Improvement of Piston Skirt Scuffing Problem Using 3D Piston Motion Simulation

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***Abstract**: This paper shows a study for solving a piston skirt scuffing problem in diesel engine. We propose to solve this scuffing problem by studying the piston dynamics analysis using commercial S/W; ABAQUS. The first approach was to develop the piston secondary dynamic analysis method based on the Finite Element Method. The second approach was to clarify the root cause of the diesel piston scuffing case. The last approach was to optimize the piston skirt profile and cylinder block design for reducing the scuffing index. The solution proposed in this study was adopted in the piston and block design.*

***Keywords**: piston scuffing bore distortion, ABAQUS implicit, wear*

1. Introduction

A rough sliding contact between piston skirt and cylinder block bore affects friction loss at the engine. Engine piston reciprocates in the axis direction on the cylinder block face and has a tilting motion from side to side. This motion is called as a piston secondary motion. Piston secondary motion influences friction loss, wear, slap noise, block vibration and piston skirt scuffing. Among these effects, piston skirt scuffing increases friction loss and cause excessive blow-by gas. And, it degrades engine performance. (1)

Engine piston composed of piston head in which piston ring package inserts and piston skirt with which cylinder bore contacts. Piston skirt contact with cylinder bore in boundary lubrication condition. Piston skirt scuffing means that wear occur by metal-to-metal contact from boundary lubrication's destruction.(2) Over the past few decades, several root causes of piston skirt scuffing is researched from the analysis and experimental method. The causes are excessive contact between piston skirt and cylinder bore by large thermal deformation of piston, inappropriate piston skirt profile, a lack of lubrication and a shortage of block depth. (3)

This paper shows a study of a piston scuffing problem solving in the diesel engine piston. The piston had a scuffing problem in the thermal shock test. The first approach was to analyze the root cause of piston scuffing case in the engine dynamo test through the piston structural dynamic analysis. At the piston dynamic analysis, cylinder bore deformation, piston skirt profile and piston thermal deformation were considered. At the next approach, modified skirt profile and block bottom design were suggested to solve the scuffing problem. Through the piston dynamic analysis, the effects of design variables were analyzed and the final design was suggested. The final design passed the thermal shock dynamo test. And, the reliability of the analysis approach was verified.

2. Piston Skirt Scuffing Problem

At the thermal shock dynamo test of the diesel engine, the piston skirt scuffing phenomenon had occurred the total 5 times of the same engine. The piston scuffing had not occurred at the full load dynamo test, but the piston skirt had excessive contact pattern. At the two aspects, the piston skirt had something in common. At the first, the scuffing or contact pattern was found at the thrust side along the block bottom edge. At the second, as the figure 1, only the piston of the 1st cylinder bore had the scuffing or excessive contact pattern. At the other cylinder bore, a slightly contact pattern was founded similarly to the block bottom edge. Figure 2 shows the block bottom edge shape. The shape was applied for the crankshaft offset. Generally, the crankshaft offset is applied to decrease the friction, wear and piston slap noise. To prevent the interference between the connecting rod and the cylinder block by the crankshaft offset, the cylinder block bottom area was partially removed.

As the observed results, it was assumed that the root cause of the piston skirt scuffing had occurred by the bottom edge shape of the cylinder block and the thermal bore deformation shape of the 1st cylinder bore. In this study, the scuffing pattern of the piston skirt was simulated using the commercial S/W; ABAQUS. And, the root cause of the scuffing problem was analyzed and the modified design was suggested.

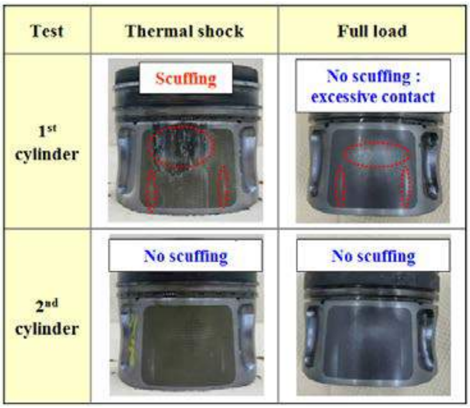


Figure 1: Piston skirt scuffing phenomenon

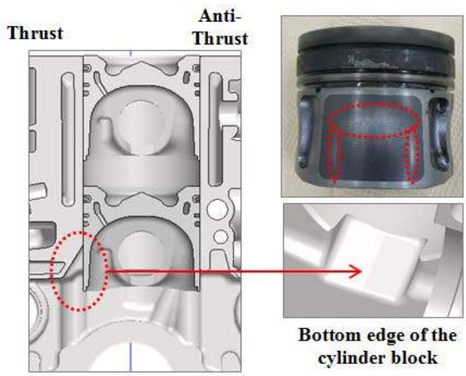


Figure 2: Bottom design of the cylinder block

3. Construction of the dynamic analysis model

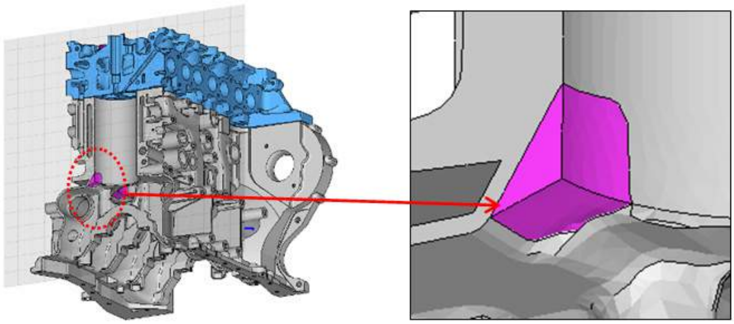
3.1 Thermal bore deformation of the cylinder block

Because the piston moves along the cylinder block bore face, the thermal bore deformation of the cylinder block was main factor for the piston dynamic analysis. Especially, for that the scuffing pattern of the piston skirt was founded at the 1st cylinder bore, the thermal bore deformation analysis of each cylinder is necessary and the piston dynamic analysis with the deformed cylinder bore shape is essential.

Bore deformation of the cylinder block was obtained through the cylinder head-block thermal-mechanical structural analysis. At this analysis, the head bolt pretension force was considered and hot temperature at the rated rpm was applied as the thermal loading condition. At the piston dynamic analysis, the thermal bore deformation shape was considered after the calculation of the roundness.

For the calculation of the roundness, the node composing the finite element must be positioned in the circle face.

But, the engine with the scuffing problem was removed partially at the bottom area for the crankshaft offset. Therefore, the bore face on the bottom area didn't form the full cylinder shape. And, for the calculation of the roundness of the bottom area, a temporary dummy component was formed as the figure 3. At this time, the thermal expansion coefficient of the temporary dummy component was applied the same as that of the cylinder block. And, the elastic modulus of the dummy component was applied as the 1/10 level of the cylinder block for the reduction of the excessive deform restraint.



Cylinder head-block analysis model **Temporary dummy component**

Figure 3: Temporary dummy component for the calculation of the roundness

3.2 Piston skirt profile

For the piston's smooth contact with cylinder block bore wall, piston skirt profile is applied at the skirt face. Generally, through the piston marking test and the thermal deformation shape of the piston, piston skirt profile is designed.

Considering the reliable dynamic behaviour of the piston, piston skirt profile in the micro millimetre unit must be applied at the piston finite element model. In the general, profile is indicated as the clearance at the room temperature condition along the depth of the skirt. Therefore, at the first, polynomial function must be calculated with the clearance data.(4) After this process, 3 dimensional profile shape is formed with this polynomial function, and is applied at the finite element model. In this study, through the in-house coding program, the piston skirt profile was applied at the analysis model automatically. The figure 4 shows the piston skirt profile of the engine with the piston scuffing problem under the room temperature.

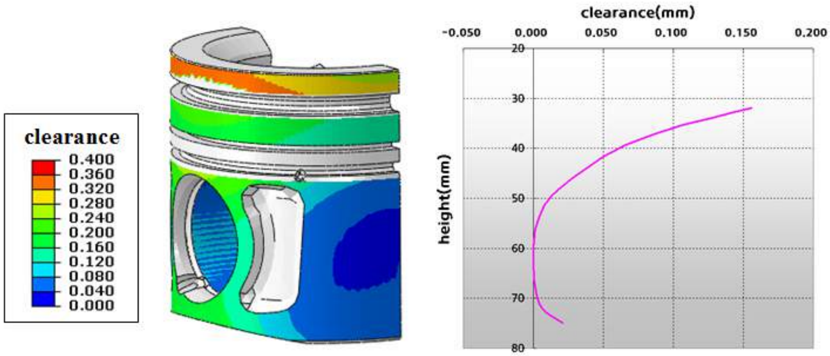


Figure 4: Piston skirt profile under the room temperature

3.3 Dynamic analysis model

Figure 5 shows the finite element model for the piston dynamic analysis. For the systematic analysis, it is constructed with piston, piston pin and connecting rod. And, for the reduction for the solving time, the sub model of the cylinder block is constructed. The thermal deformation of the cylinder bore and stiffness of the cylinder block is considered. At the piston skirt face, the clearance data under the room temperature is applied at the model. And, the expanded clearance data was calculated and applied at the skirt face under the hot temperature.

Contact condition was applied between each component. For the boundary lubrication, softening contact condition was applied between the piston skirt face and the cylinder block bore using hydrodynamic function. Also, for the exact reflections of the moving system, the crankshaft offset and piston pin offset is formed at the finite element model. And, weight center of the piston moving system is positioned exactly for the reliable calculation of the piston dynamic behavior.

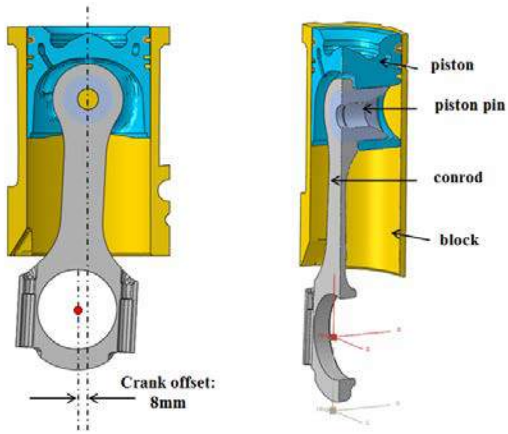


Figure 5: Construction of the piston dynamic analysis model

3.4 Analysis procedure

Overall analysis procedure was summarized as followings. Before the piston dynamic analysis, the cylinder head-block structural analysis is performed. At this analysis, the thermal deformation of the cylinder block bore is calculated. After that, the 3 dimensional bore deformation data and piston skirt profile are applied at the finite element model for the piston dynamic analysis. With the shape construction, the loading condition as the firing pressure and the rotation velocity is applied at the model. Through the solving, for the piston skirt scuffing evaluation, the contact pressure and sliding contact velocity between the piston skirt face and the cylinder block bore face is calculated. (5)Wear index for the evaluation of the piston skirt scuffing is calculated by multiplying the contact pressure with the sliding velocity. The contact pressure can reveal the position of the piston at the maximum contacting with the cylinder block bore, and the wear index indicates the wear pattern after 1 engine cycle.

4. Analysis results

4.1 Thermal deformation of the cylinder block bore

Figure 6 shows the thermal bore deformation at the bottom edge line of the cylinder bore comparing the 1st cylinder with 2nd cylinder. The amount of the deformation is filled in the table1. Only, the piston scuffing problem had occurred at the 1st cylinder bore and the mild contact pattern was expressed at the other cylinder bore. At the comparison of the thermal bore deformation, in the direction of the thrust/anti-thrust, the deformation of the 2nd cylinder bore is 20% larger than that of the 1st cylinder bore. For the explanation of the reason, the thermal deformation of the 2nd cylinder is restrained by the thermal deformation of the 1st and 3rd cylinder and was showed the same as the egg-shape. But, the thermal deformation of the 1st cylinder shows the triangle-shape owing to the non-constraint of the side. These patterns are general at the thermal bore deformation.

By the expansion in the direction of the thrust/anti-thrust, the piston moves smoothly in the cylinder bore. And, the friction between the piston skirt and the cylinder block bore decreases. From the thermal bore deformation characteristics, the 1st cylinder is more unfavourable than the 2nd cylinder at the aspect of the piston scuffing.

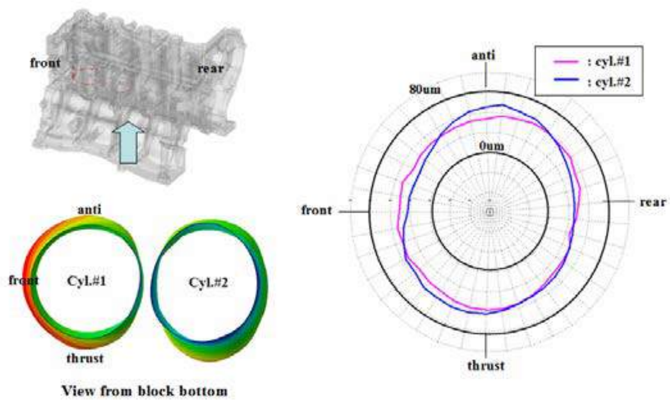


Figure 6: Thermal deformation of the cylinder block bore at the bottom edge

Deformation at the bore bottom (Diameter, um)	1st cylinder bore	2nd cylinder bore
Front / rear	87	72
Thrust / anti-thrust	113	136 (20% increase)

Table 1: The amount of the thermal deformation at the bottom edge

4.2 Contact pressure and the wear index

Through the piston dynamic analysis, contact pressure and the sliding contact velocity was obtained and the wear index was calculated with these results. The wear index is the parameter for the evaluation of the piston skirt scuffing.

At the first, the scuffing mechanism was explained with the contact pressure result. Figure 7 shows the maximum contact pressure distribution on the piston skirt in the 1st cylinder and the side force history of the piston. The maximum contact pressure is distributed along the bottom edge of the cylinder block. And, the contact pressure on the upper area is bigger than that on the side area. The maximum contact pressure pattern is similar to the piston scuffing pattern at the thermal shock dynamo test. From the side force history, examining the timing and characteristic of the contact pressure, the maximum contact pressure is not occurred at the maximum firing event, but before the BDC event; 511 degree at the crank angle. Also, at this time, the bottom area of the piston skirt was tilted in the thrust direction and was close to the bottom edge of the cylinder block bore. That is, after the combustion, the piston moves downwards following the cylinder bore face of the thrust side and, before the BDC event, the bottom area of the piston skirt was located in the bottom cutting area of the cylinder bore. By the sharp line contact between the piston skirt and the bottom edge of the cylinder bore, the excessive contact pressure was occurred and generates the piston skirt scuffing problem.

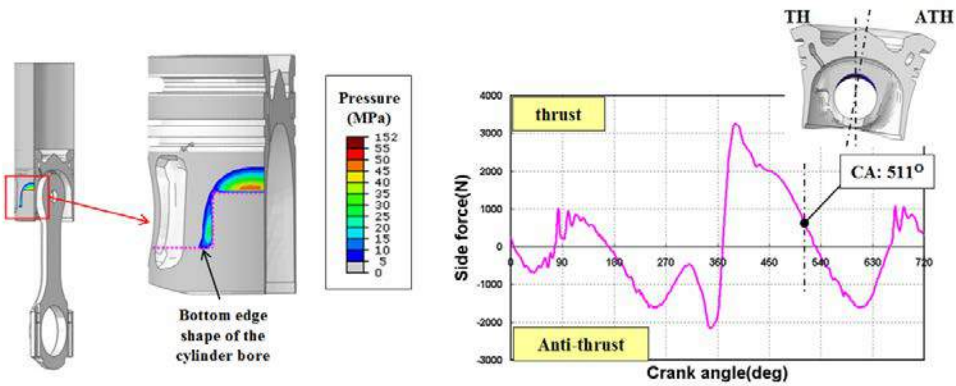


Figure 7: Contact pressure distribution and the side force history

At the figure 8, the maximum contact pressure and the wear index on the piston skirt of the 1^{st} and 2^{nd} cylinder was compared. The maximum contact pressure on the piston skirt of the 2^{nd} cylinder was 34.7% less than that of the 1^{st} cylinder, and the wear index 33.8% less than that. These results could be explained by the friction decrease of the 2^{nd} cylinder bore from that the thermal bore deformation of the 2^{nd} cylinder was 20% larger than that of the 1^{st} cylinder. And, from these analysis results, it showed that the scuffing probability at the 1^{st} cylinder was higher than at the 2^{nd} cylinder. Also, it showed that the scuffing pattern at the thermal shock test was similar to the wear index distribution. From these results, it was confirmed that the piston dynamic analysis in this study had reliability on the piston scuffing simulation. And it was identified that the construction of the analysis model and analysis process was valid. Using this analysis method, at the next approach, modified design was evaluated and the optimized design was suggested.

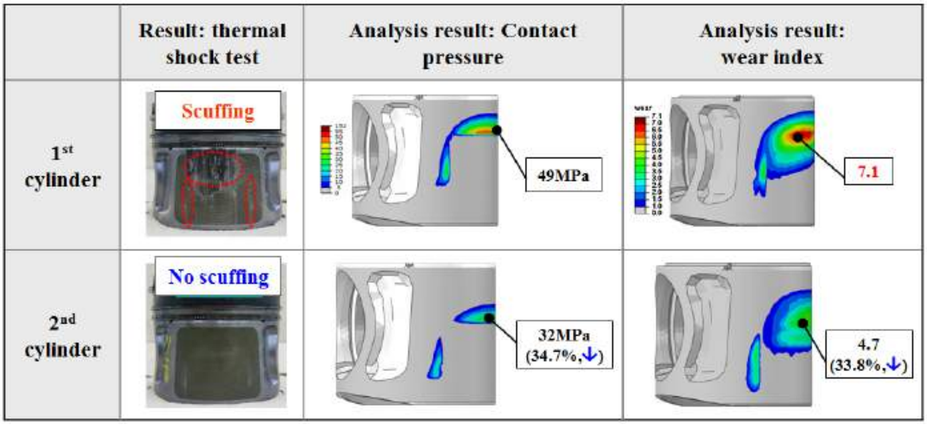


Figure 8: Contact pressure and wear index at each cylinder

5. Modified design suggestion

The piston skirt scuffing had occurred from the two root causes. It was the first that the amount of the thermal bore deformation of the 1^{st} cylinder was smaller than that of the 2^{nd} cylinder. The second cause was the bottom shape of the cylinder block bore. To avoid the first cause, there were the methods to change the shape of the water jacket in the cylinder block and to increase the nominal clearance between the piston skirt and cylinder block. But, for modifying the shape of the water-jacket, a huge change of the cylinder block is necessary. And, the increase of the nominal clearance causes the opposite effect to increase the piston slap noise. Therefore, in this study, the modified designs were suggested by changing the bottom shape of the cylinder block bore and the piston skirt profile.

As the modification of the bottom shape of the cylinder bore, for reducing the maximum contact pressure occurred by the line contact, the chamfer shape at the bottom edge was applied. And, for reducing the side force in the direction of the thrust at the BDC, the depth from the block top to the starting position of the bottom edge was increased. And, to reduce the tilting movement of the piston, the width of the bottom area was decreased. Next, as the modification of the piston profile, for decreasing the level of the maximum contact pressure at the upper area of the piston, the clearance at the upper of the piston was increased. The two design variables were depicted at the figure 9.

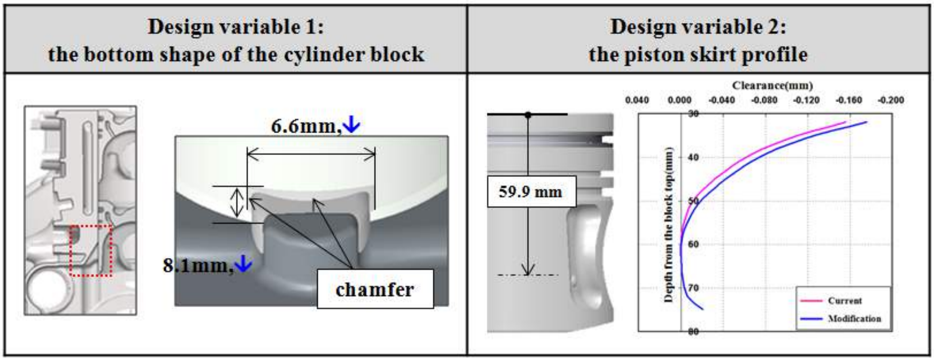


Figure 9: Design variables for reducing the piston skirt scuffing

To evaluate the wear index level of the modified design, the piston dynamic analysis was performed. Figure 10 shows the results. Only the modified piston skirt profile was applied at the case 1, and only the modification of the bottom shape of the cylinder block was applied at the case2. At the case 3, the two design variables are applied concurrently. The wear index level of the case1is 11% less than that of the current design, and that of the case2 is 52% less than that of the current design. The wear index level of the case 3 is 59% less than that of the current design. Comparing the change ratio of the wear index, it shows that the effect of the bottom shape of the cylinder block is larger than that of the piston skirt profile. In other words, it is effective to reduce the maximum contact pressure and prevent line contact by the modification of the bottom shape of the cylinder block.

The design of the case 3 was adopted at the modified design. And, the design passed through the thermal shock test with no scuffing.

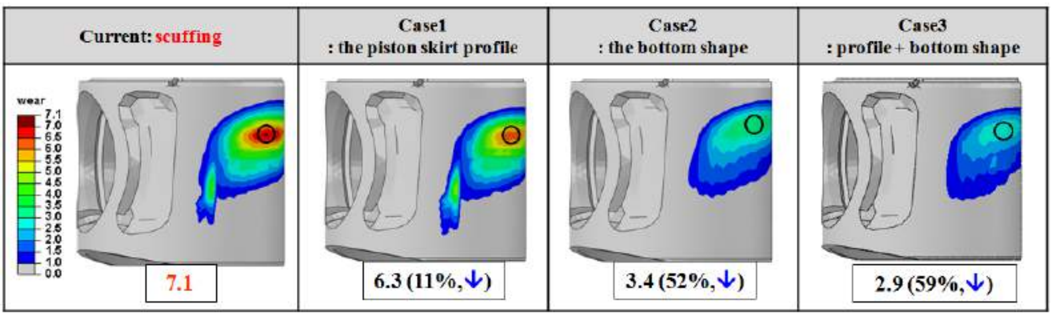


Figure 10: Wear index of the modified design

6. Conclusions

In this study, the piston skirt scuffing phenomenon was simulated using the piston dynamic analysis. The root cause of the scuffing was revealed and the modified design was suggested. The summary and conclusion were as followings.

(1) By the application of the thermal bore deformation of the cylinder and the piston skirt profile, the piston dynamic analysis model and procedure was developed,

(2) As a comparison of the bore deformation of each cylinder, the amount of the thermal bore deformation of the 1nd cylinder was 20% less than that of the 2nd cylinder. If the amount of the thermal bore deformation is small, the friction between the piston skirt and the cylinder block bore increases. And, the scuffing probability of the 1st cylinder is bigger than that of the 2nd cylinder.

(3) As the result from the piston dynamic analysis, the wear index of the 2nd cylinder is 33.8% less than that of the 1st cylinder. And, the wear index distribution of the 1st cylinder is similar to the scuffing pattern at the thermal shock test. From these results, the reliability of the piston dynamic analysis is verified.

(4) The piston skirt scuffing had occurred from the two root causes. It was the first that the amount of the thermal bore deformation of the 1st cylinder was smaller than that of the 2nd cylinder. The second cause was the bottom shape of the cylinder block bore.

(5) For reducing the wear index level, the modified design was suggested. The piston skirt profile and the bottom shape of the cylinder block bore were modified. The modified design passed through the thermal shock test with no scuffing.

7. Conclusions

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