Development of Two Layer Cylinder Liner by HIP Method*

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Increasing market demand for higher output and better fuel efficiency forces maximum combustion pressure of the engine higher and higher, requesting the same or even more reliability to the engine.

At present mono block casting cylinder liners are widely used for marine slow speed diesel engine simply because of their tribologically superior characteristics.

This paper introduces a solution of double layer cylinder liner by HIP (Hot Isostatic Pressing) method. This liner consists of two different materials. Inside material is tribologically superior material, in this case cast iron. On the other hand outside material is high strength material. Inside and outside material are fixed together using HIP method. The successful test results using test engine and production engine were also explained here.

1. Preface

At present about 80c/o of large ocean going vessels are powered by 2 stroke slow speed cross-head engines. Mono block cast iron construction is commonly used for many years to cylinder liners of these engines. However, recent technical market requirement to these engine are in the field of higher output and higher reliability. It is becoming difficult to meet to these needs by the conventional cylinder liners.

Authors tried to develop new cylinder liners, which can be used to the higher output future marine diesel engines, applying modem production technology.

2. Needs of the high strength cylinder liner

2.1 Needs from engine performance

Engine output is increasing year by year. Increasing engine output while keeping engine size, means cutting down engine manufacturing cost per output. This tendency will never stop in future also. On the other hand, there is a continuing strong needs toward energy saving. Therefore, engine designers have to make effort both for higher output and lower fuel consumption.

The best measure to get both higher output and lower fuel consumption at the same time is to increase maximum combustion pressure. Actually maximum combustion pressure is increasing year by year. Fig. 1 shows the history of engine output in case of Mitsubishi UE engine. Fig. 2 shows the history of max. combustion pressure.

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Increased combustion pressure also increases the stress of combustion chamber component. In case of cylinder liner cast iron is commonly used because of their tribologically excellent performance. However cast iron is not so strong enough any more to endure future higher combustion pressure.

Conventionally engine designers have to increase the wall thickness of cylinder liner when designing new engines which has higher combustion pressure. But this means at the same time bigger engine size.

There is a strong need to develop thinner and stronger cylinder liner design keeping good tribological performance to minimize the engine size. To fulfill these two basic factors at the same time, the best way is to apply the combination of inner material which has better tribological performance and outer material which has mechanically strong characteristics. There were many kind of trials in this field in the past. Mitsubishi has already developed two layer cylinder liner consist of inner cast iron and outer cast steel casted together by centrifugal casting method.

2.2 Needs form engine reliability

As mentioned above cast iron is widely used as cylinder liner material because of their excellent tribological performance. However, recent common tendency in marine, which is less number of ship crew and difficulty of getting better quality of crew, practically makes it impossible to do heavy job like piston over-haul by ship crew. Major engine maintenance job has to be done at the time of docking of the ship when usually we can expect enough time for these kind of works. Regular docking is scheduled every two or four years period and engine should keep running within this period without troubles which require heavy job. That means marine diesel engine is expected to have the high reliability of at least 15,000(V30,000 hr.

Conventional cast iron cylinder liners already have this ability at present. But in future marine diesel engines have to have the same or more reliability at higher output and less cylinder lubricating oil consumption. For this purpose new cylinder liner of new concept is expected.

Mono-block construction of cast iron has already reached to its limit and new conception of two layer construction seems to be the ideal to realize the technical requirement.

3. Results of basic research

Basic test for developing HIP cylinder liners has been conducted and the following results were obtained.

3.1 Selection of outer layer material

Two candidate materials for outer layer, SCPH21 and SCPH22, have been selected and metallurgical characteristics were tested. To confirm the strength of the material after HIP treatment which shall affect the material strength due to thermal cycle, we have applied soft heat treatment and observed the material structure in addition to measuring hardness and tensile strength. And also we have conducted the same kinds of tests including quantitative evaluation of structure examination results by image processing method for inner material, in this case Tarkalloy which is equivalent to FC300 of JIS.
Structure change due to heat cycle is shown in Fig. 3. The material heated over 800°C shows mixed structure with ferrite and perlite instead of original martensite structure. Grain size growth which has the influence to the material strength is observed when heating temperature is raised.

Fig. 4 shows test results of tensile strength after and before heat treatment of the candidate materials for outer layer. Even though reduced strength by heat treatment, it was confirmed that the tensile strength was over target figure of 50 kgf/mm² under all tested conditions. Fig. 4 also shows test results of tensile strength for inner material (Tarkalloy).

Judging form the test results we have selected the SCPH21 for the outer liner material of engine test cylinder liner. However, if the tensile strength is over 50 kgf/mm², another material such as SC or steel pipe could be used.

3.2 Tribological characteristics after HIP treatment

Effects on tribological performance, when the material experienced heat cycle by HIP method, are also investigated from the structure of the material.

The structure of inner layer material, in this case Tarkalloy, is basically consist of distributed graphite and carbonized stedite (Fe₃P+Carbonized Fe₃C) into perlite base.

![Fig. 5 Typical micro structure of Tarkalloy](image)

Areas of each component, graphite, stedite and perlite, under different heat treatment conditions were calculated by image processing method. Table 1 shows the results of structure examination.

It is considered that the graphites increase self lubricating performance of the material and stedite increases anti-wear performance. Compared with the original material, the materials treated by HIP show no significant change in the area of each components.

Final confirmation by wear testing will be necessary to apply this liner material to a production engine. However, judging from the structure of material after HIP treatment, there will be no significant change on anti-wear performance and tribological performance.

3.3 Pressing condition and binding strength

There will be three key factors - pressure, temperature and holding time - to keep the quality of HIP method as shown in Fig. 6. The authors tried to find out the best condition of process temperature and holding time under the constant pressure (1000 kgf/mm²). Construction and dimensions of test piece are shown in Fig. 7. The test piece consists of inner and outer double cylinder and the canning container is arranged to the inner material side. The remaining air inside the test pieces was discharged after sealing by welding. The test condition is shown in Fig. 6. Test pieces were

![Graphite Perlite Stedite Matrix](image)

![Fig. 4 Mechanical characteristics of the material after HIP treatment](image)

![Table 1 Structure of Tarkalloy after HIP treatment](image)

<table>
<thead>
<tr>
<th>Component</th>
<th>Original</th>
<th>800°C × 1hr</th>
<th>900°C × 1hr</th>
<th>1000°C × 1hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graphite</td>
<td>6.6%</td>
<td>5.5%</td>
<td>5.3%</td>
<td>6.1%</td>
</tr>
<tr>
<td>Stedite</td>
<td>7.4%</td>
<td>6.7%</td>
<td>6.7%</td>
<td>6.0%</td>
</tr>
<tr>
<td>Perlite</td>
<td>Rest</td>
<td>Rest</td>
<td>Rest</td>
<td>Rest</td>
</tr>
</tbody>
</table>

*1 This condition was adopted to test cylinder liner
cut out to check the tensile strength after HIP treatment and the results are shown in Fig. 8. Results clearly show that bonding strength between inner and outer material reaches maximum at the condition of 900°C. There was no significant difference when changing the holding time within a practically applicable range, 1 to 3 hours. The fracture point when testing tensile strength was always Tarkalloy side. The test piece shown in Fig. 7 was HIP treated at the condition of 900°C x 1 hr. Fig. 9 and Fig. 10 show the macro and micro structure of the test piece and Fig. 11 shows distribution of hardness at different process temperatures.

At the condition of process temperature of 1000°C, some amount of increase of hardness and widened area of diffusion to the SCPH side at the border were observed. On the other hand, at the condition of 800°C the area of diffusion was not enough to keep the good bonding strength. From these test results the HIP condition of 900°C x 1 hr was finally selected.

4. Strength of two layer cylinder liner

The authors analyzed mechanical stress, thermal stress and life evaluation using UEC37LA engine (370 mm bore) as an example.

4.1 Conception of strength

Basic conception of two layer cylinder liner strength is as follows. Inside material which has running surface for piston ring require better tribological performance. Therefore authors selected conventional cast iron and the thickness of inner material is decided only by wear life. Outer material is considered as a strength member and material should have enough strength to endure for maximum combustion pressure.

Inside tangential stress of mono block cylinder liner is shown in following formula

$$\sigma_{1} = \frac{cE_1}{t_1} = \frac{PD}{2t_1}$$  \hspace{1cm} (1)

and the stress of two layer cylinder liner is as follows.

$$\sigma_{2} = \frac{P}{2t_2}$$  \hspace{1cm} (2)

where, \(P\); Maximum combustion pressure, \(D\); Cylinder bore, \(c\); Strain, \(E_1\); Young's modulus of cast iron; \(E_2\);
Young's modulus of outer material of two layer cylinder liner, $t_1$; Wall thickness of mono block cylinder liner, $t_3$; Outer material wall thickness of two layer cylinder liner. If we keep tangential stress at the same level, $O_{1g1} = O_{1g2}$

$$\varepsilon = \left[ \frac{1}{(2t_1E_1)} \right] = \left[ \frac{1}{(2t_3E_3)} \right]$$  \hspace{1cm} (3)

When applying cast steel for outer layer material $E_2$ is 20000 kgf/mm² can be used instead of $E_1 = 10000$ kgf/1mm² of cast iron. That means $E_2 = 2E_1$ and can be obtained the following formula.

$$2t_1E_1 = 2t_3(2E_1)$$  \hspace{1cm} (4)

And then

$$t_3 = \left( \frac{1}{2} \right) t_1$$  \hspace{1cm} (5)

This formula clearly shows that two layer cylinder liner can save the wall thickness of it by half.

### 4.2 Mechanical stress

Fig. 12 shows the results of calculated mechanical stress of UEC37LA engine. When keeping inside mechanical stress to the same level, in this case 3.6 kgf/mm², two-layer liner has the wall thickness of 43 mm instead of 75.5 mm of mono-block cast iron construction. If we apply two layer cylinder liner, we can obviously cut the wall thickness almost by half.

### 4.3 Thermal stress

Temperature difference between inside and out-side material causes thermal stress on cylinder liner which is shown in the calculation model of Fig. 13. Analyzed results show that thermal stress on the border area between two materials is in compression side. In case of two layer cylinder liner, it will be able to reduce the wall thickness which makes possible to apply a direct jacket cooling system and avoids a complicated cooling system like a conventionally widely used bore cooling system. This means an advantage of more preferable construction from the fatigue strength point of view.
Thermal stress $\sigma_{th}$ as shown in formula (6) basically depends on temperature differences between out-side and inside.

$$\sigma_{th} = \frac{(|E|\Delta T)}{(2(1-\nu))} \quad (6)$$

where, $E$: Young’s modulus, $\nu$: Cylinder bore, $\Delta T$; Coefficient of linear thermal expansion.

### 4.4 Fatigue life

Fig. 14 shows analyzed results of combined fatigue strength with mechanical stress and thermal stress. Required fatigue life for an average marine diesel engine will be around 10^4 cycle, calculating from 30 years life time of a ship and daily start and stop.

In case of two layer cylinder liner of UE C37LA engine the calculated combined fatigue life is, for both inner and outer layer, over 10^4 cycle, which shows good reliability. Furthermore the thermal stress of inner material (cast iron) is in compression which is more softy side. Judging from the stress level, even taking account of additional residual stress by HIP treatment, this liner seems to be quite practicable.

### 5. Engine tests

#### 5.1 NC45 test engine

The two layer test cylinder liner for 450 mm bore test engine which has wall thickness of 55 mm and length of 1265 mm was manufactured under the HIP condition of 900°C x 2 hr.

To check the quality of border area between inner and outer material super sonic test has been conducted. Also test piece has been taken off from the cylinder liner and checked tensile strength to confirm the quantity.

Fig. 15 shows the appearance of a conventional liner and the test two layer liner. It is very clear that the two layer liner is compact because of thin wall thick-ness. Fig. 16 shows the comparison of cross-section of the two liners. Table 2 shows the test condition of test engine.

While running the engine, working stresses and temperatures of the test cylinder liner were measured.

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The maximum working stress of cylinder liner at 1007o load condition was 4 kgf/mm² and this level is quite acceptable for production engine. Measured maximum temperature difference between outside and inside was 100 °C as expected by simulation. The temperature at piston ring running surface was also normal and all the tests were conducted under quite satisfactory condition. This test cylinder liner was installed to NC45 test engine and continuously used as standard cylinder liner of the test engine even after the series of HIP tests.

5.2 UEC33LS II engine

![Diagram showing stress analysis](image)

**Fig. 14 Analysis of low cycle fatigue**

Test results by NC45 test engine was successful. We had the confidence of the possibility to apply this cylinder liner for production engines. We have selected the latest UEC33LS II engine for the test.

Table 3 shows the principal particulars of this engine and Fig. 17 shows the cross-section of test cylinder liner. In this case only upper part of the cylinder liner where strength and tribological performance are really required was two-layered to minimize the production cost.

The temperature distribution and major stress of each parts has been measured and found as expected by calculation. Fig. 18 shows the calculated results of temperature distribution by FEM simulation. The endurance test is scheduled to be followed.

6. Conclusion

Authors has tried to develop practical two layer cylinder liner and conducted basic research and followed by engine test both on test engine and production engine. Test results show HIP cylinder liner will meet the future requirement for new engine and will be the practical solution. However this method still need to clear the manufacturing cost, size restrictions from HIP treatment system. We hope this will be solved in near future and want to bring HIP cylinder liner into commercial production.

![Image of cylinder liners](image)

**Fig. 15 Appearance of conventional cylinder liner and test cylinder liner**
Development of Two Layer Cylinder Liner by HIP Method

Fig. 16 Comparison of cylinder liner dimensions

Table 2

(1) Engine specification

<table>
<thead>
<tr>
<th>Item</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylinder liner</td>
<td>HIP two layer liner</td>
</tr>
<tr>
<td>Scavenging air port</td>
<td>Type C port (Port piece type)</td>
</tr>
<tr>
<td>FO &amp; Exhaust system</td>
<td>EFFEC (Electronically controlled)</td>
</tr>
<tr>
<td>Fuel injection valve</td>
<td>C51 (0.75 × 4)</td>
</tr>
<tr>
<td>Piston</td>
<td>NC45 standard</td>
</tr>
<tr>
<td>Cylinder cover</td>
<td>NC45 standard</td>
</tr>
</tbody>
</table>

(2) Running condition

<table>
<thead>
<tr>
<th>Item</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load setting</td>
<td>LA type engine</td>
</tr>
<tr>
<td>Fuel oil</td>
<td>Marine diesel oil</td>
</tr>
<tr>
<td>Cylinder lube oil</td>
<td>T 204</td>
</tr>
<tr>
<td>Cooling water temp.</td>
<td>T = 80°C at cyl. cover outlet</td>
</tr>
</tbody>
</table>

(3) Load setting

<table>
<thead>
<tr>
<th>Load</th>
<th>25</th>
<th>50</th>
<th>75</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine speed (rpm)</td>
<td>99.5</td>
<td>125.4</td>
<td>143.6</td>
<td>158.0</td>
</tr>
<tr>
<td>Output (PS)</td>
<td>274</td>
<td>595</td>
<td>921</td>
<td>1249</td>
</tr>
<tr>
<td>Mean press. (kg/cm²)</td>
<td>5.55</td>
<td>9.58</td>
<td>12.96</td>
<td>15.97</td>
</tr>
</tbody>
</table>

Table 3 Principal particulars of UEC33LS II

<table>
<thead>
<tr>
<th>Type of engine</th>
<th>UEC33LSII</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylinder bore</td>
<td>330 mm</td>
</tr>
<tr>
<td>Piston stroke</td>
<td>1,050 mm</td>
</tr>
<tr>
<td>Output at PI</td>
<td>733 PS/cyl (539 kW/cyl)</td>
</tr>
<tr>
<td>Engine speed at PI</td>
<td>210 rpm</td>
</tr>
<tr>
<td>Mean effective pressure</td>
<td>17.49 kgf/cm² (17.15 bar)</td>
</tr>
<tr>
<td>Mean piston speed</td>
<td>7.35 m/s</td>
</tr>
</tbody>
</table>

Fig. 17 Cross-section of HIP liner for UEC33LSII engine
Fig. 18  Simulation of temperature distribution of HIP cylinder liner by FEM