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Thermo-structural Comparative Analysis of Internal Combustion Engine Piston by Finite Element Methods

Kannie Winston Kuttin [a,b*], Alexander Osei Yaw [c], Enock A. Duodu [c] and Anidrah Winston Kuttin [c]

[a] Institute of Clean Coal Technology, East China University of Science and Technology, Shanghai- 200237, China.
[b] Engineering Research Centre of Resource Utilization of Carbon-Containing Waste with Carbon Neutrality, Ministry of Education, China.
[c] Akenten Appiah Menka University of Skill Training and Entrepreneurial Development, Kumasi, Ghana.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

The piston is often considered the "heart" of the engine, operating under some of the most challenging conditions among its components. Therefore, conducting a structural analysis of the piston is crucial. This study focuses on evaluating the piston to enhance and optimize its design.

**Corresponding author: Email: zigoshone@gmail.com;*

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The piston is subjected to cyclic gas pressure and inertial forces, which can lead to fatigue damage, including side wear and head cracks. Research indicates that an ideal piston effectively dissipates heat from burned gases, contributing to overall engine efficiency. One key design objective is to reduce the piston structural weight, which in turn decreases fuel consumption. This has been achieved through advancements in engine design, incorporating lightweight materials such as ultrahigh tensile strength steels, aluminium, magnesium alloys, polymers, and carbon-fibre composites. In this study, the piston lifespan is extended by introducing a composite matrix of aluminium mixed with silicon carbide particulates, which enhances wear resistance while maintaining similar performance. The piston is designed and analysed using a 2:3 ratio of aluminium to silicon carbide. A parametric model and finite element analysis are conducted to assess stresses, strains, deformations, and temperature distributions, ultimately identifying the most suitable materials for internal combustion engines based on the results. The results indicated a better performance for AlSiC-12 than Al-6061, although, both models were in satisfactory performance range, the lightness of AlSiC-12 will make it the best choice.

Keywords: FEA; piston; Al-6061; AlSiC-12; stress; strain.

1. INTRODUCTION

The piston is one of the most critical components in mechanisms like reciprocating engines, pumps, gas compressors, and pneumatic cylinders. It plays a vital role in converting the chemical energy from fuel combustion into mechanical power by transmitting the expansion of gases to the crankshaft through the connecting rod. Essentially a cylindrical plug, the piston moves up and down within the cylinder, using piston rings to maintain a tight seal against the cylinder wall. The piston's performance directly influences engine efficiency and emissions. Pistons work in harsh condition and its reliability has become the key factors to improve engine reliability. They produce high stress and deformation due to periodic load effect from high gas pressure, high speed reciprocating motion from the inertia force, lateral pressure, and friction. Burning of the high-pressure gas products at high temperature expands piston which produces thermal stress and deformation. Therefore, it is essential to analysis the thermal stress and strain, temperature fields, heat transfer, thermal and mechanical load coupling of the piston in order to improve the thermal stress distribution and improve its working reliability during the piston designed. In recent years, digital simulation technologies have been developing rapidly with the capability of simulating the product in the real-life environment. The results of these simulations are used to optimize design, in order to reduce the design cost and improve the quality of products. Recently, there has been studies to improve the working performance of internal combustion engine piston.

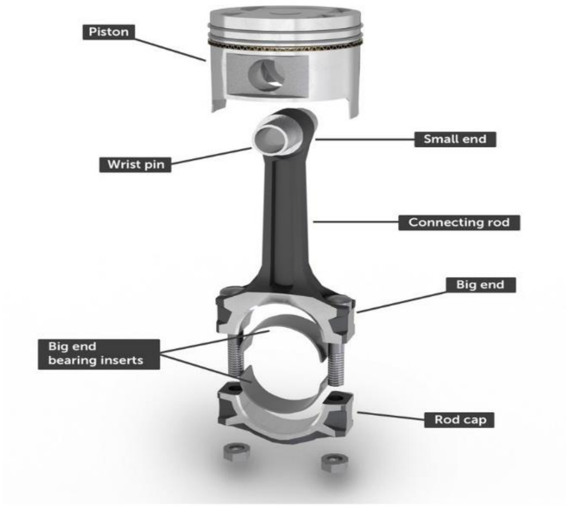

Fig. 1. Simple construction of a piston
(Manjunatha, 2013)

Aluminium pistons can be either cast or forged. The forged piston is denser and forms a better heat path to allow the heat to get away from the piston head. It has a grain flow also that improves its wearing ability. The forged aluminium piston is also lighter in comparison with the cast iron piston. Thus, it produces lower inertia forces as it accelerates and decelerates in the cylinder. Lightness reduces the weight of the reciprocating masses and so enables higher engine speeds. Good heat conductivity reduces the risk of detonation so allowing a higher compression ratio.

"Cast iron has been a universal material since early years because it possesses an excellent wearing quality, coefficient of expansion, and general suitability in manufacture. Due to the reduction of weight in reciprocating parts, the use of aluminium for piston has become essential. To obtain equal strength a greater thickness of metal is necessary, the advantage of the light metal is lost when this principle is used. Aluminium is inferior to cast iron in strength and wearing qualities, and its greater coefficient of expansion necessitates greater clearance in the cylinder to avoid the risk of seizure. The heat conductivity of aluminium is about three times that of cast iron, and this combined with the greater thickness necessary for strength, enables an aluminium alloy piston to run at much lower temperatures than a cast-iron one (200°C to 250°C as compared with 400° to 450°C)" (Javidani & Larouche, 2014). "As a result, carbonized oil does not form on the underside of the piston, and the crankcase, therefore, keeps cleaner" (Koech, 2012). This cool-running property of aluminium is now recognized as being quite as valuable as its lightness, also pistons are sometimes made thicker than necessary for strength in order to give improved cooling. The piston is subjected to highly rigorous conditions and must therefore have enormous strength and heat resistant properties to withstand high gas pressure. Its construction should be rigid enough to withstand thermal and mechanical distortion. To maintain piston temperature within limits, the heat from the crown of piston must be dissipated quickly and efficiently to the rings and bearing area and then to the cylinder walls. Numerous studies have been conducted to improve the design and material properties of the internal combustion engine piston.

Buyukkaya and Cerit (2007) "also conducted thermal analyses on a conventional (uncoated) diesel piston, made of aluminium silicon alloy and steel. Secondly, thermal analyses are performed on pistons, coated with MgO–ZrO_2 material by means of using a commercial code, namely ANSYS. It has been shown that the maximum surface temperature of the coated piston with material which has low thermal conductivity is improved approximately 48% for the AlSi alloy and 35% for the steel". Junju et al. (2012) "investigated the effect of thermal barrier coatings on diesel engine performance his results indicate a reduction in fuel consumption and an improvement in the efficiency of the diesel engine". Durat et al. (2012) "investigated the thermal barrier coating development for diesel engine aluminium piston and found that the resulting predicted temperatures and stresses on the piston, together with material strength information, the primary cause of coating failure is proposed to be low cycle fatigue resulting from localized yielding when the coating is hot and in compression". Srinadh and Rajasekhara (2015) "investigated 1300cc diesel engine piston and piston rings using Pro/Engineer and ANSYS software to study the stress and displacement on cast iron, aluminium alloy A360 and Zamak by applying structural pressure. The thermal flux and temperature distribution are also analysed by applying temperatures on the piston surface in thermal analysis". Kumar (2016) "conducted finite element analysis (FEA) of a four-stroke engine piston to compare aluminium alloy and Silicon carbide reinforced Zirconium diboride using CREO software for the model and ANSYS software for analysis. The study further analysed the natural frequency and Vibration mode of the piston and rings". Liu et al. (2024) "conducted a finite element analysis of piston under thermal, mechanical and thermo-mechanical loads coupling by using the ANSYS software. By analysing the heat and force distributions on the piston, to determine the maximum stress concentration areas the results indicated that the highest temperature on the piston appears at the top of the combustion chamber bulge, where the deformations of the piston and combustion chamber are the most serious. Computer Aided Engineering Tools (CAET) propose the incredible benefit to enabling designers to consider virtually any modelling option without incurring the expensive actual manufacturing of the machine component. The ability to try new methodology on the computer concedes the chance to omitted the problems before production. Additionally, designers can easily and shortly identify the sensitivity of specific modeling parameters on the quality and production of the final part. The complex parts of the component can be simply simulated by computer aided engineering tools (CAET)".

Due to improvements in IC engine power and performance, the pistons in the combustion chamber are subjected to increasingly higher thermal and mechanical loads. The cyclic changes in thermal and mechanical stresses seriously affect the piston fatigue life. Therefore, it is necessary to analyze the strength of the piston in the design process. The main purpose of the study is to model and simulate a three-dimensional internal combustion engine piston in Solidworks. Aluminium alloy (Al-6061) and Aluminium Silicon-Carbide (AlSiC-12) will be assigned to the designs and develop meshing and analysis of piston in ANSYS Workbench 20.1 to determine various thermo-mechanical (structural) analysis variables like total deformation, directional deformations, equivalent elastic strain, equivalent Von Mises stress, Strain Energy, thermal Strain and factor of safety.

2. MATERIALS AND METHODS

The most commonly used materials for pistons of I.C. engines are cast iron, cast aluminium, forged aluminium, titanium, cast steel and forged steel (Kumara & Charooa, 2024). The cast iron pistons are used for moderately rated engines with piston speeds below 6 m/s and aluminium alloy pistons are used for highly rated engines running at higher piston speeds (Al-Samarai & Al-Douri, 2024). It may be noted:

I. The coefficient of thermal expansion for aluminium is about 2.5 times that of cast iron, therefore, a greater clearance must be provided between the piston and the cylinder wall 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 'piston slap' while it is cold and this tendency increases with wear. The less clearance between the piston and the cylinder wall will lead to seizing of piston.
II. The 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.
III. The 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°C.

2.1 Aluminium Alloy (Al-6061)

Aluminium /Aluminium alloys have high ductility and corrosion resistance. At sub-zero temperatures, their strength can be increased. However, their strength can be reduced at high temperatures of about 200-250°C hence the inclusion of titanium. Aluminium /Aluminium 6061 alloy is an age harden able alloy containing magnesium and copper. Table 1 shows the chemical composition of Aluminium 6061 alloy.

The physical and mechanical properties of the Aluminium alloy are tabulated in Table 2.

2.2 AlSiC-12

AlSiC-12 is a metal matrix composite consisting of aluminium matrix with silicon carbide particles. It has high thermal conductivity (180–200 W/m K), and its thermal expansion can be adjusted to match other materials e.g., silicon and gallium arsenide chips and various ceramics (Khan et al., 2024). AlSiC-12 composites are suitable replacements for copper-molybdenum (CuMo) and copper tungsten (CuW) alloys; they have about 1/3 the weight of copper, 1/5 of CuMo, and 1/6 of CuW, making them suitable for weight-sensitive applications; they are also stronger and stiffer than copper (Walser & Shields, 2007). The material is fully dense, without voids, and is hermetic. Its high stiffness and low-density suits larger parts with thin walls such as fins for heat dissipation. AlSiC can be plated with nickel and other metals by thermal spraying. The aluminium matrix contains high number of dislocations, responsible for the strength of the material. The dislocations are introduced during cooling by the SiC particles, due to their different thermal expansion coefficient (Kustov et al., 2001). Table 3 shows the chemical composition of Aluminium 6061 alloy.

The physical and mechanical properties of the AlSiC-12 are tabulated in Table 4.

2.3 Model Assumptions and Process

Numerical modeling assumptions are crucial for simplifying complex systems, making computations feasible, and focusing on key variables. They help reduce the computational burden, ensure models are analytically tractable, and align models with available data for validation. Assumptions also define the scope of the model by setting boundary and initial conditions, while managing uncertainties and unknowns, ensuring that the model remains practical, relevant, and applicable to real-world scenarios.

2.3.1 The model assumptions

1. The specific heat of the materials used are constant throughout and does not change with temperature.
2. The thermal conductivity of the material used for the analysis is uniform throughout.
3. Only ambient air-cooling is considered and no forced convection is taken.
4. The piston is stress free before the application of analysis.
5. Inertia and body force effects are negligible during the analysis.
6. The piston material is considered as homogeneous and isotropic.

2.3.2 Model process

The geometrical 3D model was created in Solidworks and then exported to ANSYS for pre-processing. Pre-processing of model consist of meshing, selection of material properties, creation of load collectors and apply boundary conditions on model.

2.3.3 Model design considerations

In designing the piston, the following points were taken into consideration:

I. Minimum weight to withstand the inertia forces.
II. Sufficient bearing area to prevent undue wear.
III. Effective oil sealing in the cylinder.
IV. Strength to withstand the high pressure.
V. High speed reciprocation without noise.
VI. Sufficient support for the piston pin.
VII. Sufficient rigid construction to withstand thermal and mechanical distortions.

Solidworks software was used to model the piston considering the symmetry of the piston geometry structure and adopt one-half model to analyse the piston, which can simplify the calculation process of finite element, shorten the time of analysis and also can get a good analysis result.

2.4 Specification of the Engine

A piston of C-280 engine was considered with the specifications stated in Table 5.

Theoretical designing of piston was done using standard design procedure and the selected parameters are listed in Table 6.

Table 1. Chemical compositions of AL-6061 (Ikpe, 2020)

Element	Contents (%)
Aluminium	94.0
Nickel, Ni	0.8
Iron, Fe	1.1
Magnesium, Mg	0.90
Copper, Cu	3.20

Table 2. Physical and mechanical properties of AL-6061 (Ikpe, 2020)

Properties	Value (Metric)
Density	3.12 g/cm^3
Elastic modulus	69-81 GPa
Fatigue strength	128 MPa
Shear strength	257 MPa
Yield strength	358 MPa
Ultimate strength	412 MPa
Melting point	690°C
Elongation	9%
Poisson's ratio	0.32

Table 3. Chemical compositions of AlSiC-12 (John et al., 2015)

Element (AlSiC-12)	**Contents (%)**
Aluminium	61.2
Silicon, Si	28.4
Carbide, C	13.1
Magnesium, Mg	0.4
Titanium, Ti	0.41
Iron, Fe	0.35
Copper, Cu	0.06
Nickel, Ni	0.04

Table 4. Physical and mechanical properties of AlSiC-12 (John et al., 2015)

Properties	**Value**
Density	2.78 g/cm^3
Thermal conductivity	191 W/m K
Flexural strength	390 MPa
Elongation	4.3%
Poisson's ratio	0.24
Elastic modulus	158 GPa
Fatigue strength	152 MPa
Shear strength	295 MPa
Yield strength	398 MPa
Ultimate strength	341 MPa
Melting point	821°C

Table 5. Engine specifications (Balahari Krishnan et al., 2017)

Engine Type	**4-Stroke**
Bore × Stroke (mm)	58×57.9
Compression Ratio	8.45/1
Maximum Torque	14.4 Nm at 6100rpm
Maximum Power	12.8 bhp at 7900rpm
Displacement	655

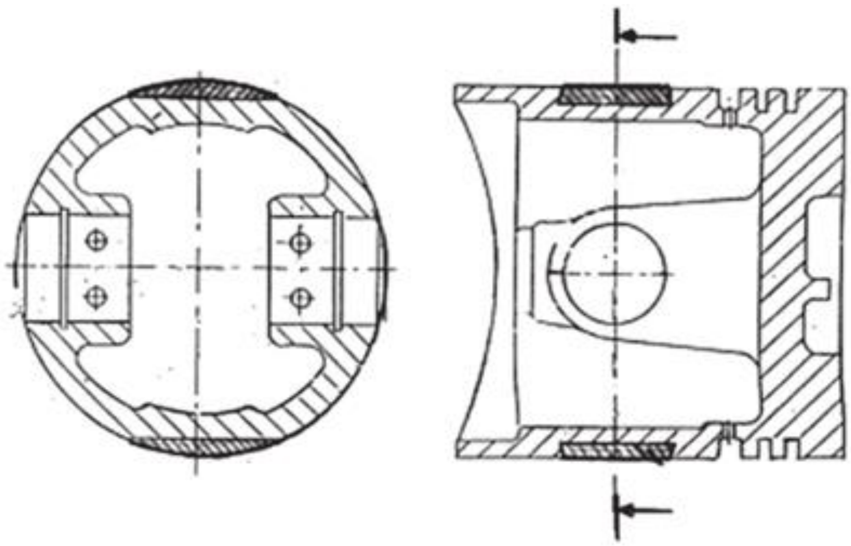

Fig. 2. Cross sectional area of a piston
(Sharipov et al., 2016)

Table 6. Piston specifications (Shinde et al., 2016)

Parts of the Piston	Measurement (Quantity)
Total length of piston	49.50 mm
Length of skirt	29.9 mm
Diameter of piston boss	31.62 mm
Piston pin diameter	18.1 mm
Thickness of piston barrel at open end	1.727 mm
Thickness of piston barrel at top end	9.61 mm
Radial depth of piston ring groove	3.1 mm
Width of ring land	1.38 mm
Width of top land	7.05 mm
Number of piston rings	3
Axial thickness of piston ring	1.7 mm
Radial thickness of piston ring	2.5 mm
Thickness of the piston head	8.11mm

2.5 Finite Element Method

The Basic concept in FEA is that the structure is divided into smaller elements of finite dimensions called finite elements. The original structure is then considered as an assemblage of these elements connected at a finite number of joints called nodes. Simple functions are chosen to approximate the displacements over each finite element. This will represent the displacement with in the element in terms of the displacement at the nodes of the element. The finite element method is a mathematical tool for solving ordinary and partial differential equations and has the ability to solve the complex problems that can be represented in differential equations form. Ansys mechanical software was selected to perform the analytical task due to its ability to handle both linear and non-linearities associated with the design.

2.5.1 Boundary conditions for structural analysis

A static analysis calculates the effects of steady loading conditions on a structure, while ignoring inertia and damping effects, such as those caused by time varying loads. A static analysis can, however, include steady inertia loads (such as gravity and rotational velocity), and time-varying loads that can be approximated as static equivalent loads. Static analysis determines the displacements, stresses, strains, and forces in structures or components caused by loads that do not induce significant inertia and damping effects. Steady loading and response conditions are assumed; that is, the loads and the structure's response are assumed to vary slowly with respect to time. The types of loading that can be applied in a static analysis include:

i. Imposed (non-zero) displacements
ii. Steady-state inertial forces
iii. Externally applied forces and pressures

Combustion of gases in the combustion chamber exerts pressure on the head of the piston during power stroke. Fixed support was given at surface of pin hole. The piston moves from top dead centre (TDC) to bottom dead centre (BDC) with the help of fixed support at pin hole and the pressure acting on piston is 4 N/mm^2.

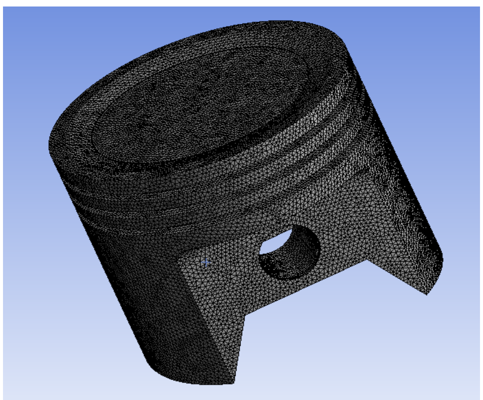

Fig. 3. Mesh: nodes:188577 element:105885

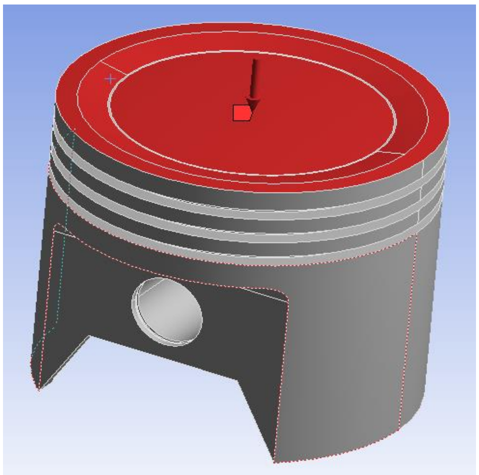

Fig. 4. Structural boundary condition (Pressure)

2.5.2 Boundary condition for thermal analysis

The thermal boundary conditions consist of applying a heat flux and the bulk temperature distribution, and they are applied to the piston crown, land sides, piston skirt. The upper surface of the piston is subjected to hot gases which take different values of temperature of gases and convective heat transfer coefficient for the different crank angles. The thermal boundary conditions for the current study is presented in Table 7.

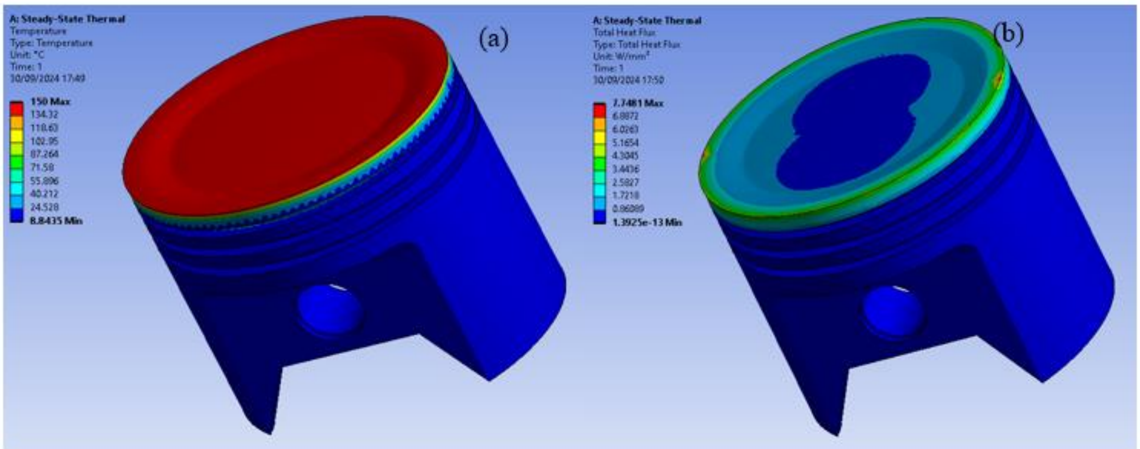

Fig. 5. Thermal boundary conditions: (a) temperature distribution and (b) heat flux

Table 7. Thermal boundary conditions of the piston (Havale & Wankhade, 2017)

Variable	Quantity
Heat flux	$3.8598\times^{-3}$ W/mm^2
Temperature level of piston bottom portion	78°C
Heat transfer coefficient on piston skirt	0.5 W/m^2°C
Maximum temperature at edges of piston	240°C
Heat transfer coefficient on piston surface	1.2 W/m^2°C
Bulk temperature	225°C
Maximum on piston head temperature	300°C

3. RESULTS

The dynamics of the whole piston in the form of input temperature and pressure will be considered and then thermo-structural analysis of both models will be presented. Two models with the same input parameters and control schemes but different materials assignment is developed for the study. A model scalar of 1:1 is applied to obtain equal order models that are suitable for real life dynamic analysis and control design. The measuring variables analysed in the current are the total deformations, directional deformations, strain energy, thermal strain, stresses, strains and factor of safety.

3.1 Thermo-structural Analysis

3.1.1 Total deformation and directional deformations in X-Y-Z axis

The three-dimensional finite element model was analysed using the Ansys mechanical commercial code to determine the total deformation and directional deformations of both models; the analysis was performed in two parts: (1) steady state thermal (i.e., heat transfer) solution was obtained generating the nodal temperatures and (2) static structural solution was obtained by imposing the nodal temperatures and the pressure loads. The resultant out-of-plane varying deformations of the whole surfaces of heat pistons for Al6061 and AlSiC are shown in Figs. 6 (a) and (b) respectively. The X, Y and Z directional deformation for Al6061 and AlSiC are presented in Fig. 7 (a and b), (c and d) and (e and f) respectively. The deformations were calculated relative to the centre point of the full dome top. These plots indicate a measurable hump (or a deflection peak) located around the rim on the plane of symmetry. According to Figs. 6 and 7 there is a high deformation around the fit rim and the ring grooves. As a general mechanical design principle, more grooves in the body will decrease the mechanical strength of any design.

3.2 Elastic Strain Analysis

Fig. 8 (a) and (b) present the piston equivalent strain (von mises) distributions of Al6061 and AlSiC respectively. The high temperature area near the apex of the piston dome had a large expansion, and it gradually decreased away to the rim. The equivalent strain distributions showed similar distributions amongst both designs. The maximum equivalent strain value for Al6061 and AlSiC were discovered to be 3.55×10^{-3} and 1.71×10^{-3} respectively for the given loading condition. It was observed that the equivalent elastic strain in both models was more pronounce at the piston rings groove.

3.3 Stress Distribution

Fig. 9 (a) and (b) are the results of the Von Mises stresses of Al6061 and AlSiC. The maximum stresses were found around the ring grooves and the rim stretch where there is concentration of both pressure and temperature in both cases. The pistons maximum local von-Mises stresses values were 708.48 and 342.21 MPa for both thermal and pressure loading cases for Al6061 and AlSiC respectively. These figures confirmed

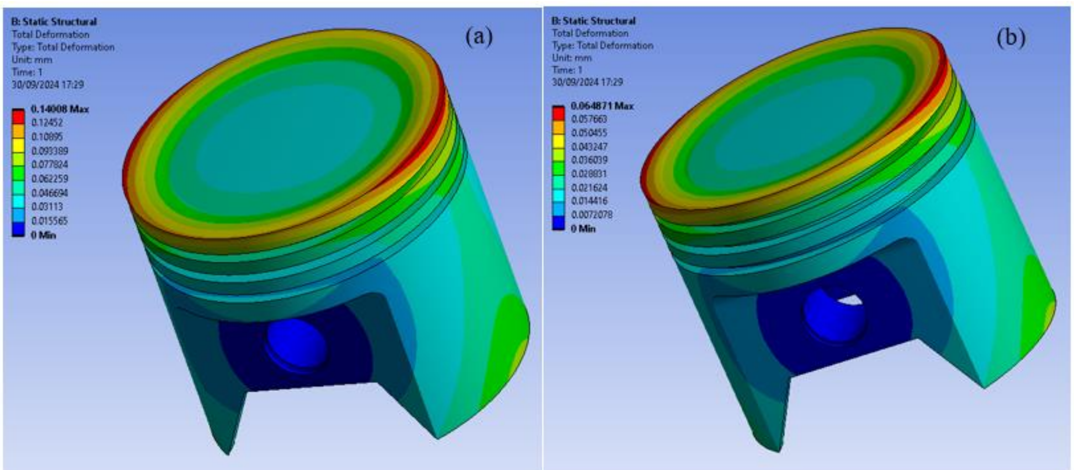

Fig. 6. Total deformation of (a) Al6061 and (b) AlSiC

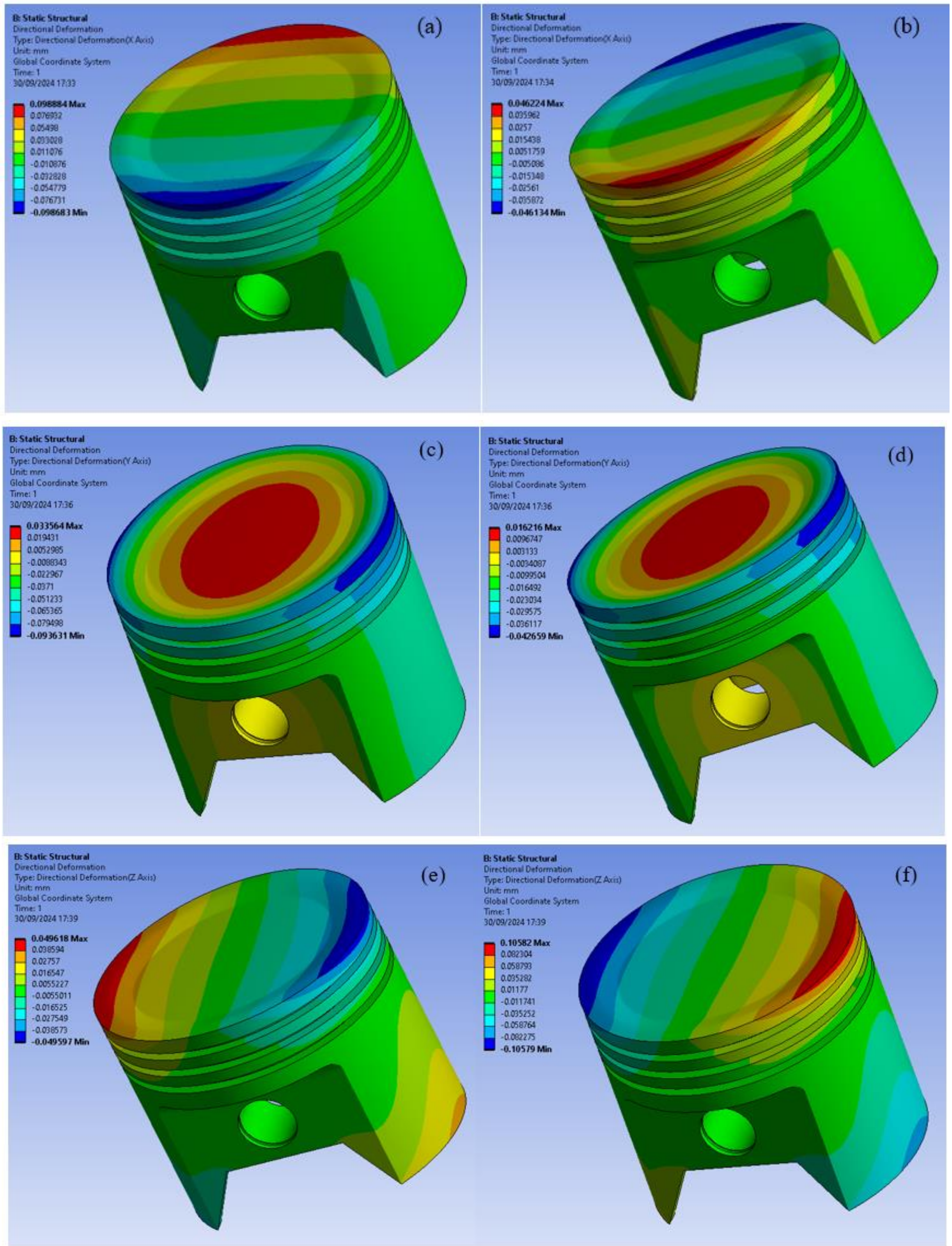

Fig. 7. Directional deformation (X-Y-Z-Axis) of (a, c, e) Al6061 and (b, d, f) AlSiC

that these stress values are lower than the allowable stress values for normal plunger piston. The sum of the membrane stress was 183 MPa, which is lower than the constraint value (1.5 × allowable stress value). Therefore, the stress state of the piston satisfied the International Automobile Standard (IAS) criteria (Altshuler, 1984).

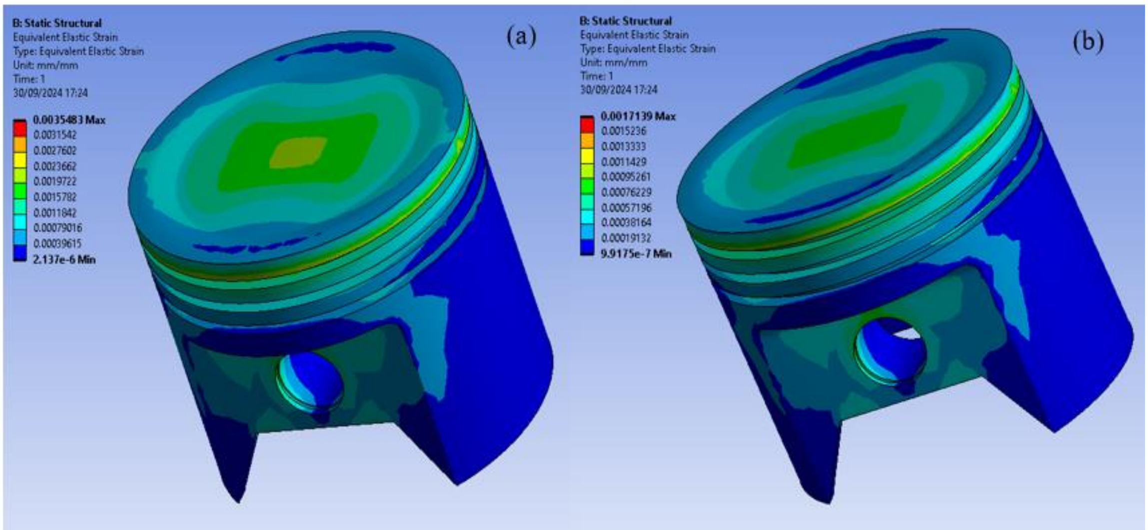

Fig. 8. Equivalent elastic strain of (a) Al6061 and (b) AlSiC

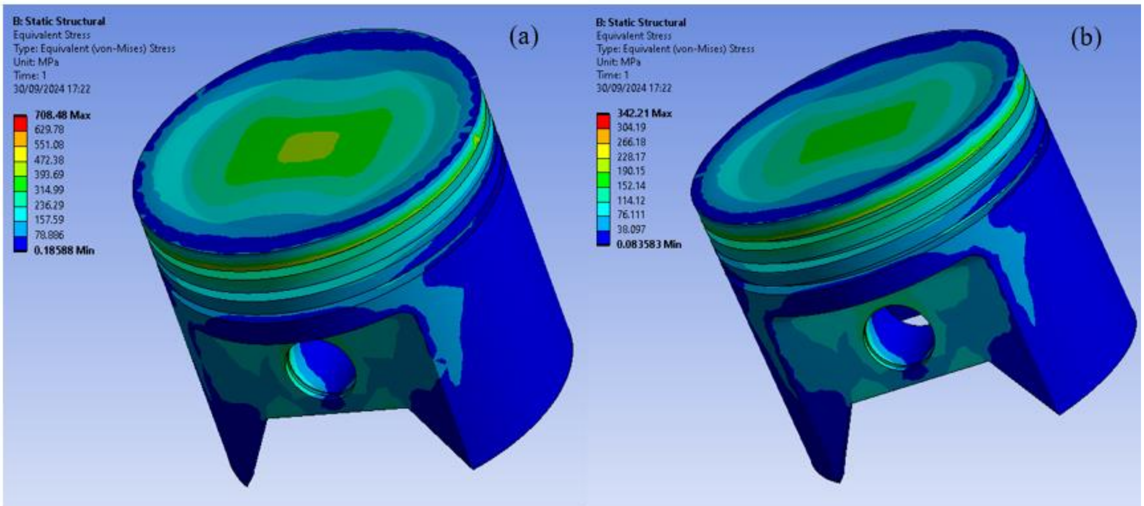

Fig. 9. Equivalent (Von-Mises) stress of (a) Al6061 and (b) AlSiC

3.4 Factor of Safety (FOS)

Fig. 10 (a) and (b) present the maximum damage and failure concentration areas as observed in the Al6061 and AlSiC models. As expected highest failure zone is observed at the top brim and inside of the ring grooves of the pistons where the FOSs are 1.22×10^{-1} and 2.51×10^{-1} nearing zero for Al6061 and AlSiC models, due to the concentration of high temperatures and pressures around these areas.

Generally, the theoretical FOS of the plunger piston for an internal combustion engine is 5.8 (Sterling, 1917). The maximum generated FOS of both models have magnitude of 15. The maximum FOS was observed to be more profound at the skirt of the models. The theoretical FOS value of 5.9 is within the range of factor of safeties of both models of the current models generated. Therefore, both models are very safe.

3.5 Strain Energy

The strain energy being the energy stored in the piston due to all direction deformations, appeared scattered in the ring grooves and the dome surface with maximum matrix value of 1.36 and 3.88×10^{-1} m^3 for Al6061 and AlSiC models respectively as presented in Fig. 11 (a) and (b).

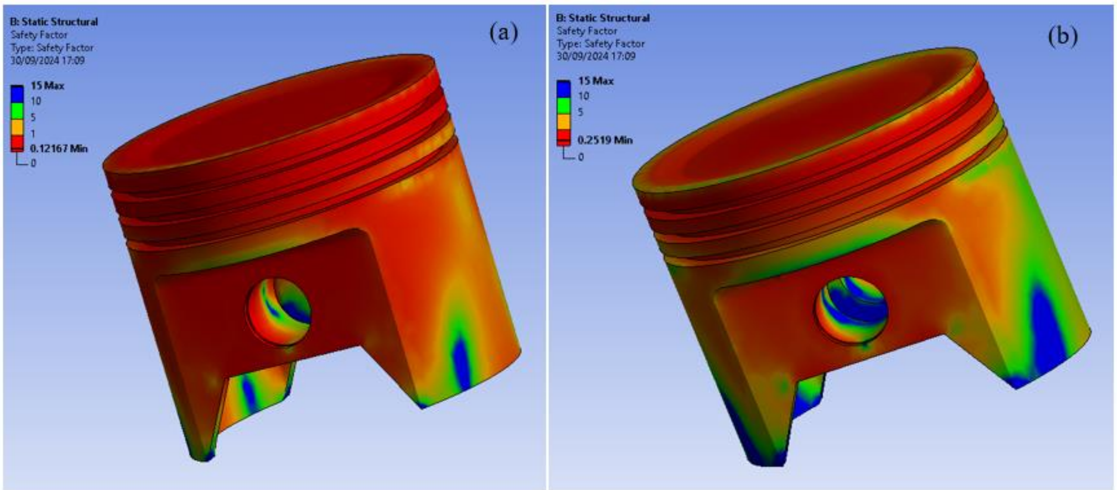

Fig. 10. Factor of Safety of (a) Al6061 and (b) AlSiC

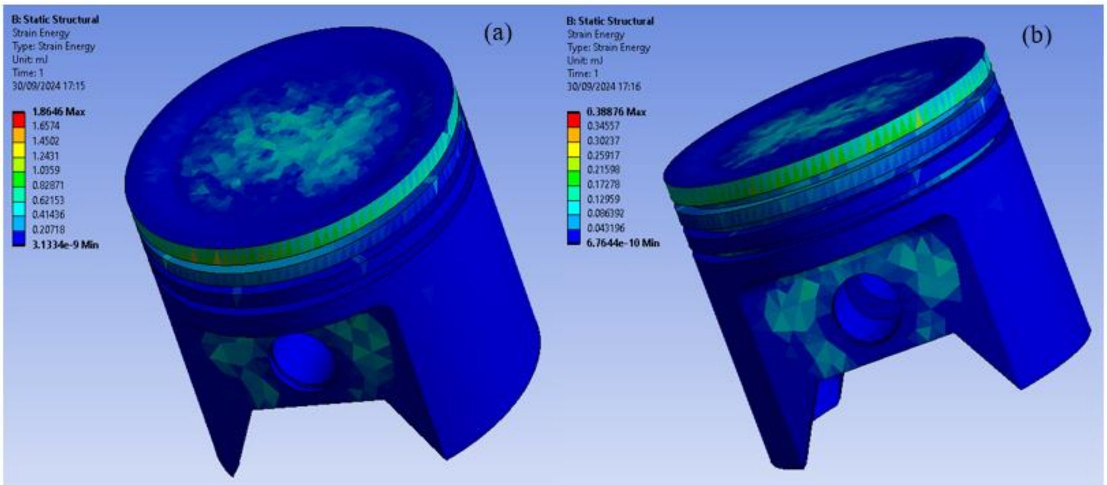

Fig. 11. Strain energy of (a) Al6061 and (b) AlSiC

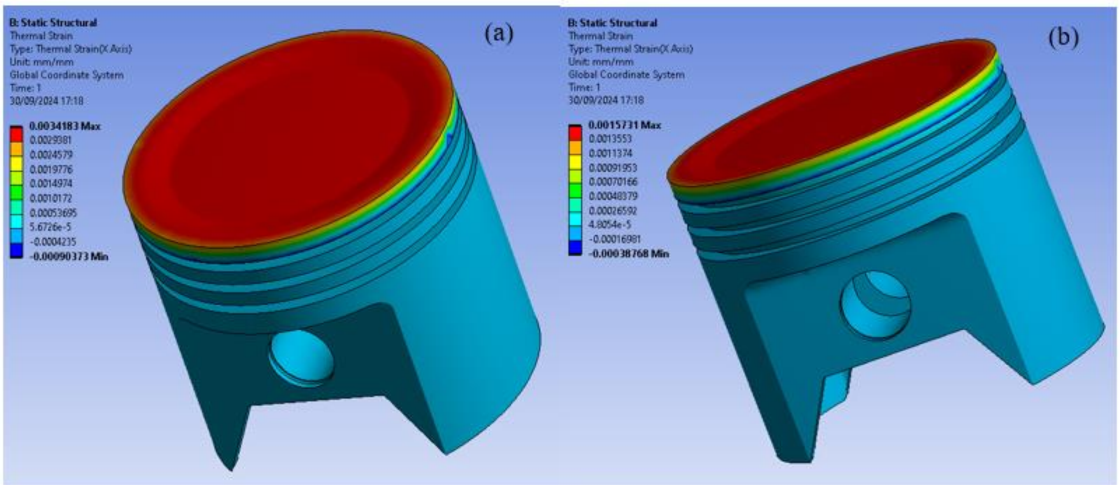

Fig. 12. Thermal strain of Al6061 and AlSiC

3.6 Thermal strain

Fig. 12 shows thermal strain levels in Al6061 and AlSiC piston. The maximum thermal strains for Al6061 and AlSiC models are 3.41×10^{-3} and 1.57×10^{-3} mm/mm respectively. As comparing the Al6061 and AlSiC materials the maximum thermal strain value is decreased in AlSiC material by 1.84 mm/mm.

4. DISCUSSION

The Table 8 display predicted simulated result for aluminium alloy Al6061 and aluminium silicon carbide (AlSiC) piston models for four-cylinder IC engine. The variables analysed are the total deformations, directional deformations, strain energy, thermal strain, stresses, strains and factor of safety and comparison is done for the selected materials. The focus here is on the performance of the components so with Al6061 having a high stress value means AlSiC can give a high performance and long operating duration under the same operating conditions, in comparison with Al6061. AlSiC is suggested as a possible alternative material for piston with moderate temperature because it will provide high strength to weight ratio. As the effect of strain energy density on the mechanical behaviour of the material can be significant. The change in strain energy density for deformations out of the residually stressed configuration that quantify the contribution of a residual stress to the mechanical behaviour of the elasticity of the materials, residual stress field and the mechanical response were examine in relation to the directional deformations. The change in strain energy density at any axial point of all the three directional deformation was measured to the extent at which the material at that point is loaded or unloaded by a deformation. Due to the strain energy density values obtained which shows slight difference between the two materials, though Al6061 value is high its weight can compensate for the energy-mass ratio. The low strain energy for AlSiC can be used in conjunction with the stress and strain fields to develop a clear physical interpretation of the universal mechanical behaviour of a residually stressed of the material. These value of AlSiC in the presence of the residual stress field and equivalent stress-free body under all of the deformations has the effect of making the body more compliant than the Al6061.

In a way to validate the results obtained from the finite element analysis, the experimental weighing results of grey cast iron piston were compared. The weights of the two models were compared with Chilled grey cast iron using the ANSYS mechanical mass calculator, the AlSiC-12 model weighed 0.286kg representing 26% whiles the AL-6061 model weight 0.795kg representing 74%. With the weight variations indicating light weight ratio in favour of AlSiC-12 makes it more efficient mechanically. Hence, the main objective of using AlSiC-12 alloy to design piston of internal combustion engine for weight reduction has been achieved.

4.1 Modal Analysis

The modal analysis presented the natural incidence deformation in relation to equivalent stress and equivalent strain of the both models at different modes for all the selected materials. Incidence range of the AlSiC shows a very good match with the incidence range of Al6061 and better than chilled grey cast iron used as the base standard material for plunger pistons. The obtained incidence range of the existing material piston was 7199.8 Hz to 7893.2 Hz and for modified material was 7016.7 Hz to 7932.8 Hz. As the incidence range of the modified piston is within the incidence range of existing piston, the modified design proves to be safe. The total

Table 8. Summary of the measuring variables

Parameter	Al6061		AlSiC-12	
	Minimum	Maximum	Minimum	Maximum
Von Mises Stress (MPa)	1.85×10^{-1}	708.48	8.352×10^{-2}	342.21
Elastic Strain (mm/mm)	2.18×10^{-6}	3.55×10^{-3}	9.91×10^{-7}	1.71×10^{-3}
Total Deformation (mm)	0	1.40×10^{-2}	0	6.48×10^{-2}
Directional Deformation X (mm)	-9.86×10^{-2}	9.88×10^{-2}	-4.61×10^{-2}	4.62×10^{-2}
Directional Deformation Y (mm)	-9.36×10^{-2}	3.36×10^{-2}	-4.27×10^{-2}	1.62×10^{-2}
Directional Deformation Z (mm)	-4.95×10^{-2}	4.96×10^{-2}	-1.06×10^{-2}	1.07×10^{-2}
Thermal Strain (mm/mm)	-9.03×10^{-4}	3.41×10^{-3}	3.80×10^{-4}	1.57×10^{-3}
Factor of Safety	1.22×10^{-1}	15	2.51×10^{-1}	15
Strain Energy (MJ)	3.13×10^{-9}	1.36	6.76×10^{-10}	3.88×10^{-1}

Table 9. Incidence range against deformation with different modes of Al6061 Piston

Mode	Incidence range (Hz)	Deformation
1	7199.8	11134×10^{-1}
2	7215.3	16174×10^{-1}
3	7480.0	2.0416×10^{-1}
4	7497.0	2.6544×10^{-1}
5	7870.8	2.9231×10^{-1}
6	7893.2	3.1634×10^{-1}

Table 10. Incidence range against deformation with different modes of AlSiC Piston

Mode	Incidence range (Hz)	Deformation
1	7016.7	4.4899×10^{-2}
2	7136.9	5.5023×10^{-2}
3	7327.8	6.4893×10^{-2}
4	7536.6	7.5153×10^{-2}
5	7737.7	7.7304×10^{-2}
6	7932.8	8.4129×10^{-2}

deformation of AlSiC is less compared to Al6061. This indicates change of the Al6061 piston to AlSiC piston results in high incidence range due to lowest weight value and the deformation close to the existing piston material under the same operating conditions. The strain value of AlSiC is low compared to Al6061 which is close and at the same time deformation in both materials are less than standard deformation bridge for non-static IC engines components.

5. CONCLUSION

This study considered two analytical methods which are static structural and thermal analysis. The parameters considered under the thermo-static (thermal-structural) analysis were total deformation, directional deformations, equivalent elastic strain, equivalent Von Mises stress, strain energy, thermal strain and factor of safety of Al6061 and AlSiC-12. The following conclusions were made from the study into modelling and simulation of the piston of an internal combustion engine using AL-6061 and AlSiC-12.

It was revealed from the study that when the structural load of 49637.2N and thermal load of 300°C were imposed on the piston of the AlSiC-12 and AL-6061 and their deformations compared, their maximum deformations were 6.48×10^{-2} and 1.40×10^{-2} mm respectively. The comparison showed that AlSiC-12 piston deformed less in relation to the two selected materials, though both materials were within the percentage reductions of the materials hence all the pistons were found to be satisfactory.

Moreover, when the equivalent elastic strains of the pistons were compared, it was revealed that, the maximum and minimum elastic strain of the AlSiC-12 piston were 1.71×10^{-3} and 9.91×10^{-7} respectively whiles the maximum and minimum elastic strain of Al-6061 was 3.55×10^{-3} and 2.18×10^{-6} respectively.

The maximum Von Mises stresses induced in AlSiC-12 and Al-6061 piston was 342.21 and 708.48 MPa respectively. The observation from the data showed that, the Mises stresses induced in both pistons were below the compressive yield strengths of the individual materials, hence the pistons can withstand the load imposed.

When the factor of safeties of the pistons were compared, it was found that the AlSiC-12 piston has high minimum value than Al-6061 which makes it more suitable material in terms of failure as against Al-6061 with a low minimum safety factor of 1.22×10^{-1}as against 2.51×10^{-1} for AlSiC-12.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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