Design and Structural Analysis of Aluminum Cylinder Head Gasket under Engine Operation

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***Abstract* - 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. In this investigation, both the distribution of the contact pressure on the gasket, and the stresses of the cylinder head at different loading conditions, such as cold assembly, hot assembly, cold start, and hot firing, are explored by numerical calculation based on the finite element method (FEM). The FEM model contains the upper part of the crankcase and the entire cylinder head. Heat transfer coefficients at the water jackets were obtained from a CFD calculation and used at the heat transfer analysis to evaluate the thermal stresses. This research also conducts the parametric analyses for the pre-stressing force of the bolts and compares the differences between cold assembly and cold start conditions. The cylinder head design shall consider its application, taking into account high combustion peak pressures to attempt the current environmental legislation and higher engine output power required by modern vehicular applications.**

***IndexTerms* - Cylinder head, Gasket, Pre-stressing of bolts, Contact pressure**

I. INTRODUCTION

Both the design and the development of the automobile engine are complicated processes. To acquire the best performance of an engine in any operating condition in harsh natural environments, many analytical tools and experimental methods are used to find the optimum parameters for engine design. The modern calculation methods, allow a precise calculation of the stresses at the parts, as well the evaluation of the fatigue strength. By this way, it is possible to determine safety factors that guarantee a sufficient reliability to avoid failures at the field and over-sizing of the components.

Due to the interface between the cylinder head and the 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. To calculate the stresses in the cylinder head it is necessary to determine the actuating loads during the critical operational cycles. The load cases that will be considered at the analyses are: The assembly loads, combustion peak pressure and the thermal stresses.

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. Montgomery provided six different kinds of approaches to describe the pre-stressing force of the bolts.

II. FUNDAMENTAL THEORY

A. Contact theory

The main focus of this research is to explore the efficiency of gasket sealing. In accordance with the distribution of contact pressure on the gasket, the location of the minimum contact pressure can be determined. The possibility of gas escaping is extremely high in the region of the weakest contact pressure. 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.

B. Thermal Stresses

Due to the analyses of the operating conditions for the engine, both the hot assembly and the hot firing are included in this research. Hence, the heat transfer analysis concerning the cylinder head must be carried out prior to the structural analysis. According to the principle of conservation of energy, the heat condition equation in the material can be expressed as

$$\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}=0$$

where T is the temperature. The temperature distribution in the material can be obtained with appropriate boundary conditions.

III. Finite Element Model

The entire cylinder head was modeled considering solid parabolic tetrahedron elements. The upper part of the crankcase was also modeled to consider the actual stiffness of the assembling. As the analysis is focused only on the component structural strength verification, the cylinder head gasket is considered presenting linear properties behavior.

Figure 1 shows the FEM model used for the stress analysis.

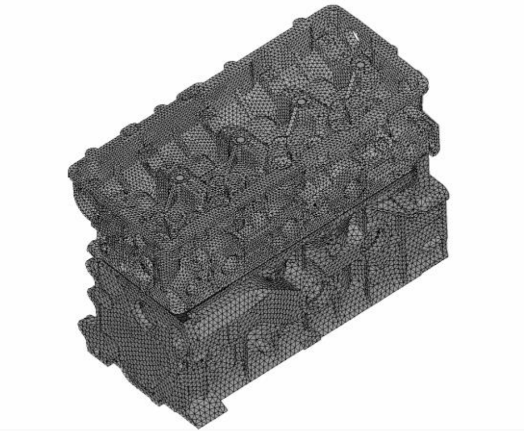

Figure 1: Finite element model.

To establish the analytical methodology of the cylinder head in respect to the structure, the line style of a gasoline engine, having 4 cylinders and 4 strokes, is adopted in this research. The Pro/E model provided by China Engine Corporation for investigating the efficiency of gasket sealing is displayed in Figure 2.

For the convenience of the observation of the distribution of contact pressure on the gasket, only 1 cylinder head is considered in this study. It must be noted that the procedure as described above has other advantages, including:

(a) Reduction of the complications of boundary conditions considered in the analytic processes,

(b) Economizing on the element counts of the finite element analysis. In other words, the computed time can be shortened substantially.

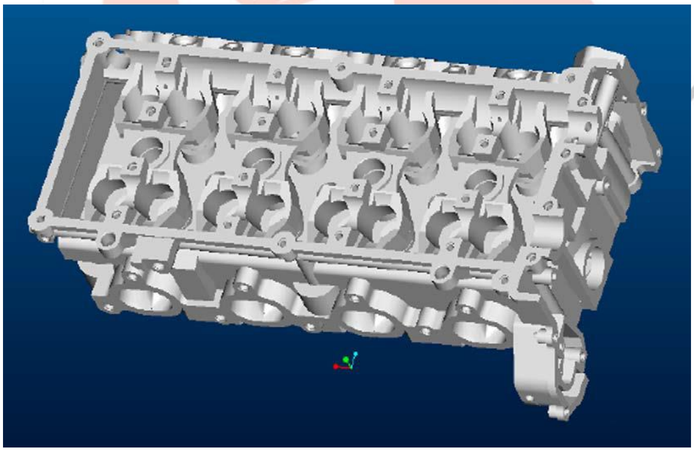

Figure 2: Top view of 2.0 L cylinder head.

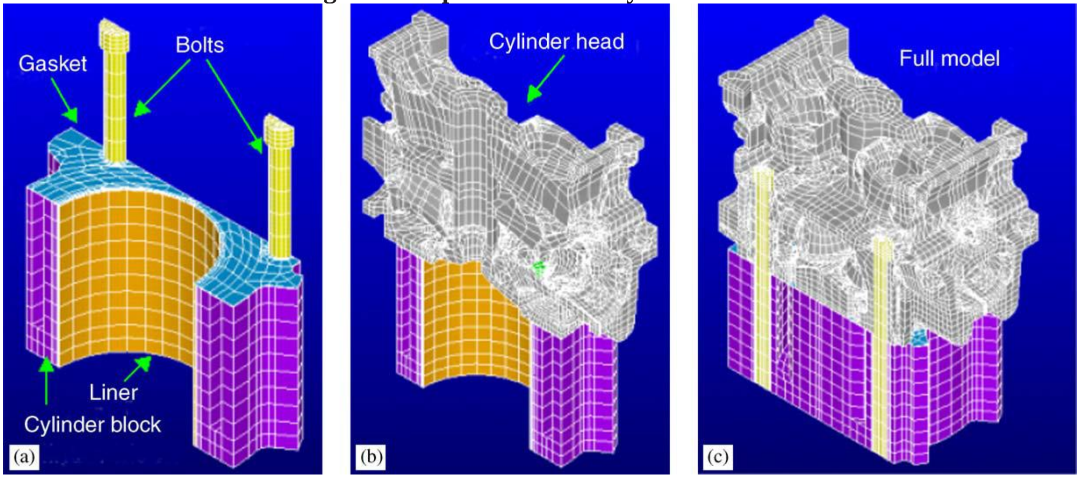

Figure 3: The FEM model for the structural analysis. (a) Other components. (b) Half of the 2nd cylinder head. (c) The full FEM model of the 2nd cylinder head.

IV. BOUNDARY CONDITIONS

RESTRAINTS – The displacements in all directions were restrained at the region of the crankcase main bearings.
PEAK CYLINDER PRESSURE – The cylinder head was analyzed at over-pressure condition. Generally, this is the most critical mechanical loading for the component.
Figure 4 presents a typical way for the combustion pressure application at the model.

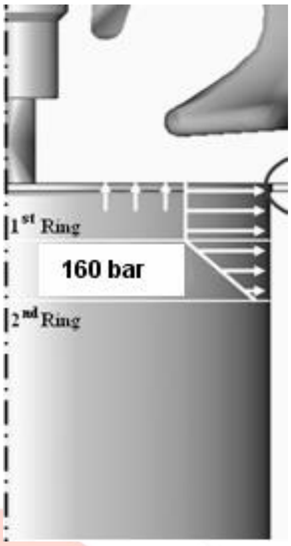

Figure 4: PCP load application.

BOLTS ASSEMBLY LOAD – The tightening force of the cylinder head bolts were introduced into the model as a preload at the beam elements. This load can be considered as being the nominal tightening force.
THERMAL LOADING – By the proposed formulation on this section, it is possible to estimate the convection coefficients and surrounding temperatures that are necessary to compute the nodal temperatures in all regions of the FEM model.

V. RESULTS AND DISCUSSIONS

In this research, the location of the weakest contact pressure on the gasket is used to investigate the efficiency of the gasket sealing. The analytical results under different operating processes of the engine will be discussed in detail.

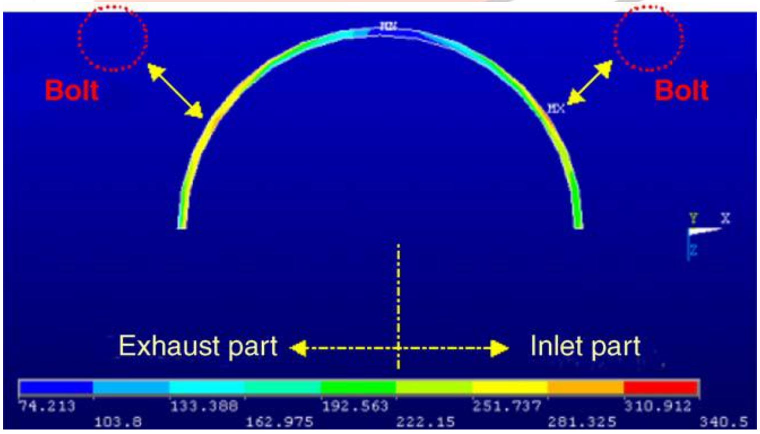

Figure 5: The distribution of the contact pressure on the gasket with raised portion

1.1 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 maximum contact pressure on the surface of the gasket at the inlet part is slightly different from the exhaust part by virtue of the structural asymmetry.

1.2 Cold Starts

The operating condition of a cold start is simulated by means of the loading composed of both the assembly loading and the gas pressure. The distribution of the contact pressure on the protruding portion of the gasket, and the position of the least effective gasket sealing are the same as with the condition of the cold assembly.

1.3 Hot Assembly

The loadings made up by the pre-stressing force of the bolt and the thermal loading are used to simulate the state of thermal balance reached by the burst of gas being fired repeatedly. It should be noted that the thermal loading comes from the temperature distribution of the nodal result in the heat transfer analysis.

The analytical result shows that the distribution of temperature in the internal structure of the cylinder head has an influence on the distribution of the contact pressure on the gasket. The original position of the weakest contact pressure during cold assembly and cold starts becomes the maximum point as a result of the effect of thermal stress.

1.4 Hot Firing

In the hot assembly, the operating process of hot firing is to simulate the moment of the spark plug firing. Therefore, in this case gas pressure is added into the applied loadings. The distribution of the contact pressure on the surface of the gasket is almost the same as the condition of the hot assembly except for the fact that the contact pressure is reduced. However, the sealing capacity of the gasket falls within the safety factor of the design criteria.

VI. Conclusion

Cyclic load without considering the thermal effects could be also evaluated, since such loads actually occur during the engine's life. However, the values obtained for that analysis are far below the ones evaluated for "hot" engine. So, in the design criteria are taken into account only the cyclic load with thermal stresses, as defined earlier in this paper. The location of the weakest contact pressure on the raised portion of the gasket can be transferred as a result of the effect of thermal stress/strain. In this investigation the analytical results indicate that the thermal stresses provide a positive support for the efficiency of gasket sealing. 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. 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. This is especially true for the raised portion.

VII. Acknowledgement

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