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Design and Analysis of Cylinder Head Gasket under Engine Cold Assembly Condition

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Abstract – The gas escaping from the engine not only affects the output efficiency of the engine substantially, but also pollutes the environment. The pre-stressing force of the bolts as well as the gasket design is critical factors in enhancing the efficiency of the sealing of the gasket. Therefore, the guarantee that the assembly between the cylinder head, bolts, and gasket is reliable and effective, through proper analytical procedures and tests becomes extremely important. For solving these issues, the thermal and structural analyses must be adopted in the engine design to save the time of actual modifications.

In this investigation, the distribution of the contact pressure on the gasket at cold assembly condition at different magnitude of pre-stressing force is explored by numerical calculation based on the finite element method (FEM). The results reveal that the efficiency of the sealing of the head gasket depends on the pre-stressing force of the hold-down bolts, without taking into consideration any thermal stresses resulting from the temperature distribution in the cylinder head.

The present work is focused on design and analysis of the cylinder head gasket of bolted joined structure subjected to pre-stressing force of bolts based on contact theory in order to investigate the efficiency of gasket sealing by finding the location of weakest contact pressure and deformation of cylinder head gasket. The structural analysis is carried out by using commercial FEM code ANSYS 16.2.

Keywords: Cylinder Head Gasket, Pre-Stressing Force of Bolts, Finite Element Analysis, Normal Gasket Pressure, Contact Pressure

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1. INTRODUCTION

A cylinder head gasket is required to affect a seal between the cylinder head and block of a gasoline or diesel engine. It is an integral component of the engine and is required to perform many functions at the same time during engine operation. The head gasket must maintain the seal around the combustion chamber at peak operating temperature and pressure. The gasket must seal against air, coolants, combustion and engine oil at their respective peak operating temperature and pressure. The materials used and design employed must be thermally and chemically resistant to the products of combustion and the various chemicals, coolants and oils used in the engine. It supports the cylinder head along with its operating components. It must be able to withstand the dynamic and thermal forces that are transmitted from the head and block. The type of engine application will be the determining factor in cylinder head gasket design.

If the engine overheats and exceeds its normal operating range, the elevated temperatures can cause extreme stress in the cylinder head, which may result in a head gasket failure. This is especially true with aluminum cylinder heads because aluminum expands about two to three times as much as cast iron when it gets hot. The difference in thermal expansion rates between an aluminum head and cast iron block combined with the added stress caused by overheating can cause the head to warp. This, in turn, may lead to a loss of clamping force in critical areas and cause the head gasket to leak.

Due to the interface between the cylinder head and gasket, as well as the interface between the cylinder head and the bolts, contact behavior takes place. The FEM used to deal with the contact problem of surfaces with a complicated geometry of the contact surface is more effective than the boundary element method. Chan and Tuba developed the method to solve some contact problems. However, the temperature inside the engine structure is produced through various operating processes and loading conditions. Consequently, the mechanical problems of thermal contact need to be considered for the gasket sealing process. The behavior of thermal contact was studied by many researchers in the past.

Besides the aspect of contact problem, the behaviors of heat conduction between the body of the engine and the other components are also extensively investigated by FEM. The engine sealing components must be designed to provide an adequate seal between engine components without leakage; however, they must not induce engine component stresses that may hinder performance and/or function of the engine (Frank Popielas 2000). To avoid the escaping gas from the engine affecting the overall performance of the engine during operation, both the proper pre-stressing force of the bolts as well as the gasket design are critical factors in enhancing the efficiency of the sealing of the gasket. The efficiency of the sealing of the head gasket depends on the pre-stressing force of the hold-down bolts, without taking into consideration any thermal stresses resulting from the temperature distribution in the cylinder head. Therefore, an effective method was proposed to enhance the sealing capacity of the gasket by increasing the magnitude of the assembly force without exceeding the material strength of each component in the engine structure (Chang chun lee 2005). The compression in the cylinder will cause a leak to form in the gasket and the gasket will have to be replaced, or severe damage can take place (a "blown" head gasket). In carbon fiber, Kevlar fiber, pyrosic ceramic glass fiber has a much greater thermal expansion rate, which in turn causes a great deal more stress to be placed on the head gasket. (M.Srikanth, B. M.Balakrishnan 2015).

Multi-layer steel head gaskets are currently the favorable choice for the internal combustion engine and are a growing technology in the heavy duty diesel industry. There are many reasons for the popularity, such as improved reliability, increased sealing with minimal stud forces, better chemical and thermal resistance, higher control of clamped gasket thickness, decreased bolt force fluctuations, improved levels of dynamic response and enhanced emission control

The pre-stressing force of bolts maintains the efficiency of the gasket sealing between the cylinder head and the cylinder block. Therefore, the applied approach of the pre-stressing force is significant for the calculation of the numerical simulation. However, another critical factor that affects the sealing efficiency is the behavior of the gasket material. (Roub 1992) analyzed the response to the non-linear phenomenon of the gasket by means of a simplified model, with one degree of freedom in the direction of the thickness of the gasket. By using the analytical element of the ANSYS software (Solid 185) combined with the curve of the pressure versus the displacement obtained from the experiment, the demand of the model for memory can be reduced by a substantial amount. (Shinji 1999) used a methodology with axial symmetry to solve the non-linear behavior of a gasket in the direction of its thickness. The main idea of this literature was to introduce the pre-tension element into the simulation of the bolted assembly with the other components. Compared with the traditional method, the pre-tension element has many advantages over the method of controlling the raising and lowering of the temperature. However, owing to the complicated engine structure and the lack of experimental data on engine performance, especially of the cylinder head, there is little literature available that fully discusses the structural analysis of the cylinder head.

In this research, the commercial FEM code ANSYS, is used for the numerical simulation of the structural analysis. This research is based on contact theory in order to investigate the efficiency of gasket sealing and stress/strain behavior of cylinder head gasket under various loading conditions. Furthermore, the parametric analyses of the pre-stressing force of bolts at cold assembly condition are discussed in this work. Also the work is carried out on determination of contact pressure generated on gasket for the motions between cylinder head and gasket, gasket and block, as well as between gasket layers, total deformation of gasket due to pretention to acquire the best performance of engine.

2. CONTACT THEORY

All Generally speaking, penalty methods like the Lagrange multiplier methods and augmented lagrangian method are widely used in the mechanical contact finite element simulation. However, the penalty methods suffer from ill-conditioning that worsens as the penalty values are increased. The Lagrange multiplier method introduces extra unknowns, and the resulting equation system is not necessarily positive-definite. The augmented Lagrangian method combines the penalty methods and the Lagrange multiplier methods, and inherits the advantages of both methods. The variational weak form of the augmented Lagrangian method on the contact region (rc) could be expressed as:

$$\delta\pi = \int \delta(\tau y_N + \frac{\alpha}{2}\gamma^2 N)dr \quad (1)$$

Where λ is the Lagrange multiplier a is the penalty value and y_N is the interpenetration rate of two contact bodies. Through the variation calculation, Equation (1) could be transformed to its relative strong form as

$$M_a + f^{int} - f^{ext} + G^T\tau + P_c d = 0 \qquad (2)$$

$$G_v \leq 0 \quad (3)$$

Where v refers to the velocity field in both bodies; the Lagrangian multiplier is denoted by λ, and GTA is the contact force; the contact stiffness is denoted by PC, and Pcd is the contact force (penalty force). The, f^{int}, f^{ext} and Ma are the internal, external and inertial forces, respectively. Equation (2) is the

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governing equation of the contact finite element computation. Equation (3) is the inequality constraints that describe the contact boundary of two contact bodies.

The chief benefit of the augmented Lagrange method for the contact problem is that it provides the robustness and stability for the penalty method, while at the same time being a simple procedure that does not involve additional equations for the discrete system. To accurately simulate the contact behavior between the cylinder head and the gasket under various conditions of engine operation, the augmented Lagrangian method is adopted in the finite element analysis.

3. FINITE ELEMENT MODELS AND ANALYSIS PROCEDURE

3.1 Finite element models-

To establish the analytical methodology of the cylinder head in respect to structure, four stroke diesel engines, having 12 cylinders is adopted in this research. The Pro/E model provided by Greaves cotton ltd for investigating the efficiency of gasket sealing is displayed in Figure 1, Figure 2 and Figure 3. For the convenience of the observation of the distribution of normal pressure on the gasket only one cylinder head is considered in this study because of that there is reduction of the complications of boundary conditions considered in analytic process and economizing on the element counts of the finite elements analysis. Table 1 lists the material properties of each component for the structural analysis in this research. The main body of cylinder head, block and liner are made of cast iron. The pre-stressed bolts are made of carbon steel (SCM 435). At same time the internal part of gasket is in contact with different component having dissimilar material characteristic shown in Figure 4 which displays multilinear-elastic material property of the gasket used in structural analysis. (Suresh kumar kandreegula 2015)

Table 1 Material properties of component

Component	Material	Young's modulus	Poisson's ratio
Head	Cast iron	118	0.26
Block	Cast iron	137	0.26
Liner	Cast iron	107	0.29
Bolts	Carbon steel	205	0.29

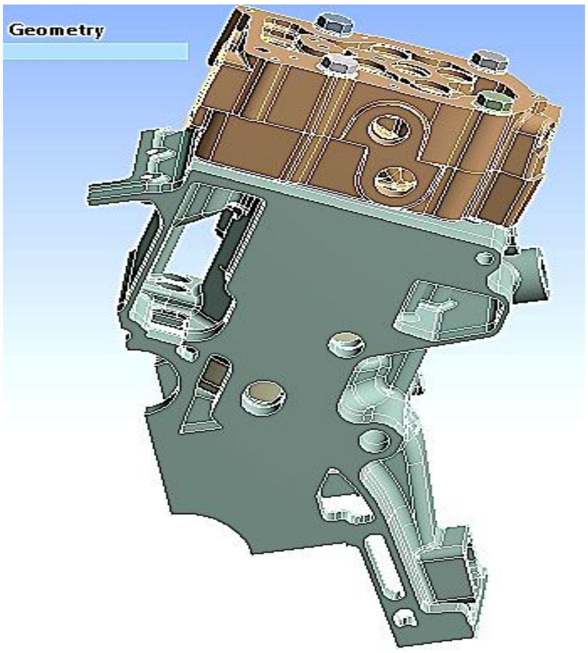

Figure1. Solid model of cylinder head gasket

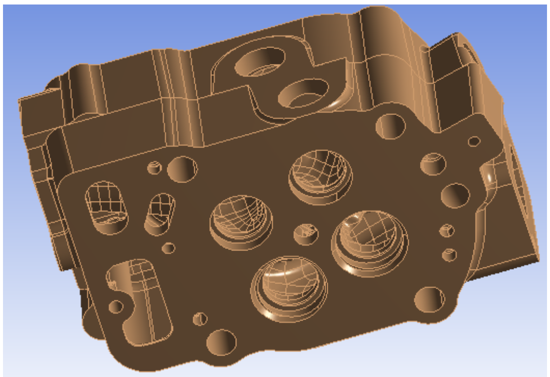

Figure 2 Cylinder Head

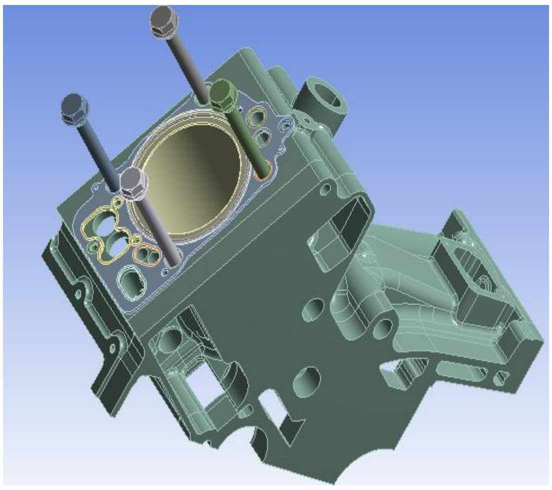

Figure 3.Block, Liner , Gasket and Bolts

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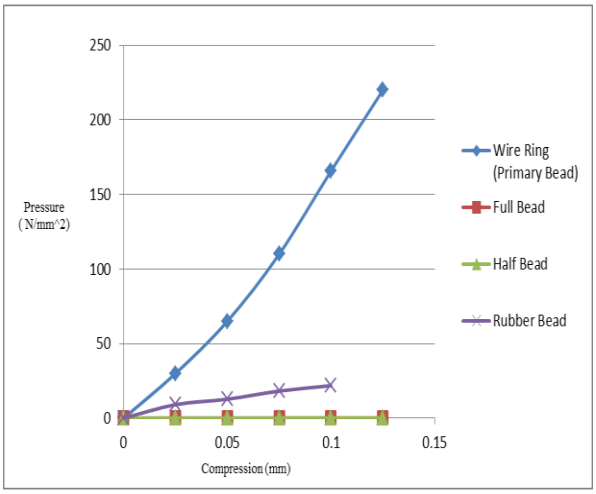

Figure 4. The relation between pressure and compression in the gasket.

The software based on the FEM ANSYS 16.2 is used to structural analysis. Several assumptions are made with regard to modeling the structure of cylinder head and they are

1. The 12 cylinder heads possess a structural symmetry hence only one cylinder head removed from complete model in order to reduce the calculated time and to set a simple boundary.

2. For the pre-stressing of the bolts, the construction of a partial block is needed to look into the efficiency of gasket sealing.

3. According to the actual dimensions, the full thickness of the gasket is 2.8mm considering thickness of half bead at bolt hole, full bead and inner ring at combustion area.

The area-to-area contact pair has made use of simulating the contact condition at the interface between cylinder head, gasket, block, liner and bolts. Pre-stressing of bolts to simulate the tightening level in the assembly process of engine is applied in the direction of applied force. The total amount of the elements and nodes in the FEM model are 1010514 and 699901 respectively.

3.2 Structural analysis procedure –

According to applied loadings the analytical procedure could be divided into three load steps for simulating varies operating processes of the engine.

1. Assembly loading

2. Gas pressure

3. Thermal loading

From that only assembly loading and gas pressure is considered for this work and the final results are of this structural analysis are composed of the outputs of these load steps. (D. Vinod kumar 2013)

1. Assembly loading-

Maximum load is applied to the engine is assembly loading that is pre-stressing force of bolts and it plays an important role in preventing gas leakage from internal part of engine. In this case to avoid insufficient sealing of gasket 70 KN pre-stressing force of each bolt is applied which is calculated. The displacements of the nodes at the bottom of block are fixed to avoid the rigid body motion and frictionless at both sides of block.

2. Gas pressure

Gas pressure generated due to firing is imposed on the surface of the combustion chamber and the magnitude of gas pressure varies with different duration of cycle. For steady state analysis 20 Mpa gas pressure is introduced into the loading conditions for the numerical simulation of cold start condition.

4. RESULTS AND DISCUSSIONS

In this research the location of normal pressure and contact pressure generated on gasket is used to investigate the efficiency of gasket sealing. The analytical results are discussed at cold assembly condition using different magnitude of pre-stressing force of bolts.

4.1 Cold assembly

The gasket sealing of the automobile in a motionless state is considered to be purely without any other external loading. Therefore, the maximum source of loading in this case is the pre-stressing of the bolts. In addition, the magnitude of pre-stressing the bolts with regards to dissimilar styles of engine structure and stroke volume is not identical. For this reason, the parametric analysis for the pre-stressing of bolts is implemented. The results clearly reveal that the minimum normal pressure and maximum contact pressure on the gasket appears at the location of the wire ring. Variation of normal gasket pressure and contact pressure at 70 KN pre-stressing force of bolt are shown in figure 5 and Figure 6. Gasket total deformation is shown in Figure 7. It should be noted that the efficiency of gasket sealing dependence mainly upon the magnitude of pre-stressing force under cold assembly condition.

The results for pre-stressing force of bolts with parametric analysis are shown in figure 8. Similar procedure is adopted for the analysis for 40 KN, 50 KN, 60 KN and 70 KN pre-stressing force on each bolt. All results in this case indicate that the weakest contact pressure on gasket occurs at the same position. The contact pressure decreases from 158.47 Mpa to 123.41Mpa as the pre-stressing force of bolts decreases from 70 KN to 40 KN hence it should be noted that the phenomena of efficiency of gasket sealing depends upon the magnitude of pre-stressing force of bolts under cold assembly condition.

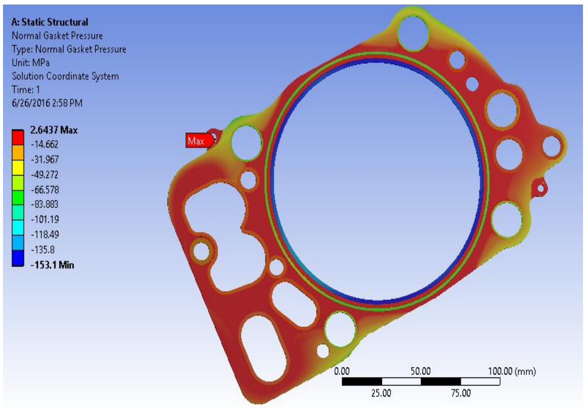

Figure 5. The distribution of the normal gasket pressures

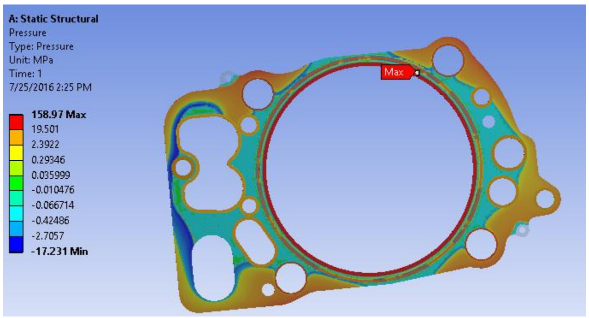

Figure 6. Gasket contact pressure

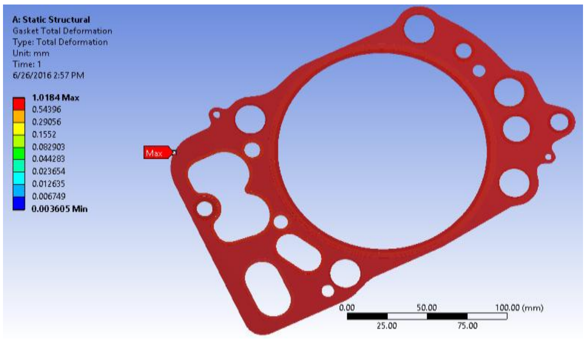

Figure 7. Gasket total deformations

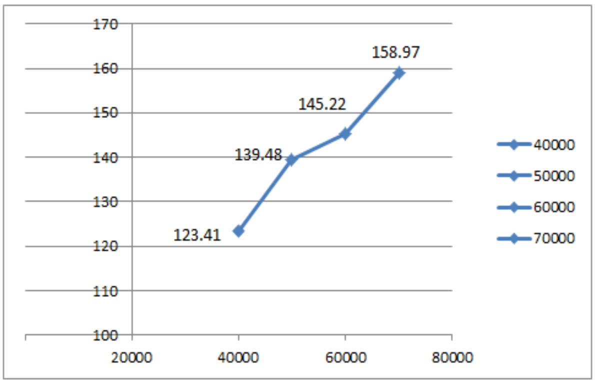

Figure 8.Weakest contact pressure on gasket at different magnitude of the pre-stressing force

5. CONCLUSIONS

In this research, the structural analysis of a cylinder head gasket under assembly condition is accomplished by means of the numerical simulation of finite element analysis. The capacity of gasket sealing mainly depends upon the pre-stressing force of bolts which are the source of external loading and gasket material behavior. Increases the pre-stressing force of bolts increases the contact pressure generated on gasket which helps to finding location of weakest contact pressure because where weakest contact pressure there is leakage. The resolution of results is based on element sizes of the gasket and deck faces; decreasing the size of the element resulted in higher resolution of results at the expense of computational cost. Therefore an effective method was proposed to enhance the sealing capacity of the gasket by finding the location of gasket pressure. At the same time, the structure of the gasket in the region of the worst sealing can be improved in the early stages of design.

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