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Static Structural and Thermal Analysis of Marine Engine Pistons with Different Materials

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Abstract

The piston of an internal combustion engine is one of the key players in determining energy efficiency and it is constantly subjected to very high temperatures and pressure. As a result, the amount of structural and thermal stresses on a piston are very high due to its continuous reciprocating motion. In case of bad structure or material selection, the piston may fail. So, an analysis of the thermal and static structural stresses has been done considering the piston of the "Wärtsilä 32" marine diesel engine. The Wärtsilä 32 engine is one of the most commonly used and affordable marine engines that has been in production for over 30 years. It was introduced to address the market demand for a new engine in the 320 mm cylinder bore class. Since its launch in 1998, a large number of units of this engine have been sold to the marine market. The piston is designed using the SolidWorks software taking the dimensions from the resources on the internet and the analysis was carried out using ANSYS. Different materials were taken such as Stainless Steel, Gray cast iron, Aluminium alloy, and Titanium alloy in a search for better material. The best material among these materials has been suggested based on the results of the analysis.

Keywords: Energy Efficiency, Marine Engine, Materials, Thermal Analysis, Wartsila 32

1.0 Introduction

In 1903, the Branobel company introduced the diesel electric river tanker Vandal, which marked the debut of in- ternal combustion marine diesel engines[1]. For several years, diesel engines had a lower power-to-space ratio compared to steam turbines, despite their higher efficiency. Nevertheless, the introduction of turbocharging enhanced the situation, enabling greater power densities. Reciprocating diesel engines have become a popular choice for prime movers in modern ships due to their simple design, durability, and superior fuel efficiency in comparison to other prime mover mechanisms. The design of piston in these engines is one of the most crucial factors in providing these advantages.

The piston has several functions in an engine, including transferring force from the combustion gas, handling cyclic gas pressure and inertial forces, and enduring the risk of fatigue damage such as piston wear, cracks, etc. Fatigue failure is primarily caused by stress concentration, which is most significant at the upper end of the piston[2-4]. Additionally, piston seizure caused by overheating can occur when the lubricating oil layer between the piston and cylinder wall is depleted or removed by burning or scraping. In recent decades, there has been continuous improvement in engine piston design, with research exploring new geometries, materials, and manufacturing techniques[6,7]. Hence, analyzing various factors such as stress distribution, temperature distribution, heat transfer, and mechanical load is imperative to minimize stress on the piston at different loads. In this regard, ANSYS software is utilized in this research to examine and evaluate the distribution of thermal and mechanical stresses on pistons made of different materials in marine diesel engines[8,9].

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2.0 Materials Used

In I.C. engines the most commonly used materials for pistons are Iron, Aluminum alloys, Steel, and Titanium Alloys.

Cast iron is an alloy of iron that has a carbon content ranging from 2 to 4 percent and contains differing amounts of silicon, manganese, and small quantities of impurities like sulfur and phosphorus. The production process involves the reduction of iron ore in a blast furnace. Cast iron is a material that can be classified into different types based on its composition and properties. Two of the most prevalent types are gray iron and white iron. Gray iron contains a higher percentage of silicon, which makes it softer and easier to machine compared to white iron. Despite both being brittle materials an 18^{th} century French process of prolonged heat treatment led to the development of a more ductile form of cast iron[10]. Stainless steel is an alloy steel composed of chromium, which typically makes up 10 to 30 percent of its composition. The addition of chromium to low-carbon steel provides exceptional resistance to both heat and corrosion. To increase its resistance to particular environments or confer unique characteristics, other elements such as nickel, molybdenum, etc. may be added[11].

An aluminum alloy is primarily composed of aluminum, with the addition of other elements. To create the alloy, the elements are blended into molten aluminum, which solidifies into a uniform solution as it cools. Alloying elements typically constitute a maximum of 15% of the overall weight of steel. The strategic addition of these elements significantly enhances the mechanical properties of the alloy, including its strength, electrical conductivity, density, and many other properties when compared to pure steel. By carefully selecting the composition and proportion of alloying elements, engineers can tailor the characteristics of steel to meet specific application requirements. Furthermore, aluminum alloys, renowned for their lightweight nature, higher strength per unit weight, and remarkable resistance to corrosion, offer an excellent alternative to conventional steel in various industries. In our current study, we conducted detailed investigations using the AlSi10Mg alloy, which demonstrates remarkable performance and exhibits a balanced combination of strength, toughness, and weldability[12,13].

Titanium is renowned for its strength, heat resistance, resistance to water and salt, and lightweight properties, which make it a highly sought-after metal for various applications. Some examples of its uses include jewelry, airplanes, ships, and dental implants. The incorporation of other metals into titanium alloys allows them to maintain their strength and corrosion resistance, while also increasing their flexibility and malleability. Pure titanium is available in six different grades, namely 1, 2, 3, 4, 7, and 11, each offering specific characteristics for various applications. Conversely, titanium alloys, which are widely utilized in industries such as aerospace and medical, are composed of trace amounts of elements like aluminum, molybdenum, vanadium, niobium, tantalum, zirconium, manganese, iron, chromium, cobalt, nickel, and copper. Notably, the four primary types of titanium alloys are Ti 6AL-4V, Ti 6AL ELI, Ti 3Al 2.5, and Ti 5Al-2.5Sn.2.0, each having distinct applications in various fields, such as structural components, implants, and high-performance equipment.

3.0 Aim

The aim of the study is to conduct static structural and thermal analysis of the Wärtsilä 32 engine's piston. The piston is designed using the SolidWorks software taking the dimensions from the resources on the internet and the analysis was carried out using ANSYS[3]. Different materials were taken such as Stainless Steel, Gray Cast Iron, Aluminium Alloy and a Titanium Alloy with a search for a better material. The most appropriate material among these materials has been suggested based on the results of the analysis.

4.0 Methodology

The Marine Engine used is "Wartsila 32". It is a four-stroke diesel engine which was designed considering great efficiency along with ease of maintenance. The specifications of the engine are tabulated below:

- D = Cylinder bore (mm) = 320mm
- L = Length of stroke (mm) = 400mm
- N = Engine speed (rpm) = 750 rpm
- P_{max} = Max. Gas Pressure (MPa) = 18 MPa
- S_{ut} = Tensile Strength at break (MPa) = 480 MPa
- F.O.S. = Safety Factor = 2.5

- S_t = Allowable Tensile Strength (MPa) = S_{ut}/FOS = 192 MPa

4.1 Calculation of Piston Dimensions

Piston head Thickness (th -

The thickness of the piston head is calculated by using the following formula, $t_h = D^*(((3\ P_{max})/(16\ S_t))^{0.5})$ in mm–(1)

By substituting these values in above equation (1), Thickness of piston head (t_h) = 42.4mm ≈ 45mm

Ring's Radial Thickness (t1 -

t1 = $D^*((3Pw)/S_t)_{0.5}$) in mm—-(2)

Pw = Pressure of fuel on cylinder wall (MPa) = 0.06 MPa St = 192 MPa

D = 320 mm

By substituting these values in equation (2), Radial thickness of ring (t_1) = 9.79mm ≈ 10mm

Axial thickness of ring (t2 -

$t_2 = 0.8t_1$ in mm—–(3) Considering $t_2 = 0.8t_1$,

By substituting t_1 value in equation (3), Axial thickness of ring (t_2) = 8mm

Width of top land (h1 - Width of other lands (h2 -

$h_2 = 0.75\ t_2$ to t_2 ——(5)

Considering $h_2 = t_2$,

By substituting t_2 value in equation (5), Width of other lands (h_2) = 8mm

4.2 Modelling of the Piston

A vital aspect of the design and analysis of an internal combustion engine is the modeling of its piston. The piston is responsible for transferring force from the combustion chamber's expanding gas to the crankshaft, which provides the vehicle's power. To achieve this, we used SolidWorks software to create a model of the piston based on the dimensions we previously calculated.

Modeling is a design process that involves creating a statistical representation of a 3D object. In this study, solid modeling software was used to create a model, which was then converted to an IGS design file and imported into ANSYS software for analysis. By comparing pistons made of different materials and analyzing their results, conclusion can be drawn. The following steps were taken in the analysis:

- Model creation
- Assigning physical properties to the model
- Applying boundary conditions
- Meshing
- Static analysis
- Thermal analysis.

Figure 1 shows the SolidWorks model, Figure 2 shows the Sketch dimensions of piston and Figure 3 shows the Meshing of piston.

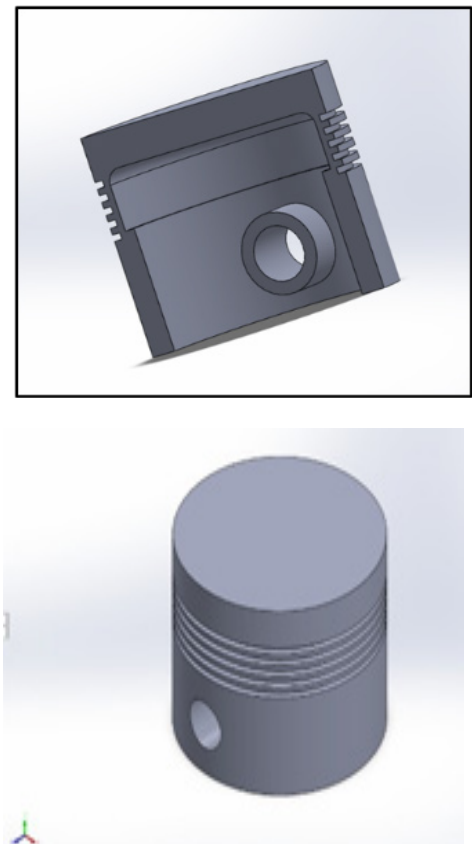


Figure 1. SolidWorks model.

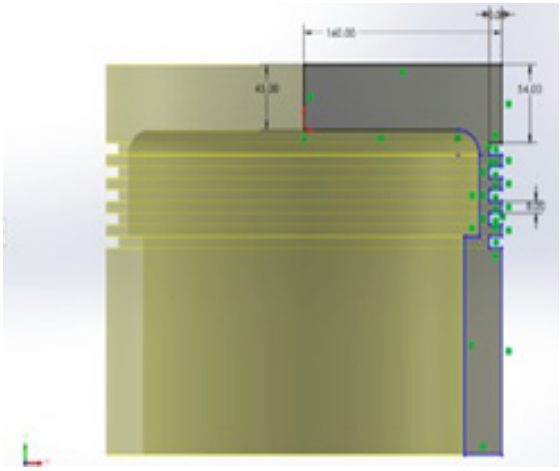


Figure 2. Sketch dimensions of piston.

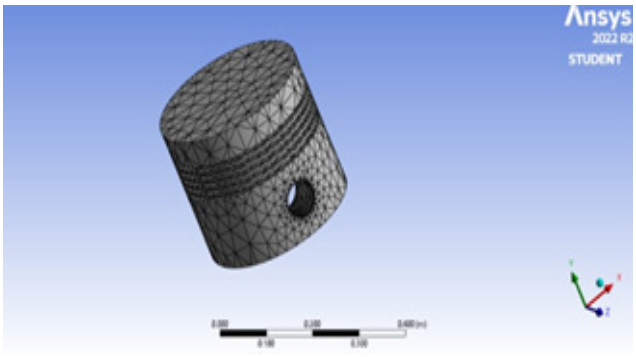


Figure 3. Meshing of piston.

5.0 Results and Discussions

5.1 Static Structural

In this, the holes for the piston pin are considered to be fixed points, and the maximum pressure of 1.80 MPa is applied on the top of the piston crown in the normal direction. Pressure Exertion on the piston leads to the induction of stress, such that the material should withstand high pressure and for that Equivalent Stresses, Maximum Principal Stresses, and total deformation of the material is obtained. Table 1 shows the Results of Equivalent Stress, Max. Principal Stress and Total deformation of all materials.

5.2 Stainless Steel

Figure 4-6 shows the analysis on Stainless Steel piston.

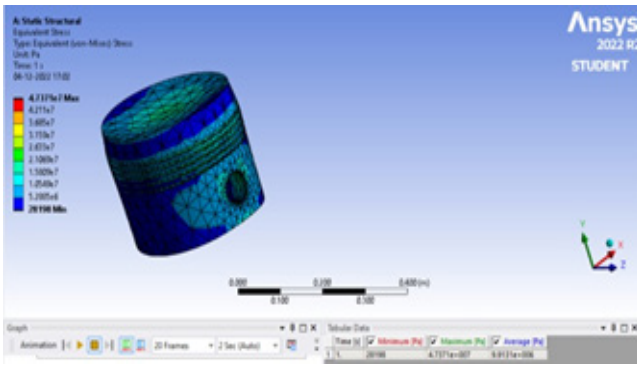


Figure 4. Analysis of equivalent stress on stainless steel piston.

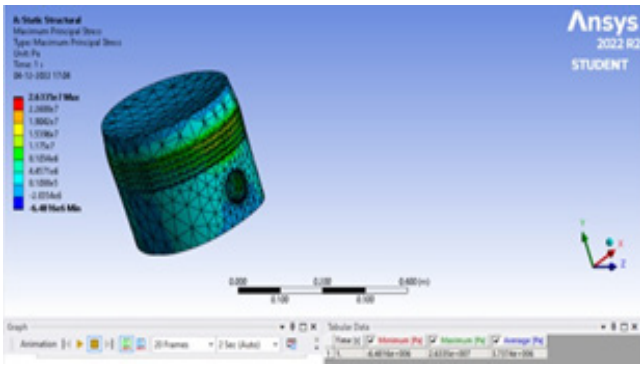


Figure 5. Analysis of maximum principal stress on stainless steel piston.

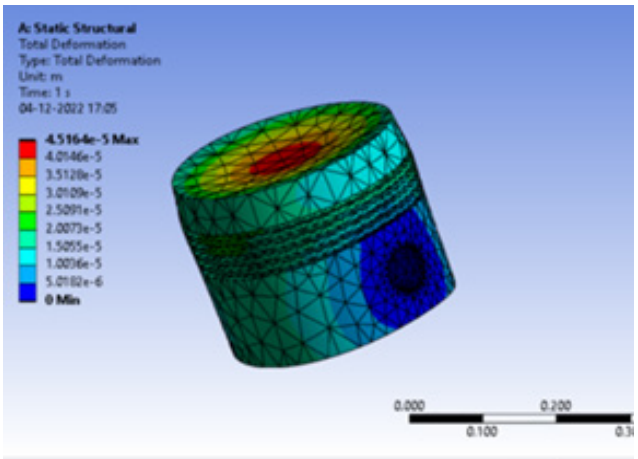


Figure 6. Analysis of deformation on stainless steel piston.

5.3 Gray Cast Iron

Figure 7-9 shows the analysis analysis on gray cast iron piston.

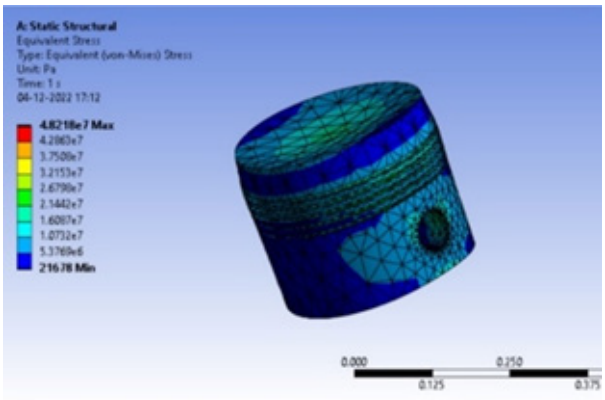


Figure 7. Analysis of equivalent stress on gray cast iron piston.

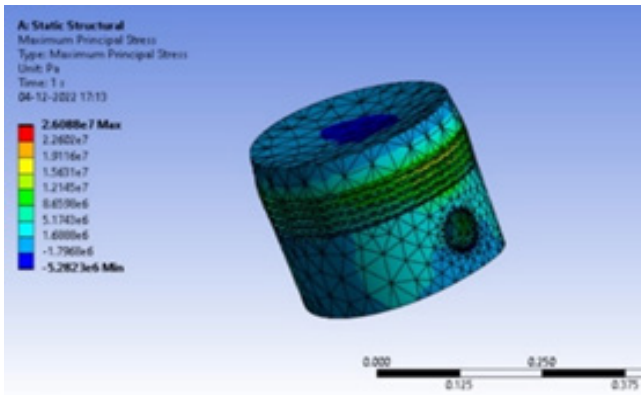


Figure 8. Analysis of maximum principal stress on gray cast iron piston.

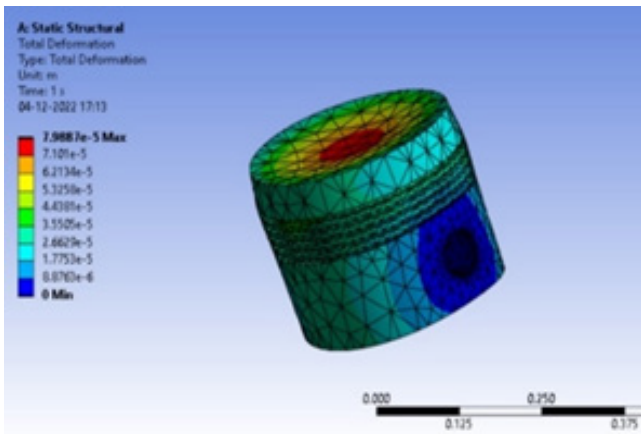


Figure 9. Analysis of deformation on gray cast iron piston.

5.4 AlSi10Mg (Aluminium Alloy)

Figure 10-12 shows the analysis analysis on Gray Cast Iron piston.

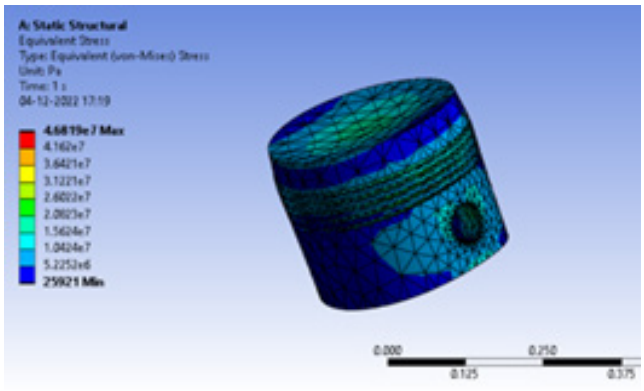


Figure 10. Analysis of equivalent stress on AlSi10Mg piston.

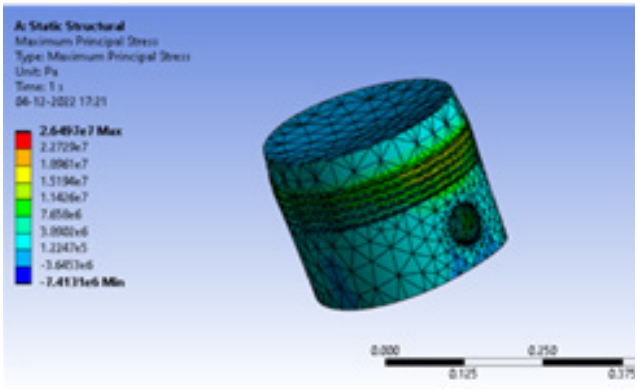


Figure 11. Analysis of maximum principal stress on AlSi10Mg piston.

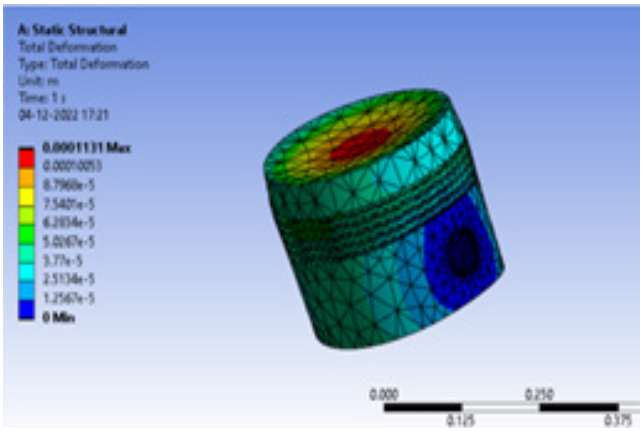


Figure 12. Analysis of maximum principal stress on AlSi10Mg piston.

5.5 Ti-6Al-4V (Titanium Alloy)

Figure 13-15 shows the analysis analysis on Ti-6Al-4V piston

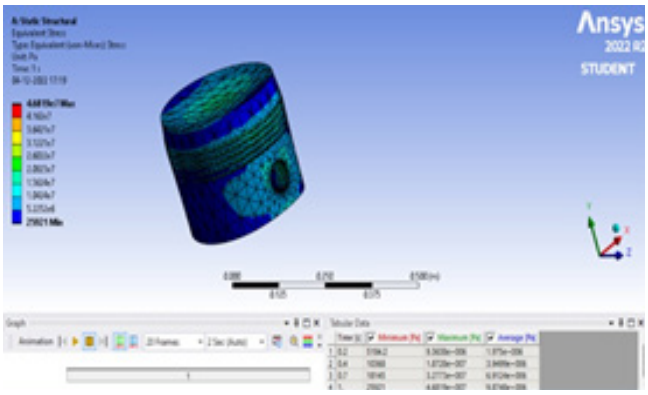


Figure 13. Analysis of equivalent stress on Ti-6Al-4V piston

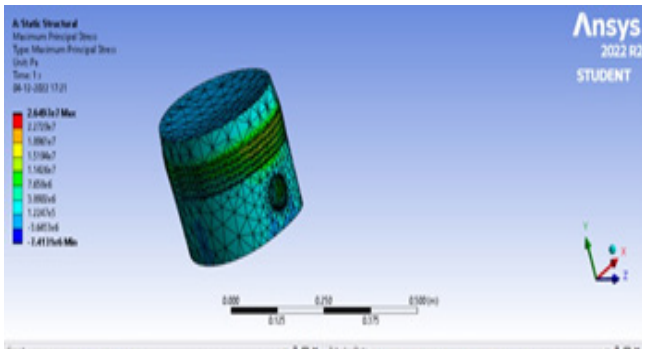


Figure 14. Analysis of maximum principal stress on AlSi10Mg piston.

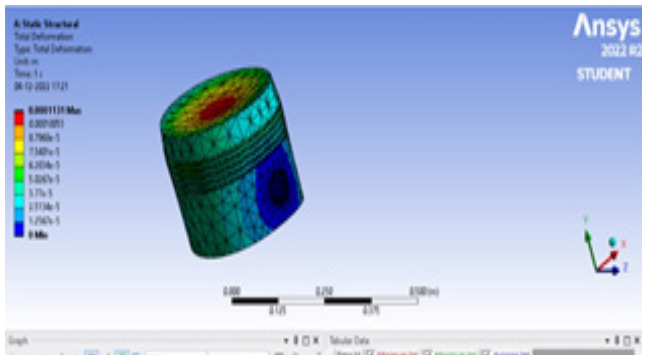


Figure 15. Analysis of deformation on Ti-6Al-4V piston.

1. Minimum Equivalent stress is found in AlSi10Mg which is 46.819 MPa and maximum is found in Gray Cast Iron which is 48.218 MPa.

2. Minimum Max. Principal stress is found in Gray Cast Iron which is 26.088 MPa and maximum is found in AlSi10Mg which is 26.497 MPa.

3. Minimum Deformation is found in Stainless Steel which is $4.516X10^{-2}$ mm and maximum is found in AlSi10Mg which is $1.131X10^{-1}$.

5.6 Steady State Thermal

The temperature distribution and heat transfer were analyzed using steady-state thermal analysis. The temperature on the piston head was taken as 900°C and the film coefficient for convection was taken as 100 W/m 2°C. Table 2 shows the Results of Total heat flux and directional heat flux of all materials.

5.7 Stainless Steel

Stainless Steel: It has lower heat flux values compared to gray cast iron and AlSi10Mg, having a total heat flux of 1.97e5 W/m^2 and directional heat flux value of 1.08e5 W/m^2.

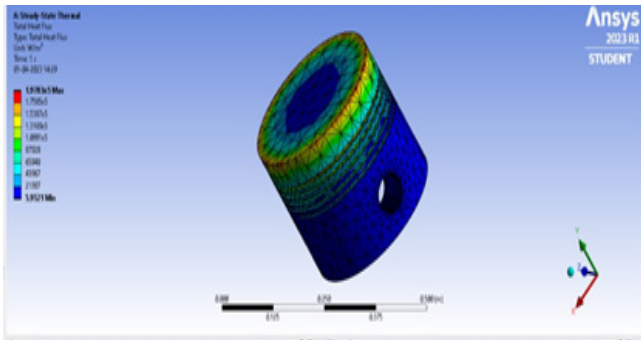


Figure 16. Analysis of total heat flux in stainless steel piston.

Table 1. Results of equivalent stress, max. principal stress and total deformation of all materials

S. No.	Material	Equivalent Stress	Max. Principal Stress	Total Deformation
		(MPa)	(MPa)	(mm)
1.	Stainless Steel	47.371	26.335	4.516×10^{-2}
2.	Gray Cast Iron	48.218	26.088	7.988×10^{-2}
3.	AlSi10Mg	46.819	26.497	1.131×10^{-1}
4.	Ti-6Al-4V	47.008	26.411	8.121×10^{-2}

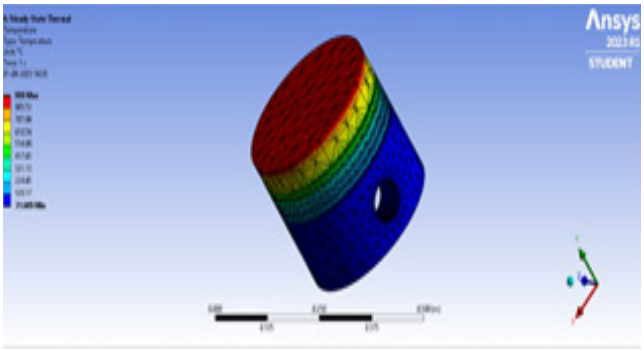


Figure 17. Analysis of temperature distribution in stainless steel piston.

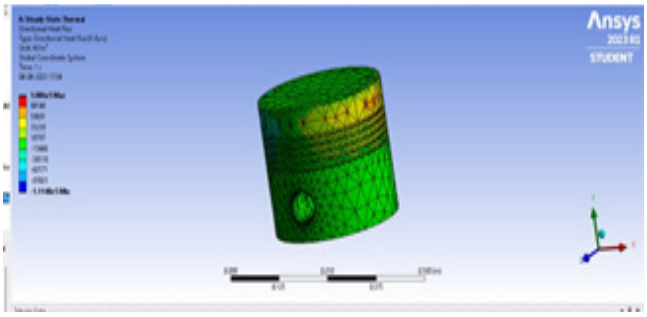


Figure 18. Analysis of directional heat flux in stainless steel piston.

Figure 16-18 shows the analysis analysis on Stainless Steel piston

5.8 Gray Cast Iron

Gray Cast Iron: It has higher total heat flux (5.22e5 W/m^2) and directional heat flux (2.39e5 W/m^2) than Stainless Steel and Ti-6Al-4V

Figure 19-21 shows the analysis analysis on Gray Cast Iron piston

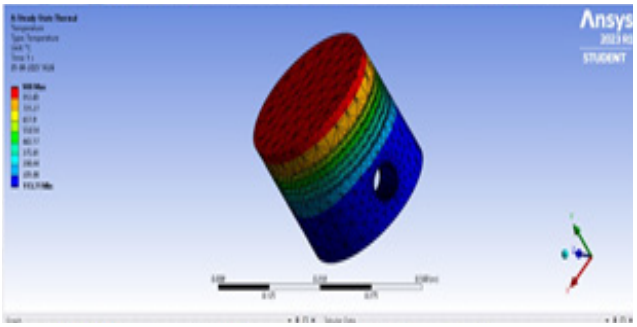


Figure 19. Analysis of temperature distribution in gray cast iron piston.

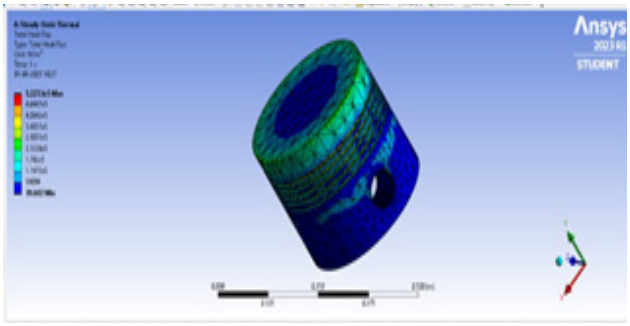


Figure 20. Analysis of total heat flux in gray cast iron piston.

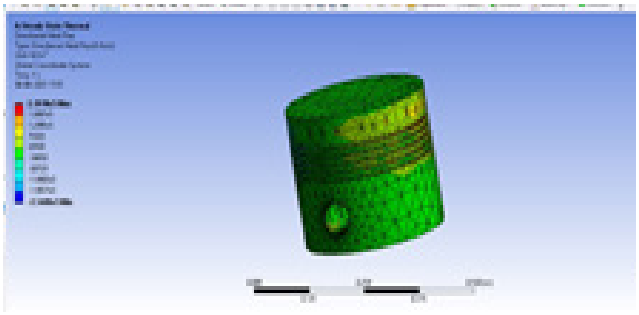


Figure 21. Analysis of directional heat flux in gray cast iron piston.

Table 2. Results of total heat flux and directional heat flux of all materials

S. No	Material	Total heat Flux (W/m^2)	Directional Heat Flux (W/m^2)
1.	Stainless Steel	1.97e5	1.08e5
2.	Gray Cast Iron	5.22e5	2.39e5
3.	AlSi10Mg	7.28e5	2.95e5
4.	Ti-6Al-4V	1.7e5	0.779e5

5.9 AlSi10Mg (Aluminium Alloy)

AlSi10Mg: It has the highest heat flux values, having a total heat flux of 7.28e5 W/m^2 and directional heat flux value of 2.95e5 W/m^2.

Figure 22-24 shows the analysis analysis on AlSi10Mg piston

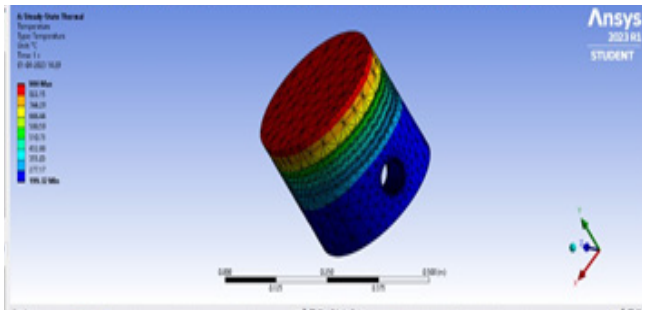


Figure 22. Analysis of temperature distribution in AlSi10Mg piston.

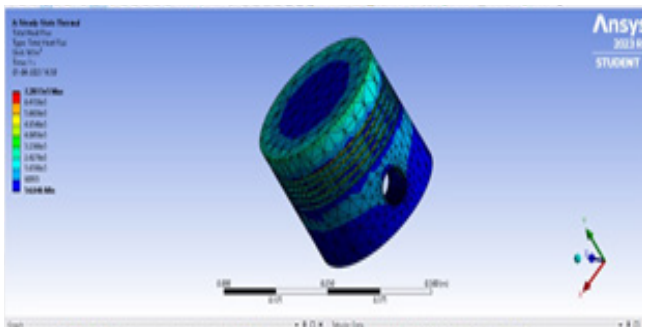


Figure 23. Analysis of total heat flux in AlSi10Mg piston.

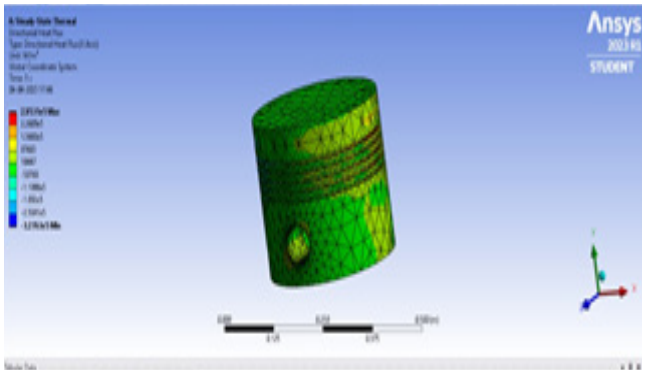


Figure 24. Analysis of directional heat flux in AlSi10Mg piston.

5.10 Ti-6Al-4V (Titanium Alloy)

Ti-6Al-4V: It has the lowest total heat flux (1.7e5 W/m^2) and directional heat flux (0.779e5 W/m^2) among the listed materials.

Figure 25-27 shows the analysis analysis on Ti-6Al-4V

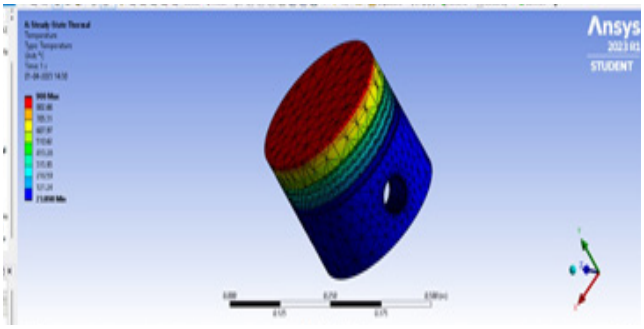


Figure 25. Analysis of temperature distribution in Ti-6Al-4V piston.

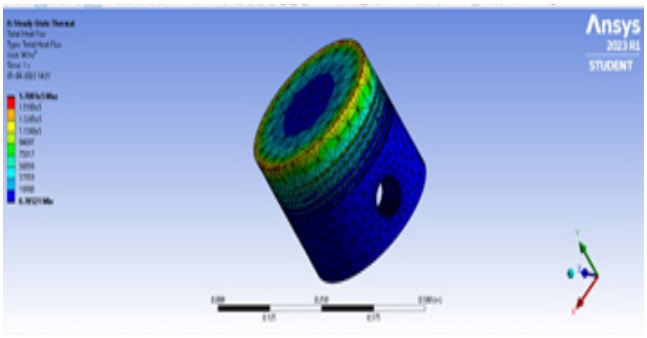


Figure 26 Analysis of total heat flux in Ti-6Al-4V piston.

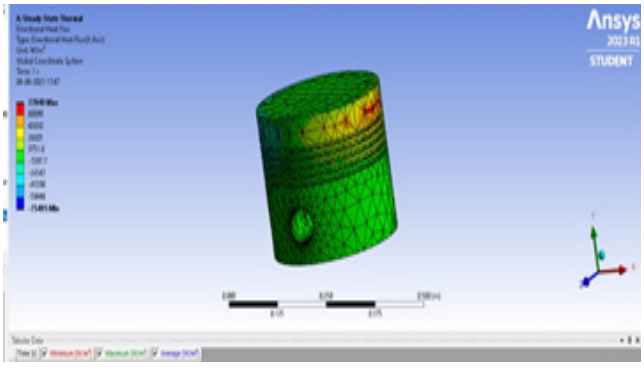


Figure 27. Analysis of directional heat flux in Ti-6Al-4V piston.

Based on the observations from Static Structural Analysis and Steady State Thermal Analysis, Stainless Steel could be a suitable choice for a marine engine piston where minimizing stress and heat transfer is desirable as it exhibits lower stress levels, lower deformation, lower total heat flux, and lower directional heat flux. However, other factors such as strength, durability, weight, thermal expansion, cost and other manufacturing considerations are important to consider when selecting the best material for a marine engine piston.

6.0 Conclusion

From the obtained results, it can be inferred that stainless steel is the most appropriate material for the piston considering the observations from static structural and thermal analysis but the choice of material for an engine piston also depends on several factors such as:

- Strength and Durability: Engine pistons experience high pressures, temperatures, and mechanical loads. Aluminum alloy and titanium alloy often exhibit superior strength and durability compared to stainless steel, making them better suited to withstand the demanding conditions and extend the lifespan of the piston.
- Weight Considerations: Engine design often aims to optimize weight to improve performance and efficiency.
- Aluminum alloy and titanium alloy are known for their lightweight properties, which can help in minimizing the piston's weight and enhancing the fuel efficiency. Stainless steel, on the other hand, tends to be denser and heavier.
- Thermal Expansion: Engine pistons are subjected to high-temperature differentials during operation. Mate- rials with compatible thermal expansion coefficients are preferred to ensure proper functioning and minimize the risk of piston seizure. Aluminum alloy and titanium alloy generally offer better thermal expansion characteristics compared to stainless steel.
- Manufacturing Considerations: The ease of manufacturing and compatibility with existing production processes and equipment are crucial factors in material selection. Aluminum alloy and titanium alloy are commonly used in engine piston manufacturing due to their well-established fabrication techniques and widespread industry acceptance.
- Cost: Cost is a significant consideration in material selection for mass-produced components like engine pistons. Stainless steel can be more expensive than aluminum alloy and titanium alloy, making it less economically viable for certain applications.

So, it can be said that material selection for engine piston involves a complex evaluation process that considers multiple factors such as strength, durability, weight, thermal expansion, cost, etc. Considering these factors, aluminum alloy and titanium alloy can be preferred over stainless steel as it is important to strike a balance between various requirements to ensure optimal performance, reliability, and cost efficiency in piston design.

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