A comparative study of structural and thermal analyses on piston materials

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Abstract: **A design of piston of an internal combustion engine involves selection of appropriate materials. The piston material needs to have great fatigue resistance and good heat transfer properties with low weight. The results of structural and thermal calculations using finite element analysis are compared on aluminum alloy, carbon graphite and tungsten as piston materials. The theoretical value of stress is used to find the mechanical strength of materials. The total heat fluxes on the materials are also used to estimate their thermal behaviors. It is found that either carbon graphite or tungsten may be used instead of aluminum alloy.**

Keywords: **piston, thermal, structural, graphite, tungsten**

I.INTRODUCTION

A piston is a cylindrical reciprocating part of an internal combustion (IC) engine which is placed inside the cylinder. Its purpose is to compress the gas for combustion and to transfer force from expanding gas in the cylinder to the crankshaft through a connecting rod. It dissipates large amount of heat generated by combustion of gases inside the combustion chamber to the cylinder wall. The piston has to sustain more mechanical and thermal stresses. It is the first component to fail compared to engine block, valves and cylinder head. The piston must have sufficient mechanical and thermal stress resistances. The gas force from cylinder pressure and inertia force from reciprocating motion of the piston contributes the mechanical load. The piston forces are calculated using advanced Finite Element Analysis (FEA) techniques. The pistons are designed heavier with more mass to bear higher mechanical stress due to higher pressure. The thermal load on the piston is due to gas temperatures in the combustion process. It is reduced, interrupted, or cooled during gas exchange. The heat transfer from hot combustion gases to the piston occurs by convection and radiation. The thermal resistance is also increased by adding more mass to the piston. The piston with more mass has high dynamic forces due to high inertia during high engine speed. The load capacity of the piston is determined by the strength of the material. The static and dynamic strength of piston material must be good enough to overcome changes in loads. The thermal conductivity must be also high for uniform temperature distribution throughout the piston. The material must be resistant to thermal stress induced due to the cyclical loads which can sometimes exceed the elastic limit. There are obvious benefits for engine balancing if a lighter alloy is used instead of cast iron. The aluminum alloys are widely used particularly in cylinder blocks and crankcases of automotive engines because of possible weight savings. The most commonly used materials are cast iron and aluminum alloy. The aluminum alloy 4032 is a wrought product which offers excellent service in both low and high temperature. It has more silicon content so that the manufactured pistons more durable and lighter. The high silicon content reduces overall ductility and reduces the resistance of the piston to higher impact loads. The carbon graphite pistons operate under thermal loads that cause aluminum pistons to seize or sustain deterioration damage due to excessive thermal growth and thermal distortion. It is about 30 percent lighter than aluminum which provides the benefit of reduced reciprocating mass to reduce dynamic forces. Moreover it also has the advantage of retaining room temperature strength and stiffness at high temperatures. The tungsten has the highest melting point and dull silver color. It is more resistant to fracture than diamond and is much harder than steel. Its unique properties are its strength and ability to withstand high temperatures. This research work used the reverse engineering principle to obtain an existing physical model of piston by measuring dimensions using instruments. Then, a three-dimensional piston has been created with the help of SOLIDWORKS and it is imported to ANSYS for the static structural analysis and steady-state thermal analysis.

II.LITERATURE REVIEW

Many research articles have been published in and around this research work. Among them specific articles are reviewed to establish the foundation for this work on comparative study of piston materials namely aluminum 4032, carbon graphite and tungsten. It has become necessity to calculate the temperature distribution of piston in order to control thermal stress and deformations within acceptable levels. The temperature distribution enables the designer to optimize the thermal aspects of the piston design at lower cost [1]. Srinadh et.al.[2] concluded that Zamak is having low deformation and high heat flux properties compare to other materials namely cast iron and aluminum. As per their results piston with Zamak is having high heat flux value than traditional materials. The piston with SiC reinforced ZrB2 composite material is having less deflections than aluminum alloy and grey cast iron for the applied temperatures and pressures. It is also observed that the stress for all the materials is within the allowable limits of the respective material [3]. The aluminum silicon carbide is found to have lesser deformation, lesser stress and good temperature distribution than aluminum [4].The engine operates at higher load and speed due to combustion of fuel at high pressure and high temperature inside the engine cylinder. The high thermal and structural stresses in the piston are produced inside the engine cylinder and if these stresses exceed the designed values, the failure of piston take place [5]. Krishna Dutta Pandey et al. [6] compared the structural steel and graphite for piston material using FEA. Their analysis shows that graphite is better for piston material by having better thermal behavior and reduced weight. The results show that maximum heat is transferred in the piston made of carbon graphite as compared to aluminum alloy 2618 due to higher thermal conductivity and low specific heat capacity. The carbon graphite is lighter in weight than aluminum alloy 2618 as well as low thermal expansion coefficient [7]. Kumar et al. [8] conducted the static structural analysis, steady-state temperature analysis and transient temperature analysis of an aluminum alloy Al-4032 piston using ANSYS. It is found that the stresses induced are the major factor of the piston failure. The variations of temperature and heat flux with time are determined in transient analysis. The maximum displacement is observed on the top of the piston of aluminum alloy and grey cast iron. The largest value of maximum temperature found in piston is due to thermal conductivity of the materials and the total maximum heat flux is absorbed in both the piston materials. Thus, further research can be carried with the advanced materials [9].The total heat flux is different for the different types of materials. The total heat flux for structural steel and grey cast iron is calculated for the same meshing properties with similar geometry. The heat flux result shows that the variation in heat flux is not so much higher either by simulation or analysis. It also shows the simulated heat flux values are quite nearer able to theoretical values calculated through formula [10]. The review shows that simulation using FEA produces similar results as analytical one. So, FEA is adopted in this work for static structural analysis and steady state thermal analysis. The structural analysis is essential to find the impact of mechanical loads on piston materials. The temperature distribution on piston due to thermal conductivity of different material are shown using thermal analysis. The new material tungsten has been selected for piston based on the review. It has been decided to compare this with other piston materials namely aluminum alloy-4032 and carbon graphite.

III.METHODOLOGY

The reverse engineering principle is applied for design of piston in this research work. The data regarding piston design has been collected from various sources. It is found that selection of material plays major role in determining both the static structural analysis and steady state thermal analysis. An air cooled 4 stroke single cylinder engine has been considered for our study. The dimensions of the piston are measured using instruments like vernier caliper, screw gauge, scale etc. The 3D model of the piston is created with measured dimensions using SOLIDWORKS. The boundary conditions of maximum gas pressure at the top surface of the piston 5MPa and temperature 400°C are fixed. Three types of materials are selected from the software library for the piston design. The FEA is carried out using ANSYS to determine mechanical deformation and stress. The steady state thermal analysis is estimated with range of temperature distribution on the surface and total heat flux.

IV.RESULTS AND DISCUSSIONS

The behaviors of piston materials are shown in the following figures and tables for both structural and thermal analysis. The aluminum alloy 4032 is most commonly used material for piston of an IC engine. Its physical properties show its robustness to with stand high pressure. The carbon graphite is well known as strong material. The tungsten is very heavy metal with high melting point. The same meshing parameters are followed for all the three materials selected for this study.

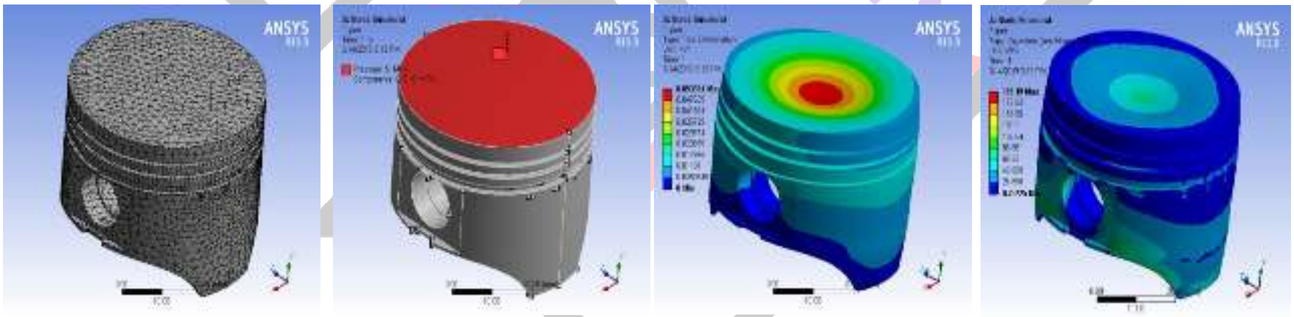

Fig.1. Static structural analysis of aluminum alloy – 4032

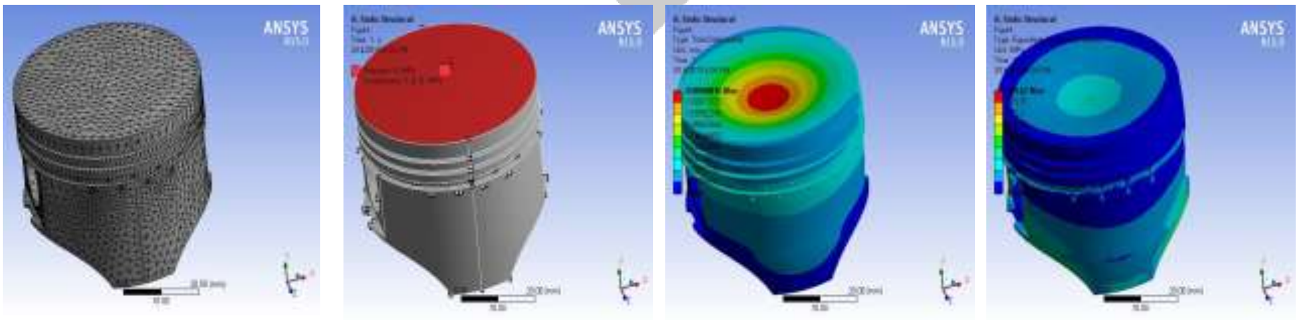

Fig.2. Static structural analysis of carbon graphite

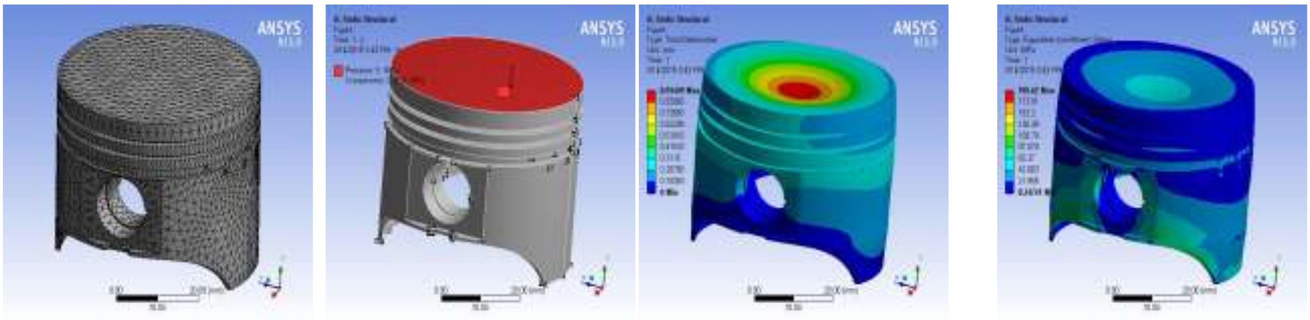

Fig.3. Static structural analysis of tungsten

Table 1. Static structural analysis

Material	Pressure (Load applied) MPa	Total deformation mm		Stress(equivalent Von- mises) MPa	
		Minimum	Maximum	Minimum	Maximum
Aluminum alloy-4032	5	0	0.053594	0.23725	195.19
Carbon Graphite	5	0	0.00080016	0.2474	195.62
Tungsten	5	0	0.93449	0.24741	195.62

The table 1 and figures 1,2 and 3 show the comparative analysis of piston materials based on structural analysis. The same load of pressure of 5 MPa is applied uniformly to all the materials. The total deformation of carbon graphite is much lesser than other two materials. The tungsten has more deformation than others for same load. The equivalent von- mises stress is a theoretical value used to determine yield or fracture. The carbon graphite and tungsten are having same range of von-mises stress. The aluminum alloy has slightly lesser stress values of 195.19 MPa. This shows that other two materials are having more mechanical strength.

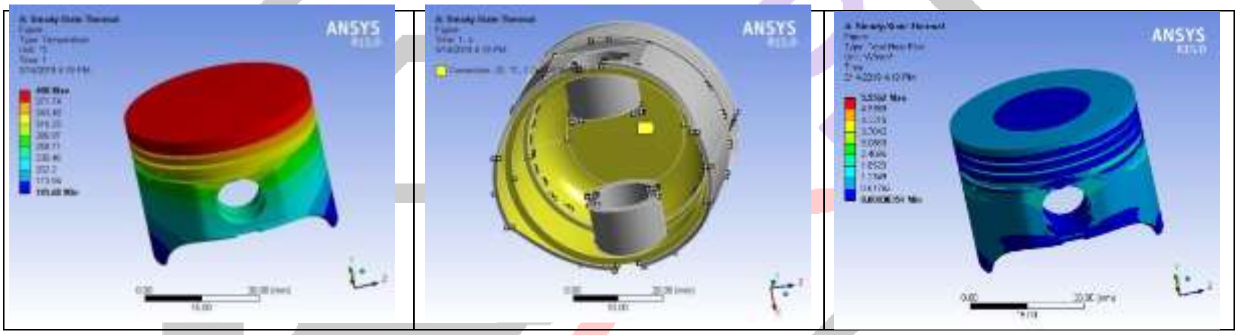

Fig.4. Steady state thermal analysis of aluminum alloy – 4032

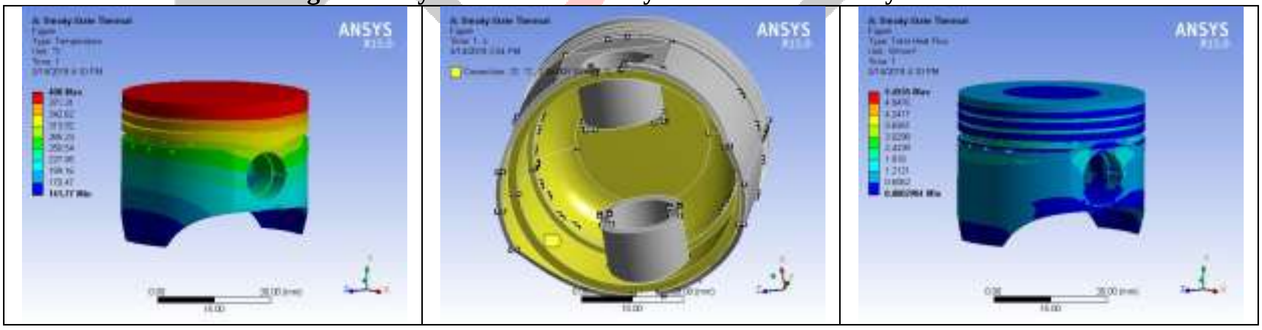

Fig.5. Steady state thermal analysis of carbon graphite

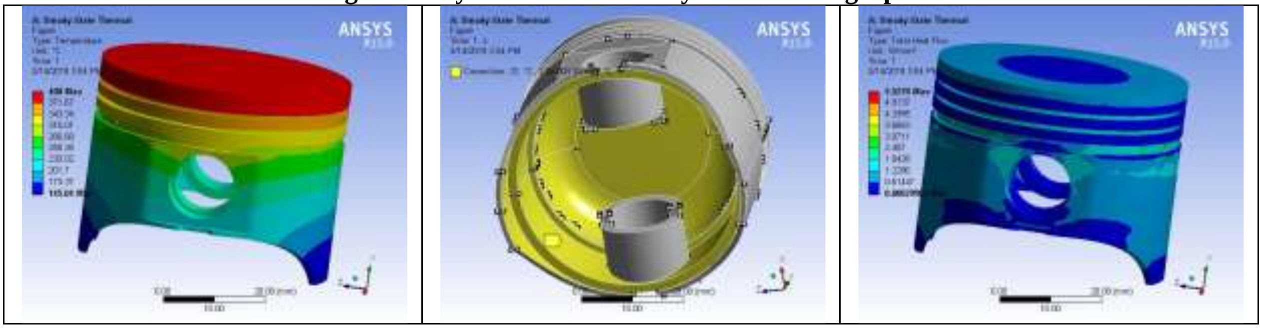

Fig.6. Steady state thermal analysis of tungsten

Table 2. Steady state thermal analysis

Material	Convention coefficient at 22^{0}C W/mm^2·°C	Temperature distribution ^{0}C		Total heat flux W/mm^2	
		Minimum	Maximum	Minimum	Maximum
Aluminum alloy-4032	1.2e-003	145.68 °C	400°C	3.0354e-004	5.5562
Carbon Graphite	1.2e-003	141.77 °C	400°C	2.904e-004	5.4535
Tungsten	1.2e-003	145.04°C	400°C	2.9902e-004	5.5278

The table 2 and figures 4,5 and 6 show the steady state thermal analysis for piston materials considered for study. The thermal conductivity is the heat transfer due to thermal conduction inside one material. The heat transfer coefficient describes heat transfer between two different materials due to thermal convection. The convention coefficient is same for all the three materials. The heat lost is the heat load to the mechanical structure by thermodynamic principle. The unusual temperature distribution causes uneven thermal expansion of the piston materials and generates mechanical stress. The piston has limits to withstand the mechanical loads. The high frequency and low frequency loads act simultaneously on piston, resulting in a pulsating load which leads to failures by fatigue. The low frequency loads are associated with engine warm up and cool down at each stage. The high frequency loads are generated by the sudden pressure and temperature increase associated with the combustion at each cycle. The carbon graphite has wider range of temperature variation between 141.77 °C and 400°C among other two materials. The maximum temperature is kept at 400°C for all the three materials. The total heat flux is the amount of heat transferred per unit area per unit time to or from a surface. It is a derived quantity since it involves the principle of two quantities namely the amount of heat transfer per unit time and the area to or from which the heat transfer occurs. The aluminum has maximum total heat flux of 5.5562 W/mm^2 and carbon graphite has wider range of heat transfer from 2.904e-004 W/mm^2 up to 5.4535 W/mm^2. The tungsten shows lesser maximum heat flux than other two piston materials.

V.CONCLUSION

The piston of internal combustion engine is subjected to both mechanical and thermal loads when it moves inside the cylinder. The selection of materials for piston plays major role in design. Three different materials are applied on 3D model of piston which is created by using reverse engineering. The FEA calculations are made to estimate the structural and thermal strengths of the materials. The carbon graphite and tungsten are having more strength than aluminum alloy. Even though aluminum alloy has higher heat transfer coefficient but it has lesser range of temperature variation. Finally either carbon graphite or tungsten may be considered as alternative material for piston design. This work may be extended by considering tungsten composites as alternative materials for design of piston.

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