STATIC STRUCTURAL, FATIGUE AND THERMAL ANALYSIS OF MARINE ENGINE PISTON AND PISTON RINGS COMPARING WITH THREE DIFFERENT MATERIALS

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Abstract

The Wartsila RTA 96C ship diesel engine piston is studied. For the marine ship the power generated for the running of the ship will be done in the combustion engine. The engine comprises of the engine parts which include piston crown, piston rings, piston rod, stuffing box, connecting rod connected to cam shaft. The combustion of the fuel is done in the combustion chamber .The piston is the first and foremost part which will be affected to the combustion temperature and the high pressures generated. So we considered the piston crown and piston rings for our project.

The piston is designed in the modelling software. The software used for the modelling of the piston is SolidWorks. The dimensions for the piston are taken from the dimensions of the Wartsila RTA 96C ship. AISI 4140, the material by which the piston of the ship is made is studied with all its properties.

The designed piston is analysed for stresses in static structural, life of the piston in fatigue analysis and total heat flux in thermal analysis of ANSYS software. To improve the results shown in the ANSYS software, the search for the better materials is done. In the search the materials like Hiduminium has come into play. As the search is continued we were ended with two other materials Titanium alloy Ti-6-Al-4V and Stainless Steel. The best material for the piston with better properties for the actual loads being applied in the engine are suggested.

Keywords: Wartsila RTA 96C Ship, Marine Engine Piston, Solidworks, ANSYS Workbench, AISI 4140,Hiduminium,Ti-6Al-4V,Stainless Steel.

1. Introduction

An engine is a machine designed to convert one form of energy into mechanical energy. Heat engines, like the internal combustion engine, burn a fuel to create heat which is then used to do work. Electric motors convert electrical energy into mechanical motion, pneumatic motors use compressed air, and clockwork motors in wind-up toys use elastic energy. In biological systems, molecular motors, like myosins in muscles, use chemical energy to create forces and ultimately motion.

2. Literature Review

Gadde Anil Kumar [1] has done design and analysis of an IC engine piston using three different materials. They took pulsar 220cc piston dimensions for different materials (grey cast iron, aluminum alloy, AL-SIC) have been selected for structural and thermal analysis of piston and piston rings.

Design of the piston is carried out using CATIA software, static and thermal analysis is performed using Finite Element Analysis (FEA). They created pressure on piston head 13.65Mpa and 19.649N on these three materials, and they applied temperature 4000C on piston crown and 3000C on piston rings. Finally they found out which material is suitable on the piston from the three materials.

M. Nageswari [2] has done static and thermal analysis on piston made of aluminium-silicon alloy, zirconium and aluminium-MgSi material. The analysis is performed on piston by using a CAE tool namely ANSYS. The main purpose is to find the real behavior during combustion process i.e., static structural and thermal stresses are found.

The structural model of a piston is designed in CATIA V5 software and then imported into ANSYS 14.5 software for finite element analysis. In this work, the main emphasis is placed on the study of thermal behavior of functionally graded coatings obtained by means of using a commercial code, ANSYS on aluminium and zirconium alloyed aluminium piston surfaces.

V G Cioata [3] in this paper the mechanical and thermal stresses are determined using the finite element method, stress and displacement distribution due to the flue gas pressure and temperature, separately and combined.

The FEA is performed by CAD and CAE software. The results are compared with those obtained by the analytical method and conclusions have been drawn.

Siliveri Naresh [4] has designed a piston, analyzed and studied the manufacturing process. In this project the piston is modelled and assembled with the help of CATIA software and component is meshed and analysis is done in ANSYS software and the thermal and static behavior is studied and results are tabulated.

The various two materials are aluminium alloy A360 and alloy 242. Temperature distribution and heat flow through the piston of the engine, FEA analysis of the piston to measure temperature at the points where it is not possible to find out practically and to observe the heat flow inside the piston.

A. R. Bhagat [5] This paper describes the stress distribution of the seizure on piston four stroke engine by using FEA. The finite element analysis is performed by using computer aided design (CAD) software. The main objectives is to investigate and analyze the thermal stress distribution of piston at the real engine condition during combustion process. The paper describes the mesh optimization with using finite element analysis technique to predict the higher stress and critical region on the component. The optimization is carried out to reduce the stress concentration on the upper end of the piston i.e., (piston head/crown and piston skirt and sleeve). With using computer aided design (CAD), Pro/ENGINEER software the structural model of a piston will be developed. Furthermore, the finite element analysis performed with using software ANSYS.

Preeti Kumari [6] Piston is a reciprocating part of engine which converts thermal energy into mechanical energy. There is thermo-mechanical load on the Piston. There is fatigue failure due to cyclic thermal and mechanical loading .To increase the life of the piston, there has been more research going on in modifying the design of the piston, changing the material and also changing the method of the manufacturing. In this paper thermal stress distribution is shown for the simple piston and reduced skirt length piston. By changing the geometry of the piston and it is suggested that which piston is better for same thermal load. Steady state thermal analysis of the Piston have been done in ANSYS 14.5.

G. V. N. Kaushik [7] In IC engine, Piston is one of the most important and complex part. With increasing power and performance of engine, higher thermal load and the thermal stresses are acting on piston, thereby, decreasing its life time. It is important to maintain Piston in good condition in order to maintain the proper functioning of the engine. Piston mainly fails due to thermal Conditions. In this paper 3D model of piston is developed, structural and thermal analysis is done by ANSYS using 5 different materials to find out the temperature and thermal stress distribution, theoretically finding the total heat flux and compare with the practical values of different Piston Materials used.

K. Raja Sekhar [8] A piston is a component of reciprocating engines, reciprocating pumps, gas compressors and pneumatic cylinders, among other similar mechanisms. It is the moving component that is contained by a cylinder and is made gas-tight by piston rings Piston that transfer the combustive gases power to the connecting rod. To improve the efficiency of the engine there is a need to study about the piston. Pistons that are usually made up with alloy steels that show the great resistant against thermal loads and structural loads. In the project we design a piston by using solid works 2016 design software and we did the structural load analysis and thermal analysis by applying various materials such as composites on piston in ANSYS workbench software.

Andrzej Adamkiewicz [9] This article presents operational evaluation of piston ring wear in large marine diesel engines based on inspection through cylinder liner scavenge ports. It contains a description of verification methods of piston rings based on visual inspections, clearance measurement of piston rings in piston grooves and piston rings gap measurement. Moreover, it is indicated that piston ring gap measurements can lead to an evaluation of piston ring wear and by calculating into running hours can be treated as a reference parameter at next inspections and a parameter determining wear trends. Furthermore, application of chromium layers on working surfaces of piston rings enforces the need to control chromium layer wear by measuring the layer thickness by induction and eddy current methods. Concluding, the authors discussed constructional – operational methods of improvement between tribological pair – liner and piston rings in working conditions.

Waleed Alturki [10] Marine diesel engines are mostly preferred for its reliability and fuel efficiency. To understand the function of marine diesel engines, the identification and description of its parts are necessary for its proper maintenance. Component parts of the marine diesel engine are divided into fixed and moving parts. These parts are described in detail. Recommendations for identifying and understanding the different classification schemes should gain increased familiarity with the nature of the specific parts as well as the approaches to the repair and maintenance.

Ifunanya Stella Ezeoye [11] This project will investigate the causes and effects of high gas pressure and temperature on marine two-stroke diesel engine piston. The investigation has shown that stress-related piston damages play a dominant role mainly due to mechanical and thermal stress or a combination of both. The simulation parameters that will be considered in this report are piston material, combustion temperature, and combustion pressure. In the present study, conventional marine two-stroke diesel engine piston will be modeled using Autodesk Inventor software. The working condition of the piston will be simulated based on the selected parameters using a finite element analysis method to analyze the magnitude of mechanical stresses acting on the piston. The piston will be re-designed using a material superior to the conventional piston material and will be optimized by reducing the stresses acting on the piston. Two materials will be used in the analysis after which the results will be compared and the best will be proposed. The structure and stress analysis of the design will be modeled using the software mentioned earlier.

Elijah Musango Munyao [12] This paper involves simulation of a 2-stroke 6S35ME marine diesel engine piston to determine its temperature field, thermal, mechanical and coupled thermal-mechanical stress. The distribution and magnitudes of the aforementioned strength parameters are useful in design, failure analysis and optimization of the engine piston. The piston model was developed in solid-works and imported into ANSYS for preprocessing, loading and post processing. Material model chosen was 10-node tetrahedral thermal solid 87. The simulation parameters used in this paper were piston material, combustion pressure, inertial effects and temperature. The highest calculated stress was the thermal-mechanical coupled stress and was below the yield stress of the piston material (580Mpa) at elevated temperatures hence the piston would withstand the induced stresses during work cycles.

Andrzej ADAMKIEWICZ [13] This paper presents an operational evaluation of piston-piston rings-cylinder liner (PRC) assembly wear in marine diesel engines of high power. It is based on visual inspection through cylinder liner scavenge ports. Clearance measurements of piston rings in piston grooves and piston ring gap measurements were used to evaluate the extent of wear of the PRC assembly. Moreover, it is shown that piston ring gap measurements can be used as a reference parameter in wear trend analysis to predict the length of time periods between overhauls (TBO). Furthermore, it has been shown that controlling the wear of chromium (protective) layers of piston ring working surfaces by measuring their thickness with induction and eddy current methods is highly useful. They were accepted as a source of information on PRC lubrication correctness and as a symptom of its technical condition.

Factors indicating the necessity of an overhaul and introducing operational methods of improving working conditions between the tribological pair liner and piston rings have been determined.

3. Design Procedure And Modelling

3.1 Definition of Problem

The present work deals with determining the stresses induced due to pressure loads, heat flux and life time on piston used in Marine Engine.

Generally the pistons are in cylindrical shape and reciprocate within the cylinder due to gas forces which vary continuously throughout the cycle. Generally, the pistons are subjected to high temperature on the top surfaces during combustion of fuel and this high temperature prevails for a very short duration of cycle.

3.1.1 Engine specifications

The Marine Engine used is "Wartsila RTA 96C" Sulzer engine is a two-stroke turbocharged low-speed diesel engine and it has 14 cylinders.

The engine specifications are tabulated below:

D = Cylinder bore (mm) = 960mm

t_h = thickness of piston head (mm)

L = length of stroke (mm) = 2500mm

N = engine speed (rpm) = 22-120 rpm

P_{max} = maximum gas pressure (MPa) = 18 MPa S_{ut}

= ultimate tensile strength (MPa) = 655 MPa **FOS**

= factor of safety = 2.5

S_t = allowable tensile strength (MPa) = S_{ut}/FOS = 262 MPa

3.2 Calculations of Dimensions of Piston

3.2.1 Thickness of piston head (t_h):

- 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 the values in above equation (1),
- Thickness of piston head (t_h) = 110mm

3.2.2 Radial thickness of ring (t_1):

- $t_1 = D*((3Pw)/S_t)^{0.5})$ in mm (2)
- P_w = pressure of fuel on cylinder wall (MPa) = 0.0935 MPa
- S_t = 262 MPa
- D = 960 mm
- By substituting the above values in equation (2),
- Radial thickness of ring (t_1) = 25mm

3.2.3 Axial thickness of ring (t_2):

- $t_2 = 0.7t_1$ to t_1 in mm-----(3)
- Considering $t_2 = 0.8t_1$,
- By substituting the t1 value in equation (3),
- Axial thickness of ring (t_2) = 20mm

3.2.4 Width of top land (h_1):

- $h_1 = t_h$ to $1.2th$ in mm (4)
- Considering $h1 = 1.2t_h$,
- By substituting the t_h value in equation (4),
- Width of top land (h_1) = 135mm

3.2.5 Width of other lands (h_2):

- $h_2 = 0.75\ t_2$ to t_2 in mm ------(5)
- Considering $h_2 = t_2$,
- By substituting the t_2 value in equation (5),
- Width of other lands (h_2) = 20mm

3.3 Modelling of Marine Engine Piston

- The model of marine engine piston is designed by using SolidWorks software.
- The dimensions of the piston are shown above in the calculation part.

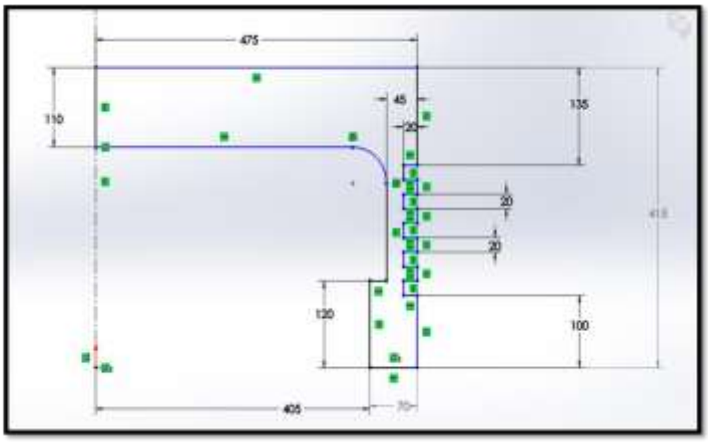

Fig 1: Sketch Dimensions of piston

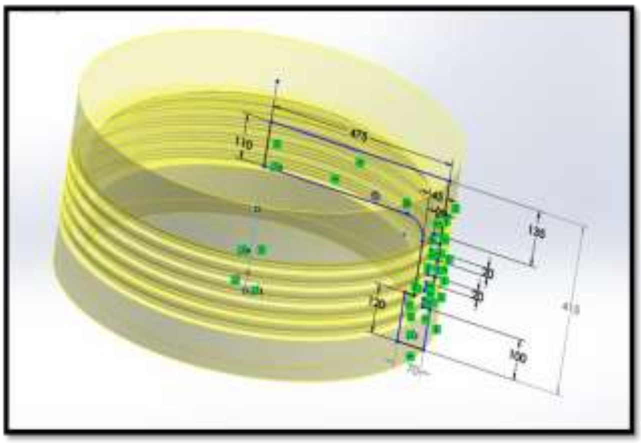

Fig 2: Revolved Base of piston

Fig 3: Piston 3D Model

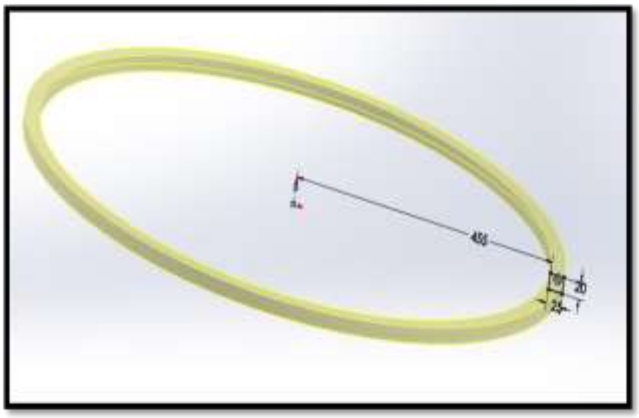

Fig 4: Revolved base of piston ring

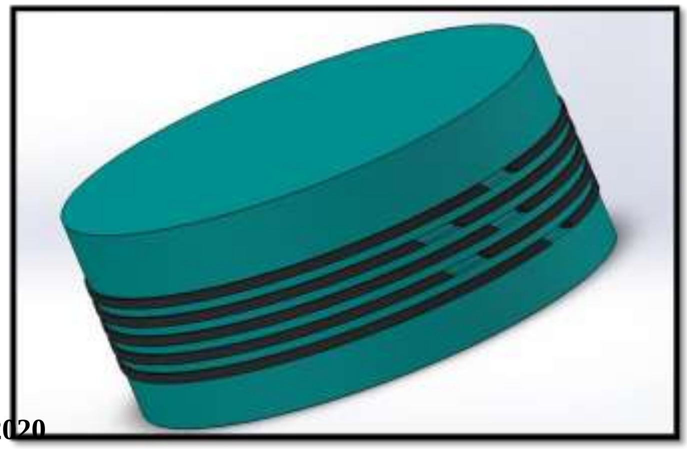

Fig 5: Complete Assembly of Piston and piston rings

The designed piston is analysed in the ANSYS workbench with three different materials like Hiduminium, Ti-6Al-4V, Stainless Steel.

4. Results & Discussions

AISI 4140 is the basic material used in the marine engine piston. So we executed the Static structural, thermal, and fatigue analysis and compared the results with Hiduminium, Ti-6Al-4V, Stainless Steel. The compared values are tabulated and a graph is plotted based upon their results.

4.1. Static Structural

In the Static Structural the piston rings of the marine engine piston is considered to be fixed point and the maximum pressure of 1.96 MPa is applied on the top on marine crown in normal direction. When the pressure is exerted on the piston it induces stress, such that the material should withstand at high pressure and for that Equivalent Stresses and Maximum Principle Stresses of the material is determined.

4.1.1 Equivalent stress:

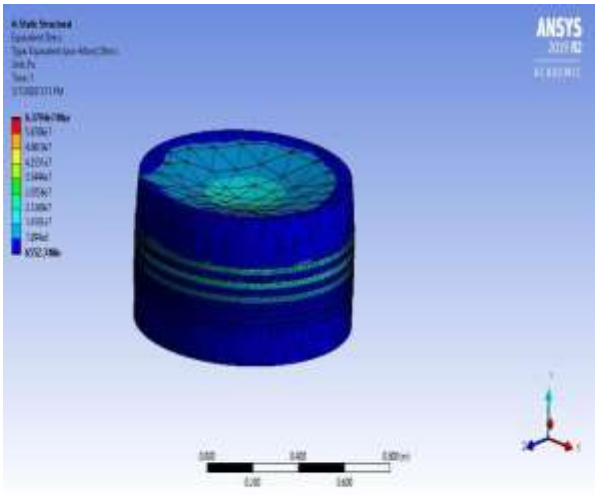

Fig 6: AISI 4140 Steel

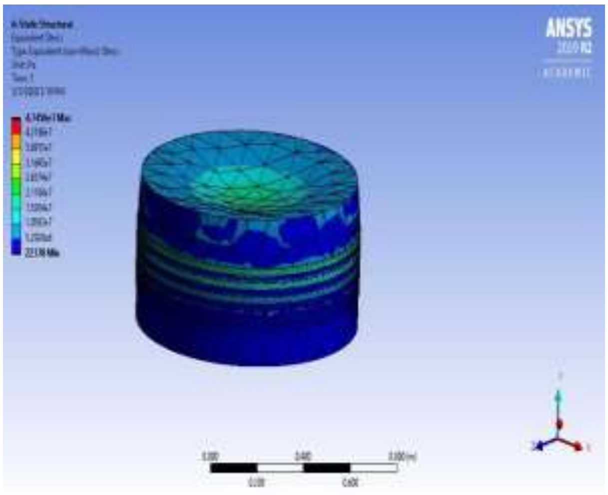

Fig 7: Hiduminium

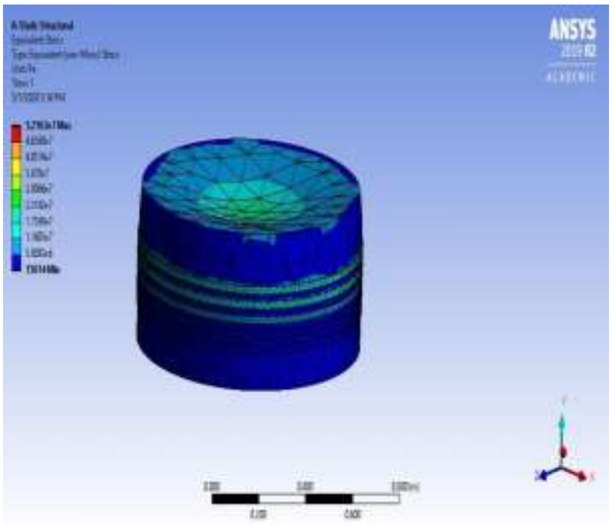

Fig 8: Ti-6Al-4V

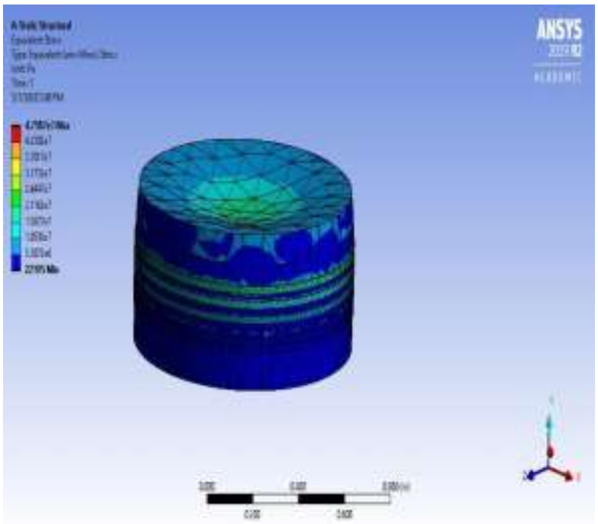

Fig 9: Stainless Steel

4.1.2 Maximum Principle Stress:

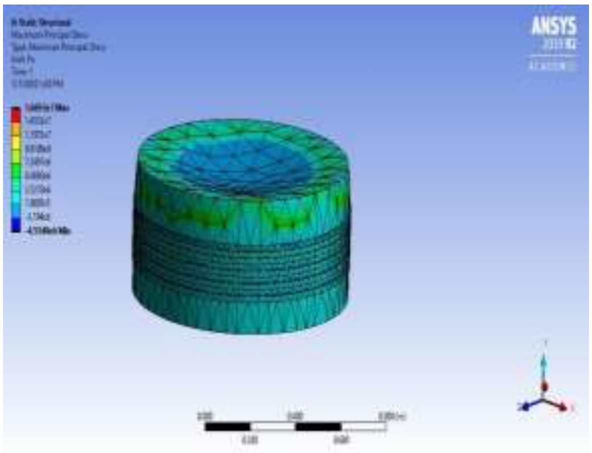

Fig 10: AISI 4140 Steel

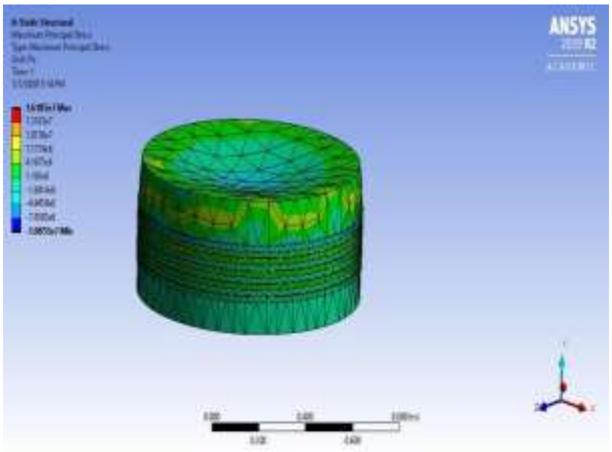

Fig 11: Hiduminium

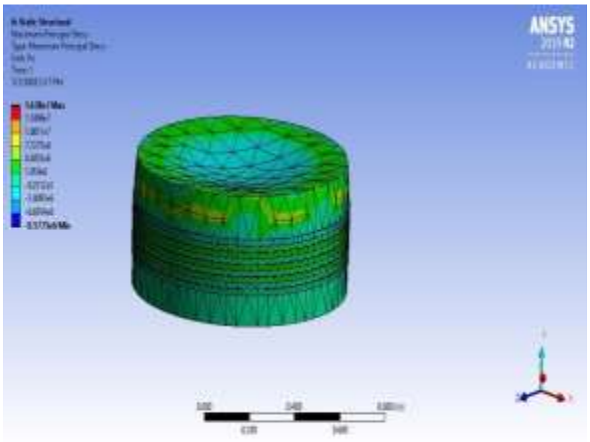

Fig 12: Ti-6Al-4V

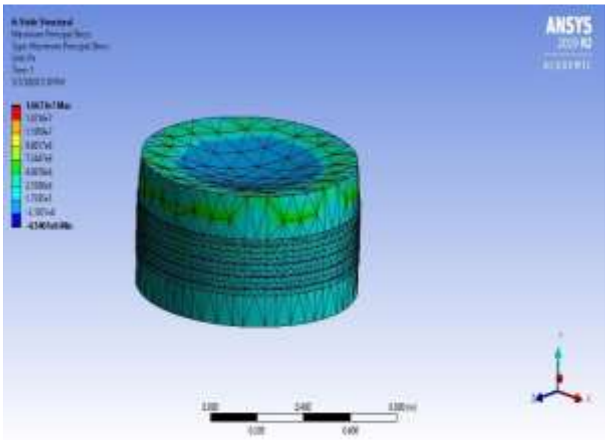

Fig 13: Stainless Steel

Table-1: Results of Equivalent Stress and Max. Principle Stress of all materials

S.No	**MATERIAL**	**EQUIVALENT STRESS (Pa)**	**MAXIMUM PRINCIPAL STRESS (Pa)**
1.	AISI 4140 STEEL	4.7456×10^7	1.669×10^7
2.	HIDUMINIUM	6.3794×10^7	1.6185×10^7
3.	Ti-6Al-4V	5.2163×10^7	1.638×10^7
4.	STAINLESS STEEL	4.7587×10^7	1.6673×10^7

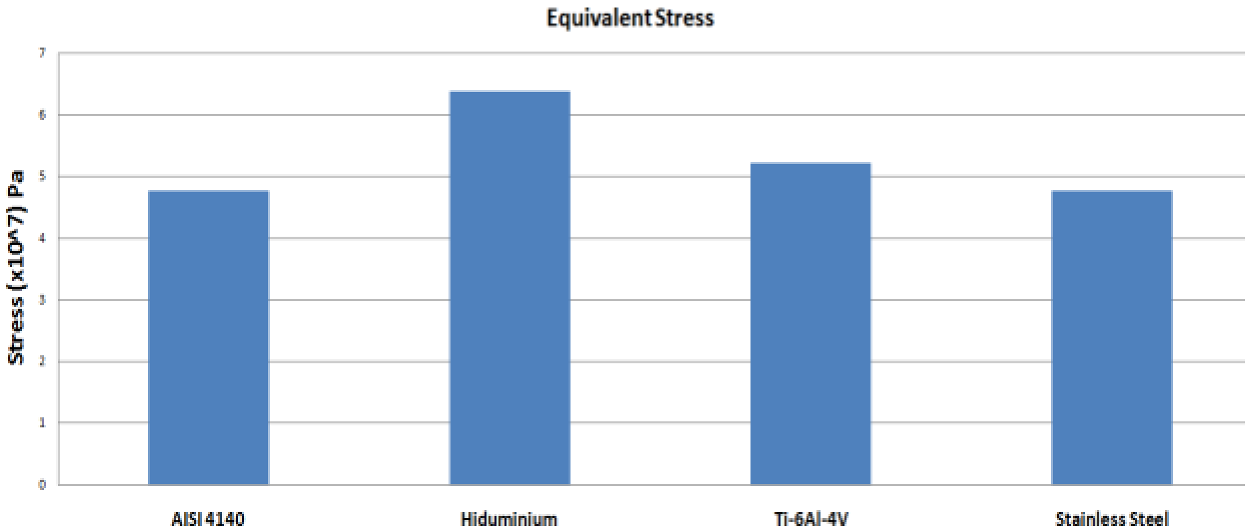

Fig 14: Comparison of all materials in Equivalent Stress

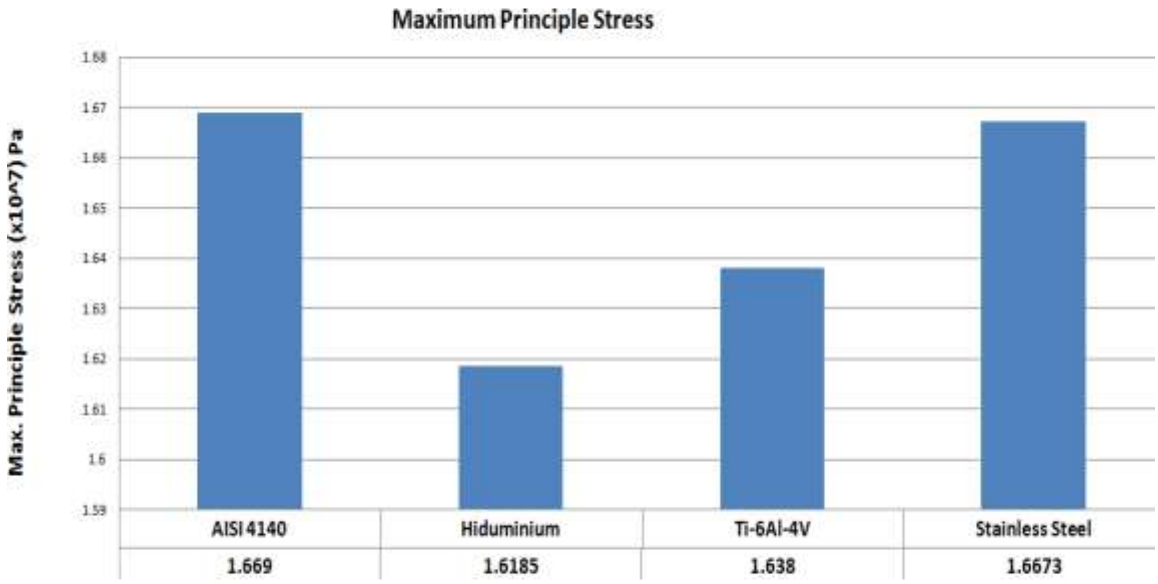

Fig 15: Comparison of all materials in Maximum Principle Stress

The Maximum Principle Stress of all the materials i.e.,AISI 4140 Steel,Hiduminium,Ti-6Al-4V,Stainless Steel are near to same value. So, the Maximum stress that these 4 materials can withstand is same and near to the range of $1.6x10^7$ Pa.

4.2 Fatigue

Fatigue is the weakening of a material caused by the cyclic loading that results in progressive and localized structural damage and growth of cracks, thus resulting in the deformation of the material. To analyzing this we considered giving cyclic loads by SN curve (Endurance-Number of Cycles).The SN curve is plotted between the endurance of the material and the No. of Cycles and thus the life of the material is determined.

4.2.1 Life:

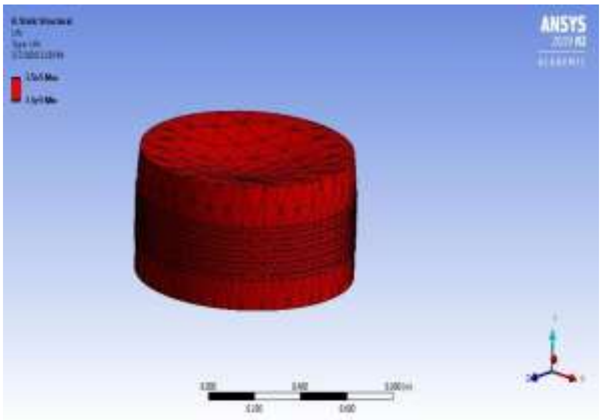

Fig 16: AISI 4140 Steel

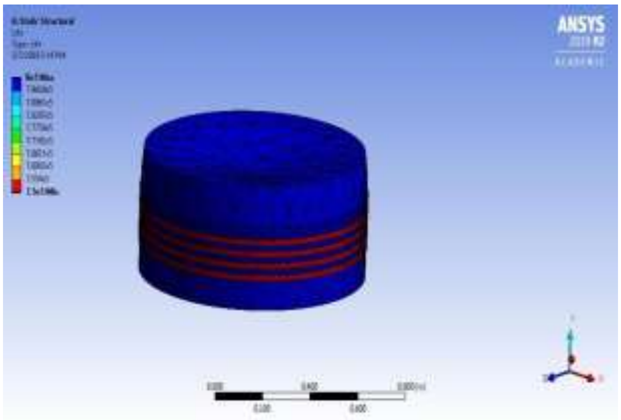

Fig 17: Hiduminium

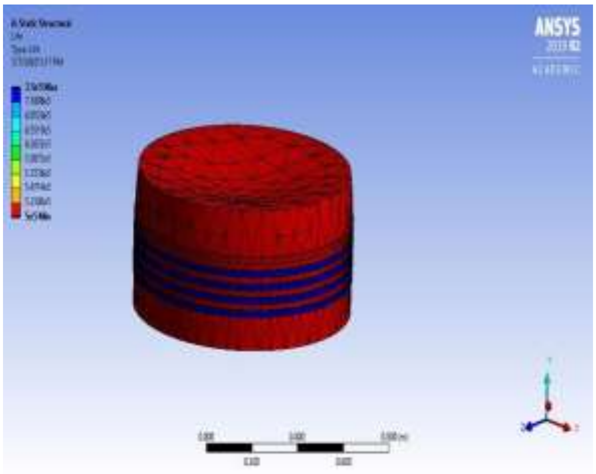

Fig 18: Ti-6Al-4V

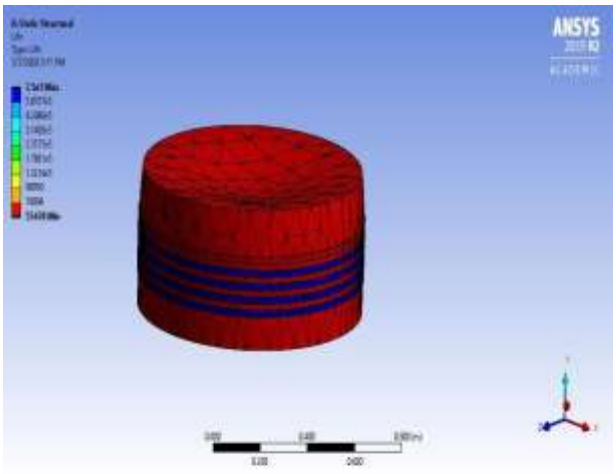

Fig 19: Stainless Steel

Table-2: Results of No. of Cycles of all materials

S.No	MATERIAL	LIFE
1.	AISI 4140 STEEL	$7.5x10^5$
2.	HIDUMINIUM	$8\ x10^5$
3.	Ti-6Al-4V	$7.5x10^5$
4.	STAINLESS STEEL	$7.5x10^5$

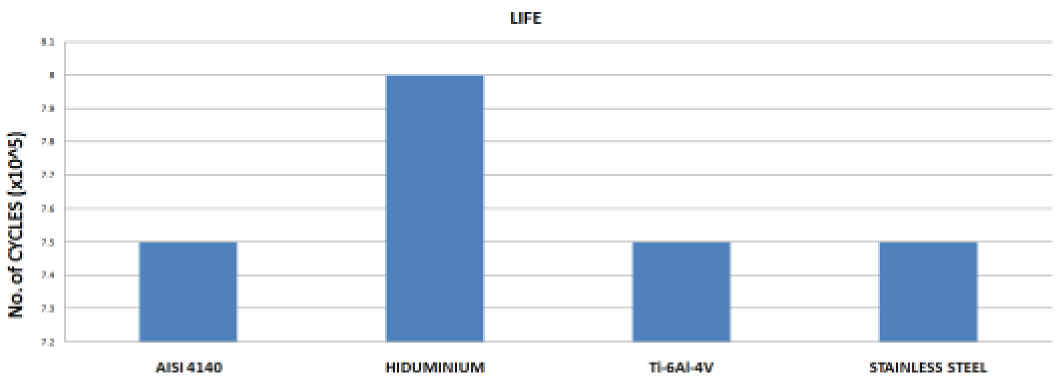

Fig 20: Comparison of all materials in No. of Cycles

4.3 Steady State Thermal

The main stress exerted on the piston is thermal stress. The material of the piston should be thermal - resistant such that it should withstand at high temperatures. We have given, the maximum temperature exerting on the piston is 550^{0}C. The Ambient temperature is given as 36^{0}C and thus, the Total Heat Flux is determined.

4.3.1 Total Heat Flux

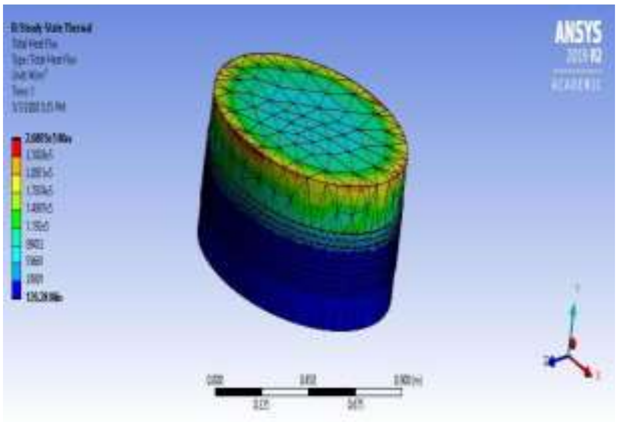

Fig 21: AISI 4140 Steel

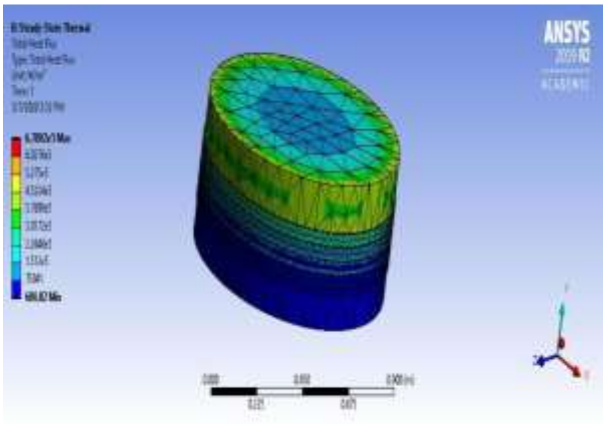

Fig 22: Hiduminium

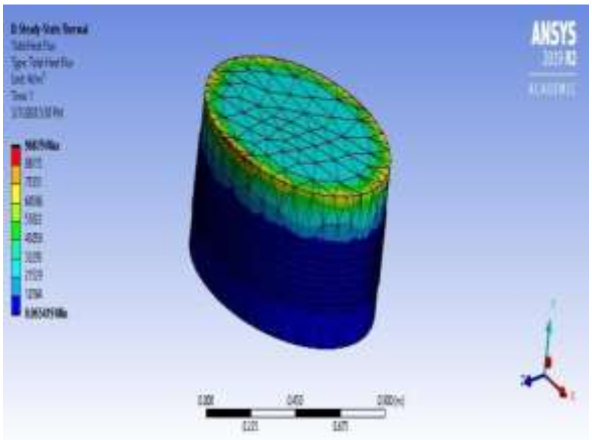

Fig 23: Ti-6Al-4V

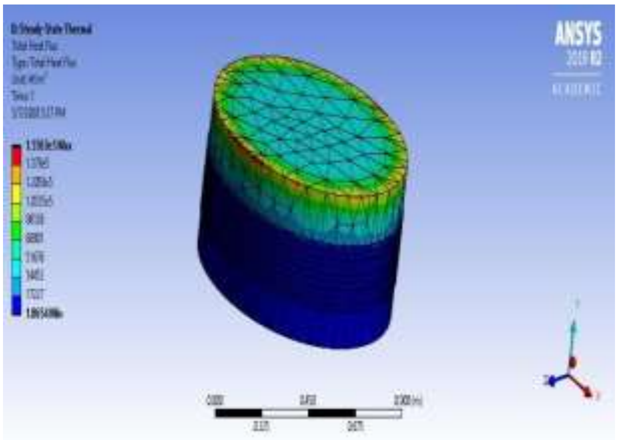

Fig 24: Stainless Steel

Table-3: Results of Total Heat Flux of all materials

S.No	MATERIAL	TOTAL HEAT FLUX (W/m^2)
1.	AISI 4140 STEEL	2.6805x10^5
2.	HIDUMINIUM	6.7802 x10^5
3.	Ti-6Al-4V	96879
4.	STAINLESS STEEL	1.5503 x10^5

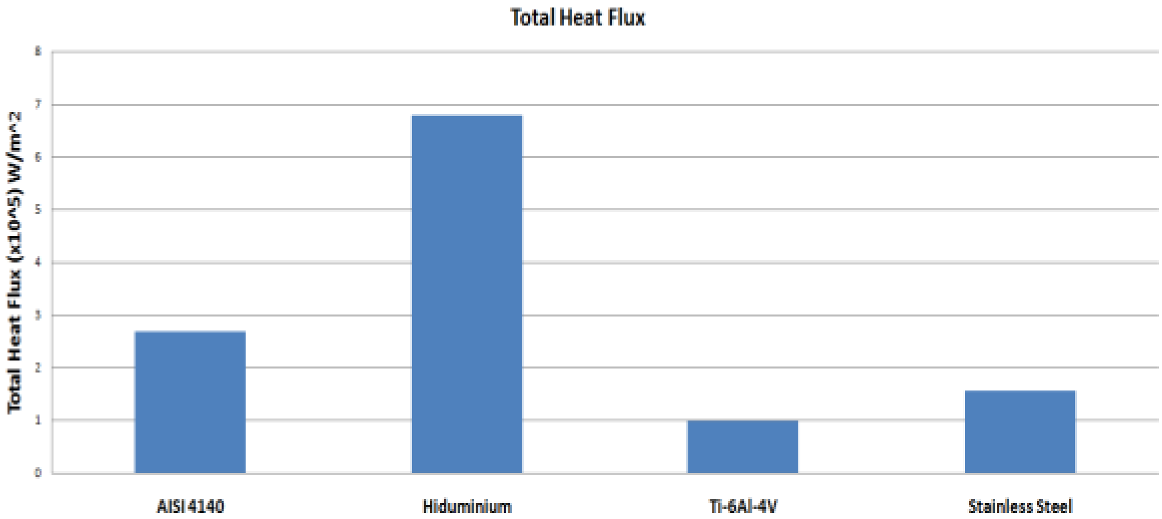

Fig 25: Comparison of all materials in Total Heat Flux

5. Conclusion

The objective of the work is to study the behavior of marine engine piston designed with the specifications of the Wartsila RTA 96 C Ship under Static Structural , Steady State Thermal and Fatigue conditions. The piston is studied with the basic material by which the piston is made of that is AISI 4140 and other materials like Hiduminium , Ti-6Al-4V , Stainless Steel and following conclusions are drawn from this work:

1. The piston is designed in SOLIDWORKS and the analysis is done in ANSYS 19.2. The values of the equivalent and maximum principal stress are compared from static structural analysis.

2. The maximum principal stresses of all the materials are in the same range of $1.6x10^7$ Pa.

3. The equivalent stress in Hiduminium is increased to 34 percent than that in the AISI 4140. Other two materials have the same range of equivalent stress as that of AISI 4140 and it is $4.74x10^7$ Pa.

4. The values of total heat flux are compared for all the materials from steady state thermal analysis.

5. The Total Heat flux of Hiduminium is 2.57 times that of AISI 4140.

6. The Ti-6Al-4V has got the least Total heat flux value among all the materials and it is 96869 W/m^2

7. The life of the piston is compared for all the materials from fatigue analysis.

8. The life in Hiduminium is increased by 50,000 cycles to that of all other three materials.

Taking the results of analysis into consideration it can be finally concluded that hiduminium shows the better and optimized values in total heat flux and life when compared to other materials i.e. AISI 4140 ,TI-6AL-4V , Stainless steel.

6. Future scope:

1. Design modifications can be done to withstand high stresses generated in the piston.

2. Dynamic structural analysis can be done where the effect of inertia forces can also be studied.

3. The meshing size can be reduced to greater extent and can be analyzed for accurate values.

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