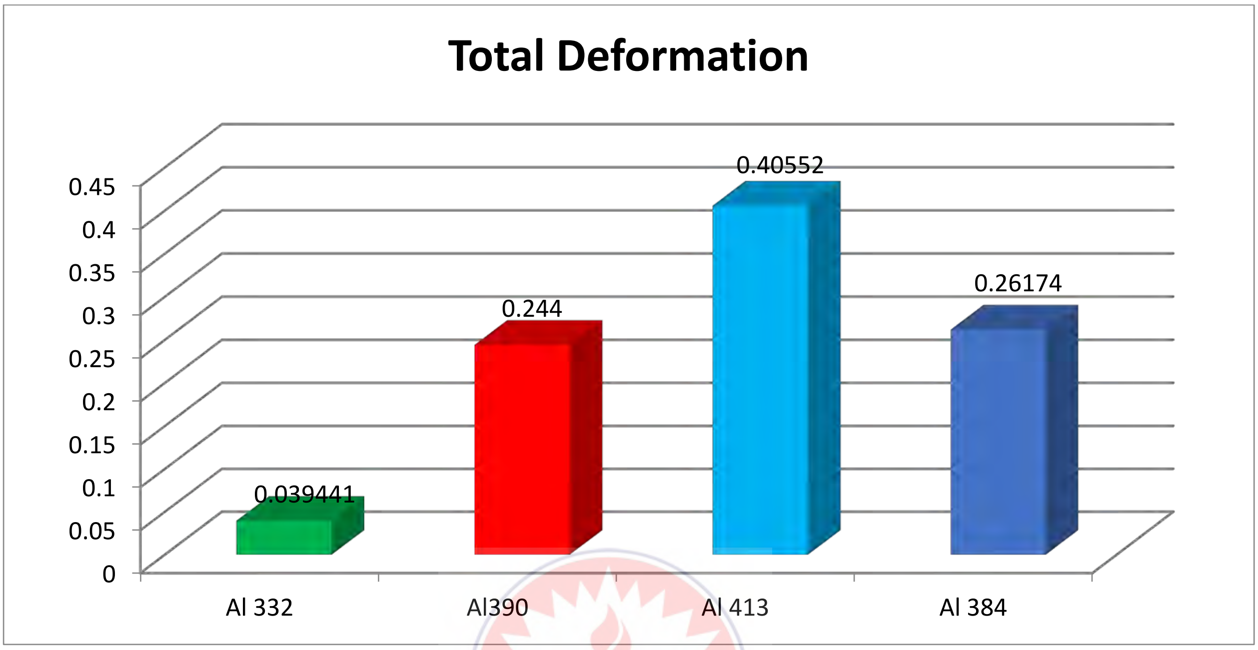


Figure 4. 21: Comparison of Total Deformation of the four different materials

Figure 4.21 shows 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 on total deformation were compared as presented in Figure 4.21 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 representing27.53%. 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 describe to be fit for purpose.

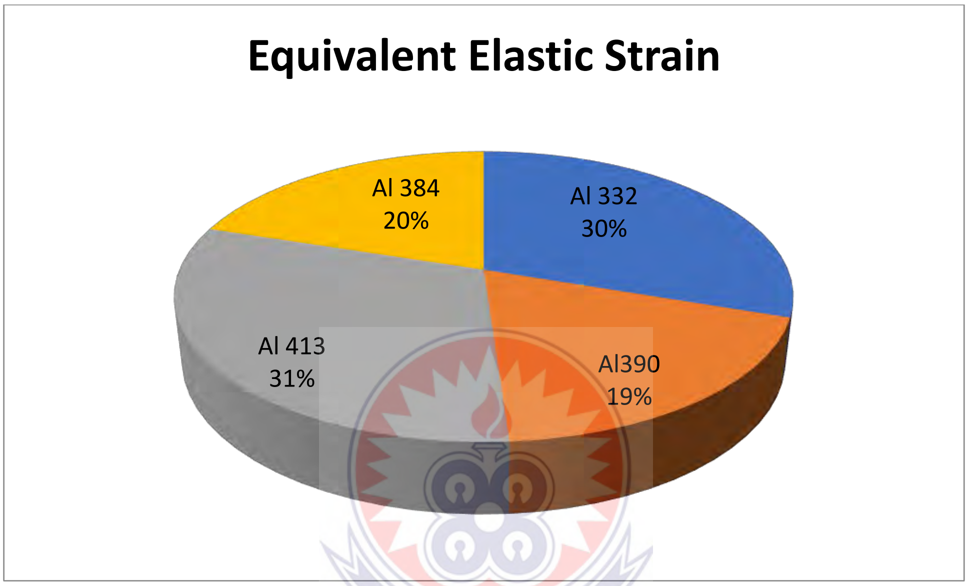


Figure 4. 22: Comparison of Equivalent Elastic Strain of all the Four Materials

Figure 4.22 shows the comparison of equivalent elastic strains of the piston of four different materials, namely: aluminium 390 alloy, aluminium 332 alloy, aluminium 413 alloy and aluminium 384 alloy. The equivalent elastic strain was used to measure the extent of deformation or the impact made by the deformation on the. When the results were compared, it was observed that, aluminium 390 alloy suffered an equivalent elastic strain of 003777 mm representing 19 % of the total elastic strain suffered by the four pistons made of the different materials, aluminium 332 alloy suffered equivalent elastic strain of 0.006105 mm representing 30 %, the implementing material which is aluminium 413 alloy piston suffered an equivalent elastic strain of 0.0062772 mm representing 31 %, and aluminium 384 alloy piston suffered an equivalent elastic strain of 0.0040517 mm representing 20%. It was evident from Figure 4.22 that, aluminium 390 alloy piston suffered the least equivalent elastic strain of 0.003777 mm. The difference in percentage terms between the implementing material which is aluminium 413 alloy and aluminium 332 alloy is just 1.0 % which is woefully insignificant to bring any changes between the equivalent elastic strains of the pistons made of these two materials. Hence, it is convenient to say that, aluminium 390 alloy have superior properties to resist elastic strain better than the remaining three materials. In general, the equivalent elastic strain suffered by the pistons of all the four materials is not significant enough to affect the operation of the piston in a live internal combustion engine. Therefore, all the pistons made of these materials will be fit for purpose.

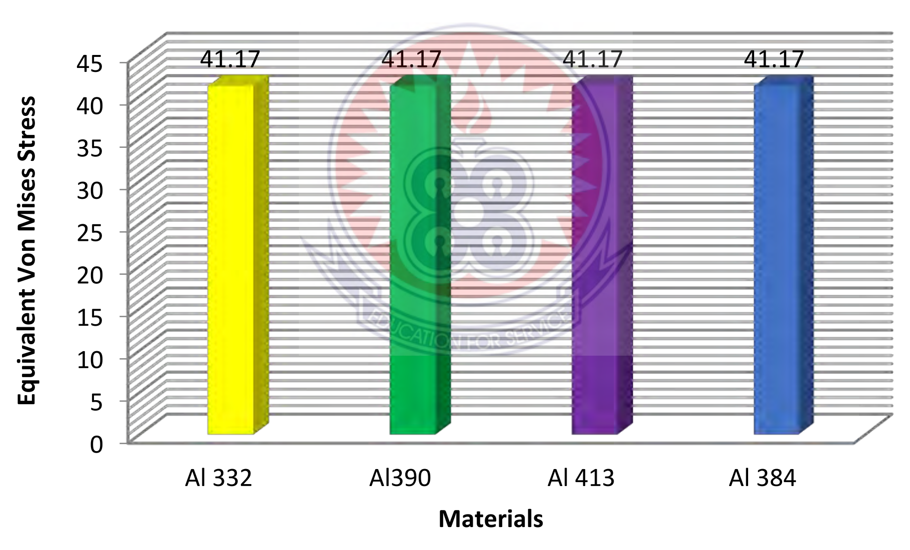


Figure 4. 23. Comparison of Equivalent Von Misese Stress of all the Four Materials

Figure 4.23 presents the results of the equivalent Von Mises stresses, of the model 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. When the Von Mises stresses induced in the piston made of the four different materials were compared as shown in Figure 4.23, the results shows that the induced stress yielded in the aluminium 390 alloy piston was 41.17MPa representing 25%. It was very interesting 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.

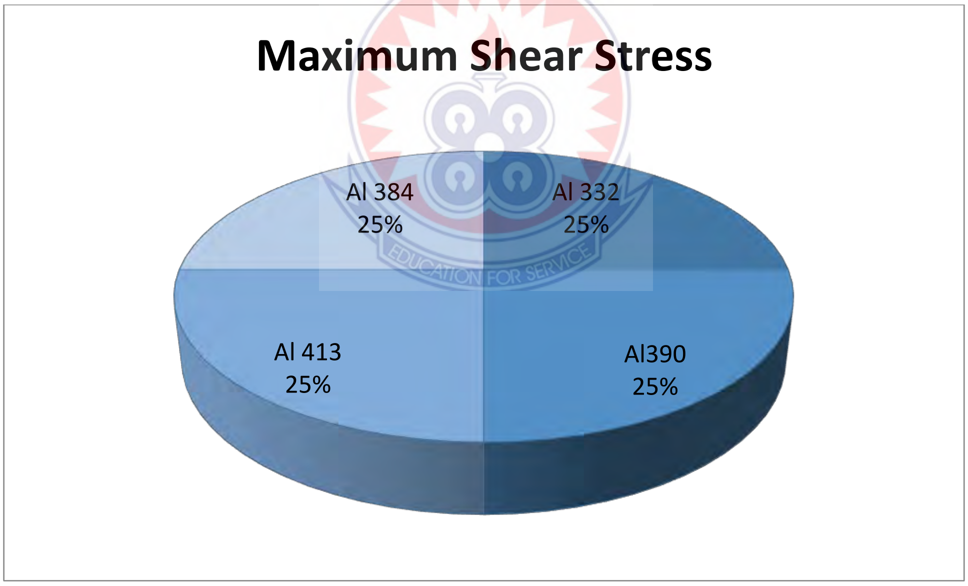


Figure 4. 24. Comparison of Maximum Shear Stress of all the Four Materials

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 the pie chart in Figure 4.24 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 4. 5 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

Table 4.5 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 4.5 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 enough factor of safety to be able to carry the intended load.

4.3 Thermal analysis of the pistons made of the four different materials

Introduction

The thermal analysis of the piston made with the four different materials was done in Ansys software version 2020 R2. 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 of 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 thermal analysis were: temperature, total heat flux, directional heat flux, of the four (4) different materials assigned to the model piston.

A. Aluminium 413

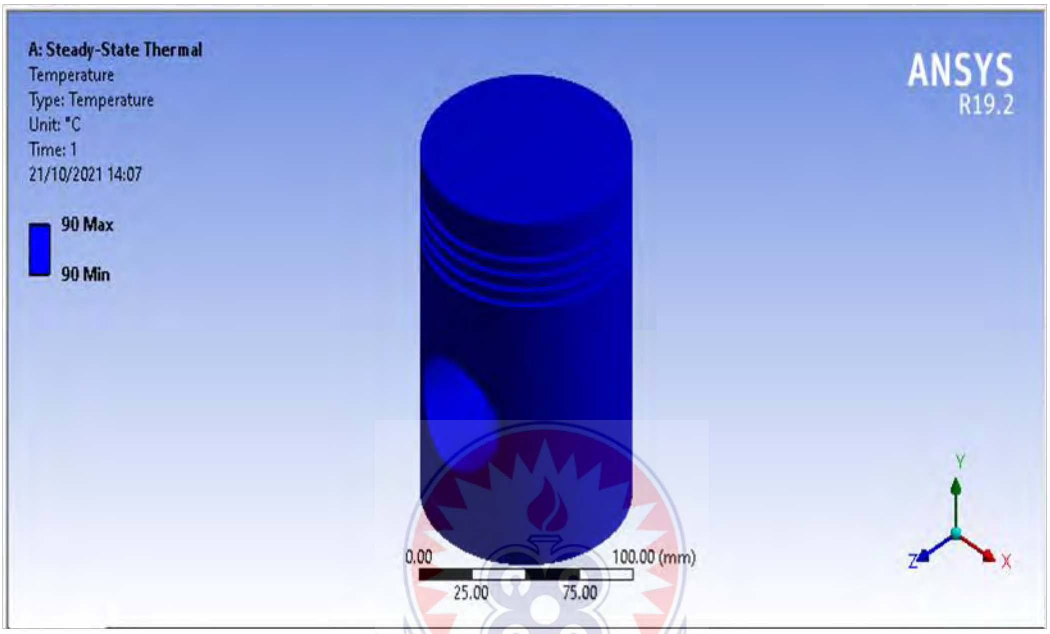


Figure 4. 25: Temperature distribution in Al 413

The thermal analysis was conducted by subjecting the pistons made of the four different materials under a temperature of 90 °C. Figure 4.25 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 will be suitable for the purpose.

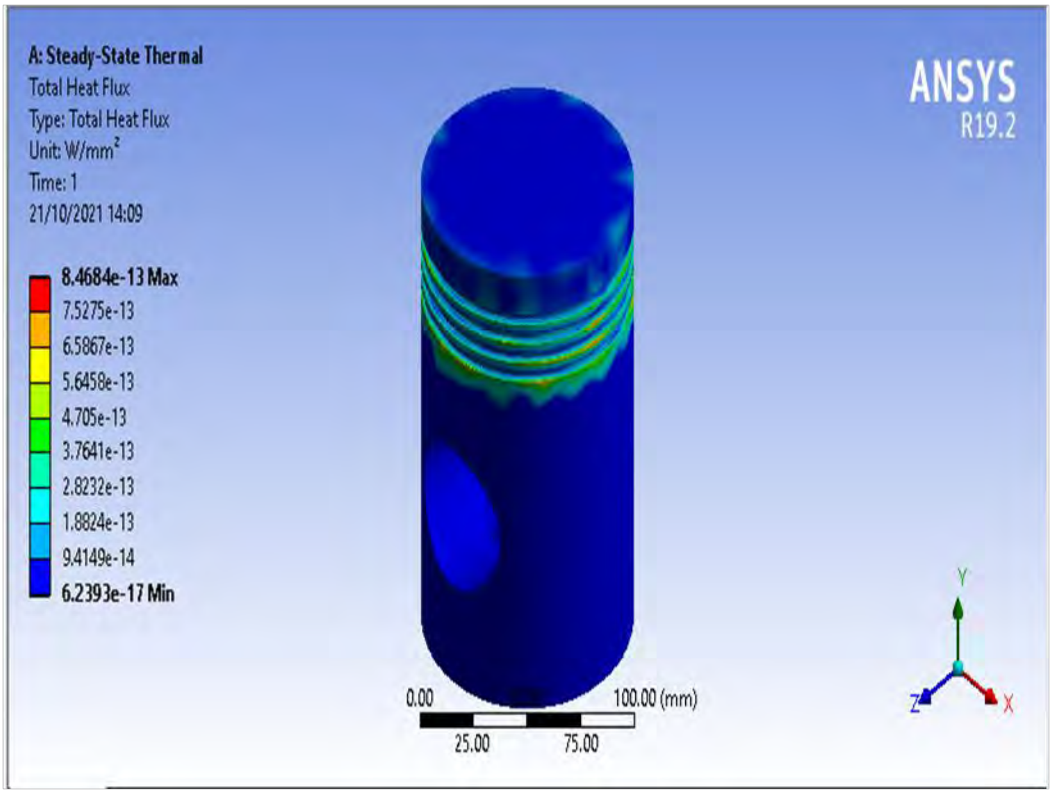


Figure 4. 26: Total Heat Flux in Al 413 Piston

Heat flux is the rate of thermal energy flow per unit surface area of heat transfer surface such as heat in an internal combustion engines. Heat flux is the main parameter used in calculating heat transfer. Figure 4.26 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 $4.705 \times 10^{-13}\,\mathrm{W/mm^2}$ 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 maximum total heat flux *of* $8.4684 \text{ x } 10^{-13}\,\mathrm{W/mm^{-13}}$ 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.

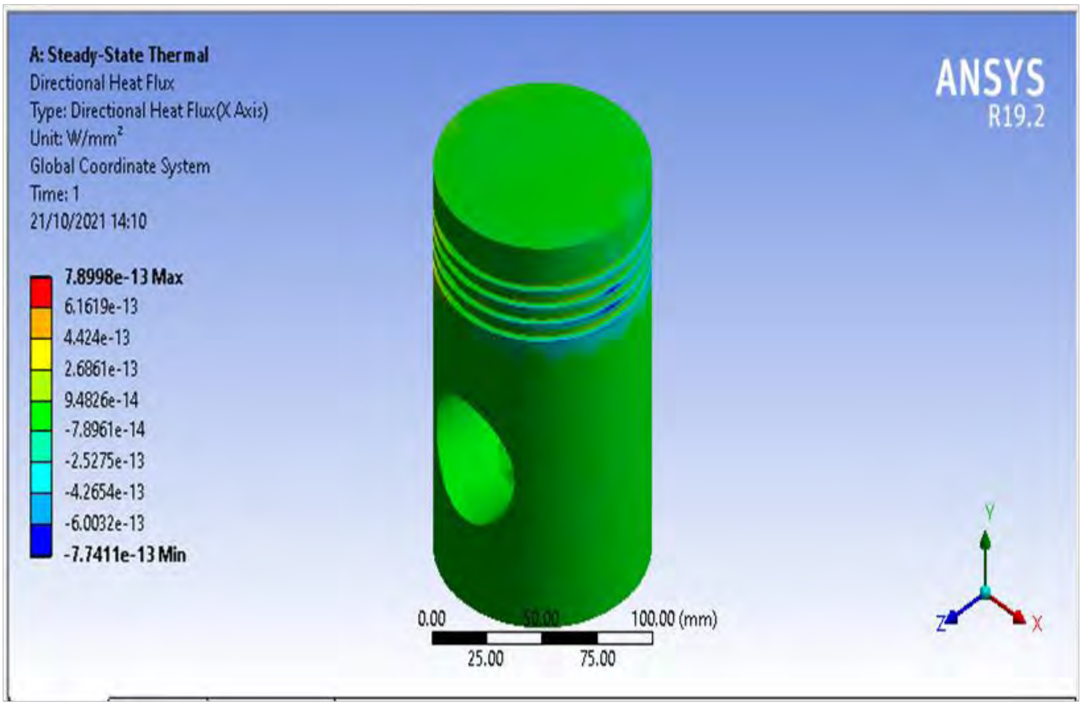


Figure 4. 27: Directional heat flux of Al 413

Heat flux is the rate of thermal energy flow per unit surface area of heat transfer surface such as heat in an internal combustion engines. Heat flux is the main parameter used in calculating heat transfer. Heat flux has both a direction and a magnitude, and so it is a vector quantity. Figure 4.27 shows the directional heat flux of aluminium 413 alloy material. It was observed that, the induced maximum directional heat flux in the aluminium 413 piston was $7.8998 \times 10^{-13}\,\mathrm{W/mm^2}$. 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 $-7.7411 \times 10^{-13}\,\mathrm{W/mm^2}$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 can therefore be considered to be fit for purpose since it can withstand the given heat condition.

B. Aluminium 384

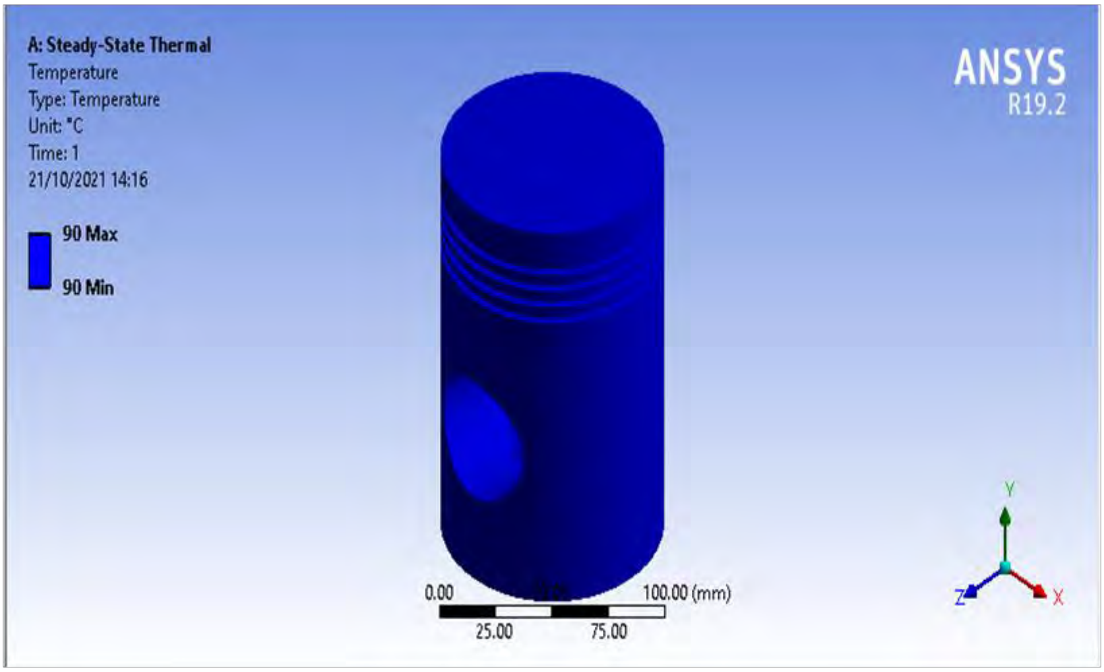


Figure 4. 28: Temperature induced in Al 384 Piston

The thermal analysis was conducted by subjecting the pistons made of the four different materials under a temperature of 90 °C. Figure 4.28 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.

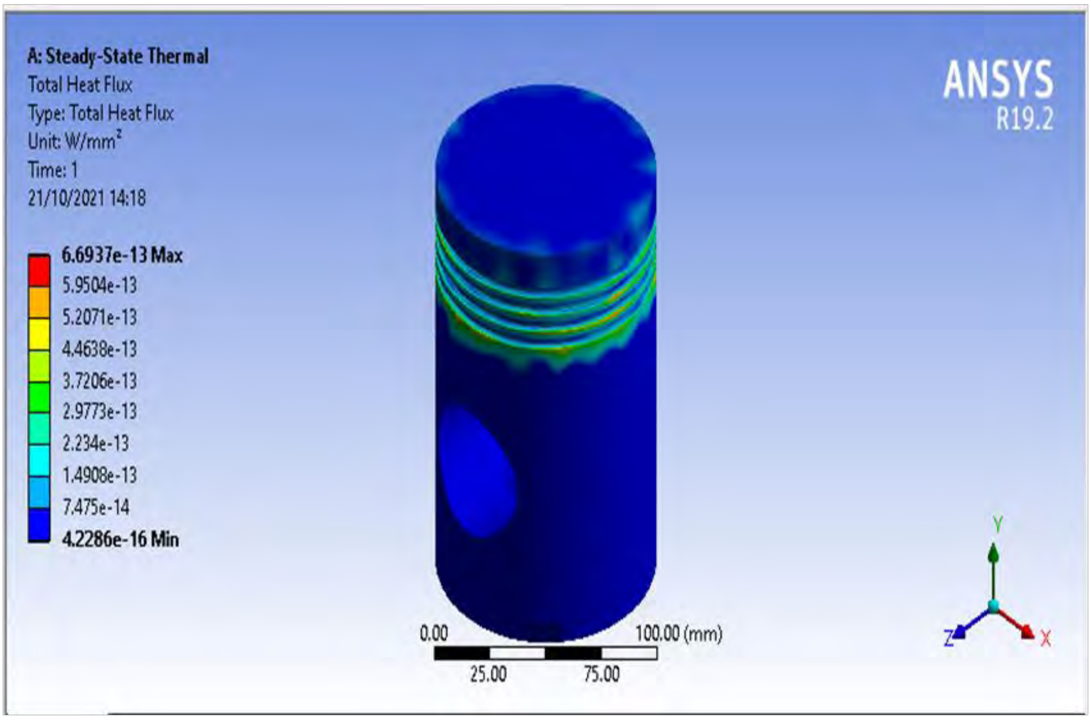


Figure 4. 29: Total heat flux induced in Al 384 piston

Figure 4.29 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 6.6937×10^{-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 engine.

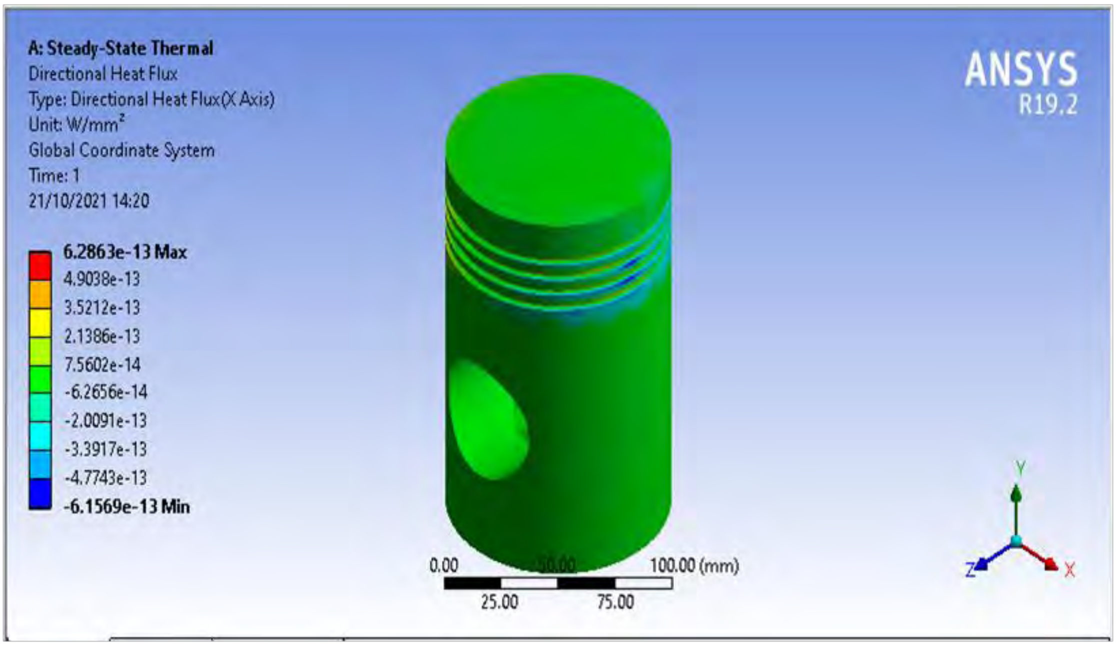


Figure 4. 30: Directional heat flux induced in Al 384 piston

Heat flux has both direction and magnitude, and so it is a vector quantity. Figure 4.30 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 $7.5602 \times 10^{-14}\,\mathrm{W/mm^2}$. The minimum induced directional heat flux of $-4.7743 \times 10^{-13}\,\mathrm{W/mm^2}$was observed to have occurred around the piston grooves. Generally, it was observed that the maximum directional heat flux of about $7.5602 \times 10^{-14}\,\mathrm{W/mm^2}$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 be considered to be fit for purpose since it can withstand the given heat condition.

C. Aluminium 390

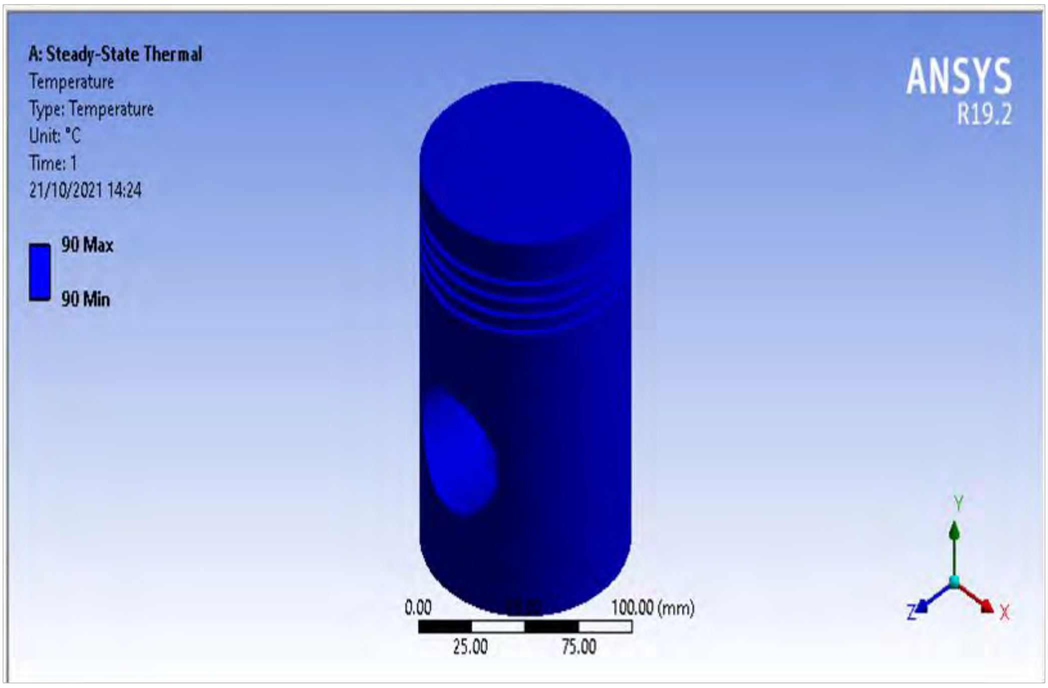


Figure 4. 31: Temperature induced in Al 390 piston

The thermal analysis was conducted by subjecting the pistons made of the four different materials under a temperature of 90 °C. Figure 4.31 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 temperature imposed. This shows that Al 390 material will be suitable for the intended purpose.

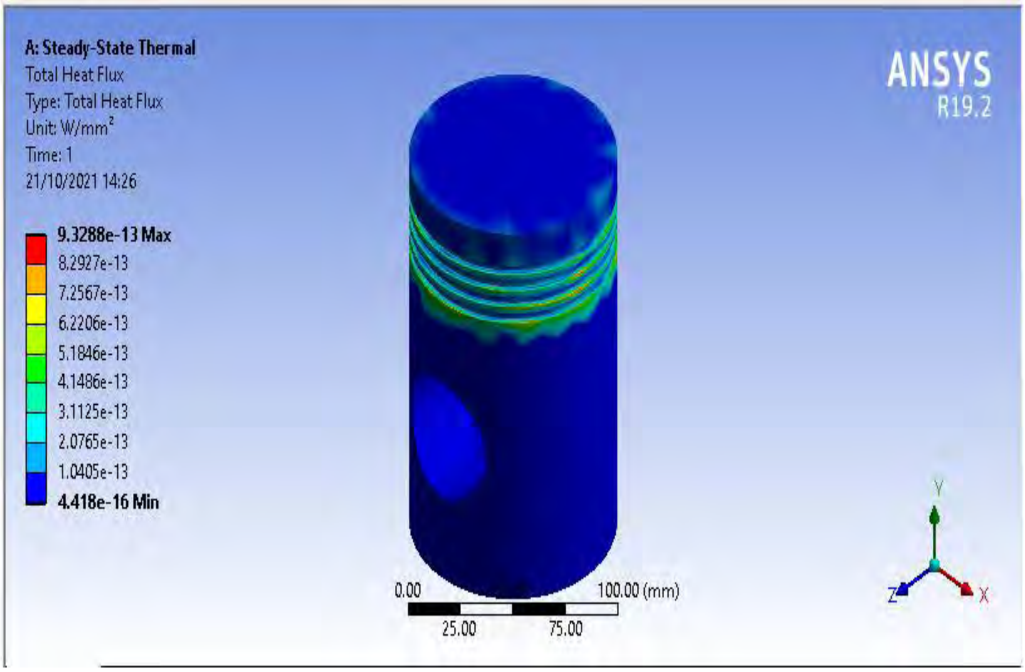


Figure 4. 32: Total heat flux induced in Al 390 piston

Figure 4.32 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 $9.4602 \times 10^{-13}\,\mathrm{W/mm^2}$ 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 engine.

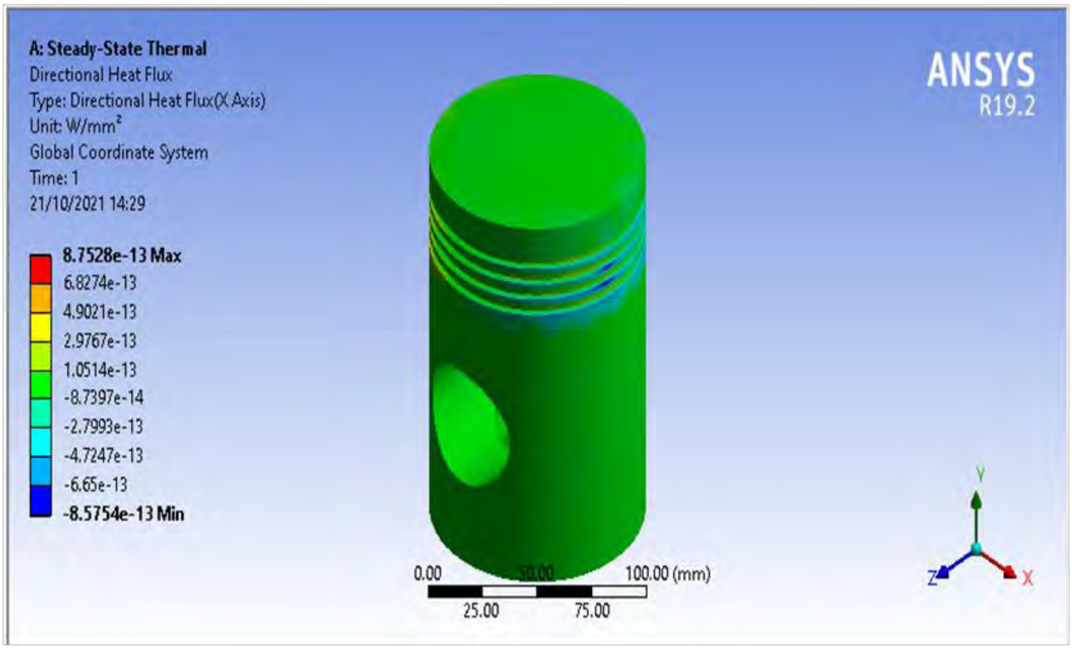


Figure 4. 33: Directional heat flux induced in Al 390

Figure 4.33 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 $8.7528 \times 10^{-13}\,\mathrm{W/mm^2}$. 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 $-8.7397 \times 10^{-13}\,\mathrm{W/mm^2}$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 considered to be fit for purpose since it can withstand the given heat condition.

D. Aluminium 332

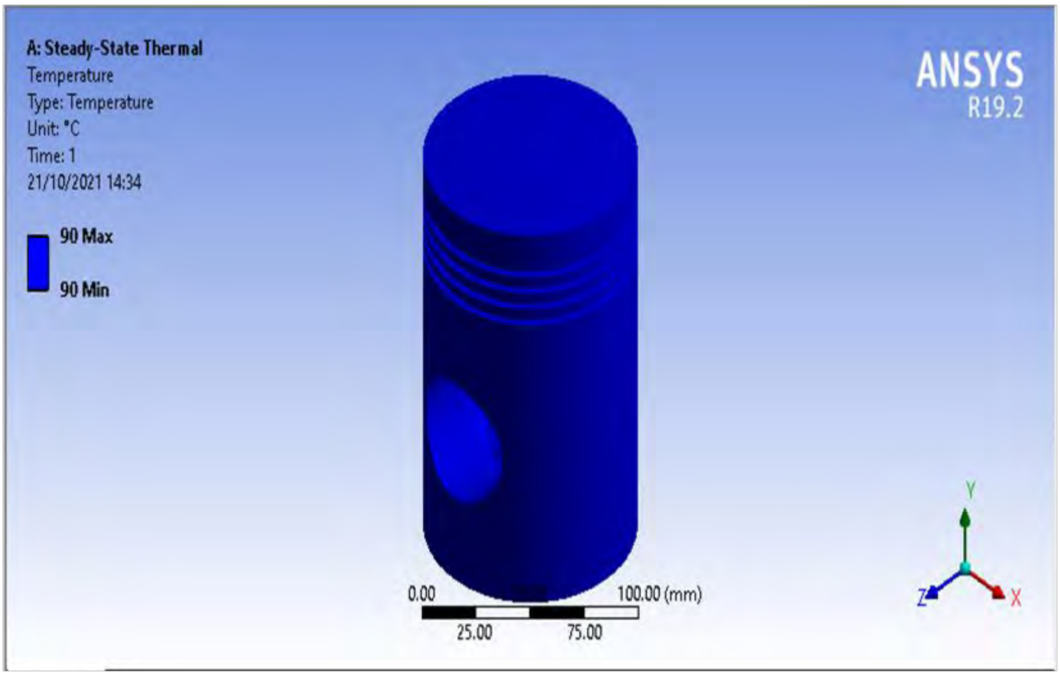


Figure 4. 34: Temperature induced in Al 332 piston

The thermal analysis was conducted by subjecting the pistons made of the four different materials under a temperature of 90 °C. Figure 4.34 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 temperature imposed. This shows that Al 332 material will be suitable for the intended purpose.

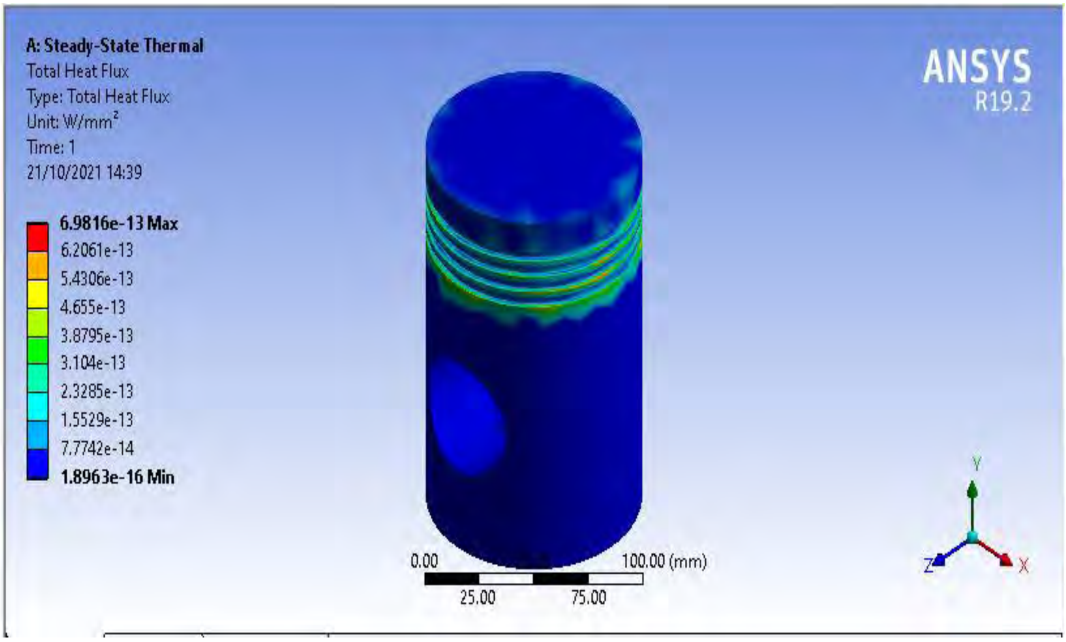


Figure 4. 35: Total heat flux induced in Al 332 piston

Figure 4.35 shows the total heat flux of aluminium 332 alloy piston when subjected under a temperature of 90 ℃. It was observed that, the maximum total heat flux of $6.9816 \times 10^{-13}\,\mathrm{W/mm^2}$ 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.

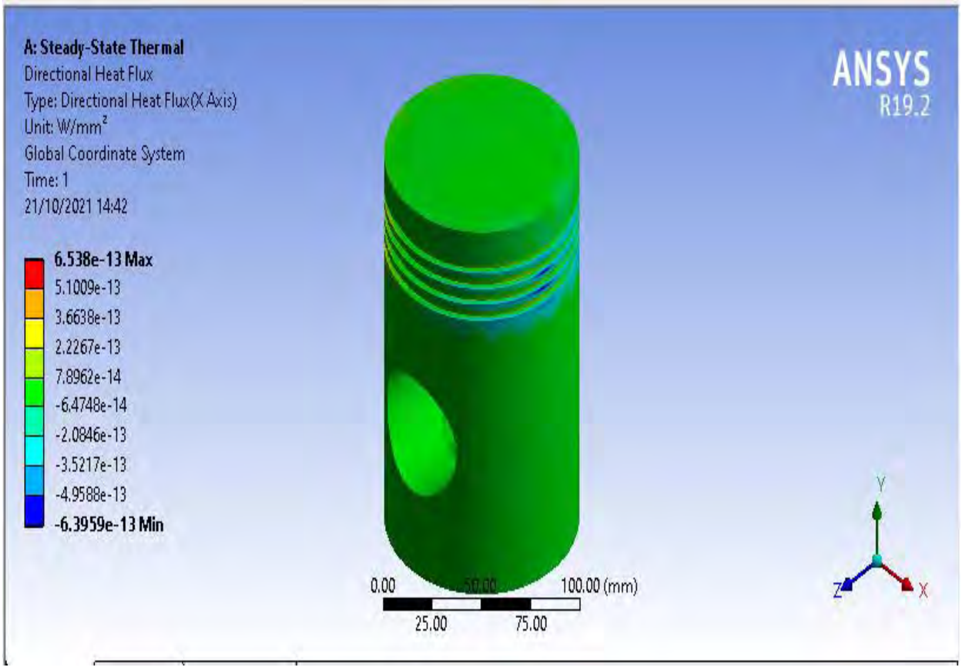


Figure 4. 36: Directional heat flux induced in Al 332

Heat flux has both direction and magnitude, and so it is a vector quantity. Figure 4.36 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 $6.538 \times 10^{-13}\,\mathrm{W/mm^2}$. 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 $7.8962 \times 10^{-14}\,\mathrm{W/mm^2}$ 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 considered to be fit for purpose since it can withstand the given heat condition.

4.4 Comparison of Thermal Analysis Results of the Four Different Materials

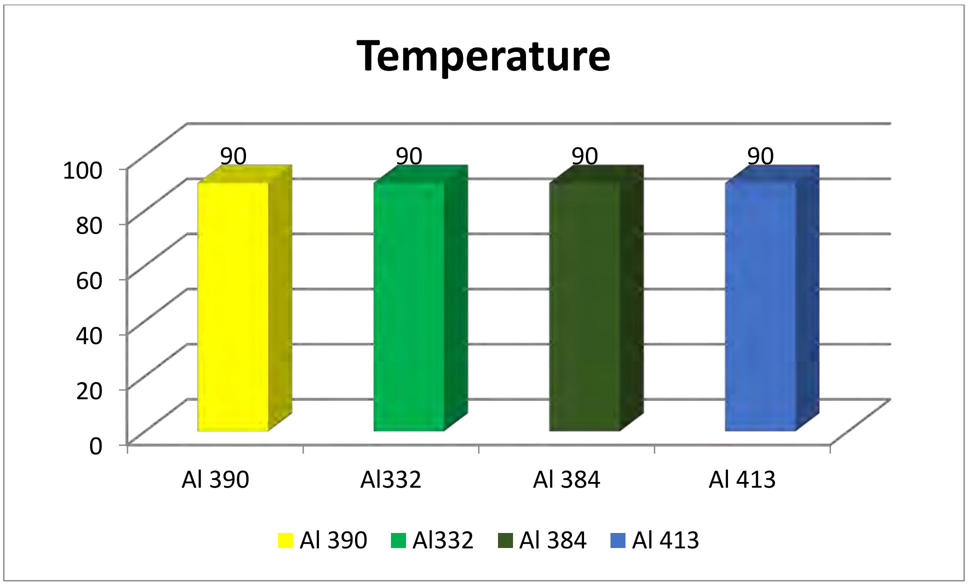


Figure 4. 37. Comparison of Temperature of all the Four Piston Materials

Figure 4.37 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 4.37 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

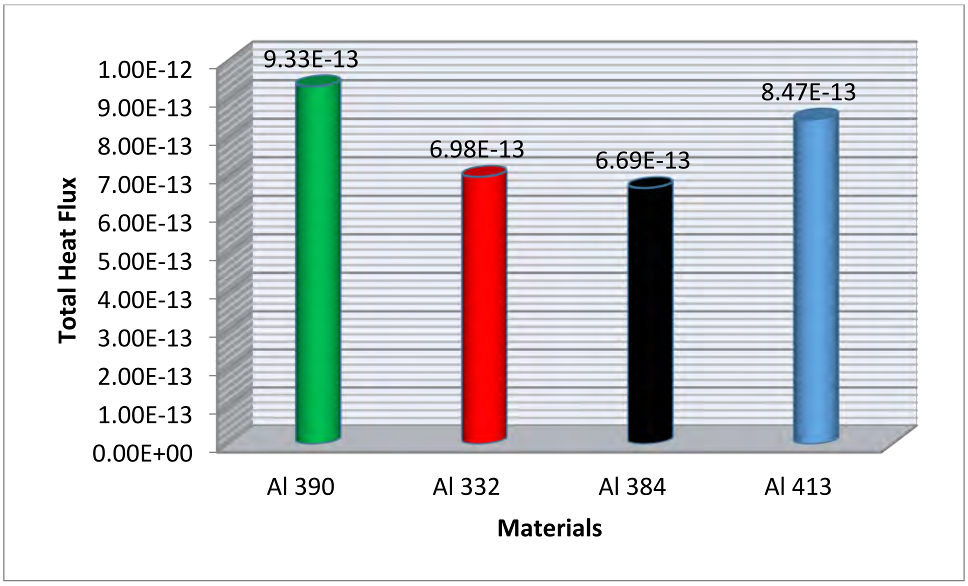


Figure 4. 38: Comparison of Total Heat Flux of all the Four Piston Materials

Figure 4.38 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 $9.33 \times 10^{-13}\,\mathrm{W/mm^2}$, 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 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 thermal conductivitie 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.

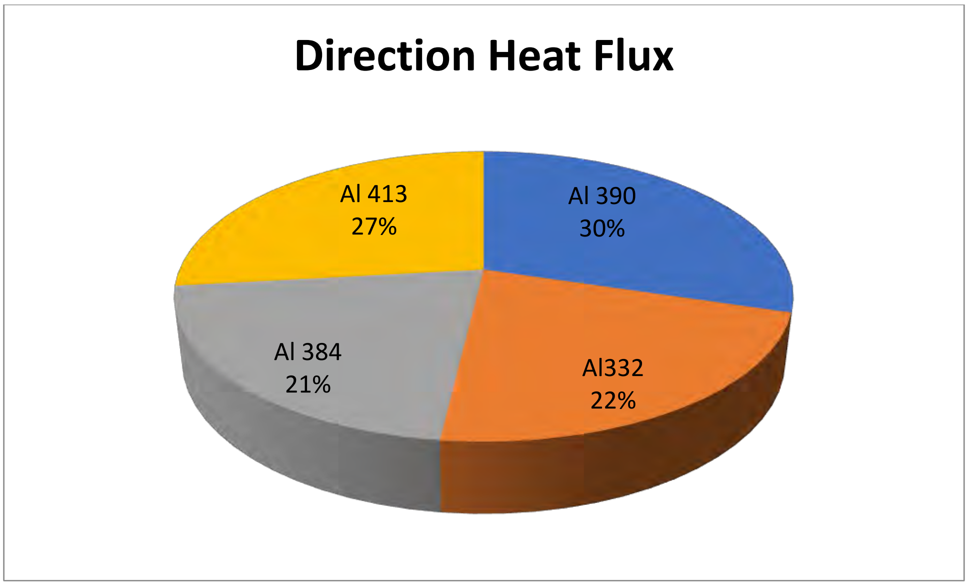


Figure 4. 39: Comparison of Directional Heat Flux of all the Four Piston Materials

Figure 4.39 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 was consistent with the results of the total heat flux.

4.3 Fatigue analysis of the pistons made of the four different materials

a. Aluminium 332 Alloy Material

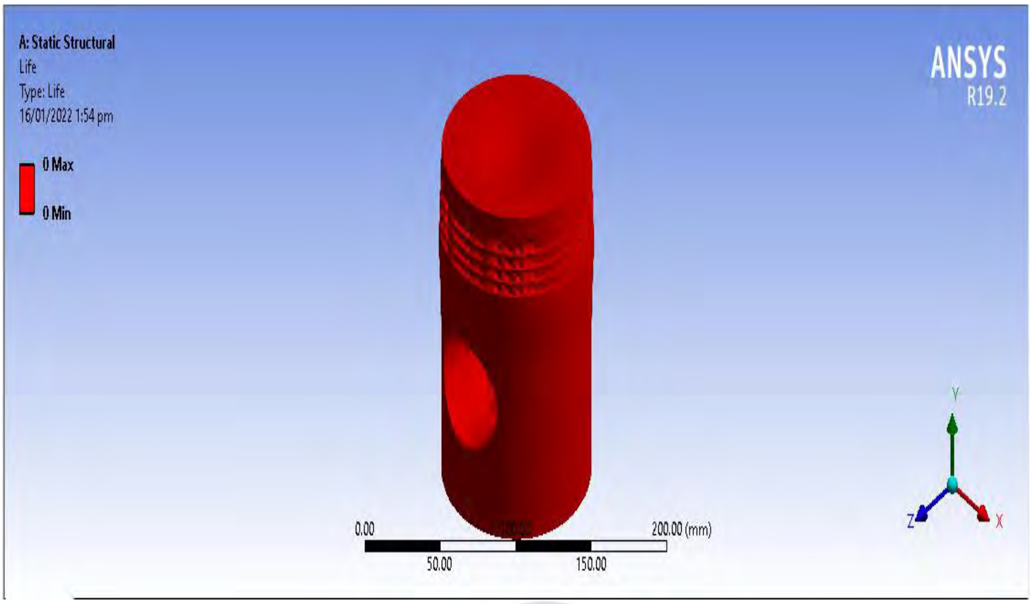


Figure 4. 40: Fatigue Life of aluminium 332 alloy piston

Figure 4.40 shows the fatigue life of aluminium 332 alloy piston when subjected under the maximum cyclic loading. The three main inputs for fatigue life analyses are processed using various life estimation tools depending on whether the analysis is for crack initiation, total life and crack growth. This analysis employed total fatigue life to determine the life of the aluminium 332 alloy piston. From Figure 4.40, it was observed that, the maximum fatigue life cycle of the aluminium 332 alloy piston was zero (0) cycles. These maximum life cycles was observed to be widespread across the entire aluminium 332 alloy piston. This result shows that, the life of aluminium 332 alloy piston cannot be predicted.

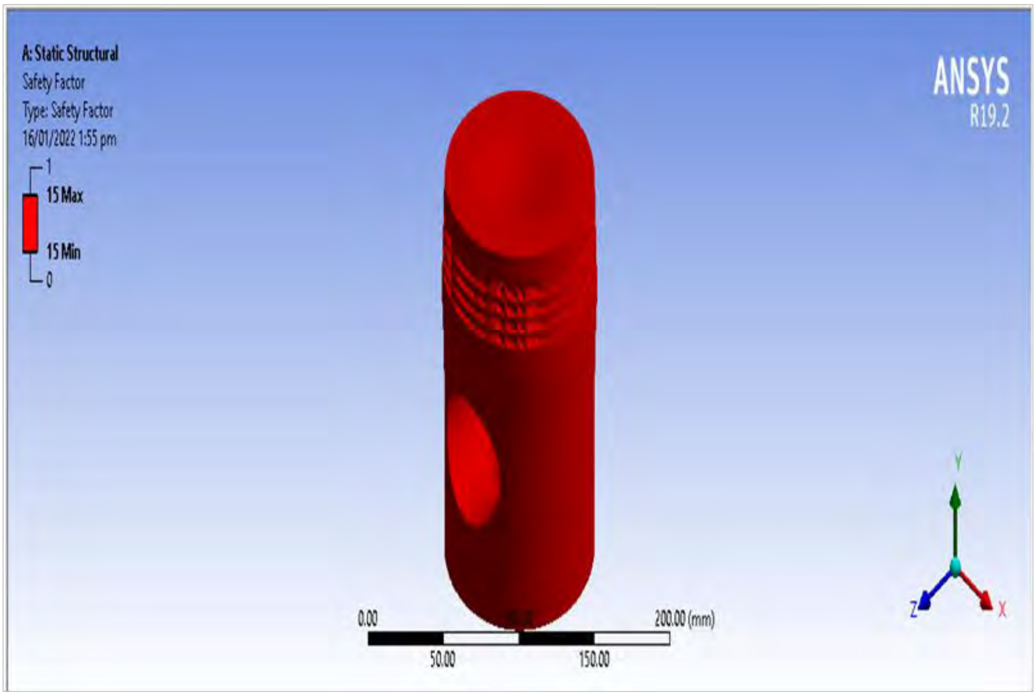


Figure 4. 41: Fatigue Factor of Safety of Aluminium 332 Alloy Piston

Figure 4.41 shows the fatigue factor of safety of aluminium 332 alloy piston. The Ansys generated fatigue factor of safety of the model aluminium 332 alloy piston has a maximum fatigue factor of safety value of 15 and minimun fatigue factor of safety magnitude 15. It was observed that the maximum fatigue factor of safety of 15 was widespread across the entire aluminium 332 alloy piston. This shows that, aluminium 332 alloy piston has a very good fatigue factor of safety. This result is consistent with the factor of safety obtained when static structural analysis was conducted on the same material. Hence, the aluminium 332 alloy piston is very safe in operation.

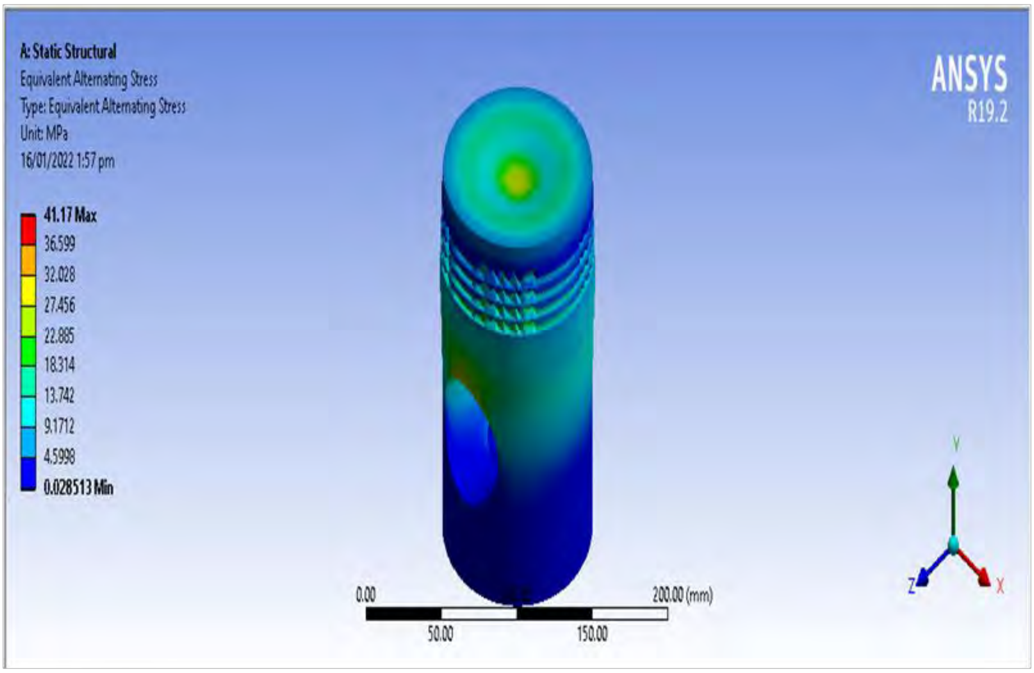


Figure 4. 42: Fatigue Alternating Stress of aluminium 332 alloy piston

Figure 4.42 shows the fatigue alternating stress of aluminium 332 alloy piston. Fatigue alternating stress is also one of the most important parameters that were used to determine the suitability of aluminium 332 alloy for piston design. It is the stress that is induced in a material as a result of a variable load or cyclical loading. Fatigue impact is variable; hence the material should have good strength enough to be able to withstand shock impact. It was observed from Figure 4.42 that, the maximum fatigue alternating stress of 41.17 MPa occurred at the centre of the piston crown and around the piston rings grooves of the aluminium 332 alloy piston while the minimum fatigue alternating stress of 0.028513 MPa occurred at the first land of the piston and below the piston boss. It was also observed that, the maximum induced fatigue alternating stress is far below the fatigue strength of aluminium 332 alloy of magnitude 90 MPa. Hence, the piston made with the aluminium 332 alloy material will be able to withstand the fatigue impact.

b. Aluminium 390 alloy Material

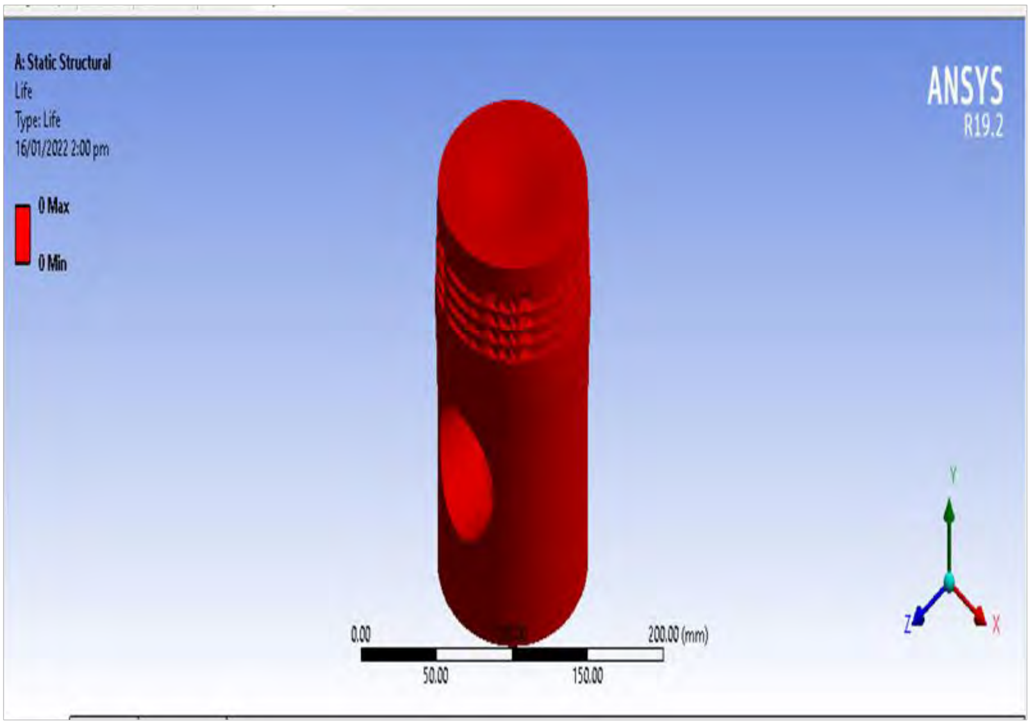


Figure 4. 43: Fatigue Life of Aluminium 390 Alloy Piston

Figure 4.43 shows the fatigue life of aluminium 390 alloy piston when subjected under the maximum cyclic loading. The three main inputs for fatigue life analyses are processed using various life estimation tools depending on whether the analysis is for crack initiation, total life and crack growth. This analysis employed total fatigue life to determine the life of the aluminium 390 alloy piston. From Figure 4.43, it was observed that, the maximum fatigue life cycle of the aluminium 390 alloy piston was zero (0) cycles. These maximum life cycles was observed to be widespread across the entire aluminium 390 alloy piston. This result suggests that, the life of aluminium 390 alloy piston cannot be predicted.

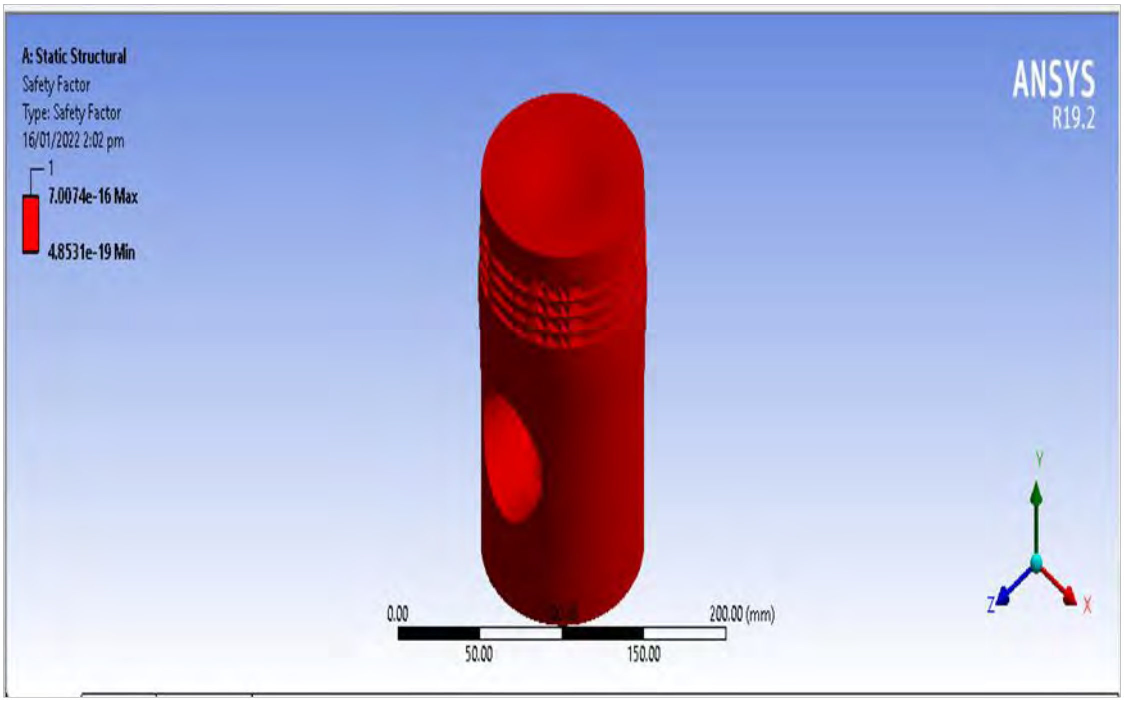


Figure 4. 44: Fatigue Factor of Safety of Aluminium 390 Alloy Piston

Figure 4.44 shows the fatigue factor of safety of aluminium 390 alloy piston. The Ansys generated fatigue factor of safety of the model aluminium 390 alloy piston has a maximum fatigue factor of safety value of $7.8074 \times 10^{-16}$and minimun fatigue factor of safety magnitude 4.8531×10^{-19}. It was observed that the maximum fatigue factor of safety of 7.8074×10^{-16} of aluminium 390 alloy piston was not significant enough. This result suggests that, aluminium 390 alloy piston has a very bad fatigue factor of safety.

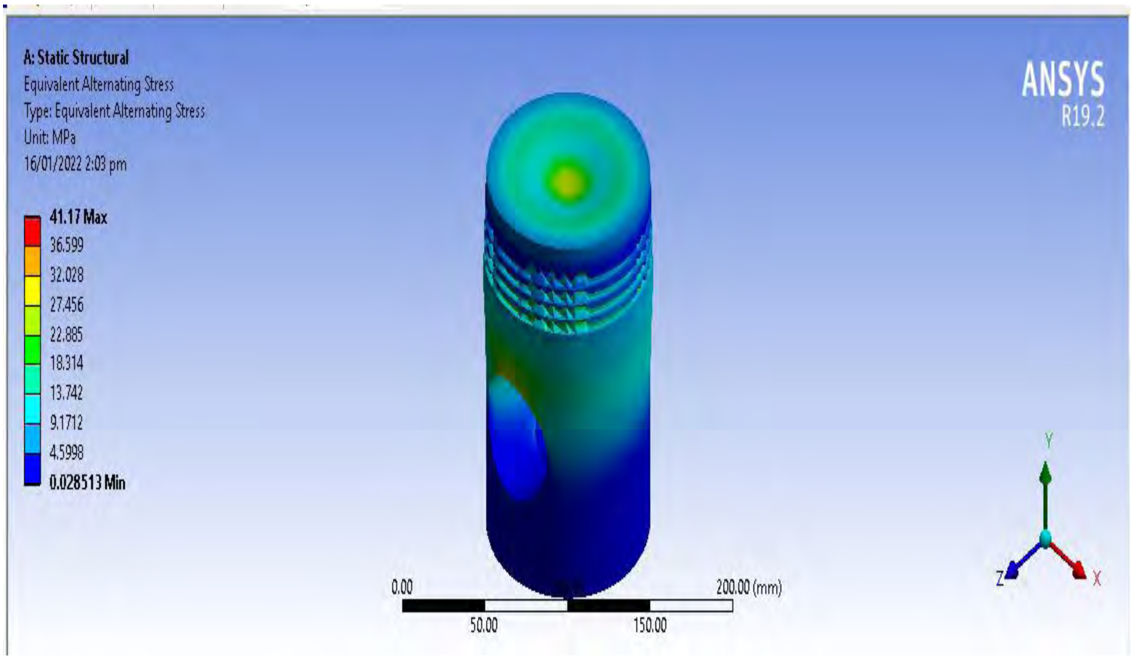


Figure 4. 45: Fatigue Alternating Stress of Aluminium 390 Alloy Piston

Figure 4.45 shows the fatigue alternating stress of aluminium 390 alloy piston. Fatigue alternating stress is also one of the most important parameters that were used to determine the suitability of aluminium 390 alloy for piston design. It is the stress that is induced in a material as a result of a variable load or cyclical loading. Fatigue impact is variable; hence the material should have good strength enough to be able to withstand shock impact. It was observed from Figure 4.45 that, the maximum fatigue alternating stress of 41.17 MPa occurred at the centre of the piston crown and around the piston rings grooves of the aluminium 390 alloy piston while the minimum fatigue alternating stress of 0.028513 MPa occurred at the first land of the piston and below the piston boss. It was also observed that, the maximum induced fatigue alternating stress is far below the fatigue strength of aluminium 390 alloy of magnitude 138 MPa. Hence, the piston made with the aluminium 390 alloy material will be able to withstand the fatigue impact.

c. Aluminium 413 Alloy Material

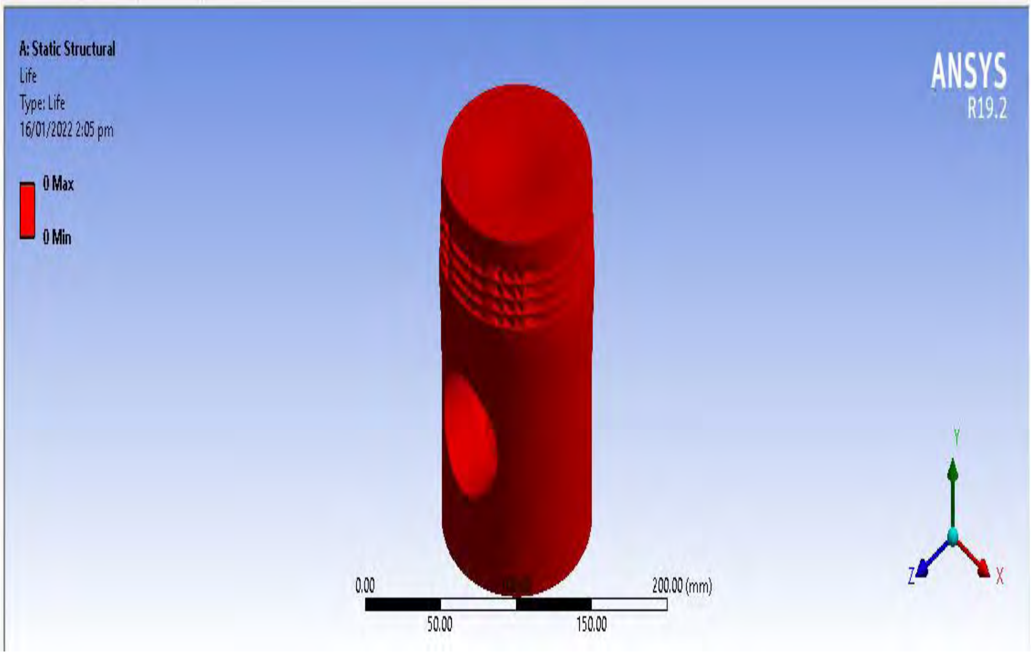


Figure 4. 46: Fatigue Life of aluminium 413 alloy piston

Figure 4.46 shows the fatigue life of aluminium 413 alloy piston when subjected under the maximum cyclic loading. The three main inputs for fatigue life analyses are processed using various life estimation tools depending on whether the analysis is for crack initiation, total life and crack growth. This analysis employed total fatigue life to determine the life of the aluminium 413 alloy piston. From Figure 4.46, it was observed that, the maximum fatigue life cycle of the aluminium 413 alloy piston was zero (0) cycles. These maximum life cycles was observed to be widespread across the entire aluminium 413 alloy piston. This result suggests that, the life of aluminium 413 alloy piston cannot be predicted.

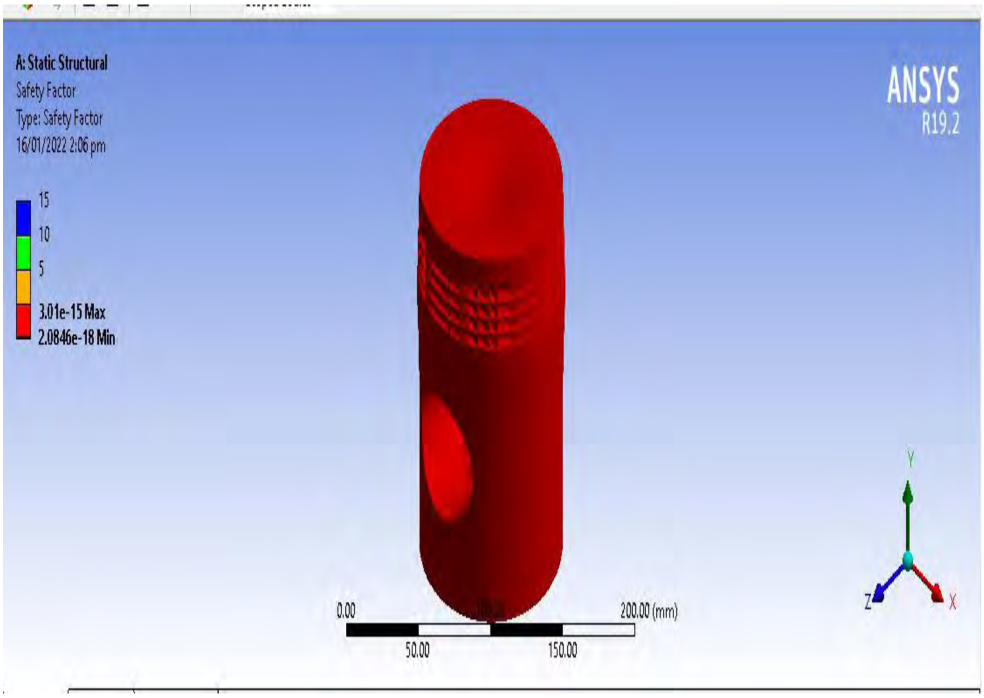


Figure 4. 47: Fatigue Factor of Safety of Aluminium 413 Alloy Piston

Figure 4.47 shows the fatigue factor of safety of aluminium 413 alloy piston. The Ansys generated fatigue factor of safety of the model aluminium 413 alloy piston has a maximum fatigue factor of safety value of 15 and minimun fatigue factor of safety magnitude 2.0846×10^{-18} . It was observed that the maximum fatigue factor of safety of 15 did not appear on the model piston made with aluminium 413 alloy pistion. The minimum factor of safety of 2.0846×10^{-18} was widespread across the entire aluminium 413 alloy piston. This shows that, aluminium 413 alloy piston has a very bad fatigue factor of safety.

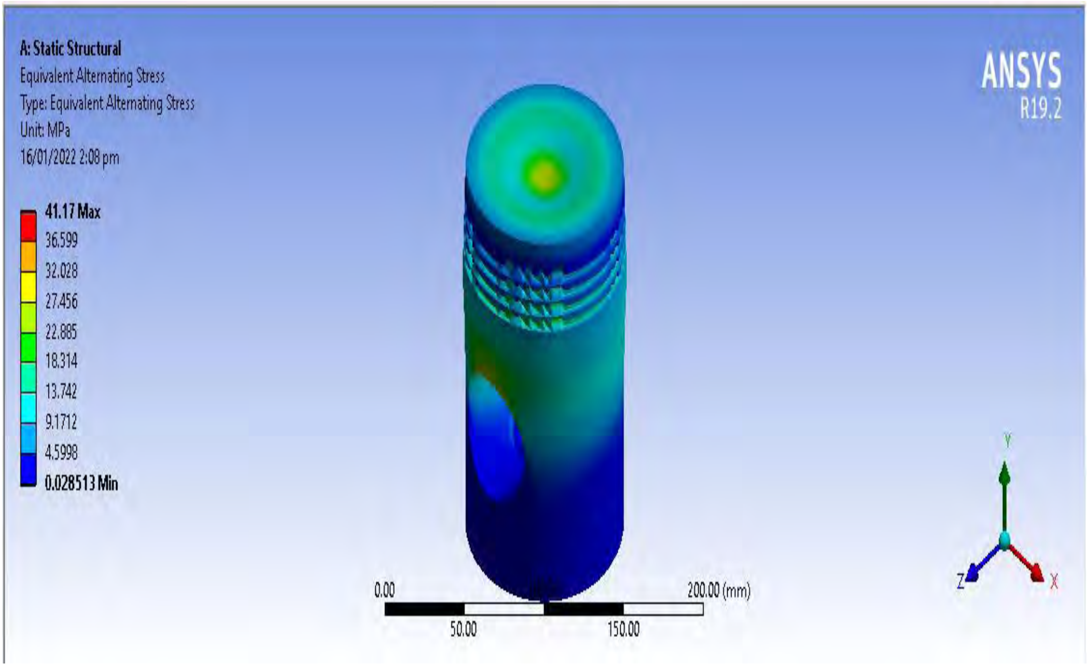


Figure 4. 48: Fatigue Alternating Stress of Aluminium 413 Alloy Piston

Figure 4.48 shows the fatigue alternating stress of aluminium 413 alloy piston. Fatigue alternating stress is also one of the most important parameters that were used to determine the suitability of aluminium 413 alloy for piston design. It is the stress that is normally induced in a material as a result of a variable load or cyclical loading. Fatigue impact is variable; hence the material should have good strength enough to be able to withstand shock impact. It was observed from Figure 4.48 that, the maximum fatigue alternating stress of 41.17 MPa occurred at the centre of the piston crown and around the piston rings grooves of the aluminium 413 alloy piston while the minimum fatigue alternating stress of 0.028513 MPa occurred at the first land of the piston and below the piston boss. It was also observed that, the maximum induced fatigue alternating stress is far below the fatigue strength of aluminium 413 alloy of magnitude 130 MPa. Hence, the piston made with the aluminium 413 alloy material will be able to withstand the fatigue impact.

d. Aluminium 384 Alloy Material

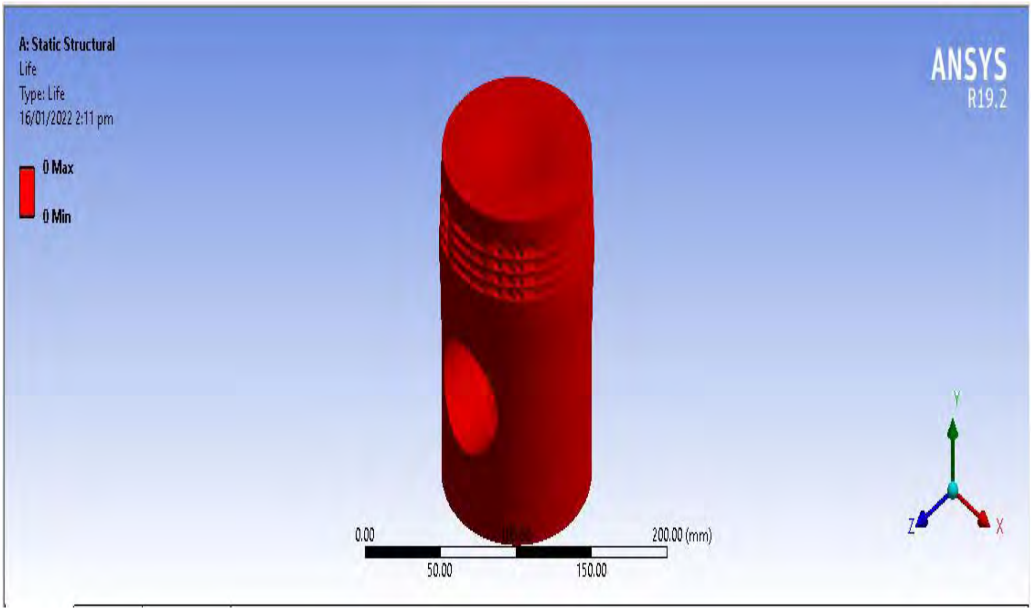


Figure 4. 49: Fatigue Life of Aluminium 384 Piston

Figure 4.49 shows the fatigue life of aluminium 384 alloy piston when subjected under the maximum cyclic loading. The three main inputs for fatigue life analyses are processed using various life estimation tools depending on whether the analysis is for crack initiation, total life and crack growth. This analysis employed total fatigue life to determine the life of the aluminium 384 alloy piston. From Figure 4.49, it was observed that, the maximum fatigue life cycle of the aluminium 384 alloy piston was zero (0) cycles. These maximum life cycles was observed to be widespread across the entire aluminium 384 alloy piston. This result suggests that, the life of aluminium 384 alloy piston cannot be predicted.

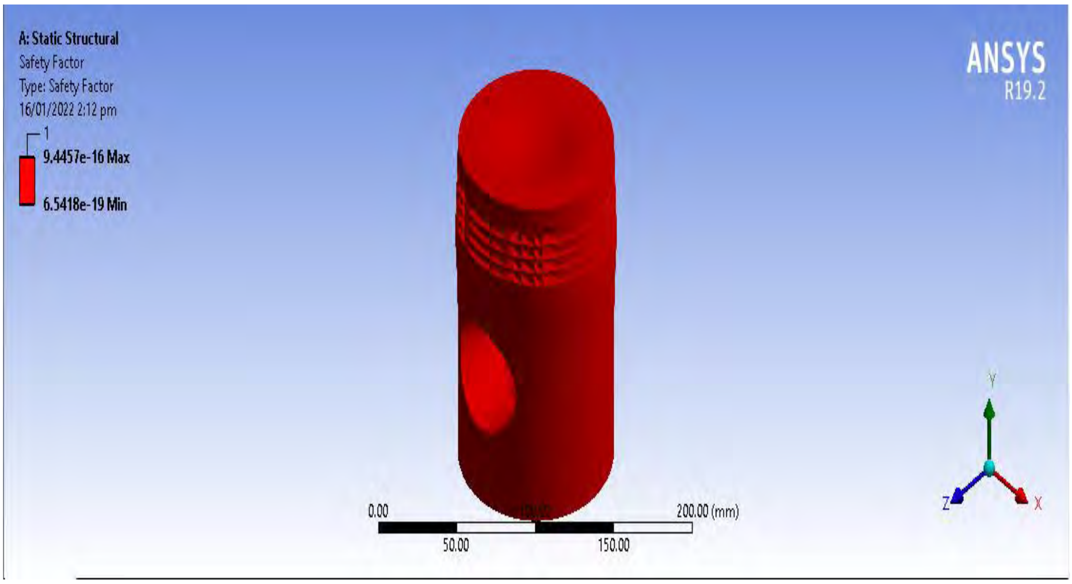


Figure 4. 50: Fatigue Factor of Safety of Aluminium 384 Alloy Piston

Figure 4.50 shows the fatigue factor of safety of aluminium 384 alloy piston. The Ansys generated fatigue factor of safety of the model aluminium 384 alloy piston has a maximum fatigue factor of safety value of 9.445×10^{-16} and minimun fatigue factor of safety magnitude 6.5418×10^{-19}. It was observed that the maximum fatigue factor of safety of 9.445×10^{-16} although not significant but was widespread across the entire aluminium 384 alloy piston. This shows that, aluminium 384 alloy piston has a very bad fatigue factor of safety.

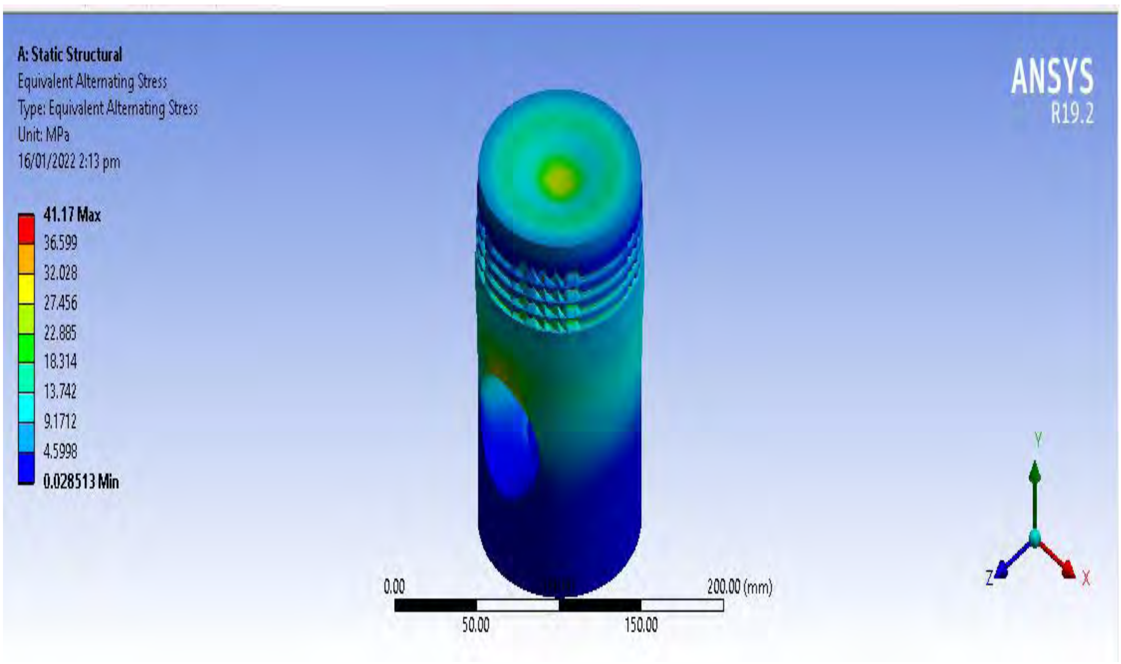


Figure 4. 51: Fatigue Alternating Stress of aluminium 384 alloy piston

Figure 4.51 shows the fatigue alternating stress of aluminium 384 alloy piston. Fatigue alternating stress is also one of the most important parameters that were used to determine the suitability of aluminium 384 alloy for piston design. It is the stress that is normally induced in a material as a result of a variable load or cyclical loading. Fatigue impact is variable; hence the material should have good strength enough to be able to withstand shock impact. It was observed from Figure 4.51 that, the maximum fatigue alternating stress of 41.17 MPa occurred at the centre of the piston crown and around the piston rings grooves of the aluminium 384 alloy piston while the minimum fatigue alternating stress of 0.028513 MPa occurred at the first land of the piston and below the piston boss. It was also observed that, the maximum induced fatigue alternating stress is far below the fatigue strength of aluminium 384 alloy of magnitude 138 MPa. Hence, the piston made with the aluminium 384 alloy material will be able to withstand the fatigue impact.

4.4 Discussion and Comparison of Fatigue Alternating Stress Results

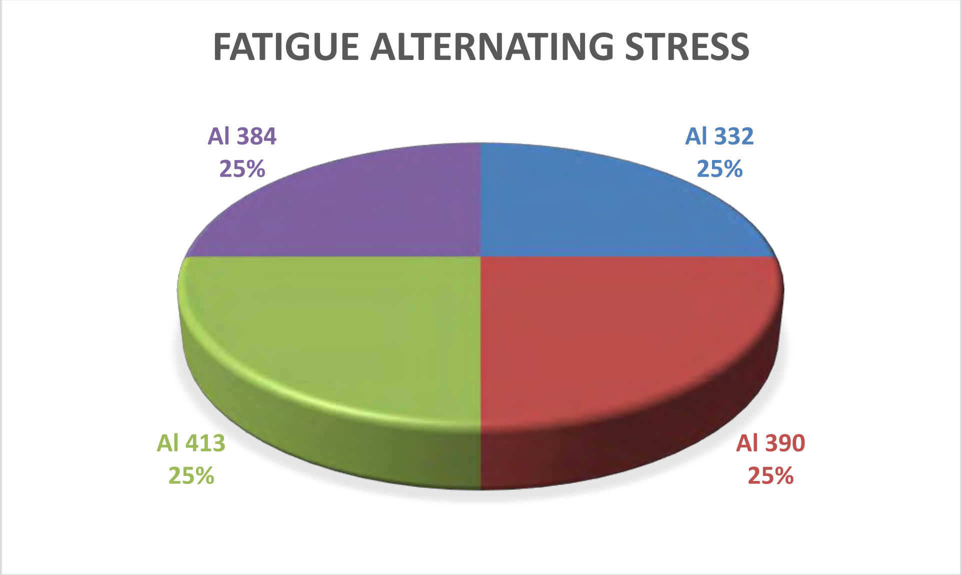


Figure 4. 52: Comparison of Fatigue Alternating Stress of Piston Materials

Figure 4.52 shows the comparison of the fatigue alternating stress induced in the pistons of aluminium 332 alloy, aluminium 390 alloy, aluminium 384 alloy and aluminium 413 alloy. It was evident from Figure 4.52 that, the pistons of aluminium 332 alloy material yielded Fatigue alternating stress of 41.17 MPa representing 25 %, aluminium 390 alloy piston yielded fatigue alternating stress of 41.17 MPa representing 25 %, aluminium 384 alloy piston yielded fatigue alternating stress of 41.17 MPa representing 25 %, and aluminium 413 alloy piston yielded fatigue alternating stress of 41.17 MPa representing 25 %. It was observed that, all the pistons made with aluminium 332 alloy, aluminium 390 alloy, aluminium 384 alloy and aluminium 413 alloy yielded the same fatigue alternating stress of 41.17 MPa representing 25 %. The fatigue alternating stress induced in the pistons is far lower compared to the fatigue strengths of all the four different materials. It can therefore be concluded that, all the pistons made with the four different materials have equal qualities to withstand the fatigue stress induced in the pistons.

CHAPTER FIVE

SUMMARY OF FINDINGS, CONCLUSIONS AND RECOMMENDATIONS

5.0 Introduction

This chapter presents the summary of findings of the study into piston design and manufacture using aluminium 332 alloy, aluminium 390 alloy, aluminium 384 alloy and the implementing material, aluminium 413 alloy. Conclusions were drawn based on the findings discovered in the study. Recommendations were made to guide policy holders, Automotive component manufacturers and vehicle assembly companies in Ghana and beyond.

5.1 Summary of Findings

The following findings were made from the study into modelling and simulation of pistons made of four different aluminium alloy materials for an internal combustion engine.

1. The study found that, the common aluminium alloys recommended for piston casting were categorised into three groups. These grouping were found to be eutectic aluminium alloy group, hypereutectic aluminium alloy group and Special eutectic aluminium alloy group. Interestingly, it was revealed that each of these groups have unique properties with varied strengths. These metals are used for designing components that requires high strength and can withstand high temperatures such as what exist in an internal combustion engines. The implementing material was aluminium 413 alloy, this material is not part of any of the three groupings. When the maximum gas load was imposed on the pistons made of aluminium 384 alloy from the eutectic aluminium alloy group, aluminium 390 alloy from the hypereutectic aluminium alloy group and aluminium 332 alloy from Special eutectic aluminium alloy group. It was found that, all the four materials have equal abilities to endure the

same amount of stress. It was discovered that when the compressive gas load of 56124.6 N was applied to the pistons made of the four different aluminium alloys, all yielded an induced stress of 41.17 MPa which is far lower than the yield strengths of all the four aluminium alloys materials. Hence, all the four aluminium alloy materials were found to be suitable for piston design and manufacture.

2. It was again revealed from the study that when the load 56124.6 N was imposed on the pistons of the four different materials and their deformations compared, it was found that, aluminium 332 alloy material from special eutectic aluminium alloy group yielded the least total deformation of 0.039441 mm representing 4.15% and the implementing material which is aluminium 413 alloy yielded the highest total deformation of 0.40552 mm representing 42.65%. The percentage difference between the least deformed piston and highest deformed piston was 38.5% which is significant. The study revealed that special eutectic aluminium alloys have superior ability to resist deformation better than eutectic aluminium alloys, hypereutectic aluminium alloys and the implementing material. The induced total deformations in all the pistons were found not to be significant enough to affect the pistons in operation, hence all the pistons were found to be satisfactory.
3. Moreover, when the equivalent elastic strains of the pistons were compared, it was revealed that, aluminium 390 alloy yielded the least equivalent elastic strain of 0.003777 representing 19 % and again the implementing material yielded the highest equivalent elastic strain of 0.0062772 mm representing 31%.
4. When the thermal analysis results were compared, it was found that aluminium 390 alloy yielded total heat flux of $9.33 \times 10^{-13}\, W/mm^2$ representing 29.65 %, aluminium 332 alloy yielded $6.98 \times 10^{-13}\, W/mm^2$ representing 22%, aluminium 384 alloy yielded a total heat flux of $6.69 \times 10^{-13}\, W/mm^2$ representing 21% and

aluminium 413 alloy yielded a total heat flux of $8.47 \times 10^{-13}\,W/mm^2$ representing 26.91%. it study revealed that, aluminium 390 alloy from hypereutectic aluminium alloy family has the ability to conduct and dissipate heat more faster than the remaining aluminium materials. The implementing material was found to be the second material which has the ability to conduct and dissipate more heat. It was found that, the total heat flux induced in the pistons made with the four different materials were far below the thermal conductivities of all the materials. Hence, all the materials were found to be satisfactory enough to be able to withstand the operating temperature in the cylinders.

5. When the fatigue analysis results were compared, it was found that, all the pistons made with aluminium 332 alloy, aluminium 384 alloy, aluminium 390 alloy and aluminium 413 alloy which is the implementing material yielded the same fatigue alternating stress of 41.17 MPa representing 25% for all the piston materials. The induced fatigue alternating stresses in all the materials were found to be far lower than the fatigue strengths of all the materials. It was very instructive to find that, although the materials have the ability to withstand the fatigue alternating stress but the fatigue life cycle of the material was not able to be predicted. Hence, the pistons made with aluminium 332 alloy, aluminium 390 alloy, aluminium 384 alloy and the implementing material, aluminium 413 alloy were all found to be quiet satisfactory.
6. When the factor of safeties obtained from the static structural analysis of the pistons were compared, it was found that all the piston materials have very good factor of safety.

5.2 Conclusions

This study considered three methods of analysis which were static structural, thermal analysis and fatigue analysis. The parameters that were considered under the static structural analysis were: total deformation, equivalent elastic strain, 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 hiace mini bus. 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 drawing interface of the Autodesk inventor was lunched and the piston was modelled using 2D drawing and later converted through extrusion into a 3D drawing. The 3D piston was save in an imported stp (step) format for easy importation into Ansys. The analysis of the piston was done using Ansys 2020R2 student's software. The pistons in the Ansys were subjected to a compressive load of 56124.6 N.

Then Finite Element Analysis technique was used to determine the total deformation, equivalent elastic strain, 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 was 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. The fatigue analysis results also revealed that all the selected aluminium alloy materials

5.3 Recommendations

Upon careful consideration, the following recommendations have been arrived at based on the summary of findings revealed by the study:

1. The implementing material which is aluminium 413 alloy should be considered as one of the aluminium alloy materials for piston design and manufacture. This is because the material has good properties to endure more stress, to withstand high temperature and also can take more fatigue loads.
2. It is again recommended that, the local automotive component manufacturers should consider using aluminium 413 alloy to mass produce pistons locally to feed the local automotive assembly plants in Ghana because, the material is readily available in Ghana.
3. It is further recommended that, more of this study should be encourage for the discovering of more local materials that can be produce products to feed the local industries.

4. Ghanaian entrepreneurs should be encouraged to set up automotive components manufacturing companies for skilful graduates from our skill training institutions to help nurture their talent for the automotive industry.

5.4 Future Studies

Future studies into piston design and simulation should concentrate on the following areas:

1. Future study into using aluminium alloy to design and manufacture pistons of an internal combustion engine should consider finding out the best method of manufacturing that is suitable for aluminium alloy pistons production.
2. Further study into pistons design and manufacture should also consider conducting further test by fixing the prototype pistons in a real engine to identify any issues with the design.
3. Further study into pistons design and manufacture should also consider conducting dynamic tests to identify if there are any issues with the design.

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APPENDICES

CASTING PISTON

The researcher used wood material to design the patterns. After creating patterns he set the drag, using split patterns for inner and outer mold. And start melting the molten metal to require temperature. Then before start puring in the molten material the researcher must consider the following before puring melting material shrinkage, machine, drag, shake, distortion allowances. Before puring and considering factors mention above allow 10mins before remove patterns and sand mold. After piston cast you send it to machine shop for lathing, milling and drilling.

In the machine shop the researcher have to through the following operations to get the piston done.

Machine shop, Lathe machine, Milling machine and drilling machine was used to finished the piston.

S/NO.	OPERATION SEQUENCE	TOOLS AN EQUIPMENT
1	Cross check overall length and diameter of the work piece	Steel rule, measuring tap, vernier calliper, vernier high gauge, micrometer .
2	Set up work in three or four-jaw chuck on lathe, face top part (crown) to length and turn out side diameter (skirt) to size by half of the length.	Lathe machine, three or four-jaw chuck, scribing block, facing tool, turning tool, vernier caliper.
3	Reverse work in chuck, turn parallel to the outside diameter (skirt).	Scribing block, turning tool, vernier caliper. Dept gauge.
4	Mount recesses tool, turn the groves	Recesses tool, vernier.

	for the ring belt to size.	
	MILLING	
1	Mark out all dimensions on the work piece.	Vernier calliper, micrometer, scriber, vernier high gauge, engineering blue, surface table etc.
2	Set work on the milling machine table and milled one side of ( ) to size.	Machine vice, vee block, parallel strips, and clamps
3	Revers work in the setup and repeat same processes to other end	
	Drilling	
1	Mark out for drilling connecting rod pin hole	Vernier calliper, micrometer, scriber, vernier high gauge, engineering blue, surface table, center pouch etc.
2	Set up work on to the drilling machine table.	Vee block, machine vice, clamps.
3	Select correct size drill bit and drilled through both sides for connecting rod pin.	Diameter 29mm drilling bit
4	Remove work from set up and clean	Spanner, smooth file, emery cloth.

	sharp edges.	
5	Check all sizes	Vernier calliper, micrometer, steel rule, vernier high gauge etc.

Alloy Designation System (Wrought Alloys)

1. First digit - Principal alloying constituent(s)
2. Second digit - Variations of initial alloy
3. Third and fourth digits - Individual alloy variations (number has no significance but is unique)

- 1xxx - Pure Al (99. 00% or greater)
- 2xxx - Al-Cu Alloys
- 3xxx - Al-Mn Alloys
- 4xxx - Al-Si Alloys
- 5xxx - Al-Mg Alloys
- 6xxx - Al-Mg-Si Alloys
- 7xxx - Al-Zn Alloys
- 8xxx - Al+Other Elements
- 9xxx - Unused series

1xxx - Pure Al

- Strain hardenable
- High formability, corrosion resistance and electrical conductivity
- Electrical, chemical applications

- Representative designations: 1100,1350
- Typical ultimate tensile strength range:10-27 ksi

The 1xxx series represents the commercially pure aluminium, ranging from the baseline 1100 (99.00% min. Al) to relatively purer 1050/1350 (99.50% min. Al) and 1175 (99.75 % min. Al). Some, like 1350 which is used especially for electrical applications, have relatively tight controls on those impurities that might lower electrical conductivity. The 1xxx series are strain-hardenable, but would not be used where strength is a prime consideration. Rather the emphasis would be on those applications where extremely high corrosion resistance, formability and/or electrical conductivity are required, e.g., foil and strip for packaging, chemical equipment, tank car or truck bodies, spun hollowware, and elaborate sheet metal work.

2xxx - Al-Cu Alloys

- Heat treatable
- High strength, at room & elevated temperatures
- Aircraft, transportation applications
- Representative alloys:2014,2017, 2024,2219,2195
- Typical ultimate tensile strength range:27-62 ksi

The 2xxx series are heat-treatable, and possess in individual alloys good combinations of high strength (especially at elevated temperatures), toughness, and, in specific cases, weldability; they are not resistant to atmospheric corrosion, and so are usually painted or clad in such exposures. The higher strength 2xxx alloys are primarily used for aircraft (2024) and truck body (2014) applications; these are usually used in bolted or riveted construction. Specific members of the series (e.g., 2219 and 2048) are readily welded, and so are used for aerospace applications where that is the preferred joining method. Alloy 2195 is a new Li-bearing alloy for space applications providing very high modulus of elasticity along with high strength and weldability. There are also high-toughness versions of several of the alloys (e.g., 2124, 2324, 2419), which have tighter control on the impurities that may diminish resistance to unstable fracture, all developed specifically for the aircraft industry. Alloys 2011, 2017, and 2117 are widely used for fasteners and screw-machine stock.

3xxx - Al-Mn Alloys

- High formability, corrosion resistance, and joinability; medium strength
- Heat transfer, packaging, roofing-siding applications
- Representative alloys:3003,3004,3005
- Typical ultimate tensile strength range:16-41 ksi

The 3xxx series are strain-hardenable, have excellent corrosion resistance, and are readily welded, brazed and soldered. Alloy 3003 is widely used in cooking utensils and chemical equipment because of its superiority in handling many foods and chemicals, and in builders' hardware. Alloy 3105 is a principal for roofing and siding. Variations of the 3xxx series are used in sheet and tubular form for heat exchangers in vehicles and power plants. Alloy 3004 and its modification 3104 are among the most widely used aluminium alloys because they are drawn and ironed into the bodies of beverage cans.

4xxx - Al-Si Alloys

- Heat treatable
- Good flow characteristics, medium strength
- Pistons, complex-shaped forgings;
- Representative alloys:4032 and filler alloy 4043

- Typical ultimate tensile strength range:25-55 ksi

Of the two most widely used 4xxx alloys, 4032 is a medium high-strength, heat treatable alloy used principally for forgings in applications such as aircraft pistons. Alloy 4043 on the other hand is one of the most widely used filler alloys for gas-metal arc (GMA) and gas-tungsten arc (GTA) welding 6xxx alloys for structural and automotive applications. The same characteristic leads to both applications: good flow characteristic provided by the high silicon content, which in the case of forgings ensures the filling of complex dies and in the case of welding ensures complete filling of crevices and grooves in the members to be joined. For the same reason, other variations of the 4xxx alloys are used for the cladding on brazing sheet, the component that flows to complete the bond.

5xxx - Al-Mg Alloys

- Strain hardenable
- Excellent corrosion resistance, toughness, weldability; moderate strength
- Building & construction, automotive, cryogenic, marine applications
- Representative alloys: 5052,5083,5754
- Typical ultimate tensile strength range:18-51 ksi

Al-Mg alloys of the 5xxx series are strain hardenable, and have moderately high strength, excellent corrosion resistance even in salt water, and very high toughness even at cryogenic temperatures to near absolute zero. They are readily welded by a variety of techniques, even at thicknesses up to 20 cm. As a result, 5xxx alloys find wide application in building and construction, highways structures including bridges, storage tanks and pressure vessels, cryogenic tankage and systems for temperatures as low as -270°C (near absolute zero), and marine applications. Alloys 5052, 5086, and 5083 are the work horses from the structural standpoint, with increasingly higher strength associated with the increasingly higher Mg content. Specialty alloys in the group include 5182, the beverage can end alloy, and thus among the largest in tonnage;5754 for automotive body panel and frame applications; and 5252,5457, and 5657 for bright trim applications, including automotive trim. Care must be taken to avoid use of 5xxx alloys with more than 3% Mg content in applications where they receive continuous exposure to temperatures above 100°C (212°F). Such alloys may become sensitized and susceptible to stress corrosion cracking. For this reason, alloys such as 5454 and 5754 are recommended for applications where high temperature exposure is likely.

6xxx - Al-Mg-Si Alloys

- Heat treatable
- High corrosion resistance, excellent extrudability; moderate strength
- Building & construction, highway, automotive, marine applications
- Representative alloys: 6061,6063, 6111
- Typical ultimate tensile strength range:18-58 ksi

The 6xxx alloys are heat treatable, and have moderately high strength coupled with excellent corrosion resistance. They are readily welded. A unique feature is their extrudability, making them the first choice for architectural and structural members where unusual or particularly strength- or stiffness-criticality is important. Alloy 6063 is perhaps the most widely used because of its extrudability; it was a key in the recent all-aluminium bridge structure erected in only a few days in Foresmo, Norway, and is the choice for the Audi automotive space frame members. Higher strength 6061 alloy finds broad use in welded structural members such as truck and marine frames, railroad cars, and pipelines. Among specialty alloys in the series:6066-T6, with high strength for forgings;6111 for automotive body panels with high dent resistance; and 6101and 6201 for high strength electrical bus and electrical conductor wire, respectively.

7xxx - Al-Zn Alloys

- Heat treatable
- Very high strength; special high toughness versions
- Aerospace, automotive applications
- Representative alloys: 7005,7075, 7475, 7150
- Typical ultimate tensile strength range:32-88 ksi

The 7xxx alloys are heat treatable and among the Al-Zn-Mg-Cu versions provide the highest strengths of all aluminium alloys. There are several alloys in the series that are produced especially for their high toughness, notably 7150 and 7475, both with controlled impurity level to maximize the combination of strength and fracture toughness. The widest application of the 7xxx alloys has historically been in the aircraft industry, where fracture-critical design concepts have provided the impetus for the high-toughness alloy development. These alloys are not considered weldable by routine commercial processes, and are regularly used in riveted construction. The atmospheric corrosion resistance of the 7xxx alloys is not as high as that of the 5xxx and 6xxx alloys, so in such service they are usually coated or, for sheet and plate, used in an alclad version. The use of special tempers such as the T73- type are required in place of T6-type tempers whenever stress corrosion cracking may be a problem.

8xxx - Alloys with Al+Other Elements (not covered by other series)

- Heat treatable

- High conductivity, strength, hardness
- Electrical, aerospace, bearing applications
- Representative alloys: 8017,8176, 8081, 8280, 8090
- Typical ultimate tensile strength range:17-35 ksi

The 8xxx series is used for those alloys with lesser used alloying elements such as Fe, Ni and Li. Each is used for the particular characteristics it provides the alloys: Fe and Ni provide strength with little loss in electrical conductivity and so are used in a series of alloys represented by 8017 for conductors. Li in alloy 8090 provides exceptionally high strength and modulus, and so this alloy is used for aerospace applications where increases in stiffness combined with high strength reduces component weight

Alloy Designation System (Casting Alloys)

1. First digit -Principal alloying constituent(s)
2. Second and third digits - Specific alloy designation (number has no significance but is unique)
3. Fourth digit - Casting (0) or ingot (1,2) designation

- lxx.x - Pure Al (99.00% or greater)
- 2xx.x - Al-Cu Alloys
- 3xx.x - Al-Si + Cu and/or Mg
- 4xx.x - Al-Si
- 5xx.x - Al-Mg
- 7xx.x - Al-Zn
- 8xx.x - Al-Sn
- 9xx.x - Al+Other Elements

- 6xx.x - Unused Series

2xx.x - Al-Cu Alloys

- Heat treatable/sand and permanent mould castings
- High strength at room and elevated temperatures; some high toughness alloys
- Aircraft, automotive applications/engines
- Representative alloys: 201.0, 203.0
- Approximate ultimate tensile strength range:19-65 ksi

The strongest of the common casting alloys is heat-treated 201.0/AlCu4Ti. Its castability is somewhat limited by a tendency to microporosity and hot tearing, so that it is best suited to investment casting. Its high toughness makes it particularly suitable for highly stressed components in machine tool construction, in electrical engineering (pressurized switchgear casings), and in aircraft construction. Besides the standard aluminium casting alloys, there are special alloys for particular components, for instance, for engine piston heads, integral engine blocks, or bearings. For these applications the chosen alloy needs good wear resistance and a low friction coefficient, as well as adequate strength at elevated service temperatures. A good example is the alloy 203.0/AlCu5NiCo, which to date is the aluminium casting alloy with the highest strength at around 200°C.

3xx.x - Al-Si+Cu or Mg Alloys

- Heat treatable/sand, permanent mould, and die castings
- Excellent fluidity/high strength/some high-toughness alloys
- Automotive and applications/pistons/pumps/electric Al
- Representative alloys:356.0, A356.0 ,359.0, A360.0
- Approximate ultimate tensile strength range:19-40 ksi

The 3xx.x series of castings are one of the most widely used because of the flexibility provided by the high silicon contents and its contribution to fluidity plus their response to heat treatment which provides a variety of high-strength options. Further the 3xx.x series may be cast by a variety of techniques ranging from relatively simple sand or die casting to very intricate permanent mould, lost foam/lost wax type castings, and the newer thixocasting and squeeze casting technologies. Among the workhorse alloys are 319.0 and 356.0/A356.0 for sand and permanent mould casting, 360.0, 380.0/A380.0 and 390.0 for die casting, and 357.0/A357.0 for many type of casting including especially the squeeze/forge cast technologies. Alloy 332.0 is also one of the most frequently used aluminium casting alloys because it can be made almost exclusively from recycled scrap.

4xx.x - Al-Si Alloys

- Non-heat treatable/sand, permanent mould, and die castings
- Excellent fluidity/good for intricate castings
- Typewriter frames/dental equipment/marine/architectural
- Representative alloys:413.0,443.0
- Approximate ultimate tensile strength range:17-25 ksi

Alloy B413.0/AlSi12 is notable for its very good castability and excellent weldability, which are due to its eutectic composition and low melting point of 570°C.It combines moderate strength with high elongation before rupture and good corrosion resistance. The alloy is particularly suitable for intricate, thin walled, leak-proof, fatigue resistant castings.

5xx.x - Al-Mg Alloys

- Non-heat treatable/sand, permanent mould, and die
- Tougher to cast/provides good finishing characteristics
- Excellent corrosion resistance/machinability/surface appearance
- Cooking utensils/food handling/aircraft/highway fittings
- Representative alloys:512.0, 514.0, 518.0, 535.0
- Approximate ultimate tensile strength range:17-25 ksi

The common feature which the third group of alloys have is good resistance to corrosion. Alloys 512.0 and 514.0 have medium strength and good elongation, and are suitable for components exposed to sea water or to other similar corrosive environments. These alloys are often used for door and window fittings, which can be decoratively anodized to give a metallic finish or in a wide range of colours. Their castability is inferior to that of the Al-Si alloys because of its magnesium content and consequently long freezing range. For this reason, it tends to be replaced by 355.0/AlSi5Mg, which has long been used for similar applications. For die castings where decorative anodizing is particularly important, the alloy 520.0 is the most suitable.

7xx.x - Al-Zn Alloys

- Heat treatable/sand and permanent mould cast (harder to cast)
- Excellent machinability/appearance
- Furniture/garden tools/office machines/farm/mining equipment
- Representative alloys: 705.0,712.0
- Approximate ultimate tensile strength range:30-55 ksi

Because of the increased difficulty in casting 7xx.x alloys, they tend to be used only where the excellent finishing characteristics and machinability are important.

8xx.x - Al-Sn Alloys

- Heat treatable/sand and permanent mould castings (harder to cast)
- Excellent machinability
- Bearings and bushings of all types
- Representative alloys:850.0, 851.0
- Approximate ultimate tensile strength range:15-30 ksi.

Like the 7xx.x alloys, 8xx.x alloys are relatively hard to cast and are used only where their unique machining and bushing characteristics are essential. In concluding this section on casting, it is worth noting that conventional die casting tends to yield parts with relatively low elongation values, which are therefore unsuitable for safety-critical components. In recent years, higher pressure types of casting (e.g., squeeze casting and thixocasting) have been developed to a commercial level. As a result, elongation values of well over 10% are now attainable, together with higher strengths. This considerably widens the range of application of aluminium alloy castings.

According to the Aluminium Automotive Manual, the common aluminium alloys with high heat resistance for piston design are as summarised in Table 2.1.

Table 2.1: Aluminium Alloys for Internal Combustion Pistons

Temperature	**Eutectic Alloy (AISI12 Cu, Mg, Ni)**		**Hypereutectic Alloy (AISI18 Cu, Mg, Ni)**		**Special Eutectic Alloy AISI12 Cu_4, N_{12}, Mg**
	Cast	**Forged**	**Cast**	**Forged**	**Cast**
Yield Strength (MPa) at Temperature					
20 ^{0}C	190-230	280 -310	170 - 200	220 - 280	200 – 280

150 °C	170-220	230 - 280	150 - 190	200 - 250	-
200 °C	120-170	-	100 - 150	-	150 - 200
250 °C	80 - 110	90 - 120	80 - 120	100 - 140	100 - 150
300 °C	50 - 80	-	60 - 80	-	85 - 100
Ultimate Tensile Strength (MPa) at Temperature					
20 °C	200 -250	300 - 370	180 - 230	230 - 300	210 - 290
150 °C	180 -230	250 - 300	170 - 210	210 - 260	-
200 °C	160 - 200	-	160 - 190	-	170 - 210
250 °C	100 - 150	110 - 170	110 - 140	100 - 160	130 - 180
300 °C	80 - 100	-	90 - 130	-	100 - 120
Elongation to Fracture (%)					
20 °C	0,3 – 1,5	1 – 3	0,2 – 1,0	0,5 – 1,5	0,1 – 0,5
Hot Hardness					
20 °C	90 - 125	90 – 125	90 - 125	90 - 125	100 - 150
150 °C	80 - 90	80 – 90	80 - 90	80 - 90	80 - 115
200 °C	60 – 70	60 – 70	60 - 70	60 - 70	60 - 75
250 °C	35 - 45	35 – 45	35 - 45	35 - 45	45 - 50
300 °C	20 - 30	20 – 30	20 - 30	20 - 30	30 - 40
Fatigue Strength (N/Mm^2)					
20 °C	80 - 120	110 - 140	80 - 110	90 - 120	90 – 120
150 °C	70 - 110	90 - 120	60 - 90	70 - 100	90 – 120
250 °C	50 - 70	60 – 70	40 - 60	50 - 70	60 – 80
300 °C	-	-	-	-	45 – 60
Density (Kg/Cm^3)					
20 °C	2.70	2.70	2.68	2.68	2.80
Linear Thermal Expansion Coefficient (^{1}/K)					
20°C–200 ^{0}C	20.5 – 21.5	20.5 – 21.5	18.5 – 19.5	18.5 19.5	20.5 – 21.5
Thermal Conductivity (W/Cm. K)					
20 °C	1.43 – 1.55	1.47 – 1.60	1.34 – 1.47	1.43 –	1.30 – 1.40

				1.55	
Specific Heat (J/g. K)					
100 °C	0.96	0.96	0.96	0.96	0.96
Young's Modulus (MPa)					
20 °C	80 - 81	81	83 - 84	84	82
200 °C	73 - 74	-	75 - 76	-	78
250 °C	68 - 72	74	-	76	72
300 °C	-	-	-	-	70

Source: The Aluminium Automotive Manual