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Structural and Thermal Analysis of Cylinder Head Gasket

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Abstract— A cylinder head gasket is a thin plate like component which sits between the cylinder head and the engine block. It is an integral component of the engine and is required to perform many functions at the same time during engine operation. Its purpose is to seal the combustion gases within the cylinder and to avoid coolant or engine oil leaking into the cylinder. The gasket must provide a seal such that no impurities such as air, dirt enters into the cylinder and also prevent coolants, water and engine oil from leaking out. Hence, the material used must have good thermal and structural properties to perform optimally. This project focuses on the structural and thermal analysis of different cylinder head gasket materials, compare their structural and thermal properties and behaviors for each individual material and also determine the possible areas of crack generation of the gasket and the cycle life of the gasket.

Index Terms— Cylinder head gasket, FEM analysis, usage of different materials, structural, thermal, fatigue, possible areas of crack generation.

1 INTRODUCTION

A gasket is a mechanical seal which placed in the area between two or more surfaces under contact to stop leakages into or from the joined objects while under load, usually compression. Gaskets are manufactured in a variety of designs based on their usage, cost, what type of chemicals they are in contact with and the amount of pressure they are subjected to, such as sheet gaskets, solid material gaskets, double-jacketed gaskets, flange gaskets etc. Gaskets are usually made from materials such as rubber, Teflon, (Polytetrafluoroethylene), neoprene, fiber glass, silicon etc. [1]

Gaskets are produced as sheets by cutting the materials. A cylinder head gasket is an important part of an engine, which is located between the cylinder head and engine block of an engine. [2] The main function of the cylinder head. gasket is to provide a seal to prevent the leakage of the combustion gases from the cylinder and to avoid coolant or engine oil from flowing into the cylinder. Leaks in the head gasket can lead to poor engine running and overheating.[3] Within an average everyday used IC engine, there are primarily three fluids which circulate in between the engine block and the cylinder head:

- Combustion gases (unburned air/fuel mixture and exhaust gases) in the cylinders
- Water-based coolant in the coolant pipes
- Lubricating oil in the oil tanks.

Proper functioning of the engine mandates that these circuits do not drop pressure at the contacting point of the cylinder block and cylinder head. These leaks and pressure losses are prevented by the seal which is provided by the cylinder head gasket. One of the most important tasks for the manufacture of the gasket is to select a proper material for the gasket. Material of the gasket is of utmost importance, as the gasket should be able to withstand high temperatures and different loading conditions. If the material cannot withstand the load, it will lead to gasket failure or a blown head gasket and leaking of fluids, which can lead to a variety of problems. Thus, the material selected should have good structural and thermal properties in order to withstand the compression from the cylinder head and the heat from the engine.

Most modern vehicles use MLS type gasket, which although can hold well, due to the presence of asbestos can pose a lot of severe health issues. This project focuses to use different materials to make the cylinder head gasket for a 4-cylinder automobile engine, compare and analyze all materials structurally and thermally and to observe and review the results obtained and suggest on which material is more structurally stable, thermally stable, and which material poses good elastic properties and has a superior gasket cycle life and comparatively pose less health risks.

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2 METHODOLOGY

2.1 Selection of Materials

The material selection for the cylinder head gasket is of utmost importance, as the gasket needs to withstand the pressure and temperature of the engine during engine operating conditions. The gasket should not deform easily with change in temperature and pressure and should have a good cycle life. Taking these properties and materials into consideration, the materials which have been selected for this analysis of the cylinder head gasket are:

- Stainless Steel – Stainless steel is one of the most widely used

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materials due to its high thermal and structural properties, even at high temperatures and pressures. Stainless steel has reasonable resistance to corrosion, tensile strength and can withstand elevated temperatures. They are mainly used in high temperature applications, like internal combustion engine.

• Polytetrafluoroethylene (PTFE) – PTFE has excellent chemical resistance and good thermal and good sealing performance. PTFE has very low coefficient of friction, which reduces the energy wastage in overcoming the friction, and very good compressibility. There have been experiments conducted where PTFE gaskets have been used at high pressures and they held very well and provided excellent sealing. They are mainly used in corrosion prone environments.

• Pyrophyllite – Pyrophyllite has excellent thermal properties and provides excellent sealing performance. It has extremely good pressure flow properties, excellent thermal stability and it has good machinability.

• Carbon Fibre – Carbon Fibre is a material with excellent mechanical and thermal properties. It has high stiffness, high tensile strength, low weight to strength ratio, high chemical resistance, high temperature tolerance and low thermal expansion. These properties have made Carbon Fibre an immensely useful and applicable material in the field of aerospace and civil engineering.

• Kevlar – Kevlar is an extremely strong and heat resistant material, which is used to make bullet proof vests and as a replacement for steel in racing tyres. It is five times stronger than steel and is considered as one of the toughest materials.

2.2 Modelling

Modelling is the defining of the basic structure of the component which is basically outlining the dimensions and shape of the component to help the computer understand it in a mathematical way. The mathematical illustration helps in displaying the image of the component designed and is manipulated by different codes of the software executed through the processor. The modelling was done using CATIA V5R21 software. The model is for a 4-cylinder automobile engine of piston diameter 80mm, which is the norm for most basic mid-range cars in the market today. The model in consideration is of a basic model car engine.

2.3 Analysis

The FEM analysis was carried out using ANSYS Workbench 19.2 software, considering the properties shown in Table 1 for all the materials.

Meshing is a very important process of the simulation process for the computer-aided engineering analysis. The accuracy of the solution, the convergence of the solution and the speed of the solution heavily depends upon the meshing done on the component or the element. Also, the most time-consuming portion to get results from an analysis is the part where the CAD model is created and meshed, according to the requirement. The meshing used in this analysis is **Tetra Dominant Meshing Method**. The model after meshing comprises of 2256 elements and 5581 nodes.

The boundary conditions considered for the analysis are as follows:

- The gasket is stationary, as it is fixed between the cylinder block and cylinder head with the help of bolts. The gasket is fixed to provide efficient sealing.
- The pre-stress on the gasket, which comprises of the stress induced by the bolts and the weight of the cylinder head, is 30 KN
- The combustion pressure varies from 2 MPa to 8 MPa, depending upon the rate of combustion during engine operation.
- The temperature varies from 0.156^{O} C to 200^{O} C during engine on and off conditions.

The analysis is carried out using ANSYS Workbench 19.2 software.

TABLE 1
MATERIAL PROPERTIES CONSIDERED

Material	Tangent Modulus (N/m2)	Density (kg/cm3)	Yield Strength (MPa)
Stainless Steel	5500	7750	535
PTFE	1100	2200	23
Pyrophyllite	2100	2840	50
Carbon Fibre	20000	1780	663
Kevlar	23000	1404	2000

3 RESULTS AND ANALYSIS

3.1 Static Structural Analysis

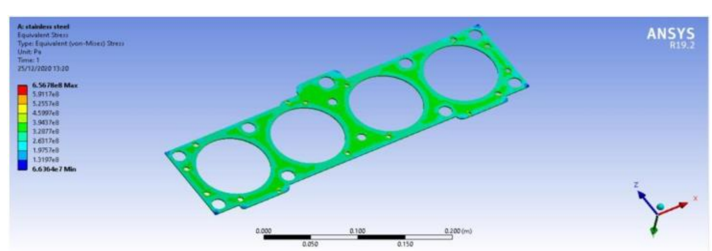

Fig 1 : Equivalent Stress (Stainless Steel)

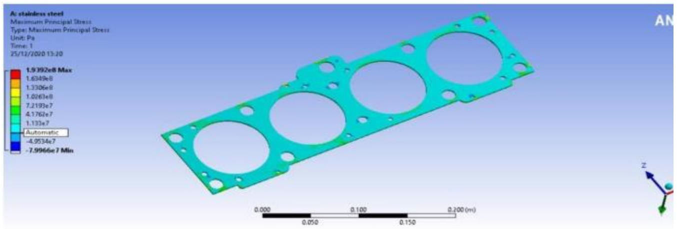

Fig 2: Maximum Principal Stress

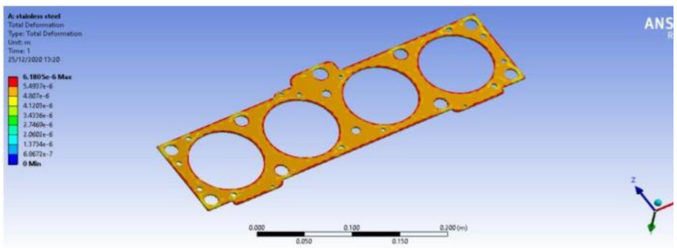

Fig 3: Total Deformation (Stainless Steel)

3.2 Steady State Thermal Analysis

Steady-state thermal analysis is the analysis which is done to find out the temperatures, heat flow rates, heat fluxes and thermal gradients in an object that are caused by thermal loads that do not change with respect to the duration of the load acting. A steady-state thermal analysis determines the consequences the thermal stresses have on a system or a component. Engineers usually carry out a steady-state analysis before executing a transient thermal analysis. A steady-state analysis also can be the final stage of the transient thermal analysis, which is usually executed after all the transient analysis features have declined. This analysis is focused on finding the total heat flux and directional heat flux of the materials. The temperature of the analysis ranges from 0.156° C to 200° c. Heat flux can be stated as the heat flow per unit area through a body in unit time. Directional heat flux is the heat flux flowing only through a particular direction.

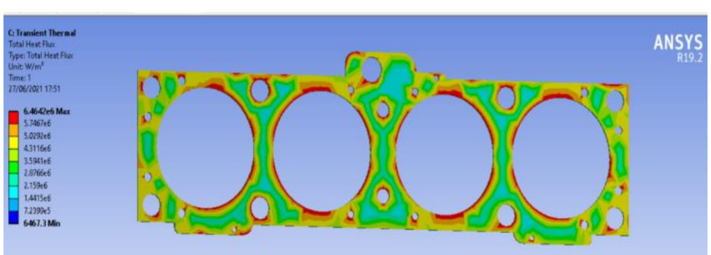

Fig 4: Total Heat Flux

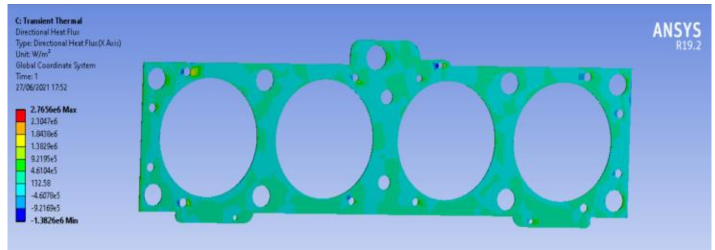

Fig 5: Directional Heat Flux

In the Transient Thermal Analysis for Carbon Fibre cylinder head gasket, the maximum total heat flux is found to be 6464200 W/m² and the maximum directional heat flux (X Axis) is found to be 2765600 W/m².

3.3 Transient Thermal Analysis

Transient thermal analysis is the analysis which is done to find out the temperatures, heat flow rates, heat fluxes and thermal gradients in an object that are caused by thermal loads that do change with respect to the duration of the load acting, or the effect of temperature change on a body. Transient thermal analyses usually give a better view on the real-world interaction when compared to a steady state analysis. The temperature of the analysis ranges from 0.156° C to 200° C. In this analysis, here, the lower surface of the gasket is at a higher temperature and the heat flux as the temperature change occurs is determined.

Heat flux can be stated as the heat flow per unit area through a body in unit time. Directional heat flux is the heat flux flowing only through a particular direction.

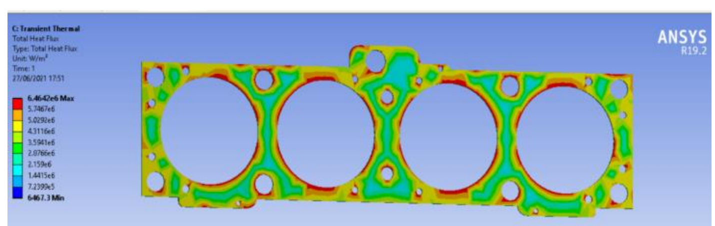

Fig 5: Total Heat Flux

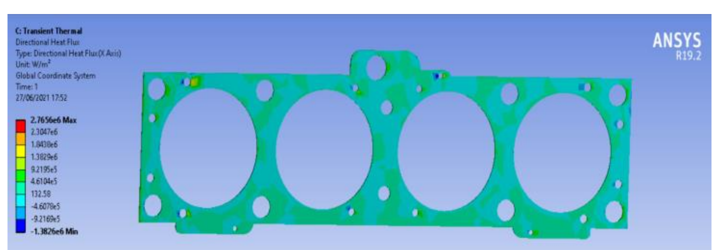

Fig 6: Directional Heat Flux

In the Transient Thermal Analysis for Carbon Fibre cylinder head gasket, the maximum total heat flux is found to be 6464200 W/m^2 and the maximum directional heat flux (X Axis) is found to be 2765600 W/m^2.

3.4 Possible areas of Crack generation

For any particular object which is subjected to variations of temperature and pressure, there will come a time where said object will not be able to completely resist the environmental changes and will cause the object to develop deformations in its shape. These deformations, over a period of time, will cause the object to develop certain weak spots which are affected more to the pressure and temperature changes, which will make the material lose their elasticity These spots will be formed mainly due to curves and irregularities in the shape of the object. Eventually, as time progresses with usage of the object and continuous cycles of pressure and temperature fluctuations, these weak spots might lead to the formation of cracks, which will progress and lead to the failure of said object.

Taking the object in this analysis which is the cylinder head gasket, it is subjected to a lot of pressure and temperature changes. From the structural and thermal analyses which have been conducted, we can make certain assumptions of where these possible areas of crack generation might be.

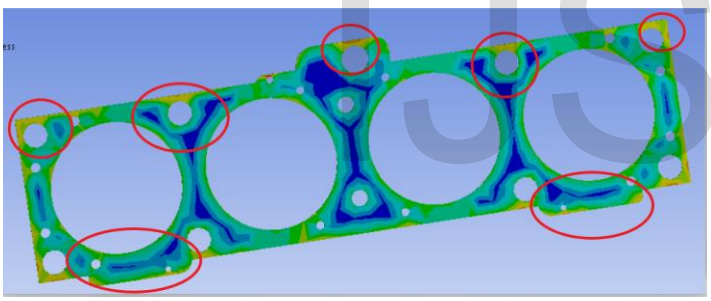

Fig 7: Possible areas of crack generation

From the structural analysis above, we can see the color variation, which shows the different stress levels associated with each part of the cylinder head gasket. It is clear that the corners of the gasket have higher stress values when compared to other areas. Also, the top portion of the gasket where there are sharp corners are present also susceptible to high stress when compared to other regions of the gasket.

Also, the area around the holes of the gasket also affected more by the pressure, and therefore have higher stress values.

Hence, due to increased stress at these particular points, the elasticity at these points decreases over time. Therefore, these points may be points of possible crack generation.

3.5 Cycle-life Estimation

Fatigue is a material or structure under the action of alternating load, in more than one place or cause permanent damage. With the increase of cycling time, it can cause crack and fracture process. In fatigue design, the linear fatigue damage accumulation theory is most widely used. The most typical theory is the miner damage theory, which can be given by

$$D = \frac{n_1 D}{N_1} + \frac{n_2 D}{N_2} + \frac{n_3 D}{N_3}$$

where D is the maximum value of the final fracture of the material;

n(i=1,2,3….) is the number of cycles under the max principal stress, middle principal stress, min principal stress, respectively;

N(i=1,2,3….) is the number of cycles to achieve the final fracture threshold for the max principal stress, middle principal stress, min principal stress, respectively.

The S-N curve of the material is usually made using symmetrical loads. Due to different load types, the fatigue aging is different, therefore, it needs to be corrected.

In this analysis, we are using the Goodman linear model.

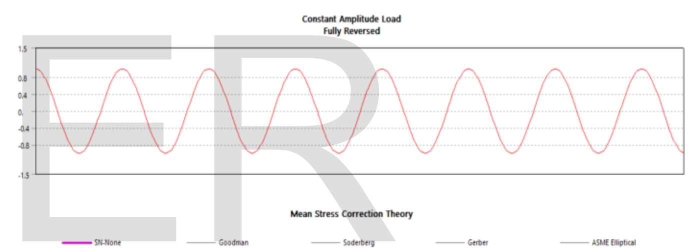

Fig 8: Loading for the cycle life estimation

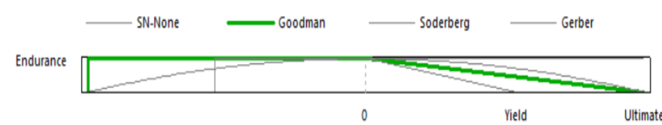

Fig 9: Correction for the cycle life estimation

After simulation analysis, the cycle life-time of the cylinder head gasket is shown.

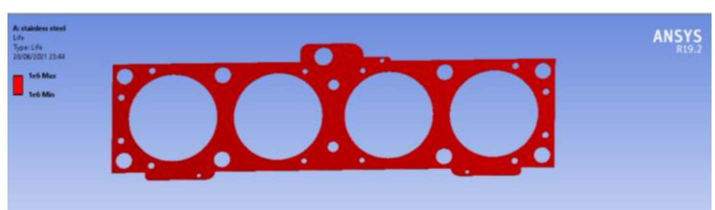

Fig 10: Cycle life estimation

The cycle life of the gasket is given as **$1E^6$.** Since the entire cylinder head gasket is subjected to the same load and pressure, the entire cycle life will remain the same for the entire gasket.

Usually, objects start losing their elasticity at completion of 3/4th the total cycle-time, which will hold good for this analysis as well.

3 Results and Conclusion

3.1 Results

The results of all the analysis done on cylinder head gasket are given below:

TABLE 2
RESULTS OF ALL ANALYSIS

Material	Max Principal Stress (MPa)	Max Deformation (mm)	Total Heat Flux (Steady State Thermal) (W/m^2)	Total Heat Flux (Transient Thermal) (W/m^2)
Stainless Steel	192	0.00618	15494.01	155020
PTFE	3.77	0.127	2660.70	86275
Pyrophyllite	1.34	0.0970	0.10403	272260
Carbon Fibre	0.543	0.000363	214545	6464200
Kevlar	2.7866	0.000312	4104	4586.9

3.2 Conclusion

From the above table 5a, and from the entire analysis, the following inferences and conclusions can be drawn -

- The total deformation under static conditions is least for the Kevlar cylinder head gasket and Carbon Fibre cylinder head gasket and the highest deformation is for the PTFE cylinder head gasket.
- the total heat flux of the Carbon Fibre cylinder head gasket in the thermal analyses is greater than other materials, which is a major means that it the heat from the gases and cooling oils which it comes in contact with, thereby cooling and reducing the temperature of the cylinder block.
- The maximum principal stress of the Carbon Fibre cylinder head gasket is also less when compared to other materials in the analysis, meaning it is not affected that much by the gas pressure and the pre-stressing of bolts.
- Also, from the cycle life analysis, we have determined that the cycle life of the cylinder head gasket is **1E^6** cycles of usage of maximum and minimum pressure and temperature changes, and will start lose its elasticity at the completion of 3/4th of cycle time.
- From the structural and thermal analyses, we have also zeroed in on possible areas of crack generation in the gasket where the changes in temperature and stress are affected the most.

Therefore, the Carbon Fibre and Kevlar cylinder head gaskets have the least deformation with respect to boundary conditions.

However, the Carbon Fibre cylinder head gasket showed better properties for the thermal analysis.

Therefore, in conclusion, the Carbon Fibre cylinder head gasket will be a suitable replacement for the existing steel cylinder head gasket weaved with asbestos, as the Carbon Fibre gasket is more environment friendly and also can withstand the pressure and temperature changes a cylinder head gasket is normally subjected to.

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