論文 **Original Paper**

Dynamic Characteristics of Head Bolt Load and Relative Displacement between Cylinder Head and Block by Abruptly Change of Cooling Water

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Abstract: Experiments on a small, one-cylinder, high-speed diesel engine were performed by changing the temperature of cooling water and also by changing the material and the configuration of the cylinder head gaskets. Three kinds of cylinder head gaskets were made. The temperatures at several points of the cylinder head gasket and its peripheral region, the relative displacement between cylinder head and cylinder block, the loads of the cylinder head bolts, the indicator diagram, the pressure of gasket surface and the combustion gas leakage were measured by the abrupt change of the cooling water temperature. The sealing characteristics in the transient state and the steady state of the cooling water temperature were investigated from an experimental standpoint. The effect of the temperature differences between the cylinder head, cylinder block and head bolts on the loads of the head bolts and the relative displacement between the cylinder head and cylinder block were observed for the test gaskets.

Keywords: Internal Combustion Engine, Diesel Engine, Automotive, Engine Component, Parts, Experiment, Cylinder Head Gasket, Seal, Dynamic Characteristics

1. Introduction

The cylinder head and the cylinder block of high-speed diesel engines for automobiles have lost their rigidity because of weight reduction, utilizing aluminum material and thinner wall thickness[1]-[3]. Moreover, both higher output engines and highly turbo charged engines caused gas leakage of the cylinder head gasket (hereafter called "gasket") through unbalanced sealing conditions[4]-[11]. However, the gasket should not leak and should have the durability under high output and highly turbo charged conditions[12]-[29]. This experimental study shows the measurement results of (1) the gasket temperature, (2) the cylinder head bolt force, (3) the combustion pressure and (4) the relative displacement between the cylinder head and the cylinder block, under the forced heating and the forced cooling conditions by exchanging cooling water abruptly (hereafter called "heating and cooling temperature cycle") and also under the constant engine operating conditions. Moreover, the gasket contact pressure was measured, the combustion gas leakage measured[30]-[32]. The investigation on the gas sealing characteristics in the transient and steady states is the main purpose of this experimental study.

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2. Outline of Tested Gaskets

Cross sectional views of the three tested gaskets are shown in **Table 1**. The gasket structures, which are composed of the body, the combustion sealing part, the coolant and the sealing part, are described for each gasket in the following. **Figure 1** depicts the shape and the dimension of the gasket[1]-[3].

2.1 Gasket Body Structure

Three kinds of gaskets ((1) soft facing gasket with perforated core, (2) soft facing gasket with flat core and (3) metal gasket) were tested[1]-[3].

(1) Soft facing gasket with perforated core

The gasket body (the base sheet) is composed of soft gasket sheet facing in which fiber, filler and rubber binder are mixed and compressed together, on both sides of a perforated steel core. It has high compressibility and high adaptability.

(2) Soft facing gasket with flat core

The gasket body utilizes a flat steel core instead of the perforated steel core. The soft gasket facing is bonded on both sides of the flat steel core.

(3) Metal gasket

The gasket body is composed of five layers. The first, the third and the fifth layers are made of stainless steel

Table 1 Cross Section Construction of Test Cylinder Head Gasket

Name of Gasket	Base Sheet	Combustion Gas Seal	Water or Lubricating oil Seal
Soft Facing Gasket with Perforated Core	Soft Facing Perforated Core	Stainless Armor Wire Ring	
Soft Facing Gasket with Flat Core	Soft Facing Flat Core	Stainless Armor Wire Ring	Rubber Ring
Metal Gasket	Stainless Steel	Stainless Armor Wire Ring	Rubber Ring

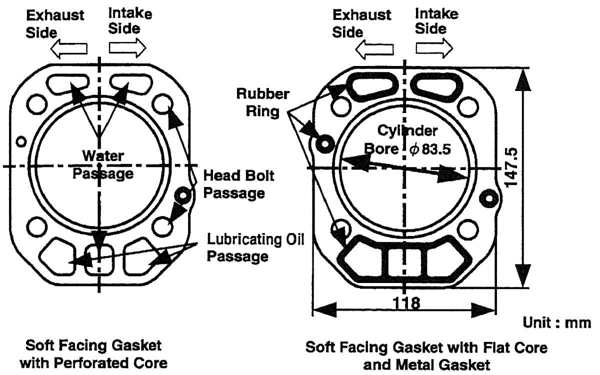

Fig. 1 Shape and Dimensions of Test Cylinder Head Gaskets

plates coated with FKM rubber on both sides of each plate. The second and the fourth layers are plain stainless steel plates. Each mating surface, including cylinder head and cylinder block, is isolated from metal contact.

2.2 Combustion Gas Sealing Structure

The combustion gas sealing area of each gasket is made of a steel wire ring which is folded over on the gasket body by the stainless steel armor. High contact pressure is generated on the part of the wire for gas sealing[1]-[3].

2.3 Coolant and Lubricating Oil Sealing Structures

The body itself of the soft facing gasket with perforated core seals coolant and lubricating oil. The soft facing gasket with flat core and metal gasket have rubber rings inserted into the gasket body for coolant and lubricating oil sealing[1]-[3].

3. Experimental Equipment and its Procedure

A single cylinder, direct injection high-speed diesel engine was prepared for this experiment. Maximum output of the engine is 5.58 kW/2600 r/min. The engine was operated under (1) Start-up, (2) Warm-up (800 r/min), (3) 1/2 load (1400 r/min) and (4) Shift to heating and cooling temperature cycle on keeping the engine at 1/2 load (1400 r/min). In the heating and cooling temperature cycle, the

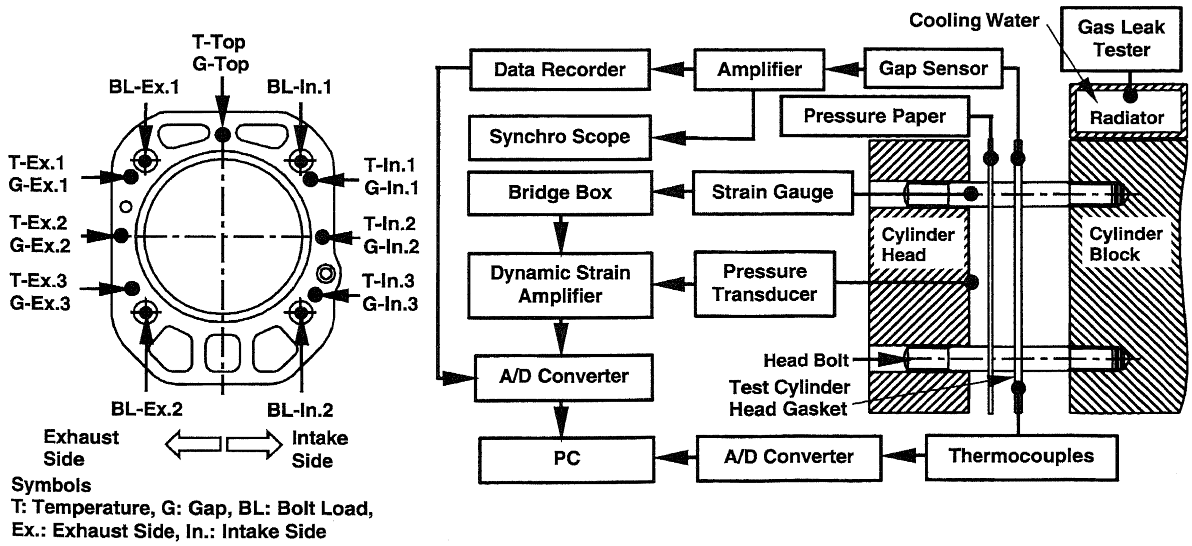

Fig. 2 Measuring Points and a Schematic Diagram of Measuring System

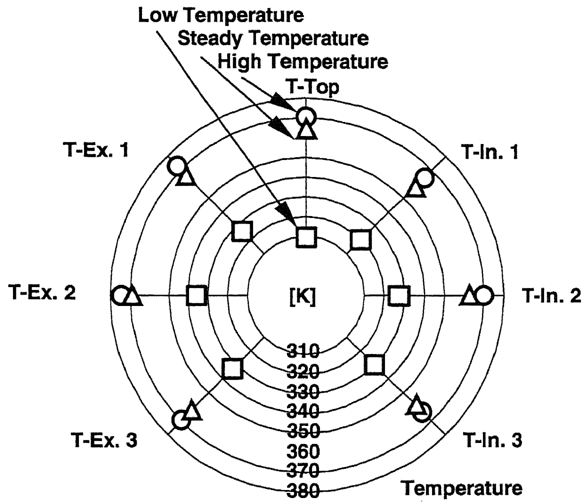

Fig. 3 Temperature Distribution of Metal Gasket

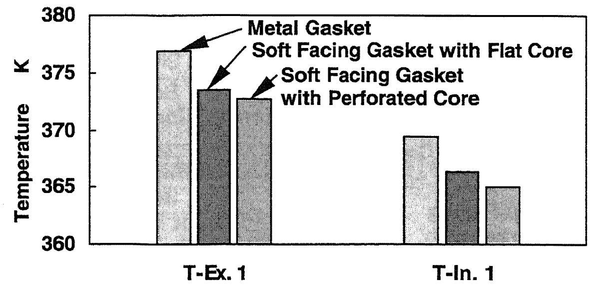

Fig. 4 Temperature of Test Cylinder Head Gasket

coolant was replaced by the new coolant whose temperature was 373 K for rapid heating (hereafter called "High-Temp"). After the engine coolant temperature returned to the stationary state (hereafter called "Const-Temp"), the coolant was abruptly replaced by the new coolant whose temperature was 273 K for rapid cooling (hereafter called "Low-Temp")[1]-[3],[22]-[24]. Under this temperature exchange, the coolant temperature was in three states, namely, High-Temp, Const-Temp and Low-Temp. Various measurements were repeated in the transient state and in the steady state. **Figure 2** shows the schematic diagram of measuring points and system. The ambient temperatures of the gaskets were measured by K type thermocouple. The loads of the cylinder head bolts on the intake and the exhaust sides were measured by the strain gauges. The relative displacements between the cylinder head and the cylinder block were measured by gap sensors which were installed on the intake and exhaust sides of the gasket body. The static contact pressures were measured by pressure sensitive papers which were installed in both sides of the gasket body, which were located between the cylinder head and the cylinder block. Gas leakage, on the supposition that some of the combustion gas contents will dissolve in the coolant which circulates in the cylinder head and the cylinder block through the water passages, was checked using the coolant in the radiator by the change of color of the coolant against a testing liquid. Moreover, the gas leakage was visually evaluated from the attached carbon on the gasket surface. The combustion pressure was measured by the pressure indicator.

4. Experimental Results and Examinations

Various measurement results in the heating and the cooling temperature cycles are indicated in the following. The coolant temperatures in the High-Temp state, the Const-Temp state and the Low-Temp state are observed and studied.

4.1 Temperature Measurement Results

The ambient temperatures of the metal gasket are indicated in **Figure 3** as an example of the temperature measurement results in the heating and cooling temperature cycles of the steady temperature state on the engine operating conditions. The experimental results of the temperatures indicate each engine coolant temperature in the High-Temp, the Const-Temp and the Low-Temp state. It can be observed that the gasket temperature at the exhaust side is higher than that at the intake side in the Const-Temp state of the engine coolant temperature. This result can be considered as the influence of the high exhaust gas temperature. The gasket temperature at the High-Temp state is not so different from that at the Const-Temp state. It can be considered that the engine coolant temperatures in both states is not so different. It is obvious that the gasket temperature was decreased rapidly by the Low-Temp state of the engine coolant temperature. As compared with the gasket temperature at the High-Temp state of the engine coolant temperature, much temperature difference can be observed at the measurement points; namely T–In. 1 in the intake side, T–Ex. 1 in the exhaust side and T–Top in the upper area. The gasket has the coolant passages in the upper part, so the high coolant temperature has much effect on these temperature differences. It can also be considered that the cylinder head bolts, which are located in the upper side of the gasket, are influenced considerably and that their temperatures increase rapidly. The changes of the bolt load, the gasket contact pressure and the relative displacement between the cylinder head and the cylinder block occur directly as a necessary consequence. **Figure 4** indicates the comparison of the gasket temperature difference at the intake side with that at the exhaust side in the steady state. The temperature of metal gasket is higher than other soft type gaskets at both the intake and the exhaust sides. This result can be considered as the influence of the different materials and structures of each gasket. Moreover, the soft facing gasket with perforated core was found to have the highest heat insulating property. In order to investigate the change of the temperature of the gasket's peripheral-region. **Figure 5** shows the temperature change of the cylinder head, the cylinder block and the cylinder head bolt by exchanging the cooling water for the fresh cool one. The temperature

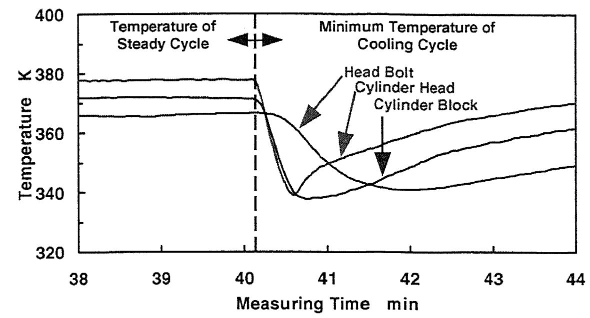

Fig. 5 Temperature Change of Cylinder Head, Cylinder Block and Head Bolt

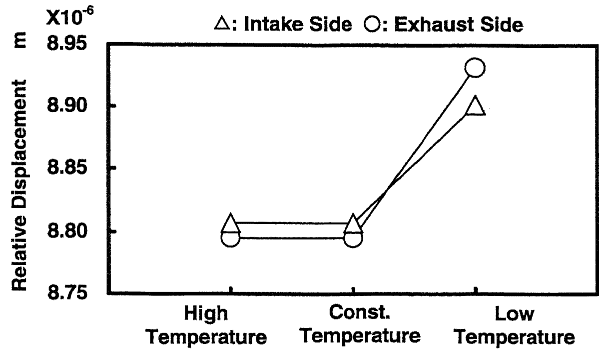

Fig. 7 Relative Displacement of Metal Gasket

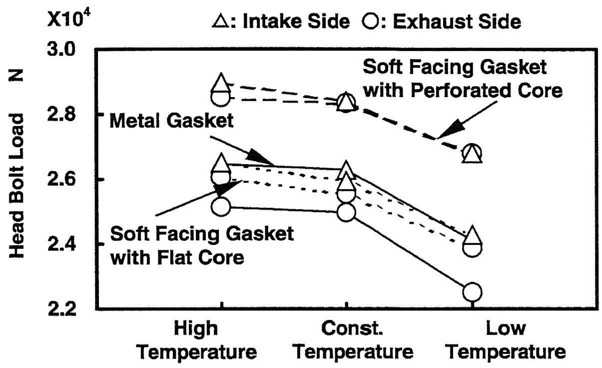

Fig. 6 Change of Head Bolt Load

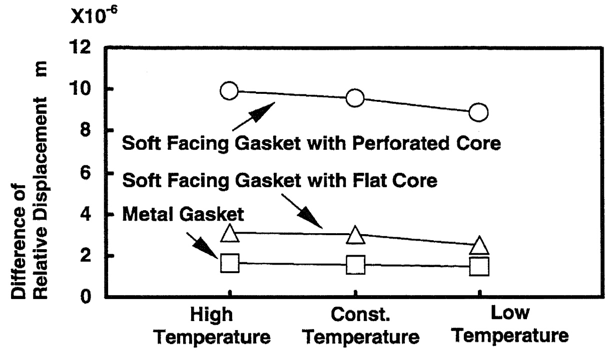

Fig. 8 Difference of Relative Displacement

of the cylinder head and block is abruptly reduced. But it is shown that the temperature of the cylinder head bolt is gradually reduced. Therefore, there are the phase difference of the temperature between the cylinder head bolt and the cylinder head and block then, the phase difference of the temperature effect on the load of the cylinder head bolt.

4.2 Measuring Results of Cylinder Head Bolt Load

Based upon the measured results of the gasket temperatures, attention is paid to the cylinder head bolts on the upper part. The cylinder head bolt loads in BL–In point of the intake side and in BL–Ex point of the exhaust side for three kinds of gaskets are shown in **Figure 6**. The values of the bolt loads are the maximum values in each temperature state. In the result, the bolt loads in the Const-Temp and the High-Temp states do not change so much for each type of gasket. This result is attributable to the similar values of the coolant temperatures at the Const-Temp and the High-Temp states. However the lowering of the bolt loads at the Low-Temp state are remarkable in comparison with those at Const-Temp and the High-Temp states. It can be considered that the cylinder head and the cylinder block shrink at the Low-Temp state faster than the cylinder head bolt during the rapid cooling condition. The load of the cylinder head bolt at the exhaust side is lower than that at the intake side.

4.3 Relative Displacement between Cylinder Head and Cylinder Block

The measurement of the relative displacement between the cylinder head and the cylinder block was focused on the measuring points between the cylinder head bolt at G–In. 2 point of the intake side and at G–Ex. 2 point of the exhaust side. **Figure 7** shows the measurement result of the relative displacement of the metal gasket, as an example. The values of the relative displacements are the maximum values at each temperature state. In the result, the relative displacements at the Const-Temp state and the High-Temp state do not change so much. This result is caused by the loads of the cylinder head bolts which are similar values at both temperature states. The relative displacements between the cylinder head and the cylinder block increase at the Low-Temp state. This result is related to the decrease of the cylinder head bolt load during the Low-Temp state.

The relative displacement caused by the load change of the cylinder head bolt at the exhaust side is larger than that in the intake side at the Low-Temp state. The loads of the cylinder head bolts greatly influence the relative displacements between the cylinder head and the cylinder block and also largely influence the gasket contact pressure distribution. **Figure 8** indicates the difference between the maximum and minimum values of the relative displacement at each coolant temperature state for the three kinds

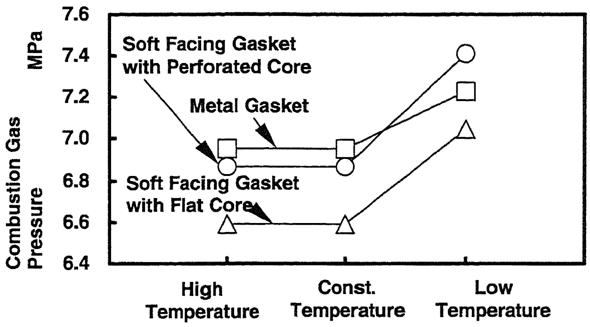

Fig. 9 Change of Maximum Gas Pressure

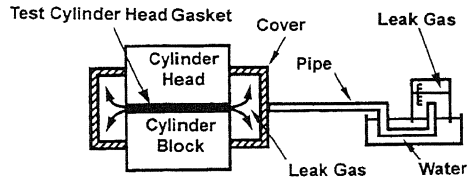

Fig. 10-(a) Schematic Diagram of Measuring System of Outside Gas Leak

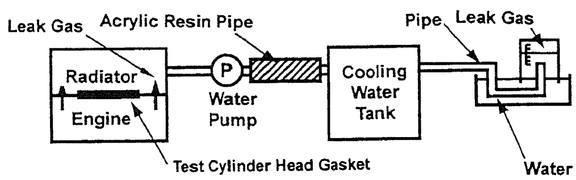

Fig. 10-(b) Schematic Diagram of Measuring System of Inside Gas Leak

of gaskets. In the result, the soft facing gasket with perforated core has the largest difference of the relative displacement in each temperature state. The soft facing gasket with flat core has the second largest difference and the metal gasket has the minimum difference of the relative displacement at each temperature state. This result is due to the difference of the gasket structure and its rigidity.

4.4 Maximum Gas Pressure

Figure 9 shows the cylinder pressure under each coolant temperature state for three kinds of gaskets. The cylinder pressure is the maximum value at each temperature state. The cylinder pressure rises in the low coolant temperature at the Low-Temp state. This phenomenon originates in the increase of charging efficiency due to the rapid cooling of the intake port. Moreover, the shrink of the cylinder head and the cylinder block decreases the cylinder volume.

4.5 Combustion Gas Leakage

Figure 10(a) and **(b)** illustrate the schematic diagrams of the gas leakage test devices. **Figure 10(a)** illustrates the gas leakage test device which can quantitatively measure the gas volume leaked between the cylinder head and block. As the part of the leaked gas penetrates into the cooling water and the air bubbles containing exhaust gas are produced, the babbles can be visually observed in the transparent acrylic resin pipe arranged between the water pump and the cooling water tank. And the babbles can be gathered in order to measure the gas volume shown in **Figure 10(b)**. **Figure 11** shows the photographs of the gasket and the cylinder block in which the gas leaked actually. This photographs shows that the gas escaped from

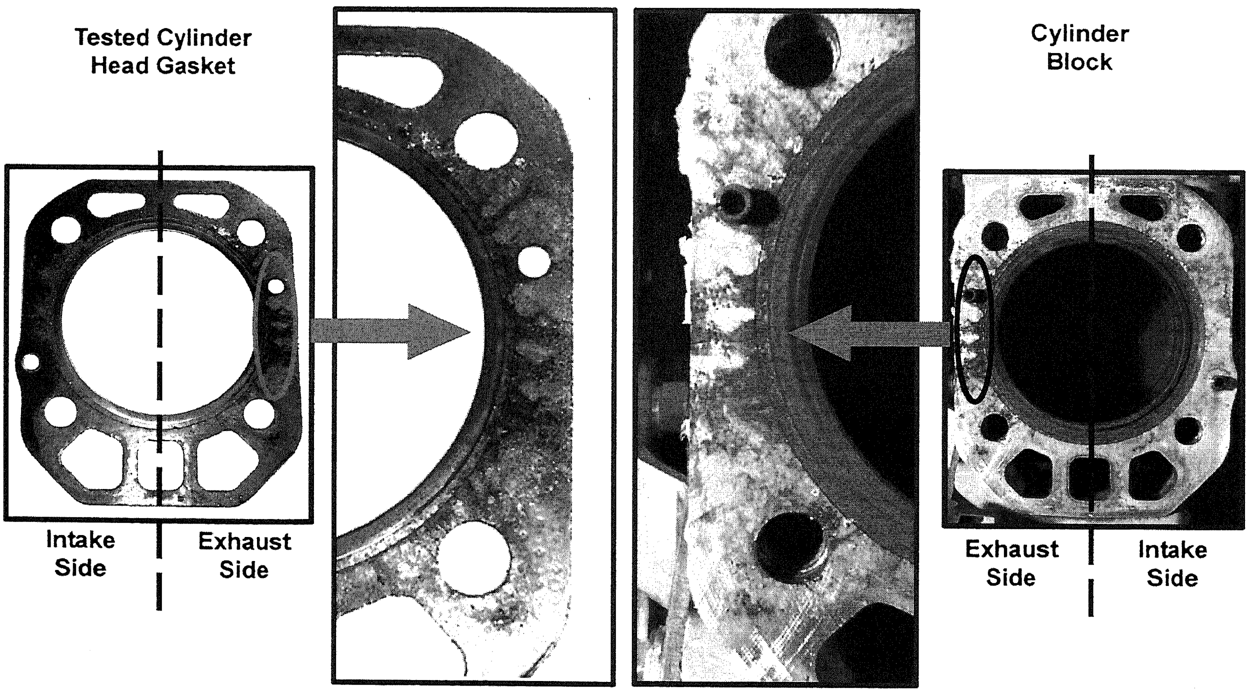

Fig. 11 Example of Combustion Gas Leak

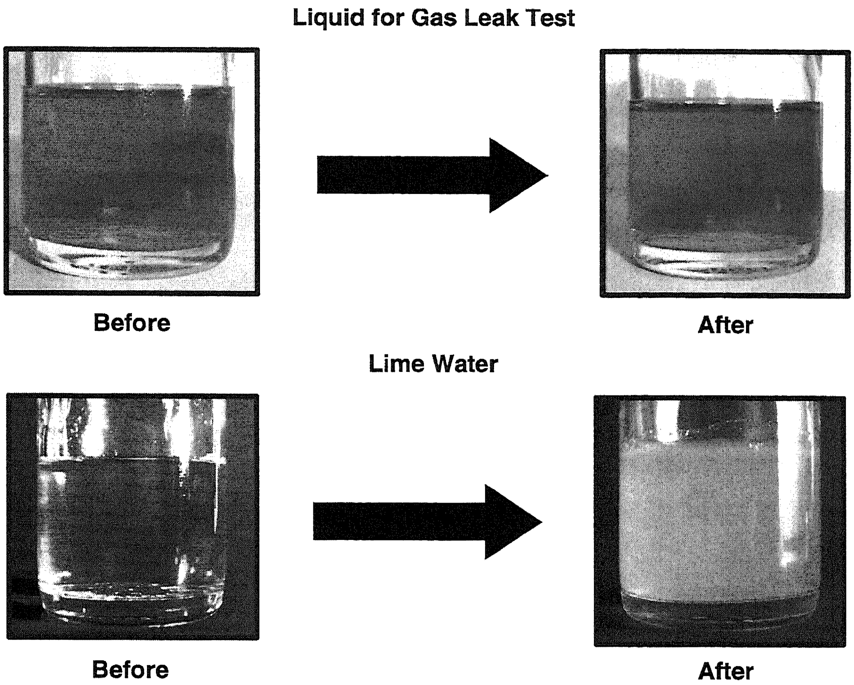

Fig. 12 Example of Gas Leak Test

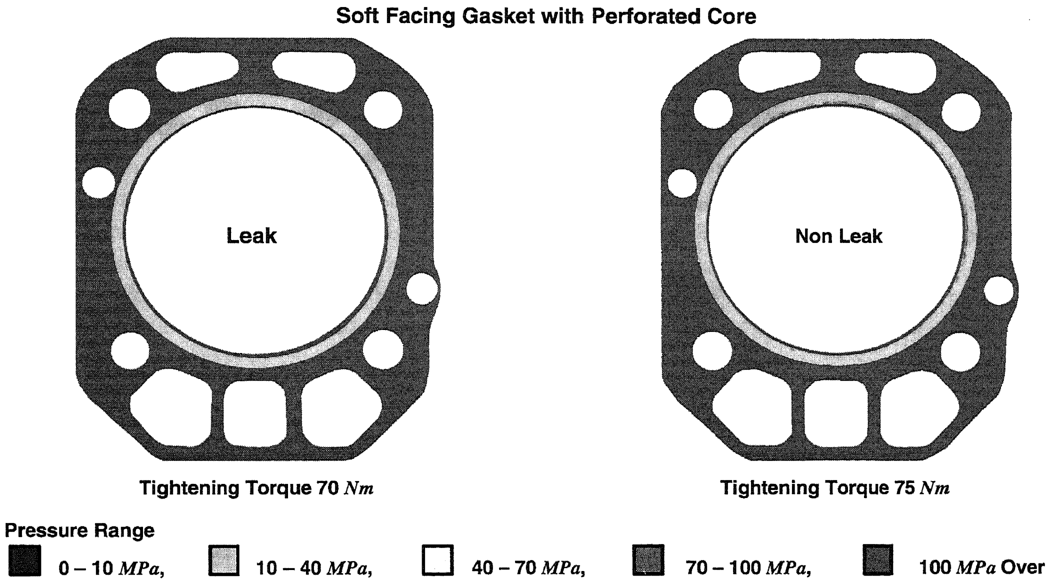

Fig. 13 Surface Pressure of Soft Facing Gasket with Perforated core

the exhaust side. The water scale can be observed in the photographs. **Figure 12** shows the comparison of the developed color conditions with the methods by adopting the exclusive check solution and the lime water. These liquids are reactive with carbon dioxide and are changed in color. This method can be adopted as the qualitative observation.

4.6 Contact Pressure Measurement Result in Combustion Sealing Area

Figure 13 and **14** illustrate the contact pressure distribution of the soft facing gasket with perforated core and the metal gasket, respectively. And also, these **Figures** shows the comparison of the contact pressure distributions before and after the gas leakage. The contact pressure distribution of the soft facing gasket with perforated core changed greatly in the part of the body after the gas leakage. On the other hand, that of the metal gasket changed scarcely. In the comparison with the gas sealing parts, that of the soft facing gasket with perforated core changed scarcely after the gas leak, but that of the metal gasket

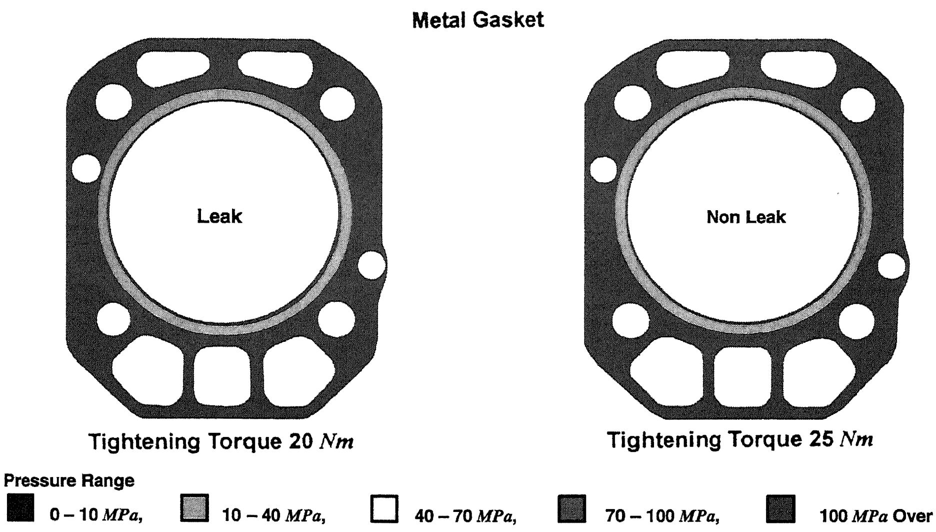

Fig. 14 Surface Pressure of Metal Gasket

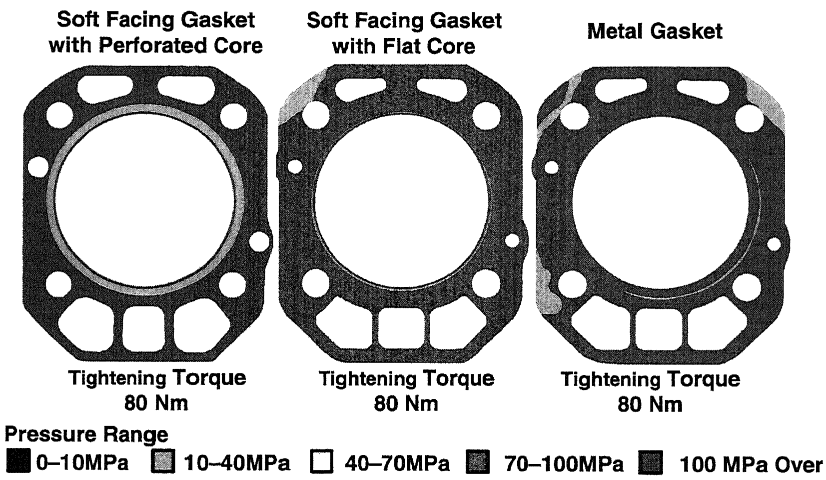

Fig. 15 Surface Pressure of Test Cylinder Head Gasket

changed greatly. From the results, it is shown that the soft facing gasket with perforated core seals the gas by the base sheet part and the metal gasket seals the gas by wire ring of the combustion gas sealing part. **Figure 15** shows the contact pressure distributions on condition that the test gaskets were tightened by the torque of 80 Nm. It is shown that the contact pressure distributions of the test gaskets are individually changed on condition of the same tightening torque. This result originates in the differences of the material and the configuration. The result of **Figure 15** is the same one of the **Figures 13** and **14**. The contact pressure in the combustion sealing area is secured by a wire ring with stainless steel armor. The measurement results of the contact pressure in the combustion sealing area for the soft facing gasket with perforated core and the metal gasket on the first tightening condition are listed in **Table 2** and indicated in **Figure 16**. The soft facing gasket with perforated core loses the contact pressure value drastically up to 50 MPa level by decreasing the tightening torque of the cylinder head bolt up to 15 Nm. In the case of the metal gasket, the contact pressure keeps a high level of 80 MPa, even if the tightening torque is decreased up to 15 Nm. This is due to the difference of the gasket body at the periphery of the stainless steel armor. It is apparent that the metal gasket keeps higher contact pressure on the combustion sealing area than the soft facing gasket with perforated core against the fluctuation of the bolt load on engine operating condition. In comparison with the contact pressure of both gaskets, the tightening torque of the soft facing gasket with perforated core requires two to three times as much as that of the metal gasket to maintain an equal level of contact pressure.

4.7 Change of Cylinder Head Bolt Load and Tightening Torque

The relationship between the cylinder head bolt load and the tightening torque of the metal gasket at the Const-Temp state is depicted in **Figure 17**. The measuring points are the points of BL–In. 1 and BL–Ex. 1. In the **Figure**,

Table 2 Surface Pressure of Combustion Gas Seal [Unit: MPa]

Tightening Torque Nm	15	20	25	40	45	50	70	75	80
Soft Facing Gasket with Perforated Core	50	—	—	—	—	80	85	90	110
Soft Facing Gasket with Flat Core	60	—	—	85	90	95	—	—	120
Metal Gasket	80	85	90	—	—	110	—	—	130

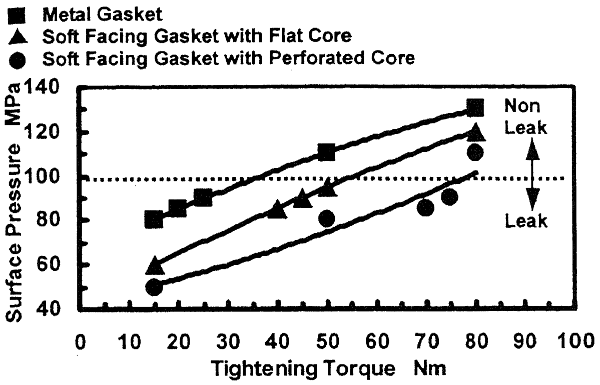

Fig. 16 Relationship between Surface Pressure and Tightening Torque in Combustion Gas Seal

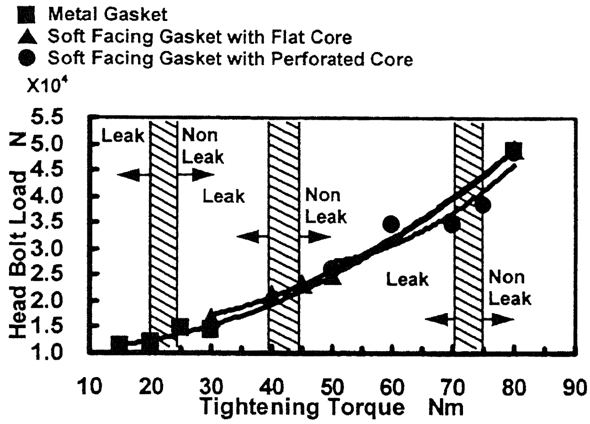

Fig. 17 Relationship between Head Bolt Load and Tightening Torque

each cylinder head bolt loads are shown against the tightening torques of 80 Nm, 75 Nm, 70 Nm, 60 Nm, 50 Nm, 45 Nm, 40 Nm, 30 Nm, 25 Nm, 20 Nm and 15 Nm, respectively. As the gas leakage of the metal gasket was observed at the tightening torque of 15 Nm by utilizing a leakage detective device during engine running, the visual check of carbon on the combustion armor was conducted after the gasket was disassembled. In case of the metal gasket, the gas leakage was observed at very low bolt tightening torque and very low bolt load conditions. In comparison with the experiment results of **Figure 16**, the soft facing gasket with perforated core is required a tightening torque of 68 Nm to maintain contact pressure of 95 MPa, and a tightening torque of 55 Nm is required for keeping a contact pressure of 80 MPa. Therefore, it can be deduced from the relationship between the tightening torque and the bolt load that the gas leakage will occur at 30% of the standard tightening torque of 80 Nm in the case of the soft facing gasket with perforated core.

5. Conclusions

(1) The cylinder head gasket exhibits large temperature differences around the coolant passage in the case of rapid change of the coolant temperature.
(2) The cylinder head bolt load decreases at the Low-Temp state of the coolant temperature. The cylinder head bolt load at the exhaust side is lower than that at the intake side.
(3) The relative displacement between the cylinder head and the cylinder block is greatly influenced by change of the cylinder head bolt load. The soft facing gasket with perforated core has the largest relative displacement between the cylinder head and the cylinder block.
(4) The contact pressure of the metal gasket on the combustion gas sealing area is higher than that of the soft facing gasket with perforated core.
(5) The combustion gas leakage is greatly influenced by the contact pressure on the combustion gas sealing area and by the cylinder head bolt load.

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