

Thermo-Structural Evaluation of Material Performance in a 4-Stroke Internal Combustion Engine Using Finite Element Analysis

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ABSTRACT

The performance and durability of a 4-stroke Internal Combustion (IC) engine are strongly influenced by the thermal behavior and material selection of its key components. Traditional design approaches relying on empirical calculations and experimental methods are often time-consuming and limited in capturing complex thermal interactions. In this study, a computational approach is adopted to evaluate thermal performance efficiently. A detailed 3D model of the engine assembly, including the piston, connecting rod, and crankshaft, was developed using SOLIDWORKS and analyzed in ANSYS Workbench under steady-state thermal conditions. Three materials Gray Cast Iron, Aluminium Alloy, and Stainless Steel were assessed based on temperature distribution and heat flux characteristics. The results show that Aluminium Alloy, despite its high thermal conductivity and low weight, exhibits higher thermal expansion, which may compromise structural stability. Stainless Steel demonstrates superior thermal stability, reduced deformation, and better resistance to high-temperature stresses, making it the most suitable material for thermally critical components. Gray Cast Iron provides moderate performance but is less effective under extreme conditions. Overall, this study highlights the effectiveness of Computer-Aided Design (CAD) and Finite Element Analysis (FEA) based analysis in optimizing material selection, reducing development time, and improving the reliability and performance of IC engines.

Keywords: Internal Combustion Engine (IC Engine), Heat Flux, Gray Cast Iron, Thermal Stress, Aluminium Alloy, Computer-Aided Design, Finite Element Analysis.

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1. INTRODUCTION

An internal combustion engine (ICE) is a heat engine where the combustion of a fuel occurs with an oxidizer (usually air) in a combustion chamber that is an integral part of the working fluid flow circuit. In an internal combustion engine, the expansion of the high-temperature and high-pressure gases produced by combustion applies direct force to some component of the engine. The force is applied typically to pistons, turbine blades, rotor or a nozzle. This force moves the component over a distance, transforming chemical energy into useful mechanical energy. The first commercially successful internal combustion engine was created by Étienne

Lenoir around 1859 and the first modern internal combustion engine was created in 1876 by Nikolaus Otto (see Otto engine). The term internal combustion engine usually refers to an engine in which combustion is intermittent, such as the more familiar four-stroke and two-stroke piston engines, along with variants, such as the six-stroke piston engine and the Wankel rotary engine. A second class of internal combustion engines use continuous combustion: gas turbines, jet engines and most rocket engines, each of which are internal combustion engines on the same principle as previously described. Firearms are also a form of internal combustion engine. In contrast, in external combustion engines, such as steam or Stirling engines, energy is delivered to a working fluid not consisting of, mixed with, or contaminated by combustion products. Working fluids can be air, hot water, pressurized water or even liquid sodium, heated in a boiler. ICEs are usually powered by energy-dense fuels such as gasoline or diesel fuel, liquids derived from fossil fuels. While there are many stationary applications, most ICEs are used in mobile applications and are the dominant power supply for vehicles such as cars, aircraft, and boats.

2. LITERATURE REVIEW

Manjunatha. T. R [1] described the design and analysis of cylinder and piston of a twostage reciprocating Air Compressor to the taken specifications for both low pressure and highpressure stages. A finite element model for cylinder and piston is built and analysis of these components is carried by using ANSYS, for both low pressure and highpressure stages during the suction and compression stroke. So as to identify the location of maximum stress concentration and to identify the areas those are likely to fail

Vaibav V. Mukkavar [2] described the stress distribution of two different aluminum alloys piston by using CAE Tools. The specifications used for the study of these pistons belong to four stroke single cylinder engine of Bajaj Pulsar 220CC motorcycle. He illustrated the procedure for analytical design of two different aluminum alloy pistons. The results predict the maximum stress and critical region on the different aluminum alloy pistons using CAE Tools. A parametric model of Piston is modeled using Solid works 2014 software and analysis of that model is carried out by using ANSYS 14.5 Software. The best aluminum alloy material is selected based on parameters like Von Misses Stress and strain, Deformation, Factor of safety and weight reduction for twowheeler piston were done in ANSYS 14.5 software.

Isam Jasim Jabir and Ajeet Kumar Rai [3] presented a work on piston and piston ring are designed for a single cylinder four stroke petrol engine using CATIA V5R20 software. Complete design is imported to ANSYS 14.5 software then analysis is performed. Three different materials have been selected for structural and thermal analysis of piston. For piston ring two different materials are selected and structural and thermal analysis is performed using ANSYS 14.5 software. Results are shown and a comparison is made to find the most suited design. Vaishali R. Nimbarte, Prof. S.D. Khamankar [4] investigated and analyzed the stress distribution of piston at actual engine condition. Pressure analysis, thermal analysis and thermo-mechanical analysis is done. The parameter used for the analysis is operating gas pressure, temperature and material properties of piston.

In I.C. Engine piston is most complex and important part therefore for smooth running of vehicle piston should be in proper working condition. Piston fail mainly due to mechanical stresses and thermal stresses. Analysis of piston is done with boundary conditions, which includes pressure on piston head during working condition and uneven temperature distribution from piston head to skirt. The analysis predicts that due to temperature whether the top surface of the piston may be damaged or broken during the operating conditions, because damaged or broken parts are so expensive to replace and generally are not easily available. Abino John, Jenson T Mathew [5] used Aluminum Silicon Carbide (AlSiC), an aluminum matrix composite for piston an alternative for aluminum. A 3D model was made using CATIA v6 and Structural and thermal analysis was done on ANSYS14. Compared to Aluminum, AlSiC has better abrasion resistance, creep resistance, dimensional stability, exceptionally good stiffness-to-weight and strength-to-weight ratios and better high

temperature performance. Fabrication of piston using AlSiC is also easier than using aluminum. Ajay Raj Singh, Dr. Pushpendra Kumar Sharma [6] described the stress distribution and thermal stresses of three different aluminum alloys piston by using finite element method (FEM). The parameters used for the simulation are operating gas pressure, temperature and material properties of piston. The specifications used for the study of these pistons belong to four stroke single cylinder engine of Bajaj Kawasaki motorcycle. This paper illustrates the procedure for analytical design of three aluminum alloy pistons using specifications of four stroke single cylinder engine of Bajaj Kawasaki motorcycle. The results predict the maximum stress and critical region on the different aluminum alloy pistons using FEA. It is important to locate the critical area of concentrated stress for appropriate modifications. Static and thermal stress analysis is performed by using ANSYS 12.1. The best aluminum alloy material is selected based on stress analysis results. The analysis results are used to optimize piston geometry of best aluminum alloy. Parag C. Thanare, R. G. Telrandhe [7] described the stress distribution on piston head by using FEA. The main objective is to investigate and analyze the thermal stress distribution of piston, piston rings at the real engine condition during combustion process. They mainly focused on the critical investigation of original piston of engine and its performance along with the different materials coatings with different thickness, mesh optimization with using finite element analysis technique to predict the higher stress and critical region on the component. Using Computer Aided Design (CAD), Pro/ENGINEER software the structural model of a piston is developed. Furthermore, the finite element analysis performed using ANSYS. Piotrszurgott. et.al [8] conducted a Thermo-mechanical FE analysis of the engine piston made of composite materials. Their results showed that the radial displacements in such pistons are four times lower than the actual one. The radial component is also much lower for the new composite pistons. Praful R. Sakharkar [9] performed Thermal analysis of IC engine piston using fea, the main purpose of this analysis was to reduce the stress concentrations of the upper end of the pistons. Different Aluminium alloys are tested for maximum stiffness. The Thermo-structural analysis is carried out for four different types of pistons having the same basic dimensions with exception being the shape and size of the bowl on the piston crown. The first step in this direction was taken by adopting the dimensions of the pistons provided by Ms. Sam Pistons Pvt. Ltd. By adopting these real time dimensions, geometrical models were created using SOLIDWORKS software. The models generated were now imported to ANSYS Workbench 14.5 version software [10].

3. PROPOSED SYSTEM

Ansys is general purpose software package. Finite element numerical method of a deconstructing a complex system into very small pieces (user designated size) called element. The software implements equations that governs the behaviour of these elements and solver them all; creating a comprehensive explanation of how the system acts as a whole. These results than can be presented in tabulate or graphical forms. This type of analysis is typically used for the designed and optimization of system for too complex to analyse by hand. Systems that make fir into this category are too complex due to their geometry, or governing equations.

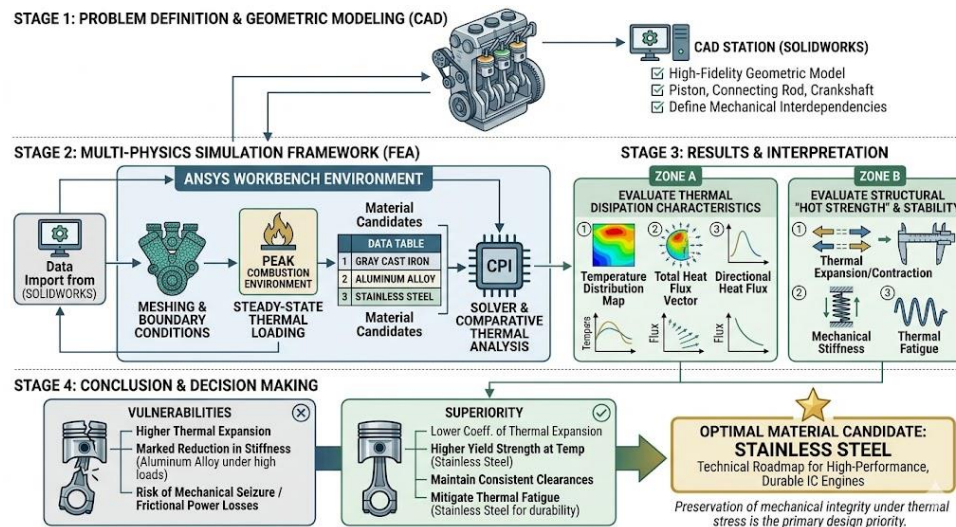


Fig. 1: Proposed system architecture.

Ansys provide a cost-effective way to explore the performance of the products and processes in a virtual environment. This type of product development is termed as virtual Prototyping. With virtual prototyping techniques users can iterate various scenarios to optimize the product long before manufacturing is started. This enables a reduction in level of risk, And in the cost of ineffective designs. The multifaceted nature of Ansys also provides a means of ensure that users are able to see the effect of designs on the whole behaviour of the product, be it electromagnetic, thermal, mechanical etc.

STRUCTURAL

Structural analysis is probably the most common application of the finite element method is as it implies bridges and buildings, naval, aeronautical and mechanical structure such as ship halls, air craft's and machines housing as well as mechanical components such as pistons, machine parts and tools. Static analysis issued to determine displacement, stresses etc. under static loading conditions

ANSYS can compute both linear and non-linear static analysis. Non linearity can include plasticity, stress stiffening, large deflection, large strain, hyper elasticity, contact surface and creep.

STATIC 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 approximately as static equivalent loads (such as the static equivalent wind and seismic loads commonly defined in many building codes).

THERMAL ANALYSIS

A thermal analysis calculates the temperature distribution and related thermal quantities in a system component. Typical thermal quantities of interest are:

- The temperature distributions
- The amount of heat lost or gained
- Thermal gradients
- Thermal fluxes.

Thermal simulations play an important role in design of many engineering applications, including internal combustion engines,turbines,heat exchangers, piping system & electronic components. In many cases,

engineers follow a thermal analysis with a stress analysis to calculate thermal stresses (i.e. stresses caused by thermal expansions or contractions).

ANSYS supports two types of thermal analysis:

- A steady-state thermal analysis determines the temperature distribution & other thermal quantities under steady-state loading condition. A steady-state loading condition is a situation where heat storage effect vary over a period of time can be ignored.
- A transient thermal analysis determines the temperature distribution & other thermal quantities under conditions that vary over a period of time.

4. RESULTS DESCRIPTION

The thermal analysis of the IC engine assembly was carried out using steady-state conditions in ANSYS Workbench. The results obtained include temperature distribution, total heat flux, and directional heat flux for different materials. These results help in understanding the thermal behavior and heat dissipation capability of the selected materials.

4.1 Gray cast iron

Fig 2 presents the mechanical and thermal properties of Gray Cast Iron used in the analysis. It includes parameters such as Young's modulus, Poisson's ratio, thermal conductivity, and coefficient of thermal expansion. These properties are essential inputs for accurate FEA simulation. The relatively moderate thermal conductivity and stiffness influence the heat transfer and structural behaviour of the material.

Gray Cast Iron	
Structural	
Isotropic Elasticity	
Derive from	Young's Modulus and Poisson's Ratio
Young's Modulus	1.1e+11 Pa
Poisson's Ratio	0.28
Bulk Modulus	8.3333e+10 Pa
Shear Modulus	4.2969e+10 Pa
Isotropic Secant Coefficient of Thermal Expansion	1.1e-05 1/°C
Compressive Ultimate Strength	8.2e+08 Pa
Compressive Yield Strength	0 Pa
Tensile Ultimate Strength	2.4e+08 Pa
Tensile Yield Strength	0 Pa
Thermal	
Isotropic Thermal Conductivity	52 W/m·°C
Specific Heat Constant Pressure	447 J/kg·°C
Electric	
Isotropic Resistivity	9.6e-08 ohm-m
Magnetic	
Isotropic Relative Permeability	10000

Fig. 2: material properties of gray cast iron

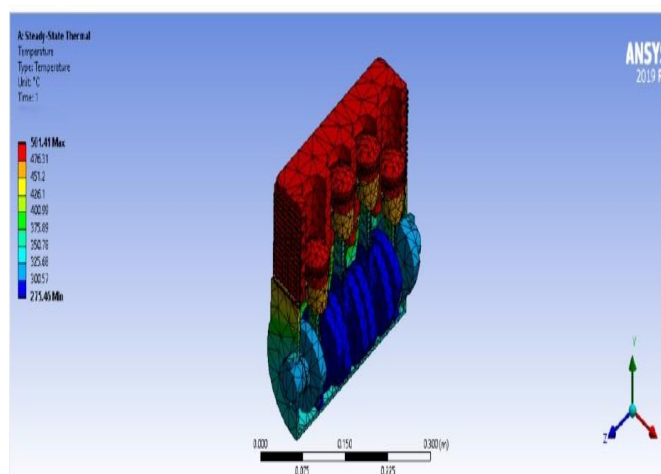


Fig. 3: temperature

Fig 3 temperature distribution plot shows the variation of temperature across the engine component. The maximum temperature is observed near the combustion region (red zone), while the minimum temperature appears at the lower regions (blue zone). This indicates a strong thermal gradient within the component. Gray Cast Iron demonstrates stable temperature distribution under thermal loading.

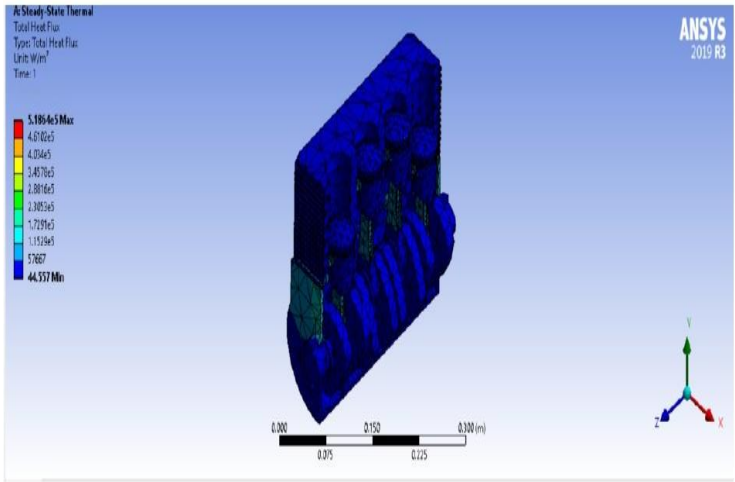


Fig. 4: total heat flux

Fig. 4 total heat flux plot represents the magnitude of heat transfer through the material. Higher heat flux regions indicate areas of intense heat flow, mainly around the combustion chamber. Lower values are observed in cooler regions of the model. This shows that Gray Cast Iron allows moderate heat transfer across the structure.

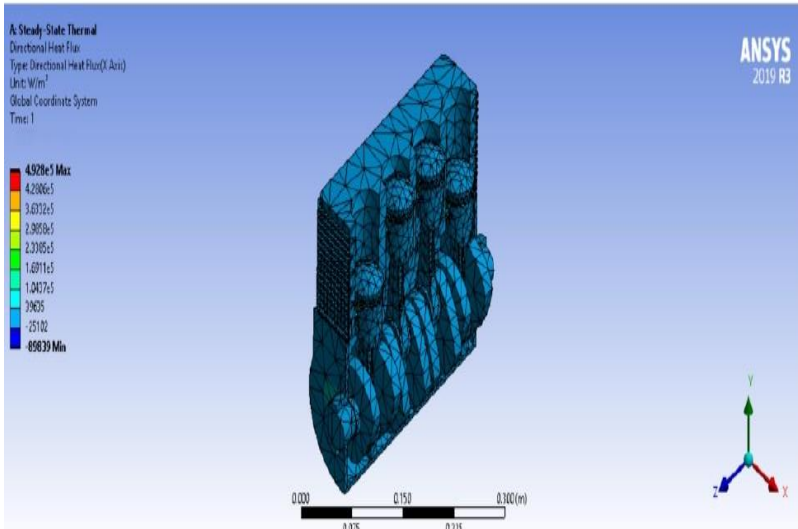


Fig. 5: directional heat flux

Fig. 5 directional heat flux plot illustrates the direction and intensity of heat flow along a specific axis. Both positive and negative values indicate the direction of heat transfer within the component. The variation in values highlights non-uniform heat flow. This helps in identifying critical regions subjected to thermal gradients.

Table 1 results of gay cast iron

Result Summary

Results	Minimum	Maximum	Units	Time (s)
Temperature	275.46	501.41	°C	1.
Total Heat Flux	44.557	5.1864e+005	W/m ²	1.
Directional Heat Flux	-89839	4.928e+005	W/m ²	1.

Table 1 results show that the temperature ranges from 275.46°C to 501.41°C, indicating significant thermal exposure. The total heat flux varies widely, reflecting different heat transfer rates across the component. The directional heat flux values confirm the presence of strong thermal gradients, which may influence thermal stresses in the material.

4.2 Aluminum alloy

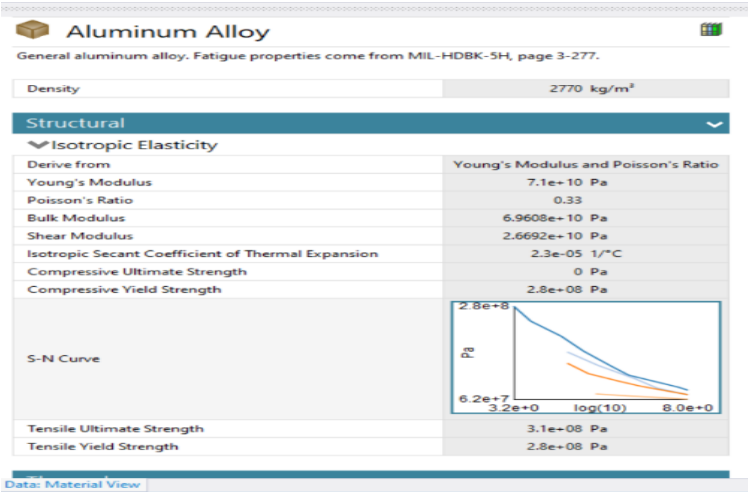


Fig. 6: material properties of aluminum alloy

Fig 6 presents the structural and thermal properties of Aluminium Alloy used in the simulation. Key parameters such as Young's modulus, Poisson's ratio, density, and thermal conductivity are defined for accurate analysis. The material exhibits high thermal conductivity and a relatively high coefficient of thermal expansion. These properties make Aluminium Alloy efficient in heat transfer but more prone to thermal deformation under elevated temperatures.

Fig. 7 illustrates the thermal analysis results, including temperature distribution and heat flux characteristics of Aluminum Alloy. The temperature contour shows higher heat concentration near the combustion region, similar to other materials. The heat flux distribution indicates increased heat transfer due to the material's high conductivity. However, the results also suggest larger thermal gradients, which may contribute to expansion and reduced structural stability.

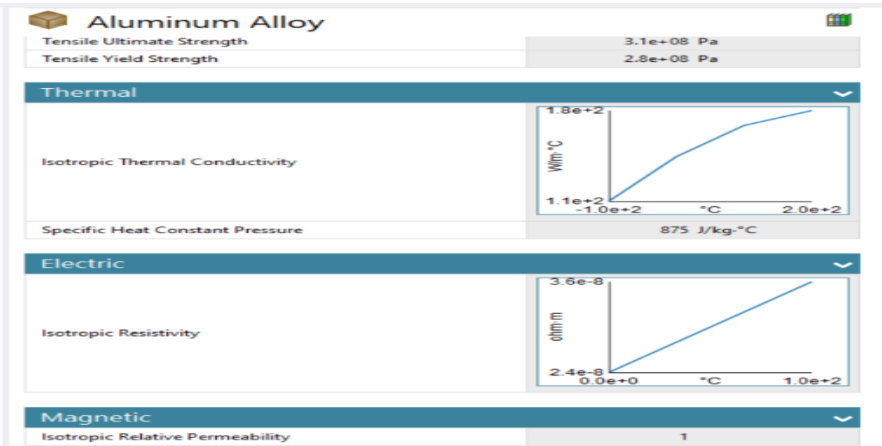


Fig. 7: results of aluminum alloy
Table 2 results of aluminum alloy

● Result Summary

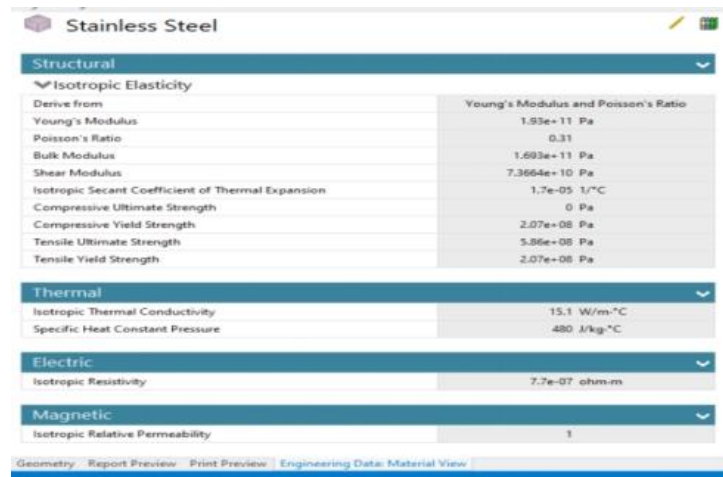
Results	Minimum	Maximum	Units	Time (s)
Temperature	406.46	500.52	°C	1.
Total Heat Flux	78.167	6.5056e+005	W/m²	1.
Directional Heat Flux	-1.1893e+005	6.1945e+005	W/m²	1.

Table 2 results indicate that the temperature ranges from 406.46°C to 500.52°C, showing higher minimum temperatures compared to Gray Cast Iron. The total heat flux reaches a maximum of 6.5056×10^5 W/m², indicating efficient heat transfer. The directional heat flux values reveal significant thermal gradients, suggesting a higher tendency for thermal expansion and deformation.

4.3 Stainless steel

Fig. 8 presents the mechanical and thermal properties of Stainless Steel used in the analysis. It includes parameters such as Young’s modulus, Poisson’s ratio, thermal conductivity, and coefficient of thermal expansion. Stainless Steel exhibits high strength and a relatively low coefficient of thermal expansion compared to Aluminium Alloy. These properties contribute to improved dimensional stability and resistance to deformation under high-temperature conditions.

Table 3 show that the temperature ranges from 121.02°C to 503.32°C, indicating a wider thermal distribution compared to other materials. The total heat flux is comparatively lower, suggesting reduced heat transfer due to lower thermal conductivity. The directional heat flux values indicate controlled thermal gradients, highlighting better thermal stability and reduced risk of thermal deformation.



Stainless Steel	
Structural	
Isotropic Elasticity	
Derive from	Young's Modulus and Poisson's Ratio
Young's Modulus	1.93e+11 Pa
Poisson's Ratio	0.31
Bulk Modulus	1.693e+11 Pa
Shear Modulus	7.3664e+10 Pa
Isotropic Secant Coefficient of Thermal Expansion	1.7e-05 1/°C
Compressive Ultimate Strength	0 Pa
Compressive Yield Strength	2.07e+08 Pa
Tensile Ultimate Strength	5.86e+08 Pa
Tensile Yield Strength	2.07e+08 Pa
Thermal	
Isotropic Thermal Conductivity	15.1 W/m·°C
Specific Heat Constant Pressure	480 J/kg·°C
Electric	
Isotropic Resistivity	7.7e-07 ohm-m
Magnetic	
Isotropic Relative Permeability	1

Fig. 8: material properties of stainless steel
Table 3 results of stainless steel

Result Summary

Results	Minimum	Maximum	Units	Time (s)
Temperature	121.02	503.32	°C	1.
Total Heat Flux	46.895	3.4235e+005	W/m ²	1.
Directional Heat Flux	-60878	3.2322e+005	W/m ²	1.

Table 4 Thermal Performance Comparison of Gray Cast Iron, Aluminium Alloy, and Stainless Steel

	Temperature (°C)		Total heat flux (w/mm ²)		Directional heat flux (w/mm ²)	
	min	max	min	max	min	Max
Gray cast Iron	275.46	501.41	44.557	5.1864e+005	-89839	4.928e+005
Aluminium alloy	406.46	500.52	78.167	6.5056e+005	-1.1893e+005	6.1945e+005
Stainless steel	121.02	503.32	46.895	3.4235e+005	-60878	3.2322e+005

Table 4 compares the thermal characteristics of Gray cast iron, Aluminium alloy, and Stainless steel in terms of temperature and heat flux. All materials reach similar maximum temperatures near 500°C, while Stainless steel records the lowest minimum temperature. Aluminium alloy exhibits the highest total and directional heat flux values, indicating superior heat transfer capability. Gray cast iron shows moderate performance across all parameters. Stainless steel, although lower in heat flux, demonstrates a wider temperature variation. Overall, Aluminium alloy performs best in heat conduction among the three materials.

5. CONCLUSION

The rigorous computational investigation of a 4-stroke IC engine assembly highlights the indispensable role of advanced CAD and FEA in modern automotive engineering. Through the utilization of SOLIDWORKS, a high-fidelity geometric model was established, encompassing the intricate mechanical interdependencies between the piston, connecting rod, and crankshaft. This structural framework served as the foundation for multi-physics simulations within ANSYS Workbench, where the components were subjected to steady-state thermal loading to simulate peak operational combustion environments. The primary objective was to evaluate

the thermal resilience and structural stability of three distinct material candidates Gray Cast Iron, Aluminum Alloy, and Stainless Steel. The comparative thermal analysis provided critical insights into the heat dissipation characteristics and structural "hot strength" of the selected materials. While Aluminum Alloy is traditionally favored for high-volume automotive applications due to its low density and superior thermal conductivity, the simulation results identified significant localized vulnerabilities. Specifically, under extreme steady-state thermal gradients, Aluminum Alloy exhibited a higher propensity for thermal expansion and a marked reduction in mechanical stiffness. In contrast, the investigation concludes that Stainless Steel represents the optimal material for superior thermal reliability and structural integrity in high-temperature environments. The superiority of Stainless Steel is primarily attributed to its lower coefficient of thermal expansion and higher yield strength at elevated temperatures. The ANSYS results demonstrated that Stainless Steel maintains more consistent clearances between the piston and cylinder liner, effectively mitigating the risk of mechanical seizure or frictional power losses during high-load cycles. Furthermore, while its lower thermal conductivity leads to higher localized temperatures on the piston crown, the material's inherent resistance to thermal fatigue ensures that these "hot zones" do not result in structural deformation or crack initiation a failure mode frequently observed in lighter alloys.

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