International Journal of Automotive Technology, Vol. 8, No. 2, pp. 243–248 (2007)

1229–9138/2007/033–14

DURABILITY IMPROVEMENT OF A CYLINDER HEAD IN CONSIDERATION OF MANUFACTURING PROCESS

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(Received 18 July 2006; Revised 21 February 2007)

ABSTRACT–The durability of a cylinder head is influenced by the thermal and mechanical history during the manufacturing process, as well as engine operation. In order to improve the durability of cylinder head, both load from engine operation and the preload conditions from the manufacturing process must be considered. The aluminum cylinder head used for a HSDI diesel engine is investigated to reduce the possibility of high cycle fatigue crack in this study. FE analysis is performed to elucidate the mechanism of high cycle fatigue crack in the HSDI diesel cylinder head. Two separate approaches to increase the durability of the cylinder head are discussed: reducing load from engine operation and re-arranging preload conditions from the manufacturing process at the critical location of the cylinder head. Local design changes of the cylinder head and modification of pretension load in the cylinder head bolt were investigated using FE analysis to relieve load at the critical location during engine operation. Residual stress formed at the critical location during the manufacturing process is measured and heat treatment parameters are changed to re-arrange the distribution of residual stress. Results of FE analysis and experiments showed that thorough consideration of the manufacturing process is necessary to enhance the durability of the cylinder head.

KEY WORDS : High cycle fatigue, Crack, Residual stress, Cylinder head, FE analysis, Manufacturing process

1. INTRODUCTION

In order to cope with reinforced exhaust emission regulations, the automotive industry is interested in research and development of HSDI (High Speed Direct Injection) diesel engines with common rail systems (Monaghan, 2000). Since a HSDI diesel engine operates under highly loaded conditions, due to increased power output, the cylinder head of the HSDI diesel engine is susceptible to high cycle fatigue cracks. High cycle fatigue cracks in the water jacket area can be predicted by using adequate CAE methods, in which only operating load conditions are considered (Kim and Chang, 2003; Steiner *et al.*, 2001; Kim and Ahn, 1997).

Since durability characteristics of the cylinder head are influenced by their complete thermal and mechanical history, however, preload conditions representing the manufacturing process as well as operating load conditions must be considered. Taking residual stress into account, which is formed during the manufacturing process, will change the value of the mean stress and influence the fatigue life of the mechanical component, such as the cylinder head (Gong *et al.*, 2001). Generally, tensile residual stress is detrimental to the component, while compressive one improves the fatigue behavior of materials. Maassen (Maassen, 2001) demonstrated that tensile residual stress formed inside the water jacket area during the manufacturing process could reduce fatigue life of the cylinder head by performing a numerical analysis. Kim *et al.* proved experimentally that the residual stress was formed during the manufacturing process (Kim *et al.*, 2006).

In this study, the improvement of durability at the critical location by changing the pretension load of the cylinder head bolt, and the local design was investigated using FE analysis. Additional improvement of durability by modification of the manufacturing process was examined experimentally.

2. HIGH CYCLE FATIGUE CRACKS IN THE CYLINDER HEAD

Durability tests are performed to verify the operational safety of the engine component in the development stage. Durability tests of full load at rated speed show that

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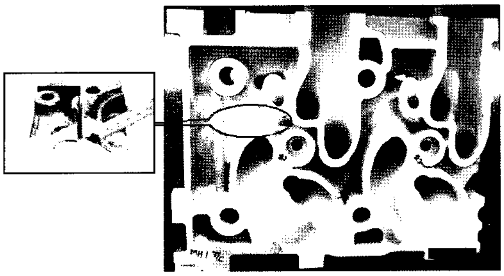

Figure 1. High cycle fatigue crack in the HSDI diesel cylinder head.

HSDI diesel cylinder heads tend to have more cracks in the water jacket area due to high cycle fatigue (Maassen, 2001). In the case of the cylinder head used in this study, repetition of the fatigue cracks was shown at the foot of a long intake port in the first cylinder (Figure 1).

The FE model, as shown in Figure 2 was used to analyze the mechanism of cracks in the cylinder head. The model was composed of a half cylinder head and half cylinder block including head bolts, liners, head gasket, valve seats, and valve guides. Solid parabolic tetrahedron elements were mainly used and the numbers of elements and nodes used in the model were about 280,000 and 500,000 respectively.

Three different cases of load condition - assembly, thermal, and firing load condition - were applied with appropriate boundary conditions (Kim and Chang, 2003). The commercial software, ABAQUS, was used to calculate the model (ABAQUS, 2004). To calculate the safety factor, it was assumed that stress amplitude by the firing load condition was added to the mean stress formed by the assembly and thermal load conditions (Kim and Chang, 2003). Safety factors for every node of the FE model were estimated by using FEMFAT to evaluate the high cycle fatigue behavior under multiaxial load conditions (Khosrovaneh *et al.*, 2004). Figure 3 shows the distribution of safety factors in the water jacket side of the bottom deck. The lowest safety factor occurred at the foot of a long intake port, in accordance with the test results.

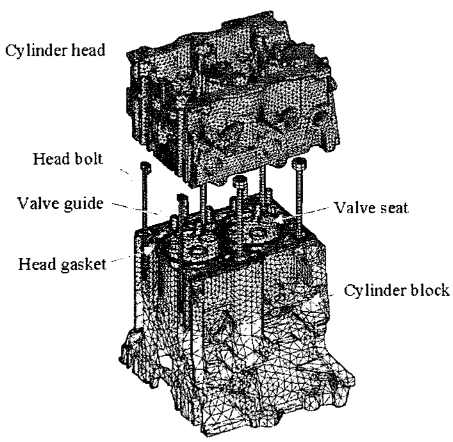

Figure 2. FE model of HSDI diesel engine assembly.

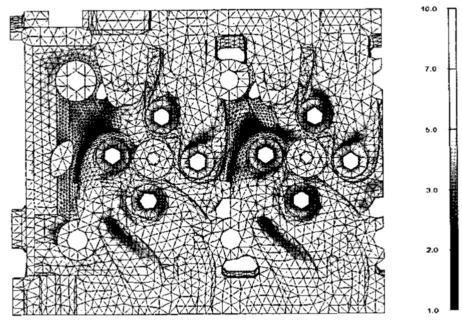

Figure 3. Distribution of fatigue safety factors in the bottom deck of the cylinder head.

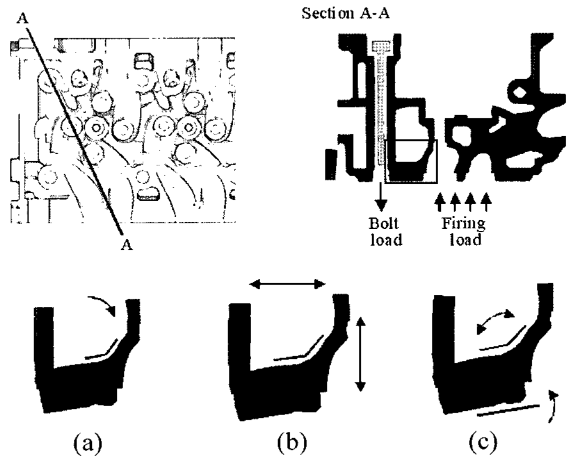

Figure 4. Deformation of the cylinder head at the crack location (65 times enlarged): (a) assembly load condition; (b) thermal load condition; (c) firing load condition.

In order to find out the mechanism of the crack, deformation at the foot of a long intake port in each load condition was investigated. A section view at the crack location in each load step is shown in Figure 4.

Section view (A-A section) of the cylinder head in the assembly load condition showed that the pretension load of the cylinder head bolt induced bending at the crack location due to the stopper height of the gasket between the cylinder head and block (Figure 4(a)). Tensile stress, formed by bending during assembly load condition, was increased by the thermal load condition (Figure 4(b)), and was maximized when the firing load was applied (Figure 4(c)).

Analysis of stress distribution in each load condition revealed high mean stress, due to the assembly and thermal load that was formed at the crack location. The

Table 1. Level of stress in each load condition and safety factor at the crack location.

Load condition	Von Mises stress (MPa)	Maximum principal stress (MPa)	Safety factor
Assembly	63.3	68.7	
Thermal	90.9	99.3	1.52
Firing	131.0	142.8	

level of stress at the crack location in the first cylinder, predicted by FE analysis, are shown with the safety factor in Table 1. Since contribution of the assembly load was remarkable as shown in Table 1, reduction of the stress from the assembly load would be effective to improve the durability of the cylinder head.

3. IMPROVEMENT OF DURABILITY BY FE ANALYSIS

In order to enhance the durability of the cylinder head, changes to the local design to increase the bending stiffness at the foot of the long intake port, and reduction of the pretension load of cylinder head bolts were examined in this study.

3.1. Effect of Change in Local Design

Different types of rib structure, as shown in Figure 5 were applied to the foot of the long intake port to discover the effectiveness on the durability at the crack location.

All three design changes are aimed to increase the bending stiffness at the crack location, which will reduce the tensile stress formed in the assembly load condition. The rib structure in Figure 5(a) has a triangular rib at the bolt boss, which indirectly increases the bending stiffness; Figure 5(b) shows a single wide rib connecting the bolt boss and the long intake port, and Figure 5(c) shows an additional triangular rib on the wide rib structure, which will increase the bending stiffness further.

Calculations on each FE model with various designs in Figure 5 were performed and their effectiveness on durability were compared in Table 2. Results of FE analysis

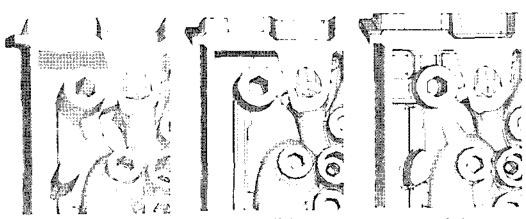

Figure 5. Various types of local design change to increase the bending stiffness at the crack location.

Table 2. Effects of local design change on the durability of cylinder head.

Type of rib	Rib width	Rib height	Safety factor
Rib at bolt boss side (Figure 5(a))	10 mm	14.5 mm	1.60
Single rib at port side (Figure 5(b))	24 mm	4.5 mm	1.37
Double rib at port side (Figure 5(c))	24 mm	12.8 mm	1.70

showed that the double rib structure of Figure 5(c) was the most effective to improve the durability of the cylinder head.

3.2. Effect of Change in the Pretension Load of the Head Bolt

Deformation of the cylinder head during the assembly load condition is mainly due to the pretension load of the cylinder head bolts. Since the pretension loads of the outside head bolts are transferred to only one cylinder, while the pretension loads of the other head bolts are shared by two adjacent cylinders, the deformation at the crack location in the first cylinder tends to be bigger than in any other cylinders. In order to reduce the stress concentration at the crack location in the first cylinder, where a major portion of the stress is due to the deformation in the assembly load condition, the pretension load of the outside head bolts (bolt #1 & #2 in Figure 6) was reduced.

Reduction in the pretension load of the outside head bolts could diminish the deformation and improve the durability at the crack location of the cylinder head.

The effect of change in pretension load of the cylinder head bolt on durability was evaluated using FE analysis, shown in Table 3. Results showed that a safety factor

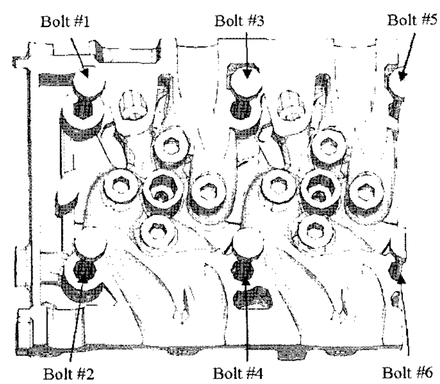

Figure 6. Location of head bolts influencing deformation of the cylinder head.

Table 3. Effect of change in pretension load on the durability of the cylinder head.

Change of pretension load	Safety factor
8.5% down	1.54
24.3% down	1.61

increased only by 5.8% as the pretension load of the cylinder head bolt decreased up to 24% from the original pretension load. Effectiveness of change in the pretension load on durability at the crack location was found to be insignificant.

4. IMPROVEMENT OF DURABILITY BY A REDUCTION OF RESIDUAL STRESS

If tensile residual stress is formed at the foot of long intake port during the manufacturing process, initiation of a crack is possible even though FE analysis predicts that the safety factor is large enough to avoid crack phenomena. Since materials in the first cylinder are arranged inhomogeneously, regions such as the foot of the long intake port, where materials are aggregated densely, are cooled more slowly than other regions during quenching at the end of the manufacturing process. This inhomogeneous cooling could cause thermal strain, as described in the following equation,

$$\varepsilon^{th} = \alpha \cdot \Delta T \quad (1)$$

where α is a coefficient of thermal expansion and ΔT is the change in temperature. This thermal strain could lead to high tensile residual stress at the foot of a long intake port (Kim *et al.*, 2006).

In order to measure the residual stress at the foot of a long intake port of the cylinder head, experiments were performed. A dissection method has been used to measure the residual stress in the cylinder heads. Since the access to a water jacket area of the cylinder head was limited, an opening, through which installations of gage and wire could be made, was necessary. A practicably small window was cut at the front of the cylinder head

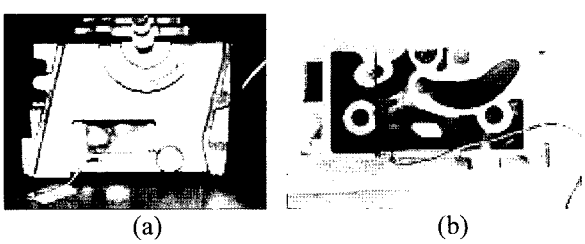

Figure 7. Installation of strain gage in the cylinder head: (a) an opening made for installation of strain gage; (b) strain gage attached at the foot of a long intake port.

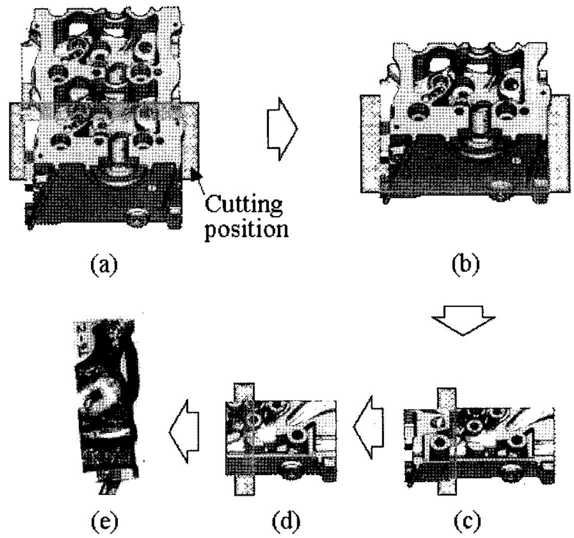

Figure 8. Parting out procedure for measurement of residual stress: (a) First cut; (b) Second cut; (c) Third cut; (d) Fourth cut; (e) Specimen at the final stage.

(Figure 7(a)) and the strain gage was attached at the foot of the long intake port, aligned in the principal direction found in the FE analysis (Figure 7(b)).

A large part of the cylinder head was cut by sawing, followed by successive removal of the part until the small parent part with the strain gage remained (Figure 8). The surface area of the specimen at the final cutting, was arranged so that the strain on the surface becomes a precise measurement of residual deformation. Careful consideration of the cutting position was given to fulfill St. Venants' condition so that the machine stresses at the edge might be neglected (SAE Information Report, 1965).

An initial reading of the strain gage before parting out was obtained and compared with the final reading of the gage when the cylinder head was reduced to its final

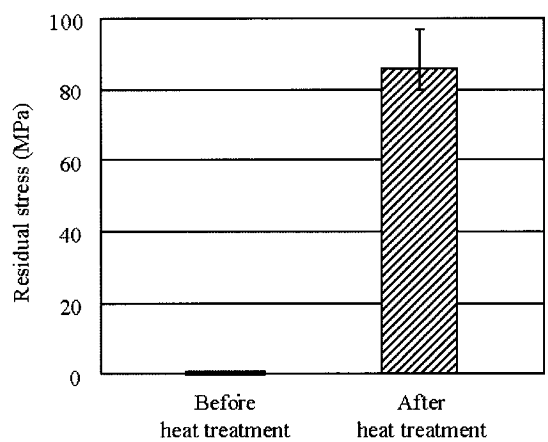

Figure 9. Results of residual stress measurements at the foot of a long intake port.

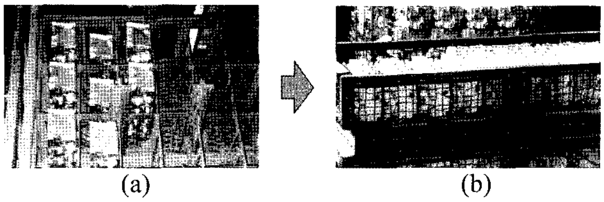

Figure 10. Arrangement of cylinder heads in the heat treatment process: (a) downward positioning of rear side; (b) downward positioning of intake side.

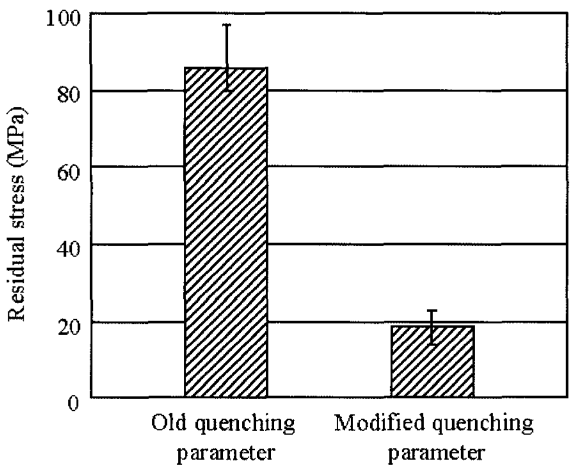

Figure 11. Reduction of tensile residual stress at the gage location with modified heat treatment parameters.

dimension. From these values, the residual stress, the parting-out stress, was obtained in the specimen using Hooke's law,

$$\sigma = E\varepsilon \tag{2}$$

where E is Young's modulus of aluminum (70 GPa) and ε is measured strain. Figure 9 demonstrates the residual stresses resulted from before and after heat treatment.

The specimens with heat treatment revealed significantly high tensile residual stress at the foot of the long intake port, while the specimens without heat treatment showed marginal levels of residual stress. The residual stresses were 80~91.3 MPa in tension at the surface where the strain gage was attached. Since the residual stress formed during the quenching process is only slightly changed by the aging and machining process (Gundlach, 1994), this level of tensile residual stress is large enough to accelerate the fatigue failure of the cylinder head.

Rapid cooling of the boundary in the first cylinder during heat treatment process causes high tensile residual stress at the gage position (Kim *et al.*, 2006). In order to reduce residual stress at the gage location, where high stresses of engine operation load were also expected, changes of heat treatment parameters were investigated. Temperature of the solution heat treatment was reduced from 535°C to 520°C, and the temperature of the quenchant was increased to 90°C from 60°C. The intake side of the cylinder head was positioned downward so that the slow cooling region inside the water jacket could undergo better cooling (Figure 10).

Test results of the cylinder head, manufactured with the modified parameters, indicated a significant reduction of the tensile residual stress at the gage location. The measured stresses were 14~23 MPa in tension; this reduction of the tensile residual stress should effectively increase the fatigue life of the cylinder head (Figure 11).

5. CONCLUSION

Load condition from engine operation were predicted and changed using FE analysis. Durability of the cylinder head was also improved by FE analysis. To avoid high cycle fatigue cracks, however, FE analysis must be performed at the early stage of the cylinder head design.

Measurements of the residual stress at the crack location proved the formation of high tensile residual stress during heat treatment of the manufacturing process. The distribution of residual stress formed in the heat treatment process could be improved by changes of heat treatment parameters, such as temperature of the solution heat treatment, temperature of quenchant and arrangement of cylinder heads.

This study shows that the preload conditions from the manufacturing process, as well as the load condition from engine operation are important in predicting durability of the cylinder head. For complete durability analysis of the cylinder head, however, load conditions for the heat treatment process must be considered in a FE analysis in order to predict the quantitative improvement.

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