

## Simulation on microscopic deformation behavior of engine gasket

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**Abstract.** Engine gasket is the thin steel plate with coatings. Its compressive deformation affects the height of engine assembly, which changes combustion chamber's volume and then influences engine performance. In this paper, the assembly simulation of head, block and gasket was studied. Then a further simulation takes the thin coatings on steel sheet into consideration. In the second simulation, gasket's partial micro-model in micron-scale meshes was established and deformation of coatings was analysed. The combination of deformations explores the cause of fluctuations of gasket's tightened thickness and obtains more precise numerical results of tightened thickness at different positions. Moreover, a lead pellet test was carried out to verify the results of tightened thickness calculation.

### 1 Introduction

As the modern automobile engines keep on pursuing higher power, economy and emission performance, the requirements of manufacture precision and reliability for each part are increasing. The cylinder gasket is the most important component in sealing system which directly affects the performance.

There are already some researches on the relationship between mechanical structures of gasket and its sealing ability which are the focus of engine sealing study.

Hettich et al. studied the characteristic of gasket under dynamic shear stress, and established corresponding constitutive relations [1]. Micheely and Kämpkes studied the overall performance of the connection in consideration of asbestos rubber gasket sealing performance, and discussed the effect of the gasket's microstructure to leakage characteristics [2]. Since 1990, nonlinear finite element simulation started to be used to research the stress distribution and deformation of the gaskets.

Ghasemi studied the deformation of the multilayer metal gasket by finite element simulation and discussed all aspects of IC engine sealing analysis [3]. S.-S. CHO carried on the parameter study of the beads on the gasket to analyze the effect of structure features to sealing ability by FEA methods [4]. H. Zhang studied the sealing pressure of the gasket's features by simulation on ANSYS. His colleague, M. Xi, studied the relationship between the parameters of beads and the sealing pressure. Although the thickness of coatings was not considered in their simulations, the experiments of Fuji pressure-sensitive film which can show different colors under different pressure confirmed that the contact stress results of simulation are precise and acceptable [5].

These researches paid more attention to the macrostructure design of steel sheets of gasket and analyzing the relationship between structures and the sealing ability. But during the assembly of engine, besides the deformation of steel sheets of gasket, there will be the hyperelastic deformation of coatings as well.

Although the thickness of coatings is small (0.01mm-0.015mm for each layer), the hyperelastic deformation will result in the fluctuation of tightened thickness of gasket at different positions and then affect compression ratio. Till now, little study has been done about the calculation of these microscopic deformations and the relationship between this deformation and fluctuation of tightened thickness.

In this research, the assembling simulation of head, block and gasket of a certain engine is studied. Based on the stress results of assembling simulation, a further microscopic simulation was studied to analyze the deformation behavior of coatings and sheets of the gasket.

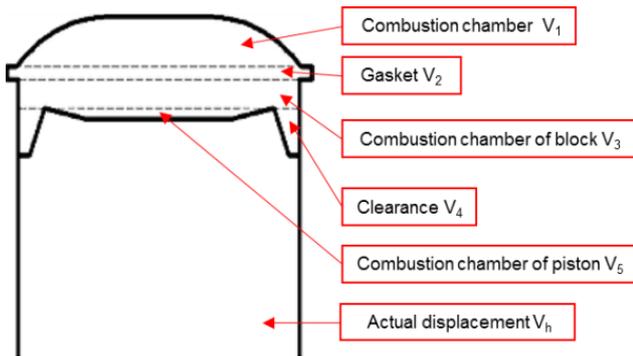
The influence of both deformation of metal gasket and the hyperelastic deformation of micron-scale coatings to the tightened thickness was investigated. A lead pellet experiment was designed to verify the simulation results. Further, several sensitive components for tightened thickness are found which could be helpful for the quality control in the engine assembly.

### 2 Effect of gasket's thickness deviation to compression ratio

As the liaison between cylinder head and block, gasket is also the component of the combustion chamber. In compression ratio calculation its thickness and diameter should be concerned. The fluctuation of thickness will

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affect combustion chamber's volume and further affect compression ratio.



**Figure 1.** Volumetric components of combustion chamber

The volume of combustion chamber can be divided into several parts which are shown in Figure 1.  $V_1 \sim V_5$  present the volume of combustion chamber of cylinder head, combustion chamber of gasket, combustion chamber of block, clearance and combustion chamber of piston respectively.  $V_h$  means the volume of cylinder displacement.

Compression Ratio of engine is a value that represents the ratio of the volume of its combustion chamber from its largest capacity to its smallest capacity. It could be presented as:

$$\varepsilon = 1 + \frac{v_h}{v_1 + v_2 + v_3 + v_4 + v_5} \quad (1)$$

The volume component of gasket is:

$$V_2 = \pi \frac{d_n^2 + h_n}{4} \quad (2)$$

$d_n$ : Diameter of the cylinder

$h_n$ : tightened thickness

Now supposing that the other components (exclude the gasket height parameters) are constants, compression ratio can be expressed as:

$$\varepsilon = f(h_n) \quad (3)$$

So the variation of compression ratio can be expressed as equation (4):

$$\Delta\varepsilon = f'(h_n)\Delta h_n \quad (4)$$

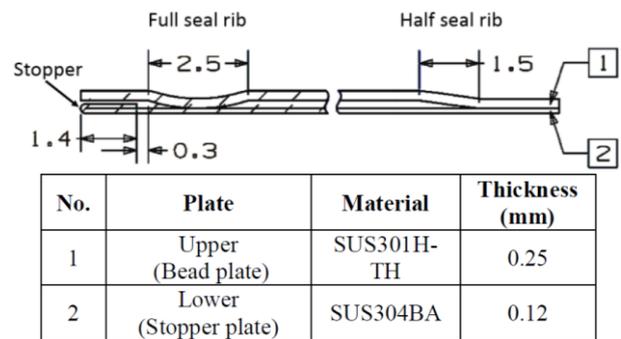
If the tolerance of tightened thickness  $h_n$  is  $\pm 0.05\text{mm}$ , it will result in 1.051% variation of compression ratio. So controlling the deviation of tightened thickness  $\Delta h_n$  will be significant for the stability of compression ratio.

### 3 Research strategy

#### 3.1 Gasket Geometric characteristics

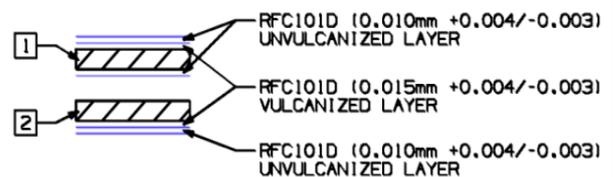
Gaskets with structure of multilayer steel plate have good mechanical properties on capacity of compression and resilience.

In this research, the gasket consists of two main plates. The upper plate (No.1 in Figure 2) contains the full seal ribs (bead) around cylinders and half seal ribs (bead) beside the edges of gaskets. The lower plate (No.2 in Figure 2) contains flangings (stopper) around cylinders. The structure of gasket is shown in Figure 2. The bead plate is about twice as thick as the stopper plate.



**Figure 2.** Structure of gasket

To achieve a good seal, RFC101D coating layers are attached on the surfaces of sheets. As shown in Figure 3, there are both unvulcanized and vulcanized layers on the outer surfaces of bead plate and stopper plate while it just needs one vulcanized layer between two plates. Coatings make it capable to resist high temperature and corrosion. Coatings' thickness increases with the roughness of machined surfaces of head and block. The coatings are very thin compared to steel sheets. But the hyperelastic deformation will occur in the engine assembly process, and which results the fluctuation of tightened thickness on the micron scale. So, coatings' deformation can never be ignored in tightened thickness analysis.



**Figure 3.** Coatings on the steel sheets

#### 3.2 Research strategy analysis

The aim of the research is to calculate the tightened thickness by FEA method and then analyse the fluctuation of thickness. The most direct method is to create all the layers in the model of assembly (including the steel sheets, coatings and other parts of engine) and use this integrated model to calculate tightened thickness. But the problem is that thickness of coatings is too thin to create in the same size model with steel sheets and other parts of engine. Actually, if the tiny meshes of coatings are created, there will be too many meshes in the simulation along with the complex contact and friction conditions which will result in non-convergence and long computing time.

The two-step solution is proposed in this research. First is the macroscopic simulation of engine assembly without

a consideration of the coatings. In this situation, result of thickness is none of significance (because coatings are not contained in model, the thickness results are untruthfulness) while the results of contact stress is reasonable (because the contact area which transmits specific bolt loads does not change with or without coatings).

The second is to establish a microscopic simulation for a partial model which is very small and considers coatings.

If the contact stress can be extracted in the first simulation and used as the input to the microscopic one, the tightened thickness can be calculated.

So, the strategy of this research consists of these two steps:

1. Use the macroscopic simulation of engine assembly to calculate the contact stress distribution on the gasket (without a consideration of the coatings).
2. Use the varying contact stress as the input, create a partial tiny model (including coatings) to calculate the tightened thickness and analyze the fluctuation of thickness.

## 4 Simulation on deformation of engine assembly

In this section, the macroscopic simulation on deformation of macroscopic geometrical features is carried out which aims to obtain the contact stress on the gasket.

### 4.1 Assumptions of simulation

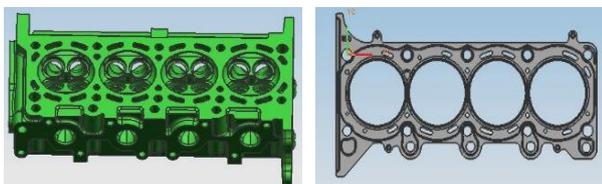
To realize the deformation behaviour of gasket when the assembly is tightened, a holistic analysis should be carried on.

In the simulation, three assumptions are made.

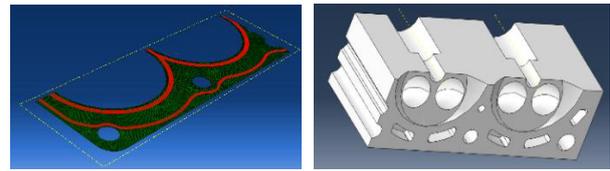
1. Quarter of the model is used to replace the whole part.
2. Cylinder block and the stainless stopper plate of gasket are treated as the rigid body.
3. As the initial simulation, coating thickness is only 25µm. Compared to the engine height 70mm, this value can be ignored.

### 4.2 Model simplification and the assembly

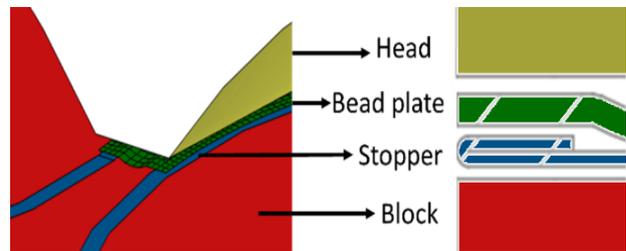
The simplification of the models retains main geometric features, including the combustion chamber, inlet, outlet and water channels of cylinder head, beads and stoppers of gasket. Figure 4 presents models before and after simplification and the assembly of simulation.



(a) Original models of cylinder head and gasket



(b) Simplified quarter models of cylinder head and gasket



(c) The assembly of model and its section view

**Figure 4.** Parts before and after simplification

The simplified cylinder head has a height 70mm, length 170mm and width 60mm. Meanwhile, the thickness of bead plate is 0.25mm.

### 4.3 Loads

The engine in the research uses torque-angle tightening process with parameters  $20 \pm 2\text{Nm}$  and  $80 \pm 2^\circ$ .

During the assemblage of cylinder head, the torque data obtained by torque wrench are about 60Nm. By the equation (6), the torque can be turned into the down force from bolts to cylinder head.

$$F = \frac{T}{K \times D} \quad (6)$$

$F$ : bolt tightening force

$T$ : Torque of bolt

$K$ : torque coefficient

$D$ : nominal diameter of bolts

The equivalent down force calculated is 30KN per bolts. This loads were applied onto three bolt holes of the quarter model by distribution force loads of Abaqus.

### 4.4 Material Properties

Material properties of each parts are shown in Table 1. Besides, other parts in this simulation are viewed as rigid bodies.

The steel plates of gasket in this paper is made of 0Cr18Ni9 stainless steel by stamping while the cylinder head is made of AC4B-T6 aluminium alloy by casting. The mechanical properties of these two materials can be found from Table 1.

**Table 1.** Material properties of parts

Part	Gasket	Head
<b>Material</b>	0Cr18Ni9 stainless steel	AC4B-T6 aluminium alloy
<b>Young modulus</b>	210GPa	74GPa
<b>Poisson's ratio</b>	0.3	0.33
<b>Density</b>	7.8g /mm <sup>3</sup>	2.68g /mm <sup>3</sup>

### 4.5 Element Meshing

Considering the large difference of the dimensions between length and thickness, the shell elements are used to present gasket in the simulation. C3D8R elements are used to present the structure of cylinder head. Because the cylinder block are simplified as a rigid, it doesn't need to apply meshes on it.

Approximate sizes and quantity of the models are shown in Table 2. In this simulation, the global size of gaskets (quarter of the model) is 1mm and quantity is more than 13000. The mesh density like this aims to guarantee that every bead which will deform during the simulation could consist of the meshes small enough. If the mesh density is smaller, the bead of the model will be consist of only one or two line of meshes which is not able to present the deformation. Considering the cylinder head will not have a large deformation and efficiency of this simulation, the globe size of meshes for cylinder head is chosen as 3mm.

**Table 2.** Meshes of parts

Part	Gasket	Head
Type of meshes	Shell S4	Solid C3D8R
Approximate global size (mm)	1	3
Quantity	13701	14582

### 4.6 Boundary Conditions

The boundary condition of contact between gasket and other parts is the most complex process in simulation. For the contact pairs, friction formulation is penalty in the tangential direction. Meanwhile, the normal behavior is Hard Contact. The sliding formulation is small sliding [5]. Because stopper hardly moves in the tangential direction, it can be considered to bear only normal force and be tied to block [6]. With the meshes extremely small, the surfaces of gasket are chosen as the slave face in contact pair [7].

**Table 3.** Definition of contact

Contact pairs	Type of contact	Friction coefficient
Head to bead plate	Surface to surface standard	0.15
Bead plate to stopper	Surface to surface standard	0.15
Bead plate to block	Surface to surface standard	0.15
Stopper to Block	Tie	—

### 4.7 Analysis Steps

If the cylinder head is directly put onto gasket and applied bolt force, the complex surface topography of gasket will result to no convergence. To solve this problem, three analysis steps are created.

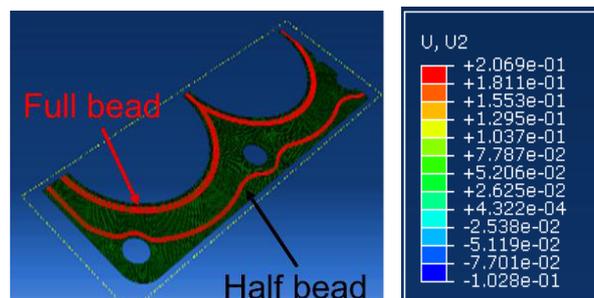
In the initial step, cylinder head and gasket are separated to a distance of 0.05mm.

In the first step, contacts are defined. Cylinder head moves down 0.1mm slowly and makes parts into contact smooth and stable.

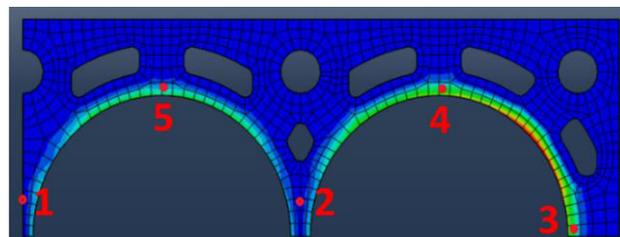
In the second step, down forces of bolts are applied onto the bolt hole.

### 4.8 Results of simulation

In Figure 5, the area between the full bead and half bead shows the largest displacement of the normal direction, which is about 0.2mm. Nevertheless, in the distribution of the contact stress, the force on this area is zero. The result presents that although the bead plate deforms visibly, it does not completely touch the upper surface of the cylinder block. Moreover, Figure 6 shows that the largest contact stress appears on inner cycles close to cylinder (To be exact, the max appears on Arc3-4). According to these results and the structure of the assembly, stoppers and full seal beads bear the majority of the down force and transmit it to cylinder block.



**Figure 5.** Result of displacement on normal direction



**Figure 6.** Result of contact stress on the lower surface of cylinder head

In my model, 5 meshes on the cylinder head are chosen to introduce the surface pressure of these meshes as the input of the simulation microscopic. The 5 points in Figure 6 present the position of the chosen meshes.

By reading the pressure data of 4 nodes of each mesh, the average pressure of the strip close to the cylinder can be calculated according the simulation result.

**Table 4.** Pressure results at different positions

Position	Description	Average Pressure (MPa)
1	Between cylinders	64.21
2	Between cylinders	62.16
3	On the stopper	158.12
4	On the stopper	159.78
5	On the stopper	104.54

The pressure data of the 5 positions are shown in Table 4. Three steps can be found in Table 4. The pressure at position 1 and 2 are about 60MPa while position 4 and 5 have the pressure of 160MPa. And pressure of position 5 is about 105MPa.

These data are used as the down force input in the microscopic Simulation.

#### 4.9 Shortage of the simulation on deformation of engine assembly

The simulation of this section doesn't consider thin coating layers. So although the data of pressure at 5 positions are quite different, there is not an obvious difference about the tightened thickness in the macroscopic simulation (compression of stainless sheets under 60MPa is 0.14µm while the compression under 160MPa is 0.4µm).

So there is no significance to use the simulation in this section to analyse the change of thickness. That's why it needs to carry out microscopic simulation of the model with coatings to calculate the tightened thickness.

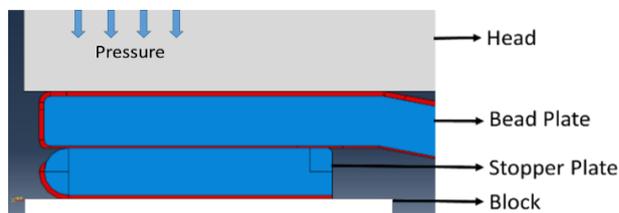
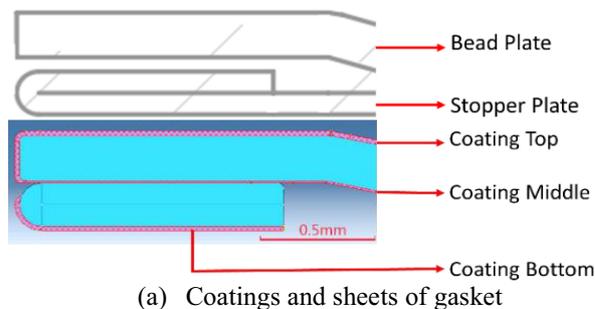
### 5 Simulation on coatings' microscopic deformation

The macroscopic simulation in section 3 does not contain coatings on the sheet for their extremely tiny scales. But actually, because the material of coatings, fluororubber, is very soft compared to the metal sheet, coatings undertake the vast majority of deformation. So it is necessary to analyse the microscopic deformation behaviour of coatings in a partial model.

#### 5.1 Model of microscopic simulation

Figure 7 shows the section view of the gasket itself and the assembly including gasket, cylinder head and block (Another clearer schematic in Figure 4(c) can help to present the structure of this tiny region). As shown in this figure, three coatings are created on steel plates. The pressure is applied on the cylinder head and then transmitted to gasket. Block in this simulation is considered as a rigid which is fixed as a support.

Because of the rotational symmetry of the cylinder, the simplified axisymmetric model in Figure 7 can represent almost all the features of the assembly. The model takes coatings into consideration and therefore it can be used to calculate the tightened thickness.



(b) The assembly of model in simulation

**Figure 7.** Section view of gasket and axisymmetric model

Actually, this structure (including head, bead plate, stopper and block) is same at each position along the inner edge of the cylinder. Nevertheless, because of the specific positions of the tightening bolts, data of pressure along the edge are quite different (as shown in Table 4). If the different pressures are used as the input to the model in Figure 7, the fluctuation of tightened thickness can be expressed numerically.

#### 5.2 Materials

The coatings are made from RFC101D fluororubber. In the simulation, the property of the fluororubber can be expressed by Mooney-Rivlin model. The strain energy density function for an incompressible Mooney-Rivlin material is as:

$$U = C_{10}(\bar{I}_1 - 3) + C_{01}(\bar{I}_2 - 3) + \frac{1}{D}(J^{el} - 1)^2$$

In the equation, where  $C_{10}$  and  $C_{01}$  are empirically determined material constants, and  $I_1$  and  $I_2$  are the first and the second invariant of the unimodular component of the left Cauchy-Green deformation tensor. And  $D$  is a material constant related to the volumetric response. In the simulation, hardness of fluororubber is 70.  $C_{10}$  and  $C_{01}$  are assigned as 0.4276 and 0.1007.  $D$  is about 0.03. In many research of simulation of rubber,  $D$  can be considered as 0 while the rubber is considered as the completely incompressible material. But in the ABAQUS/explicit product, a completely incompressible material is not allowed. So the  $D$  is assigned as a tiny value.

Materials of gaskets and cylinder head are same as the macroscopic simulation.

#### 5.3 Meshes

Meshes used in this section have several properties. In the abaqus/explicit, hyperelastic material can be only expressed by hybrid type elements. Moreover, to use the ALE adaptive method, the reduced integrated type

elements should be used. So, CAX4R elements (4-node bilinear axisymmetric quadrilateral, reduced integration, hourglass control) are used for the fluororubber material.

Arbitrary Lagrangian Eulerian (ALE) adaptive meshing used in the simulation can maintain a high-quality mesh throughout an analysis, even when large deformations.

### 5.4 Loads

Table 4 in chapter 3.8 shows the input of the simulation in this section. These inputs are applied as the pressure on the simplified cylinder head which will transmit the pressure to the gasket.

### 5.5 Results of simulation under different pressures

Figure 8 presents the extrusion of the coatings. The coatings can hardly be compressed because of the high Poisson ratio of material. But the material will deform toward the gap and because of the extrusion of material, thickness of coatings will reduce. The phenomenon is shown in Figure 8.

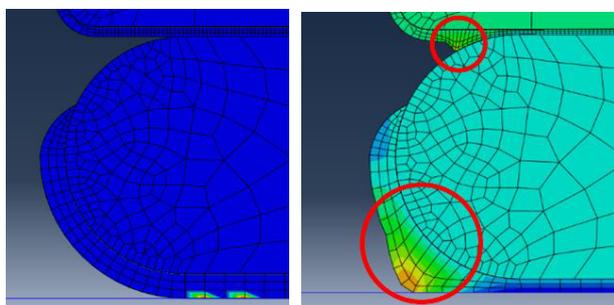


Figure 8. Examples for deformation of coatings

The thickness results of simulation are obtained by measure the distance between the lower surface of head and upper surface of block.

After measuring the displacement of the nodes on lower surface of cylinder head, groups of data under a specific pressure can be obtained. Table 6 shows the average thickness of each group. These results of thickness will be compared to experiments in next chapter.

Table 5. Average thickness under different pressures

Position	Pressure (MPa)	Average thickness (mm)
1	64.21	0.5332
2	62.16	0.5338
3	158.12	0.5148
4	159.78	0.5146
5	104.54	0.5223

## 6 Experiment comparison

### 6.1 Material and Boundary conditions

This paper uses the lead pellet test which is commonly used industrially to measure the true value of tightened thickness.

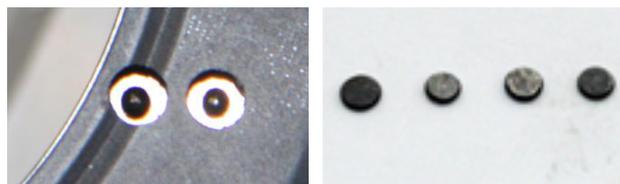


Figure 9. Lead pellets in holes on gasket and deformed pellets

After clean up the surfaces of head and block, lead pellets with a diameter of about 1.5mm are placed in holes which are 4mm in diameter (as shown in Figure 9 (left)). The holes are processed on the gasket by wire-electrode cutting.

The cylinder head is installed and bolts are tightened with the standard torque and angle. After standing for 5 minutes, the cylinder head is removed and the deformed pellets are collected to measure the thickness by micrometer caliper.

Figure 9 (right) shows the deformed pellets, the pellets are turned into discs with smooth surfaces. Lead is one of the softer metals which could easily deformer and will not spring back after removing the loads. So a lead pellet in the slit will express the tightened thickness at its position.

### 6.2 Positions measured

The experiment chose 2 groups of positions for detection which is shown in Figure 10.

Group A is placed at the edge of cylinder. Group B is placed at the corners between two cylinders.

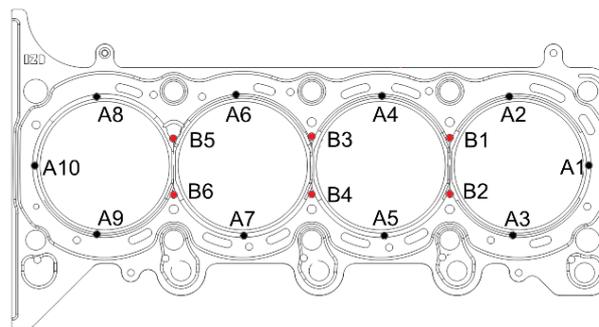


Figure 10. Positions to place the lead pellets

### 6.3 Comparison of results from simulation and experiment

With 6 gaskets of same type, 6 experiments are carried out. The 6 groups of data are averaged and the tightened thickness of each position can be obtained.

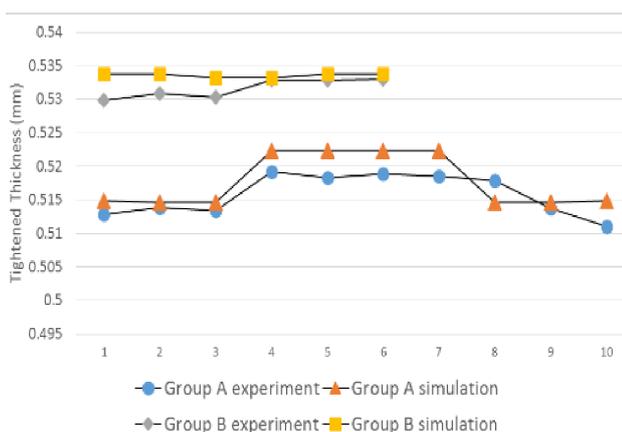
Moreover, the simulation obtains 5 data of thickness. According to the symmetry of cylinder head and gasket. The quarter model in Figure 4 can be generalized so that these 5 points can describe the thickness distribution simplistically.

The results of simulation and experiment have good agreement in figure 11 and Table 7 which verify the validity of the simulation method in this paper.

**Table 6.** Comparison of the thickness measured and simulated

Position Group A	Thickness (measured) (mm)	Thickness (simulated) (mm)	Relative error (%)
A1	0.5128	0.5148	0.3835
A2	0.5138	0.5146	0.1492
A3	0.5133	0.5146	0.2468
A4	0.5192	0.5223	0.6035
A5	0.5183	0.5223	0.7653
A6	0.5188	0.5223	0.6682
A7	0.5185	0.5223	0.7329
A8	0.5178	0.5146	0.6244
A9	0.5137	0.5146	0.1817
A10	0.5110	0.5148	0.7436

Position Group B	Thickness (measured) (mm)	Thickness (simulated) (mm)	Relative error (%)
B1	0.5298	0.5338	0.7487
B2	0.5308	0.5338	0.5589
B3	0.5303	0.5332	0.5405
B4	0.5328	0.5332	0.0688
B5	0.5328	0.5338	0.1814
B6	0.5330	0.5338	0.1501



**Figure 11.** Comparison between simulation and experiment

The data from the lead pellets test and simulation can provide two main results:

1. From Table 7, an obvious difference between group A and group B can be found. Tightened thickness data of group B are all above 0.530mm. Meanwhile, data of group A are all smaller than 0.520mm.
2. For group A, positions on the middle region (A4~A7) of gasket have a larger tightened thickness than the positions of two sides (A1~A3, A8~A10). The reason is the tiny deformation of cylinder head.

Both the results of experiments and simulation show the tightened thickness distribution when the cylinder head is installed. Under the high load of bolts, the head deforms to an arch. The middle region has a larger thickness than side region.

## 7 Conclusion

1. In this research, a method to study tiny deformation of gasket is established. Deformation of gasket compressed by cylinder head and block was divided into two steps.

First step focuses on the deformation of macroscopic geometrical structure including beads and stoppers of gasket. But because the simulation does not consider coatings which occupy large share of compressive deformation, the data of tightened thickness are not reasonable. So, the microscopic simulation of a tiny piece model near the edge of cylinder is carried out which focuses on the pure compression of the sheet and soft coatings.

These two simulations with quite different scales are linked by the contact stress. The contact stress results are taken from the first simulation and used as the input of the second microscopic simulation.

The combination of these two steps of simulation embodies almost all the deformation behaviours near the contact surface during the assembly of engine completely from which a conclusion is obtained that the fluctuation of tightened thickness mainly comes from the deformation of coatings under different contact pressure.

The lead pellet test compares the result of simulations and verifies the feasibility of the method.

2. The aim of the research is to analyse the fluctuation of tightened thickness. The results of simulations and experiments present the diversity of tightened thickness at different positions. The two side cylinders are compressed tighter than two middle cylinders. The diversity mainly comes from the structure of cylinder head and the bolt load. To avoid the difference of thickness, an effective method is to reduce the torque of bolts located at four corners. But it will result in the leakage. If it is possible to reduce the fluctuation of tightened thickness by this adjustment will be included in the next step of research.

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